Seasonal Environmental Conditions Related to Tropical Cyclone Activity in the Northeast Pacific Basin

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Abstract

This thesis presents the first in-depth study on interannual tropical cyclone activity in the Northeast (NE) Pacific, using statistical methods to investigate tropical cyclone frequency and its relationship with seasonal environmental conditions from 1972 to 1997. An improved method of calculating wind shear is first presented. It is demonstrated that the NE Pacific has more than one population of tropical cyclones with regard to causal factors, and tropical cyclones in the two regions show large differences in trends with time and in their relationships with environmental variables. Large increasing trends are found in the western development region (10°N to 20°N, 116°W to 180°W), with no significant trends in the eastern development region (10°N to 20°N, < 116°W).

No significant relationships were found in the eastern development region between tropical cyclone frequency and any of the environmental variables tested, except outgoing long-wave radiation, implying that the main causal factor here is triggering disturbances and their variations. However, in the western development region, some highly significant relationships exist. Important local variables there include relative humidity (RH) and SST. El Niño Southern Oscillation (ENSO) is also a significant factor. The local relationships are probably largely due to the intensity-frequency effect and the spatial averaging of the variables, with threshold effects acting locally to provide conducive/non-conducive conditions in different parts of the region.

Physical influences on the most important of these variables (RH) are investigated. (The reverse influence, of hurricanes on RH, is shown to be negligible.) RH is shown to be significantly influenced, via the wind field, by ENSO and the intensity of the thermal low in North America. ENSO influences provide significant inverse relationships between tropical cyclone frequencies in the western development region and the North Atlantic.

Contents

Acknowledgements 3

Abstract 4

List of Figures 9

List of Tables 14

List of Acronyms 16

Chapter 1 Introduction 18

1.1 The need to study tropical cyclones 18

1.1.1 The landfalling problem and the insurance industry 18

1.1.2 The human effect 20

1.1.3 The NE Pacific as a study region 21

1.2 Tropical cyclones: definitions, life cycle and categories 25

1.3 The tropical atmosphere 29

1.4 Triggering disturbances necessary for tropical cyclone formation 34

1.4.1 Convergence from easterly waves 34

1.4.2 Other sources of convergence 38

1.4.3 Rotation due to convergence 38

1.5 Factors affecting tropical cyclone formation 40

1.5.1 Local factors 40

1.5.1.1 Gray's six factors giving the potential for tropical cyclone formation 40

1.5.1.2 Factors relating to dynamic potential 42

1.5.1.3 Factors relating to thermodynamic potential 45

1.5.1.4 Other local factors related to tropical cyclone formation 49

1.5.1.5 Accounting for the time of the hurricane season and location of hurricanes 51

1.5.2 Global scale 51

1.5.2.1 QBO 51

1.5.2.2 ENSO 52
1.5.3 Extra-terrestrial factors 54
1.5.4 Intraseasonal factors 55
1.6 Dissipation 55
1.7 Tropical cyclones in a warmer world 56
1.8 Summary of thesis' goals and structure 56

Chapter 2 The datasets, wind shear calculation and statistical analysis technique 59
2.1 The datasets 59
2.1.1 The tropical cyclone dataset 59
2.1.2 The datasets of environmental variables 64
2.1.3 Possible problems with the environmental datasets 68
2.2 A new method for the calculation of monthly averaged wind shear 70
2.3 Statistical analysis technique 81
2.4 Limitations of the statistical analysis technique 88

Chapter 3 Two development regions of the NE Pacific basin and trends in tropical cyclones 91
3.1 Characterising NE Pacific tropical cyclones 91
3.1.1 The population of tropical cyclones in the NE Pacific basin 91
3.1.2 The identification of more than one development region in the NE Pacific basin 95
3.1.3 The NE Pacific development regions compared to the development regions in other basins 102
3.2 Trends in tropical cyclone frequency 104
3.2.1 Trends analysis 104
3.2.2 Understanding the trends of tropical cyclone frequency 109
3.2.3 Possible new mechanism for relating variations in SST to variations in tropical cyclone frequency 118
3.3 Trends in formation locations, track, longevity and intensity 122
3.3.1 Formation locations 122
a) Trends
b) Influence of ENSO regime
3.3.2 Maximum intensity of hurricanes 125
a) Trends
b) Influence of ENSO regime

3.3.3 Track 127
3.3.3.1 Track length 128
a) Trends
b) Influence of ENSO regime
3.3.3.2 Maximum longitude west 129
3.3.4 Longevity 131
a) Trends
b) Influence of ENSO regime
3.4 Summary 133

Chapter 4 Relationships between the tropical cyclone indices and the environmental variables 137

4.1 Reliability of the NCEP/NCAR reanalysis data 137
4.2 Extreme year analysis 143
4.3 *t*-statistic analysis for all years 146
4.4 Deviance test 147
4.5 The Poisson distribution in relation to the best models 153
4.6 Correlations between NTC activity and the environmental variables, and between tropical cyclone days and the environmental variables 159
4.7 Discussion of the relationships discovered 162
4.7.1 Factors relating to thermodynamic potential 162
4.7.2 Factors relating to dynamic potential 182
4.7.3 Global-scale factors 183
4.7.3.1 ENSO 183
4.7.3.2 QBO 185
4.7.3.3 MJO 186
4.7.4 Other non-local influences on tropical cyclone numbers 187
4.7.4.1 Non-local influences on western development region hurricanes 187
4.7.4.2 Non-local influences on eastern development region hurricanes 195
4.7.5 Stability of the relationships from the best models 201
4.7.6 Factors affecting tropical cyclone frequency in the eastern development region 201
4.8 Summary 204

Chapter 5 Investigation into the dominant control of hurricane formation in the western development region of the NE Pacific **207**

5.1 RH - the dominant control on hurricane formation 207

5.1.1 RH vs. tropical cyclone numbers: cause or effect? 208

5.1.2 The relationship between RH and SST 210

5.2 Factors which affect interannual variability of RH in the western development region 211

5.2.1 ENSO's effect on RH in the western development region 211

5.2.2 Other influences on RH in the western development region 219

5.2.3 Understanding the link between the thermal low and RH in the western development region 228

5.2.4 Other links with the intensity of the thermal low 247

5.3 The cause of the interannual variations in the thermal low 248

5.4 Possible teleconnections between the North Atlantic and the NE Pacific 249

5.5 Summary 254

Chapter 6 Conclusions: summary and future work **256**

6.1 Summary of results and conclusions 256

6.2 Perceived weaknesses of thesis 261

6.3 Recommendations for further study 261

Appendix 1 Calculated NTC index for the western development region **264**

References **265**

List of Figures

Chapter 1

1.1 Natural catastrophes - global impact by event (1950-1999). **19**

1.2 Global tropical cyclone climatology: Frequency per unit area. **22**

1.3 Schematic represntation of the vertical structure of a mature hurricane. **26**

1.4 Average summer pressure (mean sea level) showing the sub-tropical highs in the NE Pacific and North Atlantic, and the thermal low in between splitting the high pressure zone, July-September, 1972-1997. **32**

1.5 Model of a typical easterly wave in the Caribbean area. **37**

1.6 Divergence aloft from a TUTT causing convergence at the surface and thus a trigger for the development of tropical cyclones. **39**

1.7 Structure of thesis. **58**

Chapter 2

2.1 5-year running means of average relative intensity for the NE Pacific tropical cyclones (1963-1993). **62**

2.2 Comparison between two methods of calculating $\overline{VZ}$. **72**

2.3 Differences in $\overline{VZ}$ ($m\ s^{-1}$) for all cells on the globe, Equation 2.3 – Equation 2.2 (July-September, 1972-1997). **74**

2.4 $\overline{VZ}$ in August-October 1995 using a) Equation 2.2, b) Equation 2.3. **76**

2.5 $\overline{VZ}$ anomalies for August-October 1995 using Equation 2.3 (climatology, 1979-1995). **77**

2.6 $\overline{VZ}$ anomalies for August-October 1995/ standard deviation of the $\overline{VZ}$ time series using a) Equation 2.2, b) Equation 2.3. **78**

2.7 $\overline{VZ}$ anomalies using Equation 2.3 for the months August-October for a) 1982, and b) 1994. Climatlogy (1979-1995). **79**

2.8 *t*-statistics showing the relationship between major Atlantic hurricanes and $\overline{VZ}$, August-October (1968-1992) using a) Equation 2.2, and b) Equation 2.3. **80**

2.9 *t*-statistics showing the relationship between major Atlantic hurricanes and $\overline{VZ}$, July-September (1968-1992) using Equation 2.3. **82**

2.10 Relationship (given with a *t*-statistic) between a randomly generated **89**

list of hurricane numbers and RH in July-September, 1972-1997 using Poisson regression.

Chapter 3

3.1 Location of NE Pacific hurricanes, 1972-1997. **92**

3.2 Longitudinal distribution of hurricanes per year, July-September, 1972-1997. **93**

3.3 Location of NE Pacific hurricanes in the a) 1983 season and b) 1994 season. **94**

3.4 The longitude distribution of all a) hurricanes (185), b) tropical storms (304), and c) intense hurricanes (92) for the period 1972-1997 (unshaded plots), and for approximately half the a) hurricanes (91, from the least active years), b) tropical storms (128, from the least active years), and c) intense hurricanes (47 from the least active years)(shaded plots). **96**

3.5 Percentage of hurricanes to the west of a longitude, July-September, 1972-1997. **97**

3.6 Western development region vs. eastern development region seasonal (July-September) tropical cyclone numbers, 1972-1997. **99**

3.7 Hurricane frequency per year vs. standard deviation of longitude, July-September, 1972-1997. **100**

3.8 Average hurricane frequency per year for each longitude on the globe for a) the Northern Hemisphere, and b) the Southern Hemisphere, (July-September) 1972-1997. **103**

3.9 Time series of seasonal tropical cyclone numbers, July-September, 1972-1997. **106**

3.10 Decadal scale variation in western development region tropical cyclone numbers (July-September). **108**

3.11 Time series of NTC for the western development region, July-September, 1972-1997. **110**

3.12 Time series of the environmental variables in the western development region, July-September, 1972-1997. **113**

3.13 Eastern development region SSTs and western development region SSTs, July-September, 1972-1997. **121**

3.14 The maximum intensity of the strongest storm for each year ($m\ s^{-1}$), July-September, 1972-1997. **126**

3.15 Tracks of storms, warm and cold ENSO years, July-September, 1972-1997. **130**

Chapter 4

4.1 Scatterplot of NCEP/NCAR's model derived ULWRF vs. NOAA's satellite OLR for a) the western development region, and b) the eastern development region. **139**

4.2 Scatterplot of NCEP/NCAR's SST vs. ECMWF's SST for a) the western development region, and b) the eastern development region. **140**

4.3 RH values in the western development region for July-September, 1979-1993 showing an offset between the NCEP/NCAR model values and the ECMWF model values. **141**

4.4 Checks that the Poisson assumption for the best models is correct. **155**

4.5 Relationship (given with a *t*-statistic) between western development region hurricane numbers and the environmental variables using Poisson regression. Time is not included in the model. **163**

4.6 Plot of the environmental variables averaged over July-September (averaged over latitudes 10°N to 20°N) vs. longitude for a) all years, b) western development region five most active and inactive hurricane years. **167**

4.7 Plot of VZ (850 hPa to 200 hPa) averaged over July-September and for latitudes 10°N to 20°N for each longitude for western development region hurricane active and inactive years. **170**

4.8 RH and SST (and land temperatures) in the five most active hurricane years (a and c) and five most inactive hurricane years (b and d). **172**

4.9 Environmental variable differences in July-September between the five most active and five least active hurricane years in the western development region. **174**

4.10 Plot of the OLR averaged over July-September and latitudes 10°N to 20°N for each longitude, for eastern development region a) five most active and least active hurricane years, b) five most active and least active tropical storm years, and c) five most active and least active intense hurricane years. **180**

4.11 Relationship (given with a *t*-statistic) between western development region hurricane numbers and the environmental variables using Poisson regression. Time is included in the model. **188**

4.12 Relationship (given with a *t*-statistic) between western development region hurricane numbers and RH using Poisson regression for July-September in a) strong ENSO Niño4 years (six least and most **192**

active years in 1972-1997) and b) non-strong ENSO Niño4 years (1972-1997).

4.13 Relationship (given with a *t*-statistic) between western development region hurricane numbers and PRES using Poisson regression for July-September in a) strong ENSO Niño4 years (six least and most active years in 1972-1997) and b) non-strong ENSO years (1972-1997). **193**

4.14 Relationship (given with a *t*-statistic) between western development region hurricane numbers and PRES using Poisson regression for July-September in a) strong MJO years (six least and most active years in 1972-1997) and b) non- strong MJO years (1972-1997). **194**

4.15 Relationship (given with a *t*-statistic) between eastern development region hurricane numbers and the environmental variables using Poisson regression for July-September, 1972-1997. Time is included in the model. **196**

4.16 13-year moving *t*-statistics from a Poisson regression of the relationships between a) hurricane numbers vs. RH, b) tropical storm numbers vs. RH, c) tropical storm numbers vs. VZ and PRES, and d) hurricane numbers vs. QBO. **202**

Chapter 5

5.1 Correlation between RH and SST (and land temperatures) locally, July-September, 1972-1997. **212**

5.2 SST (and land temperatures), RH and surface winds at 10 m in the six warmest ENSO (Niño4) years (a and c), and six coldest ENSO years (b and d). **214**

5.3 SSTs (and land temperatures) and surface winds at 10 m in the six coldest ENSO (Niño4) years minus the six warmest ENSO years. **217**

5.4 Multiple correlations using OLS regression with RH as the dependent variable and ENSO (Niño4) and a) SST (and land temperatures), b) VVEL, c) PRES, d) V wind at 10 m, e) U wind at 10 m and f) wind speed at 10 m, as the independent variables, (July-September) 1972-1997. **220**

5.5 Main hypothesis for the factors affecting RH. **223**

5.6 Climatology of pressure (mean sea level), July-September, 1972-1997. **224**

5.7 Climatology of pressure (mean sea level), July-September, a) 1995, b) 1991. **225**

5.8 Time plots of ENSO (Niño4), RH in the western development region, and pressure of the thermal low, (July-September), 1972-1997. **227**

5.9 Actual RH in the western development region vs. fitted values of RH in the western development region for July-September, 1972-1997 using a model with a) ENSO only, b) thermal low only, and c) ENSO and thermal low. **229**

5.10 Multiple correlations using OLS regression with a wind variable as the dependent variable and a) ENSO (Niño4), b) ENSO (Niño4) and the thermal low, as the independent variable(s), July-September, 1972-1997. **232**

5.11 Plot of RH and surface winds (10 m) in a) six deepest thermal low years, b) six shallowest thermal low years, and c) six deepest minus six shallowest thermal low years. **235**

5.12 Actual RH in the western development region vs. fitted values of RH in the western development region for July-September, 1958-1971 using a model with a) ENSO only, b) thermal low only, and c) ENSO and thermal low. **239**

5.13 Multiple correlations using OLS regression with a wind variable as the dependent variable and a) ENSO (Niño4), b) ENSO (Niño4) and the thermal low, as the independent variable(s), July-September, 1958-1971. **242**

5.14 Multiple correlations using OLS regression with RH as the dependent variable and ENSO (Niño4) and a) U wind at 10 m, b) V wind at 10 m and c) wind speed at 10 m, as the independent variables, (July-September) 1958-1971. **245**

5.15 RH (July-September) and VZ (August-October) in an active ENSO year, 1982 (b and d) and an inactive ENSO year, 1988 (a and c). **252**

Chapter 6

6.1 Summary of results. **257**

List of Tables

Chapter 2

2.1 Hurricane occurrence by month in the NE Pacific basin (1972-1997). **63**

2.2 Definition of SST-based ENSO indices. **66**

2.3 Test for the Poisson distribution - the index of dispersion. **84**

Chapter 3

3.1 Decadal scale trends in tropical cyclone frequency for the western development region. **107**

3.2 Differences in the position of tropical cyclone formation with time for the whole NE Pacific basin. **123**

3.3 Differences in the position of tropical cyclone formation with time for the western development region. **123**

3.4 Differences in the position of tropical cyclone formation between El Niño and La Niña conditions for the whole NE Pacific basin. **124**

3.5 Differences in the position of tropical cyclone formation between El Niño and La Niña conditions within the western development region. **124**

3.6 Differences in tropical cyclone track length (in degrees) between the earlier period (1972-1984) and the later period (1985-1997). **128**

3.7 Differences in tropical cyclone track length (in degrees) with ENSO regime. **128**

3.8 Mean maximum longitude west of all storms per year and the furthest western position (°W) of the storm that travelled furthest west per year (averaged for each time period and ENSO regime). **129**

3.9 Differences in tropical cyclone longevity with time. **131**

3.10 Correlation between ENSO and tropical cyclone longevity in the western development region for the years 1972-1997. **132**

Chapter 4

4.1 Verification of NCEP/NCAR reanalysis by a comparison with ECMWF reanalysis (1979-1993). **142**

4.2 Extreme year analysis. **144**

4.3 The ratio of the tropical cyclones in the six highest and six lowest extreme years of each environmental variable. **146**

4.4 *t*-statistics from a Poisson regression between tropical cyclone numbers and the environmental variables. **147**

4.5 The reduction in deviance between a null model and a more complex model, when the environmental variable is included. **149**

4.6 The percentage of variance explained by each model. **150**

4.7 The deviance statistic for each model with time included. **151**

4.8 The deviance statistic for each model (time not included). **152**

4.9 R^2 given for the relationship between a tropical cyclone index (NTC, IH days, H days, TS days, average IH days, average H days, average TS days) and the environmental variables. **160**

4.10 Tests for the use of the normal distribution for the NTC index. **161**

Chapter 5

5.1 The relationship from an ordinary least squares regression between RH and each variable or combination of variables. **226**

5.2 *t*-statistic of each Poisson regression of North Atlantic tropical cyclone numbers vs. the NE Pacific western (west) and eastern (east) development region tropical cyclone numbers. **250**

5.3 The adjusted R^2 and deviance from a model with VZ in the Atlantic as the dependent variable and ENSO and the thermal low as the independent variable(s). **251**

List of Acronyms

CDC	Climate Diagnostic Center
ECMWF	European Centre for Medium-Range Weather Forecasts
EPIC	East Pacific Investigation of Climate Processes in the Coupled Ocean Atmosphere System
GLMs	Generalised Linear Models
HRD	Hurricane Research Division
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-tropical convergence zone
JTWC	Joint Typhoon Warning Centre
MDR	Main Development Region
NAFTA	North American Fair Trade Agreement
NCEP/NCAR	National Center for Environmental Prediction/ National Center for Atmospheric Research
NHC	National Hurricane Center
NOAA	National Oceanographic and Atmospheric Administration
OLR	Out-going longwave radiation
OLS	Ordinary least squares regression
SO	Southern Oscillation
TEXMEX	Tropical Experiment in Mexico
TPC	Tropical Prediction Center
TUTT	Tropical Upper Tropospheric Trough
WMO	World Meteorological Organisation

Tropical cyclone indices:

TS	Tropical Storm
H	Hurricane
IH	Intense Hurricane
NTC	Net Tropical Cyclone activity

Environmental variables examined:

ENSO	El Niño Southern Oscillation
KW	Klaus Wolter's ENSO index
MJO	Madden Julian Oscillation
Niño1	SSTs in the region 5°S to 0°, 90°W to the South American coast
Niño2	SSTs in the region 10°S to 5°S, 90°W to the South American coast
Niño3	SSTs in the region 5°S to 5°N, 150°W to 90°W
Niño4	SSTs in the region 5°S to 5°N, 160°E to 150°W
PRES	Pressure at Mean Sea Level
PWAT	Precipitable Water
QBO	Quasi-Biennial Oscillation
RELV	Relative vorticity at 850 hPa
RH	Relative humidity at 500 hPa
SOI	Southern Oscillation Index
SST	Sea surface temperatures
TMP	Temperature at 300 hPa
TNI	Trans-Niño Index
U	East-west winds
ULWRF	Upward Longwave Radiation Flux
V	North-south winds
VVEL	Pressure vertical velocity at 500 hPa
VZ	Wind Shear between 850 and 200 hPa

Chapter 1

Introduction

1.1 The need to study tropical cyclones

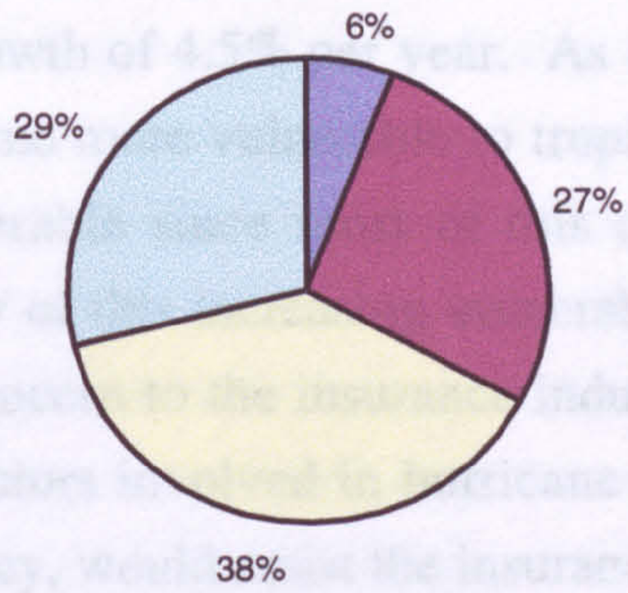
Tropical cyclones are nature's most destructive weather events and thus are important, not only financially, with hurricanes such as Andrew causing $US 38.4 billion of damage, but also in terms of loss of life, with cyclones such as that which occurred in 1970 in Bangladesh being responsible for 300,000 deaths. Therefore, although short-term forecasting of these events, through the use of the meteorological geostationary satellites, is already fairly well achievable, there is increasing interest in medium-term (several months) forecasting of tropical cyclone statistics (e.g. their frequency and intensity). Also, with increased concern over global warming, there is a demand to know how these statistics are changing. In the context of such research, an important requirement is a more detailed scientific understanding of the seasonal factors that cause tropical cyclones and give rise to variability in their frequency from year to year. Tropical cyclones are, in fact, one of the least understood topics of tropical meteorology. Even from a purely scientific point of view, as the most damaging weather events, they stimulate our curiosity as to what factors govern their properties (e.g. frequency, intensity, location and size).

This chapter sets the scene for the study described in this thesis, by exploring in more detail the need to study tropical cyclones, with particular emphasis on the NE Pacific basin. The tropical atmosphere is briefly described since its characteristics are strongly related to the factors that affect tropical cyclone formation. The convergence requirements and subsequent conditions which must be met for tropical cyclone formation to occur are then discussed in detail, before outlining the material to be presented in subsequent chapters.

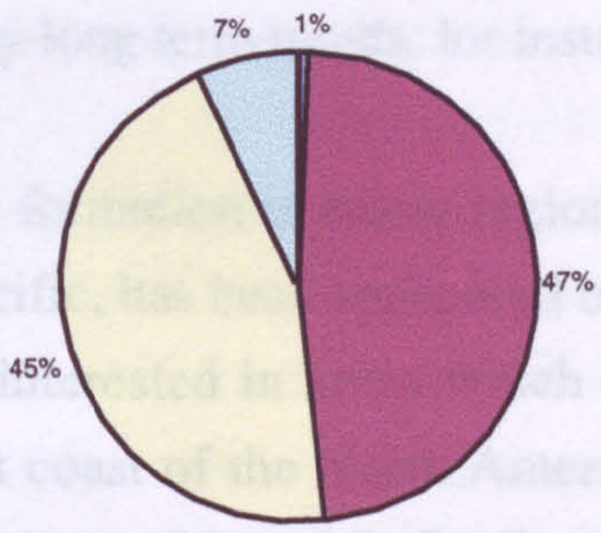
1.1.1 The landfalling problem and the insurance industry

Windstorms rank above floods and earthquakes in terms of the number of natural catastrophes they cause and in their global natural catastrophe insurance loss (see Figure 1.1). For the years 1950-1999, windstorms accounted for approximately two-thirds of global insurance losses - an average of approximately $US 2 billion per year. Tropical cyclones, in particular major (intense) tropical cyclones (with wind speeds of at least 50 m s^{-1}), are the dominant contributor to the windstorm insured loss causing over 83% of United States' losses (Pielke and Landsea, 1998). Much of this results from an increase in

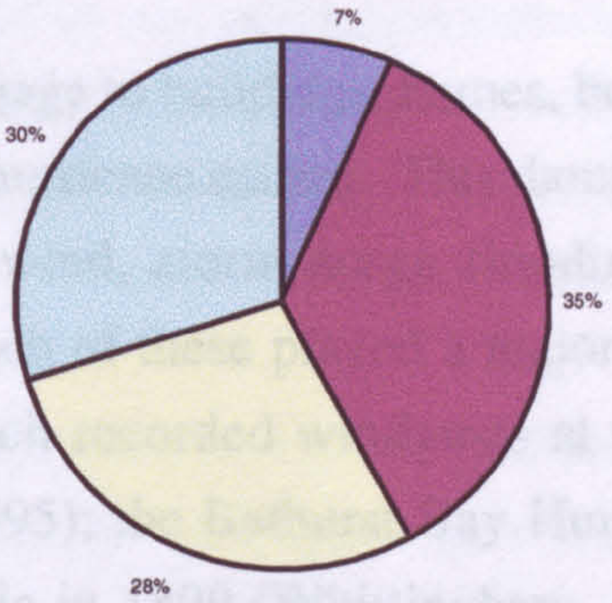
a) Number: 234



b) Fatalities: 1.4 million



c) Economic Losses: US $960 billion



d) Insured Losses: US $141 billion

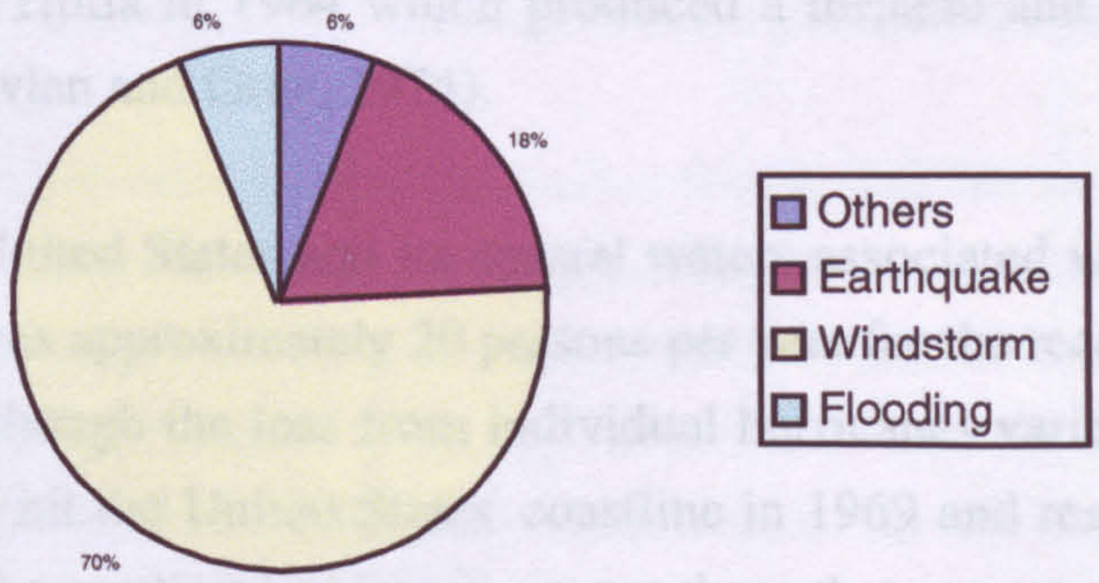


Figure 1.1 Natural catastrophes - global impact by event (1950-1999). Adapted from Munich Re. (2000).

population and industry along coastal regions, such as the coast of Texas to Miami, where there has been a population growth of 4.5% per year. As a consequence, eastern United States' coastal areas have become more vulnerable to tropical cyclones, and the insurers have also become more vulnerable since most of this coastal population can afford insurance. Particularly in view of this increasing vulnerability, the annual frequency of tropical cyclones is of great concern to the insurance industry, and research involving a detailed examination of the factors involved in hurricane formation, that would aid the prediction of hurricane frequency, would assist the insurance industry. A lead time on the order of at least three months, but preferably longer, is necessary to give the insurance industry sufficient time to react and make informed strategic decisions. Furthermore, the industry is very interested in any long term trends, for instance caused by global warming.

Research into tropical cyclone formation in many regions of the world, in particular the North Atlantic and the NW Pacific, has been sponsored by the insurance and re-insurance companies who are naturally interested in areas which have a high propensity towards insurance, particularly the east coast of the North American seaboard. Less attention is given by them to other areas of the world, mainly for financial reasons.

1.1.2 The human effect

Humans are affected by the damage to buildings, homes, businesses and structures, as well as injury and loss of life, that a hurricane causes. This damage resulting from the hurricane is due to four main sources: wind, storm surge flooding, rain-induced flooding and tornadoes. Examples where each of these played a major role in the destruction include Hurricane Andrew (1992) which recorded windgusts at the National Hurricane Center (NHC) of 138 mph (Pielke, 1995); the Bathurst Bay Hurricane which produced a 13 m surge in Bathurst Bay, Australia in 1899 (Whittingham, 1958); tropical cyclone Denise which caused flooding by precipitating 1144 mm in 12 hours at Foc-Foc, La Reunion Island, in 1966; and Hurricane Hilda in 1964 which produced a tornado and killed 22 people in Larose, Louisiana (Novlan and Gray, 1974).

Loss of life in the contiguous United States and its coastal waters associated with North Atlantic tropical cyclones averages approximately 20 persons per year for the recent period 1970-1999 (Rappaport, 2000), though the loss from individual hurricanes varies greatly. For instance, hurricane Camille hit the United States' coastline in 1969 and resulted in a death toll of over 200 people. The costliest hurricanes are not those that necessarily equate to largest loss of life. For example, hurricane Andrew (1992) caused over $US 30 billion in damages, but the resulting loss of life of 53 was relatively lower than the examples given.

These problems are perhaps exacerbated in developing countries whose population is less able to be evacuated or take other precautions, and may take a while to recover from a disaster due to economic circumstances, with many people suffering from uninsured losses. One such instance is the 1970 cyclone devastating Bangladesh and causing 300,000 deaths. This was largely a result of the storm surge and flooding of the low-lying flood plain. More recently, in 2000, Mozambique suffered relentlessly, when cyclone after cyclone headed in its direction and combined with the monsoon rains resulted in 700 deaths, with 2 million people being affected by the floods (Kriner, 2000).

1.1.3 The NE Pacific as a study region

The North Atlantic basin is probably the most widely studied with regard to tropical cyclones. As will be seen later, many environmental factors vary on an interannual time-scale and thus provide important information about tropical cyclone frequency. This seasonal analysis has resulted in fruitful work in the North Atlantic, thus this seasonal time-scale is also considered here for the NE Pacific basin. Research has already indicated some factors which may be important for understanding tropical cyclone formation. Many of these factors, however, are unique to the North Atlantic basin which prevents the research from being generalised to other basins. Differences in geography (such as land topography), oceanography (such as sea surface temperatures, SSTs) and climate (such as large-scale atmospheric flow patterns), means that the causes of tropical cyclones are likely to vary from basin to basin, with only some of the factors being important to all basins, and other factors being unique to the particular basin under study.

Neumann (1993) noted the importance of tropical cyclones in the NE Pacific in terms of their frequency. Figure 1.2 shows isolines which give the frequency of tropical cyclones per hundred years expected to pass within 139 km of any point. The point on the globe which has the highest frequency of tropical cyclones is in the NE Pacific at latitude 17°N and longitude 110°W, having a frequency of 295 tropical cyclones per hundred years.

The majority of hurricane researchers are based in the United States, and this may account for most hurricane work being focused on the United States, with the North Atlantic basin receiving the most attention. However, the NE Pacific basin is also of interest to the United States, not only because the tropical cyclones may hit the United States directly, i.e. Hawaii or California, but also because devastation in Mexico has implications for the United States being so close. Such negative consequences from a hurricane, such as poverty, or disease, may spread causing problems at the border. Not only are there indirect effects to the United States from a hurricane hitting Mexico, but since the North American Free Trade Agreement

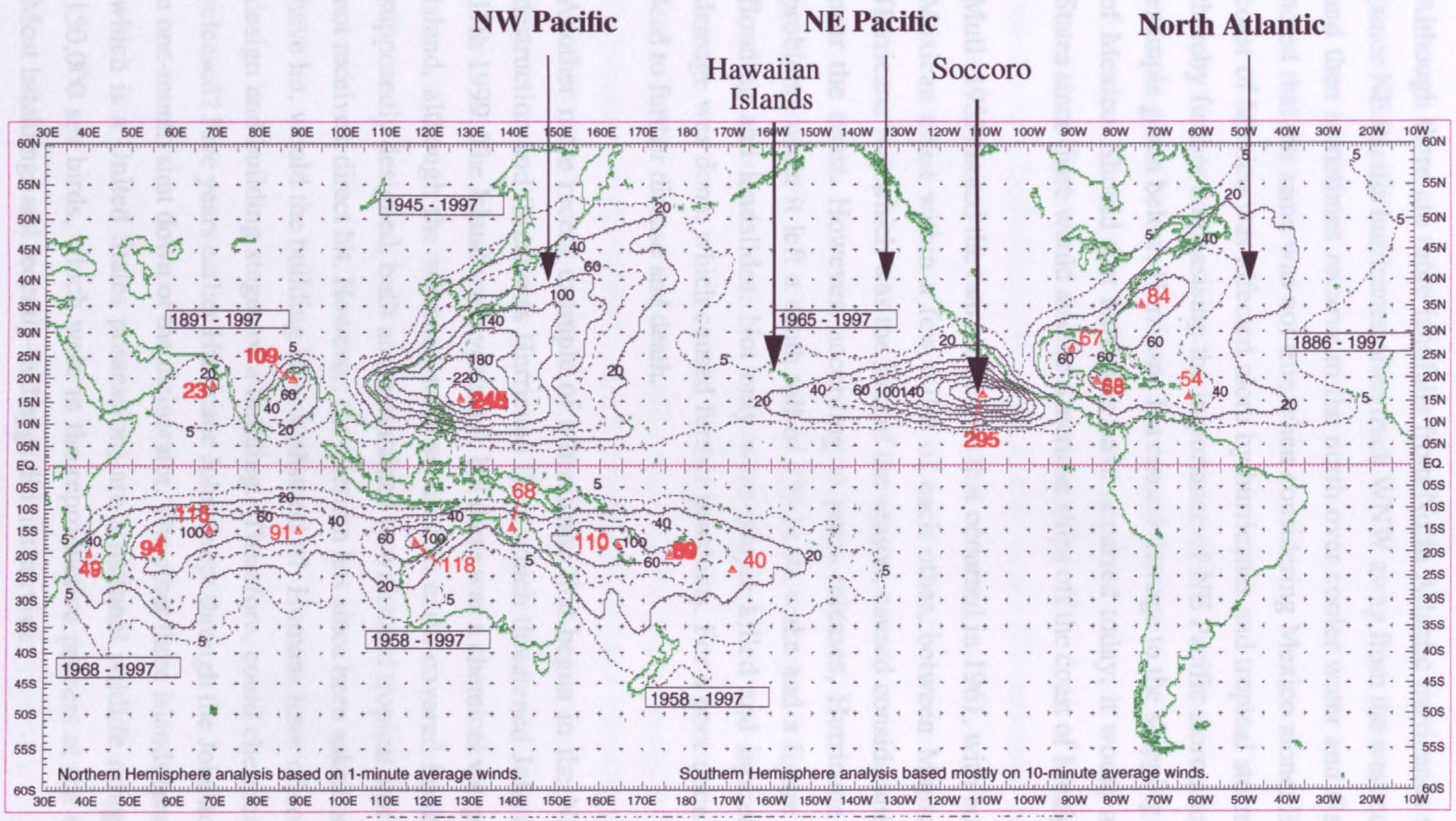


Figure 1.2 Global tropical cyclone climatology: Frequency per unit area. Isolines give number of tropical cyclones (excluding depression stage) per 100 years expected to pass within 75 nmi (139 km) from any point. Solid triangles give locations of significant maxima while values of these maxima are given by adjacent bold print. Periods of record, normalised to 100 years, are as shown. (After Neumann, 1993, updated 1998).

(NAFTA) has been set up, the United States has a direct interest in the economic well being of Mexico since many American businesses have located there.

Although there are more landfalls from North Atlantic hurricanes than NE Pacific ones (since NE Pacific hurricanes often track WNW away from the west coast of North America and then sometimes *recurve* to the north over cooler water and dissipate), Serra (1971) noted that the same was not true when considering Mexico alone. He noted that the west coast of Mexico was affected more by hurricanes and tropical storms than the east coast, thereby further emphasising the importance of NE Pacific storms to Mexico. In the 1961 example given below, Hurricane Iva caused damage to the shipping industry off the coast of Mexico. Should that hurricane have occurred today, it would also affect the United States since there would also be American ships off the coast of Mexico.

Mull (1962) noted the two hurricanes that occurred in 1961, with both of them hitting the Mexican coast within a few miles of each other, between Manzanillo and Acapulco. Hurricane Iva, which was the first of the season, caused considerable damage to shipping near the coast. However, according to press releases, Hurricane Tara caused greater problems when it left a death toll of 436 in its wake and a figure of 300 missing from flooding and landslides. Not only were people killed and injured, but environmental damage was done, which caused further problems. For a poor country, such events often lead to further disease and death.

Another more recent example of a hurricane that began in the NE Pacific and caused destruction and threat was Hurricane Dora which threatened Johnston Island on August 17th 1999. The Island was evacuated, but there was a chemical weapons incinerator on the island, although the weapons were secured in earth-covered bunkers. The facility was supposedly designed, built and maintained to withstand tropical storms, and the island did not receive a direct hit. However, the question has since been asked: should Hurricane Dora have hit, would the building have withstood it? Humans have often made mistakes at the design and building stages of a building. Therefore, could chemical weapons have been released? Five years earlier Hurricane John swept through the Johnston Island atoll, forcing a one-month shut down of the incinerator. The other three islands (part of a four-island atoll which is a United States possession) are a national wildlife refuge and home to about 150,000 sea birds, which were in the reproductive process at the time of the hurricane. Most hatchlings and recently-laid eggs did not survive.

A further impetus for researching this region was the unusually large number of intense

hurricanes in the hurricane season prior to when this work commenced (1997), the most prominent example being Hurricane Linda in October 1997 which is the most powerful hurricane in recorded history in the NE Pacific basin with one-minute average winds reaching 82 m s^{-1}. 1997 also saw several landfalling hurricanes, notably Hurricanes Pauline (one-minute wind speeds of 59 m s^{-1}) and Rick (one-minute wind speeds of 44 m s^{-1}) which hit Acapulco, and Hurricanes Nora (one-minute wind speeds of 59 m s^{-1}) and Linda which threatened San Diego.

Despite these reasons for studying the NE Pacific basin, in comparison to the North Atlantic, there has been relatively little research conducted into the factors affecting seasonal hurricane activity in the NE Pacific basin prior to the start of the current study. This is thought to be for the following reasons. Firstly, there is emphasis from insurance industries on landfalling hurricanes, mainly on the NE seaboard; secondly, as mentioned previously, most researchers are in the United States and may be somewhat nationally focused. There are many more landfalling hurricanes on the eastern rather than western seaboard of the United States and thus this naturally becomes the emphasis of their research. Lastly, and perhaps most importantly, results of the little research so far in the NE Pacific show little variation in tropical cyclone frequency with the environmental variables considered compared with that for the North Atlantic.

The research that has concentrated on the NE Pacific, generally focuses on genesis from disturbance to tropical depression rather than subsequent intensification to tropical storm, hurricane or intense hurricane strength. Gray (1979) provided a general discussion of the origin and development of tropical cyclones in this basin. Frank (1987) also gave a brief general discussion. Palmén (1956) also made general statements relating the importance of instability to hurricane formation. Previous work focusing on the seasonal time-scale in the NE Pacific includes that of Landsea and Gray (1989) who examined two environmental variables, the El Niño Southern Oscillation (ENSO) and the Quasi-Biennial Oscillation (QBO), to determine their relationship with a tropical cyclone frequency index for the whole basin. Through the use of a ratio, they compared the tropical cyclone index averages in the five strongest and weakest years of each variable. From their results showing a ratio of 1.6:1 hurricanes occurring in El Niño years compared to La Niña years, and a ratio of 2.36:1 intense hurricanes occurring in El Niño years to La Niña years, they concluded that there is a strong indication for increased tropical cyclone activity in El Niño years, especially for the strongest storms. They noted that there was a slight tendency for the QBO to act to modulate the numbers of the most intense tropical cyclones, with greater activity occurring in the westerly phase.

Landsea (2000) suggested that the western portion of the NE Pacific basin near Hawaii (140°W to the dateline) experiences more tropical cyclone genesis during an El Niño year. He noted that the remaining portion of the NE Pacific (the North Pacific Ocean from 140°W to the west coast of North America) appeared to have little ENSO-forced variations. However, with this definition of the eastern region of the NE Pacific, the differences with longitude east of 140°W are overlooked, a point which will be alluded to later in the study. Chu and Wang (1997) and Chu and Clark (1999) also examined part of the NE Pacific but only the region 140°W to 180°W. The work of Chu and Wang (1997) focuses on horizontal wind shear being a major factor to account for interannual variations of tropical cyclones in the central Pacific. Chu and Clark (1999) noted that more tropical cyclones occur near Hawaii in an El Niño than non El Niño year.

Recent concern about climate in the NE Pacific, which may have importance for tropical cyclone studies in the future, is shown through the East Pacific Investigation of Climate Processes in the Coupled Ocean Atmosphere System (EPIC) which is due to begin in late summer 2001 (Zehnder, 2001, personal communication). This is a project to make reconnaissance flights into the NE Pacific. This has been done for the Atlantic and now more research time is being given to the NE Pacific.

Despite some attempts to understand the climatology of tropical cyclones in the NE Pacific, as highlighted above, research has to date concentrated overwhelmingly on the Atlantic. However, due to the factors mentioned above (the frequency of tropical cyclones in this basin, the problems that landfalling tropical cyclones may cause and that there is relatively little research into this basin), it was decided to undertake a detailed study of this region for this thesis, concentrating on the seasonal factors influencing tropical cyclone frequency.

1.2 Tropical cyclones: definitions, life cycle and categories

'Tropical cyclone' is a generic term for a non-frontal synoptic scale low pressure system over tropical or sub-tropical waters with organised convection and definite cyclonic surface wind circulation (Holland, 1993). Tropical cyclones typically have a mean diameter of about 500 km. The structure of a tropical cyclone can be seen in Figure 1.3. As surface air spirals cyclonically towards the low pressure centre, the wind strength increases by conservation of angular momentum, and becomes a maximum at the eye wall, where the flow is tangential and approximately cyclostrophic. At the eye wall air rises and hence the deepest cumulonimbus and highest rainfall rates are found here. Outside the eye wall, clouds are arranged in spiral bands. At upper levels, near the tropopause, there is a central high pressure and the air either moves out from the centre of the tropical cyclone anti-

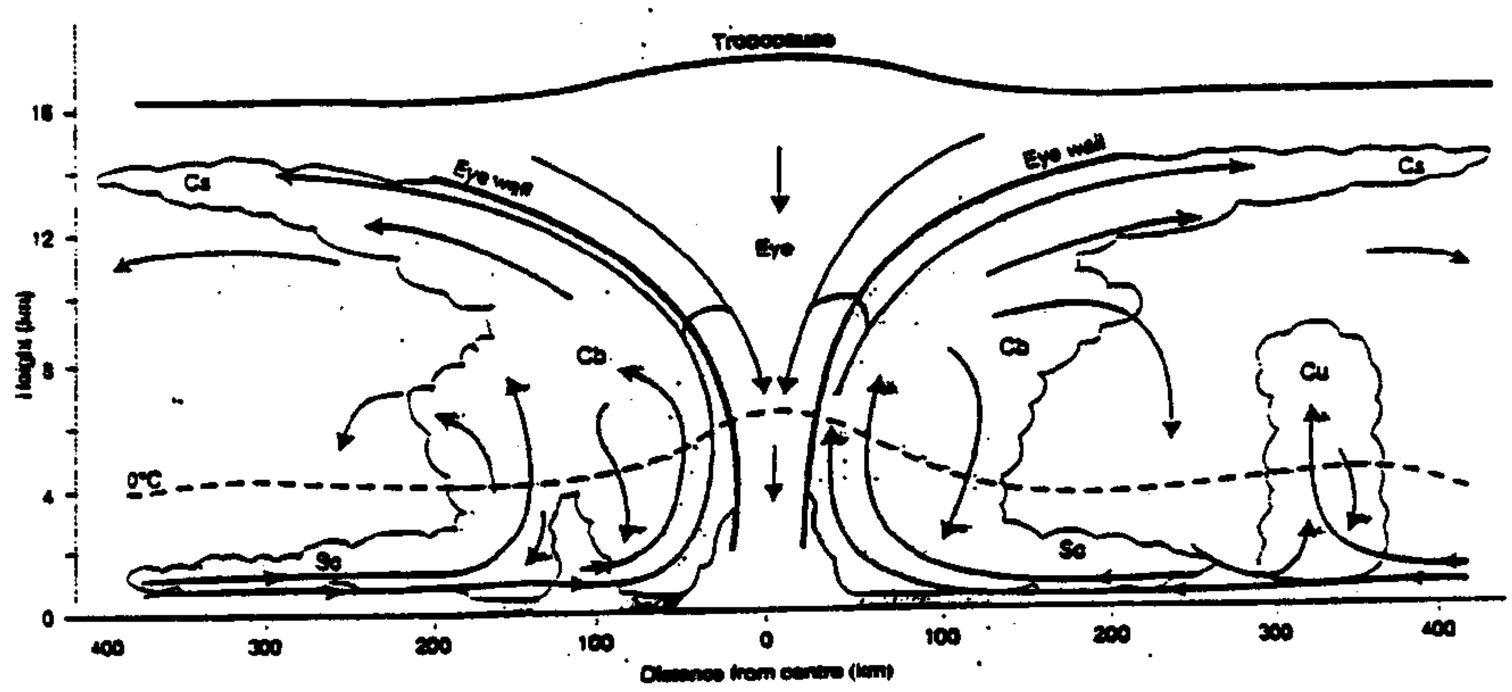


Figure 1.3 Schematic representation of the vertical structure of a mature hurricane (arrows representing airflows involved). Taken from Thompson (1998).

cyclonically, and eventually sinks towards the edges of the tropical cyclone, or descends in the central region of the tropical cyclone, known as the 'eye'. The eye has a diameter on the order of some tens of kilometres, with light winds, lightly clouded to clear sky, and light to no rain.

Tropical cyclones are formed from tropical disturbances (see Section 1.4 for more detail), which are necessary before the tropical cyclone can grow. They provide a pre-existing low pressure, with convergence at the surface, cumulonimbus production and rotation. It is now recognised that the growth and maintenance of a tropical cyclone depends on the existence of mechanisms which create a 'warm core' at its centre (e.g. Emanuel, 1988). A warm core structure is not characteristic of tropical disturbances generally and acquisition of a warm core is fundamental if intensification of a disturbance is to take place. There are thought to be several mechanisms for the production of the warm core, as compared to conditions outside the tropical cyclone. Firstly, as the strong winds increase towards the centre of the tropical cyclone they produce increased evaporation of moisture from the ocean such that the air becomes closer to saturation near sea level. This means that as the air rises in the eye wall it follows the moist adiabatic lapse rate at lower levels, and the extra latent heat release warms the column (Emanuel, 1988). Secondly, as the air travels towards the central low pressure region there is isothermal expansion involving sensible, latent and dissipative heating. (Without this heat being added it would be expected that there would be adiabatic cooling due to the expansion.) This means that rising air in the eye wall is warmer at all levels than it would be outside the hurricane (Emanuel, 1988; Bister and Emanuel, 1998; McIlveen, 1992). Thirdly, within the eye, centrifugal outward movement of air causes subsidence of dry air which warms by adiabatic compression (Emanuel, 1988).

Due to the development of a warm core, divergence occurs at upper levels as the warming causes expansion of the column and produces high pressure and an outward pressure gradient at upper levels. This in turn results in a positive feedback mechanism where the system deepens as the surface pressure further reduces, providing that the upper air divergence exceeds the surface convergence. With a deepened surface low, the effect of isothermal expansion on the warm core is increased. Also, the resulting increase in surface pressure gradient force increases surface wind speeds. These stronger winds cause increases in all the methods of warm core heating described above. This results in a positive feedback where the increased warming causes more upper divergence, lower surface pressure etc., so that a mature hurricane develops.

This intensification can only occur up to a certain limit which is called the 'maximum potential intensity' (MPI, calculated as the minimum possible pressure). The MPI is different for each hurricane and depends on the given set of environmental conditions (Emanuel, 1986, 1988, 1991; Holland, 1997). Thermodynamic models show considerable skill in predicting the MPI, and the models show a particularly strong dependence of MPI on sea surface temperature, which agrees reasonably well with observations (Tonkin et al., 2000). Other relevant variables are the mean temperature near the tropopause where the heat is lost from the clouds, and the near surface ambient relative humidity for the region where the tropical cyclone develops, showing how close the air is to saturation (Emanuel, 1988). However, it has been observed that hurricanes do not generally reach their MPI. It is thought that the main limiting factors for this are vertical wind shear, hurricanes travelling over a cooler surface or land and storm-induced ocean surface cooling by mixing cooler water from below, as shown by studies which have modelled the intensification process (Emanuel, 1999; Bender and Ginis, 2000).

The terms 'hurricane' and 'typhoon' are regionally specific names for a strong tropical cyclone, where the former term is used in relation to the North Atlantic Ocean, the NE Pacific Ocean east of the dateline and the South Pacific Ocean east of 160°E, and the latter term used to describe this system in the NW Pacific Ocean west of the dateline. Other terms with similar meaning have been coined in other areas such as 'severe tropical cyclone' in the SW Pacific Ocean west of 160°E or in the SE Indian Ocean east of 90°E; 'severe cyclonic storm' in the North Indian Ocean and 'tropical cyclone' in the SW Indian Ocean. This latter term is particularly confusing as it conflicts with the generic term 'tropical cyclone' as defined above which may be used to describe a storm of a lower strength than that intended by the use of the term in the SW Indian Ocean.

There are various stages in the development of a tropical cyclone before reaching hurricane status and these can also be expressed in terms of the wind speed. The World Meteorological Organisation (WMO) expresses wind speeds over a ten-minute period. However, the WMO classification is not universally adopted. Indeed, the National Hurricane Center (NHC) and Joint Typhoon Warning Center (JTWC) of the USA use a one-minute averaging period to obtain sustained winds. Since this thesis is largely dealing with the NE Pacific and the North Atlantic basins, sustained wind speeds will therefore be expressed herein by the one-minute average. Surface wind gusts may be 30-50% higher than this sustained wind speed. A sub-division of the hurricane force systems has regional problems, one example being that typhoons of the NW Pacific are notably more intense than their equivalents in other basins.

The weakest classification for tropical cyclones is 'tropical depression' which has maximum sustained surface (at a height of 33 ft or 10 m) winds over a one-minute average of greater than 11 m s^{-1} (22 knots) but less than 17 m s^{-1} (34 knots). This may develop into a 'tropical storm' if wind speeds reach 17 m s^{-1}. At this stage a name would be assigned to the system. Another classification is made at 33 m s^{-1} (64 knots) when the term 'hurricane' or 'typhoon' is used. A further distinction is made between a hurricane and an 'intense (or major) hurricane' when 50 m s^{-1} (97 knots) is achieved. This may also be described as a major hurricane of category 3 or above, according to the Saffir-Simpson scale which describes hurricane wind speeds (Landsea, 1993; Elsner and Kara, 1999). It must be noted that it is thought that such definitions are quite arbitrary (although recent work by Emanuel (2000) showed that there is, in fact, a change of slope in the cumulative distribution function of storm lifetime maximum wind speed (above tropical storm strength) near the transition from tropical storm to hurricane category suggesting that, for the hurricane category only, the definition may have more meaning). Furthermore, classification of storms is often inaccurate since most of the intensity wind values at the surface are an estimation from satellite pictures or an extrapolation from aircraft reconnaissance, downward to the surface. Intensity also refers to the minimum sea level pressure measured.

It is important to distinguish the terms genesis and intensification. This issue has been clarified by Frank (1987) and Molinari et al. (2000) who noted that genesis describes the process whereby a tropical disturbance becomes a tropical depression (i.e. the weakest category of a tropical cyclone), whereas intensification describes subsequent development to tropical storm, hurricane or intense hurricane stage. The word 'formation', also used in the current study, describes intensification to the category examined, e.g. hurricane formation means that a tropical storm undergoes intensification and becomes a hurricane. 'Tropical cyclone formation' is therefore used generically to mean the formation of any or all of the tropical cyclone categories described above.

1.3 The tropical atmosphere

The 'meteorological' tropics are generally taken to be bounded by the axes of the surface sub-tropical high pressure belts of the two hemispheres, centred on average near 30° to 35° in both hemispheres. Delineation of the tropics is thus based on synoptic grounds with the tropics defined as forming a region where, for the most part, the weather is determined by circulation features and weather systems that differ from those that characterise the weather of middle and high latitudes. However, the tropics and the extra-tropics should not be treated in isolation as the two interact. In particular, equatorial/meridional extensions of the

trough in the upper westerlies of higher latitudes can have a major impact on the weather and the behaviour of weather systems in the deep tropics, as will be described in more detail in Section 1.4.

The basic features of the tropical atmosphere and its circulation are described in most meteorological text books and may be summarised as follows, with particular reference to the NE Pacific in the summer months. The air flow in the atmosphere is determined by temperature and pressure. A basic Hadley cell circulation arises due to the equatorial regions receiving more of the sun's energy than the higher latitudes as a consequence of the curvature and orientation of the Earth. This results in north-south temperature gradients and an air circulation cell. The warm air near the equator rises by convection and by convergence of surface winds (see below). After reaching the tropopause which acts as a barrier to vertical ascent and causes the air to be transported laterally, the air travels poleward in the upper troposphere. The Coriolis force deflects this poleward flow to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, producing westerly winds aloft in both hemispheres. When air moves towards the sub-tropics, it cools by radiation and subsides in the sub-tropical high pressure regions. The subsidence causes a subsidence inversion at a few km altitude. Where this occurs in the region of the trade winds (see below) it is known as the 'trade wind inversion'. The reason for the existence of the sub-tropical highs is not very well understood. From this region, some of the surface air moves back towards near the equator, which is at a lower pressure, being situated between the sub-tropical highs of the two hemispheres. This surface flow again is deflected by the Coriolis force, and balanced by friction, causing it to blow from the northeast in the Northern Hemisphere and the southeast in the Southern Hemisphere (the so-called 'trade winds'). Near the equator the northeast trades converge with the southeast trades along a boundary referred to as the inter-tropical convergence zone (ITCZ). In this region of surface convergence, air rises and the cellular circulation continues.

This Hadley cell circulation, described above, is complicated by several factors, the most important of which are described below. Firstly, as well as the general meridional circulation of the Hadley cell, there is also a zonal circulation, which is centred along the equator and is known as the Walker circulation. Normally, the Pacific is characterised by rising air in the western Pacific and subsiding air in the eastern Pacific off the coast of South America. However, there are pressure variations across the equatorial Pacific, known as the Southern Oscillation (SO), which are linked to sea surface temperature variations. The coupled atmospheric-oceanic phenomena is known as El Niño Southern Oscillation (ENSO) and oscillates on a scale of a few years. When the SO is large and

positive, atmospheric pressure in the eastern Pacific is well above normal (in the western Pacific the atmospheric pressure is well below normal), and the Walker circulation gains in intensity. Therefore more subsidence occurs in the eastern Pacific. However, when the SO is large and negative, the atmospheric pressure in the eastern Pacific is well below normal and the Walker circulation reduces in intensity (McGregor and Nieuwolt, 1998). The effects of changes in this circulation are felt even in remote regions, and occur through a series of complex teleconnections. The effects on the Hadley cell are often seen through a strengthening of it in some regions and a weakening of it in other regions. During a large and negative SO phase, when the warm pool of water in the western Pacific spreads east (also known as an El Niño phase), there is strengthening of the local Hadley cell over the central Pacific, and it is thought that there is a weakening of the Hadley cell in the North Atlantic. The opposite is seen in a large and positive SO or La Niña phase. This effect is discussed in more detail in relation to tropical cyclones in Section 1.5.2.2.

Secondly, the Hadley cell in the summer is also disrupted by the seasonal heating of the large land masses which creates surface pressure reversals. A surface 'thermal low' is produced as the air column is heated by the warm surface and expands, causing a local high pressure aloft, with consequent air loss from the column. This disrupts the trades of the summer hemisphere. This explains why the sub-tropical highs are not continuous belts, but are located over the oceans and divided by a low pressure region in the summer months (see Figure 1.4).

It is these non-continuous sub-tropical highs that determine the broadscale circulation of the trade wind systems. These highs affect where winds on either side of the ITCZ will cease converging and where they will start to flow parallel to each other and then later diverge from the axis of the trough. This will tend to occur in longitudes corresponding to the western peripheries of the respective highs. Parallel or divergent flow on both sides of the trough occurs when the sub-tropical oceanic highs on either side of the trough are of similar intensity and are centred at much the same longitude. Central surface pressure in the trade wind trough does not vary very much so changes in the intensities of the oceanic highs and land thermal lows will determine, in broad terms, changes of speed of the trade wind flow.

Strengthening of the trades arising from intensification of the sub-tropical oceanic highs mostly takes place in the form of surges emanating from their eastern equatorial quadrants. The surges, with weaker flow ahead of them, will be accompanied by convergence along their leading edges resulting in convective cloud along the surge front. Initially the convergence arises from speed convergence. But, during its equatorward movement, the

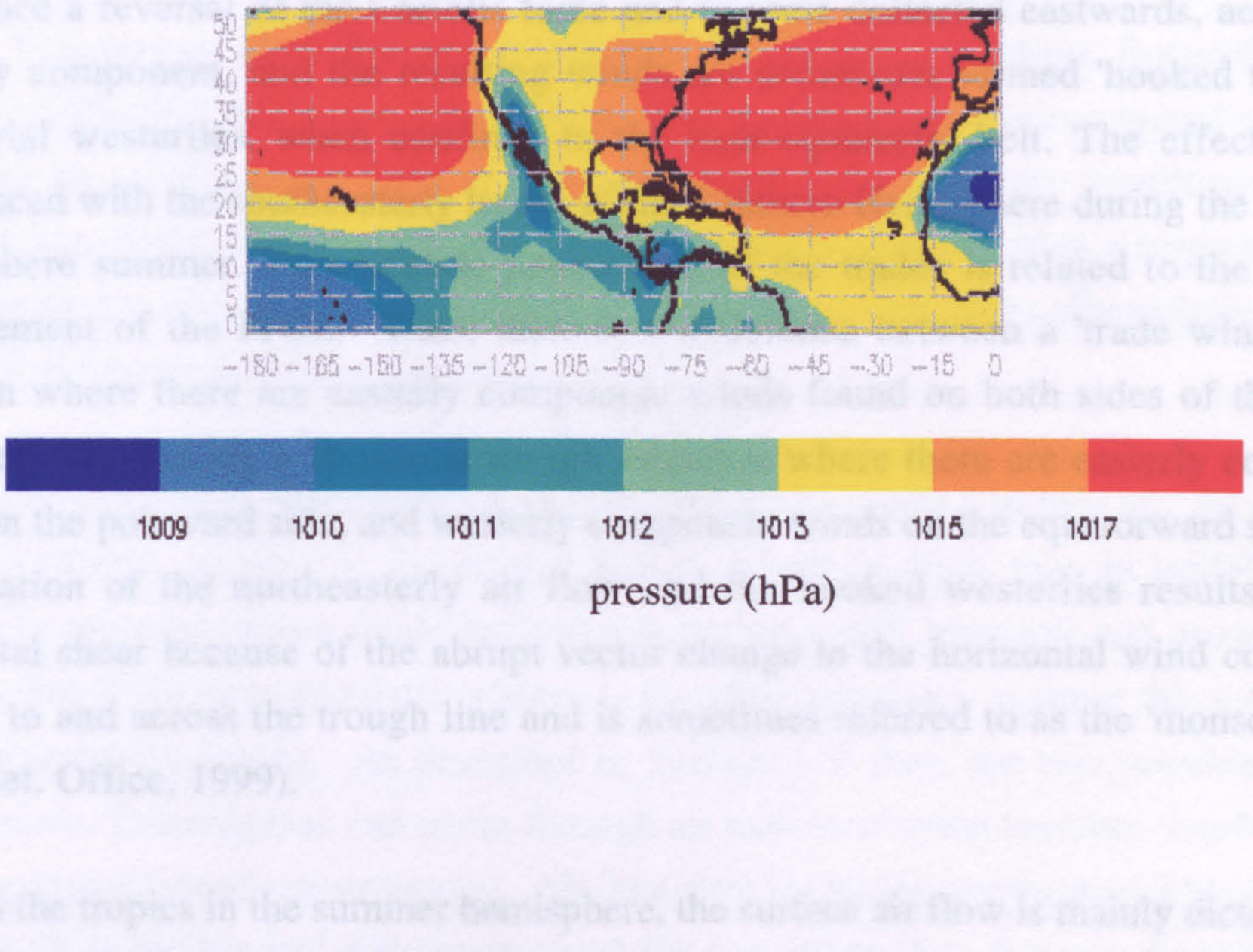


Figure 1.4 Average summer pressure (mean sea level) showing the sub-tropical highs in the NE Pacific and North Atlantic, and the thermal low in between splitting the high pressure zone, July-September, 1972-1997.

surge becomes oriented roughly east-west and the convergence at this time arises primarily from shear considerations.

The trades of the winter hemisphere are able to cross the equator where they subsequently experience a reversal of the Coriolis force and become deflected eastwards, acquiring a westerly component, and the resulting winds are sometimes termed 'hooked trades' or 'equatorial westerlies' when confined to the near-equatorial belt. The effect is most pronounced with the southeasterly trades of the Southern Hemisphere during the Northern Hemisphere summer. This latitude penetration of the trades is related to the seasonal displacement of the ITCZ. Thus, there is a difference between a 'trade wind trough' situation where there are easterly component winds found on both sides of the trough compared with having a 'monsoon trough' situation where there are easterly component winds on the poleward side, and westerly component winds on the equatorward side. The combination of the northeasterly air flow and the hooked westerlies results in large horizontal shear because of the abrupt vector change in the horizontal wind component parallel to and across the trough line and is sometimes referred to as the 'monsoon shear line' (Met. Office, 1999).

Thus, in the tropics in the summer hemisphere, the surface air flow is mainly dictated by a) the Hadley and Walker circulations; b) the sub-tropical ocean highs which cause air to flow out of this area; c) the continental thermal lows; and d) the near equatorial trough (also known as the ITCZ, the trade wind trough or monsoon trough). In the tropics, the horizontal gradients of temperature and pressure are generally weak in comparison to their temperate counterparts and airflow is thus barotropic, and involves an air mass whose physical properties, especially temperature, moisture content and lapse rate, are more or less uniform horizontally for hundreds of kilometres. As the relatively cool surface air leaves the sub-tropical high and moves towards the equator it gains more heat and moisture and becomes progressively more unstable to convection. Although the tropical atmosphere is generally unstable, particularly in the low levels, it does usually require surface convergence to initiate convective activity.

With converging flow, convective activity in the trade wind trough will depend on the angles at which the trades converge into the trough, i.e. the degree of confluence, and the deceleration that accompanies them. If wind speeds decrease downstream, there will be speed convergence which will reinforce the streamline convergence. If wind speeds increase downstream there will be speed divergence. This will at least partially offset the streamline convergence and may even result in net divergence. With a monsoon trough,

maximum confluence occurs along the axis where the westerlies on the equatorward side meet the easterlies on the poleward side of the trough. However, although there is extensive convection here, maximum convective activity occurs in the westerly flow (Met. Office, 1995).

1.4 Triggering disturbances necessary for tropical cyclone formation

Challa and Pfeffer (1990) noted that whilst there are necessary environmental conditions that must be satisfied (see Section 1.5) and whilst most necessary conditions may be satisfied, it is critical to have some external forcing mechanism to initiate a tropical cyclone. It is important to consider these triggering disturbances as well as the climatological factors necessary for tropical cyclone formation.

The triggering tropical disturbances have converging and rotating surface air. According to Emanuel (1991), rotation is the crucial factor, where he finds that an initial 'kick' of rotation is required before modelled tropical cyclones will intensify and grow. Surface convergence within a tropical disturbance is therefore necessary to cause this rotation and start the tropical cyclone. As described in Section 1.3, there are two possible types of convergence. Convergence can occur through air masses flowing together (confluence) or changing speed (speed convergence). Air then rises by forced convection. There may also be rising air in the tropical disturbance from the free convection, but it is the convergence which reinforces the rising of the air and also promotes rotation. The tendency towards rotation is then caused by the convergence, due to the conservation of angular momentum.

1.4.1 Convergence from easterly waves

There are several disturbances in the trade wind flow that result in convergence, easterly waves being the primary one. Easterly waves mainly have their origin over Africa. An easterly wind speed maximum is found near the 700 hPa level, resulting from the strong thermal gradient generated by the hot desert air to the north compared to the cooler rainbelt of the south, and it is this jet type feature which provides the essential dynamical ingredient for the formation and maintenance of the easterly waves.

Easterly waves are primarily a feature of the Northern Hemisphere in the summer months. It is debatable as to whether Southern Hemisphere easterly waves occur. Easterly waves were first recognised in the Caribbean region and it was from the general structure and behaviour of these waves that the classical model of the easterly wave was developed. Indeed, the frequency of occurrence is greater in the Atlantic and Caribbean than in the Pacific.

Many North Atlantic hurricanes, in particular, can be traced to convergence from easterly waves that form off Africa. In the east, over Africa, the depth of the easterly flow is deep and there is a lot of moisture. Further west over the Atlantic and in the Caribbean it is more variable. Being more variable, this will affect the intensity and number of waves reaching or affecting the region to the west. In the North Atlantic, in the years where there is a strong westerly upper air component, this leads to a much lower incidence of active easterly waves compared to normal.

The origin of easterly waves in the NE Pacific is not clearly understood. Murakami et al. (1984) showed V component time series (i.e. the meridional wind direction) that seemed to indicate that at 850 hPa, waves from Africa could be followed all the way to the western Pacific. They argued that this would seem likely when there is an El Niño or at least during years when the off-equatorial waters are warmer, thus allowing convection to be maintained. Avila (1991) also noted that it is thought that a large number of waves in the NE Pacific are of Atlantic/African origin, which pass the Caribbean sea, traversing the isthmus of Central America to generate tropical cyclones in the NE Pacific.

However, other research has contradicted these African origin theories and have sought for a more local explanation. Tai and Ogura (1987) demonstrated that the variability in the wind field in the NE Pacific was only weakly correlated with activity near west Africa and suggested that disturbances were generated locally near the west coast of Mexico. Such sources of initial disturbances may include the breakdown of the ITCZ or the propagation of mesoscale convective systems, which form over inland Mexico and propagate into the Pacific.

Molinari et al. (1997, 2000) later showed that there is a potential easterly wave breeding ground in the NE Pacific. Over the NE Pacific, easterly waves are largely confined to the eastern part of the ocean. Molinari et al. (1997) suggested that localised easterly waves might not hold together over a long stretch of cool water without further convection. They claimed that the waves that form off Africa therefore may not make it across the North Atlantic. In a detailed analysis they identify two regions, one in the Caribbean and a smaller region in the NE Pacific where there is a change of sign in the potential vorticity compared to that in the immediate northern and southern latitudes, and this may initiate easterly waves to form in these areas; or in the case of the Caribbean, where a tropical wave has weakened from traversing over a cool ocean in the North Atlantic, it may help the wave to re-intensify. Since the NE Pacific gets colder west of 120°W, again the waves would have to

make it through that region without help from convection, and again may weaken or lose their structure before reaching the central Pacific. This would suggest that hurricanes may not be able to form from easterly waves after they have lost their form, i.e. west of approximately 120°W. However, they may still form from a cold upper level trough or monsoon trough (see below).

The most important effect of easterly waves is that convergence in the system causes a break in the trade wind inversion. Within the trade wind inversion a stable environment exists. However, convergence, heat and moisture may create an unstable environment, and a breach of the inversion. In the neighbourhood of such a break, moist air can ascend rapidly leading to the formation of extensive masses of convective cloud.

These easterly waves set up the initial organisation that is required for hurricanes to form (see Figure 1.5). As can be seen in Figure 1.5, on the easterly side of the trough of low pressure, southeasterly winds converge. This can be explained by the potential vorticity (PV) equation where

$$PV = \frac{f + \zeta}{\Delta p} \tag{1.1}$$

where f = the Coriolis parameter, ζ = relative vorticity (cyclonic positive) and Δp = the depth of the tropospheric air column.

As the air flows around the trough it steers poleward, thus the Coriolis parameter increases. As the air flows around the trough, it also picks up cyclonic curvature, thus relative vorticity increases. For the expression to remain constant, if the parameters in the numerator increase, then the parameter in the denominator, Δp, must also increase. Thus the air column must expand vertically. This vertical expansion necessitates horizontal contraction, i.e. convergence.

In the main, easterly waves are a steady-state system with only a very small proportion of them intensifying into something stronger, such as a tropical storm. On average these waves form approximately every three days, but only a small fraction of these develop into hurricanes. During the warmer months in the North Atlantic, at least one westward disturbance is present every day, but an average of only 8 disturbances per year become tropical storms, and about 60% of these achieve hurricane strength (Palmén and Newton, 1969). Thus only a very small proportion of disturbances develop into tropical storms, but

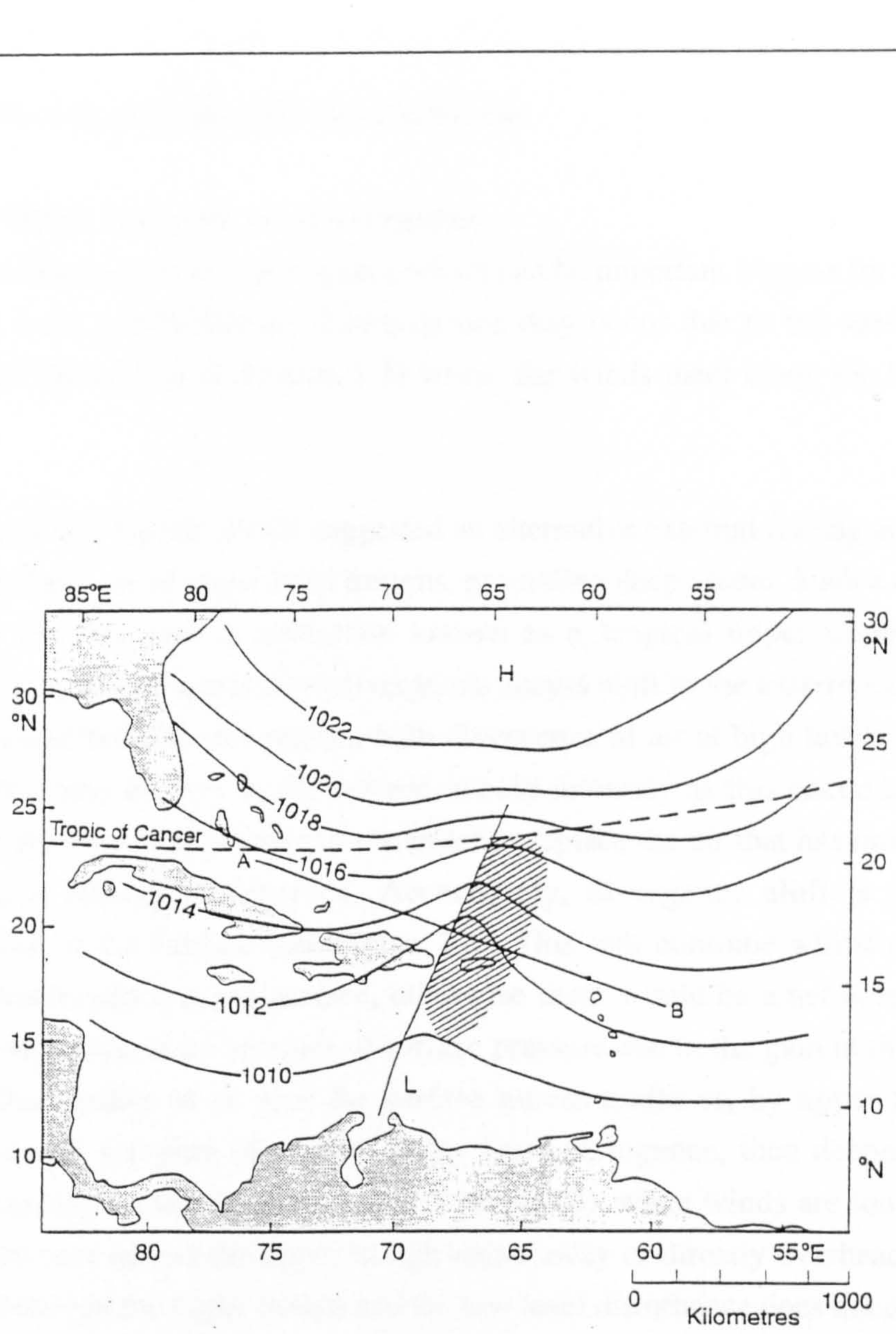


Figure 1.5 Model of a typical easterly wave in the Caribbean area. Hatched areas indicate region of convergence (after McGregor and Nieuwolt, 1998).

those that do will often intensify into a hurricane.

1.4.2 Other sources of convergence

There are other sources of convergence which can be important triggers for tropical cyclone formation from a disturbance. Convergence may occur due to the surface flow in the Hadley cell (described in Section 1.3) where the winds meet along the boundary of the ITCZ.

Montgomery and Farrell (1993) suggested an alternative external forcing agent, upper level support, in the form of upper level troughs, promoting deep ascent. Such a cold upper-level trough of low pressure is otherwise known as a 'tropical upper tropospheric trough' (TUTT). A region of upper level divergence occurs aloft to the eastern side of the trough. A low situated beneath this region, with divergence of air at high levels greater than the convergence into the low at the surface, would intensify as this encourages the upward motion of air from beneath to occur in order to replace the air that has moved on from the upper space through divergence. Accordingly, divergence aloft is associated with convergence at the surface (see Figure 1.6). This will continue whilst divergence aloft exceeds convergence at the surface, otherwise there would be a net accumulation of air which would result in an increase of surface pressure due to the gain in the mass. If a pre-existing disturbance at or near the surface moves under or, by upper level advection, becomes under a region of marked upper level divergence, then deepening can occur. Thus, according to Montgomery and Farrell (1993), when winds are too strong at upper levels, they may advect the upper trough either away or directly overhead so that vertical coupling between the upper trough and the low level disturbance does not occur.

1.4.3 Rotation due to convergence

Where convergence occurs towards a region of low pressure, an air parcel will circulate due to the imbalance of the pressure gradient force and the Coriolis force. This circulation is cyclonic and acts in the same direction as the Earth's spin. The relative vorticity here adds to the Earth's vorticity to induce a higher absolute vorticity. As the air spirals towards the low pressure region, it circulates faster due to the conservation of angular momentum.

In order for tropical cyclogenesis to occur, vorticity that extends through most of the troposphere must exist and must be cyclonic at low levels and anti-cyclonic at higher levels. Even if the convergence and rotation requirements, as described above, have been met, there is a requirement for various surface and upper air conditions to be 'right' in order that a tropical cyclone may form. One of these, as will be seen, is a need for a general

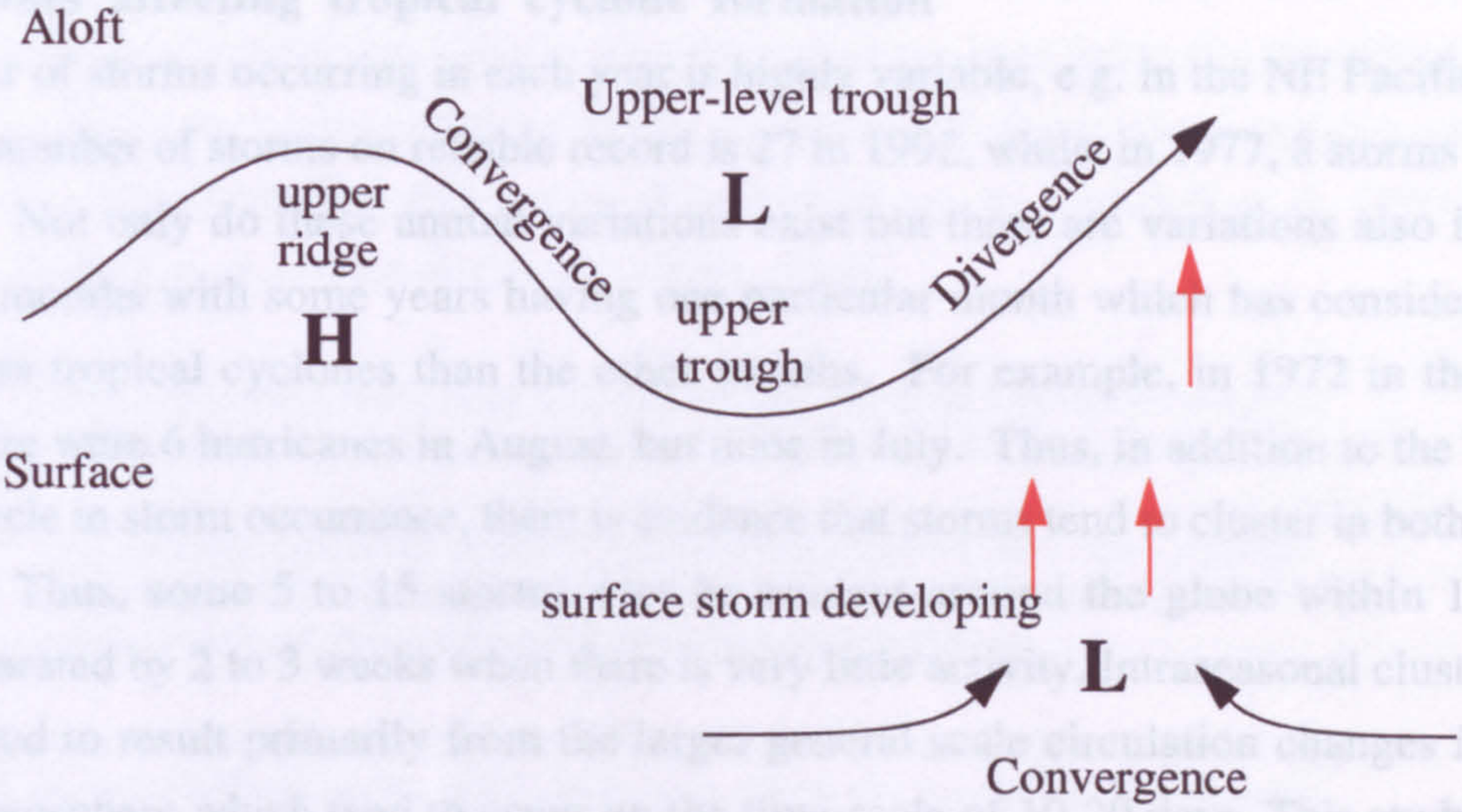


Figure 1.6 Divergence aloft from a TUTT causing convergence at the surface and thus a trigger for the development of tropical cyclones.

environmental level of positive vorticity to exist to aid the initial rotational 'kick'.

1.5 Factors affecting tropical cyclone formation

The number of storms occurring in each year is highly variable, e.g. in the NE Pacific, the maximum number of storms on reliable record is 27 in 1992, whilst in 1977, 8 storms were recorded. Not only do these annual variations exist but there are variations also in the individual months with some years having one particular month which has considerably more or less tropical cyclones than the other months. For example, in 1972 in the NE pacific, there were 6 hurricanes in August, but none in July. Thus, in addition to the basic seasonal cycle in storm occurrence, there is evidence that storms tend to cluster in both time and space. Thus, some 5 to 15 storms may be evident around the globe within 1 to 2 weeks, separated by 2 to 3 weeks when there is very little activity. Intraseasonal clustering is considered to result primarily from the larger general scale circulation changes in the tropical atmosphere which tend to occur on the time-scale of 10-20 days. This study will generally examine the seasonal rather than intraseasonal time-scale, i.e. concentrating on interannual variations.

Interannual variation of storm occurrence results from either the variation in the number of triggering disturbances (described in Section 1.4), (however there are no datasets of these going back to 1972), or variations in the environmental conditions in which the disturbances find themselves. The next section will examine the environmental factors that affect tropical cyclone formation. They have been divided into local, global and extra-terrestrial factors.

1.5.1 Local factors

Several authors have contributed to identifying variables which are necessary for the formation of tropical cyclones. Palmén (1948) was the first to introduce the idea of a critical sea surface temperature for tropical cyclone development, relating it to atmospheric instability. Namias (1954) also emphasised the importance of instability. It was Riehl (1954) who originally formulated a set of conditions which are necessary for the formation of tropical cyclones, but these were a mixture of environmental factors, such as water vapour, and tropical cyclone characteristics, such as radial motion. However, Gray (1979) is widely quoted as the first person to list a set of environmental variables which may affect tropical cyclone development.

1.5.1.1 Gray's six factors giving the potential for tropical cyclone formation

After the convergence requirement has been met through the triggers described in Section

1.4, the local environmental conditions are important in determining which tropical disturbances grow into tropical cyclones and which do not. Empirically-based studies on the spatial and interseasonal occurrence of tropical cyclones have led to the identification of six criteria which, on a seasonal time-scale, are necessary for tropical cyclone genesis (Gray, 1979). The list below follows the summary given by Lighthill et al. (1994) and Henderson-Sellers et al. (1998) of Gray's (1979) criteria.

(i) There must be a sufficient amount of pre-existing low-level positive relative vorticity in the atmosphere to aid the cyclonic spin-up.

(ii) The latitude must be at least 5°. Equatorward of this, the Coriolis force is insufficient to provide the necessary initial cyclonic motion around the low pressure to prevent it filling.

(iii) Values of vertical shear must be sufficiently low to prevent heat and moisture from being advected away from the incipient disturbance.

(iv) The sea surface temperature (SST) must be above 26-27°C to a depth of at least 60 m. The ocean surface provides the thermal energy source for the tropical cyclone.

(v) The environmental lapse rate must be steep enough to allow free convection and the creation of cumulonimbus clouds.

(vi) The middle troposphere relative humidity must be high enough to avoid drying out of the air in the convective clouds when mixing with the surrounding atmosphere.

To predict the geographical distribution of tropical cyclones, Gray quantified these six factors and divided them into two circulation factors (i and iii) and a geographic factor (ii) (whose product gives the 'dynamical potential' for tropical cyclone formation (Gray, 1979)) and three thermodynamic parameters (iv, v and vi) whose product gives the 'thermal potential' or 'potential for cumulonimbus convection' (Gray and Sheaffer, 1991). These last three criteria, in particular, are not independent. This will be discussed in Section 1.5.1.3. In general, these conditions may be satisfied over the tropical oceans at any given time, especially during the summer months, but all six conditions must be met for storm development to take place. However, even if these conditions are met on a seasonal time-scale, as they are mostly in the summer, this does not necessarily mean that any given disturbance will develop into a storm. Thus, there must be a change in one or more of these variables on a daily time-scale for the formation of a tropical cyclone to be hindered, or other factors (such as the numbers of triggering disturbances) must be responsible for their formation. Typically, low-level vorticity and vertical shear are the most variable factors, since the thermodynamic and Coriolis conditions exist over a considerable portion

of the tropical ocean for long periods of time, whereas the low level vorticity and vertical shear variables can change significantly on much smaller time-scales and space-scales (Gray, 1979; McBride, 1981b). Thus it has been hypothesised that tropical cyclogenesis occurs when above normal low level vorticity and locally weak wind shear occur within a thermodynamically favourable environment (Gray, 1979).

There seems to be confusion in the literature whether Gray's (1979) factors are important for genesis solely or formation of higher categories of tropical cyclone. Gray's six factors, which he called genesis parameters, have often been quoted as being important for formation and intensification (e.g. Lighthill et al., 1994). This is because the numbers that form in each category are largely dependent of the original number that makes genesis.

1.5.1.2 Factors relating to dynamic potential

It must be noted that hurricanes do not generally form within about 0 to 10° of the equator because although water temperatures are sufficiently high, the Coriolis force, which depends on the sine of the latitude, is too weak there to initiate the necessary rotary motion. This is not to say that incipient storms do not form at such low latitudes. Cyclonic vortices may form in the equatorial (monsoon) trough as close as 2 degrees or so to the equator but they will be weak and small in size whilst remaining in the trough. If they break away from the trough their intensification to storm or hurricane intensity is possible, but not until they have reached a more poleward latitude (Met. Office, 1995).

Even if the Coriolis parameter has been satisfied to initiate rotation, there are other vorticity requirements that must also be satisfied. A brief discussion on vorticity is already given in Section 1.4 since it is an important aspect of the triggering disturbances for tropical cyclones. Gray (1979) lists relative vorticity as one of his six seasonal environmental variables that affect tropical cyclones. He noted that tropical cyclones only develop in areas of positive low-level vorticity since if a vortex is already present, less energy will be required for the system to intensify into a hurricane. However, although listed as one of Gray's seasonal environmental variables that affect tropical cyclone frequency, it is thought that most of the North Atlantic tropical cyclones actually form in a seasonally low or negative large-scale vorticity (Gray, 1968) and most of the low level positive relative vorticity and convergence variations are a result of fluctuations on the time-scale of days (Zehr, 1992, Gray, 1968). This is particularly the case in the North Atlantic where the monsoon trough rarely forms. By contrast, in the NW Pacific, the seasonal variation in the strength of the monsoon trough affects the vorticity, through horizontal shear of the winds (see Section 1.3). The directional shear across the trough encourages vortex formation and

commonly, a series of cyclonic vortices are found centred along the trough line which are expected to play a significant role in affecting tropical cyclone activity (Chu and Wang, 1997). Vortices do not occur with trade wind troughs, where easterly winds occur on both sides of the trough, as this circulation pattern is not conducive to their formation.

Ward (1995) in a discussion of tropical cyclogenesis in the SW Pacific described that intensification from disturbance to tropical cyclone is directly proportional to low level horizontal cyclonic wind shear and inversely proportional to deep layer vertical wind shear. Horizontal and vertical wind shear thus oppose one another in the development process. A further discussion on vertical wind shear will be given later in this section.

In the NE Pacific, much low level positive relative vorticity and convergence is forced by the monsoon trough or transient vorticity features such as easterly waves. Research has shown that topography effects the relative vorticity near the surface and this can affect tropical cyclone formation. Topography alters the flow of the atmosphere. The lee (downwind) sides of large mountainous ranges are areas where cyclones often develop. The NE Pacific region is unique amongst tropical cyclone basins in that it lies downwind of a large-scale mountain range. This range is the Sierra Madre, which extends from the southwest United States to Central America and is nearly 2 km high and 600 km wide along a good portion of its length. As is shown by Renard and Bowman (1976), the region of the highest occurrence of cyclogenesis in the NE Pacific is located in the lee of the Sierra Madre between 12°N and 20°N, 105°W and 115°W.

Zehnder (1991) suggested that African waves may be modified by the Sierra Madre, resulting in enhanced regions of relative vorticity downstream of the topography and results in tropical cyclone formation. This may partially account for the fact that tropical cyclogenesis sites are concentrated near the west coast of Mexico, as noted by Renard and Bowman (1976). Zhong et al. (1993) attributed some of the variance of tropical cyclogenesis to planetary waves interacting with the Sierra Madre which thus modifies the low level relative vorticity and hence provides a suitable environment for tropical cyclone formation.

Mozer and Zehnder (1996) showed that stably stratified easterly barotropic flow over idealised topography representative of the Sierra Madre results in the production of low-level relative vorticity maxima downstream of the mountain. They associated this vorticity with a barotropically unstable jet that results from blocking of the low-level flow by the topography. The horizontal jet is the dominant feature of the flow field and is responsible

for the production of the eddies downstream of the mountain. Thus the large-scale region of cyclonic relative vorticity near the coast of Mexico provides a favourable environment for tropical cyclogenesis.

In identifying the various dynamic conditions that are necessary for tropical cyclone formation, it is necessary to consider vertical shear of the large-scale surrounding upper-level and lower-level wind fields (Gray, 1979). Yanai (1961) has also emphasised the role of favourable large-scale surrounding flow features as a requirement for genesis. Thus vertical shear must be considered. Vertical wind shear is the magnitude of the vector difference in wind velocity at two heights. Since winds at the 850 hPa level are slightly stronger than those at the 700 hPa level (Goldenberg and Shapiro, 1996) winds at the 850 hPa and 200 hPa are commonly now used. A detailed description of the calculation of wind shear is given in Section 2.2, where a more accurate method of calculating wind shear for seasonal averages is proposed, compared to the methods used in the literature to date.

Provided that other conditions are satisfied, tropical cyclone formation occurs when vertical wind shear is reduced. It was Palmén (1956) who first noticed that strong tropospheric vertical wind shear significantly inhibits tropical cyclone formation and intensification. Vertical wind shear in the vicinity of a tropical system, larger than approximately 7.5 m s^{-1} to 12.5 m s^{-1}, appears to be the threshold beyond which unfavourable conditions occur (Zehr, 1992; DeMaria et al., 1993; Zehr, personal communication, 2000). It has been noted by Gray et al. (1993) that the North Atlantic basin on average is therefore not particularly favourable for tropical cyclone development. Likewise, the NE Pacific basin, in the mean, is also not particularly favourable for tropical cyclone development.

Goldenberg and Shapiro (1996) showed a strong concurrent relationship between North Atlantic intense hurricanes and wind shear. (However, there is a possibility that they are actually showing lagged relationships, see Section 2.2). The physical reason for the importance of small or even zero shear is to accumulate moisture, enthalpy and temperature anomalies in a vertical column above the incipient disturbance, allowing warm core development which is necessary to lower surface pressure. The presence of large vertical shear, however, is said to ventilate the column by advecting the warm air and moisture away from the low level circulation centre. Thus tropical cyclone formation is inhibited (Gray, 1979).

Emanuel (1999) showed, with simulations, that factors such as wind shear and dynamical interactions with the environment (i.e. weather systems) appear to be strongly influential

during the formative stages, when the storms are comparatively weak.

Vertical wind shear is an extremely important factor in relation to tropical cyclone formation in some basins. The importance of this factor can be highlighted using the examples of the Arabian Sea and the Bay of Bengal. During the Northern summer, the SST is warm, but tropical storm frequency is at a minimum. This is due to the vertical shear caused by the monsoon and the ocean-to-land breeze. The further importance of this factor can be exemplified by the fact that few storms develop and continue to move north of 20°N in the Northern Hemisphere. Although cooler SSTs strongly contribute to their lack of existence there, the higher vertical wind shear resulting from the strengthening of the upper level westerlies as one heads north is a major consideration. Finally, the importance of vertical wind shear is shown by the intimate relationship that other factors have with this variable, such as the Quasi-Biennial Oscillation (Gray et al., 1992) or the El-Niño Southern Oscillation (Philander, 1989). This link with wind shear allows these oscillations to be associated with tropical cyclone frequency in the North Atlantic basin.

1.5.1.3 Factors relating to thermodynamic potential

The source of energy which ultimately drives a hurricane, as with all atmospheric circulations, is the sun. A hurricane requires heat and moisture for formation and development to occur. The radiant energy from the sun is absorbed by the ocean which results in an increase in ocean temperature, both the sea surface temperature and, through mixing, the layers beneath. The tropical ocean warms the most because of the near-perpendicular angle of the sun. This temperature increase in the ocean then allows the heat and moisture to be transferred to the atmosphere through atmosphere-ocean interactions.

One of the Gray (1979) criteria is usually summarised as an SST of ≥ 26-27°C which is required for tropical cyclone genesis to occur (Henderson-Sellers et al., 1998; Lighthill et al., 1994). However, in quantifying his criteria to determine geographical distributions of tropical cyclones, Gray (1979) used the thermal content of the top 60 m of the ocean as one of his seasonal parameters that influence genesis, provided that the SST was above 26°C. This implies a correlation of the SST value with tropical cyclone frequency. However, he gave no theoretical or strong empirical arguments to support this suggestion, although Saunders and Harris (1997) later gave empirical evidence for the North Atlantic Main Development Region (MDR) to support this claim. Shapiro and Goldenberg (1998) also showed that a strong relationship exists between named tropical cyclones and SST in the North Atlantic, although not for the intense hurricane category (and they note that wind shear, not SST, is the dominant factor explaining interannual variations in tropical cyclone

frequency in the North Atlantic). However, this relationship between SST and tropical cyclone frequency is not supported by Raper (1993) who concluded, in a review of the literature, that evidence suggested that there was no effect on hurricane frequency from SST values above the critical threshold. Particular support for Raper's statement comes from McBride (1981a) who examined conditions associated with developing and non-developing warm core systems in the North Atlantic and NW Pacific and noted that Gray's (1979) thermal potential parameter was the same in both cases. It can therefore be inferred that variations in SST are not important for determining tropical cyclone genesis above the threshold. Let us now consider the depth criterion and the SST criterion in turn.

The intensification and growth of a tropical cyclone, once formed, is strongly influenced by the value of the SST affecting its MPI (see Section 1.2). However, the depth of the warm sub-surface layer is also important for tropical cyclone development. There is ample evidence of a drop in SST after the passage of a storm. The process of sea cooling is partly by turbulent exchange but also by upwelling of deep cool water. Thus, although important for tropical cyclone intensification, when a tropical cyclone remains over the same stretch of water the SST becomes less important and the depth of the thermocline, which determines the height of the mixed layer above it, becomes of greater importance. This can be highlighted with a hurricane in full force where there are strong surface winds which result in rough seas, further causing the water from below to turn over. If the depth of the thermocline is shallow, this will result in cooler water from beneath being turned over which restricts the source of heat for the hurricane. Conversely, a deeper thermocline will turn over mixed warm water and allow continuance and intensification of a hurricane (Emanuel, 1999; Bender and Ginis, 2000).

According to Henson (1998), the thermocline below the surface of the tropical North Atlantic typically lies between 100 to 150 ft (30 to 46 m) in depth. This is relatively shallow and may result in the negative feedback mentioned above, where the hurricane's heat source is cut off when colder water is turned over. There are places on the Earth's oceans where the thermocline is deeper to about 300-350 ft (91 to 107 m), across an area one or two hundred miles wide, such an example being the Gulf Stream, where warm water is churned from underneath. Hurricane Andrew provides such a case in point, where the thermocline appears to be important, since it reached peak intensity as it passed over the Gulf stream just before hitting south Florida in August 1992.

It would appear that the speed at which the hurricane moves over the tropical water is also of primary importance. If a hurricane moves slowly and perhaps sits over a particular area,

it will draw out much of the heat. Once the reservoir of heat has been removed, if the hurricane remains over this area it will dissipate as its fuel has gone since the surface heat has been taken up and there is mixing of cooler water from beneath (Emanuel, 1999; Bender and Ginis, 2000). A hurricane that moves with greater speed has a continually renewed reservoir of heat on which it can draw, in particular the surface heat, as long as the hurricane does not drift too far polewards where the SSTs are cooler.

Thus, both the SST value and the depth of the thermocline can influence the intensification and growth of a tropical cyclone, once formed. However, although the SST and thermal energy of the ocean are important for tropical cyclone intensity and maintenance, the value of SST being above the 26°C threshold, in the context of tropical cyclone *genesis*, is important to provide atmospheric instability, through a steep enough lapse rate, and encourage deep convection. This was first calculated as a theoretical limit by Palmén (1948), and more recently emphasised by Emanuel (1986) and Henderson-Sellers et al. (1998).

Stabilisation of the atmosphere and hence restriction of convection and tropical cyclone genesis can occur not only from having cooler air at the surface, which causes the environmental lapse rate to decrease, but also from having a warmer atmosphere aloft. This may commonly occur through subsidence when an entire layer of air sinks. The upper part of the subsiding air layer will be warmed by adiabatic compression, more so than the lower portion since the upper part sinks further. This causes a subsidence inversion and inhibits the genesis of a tropical cyclone. Such subsidence inversions are the norm in the sub-tropical high pressure and nearby trade wind regions of the Hadley circulation.

Emanuel (1988) noted that the MPI of tropical cyclones also falls to zero in regions with SST generally less than 26°C. He attributed this to the stable atmosphere which results from the trade wind inversion that occurs over the cooler water which greatly limits the altitude to which convective clouds can ascend and, therefore, the thermodynamic efficiency of the energy cycle. However, easterly waves form within the trade wind region and disrupts this layer. On the one hand, relationships between hurricane frequency and SST values have been found. As mentioned, Saunders and Harris (1997) noted a link between hurricane formation frequency and SST values and suggested that high SSTs will enable vigorous convection so that cumulus clouds can penetrate through the trade wind inversion at 1-2 km altitude, thereby leading to the onset of deep convection. On the other hand, lack of relationships in the NE Pacific basin have also been published, e.g. Zhong et al. (1993) who examined SSTs and tropical cyclones in the NE Pacific from 1979 to 1987.

Zhong et al. (1993) defined the NE Pacific region as 10°N to 20°N, 110°W to the North American coastline.

Relative humidity (RH), which is a measure of the moisture in the atmosphere, is another of Gray's factors which relates to the thermodynamic potential of a tropical cyclone and this is strongly related to the SST and instability of the atmosphere mentioned above. RH is the ratio of the air's actual water vapour content compared to the amount of water vapour required for saturation at that temperature. RH therefore changes if water vapour is added or subtracted, or if the temperature changes. Without an unstable environment and a steep lapse rate, the moist surface air will not rise to high enough altitudes. Gray (1979) noted that tropical cyclone genesis is usually related to the seasonal values of the (average of the 500 hPa to 700 hPa) RH, with a threshold value of 40% being important. Gray (1979, p. 171) in particular noted that, "Other factors being equal, an environment of high middle-level humidity is more conducive to deep cumulus convection and greater vertical coupling of the troposphere because entrainment of moist air into updraughts inhibits their growth less than entrainment of dry air." The entrainment of drier environmental air into developing tropical cyclone systems results in less buoyancy for the system as well as diminished upper level warming due to decreased release of latent heat. The dry air allows water vapour in the storm clouds to evaporate. Middle level drying is thought to be associated with increased subsidence or reduced low level convergence. For example, with a trade wind inversion, the air above the inversion is dry and subsiding, with a low RH.

Tulich and Kimberlain (1999) gained an increased understanding of the physical mechanisms which control North Atlantic tropical cyclone climate and variability. Through a study of satellite observations of deep convective cloud activity, they showed that tropical cyclones tended to form in regions where the deep convective cloud amount is greater than 2.5% and mean deep convective cloud brightness temperatures are less than 230 K. This agrees with these other thermodynamic variables discussed and with Emanuel (1997, p. 62) who pointed out that, "a necessary and perhaps sufficient condition for genesis is the establishment of a pillar of very humid air".

Therefore, it has been shown that Gray's (1979) thermodynamic factors (SST, lapse rate, RH) are not independent. For example, it has been shown that the 26°C criterion is necessary to allow a steep enough lapse rate for deep convection (Emanuel, 1986) and thus in turn provides adequate RH in the middle troposphere. Not only does the SST allow tropical cyclone development through the methods described above, but it is thought that SSTs indirectly influence tropical cyclones as well through their effect on surface pressure,

for which there is an inverse relationship. With warm waters, the warming encourages a thermal expansion of the column, which in turn causes an upper-level high pressure. The pressure gradient force outwards from this causes divergence aloft and encourages a thermal low to form at the surface, with air moving into this low. Weisberg and Wang (1997) noted that SSTs influence sea level pressure and not the other way round, as they showed that SSTs lead sea level pressure. Lower sea level pressure also results in weaker vertical wind shear due to the trades being weaker from the weaker pressure gradient between the region and the equator (see also Section 1.5.1.4). Finally, it should be noted that in general, the role of SST in determining tropical cyclone frequency is important from the view of medium-term prediction, as SST fields are often predictable with lead times of months.

1.5.1.4 Other local factors related to tropical cyclone formation

Various other environmental factors have been suggested as being important for tropical cyclone genesis, and these are described below. However, it will be seen that these act to influence the Gray parameters. Landsea et al. (1998) suggested that precipitable water may be a variable that affects hurricane formation. Stephens (1990) established a statistical link between mean SST and mean precipitable water over the ocean. The relationship is almost linear for SSTs greater than 20°C. Therefore, it would be expected that there would be a relationship between mean precipitable water and tropical cyclone frequency, if there is a relationship between SST and tropical cyclone frequency. The link between precipitable water and tropical cyclone frequency would be similar to that found with relative humidity and hurricanes, i.e. through providing the necessary moisture to allow the cumulonimbus to develop.

A further local factor which may be related to tropical cyclones is sea level pressure. Although already mentioned in Section 1.5.1.3 in terms of its relationship with SST, there have been several theories relating sea level pressure to tropical cyclone frequency in the North Atlantic, all of them allowing for the observed negative correlation between them, i.e. lower pressure is associated with more tropical cyclones, a fact which has been well established as early as 1906 (Garriott, 1906). 1933 was a very active season in the North Atlantic and research showed a clear relationship with the low sea level pressure both preceding and during the hurricane season (Ray, 1935; Brennan, 1935). Later, Namias (1955, 1968), Ballenzweig (1959) and Shapiro (1982) examined the relationship between tropical cyclone activity and sea level pressure to explain year to year variations. Shapiro (1982) noted that one-sixth of the North Atlantic basin's tropical cyclone activity can be explained by variations of sea level pressure, though it must be noted that Shapiro

calculated sea level pressure only for locations north of 20°N. More recently Gray (1984) adopted this variable to forecast North Atlantic basin tropical cyclone activity. However, again he did not use the local sea level pressure to the MDR, but used sea level pressure over the Caribbean Sea.

Knaff (1997) noted that the observational evidence suggests that there is not one simple pressure-tropical cyclone relationship, rather that there are complex interactions between several factors. Gray et al. (1993) suggested that the lower pressure is an indication of the northward displacement of the ITCZ. Thus, in years where there is lower pressure, the ITCZ has moved further north. Alternatively the low pressure could be due to the strengthening of the ITCZ. In either case, these situations would lead to greater convection and moisture in the atmosphere which aids in the genesis of a tropical cyclone, i.e. via Gray's parameters. Furthermore, enhancement of the ITCZ allows greater low-level cyclonic vorticity (Gray, 1968), thus aiding in a favourable environment for the tropical cyclone.

Another theory recognises the effect of pressure upon another one of Gray's parameters, wind shear, and then the effect of wind shear upon hurricanes in the North Atlantic, where below normal sea level pressure in the MDR reduces the pressure gradient between that region and the equator, and thus weakens the easterly trade winds which in turn leads to less shear (Gray et al., 1993, 1994).

Knaff (1997) noted a positive feedback mechanism which explains why conditions are similar, i.e. usually low pressure or usually high pressure throughout the season. In the higher pressure situation, where there is subsidence which reduces the net amount of cloudiness, this increases the amount of atmospheric long-wave cooling to space (Stephens et al., 1994). Thus, there is extra cooling, not only from the dry mid-levels, but also due to this long-wave cooling to space, which results in increased surface pressure and more upper and mid-level subsidence. A stronger TUTT (see Section 1.4.2) evolves as subsidence from the stratosphere results and warms the upper troposphere (about 100 hPa), causing a temperature difference which dynamically results in a stronger TUTT. There is a particularly strong relationship in the Caribbean with the TUTT that is less evident in other basins. Higher pressure gives colder mid-level air and strengthens the TUTT, which strengthens westerly winds around it on the equatorward side at the 200 hPa level and causes increased vertical wind shear and less tropical cyclones. Although Knaff (1997) examined sea level pressure in the Caribbean, he noted that, though the moisture differences at 500 hPa are greatest over the Caribbean between high and low sea level

pressure years, there is an increase in moisture in the mid-levels associated with low pressure throughout the tropical North Atlantic. Thus, again this mechanism operates via the Gray (1979) parameters.

1.5.1.5 Accounting for the time of the hurricane season and location of hurricanes

Due to the requirement for the SST to be greater than 26°C, the time and the location of tropical cyclones can be largely explained. Tropical cyclones develop most often in summer when ocean temperatures have reached 26°C or higher. This temperature requirement also accounts for hurricanes occurring in the tropics and not poleward of about 20° latitude. However, as noted in Section 1.5.1.1, the warmer SSTs are not the only factor in determining the timing and location of the hurricane season. The shift poleward of the ITCZ is an important factor. Seasonally, the mean latitude of storm formation moves poleward in the first half of the season and then retreats equatorward, being largely a reflection of the seasonal migration of the ITCZ. In the NE Pacific, storms form mainly in July through to September when the monsoon trough is at or near its northern most position. Alpert (1946) mentioned that there is a big difference from April's to May's circulation when the southern monsoon pushes north rapidly. He noted that this burst of activity is reflected in the rainfall of Central America where the rainy season appears suddenly in May. Similarly, tropical cyclone activity starts to increase in this month (see Table 2.1). Hence warm SSTs alone in May are not the only determinant of the hurricane season.

1.5.2 Global-scale

There are two major global-scale meteorological variables which have been found to affect seasonal tropical cyclone formation - the QBO and ENSO (Gray, 1993). However, whereas the local factors mentioned above affect hurricane formation in the same way for all the basins, the QBO and ENSO are suggested to have different effects in different basins.

1.5.2.1 QBO

The QBO was first described by Angell et al. (1969) who noticed that there are variations on a quasi-biennial time-scale in the location and intensity of the sub-tropical high pressures. They also note a link with hurricanes, in that hurricane (in the North Atlantic) and typhoon (NW Pacific) frequencies are above average when their respective sub-tropical highs are above average intensity. They found an in-phase relationship between sub-tropical high pressure and storm frequency in the NW Pacific with a correlation of 0.35

which is significant using the Fisher test.

Angell et al. (1969) also suggested a link between typhoon frequency and the direction of the winds in the low equatorial stratosphere. This link to wind direction has been followed up in further studies by Gray (1993) who describes the QBO as an oscillation of the zonal wind in the lower to middle stratosphere of the deep tropics with a mean period of 26 months. This definition of the QBO is used in the current study. The extreme zonal wind speeds of the QBO are located about the 30 hPa to 50 hPa level and above the equator, with the wind speed pattern of the QBO being symmetric about the equator. The maximum amplitude decreases both downward and poleward with the influence of the QBO, spanning about 15 degrees both north and south of the equator.

In the North Atlantic, during the easterly phase of the QBO, it has been observed by Gray (1993) that the westward moving systems in these latitudes are inhibited from developing into tropical cyclones, whereas the QBO winds in the westerly phase typically enhance formation. Since the QBO is ill-defined at 100 hPa (the mean tropical tropopause), it would appear that the QBO is disconnected from the tropospheric flow; nevertheless it has been suggested that the two are in some way connected. The link between these winds and hurricanes is hypothesised to be due to variations in the vertical wind shear between the upper troposphere and the lower stratosphere during the hurricane season, such that an east QBO phase, which typically lasts 12-15 months, forces strong easterly winds in the lower stratosphere between 10°N and 15°N and with it large vertical shear between the upper troposphere (with its westerlies) and the lower stratosphere. On the contrary, the west QBO phase, which typically lasts 13 to 16 months, allows for weak easterly winds in the tropical North Atlantic stratosphere, and for little vertical shear. In the NE Pacific Ocean, Landsea and Gray (1989) noted that the east phase of the QBO also forces strong easterly winds in the lower stratosphere between 10°N and 15°N causing a relationship between the QBO and the numbers of intense hurricanes in particular.

Because winds in the equatorial stratosphere have very little variation with longitude, time series of the zonal winds at 50 hPa at Balboa (9°N, 80°W) are used to represent the stratospheric QBO. This location is near the NE Pacific development region, although these data are used to correlate QBO further away in other studies, e.g. in the NW Pacific (Chan, 1995).

1.5.2.2 ENSO

The ENSO phenomenon was described in Section 1.3, where is was mentioned that it is a

global phenomenon, effecting regions local to and remote from the equatorial Pacific. There is a rich and controversial background of literature concerning this topic and continuing confusion as to how ENSO affects tropical cyclone activity. Indeed, ENSO appears to alter the circulation in many ways, so that there is more than one way in which ENSO can affect tropical cyclones. The effects of ENSO can be felt locally in the tropical Pacific where there is often a direct effect from the SST, but there are also remote effects in which there is a complex indirect link through alterations in the tropospheric flow features. The combination of the proximity of the NW Atlantic to the East Pacific El Niño area and to the atmospheric circulation anomalies associated with El Niño is such that the upper tropospheric climate in the Atlantic-Caribbean basin is strongly affected by major El Niño events (Gray and Sheaffer, 1991). The association between ENSO and North Atlantic hurricanes is due to the position of the Atlantic-Caribbean basin being directly downwind (in terms of the upper level winds) from the area of the major East Pacific El Niño warming. It can be physically explained by the alteration of the flow patterns in the upper troposphere, which is a result of large changes in the Walker and Hadley cells (Philander 1989) and results in changes of the vertical shear profile. On the one hand, when El Niño occurs, it is observed that the atmosphere over the tropical North Atlantic and the Caribbean has a much higher vertical shear due to the increased westerlies at 200 hPa, which consequently results in a reduction of the number of hurricanes forming. On the other hand, during La Niña, there are easterly wind anomalies at 200 hPa resulting in reduced vertical wind shear and a higher number of hurricanes forming. During an El Niño, strengthened trades in the North Atlantic result from either the shift in the Walker circulation, which in turn causes changes in the Hadley circulation, or alternatively may be the result of an anomalous low pressure centre which is located over the southeastern United States. This would cause an anomalous northeasterly flow over the North Atlantic. Since the mean wind vector in the North Atlantic is northeasterly, the anomalous wind strengthens the magnitude of the northeasterly wind, leading to strengthened trade winds. Strengthened trades necessitate that there will be increased evaporation which will lead to an increased net heat flux out of the ocean leading to cooling there (Klein et al., 1999).

There are atmospheric pressure changes related to ENSO which also affect tropical cyclone numbers. For example, over the western Pacific, high air pressure during an El Niño increases convective stability and decreases convection, thereby reducing the frequency of tropical cyclones. The influences of ENSO in the other basins are discussed in detail in the RPI (1997).

The role of ENSO in the NE Pacific is still in debate. Since the NE Pacific is local to the

ENSO phenomenon, one might expect that this area would receive direct ENSO effects, such that, with the warm ocean anomaly extending north, and with the relationship between warmer SSTs and tropical cyclone formation described in Section 1.5.1.3, an enhancement of the possibility of tropical cyclones would be expected. However, Murillo (1999, personal communication) indicated that El Niño does not significantly increase the number of storms but does affect landfalling storms. Murillo used 25°N-30°N to define landfalling and El Niño defined as the year it starts in. In this study it was found that there was a better association to cold events, such that there was a stronger relationship with La Niña, which decreases landfalling storms.

This school of thought is contrary to Kimberlain (1999, personal communication), who found a relationship between tropical storm numbers and ENSO, and noted that in an El Niño, the storms are longer lived and stronger, the central Pacific is more active, the median latitude and longitude are further south and west, and the tracks extend further north towards Baja California.

Similarly Chu and Wang (1997) who concentrated on the central Pacific (but also included tropical cyclones that moved in from the east) found, in agreement with Kimberlain (1999) and Landsea and Gray (1989) who considered storms in the NE Pacific, that the mean number of tropical cyclones in the vicinity of Hawaii during an El Niño year is higher than during a non-El Niño year. They also explored a relationship with tracks of tropical cyclones. They offer an argument of increased horizontal vorticity due to the monsoon trough to account for this relationship. Clark and Chu (1999) looked at the strongest events in the central North Pacific. In this study they found differences in tropical cyclone tracks and number in warm vs. cold years.

In conclusion, it is clear that no part of the atmosphere exists in isolation or can be understood without examining wider regions. The hurricane is part of the general atmospheric circulation, whose behaviour is influenced by the atmospheric and oceanographic conditions in other areas. Thus, ENSO and the QBO can affect Gray's (1979) local thermodynamic and dynamic factors and hence can modulate tropical cyclone frequency. A variable which is predictable or partially predictable on a time-scale of months or years, e.g. one which regularly changes sign every few years such as the QBO, is of great use in long-term predictions as it has a substantial lead relationship.

1.5.3 Extra-terrestrial factors

Since the sun is the source of the heat energy for the hurricane, there have been a number of

studies which have suggested a solar influence (Meldrum, 1872; Poey, 1873; Cohen and Sweetser, 1975). These studies generally did not suggest mechanisms for this influence, and in any case, it is likely that it would operate through the local factors already noted. It has been suggested that greater solar activity and higher solar irradiance can be expected to increase the tropical ocean temperatures by a few tenths of a degree Celsius (Hoyt and Schatten, 1997) and lead to variations in Northern Hemisphere near-surface temperatures (van Loon and Labitzke, 1988). Much solar work, therefore, has concentrated on the solar cycles (e.g. Cohen and Sweetser, 1975). However, with the NE Pacific basin only having about 30 years of reliable tropical cyclone data, it is not feasible to detect any such cycles in the tropical cyclone data.

1.5.4 Intraseasonal factors

The relationship between the Madden Julian Oscillation (MJO) and tropical cyclones has recently been established on an intraseasonal time-scale. The MJO is a cycle of tropical winds and precipitation that has a repeat time on the order of 30-60 days. It starts as convection over the Indian Ocean. The coupled wave moves eastward along the equator. From the Indian Ocean to the Eastern Pacific, the signal takes about two weeks to cross the Pacific Ocean. Maloney and Hartmann (2000) noted that tropical cyclones are four times as likely in the westerly than easterly phase of the MJO. During an active MJO, there are enhanced westerlies at 850 hPa and, therefore, enhanced cyclonic shear (Molinari et al., 1997). Low-level westerlies with the MJO create an environment for wave accumulations, i.e. convergence (Holland, 1995). There is also a higher 500 hPa RH in active MJOs.

1.6 Dissipation

This chapter has established that a tropical cyclone needs a variety of local factors to be present for genesis to occur - a significant Coriolis force and relative vorticity, high ocean temperatures, a high moisture content, instability of the atmosphere, lack of subsidence, and low vertical wind shear. Some of these local factors are in turn promoted by regional and global factors. The role of ocean overturning in limiting the growth of hurricanes has also been noted. Generally, a tropical cyclone will dissipate when the heat and moisture sources are removed. When a hurricane heads poleward, the heat source is removed as the hurricane traverses colder waters. When the hurricane makes landfall, the moisture source of the oceans is removed, thus reducing the source of energy for the hurricane. Furthermore, when a hurricane makes landfall, there is added friction, reducing the strength of the winds and this has a further dissipating effect of causing the winds to blow more directly into the centre. This causes the low to be filled as convergence at the surface exceeds divergence aloft. This results in a rise of the central pressure and consequently the

hurricane dissipates.

1.7 Tropical cyclones in a warmer world

It has been reported by Lighthill et al. (1994) that research into the effect of global warming on hurricane numbers has so far been inconclusive. Dynamical models that have addressed the issue of tropical cyclone activity in a warmer world have been inconsistent. However, research in more recent years suggests that tropical cyclone frequency is unlikely to change with global warming (Henderson-Sellers et al., 1998). Although General Circulation Models (GCMs) suggest that the area enclosed by the 26°C isotherm will increase with global warming (Ryan et al., 1992; Royer et al., 1998; Druyan et al., 1999) and it might be thought that this would have the effect of allowing more hurricanes to form (see Section 1.5.1.3), thermodynamic modelling indicates that upper atmospheric warming will lead to an increased SST threshold for tropical cyclone formation due to the instability requirement (Henderson-Sellers et al., 1998) which requires the vertical temperature gradient between the surface temperature and the upper air temperature to be steep (see Section 1.5.1.3). Expecting that tropical cyclones will increase just because SSTs are increasing is thus too simplistic. Therefore, it can be seen that the use of Gray's parameters (1979), which were created to explain tropical cyclone frequency spatially and seasonally, does not work when incorporating them for climate change purposes since the Gray parameter criteria are tuned to some extent, particularly with regard to SST, to the present climate (Ryan et al., 1992, Broccoli et al., 1995, Royer et al., 1998; Druyan et al., 1999).

1.8 Summary of thesis' goals and structure

The overall aim of the work presented in this thesis is to carry out a thorough statistical investigation of the NE Pacific basin as regards tropical cyclone activity and its relation to seasonal environmental conditions. Specific goals are to determine any trends in tropical cyclone frequency with time, and to identify the seasonal environmental conditions that affect tropical cyclone frequency in this particular basin, whilst at the same time excluding other factors from being important. Particular emphasis will be placed on the effects of ENSO, since this phenomenon is of recent concern in many climate studies. Physical mechanisms for any trends and relationships will also be investigated. Chapter 2 describes the environmental and tropical cyclone datasets used, as well as the main statistical analysis technique used in this study. Wind shear is one of the factors which has previously been shown to be important for other basins. This variable is examined in detail, and a more accurate method of calculating seasonal wind shear is proposed, compared to the method currently used in the literature. Chapter 3 examines the longitudinal distribution of tropical cyclones to see if they should be treated as a single group, reacting in the same way to the

underlying causal factors, or whether there is indeed more than one group within the basin, divided spatially. Trends in the frequency of tropical cyclones in two development regions are identified and an examination of the causes of such trends is conducted. Chapter 4 takes these development regions and uses various statistical procedures to test the significance of the relationship between certain environmental variables and tropical cyclone frequency. Both local and non-local factors are examined. A discussion of the influence of each of the significant variables on tropical cyclone frequency is given, backed up with supporting literature. The dominant variable affecting tropical storms, hurricanes, and intense hurricanes is noted. Chapter 5 uses statistical and physical arguments to examine, for the hurricane category, the mechanisms by which the dominant environmental variable varies from year to year. This variable is first examined in greater detail to confirm that the direction of the relationship is such that the environmental variable is largely affecting hurricane frequency, and not vice versa. An inter-basin comparison of tropical cyclone numbers between the NE Pacific regions and the North Atlantic is made. Chapter 6 concludes this thesis with a summary of the most important results and a discussion of suggested future work. Figure 1.7 summarises the structure of this thesis as just described.

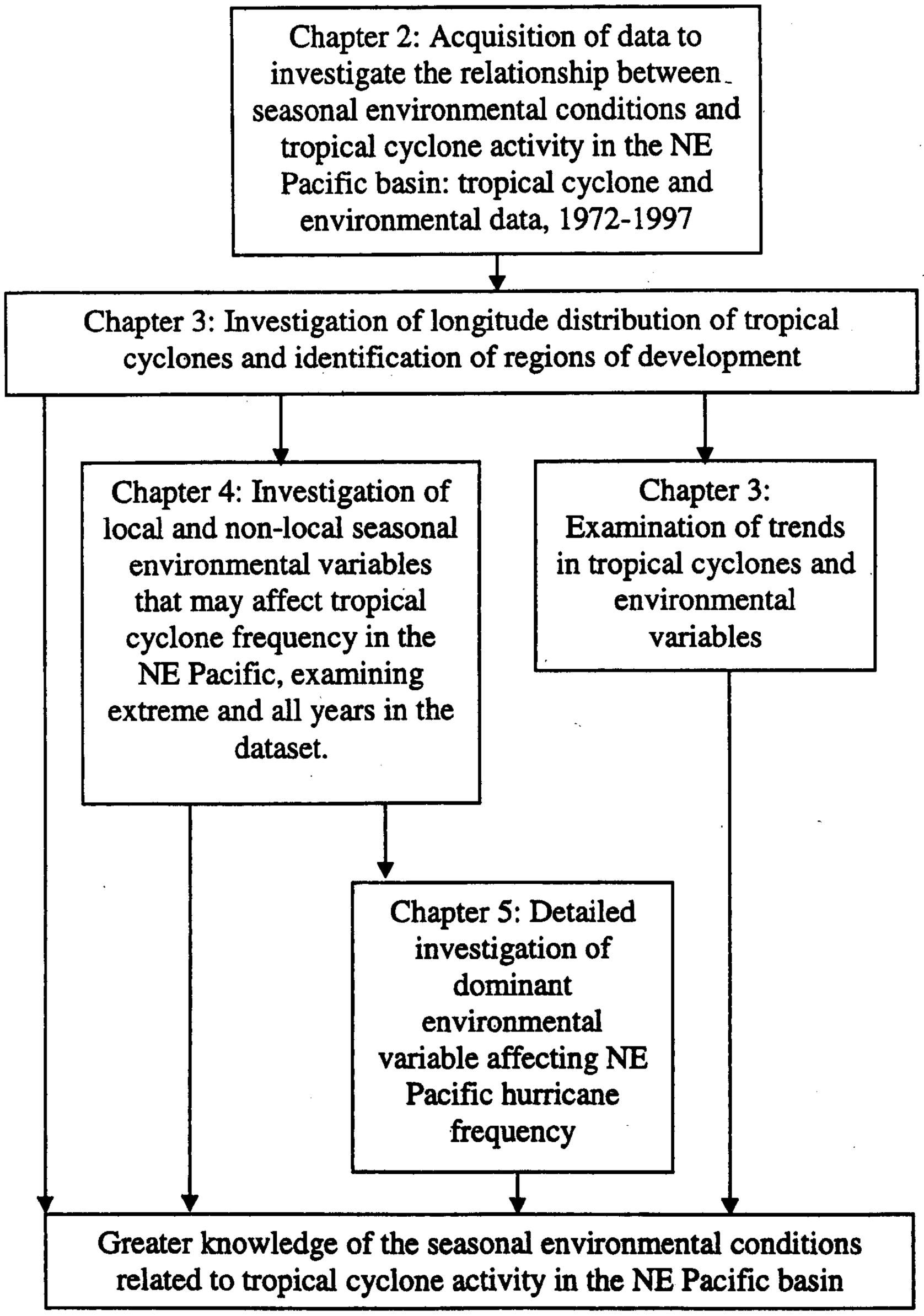


Figure 1.7 Structure of thesis.

Chapter 2

The datasets, wind shear calculation and statistical analysis technique

This section will describe both the tropical cyclone and environmental datasets used. Since wind shear has been shown to be a dominant control of tropical cyclones in the North Atlantic (see Section 1.5.1.2), it is examined in detail for the NE Pacific basin (see also Chapter 4). This examination includes an appraisal of the calculation of wind shear currently employed in the literature, which will be given in this section. An alternative and more accurate method of calculating wind shear is given and compared to that currently adopted in the literature. After these datasets have been examined, this section will conclude by describing the statistical analysis technique used throughout the study.

2.1 The datasets

2.1.1 The tropical cyclone dataset

The source for the tropical cyclone indices used in this study is the official historical tropical cyclone track database obtained from the Tropical Prediction Center/National Hurricane Center (TPC/NHC) best track file for the NE Pacific (Brown and Leftwich, 1982; TPC, 2000) and North Atlantic basins (Jarvinen et al., 1984; TPC, 2000). These data represent the most complete and reliable source of all NE Pacific and North Atlantic tropical cyclones. The best track data records were compiled from various publications and represent a rigorous, post-season analysis of all tropical cyclone intensities and tracks at six-hourly intervals. Categories of tropical cyclone considered include tropical storm, hurricane and intense hurricane. For each category of tropical cyclone the location used in the analysis is the point where the storm reached the wind speed appropriate to the category (34 knots (17 m s^{-1}), 64 knots (33 m s^{-1}) and 96 knots (50 m s^{-1}) respectively). When considering the numbers of each, the categories are not exclusive in that if a hurricane is considered, it will be given a count for both hurricane category and tropical storm category if it reached these categories within the same region. Tropical depressions, the weakest category of tropical cyclone, are not considered since the data are considered unreliable. There has been much uncertainty in classifying a tropical depression and often it is just confused with a cloud cluster (Bracken and Bosart, 2000). A fourth measure, the net tropical cyclone activity index (*NTC*), is also considered. Gray et al. (1994) calculated this index for the North Atlantic and it is described by the equation

$$NTC = (\%NS + \%H + \%IH + \%NSD + \%HD + \%IHD)/6 \qquad (2.1)$$

where *NS* is the number of named tropical storms, *H* is the number of hurricanes, *IH* is the number of intense hurricanes, *NSD* is the number of named tropical storm days, *HD* is the number of hurricane days, *IHD* is the number of intense hurricane days, and each season's percentage value of the long period mean is used for the six measures of seasonal activity.

In this study, the NTC is calculated for the NE Pacific western development region identified in Section 3.1.1 (see Appendix 1). The NTC index provides a good measure of 'overall' tropical cyclone activity (Gray et al., 1994). Some authors have adopted this index in the recent literature (e.g. Landsea et al, 1998).

Before the advent of operational meteorological satellites, information on tropical cyclones in the NE Pacific basin was provided by land stations, ships at sea, and aerial reconnaissance reports. The greatest number of reports were received from ships at sea. Generally these ships were travelling on the periphery of a storm's circulation, and the distance to the storm's centre was unknown. As warnings became better even fewer ships encountered the central regions of the storms. Furthermore, hurricanes in this area typically track WNW away from land and shipping lanes. Aerial reconnaissance was infrequent and concentrated on periods when a storm was threatening land areas. Passage of a storm directly over a land station was also infrequent. Therefore, undoubtedly some weaker and short lived storms in remote oceanic areas were not detected. The importance of satellites for detecting and tracking storms in the NE Pacific and central North Pacific is supported by the increase in the mean number of observed tropical cyclones per year from 8.6 for the period 1949-1964 to 14.8 for the period 1965-1983 (Davis et al., 1984). It is estimated that before the advent of geostationary satellite pictures, the number of NE Pacific tropical cyclones was undercounted by a factor of about two (Landsea, 1998, personal communication). Furthermore, prior to 1966, tracks were only documented for tropical storms and hurricanes, not tropical depressions. Mayfield and Rappaport (1998) pointed out the need for exclusion prior to 1966, stressing that the file may be incomplete prior to the advent of consistent satellite monitoring. Hence, tropical cyclone frequencies before satellite coverage in 1966 cannot be considered reliable and are not used in this study. Despite overcoming detection problems, it must be mentioned that the record still has problems post-satellite since position estimates may be in error by tens of miles and wind speeds maybe in error by tens of knots (AMS, 2000).

Instead of beginning the record in this study at 1966 due to the reason mentioned above, records are only considered reliable since 1972 when the Dvorak technique (Dvorak, 1975) for estimating the intensity of tropical cyclones was employed operationally (Gaby et al.,

1980). Methods for the evaluation of the intensity of a tropical cyclone based on satellite images were being developed from the mid-1960s (e.g. Fritz et al., 1966). However, the Dvorak technique, which is used today was tested in 1971 and used officially in 1972 in the NE Pacific basin. The resulting relatively short dataset of 26 years (from 1972-1997) inevitably provides an inherent limitation to the current study.

Caution should, however, be used even in the evaluation of this period, since there appears to be a change in the average relative intensity of the storms (Whitney and Hobgood, 1997). Throughout the period from 1972 to 1987, the average relative intensity (computed by dividing the maximum wind speed by the MPI) remained fairly constant, and this may reflect the consistent analysis of the intensities of the tropical cyclones over the NE Pacific Ocean over that period. However, between 1988 and 1993 the average relative intensity increased by approximately 10 percentage points (see Figure 2.1). On the one hand, this may reflect the fact that some of the most intense storms over this region occurred during these years. On the other hand, it must be noted that the forecasting responsibility of the NE Pacific was with the Eastern Pacific Hurricane Center in Redwood City, California until 1988 when the NHC, Miami assumed responsibility for the NE Pacific. Therefore, some of the increase noted above may be the result of changes in the analysis of the intensities of these systems. It seems likely that some of the intensities in the best track file are underestimated for the years prior to 1988, rather than being over-estimates in the more recent period (Whitney and Hobgood, 1997).

Unlike in the North Atlantic Ocean, there are usually no aircraft measurements of maximum wind speeds for the most intense hurricanes in the NE Pacific Ocean. Therefore, at this point, with the absence of aircraft data or other direct measurements of the intensities of these tropical cyclones, it is difficult to fully evaluate the apparent recent upward trend in relative intensities.

The record of landfalling tropical cyclones is more complete. But as more places were settled, there were more reports. Therefore a bias is also included in the landfalling data. For this reason, and the fact that there are problems with the wind measurements as the tropical cyclones made landfall (see below), and that the landfalling numbers per year from the NE Pacific tropical cyclones are low (on average 2 per year over the 26-year time period), landfalling storms are not considered in the current study.

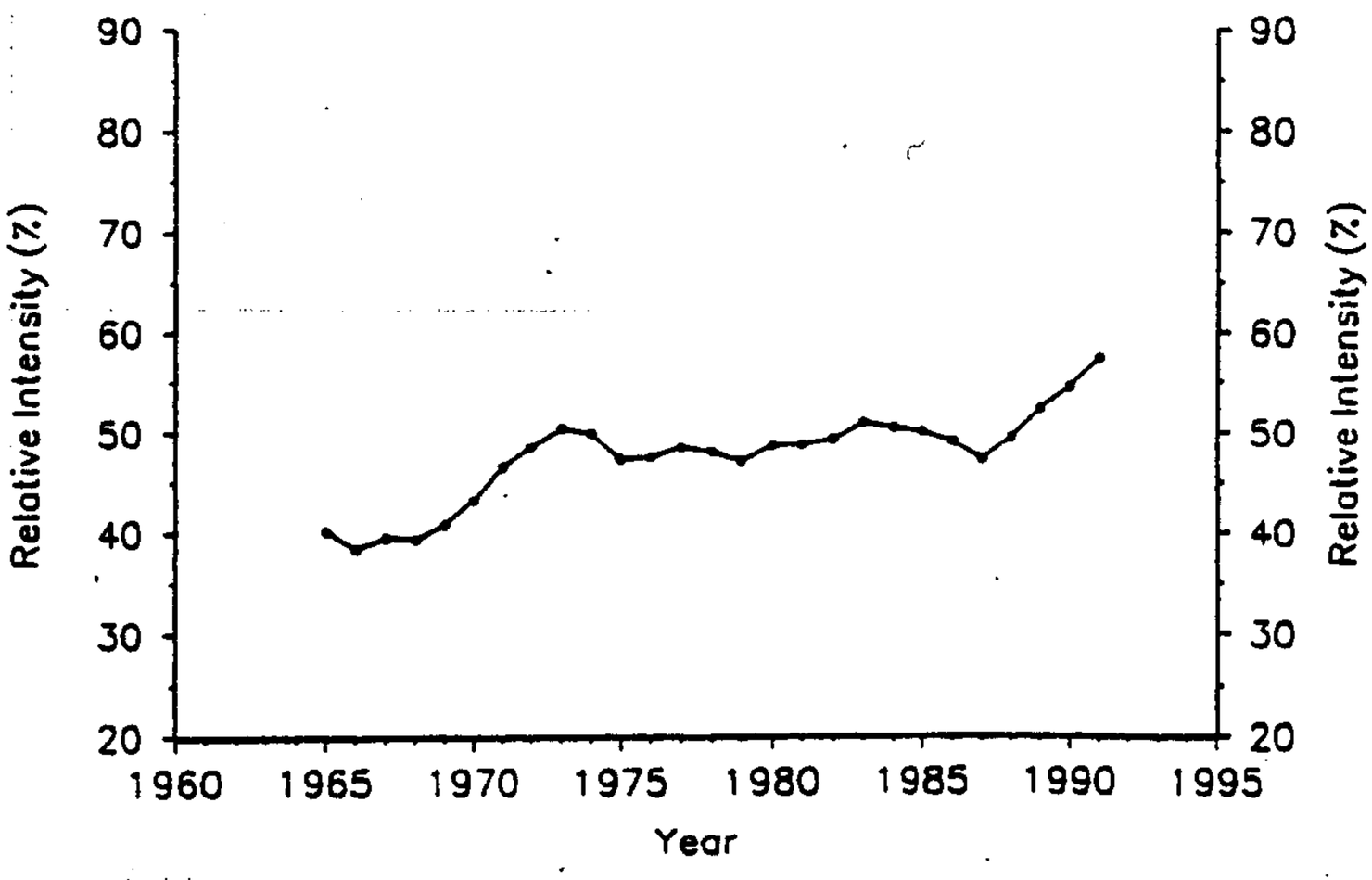


Figure 2.1 5-year running means of average relative intensity for the NE Pacific tropical cyclones (1963 to 1993). Taken from Whitney and Hobgood (1997).

The months chosen are based upon the maximum hurricane occurrence in the NE Pacific basin as depicted in Table 2.1. A subjective choice to restrict the majority of the analysis to include only tropical cyclones that began in July, August and September was made since these were the months in which the majority of hurricanes occurred, 73% collectively over the 1972-1997 time period. In addition, the monthly occurrence over each of these months is fairly uniform, compared to the preceding and subsequent months. The choice to group three months together is because in any one month the tropical cyclone numbers are relatively small and thus there is a need to investigate several months together. Furthermore, work done for the North Atlantic often examines the peak three months (which are the months where 80% of hurricanes occur during this time period) despite the official hurricane season lasting longer (i.e. from 1 June to 30 November).

Month	Total Number 1972 -1997
January	1
February	0
March	0
April	0
May	6
June	31
July	59
August	65
September	61
October	24
November	5
December	1
Total	253

Table 2.1 Hurricane occurrence by month in the NE Pacific basin (1972-1997).

Care must, however, be taken in the use of this tropical cyclone dataset since it was designed for a use other than that in this study, i.e. for short-term track forecasts and for developing statistical track models. Thus, these tropical cyclone data were not designed for climate studies, seasonal or interannual research or risk analysis. This therefore may introduce a source of error (Landsea, 1999, personal communication). In particular, as noted above, it has been noted that there are problems with wind measurements as the tropical cyclone makes landfall. It is thought that these problems mostly arose since

students digitised the maps after only one lesson. For example, there are instances where they seemed to double the wind speed and there was one hurricane which abruptly ended at 85 knots (44 m s^{-1}). To fix this latter problem, the Kaplan and DeMaria model (Kaplan and DeMaria, 1995) is being used to interpolate how a tropical cyclone would have ended.

2.1.2 The datasets of environmental variables

A large number of variables can be used to monitor the physical state of the atmosphere. Many of these variables play a part in the formation of a tropical cyclone. The environmental data can be examined in terms of a set of statistics for each of the variables which characterise the tropical atmosphere. The statistics can be displayed using various maps and graphs. These statistics are the key to understanding the climatology of the tropics, particularly the conditions affecting the hurricane.

The environmental data are mostly obtained from the NCEP/NCAR (National Center for Environmental Prediction/ National Center for Atmospheric Research) 40-year reanalysis project (Kalnay et al., 1996). The NCEP/NCAR reanalysis project has two unique characteristics, the length of the period covered and the assembly of a very comprehensive observational database. These factors make the data ideal for this study. The global data are now available from 1958-2000 on a 2.5° x 2.5° latitude/longitude grid for many vertical levels (the number of which depends on the variable in question) and have a six-hourly and monthly time resolution. Data can then be extracted for a specific latitude, longitude, six-hourly record (if required), month and year.

UK Meteorological Office historical sea surface temperature data were considered. However, this dataset was rejected since it has a spatial resolution of a 5° x 5° latitude/longitude grid which was coarser than the NCEP/NCAR dataset mentioned above. Furthermore, it was preferred that all the data be on the same grid if possible. The European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis was considered, but rejected in favour of the NCEP/NCAR reanalysis, due to the ECMWF reanalysis only being available from 1979. This dataset is used, however, in Section 4.1, but only in order to consider the reliability of the NCEP/NCAR dataset. From late 2002/early 2003, ECMWF reanalysis data will be available covering the period 1957-2001 (Stephens, 2001, personal communication).

The data chosen were included because it was felt that they either best characterised Gray's necessary conditions for tropical cyclone formation (see Section 1.5.1.1), or have been shown to have an important influence on hurricane frequency in other basins (see Section

1.5), or were necessary to examine the interannual variations of RH as seen in Chapter 5. The NCEP/NCAR reanalysis project provides the data for most of the environmental variables investigated. These are:-

1. Relative humidity at 500 hPa - RH
2. Sea surface temperature - SST
3. Temperature at 300 hPa - TMP
4. Pressure vertical velocity at 500 hPa - VVEL
5. Upward long-wave radiation flux -ULWRF
6. Lower level winds (850 hPa)
7. Lower level winds (surface - 10 m)
8. Upper air winds (200 hPa)
9. Wind shear obtained from (6) and (8) - VZ (see Section 2.2)
10. Pressure at mean sea level - PRES
11. U winds (zonal winds) at 50 hPa to obtain the QBO
12. Wind speed obtained from (7)

Pressure vertical velocity (VVEL) is a measure of convection/subsidence. VVEL is defined as dP/dt (P =pressure, t=time, dP/dt =rate of change of pressure following a parcel of air). A positive value of VVEL means that the parcel of air is subsiding, rather than a negative value which implies the air is rising.

Other data analysed are:-

1. Klaus Wolter's ENSO index (Wolter, 1987) - KW
2. The Pacific Decadal Oscillation (Mantua et al., 1997) - PDO
3. The Madden-Julian Oscillation (Maloney and Hartmann, 1998) - MJO
4. Out-going long-wave radiation (Waliser and Zhou, 1997) - OLR

Where abbreviations are used in this thesis they are as noted above.

Some of these indices will now be discussed in more detail. There does not exist one universally accepted index for ENSO, instead several ENSO indices exist. Klaus Wolter's (KW) Multivariate ENSO index (MEI), although fairly subjective in its weighting, has the advantage of including several variables into the index. The KW ENSO index is based on the six main observed variables over the tropical Pacific. These six variables are: sea-level pressure, zonal (U) and meridional (V) components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky (Wolter,

1987). A high positive/negative correlation with KW means that tropical cyclone indices are higher/lower in a positive/negative phase of ENSO respectively (El Niño/La Niña).

Another ENSO index is the SOI index, an objective index which examines the pressure difference between Darwin and Tahiti. A high positive/negative correlation with the SOI index means that tropical cyclone indices are lower/higher in a positive/negative SOI year (La Niña/El Niño) respectively. Alternatively, SSTs provide another index, where Niño 1, 2, 3 and 4 simply describe the average SST in those particular areas (see Table 2.2 for the definition of these areas).

ENSO Index	Region	
Niño1	5°S - 0°	90°W - South American Coast
Niño2	10°S - 5°N	90°W - South American Coast
Niño3	5°S - 5°N	150°W - 90°W
Niño4	5°S - 5°N	160°E - 150°W

Table 2.2 Definition of SST-based ENSO indices

Recently, Trenberth and Stepaniak (2001) suggested that for optimal characterisation of the distinct character and evolution of each El Niño and La Niña, at least two indices are required: SST anomalies in the Niño3.4 region (5°S to 5°N, 170°W to 120°W) and a new index that they have devised called the 'Trans-Niño Index' (TNI) which is defined as the difference between the normalised SST anomalies averaged over the Niño1+2 (10°S to 0°, 90°W to South American coastline) and Niño4 regions. The Niño3.4 index represents the mean equatorial SST across the Pacific from near the dateline to the South American coast, whilst the TNI represents the gradient across the same region.

As Irwin III and Davis (1999) pointed out, the classification scheme chosen may depend on the location of the area of study and the thresholds established by the various researchers. Elsner and Kocher (2000) used KW's ENSO index, whereas Trenberth (1997) used the SST based Niño3 and Niño3.4 regions and Irwin III and Davis (1999) used the SOI index. In this study, the KW, SOI and SST-based indices given in Table 2.2 are considered. The TNI is not considered since it has only recently been suggested.

The MJO is a modulation of tropical convection and winds (Madden and Julian, 1994) with variations of approximately 30-60 days. The MJO describes the magnitude of the 850 hPa zonal wind field at a particular time (Maloney and Hartmann, 1998, 2000). Although the

MJO index given by Maloney and Hartmann (1988, 2000) describes an intraseasonal oscillation, in this study it was decided to use an index based on the amplitude of the oscillation. Maloney (1999, personal communication) suggested and calculated the variance as a suitable measure. The MJO index used in this study is derived from the MJO index of Maloney and Hartmann (1998). Thus, the interannual variations of the average variance of the Maloney and Hartmann MJO index for the July-September period are examined herein in relation to tropical cyclone frequency, and this gives an indication towards strong or weak MJO events, not whether westerly phases or easterly phases are bigger.

One of the variables used in this study is out-going long-wave radiation (OLR). Liebmann and Smith (1996) advised caution in the use of satellite-derived data by describing how the complete OLR dataset is comprised. Due to satellite problems, archival problems or incomplete global coverage, data are missing in some grids. However, thorough temporal and spatial interpolation has been used to complete the dataset. The results are checked through a "buddy" test, to ensure that any value cannot deviate too far from the surrounding values, although they do take into account regions of large gradient, e.g. a land-ocean boundary where there is a distinct possibility that the value at the grid point could actually be quite different from its neighbours. Thus, although data based on observation alone are preferable, the derived fields are generally considered to be a complete and usable dataset.

Actual OLR against model-derived values (ULWRF) have been analysed for confidence in the NCEP/NCAR analyses (see Section 4.1). The OLR dataset shows the thermal radiation from cloud as it is a measure of deep convection. The higher the OLR, the lower (warmer) the cloud tops, i.e. the shallower the convection. 240 W m^{-2} is thought to be a good indicator of deep convection. NOAA OLR data between 1974-1995 is used for validating the reliability of the NCEP/NCAR reanalysis data (Waliser and Zhou, 1997). The data are available on a 2.5° resolution for 25 latitudes between 30°N and 30°S, and available for 144 longitudes with a 2.5° resolution between 180°W to 180°E. There are missing data, however, for the year 1978 due to a satellite failure.

There are some other OLR indices. Collimore has recently improved the calculation of the NASA OLR monthly anomalies. He is in process of doing this and the data should be available shortly (Collimore, 2000, personal communication).

The monthly data described above are averaged over the months July-September (to correspond with peak hurricane activity as discussed in Section 2.1.1 and because the

environmental variables are fairly constant over these months). Following Hastenrath and Wendland (1979) who averaged SST over large areas, the data are averaged over relatively large areas to obtain one single value for each year for a time-series (see Chapter 4).

2.1.3 Possible problems with the environmental datasets

In situ sampling from ships and buoys does not, in general, yield sufficient spatial or temporal data resolution over the vast ocean regions that cover more than 70% of the planet. Carefully calibrated and adjusted satellite data, sometimes blended with *in situ* observations as a data processing procedure, provide the best estimate of global ocean conditions. Given the vast regions of the ocean, and the relatively sparse sampling that occurs, almost any available data are considered useful.

There are large surface and temporal gaps in the surface station coverage. Tropical regions have been the worst in achieving the WMO's goal for more observing stations (WMO, 1989). However, although the tropical North Atlantic and NE Pacific Oceans do not have large areas of data coverage, there are a number of studies which have made successful use of the environmental analysis of NCEP/NCAR in data-sparse regions of the tropics and sub-tropics.

The large-scale climate, with which this study is concerned, is described with gridded data. Gridded data, as opposed to station data, have the advantage that they represent the full spatial distribution. However, as has been alluded to, in data-sparse areas, such as the NE Pacific, the gridded value may be more representative of the forecast models, and interpolation schemes that are used, than they are of the actual state of the climate system. Reliability is compromised when the data are interpolated to a regular grid using techniques that make assumptions about atmospheric dynamics and introduce biases that are not present in the "raw" station data. Unfortunately, when used for diagnostic purposes, it is impossible to distinguish between observed and interpolated information. Difficulties also arise because most gridded data are produced from numerical weather forecasting models and therefore are affected by changes in the forecast and analysis systems, such as better approximations in the analyses, or more advanced computer hardware.

In this study, *reanalysis* data (rather than the original *analysis* data) have been used, taking advantage of a fixed analysis system, which has done much to ameliorate this problem. As noted above, there are clearly concerns regarding the spatial and temporal noise when using gridded data, including the level of quality control and the selection of interpolation procedures used. One has to consider whether the procedures used to derive the gridded

data products have adversely affected statistical inferences. Thorough metadata (i.e. information about the data) are important to help scientists in answering these questions. Reanalysis of these gridded data provides researchers with a relatively clean series of analyses so that introduced inhomogeneities from different model numerics, physics, horizontal and vertical resolutions and other changes over time which go into these analysed grids are removed or reduced. It must be noted, however, that reanalysis data are still affected by the type of observing systems used (such as different satellites or the distribution and number of surface stations).

The inaccuracies of the radiosonde and rawinsonde data are as follows. The pressure instrument is accurate to about ±1 - 2 hPa, temperatures are accurate to ±0.5°C up to about 20 km, RH accuracy is a few percent (except at very low temperatures and at very low or very high humidities) and wind accuracies are about 3 m s^{-1}. Systematic biases in the temperature or humidity measurements can introduce large errors in the estimate of geopotential height (Shea et al., 1996).

From the examples given above, there are clearly deficiencies within the datasets. It is important to address the reliability of the NCEP/NCAR reanalysis data. Kalnay et al. (1996) noted the variables which they believe to be more reliable than others overall in the analysis. Such reliability is based upon whether the analysis of a particular variable is strongly influenced by observed data or if the variable is derived mainly from the model. The data are considered most reliable where the variables have been mainly influenced by observational data. Such variables include sea surface temperature, upper air temperature, wind, sea level pressure and relative vorticity. (Apart from coastal stations on the mainland of North America, the atmospheric station data from the NE Pacific that went into this analysis are from a rawinsonde station at Socorro (18.7°N, 110.9°W) and the Hawaiian Islands (see Figure 1.2).) Pressure vertical velocity, relative humidity and precipitable water are strongly influenced by both the observed data and the model. Upward long-wave radiation flux at the top of the atmosphere is the only variable that is derived from the model without direct observational data. This assessment gives us some confidence in most of the environmental variables used. When discussing SSTs, Hennon (2000, p. 7) noted that the "correlation between observations and the reanalysis grid points is very high". This is expected as temperature is a "high confidence" variable in the reanalysis dataset, as described above (Kalnay et al., 1996). The quality of these analyses generally varies with the density of the observational network used to derive them. The reliability of the NCEP/NCAR reanalysis data in the remote region that this study concentrates on, is of particular concern. It was mentioned above that the station data from the NE Pacific that

went into this analysis is from very few stations, hence the analysis of these atmospheric data relies heavily on model output. It has been recognised (Hobgood, 2000, personal communication) that the reanalysis tended to over-estimate with regard to sea level pressure. This was discovered when examining Socorro's data, even though Socorro's data itself went into the reanalysis. A thorough examination of the reliability of the NCEP/NCAR reanalysis data, as used in the current study, is discussed in Section 4.1.

There are various types of error that may have been included within the results, and an attempt has been made to reduce the errors as much as possible. Illegitimate errors, e.g. as described by Bevington and Robinson (1992), are those which are the easiest to identify and these result from user mistakes during measurement and computation. Since the data are secondary data, i.e. data not obtained directly by oneself, one has to assume that the researchers were thorough with their collection and recording. Further computational work in this study has been checked thoroughly in an attempt to avoid this type of error.

Errors may be introduced if incorrect distributions are chosen to represent the data in the analyses. This is particularly relevant for tropical cyclone frequency, where the Poisson rather than the normal distribution is chosen (see Section 2.3). Considerable effort was taken to ensure that the best distribution for the data, and the associated appropriate techniques, were then used in the analysis.

2.2 A new method for the calculation of monthly averaged wind shear

It was noted in Section 1.5.1.1 that vertical wind shear is one of the six factors noted by Gray (1979) which is necessary for tropical cyclone formation. This section evaluates two different approaches to calculating vertical wind shear as a seasonal average, one using monthly data and the other considering six-hourly data. Currently in the literature, the former approach is adopted, e.g. Goldenberg and Shapiro (1996) and Landsea et al. (1998). However, the results presented here show that the latter approach should be used.

Vertical wind shear is the magnitude of the vector difference in wind velocity at two heights. Section 1.5.1.2 provides a discussion of the physical mechanism involved in the relationship between vertical wind shear and tropical cyclone formation. Several authors have found relationships between seasonally averaged vertical wind shear and hurricane formation in certain regions, notably the North Atlantic. These include Goldenberg and Shapiro (1996) and Landsea et al. (1998). However, the calculation of seasonally averaged vertical wind shear in these papers may not be by the most appropriate method.

Seasonally averaged vertical wind shear has historically been calculated from the monthly mean zonal and meridional components of wind at two levels. For example, the monthly average wind shear between two pressure levels of 850 hPa and 200 hPa is given as

$$\overline{VZ} = \sqrt{(\overline{U850} - \overline{U200})^2 + (\overline{V850} - \overline{V200})^2} \tag{2.2}$$

where the bars indicate averages of the six-hourly values of each wind variable separately, over the month. *U850, U200, V850* and *V200* indicate the U and V wind components, in units of m s^{-1}, at lower and upper levels respectively. For the seasonal analysis in this section, $\overline{VZ}$ is taken to mean the seasonally averaged wind shear. All other sections use VZ to represent a seasonal average, where applicable, in accordance with the style used for the other variables.

However, for tropical cyclone studies in particular, which examine interannual variations, the aim of calculating $\overline{VZ}$ is to determine the mean (i.e. time average) of the instantaneous wind shear during the season when tropical cyclones form. Therefore, it is more physically meaningful and accurate to use a $\overline{VZ}$ calculated as the average of the six-hourly winds using the equation

$$\overline{VZ} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(U850_i - U200_i)^2 + (V850_i - V200_i)^2} \tag{2.3}$$

where n is four times the number of days in the month and each increment in i represents a time-step of six hours.

Different values of $\overline{VZ}$ will generally result from these equations. As an example, $\overline{VZ}$ is calculated below using Equation 2.2 and 2.3, setting

$n=2$

$U850_1 = 14$ m s^{-1}

$U850_2 = 6$ m s^{-1}

$U200_1 = U200_2 = 10$ m s^{-1}

$V850_1 = V850_2 = V200_1 = V200_2 = 0$ m s^{-1}

As a consequence of this, Equation 2.2 gives a $\overline{VZ}$ of 0 m s^{-1}, whereas Equation 2.3 gives a $\overline{VZ}$ of 5.66 m s^{-1}. As can be seen from Figure 2.2, Equation 2.3 will always give values of shear greater than or equal to those given by Equation 2.2. The same is true for other wind variables, such as horizontal wind shear and wind speed. (Arguably even more

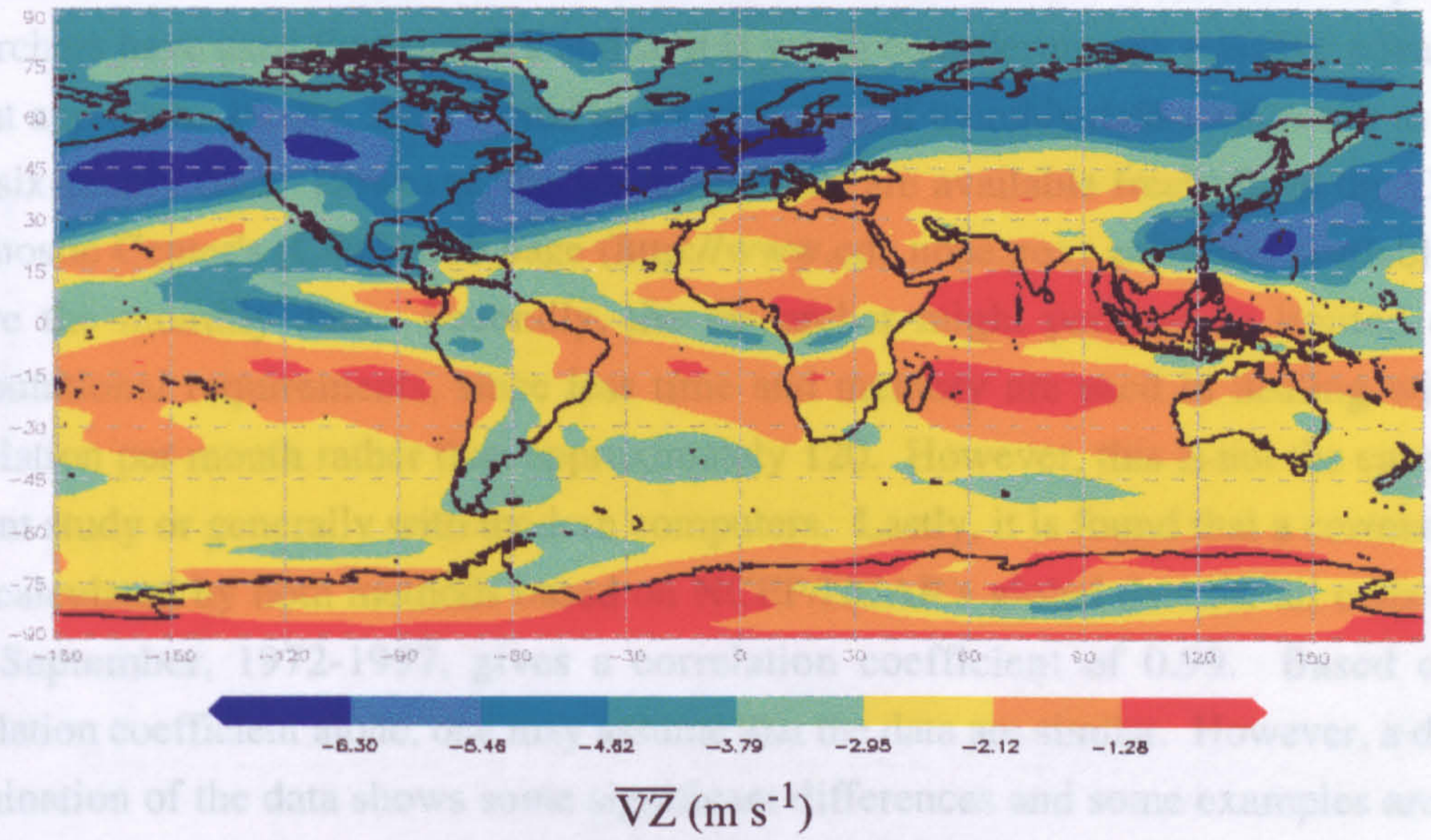


Figure 2.2 Comparison between two methods of calculating $\overline{VZ}$. Equation 2.2 - Equation 2.3 for the period (1969-1999). $\overline{VZ}$ calculated between 850 and 200 hPa, between August and October.

accurate results would be obtained from even greater time resolution, but six hours is the minimum period available.)

Therefore, this new method of averaging $\overline{VZ}$ should be adopted as a more accurate measure of the mean of the instantaneous vertical wind shear. Nevertheless, previous researchers have used Equation 2.2 and so it is worth considering any possible advantages of that approach. Firstly, there would be an advantage if monthly data were easier to obtain than six-hourly data. However, the six-hourly data are available freely from the Climate Diagnostic Center's (CDC) web page (http://www.cdc.noaa.gov) and were available even before the monthly data. Secondly, the researcher might perhaps be limited due to computational requirements, since less time and memory are used in dealing with one calculation per month rather than approximately 120. However, this is not the case in the current study or generally with modern computers. Lastly, it is found that a correlation of $\overline{VZ}$ calculated by both methods based on NCEP/NCAR's global data for all cells during July-September, 1972-1997, gives a correlation coefficient of 0.99. Based on this correlation coefficient alone, one may assume that the data are similar. However, a detailed examination of the data shows some significant differences and some examples are given below.

Using the NCEP/NCAR gridded dataset (144 longitudes by 73 latitudes) a comparison of the values obtained by both methods is made, and the results are shown in Figure 2.3 for July-September, 1972-1997. 43% of the data have a difference of $\overline{VZ}$ which is greater than or equal to 3 m s^{-1}.

Figure 2.2 gives a comparison between the two methods over the globe. It can be seen that results obtained from Equation 2.2 in the tropics are more accurate (i.e. more similar to Equation 2.3) than in the mid-latitudes of the Northern Hemisphere where differences of as much as 7 m s^{-1} are found. This is to be expected given that wind speed and direction are highly variable in the Northern Hemisphere mid-latitudes compared with the tropics. In the light of these results, it is suggested that Equation 2.2 should not be considered for work in the Northern Hemisphere mid-latitudes, although it could perhaps be used in the tropics (with some caution). In the Southern Hemisphere mid-latitudes, Equation 2.2 gives better values than in the Northern Hemisphere mid-latitudes, but again not as good as the Southern Hemisphere tropics.

An analysis of the results and conclusions of Landsea et al.'s (1998) discussion of the unusually active season of 1995 in the North Atlantic, shows that the actual values of $\overline{VZ}$

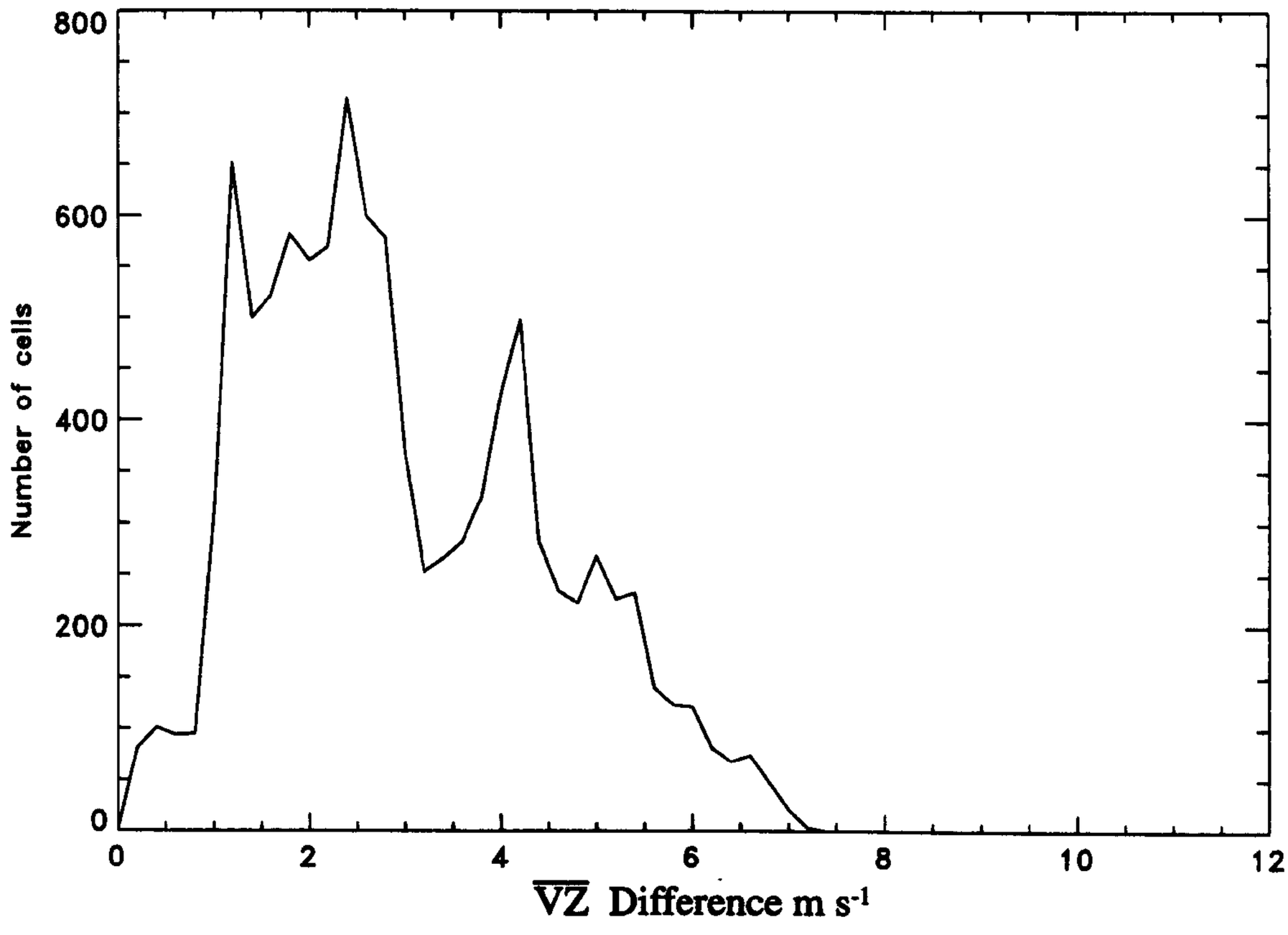


Figure 2.3 Differences in $\overline{VZ}$ (m s^{-1}) for all cells on the globe, Equation 2.3 - Equation 2.2 (July-September, 1972-1997).

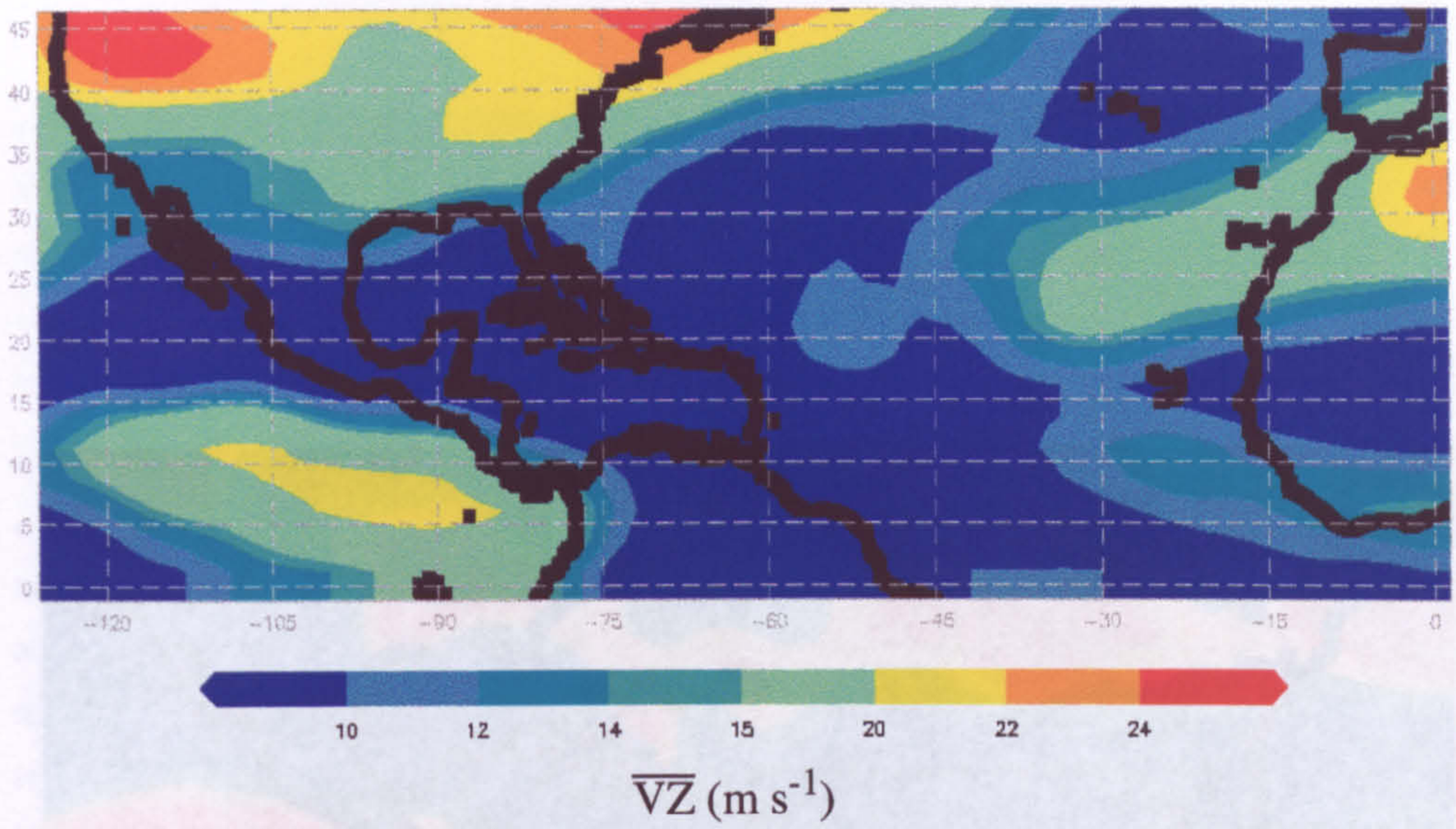
are much smaller in the North Atlantic using Equation 2.2 (as used by those authors) than Equation 2.3 (see Figure 2.4a and 2.4b respectively). Landsea et al. (1998) explain that 1995 was a particularly active season, based on critical (minimum) values of vertical wind shear for an inactive season given by Zehr (1992) and DeMaria et al. (1993) of between 7.5 and 12.5 m s^{-1}.

An examination of Figure 2.5 which shows the $\overline{VZ}$ anomalies for 1995 derived by Equation 2.3 (where the anomalies are based on the years 1979-1995, the same climatology as that given by Landsea et al, 1998), indicates that 1995 is still slightly lower than the mean in the MDR and Caribbean, a conclusion that Landsea et al. (1998) drew from using Equation 2.2. However, by taking the anomaly of 1995 divided by the standard deviation of the $\overline{VZ}$ distribution between 1979-1995, Figure 2.6 shows that Equation 2.2 makes these negative anomalies in the MDR and Caribbean much stronger than those using Equation 2.3. For example, it can be seen that in the MDR there is a region that is greater than two standard deviations less than the mean using Equation 2.2 which is not present using Equation 2.3, and that the area in the MDR which has a negative anomaly of greater than one standard deviation away from the mean is larger with Equation 2.2 than Equation 2.3. Thus, 1995 did not have such an anomalously low $\overline{VZ}$ when compared to other years in the distribution. Therefore, although the overall conclusions of Landsea et al. (1998) do not change, in that 1995 had lower than average $\overline{VZ}$, perhaps the emphasis on this variable is slightly overstated. In fact, there have been several other years with similar $\overline{VZ}$ patterns in the North Atlantic hurricane formation latitudes (typically north of 10°N) as those in Figure 2.5, but these did not have such an active season. Examples include 1982 and 1994 (see Figure 2.7), where there was only one hurricane in each of these years in the peak hurricane season (August-October), compared with nine in 1995.

Goldenberg and Shapiro (1996) correlated $\overline{VZ}$ (calculated using Equation 2.2) with major hurricane numbers in the North Atlantic. Figure 2.8 shows that the region of correlation significant to the 10% level (given by a *t*-statistic with an absolute value greater than 1.714) is much smaller and does not extend as far across the North Atlantic from the Caribbean when using Equation 2.3 than Equation 2.2. However, despite the change noted when Equation 2.3 is used, the general sign of the relationship with major hurricane numbers is similar. Thus, when an author shows a significant relationship with $\overline{VZ}$ in the tropics, the general sign of the relationship is likely to be similar whichever equation is used for the calculation of $\overline{VZ}$.

Note that Figure 2.8 is different from Figure 6 in Goldenberg and Shapiro's 1996 paper.

a)



b)

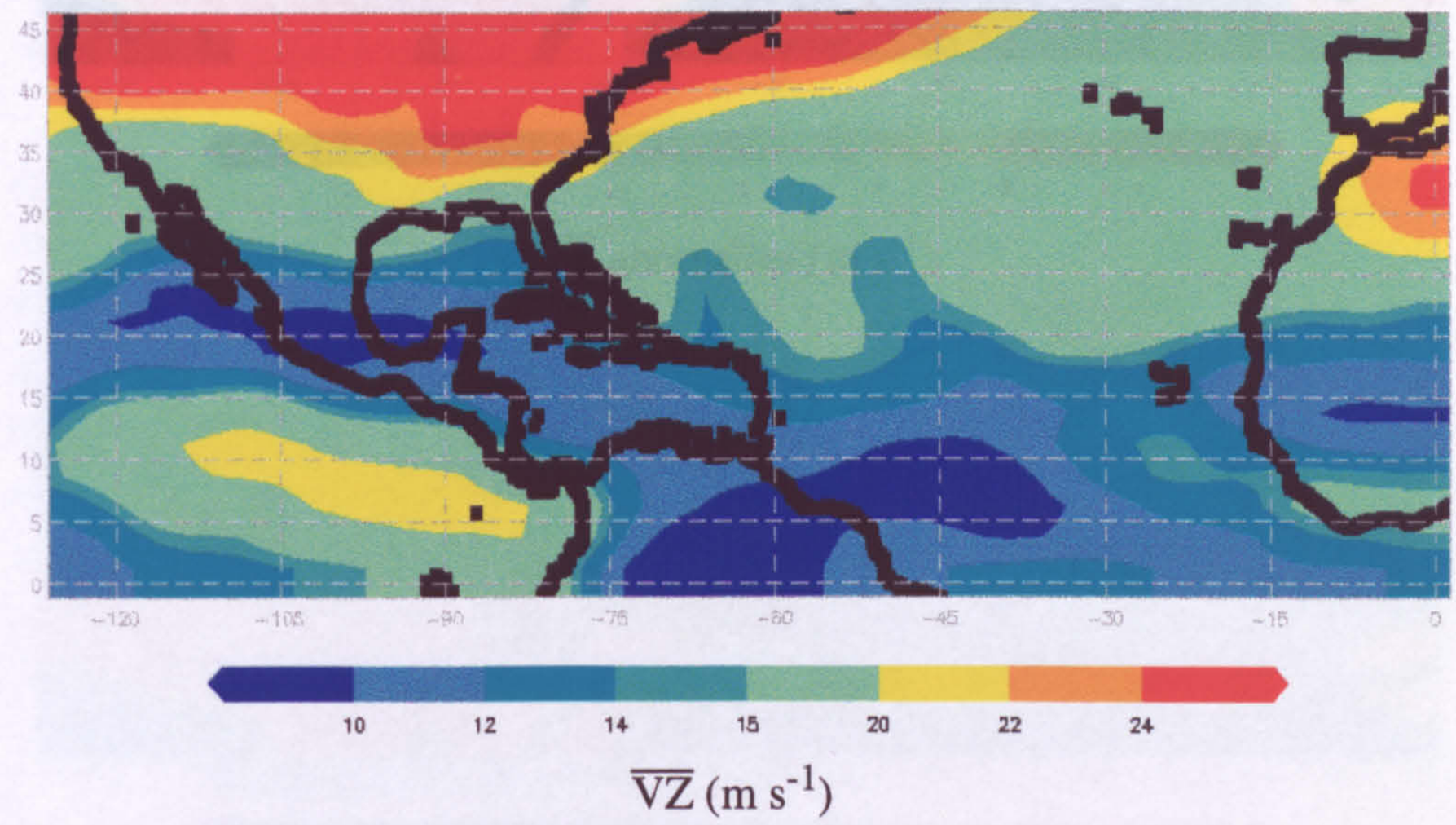


Figure 2.4 $\overline{VZ}$ in August-October 1995 using a) Equation 2.2, and b) Equation 2.3. $\overline{VZ}$ calculated between 850 and 200 hPa.

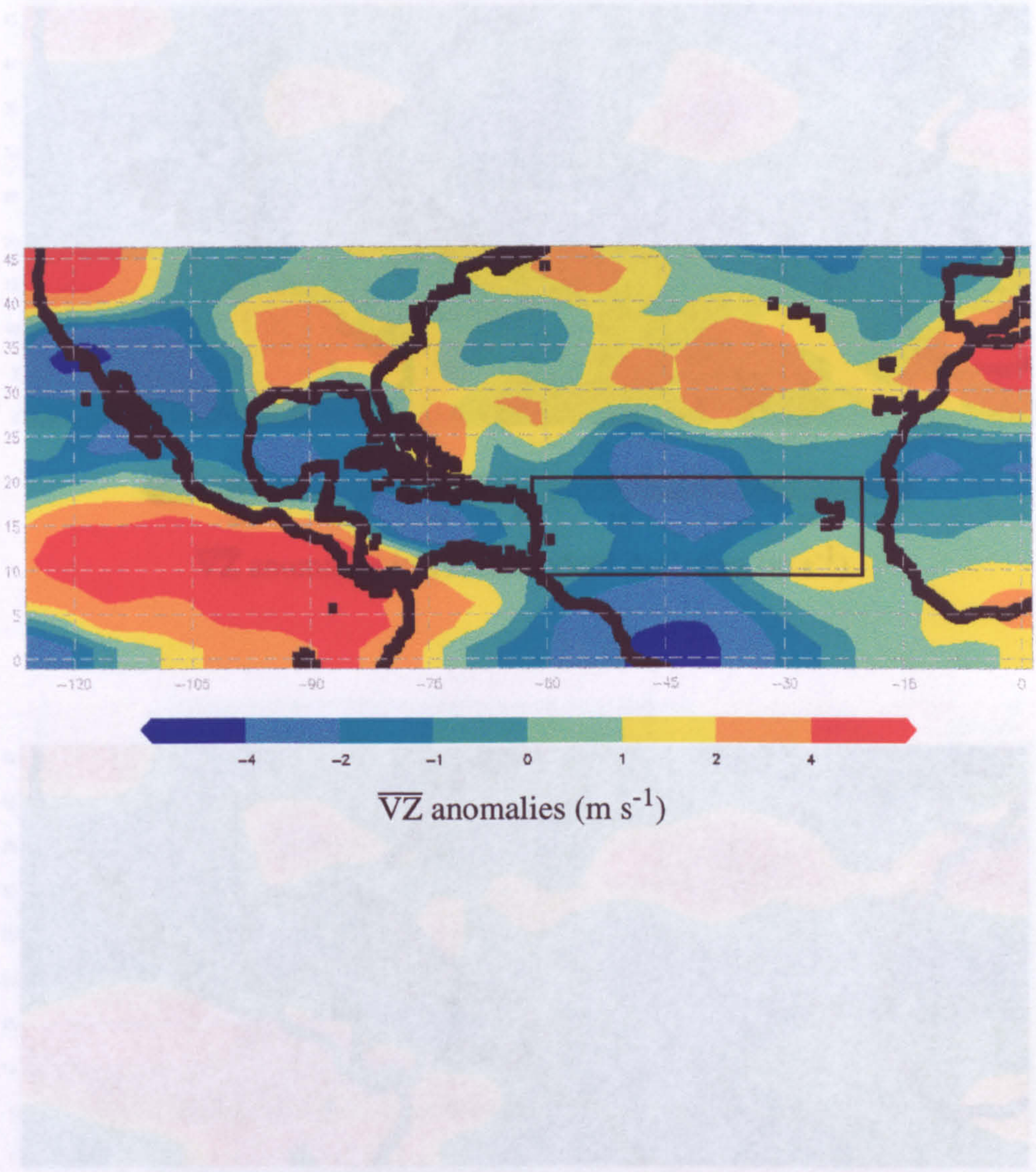
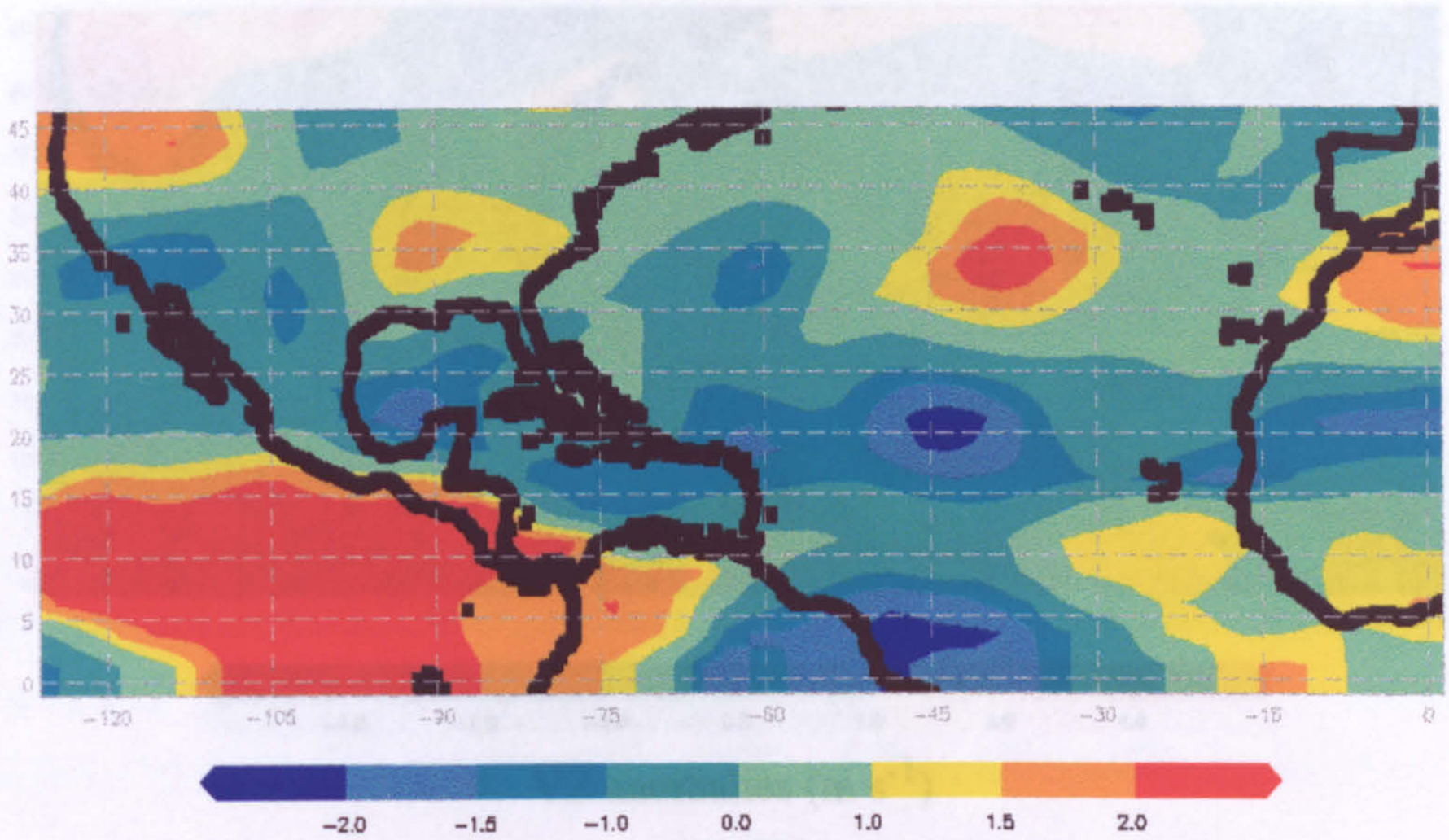


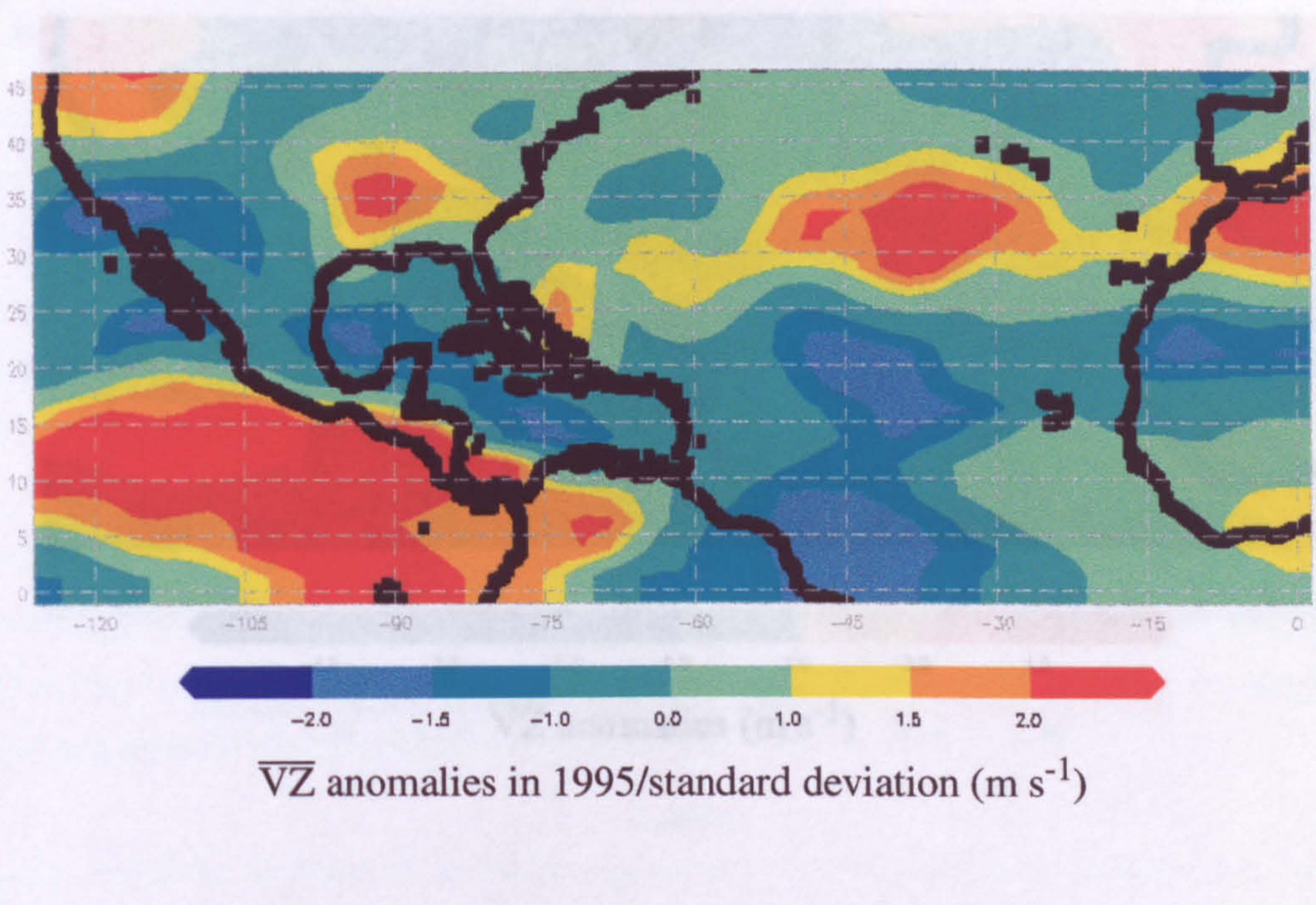
Figure 2.5 $\overline{VZ}$ anomalies for August-October 1995 using Equation 2.3 (climatology, 1979-1995). Wind shear calculated between 850 and 200 hPa. Box is the Atlantic MDR.

a)



$\overline{VZ}$ anomalies in 1995/standard deviation (m s^{-1})

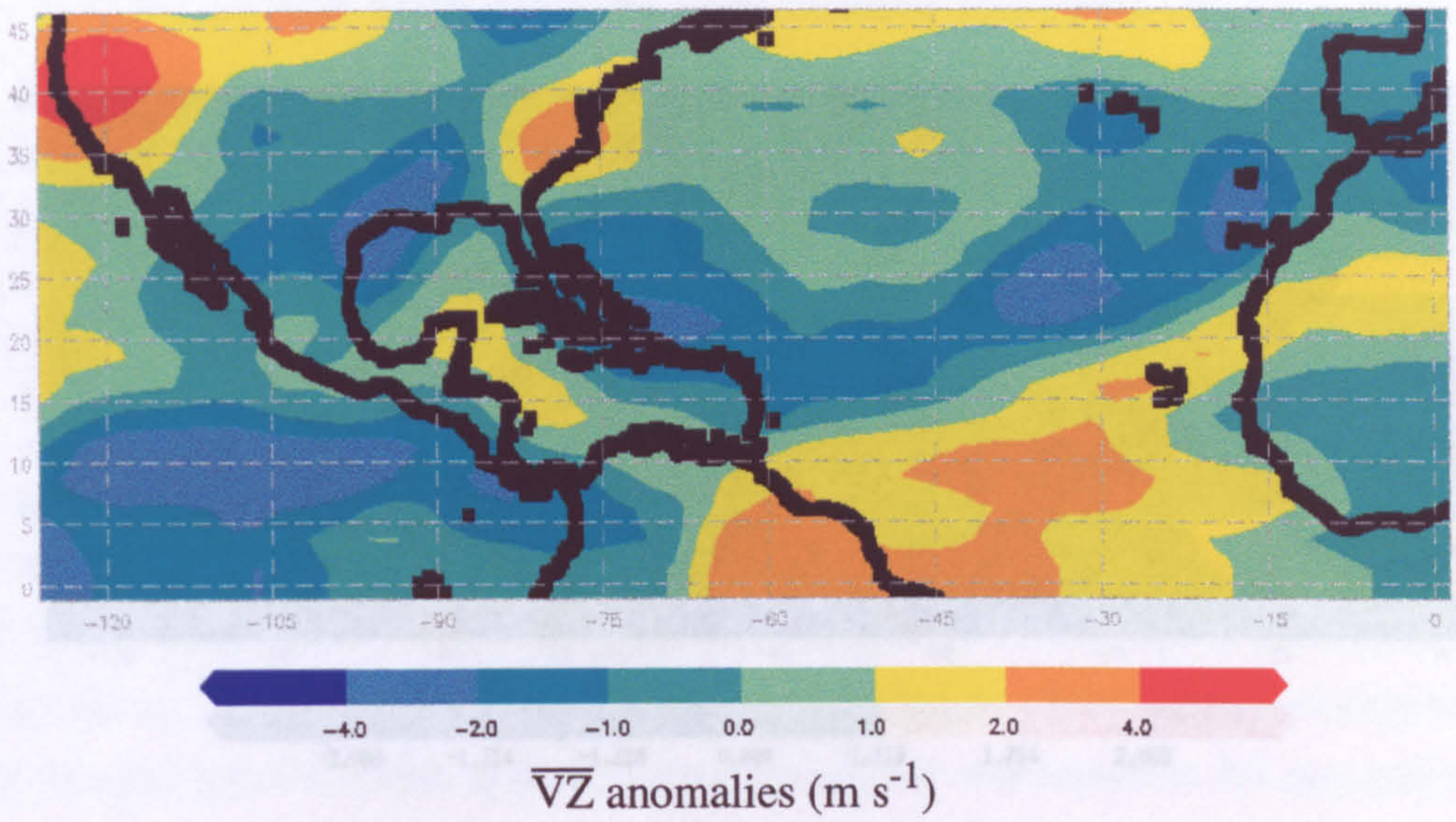
b)



$\overline{VZ}$ anomalies in 1995/standard deviation (m s^{-1})

Figure 2.6 $\overline{VZ}$ anomalies for August-October 1995/ standard deviation of the $\overline{VZ}$ time series (climatology, 1979-1995) using a) Equation 2.2, and b) Equation 2.3. $\overline{VZ}$ calculated between 850 and 200 hPa.

a)



b)

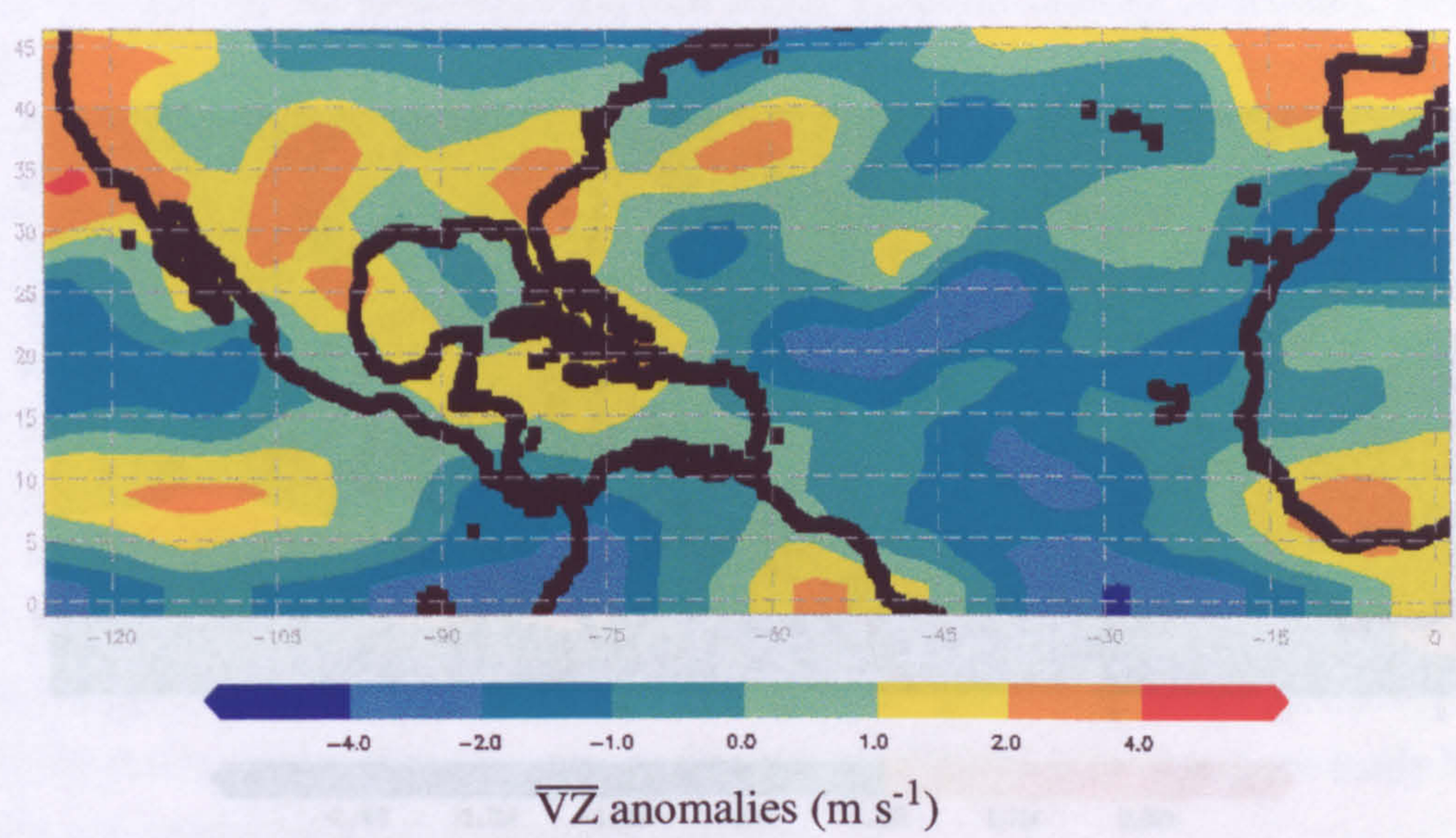
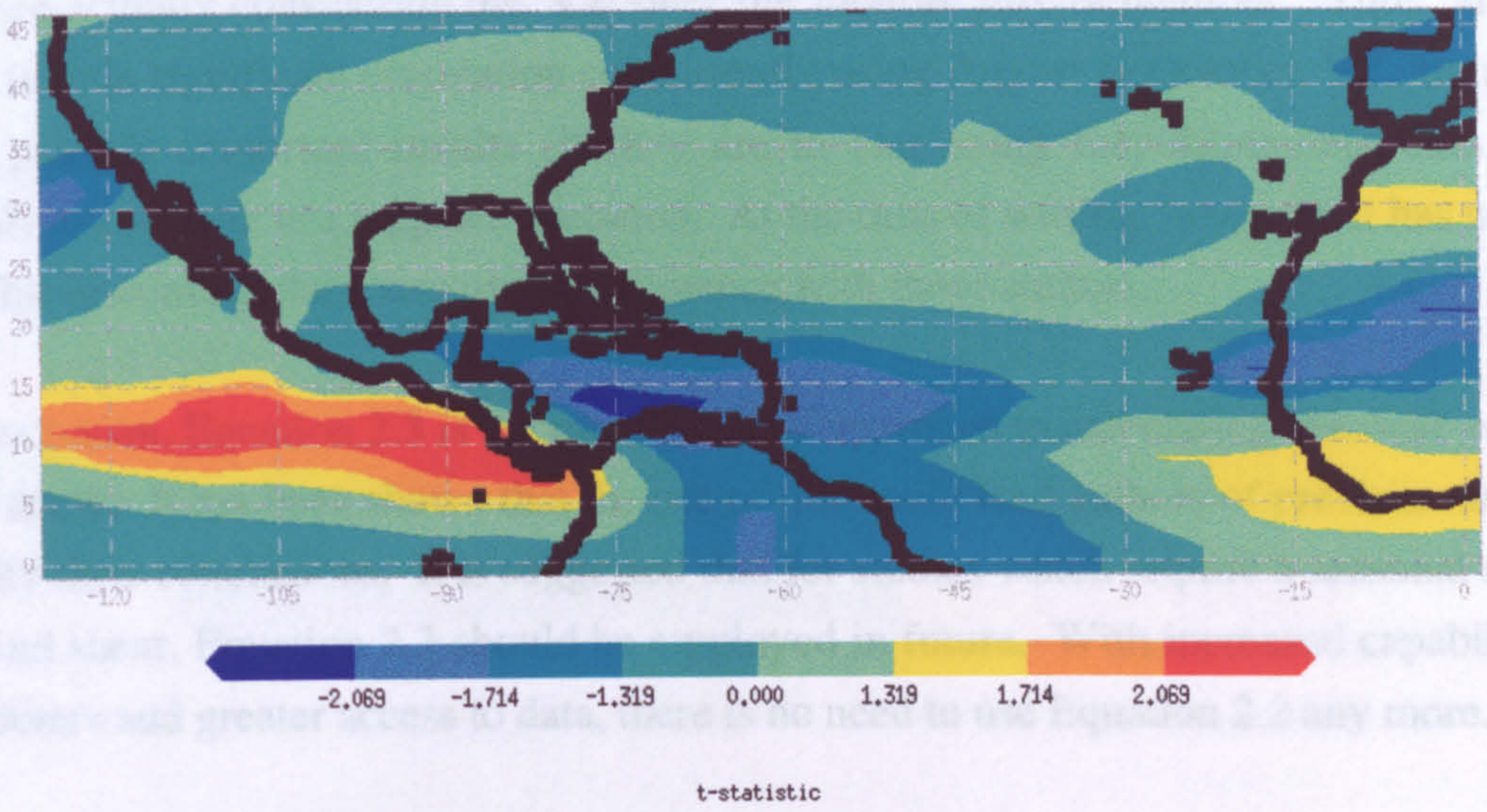


Figure 2.7 $\overline{VZ}$ anomalies using Equation 2.3 for the months August-October for a) 1982, and b) 1994. Climatology (1979-1995). $\overline{VZ}$ calculated between 850 and 200 hPa.

a)



b)

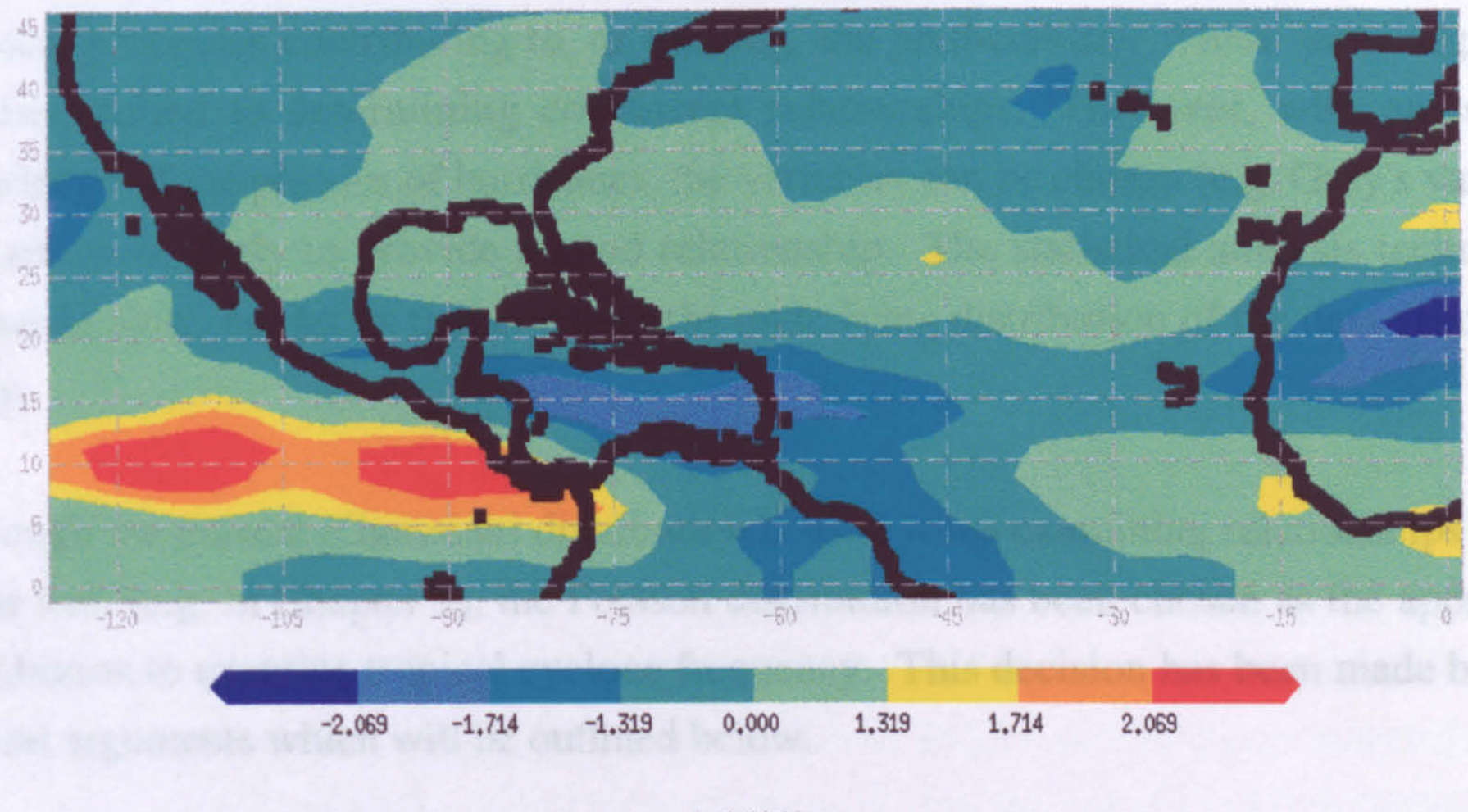


Figure 2.8 *t*-statistics showing the relationship between major Atlantic hurricanes and $\overline{VZ}$, August-October (1968-1992) using a) Equation 2.2, and b) Equation 2.3. $\overline{VZ}$ is calculated between 700 and 200 hPa. *t*-statistics are given with absolute values of 1.714 and 2.069 representing associations with greater than 10% and 5% significance respectively. Figure 2.8a is slightly different from Figure 6 in Goldenberg and Shapiro's (1996) paper primarily since they used analysis and not the reanalysis data.

This may be mainly because they used analysis and not reanalysis data. However, it can be shown (Figure 2.9) that when using the more accurate reanalysis data, it is possible that they are actually considering the $\overline{VZ}$ over the months July-September. Thus, although there is little significant correlation concurrently using August to October $\overline{VZ}$, their work does provide important results (if they are in fact using July-September data of the reanalysis) as there is a lagged correlation. At the time of writing, however, it has not been possible to confirm the cause of this difference with those authors.

In conclusion, Equation 2.3 is the more accurate approach to calculating seasonal averaged wind shear. It has been shown that the use of this could lead authors of previous studies to modify their conclusions. It is suggested that for studies which require a seasonal average of wind shear, Equation 2.3 should be employed in future. With increased capabilities of computers and greater access to data, there is no need to use Equation 2.2 any more.

2.3 Statistical analysis technique

Statistical analyses provide empirical knowledge that, for lagged relationships, can lead to skilful forecasts in the absence of explicit physical understanding (Barnston, 1994). The information gained in this process may provide guidance towards identification of the physical processes contributing to, or limiting, the predictability. These same arguments can be applied to determining concurrent relationships. However, with an *a priori* knowledge of the physics of hurricanes, the variables can be chosen (e.g. Gray's variables) that are most likely to provide a good relationship. The statistical analysis technique is outlined below, but let us first consider the underlying distribution of the data used in this study.

Although the normal (Gaussian) distribution is used when examining relationships of non-count data (e.g. in Chapter 5), the Poisson distribution has been chosen as the appropriate distribution to examine tropical cyclone frequency. This decision has been made based on several arguments which will be outlined below.

Tropical cyclone formation is a point process (Cox and Isham, 1980), i.e. a system in which points occur in space or time. The tropical disturbances that seed tropical cyclones have been discussed in Section 1.4. There are many easterly waves (about 70-100 form off Africa per year, as well as some that form around the NE Pacific). A small proportion of these become tropical cyclones, and again only some of these become tropical storms and then hurricanes. Although the easterly waves occur at fairly regular time intervals (i.e. they are a non-Poissonian process), at each stage there is a random deleting mechanism

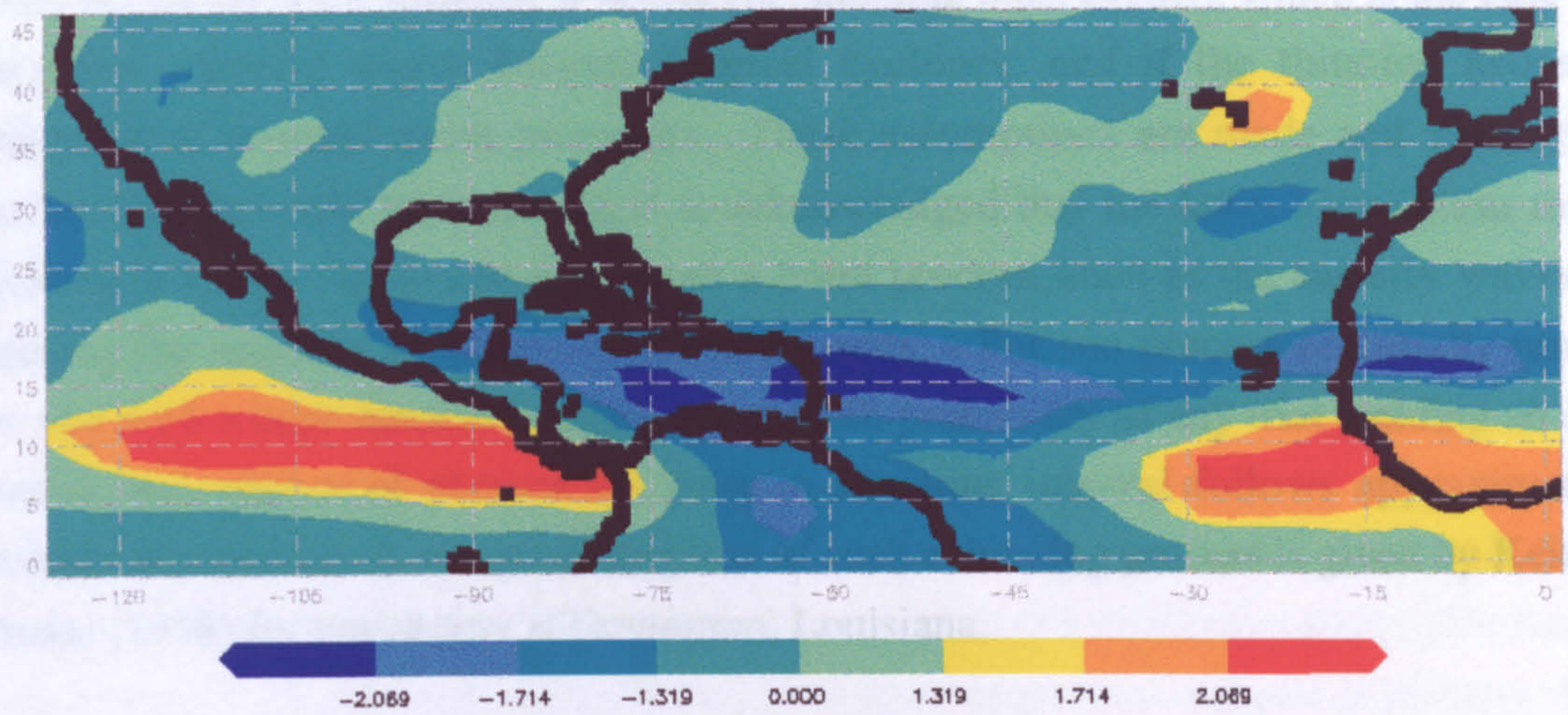


Figure 2.9 *t*-statistics showing the relationship between major Atlantic hurricanes and $\overline{VZ}$, July-September (1968-1992) using Equation 2.3. $\overline{VZ}$ is calculated between 700 and 200 hPa. *t*-statistics are given with absolute values of 1.714 and 2.069 representing associations with greater than 10% and 5% significance respectively.

occurring. This deletion mechanism results in a thinned process which is approximately a Poisson process if the thinning is severe (i.e. deleting most events), which is the case since very few easterly waves become tropical cyclones; and if the thinning process is independent of other point processes. These assumptions are made and although the former is reasonable to conclude, it is acknowledged that the latter assumption may be violated at times. In conclusion, given a point process, such as the easterly waves, and deleting the majority of randomly selected events, a Poisson process essentially remains, i.e. one with a large number of trials, but a small probability of any trial yielding an event. Hence, the number of tropical cyclones in any time interval follows approximately a Poisson distribution. A similar description of such a thinning process is given by Keim and Cruise (1998) for nor'easters at Covington, Louisiana.

A further reason for the choice of the Poisson distribution is that when dealing with tropical cyclone numbers in the NE Pacific which are count data, small numbers are considered, and thus they are not at all representative of a normal distribution. The annual incidence of events that is required to be predicted in each region is low - on average fewer than 3.1 tropical storms per season, and yet fewer hurricanes and intense hurricanes, which thus are rare events. The Poisson approximates to the normal for an average of approximately thirty events. Therefore least-squares fitting, assuming a Gaussian distribution, will not be appropriate for small numbers of tropical cyclones as the errors are not normally distributed. Furthermore tropical cyclone numbers in the NE Pacific are discrete, non-negative values which a Poisson distribution can account for, whereas the normal distribution does not rule out the possibility of negative numbers. When considering hurricane numbers which clearly cannot go below zero, the normal distribution would thus present a problem.

Hope and Neumann (1969) show that, for the North Atlantic basin, the frequency of discrete numbers of storms passing through a given area over a given time interval is described by the Poisson distribution. Furthermore, Elsner and Schmertmann (1993) used such a regression and gave a discussion based on skill of the benefits of Generalised Linear Models (GLMs, see below) using the Poisson as opposed to the least absolute deviation method as adopted by Gray (1992).

Finally, the tropical cyclone data were tested for the Poisson process using a common technique (e.g. see Keim and Cruise, 1998) called the variance-mean ratio (also referred to as the index of dispersion, I) where

$$I = \frac{\text{Sample Variance}}{\text{Sample Mean}} \tag{2.4}$$

This technique makes use of the fact that, for a stationary Poisson process with a mean expectancy rate, the number of events in any region follows a Poisson distribution with an equal mean and variance. If the process is stationary Poisson

$$(M-1)I \sim \chi^2_{M-1} \tag{2.5}$$

where M is the number of bins of count data of equal-sized intervals. Thus $(M-1)I$ is tested against the χ^2 distribution. Keim and Cruise (1998) noted that this is reasonable based on the relationship noted between I and the χ^2 Fisher dispersion statistic (Cunnane, 1979). The approximation in Equation 2.5 is adequate providing that $M > 6$, and that the mean number of events per interval is at least 1 (e.g. Diggle, 1983, Section 3.2.1). In this case, this is true since M is the number of years (26), and the average number of intense hurricanes is 1.35 for the western development region (see Chapter 3), and the number of tropical cyclones of lower categories would be naturally more. A two-tailed test is conducted to allow for over or under-dispersion. Thus, the null hypothesis that the tropical cyclones may come from a Poisson distribution can be rejected at the 5% level if $(M-1)I$ is less than 13.12 and greater than 40.65. It can be rejected at the 1% level if $(M-1)I$ is less than 10.52 and greater than 46.93.

Category	Region	(M-1)I
Hurricane	Whole NE Pacific	**18.75**
	Western development region	**36.62**
	Eastern development region	**15.5**
Intense Hurricane	Whole NE Pacific	**25.56**
	Western development region	41.51
	Eastern development region	**21.91**
Tropical Storm	Whole NE Pacific	1.11
	Western development region	48.69
	Eastern development region	**14.87**

Table 2.3 Test for the Poisson distribution - the index of dispersion. Values in bold indicate that the null hypothesis, which states that the tropical cyclones may come from a Poisson distribution, cannot be rejected at the 5% level.

Table 2.3 gives the values for $(M-1)I$ for the NE Pacific tropical cyclone regions, the whole

region, and the eastern and western development region (identified in Chapter 3). It can be seen that for the hurricane category, there is no reason to reject the null hypothesis for any region. For the intense hurricane category, there is no reason to reject the null hypothesis for the whole NE Pacific region and the eastern development region. For the western development region, the null hypothesis is rejected at the 5% level, but not at the 1% level. For the tropical storm category, the null hypothesis can be rejected for both the whole region and the western development region at the 1% level.

Based on the above discussion of both the literature and the index of dispersion test, the Poisson distribution is assumed in this study. (However, it must be noted that this may not be the ideal distribution, particularly for the tropical storm category with regard to the whole NE Pacific and western development regions.) In this study, therefore, a more appropriate model than ordinary least squares (OLS) is considered when examining tropical cyclone frequency - a generalised linear model (GLM) with Poisson errors (McCullagh and Nelder, 1989) as described above. This technique allows a straight line fit through the data according to the assumption that the random component of the variable is Poisson distributed.

GLMs provide a flexible and rigorous framework within which to distinguish between different possible variables that affect tropical cyclone activity. Generalised linear modelling is, as the name implies, a generalisation of linear modelling which allows observations to be realisations of a non-Gaussian distribution. The following section discusses the use of this technique in the current study.

In regression analysis, the relationship between the dependent variable and one or more independent variables is examined. The dependent variable is associated with the independent variables by a function, known as the regression function, which involves a set of unknown parameters. Values of the parameters which provide the best fit to a given set of data are obtained. There are different types of regression models. The simplest form of regression is linear regression based on a normal or Gaussian distribution. Other regressions can involve non-Gaussian distributions, or be non-linear.

With OLS regression, a linear regression of the dependent variable, Y, on a single independent variable, x, is expressed as

$$Y_i = a + bx_i + e_i \tag{2.6}$$

where a is the intercept and b is the slope or fit parameter (the parameters whose values are to be estimated) and e are the errors of this fit for observation i which have a mean of 0 and a Gaussian distribution. In OLS, the method used to determine the values for the parameters, based on a given set of data, is to minimise the sum of the squares of the differences between the observed values of the dependent variable and the values predicted by the regression equation for the data.

Therefore, to obtain expected Y's, the x's are replaced in Equation 2.6 with the appropriate value of the environmental variable for that year. When used in conjunction with a and b values obtained through minimising the sum of squares (S with respect to a and b) (Equation 2.7), Equation 2.8 provides an estimate of the mean activity rate.

$$S_{(a,b)} = \min(\sum_{i=1}^{n} e_i^2) \tag{2.7}$$

$$\lambda_i = a + bx_i \tag{2.8}$$

where λ is the expected value of Y.

When dealing with Poisson regression, as in the case of this study for examining correlations with tropical cyclone frequency, maximum likelihood theory is used to examine the maximum probability that a series of events has values which are consistent with those from a particular model. A link function is an equation which links the mean of the distribution to a set of underlying predictors. When a Poisson distribution is assumed, the logarithmic link function can be used. When considering the Poisson distribution, the logarithmic link function is the most mathematically convenient link and has the feature that rate parameters are non-negative, a valid assumption when dealing with tropical cyclone numbers. This means that the "straight line fit" gives a straight line function with the logarithm of the independent variable, rather than with the independent variable directly.

The expected number of tropical cyclones are thus calculated using the logarithmic link function (using the Numerical Algorithms Group (NAG) routine G02GCF) and consequently the fitted model is of the form

$$\lambda_i = \exp(a + bx_i) \tag{2.9}$$

where λ is the expected value of the tropical cyclones. Note that the terms in this equation (i.e. in the exponential function) are linear. It is common practice to use linear techniques, though non-linearity can in principle be addressed. However, since good relationships are found using the linear form, it is not considered necessary to examine the relationships in other ways. Furthermore, an examination of the scatterplots between the tropical cyclone indices and the variables did not indicate that non-linear functions should be fitted.

For a Poisson distribution with a mean value of λ, the probability $P(n, \lambda)$ of exactly n tropical cyclones occurring in a given year is

$$P(n,\lambda) = \exp(-\lambda)\lambda^n / n! \tag{2.10}$$

A maximum likelihood procedure is used to estimate λ from Equations 2.9 and 2.10. For a given a and b, λ is calculated from each year's x array from Equation 2.9 and then the likelihood of the number of tropical cyclones is estimated from the Poisson distribution using Equation 2.10. Considering all years, the likelihood function is given by

$$L(x) = \prod_{i=1}^{N} \exp(-\lambda_i)\lambda_i^n / n! \tag{2.11}$$

where L is the likelihood based on the variables (x), and N is the number of years.

The values of a and b above, which maximise the likelihood function, are the most likely values to give rise to values of λ which realise the observations.

In Sections 4.3 and 4.7.4, Poisson regression is carried out with two independent variables, the environmental variable and time. Time was included to eliminate any effects of long term trends since this study is concerned with interannual variation. This is dealt with in the OLS regressions by detrending the data first. However, as mentioned above, one of the assumptions of Poisson regression is that the data are integers. Detrending produces continuous, non-integer data, thus time needs to be considered in a different way. Consequently the fitted model is of the form

$$ln(\lambda_i) = a + bx_i^* + ct_i^* \tag{2.12}$$

where λ is the expected number of tropical cyclones, x^* and t^* represent the environmental variable and time respectively which have been standardised to give a mean equal to 0 and a

standard deviation equal to 1 such that

$$e^* = (e - \bar{e}) / \sigma(e) \tag{2.13}$$

where e is either x or t, and $\sigma(e)$ is the standard deviation of e.

The parameters are normalised to ensure no misleading results due to the predictor variable having non-zero mean (Chandler, 1998). The standard deviation is incorporated into Equation 2.13 so that the computer does not produce rounding errors when considering large numbers. This is necessary for the NAG minimisation routine.

2.4 Limitations of the statistical analysis technique

To examine links (e.g. Section 4.7.4), spatial correlation maps (see Section 4.7.1 for further discussion of these maps) have been used (given the methodology described above). It should be noted that, when N independent tests are made, it is expected that 5% of them will be significant by chance (when considering the 5% significance level). To demonstrate how some chance areas may emerge as significant, 100 simulations were therefore conducted with 100 groups of 26 randomly generated hurricane numbers (which were created using a Poisson distribution with a mean equal to the mean of the real hurricane series). Regressions were made with each set and the same environmental variable each time. It was found that on average 4.03% of each plot was significant to the 5% level with a standard deviation of 3.70% and a minimum of 0.03% and a maximum of 16.25%. When examining a global spatial plot it would be expected, therefore, that some of the relationships may not actually be meaningful. This is shown in Figure 2.10 which shows one of the set of 100 randomly generated hurricane numbers against RH. It can be seen that significant areas emerge but these do not have any physical relevance. Furthermore, it can be seen that no large significant areas emerge. This helps to show that the relationships obtained in Section 4.7.4 are real. In addition, 'significant' areas may emerge due to systematic errors in the reanalysis data. Particular areas of concern include the Arctic and Antarctic, as there were problems with snow cover calculations that went into the reanalysis (Kalnay, 1997, personal communication).

Therefore, when exploring relationships with maps, not all the areas that emerge as significant are genuine. Thus, it is important to examine large areas of significance or areas that are either relatively local or have a physical link. Hence, it should be noted in Section 4.7.4 that there are some areas which are shown to be significant to the 5% or 1% level but are not highlighted as influences on tropical cyclone activity, whereas other

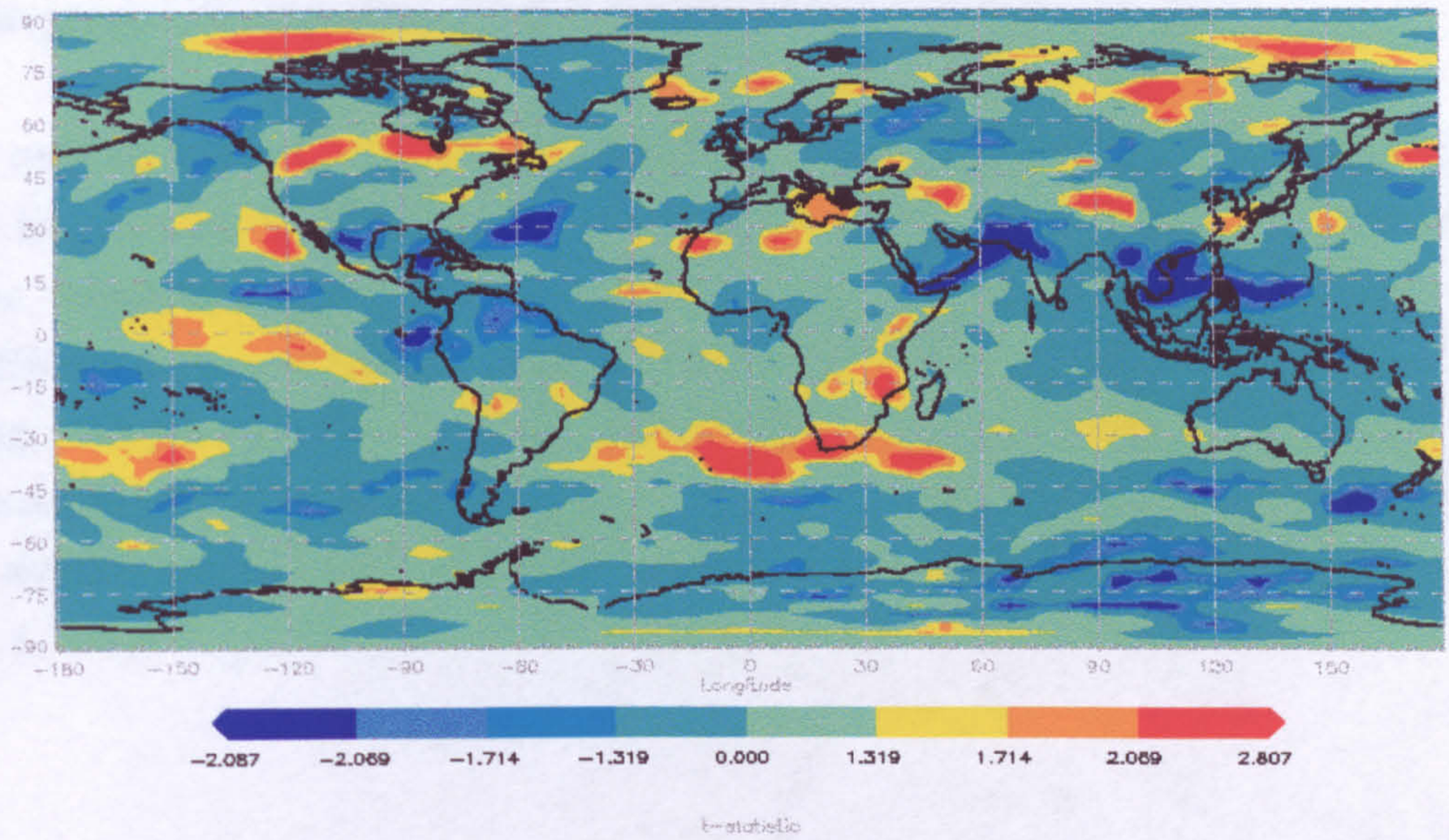


Figure 2.10 Relationship (given with a *t*-statistic) between a randomly generated list of hurricane numbers and RH in July-September, 1972-1997 using Poisson regression. *t*-statistics are given with absolute values of 1.319, 1.714, and 2.069 representing associations with greater than 20%, 10% and 5% significance respectively.

areas significant to this level are highlighted as possibly influencing tropical cyclone activity. The reasoning for including the latter is, generally, that the areas of significance are larger and also that there are physical arguments for including them.

Not only should one consider the spatial dimension, but the temporal dimension should also be considered. When considering a time period, if a relationship remains about the same throughout (i.e. consistently weak or consistently strong), this yields some confidence in the relationship obtained. Section 4.7.5 will consider such stability over time using a 13-year moving average. Relationships that are not stable over time possibly indicate that the relationship observed is random or that there has been a climate shift and the relationship holds for a specific period of time only. This is considered in Section 5.2.3.

Chapter 3

Two development regions of the NE Pacific basin and trends in tropical cyclones

3.1 Characterising NE Pacific tropical cyclones

This chapter will examine the location where the tropical cyclones reach their appropriate categories to identify any characteristics, and to ascertain whether the NE Pacific basin should be treated as one entity, with respect to tropical cyclone formation, or divided into separate sub-regions based on a longitude distinction. Once the NE Pacific basin has been characterised, trends in tropical cyclone frequency with time are examined.

3.1.1 The population of tropical cyclones in the NE Pacific basin

Figure 3.1 is a plot of the formation position of all hurricanes in the NE Pacific basin during the main hurricane season (July to September) between 1972 and 1997. It can be seen that hurricanes form in the NE Pacific basin from the west coast of North America to the international dateline (180°W) and they cluster around 10°N to 20°N within this basin.

Previous studies investigating the causes of NE Pacific tropical cyclones, which have been rather inconclusive, have treated the region as if the tropical cyclones formed a single group, all reacting to the same causal factors in the same way. However, if the longitudinal distribution of the hurricanes in individual years is investigated (Figure 3.2), it appears that in some years the hurricanes are confined to the eastern part of the basin (e.g. 1983 and 1996), whereas in other years they also occur further west (e.g. 1987 and 1994). This is also true of the other tropical cyclone categories. Figure 3.3 shows two of these years where a) is a typical case of hurricanes being clustered to the eastern part of the basin and b) is a typical year where hurricanes are more scattered and hurricanes occur not only in the eastern part of the basin but also further west. It therefore seems possible that there is more than one population with regard to the causal effects, separated mainly by longitude. (Note that here, and in the remainder of the thesis, the word 'population', in the context of development regions, is used in this general sense, rather than a purely statistical sense.) In this chapter this possibility is explored in detail, and the two identified development regions are examined for trends in seasonal tropical cyclone frequency. Other tropical cyclone characteristics are also examined.

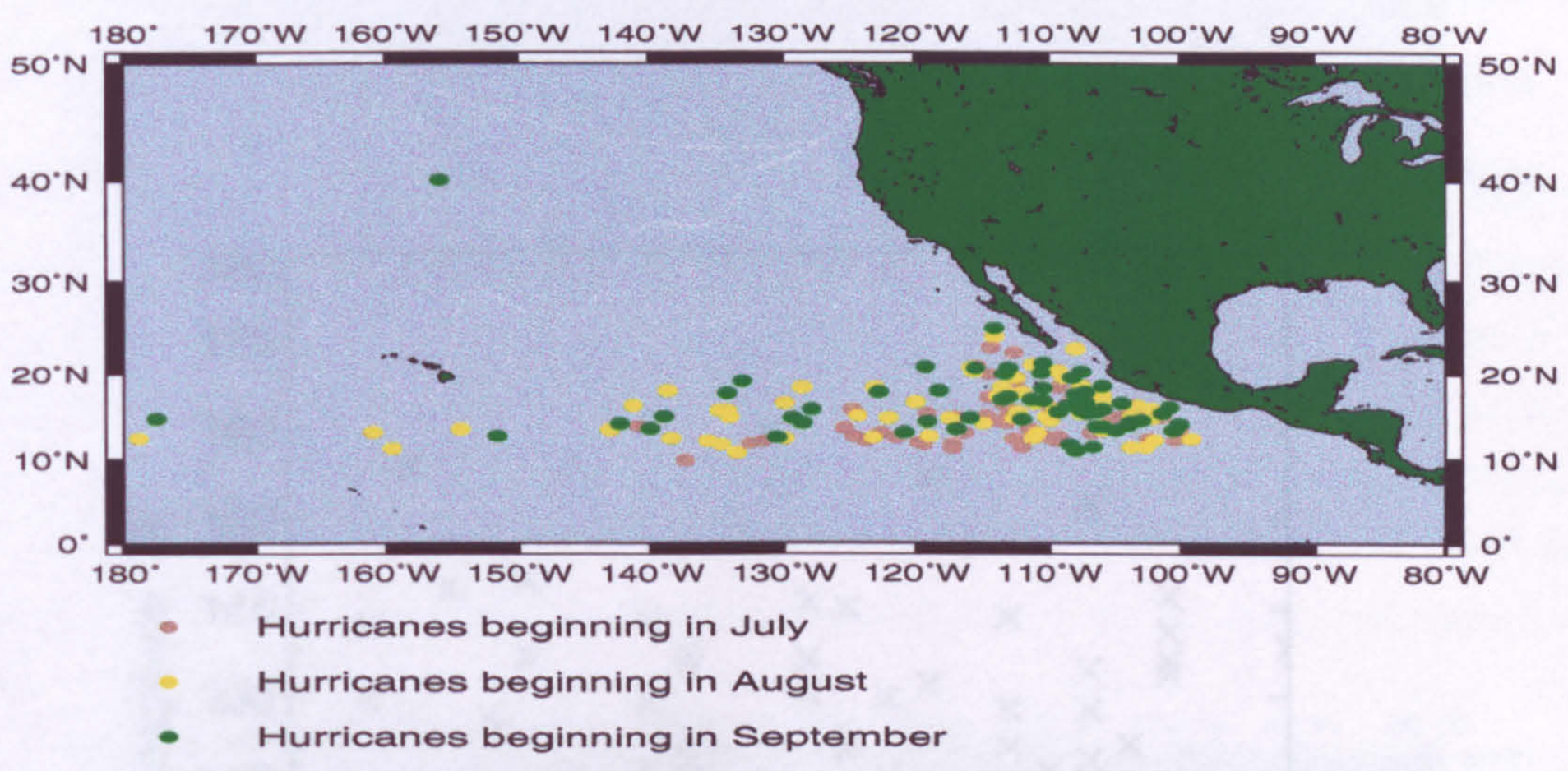


Figure 3.1 Location of NE Pacific hurricanes, 1972-1997.

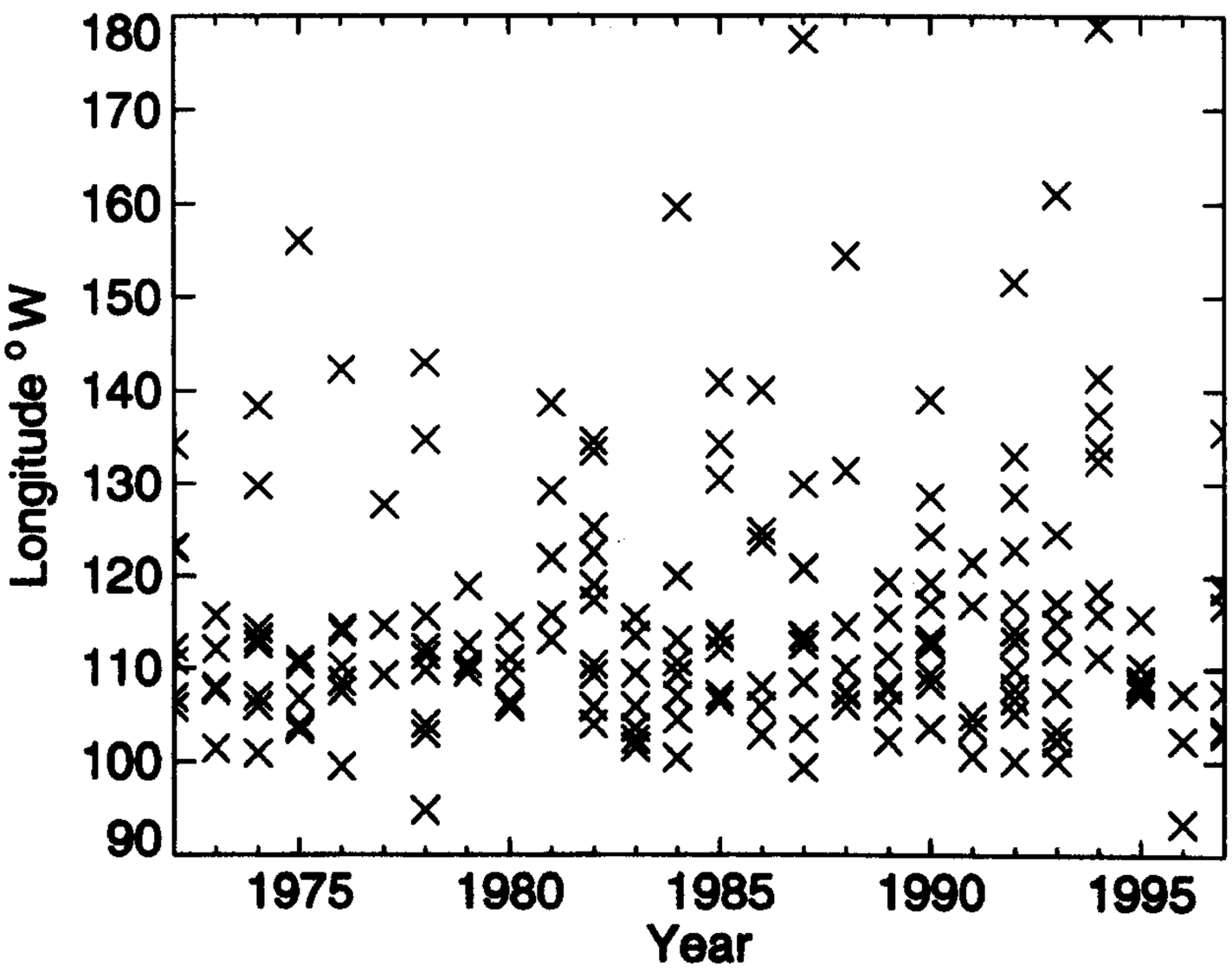


Figure 3.2 Longitudinal distribution of hurricanes per year, July-September, 1972-1997.

a)

b)

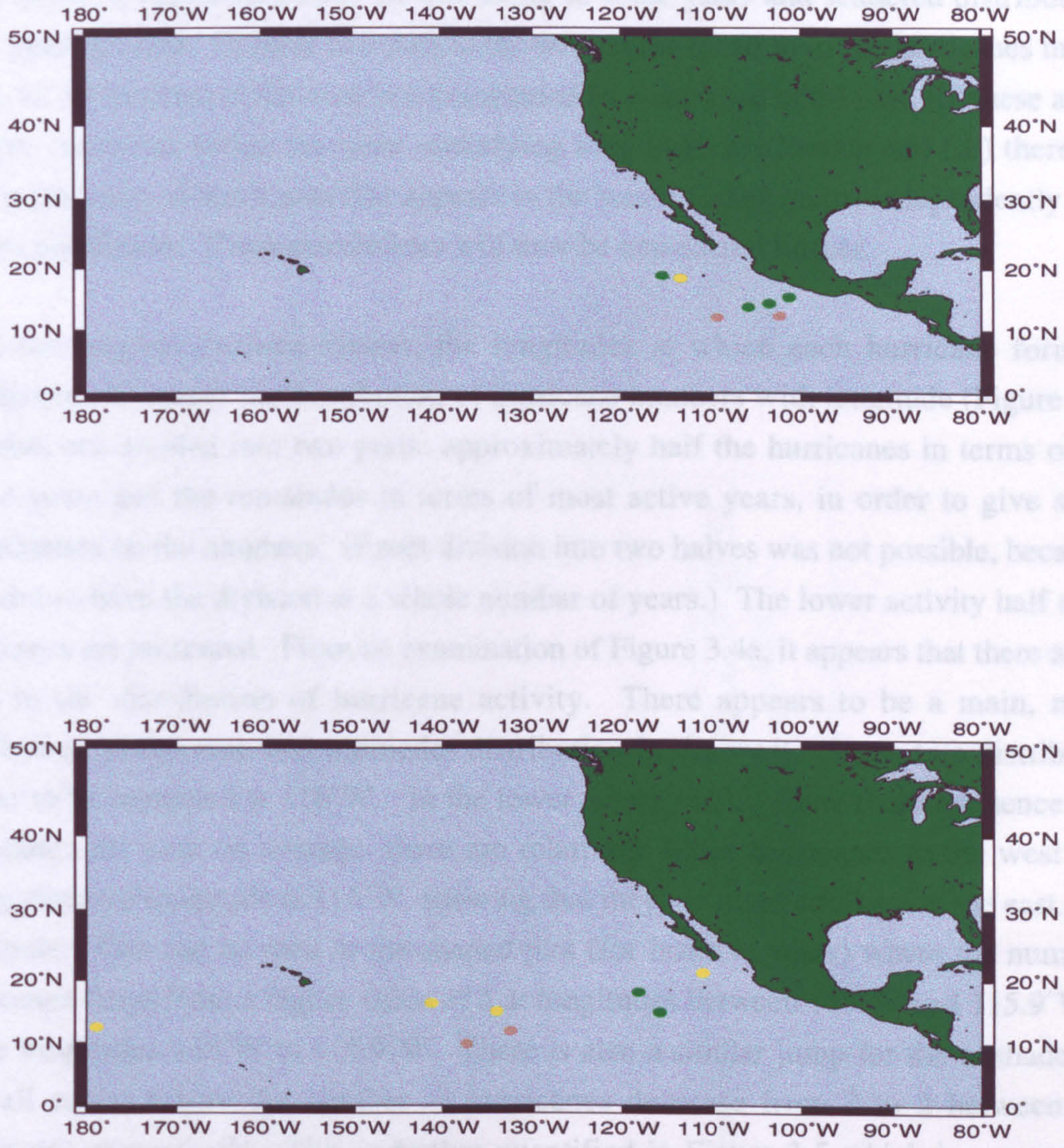


Figure 3.3 Location of NE Pacific hurricanes in the a) 1983 season and b) 1994 season.

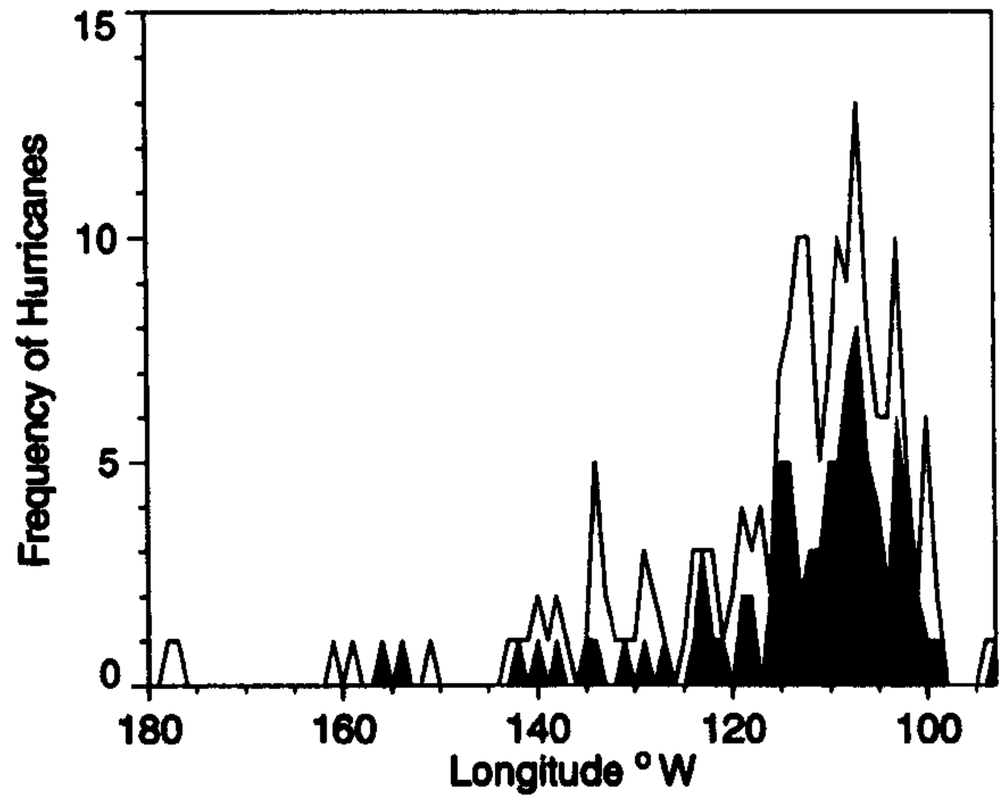
3.1.2 The identification of more than one development region in the NE Pacific basin

Three possible explanations for the clustering in some years and scattered distribution in other years are that: (i) there is a shift to the west in the location of the hurricanes in some years, i.e. an increase in the west is accompanied by a decrease in the east, (ii) these are just random variations within the same underlying longitude distribution and (iii) there is an extra population of hurricanes that appears in the west in some years, independently of the eastern population. These possibilities will now be considered further.

From the tropical cyclone dataset, the longitudes at which each hurricane forms are established. Consider the distribution of hurricane numbers with longitude (Figure 3.4a). The data are divided into two parts: approximately half the hurricanes in terms of least active years and the remainder in terms of most active years, in order to give similar uncertainties on the numbers. (Exact division into two halves was not possible, because of the need to have the division at a whole number of years.) The lower activity half and all hurricanes are presented. From an examination of Figure 3.4a, it appears that there are two parts to the distribution of hurricane activity. There appears to be a main, narrow distribution in the east, and a broader distribution in the west. These two distributions appear to be separated at 116°W. In the lower activity half, where there are hence fewer hurricanes per year on average, there are relatively fewer hurricanes to the west and a strong dividing longitude at 116°W, showing that they are more confined to the east of this longitude. This can be seen in the shaded plot (for inactive years) where the number of hurricanes drops from a higher value of 5 at longitudes between 115°W and 115.9°W to 2 at the longitudes 116°W to 116.9°W. There is also a similar jump for the unshaded plot (for all years) where the number of hurricanes decrease from 7 to 2 between these longitudes respectively. This is further quantified in Figure 3.5 which is a cumulative frequency distribution showing that the percentage of hurricanes to the west of a longitude in the inactive years decreases rapidly from east to west until 116°W is reached. At this point the percentage to the west decreases less dramatically. This division into two development regions, east and west of 116°W, appears not only for the hurricane category (Figure 3.4a), but also for the tropical storm (Figure 3.4b) and intense hurricane category (Figure 3.4c).

Having established two development regions on the basis of the distribution shape, let us examine the first hypothesis above, namely that there may be more tropical cyclones forming in the western development region because there are less tropical cyclones forming in the eastern development region (e.g. due to a delay in formation, or a geographical shift

a)



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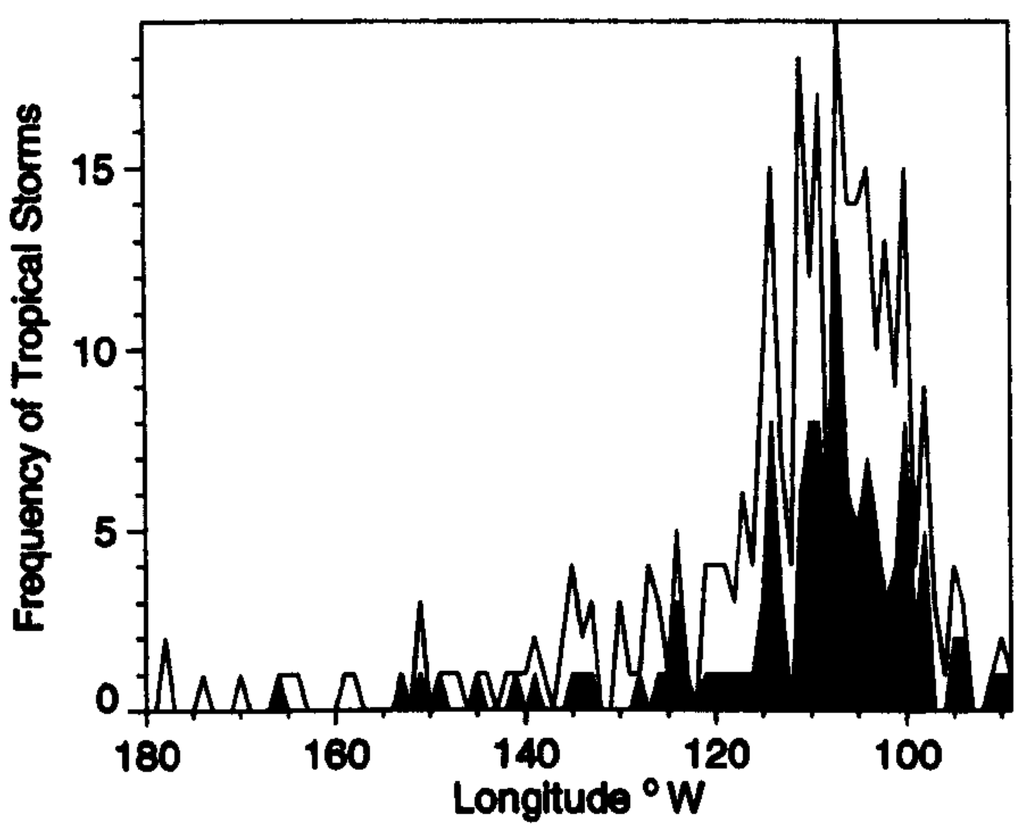

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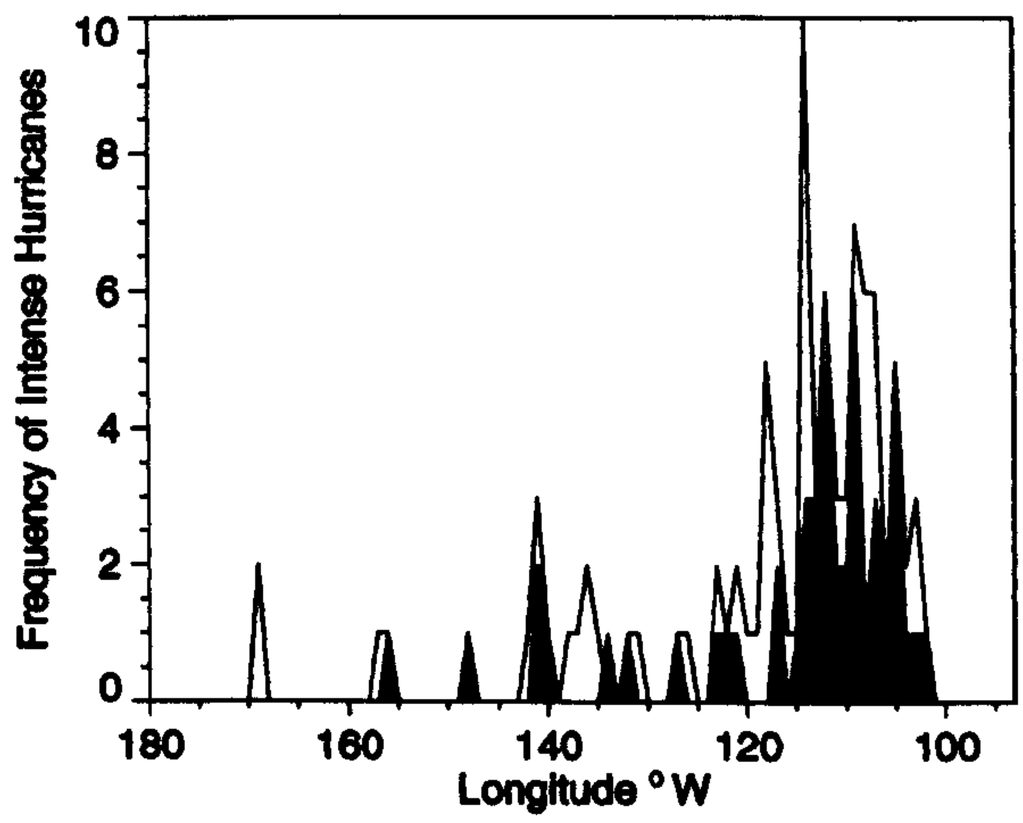


Figure 3.4 The longitude distribution of all a) hurricanes (185), b) tropical storms (304), and c) intense hurricanes (92) for the period 1972-1997 (unshaded plots), and for approximately half the a) hurricanes (91, from the least active years), b) tropical storms (128, from the least active years), and c) intense hurricanes (47 from the least active years)(shaded plots).

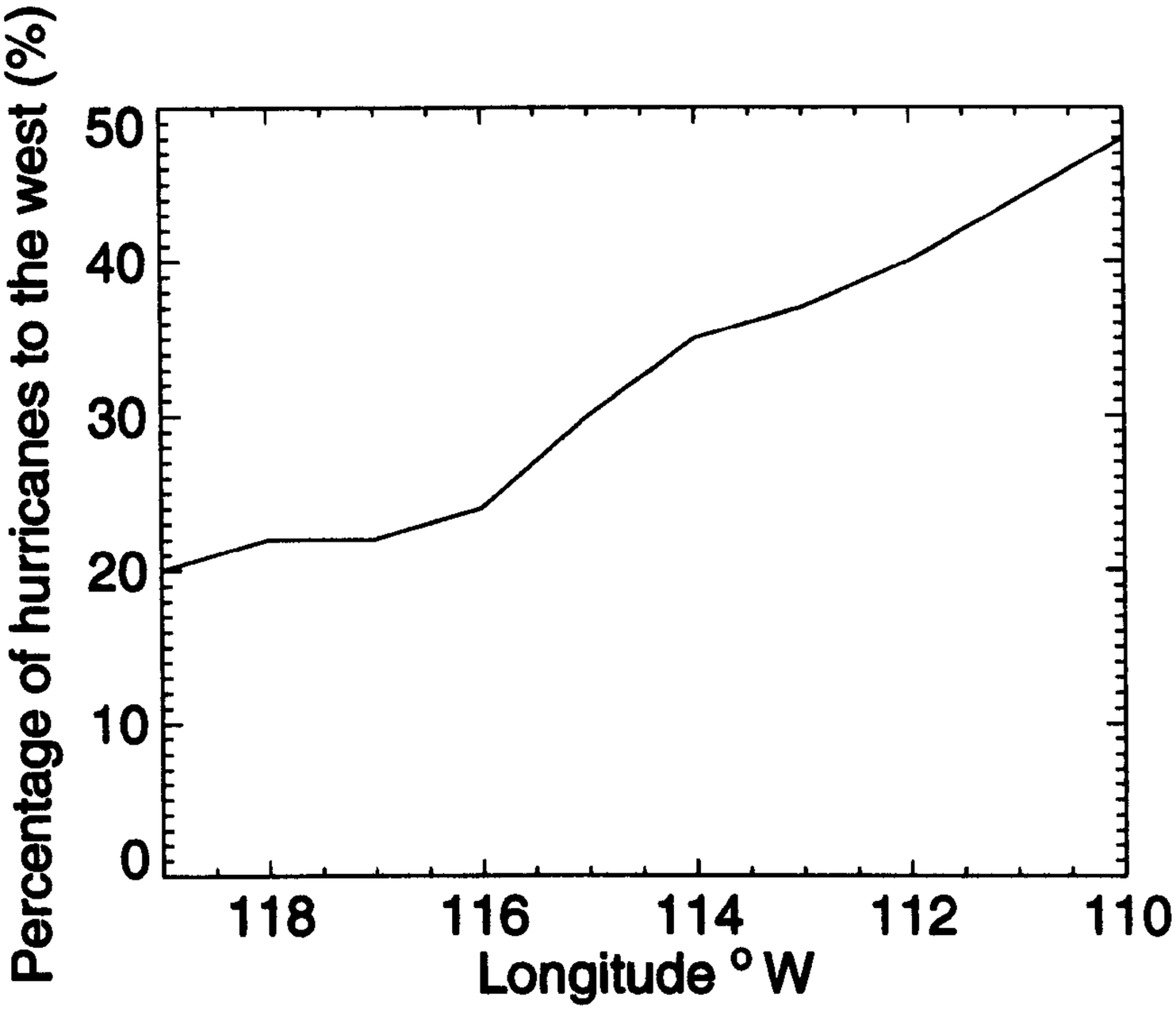


Figure 3.5 Percentage of hurricanes to the west of a longitude, July-September, 1972-1997.

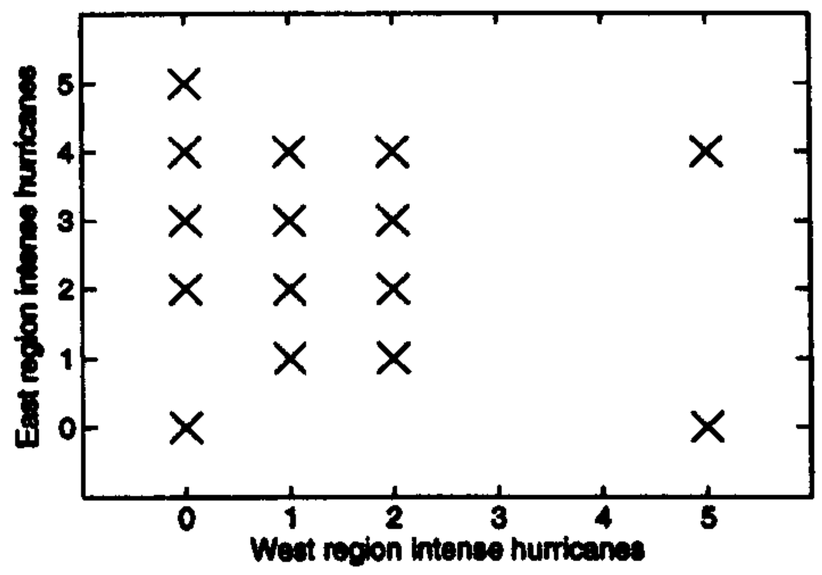
in conducive conditions). In this case, one would see an anti-correlation between the annual frequencies in the two regions. However, Figure 3.6 shows that for all categories of tropical cyclone, there are no significant relationships between the two regions.

Let us therefore now examine the second hypothesis noted earlier, namely that there might be a constant underlying longitude distribution over the whole basin, and the fluctuations seen in the west just represent random variations within this distribution from year to year (particularly in view of the large variation in total number of cyclones from year to year). In Figure 3.4a, when all 26 years are considered (unshaded plot) there are approximately twice the number of hurricanes but there is a significant change in the shape of the distribution in longitude compared with the shaded plot (for the least active years). For a constant underlying distribution shape, the numbers in any longitude range would increase in the same proportion. Instead, there are relatively more hurricanes west of 116°W indicating that the spread of hurricane longitudes is greater for years with a greater number of hurricanes. The percentage of hurricanes to the west of 116°W is 24% (39%) for the least (most) active years, a difference which is significant at the 5% level based on a chi-squared test. This is confirmed through a graph depicting the standard deviation of the hurricane longitudes against seasonal hurricane numbers (Figure 3.7). There is a higher standard deviation with an increase in hurricane numbers (a result which is significant to the 1% level). Thus, in years when there are more hurricanes, there is a longer tail of hurricanes to the west. For a constant underlying distribution, there should be no change in standard deviation with number.

Similarly, when considering the other tropical cyclone categories, when all years are considered compared to only the inactive years, there is likewise relatively more of these tropical cyclones to the west of 116°W. The percentage of tropical storms to the west of 116°W is 18% (32%) for the least (most) active years, and the percentage of intense hurricanes to the west of 116°W is 27.7% (48.8%) for the least (most) active years. Results for both these categories are also significant to at least the 5% level.

These results all lend support to the third hypothesis noted earlier, namely that in some years the tropical cyclones form entirely in the eastern region (east of 116°W), whereas in other years there is a tendency for tropical cyclones to form not only in the eastern development region, but also in the western development region (equal to or greater than 116°W). Hence, the evidence above suggests that the tropical cyclones in the western development region are seen as additional to the ones in the eastern region in some years and hence the two development regions emerge. An additional result in support of this third

a)



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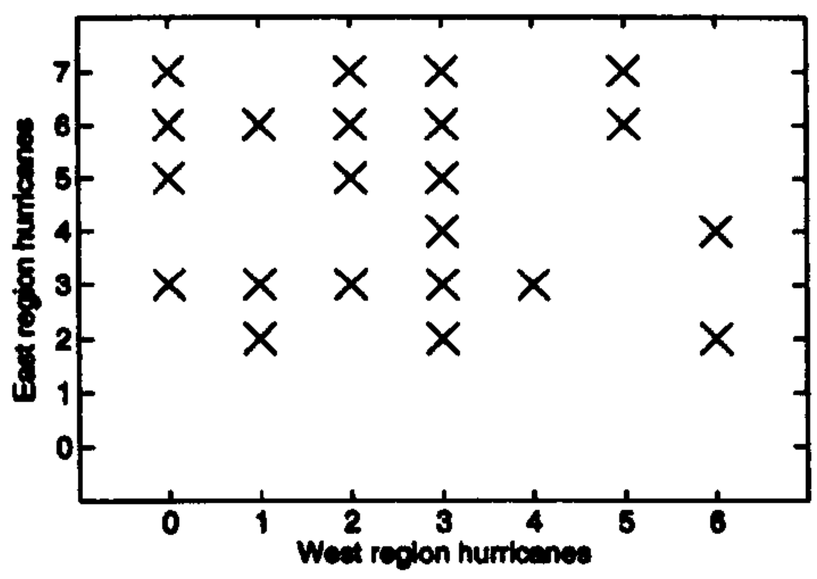

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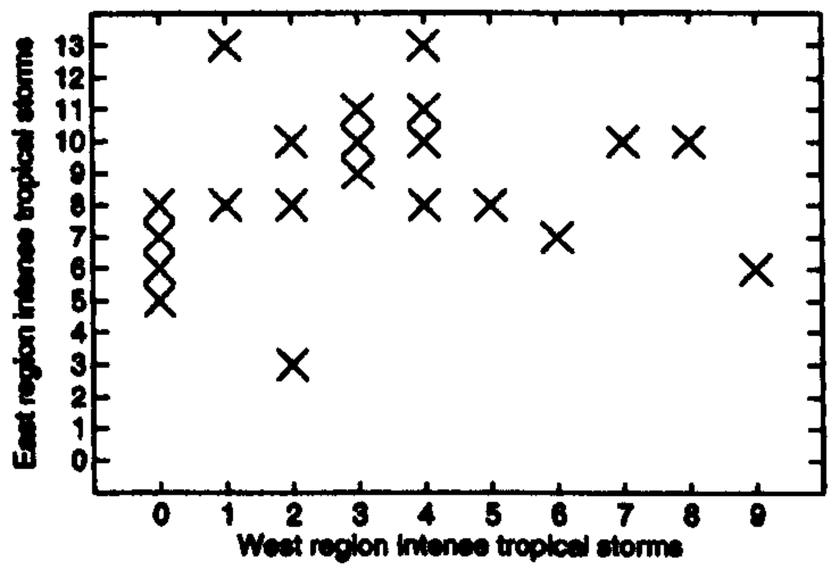


Figure 3.6 Western development region vs. eastern development region seasonal (July-September) tropical cyclone numbers, 1972-1997. a) intense hurricanes, b) hurricanes, c) tropical storms.

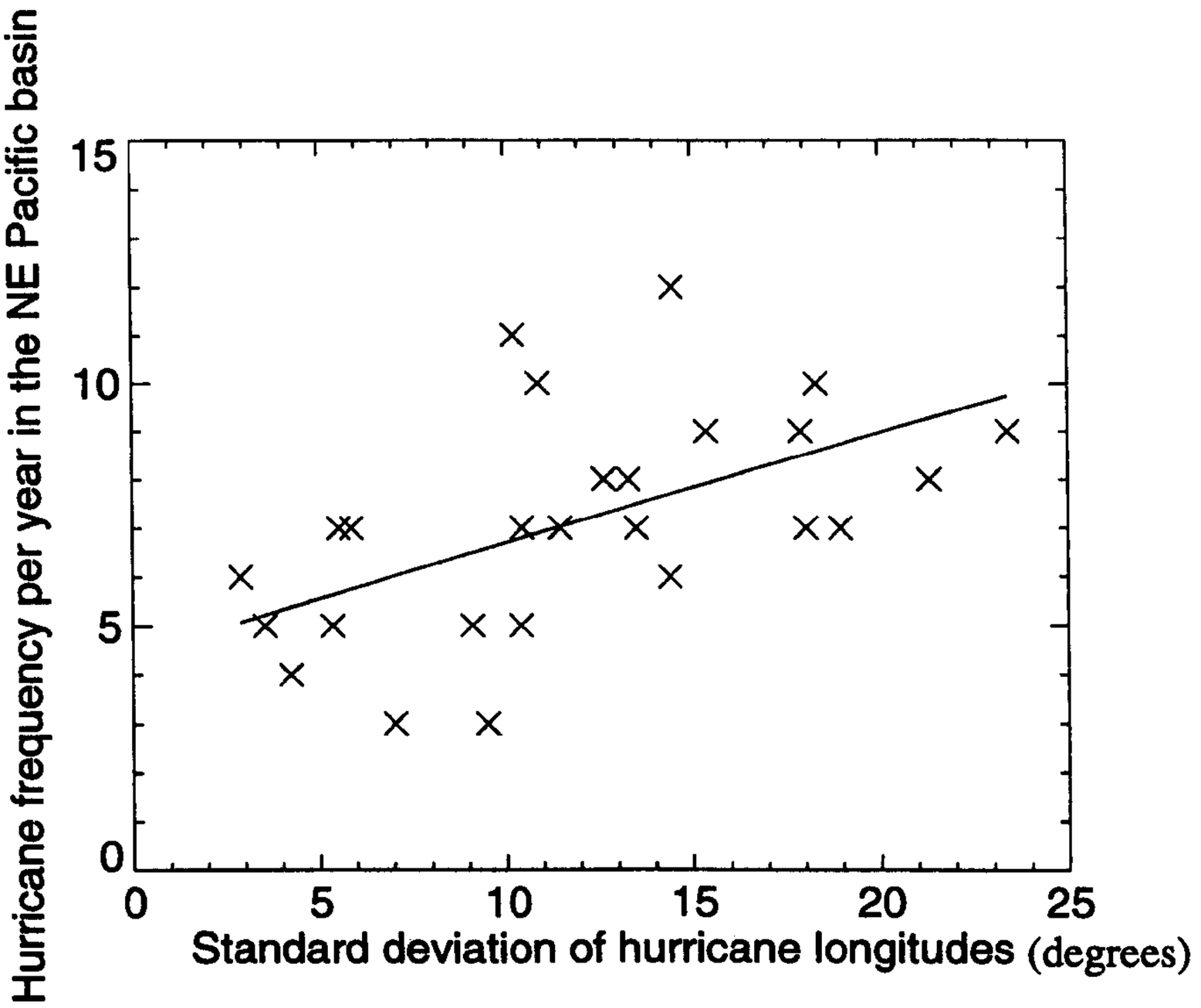


Figure 3.7 Hurricane frequency per year vs. standard deviation of longitude, July-September, 1972-1997. The line indicates the straight line Poisson fit (not using the log link, see Section 3.2.1).

hypothesis is that there is no positive correlation between numbers in the western and eastern regions (Figure 3.6), implying that the western cyclones are occurring independently of the eastern ones, responding to different causal factors.

Nevertheless, because of the small numbers of events involved, there is still considerable uncertainty in all the statistical results above, and so alternative possibilities cannot completely be ruled out. The most likely alternative is that the western region is merely the sensitive periphery of the eastern region (where conditions are generally conducive for development), so that the two regions do not really contain independent populations of tropical cyclones with respect to causal factors. However, the evidence as a whole seems to favour the idea that there are two distinct regions. The longitude distributions themselves (Figures 3.4 and 3.5), especially the cumulative distribution (Figure 3.5) are particularly compelling, in that they certainly appear to be made up of two different distributions on either side of 116°W. Convincing support for the idea of two distinct regions with regard to causal factors is also provided by the results of the analysis of tropical cyclone frequency in the two regions that will be presented later in this thesis. The trend analysis (later in this chapter) shows different trend values for the two regions, and the investigations of the relationship between seasonal environmental factors and tropical cyclone frequency (in Chapter 4) show that the factors influencing frequency in the two regions are different. In addition, the environmental variables themselves display year-to-year variations that are largely independent for the two regions (see Section 4.7.1). Finally, recent modelling results (McDonald et al., 2001) also predict different frequency trends for tropical cyclones in approximately the same two regions.

Thus for all subsequent analysis, the NE Pacific basin will be divided into two development regions. There may be, in fact, other regions, but due to the practicality of requiring reasonable numbers to examine relationships, the simplest hypothesis that there are two regions will be used, given that the above analysis implies that there is likely to be more than one population.

As regards the dividing longitude for the two regions, this is likely to be at 116°W. Figure 3.2 also suggests it is around 115°W to 120°W for the hurricane category. However, in order to show that it is in this vicinity and that the exact longitude is of less concern than the fact that the whole NE Pacific basin should be divided, some of the later results (see Chapter 4) have been tested with the division at 117°W and there appears to be no significant difference between this and the 116°W division. An important example is in Section 4.3 that shows RH to affect hurricane frequency. Using the 116°W boundary, this

result is significant at the 1% level with a *t*-statistic of 4.05 and based on the 117°W boundary a similar *t*-statistic of 4.08 is obtained. Hence, subsequent analysis considers the NE Pacific divided into two development regions, to the east and west of 116°W and defined as the 'eastern development region' and 'western development region' respectively. Where appropriate, the environmental variables are averaged over each area, 10°N to 20°N by 93°W to 115°W and 10°N to 20°N by 116°W to 180°W (excluding land areas), and the tropical cyclones are separated into each region based on the longitude where the storm reached the appropriate wind speed for each tropical cyclone category.

3.1.3 The NE Pacific development regions compared to the development regions in other basins

The NE Pacific is unique in its distribution of hurricane locations. No other basin shows such a marked difference between a main development area, termed here the eastern development region where the majority of hurricanes form, and an area next to it (the western development region) where hurricanes form, but the numbers drop dramatically (see Figure 3.8). (Note that this is equivalent to the unshaded plot of Figure 3.4a, not the shaded plot). In fact it is interesting to note that what is called the 'main development region' in the North Atlantic Ocean (which is between 60°W and 20°W) is only called 'main' because it has been classified as being over a larger area than areas such as the Gulf (which is no more than 20 degrees in longitude). Hence, being a larger area, it would naturally have a larger number of hurricanes that form there. However, when one looks at the situation of the chance of a hurricane forming per degree throughout the whole of the North Atlantic basin, there is not one particular region that shows the characteristics of a main development region in terms of most of the hurricanes forming there (see Figure 3.8a). Figure 3.8 also shows all other regions of the globe and it can be seen that, although the NW Pacific has a higher probability of a hurricane forming there than anywhere else, the main region of development is not so well defined and different from adjacent regions of hurricane development as in the NE Pacific.

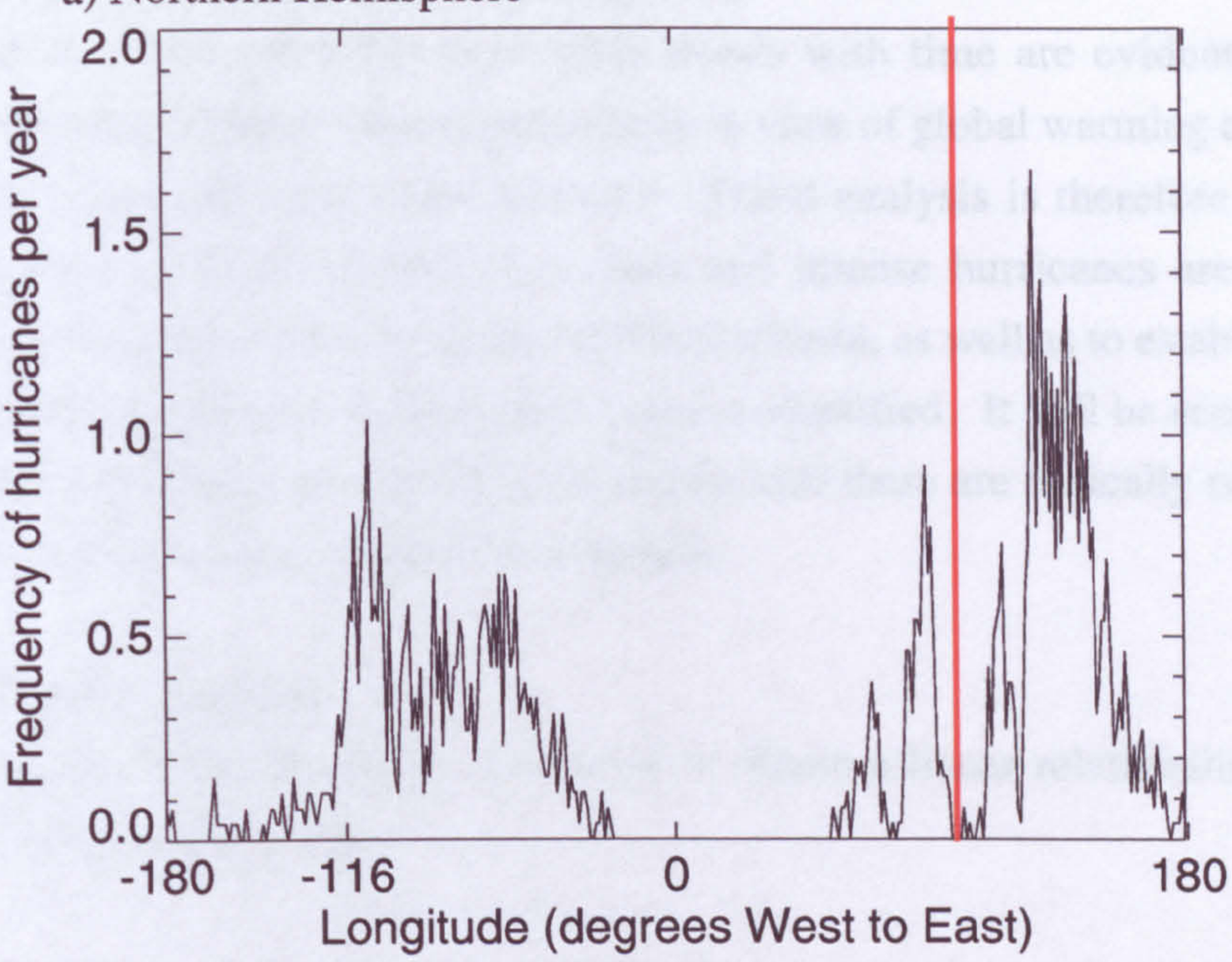


Figure 3.8 Average hurricane frequency per year for each longitude on the globe for a) the Northern Hemisphere, and b) the Southern Hemisphere, (July-September) 1972-1997. In the Northern Hemisphere, 116°W in the NE Pacific is shown. The red line marks the boundary between the NW Pacific to the east and the North Indian basin to the west.

3.2 Trends in tropical cyclone frequency

A key issue in recent years has been what trends with time are evident with tropical cyclones within the different basins, particularly in view of global warming and its possible impact on hurricane frequency and intensity. Trend analysis is therefore conducted, to establish whether tropical storms, hurricanes and intense hurricanes are increasing or decreasing in frequency with time in the NE Pacific basin, as well as to establish if there are differences between the two development regions identified. It will be seen that this also provides further evidence in support of the theory that there are basically two populations with regard to causal effects divided by longitude.

3.2.1 Trends analysis

Poisson regression (see Section 2.3) is used to obtain a linear relationship between the tropical cyclone index and time

$$\lambda = a + bt \tag{3.1}$$

where λ is the expected number of tropical cyclones, and t is the time. This is in contrast to Equation 2.12 where the relationship between the tropical cyclone index, environmental variable and time is exponential. For the purpose of trend analysis, the log link is not appropriate since it does not give a linear fit showing a linear increase per year, but an exponential fit.

The trends are expressed in two ways in terms of (a) the change in the number of tropical cyclones per year, T, and (b) the relative trend T_r given by

$$T_r = 100[T(N-1)/\bar{y}] \qquad \% \tag{3.2}$$

where N is the number of years in the time series and $\bar{y}$ is the mean of the time series under consideration. (T_r is positive in the case of an increasing trend, T_r is negative in the case of a decreasing trend.)

The term T_r/s_e (s_e=standard error) leads to an assessment of the significance of the relative trend. It assesses the trend-to-noise ratio. If the data time series are Gaussian distributed, this simple ratio would allow confidence statements. Here, the data is Poisson distributed, but this does approximate to the normal distribution for large numbers of hurricanes, so although the significance results are not accurate for the Poisson distribution, they are reasonably close (Schonwiese and Rapp, 1997).

Raper (1993) found a large rise in the number of recorded storms in the NE Pacific during the 1960s when she examined their trend through the period 1952-1971. However, the problem of using data for tropical cyclones before 1972 has been mentioned in Section 2.1.1 and Raper herself recognises that the trend for this period can be attributed to the more recent use of satellite surveillance. This section will investigate trends of tropical cyclones with time for the reliable period 1972-1997, and in particular will examine the two development regions separately. Figure 3.9a(1) shows the time series of seasonal *intense hurricane* numbers for the whole of the NE Pacific basin. A significant upward trend is observed where the trend is 2.4 intense hurricanes over the 26-year period (T is 0.091 per year). This value is large if one compares it to the mean of the region which is 3.5 (T_r is 65%). Figures 3.9a(2) and 3.9a(3) show that this upward trend is largely due to the strong upward trend of intense hurricanes in the western development region with a significance to the 1% level, where T is 0.07 per year, i.e. 1.7 intense hurricanes over the 26-year period (T_r is 124%). In the eastern development region, the increase of intense hurricanes (T is 0.02 per year) is only 0.5 for the 26-year period (T_r is 23%). The trend is not significant in the eastern development region.

Trend analysis is also conducted for *hurricane* numbers with time (see Figure 3.9b(1)) for the whole region, where it is found that there is no significant trend. Again, however, hurricanes in the western development region (Figure 3.9b(2)) show an upward trend significant at the 5% level, where T is 0.08 hurricanes per year representing an increase of 2 hurricanes in the 26-year period (T_r is 84%). These results are consistent with Chu and Clark (1999) who noted that, in the central Pacific, tropical cyclone activity has been increasing from 1966 to 1997. They include not only those hurricanes that formed in the central Pacific (defined as 140°W to 180°W, i.e. approximately the western half of the western development region), but also those that come into this region from the east. They note that more hurricanes traversed into the central North Pacific from the east of 140°W during 1982-1997, than the earlier period they looked at, 1966-1981. Although they have only dealt with the central Pacific (which inherently has fewer tropical cyclones than the entire western development region explored here), their work supports the trends observed in this study. The trends in this study show that as there were more hurricanes in these later years, it is likely that there will be a higher chance that these may form in or enter the central Pacific. Again there is no significant change of the hurricane numbers with time in the eastern development region (Figure 3.9b(3)).

Finally, the relationship of *tropical storms* with time is examined (see Figure 3.9c). Results show no significant trend in any region, although trends in the western development region

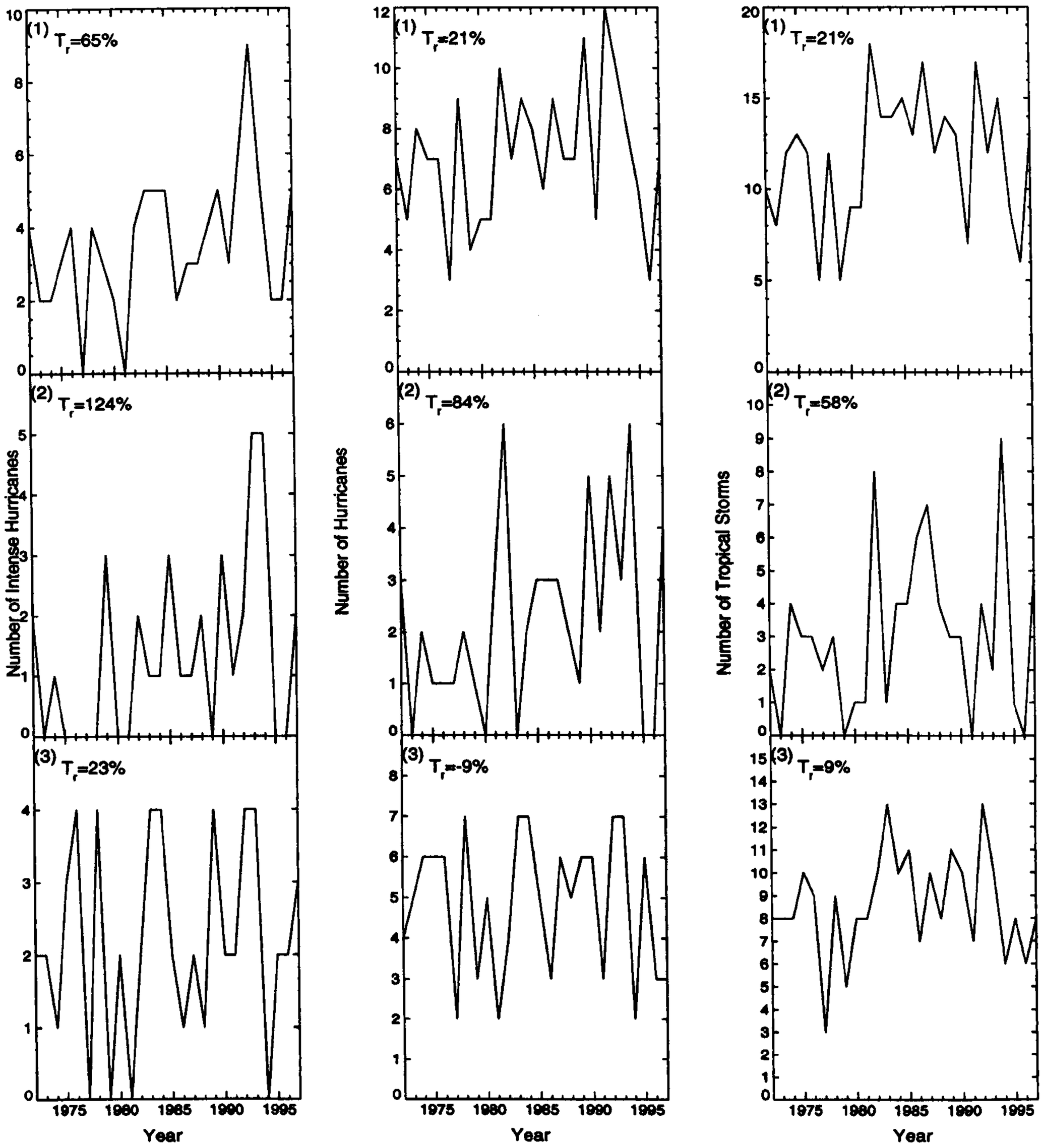


Figure 3.9 Time series of seasonal tropical cyclone numbers, July-September, 1972-1997. a) intense hurricane numbers, b) hurricane numbers and c) tropical storm numbers for the three regions, 1) Whole NE Pacific, 2) Western development region, and 3) Eastern development region.

(Figure 3.9c(2)) are almost significant at the 10% level where T is 0.071 tropical storms per year representing an increase of 1.85 tropical storms in the 26-year period (T_r is 57.9%). The sharply rising trend for intense hurricanes in all of the NE Pacific compared with the more gradual rise for hurricanes suggests, perhaps, that in later years, hurricanes are more likely to intensify once they are established.

These trends in the western development region can alternatively be quantified by looking at the decadal scale. The dataset is split into half the years to examine the difference between the earlier period and later period (see Figure 3.10). Table 3.1 shows the number of tropical cyclones in the two periods and the p-value from a t-test to examine whether the differences are statistically significant. The intense hurricane category shows a distinct decadal variability as it shows a significant upward trend between the two periods. Although there is an upward decadal trend for the hurricane and tropical storm category, it is not significant at the 10% level in either case.

	Western Development Region			
Variable	1972 -1984	1985 -1997	p-value	Significance %
TS	32	48	0.21	21
H	22	37	0.11	11
IH	10	25	0.05	5

Table 3.1 Decadal scale trends in tropical cyclone frequency for the western development region. The numbers given are the total number of storms in each category for each period, the p-value from a t-test and the significance associated with this p-value.

Due to the lack of long records of tropical cyclone occurrence, it is difficult to establish whether these positive trends represent part of a long-term trend in cyclone climatology or whether they are part of a cyclic change and may, in time, even out or even become negative. All that can be said with some certainty is that, to date, from the beginning of the reliable period, intense hurricane and hurricane numbers in the western development region are increasing with time.

Provided that they are not artefacts of the data (checked below), these different trends in tropical storms, hurricanes and intense hurricanes to the west and east of 116°W suggest that the causal factors to the west are varying differently from the ones to the east, and/or that hurricanes to the west are more responsive to these changes. In any case, there is no consistency in the trends of hurricanes and intense hurricanes between the different regions,

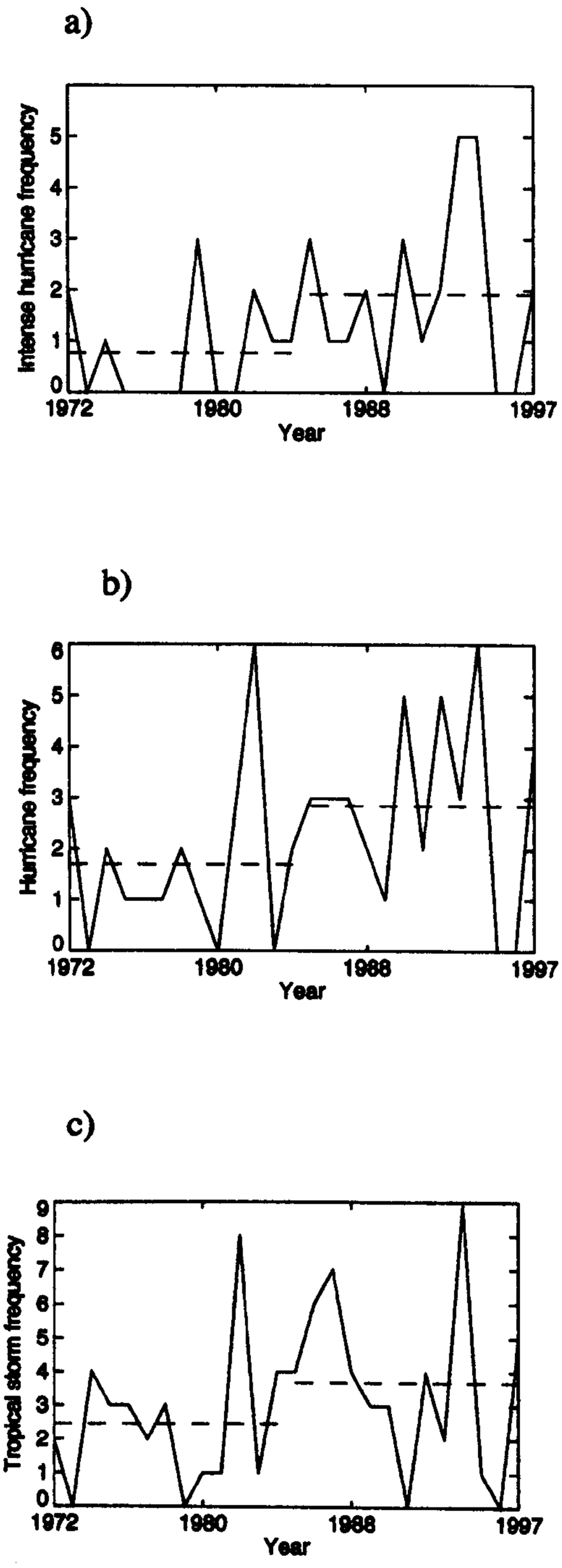


Figure 3.10 Decadal scale variation in western development region tropical cyclone numbers (July-September). a) Intense hurricanes, b) Hurricanes, c) Tropical storms. The dashed lines shows the average for 1972-1984 and 1985-1997 respectively.

indicating again that the two regions should be examined separately.

Further trend analysis has been conducted since this work, based on the years 1972-1997, due to more data availability for the most recent years of record. The intense hurricane trend is still significant for the years 1972-2000 at a significance level of 5%. However, the hurricane and tropical storm trend is examined with the more recent data and a significant linear trend is not evident in either case (the significances are 20% and 31% respectively) because the last couple of years have seen below average numbers of hurricanes and 1998 and 1999 saw below average numbers of tropical storms in the western development region (e.g. 1998 saw zero tropical storms). Trends in the eastern development region for each category and for the corresponding longer time periods remain insignificant.

There is also a significant time trend for the period 1972 - 1997 (up to the 5% level) with net tropical cyclone activity in the western development region (see Figure 3.11) with an NTC of 4.56 per year (114 over the 26-year period). This would be expected since the NTC index includes tropical cyclone frequency which was just examined.

3.2.2 Understanding the trends of tropical cyclone frequency

Whilst globally it is thought that there are no discernible trends in tropical cyclone frequency (Henderson-Sellers et al., 1998), individual basins have shown trends, though there is no common pattern of variation. Extensive analyses have been conducted for the North Atlantic basin. Lighthill et al. (1994) noted that there was no apparent secular variation in the annual tropical cyclone numbers in the North Atlantic. Although there was no significant trend for tropical storms, there has been a significant downward trend in intense hurricanes noted from the 1940s to 1990s, despite extremely active years in 1995 and 1996 (Landsea et al., 1996). In the NW Pacific basin, Chan and Shi (1996) showed that tropical cyclones decreased by about 30% from 1960 to the late 1970s but thereafter increased through 1994. In the Australian region (105°E-160°E), since 1970, there has been a decrease of about 70% in the frequency of moderate tropical cyclones (with minimum pressures between 970 hPa and 990 hPa), and a small increase in the frequency of intense (<970 hPa) hurricanes (Nicholls et al., 1998). Over the same period, the North Indian basin shows a notable downward trend in frequency, but the SW Indian basin and the SW Pacific region (east of 165°E) show no long term trends (Henderson-Sellers et al., 1998). In the central Pacific, from 1966 to 1997, there have been strong upward trends in tropical cyclone frequency in the extreme west of the basin as noted above (Chu and Clark, 1999). However, it has been noted in Section 2.1.1, that tropical cyclone data only from

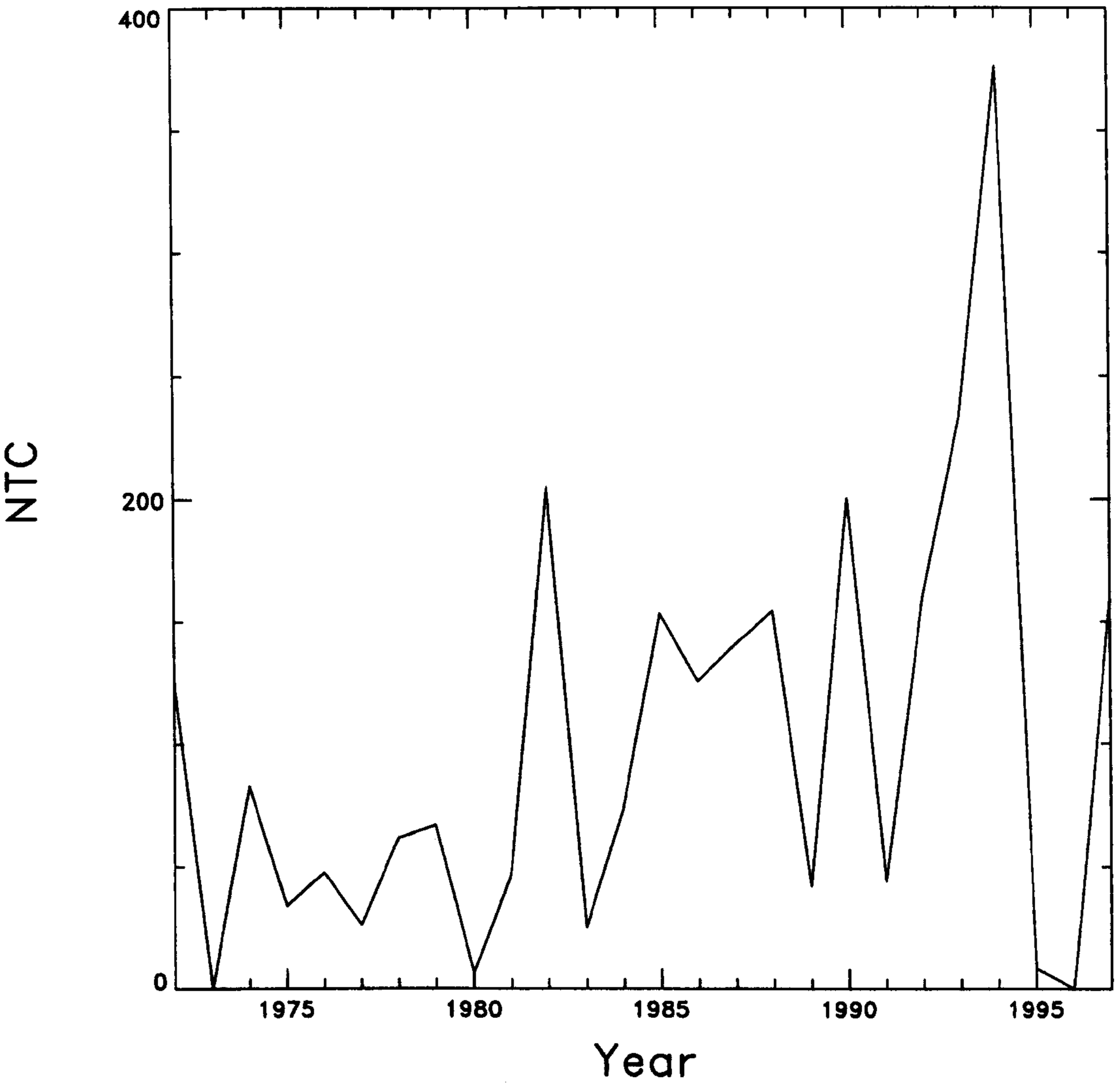


Figure 3.11 Time series of NTC for the western development region, July-September, 1972-1997.

1972 in this basin should be considered reliable. The work presented in Section 3.2.1 shows that there are significant upward trends of hurricanes and intense hurricanes in the broader western development region of the NE Pacific basin (116°W to 180°W) from 1972-1997. This work also shows that no discernible trends are evident east of this to the North American coastline during this same time period.

The causes for these observed increasing trends in the western development region of the NE Pacific basin are not certain. Possible mechanisms fall into three main categories: 1) the trends are an artefact of the data, 2) the trends are a result of increases in the number of triggering tropical disturbances such as easterly waves, or changes in other external influences and/or 3) the trends are a result of conducive environmental variables changing through a) global warming and/or b) natural variability.

Let us first consider the possibility that the trends may not be real but may be an artefact of the data. Nicholls (1995) and Henderson-Sellers et al. (1998) noted the problems of observing hurricane trends, particularly that direct observations of hurricanes are difficult, and accurate records using reconnaissance aircraft or satellites are limited. One possible explanation for the increase in tropical cyclones is that there was better recording of these storms in more recent years. However, these trends are not due to observational omissions since there was satellite coverage in this area from 1966. Therefore, all tropical storms would have been detected. Furthermore, in 1972 the Dvorak technique (Dvorak, 1975) was introduced to measure the intensity of the tropical cyclone, which means that observing tropical cyclone intensities has been consistent in the 26-year period. The Dvorak technique is subjective and thus there will be over- and under- estimates, but this is likely to be random throughout the time period.

When examining these trends, attention should be given to the fact that prior to 1988 the responsibility for the NE Pacific was assigned to the Eastern Pacific Hurricane Center in Redwood City, California. The responsibility was transferred to the NHC, Miami in 1988 as part of a reorganisation of the National Weather Service in response to budgetary problems. Hence, two different organisations were responsible for the intensity estimates in these two different time periods, and a change in the intensities recorded is possible (see Section 2.1.1). However, since it would appear from the data that tropical cyclone numbers were already increasing before 1988, the change in these wind estimates between the different organisations does not seem to explain the upward trend observed. Furthermore, the relationships with environmental variables (see Section 4.4) are similar whether or not time is included as an additional variable. This indicates that there is not an independent

factor such as a time-varying data artefact causing any trends. Therefore, the possibility that the increasing trends are an artefact of the data can largely be eliminated (although it was mentioned in Section 2.1.1 that there are no aircraft measurements of maximum wind speeds for the most intense hurricanes in the NE Pacific, and thus data used in this study cannot be checked with independent data).

The possibility that the trends in tropical cyclone numbers are a result of increases in the number of triggering disturbances can largely be rejected based on the relationships with the environmental variables and the tropical cyclones which will be seen in Chapter 4. However, since the correlations are not perfect, there is still some possibility of the disturbances influencing the variations and the trends in tropical cyclones. Although it is thought that African easterly waves can traverse into the NE Pacific (e.g. Avila, 1991), it is likely that there is also an origin of these disturbances locally (e.g. Molinari et al., 2000). Currently, there is no dataset of these disturbances to examine their trends.

Another external influence that might be considered is pollution. Humans have affected the atmosphere not only by emitting into the atmosphere pollutants such as carbon dioxide, which is a greenhouse gas and results in global warming, but they have also emitted other substances and thus have polluted the local environment. A local anthropogenic influence that could be considered involves the effects of industries in Mexico which cause high pollutant levels. It has been reported (Cerveny and Balling, 1998) that more hurricanes occur during the week in the North Atlantic rather than weekends, possibly due to more pollutants being emitted on weekdays, and these act as important condensation nuclei. Therefore, with increasing industry, in turn causing the pollution problem to get worse in Mexico in more recent years, there are in turn more condensation nuclei which leads to the possibility of more hurricanes. Research into the effects of Mexico's pollution on hurricane formation is currently being carried out, though the results are not yet published (Cerveny, 2001, personal communication). However, since a trend does not exist in the eastern development region which is closest to Mexico, the idea of a local anthropogenically induced climatic effect affecting tropical cyclone trends through this source is not supported.

Therefore, it seems most likely that the trends are a result of the conducive environmental variables changing through time which may be a result of global warming or natural variability. Figure 3.12 shows how the environmental variables examined in Chapter 4 have been changing with time. Those with a significant trend (at least to the 5% level) are shown in red. Trends in some of these variables have been noted by other authors, e.g.

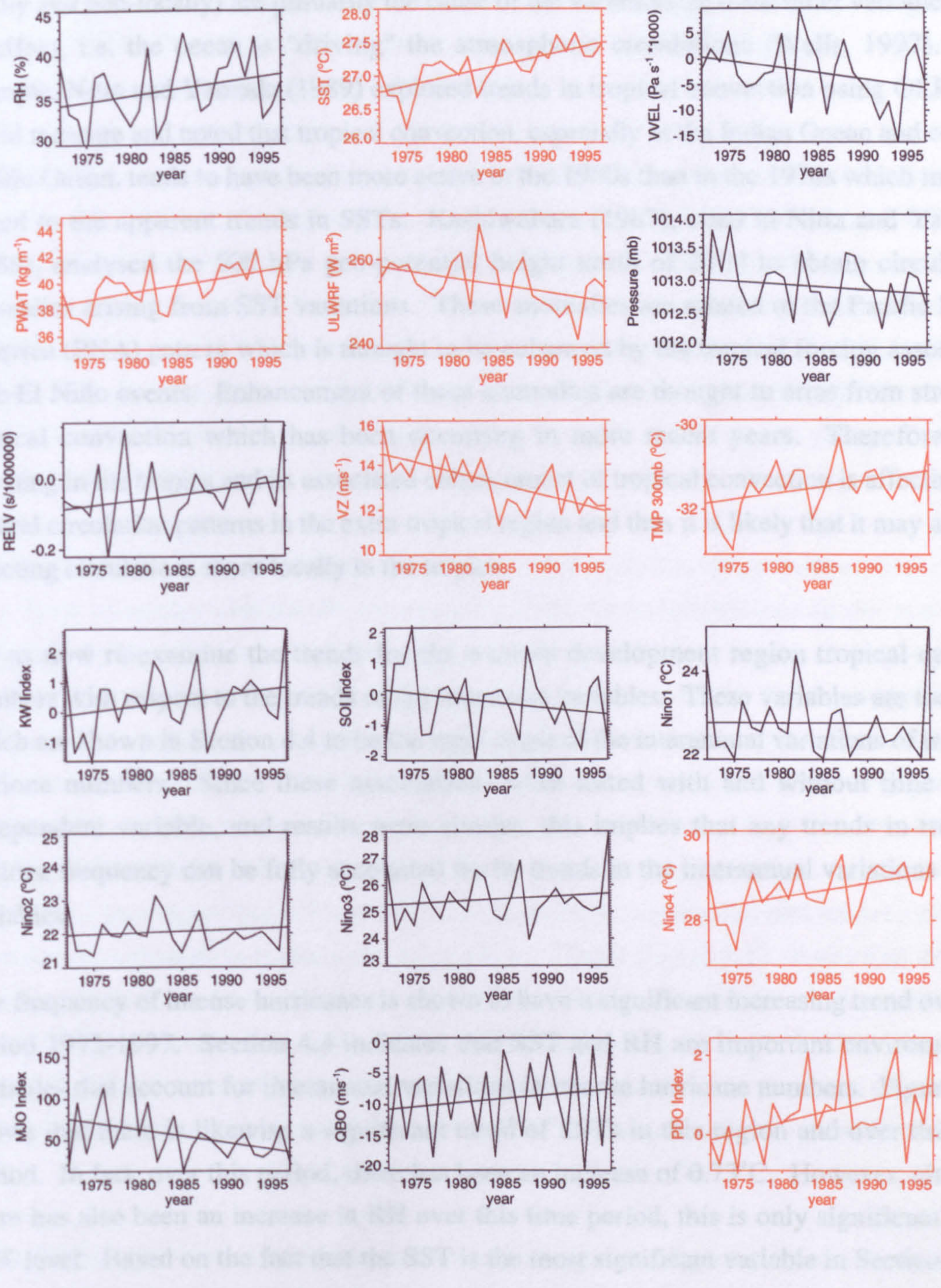


Figure 3.12 Time series of the environmental variables. Variables with significant trends at least to the 5% level are shown in red. (Note: in figure 1mb = 1 hPa).

for SST (see below) and OLR (Nitta and Yamada, 1989). It is thought that SSTs (both locally and non-locally) are primarily the cause of the variations in these other variables, not an effect, i.e. the ocean is "driving" the atmospheric circulations (Wells, 1997). For example, Nitta and Yamada (1989) explored trends in tropical convection using OLR as a useful measure and noted that tropical convection, especially in the Indian Ocean and central Pacific Ocean, tends to have been more active in the 1980s than in the 1970s which may be linked to the apparent trends in SSTs. Kashiwabara (1987), cited in Nitta and Yamada (1989), analysed the 500 hPa geo-potential height north of 20°N to obtain circulation anomalies arising from SST variations. These anomalies are related to the Pacific North America (PNA) pattern which is thought to be enhanced by the tropical forcing associated with El Niño events. Enhancement of these anomalies are thought to arise from stronger tropical convection which has been occurring in more recent years. Therefore SST warming in the tropics and its associated enhancement of tropical convection is affecting the general circulation patterns in the extra-tropical region and thus it is likely that it may also be affecting circulations more locally in the tropics.

Let us now re-examine the trends for the western development region tropical cyclone numbers with respect to the trends of the important variables. These variables are the ones which are shown in Section 4.4 to be the main cause of the interannual variations of tropical cyclone numbers. Since these associations were tested with and without time as an independent variable, and results were similar, this implies that any trends in tropical cyclone frequency can be fully accounted for by trends in the interannual variations of the variables.

The frequency of intense hurricanes is shown to have a significant increasing trend over the period 1972-1997. Section 4.4 indicates that SST and RH are important environmental variables that account for interannual variations in intense hurricane numbers. Figure 3.12 shows that there is likewise a significant trend of SSTs in this region and over this time period. In fact, over this period, there has been an increase of 0.73°C. However, although there has also been an increase in RH over this time period, this is only significant at the 11% level. Based on the fact that the SST is the most significant variable in Section 4.4 to explain the interannual variations in intense hurricane numbers, and that there has also been a significant increase of SSTs in this area, it is suggested that this variable explains the large significant increase in intense hurricanes. The mechanism by which SST may influence intense hurricane frequency is discussed later. Chapter 5 examines causal mechanisms for the interannual variations of SSTs in this region, and ENSO (Niño4) is suggested primarily to be the cause. Figure 3.12 also shows significant increasing trends (at the 5% level) in

Niño4 region SSTs, where there has been an increase in SSTs of 0.82°C over the 26-year period. This is consistent with the mechanism proposed in Chapter 5 which can explain the trends in SSTs. Therefore the trend in the frequency of intense hurricanes is considered to be largely a result of the trend in ENSO (Niño4).

Considering variations in hurricane frequency, Section 4.4 shows that RH is the dominant control, with SST also being important. The mechanisms by which RH and SST may influence hurricane frequency are discussed in Chapter 4. Although RH does not have a significant trend to the 5% level, it is increasing. Furthermore, Chapter 5 proposes that ENSO (Niño4), which has been shown here to have an increasing trend, affects SSTs in the western development region which are associated with convection and thus ENSO affects the RH. Therefore, the trend in hurricanes is again believed to be largely a result of the trend in ENSO (Niño4).

An examination of the tropical storm category indicated that these storms tended to be increasing in number over the 26-year period and this result is significant almost to the 10% level (unlike the other tropical cyclone categories examined whose trends are significant to a higher level). Section 4.4 also indicates that RH is the variable that best explains the variations in tropical storm numbers when considering the best single model. Again the causal mechanism for this link is discussed later. As mentioned, RH is increasing, though the result shown is also significant at just under the 10% level. As RH is the dominant single variable model, this may explain why the trends in tropical storms are not stronger. Section 4.4 also shows that VZ and PRES act together to produce the best model overall for explaining variations in tropical storm numbers. Whilst Figure 3.12 shows that although VZ has a significant decreasing trend with time towards more conducive values for tropical storm formation, there is no significant trend in PRES during this period. Thus, despite the significant trend in the VZ, there is no significant trend in tropical storms at the 5% level and this may be because the lack of trend in PRES is counteracting the trend effects of the VZ.

The trends in the environmental variables may be a result of global warming or may be a result of trends in the natural variability of the climate system. It has already been alluded to that ENSO is considered in Chapter 5 to cause the interannual variations in SST and it is also shown above that ENSO (Niño4) also has an increasing trend. So based on the theory proposed in Chapter 5 (which relates to its geographical position near the western development region) this is likely to explain increases in tropical cyclone frequency. However, for completeness, let us consider another possible cause for the trends in the

variables, which may in turn cause trends in the number of intense hurricanes and hurricanes - global warming. Let us consider this, with particular reference to SST, which has been shown above (and in Chapters 4 and 5) to be largely responsible for these trends.

Nitta and Yamada (1989) agree with the plot shown in Figure 3.12 which shows the trend of SSTs in the western development region. They noted a large positive SST difference between 1967-1976 and 1977-1986 with an amplitude to about 0.8°C in the NE Pacific around 20°N and 120°W.

There is no general consensus whether these trends in SSTs are a result of global warming or due to some natural variability in the climate system. The 1995 IPCC (IPCC, 1996) report does not suggest a mechanism for such an increase, other than indicating that it could be due to human-induced global warming. This is supported by Bryan et al. (1982) who have studied the transient response of the climate to increasing atmospheric carbon dioxide. Through the use of a three-dimensional climate model they determined that the initial response to a sudden rise in atmospheric carbon dioxide is a sharp rise of SSTs in the tropics. Though it can be seen that there is a large increase in SSTs, global warming affects the upper temperatures as well (see Section 1.7). Knutson and Tuleya (1999) noted that there will be a larger increase in the temperature of the air aloft. Figure 3.12 shows that whilst the temperature at 300 hPa is increasing (significant at the 5% level), this increase is not as strong as the SST increase. This suggests that most of the observed SST increase is caused by something other than global warming.

Chu and Clark (1999) asserted that since global warming is a gradual process, it cannot explain why there is a steplike change in the tropical cyclone incidences in the early 1980s for the central Pacific. Likewise, with this reasoning, it cannot similarly explain the steplike change in tropical cyclone activity that is observed in the NE Pacific (see Table 3.1). Instead, the work done for the NE Pacific in Section 3.2.1 and by Chu and Clark (1999) for the central Pacific indicates a decadal scale variability. For the first half of their period (1966-1981) they noted that the mean number of tropical cyclones is three whilst in the latter half (1982-1997) the mean number of tropical cyclones doubles to six. Chu and Clark (1999) give a more plausible explanation than global warming for this step-like increase which invokes the decadal scale variability of SST in the Pacific Ocean (e.g. Nitta and Yamada 1989).

Certainly, in other basins, global warming has been rejected as a cause of possible trends in tropical cyclone frequency. For example, in the NW Pacific, temperatures have increased

by 0.5°C since the 1960s, but the number of tropical cyclones did not steadily increase and since the mid-1990s have been decreasing. The North Atlantic has seen a downward trend in intense hurricanes as noted by Landsea (1993) but has recently entered an active era. However, such activity has been experienced in the past, such as in the late 1940s and 1950s when global temperatures were lower. Gray et al. (1997) speculated that such a return to active conditions may be a result of a natural cycle associated with the North Atlantic Conveyor Belt. Furthermore, when considering the North Atlantic basin, Elsner et al. (2000) noted a decadal scale variability where they indicated that there have been three major changes in the rate of hurricanes per year, one at 1943 (going from a low to a high rate), one at 1965 (returning to a low rate) and one at 1995 (returning to a high rate). Elsner et al. (2000) postulated an alternative source of natural variability involving the North Atlantic Oscillation, which complements the North Atlantic Conveyor Belt theory proposed by Gray et al. (1997). The decadal change noted by Elsner et al. (2000) for tropical cyclones in the North Atlantic is a step-like rather than steady change, and thus, like the increases in the central Pacific and western development region, is not indicative of global warming according to the argument of Chu and Clark (1999). Therefore, sources of natural variability in the climate system, rather than global warming, are generally thought to be the cause of any trends in all the basins.

In recent work by McDonald et al. (2001) which examines future trends, tropical cyclone numbers have been modelled under a greenhouse induced environment and compared with a model based on the natural variability of the present time. Interestingly, this work confirms the existence of a division in the NE Pacific basin around 116°W. It is found, in the western development region, that substantial increases in tropical cyclone numbers occur in the future, due to global warming. Therefore, this work suggests that at least some of the trend observed in the western development region, in the current study, may be the beginning of a global warming trend and that the trends observed in the western development region may not be entirely cyclical but may include a long term component. Decreases in tropical cyclone numbers are found in the eastern development region in the model under global warming conditions. It is suggested by these authors that the future decrease in tropical cyclones in the east of the basin is linked to the 850 hPa relative vorticity and the convective rainfall rate which decreases, and the vertical wind shear which increases.

In summary, it has been shown that there are increases with time in tropical cyclone numbers in the western development region. Several theories have been provided to explain the increases. Some have been discounted, such as changes in recording methods

and the changeover in the area of responsibility of the NE Pacific basin, and the analysis of Chapter 4 suggests that the trends are not due to data artefacts or a variation in numbers of triggering disturbances, but occur due to trends in the environmental variables. There is also a large body of evidence which suggests that global warming does not provide the answer although McDonald et al. (2001) showed that rising trends in the western development region do occur in their model of a greenhouse warmed climate. Based on the trends of the environmental variables in the western development region, particularly SST, and later analysis on the links between SST and tropical cyclone frequencies, it is clear that the trends in tropical cyclone frequency are likely to be a response to these trends. Given the increasing frequency of El Niños (based on the Niño4 index), the proximity of ENSO (Niño4) to the western development region, and the relationship between ENSO and SSTs (and between SST and RH) in the western development region (see Chapter 5), it is likely that natural variability, mainly in the form of ENSO, can largely explain the trends in tropical cyclone frequency in the western development region of the NE Pacific basin. It is possible that the ENSO trends are due to a greenhouse gas enhancement. However, currently it is unclear if and how global warming affects ENSO events.

3.2.3 Possible new mechanism for relating variations in SST to variations in tropical cyclone frequency

Various theories have been proposed regarding the effect of SST on tropical cyclone frequency (see Section 1.5.1.3). However, this section provides an alternative idea, where the frequency changes in the high categories of tropical cyclones may be accounted for by a change in tropical cyclone intensity.

In the literature there has been a strong tendency to consider frequency and intensity independently with regard to changes and the causes of change. Early studies (e.g. Gray, 1979) were largely confined to frequency and considered the genesis of all tropical cyclones largely on a geographic basis. Since then there have been studies of intensity as well (e.g. Emanuel, 1986) but these are largely independent of frequency. Emanuel, in particular, has always stressed that frequency and intensity should be treated as separate effects (e.g. Emanuel 1987 and 1995). Emanuel (1987) made it clear that he does not make a link between MPI and frequency. Emanuel (1995, p. 2241) noted that, "... the issues of tropical cyclone frequency and intensity are largely separate: there may be few storms under circumstances that support large intensity or many storms in conditions that support small intensity". In the context of these papers he considered the frequency of *all* tropical cyclones i.e. genesis. However, this separation of frequency and intensity is not valid when *categories* of tropical cyclone are considered. This is because a general increase in

the intensity of tropical cyclones will tend to increase the frequency in the higher categories as more storms are pushed into those categories. For example, Idso et al. (1990) noted that for landfalling storms, a decline in intensity would lead to a decrease in the frequency of higher category tropical cyclones and an increase in the frequency of lower category tropical cyclones. Likewise, Landsea et al. (1999, p. 101) noted that the variations in the mean intensity of North Atlantic tropical cyclones, from a strong mean intensity (mid 1940s - 1960s) to a weak mean intensity (1970s - early 1990s), are primarily, "...driven by decreases in the number of intense hurricanes...". Empirical studies have inevitably needed to categorise storms by intensity (which is also desirable from the view of their impacts on society). However, many of these studies concern *frequency* of the various categories of tropical cyclone (e.g. Nicholls et al., 1998) or *intensity* (e.g. Evans, 1993), but not both, and generally do not stress this intensity-frequency link. One may speculate that this is perhaps due to confusion between genesis and the formation of the categories of tropical cyclones (clarified by Molinari et al., 2000 (see Section 1.2)) and, therefore, a mis-interpretation of Emanuel's (1995) separation of frequency and intensity comments.

It is suggested, herein, that this rarely mentioned link between intensity and frequency (for categorised tropical cyclones) might be of great importance when considering the impact of SST changes. It has become possible to propose a detailed mechanism for this, because although the link between MPI and SST has been established for some time, it is only recently that the distribution of intensities has been understood (Emanuel, 2000). Emanuel found that the frequency distribution of hurricane intensities relative to their MPI is flat, i.e. "a given storm is equally likely to attain any intensity between hurricane force [strictly, half its potential intensity] and its potential intensity" (Emanuel, 2000, p. 1141). For storms less than half their MPI, the distribution is also flat but the frequency per unit wind speed is approximately two times higher.

The mechanism is as follows. Noting the trends of SST in the previous section, either as a result of global warming and/or natural variability, there should be an associated increase in the storm's MPI as quantified by Holland (1997) and Tonkin et al. (2000). Therefore, the actual intensities of the storms should also increase provided that the intensity distribution relative to the MPI remains flat (Emanuel, 2000). This would result in increasing trends in frequency for categorised tropical cyclones. Note that, unlike the case of landfalling storms above, all categories will show positive frequency increases because the categories are not exclusive (see Section 2.1.1). However, it is important to note that Emanuel has strong grounds for separating frequency and intensity in relation to *global warming*, where he states (Emanuel, 2000, p. 1151) that, "...if global warming were to result in a 10%-20%

increase in potential wind speed ... the wind speeds of real events would, on average, rise by the same percentage. What might happen to the overall frequency of events [i.e. their genesis] is, of course, a different question". With global warming, many factors come into play (such as the upper atmospheric temperature) and the link between frequency and intensity may be masked by these other effects on the overall genesis of tropical cyclones. With natural variability, however, the link is perhaps more likely to become evident. Hence, such an effect may account for some of the hurricane and intense hurricane trends in the western development region and may possibly account for all of them. The same effect might also account for some or all of the relationships between tropical cyclone frequency and SST in the western development region (see Chapter 4). However, if this is the case, it is necessary to explain why there are no significant trends or correlations in the eastern development region. An important difference is that SSTs in the eastern development region are higher than those in the western development region, though the ranges are similar (see Figures 3.13 and 4.6). DeMaria and Kaplan (1994), when considering the North Atlantic basin, found that the MPI vs. SST curve flattens above 28°C, e.g. for SSTs between 28°C and 28.5°C they showed an MPI difference of approximately 2.5 m s^{-1} compared with a difference of approximately 7 m s^{-1} for SST values between 27.5°C and 28°C. In the eastern development region, 65% of the average SST values are greater than 28°C (and 85% are above 27.8°C), whereas in the western development region all the values are below 28°C (actually all are below 27.7°C). In addition, Tonkin et al. (2000) shows that Emanuel's hurricane intensification model (see Section 1.2) also gives a rapid flattening of the MPI vs. SST curve at 28°C. However, it should be noted that Holland's model and some observational data put the flattening closer to 29°C (Tonkin et al., 2000). Therefore, with the higher SSTs in the eastern development region, and with research showing the flattening of the MPI vs. SST curve at temperatures higher than 28°C, it might be expected that the intensity-frequency effect would not be as strong in the eastern development region, which could help to account for the lack of trends with time and correlations between SST and tropical cyclone frequency observed in this region.

An additional possible reason for a lack of the intensity-frequency effect in the eastern development region relates to the intensity distribution. Whitney and Hobgood (1997) noted that only 11% of NE Pacific storms reach 80% of the MPI, while 19% of the North Atlantic storms reach that proportion of their MPIs. However, they noted that tropical cyclones that develop west of 110°W tend to reach a higher percentage of their MPI than storms developing further east. Therefore, whilst it would appear that Emanuel's distribution is reasonable to use for the western development region of the NE Pacific, as this is closer to the North Atlantic situation, in the eastern development region, Emanuel's

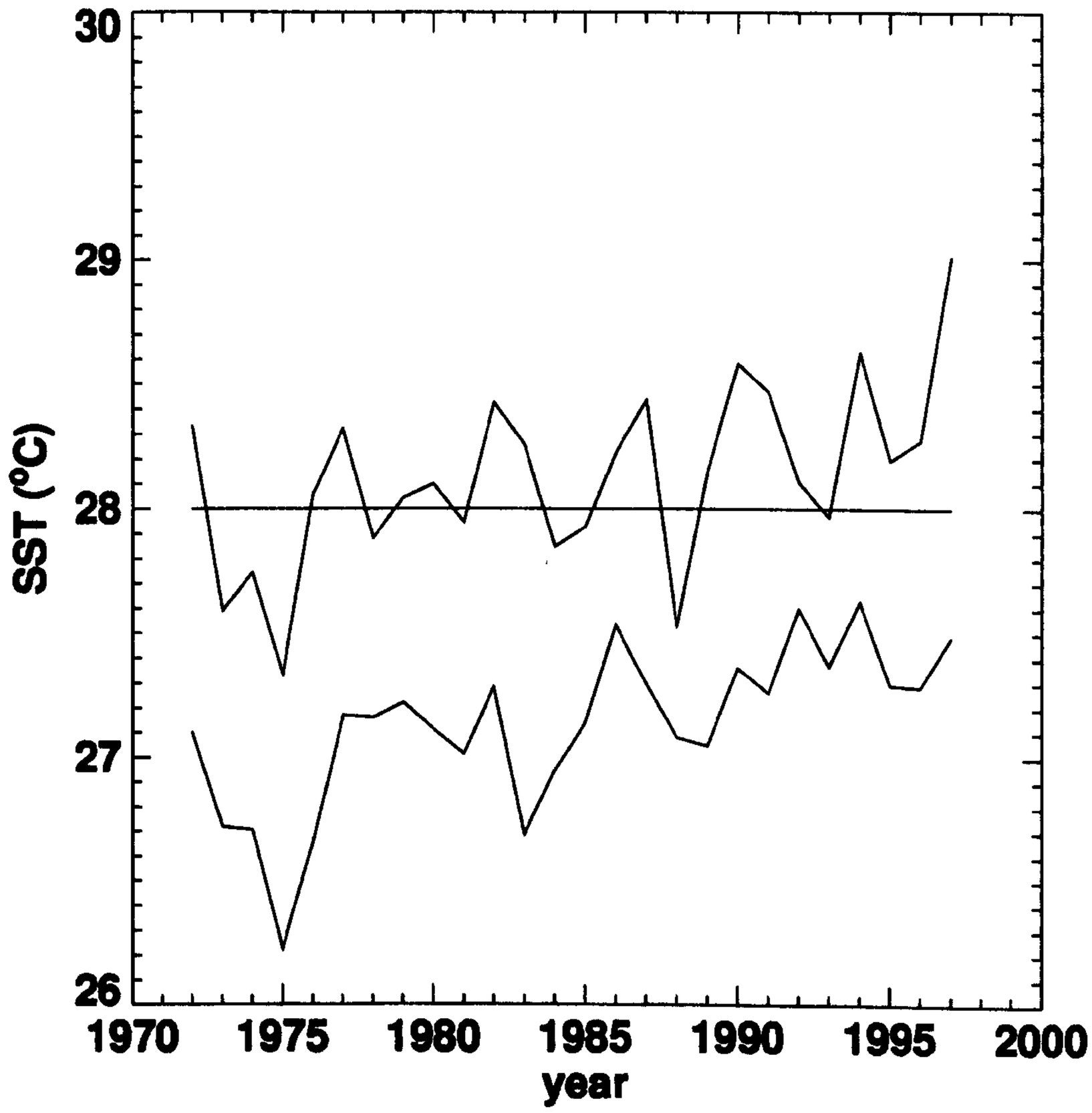


Figure 3.13 Eastern development region SSTs (top) and western development region SSTs (bottom), July-September, 1972-1997.

distribution may not be accurate. With no more than 11% of storms reaching their MPI here, this indicates that there is even less chance of storms reaching the higher categories and, therefore, even less chance of seeing the intensity-frequency effect.

One way of assessing the magnitude of any intensity-frequency effect would be to carry out a simulation study. However this is not particularly straightforward, and is suggested as a subject for future investigation. One difficulty is that it is not possible to pick a single SST value for each year, since there is a wide range of local SST values for each year within each development region, and SST also varies for each tropical cyclone along its track. Another difficulty is that ideally the use of tropical *depression* numbers is required to provide a constant mean frequency for "all" tropical cyclones allowing the examination of the effects on tropical storms, as well as hurricanes and intense hurricanes. However, due to the unreliability of tropical depression data (see Section 2.1.1), this is not possible. Furthermore, when examining the actual maximum intensity of storms with respect to their MPI, Emanuel's intensity distribution (Emanuel, 2000, Figure 4b) only considers tropical cyclones of tropical storm strength or greater.

3.3 Trends in formation locations, track, longevity and intensity

Section 3.2.1 discusses the trends of tropical cyclone numbers with time. It is shown that ENSO is most likely to be responsible for these trends in the western development region, given the arguments of Section 4.7.3.1 which examines the interannual variability of ENSO and links this with tropical cyclone frequency in the western development region. However, there are other characteristics of tropical cyclones, such as their formation locations, longevity, track and maximum intensity that can be explored in terms of trends and the effect of ENSO, using the tropical cyclone dataset discussed in Section 2.1.1, now that two development regions have been established. This section will now concentrate on the whole region and the western development region, which was shown to have significant trends in the previous section. The eastern development region is not considered, mainly because when considering some of these factors, e.g. track or maximum intensity, these may occur in the western development region, despite the formation occurring in the eastern development region. Thus, only the frequency of tropical cyclone formation is considered for the eastern development region, as in Section 3.2 and Chapter 4.

3.3.1 Formation locations

a) Trends

Section 3.2.1 shows that more tropical cyclones occur in the western development region in

the later period 1985-1997 than the earlier period 1972-1984, and no trends are observed in the eastern development region. Therefore, with an examination of the whole region, it is expected that the median position of tropical cyclone formation may shift further to the west also in this latter period if there are more tropical cyclones forming there. This study shows, however, that although the median longitude position of the tropical cyclones is further to the west in the latter period (for all stages of tropical cyclone), the difference is not significant indicating no significant trends in time of where the tropical cyclones form in the NE Pacific basin. This is shown by Table 3.2 which gives the median longitude of formation for the earlier and later period for each tropical cyclone category. The significance is shown by the *p*-value obtained from the Mann-Whitney U test, which is an appropriate test of significant differences between medians. A *p*-value of less than 0.05 shows a significant result at the 5% level. The fact that these trends are so small and insignificant is probably related to the fact that the tropical cyclone numbers are dominated by those in the eastern development region.

	Whole NE Pacific Region			
Variable	1972 -1984	1985 -1997	*p*-value	Significance %
TS	109.0	109.7	0.49	49
H	111.0	112.8	0.41	41
IH	112.5	114.8	0.13	13

Table 3.2 Differences in the position of tropical cyclone formation with time for the whole NE Pacific basin. The median longitude (°W) for each period for each tropical cyclone category is given and compared using the Mann-Whitney U test, to test if they are significantly different.

When considering the western development region alone, it can be seen from Table 3.3 that the median longitude is very similar in both time periods, with the earlier time period actually seeing the tropical cyclones form slightly further west. This result, however, is not significant.

	Western Development Region			
Variable	1972 -1984	1985 -1997	*p*-value	Significance %
TS	128.0	127.6	0.38	38
H	129.3	128.6	0.50	50
IH	129.9	128.8	1.00	100

Table 3.3 Differences in the position of tropical cyclone formation with time for the western development region. The median longitude (°W) for each period for each tropical

cyclone category is given and compared using the Mann-Whitney U test, to test if they are significantly different.

b) Influence of ENSO regime

Section 4.7.3.1 will show that there exists a relationship with tropical cyclone numbers and ENSO in the western development region with more tropical cyclones occurring in El Niño years (particularly for the Niño4 and SOI index). Therefore, it is to be expected that the median longitude of formation occurs to the west in El Niño years. This is confirmed in Table 3.4 which shows that for the whole NE Pacific basin, for each stage of tropical cyclone, they form further to the west in El Niño rather than La Niña years (the results are significant to the 5% level for the tropical storm and hurricane category). Again a Mann-Whitney U test is conducted.

	Whole NE Pacific Region			
Variable	El Niño	La Niña	*p*-value	Significance %
TS	111.8	107.2	0.03	3
H	116.9	108.6	0.03	3
IH	116.6	111.7	0.21	21

Table 3.4 Differences in the position of tropical cyclone formation between El Niño and La Niña conditions for the whole NE Pacific basin. The median longitude (°W) for both phases of ENSO and for each tropical cyclone category is given and compared to test if they are significantly different.

This work agrees with Irwin III and Davis (1999) who acknowledged that more tropical cyclones originate (and remain) closer to the Mexican coast during positive SOI seasons than during other ENSO phases.

An examination of the western development region only (Table 3.5) shows that tropical cyclones actually tend to form further west within this region in a La Niña rather than El Niño phase. Thus, whilst more form there in an El Niño rather than La Niña phase, they tend to form further to the east of the western development region (a result which is significant at least to the 10% level for the hurricane and intense hurricane categories).

	Western Development Region			
Variable	El Niño	La Niña	*p*-value	Significance %
TS	127.5	128.1	0.82	82
H	127.0	138.4	0.09	9
IH	128.4	141.7	0.05	5

Table 3.5 Differences in the position of tropical cyclone formation between El Niño and La Niña conditions within the western development region. The median longitude (°W) for

both phases of ENSO and for each tropical cyclone category is given and compared to test if they are significantly different.

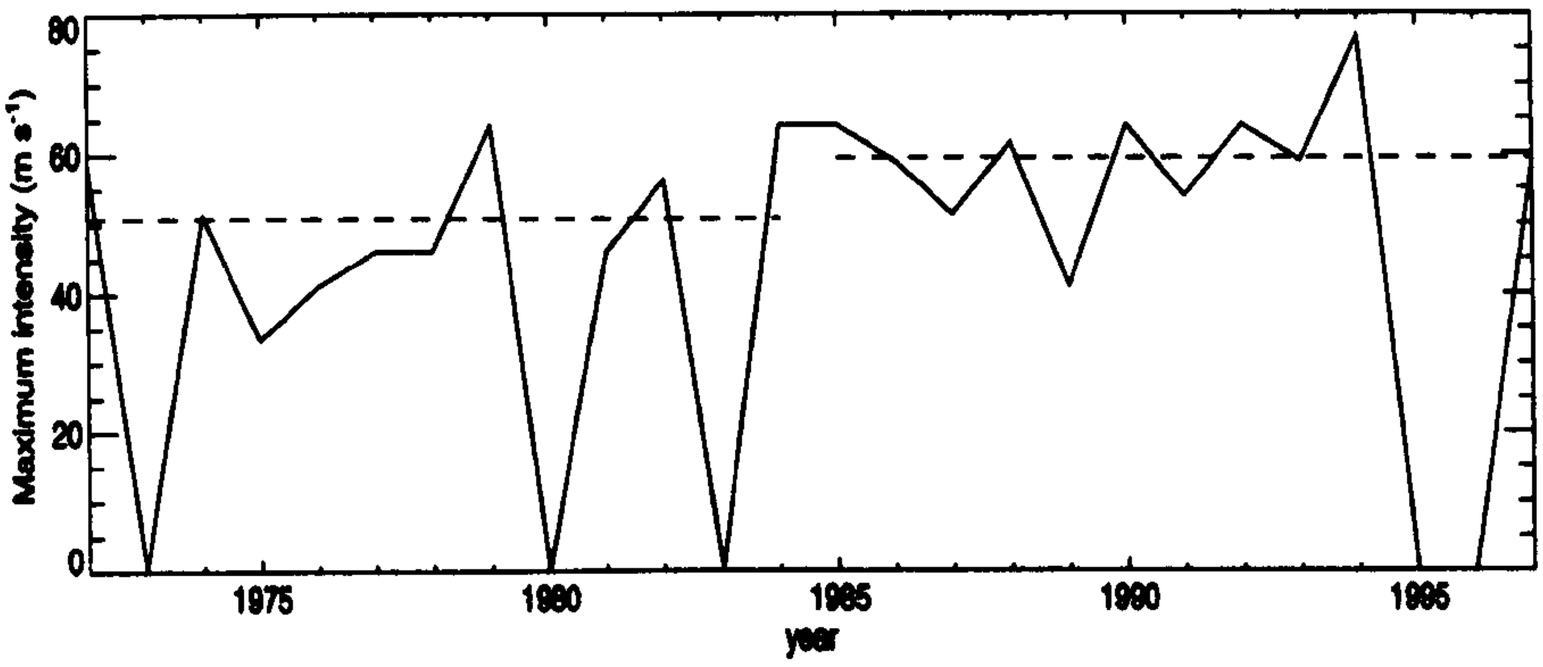
3.3.2 Maximum intensity of hurricanes

a) Trends

Not only have there been trends in frequency for the western development region, but there have clearly also been trends in intensity (with the intense hurricane trend being much higher than the hurricane and tropical storm trend, see Section 3.2.1). Section 3.2.3 gives a detailed analysis of the trends in tropical cyclone frequency and relates them, at least partially, to trends in intensity related to increased SSTs. This section will examine the trends in intensity in more detail. As a measure of the intensity of tropical cyclones, the maximum sustained wind speed from the strongest hurricane for each year is selected for those storms originating in the western development region of the NE Pacific, as done by Landsea et al. (1996) for the intensity of North Atlantic hurricanes. Figure 3.14a shows the maximum intensity of the strongest storm in each year for the western development region. The intensity index seems to fluctuate at a lower level during the first half of the period (1972-1984) compared to the second half of the record (1985-1997). On average (mean), the maximum wind speed is 51 m s^{-1}, in contrast to 59 m s^{-1} in the second half. This is a result which is significant at the 5% level using a *t*-test. Likewise, when examining the whole region (Figure 3.14b), the intensity fluctuates from the former period at 62 m s^{-1} to the latter period at 67 m s^{-1} (also significant to at least the 5% level).

Hobgood and Kimberlain (2000, personal communication) noted a possible under-estimation of wind speed by about 3.1 m s^{-1} before 1988, when the Eastern Pacific Hurricane Center at Redwood, California was responsible for the area. The word under-estimation is used when referring to the first period, rather than over-estimation when referring to the later period, as it is likely that it is the first half of the record that needs to be adjusted rather than the second half of the record, since there is more confidence in the NHC forecasters and their methods in more recent times. For example, in 1997 there were several intense hurricanes recorded including Linda, the most intense hurricane in the NE Pacific on record. Hurricane Guillermo also occurred in the same year. An aircraft actually flew into this storm recording a pressure of 920 hPa, so there is more confidence in assigning the correct wind speed. However, if the under-estimation is added to the mean maximum wind speed observed in the early years for either the western development region or the whole NE Pacific basin, the intensity of hurricanes still appears to be slightly stronger in more recent years. Without correcting for these biases (which for a full correction would involve checking the synoptics of each storm through the satellite pictures

a) Western development region



b) Whole NE Pacific region

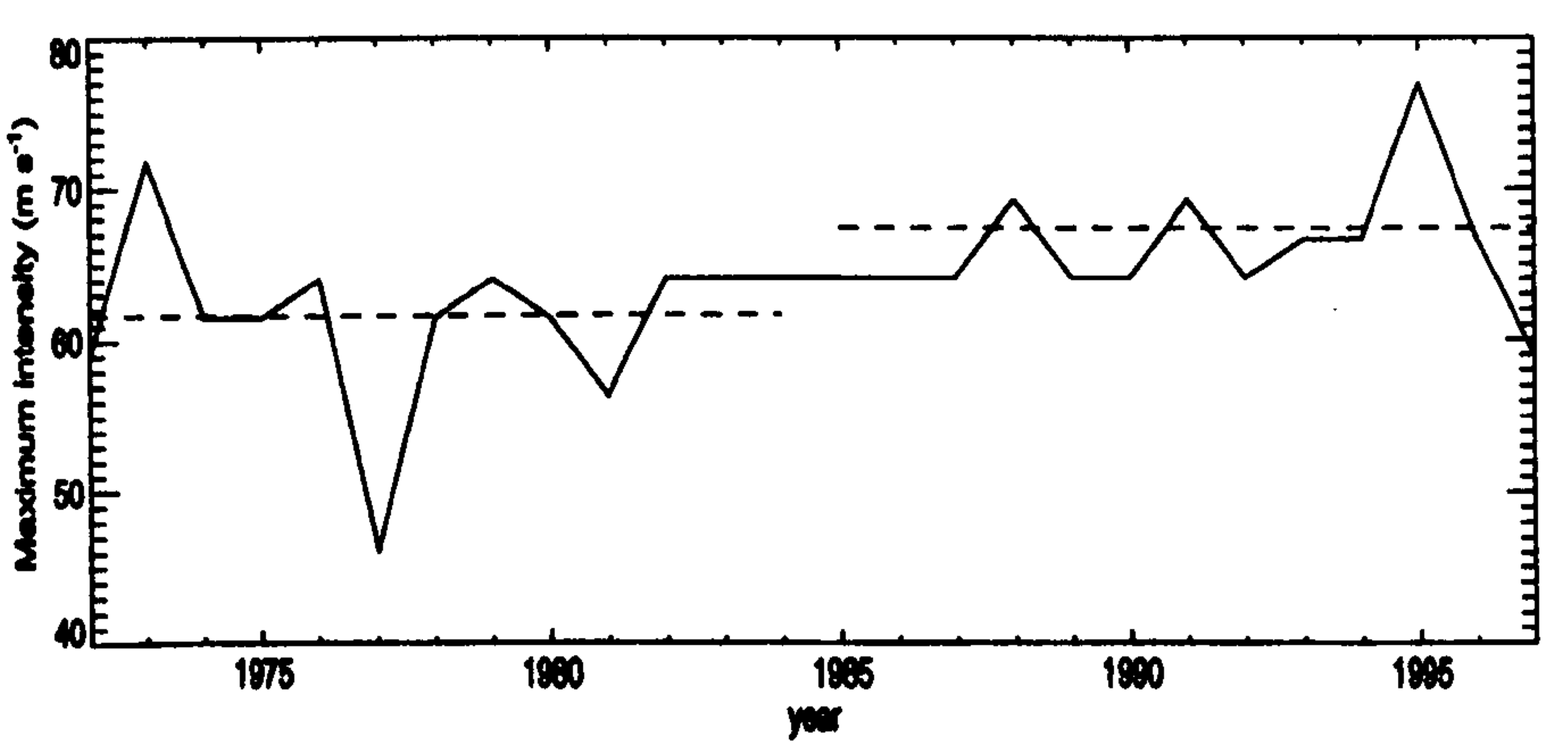


Figure 3.14 The maximum intensity of the strongest storm for each year (m s^{-1}), July-September, 1972-1997.

to agree with the intensities recorded) there is an inherent limitation of the NE Pacific tropical cyclone dataset due to these intensity biases.

Not only is there an intensity bias due to the changeover of responsibility, but there may also be an intensity bias as a result of satellite estimation. This is noted by Gaby et al. (1980) with respect to the North Atlantic, where they noted that the best track file contains maximum sustained winds for the six-hourly intervals which were estimated primarily from satellite imagery except in cases where aerial reconnaissance or ship reports were available. When comparing the estimates obtained from the satellite imagery to those obtained from the other means mentioned, an average absolute difference of 3.8 m s^{-1} was calculated. Applying this, which may be a reasonable assumption to the NE Pacific, the maximum sustained winds may be under-estimated, particularly in the early years when it is believed that there was already an under-estimation, as noted above.

b) Influence of ENSO regime

The maximum intensity of the strongest tropical cyclone was averaged over the six strongest El Niño years (1982, 1987, 1991, 1992, 1994 and 1997) and La Niña years (1973, 1974, 1975, 1976, 1988 and 1989) based on the Niño4 index. The results showed a significant intensity increase in El Niño compared to La Niña years in the western development region, with an average maximum intensity for El Niño years of 60.3 m s^{-1} and for La Niña years of 45.6 m s^{-1} (significant at the 5% level). For the whole NE Pacific region there was a difference between warm and cold ENSO regimes with a mean of 70.9 m s^{-1} and 64.5 m s^{-1} respectively (significant at the 10% level). Thus, with the relationship observed in Section 5.2.1 between El Niño and SSTs in the western development region and the well-known relationship between SSTs and tropical cyclone intensities noted in Sections 1.2 and 3.2.3, it is perhaps expected then to see higher maximum intensities in El Niño years.

3.3.3 Track

In this study, track has been examined in two ways. Firstly, tracks were assessed in terms of the track length which is expressed by calculating the distance (in degrees, as there is little difference in km between a latitude degree and a longitude degree) between each six-hourly record from the storm's first to last position in the record. Pythagoras' theorem was used to calculate the length between successive points of latitude and longitude. Secondly, tracks were examined in terms of the maximum longitude west that the tropical cyclones travel. These analyses will reveal whether tropical cyclones travel greater distances in some years more than others and if they extend further west in some years more than others and hence pose a greater risk to the Hawaiian Islands. A *t*-test is used to examine the

difference between the means.

3.3.3.1 Track length

a) Trends

It was expected that since there have been more high Niño4 years in recent years (see Figure 3.12), that this may cause the track length of the storms to be greater in more recent years. (The reason for this is that the more conducive values of the environmental variables during high Niño4 years may fuel the storm for longer. These conducive values are discussed in Chapters 4 and 5.) Track length and duration are similar measures, hence if they have longer duration (travelling at the same speed), they will have a longer track. This study shows that although the track length is longer in the latter time period (when Niño4 was higher) this difference in track length is not significant between the two periods when either the whole region or the western development region are examined (see Table 3.6).

Variable	1972 -1984	1985 -1997	*p*-value	Significance %
Track Length (Whole)	25.40	29.10	0.12	12
Track Length (West)	24.14	27.08	0.56	56

Table 3.6 Differences in tropical cyclone track length (in degrees) between the earlier period (1972-1984) and the later period (1985-1997). The mean track length for each period is compared to test if they are significantly different. (Whole) is whole NE Pacific region, (West) is the western development region.

b) Influence of ENSO regime

Again, although there is a longer track with warmer ENSOs as expected from above, the difference is not significant. This is shown in Table 3.7.

Variable	El Niño	La Niña	*p*-value	Significance %
Track Length (Whole)	31.20	25.79	0.12	12
Track Length (West)	25.03	22.21	0.60	60

Table 3.7 Differences in tropical cyclone track length (in degrees) with ENSO regime. The mean track length for each ENSO regime is compared to test if they are significantly different. (Whole) is whole NE Pacific region, (West) is the western development region.

3.3.3.2 Maximum longitude west

Although the effect of ENSO on track length is not significant, it is clear from Figure 3.15 that ENSO greatly affects the tracks of the storms, with more storms extending further west in warm ENSO phases. However, one could ask if this is more a case that there are more storms in warm ENSO phases in the western development region and the median longitude of formation is further west in warm rather than cold ENSOs. This can be checked by examining the maximum longitude west between warm and cold ENSO periods and conducting a *t*-test which will take into account that there are more hurricanes in the warm ENSO years.

The maximum longitude west has been explored in terms of a) the average maximum longitude west for each year, so that the maximum longitude west for each storm of the season is considered, and then an average is taken and b) the furthest west any storm out of a particular year may travel. Thus, for the storm that travels furthest west, the longitude of its westernmost point is considered (see Table 3.8).

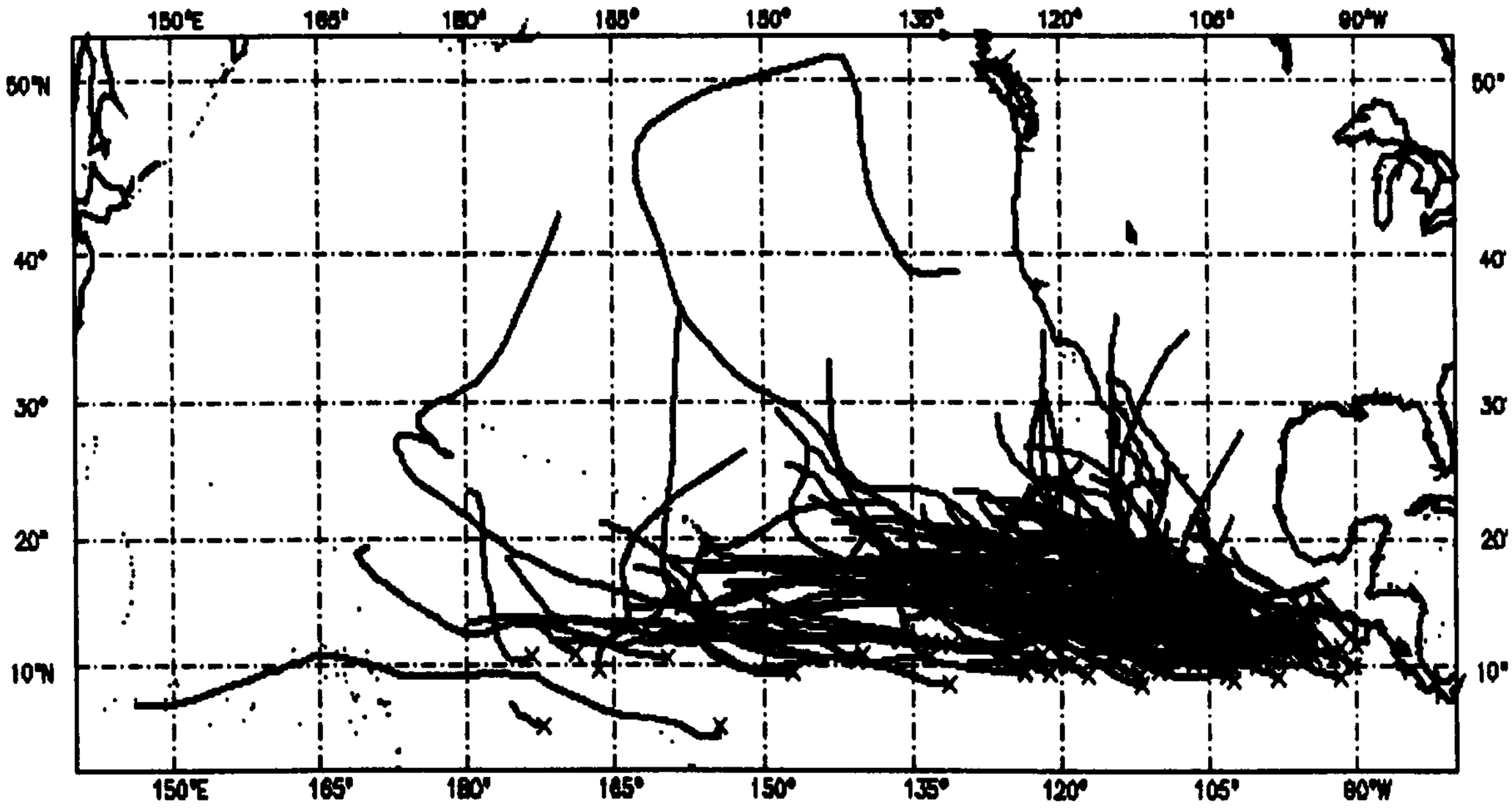
	Average position west					
Variable	1972 -1984	1985 -1997	*p*-value	El Niño	La Niña	*p*-value
Whole	-129.96	132.95	0.34	-138.29	-129.66	0.05
West	-149.49	-153.66	0.55	-153.95	-146.80	0.36

	Furthest position west					
Variable	1972 -1984	1985 -1997	*p*-value	El Niño	La Niña	*p*-value
Whole	-162.98	-169.30	0.40	-171.47	-169.67	0.82
West	-158.83	-171.14	0.22	-170.44	-163.48	0.59

Table 3.8 Mean maximum longitude west of all storms per year and the furthest western position (°W) of the storm that travelled furthest west per year (averaged for each time period and ENSO regime). (Whole) is whole NE Pacific region, (West) is the western development region.

For a), whilst there is no significant trend in time (for either the western development region or the whole NE Pacific region), and there are no significant differences between the ENSO regimes for the western development region, there is a significant difference (at the 5% level) between the ENSO phases when the whole NE Pacific region is considered, with the average maximum longitude west being 138.29° in the six strongest El Niños, compared to 129.66° in the six strongest La Niñas. This is consistent with the fact that the median longitude of formation is further west in El Niños (Section 3.3.1), thus it would be

a) Warm ENSO years



b) Cold ENSO years

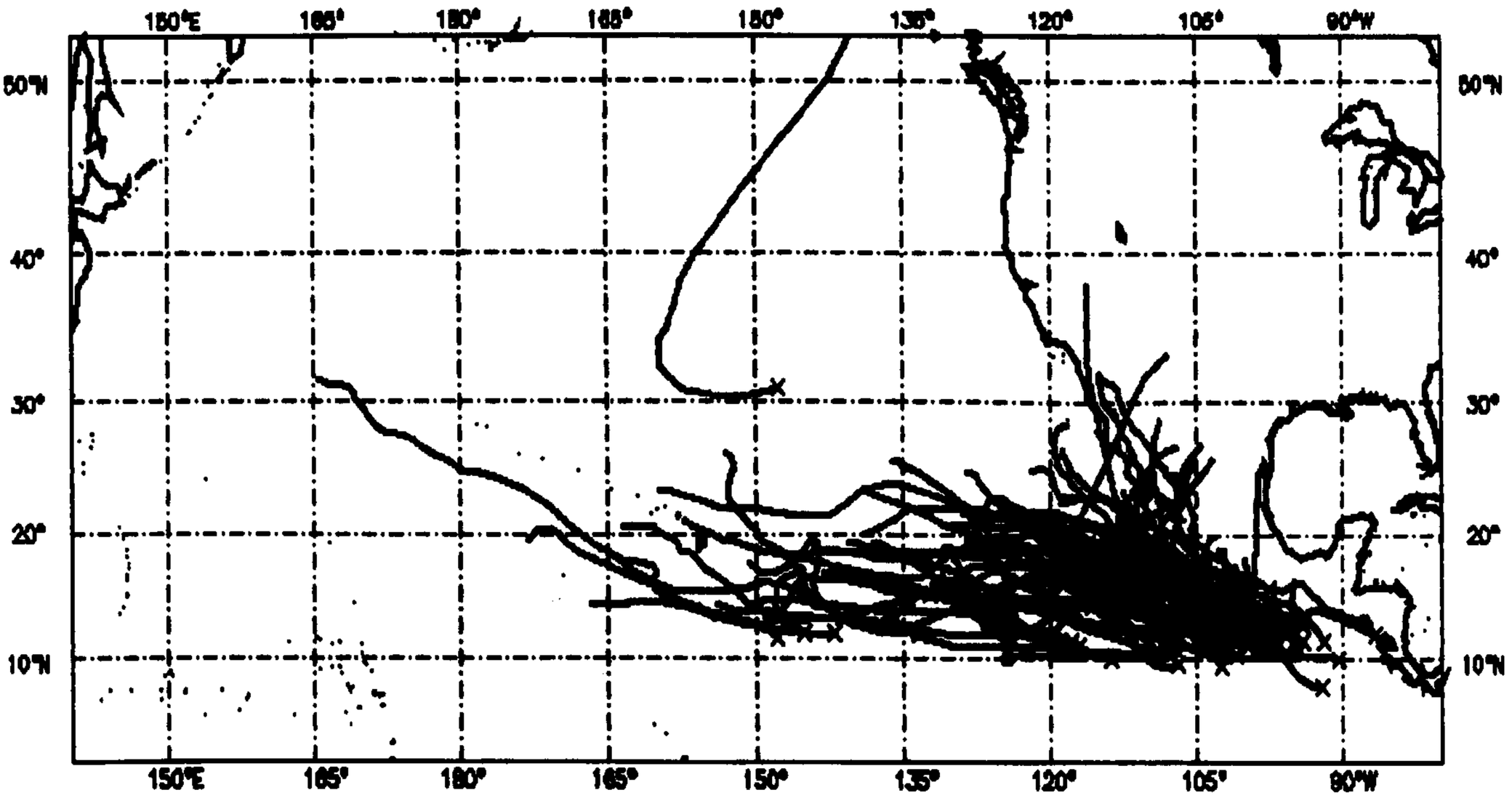


Figure 3.15 Tracks of storms, warm and cold ENSO years.

expected that if more began further west, then they would be able to track further west (assuming a constant track length between the two regimes). This assumption is valid given Section 3.3.3.1 above where there does not appear to be a significant difference in track length between the two ENSO regimes. This has implications particularly for Hawaii if they extend on average further west in warm rather than cold ENSO events. However, for b) it should be noted that when just taking the single storm that tracked the furthest west, instead of an average, then there is not only no trend between the former and latter periods, but there is also no significant difference between the ENSO regimes in either of the regions considered.

3.3.4 Longevity

a) Trends

It can be seen from Table 3.9 that for the hurricane and intense hurricane category, in the western development region, there is a significant difference in their average duration from the earlier period, 1972-1984 to the later period, 1985-1997, although this trend is not observed for the tropical storm category. An examination of the whole region again shows significant differences in their average duration from the earlier period, 1972-1984 to the later period, 1985-1997, for the hurricane and intense hurricane category, but again not the tropical storm category. Since there is no significant track length trend (Section 3.3.3.1), these significant trends in longevity imply that there is a reduction in speed in the later time period. This could be a result of the more frequent high ENSO (Niño4) years, with their associated increased upper-level westerlies, which work in the opposite direction to the storm's track, and hence may slow the storm.

a) western development region

Variable	1972 -1984	1985 -1997	*p-value*	Significance %
TS	3.89	4.53	0.53	53
H	3.00	4.40	0.07	7
IH	0.71	2.13	0.01	1

b) whole NE Pacific region

Variable	1972 -1984	1985 -1997	*p-value*	Significance %
TS	4.68	5.34	0.18	18
H	3.27	4.10	0.04	4
IH	1.39	2.41	0.01	1

Table 3.9 Differences in tropical cyclone longevity with time. The average duration (in days) of tropical cyclones for each period are compared to test if they are significantly different.

b) Influence of ENSO regime

Kimberlain (1999) found no evidence for a relationship between longevity of tropical cyclones and ENSO when taking the NE Pacific as one entity (except for the tropical storm category where he found a significant relationship with a p-value of less than 0.02). Kimberlain and Elsner (1998) defined hurricane days as the total hurricane days (i.e. the total number of days when a hurricane is present) in the season. Although this does provide valuable information, it does not separate from frequency, as an index, since there would be an obvious link between hurricane days and frequency, with generally more hurricane days resulting in years when there are more hurricanes. Hence, a better measure to examine duration (which is also used in a) above) is average hurricane days, so that for each year (i.e. season), the hurricane days from all the storms are divided by the number of hurricanes. From Table 3.10, it can be seen that ENSO is shown to have no significant correlation with any of the categories when examining the whole NE Pacific region. This may appear to be contrary to Kimberlain (1999), who showed a significant effect for the tropical storm category; however, he was examining total duration, as described above, rather than average duration. On examination of the western development region, a significant effect on the duration of the most intense storms only exists with ENSO.

a) whole NE Pacific region

Variable	ENSO (Niño4) r
TS days west	0.21
H days west	0.11
IH days west	0.20

b) western development region

Variable	ENSO (Niño4) r
TS days west	0.14
H days west	0.20
IH days west	**0.52**

Table 3.10 Correlation between ENSO and tropical cyclone longevity in the western development region for the years 1972-1997. The correlation coefficient is given and bold with underlining if significant to the 1% level.

In summary, whilst this study concentrates primarily on the factors that are responsible for tropical cyclone formation, other traits of tropical cyclones cannot be ignored. It is useful to the hurricane community to have an appreciation of how intensity, track and duration of a storm is changing with time and with ENSO regimes. This study has already shown that there are trends of tropical cyclone numbers in the western development region with time (Section 3.2.1) and that there is a relationship there between the phase of ENSO and tropical cyclone frequency (although some slight differences exist depending on the ENSO index used, e.g. see Section 4.4).

As expected from the earlier results, this section has shown that there is also a significant difference for tropical storms and hurricanes in terms of the position of formation, when considering ENSO phases in the whole region, with these storms tending to shift west in an El Niño phase. Again, in line with the frequency trend results, with the trends being greater for intense hurricanes, it has been shown that there is a relationship, in both the whole region and western development region, with the maximum intensity of the strongest storm for each year, when one compares the earlier period (1972-1984) with the later period (1985-1997). It has also been shown that, in the whole region and western development region, there is a strong relationship between the maximum intensity of the strongest storm for each year and the phase of ENSO, with warm phases producing the strongest storm of the year, cold phases producing weaker storms. It has also been shown that the average maximum position west is further west in El Niños on average than during La Niñas for the whole region, which is consistent with, and largely a result of, having a median location of formation further west. Furthermore, it has been shown that hurricanes and intense hurricanes have greater longevity in the latter period than the earlier period when both the whole region and the western development region are examined, and there is a strong relationship between ENSO and longevity of intense hurricanes in the western development region. These results are also consistent with the relationships between environmental variables and tropical cyclone frequency in the western development region, which are discussed in Chapter 4. Having a greater maximum intensity, longevity and storms that originate and track further west in El Niños rather than La Niñas puts Hawaii at greater risk during the warm ENSO periods from not only being hit, but also, if it is hit, of the storm being very strong.

3.4 Summary

This chapter has identified and examined a crucial aspect to consider when investigating trends and the factors that influence NE Pacific tropical cyclones. Based on statistical

analysis of the tropical cyclone longitude distribution, trends and ENSO relationships, it has been shown that there is more than one population of tropical cyclone numbers in the basin with respect to causal factors. We can, therefore, disprove the null hypothesis that the two datasets are drawn from the same population distribution function with respect to causal factors. Two regions have been identified by longitude which are defined as the eastern and western development regions. The division of longitude to define these regions is likely to be around 116°W. This study does not rule out a further division of the western development region into more populations, but for the practicality of requiring reasonably large numbers to examine relationships, only two regions have been considered here. This information means that one is in a position to examine the factors that may affect hurricane formation in a more useful way than previous researchers, by considering each region separately, rather than considering only the entire region, which, as has been shown in this work, tends to obscure relationships, particularly in the western development region. The division by geographical region (and given the lack of spread in latitude of tropical cyclone positions, by longitude) seems a very reasonable thing to do. Indeed, Whitney and Hobgood (1997) made a longitude division at 110°W for examining intensity, although it can be clearly seen (see Figure 3.4) that from the view of investigating frequency, 116°W provides a better division than this. Such divisions have also previously been made for the North Atlantic basin. For example, Kimberlain and Elsner (1998) gave a division which Landsea et al. (1999) summarised as being latitudinal at the Tropic of Cancer to represent storms that are baroclinically enhanced to the north and tropical only to the south. Saunders (personal communication, 2000) has divided the North Atlantic up into four regions for forecasting purposes.

The analysis of tropical cyclone frequency trends not only reinforces the important distinction between the eastern development region and the western development region, but also shows significant increasing trends in the western development region, which are greater the higher the category of tropical cyclone. When examining the causes of the trends in western development region tropical cyclones, it was suggested that for a given trend in average western development region SST, there may be an "intensity-frequency effect", i.e. by affecting tropical cyclone intensity, the SST trend generates a trend in hurricane frequency and a greater trend in intense hurricane frequency, even with no trend in the overall frequency of tropical storms. This effect has not been suggested before, with previous studies generally concentrating on frequency or intensity, but not both, and with the intensity distribution of tropical cyclones not being known until recently.

Other sources for the observed trends were discussed, and the possibility that they resulted

due to a data artefact was largely discounted since data has been used since satellite coverage and since the consistent use of the Dvorak technique. Thus, omissions in the dataset are unlikely. Furthermore, although the responsibility for forecasting of this area shifted from the Eastern Pacific Hurricane Center in Redwood City, California to the National Hurricane Center, Miami in 1988, increasing trends were already observed before this changeover, and thus this possible source of data artefact can be largely eliminated. Finally, it was noted that since the relationships with environmental variables are similar with and without time, this indicates again that there is not an independent factor such as a data artefact causing any trends. An alternative theory is that some local anthropogenic influences may be a possible cause of these trends. However, since there were no trends in the eastern development region, this idea was ruled out. Lastly, the conducive environmental variables changing through time which may be a result of global warming or natural variability were considered. Natural variability is a possible source of the trends, with a trend in the SSTs in the Niño4 region causing associated trends in the thermodynamic variables in the western development region. However, whilst it has been shown that there is some evidence that the trends in tropical cyclone frequency are not a result of global warming (i.e. the increasing trend of temperature at 300 hPa is not as strong as the SST increase and that it was observed that there was a steplike change in the tropical cyclones, not a gradual change), there is also some evidence that the trends in tropical cyclones may be at least partly a result of global warming (i.e. McDonald et al. (2001) found increasing trends in frequency in their study which examined changes in tropical storm frequency under a global warming scenario) and, therefore, the influence of global warming on these trends cannot be eliminated.

The trend analysis shows that, not only are there significant increasing trends in the western development region in terms of frequency, but there are also significant trends in terms of the maximum intensity of the strongest storm. These have significant consequences for Hawaii. Important distinctions between a warm and cold ENSO regime have also been highlighted in terms of longevity, maximum intensity of the strongest storm and formation position (although it was noted that with formation position, there was a tendency for the storms to occur further east of the western development region in warm rather than cold ENSO phases).

Having identified the two development regions, trends in tropical cyclone frequency, and trends and ENSO relationships with other tropical cyclone variables, the next chapter now provides a detailed investigation of the effect of a wide range of environmental variables (both local and non-local, including ENSO) on tropical cyclone frequency. This is

conducted for both the development regions identified in this chapter and incidentally provides further evidence that there is not merely one tropical cyclone population.

Chapter 4

Relationships between the tropical cyclone indices and the environmental variables

There has been no general study published regarding the key factors that are responsible for interannual variations of tropical cyclone formation in the NE Pacific, unlike for the North Atlantic, although ENSO has been shown to have some influence (see Section 1.5.2.2). As will be seen, this is probably because, to date, it has been considered as a single development region. Section 3.1.1 has shown that there is more than one development region with respect to tropical cyclone formation in the NE Pacific basin. Also, Section 3.2.1 shows that when the region is divided into two development regions, significant trends with time emerge in the western development region. Therefore, the current section will also sub-divide the region in the same manner to examine relationships with environmental variables. This should lead to greater understanding of the factors responsible for tropical cyclone formation in this basin.

4.1 Reliability of the NCEP/NCAR reanalysis data

It is necessary to examine the reliability of the NCEP/NCAR reanalysis dataset from which most of the environmental data are obtained before investigating the relationships between the environmental data and the tropical cyclone indices. The results of this analysis will aid subsequent sections, as it will give us further confidence in the results should a reliability study be favourable.

NCEP/NCAR reanalysis data are used for numerous studies. However, it is surprising how little literature is available discussing their reliability. Certainly this is a topic lacking in the NE Pacific. However, it is important to address this issue, particularly for a remote region such as the NE Pacific, where there are few observational stations.

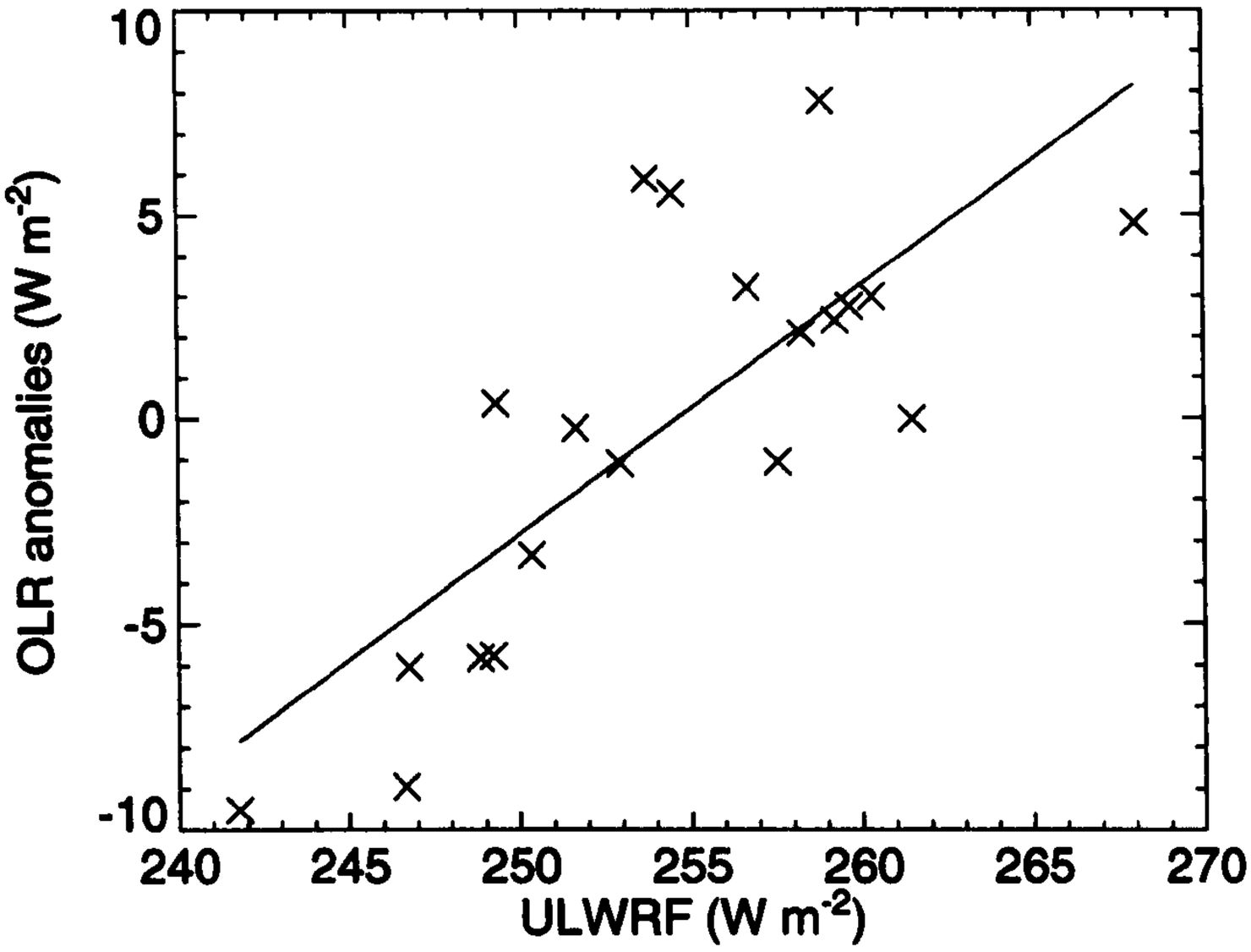
Section 2.1.2 gives a discussion of the NCEP/NCAR reanalysis data and explains that confidence of the environmental variables firstly depends on whether the variables are mainly based on observations, a combination of modelling and observations, or modelling alone. The former gives us the most confidence, the latter the least confidence (Kalnay et al., 1996). Verification of the NCEP/NCAR reanalysis will be sought mainly by comparing it with the ECMWF reanalysis data. Inter-model comparison is not ideal (as the models may introduce similar biases and deviations) but is the best that can be done in the

absence of other independent observational data. However, since ULWRF is the least reliable variable used (see Section 2.1.2), an analysis of actual out-going long-wave radiation (OLR) against the NCEP/NCAR model-derived values of ULWRF is also conducted. There is no complete dataset back to 1972 (Collimore, personal communication, 1998). Therefore, NOAA's OLR index from 1974 until 1996 (though there is a data gap in 1978) is used (Waliser and Zhou, 1997).

Regarding the ULWRF/OLR comparison, correlations between the environmental values after they have been detrended are made. The resulting 'Product Moment Correlation Coefficient' *r* value gives a measure of how two variables are related. A correlation can run on a scale from -1 to +1. A correlation close to +1, for example, indicates that a high (low) value of an environmental variable is strongly linked to a high (low) value of another environmental variable. On the other hand an *r* value close to zero may be obtained, which indicates that there is little relationship between the two variables. Correlation coefficients for the relationship between ULWRF and OLR from 1974-1995 (omitting 1978) are 0.66 for the western development region and 0.11 for the eastern development region implying that ULWRF is fairly reliable in the west, but must be considered unreliable in the east (see Figures 4.1a and 4.1b). The standard deviation of the differences between the two datasets is also larger for the east (4.08 W m^{-2} for the west and 6.13 W m^{-2} for the east), again implying that the data are less reliable in the east. This conclusion is supported by a comparison between the NCEP/NCAR ULWRF and the ECMWF ULWRF (see below).

As regards the comparison between NCEP/NCAR reanalysis data and ECMWF reanalysis data, this was made for the years 1979 - 1993 as these are the years available for July-September in the ECMWF reanalysis. The investigation was carried out for both the eastern and western development regions. Table 4.1 shows that the environmental variables vary with degree of agreement. The strongest relationships are found with SST in both regions. Figure 4.2 is a scatter plot of the relationships of SST between NCEP/NCAR reanalysis and ECMWF reanalysis in both regions, showing a close relationship. It must be noted, however, that although the environmental variables may show a high degree of correlation (thus showing agreement in the interannual variation), there is often an offset in the actual values of the environmental variables. This is shown for example in Figure 4.3 for RH. The reasons for such differences between the models are unknown but since this study is concerned with the interannual variability (which is highly correlated) the actual values are of less importance.

a) Western development region



b) Eastern development region

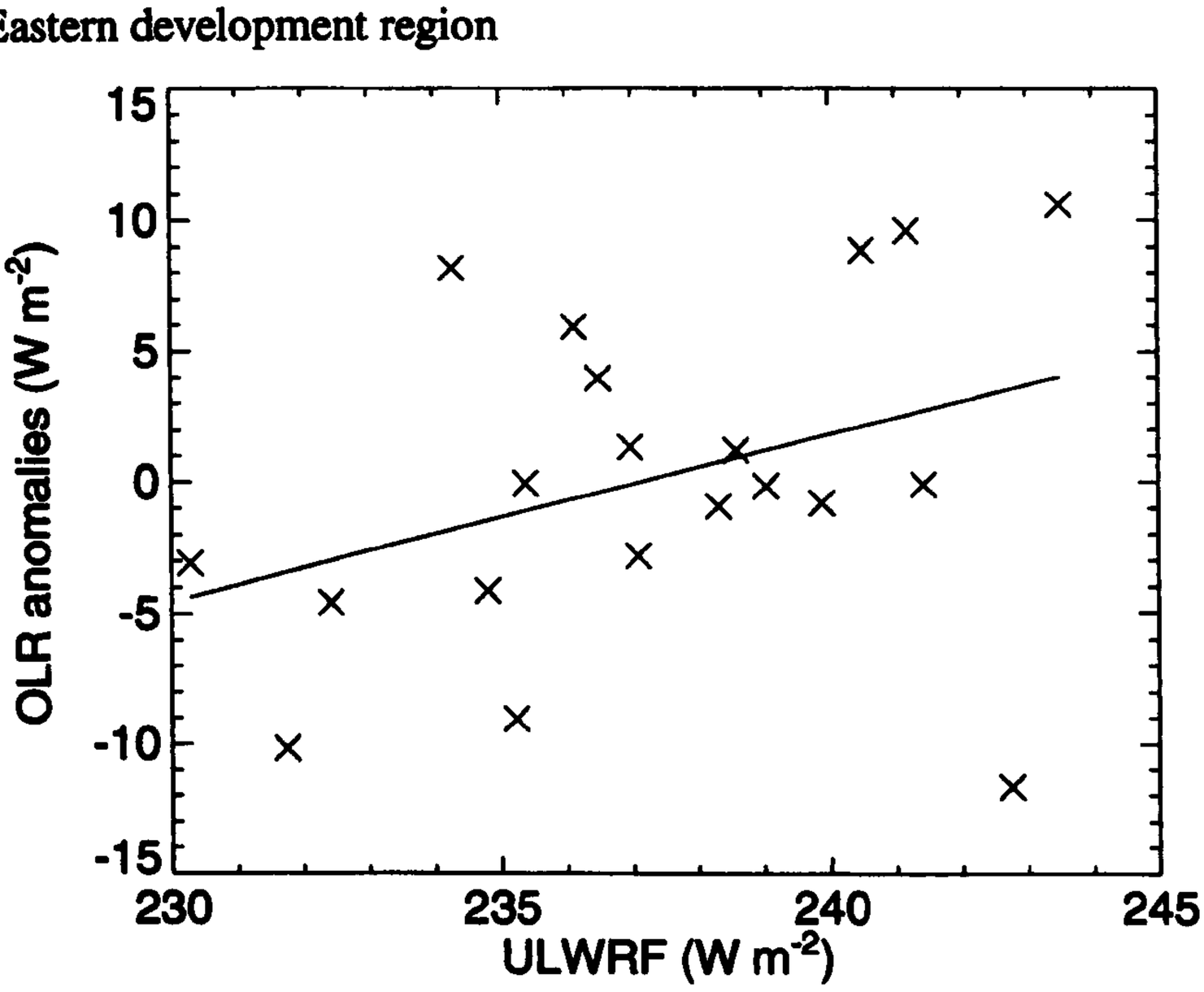
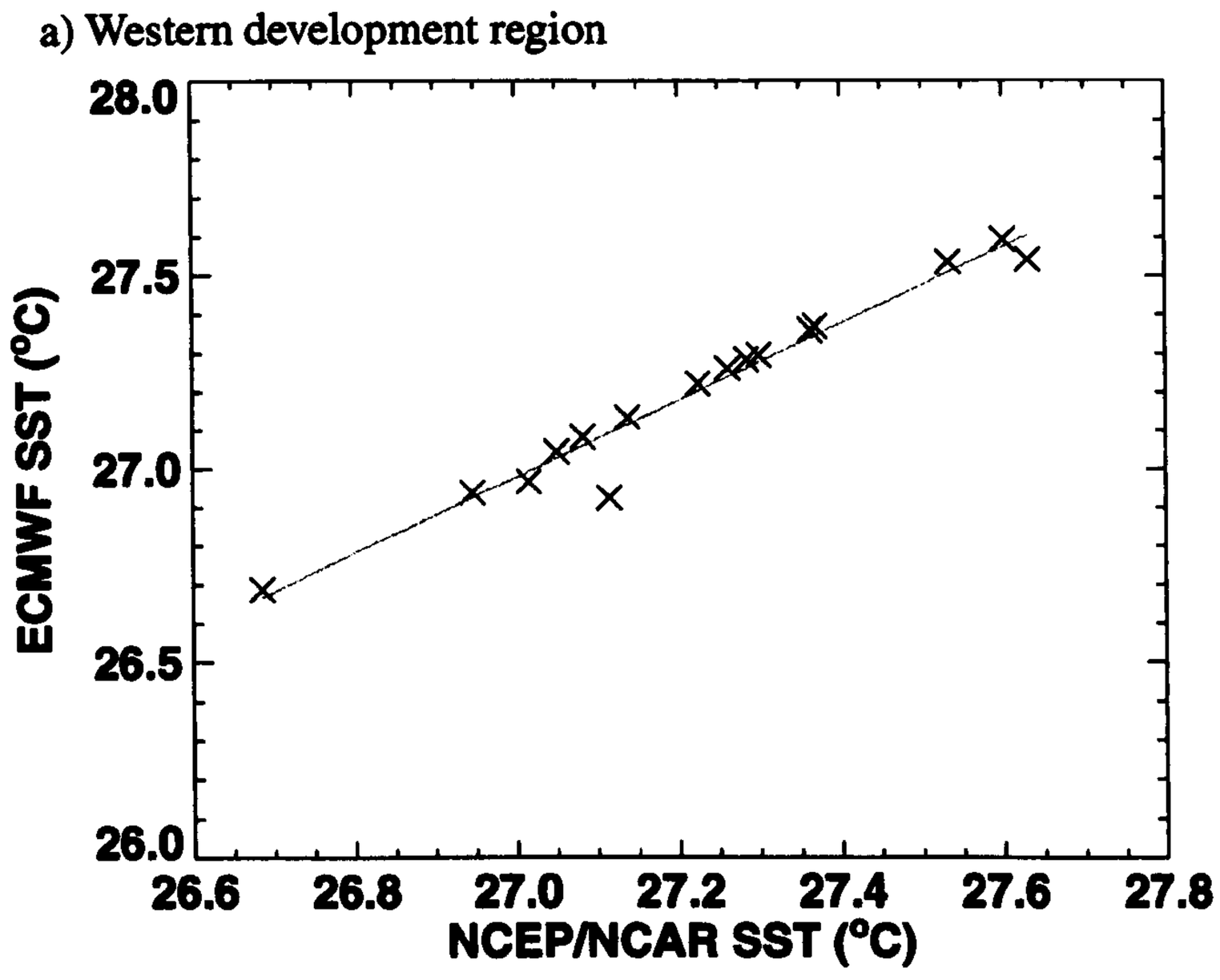


Figure 4.1 Scatterplot of NCEP/NCAR's model derived ULWRF vs NOAA's satellite OLR for a) the western development region, b) the eastern development region. In order to show the real values, plots are shown with the raw values rather than detrended values as it was observed that there was little difference between the two. Values for July-September, 1974-1995 (omitting 1978) are given.



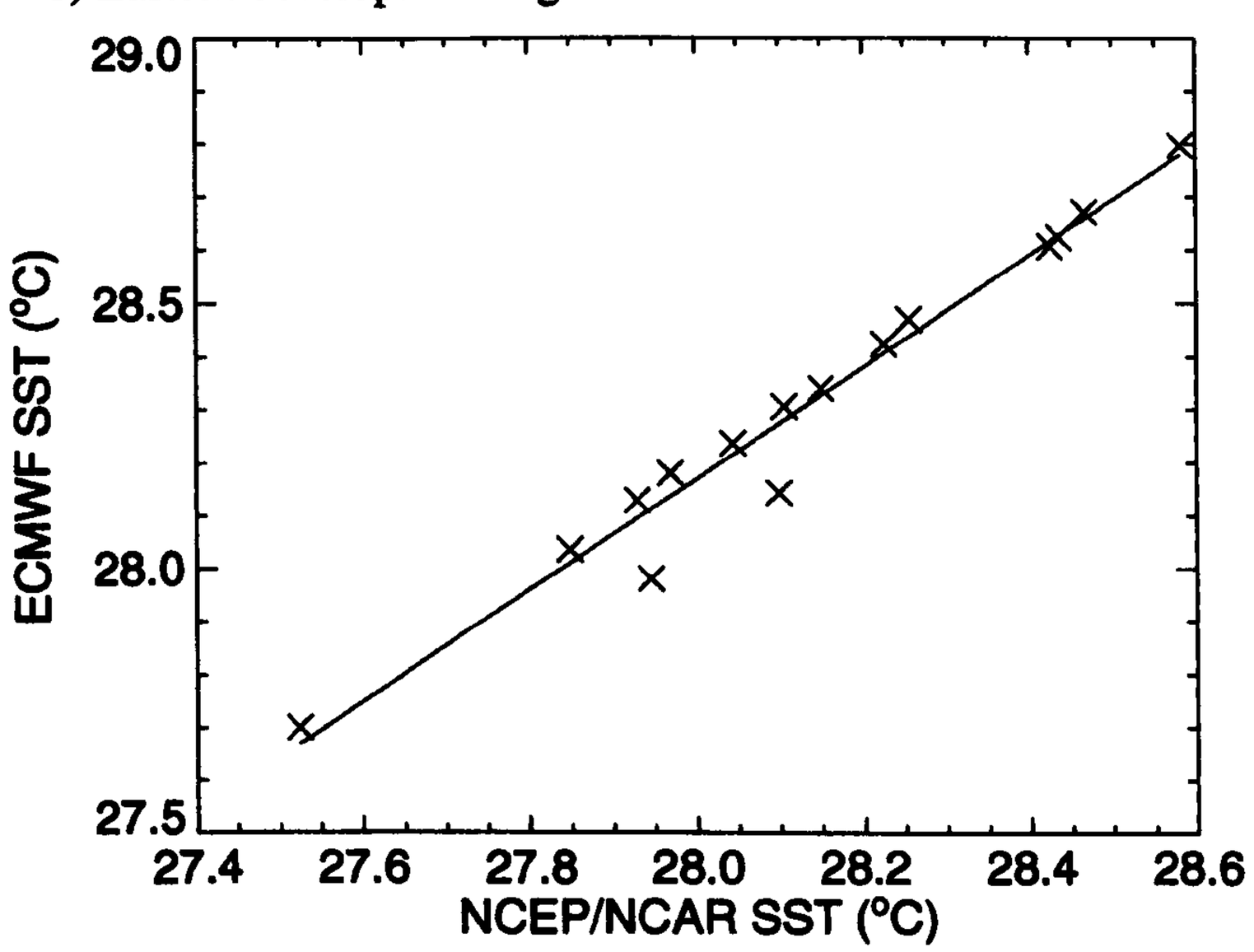


Figure 4.2 Scatterplot of NCEP/NCAR's SST vs ECMWF's SST for a) the western development region and b) the eastern development region. In order to show the real values, plots are shown with the raw values rather than detrended values as it was observed that there was little difference between the two. Values for July-September, 1979-1993 are given.

Figure 4.3 RH values in the western development region for July-September, 1979-1993 showing an offset between the NCEP/NCAR model values and the ECMWF model values. Dashed line is the NCEP/NCAR reanalysis data, solid line is the ECMWF reanalysis data.

	Western Development Region			Eastern Development Region			Atlantic MDR
Variable	*r*	*sdev*	*sdevdiff*	*r*	*sdev*	*sdevdiff*	*r*
RH	0.84	3.68	2.15	0.42	2.19	2.80	0.81
SST	0.98	0.23	0.05	0.98	0.28	0.06	0.99
VVEL	0.75	6.39	5.32	0.12	5.99	8.40	0.75
PWAT	0.81	1.43	1.37	0.54	0.76	1.03	0.78
ULWRF	0.71	6.34	5.12	0.05	3.47	6.00	0.43
PRES	0.89	0.38	0.29	0.62	0.37	0.32	0.98
RELV	0.71	0.79	0.58	0.72	1.69	1.18	0.90
VZ	0.85	0.99	0.63	0.95	1.54	0.59	0.93
TMP	0.75	0.42	0.42	0.71	0.42	0.33	0.88

Table 4.1 Verification of NCEP/NCAR reanalysis by a comparison with ECMWF reanalysis (1979-1993). Correlation coefficients (*r*) are given for detrended data ($r = 0.64$ is significant at 1%, $r = 0.51$ at 5%, $r = 0.44$ at 10%). *sdev* is the standard deviation of the variable for the NCEP/NCAR reanalysis data. *sdevdiff* is the standard deviation of the differences between the two models. Atlantic MDR is defined as 10°N-20°N, 60°W-20°W. The variables are relative humidity (RH) at 500 hPa, sea surface temperature (SST), pressure vertical velocity (VVEL) at 500 hPa, precipitable water (PWAT), upward long-wave radiation flux - top of the atmosphere (ULWRF), mean sea level pressure (PRES), relative vorticity (RELV), vertical wind shear (VZ) between 850 and 200 hPa and temperature (TMP) at 300 hPa.

The following conclusions are drawn:

- All variables show high correlations between NCEP/NCAR and ECMWF reanalysis in the western development region, giving confidence in the reliability of the NCEP/NCAR data there.

- Kalnay et al.'s highest reliability variables (SST, VZ, TMP, RELV and PRES) also show good correlations in the eastern development region, giving confidence in their reliability there as well.

- PWAT and RH show poorer correlations in the eastern development region (though still significant at the 5% and 10% level respectively). However, some of this reduction in the correlation in the eastern development region may be because there is less variability in the variables there from year to year (the standard deviation of the variable is smaller compared with that of the western development region). This is supported by the fact that the standard deviation of the differences for the two development regions is quite similar. Therefore, their reliability in the eastern development region is not necessarily as poor as

the correlation coefficient might suggest.

- VVEL and ULWRF show no correlation in the eastern development region. As regards VVEL, the reliability of the NCEP/NCAR data in the east can, therefore, not be established and ULWRF is already established as being unreliable in the eastern development region by the OLR comparison. The null results there (which will be shown in Tables 4.2 - 4.8) therefore need to be treated with caution.

Finally, an examination of the correlation coefficients between NCEP/NCAR data and ECMWF data for the Atlantic MDR reveals generally comparable results to the western development region (see Table 4.1). Therefore it is not felt, based on this comparison, that the data in the western part of the NE Pacific is poorer compared to the Atlantic MDR (which one could hypothesise since the western development region of the NE Pacific has less observational coverage).

To conclude this section, the reliability of the NCEP/NCAR data has been considered. A comparison between NCEP/NCAR and ECMWF reanalysis data for the years 1979 to 1993, and between NCEP/NCAR ULWRF and NOAA OLR data available from 1974 to 1995 (excluding 1978), shows high correlations for all variables considered in the western development region, and for SST, VZ between 850 hPa and 200 hPa, TMP at 300 hPa, RELV at 850 hPa and PRES in the eastern development region, providing confidence in those results. These variables are also considered most reliable by Kalnay et al. (1996). In the eastern development region, VVEL at 500 hPa has a low reliability and ULWRF must be considered unreliable. The NCEP/NCAR reanalysis is the only dataset that can be used for most variables, since the ECMWF reanalysis and other datasets do not extend back in time to 1972, so therefore it has had to be used for the current study. However, the tests considered above give us confidence in using the data.

4.2 Extreme year analysis

Following Landsea and Gray (1989), it was first decided to consider differences in total tropical cyclone numbers between extreme years of particular environmental variables. To obtain this information, for each region, the probability under a binomial distribution that tropical cyclone totals did not occur by chance in each extreme group is calculated. The total number of tropical cyclones from the extreme six years of each variable (approximately a quarter of the total) is calculated to provide the upper and lower extreme values. The hypothesis is tested that the probability of a tropical cyclone occurring in the upper extreme years is 0.5. The use of ratios, though valuable for indicating the variations between

extreme years (see below), has limitations when attaching a significance as it appeals to normal distribution theory which is inappropriate for small counts. Exact significance levels can be obtained from the binomial distribution.

Table 4.2 shows the results of examining the extreme years. With a p-value at 5% significance or greater (p less than or equal to 0.05), the null hypothesis that there is no statistical significance between the totals of the two groups can be rejected. The p-value is doubled to allow for uncertainty in the sign of the relationship between the environmental variables and tropical cyclone numbers (despite the proposed theories of causal effects for most of the variables (Gray, 1979; 1988)). This allows for a conservative estimate.

	Western Development Region			Eastern Development Region			Whole NE Pacific Region		
Variable	IH	H	TS	IH	H	TS	IH	H	TS
RH	0.02	**<0.01**	**<0.01**	0.69	1.00	0.69	0.64	0.40	0.05
SST	**<0.01**	**<0.01**	0.05	0.56	0.16	0.61	0.56	0.36	0.27
VVEL	**0.01**	**<0.01**	0.02	1.00	1.00	0.84	0.29	0.17	0.52
PWAT	**<0.01**	**<0.01**	**<0.01**	0.54	0.51	0.40	0.14	0.13	0.08
ULWRF	**0.01**	**<0.01**	**<0.01**	0.38	0.80	0.70	0.87	0.35	0.33
PRES	0.04	**<0.01**	**<0.01**	0.84	0.79	0.69	0.54	0.20	0.18
RELV	0.11	0.13	0.07	0.33	0.25	0.37	0.53	0.74	0.67
VZ	0.12	0.06	**<0.01**	0.48	0.48	0.92	0.16	0.08	**<0.01**
TMP	0.18	0.08	0.24	0.54	0.60	0.49	1.00	1.00	0.81
ENSO									
(KW)	0.17	0.09	0.36	0.58	0.90	0.85	0.15	0.47	0.47
(SOI)	0.04	**0.01**	**<0.01**	0.52	0.89	0.84	0.05	0.19	0.05
(Niño1)	0.21	0.61	0.45	1.00	0.69	1.00	0.55	0.82	0.80
(Niño2)	0.33	0.11	0.26	0.84	0.79	0.85	0.35	0.58	0.40
(Niño3)	0.58	0.25	0.29	1.00	0.62	0.93	0.77	0.84	0.47
(Niño4)	0.03	**0.01**	0.03	1.00	0.30	1.00	0.29	0.35	0.23
MJO	**<0.01**	**<0.01**	**<0.01**	0.84	0.58	0.84	0.14	0.17	0.67
QBO	0.31	0.72	0.87	0.40	0.35	0.18	0.14	0.28	0.35
PDO	0.48	0.85	1.00	0.20	0.25	0.10	0.11	0.25	0.13

Table 4.2 **Extreme year analysis.** The table gives the probabilities that a significant difference in tropical cyclone numbers occurs when the environmental variables experience extreme years (six highest and lowest). Entries in bold face and underlined are significant to the 1% level, those underlined to the 5% level. For each significant result, the sign of the relationship is the same as that noted in Table 4.4. The tropical cyclone categories are intense hurricane (IH), hurricane (H) and tropical storm (TS). The NCEP/NCAR variables are defined in Table 4.1, the other variables are ENSO indices (KW, SOI, Niño1, Niño2, Niño3, Niño4), the Madden-Julian Oscillation (MJO), the Quasi-Biennial Oscillation (QBO) and the Pacific Decadal Oscillation (PDO).

There are two important aspects of these results. Firstly, it can be seen from the *p*-values above 5% significance, that there are strong significant relationships between some of the environmental variables and the tropical cyclone indices in the western development region of the NE Pacific. Conversely, an examination of the eastern development region shows no significant relationships with any of the environmental variables studied. Likewise, when investigating the whole NE Pacific basin, the environmental variables generally showed no significant relationships. This is because the total number of storms is dominated by those in the eastern development region. Secondly, within the western development region of the NE Pacific basin, seven out of the twelve variables investigated (excluding ENSO) are significant to at least the 5% level for all categories of tropical cyclone. These are RH, SST, VVEL, PWAT, ULWRF, PRES and the MJO. When considering ENSO, the SOI was also significant for all categories at the 5% level (and to the 1% level for the hurricane and tropical storm category) and the Niño4 index was significant to the 5% level for intense hurricanes and tropical storms and to the 1% level for hurricanes. Interestingly, the null hypothesis could not be rejected either for the other ENSO indices (Niño1, Niño2, Niño3 and KW) or for the QBO.

The variation in tropical cyclone frequency with each of the variables is indicated by the ratio of tropical cyclones between the six highest and six lowest extreme years of the variable (see Table 4.3). Frequency ratios for intense hurricanes, hurricanes, and tropical storms for all the variables in the eastern development region were low, varying from only 1:06 to 1.73:1, 1:1 to 1.5:1 and 1:1 to 1.41:1 respectively. QBO in the eastern development region also gave low ratios of 1.55:1, 1.33:1 and 1.34:1 respectively. Ratios for ENSO were also low, e.g. the KW index gave ratios of 1.31:1, 1.06:1 and 1.05:1 respectively. This study shows, however, that the ratios are greatly increased when one examines the western development region only. Here the ratios for intense hurricanes, hurricanes and tropical storms are respectively, 4:1, 6:1 and 2.58:1 for low to high PRES years, 4.33:1, 5.2:1 and 2.57:1 for high to low RH years and 6:1, 4.33:1 and 1.93:1 for high to low SST years, to name a few of the highest ratios. Respective ratios for the QBO, on the other hand, are only 1.67:1, 1.21:1 and 1.11:1 in a westerly than easterly phase and for ENSO (KW) they are only 2.16:1, 2.11:1 and 1.38:1 in an El Niño year compared to a La Niña year, although the SOI and Niño4 index gave higher ratios (e.g. Niño4 gave ratios of 4.33:1, 3.71:1, 1.94:1 respectively). Therefore, although ENSO gives a higher ratio between extreme years in the western development region than in the eastern development region, this index gives a much lower ratio compared with other variables. This supports the above result of the null hypothesis from the binomial test not being disproved for many of the ENSO indices.

	Western Development Region			Eastern Development Region		
Variable	IH	H	TS	IH	H	TS
RH	4.33:1	5.20:1	2.57:1	1.27:1	1.03:1	1.10:1
SST	6.10:1	4.33:1	1.93:1	1.36:1	1.50:1	1.13:1
VVEL	4.00:1	3.13:1	2.23:1	1.07:1	1.00:1	1.06:1
PWAT	5.00:1	3.63:1	2.69:1	1.40:1	1.23:1	1.20:1
ULWRF	4.00:1	3.57:1	2.23:1	1.46:1	1.10:1	1.20:1
PRES	4.00:1	6.00:1	2.58:1	1.18:1	1.12:1	1.10:1
RELV	4.00:1	2.14:1	2.00:1	1.60:1	1.40:1	1.22:1
VZ	2.33:1	2.22:1	2.89:1	1.57:1	1.27:1	1.04:1
TMP	3.50:1	2.50:1	1.57:1	1.40:1	1.19:1	1.17:1
ENSO						
(KW)	2.16:1	2.11:1	1.38:1	1.31:1	1.06:1	1.05:1
(SOI)	4.00:1	2.88:1	2.83:1	1.44:1	1.08:1	1.01:1
(Niño1)	1.88:1	1.27:1	1.67:1	1.07:1	1.15:1	1.00:1
(Niño2)	1.83:1	2.13:1	1.53:1	1.18:1	1.11:1	1.06:1
(Niño3)	1.60:1	1.70:1	1.44:1	1.06:1	1.16:1	1.04:1
(Niño4)	4.33:1	3.71:1	1.94:1	1.44:1	1.42:1	1.00:1
MJO	4.25:1	3.37:1	2.82:1	1.18:1	1.21:1	1.06:1
QBO	1.67:1	1.21:1	1.11:1	1.55:1	1.33:1	1.34:1
PDO	1.57:1	1.15:1	1.05:1	1.73:1	1.38:1	1.41:1

Table 4.3 The ratio of the tropical cyclones in the six highest and six lowest extreme years of each environmental variable. The sign of the relationships is the same as that noted in Table 4.4. The variables are defined in Tables 4.1 and 4.2.

4.3 *t*-statistic analysis for all years

Relationships between tropical cyclone frequency and the environmental variables for *all* years in the dataset are now examined. Section 2.3 notes that the use of the normal distribution is inappropriate for the NE Pacific tropical cyclone dataset when considering frequency. Therefore the use of the correlation coefficient, which is often used when relating one dataset with another, is also inappropriate. Instead, a *t*-test on the ratio b/s_e is conducted to assess the significance of the b parameter in Equation 2.9, where b is the fit parameter associated with the environmental variable in the regression and s_e is the standard error of b. The ratio b/s_e is called the *t*-statistic. For 26 years of data, if the absolute value of the *t*-statistic exceeds 2.069, b is significant at the 5% level. A negative relationship is just as important as a positive one as either gives important information regarding variations in tropical cyclone frequency. The *t*-statistics are given in Table 4.4 to examine the

significance of the relationship between tropical cyclone frequency and the environmental variables described above when all years are considered. Again, there are no significant relationships in the eastern development region. In the western development region, however, it can be seen that there are significant relationships. RH, SST, VVEL and PWAT are variables that are common to all categories of tropical cyclone which are significant to at least the 5% level. Therefore, the significant variables in Table 4.4 include those which are found to be significant for the extreme years only, as shown in Table 4.2.

	Western Development Region			Eastern Development Region		
Variable	IH	H	TS	IH	H	TS
RH	2.51	**4.05**	**3.61**	1.49	1.74	1.82
SST	2.47	**3.23**	2.10	-0.81	-1.67	0.91
VVEL	-2.44	**-3.42**	**-3.23**	-0.53	-0.62	0.32
PWAT	2.20	**3.68**	**3.28**	0.44	1.19	0.85
ULWRF	-2.01	**-3.09**	-2.76	-1.15	-1.41	-0.42
PRES	-1.92	**-3.78**	**-3.27**	-0.56	-0.20	0.16
RELV	1.08	1.31	1.31	1.33	1.91	1.19
VZ	-0.10	-0.84	**-3.20**	-1.24	0.04	-0.64
TMP	0.46	-0.14	0.01	1.19	0.99	1.31
ENSO						
(KW)	1.34	2.09	1.74	0.15	-0.86	-0.12
(SOI)	-2.00	-2.89	-2.84	0.09	1.03	0.13
(Niño1)	0.71	1.88	1.77	0.14	-1.19	-0.22
(Niño2)	0.72	1.74	1.80	0.31	-0.91	-0.01
(Niño3)	0.61	1.52	1.46	0.51	-0.66	0.52
(Niño4)	1.87	2.87	1.95	-0.88	-1.35	-0.75
MJO	-1.06	-2.19	-2.73	0.24	-0.29	-0.75
QBO	-0.51	-1.34	-2.05	1.15	1.10	1.02
PDO	0.46	-0.14	0.01	1.19	0.99	1.31

Table 4.4 *t*-statistics from a Poisson regression between tropical cyclone numbers and the environmental variables. Entries in bold face and underlined are significant to the 1% level and those underlined to the 5% level. Positive results indicate that more tropical cyclones occur with larger values of the environmental variable. Negative results indicate an inverse relationship, where there are fewer tropical cyclones with larger values of the environmental variable.

4.4 Deviance test

An alternative test to the *t*-statistic is to test the deviance. Normally, a large sample is needed to detect a small effect. However, deviance is more powerful than any other test to

identify any effect with any given sample size. This is explained by the Neyman-Pearson lemma (Cox and Hinkley, 1974). The deviance function is now appearing in the hurricane literature (Elsner et al., 2001).

Deviance is a measure of fit and its general form is given (McCullagh and Nelder, 1989) by

$$D(\mathrm{y};\hat{\mu}) = 2\{l(\mathrm{y};\mathrm{y}) - l(\hat{\mu};y)\} \tag{4.1}$$

where D is the deviance, y is a vector containing the number of hurricanes, $\hat{\mu}$ is the corresponding vector of fitted y values and l is the log-likelihood function.

Deviance in the Poisson is equal to

$$D(y;\hat{u}) = 2\sum_{i=1}^{n}\{y_i \log(y_i / \hat{u}_i) - (y_i - \hat{u}_i)\} \tag{4.2}$$

For the Gaussian model, the deviance is simply the residual sum of squares.

There are three questions this section will attempt to answer using deviance. Firstly, is a model that includes an environmental variable significantly better than a null model, where nothing is assumed to affect tropical cyclone frequency (the null model consists simply of the mean of y)? Secondly, if this is so, can this model be improved upon by a more complex model (i.e. by including another environmental variable) to explain variations in tropical cyclone activity? Thirdly, is the model significantly (from a statistical point of view) worse than a perfect model?

First, the deviance of the null is compared to the deviance of a single variable model (when an environmental variable is included). The reduction in deviance between the two models is compared with a chi-squared distribution with 1 degree of freedom (to account for the variable). The critical values are 3.84 and 6.635 for 5% and 1% significance respectively. Hence, the greater the reduction, the more significant the result. The results are presented in Table 4.5 for the null case vs. a model when an environmental variable is added. A simple model, i.e. tropical cyclone numbers and one environmental variable, is used.

It can be seen that the results compare fairly well to the method described above, although there are a few small differences. For instance, Table 4.4 shows that RH has a larger *t*-

statistic than SST for the intense hurricane category (though both significant at the 5% level), whereas the deviance test (Table 4.5) indicates that SST is more important for this category.

	Western Development Region			Eastern Development Region		
Null Deviance	45.019	43.000	54.558	29.057	16.853	15.847
Variable	IH	H	TS	IH	H	TS
RH	**9.68**	**20.65**	**15.88**	0.51	1.56	0.11
SST	**12.57**	**13.98**	6.24	0.96	1.72	0.52
VVEL	**10.01**	**15.50**	**12.63**	0.36	1.06	0.53
PWAT	**10.23**	**18.36**	**12.95**	0.65	1.92	0.32
ULWRF	**8.59**	**13.48**	**9.78**	0.19	1.00	0.67
PRES	4.28	**15.10**	**11.29**	0.18	1.15	0.19
RELV	3.06	3.13	2.63	0.00	0.39	0.00
VZ	2.77	3.46	**10.95**	0.38	0.33	1.29
TMP	1.67	3.51	2.41	0.60	1.36	0.08
ENSO						
(KW)	3.82	6.28	4.14	0.08	0.83	0.19
(SOI)	6.06	**10.48**	**9.51**	0.00	1.15	0.17
(Niño1)	0.75	3.76	3.15	0.02	1.50	0.05
(Niño2)	1.19	3.84	3.72	0.14	0.91	0.00
(Niño3)	1.13	3.27	2.72	0.34	0.50	0.03
(Niño4)	**7.96**	**12.40**	5.72	0.28	1.62	0.23
MJO	3.58	**7.98**	**10.32**	0.17	0.03	0.71
QBO	0.04	1.25	3.59	1.54	1.09	1.14
PDO	2.11	0.45	0.36	1.67	0.55	1.78

Table 4.5 The reduction in deviance between the null model and a more complex model, when the environmental variable is included. Entries in bold face and underlined indicate a significant reduction in deviance to the 1% level and those underlined to the 5% level. The variables are defined in Tables 4.1 and 4.2.

Again, it can be seen that there are no significant relationships in the eastern development region. In the western development region, for the hurricane and tropical storms categories, RH is the variable with the largest reduction in deviance from the null model and thus provides the best model with one variable. The percentage of variance explained by these models are 54% and 37% respectively (see Table 4.6). These are the models with the lowest deviance and thus give the best fit. For the intense hurricane category, results indicate that again RH is an important variable, but there is a deviance reduction of 12.57 for SST compared to 9.68 for RH, indicating that SST gives a slightly better model. The percentage of variance explained by the SST model for intense hurricane formation is 28%

(see Table 4.6).

	Western Development Region			Eastern Development Region		
Variable	IH	H	TS	IH	H	TS
RH	19.0	54.0	37.0	-1.8	6.3	-3.4
SST	27.7	40.0	13.0	0.8	7.6	-0.3
VVEL	28.5	47.0	31.0	-2.5	2.7	-0.2
PWAT	24.3	58.0	33.2	-1.2	8.6	-1.9
ULWRF	25.7	40.0	12.2	-3.3	2.4	0.9
PRES	4.4	31.4	17.4	-3.3	3.6	-2.8
RELV	3.2	3.3	0.6	-4.2	-2.1	-4.2
VZ	4.6	6.7	19.0	-2.8	-2.3	4.3
TMP	-1.5	5.0	3.0	-1.2	5.6	-3.6
ENSO						
(KW)	3.8	13.6	6.0	-3.7	1.3	-4.2
(SOI)	11.7	30.4	23.0	-4.2	3.0	-3.0
(Niño1)	-2.1	8.2	3.6	-4.1	5.3	-3.8
(Niño2)	-1.2	7.7	4.6	-3.4	1.5	-4.2
(Niño3)	-1.4	5.7	2.7	-2.5	-1.0	-3.9
(Niño4)	15.2	34.8	12.2	-2.9	-6.6	-2.5
MJO	11.8	21.0	14.0	-3.6	-4.0	0.2
QBO	-4.0	0.1	5.0	2.8	2.8	3.5
PDO	1.9	2.8	3.2	5.2	-0.2	8.8

Table 4.6 The percentage of variance explained by each model. The variables are defined in Tables 4.1 and 4.2.

In the second part of the analysis the deviance of a more complex model is calculated, when another environmental variable is included, to identify models based on several variables. Multiple regressions were carried out to examine the effect of a more complex model with two or more environmental variables to see if these models significantly explained tropical cyclones better than the simpler models given above. In the hurricane and intense hurricane category, the simpler models were the best, with results showing that adding an additional variable does not significantly explain the variation in tropical cyclone numbers better than the simpler models described above. However, for the tropical storm category, a multiple regression showed that wind shear and pressure gave a slightly better model than RH alone (the reduction in deviance was 21.59 for the multiple model compared to 15.88 for the single RH variable model; the percentage of variance explained by the wind shear and

pressure model is 41%).

Time is not included in any of these 'best' models as it is shown that time, as an independent variable, does not significantly add any further information to the model (see Table 4.7 and compare with Table 4.8).

	Western Development Region			Eastern Development Region		
Null Deviance	45.019	43.000	54.558	29.057	16.853	15.847
Variable	IH	H	TS	IH	H	TS
RH	32.361	21.987	38.623	26.464	13.625	12.291
SST	32.449	27.953	48.052	28.127	13.989	14.874
VVEL	33.026	27.279	41.914	28.512	15.791	14.934
PWAT	33.933	24.445	41.239	28.597	14.657	14.981
ULWRF	34.995	29.501	44.787	27.493	14.814	14.552
PRES	**35.430**	24.510	41.778	28.474	15.691	15.459
RELV	38.046	37.920	51.063	27.019	13.128	14.308
VZ	**49.150**	38.860	42.430	27.152	16.450	14.258
TMP	**38.952**	37.913	51.456	28.418	15.443	15.703
ENSO						
(KW)	37.394	35.230	49.699	28.762	16.026	15.693
(SOI)	**35.057**	30.909	44.442	28.778	15.706	15.441
(Niño1)	**38.681**	36.325	49.826	28.676	15.253	15.658
(Niño2)	**38.670**	36.779	49.701	28.690	15.908	15.707
(Niño3)	**38.794**	37.349	50.659	28.528	16.323	15.691
(Niño4)	37.055	30.515	48.752	28.008	15.096	15.148
MJO	37.926	34.038	44.115	28.723	16.688	15.130
QBO	**38.900**	37.784	48.521	27.419	15.546	14.664
PDO	38.946	39.542	52.714	27.384	15.799	14.001

Table 4.7 The deviance statistic for each model with time included. Compare these values to Table 4.8 where time is excluded. Differences of greater than the critical value of 3.84 are highlighted in this table as bold and indicate that time is important in the relationship. The variables are defined in Tables 4.1 and 4.2.

To give an example, a model of hurricanes with RH gives a deviance of 22.35, whereas a model of hurricanes with RH and time gives a deviance of 21.99. Thus, adding this one variable does not give a deviance reduction of greater than the critical value of 3.84, therefore time is rejected from the model. It can be seen that time does not significantly improve any of the models which have been shown to be significant to the 1% level. This is an important result which implies that relationships are accounted for by the rapidly varying interannual variations rather than the longer time trends in the two variables. The observed trends in tropical cyclone frequency therefore occur naturally as a result of the particular

variations of the causal variables from year-to-year and on a longer time-scale, and are not due to some extra factor which is slowly varying or step-like, such as a data artefact.

	Western Development Region			Eastern Development Region		
Null Deviance	45.019	43.000	54.558	29.057	16.853	15.847
Variable	IH	H	TS	IH	H	TS
RH	35.341	22.348	38.674	28.544	15.294	15.739
SST	32.452	29.020	48.317	28.096	15.136	15.325
VVEL	35.006	27.496	41.929	28.697	15.792	15.314
PWAT	34.793	24.639	41.613	28.411	14.935	15.528
ULWRF	36.427	29.516	44.799	28.866	15.854	15.182
PRES	40.737	27.896	43.270	28.877	15.700	15.660
RELV	41.957	39.869	51.931	29.057	16.462	15.844
VZ	42.245	39.544	43.612	28.681	16.528	14.553
TMP	43.349	39.493	52.148	28.459	15.495	15.772
ENSO						
(KW)	41.204	36.724	50.418	28.974	16.028	15.847
(SOI)	38.958	32.518	45.047	29.056	15.707	15.676
(Niño1)	44.267	39.242	51.412	29.037	15.354	15.797
(Niño2)	43.826	39.156	50.842	28.921	15.947	15.846
(Niño3)	43.892	39.728	51.838	28.716	16.358	15.814
(Niño4)	37.055	30.599	48.835	28.781	15.232	15.616
MJO	41.435	35.017	44.244	28.885	16.824	15.137
QBO	44.976	41.752	50.971	27.514	15.763	14.706
PDO	42.913	42.548	54.194	27.390	16.299	14.071

Table 4.8 The deviance statistic for each model (time not included). Values less than 36.415 indicate that the model is not significantly different from the perfect model at the 5% level. The variables are defined in Tables 4.1 and 4.2.

In the third part of this analysis, now that the best model has been obtained (i.e. the model giving the best fit), the question is whether this model is significantly worse than a perfect model, i.e. where the deviance is zero? 95% of the chi-squared distribution with 24 degrees of freedom (to account for the constant and the environmental variable from 26 years of data) gives a value of 36.415, therefore, the model is not significantly different from the perfect model (to the 5% level) if it has a deviance of less than 36.415. In the western development region, for intense hurricanes, there is, therefore, no statistical argument for including any other predictors in the model since the simple model of SST

gives a deviance of 32.45 (see Table 4.8), which is not significantly different from the best model (to the 5% level). Thus, this gives us further confidence that this can be accepted as the best model. For the hurricane category, there is no statistical argument that there should be any other predictors in the model since the simple model with RH gives a deviance of 22.35 (see Table 4.8), which is not significantly different from the best model (to the 5% level). However, for the tropical storm category, Table 4.8 shows that none of the simple models (with just the one environmental variable) are as good as the best model since the deviance statistics for single variable models are not less than 36.415. Therefore, this indicates that these models can be improved upon. For this category only of the western development region, this confirms that despite the wide range of environmental variables examined, there is an oceanic or atmospheric variable that has not been considered that can better explain tropical storm variation on an interannual basis, or that a combination of the existing variables offers a better explanation. As shown above, this is indeed the case when the multiple regressions were examined. These showed that a model with wind shear and pressure to explain tropical storm frequency gave the greatest deviance reduction. The actual deviance from this more complex model is 32.97 which is not significantly different from the perfect model (to the 5% level).

The deviance is the only statistical method which considers whether there are any effects that have not yet been taken into account. In the case of the eastern development region of the NE Pacific basin, the relationships are significantly weak as shown from the deviance reductions in Table 4.5. However, there is no statistical argument based on the deviance being less than 36.415 at the 5% level that these can be improved upon. Thus, this points to the fluctuations in frequency being a result of variations in the number of triggering disturbances rather than in the environmental variables. Support for this in the literature is given in Section 1.5.1.2, and is further supported by an analysis of OLR in Section 4.7.1.

4.5 The Poisson distribution in relation to the best models

The equations for the best models (Equation 4.3) and best multiple model for the tropical storm category (Equation 4.4) are given below for the western development region tropical cyclone categories. These are

Best single models:

$$\ln(\text{Hurricane frequency}) = -5.59 + (0.172 \times RH) + \text{error}$$
$$\ln(\text{Intense hurricane frequency}) = -61.18 + (2.26 \times SST) + \text{error}$$
$$\ln(\text{Tropical storm frequency}) = -3.59 + (0.237 \times RH) + \text{error} \qquad (4.3)$$

where RH is in units of %, and SST is in units of °C.

Best Multiple model:

$$ln(Tropical\ storms\ frequency)=912.15+(-0.31xVZ)+(-0.90xPRES)+error \quad (4.4)$$

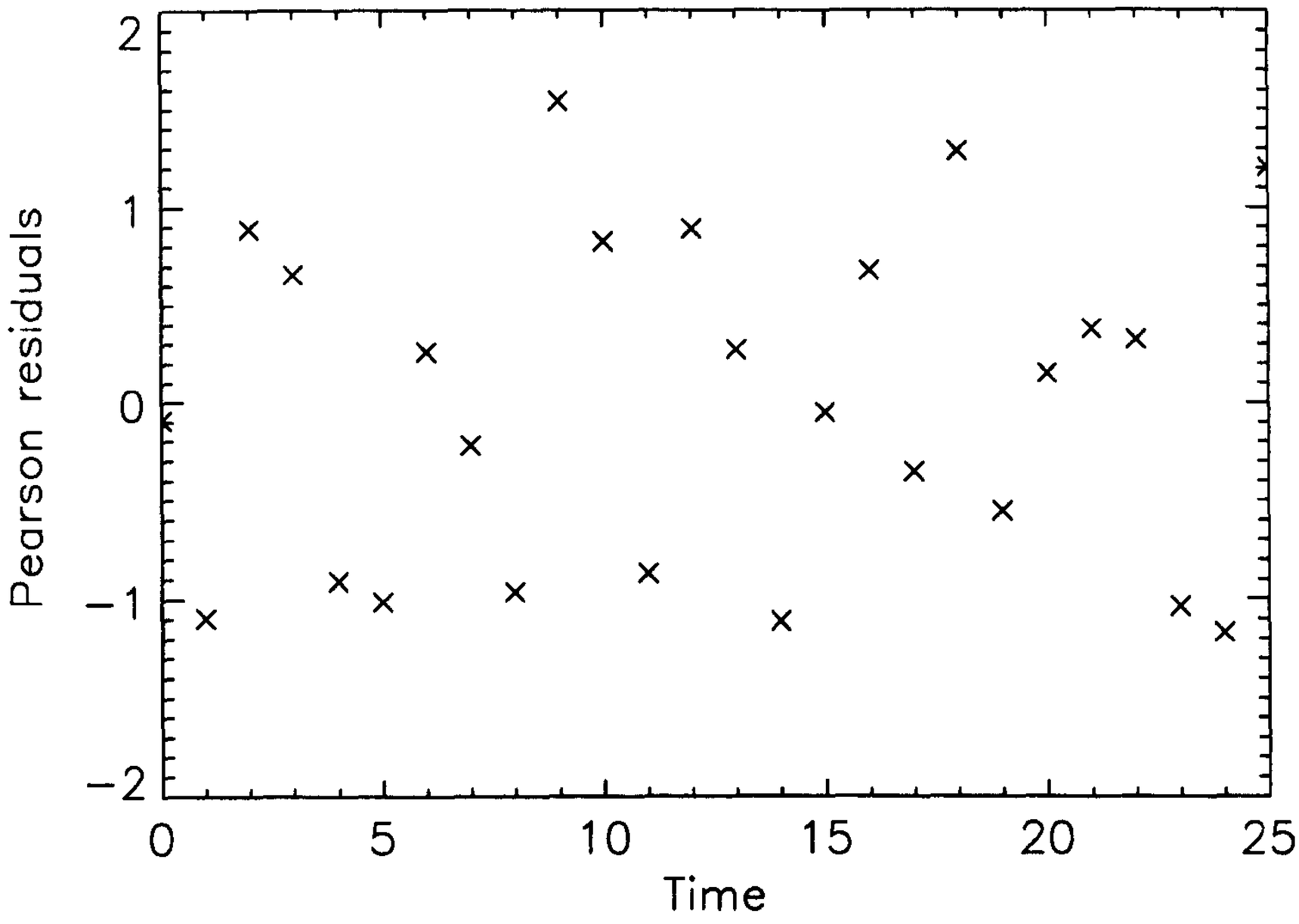
where VZ is in units of m s^{-1} and PRES is in units of hPa.

Now that the best models have been obtained, assuming the Poisson distribution for seasonal tropical cyclone numbers, it can, in fact, be shown (see Figure 4.4) that the Poisson distribution does not adequately explain hurricane and intense hurricane frequency. This is contrary to the literature (as discussed in Section 2.3), e.g. Elsner and Schmertmann (1993), who asserted that tropical cyclone formation is a Poisson process. If the model is correct, it should be expected to get Pearson residuals with a mean of 0 and a standard deviation equal to 1. Thus, at the 5% level, it would be expected that 5% of the observations lie within ±1.96. However, it can be clearly seen from Figures 4.4 a and c that all of the residuals lie well within this range for each of the models. This under-dispersion for the hurricane and intense hurricane category suggests that the distribution is not Poisson.

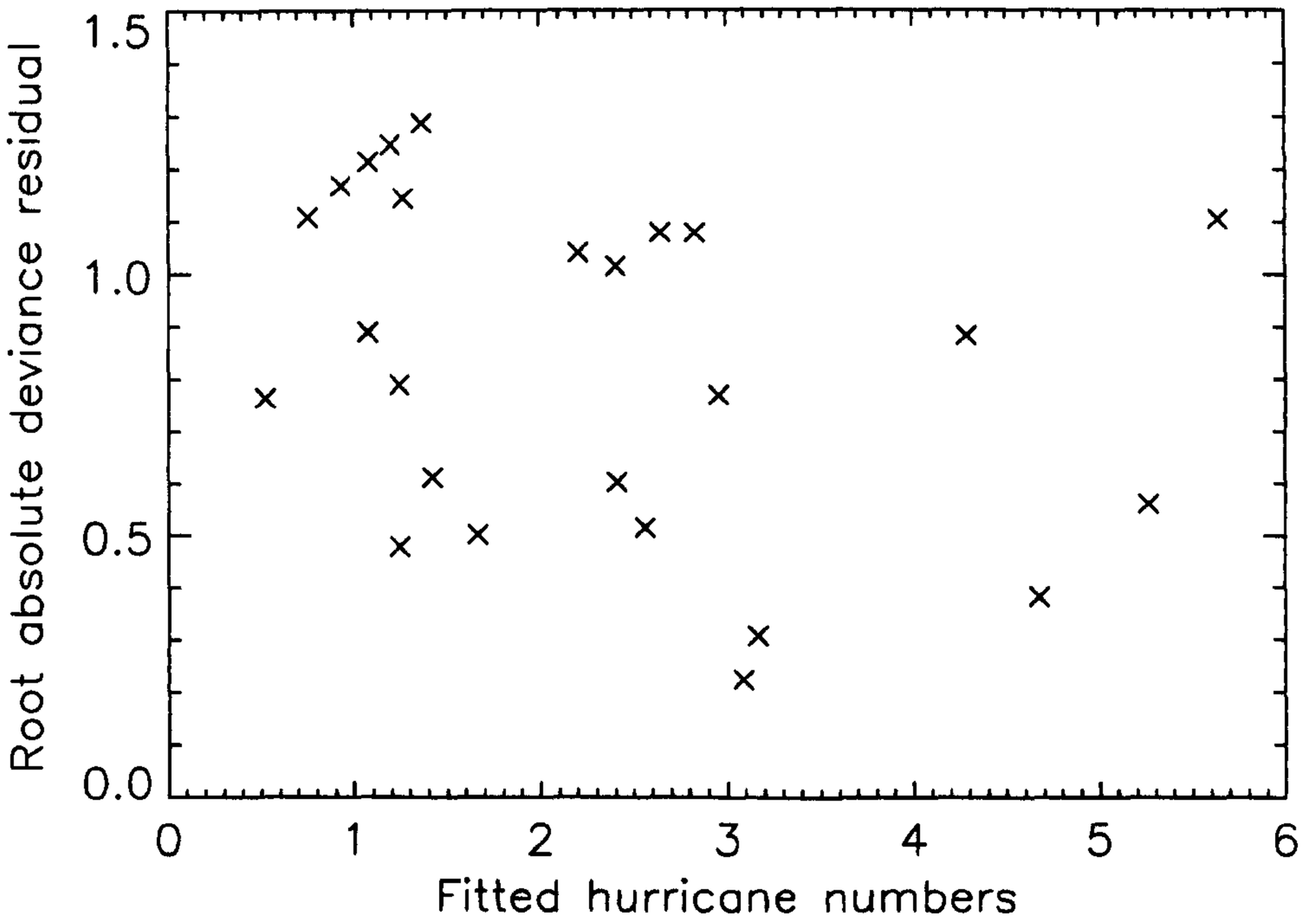
Furthermore, Figures 4.4 b, d, f and h show the root absolute deviance residuals against the fitted tropical cyclone values. If the model is correct, a mean of 0 and variance of 1 would be expected, and thus the points should be centred around 1. Figure 4.4b shows that, with more points below this (i.e. the plot is centred around 0.75), again there is less variance than would be expected from the Poisson. However, the other models (Figures 4.4 d, f, and h) seem reasonable in this respect.

The index of dispersion test in Section 2.3 indicated that the Poisson distribution should be rejected for the whole region and western development region for the tropical storm category. However, an examination of the residuals from the models examining tropical storm frequency does not support this crude test. Furthermore, although the null hypothesis that the tropical cyclones come from a Poisson distribution could not be rejected for the other categories in Section 2.3, this does not necessarily mean that they are definitely from a Poisson distribution, merely that this possibility cannot be rejected using that test. Indeed, this section now confirms that the hurricanes and intense hurricanes are not from a Poisson distribution, but from a more under-dispersed distribution.

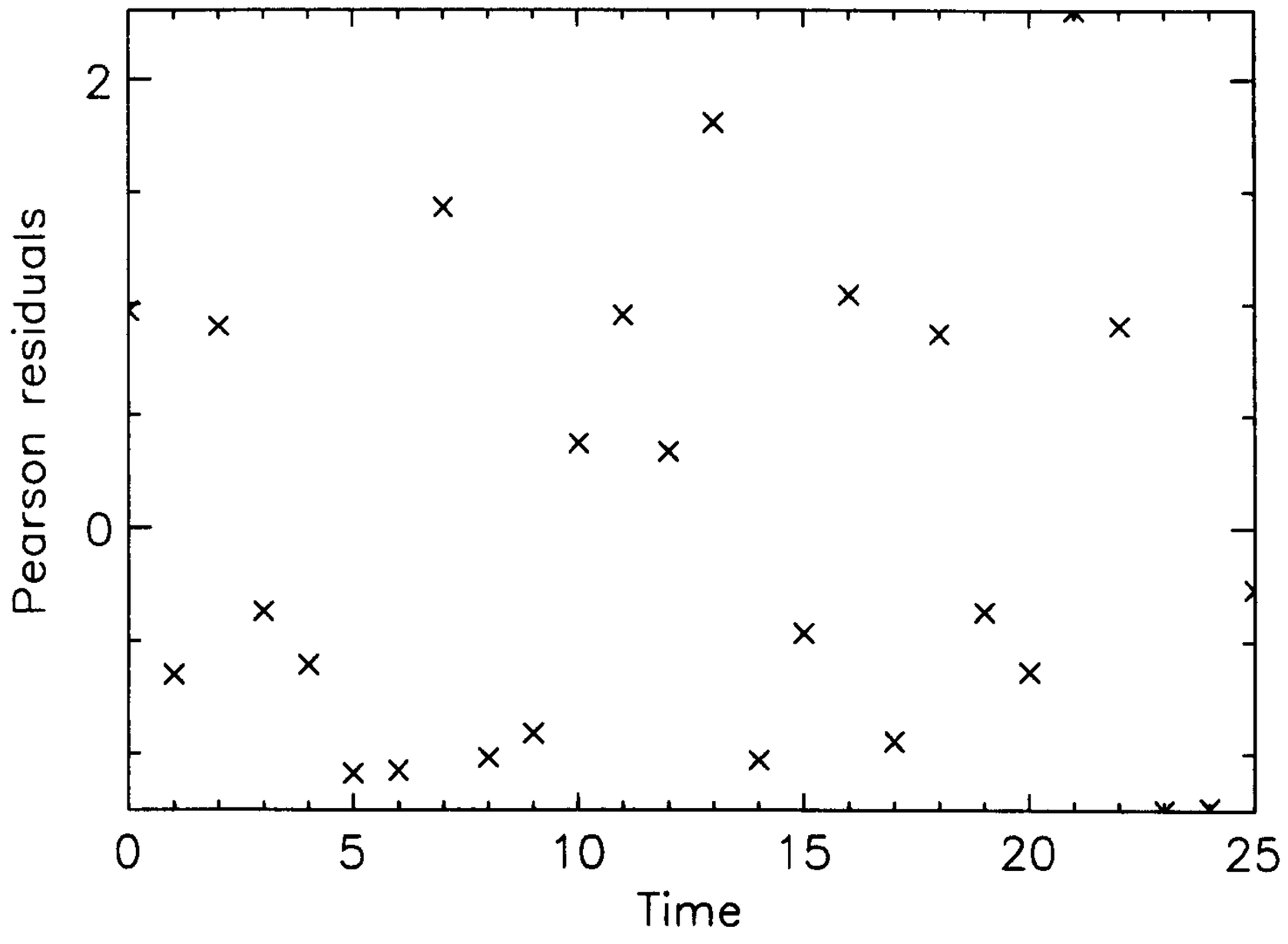
a) Hurricanes vs. RH



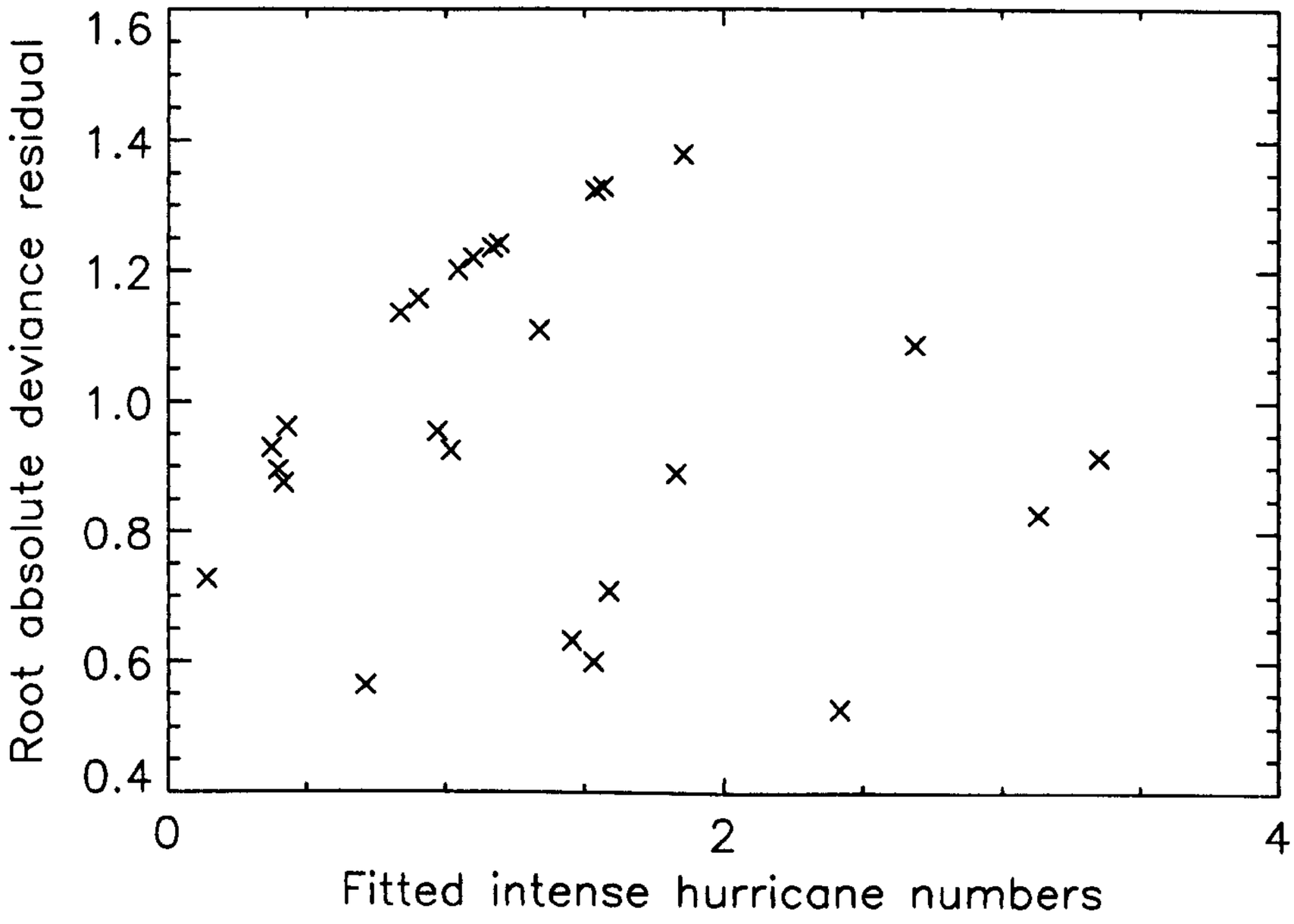
b) Hurricanes vs. RH



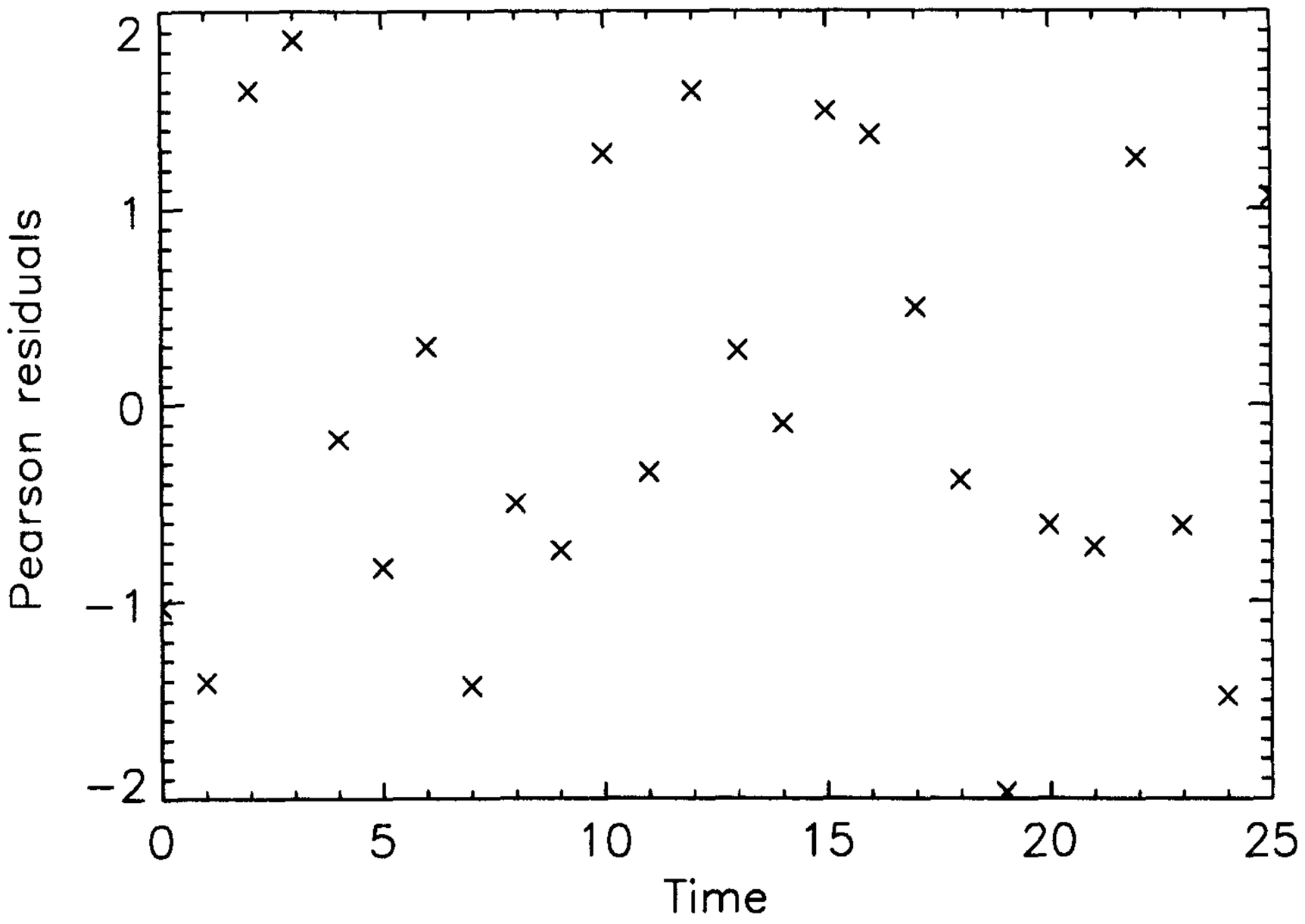
c) Intense hurricanes vs. SST



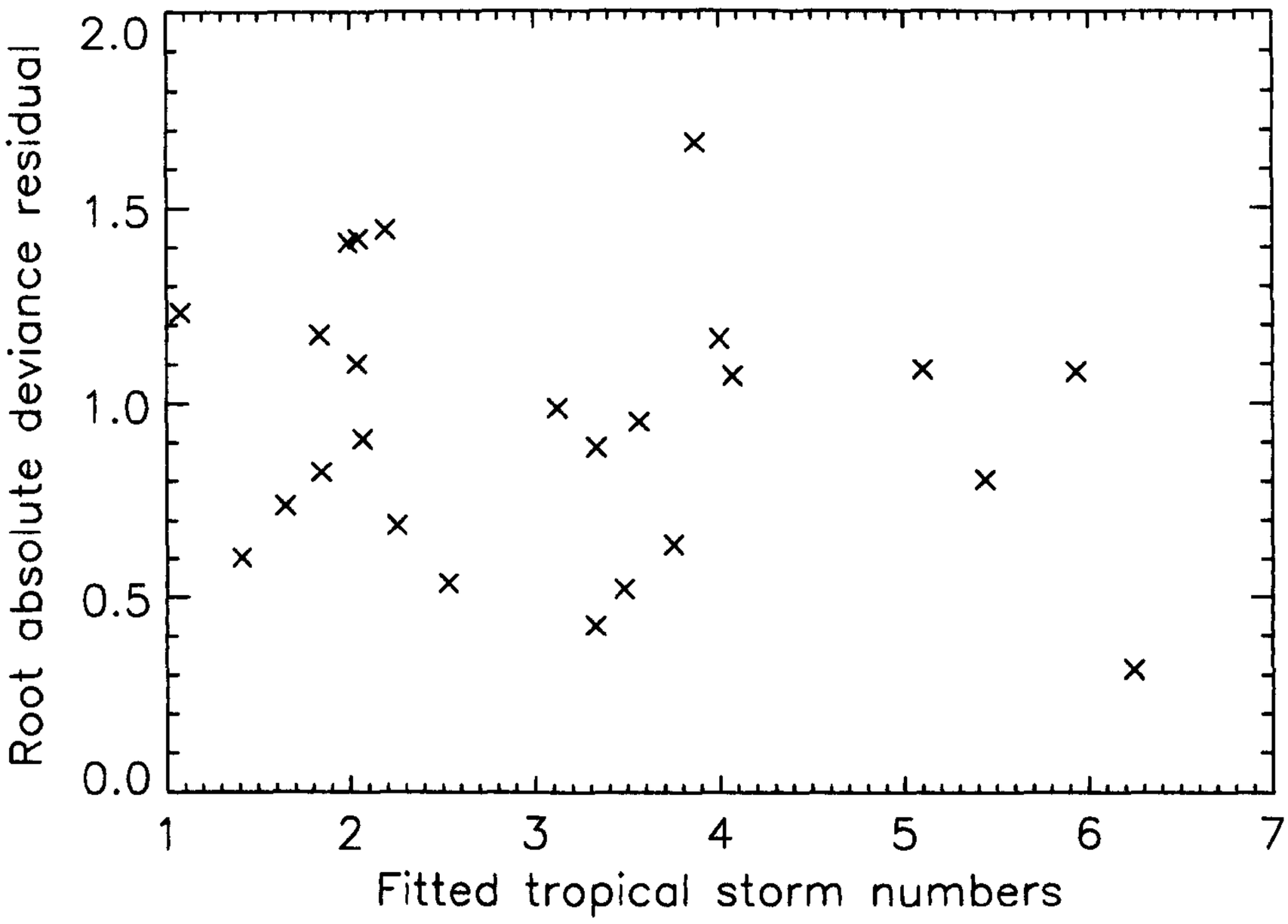
d)Intense hurricanes vs. SST



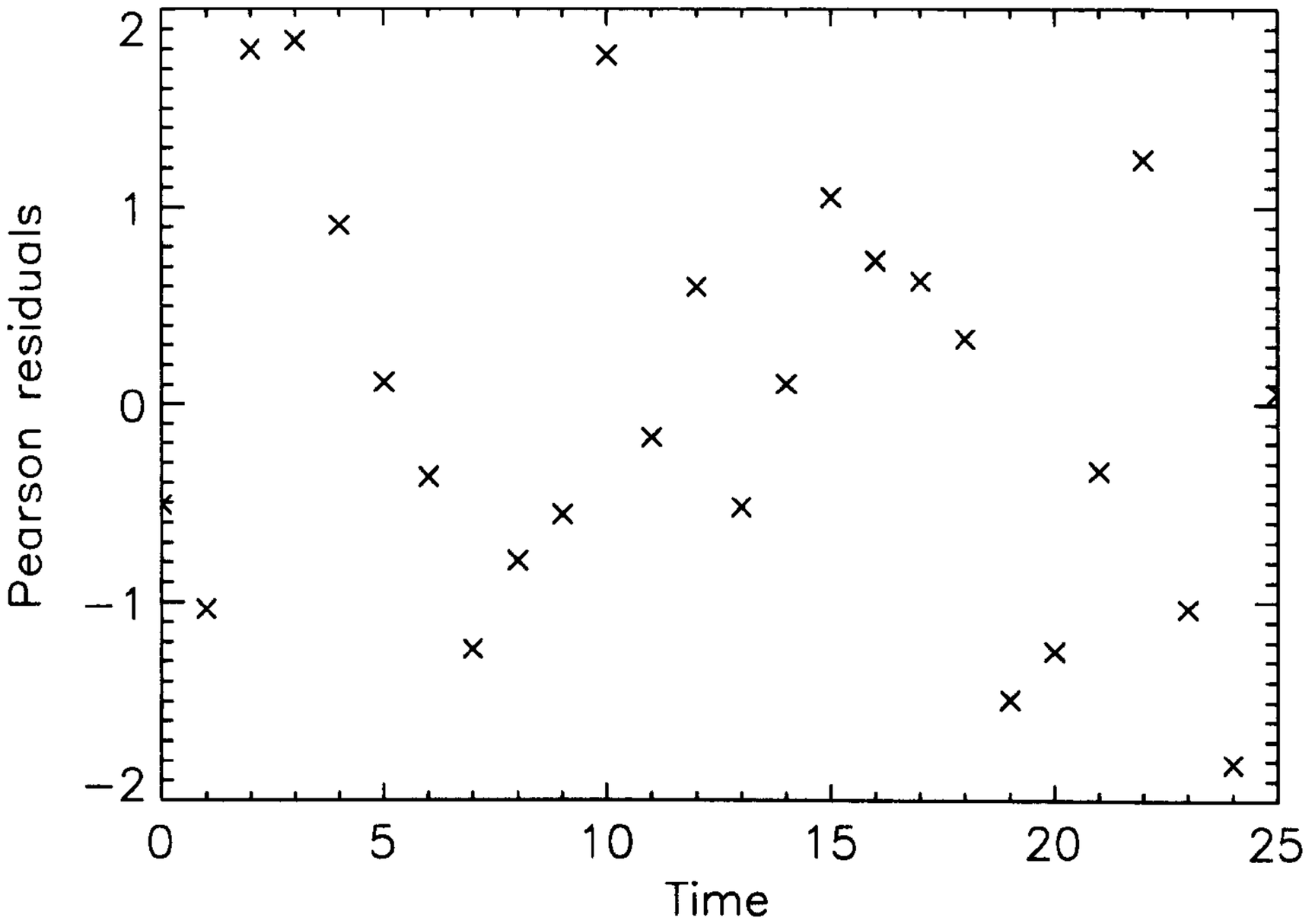
e) Tropical storms vs. RH



f) Tropical storms vs. RH



g) Tropical storms vs. VZ and PRES



h) Tropical storms vs. VZ and PRES

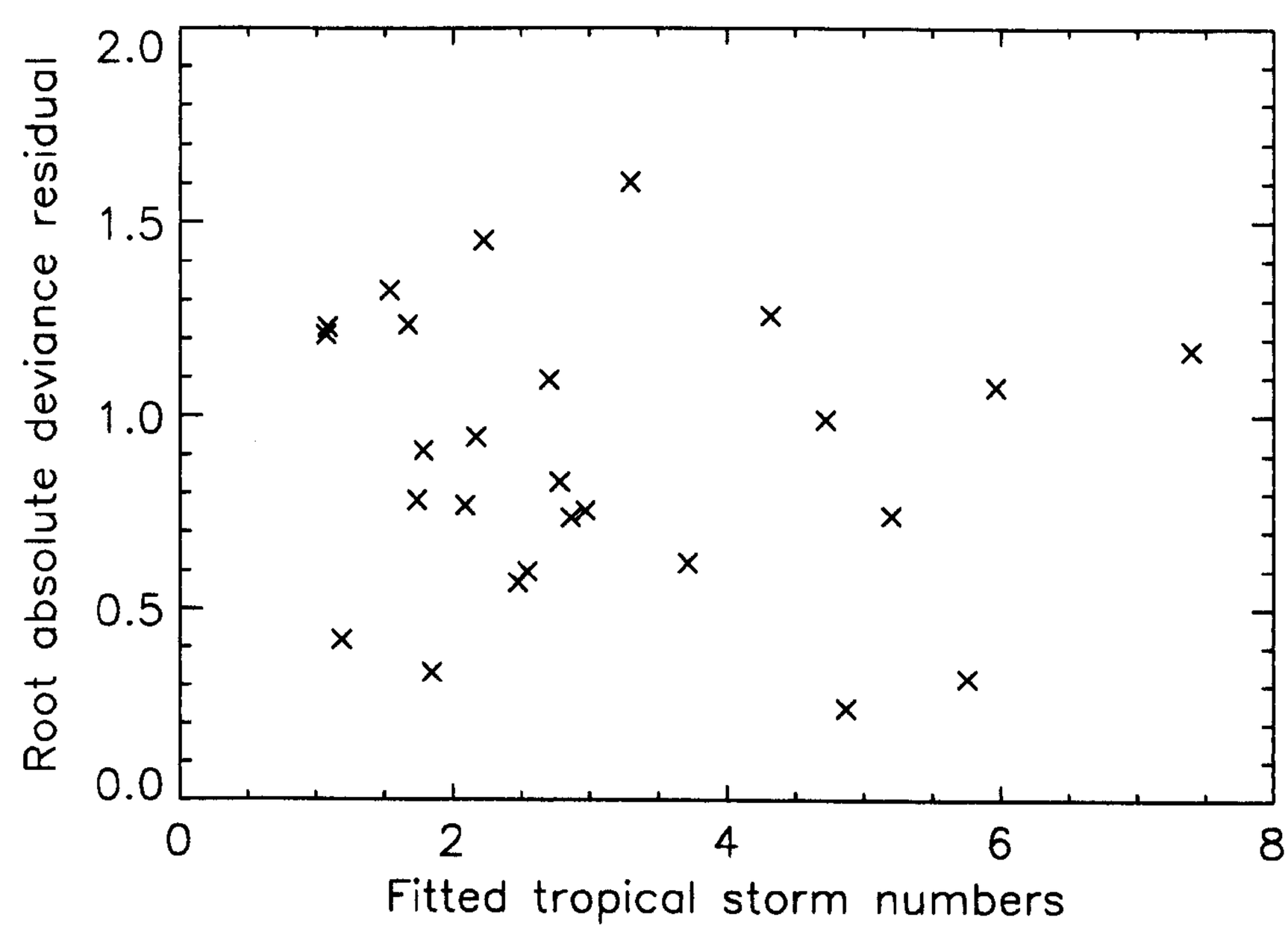


Figure 4.4 Checks that the Poisson assumption for the best models is correct. If it is correct, it would be expected in plots a, c, e and g, that 95% of the Pearson residuals lie within ± 1.96. It would also be expected that in plots b, d,f and h that the root absolute deviance residuals be centred at 1.

The arguments, therefore, for using the Poisson distribution given in Section 2.3 are invalid for these categories. This is an interesting result in itself since the latest literature suggests Poisson processes are involved even when considering these higher categories of tropical cyclone. However, this result suggests that the approximation of a Poisson process is not valid in the formation of hurricanes and intense hurricanes. Thus, the assumptions of Section 2.3, which suggested a Poisson process, are not valid for all categories of tropical cyclone. An alternative distribution, which deals with this under-dispersion, is not available in the statistical textbooks, and therefore the Poisson presently is the best that can be applied for the reasons stated in Section 2.3.

4.6 Correlations between NTC activity and the environmental variables, and between tropical cyclone days and the environmental variables

Section 2.1.1 describes the NTC activity index (a measure of frequency and duration) as first calculated by Gray et al. (1994) for the North Atlantic. This has been calculated herein for the western development region of the NE Pacific as it provides a good overall measure of activity (see Appendix 1). For each category of tropical cyclone, calculations are also made of tropical cyclone days (i.e. the total number of days in the season in which a tropical cyclone is present) and average tropical cyclone days (the average number of days that a tropical cyclone lasts). OLS regression (see Section 2.3) is used to determine any relationships between these indices and the environmental variables, and the percentage of variance explained (R^2) is determined (see Table 4.9).

OLS assumes that the errors in Equation 2.6 are:

(i) independent

(ii) normally distributed

(iii) homoscedastic (The distribution of errors all have the same variance)

If these are violated, particularly (i) and (iii), erroneous conclusions may occur.

To check for these assumptions, the following tests were implemented using the standard 5% significance level. To test for independence, a check on the first order serial correlation was conducted based on the auto-correlation function (ACF). The ACF is compared to the value of 0.39 (1.96 multiplied by the approximate asymptotic standard error). If the ACF is larger than this value, this indicates that there is a problem with serial correlation. To test for normality, the Jarque-Bera test (a Lagrange multiplier test) has been used (Jarque and Bera, 1980). This test checks whether the third and fourth moments have values consistent with the null hypothesis of normality. If the test statistic is less than the χ^2 value with two

degrees of freedom (5.99), then the null hypothesis for normality cannot be rejected. To test for homoscedasticity, a Lagrange mulitplier (LM) test (see Stewart, 1991, p. 159, Equation 5.33) for dependent variable heteroscedasticity has been used to check the null hypothesis that the variance of the residuals does not depend on the fitted values. If the test statistic is less than the χ^2 value with one degree of freedom (3.84), the null hypothesis cannot be rejected.

Variable	NTC	IH Days	IH Days Avg.	H Days	H Days Avg.	TS Days	TS Days Avg.
RH	**0.42**	0.23	**0.42**	**0.44**	0.11	**0.35**	0.07
SST	**0.29**	**0.25**	**0.40**	**0.28**	0.02	0.16	0.00
VVEL	**0.39**	**0.31**	**0.31**	**0.33**	0.05	**0.28**	0.00
PWAT	**0.37**	**0.25**	**0.42**	**0.35**	0.05	**0.28**	0.00
ULWRF	**0.32**	**0.29**	**0.26**	**0.27**	0.05	0.21	0.00
PRES	0.20	0.04	0.15	0.22	0.00	**0.26**	0.13
RELV	0.04	-0.01	0.04	0.04	0.05	0.05	0.04
VZ	0.12	0.11	0.21	0.07	-0.02	0.11	-0.04
TMP	0.03	-0.01	0.13	0.06	-0.02	0.03	-0.04
ENSO							
(KW)	0.08	0.00	0.08	0.08	-0.03	0.08	0.02
(SOI)	0.21	0.10	0.12	0.21	0.03	0.20	0.03
(Niño1)	0.00	-0.04	0.00	0.02	-0.03	0.06	0.00
(Niño2)	0.02	-0.04	0.00	0.02	-0.04	0.09	0.00
(Niño3)	0.00	-0.04	0.00	0.00	-0.04	0.03	-0.01
(Niño4)	0.20	0.13	**0.24**	0.19	-0.03	0.13	0.02
MJO	0.16	0.08	0.14	0.19	-0.02	0.17	0.11
QBO	-0.02	-0.04	-0.04	-0.03	-0.04	0.00	-0.02
PDO	-0.02	-0.04	0.04	-0.03	-0.02	-0.03	-0.01

Table 4.9 R^2 given for the relationship between a tropical cyclone index (NTC, IH days, H days, TS days, average IH days, average H days, average TS days) and the environmental variables. Entries in bold face and underlined are significant to the 1% level, those underlined to the 5% level. The variables are defined in Tables 4.1 and 4.2. The R^2 given is the adjusted R^2.

The results from these tests are given for the relationship between the NTC index for the western development region and the environmental variables examined (Table 4.10). It can be seen that, although there does not seem to be a problem with auto-correlation, many of the variables fail on one of the other tests, implying that it is necessary to be cautious about the conclusions from Table 4.9 above. However, it does appear that the significant variables which are important to explain tropical cyclone frequency (see Tables 4.2 - 4.8) are also important to account for NTC activity and tropical cyclone days.

	NTC western development region		
Variable	*HSced.*	Jarque - Bera	ACF
RH	0.03	**2.06**	**0.07**
SST	0.02	**1.22**	**0.06**
VVEL	0.02	**1.18**	**0.02**
PWAT	**0.06**	**1.56**	**0.13**
ULWRF	<0.01	**1.19**	**0.00**
PRES	**0.47**	9.75	**0.15**
RELV	**0.64**	8.99	**0.11**
VZ	**0.25**	**4.69**	**-0.04**
TMP300	**0.72**	9.67	**0.06**
ENSO			
(SOI)	**0.13**	**3.06**	**0.03**
(KW)	**0.98**	11.91	**0.06**
(Niño1)	**0.56**	12.99	**0.16**
(Niño2)	**0.64**	13.35	**0.15**
(Niño3)	**0.52**	13.80	**0.11**
(Niño4)	**0.17**	**4.03**	**0.00**
MJO	**0.32**	6.71	**-0.08**
QBO	**0.17**	**5.41**	**0.10**
PDO	**0.28**	16.14	**0.01**

Table 4.10 Tests for the use of the normal distribution for the NTC index. The values are highlighted in bold where they pass each test. *Hsced.* is the test for homoscedasticity, where values must be less than a p-value of 0.05 to reject homoscedasticity. For the Jarque-Bera test, values must be greater than 5.99 at the 5% level to reject normality. For the ACF, values must be greater than 0.39 to indicate that there may be a problem with auto-correlation. The variables are defined in Tables 4.1 and 4.2.

Although Table 4.9 does not show a relationship directly with ENSO for many of the indices (although there is a significant relationship at least to the 5% level for Niño4 vs. NTC, IH days Avg. and H days), this may be because ENSO affects frequency more than duration. It will be noted in Section 5.2.1 that ENSO affects RH in the western development region, and it can be seen here that there is a strong statistical relationship (>5%) for RH with the NTC index and tropical cyclone days, for all categories. This is expected since the total tropical cyclone days includes the frequency element in it. However, when one takes out the frequency element, by examining average storm days per year, only the duration of intense hurricanes appears to be dependent on any of the environmental variables. This implies that when the RH is higher, intense hurricanes tend to last longer on average. However, the duration of the other categories of tropical cyclone are not affected by the RH values.

4.7 Discussion of the relationships discovered

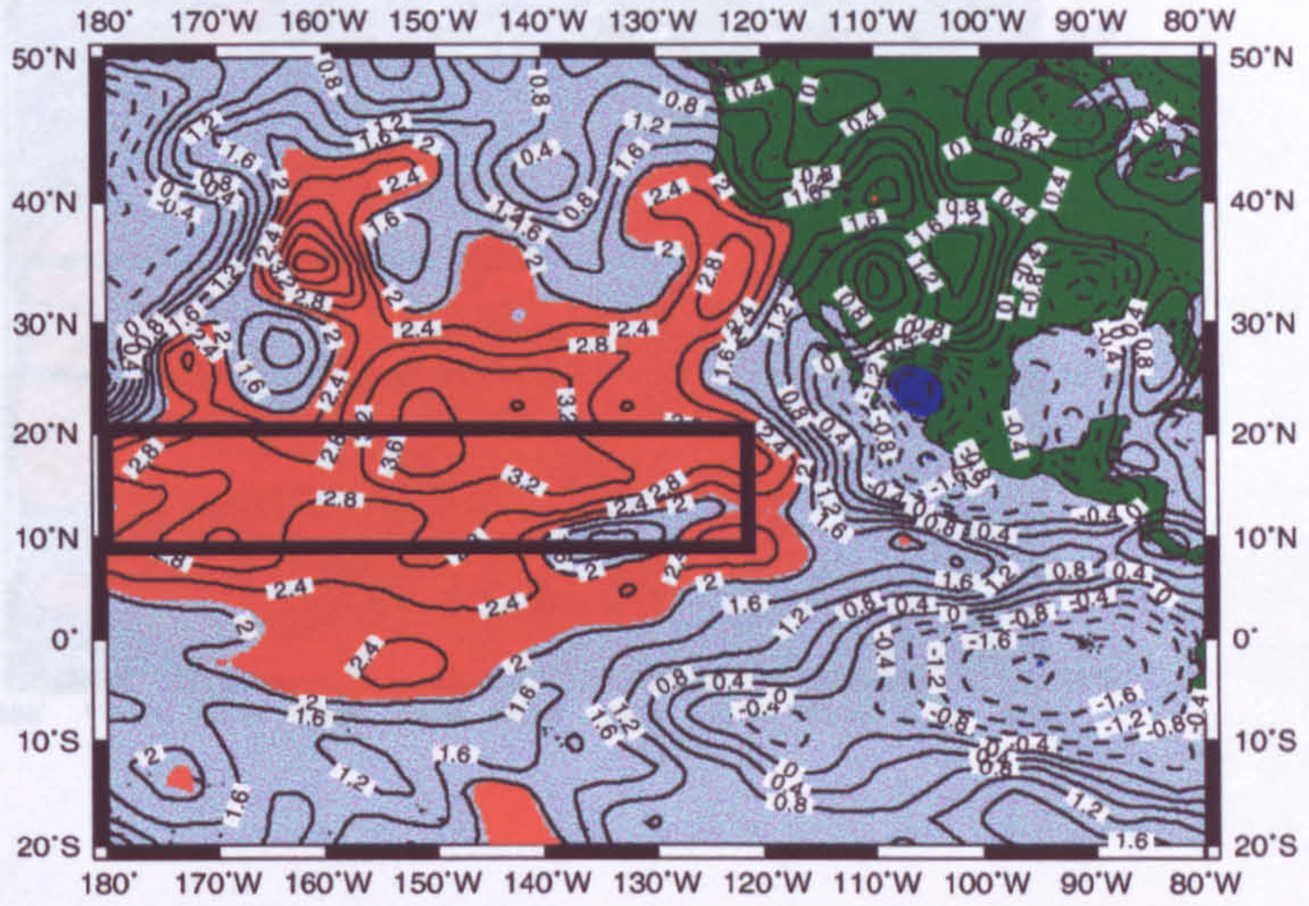
An examination of Tables 4.2 - 4.8 reveals that Gray's (1979) necessary conditions for genesis (Section 1.5.1.1) are also generally relevant in affecting the frequency of each category of tropical cyclone. The results of the relationships with the tropical cyclone indices and Gray's thermodynamic and dynamic factors (ignoring the Coriolis parameter which is not varying and initial vorticity which is considered to occur on a short time-scale), as well as associated variables, together with other interesting results, will now be discussed in more detail with particular examples taken from the hurricane category. It can be seen from Tables 4.2 - 4.8 that Gray's thermodynamic variables and associated variables examined in this study are of particular importance for understanding interannual variations in tropical cyclone formation in the western development region. Gray's dynamic variables are of less importance.

4.7.1 Factors relating to thermodynamic potential

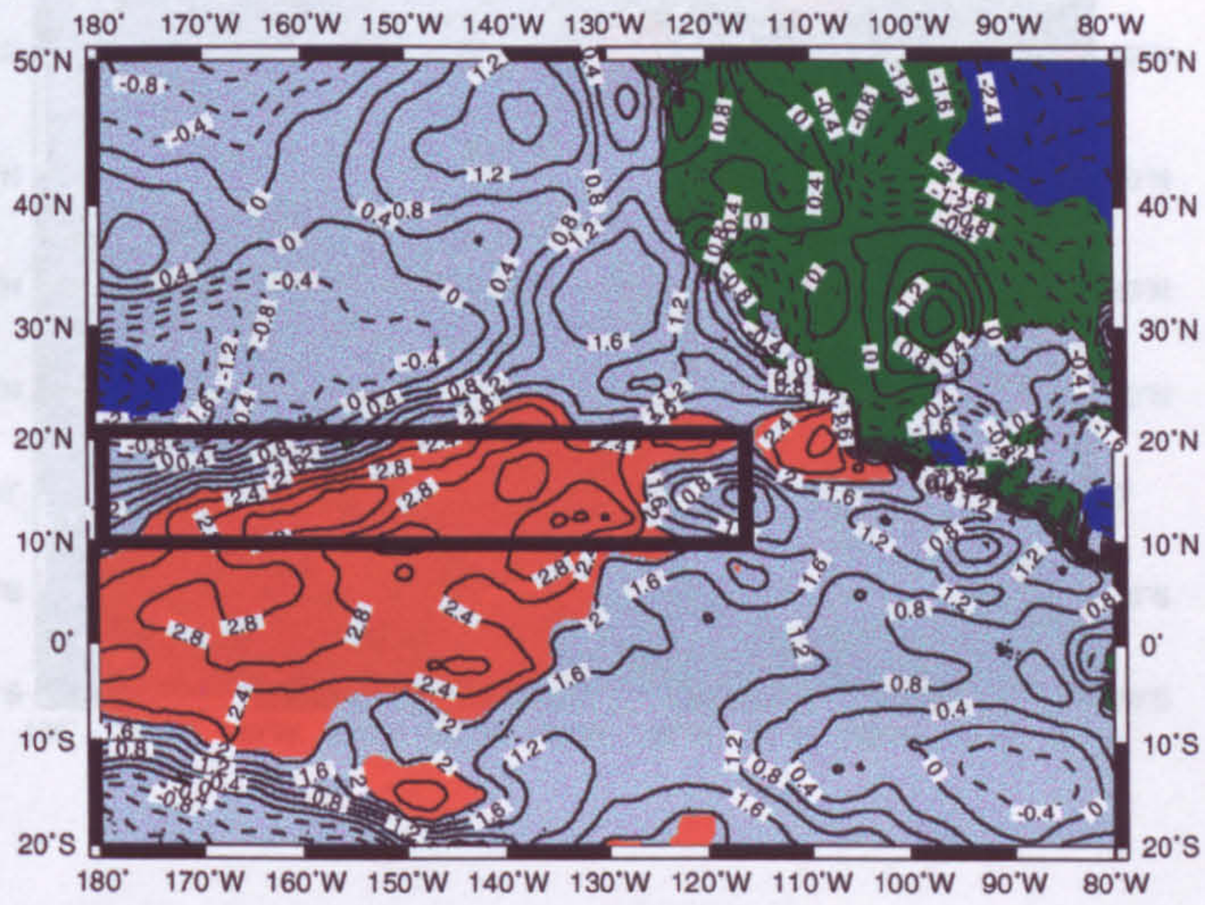
Gray's thermodynamic factors have been discussed in Section 1.5.1.3, where it was noted that variables such as RH, SST and VVEL are not independent variables, but operate together to indicate instability and the potential for cumulonimbus convection. Within this study these variables and associated variables such as PWAT (which is related to the SST, since this will affect water content in the column of air) and PRES (where lower pressure at the surface will encourage the convergence and then rising of air, as well as a low pressure being induced by high SST values, Section 1.5.1.3) are considered in relation to the various categories of a tropical cyclone for the NE Pacific basin: the whole region, and the western and eastern development regions, identified in Section 3.1.2. The results in Tables 4.2 - 4.8 indicate that variations in the thermodynamic factors are important for the western development region tropical cyclones and not important for the eastern development region tropical cyclones. The reasons for this, and further evidence for the relationships discovered, will now be examined in more detail.

Figure 4.5 shows spatial correlation plots of the local thermodynamic and related variables described above for western development region hurricanes. These spatial correlation plots allow the correlation between tropical cyclone frequency and the environmental variables to be examined spatially, and are created from the NCEP/NCAR dataset (Section 2.1.2), where the variable values are available every latitude and longitude (on a 2.5 x 2.5 degree grid). These show large areas of significant association in the western development region, confirming the results in Table 4.4, that more hurricanes occur when values of western development region RH, PWAT and SST are higher, and when values of PRES, VVEL and ULWRF are lower. On the other hand, when examining the eastern development

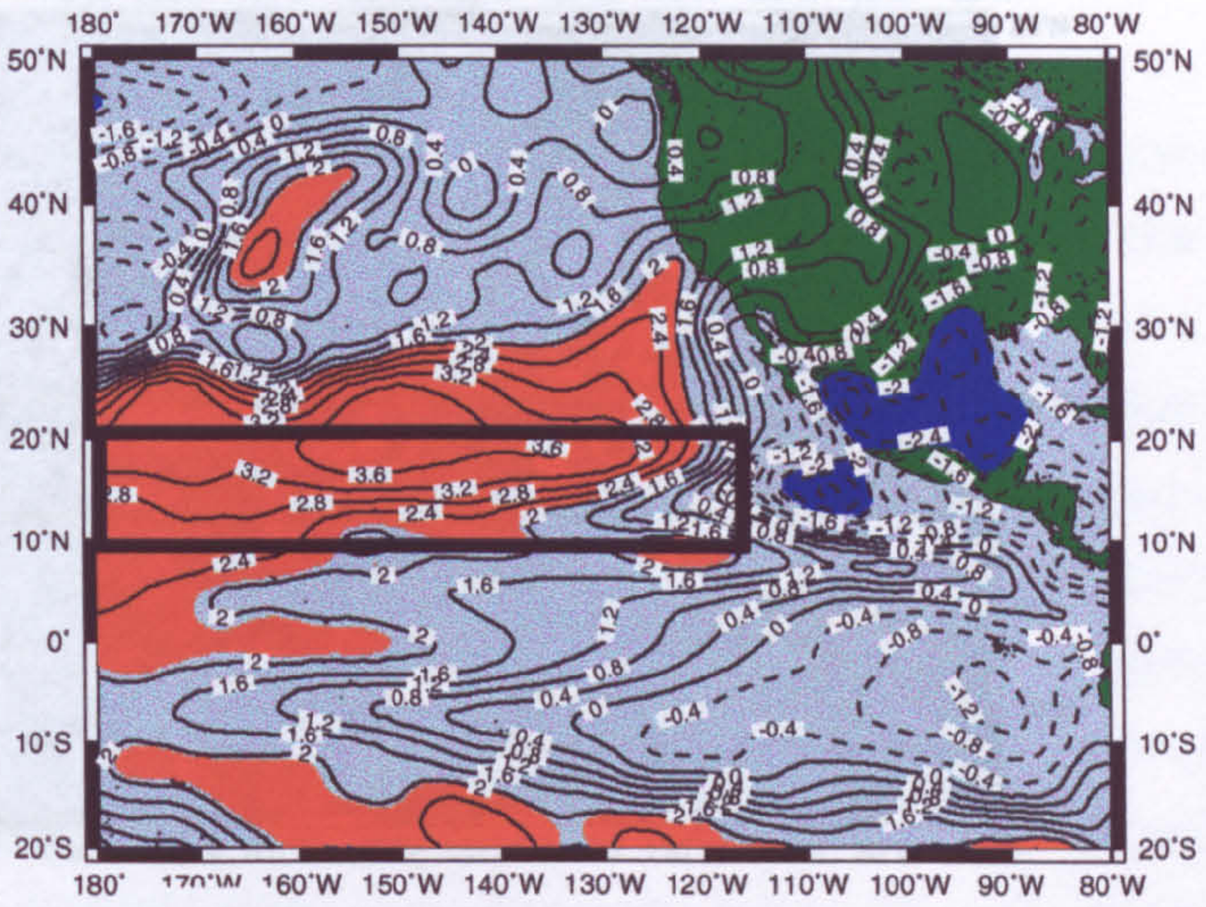
a) RH



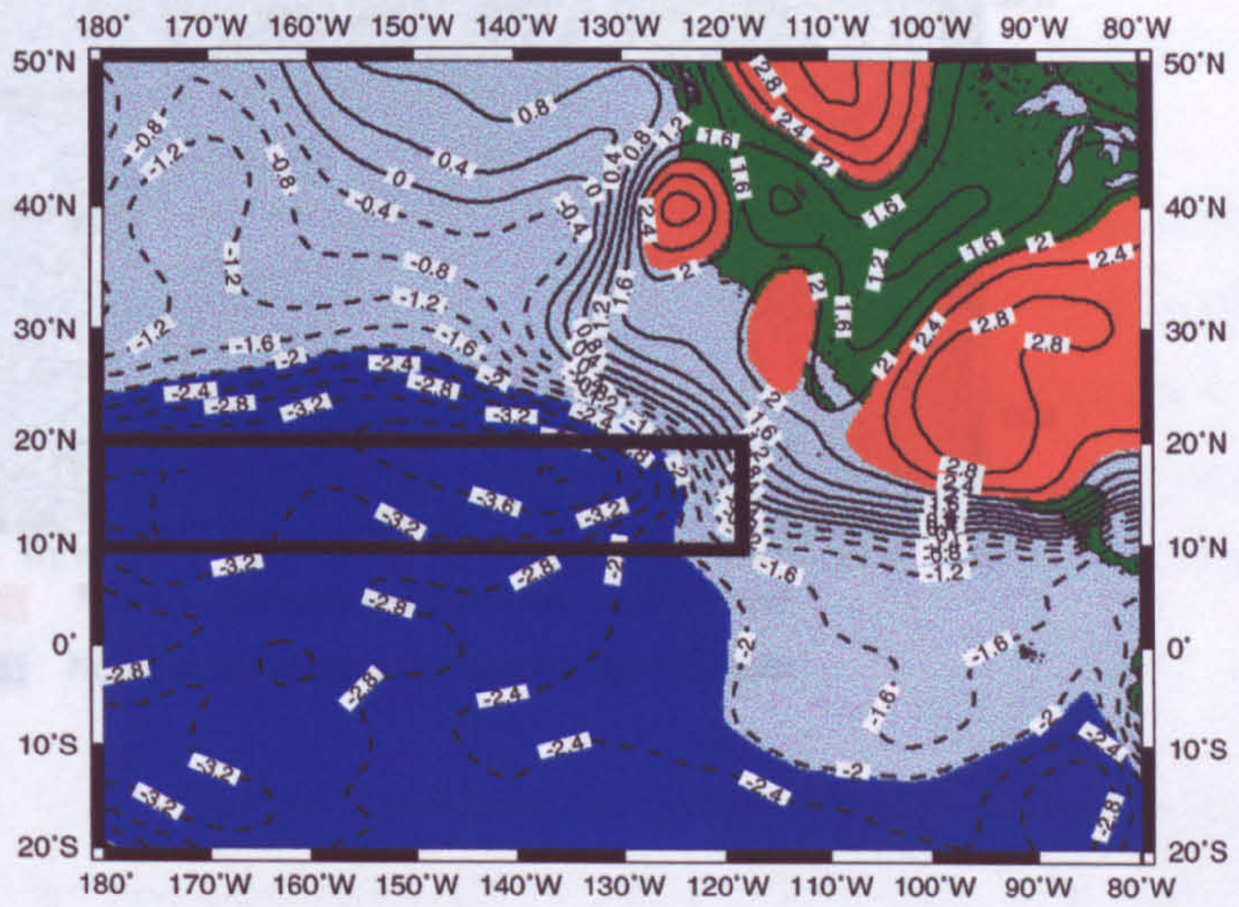
b) SST (and land temperatures)



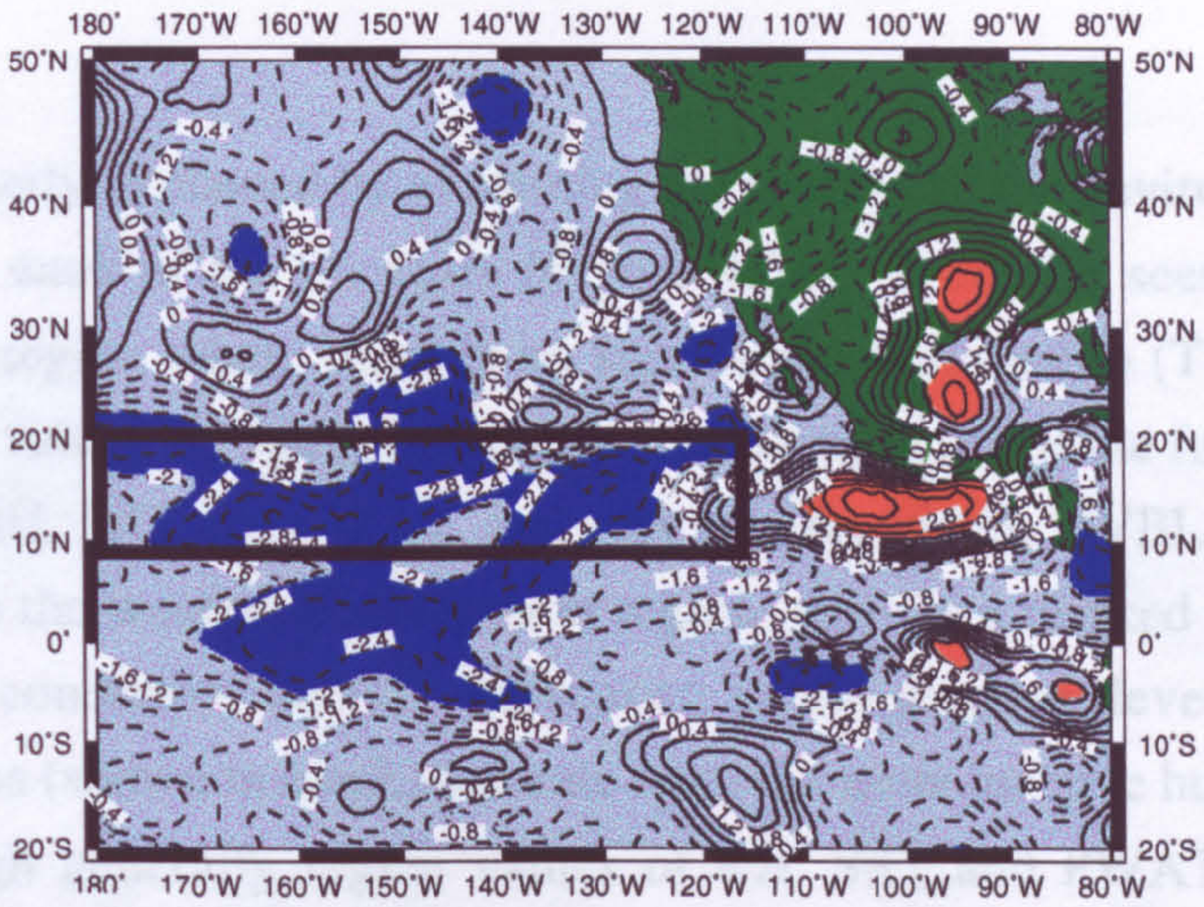
c) PWAT


180° 170°W 160°W 150°W 140°W 130°W 120°W 110°W 100°W 90°W 80°W
50°N
40°N
30°N
20°N
10°N
0°
10°S
20°S

d) PRES


180° 170°W 160°W 150°W 140°W 130°W 120°W 110°W 100°W 90°W 80°W
50°N
40°N
30°N
20°N
10°N
0°
10°S
20°S

e) VVEL



f) ULWRF

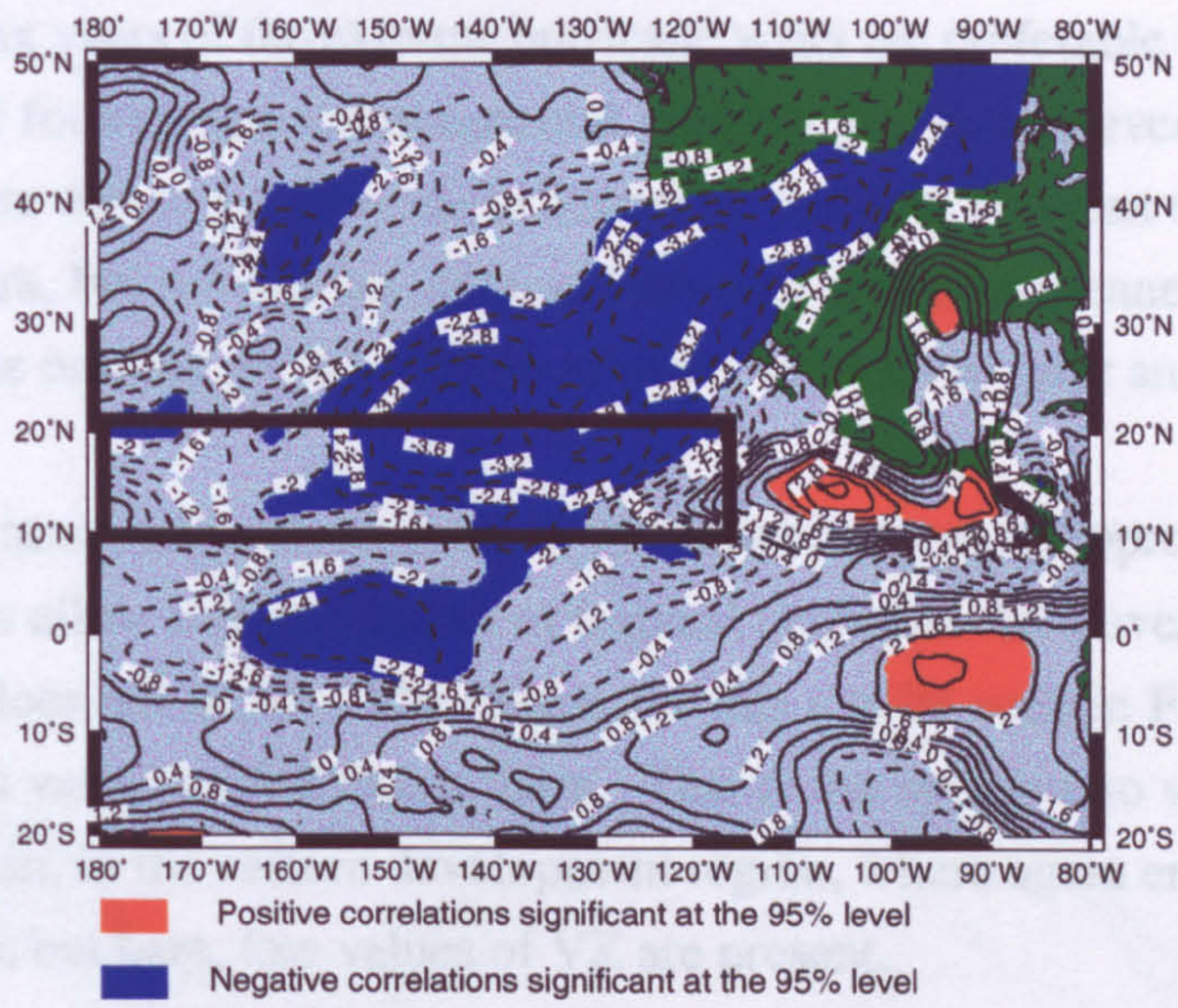


Figure 4.5 Relationship (given with a *t*-statistic) between western development region hurricane numbers and the environmental variables using Poisson regression. Values for July-September, 1972-1997 are given. Time is not included in the model. The western development region is shown with the box.

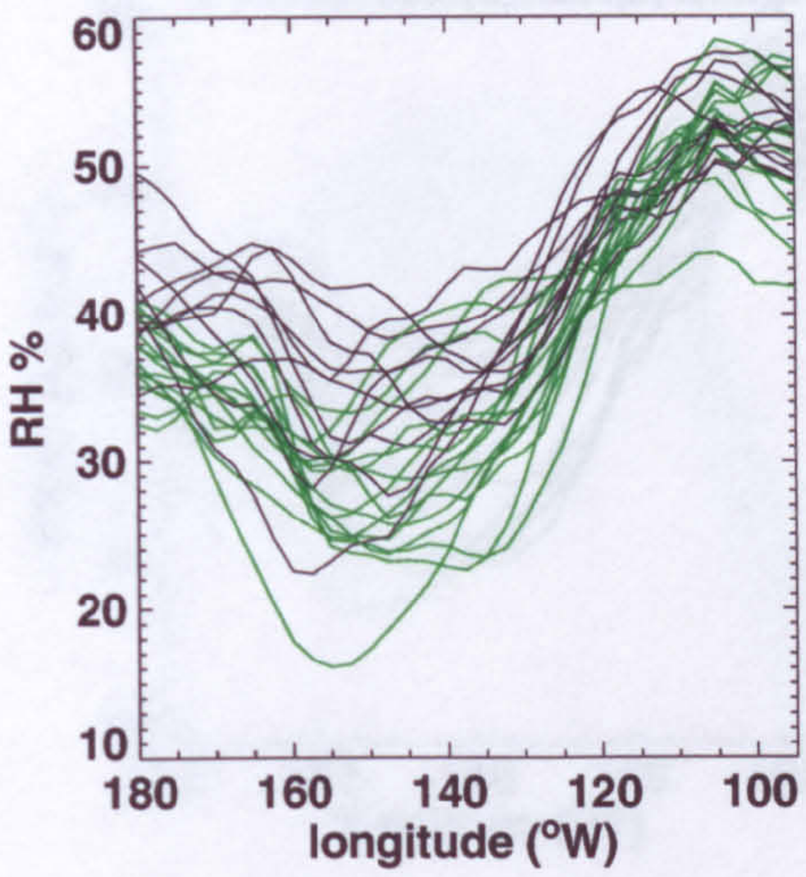
region tropical cyclones, there is no local region of significance (see the local regions of Figure 4.15).

This can be partly explained by examining the profiles of the environmental variables with longitude for each of the 26 years (Figure 4.6a). It can be seen that over the eastern development region where there is no significant relationship (Tables 4.2 - 4.8), for all variables, the values are fairly constantly conducive to hurricane formation (i.e. the values are high for RH, SST and PWAT, and very low for PRES, VVEL and ULWRF). On the other hand, in the western development region, there is a marked change in the variables towards less conducive values. Moreover, in the western development region, active hurricane years (shown in black) separate from the more inactive hurricane years (shown in green) through generally higher values of RH, SST and PWAT, and lower values of PRES, VVEL and ULWRF, in the former than the latter. The effect becomes clearer when examining the five most active (1982, 1994, 1990, 1992, 1997) and five most inactive (1973, 1980, 1983, 1995, 1996) hurricane years (Figure 4.6b). Note that, for consistency, six years of the extreme hurricane years are preferable to be examined (as used in Section 4.2 for extreme environmental variable years), however, five years of each are considered here due to a difference in hurricane numbers between the fifth and sixth active hurricane years, but not for the sixth and seventh active hurricane years. These have the same hurricane number, so it would be arbitrary to pick one year and not the other.

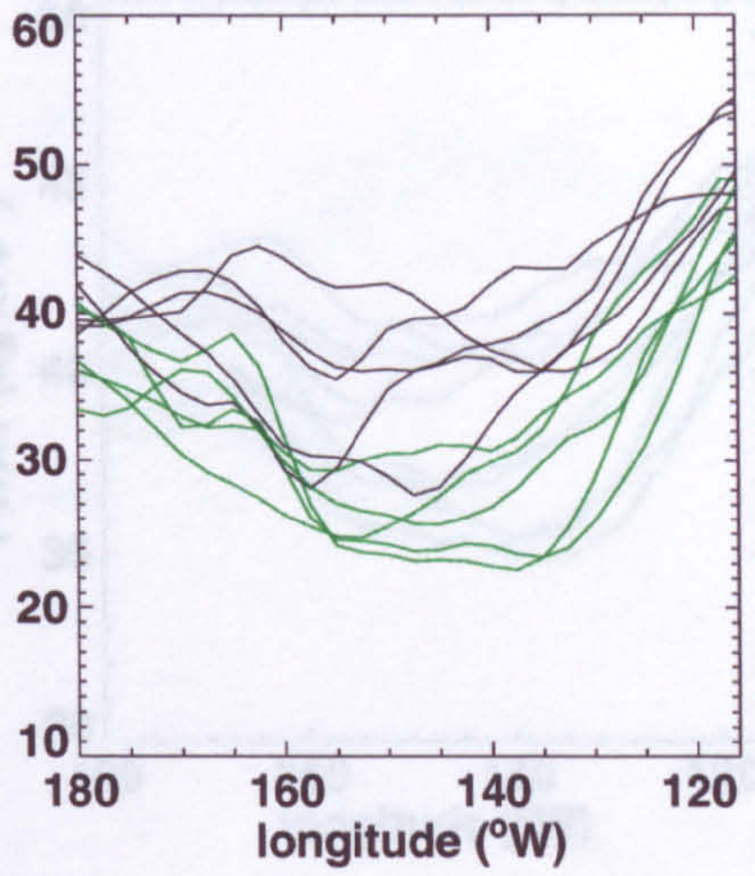
Note that the more conducive values of the variables west of approximately 160°W would be expected to allow a large number of tropical cyclones. However, it is clear from Figure 3.1 that this does not occur. The reason for this can be seen in Figure 4.7, which shows that very high values of VZ exists there. This is the opposite to what occurs in the other end of the basin, in the eastern development region, where again environmental conditions are conducive, but here, low values of VZ are present.

As noted in Section 1.5.1.3, according to Gray (1979), cyclone development is assumed not to be possible if the seasonal 500-700 hPa RH is less than 40% and the SSTs are less than 26-27°C. Since VVEL describes the rate of rising or subsiding air (Section 2.1.2), a threshold of 0 Pa s^{-1} would be important for this variable. These thresholds would partly explain the relationship with hurricanes that is observed with these variables in Figure 4.6, by explaining the presence or absence of hurricanes in particular years. When generally RH and SST are low over a large area, and VVEL is high, there are no hurricanes in the western development region as the seasonal value is not near its threshold for hurricanes to occur. In the eastern development region, since the RH and SST values are typically above

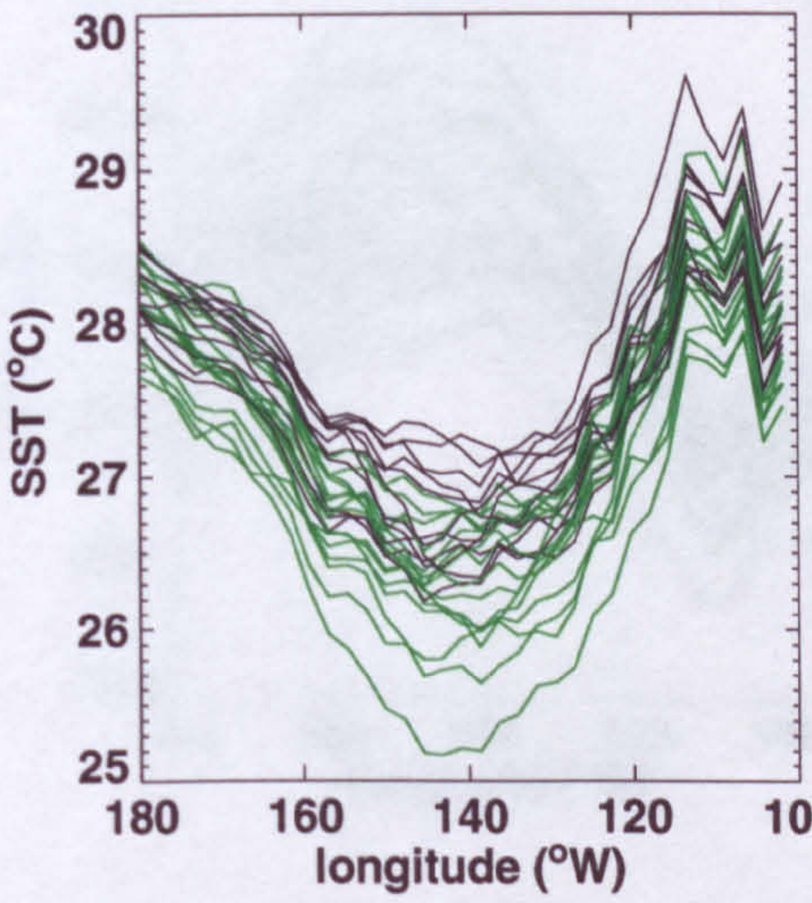
a)


60
50
40
30
20
10
RH %
180
160
140
120
100
longitude (°W)

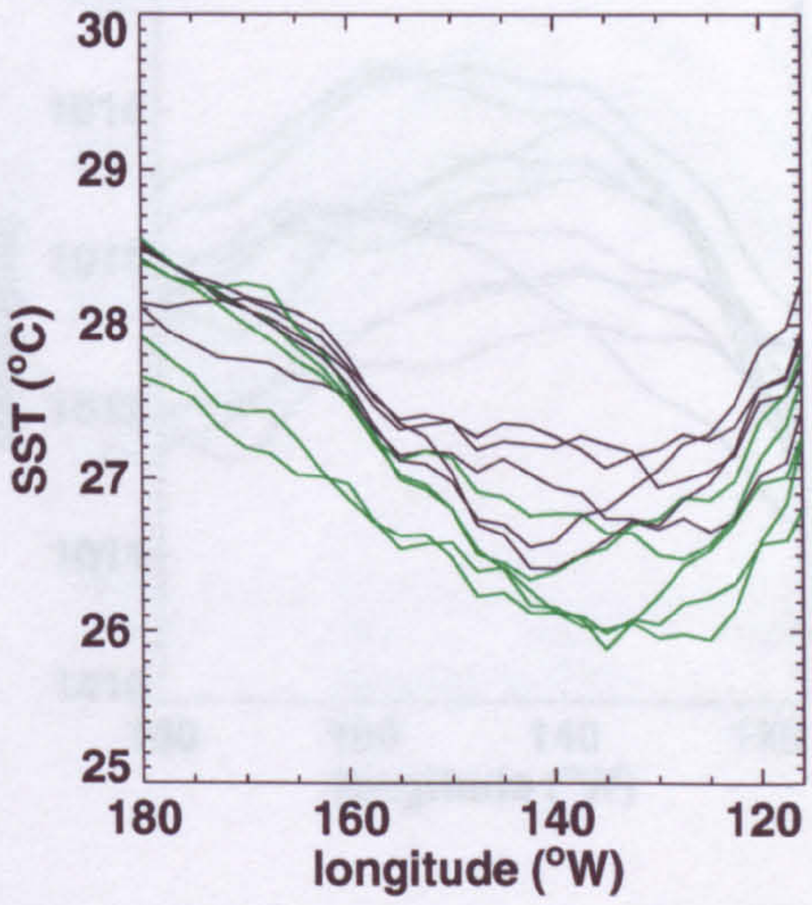
b)


60
50
40
30
20
10
RH %
180
160
140
120
longitude (°W)

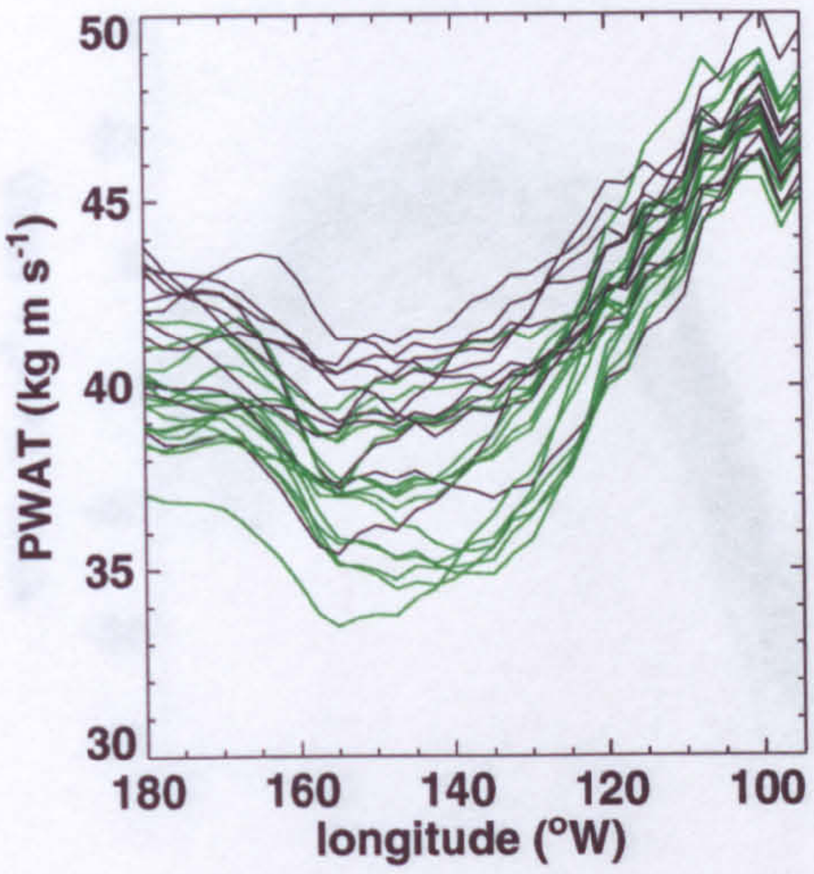
a)


30
29
28
27
26
25
SST (°C)
180
160
140
120
100
longitude (°W)

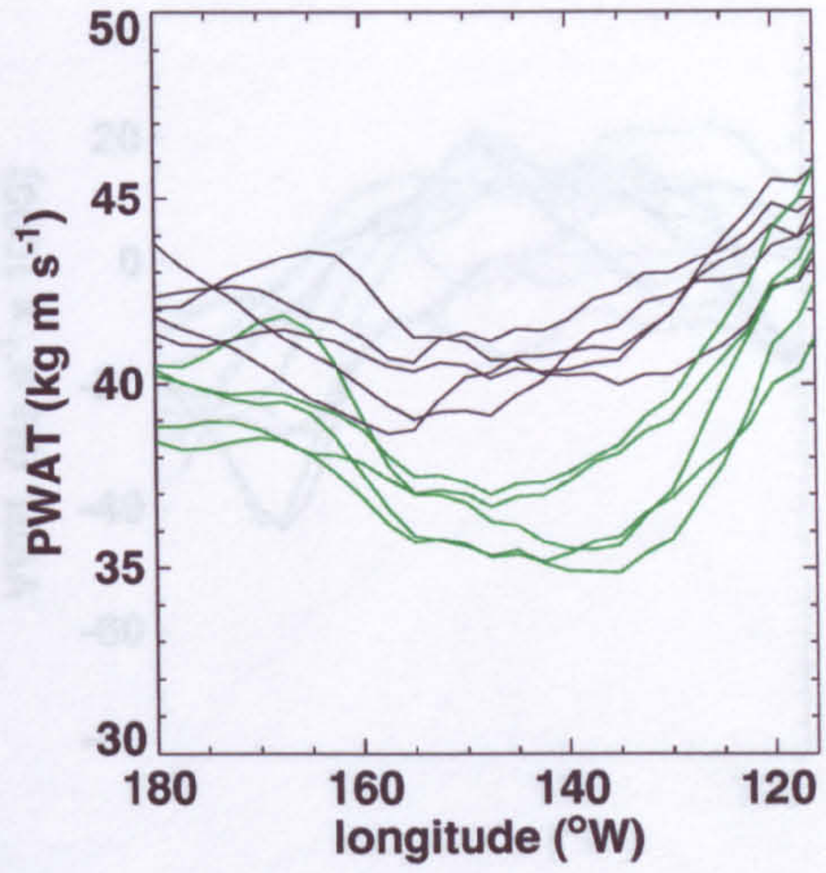
b)


30
29
28
27
26
25
SST (°C)
180
160
140
120
longitude (°W)

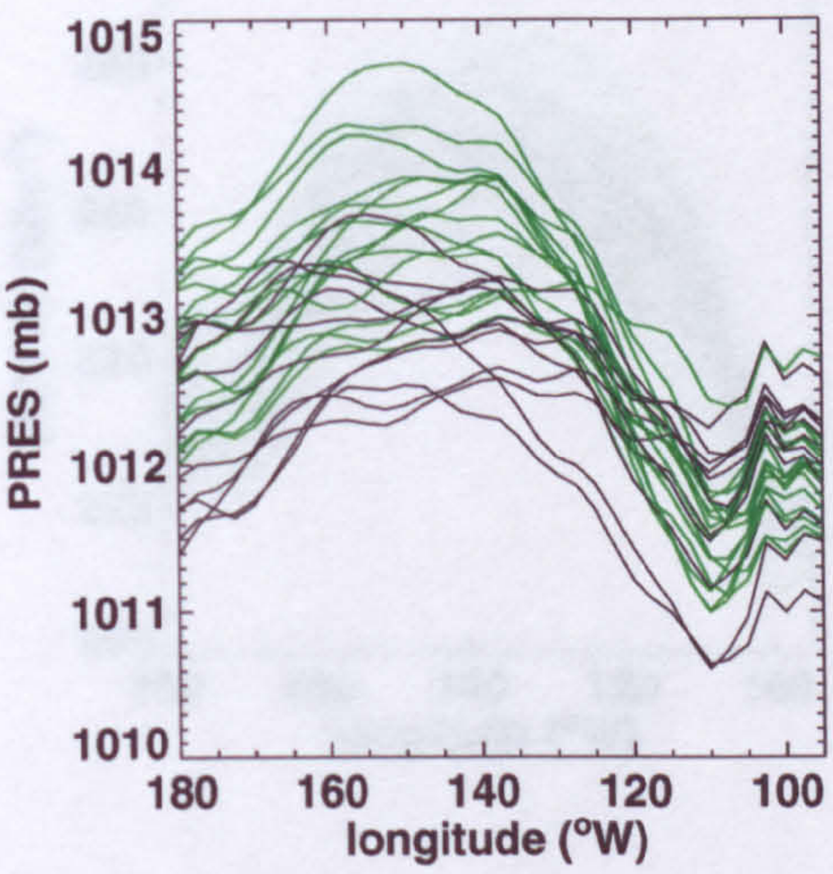
a)


50
45
40
35
30
PWAT (kg m s-1)
180
160
140
120
100
longitude (°W)

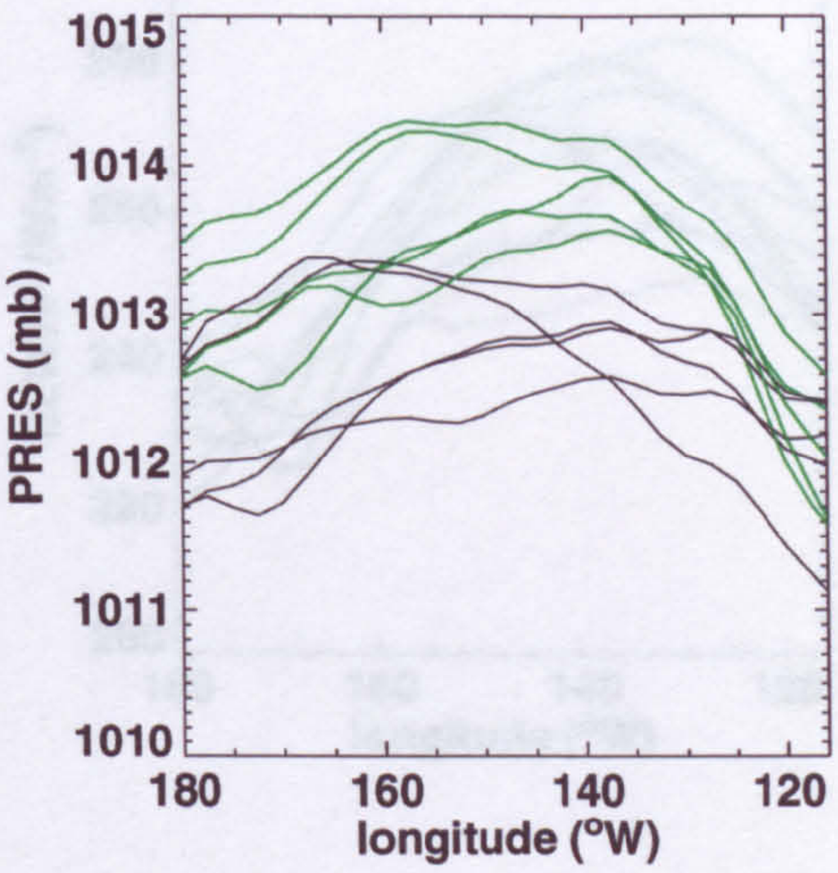
b)


50
45
40
35
30
PWAT (kg m s-1)
180
160
140
120
longitude (°W)

a)


1015
1014
1013
1012
1011
1010
PRES (mb)
180
160
140
120
100
longitude (°W)

b)


1015
1014
1013
1012
1011
1010
PRES (mb)
180
160
140
120
longitude (°W)

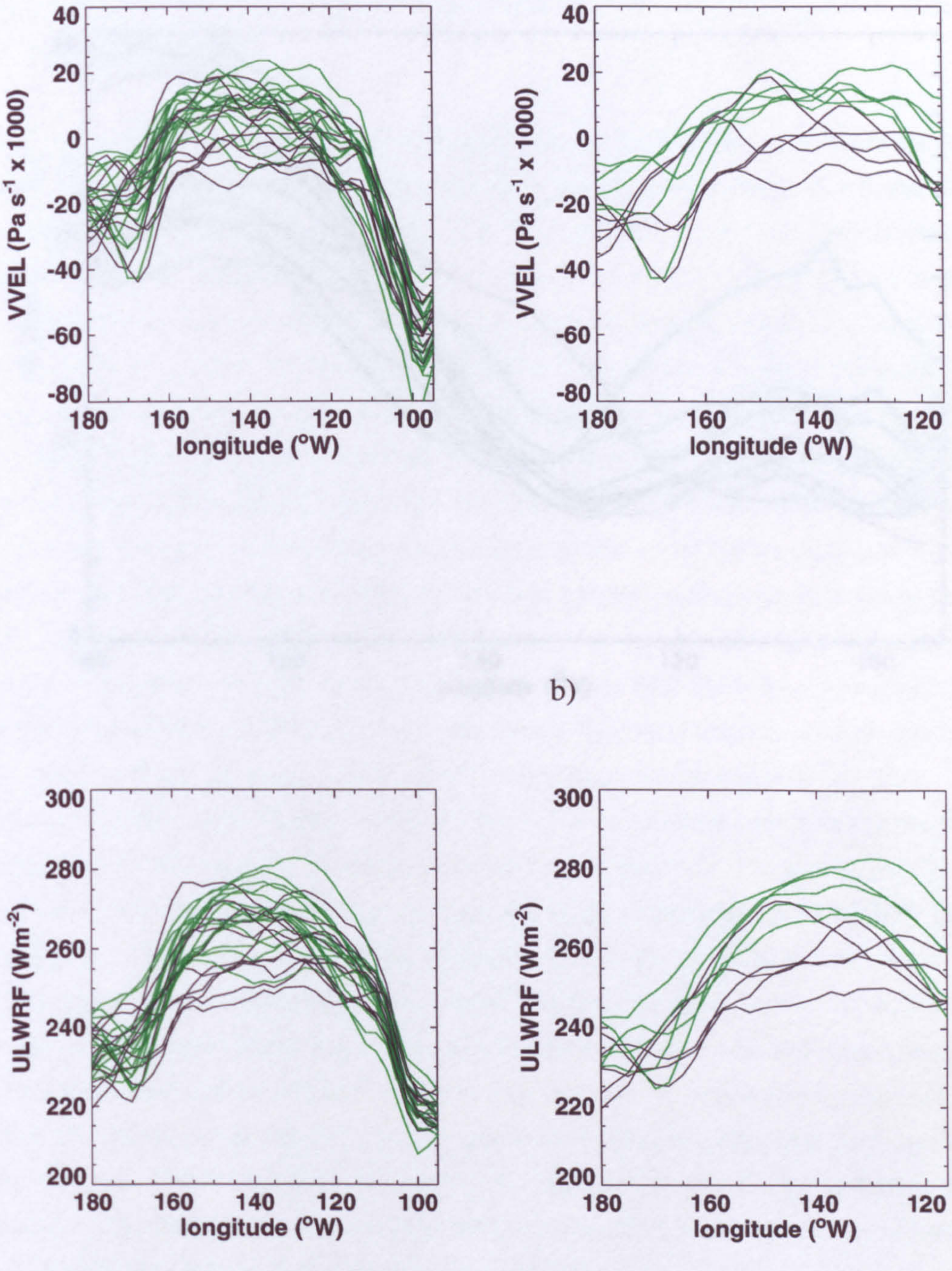


Figure 4.6 Plot of the environmental variables averaged over July-September (averaged over latitudes 10°N to 20°N) vs. longitude for a) all years (1972-1997), b) western development region five most active (1982, 1994, 1990, 1992, 1997) and inactive (1973, 1980, 1983, 1995, 1996) hurricane years. Active years are shown in black, inactive years in green. For a) years with 3-6 hurricanes are classed as active and shown in black, years with 0-2 hurricanes are classed as inactive and shown in green. (Note: in figure 1mb = 1 hPa).

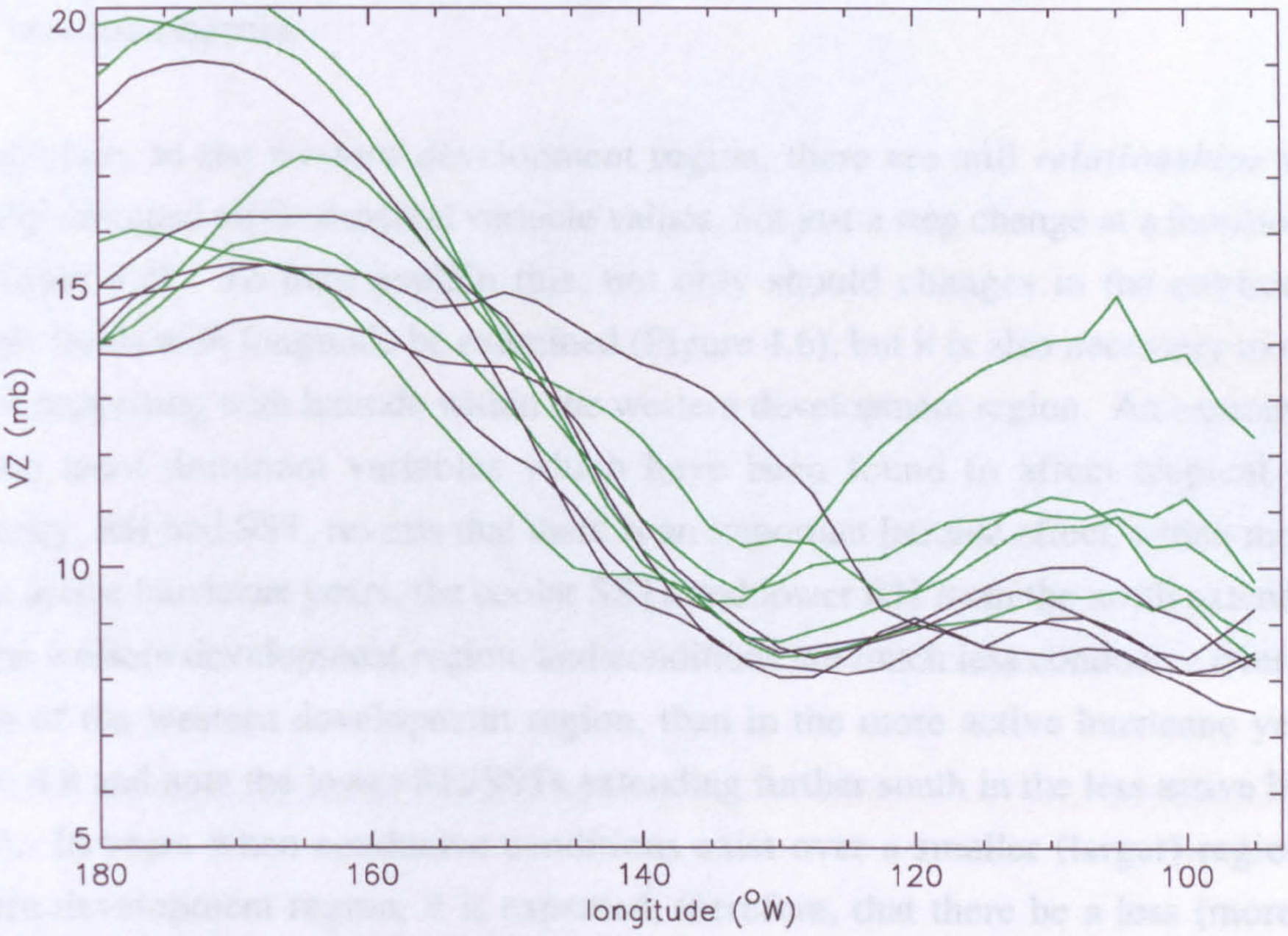


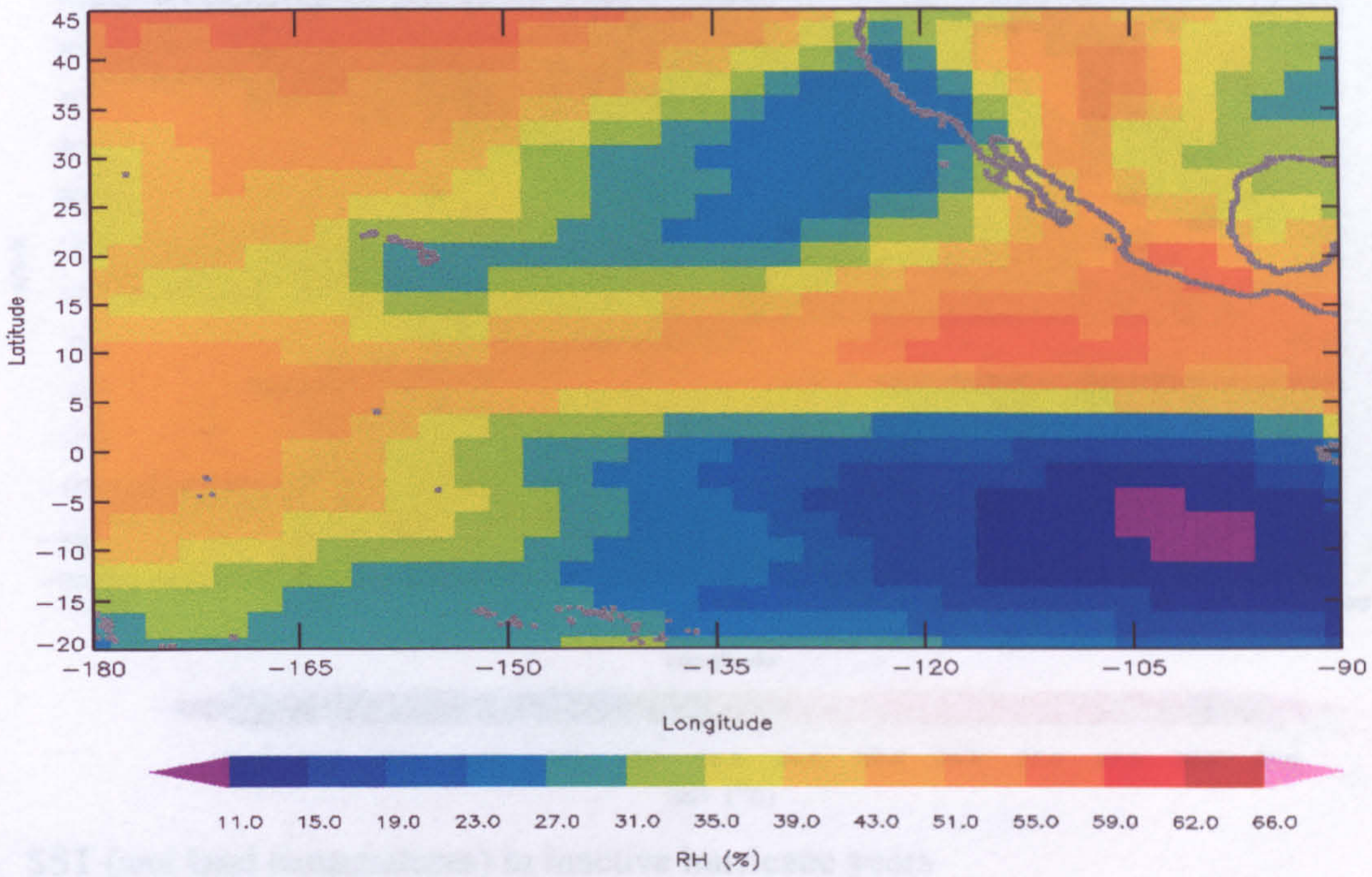
Figure 4.7 Plot of VZ (850 hPa to 200 hPa) averaged over July-September and for latitudes 10°N to 20°N for each longitude for western development region hurricane active (1982, 1994, 1990, 1992, 1997) and inactive (1973, 1980, 1983, 1995, 1996) years. Active years are shown in black, inactive years in green. (Note: in figure 1mb = 1 hPa).

these values, and VVEL below, no clear relationships emerge. This suggests that once the variables have reached their thresholds, e.g. if the SST is sufficiently warm and the air is sufficiently humid and rising, then the actual values of SST, humidity and rate of rising air, are of less consequence.

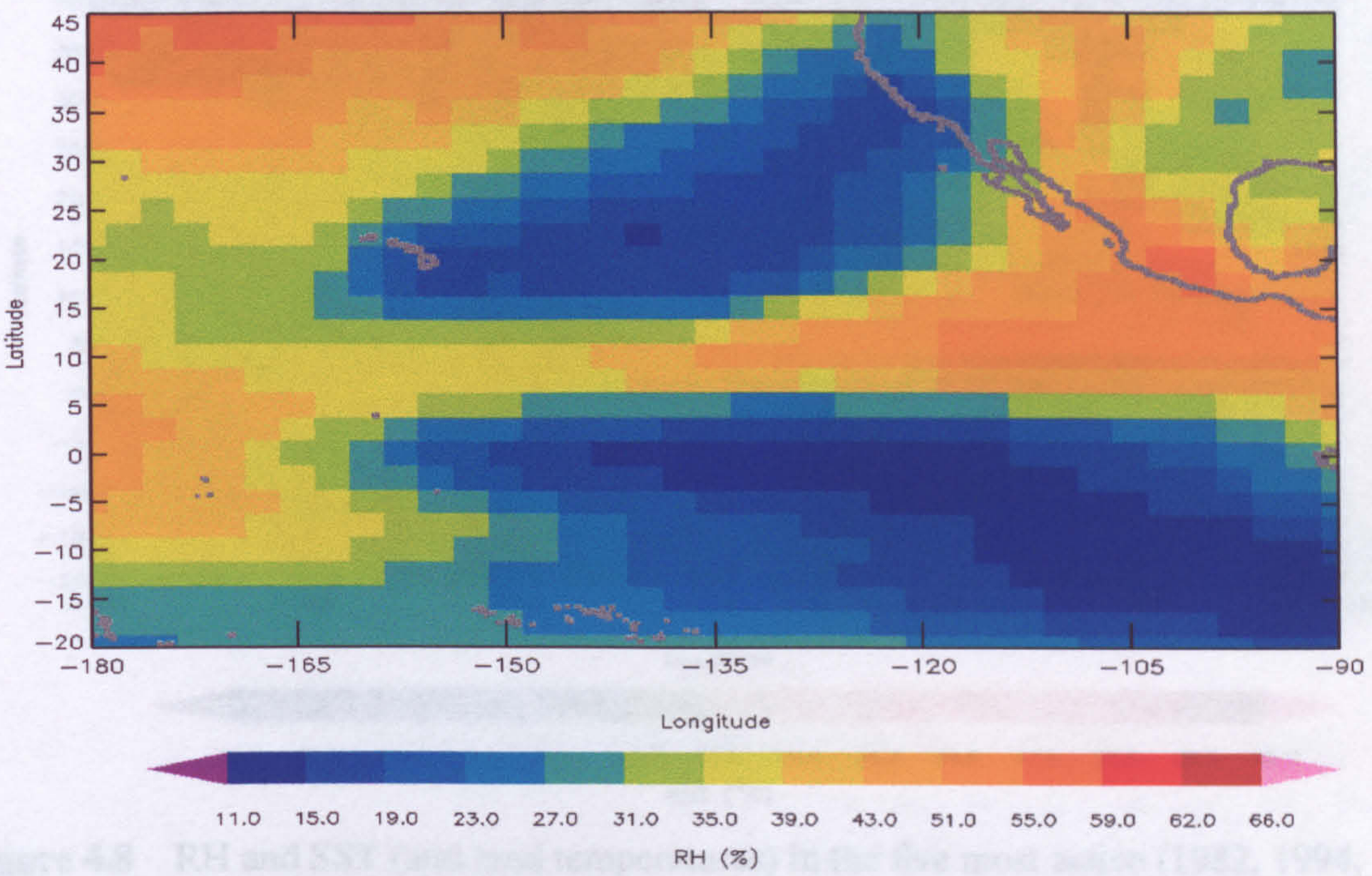
Nevertheless, in the western development region, there are still *relationships* with the spatially averaged environmental variable values, not just a step change at a threshold value (see Table 4.4). To help explain this, not only should changes in the environmental variable fields with longitude be examined (Figure 4.6), but it is also necessary to consider what is happening with latitude within the western development region. An examination of the two most dominant variables which have been found to affect tropical cyclone frequency, RH and SST, reveals that there is an important latitude effect, which means that in less active hurricane years, the cooler SSTs and lower RH from the north extend further into the western development region, and conditions are much less conducive over a larger region of the western development region, than in the more active hurricane years (see Figure 4.8 and note the lower RH/SSTs extending further south in the less active hurricane years). In years when conducive conditions exist over a smaller (larger) region of the western development region, it is expected, therefore, that there be a less (more) active hurricane season there. Therefore, these plots again highlight the importance of a threshold on tropical cyclone genesis, which affects all categories of tropical cyclone. For the inactive hurricane years (Figure 4.8b and Figure 4.8d), it can be seen that for the far south and east part of the western development region, RH and SST values are slightly higher than in the main part of the region, and just above the threshold levels of 40% and 27°C respectively. Therefore, it might be expected that tropical cyclone formation may be possible, although no tropical cyclones actually formed in these years. However, even in this part of the region, these conditions are still lower than in the active hurricane years. The fact that there are no tropical cyclones can perhaps be explained by the fact that the critical SST threshold of 26-27°C can in fact vary in position and time (e.g. Royer et al., 1998; Henson, 1998) and may sometimes be higher than 27°C. In addition, negative anomalies in the number of triggering disturbances may be occurring in some of the inactive years, independently from the environmental conditions.

Figure 4.9 is an aggregate plot of each variable (averaged over the season) showing the differences in the environmental variable between the five most active hurricane years and five most inactive hurricane years. Composite plots showing these differences reveal the environmental variables which are related to large differences in hurricane activity and is, therefore, an important tool for understanding the climate of a hurricane. This technique

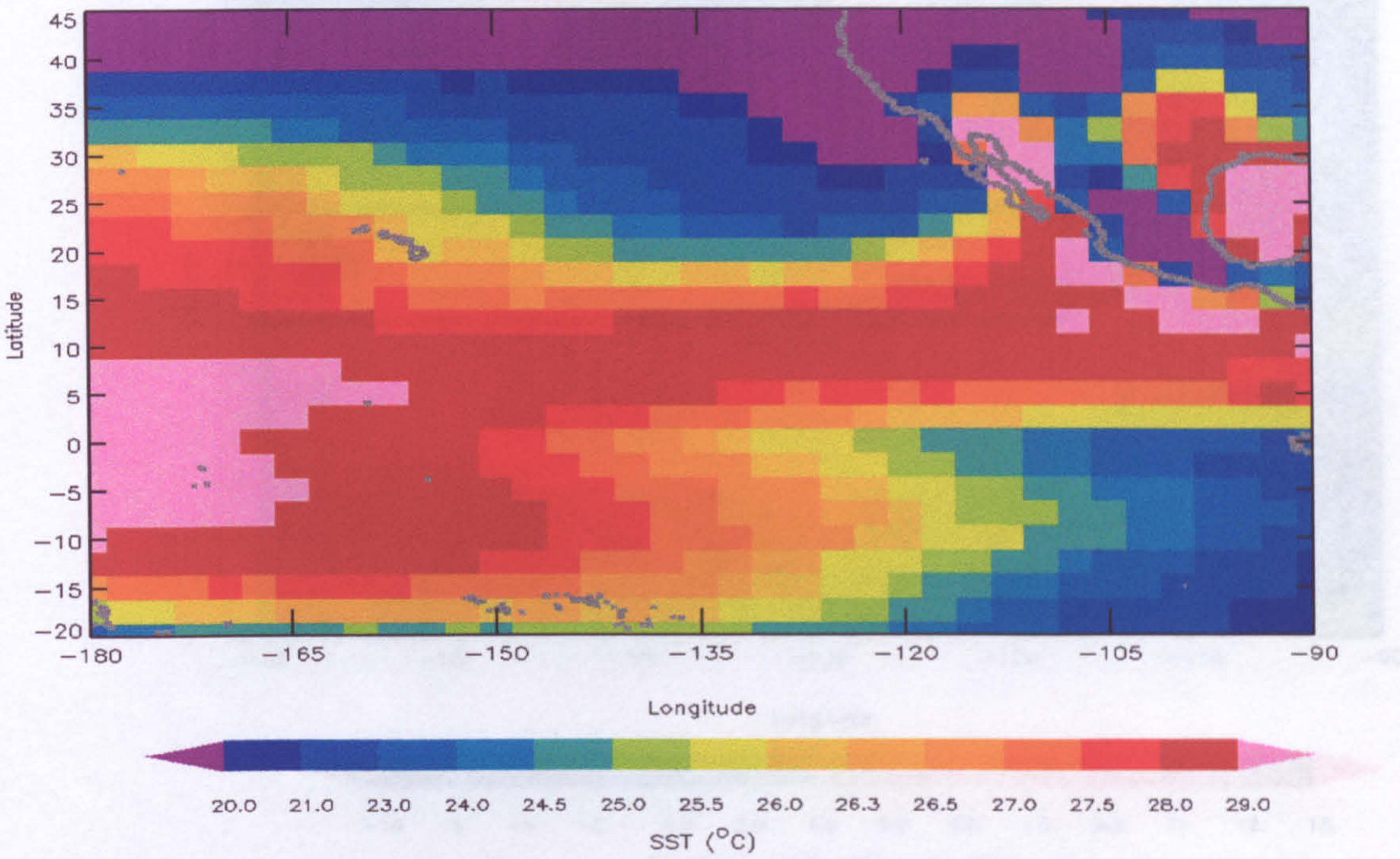
a) RH in active hurricane years



b) RH in inactive hurricane years



c) SST (and land temperatures) in active hurricane years



d) SST (and land temperatures) in inactive hurricane years

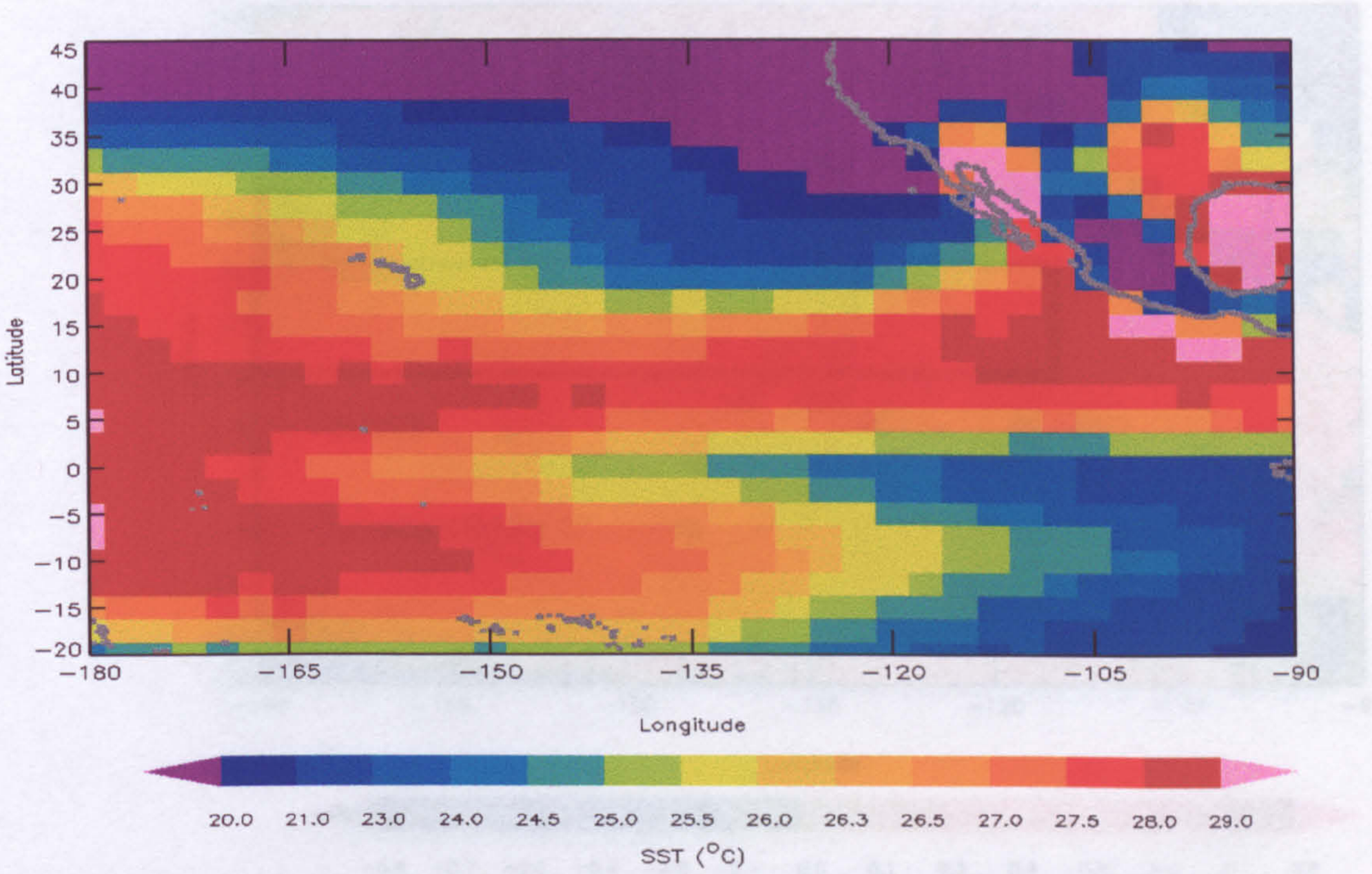
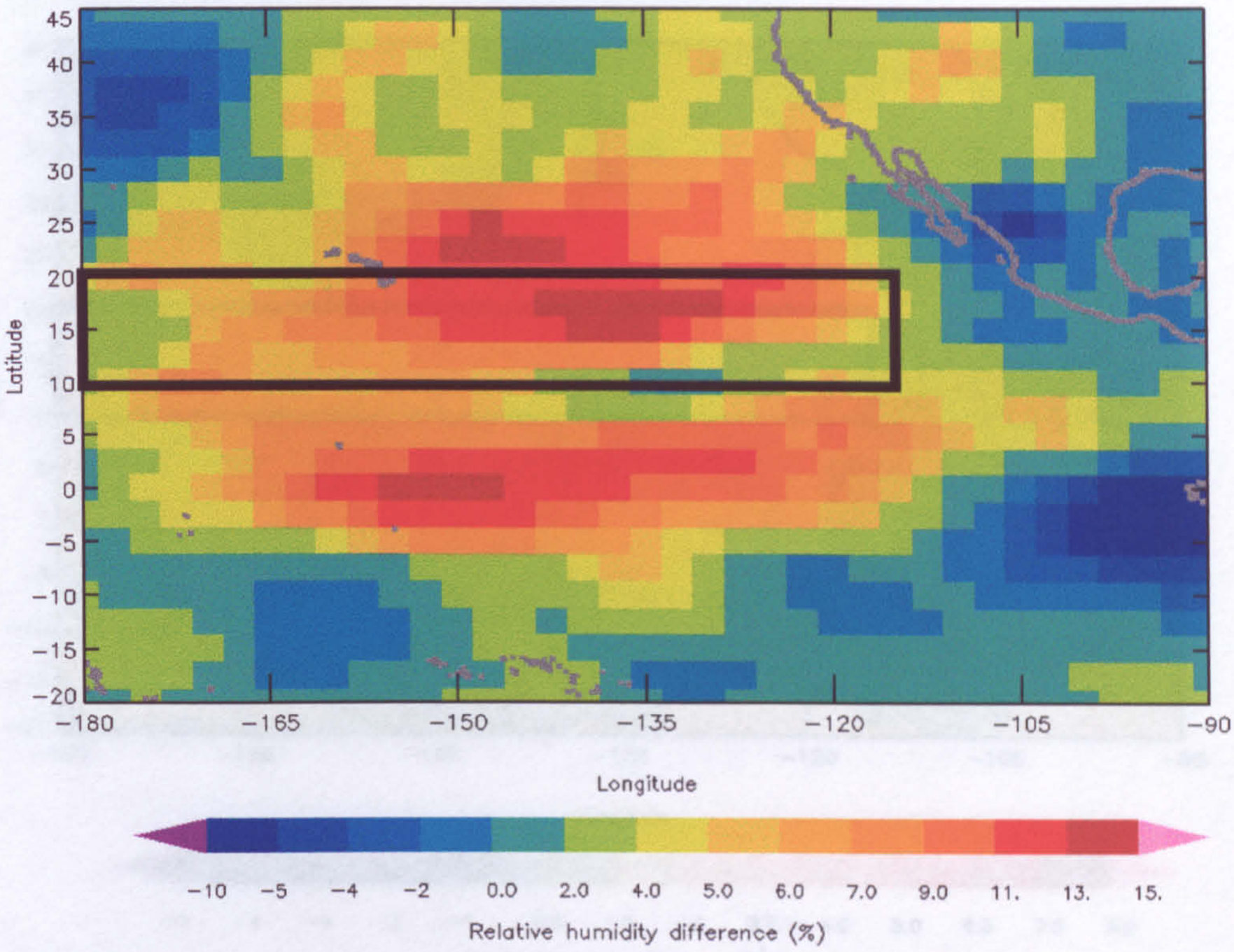
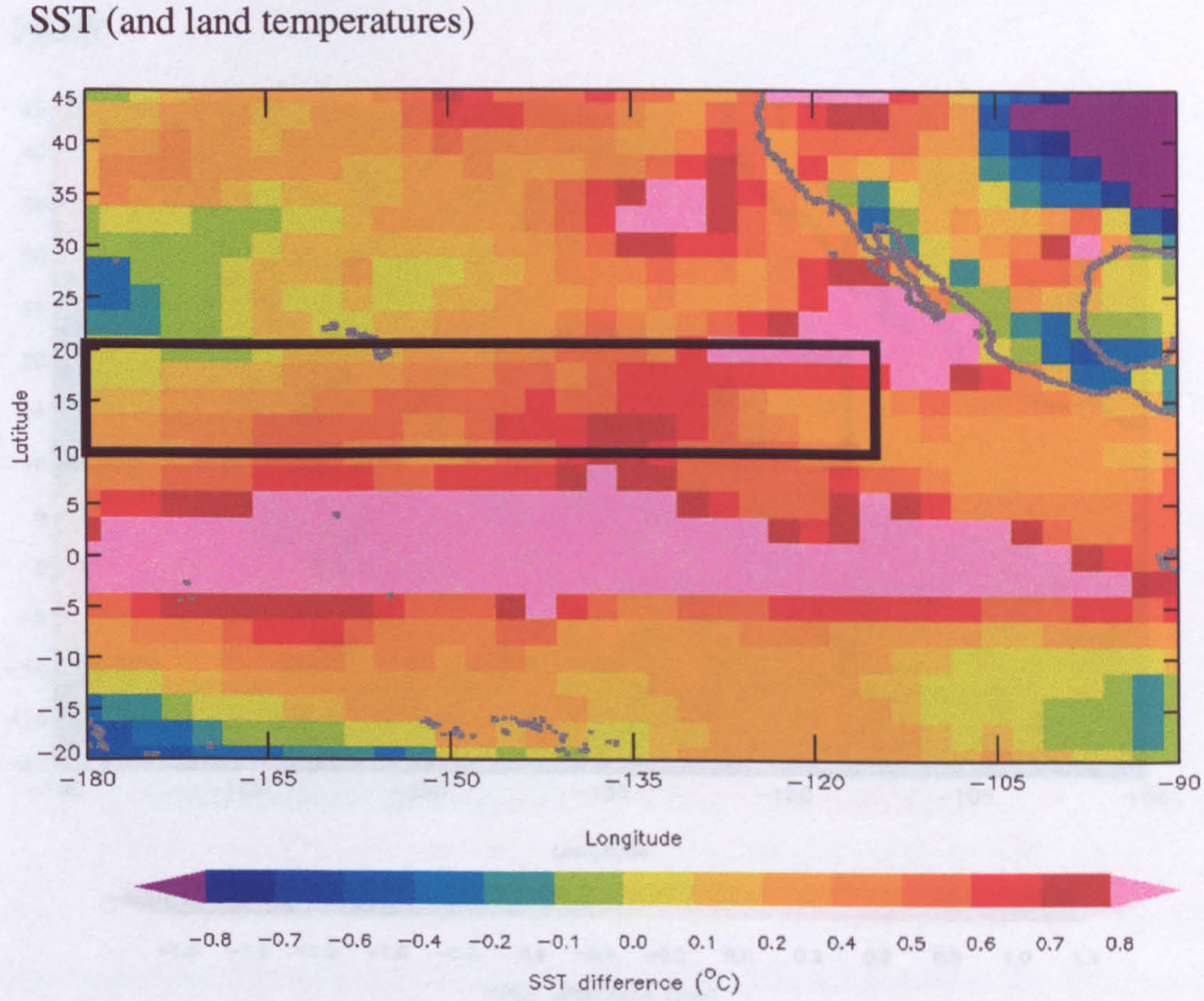


Figure 4.8 RH and SST (and land temperatures) in the five most active (1982, 1994, 1990, 1992, 1997) hurricane years (a and c) and the five most inactive (1973, 1980, 1983, 1995, 1996) hurricane years (b and d).

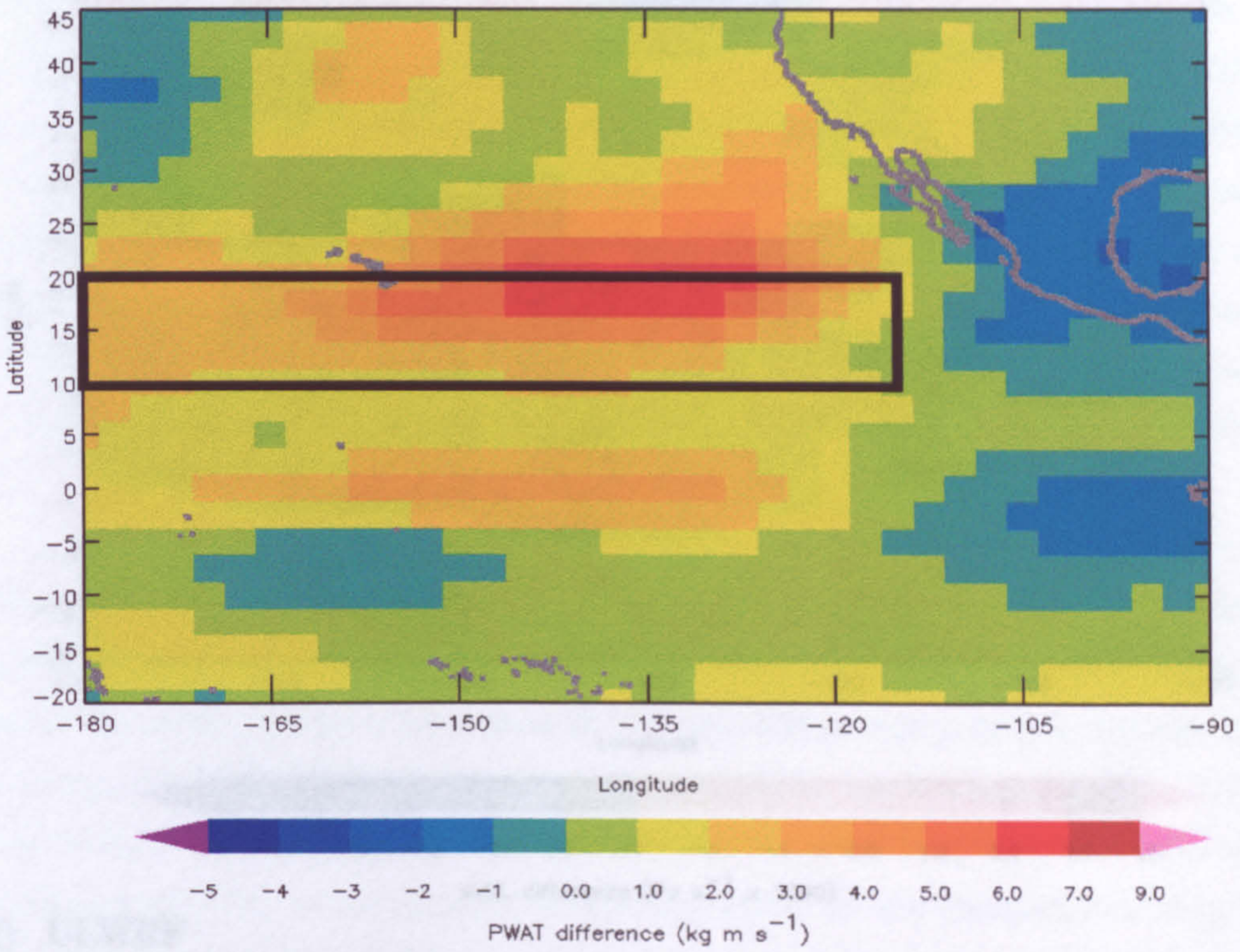
a) RH



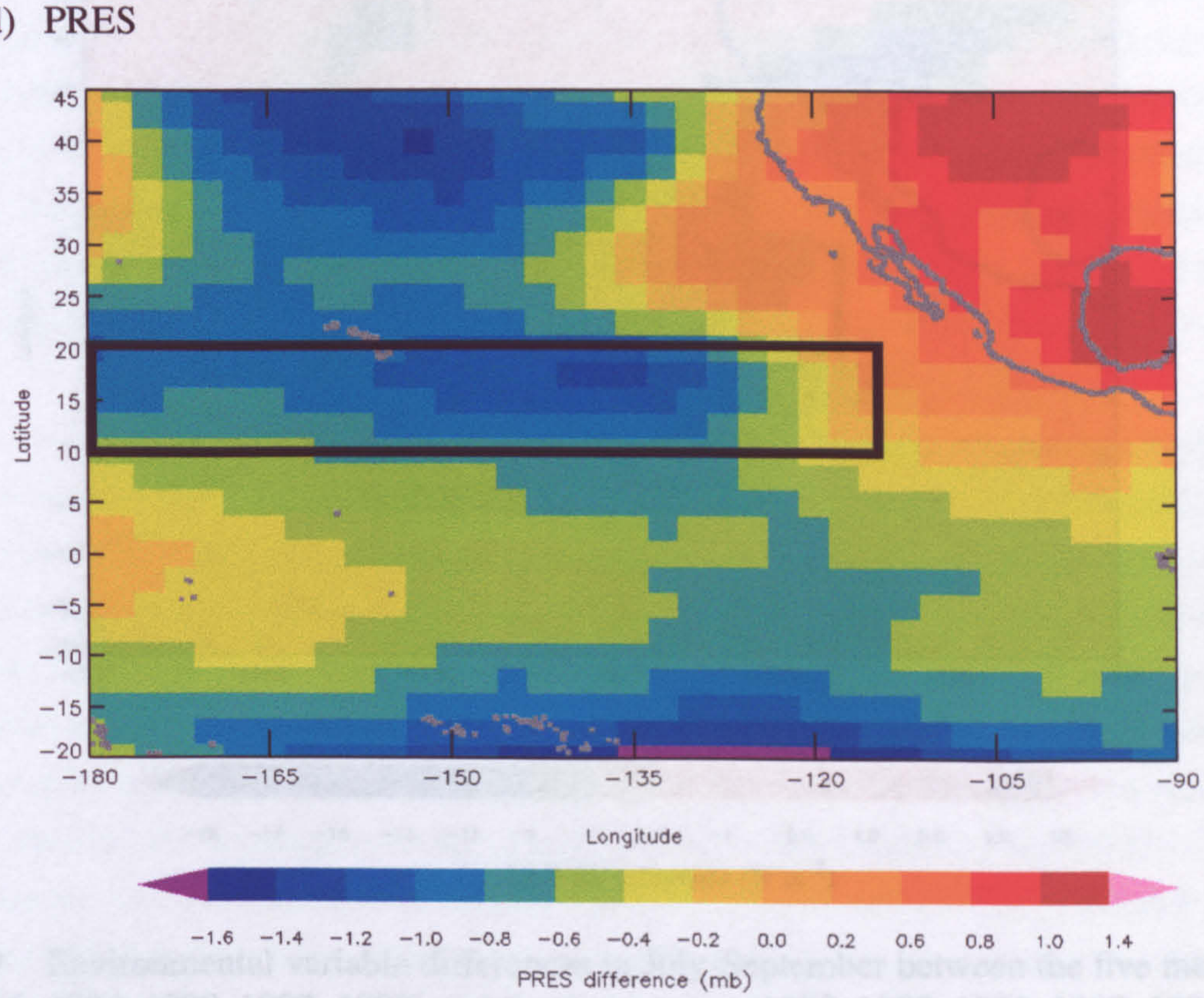
b) SST (and land temperatures)



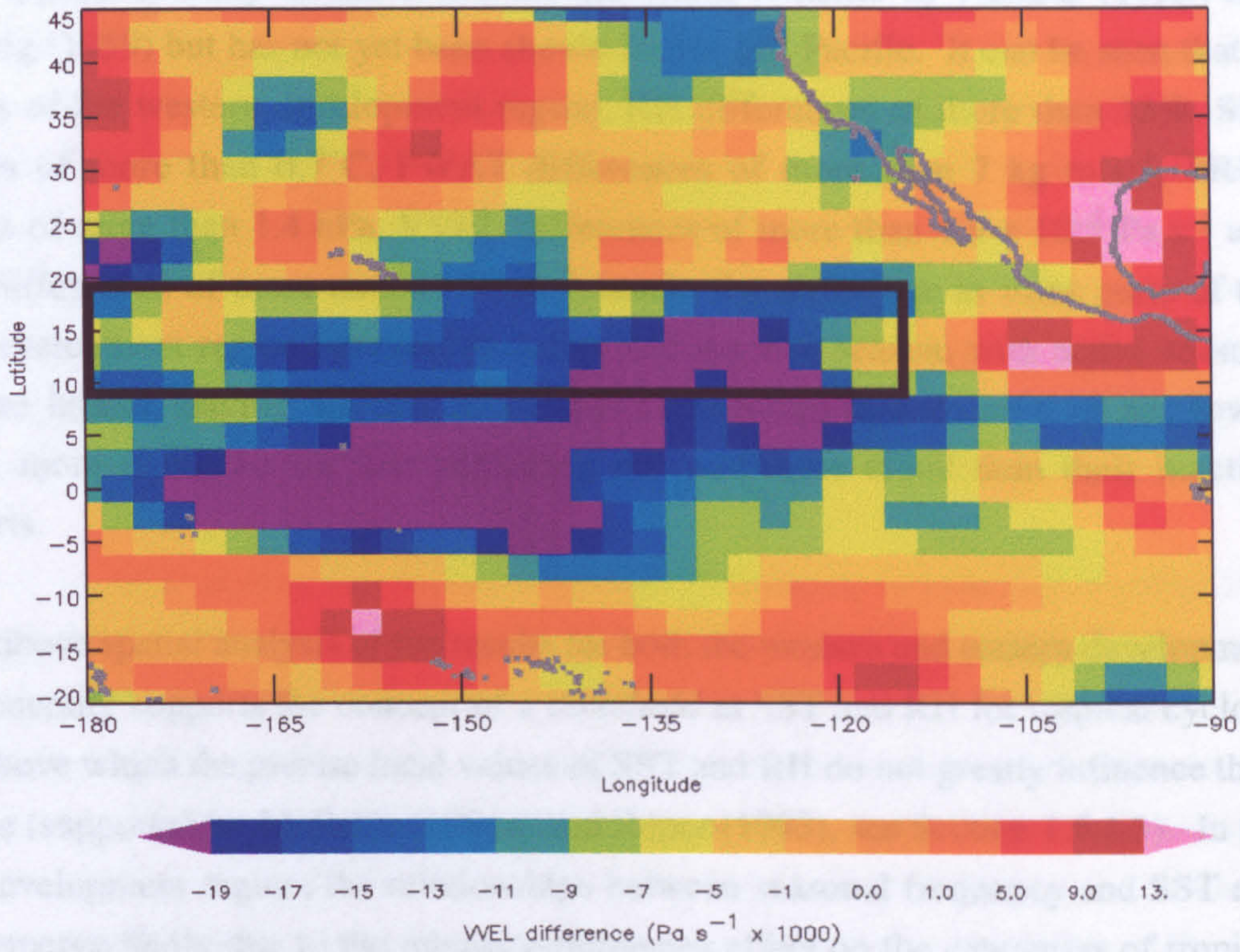
c) PWAT


45
40
35
30
25
20
15
10
5
0
−5
−10
−15
−20
Latitude
−180
−165
−150
−135
−120
−105
−90
Longitude
−5
−4
−3
−2
−1
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
9.0
PWAT difference (kg m s^{-1})

d) PRES


45
40
35
30
25
20
15
10
5
0
−5
−10
−15
−20
Latitude
−180
−165
−150
−135
−120
−105
−90
Longitude
−1.6
−1.4
−1.2
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.6
0.8
1.0
1.4
PRES difference (mb)

e) VVEL



f) ULWRF

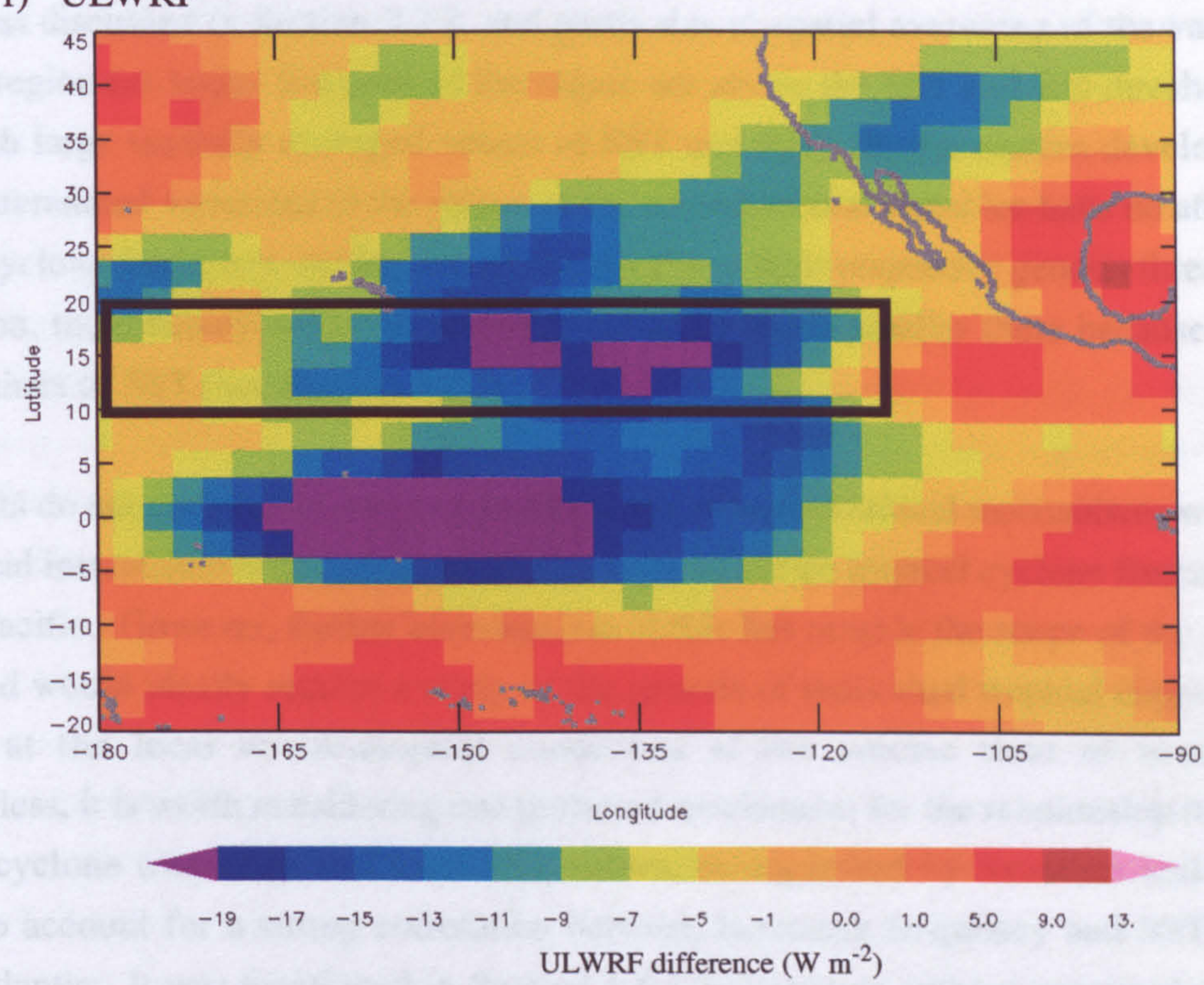


Figure 4.9 Environmental variable differences in July-September between the five most active (1982, 1994, 1990, 1992, 1997) and five least active (1973, 1980, 1983, 1995, 1996) hurricane years in the western development region. Western development region shown as black box. (Note: in figure 4.9d 1mb = 1 hPa).

has been applied as early as the 1950s for the North Atlantic by Namias (1955) and Ballenzweig (1959) but has not yet been shown for the NE Pacific. It can be seen that in some parts of the western development region, RH differences of more than 13%, SST differences of more than 0.7°C, PWAT differences of more than 7 kg m s^{-1}, PRES differences of more than 1.4 hPa, VVEL differences of more than 1.9 x 10^{-4} Pa s^{-1} and ULWRF differences of more than 19 W m^{-2}, marks the difference in some parts of the western development region between an active and inactive season, with active seasons being more humid, having warmer SSTs and more water in a column of air, lower pressures, more rising air (or less subsiding air) and more cloud than their inactive counterparts.

Thus, the above spatial analysis of the results for both the western and eastern development regions generally supports the concept of a *threshold* in SST and RH for tropical cyclone genesis, above which the precise local values of SST and RH do not greatly influence their occurrence (supported by McBride (1981a) and Raper (1993), see Section 1.5.1.3). In the western development region, the relationships between seasonal frequency and SST and RH then emerge partly due to the intensity-frequency effect on the categories of tropical cyclone, as discussed in Section 3.2.3, and partly due to spatial averaging of the variables over the region (as larger fractions of the region are above the SST and RH thresholds in years with large spatially averaged values of SST and RH). In the eastern development region, interannual variations in the values of the environmental variables have no affect on tropical cyclone frequency, as they are all always above their respective genesis thresholds. In addition, the intensity-frequency effect is probably much smaller there because of the higher values of SST (see Section 3.2.3).

The results do not completely rule out the existence of any additional mechanisms whereby actual local instantaneous environmental *values* can influence tropical cyclone frequency in the NE Pacific. However, further investigation of this lies outside the scope of the current study, and would ideally require a study of the genesis of individual tropical depressions, looking at the local environmental conditions at the precise time of formation. Nevertheless, it is worth considering one proposed mechanism for the relationship between tropical cyclone frequency and local SST values, as suggested by Saunders and Harris (1997) to account for a strong correlation between hurricane frequency and SST in the North Atlantic. It was mentioned in Section 1.5.1.3 that those authors proposed that the relationship between increasing SSTs and increasing hurricane frequency could be due to increased SST helping the storms to penetrate through the trade inversion. If this is the main mechanism in the NE Pacific, then one would expect a relationship between SSTs and

frequency, but not between RH and frequency (since RH at 500 hPa will always remain low in the presence of a trade wind inversion, as it is well above the inversion, and so SST should not be strongly correlated with RH). However, Tables 4.2 - 4.8 show that there is a strong relationship between RH and tropical cyclone frequency as well as SST and tropical cyclone frequency. (In fact, the RH relationship is the more significant for tropical storms and hurricanes based on the deviance tests.) This proposed "inversion effect" cannot, therefore, be the main factor in explaining the correlations observed in Tables 4.2 - 4.8 for the western development region of the NE Pacific, although it may still be a valid mechanism for the North Atlantic basin.

Despite this possible difference between the North Atlantic and the NE Pacific, it is interesting to note that the situation in the eastern development region has similarities with the Atlantic Gulf area, and the situation in the western development region has similarities with the North Atlantic MDR. In the eastern development region it has been shown that locally there is a lack of significant relationships between the tropical cyclones that form there and the seasonal environmental variables. The longitude plots (Figure 4.6) indicate that this is due to the environmental variables being conducive there every year. Likewise in the Gulf, the environmental variables are always conducive to tropical cyclone formation (e.g. the average value of SST in the August to October season is 28.5°C). On the other hand, conditions in the western development region are more like the North Atlantic MDR (e.g. the average value of SST in the August to October season is 27.3°C) where it has been shown that the variation of some variables are related to the variations in North Atlantic tropical cyclone frequency (see Sections 1.5.1.2 and 1.5.1.3). In the North Atlantic MDR, therefore, the variables are not always conducive from year-to-year. Furthermore, the results of the ULWRF in the western development region agree with results of Tulich and Kimberlain (1999) discussed in Section 1.5.1.3, who show that more tropical cyclones occur in the North Atlantic when there is more deep convective cloud activity.

In the eastern development region it has been shown above that no local thermodynamic environmental variable from the NCEP/NCAR reanalysis dataset was significantly related to the seasonal variation in the frequency of tropical cyclones. However, relationships between OLR and the eastern development region tropical cyclone indices were sought and significant results were found at least to the 5% level with the intense hurricane and tropical storm categories using the *t*-statistic analysis (*t*-statistics were -2.37 and -2.48 respectively), but not the hurricane category (with a *t*-statistic of -1.81). It is seen that no relationships are evident when examining ULWRF vs. tropical cyclones in the eastern

development region. Again, this supports the analysis in Section 4.1, which concludes that the ULWRF values may be unreliable.

In the eastern development region an examination of the five most and least active extreme years (being approximately a quarter of the OLR dataset) reveals that there is a significant difference at the 5% level between extreme years with the tropical storm category (p value = 0.035), with a greater frequency of tropical storms when the OLR is lower. This relationship between extremes is true of the intense hurricanes but only to the 10% level and not significant to the 10% level for hurricanes.

On the other hand, an analysis of the differences of OLR between extreme tropical cyclone years (rather than extreme OLR years as given above) indicates large differences between the extremes of these values for the hurricane and tropical storm stage of a tropical cyclone but not for the intense hurricane stage (see Figure 4.10). This work again supports Tulich and Kimberlain's (1999) results (see Section 1.5.1.3), but this time for the eastern development region, of deep convective cloud activity being related to seasonal variations in the frequency of tropical cyclones. Their work has not been previously corroborated. This is the only significant local result which has emerged in this study for the eastern development region and thus is suggested to be the dominant factor causing variations in tropical cyclone formation here. Note that low values of OLR are associated with a large number of tropical disturbances. This supports the idea (see Section 4.4) that the variability in the triggering disturbances is the main driving factor for tropical cyclone variability in the eastern development region.

To summarise, RH has been shown in this study to be the dominant factor affecting variations in hurricane formation in the western development region of the NE Pacific. This is borne out by the extreme year analysis (Section 4.2), t-statistic analysis (Section 4.3) and deviance tests (Section 4.4). Section 1.5.1.3 describes how RH affects tropical cyclones, although it has not been previously shown to be the *dominant* control on hurricane formation in any basin. Additionally, Emanuel (1997, p. 62) noted that, "a necessary and perhaps sufficient condition for genesis is the establishment of a pillar of very humid air". This statement is based on numerical simulation models and a series of field experiments performed in the early 1990s (e.g. Bister and Emanuel, 1997). The current study would agree that RH is a necessary condition and provides statistical evidence for such a statement. The other thermodynamic factors are intimately related in providing this humid pillar of air, for example SST reaching a certain threshold to trigger instability in the air and allow the warm air to rise (positive VVEL), which in turn allows middle

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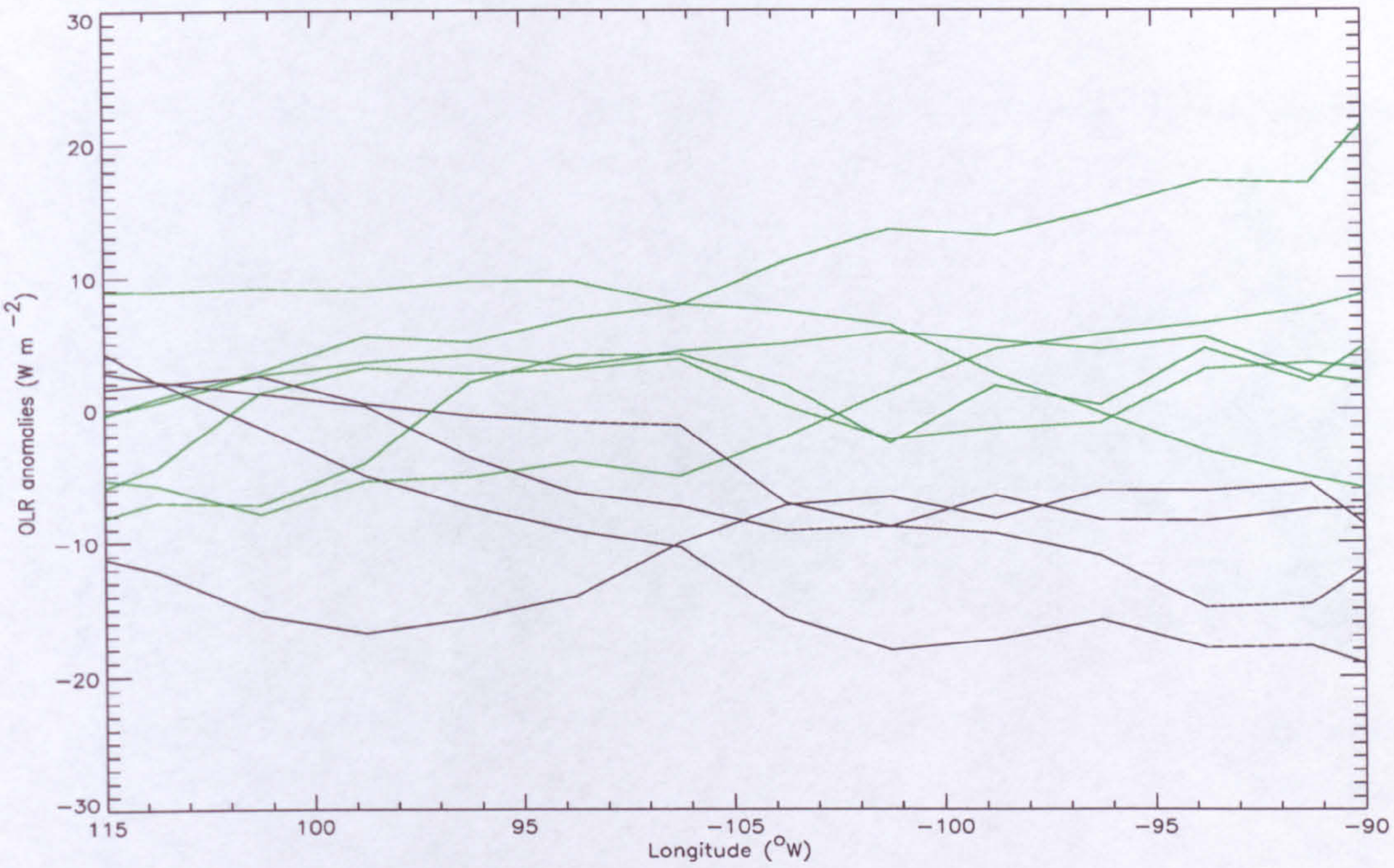
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OLR anomalies (W m $^{-2}$)
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Longitude (^{o}W)

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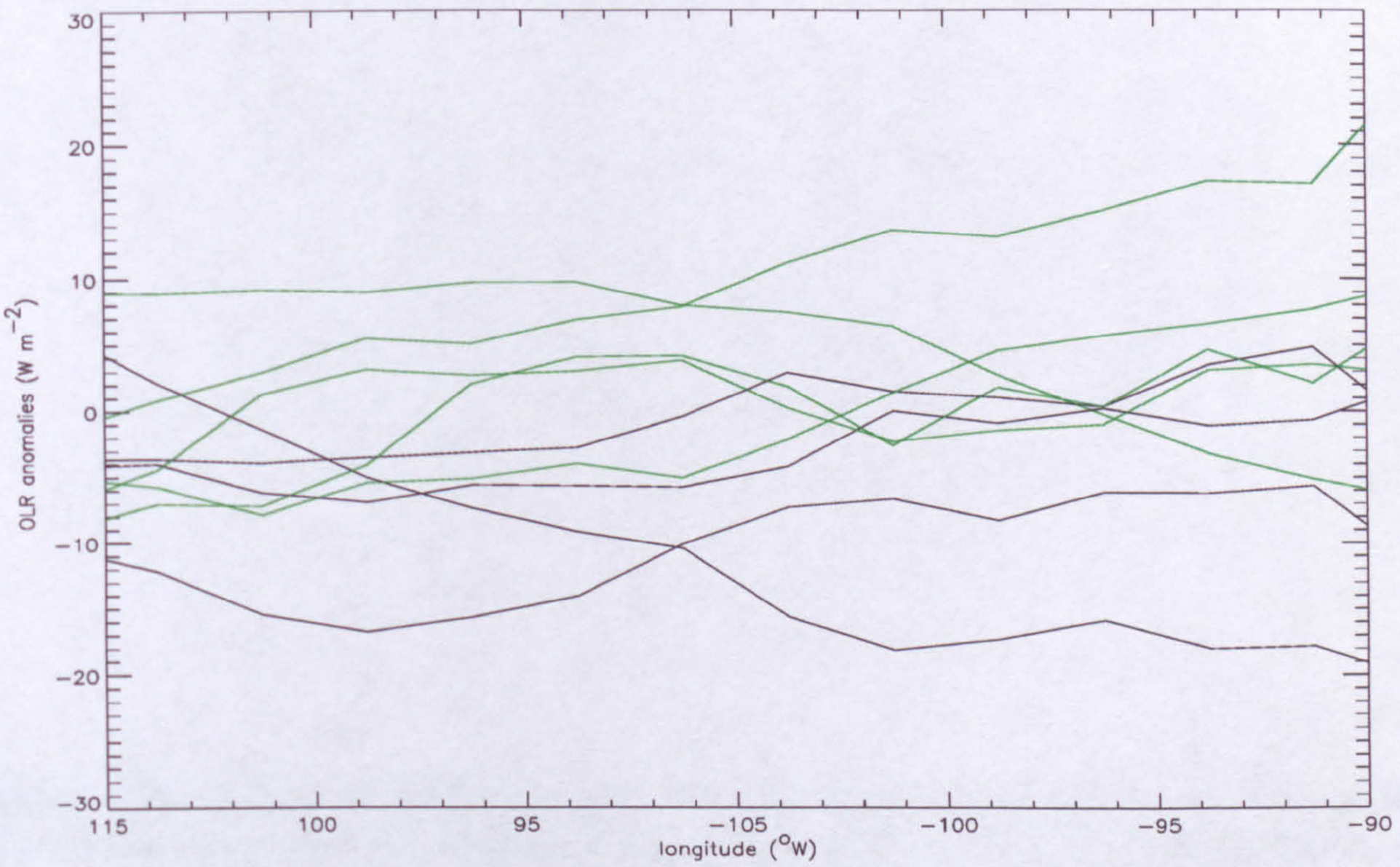
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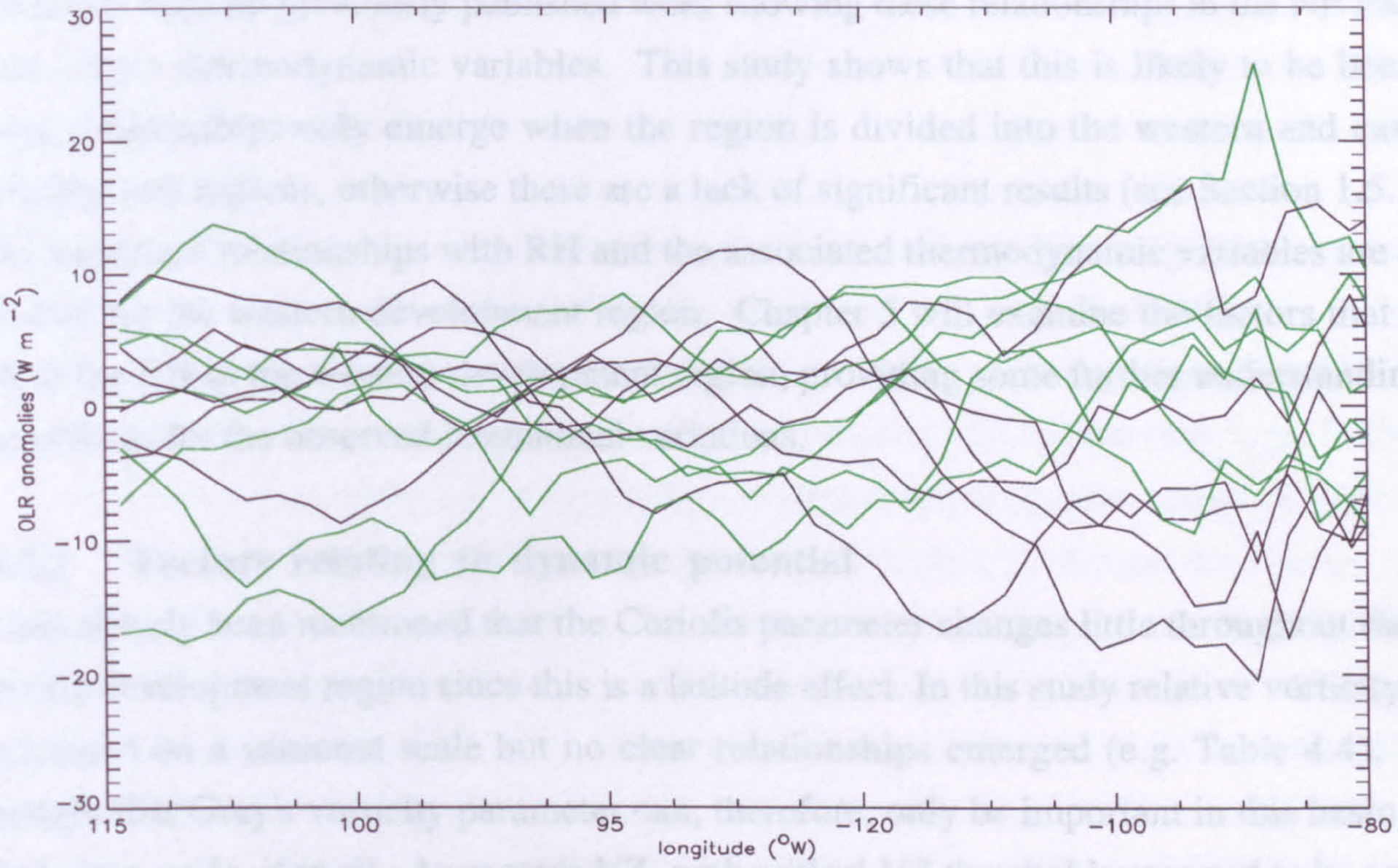

Figure 4.10 Plot of the OLR averaged over July-September and latitudes 10°N to 20°N for each longitude, for eastern development region a) five most active and least active hurricanes years, b) five most active and least active tropical storm years, and c) five most active and least active intense hurricanes years. Active years are shown in black, inactive years in green.

tropospheric RH values to be high. The VVEL can also operate to reduce the RH through air subsiding from above.

There has been no previously published work showing these relationships in the NE Pacific with Gray's thermodynamic variables. This study shows that this is likely to be because these relationships only emerge when the region is divided into the western and eastern development regions, otherwise there are a lack of significant results (see Section 1.5.1.3). The important relationships with RH and the associated thermodynamic variables are only evident for the western development region. Chapter 5 will examine the factors that may affect the RH in the western development region, providing some further understanding of the reasons for the observed interannual variations.

4.7.2 Factors relating to dynamic potential

It has already been mentioned that the Coriolis parameter changes little throughout the NE Pacific development region since this is a latitude effect. In this study relative vorticity was examined on a seasonal scale but no clear relationships emerged (e.g. Table 4.4). It is thought that Gray's vorticity parameter can, therefore, only be important in this basin on a short time-scale, if at all. As regards VZ, with critical VZ thresholds reported to be around 7.5 m s^{-1} to 12.5 m s^{-1} (Zehr, 1992; DeMaria et al., 1993), an examination of the climatology of VZ between 1972-1997 (Figure 4.7) clearly shows that there is relatively low VZ (around 8 to 13 m s^{-1}) from the west coast of North America to about 140°W, and then there is a sharp increase in VZ peaking at about 160°W to around 15 to 20 m s^{-1}. Whereas an examination of the individual years for the thermodynamic variables shows a distinct difference between the values of the variable in the eastern development region and the western development region, and hence can explain variability of hurricanes in the western development region, the same is not true when examining VZ. In addition, there is not such a clear difference between the VZ of western development region active and inactive years as there was for the thermodynamic variables. It can be seen that VZ in the western development where most of the hurricanes form (up to about 143°W) is fairly low in all years, so this suggests that low VZ is important for their formation but since VZ values are fairly low in all years, this does not allow variations in *hurricane* numbers. Thus, VZ is not an important factor for explaining variations in seasonal hurricane frequency on an interannual time-scale. On the other hand, Figure 3.12 suggests that wind shear may be important to explain decadal scale variability.

Nevertheless, Tables 4.2 - 4.8 show that, despite its generally low values, variations in VZ are important for affecting tropical cyclones at the *tropical storm* stage but not subsequently

to hurricane or intense hurricane stage. This is consistent with the findings of Emanuel (1999), as noted in Section 1.5.1.2, whose simulations show that factors such as VZ appear to be most strongly influential during the formative stages when the storms are comparatively weak.

4.7.3 Global-scale factors

4.7.3.1 ENSO

Landsea and Gray (1989) carried out an important preliminary study focusing on the seasonal time-scale in the NE Pacific, though it was never published in the refereed literature. They examined the relationships between tropical cyclone indices with ENSO for the whole basin. However, contrary to the conclusions of Landsea and Gray (1989, p. 324) who noted that, "there is a strong indication that tropical cyclone activity is increased [in El Niño years] - especially for the strongest storms", in the current study, when examining the whole region, as they did, there is in fact only a weak or insignificant correlation between the ENSO indices and the tropical cyclone indices in this study. The exception to this was the SOI index where extreme environmental variable year analyses results (Table 4.2) were significant with the intense hurricane and tropical storm categories to the 5% level. This is consistent with the findings of Irwin III and Davis (1999) and Murillo (1999, personal communication) who concluded that the total number of storms in the NE Pacific does not change with the phase of ENSO.

On the other hand, when sub-dividing the regions, as has been seen earlier, important results emerge. With some ENSO indices (KW, Niño1, Niño2 and Niño3), an examination of the strongest and weakest ENSO events (Table 4.2) does not give a significant relationship at the 5% level with tropical cyclone numbers in the western development region. However, alternative ENSO indices (SOI and Niño4) do show significant relationships with the tropical cyclones (SOI with all categories above the 5% level; Niño4, at the 5% level for the intense hurricane and tropical storm categories and at the 1% level for the hurricane category). When all years are considered with the *t*-statistic analysis (Table 4.4), a significant relationship at the 5% level is evident with the hurricane category for the SOI, Niño4 and KW indices, indicating that more hurricanes occur in the western development region in an El Niño phase, and a significant relationship at the 5% level is found in the tropical storm category with the SOI index. The deviance analysis of all years (see Table 4.5) also indicates the same relationships but in addition there is a significant relationship at least to the 5% level with Niño2 for the hurricane category, KW and Niño4 for the tropical storm category and SOI and the Niño4 index for the intense hurricane category. Certainly for all tables, the links between the tropical cyclones and the

SOI and Niño4 indices appear stronger than for the other ENSO indices. The reason for this is explored below.

Chu and Wang (1997) suggested that the relationship between ENSO and frequency of tropical cyclones in the central Pacific is related to the location of the monsoon trough. In El Niño years, the warm pool of water and the low level westerlies shift from near Indonesia towards the central Pacific and, with this, the monsoon trough also shifts eastward. Section 1.5.1.2 describes how a monsoon trough affects tropical cyclones. Thus, in a warm ENSO, the presence of a monsoon trough in the central Pacific encourages greater cyclonic horizontal shear and vorticity as the equatorial easterlies shear with the westerlies on the poleward side of the monsoon trough. In the current study, however, for the western development region there was no significant relationship on a seasonal time-scale with relative vorticity, thus Chu and Wang's (1997) hypothesis is not supported. Chu and Clark (1999) argue that due to circulation patterns changing during El Niños, the strength of the climatological vertical VZ is eroded in the central Pacific and this may subsequently affect tropical cyclones. However, for the western development region of the NE Pacific which includes the central Pacific, there is no evidence that vertical VZ is significantly reduced in warm ENSO's when average seasonal values of the region are considered (the correlation coefficient between western development region vertical VZ and Niño4 is -0.07).

Instead of the link between ENSO and tropical cyclone frequency being due to the dynamic variables, as suggested by Chu and Wang (1997) and Chu and Clark (1999), it is suggested in this study that the link between ENSO and tropical cyclone formation in the western development region is predominantly through its link with the thermodynamic variables, particularly RH, with a warm ENSO phase causing higher values of RH in the western development region, which in turn results in more tropical cyclones through the mechanisms already discussed. This link between ENSO and RH is explained in more detail in Chapter 5.

Contrary to the western development region of the NE Pacific, the relationships with ENSO are of low significance when examining the eastern development region (see Tables 4.2 - 4.8). However, some interesting results emerge. Table 4.4 shows that the sign of the relationship of ENSO with the eastern development region tropical cyclones is predominantly negative, indicating that more hurricanes occur during a La Niña rather than an El Niño phase (the SOI naturally shows a positive relationship for more hurricanes occurring in La Niña). This is also true of the extreme year analysis, e.g. for the Niño4

index, where more tropical cyclones occur in the six coldest ENSO years than in the six warmest ENSO years (a total of 34 in the former compared to 25 in the latter). This is contrary to the positive relationships for the ENSO indices (SOI gives a negative relationship here) and tropical cyclone frequency in the western development region, and of the previous findings in the literature that concluded that the affect of El Niño on NE Pacific tropical cyclones is to increase them or provide no change. However, this result agrees with the study of Murillo (1999, personal communication, see Section 1.5.2.2) who noted that there was a stronger relationship between NE Pacific landfalling tropical cyclones and the La Niña phase rather than the El Niño phase, although she did not link this to the fact that the frequency of all storms (not just landfalling) appears to be greater in a La Niña phase (probably because she did not separate the region into two development regions). Considering that the Niño4 region is nearer to the western development region (see Section 2.1.2), it may be expected that the relationship is better with western development region hurricanes than eastern development region hurricanes. However, an examination of the Niño1 and Niño2 regions, which are nearer to the eastern development region, also indicates a poor relationship in the east.

Therefore, the effect of El Niño on tropical cyclones in the eastern development region is opposite to that in the western development region (i.e. to increase tropical cyclone numbers) and similar to that in the North Atlantic (i.e. to decrease tropical cyclone numbers). However, the mechanisms by which ENSO affects the North Atlantic and the eastern development region are thought to be different, as there is no relationship between eastern development region tropical cyclone frequency and VZ. The actual mechanism for the eastern development region, however, is unclear.

4.7.3.2 QBO

Landsea and Gray (1989) noted that there is a slight tendency for the QBO to modulate the numbers of the most intense tropical cyclones in the NE Pacific basin, with greater activity occurring in the westerly phase. However, Gray (1993) later noted that there is no change in the frequency of hurricanes in the NE Pacific basin between QBO phases.

In this study, the relationship between the QBO, as with other variables, and tropical cyclones in the eastern development region of the NE Pacific was poor and insignificant. However, unlike some of the other factors examined in this study, there was also a poor relationship between QBO and western tropical cyclone numbers (see Tables 4.2 - 4.8). Ramage (1995, p. 63) would imply such a result, where he stated firmly that, "at most the QBO affects the tropospheric circulations only marginally; it affects weather not at all".

Landsea and Gray (1989) and Knaff (1993) however would disagree with this statement, as they showed that the QBO seems to have an effect in the North Atlantic basin.

Section 1.5.2.1 discusses the relationship between QBO and variations in tropical cyclone frequency, where it was discussed that wind shear between the tropical stratosphere and tropical upper troposphere may be the cause of the variations. However, since there is increased wind shear in the NE Pacific in the east QBO phase, as well as in the North Atlantic, and since the North Atlantic shows significant variations in tropical cyclone frequency between phases and the NE Pacific does not (as shown in this study), this suggests that either the wind shear mechanism is only important for some basins, with some basins being more sensitive to this than others, or the QBO has some other effects which have not yet been examined, which may account for variations in one basin and not another.

4.7.3.3 MJO

The deviance test (Table 4.4) and *t*-test on the ratio b/s_e (Table 4.3) show that the MJO variable used in this study, which shows the variance in the original MJO index (see Section 2.1.2) of Maloney and Hartmann (1998), is highly related to the frequency of western development region hurricanes and tropical storms. For the extreme year analysis (Table 4.2), the MJO is related to all categories of tropical cyclone at the 1% significance level. On the other hand, there is no relationship between the MJO and the frequency of eastern development region tropical cyclones. On the intraseasonal scale, some authors (e.g. Molinari et al., 2000) have speculated that there are important interactions between the eastward moving MJO wave and westward moving easterly waves. However this study, using a seasonal time-scale, does not, and cannot, attempt to say whether the east or west MJO phase produces more tropical cyclones, rather it does say that when there is a large amount of variance, more tropical cyclones occur in the western development region, compared to more moderate phases of the MJO. The fact that there is a relationship in the western development region, which is further from the mountains, and there is no eastern development region relationships, implies that the mountains are not important in determining this relationship on a seasonal scale. Section 1.5.4 notes that higher 500 hPa values of RH are associated with active MJOs. Since RH has been shown to be the dominant control on hurricanes in the western development region, it is possible then that the MJO is acting through the RH to affect variations in hurricane frequency. However, Chapter 5 will show that the MJO does not have a *dominant* influence on the interannual variations of RH in the western development region.

4.7.4 Other non-local influences on tropical cyclone numbers

Although it is likely that tropical cyclones will be most affected by local conditions, possible non-local influences have also been examined, as an association between a non-local variable and a tropical cyclone index may exist through links involving the atmospheric or oceanic circulation (teleconnections). To identify non-local links, spatial correlation plots have been used (see Section 2.4 for a discussion of the limitations of these plots). The most significant non-local relationships are shown below with the aid of a plot.

4.7.4.1 Non-local influences on western development region hurricanes

Figure 4.11a shows an area centred around Indonesia giving a non-local negative relationship between RH and western development region hurricanes significant to the 1% level. There is also a positive local relationship seen on the plot, as already discussed, and this turns out to be strongly related to ENSO (see Chapter 5). It is known that ENSO produces opposite effects in the eastern and central Pacific than in the western Pacific. It therefore seems plausible that the non-local relationship obtained is also an ENSO effect. Figure 4.12a examines this relationship just for the strongest (six warmest and coldest) ENSO (Niño4) years. The six warmest ENSO years are 1982, 1987, 1991, 1992, 1994 and 1997. The six coldest ENSO years are 1973, 1974, 1975, 1976, 1988 and 1989. It can be seen that the large area of significant association remains. However, when one examines the non-strong ENSO years (Figure 4.12b) the relationship does not hold. Therefore, it is concluded that the non-local relationship in Figure 4.11 is largely an ENSO-related phenomenon. (It can also be seen that the local relationship is also largely affected by ENSO, although it remains the largest significant area on the plot, even in non-strong ENSO years. This is discussed further in Chapter 5.)

Precipitable water (Figure 4.11b), VVEL (Figure 4.11c) and ULWRF (Figure 4.11d) also give a region of significant non-local relationship to the 1% significance level with western development region hurricanes which is in a similar position, near Indonesia. SSTs (Figure 4.11e), U wind at 850 hPa (Figure 4.11f) and VZ (Figure 4.11g) also give a non-local relationship to the 1% level in this general area but shifted to the east. The relationship with PRES also shows a significant area but much further to the west of Australia and in the Indian Ocean, over Africa and parts of Europe (Figure 4.11h). Figures 4.13 and 4.14 show that this region of significant relationship with PRES is influenced particularly by strong ENSO and strong MJO events but the relationship is absent in the less extreme years of these phenomena.

Some other areas of significance, at least to the 5% level, that may be important, albeit

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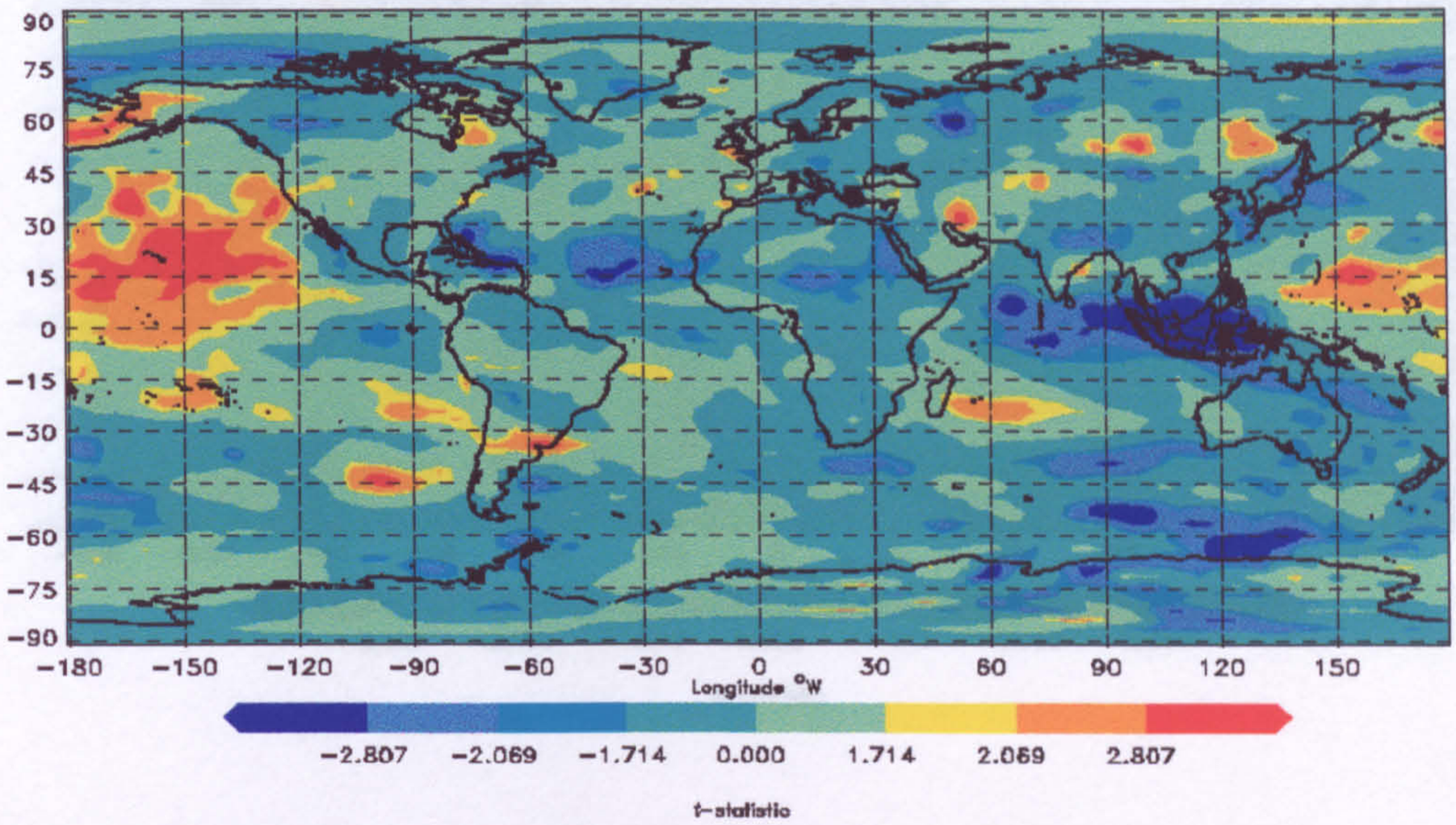
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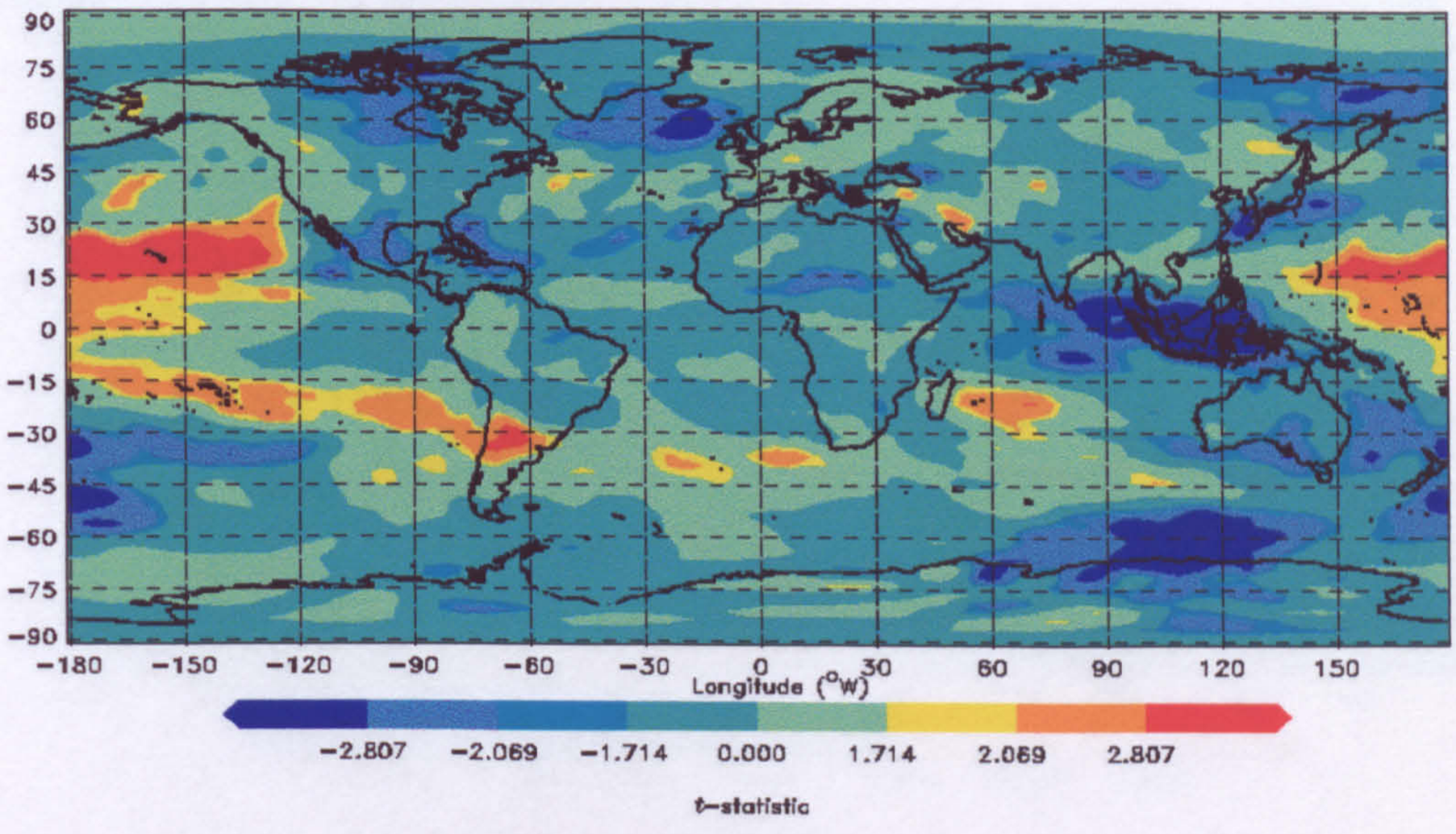
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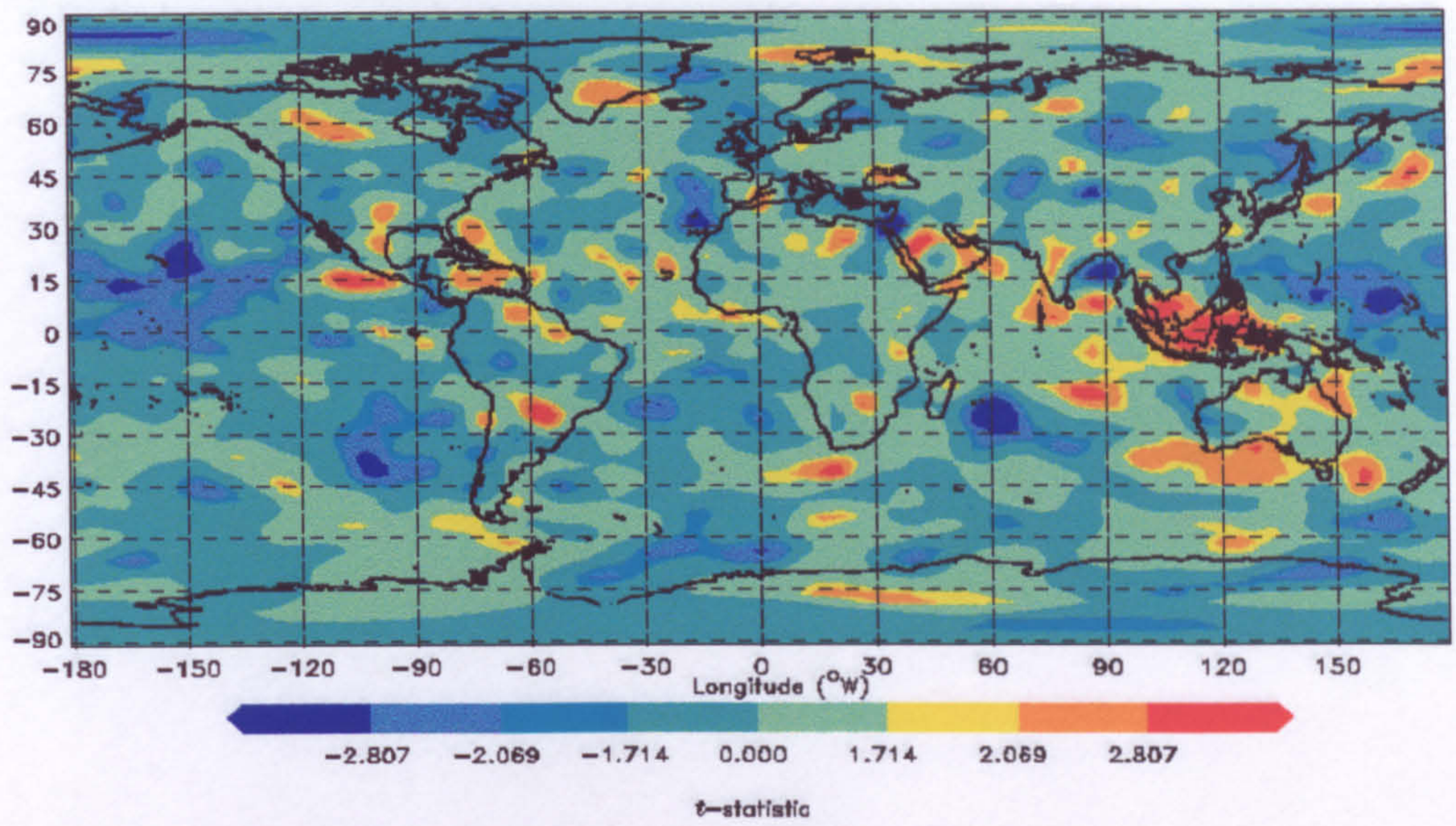
c) VVEL



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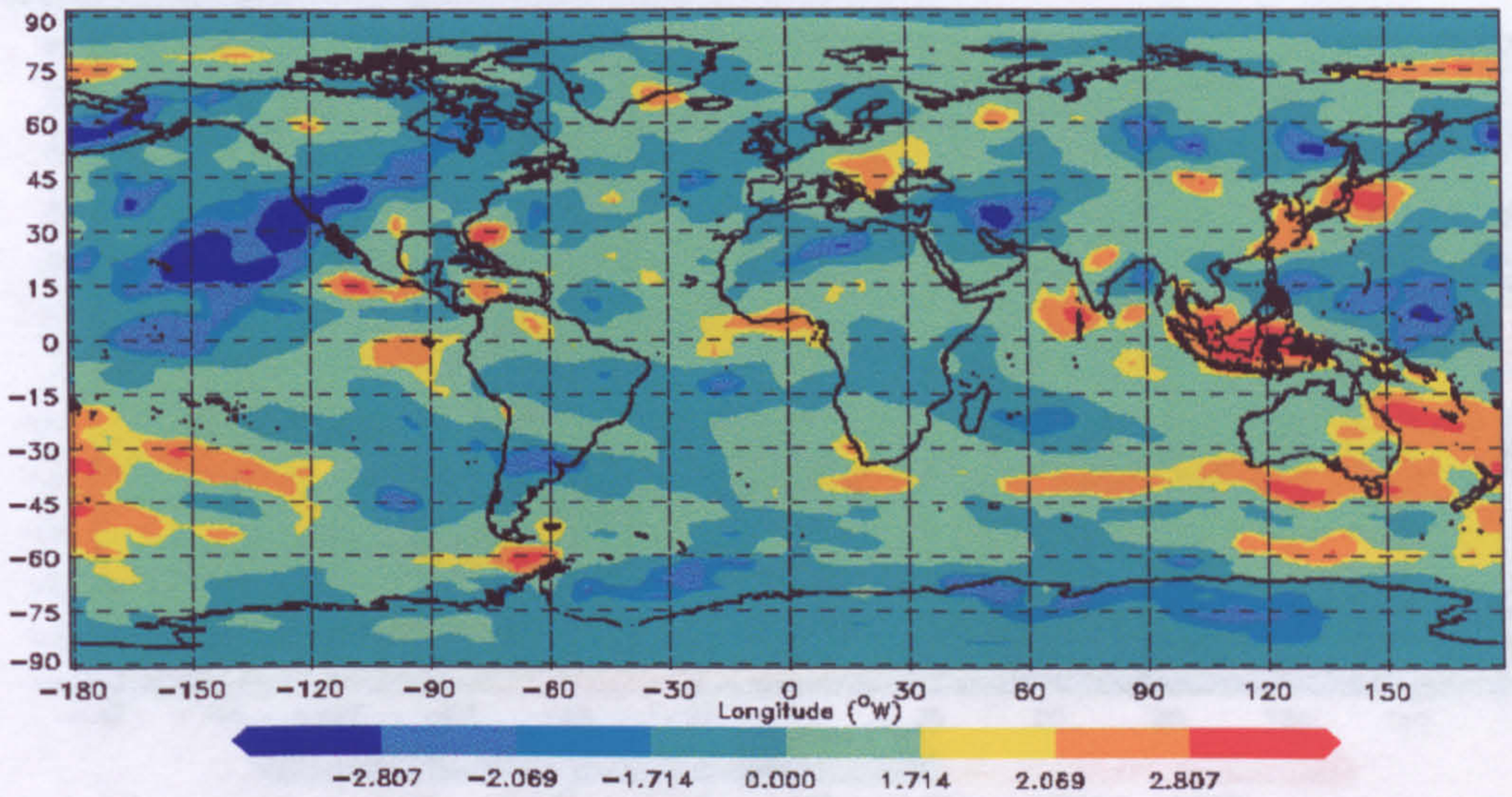
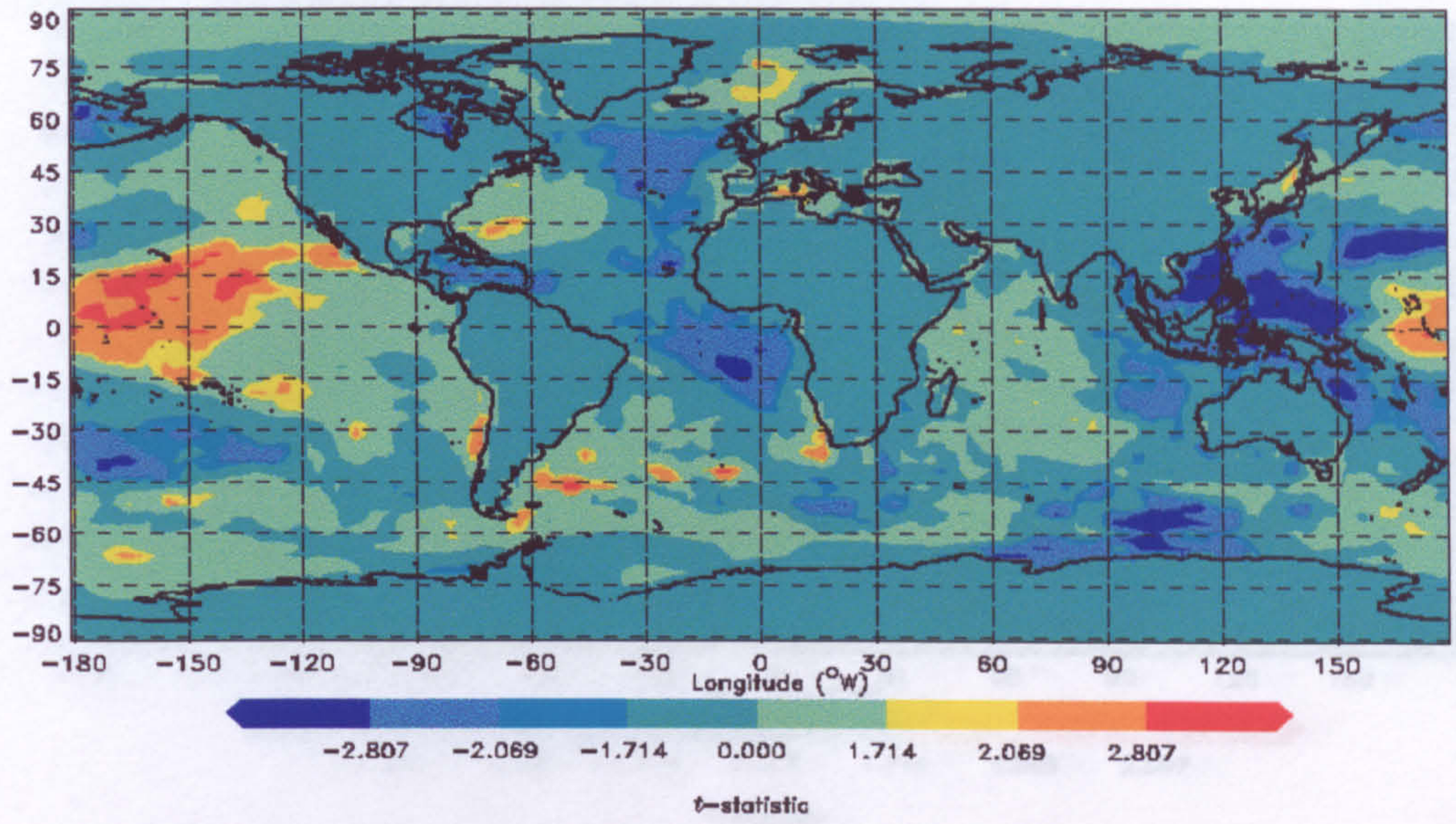
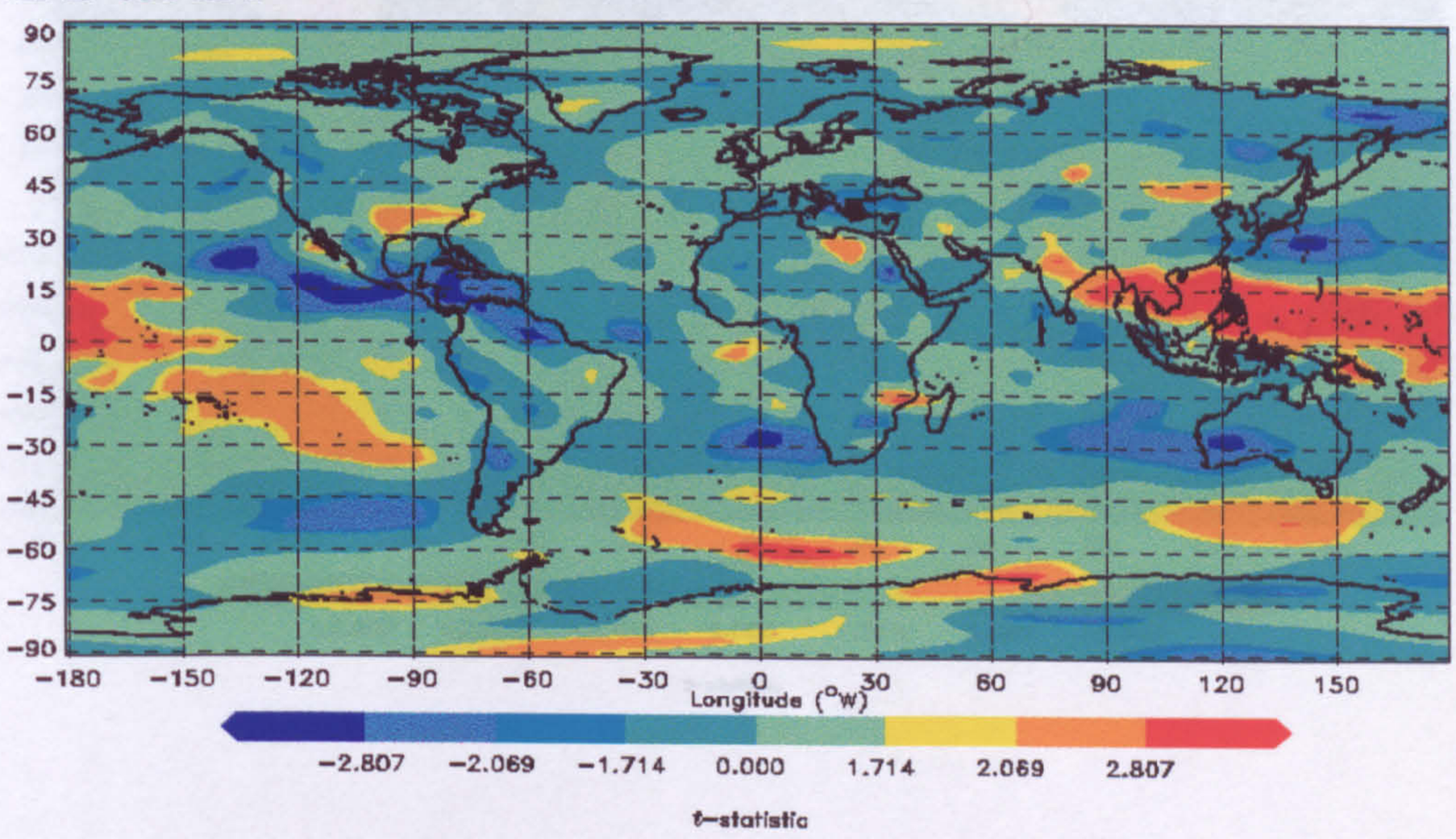


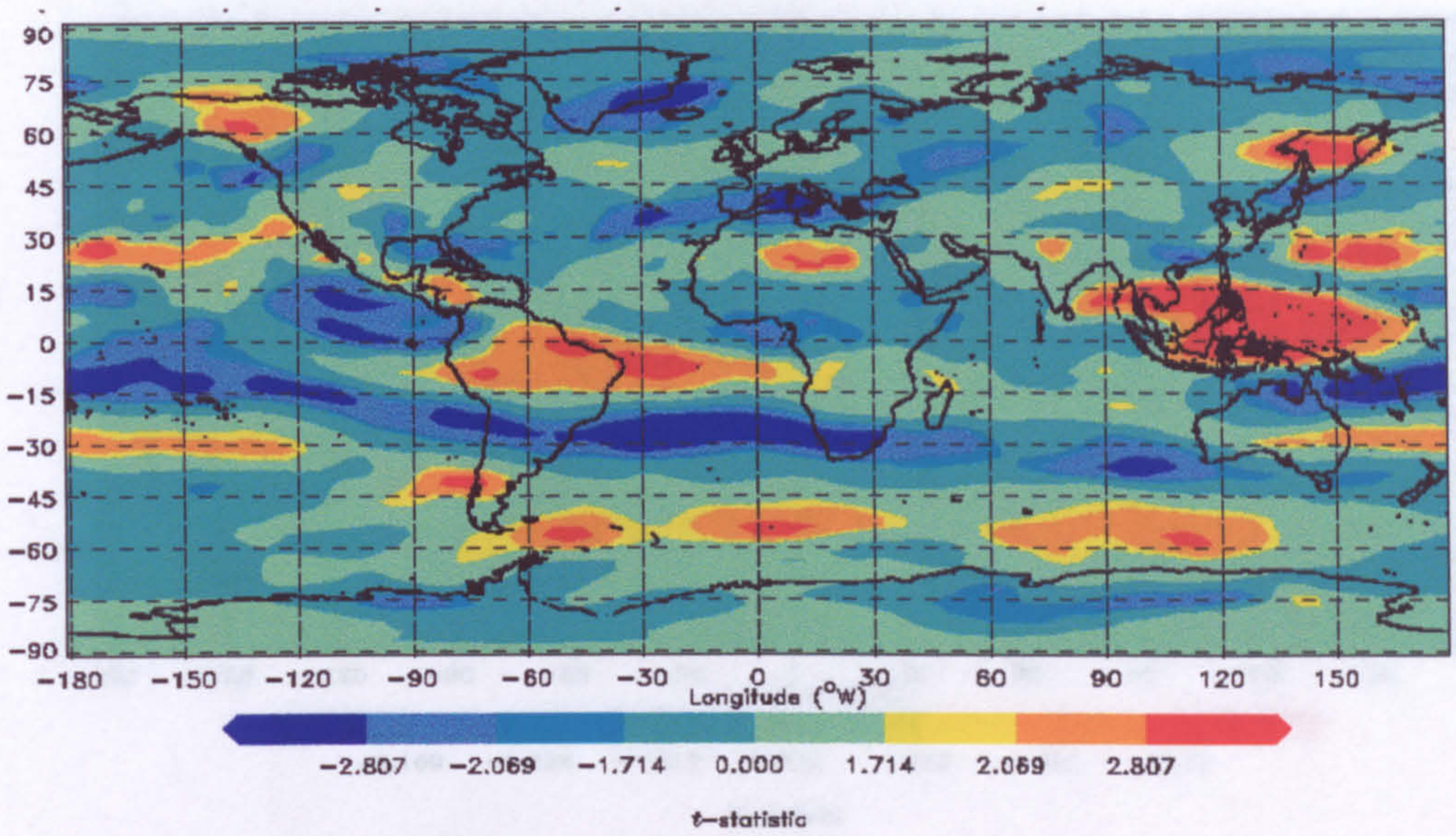
e) SST (and land temperatures)



f) U WIND 850 hPa



g) VZ



h) PRES

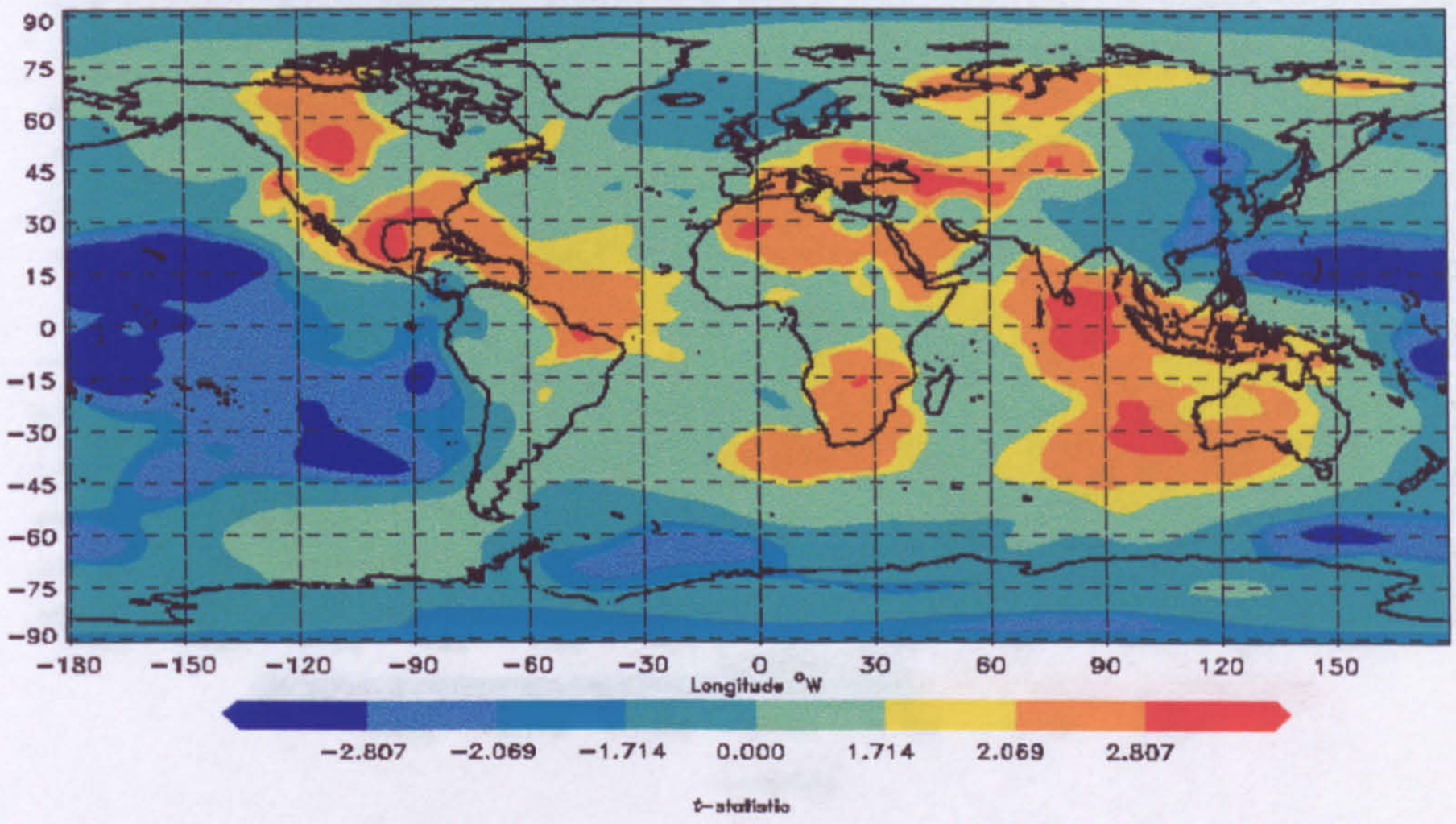
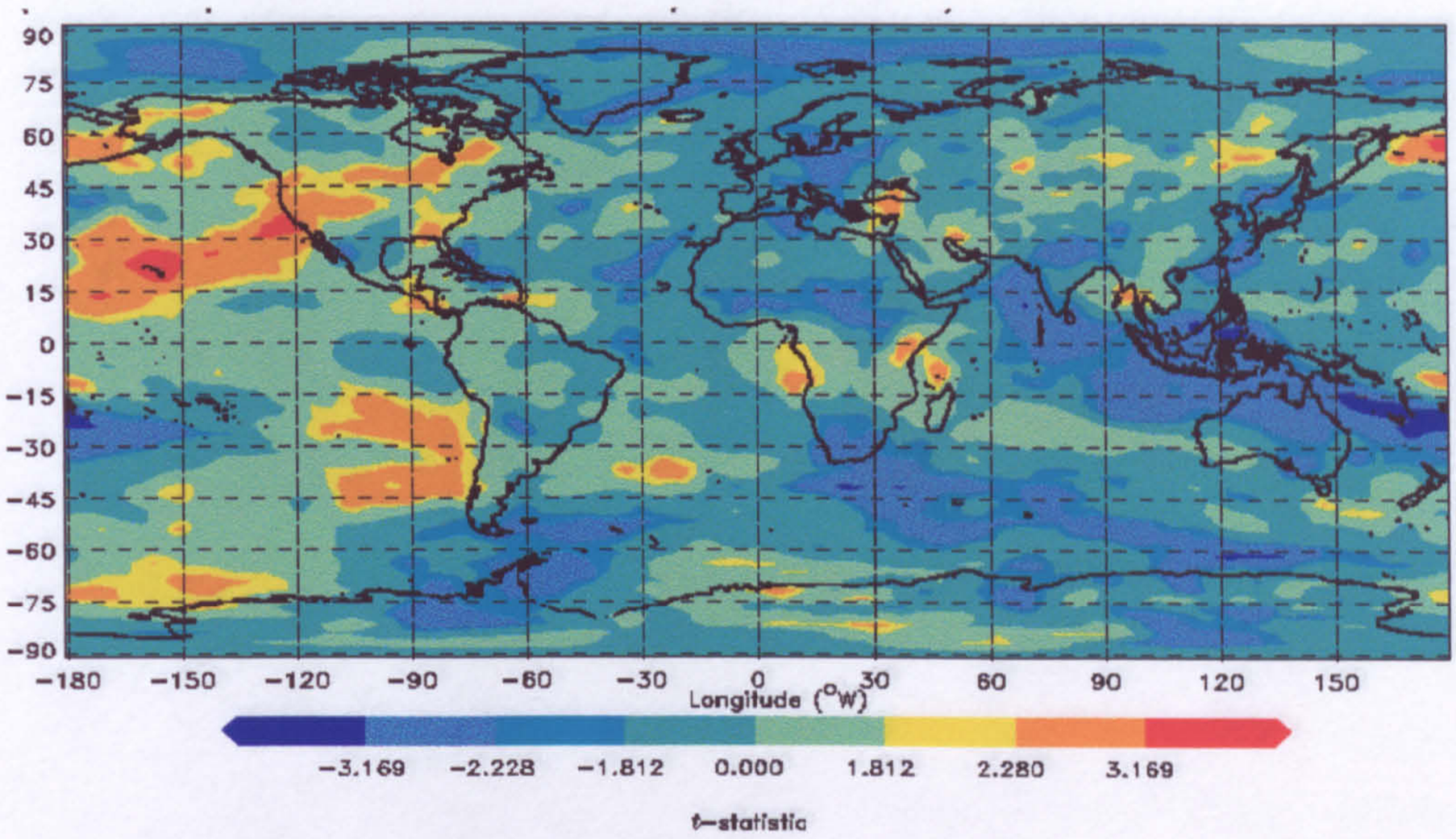


Figure 4.11 Relationship (given with a *t*-statistic) between western development region hurricane numbers and the environmental variables using Poisson regression. The period examined was July-September, 1972-1997. Time is included in the model. *t*-statistics are given with absolute values of 1.714, 2.069 and 2.807 representing associations with greater than 10%, 5% and 1% significance respectively. (Note: in figure 4.11f 1mb = 1 hPa).

a)



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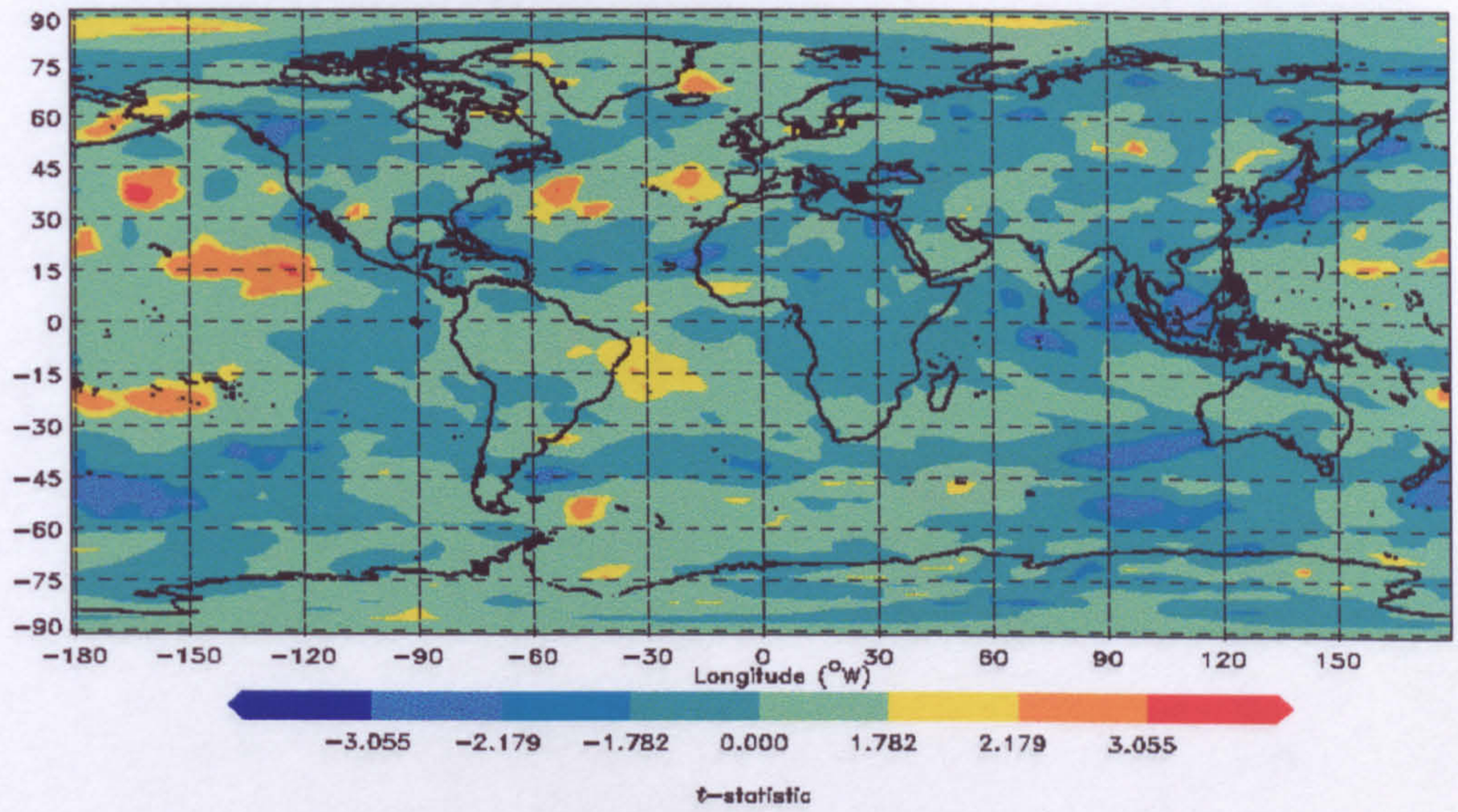
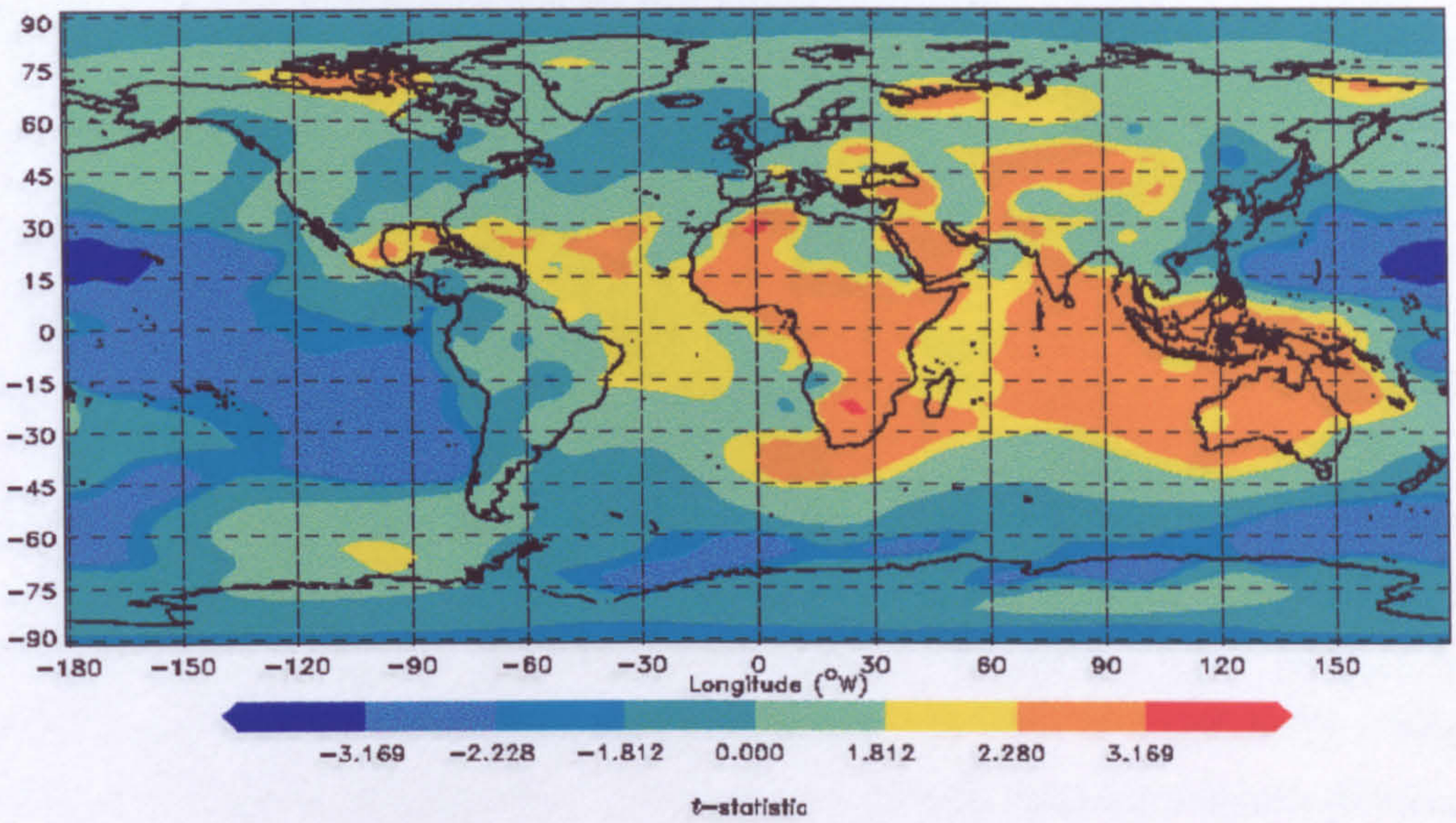


Figure 4.12 Relationship (given with a t-statistic) between western development region hurricane numbers and RH using Poisson regression for July-September in a) strong ENSO Niño4 years (six least (1973, 1974, 1975, 1976, 1988, 1989) and most (1982, 1987, 1991, 1992, 1994, 1997) active years in 1972-1997) and b) non-strong ENSO Niño4 years (1972-1997). t-statistics are given with absolute values of 1.812, 2.228 and 3.169 (1.782, 2.179 and 3.055) representing associations with greater than 10%, 5% and 1% significance respectively for strong (non-strong) ENSO years respectively.

a)



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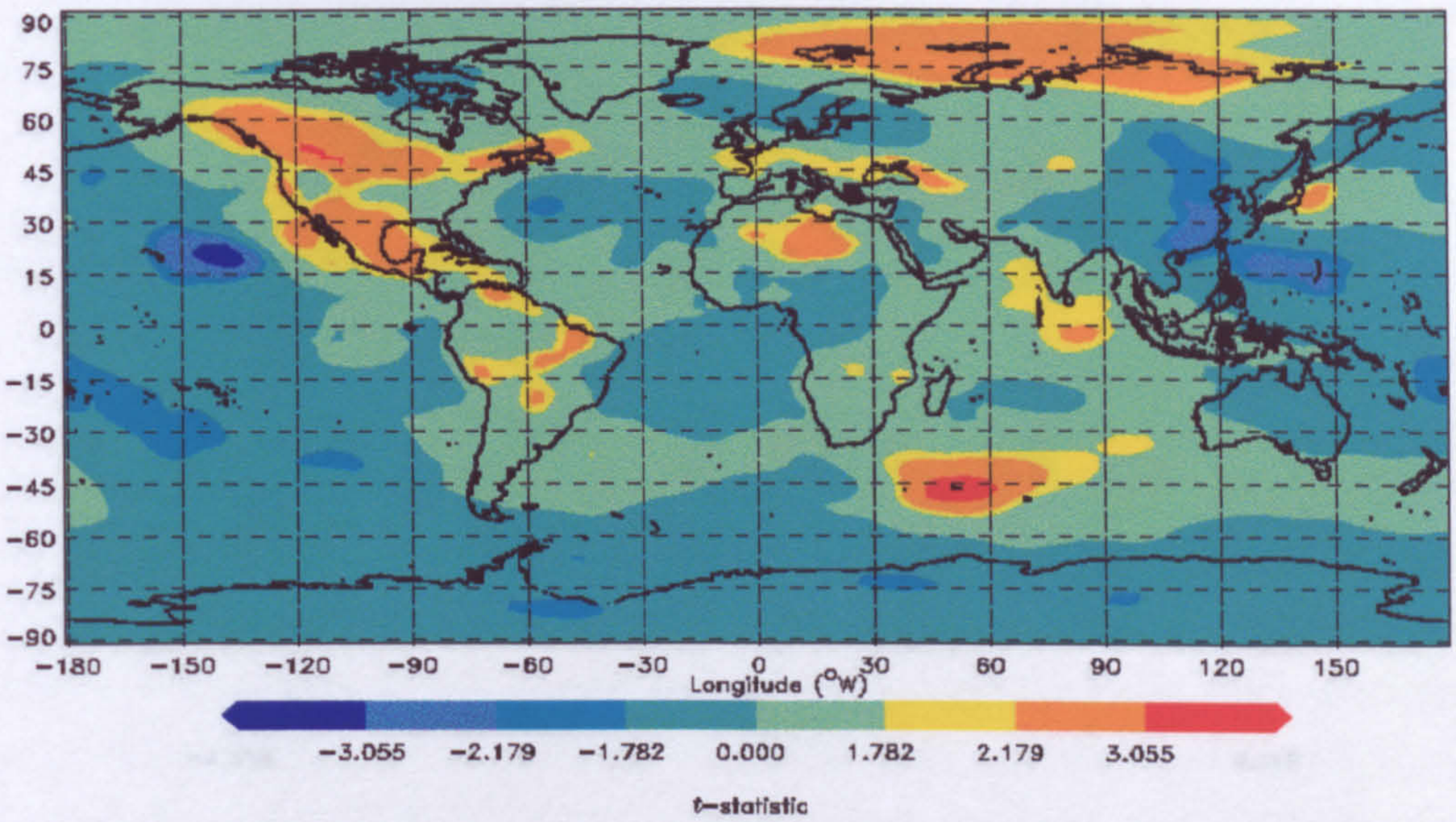
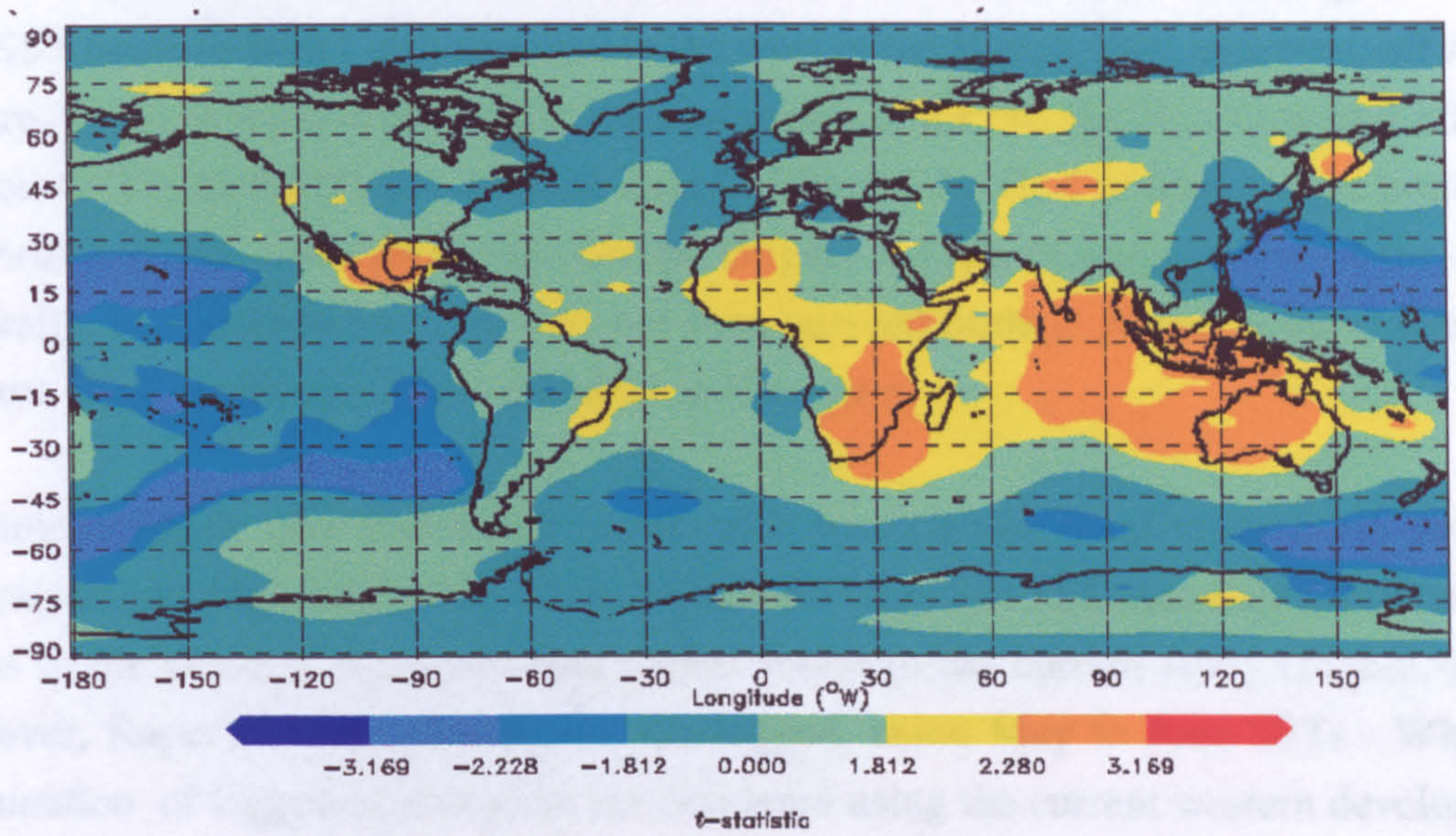


Figure 4.13 Relationship (given with a *t*-statistic) between western development region hurricane numbers and PRES using Poisson regression for July-September in a) strong ENSO Niño4 years (six least (1973, 1974, 1975, 1976, 1988, 1989) and most (1982, 1987, 1991, 1992, 1994, 1997) active years in 1972-1997) and b) non-strong ENSO years (1972-1997). *t*-statistics are given with absolute values of 1.812, 2.228 and 3.169 (1.782, 2.179 and 3.055) representing associations with greater than 10%, 5% and 1% significance respectively for strong (non-strong) ENSO years respectively.

a)



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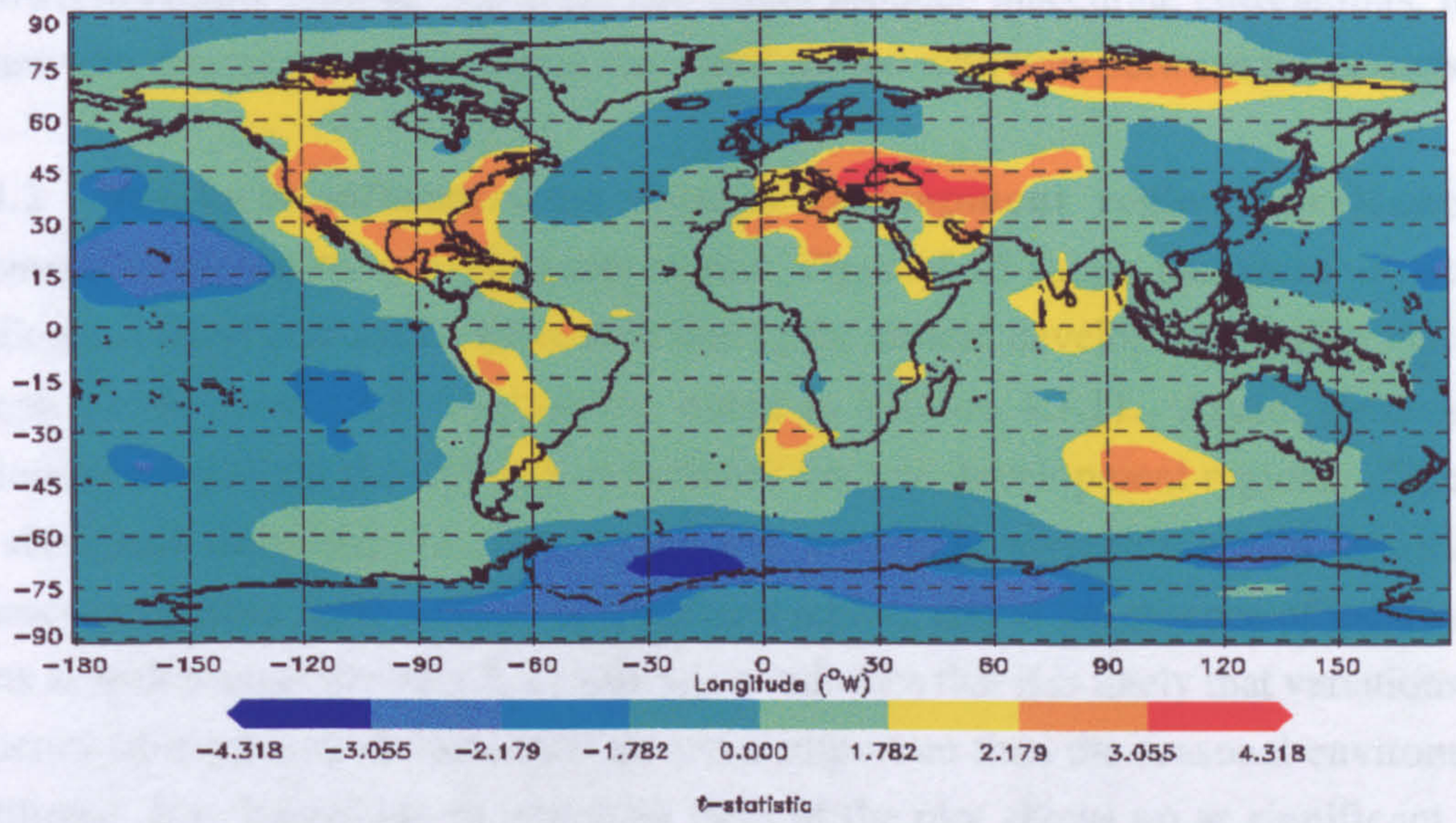


Figure 4.14 Relationship (given with a *t*-statistic) between western development region hurricane numbers and PRES using Poisson regression for July-September in a) strong MJO years (six least (1973, 1974, 1975, 1976, 1988, 1989) and most (1982, 1987, 1991, 1992, 1994, 1997) active years in 1972-1997) and b) non-strong MJO years (1972-1997). *t*-statistics are given with absolute values of 1.812, 2.228 and 3.169 (1.782, 2.179 and 3.055) representing associations with greater than 10%, 5% and 1% significance respectively for strong (non-strong) ENSO years respectively.

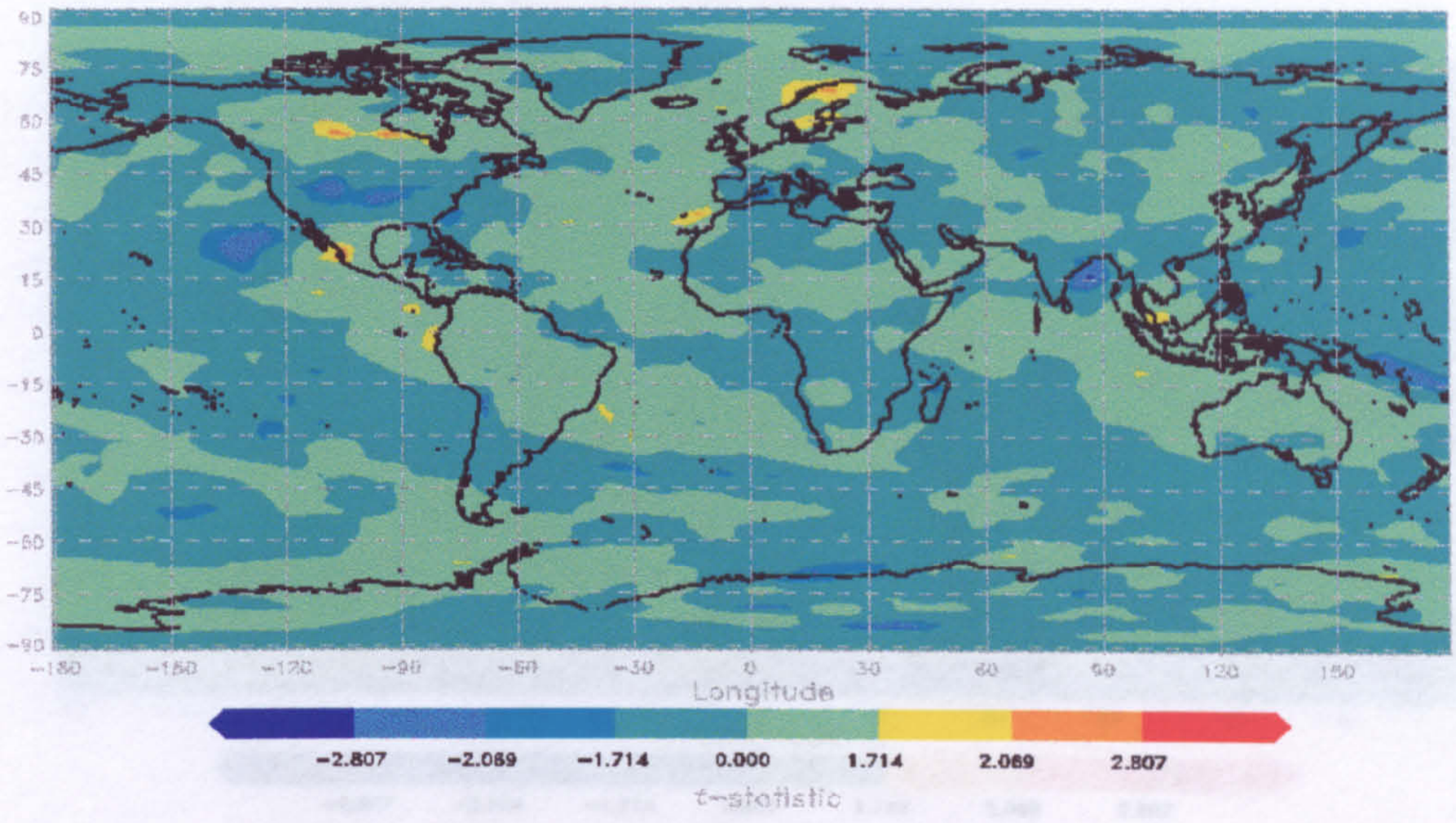
smaller in size, are found with PWAT to the northwest of the British Isles (Figure 4.11b); with SST south of Baja California, and to the west of the British Isles, and west, off Africa (Figure 4.11e); U wind at 850 hPa in the east region of the NE Pacific Ocean and off Baja California (Figure 4.11f), pressure off Baja California, the Gulf of Mexico and northwest of North America and continental Europe (Figure 4.11h), to name a few of the areas. Generally, mechanisms for these have not been pursued further. However the U wind and pressure correlations are discussed further in Chapter 5.

It is interesting to note that Raper (1993) also found a non-local relationship between tropical cyclone frequency in the whole NE Pacific basin and SST near Baja California, but this is to the north of the significant region found in the current study (Figure 4.11e). However, Raper's (1993) correlation was lagged, using May to June SSTs. When an examination of lagged relationships is considered using the current western development region datasets, a relationship closer in longitude to Baja California is in fact found, though the maximum correlation is further away from the coast than that observed by Raper. However, Raper's study also differed in that she included data from 1950 to 1971, which is known to be less reliable, and therefore might produce inaccurate correlations, though alternatively, the region of correlation may have moved with time between the periods.

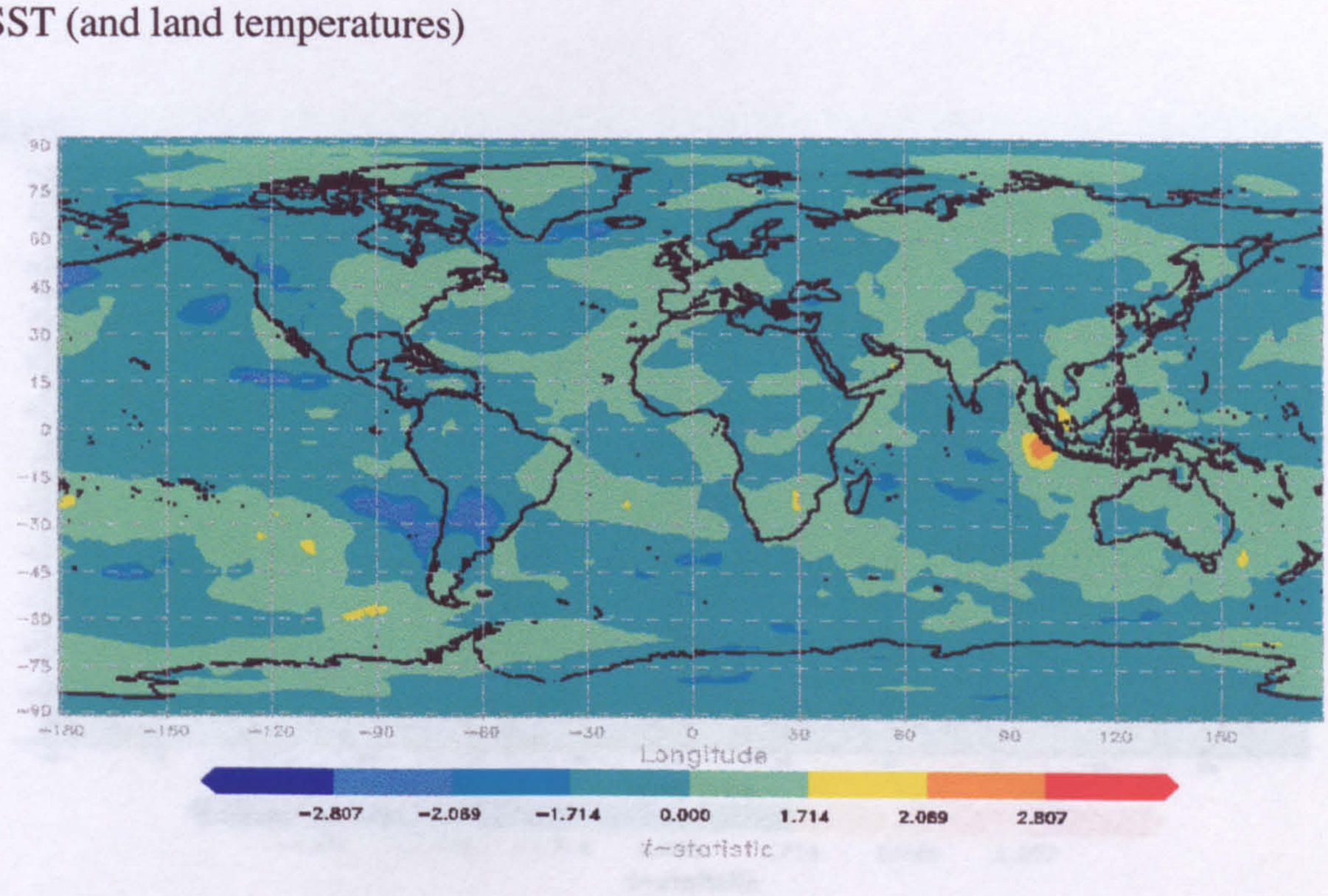
4.7.4.2 Non-local influences on eastern development region hurricanes

In contrast to the western development region, Figure 4.15 shows that there are no large significant areas of correlation when considering the eastern development region hurricanes (except for the local OLR relationship noted in Section 4.7.1). Again, these lack of relationships highlight the differences between the two development regions. Therefore, this statistical technique has not shown any non-local variables which significantly influence hurricanes in the eastern development region, and in the absence of local variable effects as well (except for the OLR), this again indicates that it is likely that variations in the frequency of triggering disturbances are more important than the seasonal environmental conditions. It is interesting to note how little of the plot shows up as significant for all variables considered for the eastern development region hurricanes, given that it was noted earlier that it is expected that there is a 5% chance that a regression produces a significant result when there is no true significance. Therefore it might be expected that 5% of the plots would show significant results by chance. However, clearly in Figure 4.15, there are some cases when not even 1% of the plot is significant to the 5% level. The reason for this is due to an effect called "multiple comparisons", i.e. spatial dependence. *N* independent tests have not in fact been conducted, in that the results from one grid node will be very similar to a neighbouring grid node. Therefore it is not entirely surprising to find whole

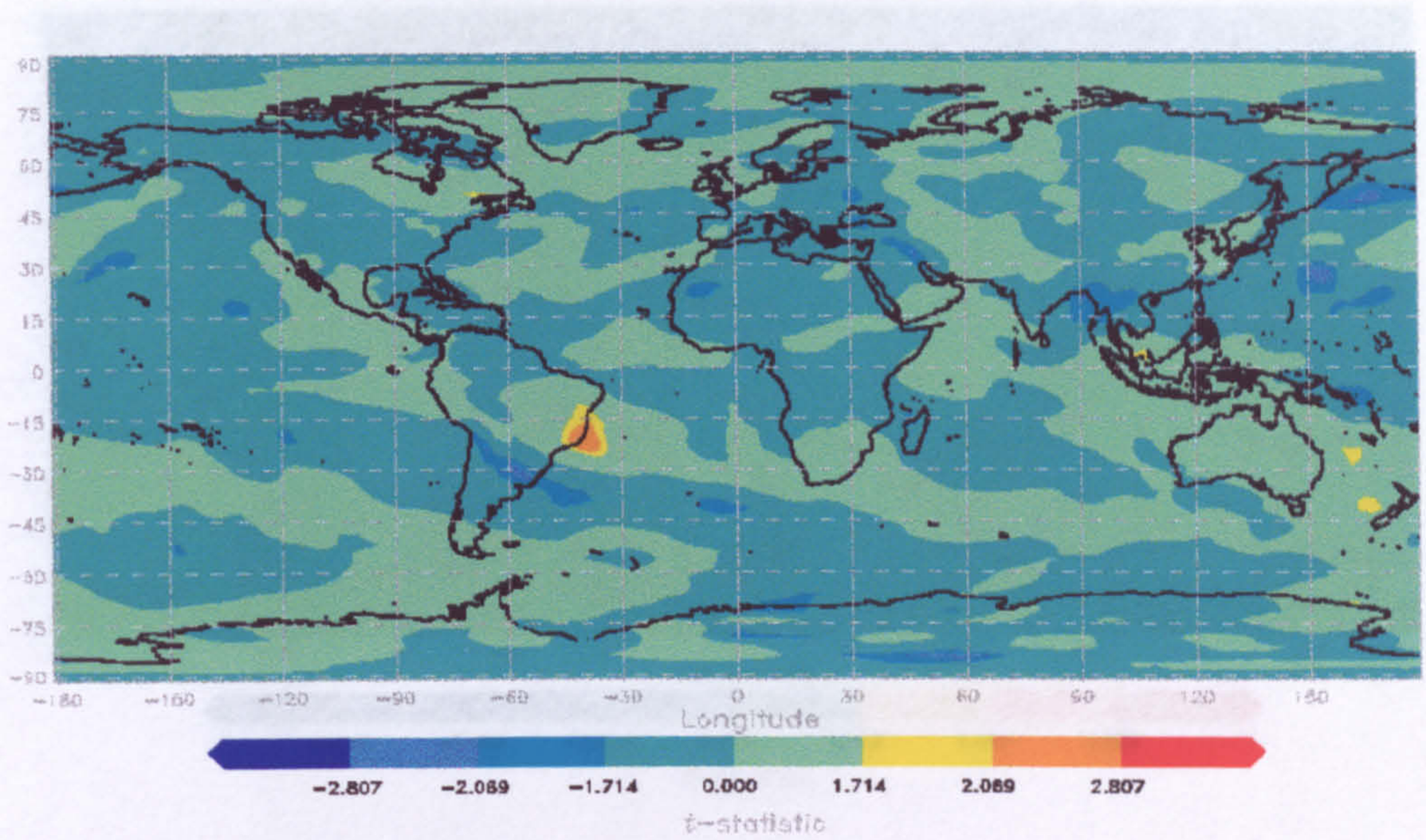
a) RH



b) SST (and land temperatures)



c) PWAT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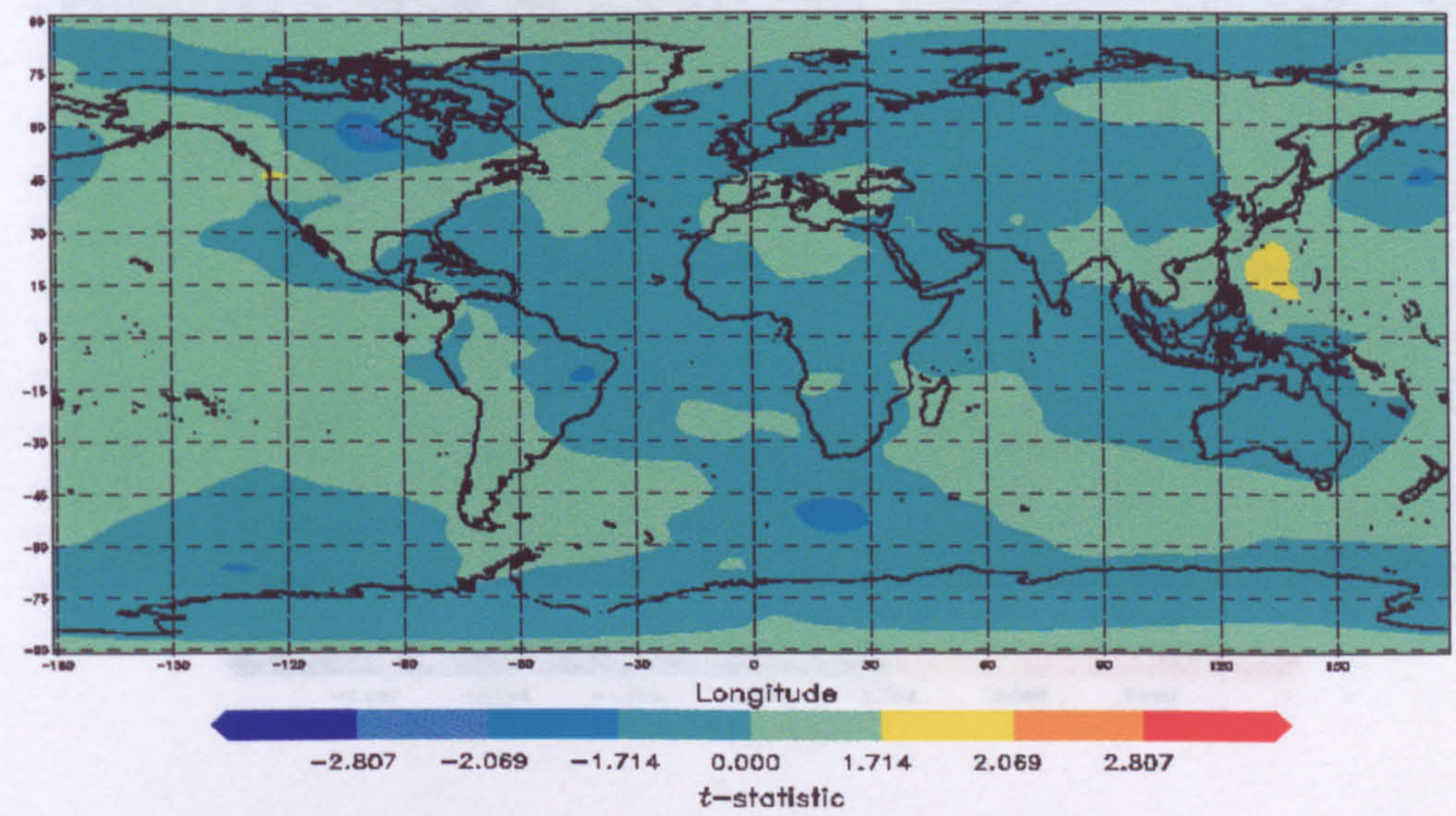
t-statistic

d) PRES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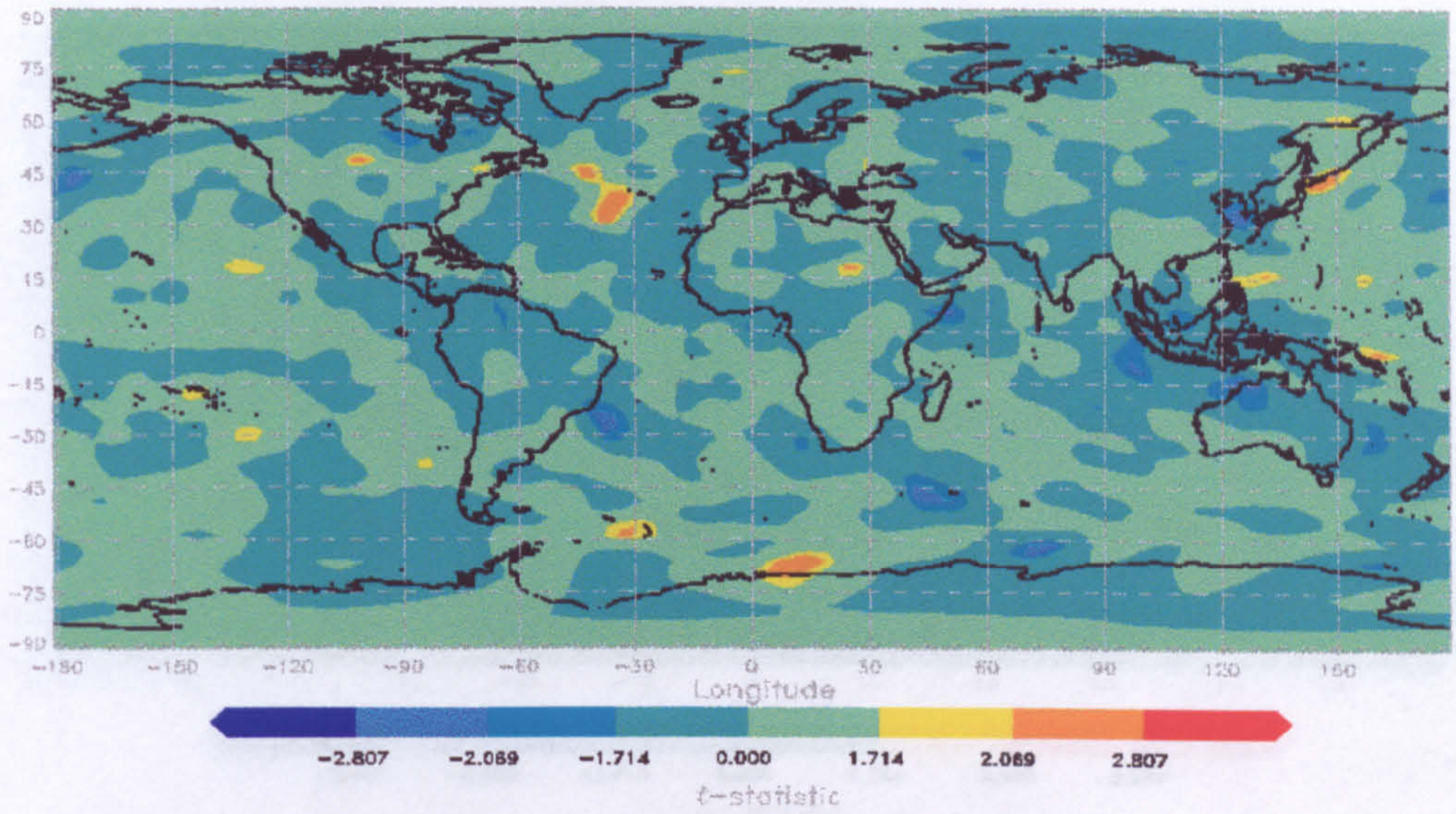
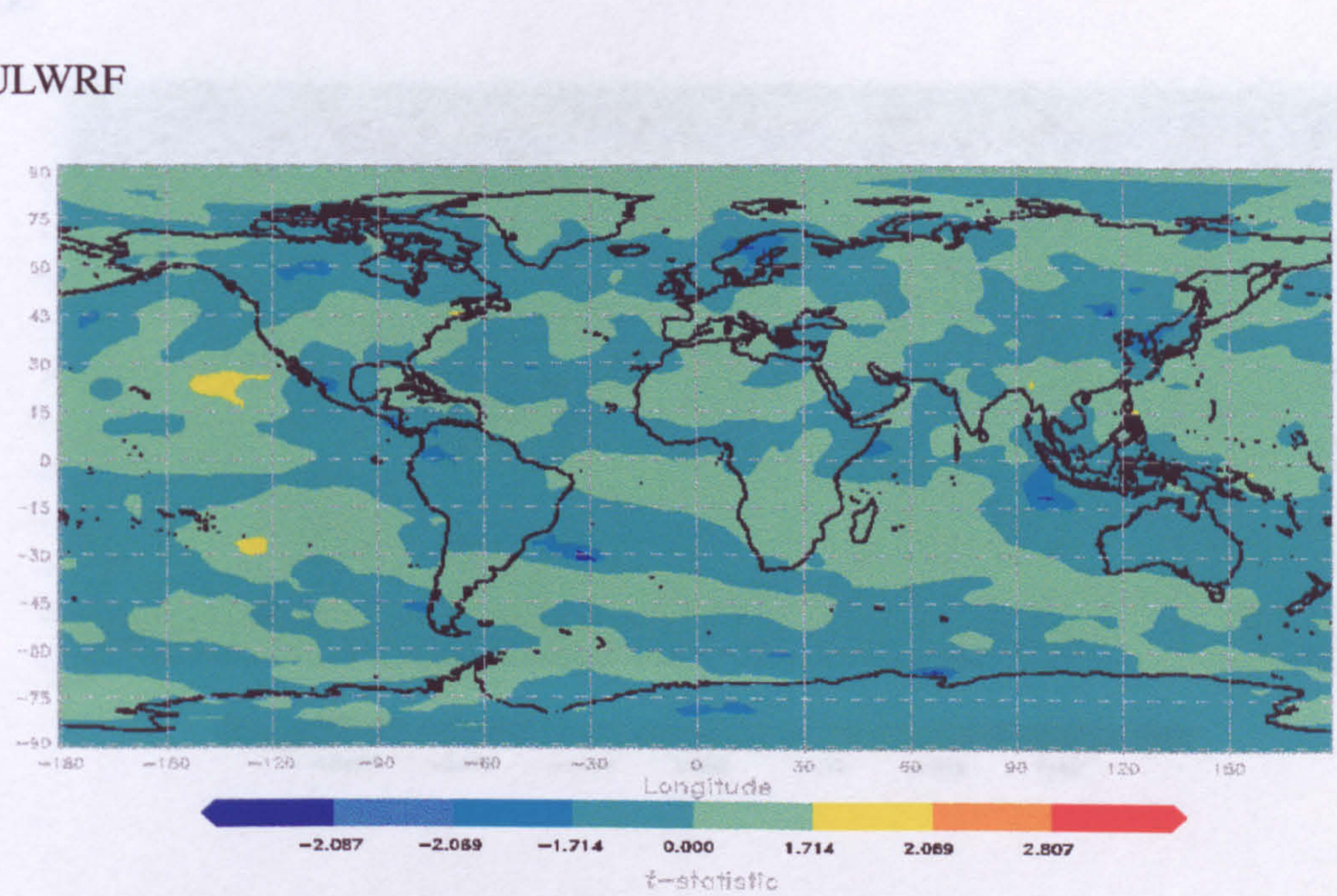
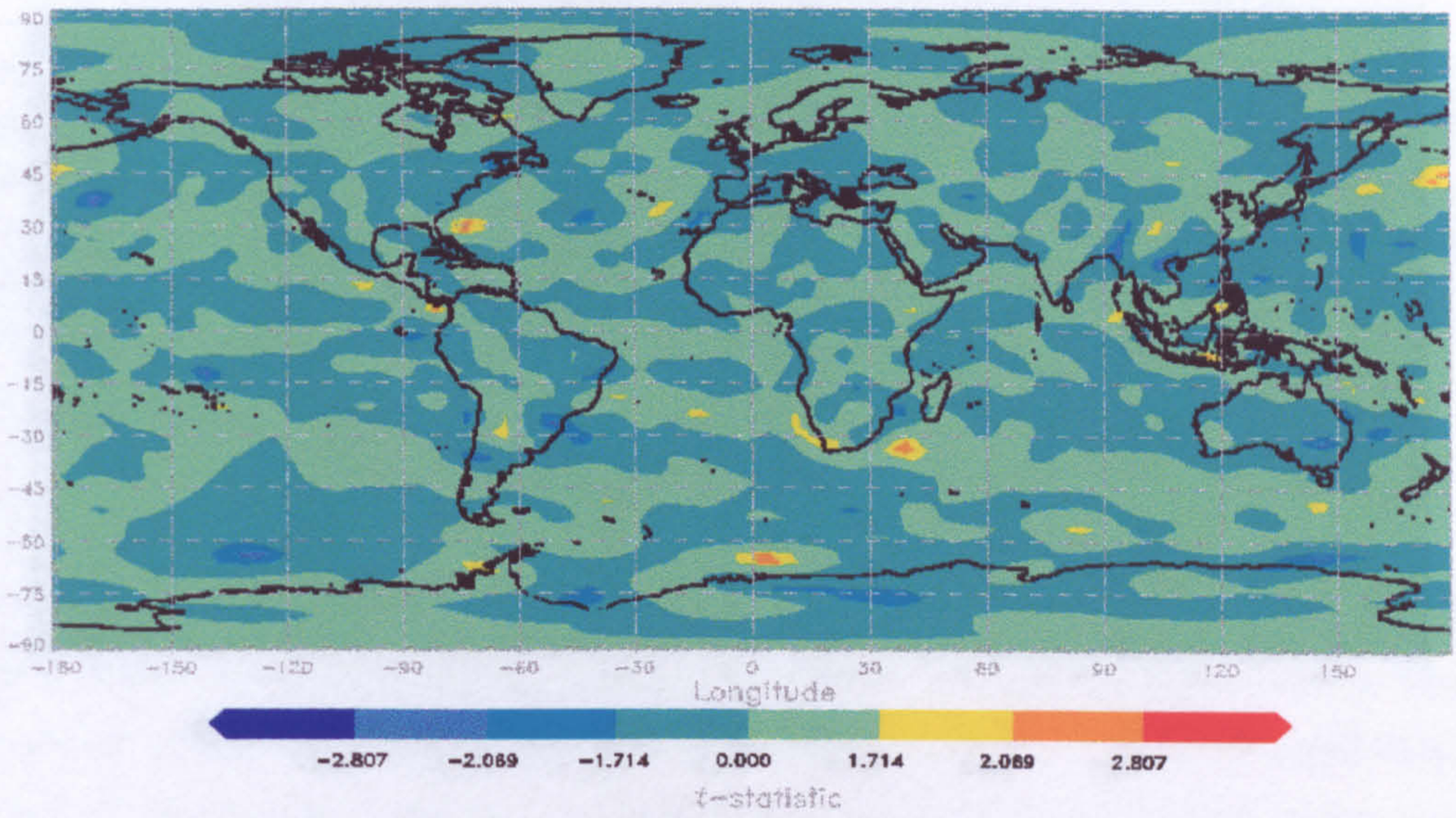
e) VVEL



f) ULWRF



g) RELV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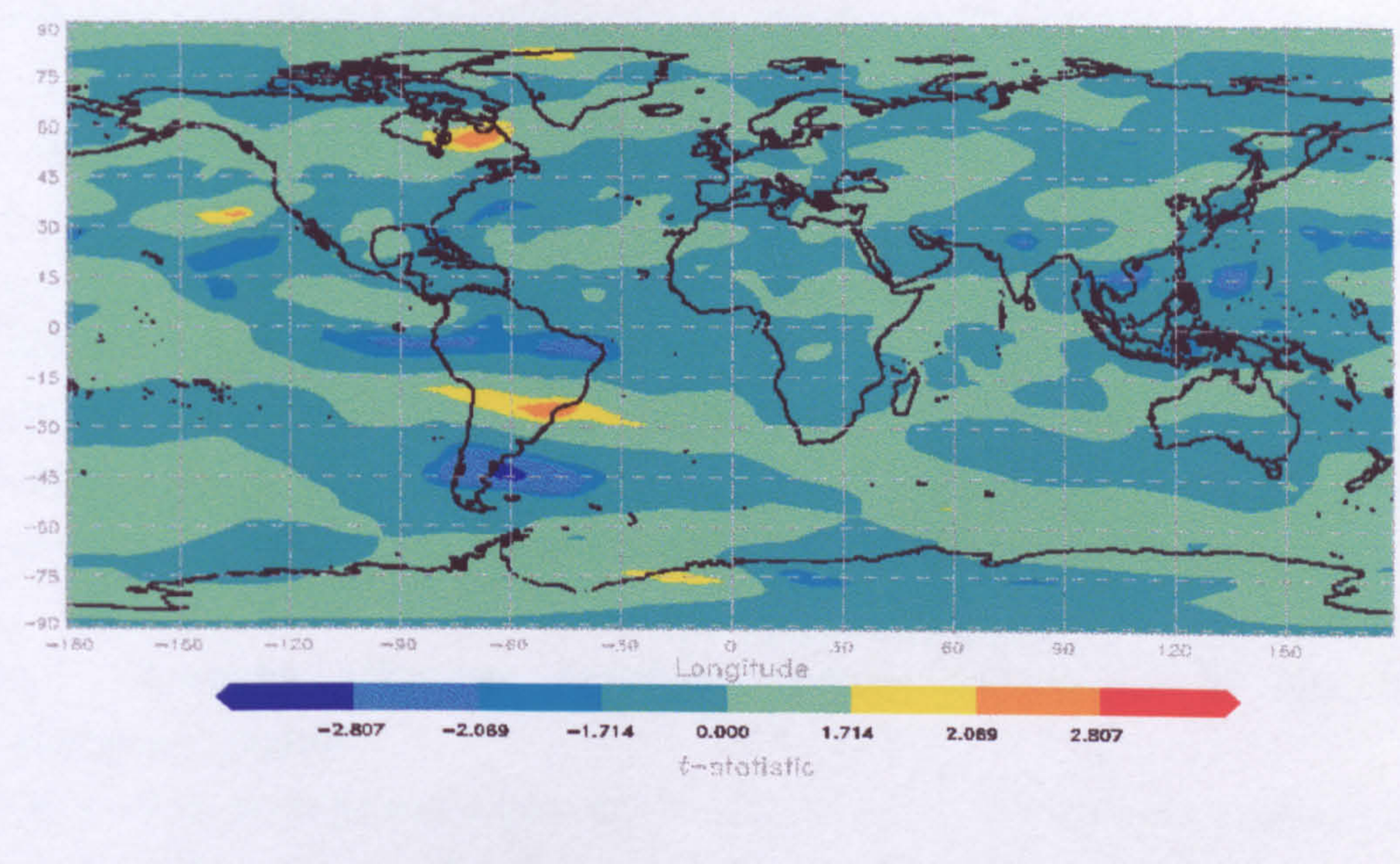
h) VZ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Longitude
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2.807
t-statistic

I) TMP

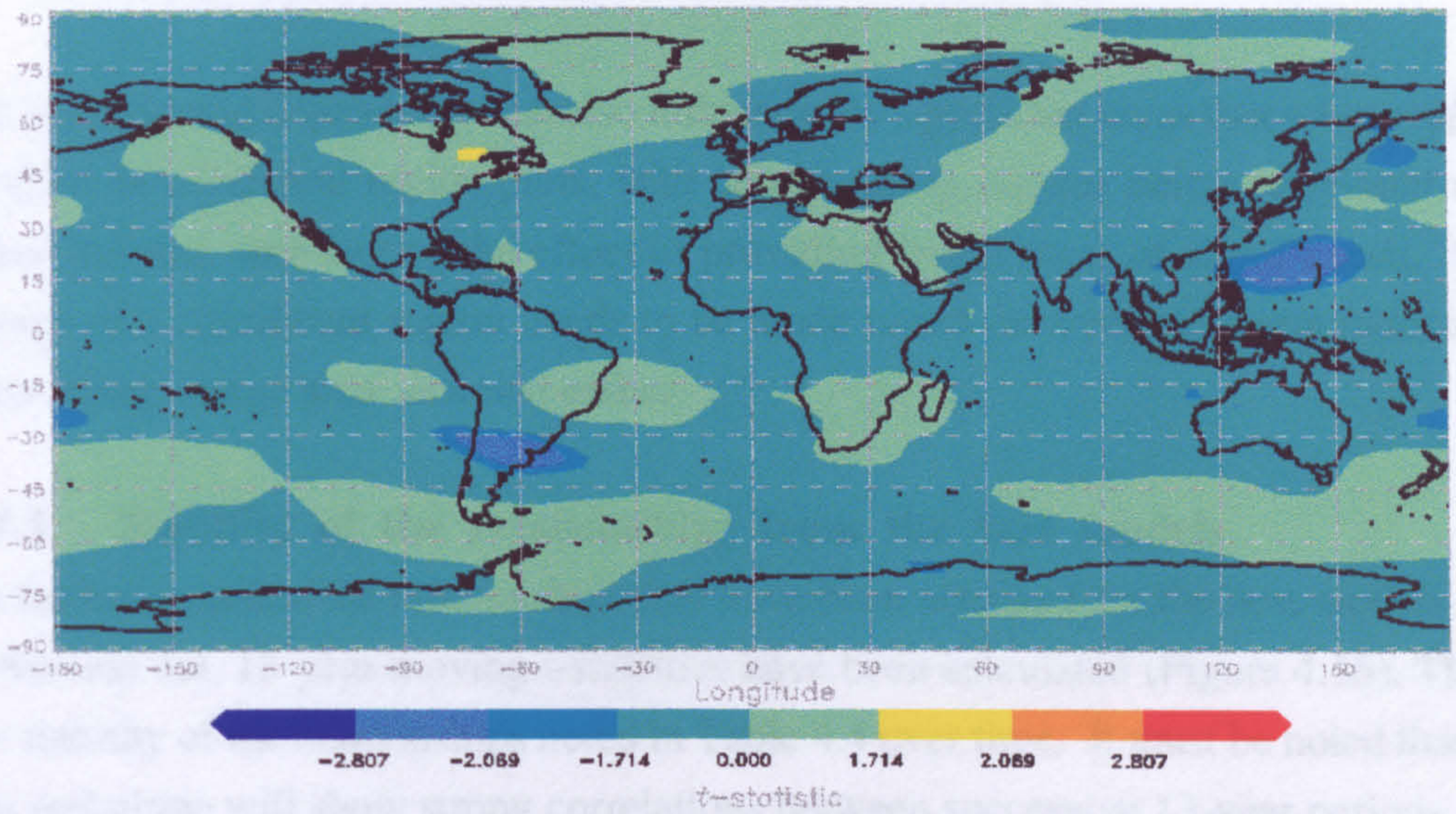


Figure 4.15 Relationship (given with a *t*-statistic) between eastern development region hurricane numbers and the environmental variables using Poisson regression for July-September, 1972-1997. Time is included in the model. *t*-statistics are given with absolute values of 1.714, 2.069 and 2.807 representing associations with greater than 10%, 5% and 1% significance respectively.

regions where nothing is significant. However, the conclusion is not altered that there is nothing significant in this plot.

The same spatial dependence can also influence the significant areas that were evident in the western development region plots, with neighbouring regions being correlated with each other, but this time having the effect of providing larger areas of significance. Therefore choice of a significant region needs to be made based on a physical argument as well as there being a large area, as noted earlier.

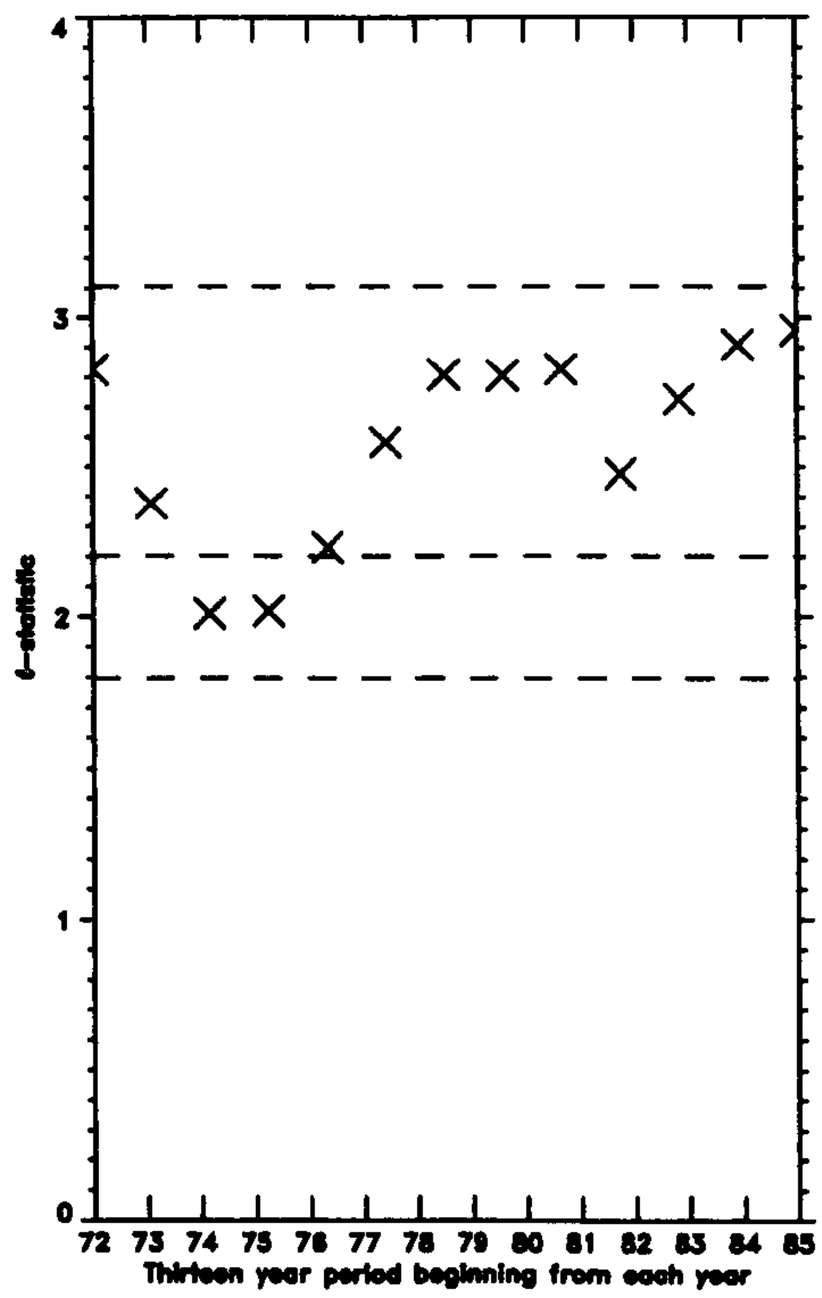
4.7.5 Stability of the relationships from the best models

To further examine the relationships that have been obtained for the best models identified in Section 4.4, 13-year moving *t*-statistics have been calculated (Figure 4.16). These show the stability of the relationships noted in Table 4.4 over time. It must be noted that although this technique will show strong correlations between successive 13-year periods, a general idea of stability can be given. It can be seen that the relationships obtained are not due to a particular group of years but are consistent throughout the whole time period. For instance, it can be seen that the relationship between hurricane numbers and RH (Figure 4.16a) is not due to specific years but is consistently significant throughout this time period. The relationship is significant at the 5% level for each 13-year period if the *t*-statistic exceeds 2.2. Similarly for the tropical storm category, the relationship of the best single model with RH (Figure 4.16b) and the best multiple model with VZ and PRES (Figure 4.16c) also show consistent significance throughout the whole time period. The intense hurricane category is not shown as the numbers within the 13-year period are very small. For an example of a poor relationship noted in Table 4.4, Figure 4.16d shows that for the relationship between hurricane numbers and QBO, although the *t*-statistic varies for the different groups of 13 years, it is consistently low and not significant. These stability checks provides confidence in the significance of the relationships obtained.

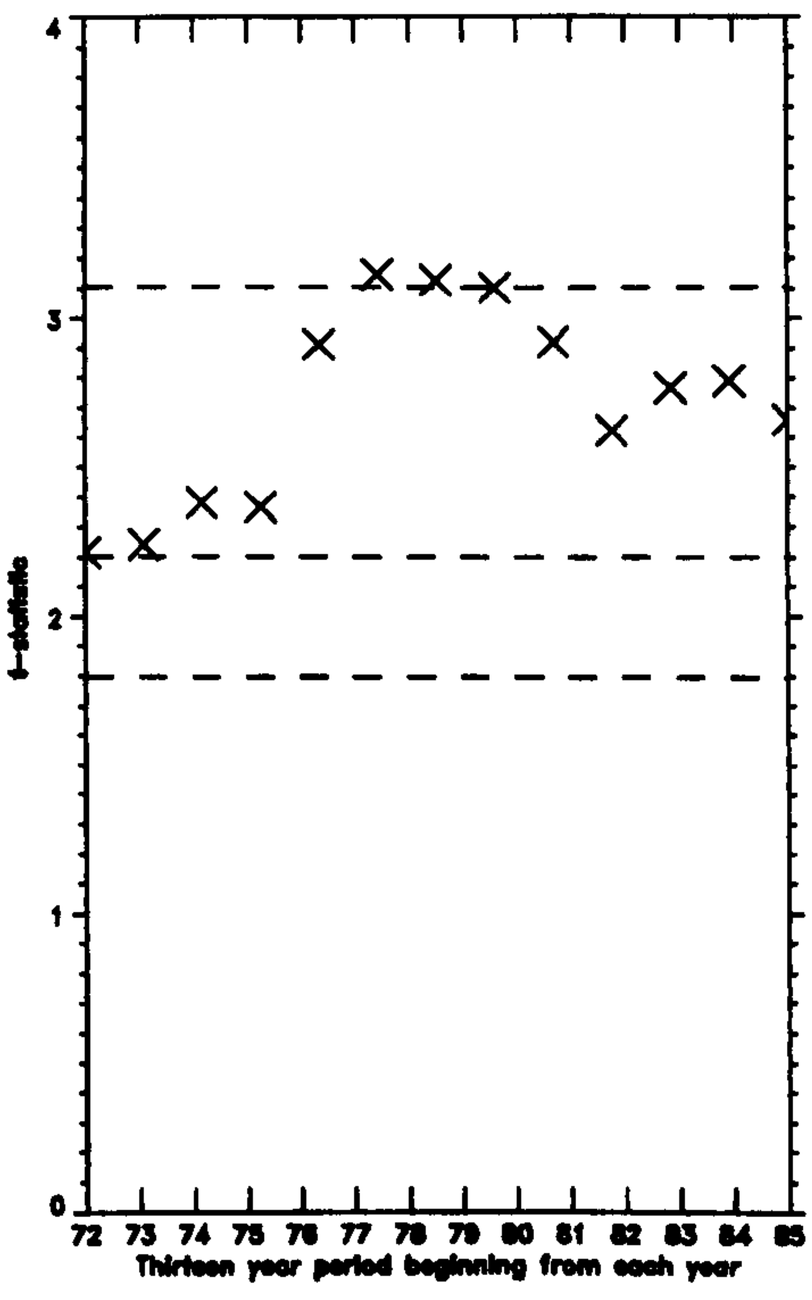
4.7.6 Factors affecting tropical cyclone frequency in the eastern development region

For the eastern development region of the NE Pacific it is found that, averaged over the season, the relevant local environmental variables (Gray, 1979) are always conducive to tropical cyclone formation and there are no observed non-local factors that affect tropical cyclone formation. (The one exception is OLR, where a negative correlation with tropical cyclone frequency is observed locally.) Therefore, it is more likely to be the "weather" which causes fluctuations in tropical cyclone activity; particularly the frequency of triggering disturbances, such as suitable easterly waves or trough-related tropical

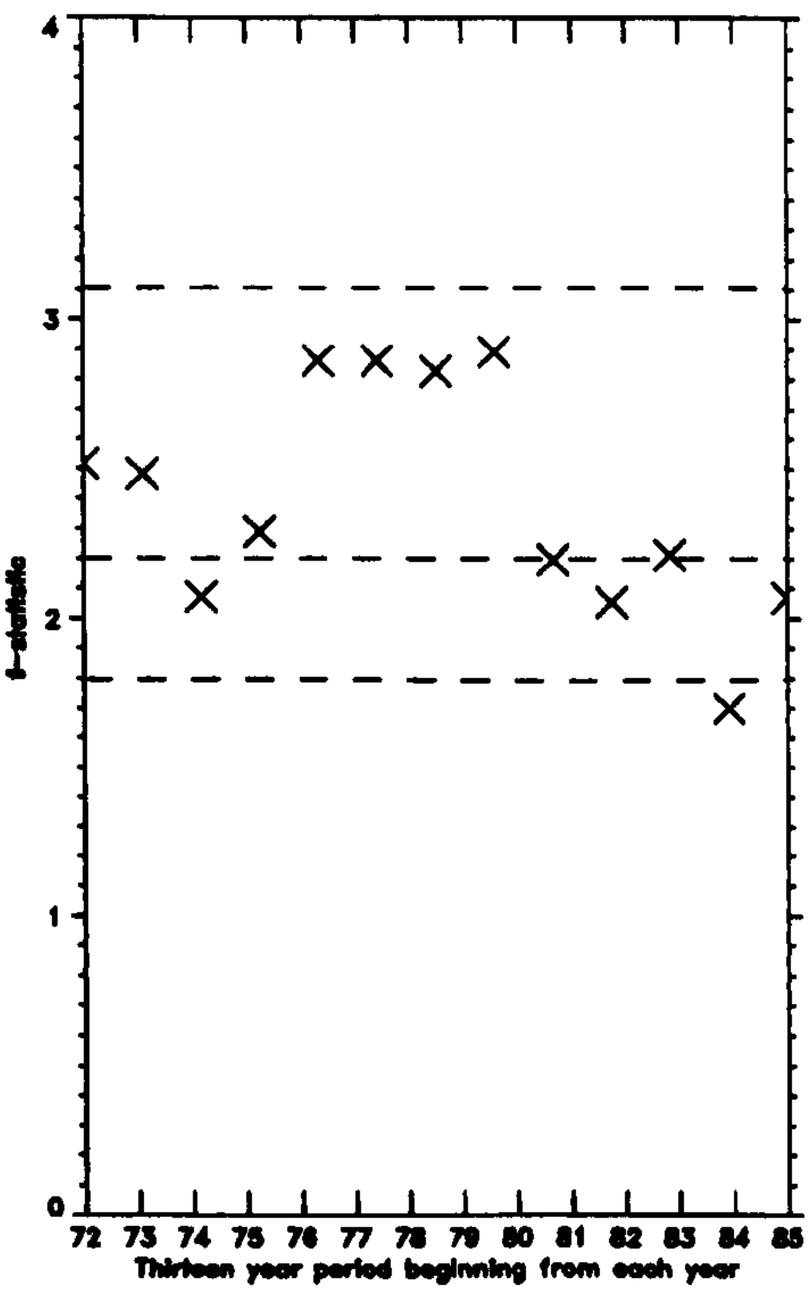
a) Hurricane numbers vs. RH



b) Tropical storm numbers vs. RH



c) Tropical storm numbers vs. VZ and PRES



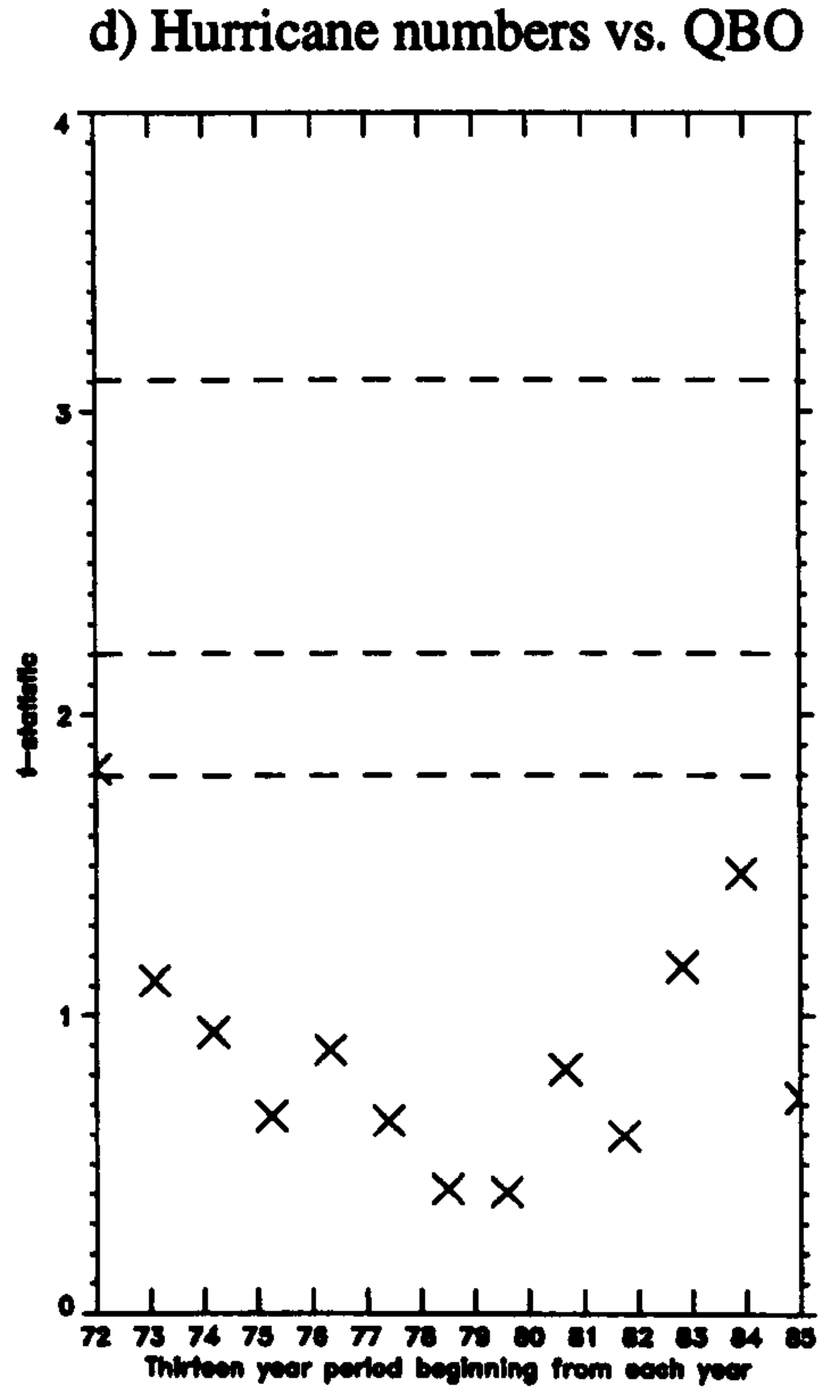


Figure 4.16 13-year moving *t*-statistics from a Poisson regression of the relationships between a) hurricane numbers vs. RH, b) tropical storm numbers vs. RH, c) tropical storm numbers vs. VZ and PRES, and d) hurricane numbers vs. QBO. Variables are averaged over July-September. All models include time, as do the relationships in Table 4.4. The dashed lines indicate the significance level based on thirteen years of data for the 1%, 5% and 10% level (from top to bottom respectively).

disturbances, having suitable convergence and rotation. Furthermore, their frequency will be negatively correlated with OLR, as noted in Section 4.7.1. This is confirmed by Frank (1987), who noted that extrapolation of wave tracks from the North Atlantic to the Pacific suggests a correlation between easterly waves and cyclone formation. Molinari (2000) has also found correlations with cyclogenesis in the NE Pacific and easterly waves from the North Atlantic. The NE Pacific is a very unique basin with the eastern development region being very close to the mountains of the Sierra Madre. As mentioned in Section 1.5.1.2, various authors have found relationships with easterly waves interacting with the mountains and causing areas of positive relative vorticity. Therefore, one would expect any impact of the terrain to affect the hurricanes to the east rather differently than the ones further away in the western development region.

4.8 Summary

Tropical cyclone formation in the NE Pacific has been poorly understood to date. It is shown that by dividing the NE Pacific basin into two development regions, east and west of 116°W (as described in Chapter 3), enhanced understanding can be achieved in terms of which climatological factors are involved, in particular, for explaining interannual variations in tropical cyclone numbers in the western development region.

For the period 1972-1997, it is shown that there is a clear lack of significant results in the eastern development region (except for OLR) indicating that the variation of tropical cyclones in this latter region is not influenced primarily by variations in the climatological values of the environmental factors. The reason for this has been suggested to be due to the climatological values in the eastern development region always being at a sufficiently conducive value (i.e. over a certain threshold value) in active and inactive years. This is similar to the Gulf region of the Atlantic, where there is locally a lack of significant relationships between the tropical cyclones that form there and the seasonal environmental variables. Likewise in the Gulf, the environmental variables are always high and can be suggested to be conducive to tropical cyclone formation. It has been suggested, therefore, that the triggering disturbances (such as suitable easterly waves) are more important for determining numbers of tropical cyclones per year in the eastern development region of the NE Pacific. This is supported by the OLR relationship, since larger numbers of tropical disturbances will provide lower values of OLR. The lack of any relationship with other environmental variables suggests that a threshold, rather than the actual values of the variables, is the main influence on tropical cyclone genesis in the eastern development region.

On the other hand, significant relationships exist between several environmental variables and tropical cyclone numbers (averaged over the peak hurricane season) in the western development region. Important variables for the western development region, common to all tropical cyclone indices examined, include RH, SST, VVEL and PWAT. These relationships are not evident when the NE Pacific basin is treated as one entity but emerge only when sub-regions of development are identified. Whilst these thermodynamic (and related) variables are important for explaining interannual variations in tropical cyclone frequency in the NE Pacific, the dynamic variables are not (although VZ seems to be very important in determining where they form within this region). These results have not previously been shown for the NE Pacific.

It is suggested that these relationships in the western development region can be largely explained by two means. Firstly, the "intensity-frequency effect" described in Section 3.2.3 will provide a relationship with SST and hence with the other associated thermodynamic variables which should be stronger, the higher the category of tropical cyclone. As noted in Chapter 3, such an effect is expected to be smaller in the eastern development region due to the higher SSTs there. Secondly, the thresholds on the environmental variables, determining whether tropical cyclones form or not, can provide a relationship with tropical cyclone frequency when spatial variations within the western development region are averaged. In active tropical cyclone years, the environmental factors are found to be above the threshold over a large fraction of the region, whereas in inactive tropical cyclone years, environmental variables are only above the threshold in a small part of the region. However, the existence of a further mechanism, whereby the actual *values* of the environmental variables affect tropical cyclone frequency, cannot be completely ruled out.

It has been shown that RH is the dominant environmental variable affecting hurricane frequency. It is also an important factor for explaining tropical storm frequency (where again it is the most important single variable) and intense hurricane frequency. This variable has a high reliability in the western development region, based on comparisons with the ECMWF data, and thus results obtained with this variable are also considered to be reliable. Good physical arguments for the importance of this variable have already been provided by other authors in relation to the North Atlantic (Gray, 1979; Emanuel, 1997). It is therefore of interest to explore the underlying causes of the interannual RH variations, as these will provide the main causal mechanisms for the interannual variations in tropical cyclone numbers. It has already been noted that RH has a strong relationship with ENSO. Therefore, an investigation of this, and other possible non-local mechanisms for the

variations in the RH, will be explored further in Chapter 5.

It has been shown in this chapter that ENSO has differing effects on tropical cyclone frequency in the western and eastern development region, with warm ENSOs tending to produce more tropical cyclones in the western development region and less tropical cyclones in the eastern development region. The measure of ENSO that is chosen is important and it has been shown that out of the SST based indices, the Niño4 one shows significant relationships with western development region tropical cyclone numbers. The lack of relationships with the other SST based indices are important in understanding the mechanism by which ENSO affects the western development region and hints to the location of the warm pool being important. This is further examined in Chapter 5.

Chapter 5

Investigation into the dominant control of hurricane formation in the western development region of the NE Pacific

A clearer understanding of the causes of interannual variations has now been achieved in Chapter 4. This chapter aims to further that knowledge by presenting an in-depth investigation into the variations of RH (relative humidity at 500 hPa), which was shown to be the dominant control on hurricane formation in the western development region. This chapter begins by explaining why this study focuses on the hurricane category. Then the cause or effect of the relationships found in Chapter 4 between hurricane frequency and RH is ascertained. The possible influence of atmospheric and oceanic factors on the interannual variation of RH is then investigated. Finally, a negative relationship between western development region tropical cyclones and Atlantic tropical cyclones is noted and, based on the work of this chapter, an explanation for such a relationship is given.

5.1 RH - the dominant control on hurricane formation

The deviance test (Section 4.4) showed that the best model to explain interannual variations of the seasonal frequency of hurricanes in the western development region of the NE Pacific, using seasonally and spatially averaged environmental variables, is with RH only. This means that no other variables are necessary to explain their frequency of formation based on statistical grounds. However, SST was of secondary importance and was the dominant factor with regards to intense hurricane formation (although RH was shown as the most important influence on intense hurricanes using the *t*-statistic analysis). The focus of this chapter is a statistical investigation of the mechanisms which influence the RH in the western development region, which in turn affects hurricane frequency. SST is also examined, not only due to its importance in affecting tropical cyclone frequency through the "intensity-frequency effect" described in Chapter 3, but also because, as will be seen, SST influences RH. This chapter focuses on hurricanes rather than the other categories since hurricane numbers are a popular index of activity (Elsner and Kara, 1999), and also they are more destructive than tropical storms and thus of more importance. Furthermore, the number of events are higher than for intense hurricanes. Firstly, however, it is important to examine the direction of the relationship between hurricane numbers and relative humidity noted in Section 4.3, to ascertain cause and effect.

5.1.1 RH vs. tropical cyclone numbers: cause or effect?

One concern when using NCEP/NCAR reanalysis data for tropical cyclone studies is that the tropical cyclones may themselves considerably affect the environmental data. For example, the tropical cyclones may significantly alter the mean RH, causing it to be higher. There is a concern whether there has been a sufficient signature left by the tropical cyclones on the seasonally averaged data. If so, this would greatly affect conclusions drawn from Tables 4.2 to 4.8. The question to answer is whether it is the high RH causing the tropical cyclones, or the tropical cyclones producing the high RH that is evident in the data. It is important to examine which is the cause and which is the effect.

Hurricanes only occur for a few days and there are not very many of them, so it is perhaps unlikely that they would affect the seasonal values of the environmental variables considerably. Namias (1955) noted that, "if the period of averaging is long, like a month or season, it becomes highly unlikely that hurricanes, which are few in number and small in extent, would materially alter the mean patterns". Raper (1993) analysed sea level pressure data to show that the relationship between tropical cyclone frequency and the intensity of a sub-tropical high is probably not due to the presence or absence of the storms themselves. According to Raper, the storms appear to have "slipped through" the observing network on most occasions and so not had much influence on the mean sea level pressure values. Knaff (1997) confirmed the statement given by Namias, and findings of Raper, where he examined the impact on sea level pressure from an average hurricane and calculated the total impact on the season based on the number of days and the area of the region. Knaff (1997, p. 800) notes that, "the impact of tropical cyclone induced pressure anomalies is minimal to those changes associated with the more interannual and decadal timescales." Indeed, Landsea et al. (1997) showed that, for the hurricane season of 1995, the lowered sea level pressures preceded the hurricane activity by several months and thus, in this case, could not have been caused by the hurricanes themselves.

Whilst the effect of hurricanes on some variables is a concern, the effect on others is less so. For example, when a significant positive relationship is found between SST and tropical cyclone numbers, there is no doubt about the direction of the relationship. The effect that a tropical cyclone has on SSTs is to lower them as the storm draws out energy from the upper sea surface as it travels. Therefore, warmer SSTs have to be the cause of the tropical cyclone, rather than the effect.

Whilst there has been much thought in the literature regarding the cause or effect of tropical cyclones and the environmental variables mentioned above, the effect on seasonal values of

RH (at 500 hPa) on the other hand has not been considered. In the present study, a significant relationship has been found between RH and tropical cyclones (Tables 4.2 - 4.8) and the conclusion drawn that a simple model with RH best explains variations in hurricane numbers (Section 4.4). Therefore, to ensure that the significant relationship is showing RH to be the cause rather than the effect, it is necessary here to consider the effect that a tropical storm would have on the RH of the atmosphere. This is examined for the western development region of the NE Pacific.

An examination based on an area-weighted average and a time weighted-average was conducted. Several assumptions are made. Firstly, when a tropical cyclone is present, the mid-tropospheric air in the area taken up by the storm is assumed to be 100% saturated. This, however, is an overestimate of reality as there are parts of the tropical cyclone that are not saturated to this level. This value is included, however, to provide a conservative estimate of the influence from a tropical cyclone. Other assumptions, such as a typical size of a tropical cyclone are mentioned below.

With these assumptions, the area-weighted average of RH in the western development region at any given time when a tropical cyclone is present, is given by

$$RH_{ts} = \left(\left(\frac{A_{tot} - A_{ts}}{A_{tot}}\right) \times 36.1\%\right) + \left(\left(\frac{A_{ts}}{A_{tot}}\right) \times 100\%\right) \qquad (5.1)$$

where RH_{ts} is the RH when a tropical cyclone is present, A_{tot} is the total area of the western development region, A_{ts} is the total area of a tropical cyclone, and 36.1% is the average RH of the region based on the July to September season. Thus, for this model, for convenience, the RH when a tropical cyclone is not present, RH_{nonts} is assumed to be 36.1%.

A_{tot} is calculated assuming 1° longitude in the western development region to be the value at 15°N (in km) and 1° latitude is 111.3 km. The area of the western development region is calculated for 65° longitude by 10° latitude. A_{ts} is calculated given that a typical diameter (d) of a tropical cyclone is approximately 500 km (Gordon et al., 1998), thus the area is $\pi d^2 / 4$. A_{tot} is therefore 77.27 km^2 and A_{ts} is 19.64 km^2, giving a value for RH_{ts} of 37.72%.

The time factor is now considered and the following equation is used to give a time

weighted average which takes into account the fraction of the season that a single tropical cyclone is present (or not present), assuming a season of 90 days.

$$RH = (\frac{\overline{N_{ts}}}{90} \times RH_{ts}) + (\frac{\overline{N_{nonts}}}{90} \times RH_{nonts}) \quad (5.2)$$

where $\overline{N_{ts}}$ is the average duration in days of a single tropical cyclone of at least tropical storm stage in the western development region (calculated at 4.21 days), whether it be from storms that originated between 10°N to 20°N, 116°W to 180°W, or storms that entered into this region. $\overline{N_{nonts}}$ is the average number of days that a tropical storm was not present during the season (85.79 days). With these values, *RH* in Equation 5.2 is found to be equal to 36.18.

Thus, on average, and with the conservative assumptions given, the presence of a single tropical cyclone has an influence of only 0.08 percentage points on the RH, which is very small compared to its average value (36.1%). For a more complete examination of this effect, a new RH index is calculated for each year, whereby the value of 0.08 is multiplied by the actual number of tropical storms entering or starting in the western development region for each year, and then this number is subtracted from the original RH index. Making these calculations for each tropical storm and for every year gives an RH index which has been adjusted for the tropical storm effect. This new index can be correlated with tropical cyclone numbers in the western development region. Obtaining a positive significant relationship indicates that the results presented in Sections 4.2 - 4.4, which finds that RH affects tropical cyclones in the western development region, are valid. Positive significant relationships were again found.

Therefore, it has been shown that the tropical cyclones, as expected, do have some effect on the RH, but this influence is extremely small (even when based on assumptions which err on the side of conservatism). Since there was little effect observed from the tropical storms on the RH using this approach, a more detailed approach (including calculating the exact size of each tropical storm, for example) is not necessary. Hence, we can conclude from this section that the relationship between RH and tropical cyclone numbers is due to the influence of RH on tropical cyclone numbers and not vice versa.

5.1.2 The relationship between RH and SST

RH and SST are both variables which have been shown by Gray (1979) to affect tropical cyclone frequency. Given the results of Chapter 4, where these two variables provide

significant models to account for tropical cyclone frequency variations, it would, therefore, be expected that there would be a local high correlation between the two variables. It can be seen from Figure 5.1 that interannual variations in RH and SST are indeed locally correlated to a high level of significance, except in the southeast region of the western development region. In this region, there is relatively little variation from year to year of RH and SST, which may help to account for the poor correlation. The standard deviation of RH and SST in the poor correlation region of 10°N to 15°N, 135°W to 116°W, shown in Figure 5.1, is 3.3 and 0.4 respectively, whereas in a well correlated region, such as 20°N to 25°N, 135°W to 116°W, the standard deviations of these variables are higher at 4.5 and 1.4 respectively. This effect is also discussed in Section 4.1. Furthermore, Table 4.1 also shows a poorer correlation in the eastern development region for RH between NCEP/NCAR reanalysis and ECMWF reanalysis, compared to the better correlation in the western development region. This southeast region of the western development region may actually, therefore, also show poorer correlations between the two models, similar to the eastern development region, indicating a possible data problem with RH in this area. However, it can be seen in Figure 4.5, that in this region, RH has a better correlation with hurricanes than SST has with hurricanes, which is probably why the western development region RH overall has a better correlation with hurricanes than SST does. In view of this difference, and the importance of RH noted above and in Chapter 4, this chapter concentrates on factors that affect variations in RH (although SST is also included within this discussion).

5.2 Factors which affect interannual variability of RH in the western development region

Section 4.4 showed that ENSO has an influence on hurricanes (Niño4 and SOI, to the 1% level), though this relationship is not as high as the RH relationship. This section therefore begins by considering whether ENSO may affect the hurricanes through its influence on RH. (Such a link would indeed provide a higher correlation with hurricane frequency for RH than ENSO.) This section will then conclude by examining other possible factors which may affect the RH. By exploring these links, it is hoped to identify the larger scale mechanisms leading to interannual hurricane frequency variations in the western development region. (Niño4 has boundaries at 5°S, 5°N, 160°E and 150°W.)

5.2.1 ENSO's effect on RH in the western development region

ENSO's influence on RH will be examined in terms of the Niño4 index. This is because Table 4.5 shows only variations in Niño4 and the SOI as significant to the 1% level when considering variations in hurricane frequency. Niño4 is therefore chosen as it is a tangible

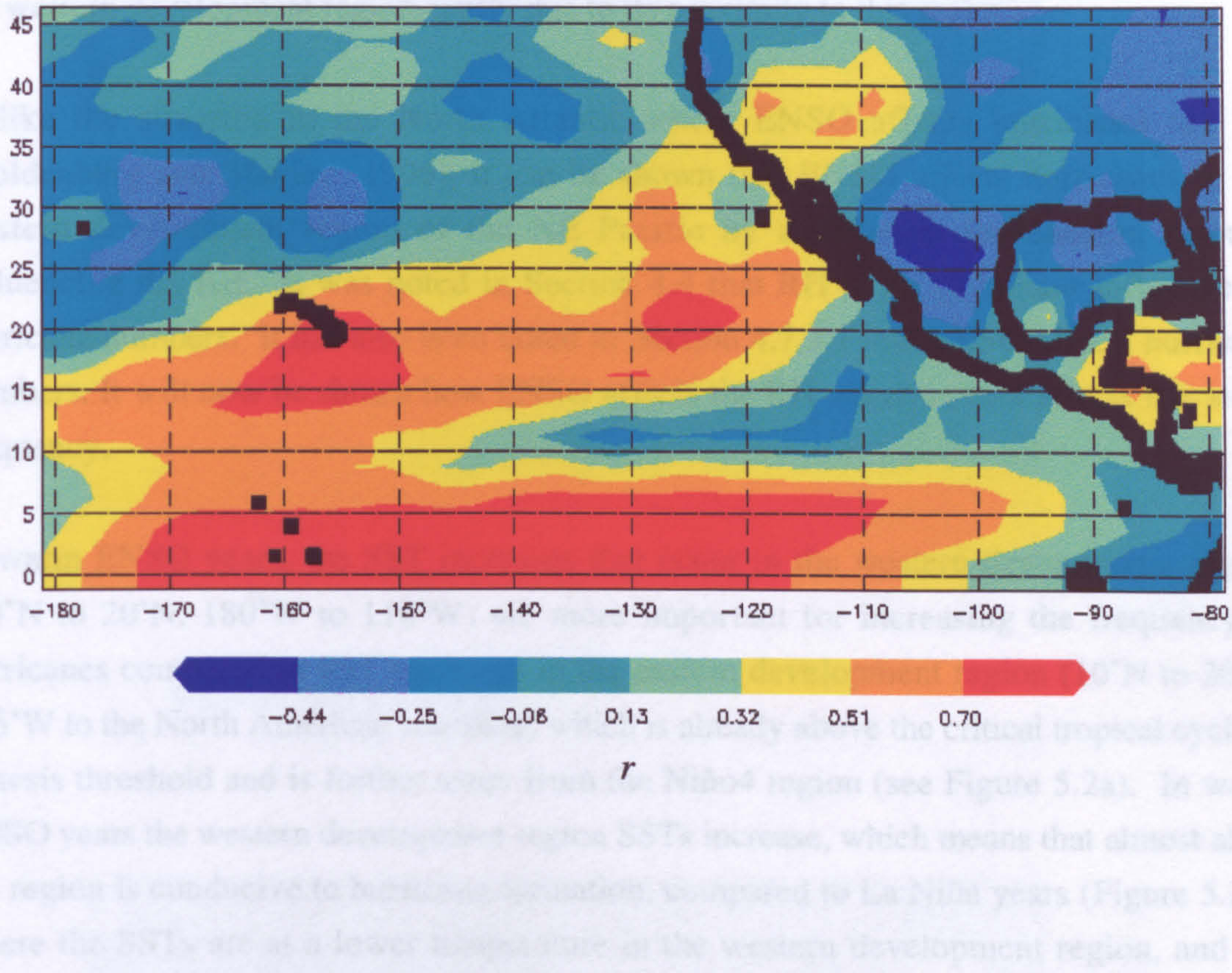


Figure 5.1 Correlation between RH and SST (and land temperatures) locally, July-September, 1972-1997.

region rather than the difference of two pressures, and is defined as a region of SST close to the western development region. It will be shown that Niño4 has an effect on the RH in the western development region, partly due to its proximity to this region.

Unlike the situation in the North Atlantic where ENSO affects hurricanes via VZ (Goldenberg and Shapiro, 1996), it can be shown that ENSO affects hurricanes in the western development region of the NE Pacific by a different mechanism, through influencing the RH. It was noted in Section 4.4 that RH is the dominant influence on hurricane numbers. It has also been noted in Section 4.7.3.1 that ENSO affects hurricane numbers. It will now be shown how ENSO affects the RH which in turn affects hurricane frequency.

In warm ENSO years, the SST increases that occur in the western development region (10°N to 20°N, 180°W to 116°W) are more important for increasing the frequency of hurricanes compared to SST increases in the eastern development region (10°N to 20°N, 116°W to the North American coastline) which is already above the critical tropical cyclone genesis threshold and is further away from the Niño4 region (see Figure 5.2a). In warm ENSO years the western development region SSTs increase, which means that almost all of the region is conducive to hurricane formation, compared to La Niña years (Figure 5.2b), where the SSTs are at a lower temperature in the western development region, and the central-north part of the region is actually at temperatures which are not conducive to hurricane formation. A similar effect can be seen when examining RH in cold and warm ENSO years (Figure 5.2c and 5.2d respectively). This spatial effect was mentioned in Section 4.7.1, where is was noted that variations can occur so that more or less of the region is conducive for hurricane formation.

It was seen in Figure 3.12 that, averaged over the whole region, there is an increasing trend of several of the environmental variables with time. Thus, the western development region of the NE Pacific basin has gone from a period of subsidence on the whole, to a period of rising air. Similarly, SSTs have gone from a colder to a warmer phase. This has also been recently pointed out by Chu and Clark (1999) who noted the rapid transition of SSTs in the central Pacific from a cold phase to a warm phase in the late 1970s. They noted that this warm phase may result in more El Niños. On the other hand, the opposite direction for the cause and effect could be suggested, with more El Niños bringing about more warm periods of SSTs in the western development region.

It can be shown that these relationships between ENSO and SST, and ENSO and RH,

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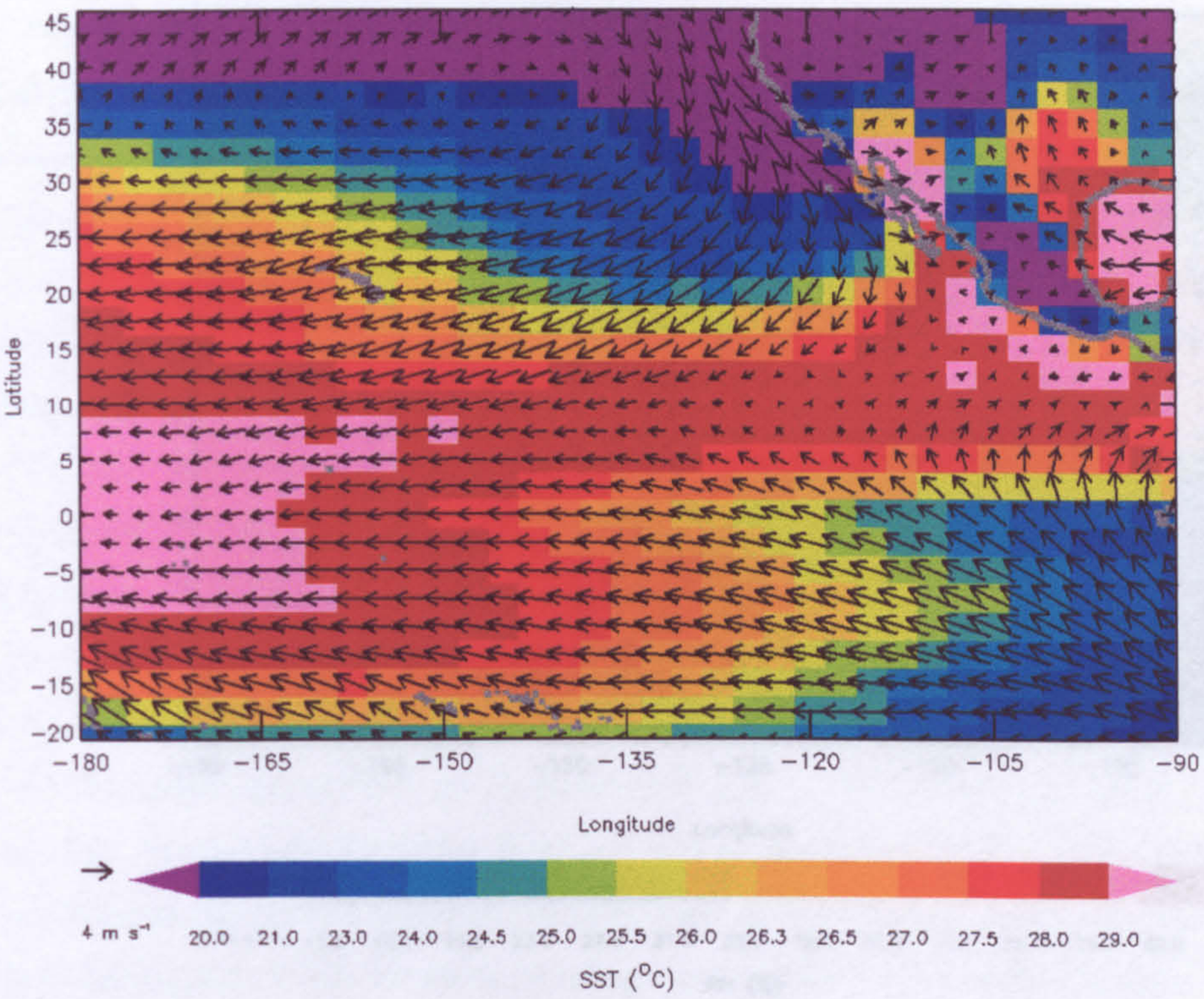
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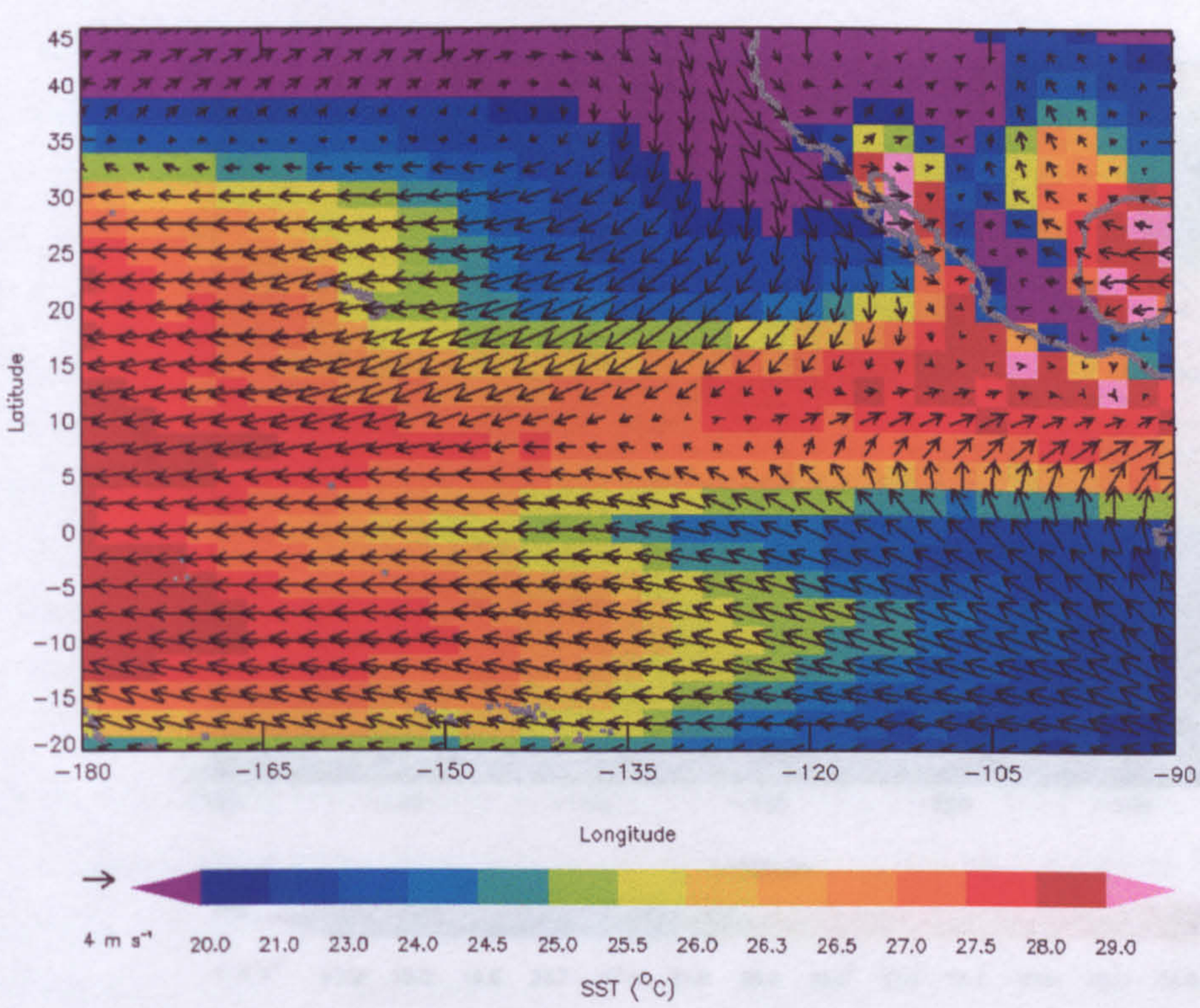
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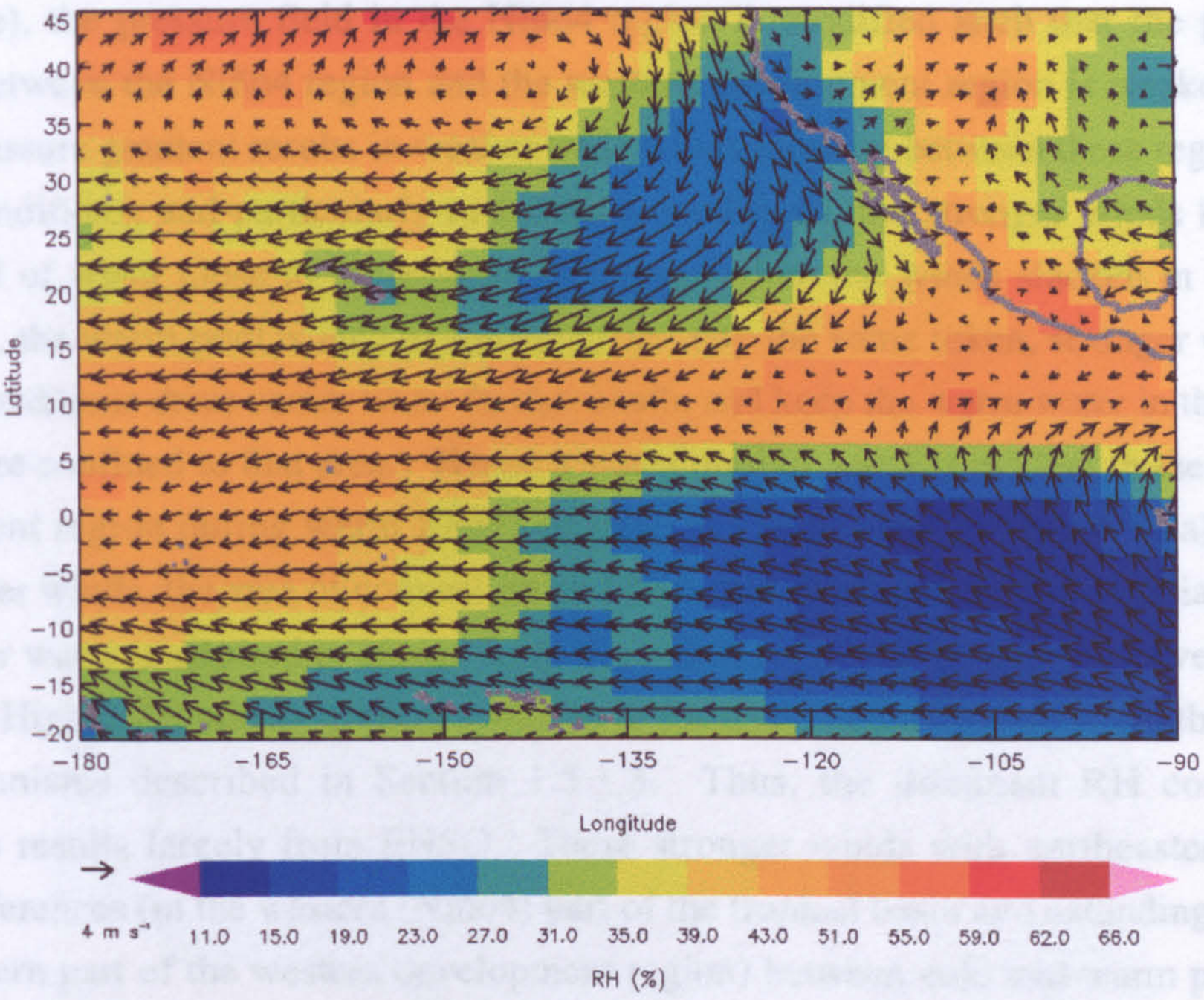

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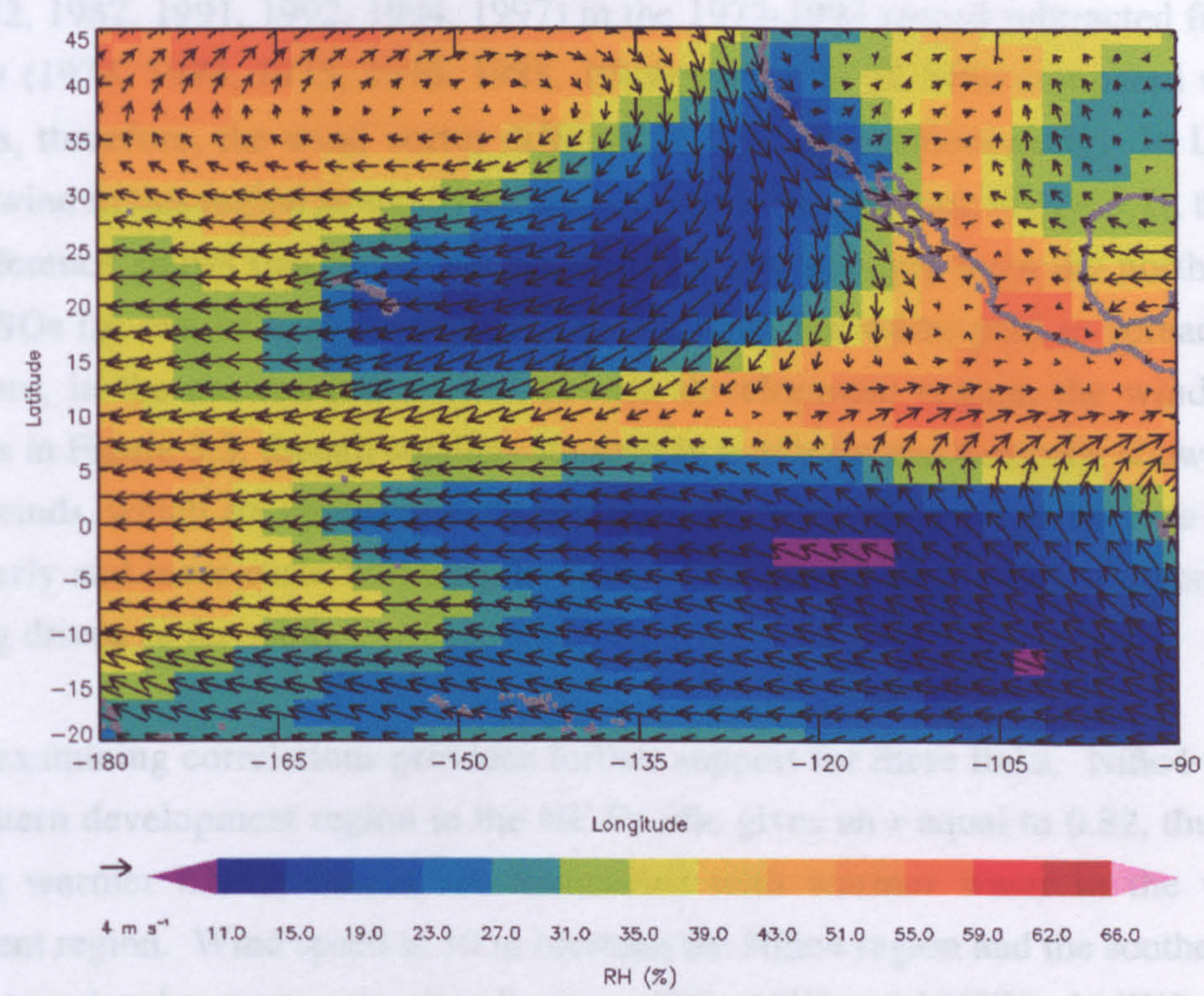

Figure 5.2 SSTs (and land temperatures), RH and surface winds at 10 m in the six warmest (1982, 1987, 1991, 1992, 1994, 1997) ENSO (Niño4) years (a and c), and six coldest (1973, 1974, 1975, 1976, 1988, 1989) ENSO years (b and d).

occur due to a link with the surface winds. During warm ENSO years (i.e. the SOI index is negative), the pressure field in the Niño4 region is modified such that the pressure gradient between the Niño4 region and the western development region is weakened. A weaker pressure gradient results in weaker trade winds blowing between these regions. In normal conditions, and particularly in La Niña conditions, the stronger winds keep the warm pool of water close to the equator. However when the winds slacken in El Niño conditions, the warm pool is able to spread north. (By the same token, stronger winds in La Niña conditions drive cooler water further south, and keep the warm water in the Niño4 region more confined to that area.) Hence a warm pool of water is evident in the western development region during warm ENSO phases (as can be seen in Figure 5.2a). Thus, with weaker winds, the area of convection and high mid-tropospheric RH associated with the warmer water is allowed to spread from the Niño4 region to the western development region. A Higher RH allows tropical cyclones to form and maintain their strength through the mechanisms described in Section 1.5.1.3. Thus, the dominant RH control on hurricanes results largely from ENSO. These stronger winds with northeasterly wind vector differences (in the western (Niño4) part of the tropical basin and extending into the southwestern part of the western development region) between cold and warm phases of ENSO can be seen in Figure 5.3, which shows a composite of the six warmest ENSO years (1982, 1987, 1991, 1992, 1994, 1997) in the 1972-1997 record subtracted from the six coldest (1973, 1974, 1975, 1976, 1988, 1989) years. In El Niño compared with La Niña years, therefore, the wind vector differences here are southwesterly. In La Niña years, the wind in this region generally blows east-north-easterly (see Figure 5.2), thus this vector difference shows that the winds are blowing less strongly from the north during warm ENSOs (as can be seen on Figure 5.2), allowing the warm pool to spread north. Furthermore, in the eastern part of the western development region, the wind vector differences in Figure 5.3, though smaller, are mainly northerly and westerly, showing that the trade winds, which are approximately northeasterly in La Niña years, become slightly less northerly and more easterly during El Niño years, preventing cooler northern water from being driven so far south.

Statistics examining correlations provides further support for these links. Niño4 vs. SST in the western development region in the NE Pacific gives an r equal to 0.82, thus again indicating warmer ENSO events are associated with warmer water in the western development region. Wind speed at 10 m between the Niño4 region and the southern edge of the western development region (i.e. between 5°N - 10°N and 180°W - 116°W) vs. SST in the western development region gives an r equal to -0.64. This supports the idea that SSTs in the western development region are warmer since the SSTs in the Niño4 region are

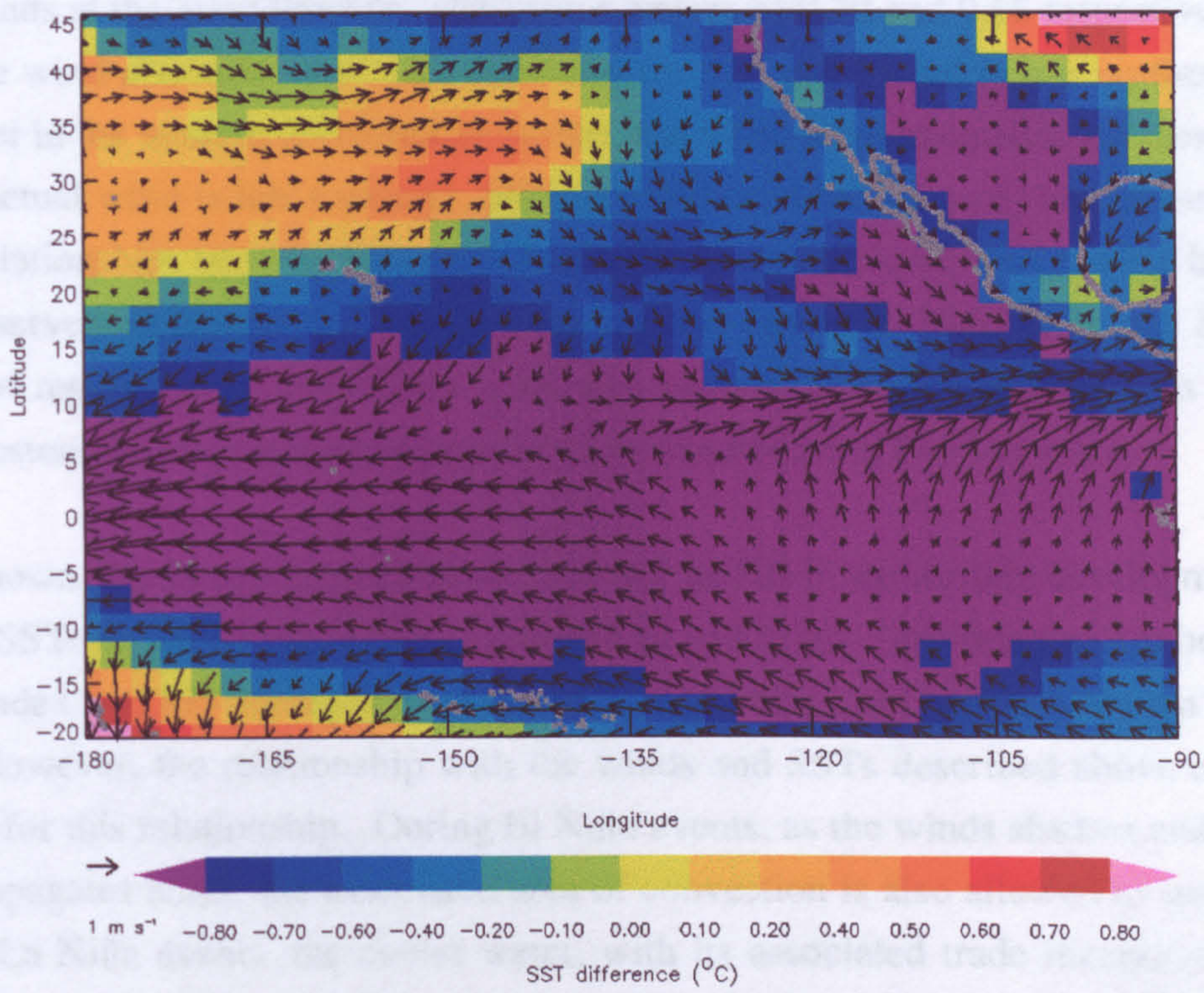

Figure 5.3 SSTs (and land temperatures) and surface winds at 10 m in the six coldest (1973, 1974, 1975, 1976, 1988, 1989) ENSO (Niño4) years minus the six warmest (1982, 1987, 1991, 1992, 1994, 1997) ENSO years.

able to spread into the western development region when there are decreased surface winds. Since winds in this region to the south of the western development region are mainly easterly in the west and mainly westerly in the east, to examine the individual wind components it is necessary to examine only the region around 5°N - 10°N, 180°W - 150°W in the west near the Niño4 region. Here, the individual components for the meridional and zonal winds at the 10 m level vs. SST give r values of 0.70 and 0.66 respectively. Thus, when the wind anomalies are more southerly (or the actual wind is less northerly), SSTs are higher in the western development region, and when wind anomalies are more westerly (or the actual wind is less easterly), SSTs are higher in the western development region. These relationships between the two vectors offer quantitative support to what has already been observed on Figures 5.2 and 5.3, namely that during El Niño years, the SSTs from the Niño4 region spread towards the north and towards the east, which explains why SSTs in the western development region would be increased during El Niño years.

It was shown that there is a relationship between the RH in the western development region and the SSTs in the Niño4 region (Figures 5.2c and 5.2d). The relationship between the Niño4 index and RH averaged over the western development region is shown by an r of 0.74. However, the relationship with the winds and SSTs described above can largely account for this relationship. During El Niño events, as the winds slacken and the warm pool propagates north, the associated area of convection is also allowed to spread north. During La Niña events, the cooler water, with its associated trade inversion, is driven further south, reducing the mid-tropospheric RH. Thus, the warmer (cooler) SSTs in the western development region can therefore cause higher (lower) levels of RH, leading to SST and RH being correlated locally with an r equal to 0.74 (also shown in Figure 5.1).

Since the trades in a La Niña phase are stronger, and a hurricane tracks west and slightly north, it means that the hurricanes are spending less time than normal in a region of warmer water and high RH, as they move into the cooler part of the western development region shown in Figure 5.2b, and thus cannot pick up extra heat and moisture needed to fuel the storm. It would be expected, therefore, that there be a stronger relationship between ENSO and average intense hurricane days than the other categories (with average hurricane days having a stronger relationship than average tropical storm days). This is also borne out from the relationship between these variables and average tropical cyclone days (see Section 4.6), and average duration of intense hurricane and ENSO (see Section 3.3.4).

It has been seen (see Tables 4.2 - 4.8) that Niño4 has little effect on variations in tropical cyclone frequency in the eastern development region. This could be explained by the fact

that the Niño4 region is far removed from this region and more local in longitudes to the western development region. However, even when other ENSO indices are examined, which are at longitudes closer to the eastern development region, again no significant effects are found. It is thought that this is due to the reason stated earlier, namely that conditions (e.g. SST, RH) are above critical values in the eastern development region in all phases of ENSO (as shown in Sections 4.7.1 and 4.7.2).

5.2.2 Other influences on RH in the western development region

An examination was conducted to identify if there are any other influences, in addition to ENSO (Niño4), that may account for the interannual variations in RH. Firstly, other large-scale climate oscillations were considered as extra variables in a multiple regression of the form

$$RH = a + bENSO + cVariable + error \tag{5.3}$$

Using deviance tests, as described in Section 4.4, the MJO and QBO showed no significant improvement to the relationship. The inclusion of the PDO (with Niño4) was found to provide a slightly improved relationship, but only to the 10% significance level (whereas the correlation between RH and Niño4 alone is significant at greater than the 1% level). Secondly, non-local variations in some of the other environmental variables were examined in terms of their effects on RH in addition to the large-scale effect of ENSO. In view of the uncertainty as to whether the PDO is a genuine influence (because its significance is only 10%), the PDO was not included as an additional variable in the following analysis. Therefore multiple regressions were again performed using Equation 5.3.

The significant relationships found are shown in Figure 5.4. It can be seen that there is a local region of SST and VVEL (Figures 5.4a and 5.4b respectively) that appears significant. However, these variables are considered to be related to RH as they are essentially Gray's thermodynamic parameters (Gray, 1979), and thus they are considered to work together, rather than being a cause and effect scenario. The same general area also shows up as a local sea level pressure correlation (Figure 5.4c). Again, this is related to Gray's thermodynamic variables (see Sections 1.5.1.3 and 1.5.1.4). However, it can also be seen that there are two non-local regions of mean sea level pressure which are significant (Figure 5.4c). The nearer of these (and the lower in pressure) is the western flank of the thermal low which forms in summer over the southwest of the United States. Since this is non-local, it can only effect the western development region RH via another variable, through a teleconnection. Figures 5.4d, 5.4e and 5.4f suggest that the surface winds may be that other variable, which also seems physically plausible. This will be examined further

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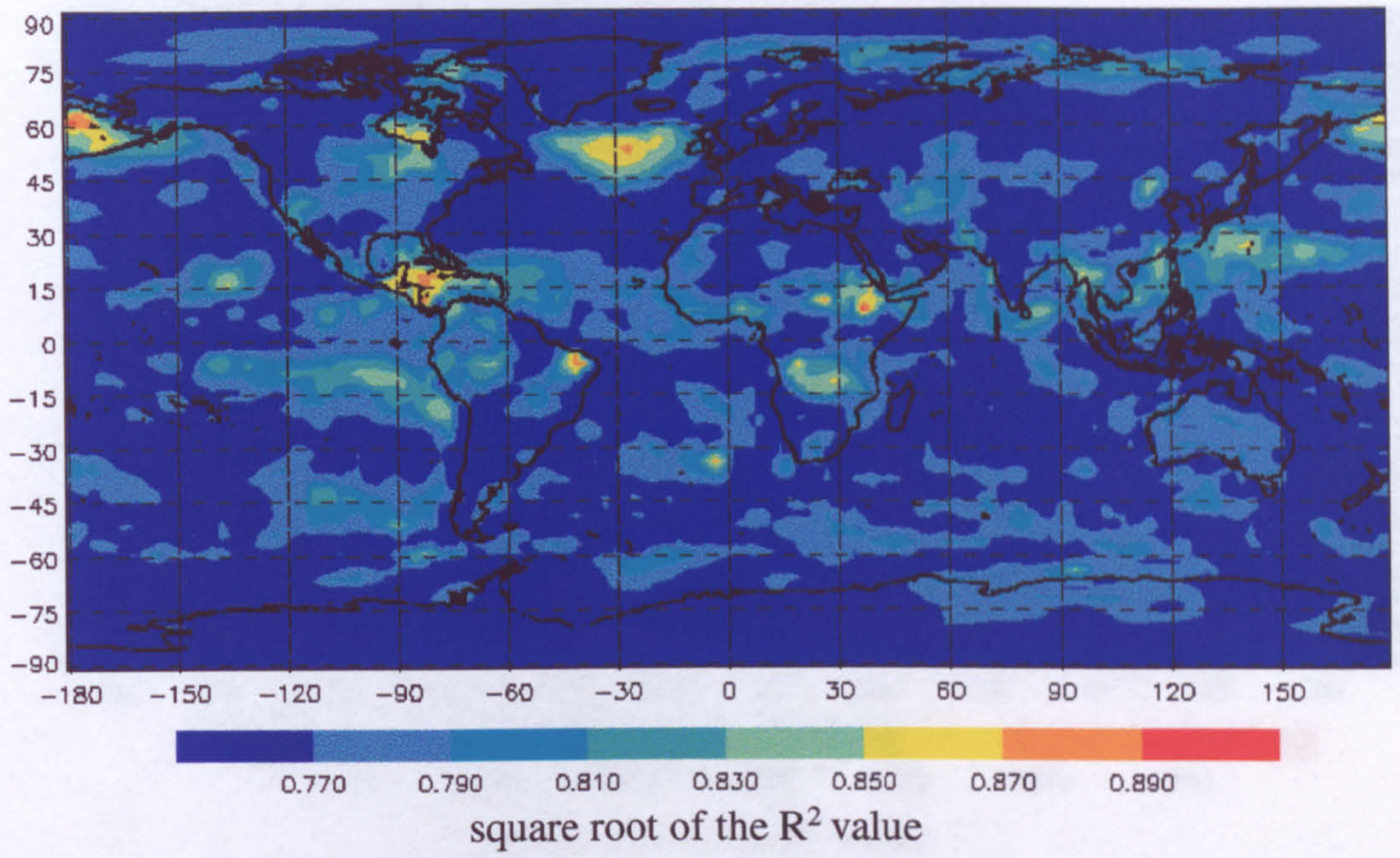

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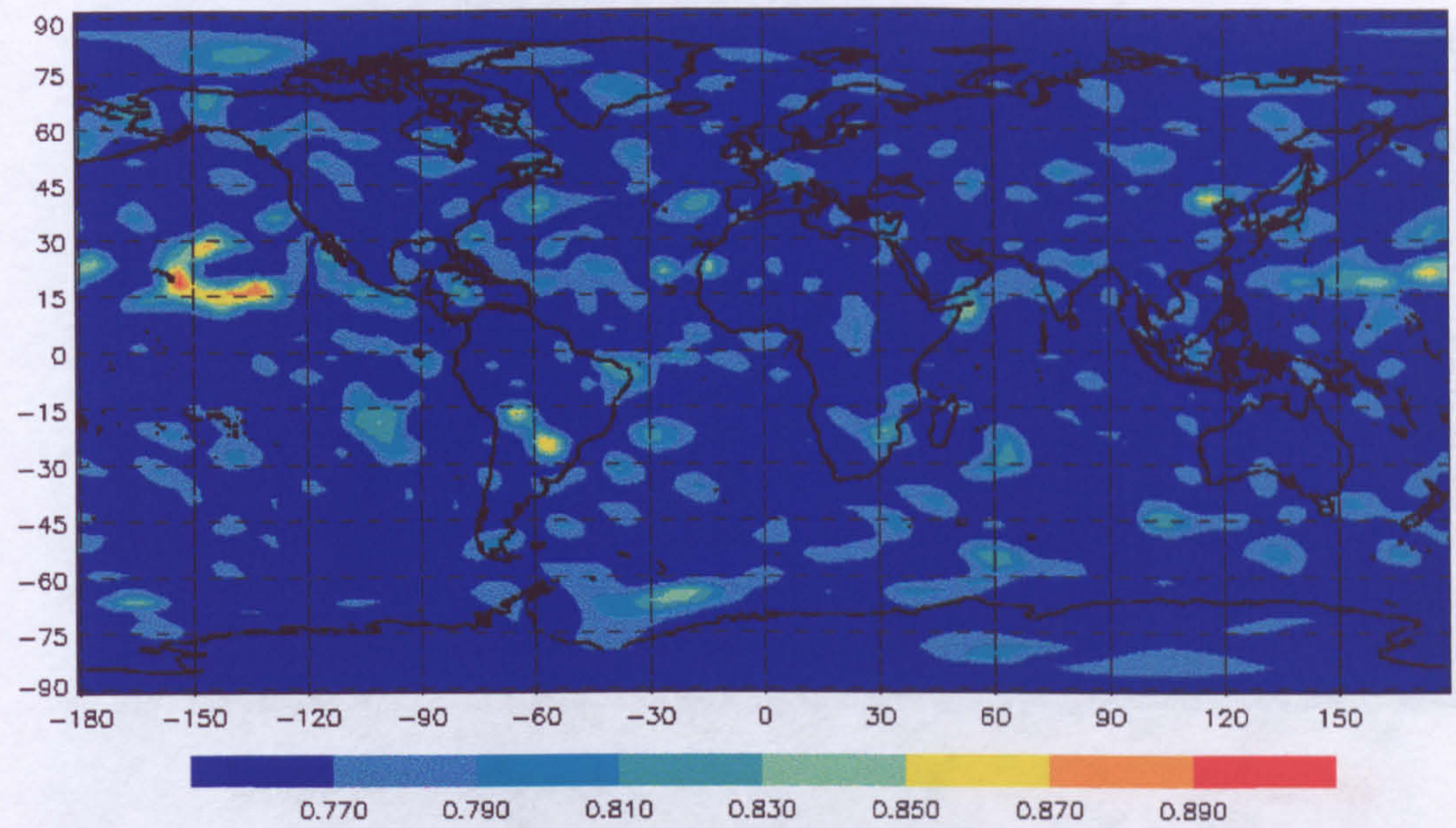

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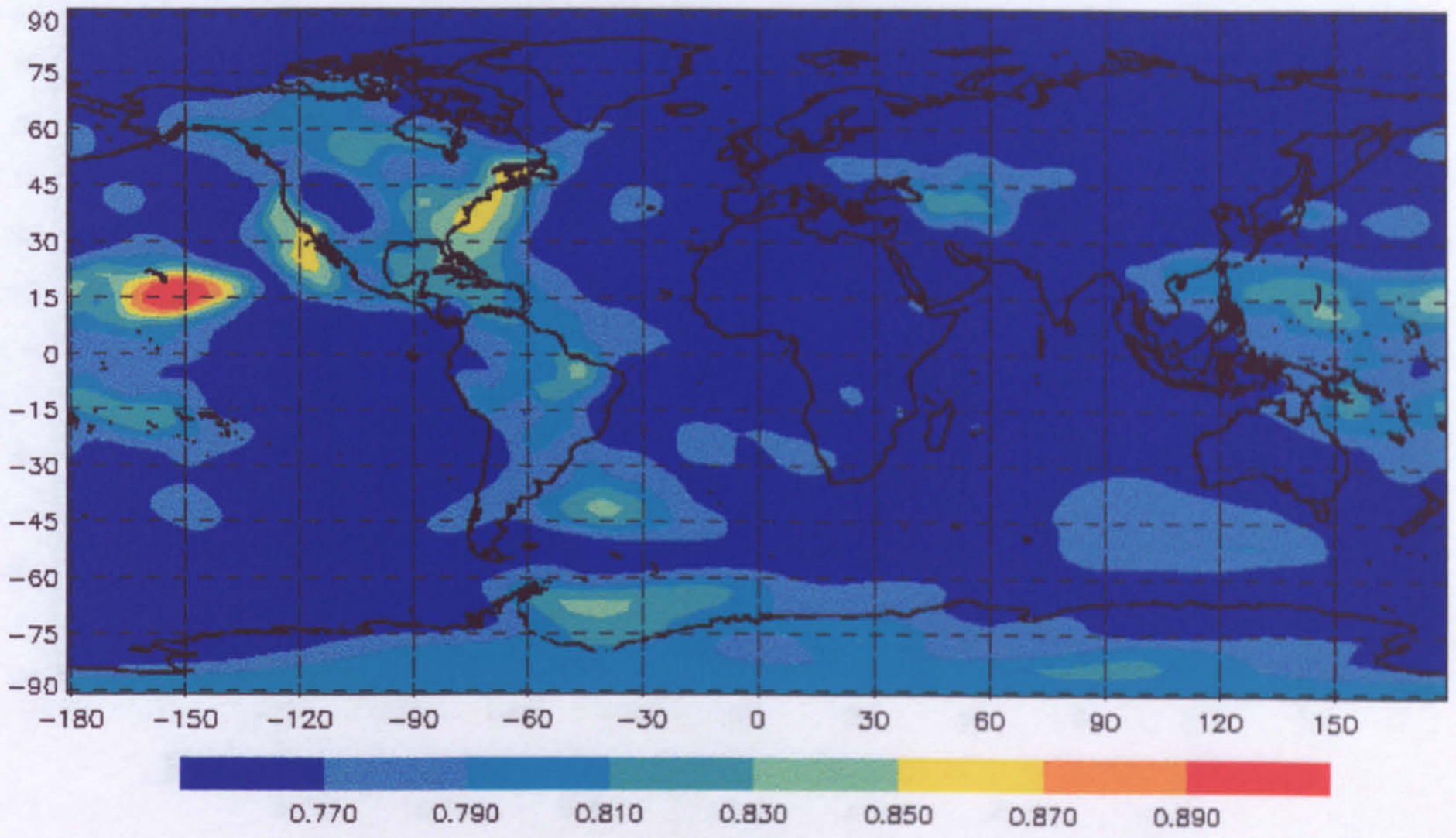

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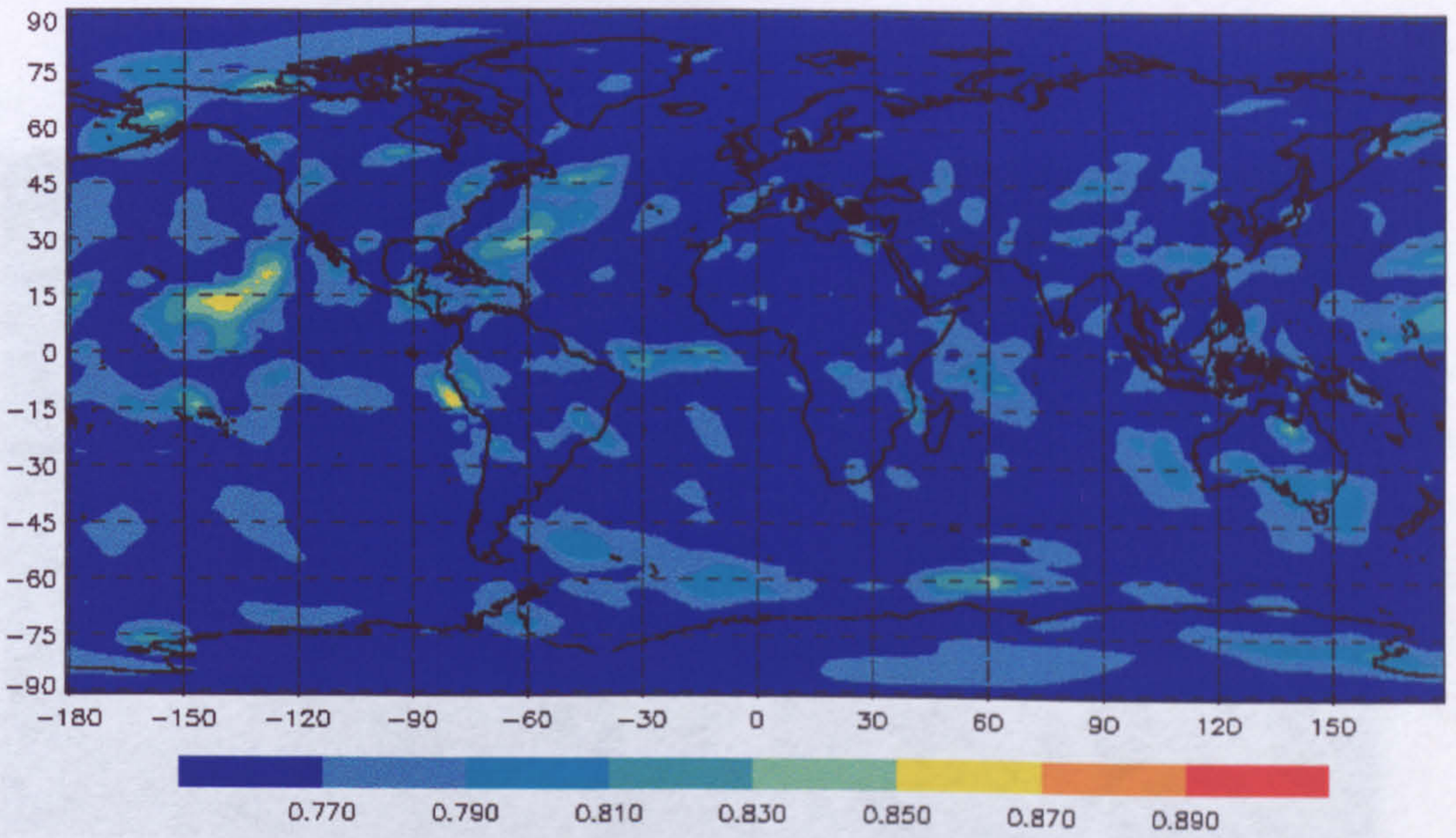

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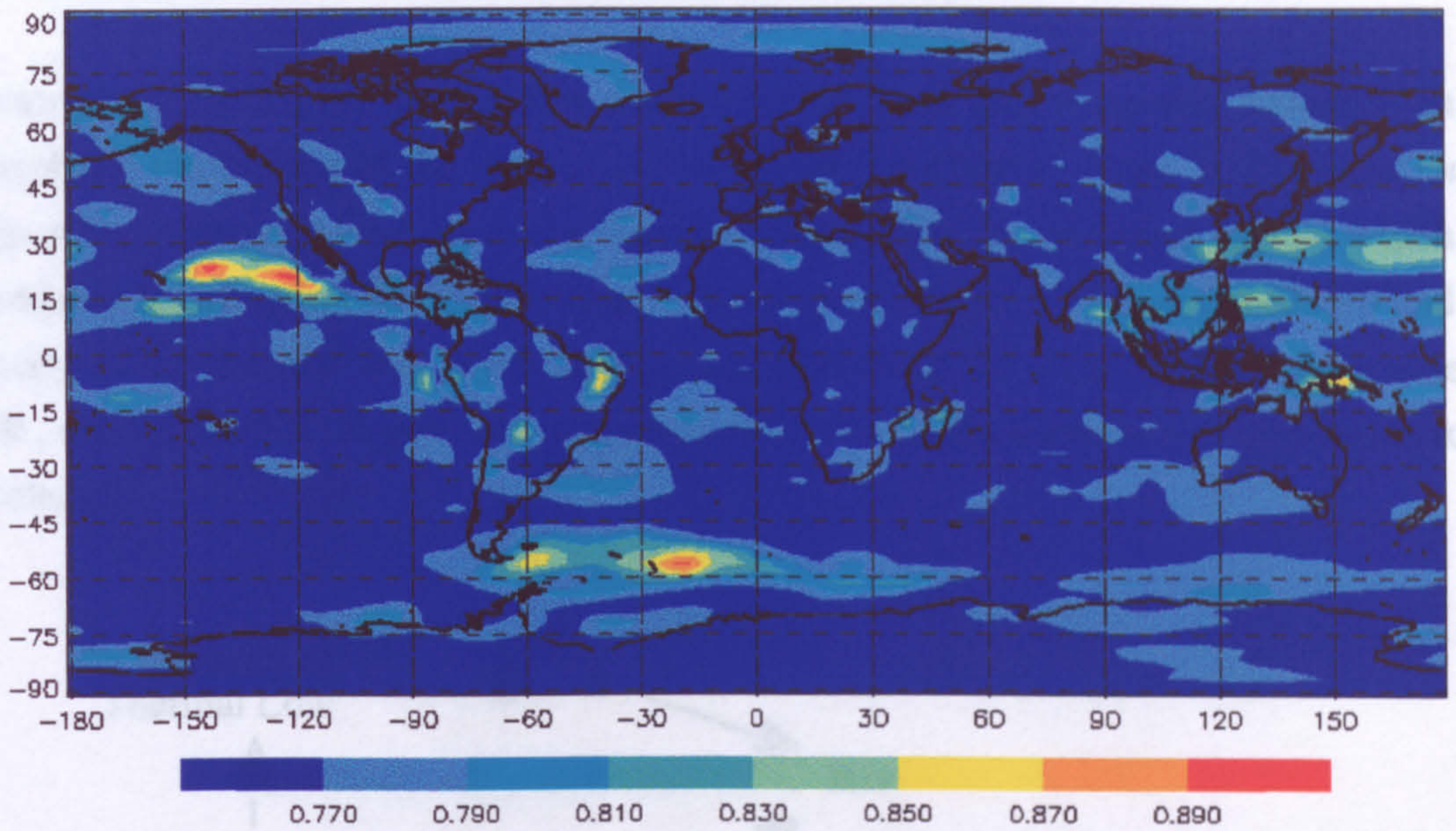

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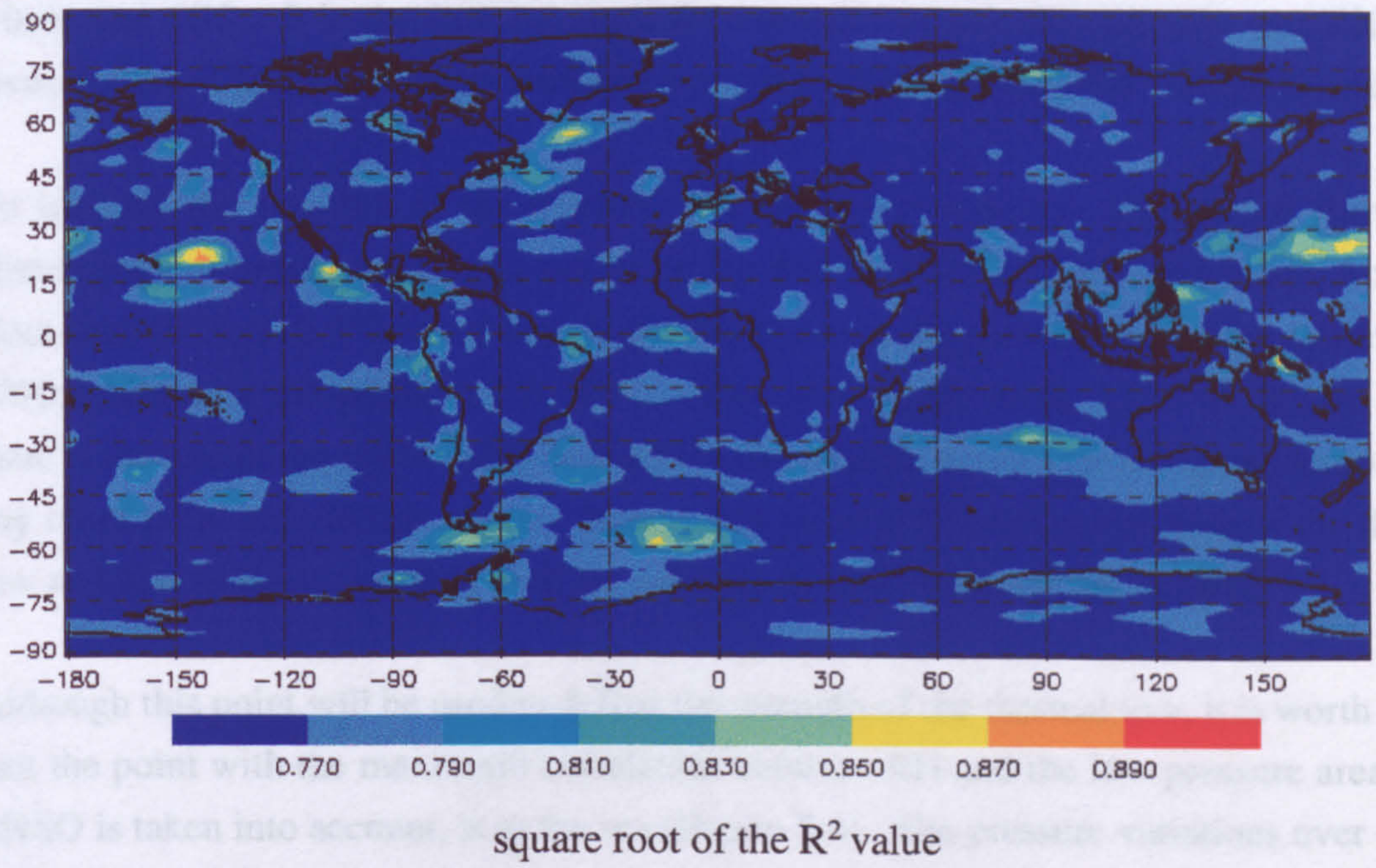


Figure 5.4 Multiple correlations using OLS regression with RH as the dependent variable and ENSO (Niño4) and a) SST (and land temperatures), b) VVEL, c) PRES, d) V wind at 10 m, e) U wind at 10 m, and f) wind speed at 10 m, as the independent variables, (July-September) 1972-1997. The square root of the R^2 value is given. The single relationship of RH and ENSO has an correlation coefficient of 0.74.

in Section 5.2.3.

It seems plausible that the thermal low could therefore be acting as another influence on the atmospheric circulation of the region, independently of ENSO. Thus, an examination of the possible influences leads us to the hypothesis that there are two main factors which are responsible for affecting RH in the western development region. These are ENSO and the intensity of the thermal low in North America, operating via other variables/processes *A* and *B* , see Figure 5.5. A possible influence of ENSO on the thermal low also needs to be considered.

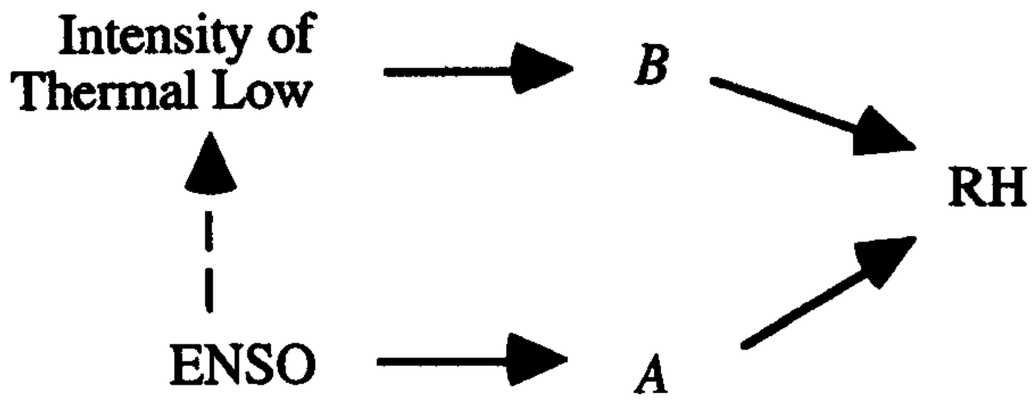


Figure 5.5 Main hypothesis for the factors affecting RH. *A* has been identified as winds and SST. *B* is the link between the intensity of the thermal low and RH to be investigated. The dashed arrow indicates a possible influence of ENSO on the thermal low.

To identify the position of the thermal low for future analysis, Figure 5.6 shows the climatology of pressure (at mean sea level) for the NE Pacific Ocean and North America. Note that 30°N, 112.5°W over land is the point where the pressure is lowest (on average 1010.4 hPa over the period 1972-1997). The same point 30°N, 112.5°W is also where there is the maximum relationship with RH in the western development region, compared to any other point around this region. Hence, this point is defined as the base of the thermal low and data from this point is used for subsequent time series of this variable.

Although this point will be used to define the strength of the thermal low, it is worth noting that the point with the maximum correlation between RH and the low pressure area when ENSO is taken into account, is in the sea (Figure 5.4). The pressure variations over land at 30°N, 112.5°W extend over the sea in some years more than others. When the thermal low is particularly low, the pressure over the nearby sea also generally gets lower and vice versa. This can be seen in Figures 5.7a and 5.7b, which show an extreme intense and less intense year of the thermal low. In the former, it can be seen that the low pressure region is broad and extends a long way over the sea. A correlation between the thermal low and the

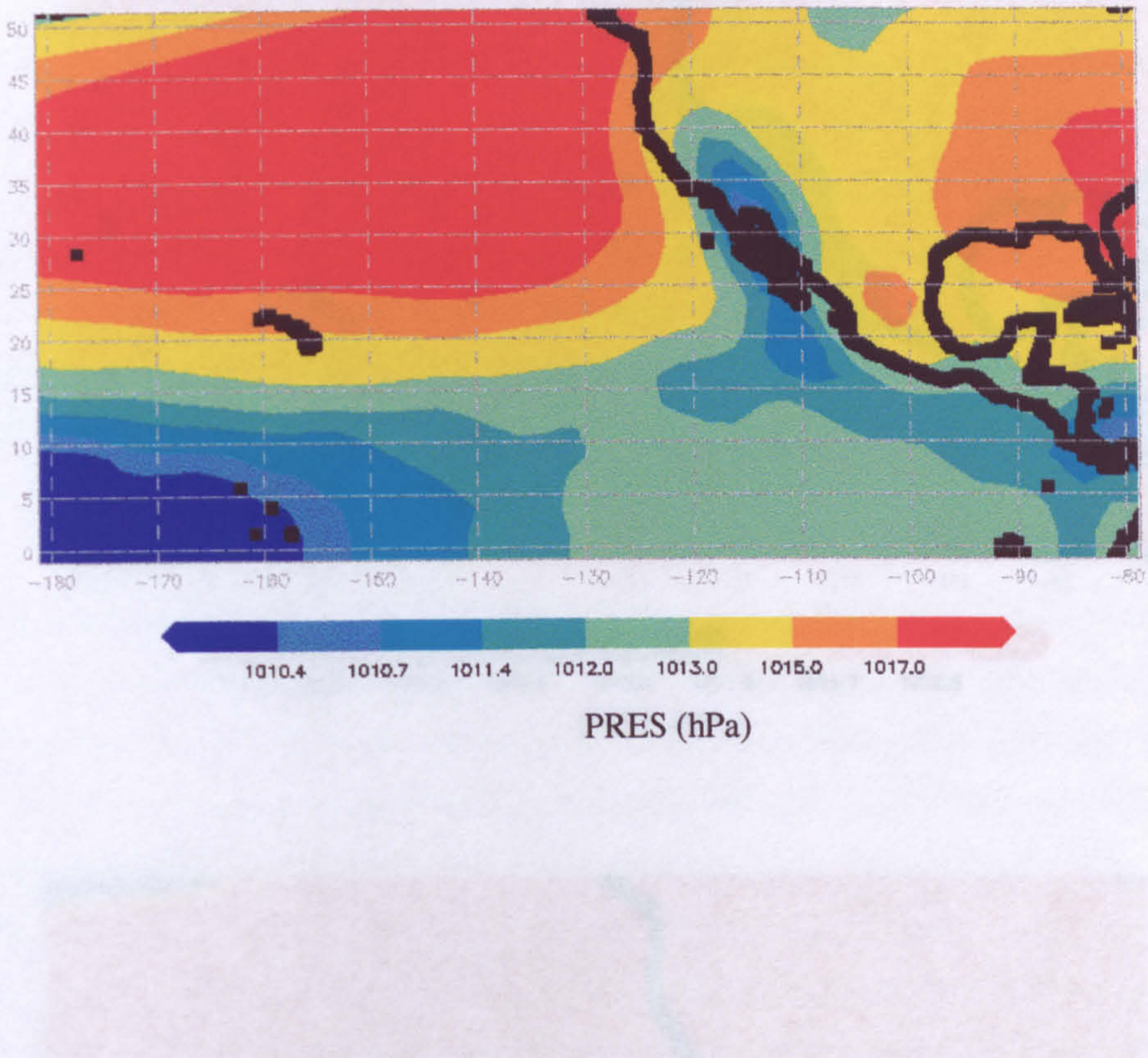
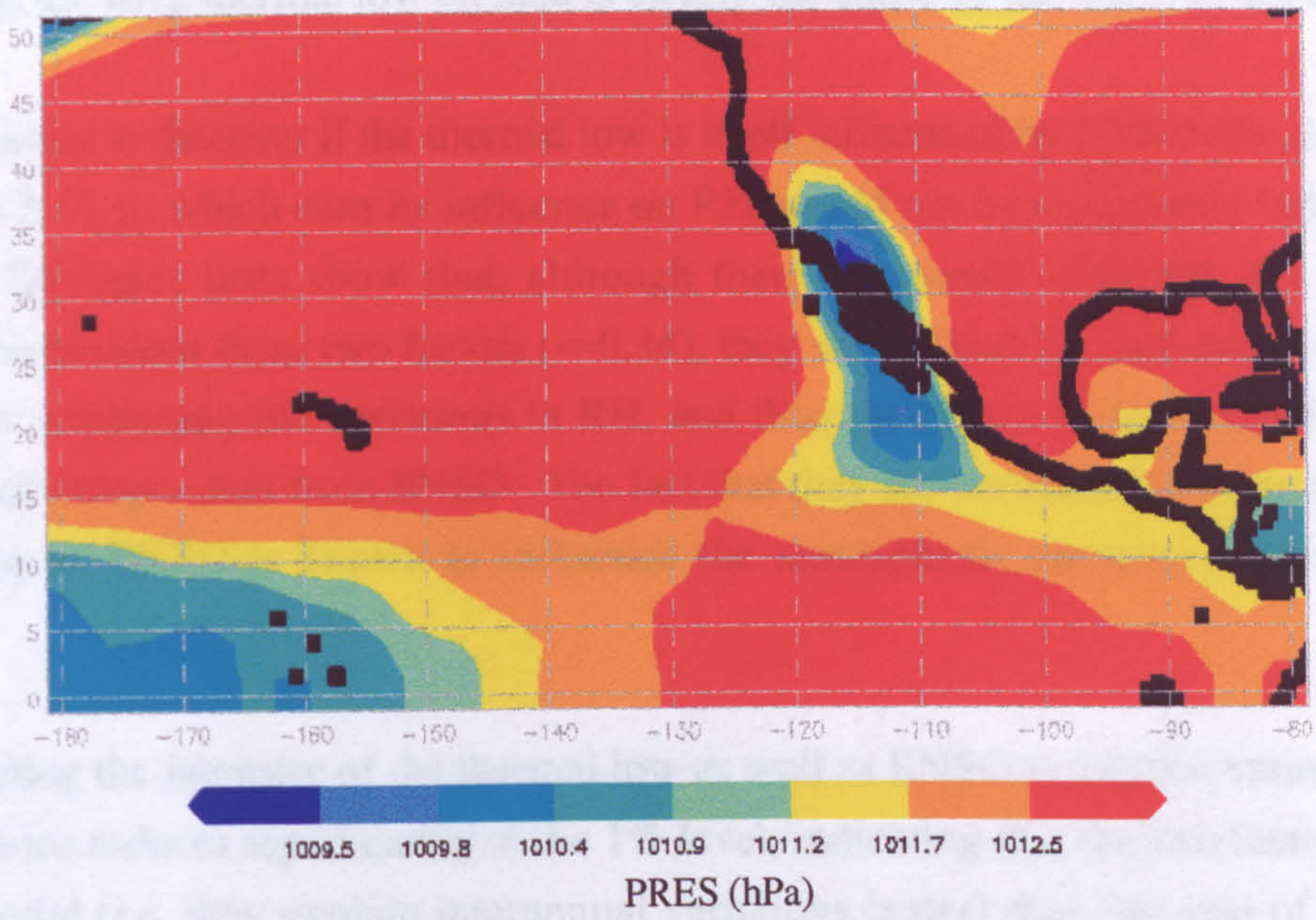


Figure 5.6 Climatology of pressure (mean sea level), July-September, 1972-1997.

a)



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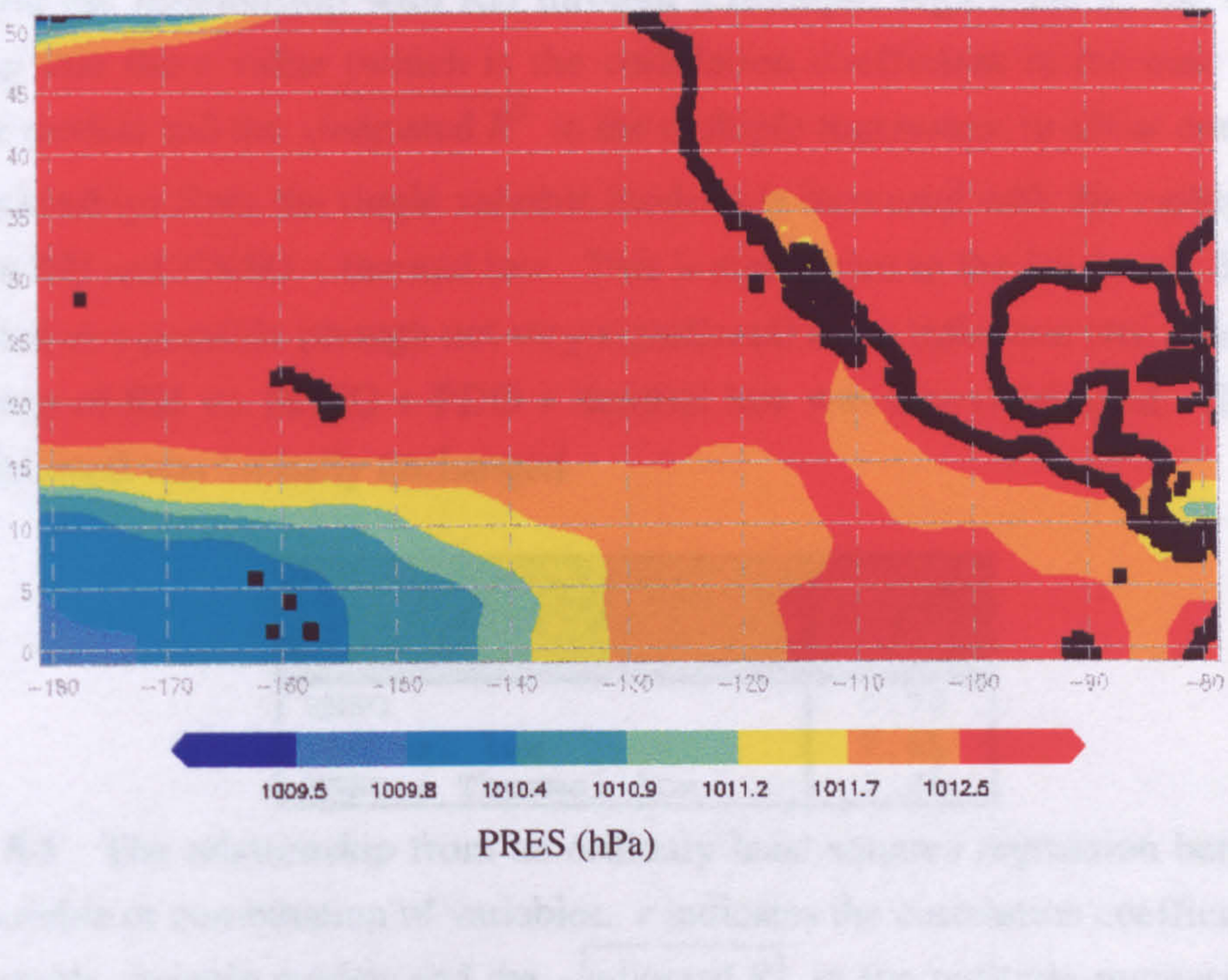


Figure 5.7 Climatology of pressure (mean sea level), July-September, a) 1995, b) 1991.

lowest sea low (at 17.5°N, 110°W) in this area gives an r of 0.80, and from physical reasoning, the deep thermal low on land is clearly the cause of the sea low, not the effect.

It is important to discover if the thermal low is itself influenced by ENSO (the dashed arrow in Figure 5.5), in which case its influence on RH would not be completely independent of ENSO. Deviance tests show that, although there is a small (although not significant) correlation between these two factors (r=0.34), they should both be included to improve the model for explaining the variations in RH, and thus the effect of the thermal low can be considered independent from ENSO. The fact that they are correlated to some degree is not surprising as ENSO is known to influence the atmospheric circulation in surrounding regions.

By including the intensity of the thermal low as well as ENSO to explain variations in RH, the deviance reduces significantly at the 1% level, indicating that the two factors provide a better model (i.e. they explain interannual variations better) than just one of them alone. Table 5.1 below shows the relationships between RH and each variable (ENSO and thermal low), and the relationship with RH through a multiple regression of the two variables showing that the r value (which is the correlation coefficient in the case of the single variable models and the $\sqrt{\text{adjusted } R^2}$ in the multiple regression, to allow comparison with the relationships from the single variable models) is increased with the multiple regression between RH and ENSO + thermal low. This is significant to the 1% level. Since the PDO was noted as a possible (though not very significant) extra influence (see above) a multiple regression of RH vs. ENSO + PDO + thermal low was also conducted. However, the r value obtained was virtually unchanged.

Relationship with RH	r
ENSO	0.74
Thermal low	0.65
ENSO + Thermal low	0.85

Table 5.1 The relationship from an ordinary least squares regression between RH and each variable or combination of variables. r indicates the correlation coefficient in the case of the single variable models and the $\sqrt{\text{adjusted } R^2}$ in the multiple regression. ENSO is defined as the Niño4 index, the thermal low is defined as the pressure (at mean sea level) at 30°N, 112.5°W.

The independent influence of ENSO and the thermal low can be seen directly in time plots of RH, ENSO and the thermal low (Figure 5.8). Let us consider a few examples starting

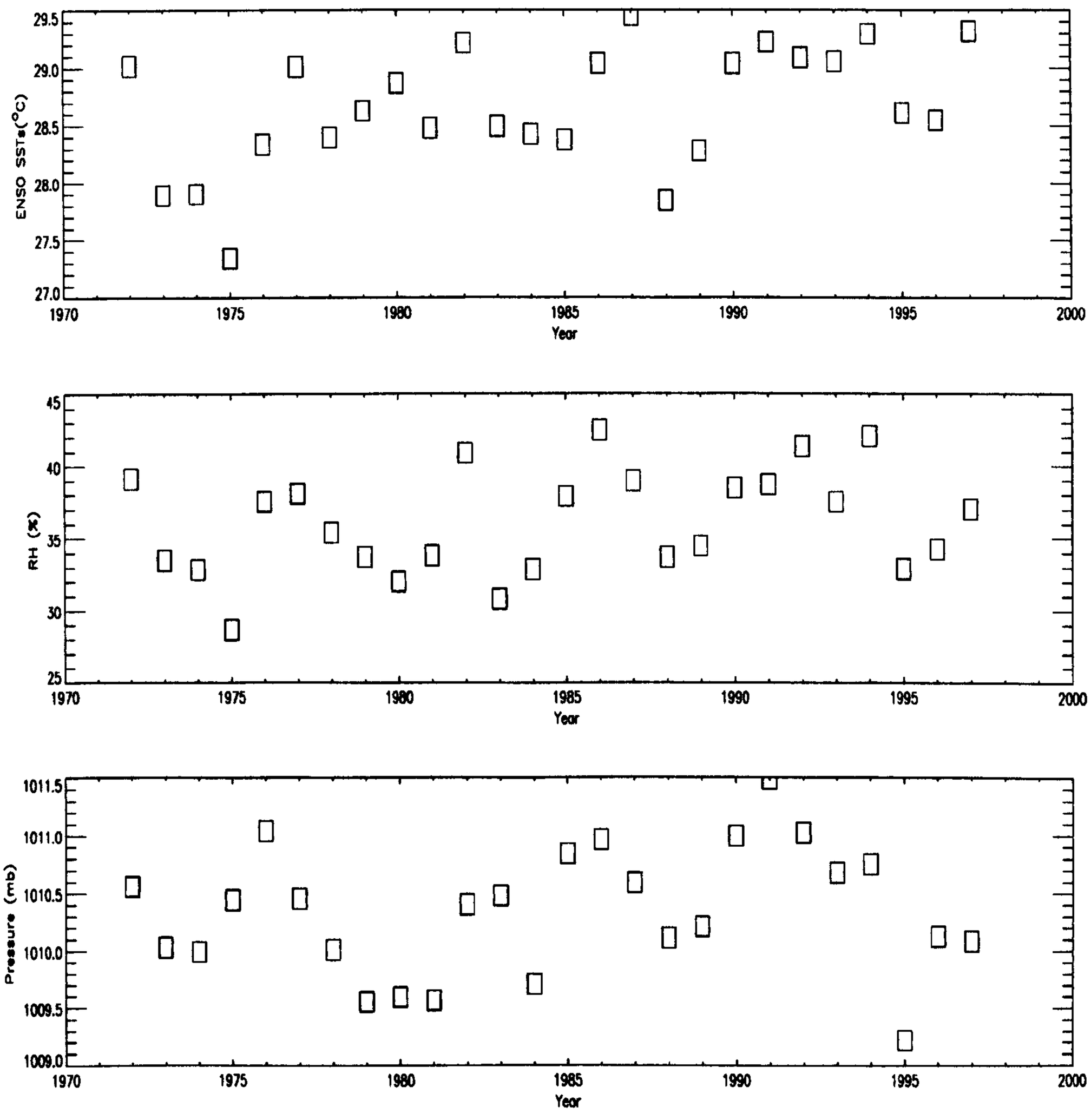


Figure 5.8 Time plots of ENSO (Niño4), RH in the western development region, and pressure of the thermal low, (July-September) 1972-1997. (Note: in figure 1mb = 1 hPa).

with the sequence 1975, 1976 and 1977. 1975 is the coldest ENSO year and the thermal low is at a moderate level, thus the main influence on RH is the cold ENSO year and therefore RH is also very low. However, if one now compares 1976 with 1977, if ENSO alone accounted for the variations in RH, it would be expected that RH would increase from 1976 to 1977 in line with the ENSO increase. However, while ENSO increases from a moderate to a high level, the thermal low changes from a high pressure value to a moderate pressure. The net effect on RH is that its value in 1977 remains about the same as its 1976 value. Between 1979 and 1981, the RH is low in line with the thermal low experiencing intense (i.e. low pressure) years (whilst the ENSO index is fairly moderate). On the other hand, 1982 sees a high RH year since ENSO is in an extreme warm phase (whilst the thermal low is moderate). Finally, if we consider the last three years, 1996 has a moderate RH, reflecting moderate values of both the model variables. In 1995, however, the RH is depressed by an intense thermal low (with a moderate ENSO) and in 1997 the RH is elevated by a strong ENSO (with a moderate thermal low).

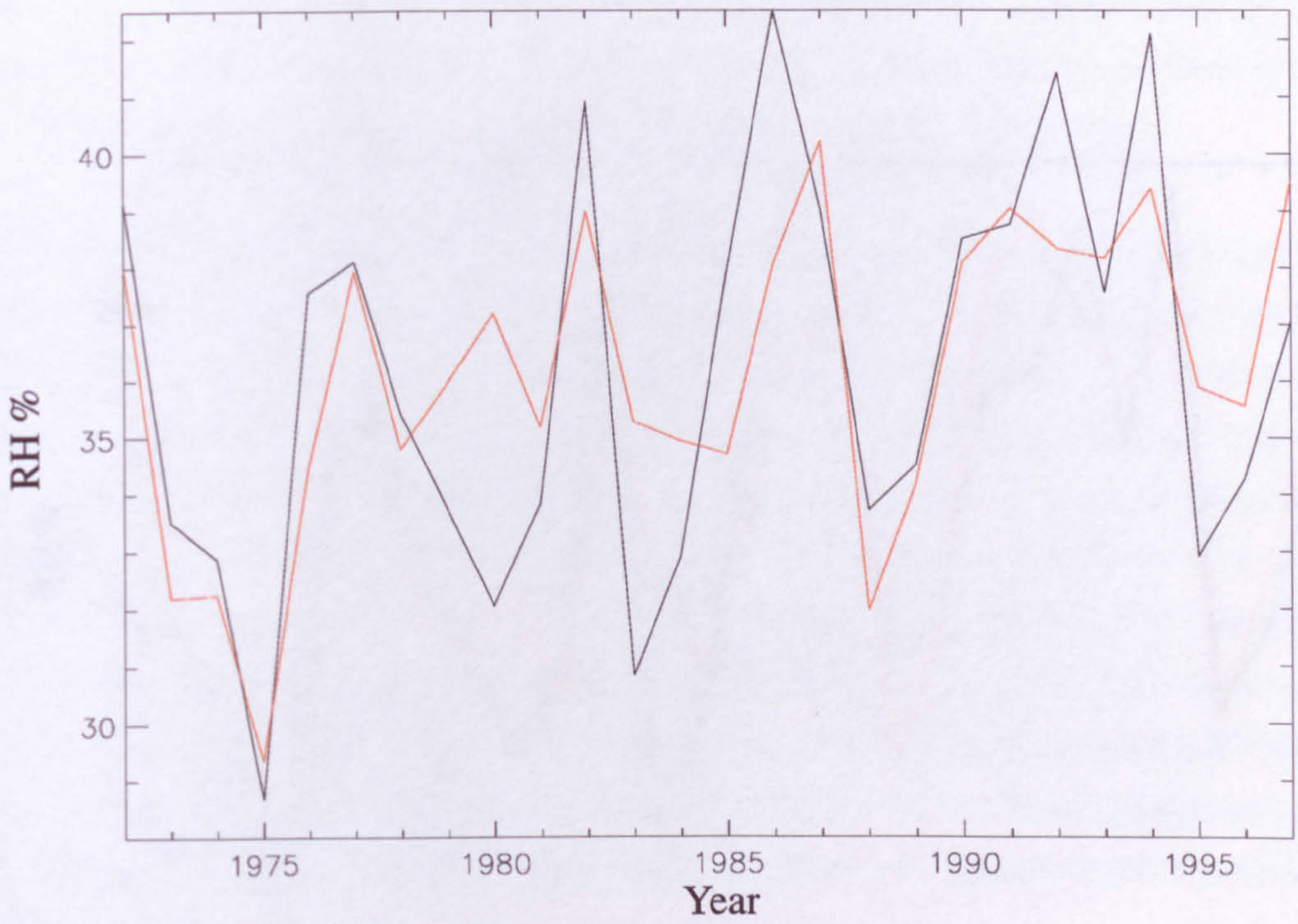
The influence of ENSO and the thermal low together on the RH of the western development region can be further exemplified by examining the actual RH with time in the western development region and comparing these with the fitted values of the RH from the models of a) RH vs. ENSO (Niño4), b) RH vs. the thermal low, and c) RH vs. ENSO and the thermal low (Figure 5.9). It can be seen that generally the fitted values from the combined model (Figure 5.9c) more closely resemble the actual values of RH, than the other two single models. For example, in 1976, the plot of RH vs. ENSO (Figure 5.9a) gives a fitted value of RH which is much less than the actual value. On the other hand, the plot of RH vs. the thermal low (Figure 5.9b) gives a fitted value of RH with a higher value than the actual RH. When combined together (Figure 5.9c), it is shown that the fitted value and actual value of RH are more similar. The opposite effects occur in 1995, where again the combined fit is much better.

It has been shown in Section 5.2.1 how ENSO influences RH in the western development region primarily through the surface winds and SST (i.e. *A* in Figure 5.5). Let us now explore how the thermal low may affect RH in the western development region (i.e. *B* in Figure 5.5).

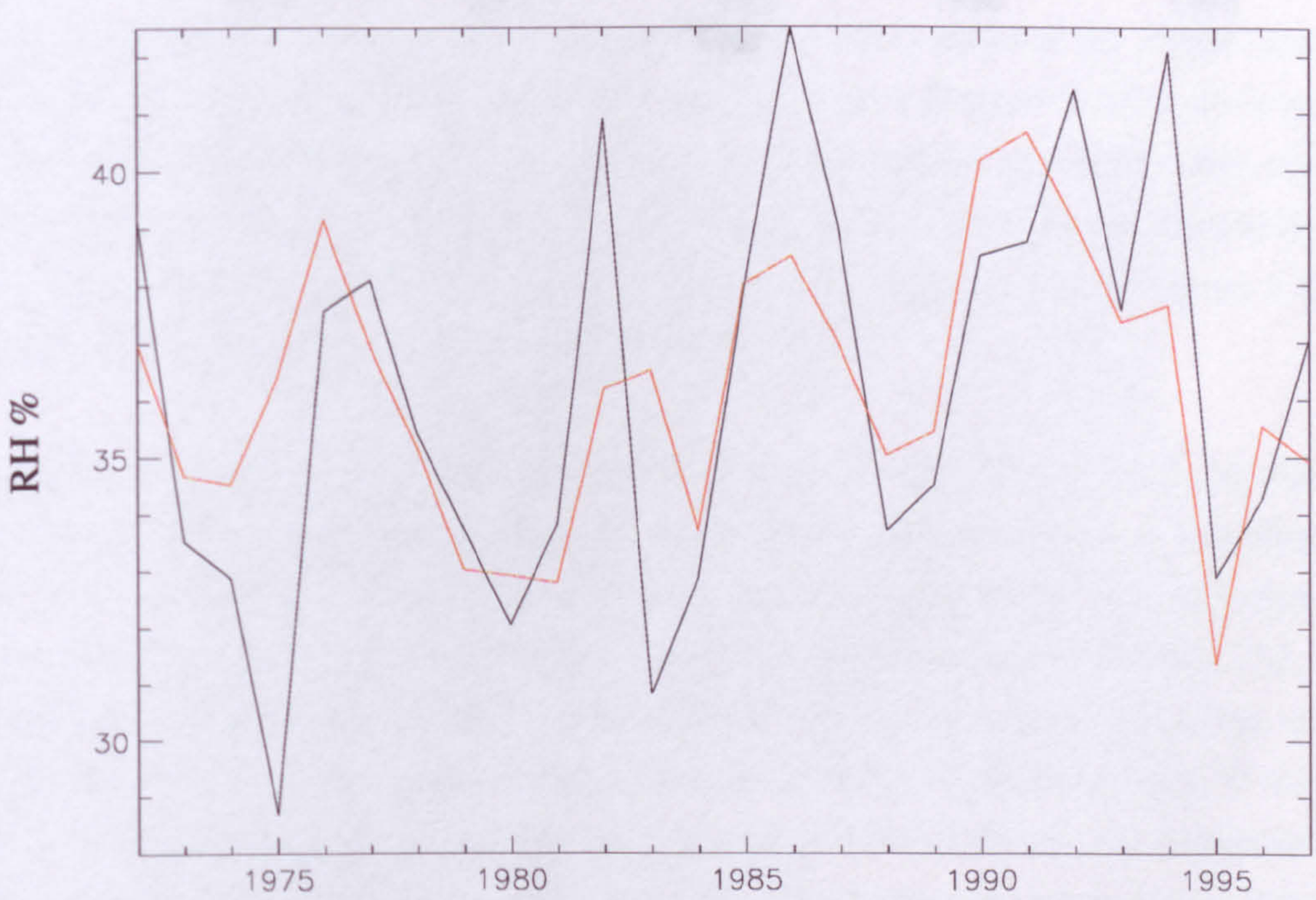
5.2.3 Understanding the link between the thermal low and RH in the western development region

The relationship with the thermal low and RH is strong. This section examines this relationship in detail to explore the mechanism for this cause and effect. Since there is a

a)


40
35
30
RH %
1975
1980
1985
1990
1995
Year

b)


40
35
30
RH %
1975
1980
1985
1990
1995
Year

c)

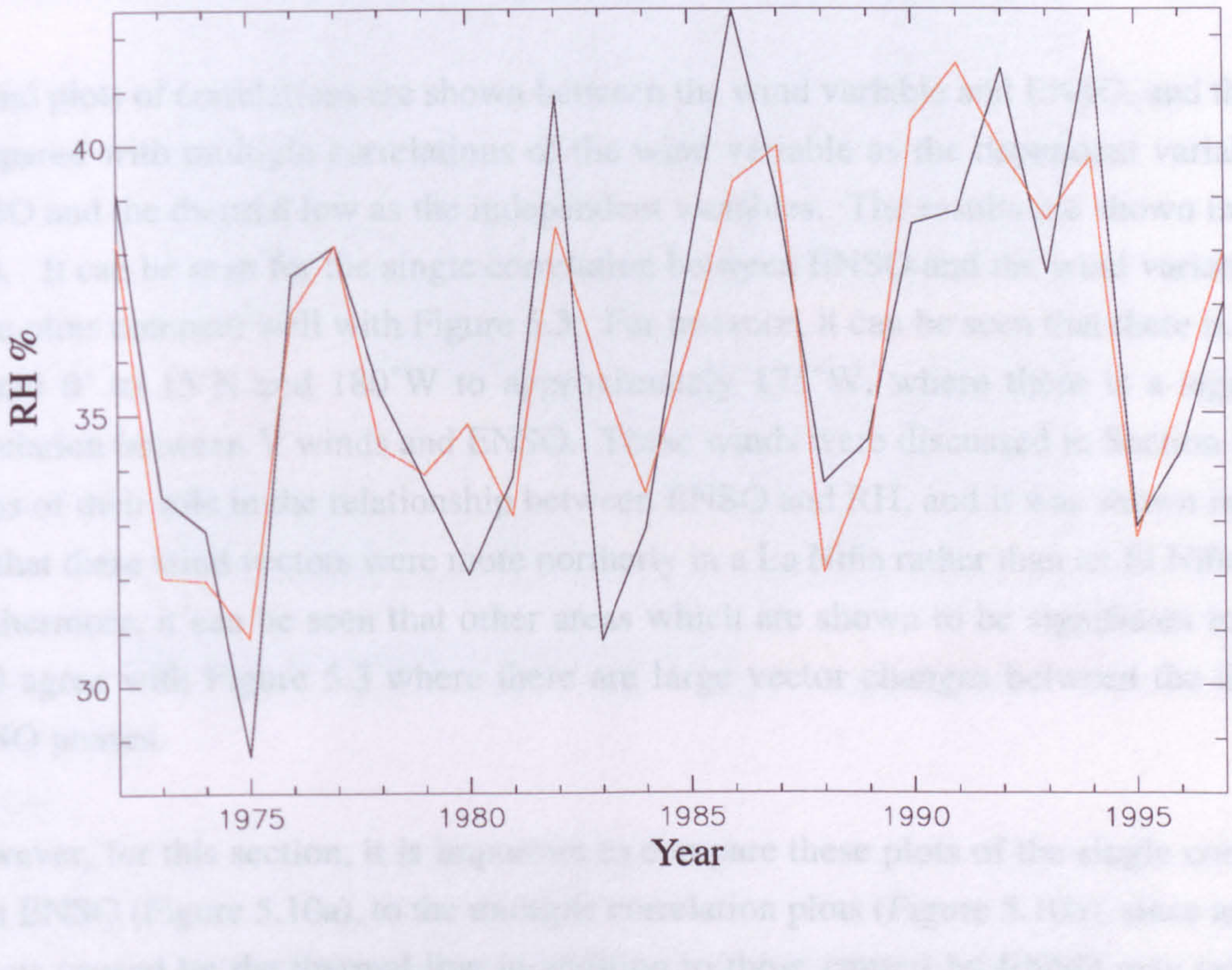


Figure 5.9 Actual RH in the western development region vs. fitted values of RH in the western development region for July-September, 1972-1997 using a model with a) ENSO only, b) thermal low only, and c) ENSO and thermal low. Actual RH is shown in black. Model fitted RH is shown in orange.

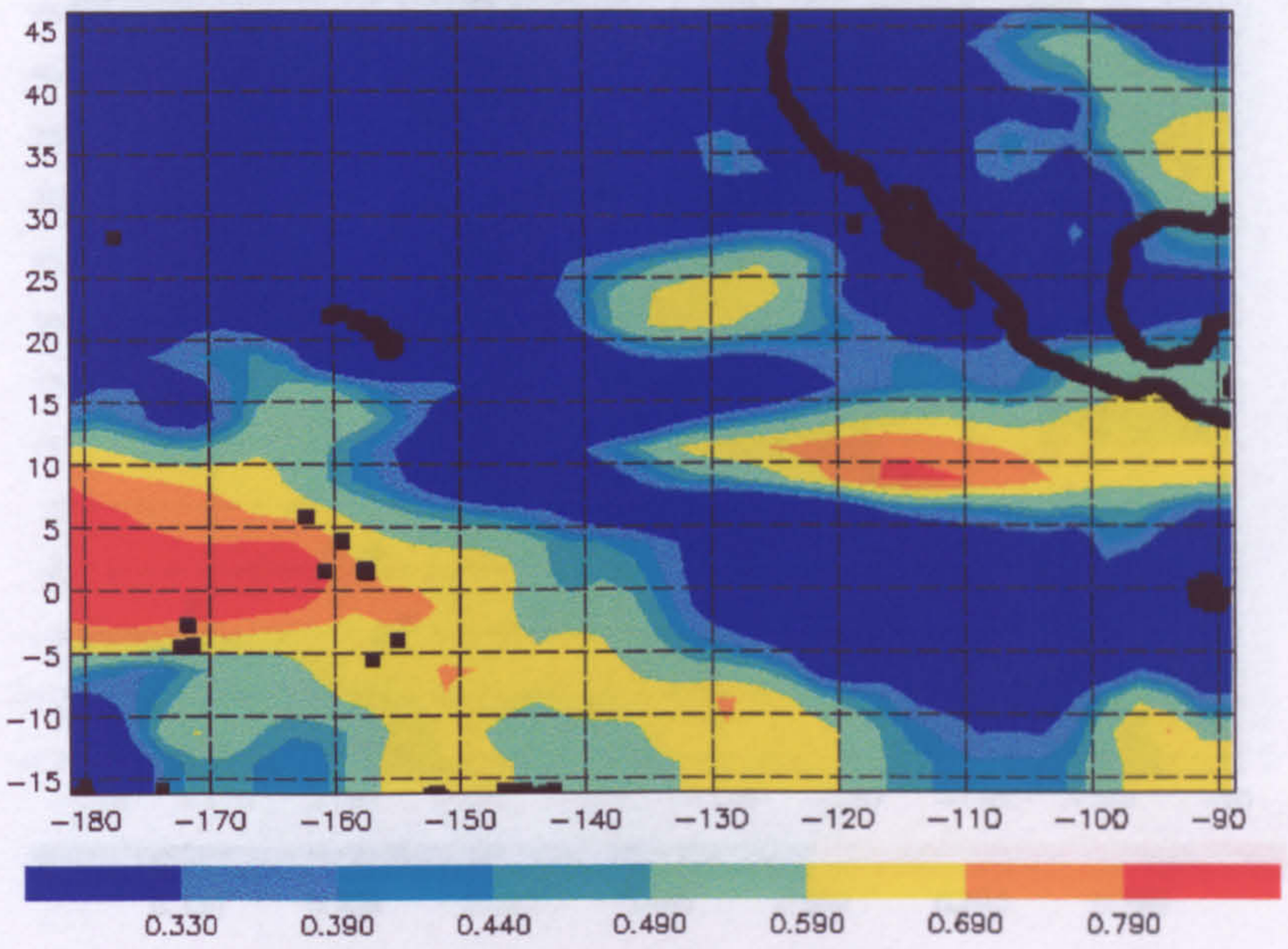
well-known relationship between pressure and winds, and since Figure 5.4d, 5.4e and 5.4f show a good relationship with the RH (when taking ENSO into account), surface winds are examined to determine their role in the relationship between the thermal low and the RH (i.e. surface winds are examined to see if they represent *B* in Figure 5.5).

Spatial plots of correlations are shown between the wind variable and ENSO, and these are compared with multiple correlations of the wind variable as the dependent variable and ENSO and the thermal low as the independent variables. The results are shown in Figure 5.10. It can be seen for the single correlation between ENSO and the wind variables that these plots compare well with Figure 5.3. For instance, it can be seen that there is an area around 0° to 15°N and 180°W to approximately 175°W, where there is a significant correlation between V winds and ENSO. These winds were discussed in Section 5.2.1 in terms of their role in the relationship between ENSO and RH, and it was shown in Figure 5.3 that these wind vectors were more northerly in a La Niña rather than an El Niño phase. Furthermore, it can be seen that other areas which are shown to be significant in Figure 5.10 agree with Figure 5.3 where there are large vector changes between the different ENSO phases.

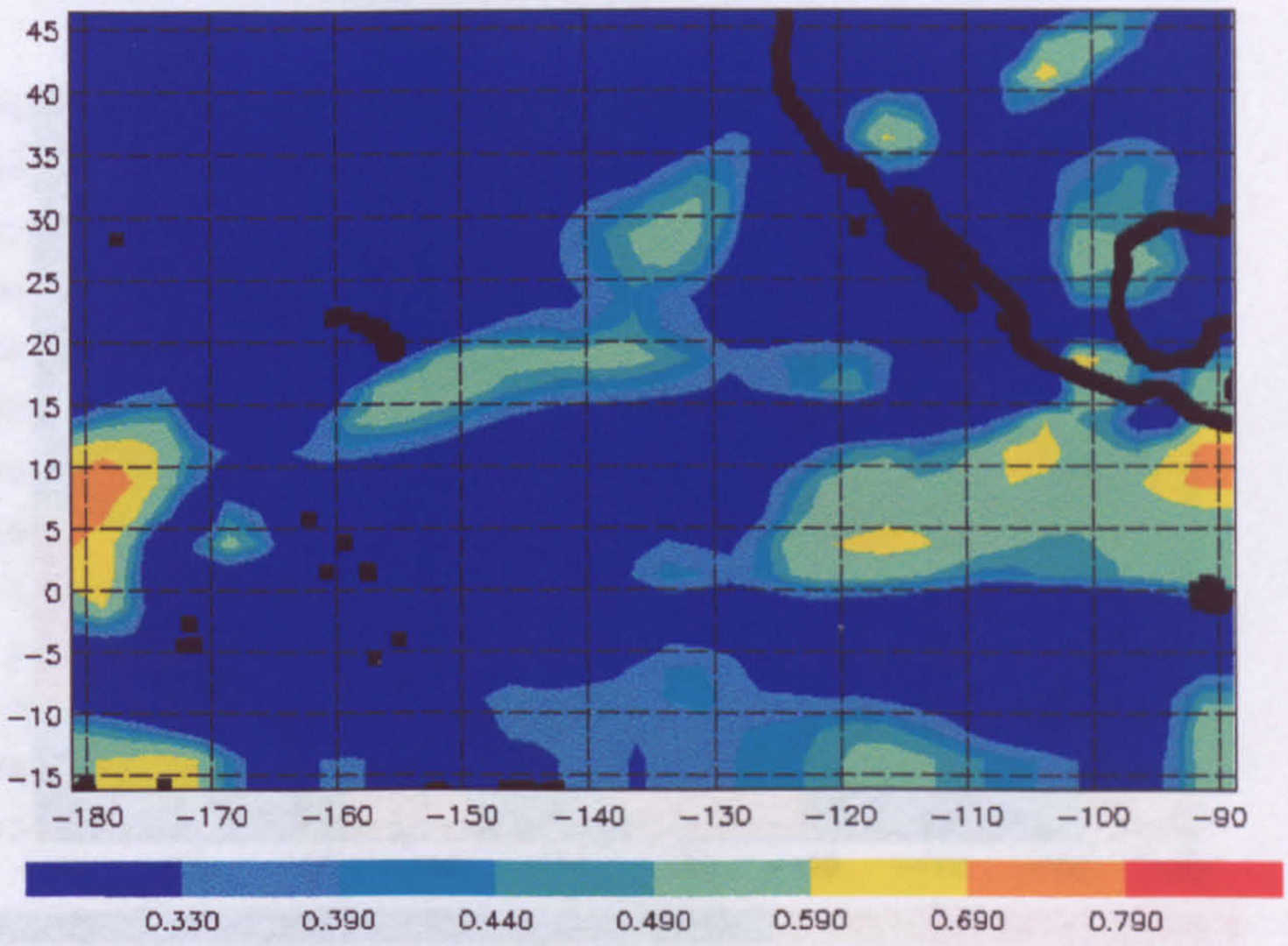
However, for this section, it is important to compare these plots of the single correlation with ENSO (Figure 5.10a), to the multiple correlation plots (Figure 5.10b), since any wind effects caused by the thermal low in addition to those caused by ENSO may emerge in Figure 5.10b. Thus, areas of relationships in Figure 5.10b that were not present in Figure 5.10a, or which were present but are of a much higher significance in Figure 5.10b, are considered as possibilities for the *B* in Figure 5.5.

A comparison of Figures 5.10a and 5.10b shows a broad region of extra correlation, over and above ENSO, in the general area of the trade winds, to the southeast of the sub-tropical high. This is discussed below. (There is also another region of extra correlation in and around the eastern development region, but this is discussed in Section 5.2.4.) The correlation plots are difficult to interpret directly, with some areas showing mainly a correlation with V wind, and others showing mainly a correlation with U wind. In addition, some areas show a correlation with U and/or V wind but no correlation with wind speed, implying a change in wind direction only. In addition, the plots do not indicate the sign of the correlations. To clarify the actual changes in the wind, Figure 5.11 shows wind speed vectors and RH values for the six deepest thermal low years (1974, 1979, 1980, 1981, 1984, 1995), the six shallowest thermal low years (1976, 1985, 1986, 1990, 1991, 1992) and the difference between these. Most of these years have fairly moderate values of

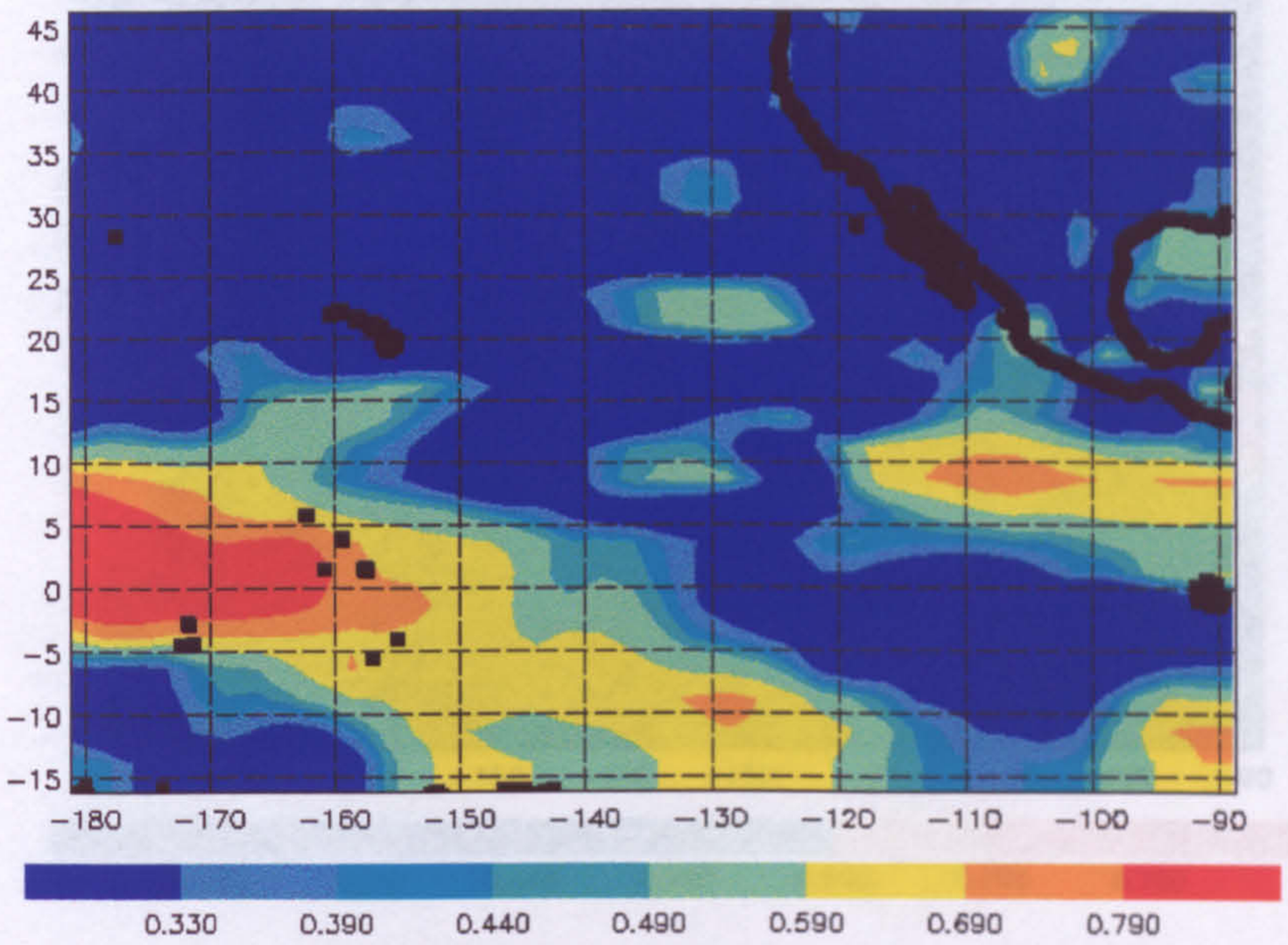
a)
U Wind



V Wind

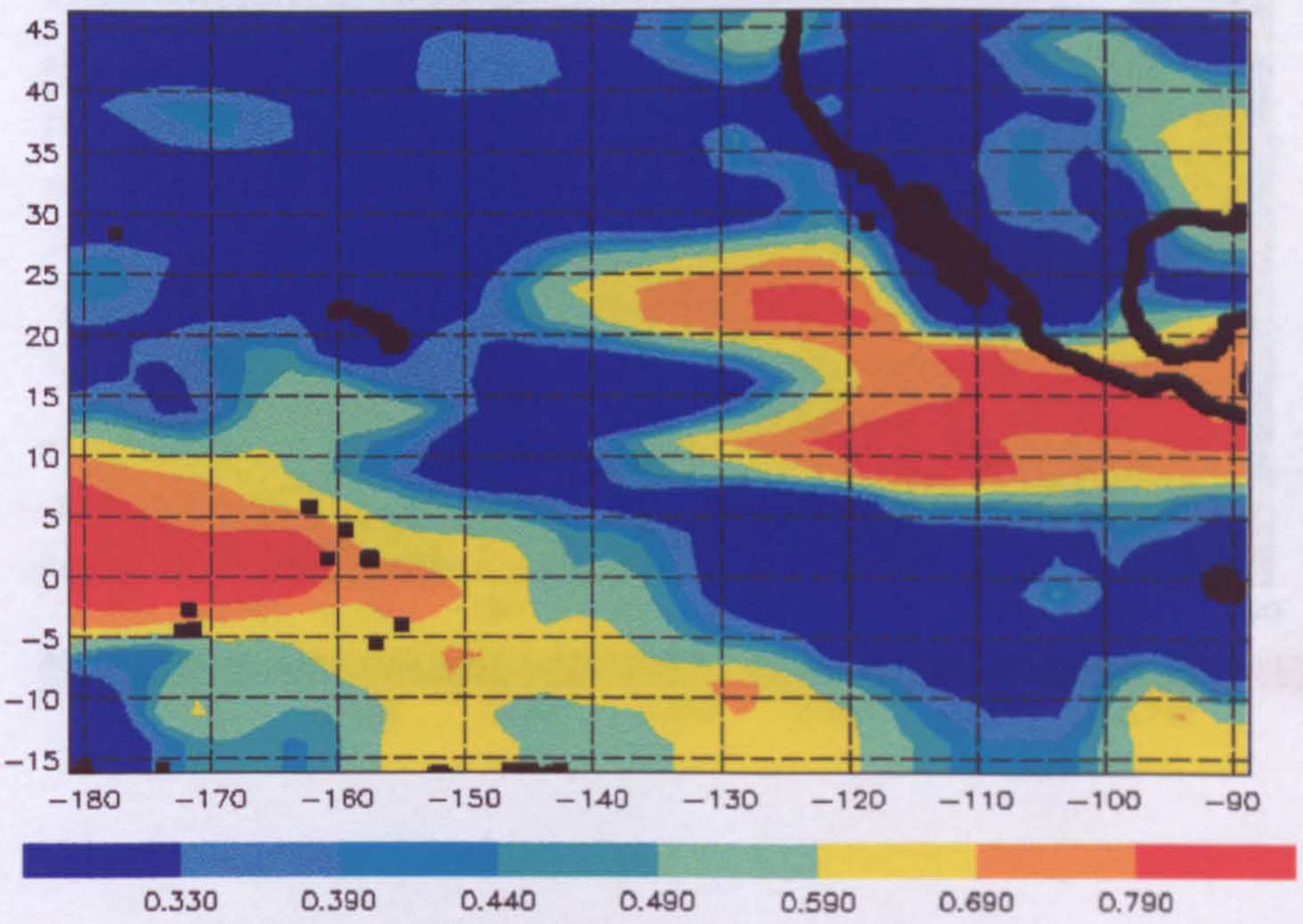


Wind Speed

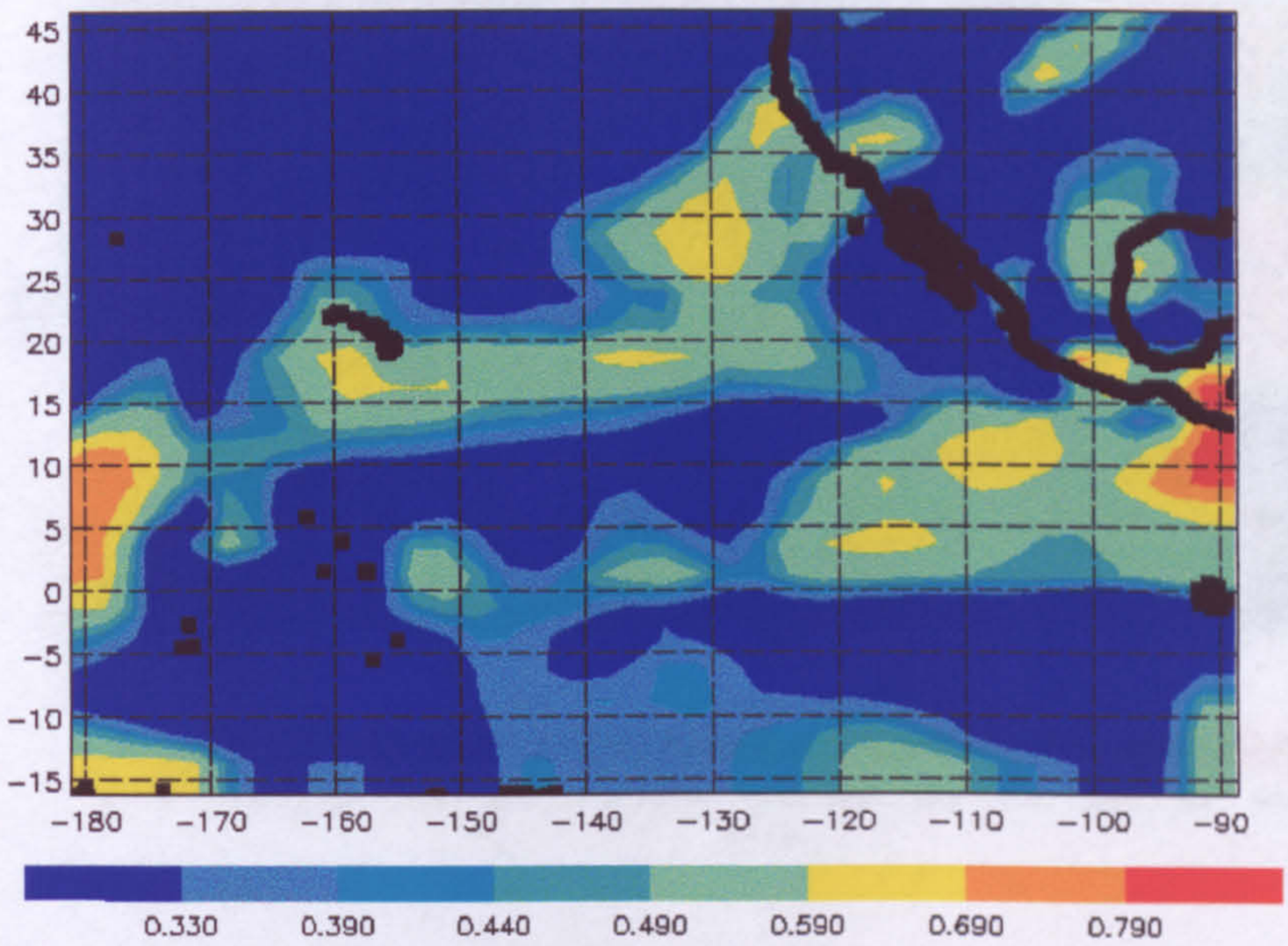


b)

U Wind



V Wind



Wind Speed

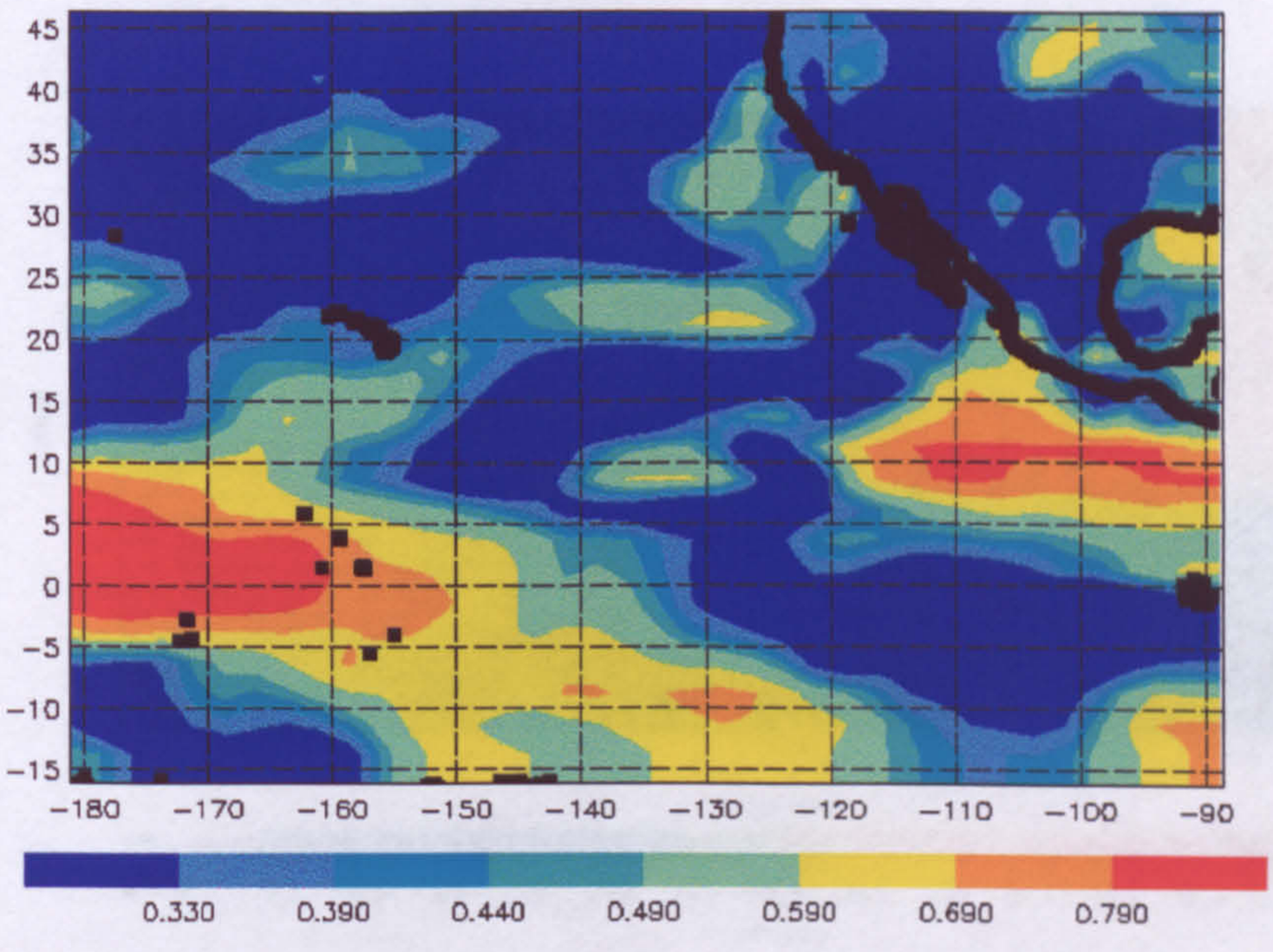
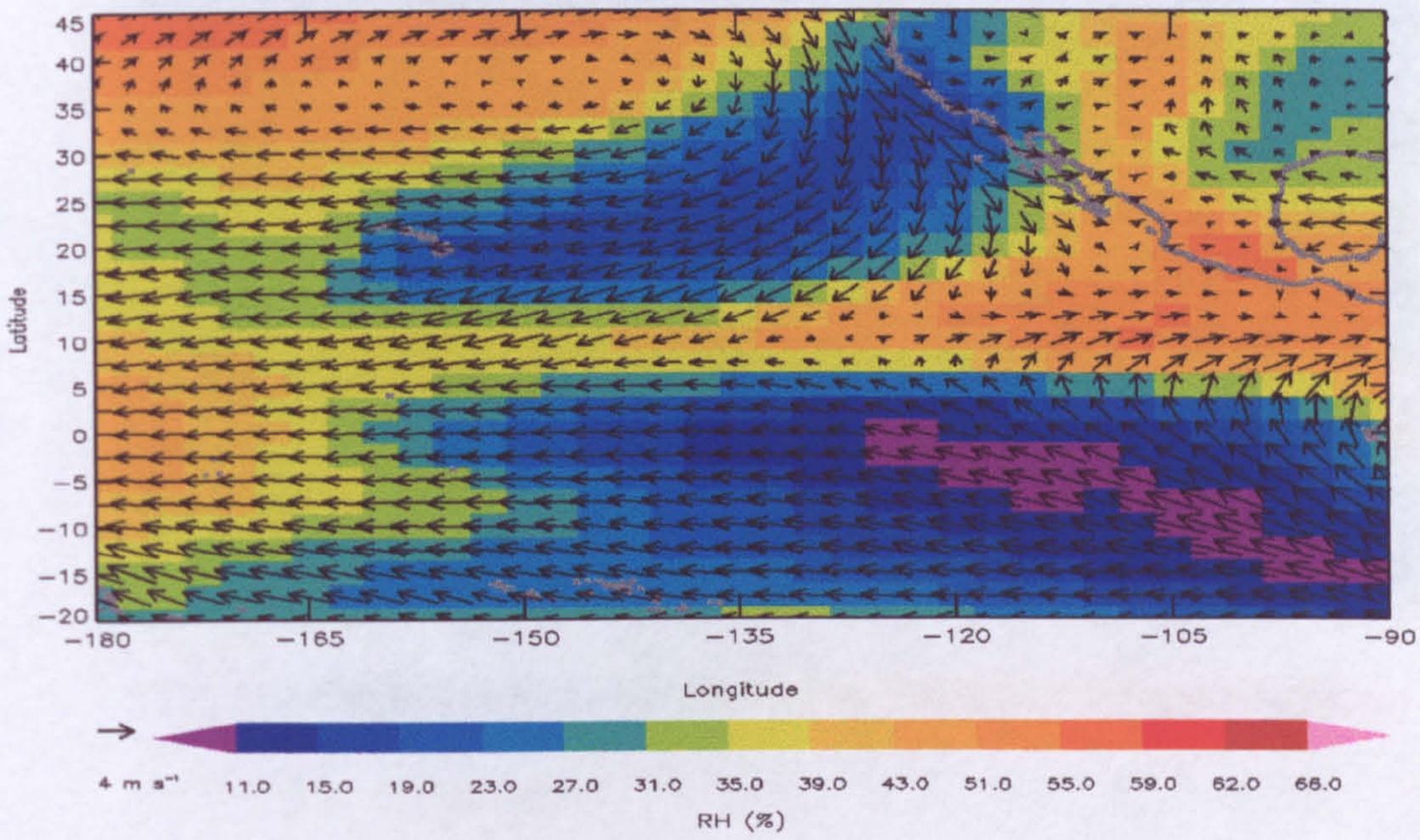
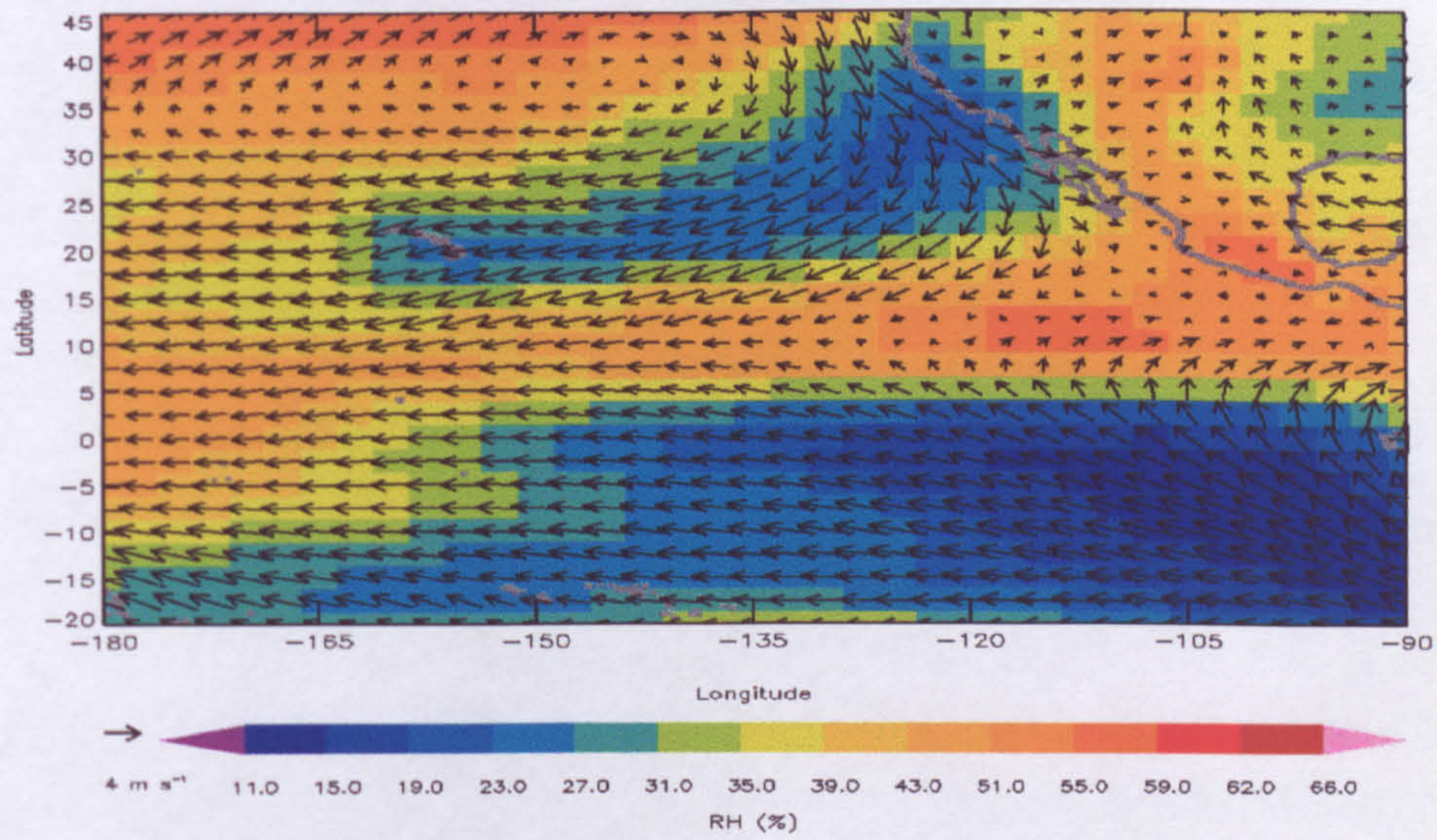


Figure 5.10 Multiple correlations using OLS regression with a wind variable as the dependent variable and a) ENSO (Niño4), b) ENSO (Niño4) and the thermal low, as the independent variable(s), July-September, 1972-1997. The square root of the R^2 value is given.

a)


45
40
35
30
25
20
15
10
5
0
−5
−10
−15
−20
Latitude
−180
−165
−150
−135
−120
−105
−90
Longitude
4 m s⁻¹
11.0
15.0
19.0
23.0
27.0
31.0
35.0
39.0
43.0
51.0
55.0
59.0
62.0
66.0
RH (%)

b)


45
40
35
30
25
20
15
10
5
0
−5
−10
−15
−20
Latitude
−180
−165
−150
−135
−120
−105
−90
Longitude
4 m s⁻¹
11.0
15.0
19.0
23.0
27.0
31.0
35.0
39.0
43.0
51.0
55.0
59.0
62.0
66.0
RH (%)

c)

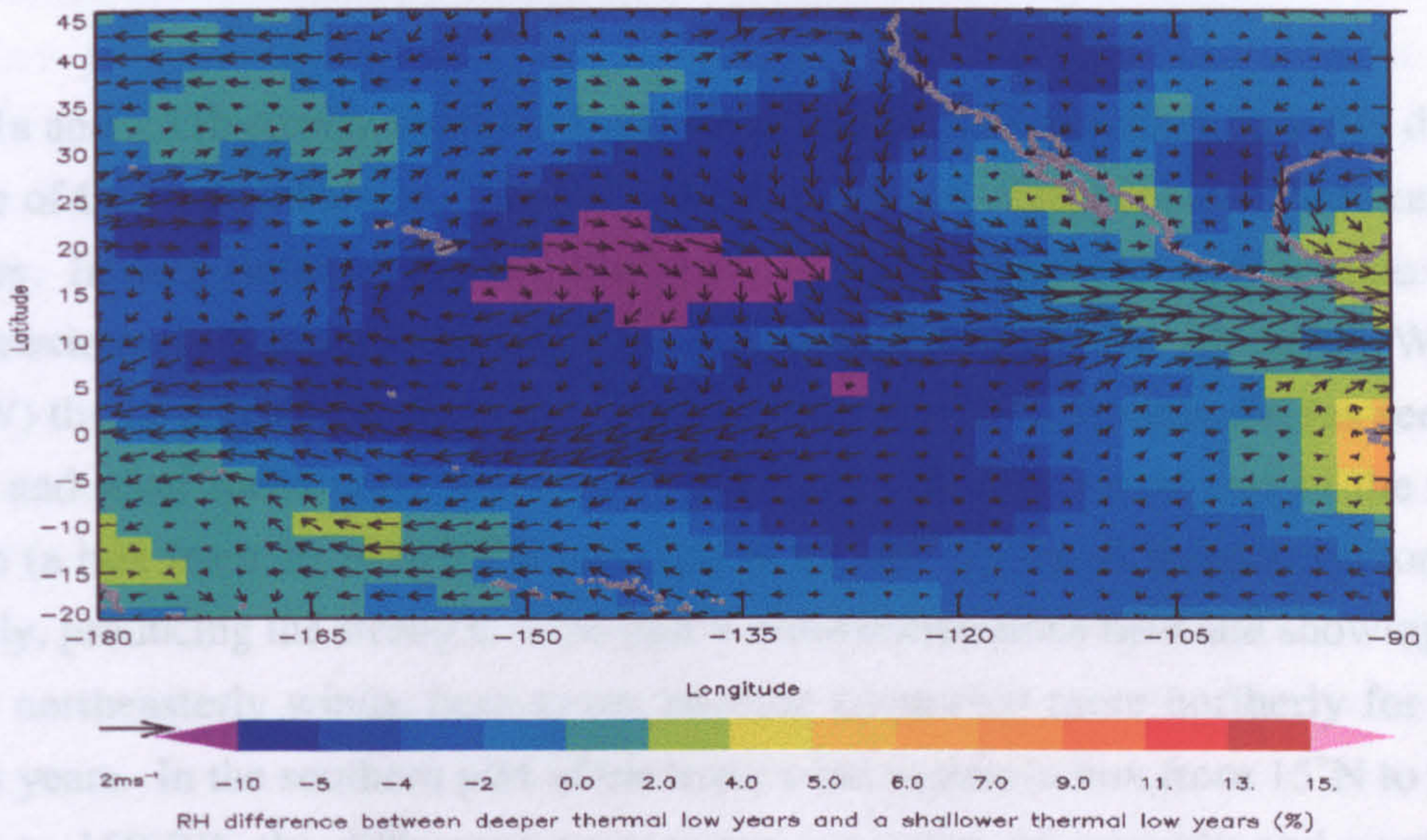


Figure 5.11 Plot of RH and surface winds (10 m) in a) six deepest thermal low years (1974, 1979, 1980, 1981, 1984, 1995), b) six shallowest thermal low years (1976, 1985, 1986, 1990, 1991, 1992), and c) six deepest minus six shallowest thermal low years. Values are averaged over July-September.

ENSO, so the ENSO influence on the plots should be relatively small. However, there is likely to be some residual ENSO effect.

Figures 5.11a and 5.11b clearly show the trade wind region, with generally low RH due to the presence of the trade inversion. Figure 5.11c shows wind vector changes between the two extremes. In deep (intense) thermal low years, in the northern part of this trade wind region (approximately a triangle bounded by the points 25°N/135°W, 25°N/125°W and 40°N/125°W) the largely northerly winds increase their northerly component (as seen by the V wind and wind speed correlations of Figure 5.10). In the central part of the trade wind region (a box from 20°N to 25°N and 120°W to 140°W) the difference vectors are northwesterly, producing the strong U wind and V wind correlations here and showing that the broadly northeasterly winds, here again, become somewhat more northerly for deep thermal low years. In the southern part of the trade wind region (a box from 15°N to 20°N and 130°W to 160°W), the difference vectors are a mixture of westerly and northerly winds, accounting for the correlations seen in Figure 5.10, and making the largely east-north-easterly winds, here again, generally more northerly and reduced in speed.

With these relationships established, the following mechanism (*B* in Figure 5.5) is postulated for the thermal low-RH relationship. The mechanism is considered in two parts. Firstly, let us consider the relationship between the thermal low and the winds. When there is a deeper thermal low, this means that the pressure gradient between the low and the sub-tropical high to the west increases (assuming that the sub-tropical high does not also vary). An increase in the pressure gradient between the low and the high would in turn narrow the isobar spacing in the region directly between the high and the low, and cause the isobars to change their direction somewhat. This results in the wind direction and speed changes mentioned above, namely the generally more northerly direction for the winds, and their increased speed in the northernmost area of the trade wind region (directly between the low and the high).

Secondly, let us consider the relationship between the winds and the western development region RH. During the years when the thermal low is deeper (i.e. more intense), there is evidence of a more northerly direction to the trade winds. Therefore, the trade wind inversion region in the north is driven further south and east into the central-north part of the western development region. The existence of the trade inversion means that the RH is low (Figure 5.11a), and thus conditions there are not conducive for hurricane formation. On the other hand, when the thermal low is shallower (i.e. less intense) and the winds are less northerly, the deep trade wind inversion remains further north mainly outside the

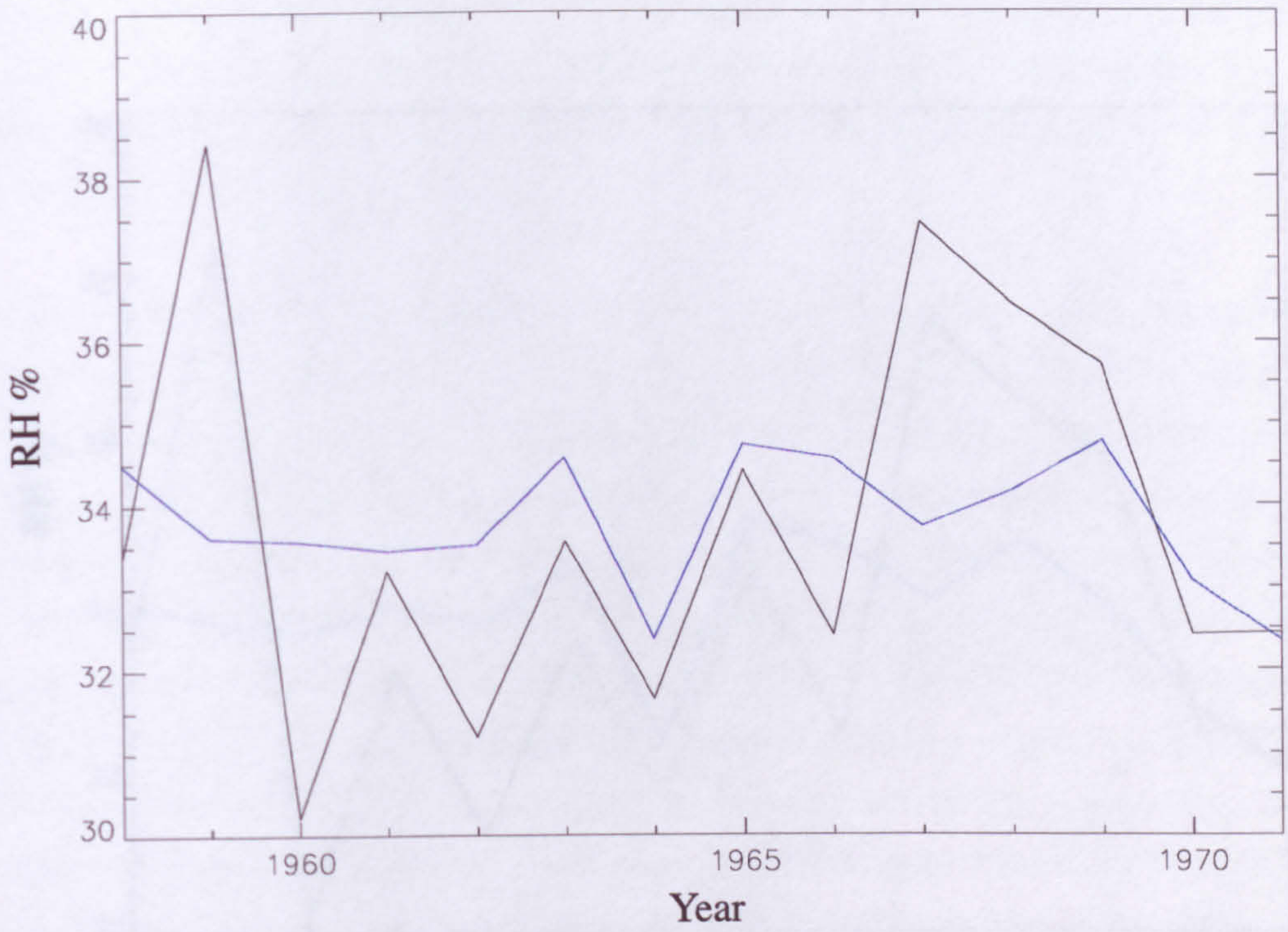
western development region, thus allowing RH to be high over most of the western development region in these years. The influence on hurricane frequency is then similar to the mechanism proposed in Section 4.7.1, where hurricane active and inactive years were characterised by high and low RH in the western development region respectively, and where higher RH values covered a smaller part of the western development region in the inactive years. In this case, less intense (i.e. shallow) and intense (i.e. deep) thermal low years are also characterised by high and low RH in the western development region respectively, where higher RH values cover a smaller part of the western development region in the intense thermal low years. Thus, like the ENSO forcings on the RH (Section 5.2.1), the thermal low link (*B* in Figure 5.5) is also through the winds. However, unlike the ENSO forcings, there seems to be little direct role of SST in the link between RH and the thermal low. Whereas the influence of the thermal low on the western development region RH is strong, as shown in Table 5.1 where the *r* is 0.65, there is, on the other hand, no significant relationship between the thermal low and western development region SST, where the *r* is only 0.19. This implies that the mechanism by which the thermal low affects the RH is more associated with the presence or absence of the trade inversion rather than the SST threshold.

Whilst relationships with tropical cyclones cannot be examined further back past 1972 (see Section 2.1.1), relationships between the environmental variables can be examined from 1958, the beginning of the NCEP/NCAR reanalysis. An examination of the RH values from the fitted models compared with actual RH values for this time period (Figure 5.12), indicates that not only is there a poor relationship in the combined model, but there is also a poor comparison with the single models.

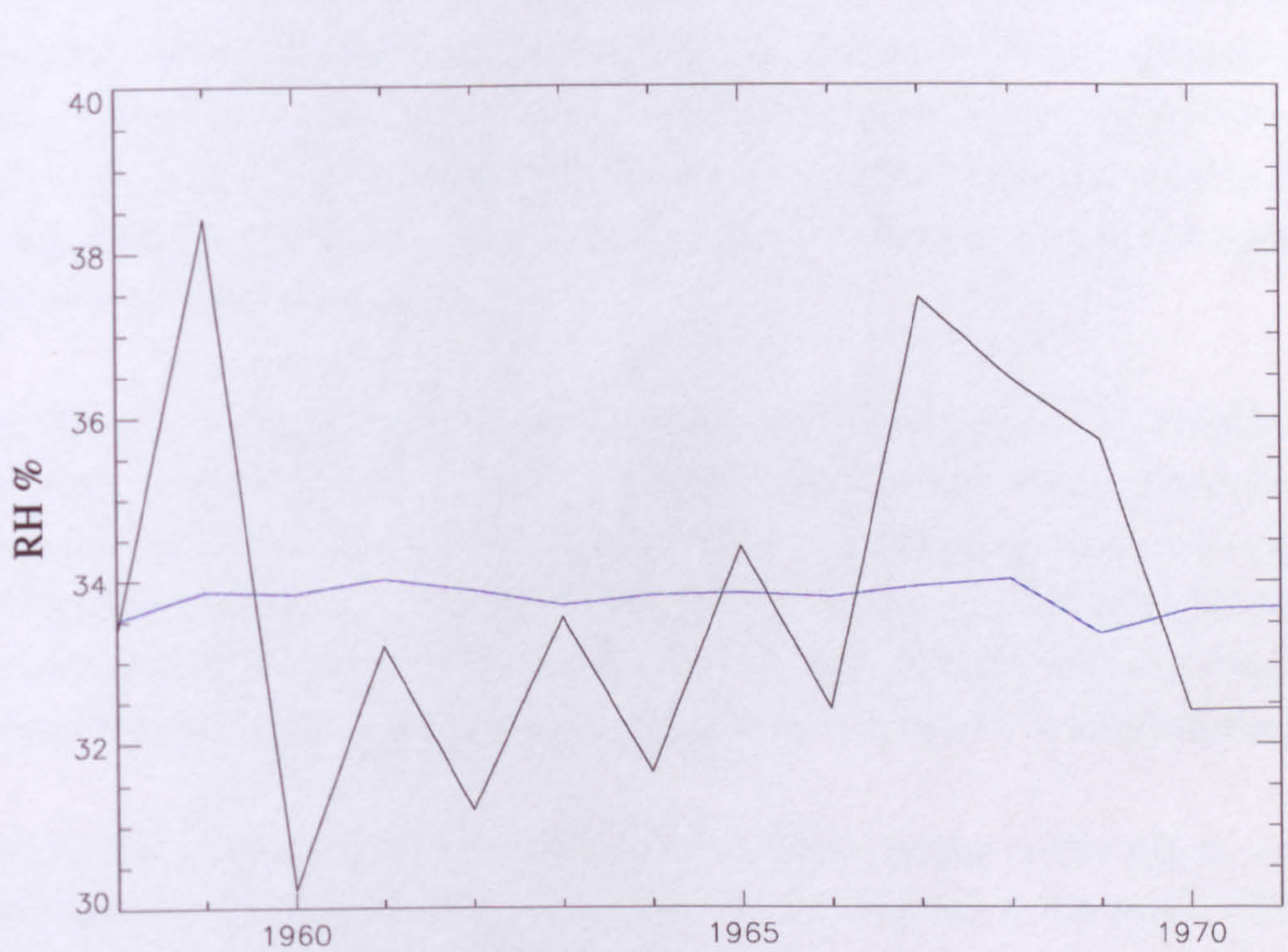
Interestingly, this is not the only study to show a breakdown in relationships between environmental variables when earlier data is included. Other studies which have noted a change in the significance of statistical relationships include Slingo et el. (1999) who found that the correlation between a global MJO index and Niño SST is weak in general but slightly greater for the period from the mid-1970s to the present than the earlier period of data record. Furthermore, Zhang and Gottschalck (2002) noted that the relationship between anomalies of SST in the equatorial Pacific during warm events of ENSO are related to the MJO for the period 1980-1999, but this relationship is not evident when examining the period up to 1979.

In the current study, the fact that the single model of RH vs. ENSO is poor for the earlier period, as well as the relationship between RH and the thermal low, suggests one of two

a)


40
38
36
34
32
30
RH %
1960
1965
1970
Year

b)


40
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36
34
32
30
RH %
1960
1965
1970
Year

c)

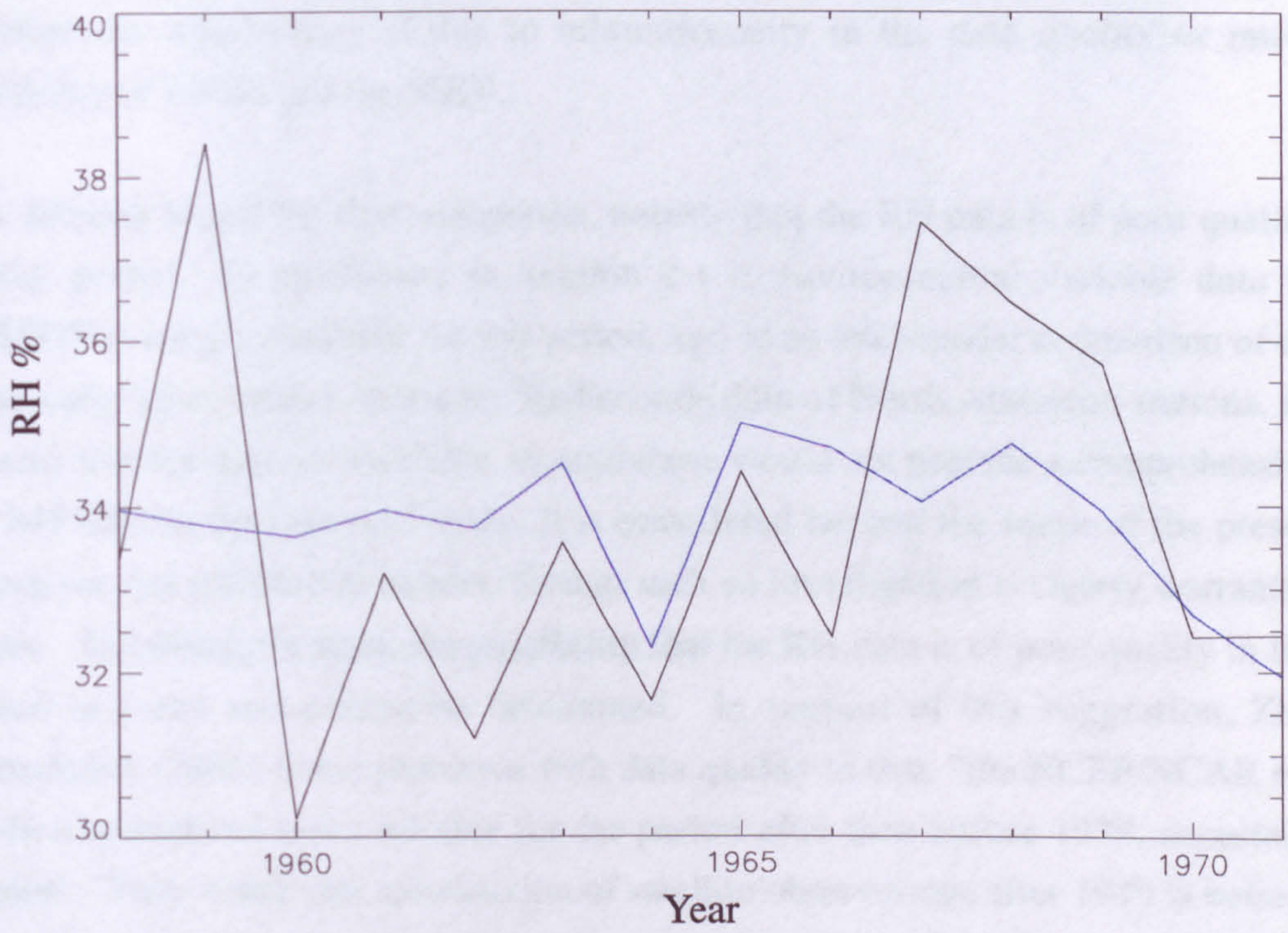


Figure 5.12 Actual RH in the western development region vs. fitted values of RH in the western development region for July-September, 1958-1971 using a model with a) ENSO only, b) thermal low only, and c) ENSO and thermal low. Actual RH is shown in black. Model fitted RH is shown in blue.

things. Firstly, the RH reanalysis data may be poor for this early time period, and/or secondly, the large-scale climate may have altered and is very different in this earlier period. Similarly, Zhang and Gottschalck (2002, p14) noted that, for their study, it is, 'unclear whether the discrepancy is due to inhomogeneity in the data quality or interdecadal variability of ENSO and the MJO'.

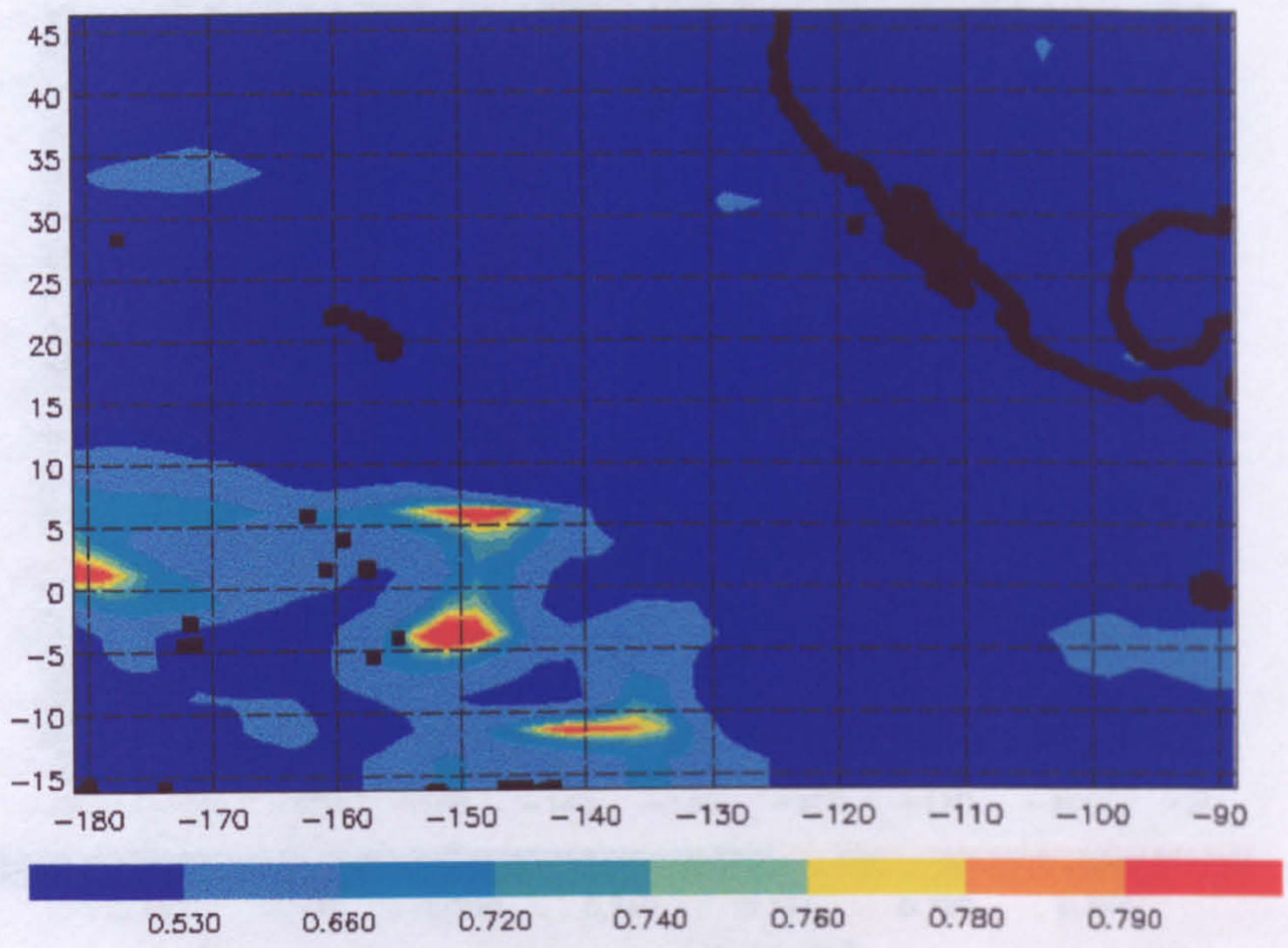
It is difficult to test the first suggestion, namely that the RH data is of poor quality for the earlier period. As mentioned in Section 2.1.2, environmental variable data from the ECMWF is not yet available for this period, and so an inter-model comparison of the RH in these early years cannot be made. Radiosonde data of North American stations, including Hawaii and Socorro are available, though these would not provide a comprehensive test of the RH field in the region of study. It is considered beyond the scope of the present study to analyse this radiosonde dataset, though such an investigation is clearly warranted for the future. Therefore, for now, the possibility that the RH data is of poor quality in the earlier period is noted and cannot be discounted. In support of this suggestion, Zhang and Gottschalck (2002) noted problems with data quality in that, "the NCEP/NCAR reanalysis is often considered more reliable for the period after than before 1979, especially in the tropics". They noted that assimilation of satellite observations after 1979 is believed to be the main reason for this, and that one piece of evidence for inhomogeneity in the data quality of NCEP/NCAR reanalysis is an unusual jump around 1979 in the anomalies of 100 hPa mean temperature. This has also been noted for mid-latitudes (Kistler et al., 2001). However, there is no direct evidence that surface winds which they used prior to 1979, or other NCEP/NCAR fields used in this study, showed problems. Hence the earlier data should not be discarded completely.

To test the second suggestion, namely that there has been a large scale climatic change between the two periods, let us examine where the causal links suggested earlier break down. An inspection of Figure 5.13 shows that there are again wind field variations caused by the variations in the thermal low in addition to those caused by ENSO (although there is a slight shift in these areas compared to the later period). However, Figure 5.14 shows that the RH is not responding to the winds in these thermal low affected areas.

Therefore, this suggests that the behaviour of the climate system in this region, and hence the relationships between climatic variables, may be different in the period 1958-1971 compared to the period 1972-1997. This may relate to an abrupt climate shift in the Pacific circulation that occurred around 1976, centred in the tropics, as noted by Trenberth and Stepaniak (2001). For instance, they noted that the character of ENSO was different before

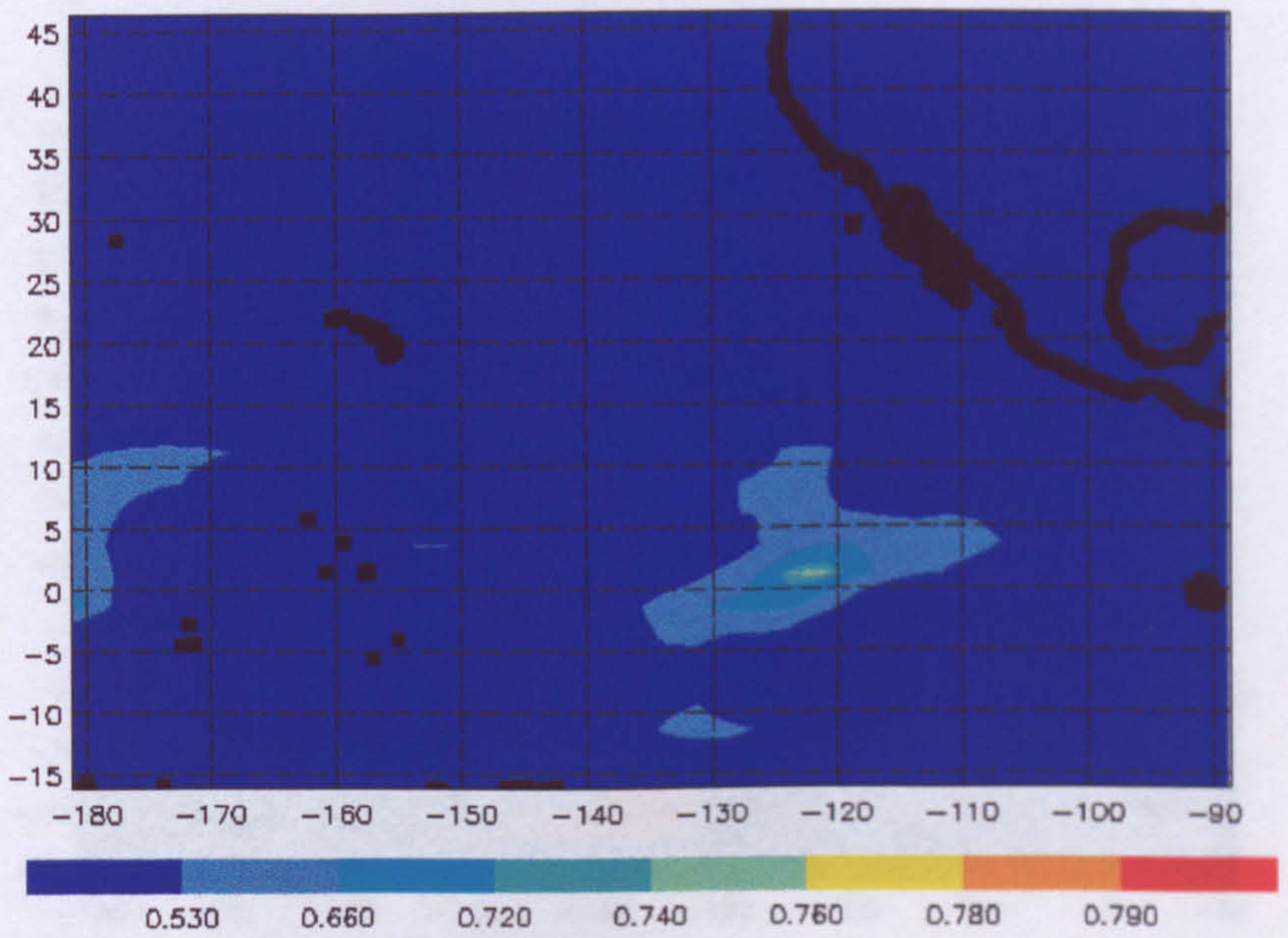
a)

U Wind



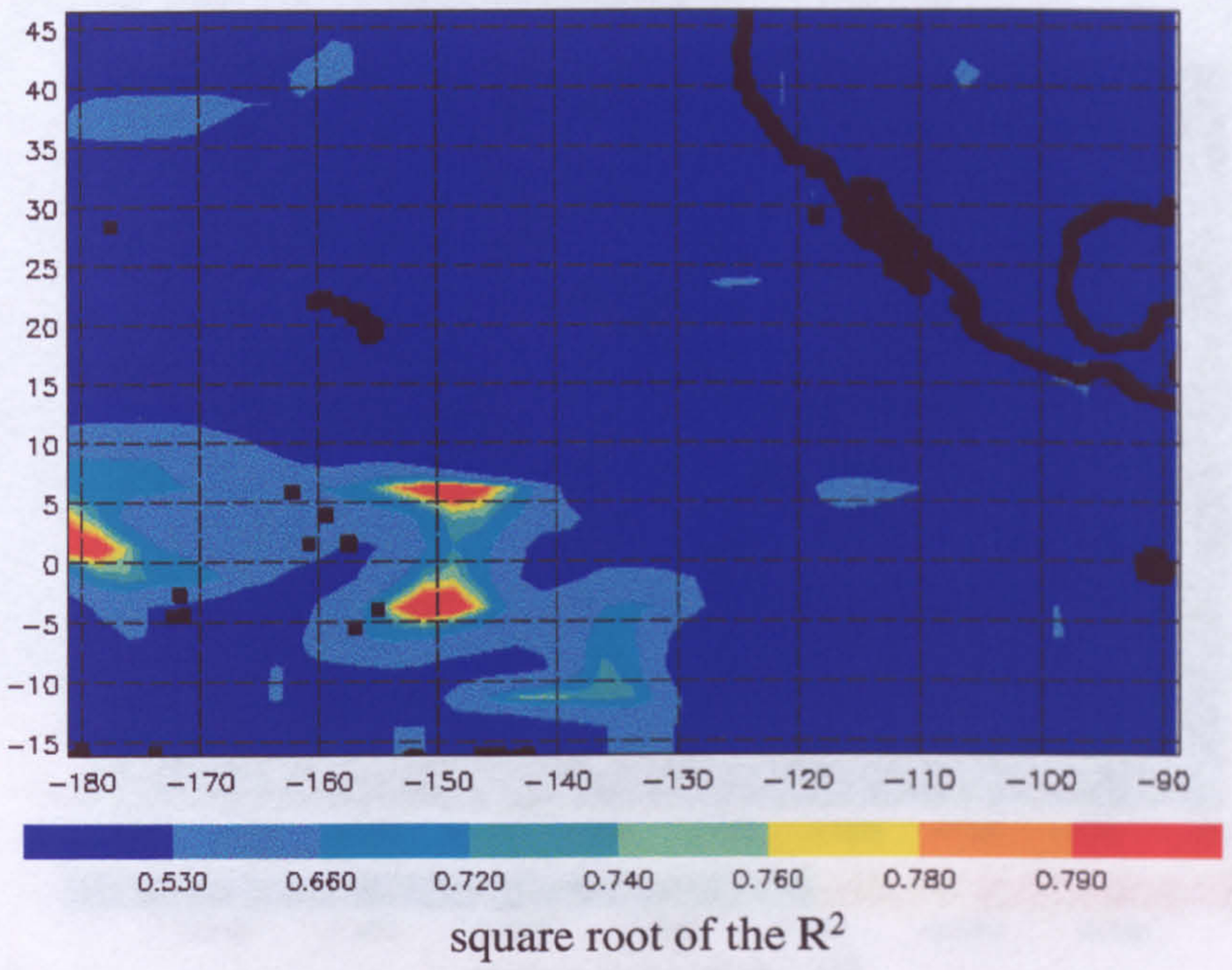
square root of the R^2

V Wind

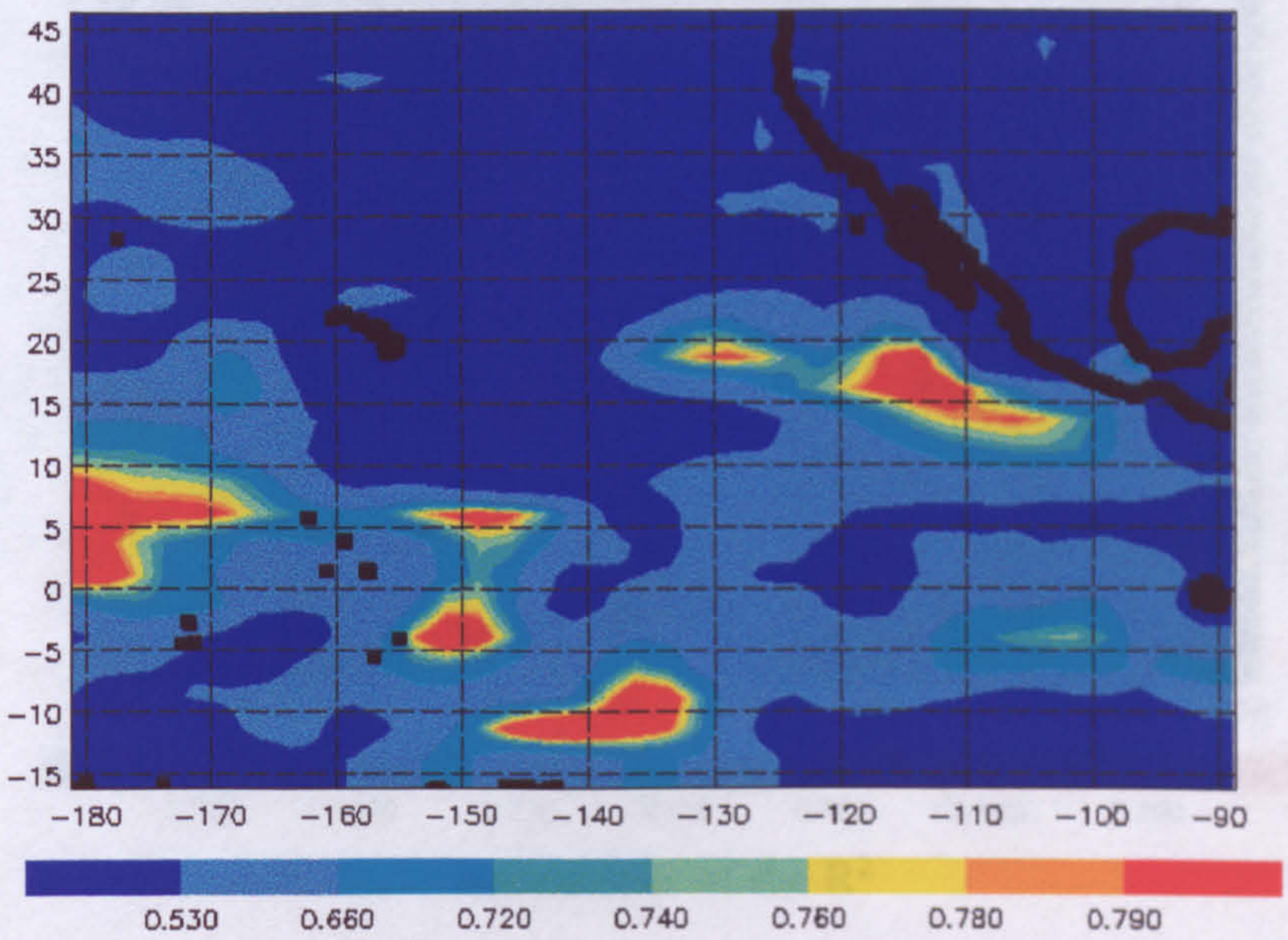


square root of the R^2

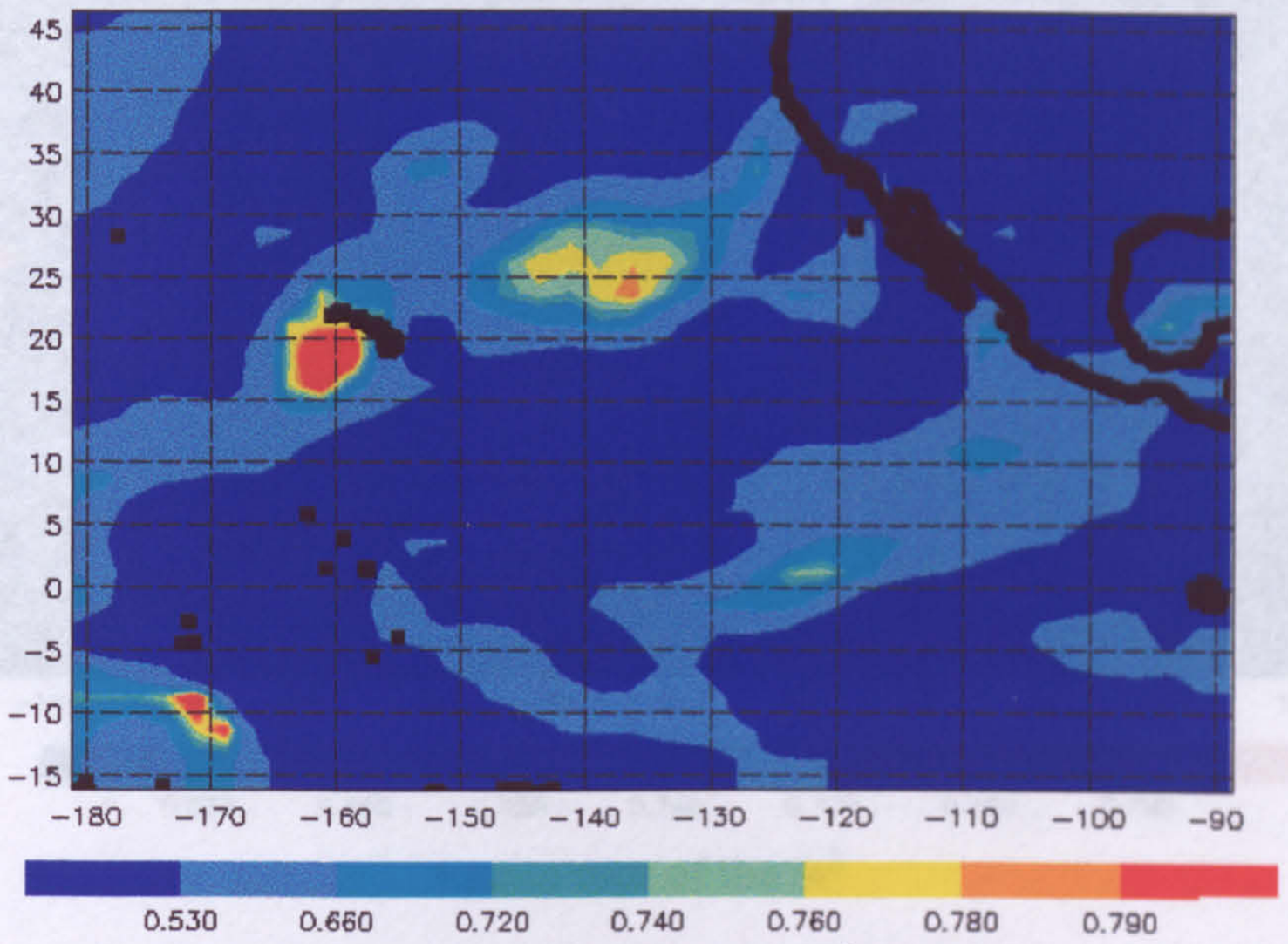
Wind speed



b)
U wind



V wind



Wind speed

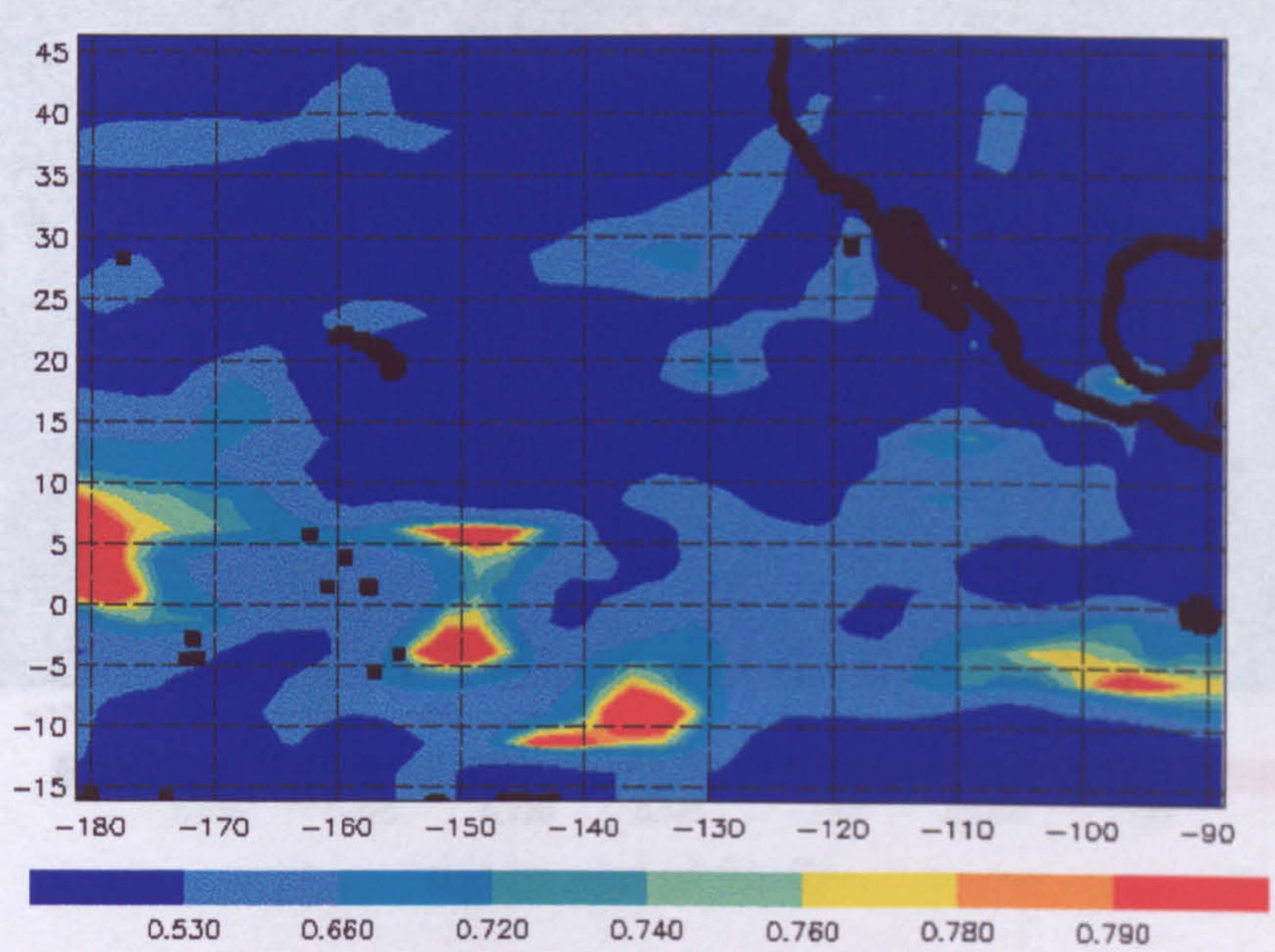
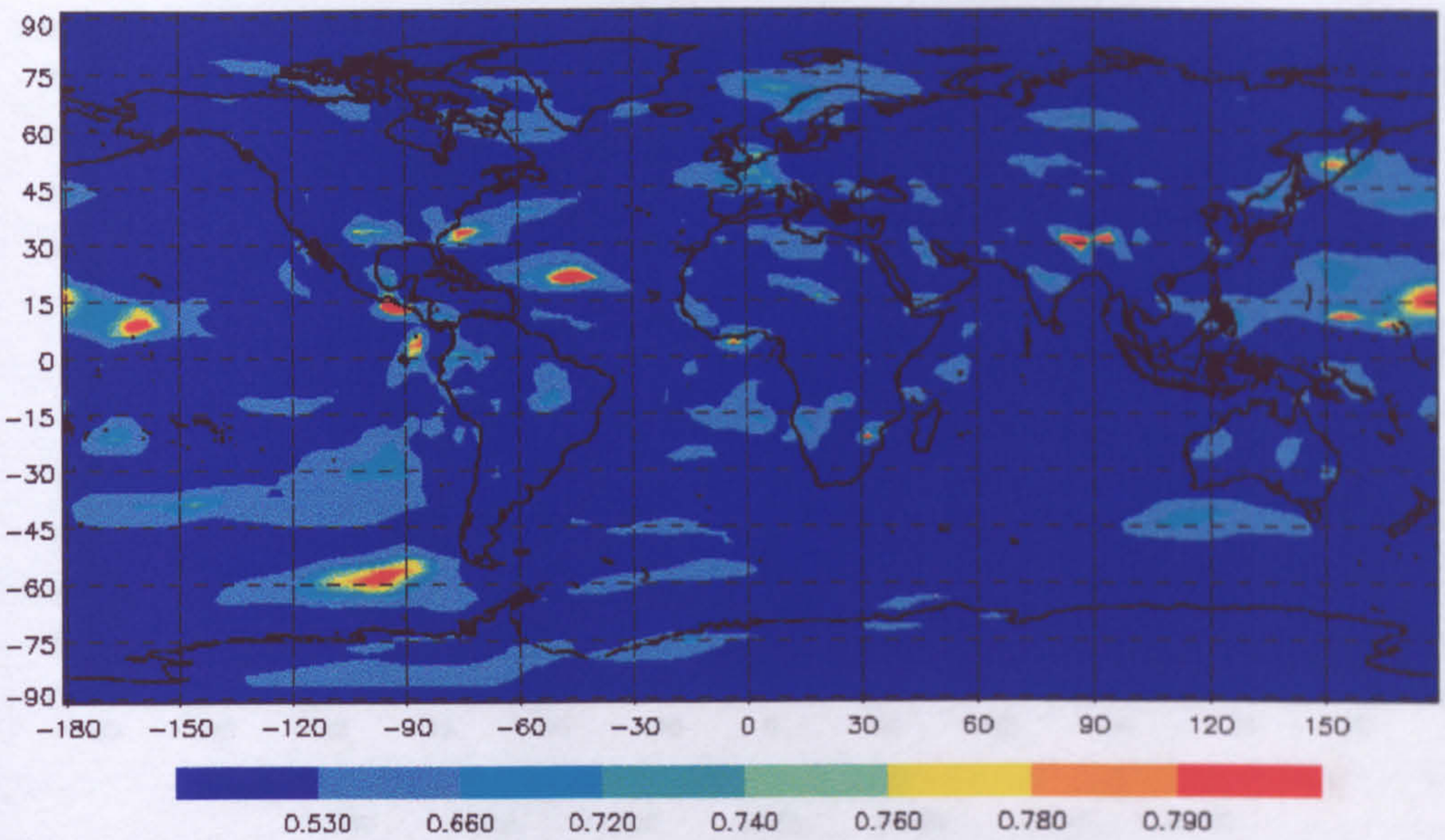


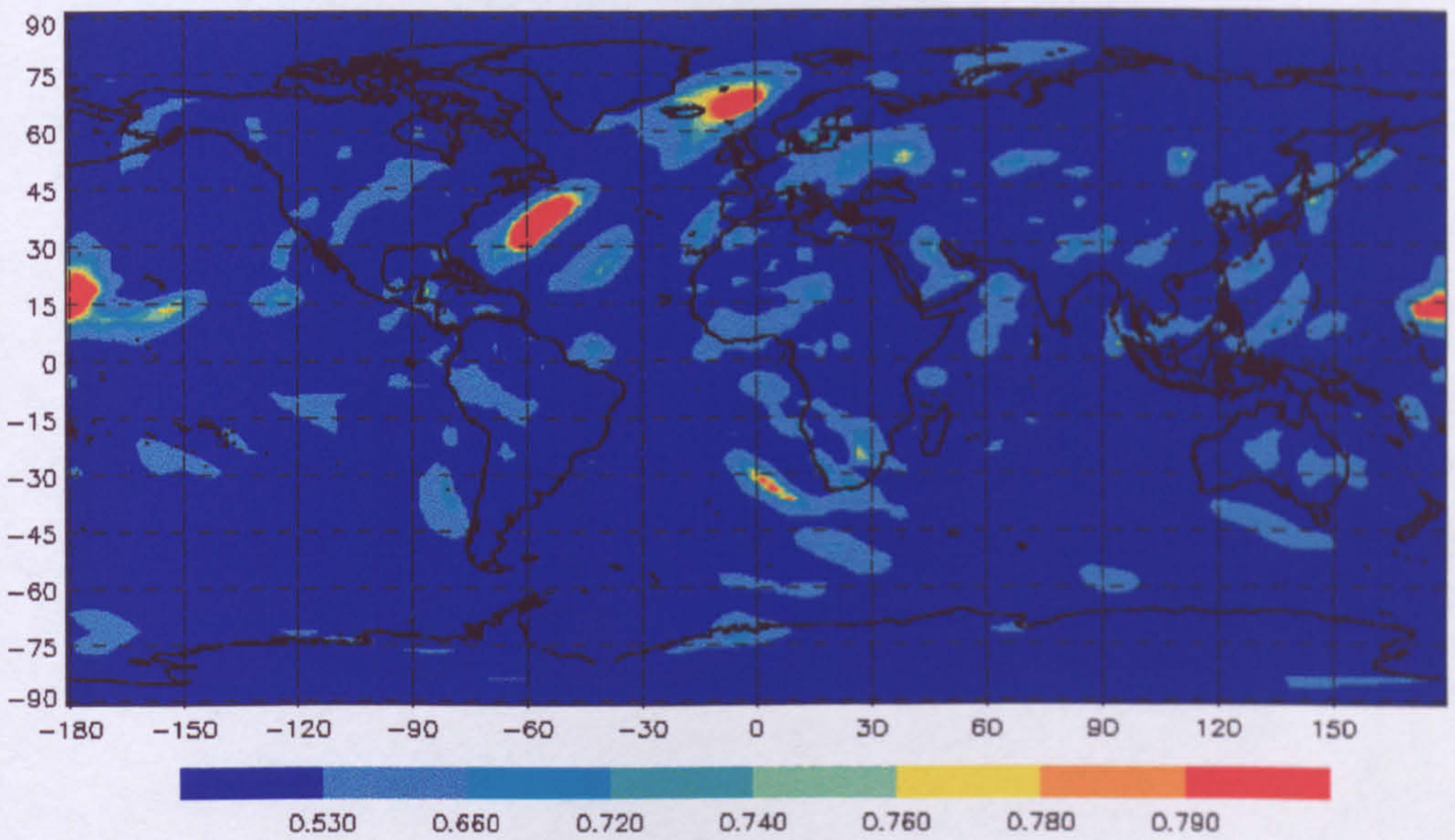
Figure 5.13 Multiple correlations using OLS regression with a wind variable as the dependent variable and a) ENSO (Niño4) , b) ENSO (Niño4) and the thermal low, as the independent variable(s), July-September, 1958-1971. The square root of the R^2 value is given.

a)



square root of the R^2

b)



square root of the R^2

c)

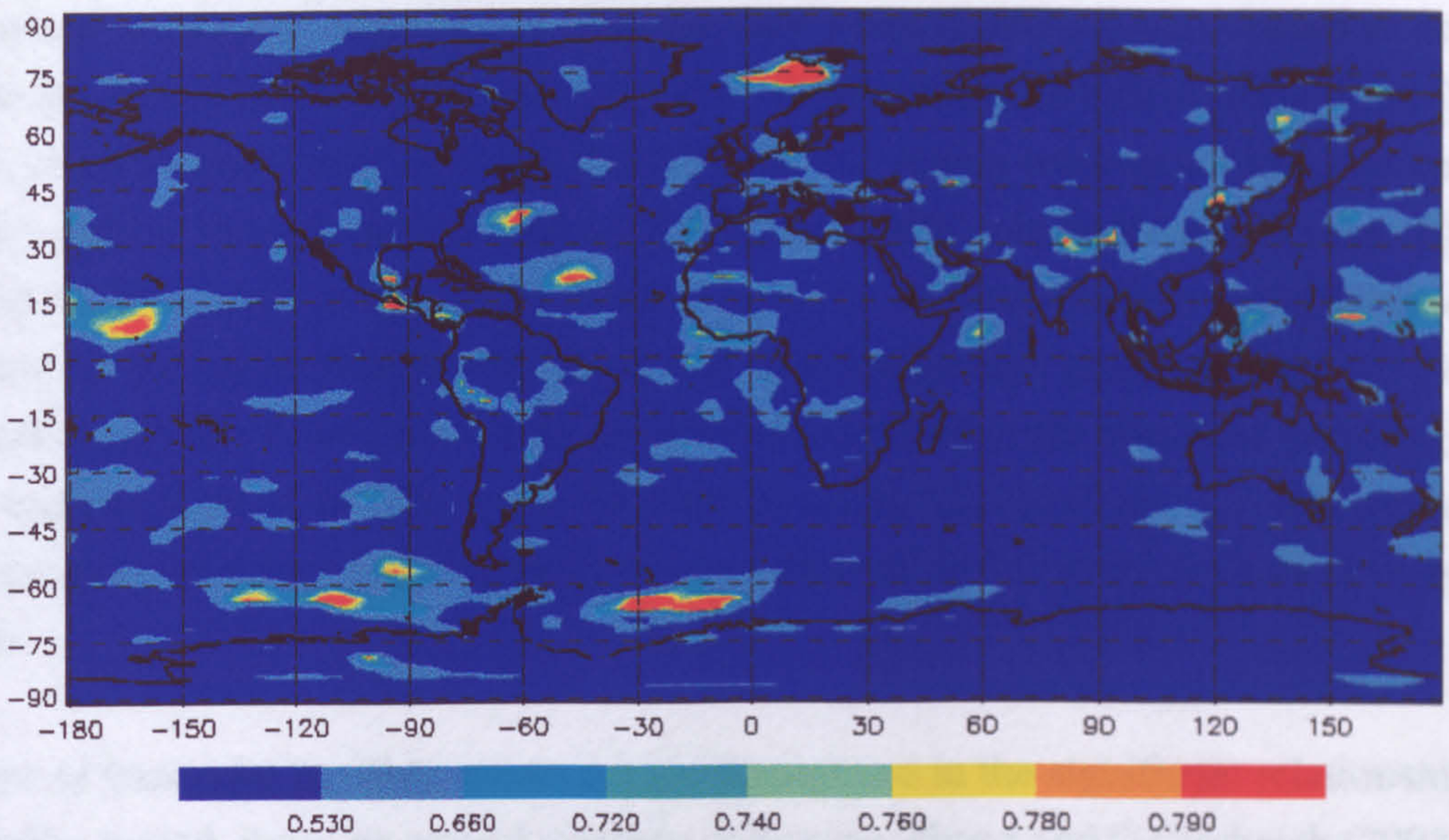


Figure 5.14 Multiple correlations using OLS regression with RH as the dependent variable and ENSO (Niño4) and a) U wind at 10 m, b) V wind at 10 m, and c) wind speed at 10 m, as the independent variables, (July-September) 1958-1971. The square root of the R^2 value is given.

this date, when El Niño events tended to develop first along the coast of South America and then spread westward, compared to after this date when El Niño events tended to develop first in the central Pacific and spread eastward. Furthermore, an examination of the Niño4 region in the current study indicates that SSTs in this region were much lower in general, with no years in the early period reaching SSTs above 29°C (characterising extreme El Niño events) as there were in the later period. Similarly, an examination of the thermal low pressures in the earlier time period shows that there are no high pressures over 1011 hPa in the earlier period. It may be that these differences between the two time periods (in the level and character of ENSO, and in the level of the thermal low) are also associated with differences in the nature and magnitude of any influence on RH in the western development region.

In view of these two possible causes for the breakdown in the significant relationships for the earlier period, it can be argued strongly, following Zhang and Gottschalck (2002), that the lack of relationships in the earlier period should not tarnish the credibility of the results for the later period. However, because of the possibility that the breakdown is caused by a climatic shift, caution should be exercised if the relationship is used for predictive purposes. In general, the relationship would probably be less valid the further into the future it is projected. It would also be important to continue to monitor and update the relationship on a regular basis.

5.2.4 Other links with the intensity of the thermal low

There is a relationship between VZ in the eastern development region and hurricanes in the western development region (see Figure 4.7). Thus, when VZ in the east is low, there are more hurricanes in the western development region. This relationship is now examined in detail. It could perhaps be hypothesised that when there is more VZ in the eastern development region, this means that these conditions make it more difficult for hurricanes to form there, and thus the easterly waves will not be used up in making the hurricanes in the east and are still available for hurricanes to form the west. If this were true, however, one would expect to see an anti-correlation between the eastern development region and western development region tropical cyclone numbers, a correlation which is not present (see Section 3.1.2).

Instead, it appears that the VZ in the eastern development region is not a cause of the hurricanes in the western development region. Rather, the VZ and the hurricane numbers appear to be an effect of something else. Since it appears from Section 4.7.1 that RH affects hurricane numbers in the NE Pacific basin, a relationship was examined between VZ

in the eastern development region and RH in the western development region, where a correlation with an r of -0.51 is observed. Examining the low-level zonal winds that was used in this wind shear calculation (i.e. those at 850 hPa) alone with RH, a relationship with an r of -0.69 is observed. Thus, when wind anomalies are more easterly in the eastern development region, there is greater RH in the western development region. Since the winds in this region are very light (around 2 m s^{-1}) it is very unlikely that advection of the moist air into the western development region would occur.

Thus, what makes these wind anomalies more easterly in some years than others, and why is there an apparent effect with RH in the western development region? To answer this we again return to the thermal low. When the thermal low is more intense, there is an extension of the thermal low southward over the sea (sea low). The correlation between the thermal land and sea low has been mentioned above (Section 5.2.2). Thus, when the low over the sea is more intense (i.e. lower), the winds will blow around it more strongly. Since wind blows anti-clockwise in the Northern Hemisphere around a low, the winds will be more westerly on the southern side of the low. On the other hand, when the thermal low in less intense, the sea low becomes less intense and the winds do not blow around the low as strongly, thus the winds are less westerly. This is illustrated by the correlations and vector differences seen in Figures 5.10 and 5.11.

Thus, it is not these less westerly winds in the eastern development region causing the RH in the western development region which in turn affects the hurricanes, it is the thermal low that affects the RH in the western development region, through the mechanism described in Section 5.2.3. In addition, when there is a thermal low that is more or less intense, a wind pattern, as described above, is observed independently, causing a change in wind shear, and zonal winds in particular, in the eastern development region.

5.3 The cause of the interannual variations in the thermal low

It has already been mentioned (Section 5.2.2) that the intensity of the thermal low is not significantly related to ENSO. Instead, it can be shown that the main cause for the year-to-year variations in the intensity of the thermal low is, perhaps unsurprisingly, due to local temperature fluctuations. A correlation between the surface temperature and the intensity of the thermal low (both at 30°N, 112.5°W) is -0.46, which is significant at the 5% level. Since the weak relationship between ENSO and thermal low will tend to obscure the relationship, the surface temperature vs. intensity of the thermal low locally was examined in strong ENSO (defined as the six highest and lowest SST values of the Niño4 index) and non-strong ENSO years. It can be seen that the relationship is stronger in non-strong

ENSO years with a correlation of -0.64 (significant at the 5% level). Thus, in non-strong ENSO years, warmer temperatures locally bring about a deeper low pressure region and vice versa. However, in strong ENSO years, the correlation was very weak at 0.04, showing that the effects of ENSO obscure the simple local temperature-pressure relationship.

5.4 Possible teleconnections between the North Atlantic and the NE Pacific

The relationship between North Atlantic hurricanes and NE Pacific hurricanes has been previously examined by Lander and Guard (1998). They looked at basin "active" and "meagre" years between 1966 and 1995 and asked the question whether there are negative correlations in some basins against other basins so that compensations are made in one basin which might account for the increases in some years in the other basins. In general their results show that this is not the case. Although they show a positive correlation between NE Pacific and NW Pacific tropical cyclones, with a correlation coefficient of 0.32 which is significant at the 10% level, this only points to a destabilisation of tropical cyclone numbers as this is a positive correlation, not a compensation. The relationship they found between the NE Pacific and the North Atlantic, for interannual variations, is negative with a correlation coefficient of -0.02. This insignificant result implies that the amount of tropical cyclone activity in the North Atlantic has little relationship with tropical cyclone activity in the NE Pacific. However, Landsea and Gray (1989) noted an inverse correlation on a decadal time-scale between North Atlantic and NE Pacific hurricane numbers. They noted that, in the NE Pacific, lower hurricane activity in the late 1960s and greater activity thereafter to 1987 is in opposite phase to North Atlantic hurricane activity where the 1950s and 1960s saw a more active time, with the 1970s and 1980s seeing a less active era.

The current study shows that it is very important to split the NE Pacific up into sub-regions (as described in Section 3.1.2) in order to find and explain anti-correlation between the NE Pacific and the North Atlantic. As mentioned, a previous statistical study by Lander and Guard (1998) showed no relationship between the NE Pacific basin and the North Atlantic basin but they treated the NE Pacific basin as a whole and therefore significant results were obscured. Since it was found that there is a relationship with ENSO in the western development region of the NE Pacific through RH (see Section 5.2.1), and it has already been noted that there is a relationship between ENSO and North Atlantic tropical cyclones via VZ (see section 1.5.2.2), it is expected that there would be an anti-correlation of tropical cyclone frequency in these regions. An inter-basin comparison was therefore carried out to provide evidence on an interannual level of Landsea and Gray's (1989) decadal observations, as described above. Furthermore, since the summer thermal low in the south

of North America has been shown to improve the explanation of hurricane frequency variations in the western development region of the NE Pacific basin, through its impact on RH (the dominant control on hurricane formation), and since it also borders the North Atlantic basin, this variable is also examined for the North Atlantic basin to see if it has any effect on tropical cyclones via VZ (as that variable gives the best model for explaining hurricane frequency variations in the North Atlantic, e.g. Goldenberg and Shapiro, 1996).

Results of the inter-basin study show that tropical cyclones in the western development region of the NE Pacific (116°W to 118°W) are, indeed, anti-correlated with tropical cyclones in the North Atlantic through the period 1972-1997. On the other hand, there is no significant relationship between the tropical cyclones in the eastern part of the NE Pacific (115°W to the coastline of North America) with those in the North Atlantic (see Table 5.2).

It might be hypothesised that there could be an anti-correlation between the NE Pacific and the North Atlantic due to the fact that many of the NE Pacific hurricanes have origins that can be traced to African easterly waves (Simpson et al., 1969; Frank, 1987; Avila, 1991). Thus, when the North Atlantic season is particularly active, more of the waves are likely to be used up in becoming North Atlantic hurricanes, thus there will be less available to traverse into the NE Pacific. If the western development region of the NE Pacific were anti-correlated with the North Atlantic for this reason, then it would be expected that the eastern development region of the NE Pacific would also be anti-correlated to the North Atlantic. Since Table 5.2 reveals that this is not the case, then one has to look for other explanations to account for the observed anti-correlation found between the western development region of the NE Pacific and the North Atlantic. With the already strong relationships noted with ENSO in both basins (western development region and North Atlantic), and by ruling out the easterly wave theory affecting the anti-correlation, one has to conclude that ENSO is the dominant cause for the anti-correlation.

	NE Pacific Basin					
	TS west	H west	IH west	TS east	H east	IH east
Atlantic Basin						
TS	-2.07	-2.18	-1.30	0.33	1.74	0.37
H	**-3.91**	-2.35	-2.45	-0.25	0.50	0.06
IH	**-3.58**	**-3.28**	**-3.03**	-0.49	0.09	-0.11

Table 5.2 *t*-statistic of each Poisson regression of North Atlantic tropical cyclone

numbers vs. the NE Pacific western (west) and eastern (east) development region tropical cyclone numbers (July-September tropical cyclone numbers are used in each case, 1972-1997). Entries underlined are significant to the 5% level, with a *t*-statistic greater than or equal to 2.069. Entries in boldface and underlined are significant to the 1% level.

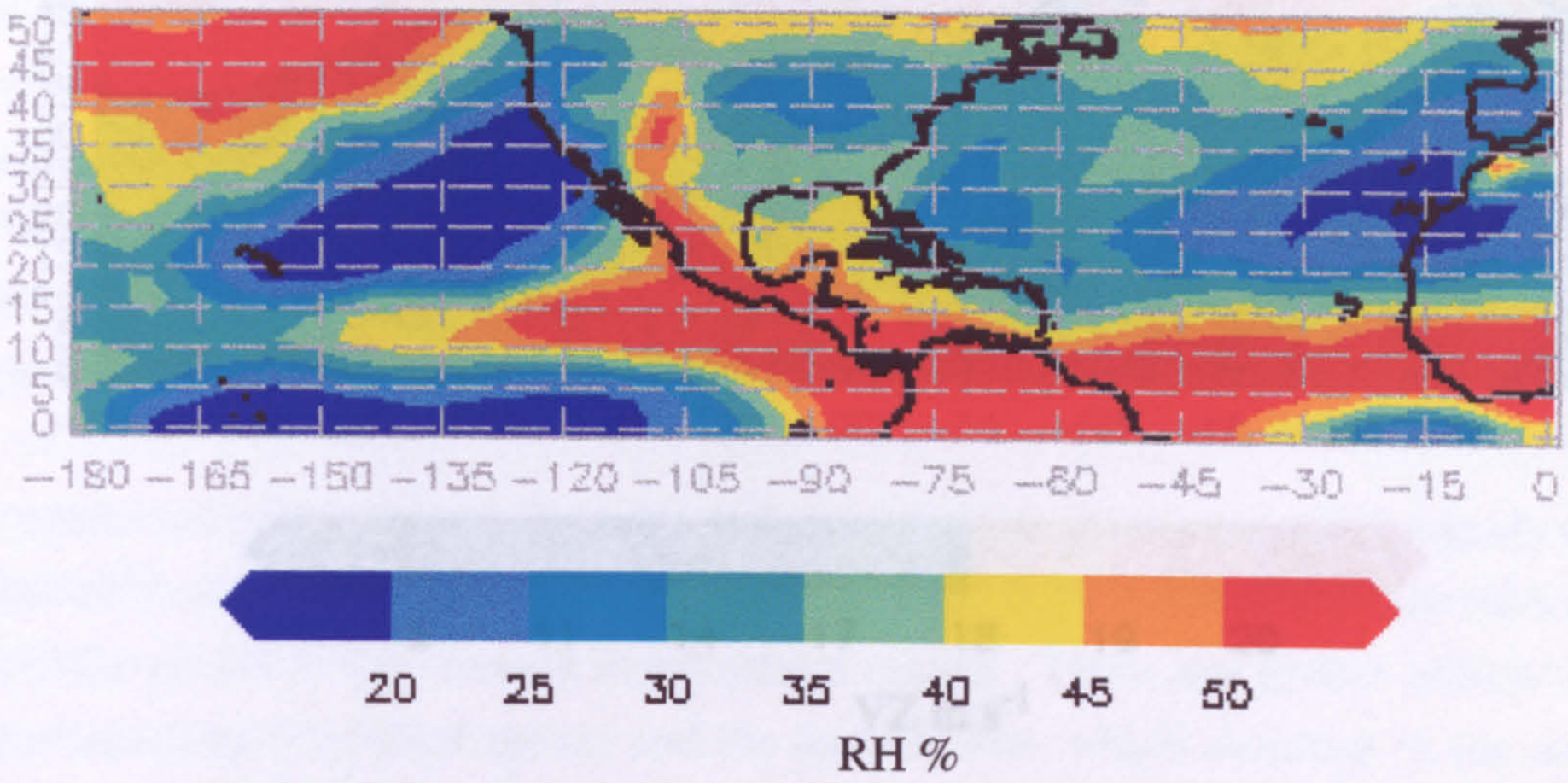
To show the effect of ENSO, by way of a few examples, the climatology of RH and VZ is shown for an active and inactive ENSO year (see Figure 5.15). 1988 was an extremely inactive ENSO year and was a very active year in terms of numbers of hurricanes in the North Atlantic (five hurricanes in the August-October season). However, in the western development region of the NE Pacific it was an inactive year (two hurricanes in the July-September season). On the other hand, 1982 was a very active ENSO year and was an inactive year in terms of numbers of hurricanes in the North Atlantic (one hurricane in the August-October season). However, in the western development region of the NE Pacific is was an extremely active year (six hurricanes in the July-September season). These are extreme cases of this anti-correlation noted above.

Since the thermal low occurs in the summer months, splitting the sub-tropical highs of the two basins (see Section 1.3), it is feasible that the thermal low also has an effect on the North Atlantic hurricanes, possibly via VZ (as that variable provides the best model for hurricane frequency in the North Atlantic). The additional effect on VZ from the thermal low, in addition to ENSO, was examined. The results are shown in Table 5.3. It can be seen from this analysis that there is no significant additional influence of the thermal low on the VZ in the North Atlantic, and thus it is concluded that the thermal low only provides additional causal information about tropical cyclone genesis for the NE Pacific western development region.

Model	Adjusted R^2	Deviance
VZ vs. ENSO (KW)	0.22	14.4708
VZ vs. ENSO (KW) + thermal low	0.19	14.3754
VZ vs. ENSO (Niño1)	0.27	13.3744
VZ vs. ENSO (Niño1) + thermal low	0.24	13.3728

Table 5.3 The adjusted R^2 and deviance from a model with VZ in the Atlantic as the dependent variable and ENSO and the thermal low as the independent variable(s). The KW and Niño1 index are shown as these give the highest relationship between VZ and ENSO. The VZ is averaged over the MDR for the months August to October, 1972-1997.

a) 1988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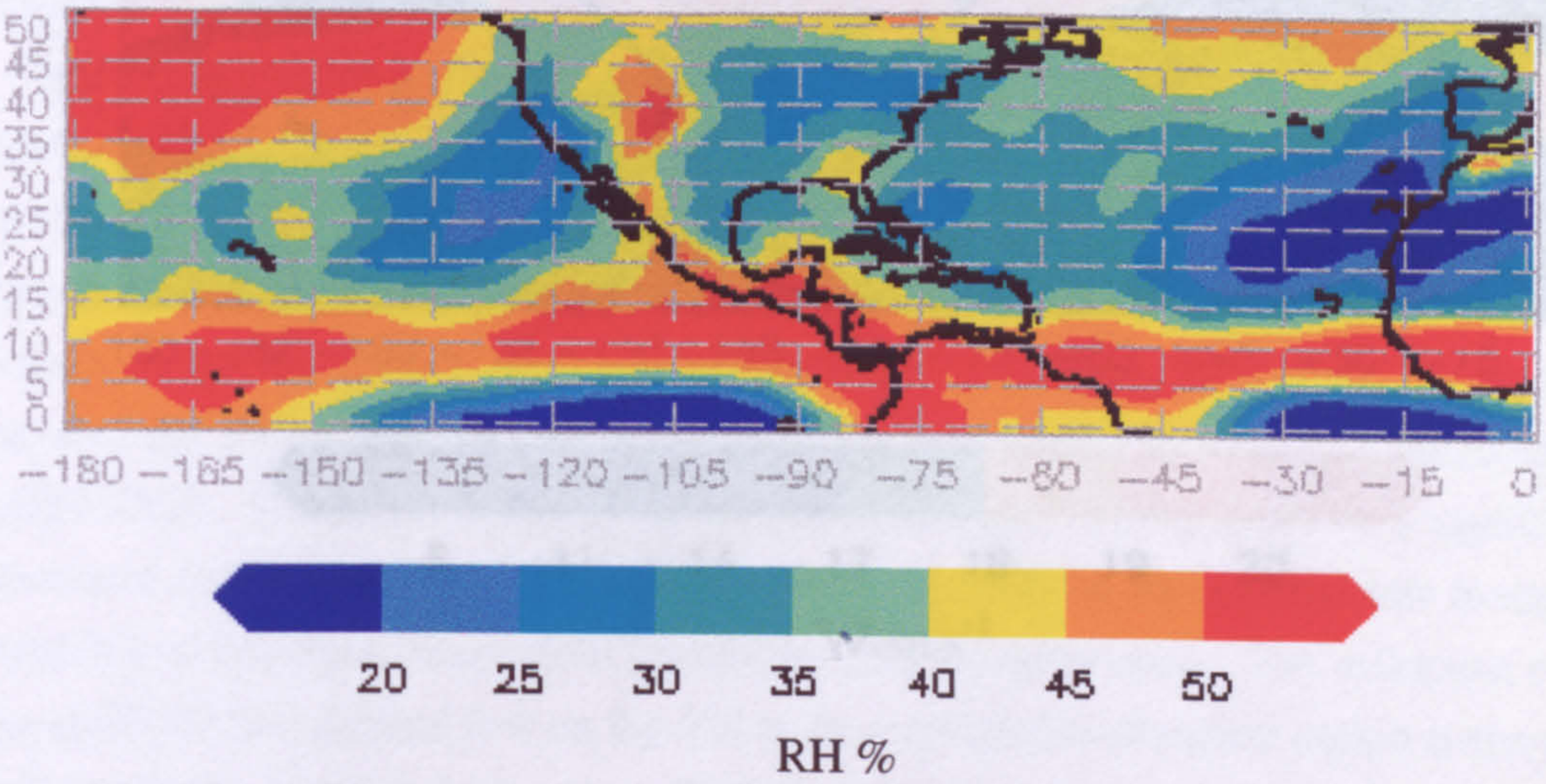
20 25 30 35 40 45 50
RH %

b) 1982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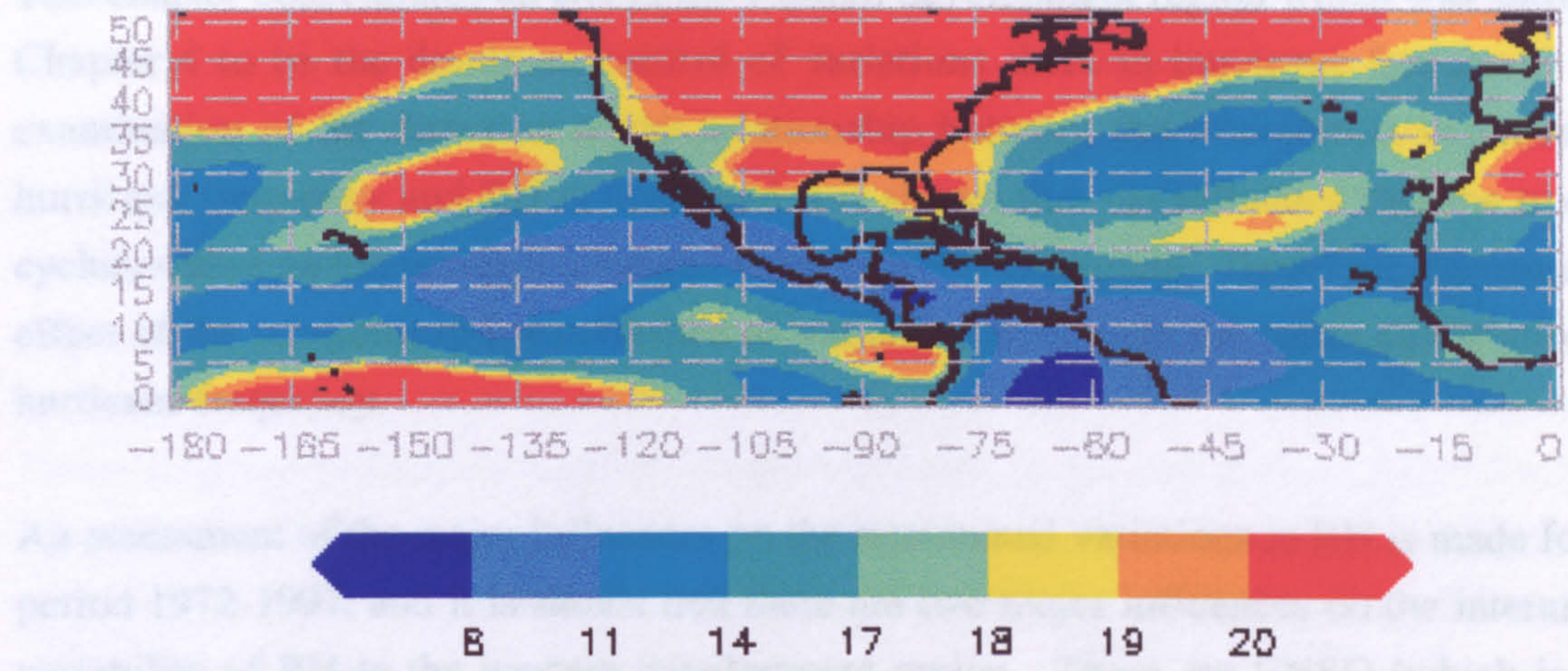
RH %

c) 1988



d) 1982

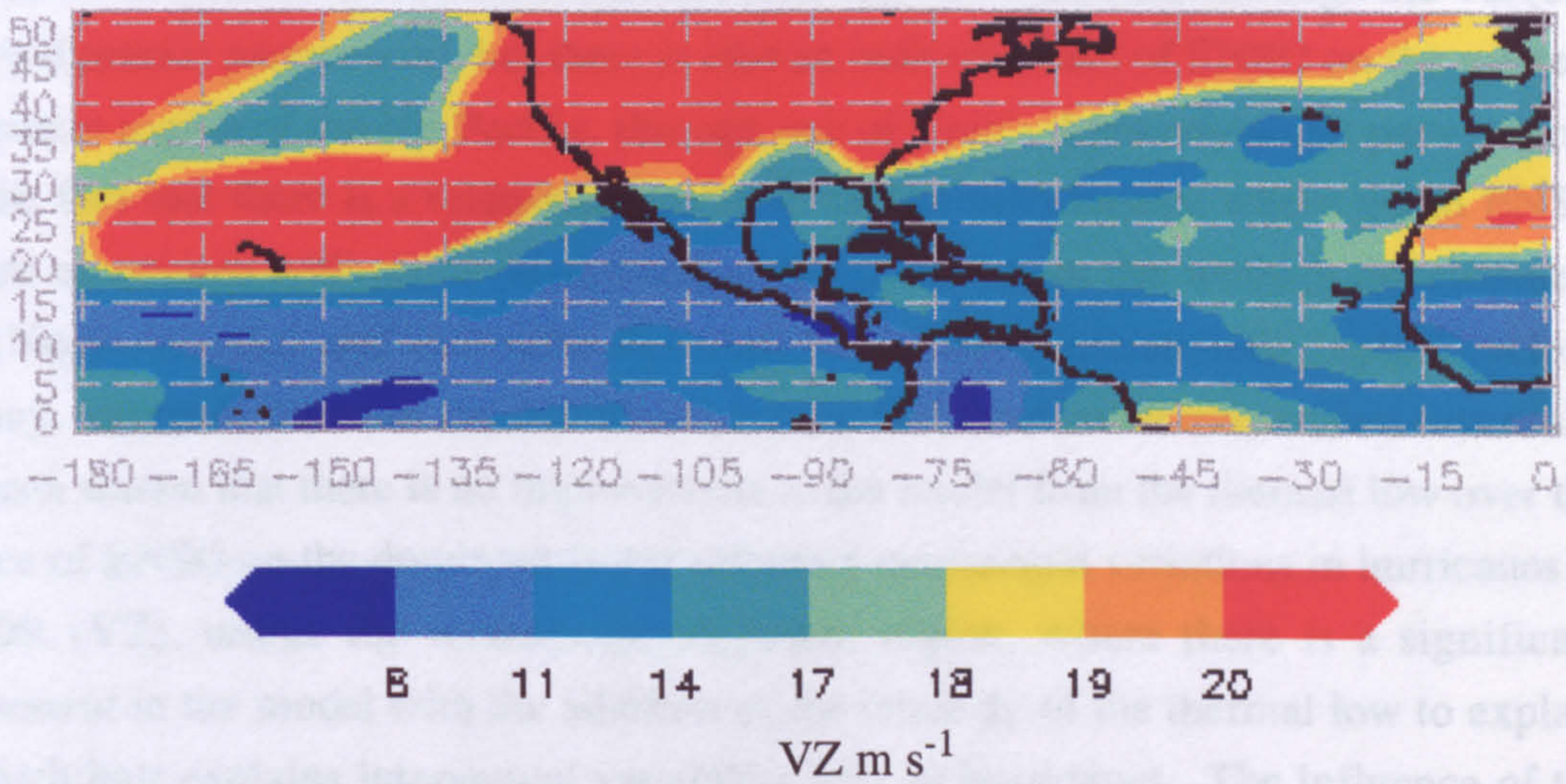


Figure 5.15 RH (July-September) and VZ (August-October) in an inactive ENSO year, 1988 (a and c) and an active ENSO year, 1982 (b and d).

5.5 Summary

This chapter concentrates on RH in the western development region which was shown in Chapter 4 to be the dominant control of variations there in hurricane frequency. An examination of the direction of the relationship between the interannual variations of hurricane frequency and RH is made and it is shown that the influence that the tropical cyclones have on the seasonal averaged value of RH is negligible. Therefore, the cause and effect of the relationship is established as variations in RH are the cause of variations in hurricane frequency.

An assessment of the major influences on the interannual variations in RH is made for the period 1972-1997, and it is shown that there are two major influences on the interannual variability of RH in the western development region. These are ENSO (which is well characterised by the Niño4 index) and the thermal low, which develops in the summer months over southern North America and is centred at 30°N, 112.5°W, and these operate largely independently from each other. It has been shown, therefore, that not only is there an indirect ENSO effect in the North Atlantic, affecting hurricanes here through the VZ (one of Gray's dynamic parameters), but there is also an indirect effect of ENSO on the western development region of the NE Pacific, through one of Gray's thermodynamic parameters - RH. The fact that there is a relationship with ENSO in both basins, where warm ENSO years are associated with more (less) conducive conditions in the western development region (North Atlantic), and vice versa, accounts for the anti-correlation of tropical cyclone frequency, observed between the two basins for the first time on an interannual timescale. It has been shown that there is no improvement in the model from the thermal low over the influence of ENSO on the dominant factor affecting interannual variations in hurricanes in the MDR (VZ), unlike the western development region, where there is a significant improvement in the model with the addition of the intensity of the thermal low to explain RH, which best explains interannual variability here of hurricanes. The influence of the non-local ENSO and thermal low on the RH in the western development region is shown to occur through the winds in both cases. ENSO affects the winds and hence the SST in the western development region, where there is an associated effect on the RH, and the thermal low affects the winds and hence the position of the trade wind inversion, which in turn affects the RH. Whilst it could appear that there may be a relationship between the surface winds in the eastern development region and the RH in the western development region, it is shown that this relationship is not a cause and effect, but only emerges due to the simultaneous influence of the thermal low, which is affecting both the RH in the western development region (through the mechanism described above) and the surface winds in the eastern development region (through the extension of the thermal low over the sea).

The period 1958-1971 is examined to investigate the influence of these two factors (ENSO and the thermal low) on RH. It is shown that there is little relationship with either the combined model or either of the single models of these variables. Whilst the possible unreliability of the NCEP/NCAR reanalysis of the RH data cannot be ruled out for the cause of this poor correlation, it is thought that the large-scale climate was sufficiently different in this earlier time period, as noted by previous authors, for this to possibly account for the poor correlations in this earlier period. In any case, the relationship between hurricane frequency and RH cannot be tested in this earlier time period due to the unreliability of the tropical cyclone dataset for this period. However, the significant relationships, both for hurricane frequency vs. RH and RH vs. ENSO and the thermal low, cannot be questioned for this later time period.

The cause for the interannual variation for the thermal low is investigated, for the period 1972-1997, and it is shown to be influenced by local temperature variations. This relationship is shown to be partly obscured by the weak correlation between the thermal low and ENSO.

Chapter 6

Conclusions: summary and future work

The work presented in this thesis provides the first in-depth study of interannual variations in tropical cyclones on a seasonal time-scale in the NE Pacific basin for the years 1972-1997. The study used statistical procedures to fulfil the objectives of this study as outlined in Section 1.8. This chapter will now examine the results obtained in this study and establish that the stated goals have been fulfilled.

6.1 Summary of results and conclusions

Figure 6.1 summarises the main findings regarding the seasonal environmental influences on tropical cyclone numbers in the western development region of the NE Pacific basin.

The following points give a detailed summary of the results and conclusions of the thesis.

- Tropical cyclone formation in the NE Pacific has been poorly understood to date. It was found that there are at least two populations of tropical cyclones, divided by longitude with respect to causal factors, which vary independently of each other in frequency. By sub-dividing the NE Pacific into two areas, east and west of 116°W, substantial progress can be made in achieving an enhanced understanding of the climatological factors that affect seasonal tropical cyclone formation. Such a sub-division, with respect to causal factors, has not previously been attempted.

- Increasing trends in tropical cyclone frequency with time are observed in the western development region which are stronger and more significant, the higher the hurricane category. The relative trend for intense hurricanes is 124%, significant at the 5% level. On the other hand, no significant trends with time emerge for any of the tropical cyclone categories in the eastern development region.

- Physical mechanisms for these trends were examined. Trends in SST and some of the other environmental variables were observed and it was shown that the tropical cyclone frequency trends can be fully accounted for in terms of interannual variations in associated environmental variables, rather than an extra long term influence. It was further argued that these are not likely to result from a data artefact or local

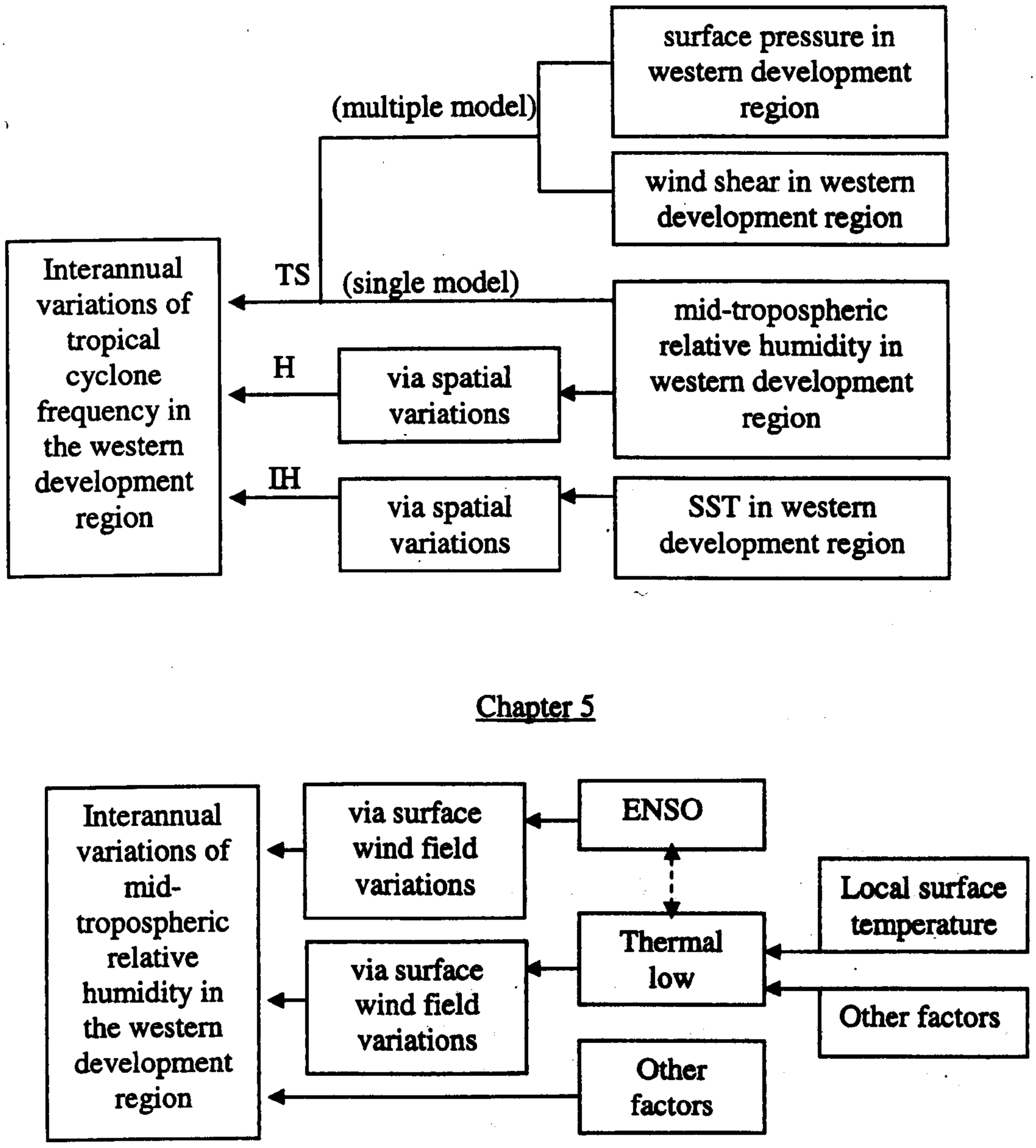


Figure 6.1 Summary of results.

anthropogenic influences, but are likely to result from natural variability, particularly as there is a significant trend in ENSO (Niño4) over this same time period. However, despite some evidence that global warming may not be responsible for the tropical cyclone frequency trends, recent predictive modelling suggests that some of the trend may be due to global warming. Furthermore, the effect of global warming on ENSO is unknown and thus the influence of global warming on these trends cannot be ruled out.

- The trend analysis shows that, not only are there significant increasing trends in the western development region in terms of frequency, but there are also significant trends in terms of the maximum intensity of the strongest storm. These have significant consequences for Hawaii. Important distinctions between a warm and cold ENSO regime were also highlighted in terms of longevity, maximum intensity of the strongest storm and formation position (although it was noted that with formation position, there was a tendency for the storms to occur further east of the western development region in warm rather than cold ENSO phases).

- A new method of calculating average wind shear for a season, which calculates averages of the instantaneous six-hourly wind shear from the six-hourly records of zonal and meridional winds, was presented. This was shown to provide a more accurate measure of wind shear than the method currently employed in the literature (which averages the zonal and meridional components for the month, before calculating the wind shear). It was also shown, through examples from tropical cyclone studies, that conclusions based on the current method in the literature may be altered when using the method proposed in this study. It was shown that, although this alternative approach of calculating wind shear does produce different results in the tropics, the biggest differences in wind shear values between the two methods are found to be in the mid-latitudes, particularly of the Northern Hemisphere. This new, more accurate method was employed in the current study.

- Relative humidity and related thermodynamic variables including SST, pressure vertical velocity and precipitable water were found to have highly significant relationships with frequency for all categories of tropical cyclone in the western development region, whilst other factors, particularly the dynamic variables (such as wind shear) and the QBO can be excluded as being important in understanding interannual variations of tropical cyclone frequency in the NE Pacific (contrary to their influence in the North Atlantic).

- Relative humidity (RH) was shown to be the dominant influence on hurricane frequency and this variable was examined in detail to determine the correct direction of the relationship. It is shown that there is a negligible influence from the tropical cyclones on the seasonal averaged RH of the western development region and, hence, the direction of the relationship is that the RH variations are the *cause* of the hurricane variations, not the *effect.* The reliability of this NCEP/NCAR variable in the western development region, as well as of other variables, is shown to be good based on an inter-model comparison with the ECMWF reanalysis data. Therefore, the results obtained with this variable are likely to be true.

- Physical mechanisms were examined to explain these interannual variations in tropical cyclone frequency. An important mechanism is likely to be a threshold effect involving the variation of the local thermodynamic variables from below conducive to above conducive values. Inactive tropical cyclone years are then characterised by unconducive conditions over a larger area in the western development region, with relationships emerging between tropical cyclone frequency and the spatially averaged variables. However, an extra direct mechanism by which the instantaneous variable values affect tropical cyclone genesis could not be ruled out.

- It was clear from the lack of significant trends or relationships in the eastern development region that the variation of tropical cyclones in this latter region is not influenced primarily from a variation in the climatological values of the environmental factors. The reason for this was suggested to be due to the climatological values in the eastern development region always being at a sufficiently high value in active and inactive tropical cyclone years. This suggests that "weather" is largely responsible, in particular providing variations in the number of triggering disturbances. The single significant result in the eastern development region, a negative relationship between tropical cyclone frequency and outward long-wave radiation flux (OLR) , provides evidence for this, where the OLR value may be an inverse indicator of the number of triggering disturbances.

- From an examination of the residuals of the best models to explain tropical cyclone frequency in the western development region, it was shown that hurricane and intense hurricane frequency does not have a Poisson distribution, contrary to the current literature. In fact, it has been noted that they come from a more under-dispersed distribution.

- In-depth analysis considering the causes of the interannual variations in RH, which was found to be the dominant control on hurricane formation in the western development region, was conducted. It was found that RH was best explained by variations in ENSO and the summer thermal low pressure region (whose lowest value is situated at 30°N, 112.5°W). Both of these factors are found to influence RH via variations in the wind field, and hence via SST (for ENSO) or via the location of the trade wind inversion (for the thermal low). Therefore, it is observed that ENSO operates though Gray's (1979) *thermodynamic* parameters in the NE Pacific to affect tropical cyclone frequency, compared to the North Atlantic, where it has been previously noted that ENSO operates via wind shear, one of Gray's *dynamic* parameters. The thermal low helps to explain RH variations in the NE Pacific. However, it was found that this provides no additional information over ENSO to explain wind shear variations in the North Atlantic. The ENSO relationships observed can account for the anti-correlations between tropical cyclone numbers in the western development region and those in the North Atlantic. Consumption of easterly waves in the North Atlantic has been shown not to account for the observed anti-correlations in tropical cyclone numbers since there was no anti-correlation with tropical cyclones in the eastern development region and the North Atlantic.

- The relationship between low-level zonal winds (and wind shear) in the eastern development region and RH in the western development region is shown not to be a direct cause and effect relationship, but results indirectly due to both of these variables being related to the thermal low. The thermal low affects the zonal winds in the eastern development region due to the expansion of the thermal low over the sea in some years more than others. This expansion would allow air to travel more cyclonically in those years which cause winds to have a westerly wind difference vector compared to normal.

- The influences on the interannual variations of the intensity of the thermal low were examined and it was seen that local temperature variations significantly accounted for the variations. However, it was noted that ENSO tends to obscure this result due to the weak correlation between the thermal low and ENSO.

- It has been shown that there is an important indirect effect from ENSO on hurricane frequency in the western development region, via RH, to increase hurricane numbers in high Niño4 years. On the other hand, there is a tendency towards fewer hurricanes in the eastern development region in these high Niño4 years. These different effects from

ENSO occurring in the same basin, the NE Pacific Ocean, has not previously been observed.

6.2 Perceived weaknesses of thesis

Having completed the investigations described in this thesis, a number of weaknesses have become apparent, and are described below:

- Section 3.2.3 discusses a suggestion that some of the relationships between tropical cyclones and the environmental variables and the significant trends observed may be due to an "intensity-frequency" effect. A mechanism for this effect is suggested, but no further investigations were carried out to determine its magnitude in the NE Pacific basin. A priority for future work is to investigate the possible magnitude of this effect, in both development regions through a simulation study using estimated tropical depression data, randomly generated tropical storm numbers, an appropriate intensity distribution and SST information.

- Section 4.11 showed that hurricane and intense hurricane frequency is, in fact, contrary to the literature, not adequately described by a Poisson process. Therefore, to improve the models which were identified to explain variations in frequency of hurricanes and intense hurricanes, a possible different distribution should be investigated and then implemented accordingly.

- Section 4.7.4 alluded to the problems of spatial dependence in identifying non-local regions that may affect tropical cyclone formation. This is a drawback of executing many hypothesis' tests to study spatial patterns. Although the maps of the *t*-statistics do give a broad indication of where associations are likely to lie, more sophisticated statistical techniques, such as principal component analysis, may allow analysis in the future to overcome the problem of spatial dependence.

6.3 Recommendations for further study

In addition to the improvements suggested in Section 6.2, and based on the findings of this study, the following work is recommended:

- Tropical cyclone numbers up to the dateline have been included in this study as this is the technical definition of the NE Pacific basin. Other authors have considered other definitions for the NE Pacific basin such as Irwin III and Davis (1999) who defined the NE Pacific as east of 160°W. The reason for this definition is that, west of this, the region is strongly influenced by Western Pacific circulations. Hastenrath and

Wendland (1979) chose an area from the United States' coastline to approximately 115°W to define the NE Pacific, as they noted that this is where the majority of tropical cyclones occur. Technically, in order to assign forecasting regions as devised by the WMO, the central Pacific/NE Pacific boundary is defined as 140°W. However, based on physical grounds, when one considers the factors that influence tropical cyclone formation, there is no reason to separate the tropical cyclones that form to the east and west of this longitude and, indeed, a cut-off at this point may arbitrarily lose some of the causal information. Figure 3.1 shows the formation position of all hurricanes in the NE Pacific region between 1972-1997. It can be seen from this that, in this region, over this period, the majority of the hurricanes form in a region between 10°N to 20°N and extend from the west coast of North America to approximately 116°W, with a secondary relatively large formation area extending from 116°W to approximately 143°W. An examination of Figure 3.1 suggests that there is, in fact, a clear gap where no hurricanes form between 143°W and 151°W. West of this there are a few (seven) spurious hurricanes which do not seem to cluster in space. The main cause of this was seen to be the large vertical wind shear in this region (Section 4.7.2). Furthermore, the longitude plots in Section 4.7.1 show that many of the environmental variables change to a different value around 143°W. Thus, for future work it may be more appropriate to re-define the west edge of the western development region, considering tropical cyclones from the west coast of North America to 143°W, excluding those to the west of 143°W as described above. Thus, the western development region would be defined as 143°W to 116°W.

- An examination of the relative humidity from the ECMWF 40-year reanalysis, which will be available from late 2002/early 2003, could be conducted to ascertain the reliability of the NCEP/NCAR relative humidity for the 1958-1971 period. Alternatively, radiosonde data could be obtained to achieve the same goal. This may show a problem with the data and explain the lack of relationship for the model of RH vs. ENSO and thermal low for this earlier period (noted in Section 5.2.3).

- Section 5.4 shows that, although ENSO has an influence on the dominant factors affecting hurricane formation in both the western development region of the NE Pacific (through RH) and North Atlantic basins (through wind shear), the thermal low has been identified as being important only for the western development region of the NE Pacific (via the RH), and not for the North Atlantic. However, again the North Atlantic is a large area, and future work, focusing on the North Atlantic basin, could examine if the thermal low has an influence on the different sub-regions in this basin, e.g. by

geographic locations, such as the Gulf of Mexico region, the Caribbean region or MDR; or by Elsner and Kara's (1999) definitions of tropical-only hurricanes or baroclinically-enhanced hurricanes.

- The interannual variations in the thermal low were seen to be largely a result of local temperature variations. Other additional affects could be examined, as well as determining what causes the interannual variations in the local surface temperature. In addition, the effects of global warming on the hurricanes via the thermal low (via the temperature or other variables) could be explored. For example, global warming could bring about a deeper thermal low which could have a very strong depressing effect on hurricane numbers.

- No seasonal forecasts have yet been made for the NE Pacific where research has lagged behind the North Atlantic and NW Pacific. This is now possible, to some extent, for the western development region, given that, through this study, a better understanding has now been achieved of the dominant factors affecting tropical cyclone formation in this region (Chapter 4), and the factors that control these (Chapter 5). RH, unlike SST, is not directly predictable but may be predictable from local SSTs or Niño4 region SSTs. (Unfortunately, variables in the atmosphere, such as RH for example, are not as easy to predict directly, due to the short memory of the atmosphere, whereas SST is to some extent predictable due to the longer memory of the ocean.) Successful prediction of SSTs a year ahead has been achieved in recent years. Of note, Latif et al. (1998) have been attempting SST prediction through statistical techniques for the purpose of ENSO prediction in the Pacific. Therefore, with the link noted between ENSO, SST and RH in the western development region, these or similar SST forecast models may be used in future to predict RH, which in turn can be used to predict hurricane activity (based on the assumption that the environment variables which have been shown in this study to affect hurricane formation in the past, will continue to do so in the immediate future). Seasonal forecasting in this area is clearly of less importance than for the North Atlantic but does have particular importance for Hawaii.

- Finally, it has been noted that in this study, one of the main limitations in examining tropical cyclone activity in the NE Pacific basin is the relatively short period of reliable record available - only 26 years when this study began. Therefore, as more years of data come available in the future, the results and conclusions drawn from the current study can hopefully be supported and further developed.

Appendix 1

Calculated NTC index for the western development region

The NTC index for the western development region of the NE Pacific Ocean:

Year	TS	TSD	H	HD	IH	IHD	NTC
1972	2	17.5	3	16	2	2	125
1973	0	0	0	0	0	0	0
1974	4	16.25	2	5.75	1	0.25	83
1975	3	7	1	0	0	0	33
1976	3	11.25	1	4.75	0	0	48
1977	2	4	1	1.5	0	0	26
1978	3	18.25	2	3.5	0	0	62
1979	0	0	1	4	3	2.25	67
1980	1	0.75	0	0	0	0	6
1981	1	6	3	5.75	0	0	47
1982	8	32.5	6	17.25	2	2.5	205
1983	1	2	0	0	1	0.75	25
1984	4	11.75	2	4.25	1	0.25	74
1985	4	11.25	3	12	3	5.25	153
1986	6	19.5	3	9.5	1	2.25	126
1987	7	27.5	3	11.5	1	1.5	141
1988	4	24.25	2	17.5	2	4.25	155
1989	3	4.75	1	6	0	0	41
1990	3	19.5	5	17	3	8	201
1991	0	0	2	6	1	0.75	44
1992	4	7	5	12.25	2	4.75	160
1993	2	20.25	3	19.25	5	11.5	234
1994	9	41	6	27	5	18	377
1995	1	2.25	0	0	0	0	8
1996	0	0	0	0	0	0	0
1997	5	22.75	4	11.5	2	4	159
Mean	3.08	12.98	2.27	8.17	1.35	2.63	100

TS is the number of tropical storms, ***TSD*** is the number of tropical storm days, ***H*** is the number of hurricanes, HD is the number of hurricane days, IH is the number of intense hurricanes, IHD is number of intense hurricane days and NTC is the net tropical cyclone activity index defined by Gray et al. (1994).

References

Alpert, A.C., 1946: The intertropical convergence zone of the Eastern Pacific region (II). *Bull. Am. Meteor. Soc.*, **27**, 15-29.

AMS Policy Statement, 2000: Hurricane research and forecasting. ***Bull. Am. Meteor. Soc.***, **81**, 1341-1346.

Angell, J.K., J. Korshover, and G.F. Cotten, 1969: Quasi-biennial variations in the "centers of action". *Mon. Wea. Rev.*, **97**, 867-872.

Avila, L.A., 1991: Atlantic tropical systems of 1990. *Mon. Wea. Rev.*, **119**, 2027-2033.

Ballenzweig, E.M., 1959: Relation of long-period circulation anomalies to tropical storm formation and motion. *J. Meteor.*, **16**, 121-139.

Barnston, A. G., 1994: Linear statistical short-term climate predictive skill in the Northern Hemisphere. *J. Clim.*, **7**, 1513-1564.

Bender, M.A. and I. Ginis, 2000: Real-case simulations of hurricane-ocean interaction using a high resolution coupled model: effects on hurricane intensity. *Mon. Wea. Rev.*, **128**, 917-946.

Bevington, P.R. and D.K. Robinson, 1992: Data Reduction and Error Analysis for the Physical Sciences (2nd edition). McGraw-Hill, Boston, 328pp.

Bister, M. and K.A. Emanuel, 1997: The genesis of Hurricane Guillermo: TEXMEX analyses and a modelling study. *Mon. Wea. Rev.*, **125**, 2662-2682.

Bister, M. and K.A. Emanuel, 1998: Dissipative heating and hurricane intensity. *Meteorol. Atmos. Phys.*, **65**, 233-240.

Bracken, W.E. and L.F. Bosart, 2000: The role of synoptic-scale flow during tropical cyclogenesis over the North Atlantic Ocean. *Mon. Wea. Rev.*, **128**, 353-376.

Brennan, J.F., 1935: Relations of May-June weather conditions in Jamaica to Caribbean tropical disturbances of the following season. *Mon. Wea. Rev.*, **63**, 13-14.

Broccoli, A.J., S. Manabe, J.F.B. Mitchell, and L. Bengtsson, 1995: Comments on 'Global climate change and tropical cyclones': Part II. *Bull. Am. Met. Soc.*, **76**, 2243-2245.

Brown, G.M. and P.W. Leftwich, 1982: A compilation of eastern and central North Pacific tropical cyclone data. NOAA Technical Memorandum NWS NHC, **16**, Miami, 13pp.

Bryan, K, F.G. Komro, S. Manabe and M.J. Spelman, 1982: Transient climate response to increasing atmospheric carbon dioxide. *Science*, **215**, 56-58.

Cerveny, R.S. and R.C. Balling, 1998: Weekly cycles of air pollutants, precipitation and tropical cyclones in the coastal NW Atlantic region. *Nature*, **394**, 561-563.

Challa, M., and R. Pfeffer, 1990: Formation of Atlantic hurricanes from cloud clusters and depressions. *J. Atmos. Sci.*, **47**, 909-927.

Chan, J.C.L., 1995: Tropical cyclone activity in the western North Pacific in relation to the stratospheric quasi-biennial oscillation. *Mon. Wea. Rev.*, **123**, 2567-2571.

Chan. J.C.L. and J.E. Shi, 1996: Long term trends and interannual variability in tropical cyclone activity over the western North Pacific. *Geophys. Res. Lett.*, **23**, 2765-2767.

Chandler, R.E., 1998: Orthogonality. In: Encyclopaedia of Biostatistics (Eds. P. Armitage and T. Cotton). Wiley and Sons, New York, 3203-3209.

Chu, P.S. and J. Wang, 1997: Tropical cyclone occurrences in the vicinity of Hawaii: Are the differences between El Niño and non-El Niño years significant? *J. Clim.*, **10**, 2683-2689.

Chu, P.S. and J.D. Clark, 1999: Decadal variations of tropical cyclone activity over the central North Pacific. *Bull. Am. Meteor. Soc.*, **80**, 1875-1881.

Clark, J.D. and P.S. Chu, 1999: Interannual variability of tropical cyclones in the central North Pacific. 23rd conference on hurricanes and tropical meteorology, Dallas, American Meteorological Society, 246-247.

Cohen, T.J. and E.I. Sweetser (1975): The spectra of the solar cycle and of data for Atlantic tropical cyclones. *Nature*, **256**, 295-296.

Cox, D.R. and Hinkley, 1974: Theoretical Statistics. Chapman and Hall, London, 511pp.

Cox, D.R. and V. Isham, 1980: Point Processes. Chapman and Hall, London, 188pp.

Cunnane, C., 1979: A note on the Poisson assumption in partial duration series models. *Water Resour. Res.*, **15**, 489-494.

Davis, M.A.S., G.M. Brown, and P.W. Leftwich, jr., 1984: A tropical cyclone data tape for the eastern and central North Pacific Basins, 1949-1983: contents, limitations, and uses. NOAA Technical Memorandum NWS NHC, 25, Miami, 16pp.

DeMaria, M., J-J. Baik, and J. Kaplan, 1993: Upper-level angular momentum fluxes and tropical cyclone intensity change. *J. Atmos. Sci.*, **50**, 1133-1147.

DeMaria, M. and J. Kaplan, 1994: Sea surface temperature and the maximum intensity of Atlantic tropical cyclones. *J.Clim.*, **7**, 1324-1334.

Diggle, P.J., 1983: Statistical Analysis of Spatial Point Patterns. Academic Press, London, 148pp.

Druyan, L.M., P. Lonergan and T. Eichler, 1999: A GCM investigation of global warming impacts relevant to tropical cyclone genesis. *Int. J. Climatology*, **19**, 607-617.

Dvorak, V.F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103**, 420-430.

Dvorak, V.F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, 47 pp. [Available from NOAA -NESDIS, World Weather Building, Washington DC 20235].

Elsner, J.B. and C.P. Schmertmann, 1993: Improving extended-range seasonal predictions of intense Atlantic hurricane activity. *Weather and Forecasting*, **8**, 345-351.

Elsner, J.B. and A.B. Kara, 1999: Hurricanes of the North Atlantic. Oxford University Press, New York, 488pp.

Elsner, J.B., T. Jagger and X. Niu, 2000: Changes in the rates of North Atlantic major hurricane activity during the 20th century. 24th conference on hurricanes and tropical meteorology, Fort Lauderdale, American Meteorological Society, 474-475.

Elsner, J.B. and B. Kocher, 2000: Global tropical cyclone activity: A link to the North Atlantic Oscillation. *Geo. Phys. Res.*, **27**, 129-132.

Elsner, J.B., B.H. Bossak and X. Niu, 2001 (in review): Multi-decadal variability of the ENSO-hurricane teleconnection.

Emanuel, K.A., 1986: An air-sea interaction theory for tropical cyclones. Part 1: Steady-state maintenance. *J. Atmos. Sci.*, **43**, 585-604.

Emanuel, K.A., 1987: The dependence of hurricane intensity on climate. *Nature*, **326**, 483-485.

Emanuel, K.A., 1988: Toward a general theory of hurricanes. *American Scientist*, **76**, 371-379.

Enamuel, K.A., 1991: The theory of hurricanes. *Ann. Rev. Fluid Mech.*, **23**, 179-196.

Emanuel, K.A., 1995: Comments on "Global climate change and tropical cyclones": Part 1. *Bull. Am. Met. Soc.*, **76**, 2241-2245.

Emanuel, K.A., 1997: Climate variations and hurricane activity: some theoretical issues. In: Hurricanes: Climate and Socioeconomic Impacts (Eds. H.F. Diaz and R.S. Pulwarty). Springer, Berlin, 55-65.

Emanuel, K.A., 1999: Thermodynamic control of hurricane intensity. *Nature*, **40**, 665-669.

Emanuel, K.A., 2000: A statistical analysis of tropical cyclone intensity. *Mon. Wea. Rev.*, **128**, 1139-1152.

Evans, J.L., 1993: Sensitivity of tropical cyclone intensity to sea surface temperature. *J.Clim.*, **6**, 1133-1140.

Frank, W.M., 1987: Tropical cyclone formation. In: A Global View of Tropical Cyclones (Ed. R.L. Elsberry). Naval Postgraduate School, 53-90.

Fritz, S., L.F. Hubert, and A. Timchalk, 1966: Some inferences from satellite pictures of tropical disturbances. *Mon. Wea. Rev.*, **94**, 231-236.

Gaby, D.C., J.B. Lushine, B.M. Mayfield, S.C. Pearce, and F.E. Torres, 1980: Satellite classification of Atlantic tropical and sub-tropical cyclones: A review of eight years of

classifications at Miami. *Mon. Wea. Rev.*, **108**, 587-595.

Garriott, E.B., 1906: The West Indian hurricanes of September 1906. *Mon. Wea. Rev.*, **34**, 416-423.

Goldenberg, S.B. and L.J. Shapiro, 1996: Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity. *J. Clim*, **9**, 1169-1187.

Gordon, A., W. Grace, P. Schwertfeger and R. Byron-Scott, 1998: Dynamical Meteorology. Wiley and Sons, New York, 325pp.

Graham, N.E. and W.B. White, 1988: The El Niño cycle: A natural oscillator of the Pacific Ocean-atmosphere system. *Science*, **24**, 1293-1302.

Gray, W M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 662-700.

Gray, W M., 1979: Hurricanes: their formation, structure and likely role in the tropical circulation. Supplement to Meteorology over the Tropical Oceans (Ed. D.B. Shaw). Published by *Royal Met. Soc.*, James Glaisher House, Grenville Place, Bracknell, Berkshire, 155-218.

Gray, W.M, 1984: Atlantic seasonal hurricane frequency. Part II: Forecasting its variability. *Mon. Wea. Rev.*, **112**, 1669-1683.

Gray, W.M., 1988: Environmental influences on tropical cyclones. *Aust. Met. Mag.*, **36**, 127-139.

Gray, W M., 1992: LAD multiple linear regression forecasts of Atlantic tropical storm activity for 1993. *Exp. Long-Lead Forecast Bull.*, **1**, 12-14.

Gray, W M., 1993: Seasonal forecasting. In: Global Guide to Tropical Cyclone Forecasting. World Meteorological Organisation Technical Document, WMO/TD - No.560. Tropical Cyclone Programme - Report No. TCP-31.

Gray, W.M. and J.D. Sheaffer, 1991: El Niño and QBO influences on tropical cyclone activity. In: Teleconnections Linking World Wide Climate Anomalies (Eds. M. Galntz, R. Katz, and N. Nicholls). Cambridge University Press, Cambridge, 257-284.

Gray, W.M., J.D. Sheaffer, and J.A. Knaff, 1992: Influence of the stratospheric QBO on ENSO variability. *J. Meteor. Soc. Japan*, **70**, 975-995.

Gray, W.M., C.W. Landsea, P.W. Mielke, Jr., and K.J. Berry, 1993: Predicting Atlantic basin tropical cyclone activity by 1 August. *Weather and Forecasting*, **8**, 73-86.

Gray, W.M., C.W. Landsea, P.W. Mielke, Jr., and K.J. Berry, 1994: Predicting Atlantic basin tropical cyclone activity by 1 June. *Wea. Forecasting*, **9**, 103-115.

Gray, W.M., J.D. Sheaffer and C.W. Landsea, 1997: Climate trends associated with multidecadal variability of Atlantic hurricane activity. In: Hurricanes: Climate and Socioeconomic Impacts (Eds. H.F. Diaz and R.S. Pulwarty). Springer-Verlag. Berlin, 15-52.

Hastenrath, S. and W. M. Wendland, 1979: On the secular variation of storms in the

tropical North Atlantic and Eastern Pacific. *Tellus*, **31**, 28-38.

Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S-L. Shieh, P. Webster and K. McGuffie, 1998: Tropical cyclones and global climate change: a post-IPCC assessment. *Bull. Am. Met. Soc.*, **79**, 19-38.

Hennon, C.C., 2000: A climatology of hurricane maximum potential intensity in the Atlantic basin. 24th conference on hurricanes and tropical meteorology, Fort Lauderdale, American Meteorological Society, 7-8.

Henson, R., 1998: How strong will a hurricane get? *Weatherwise*, September/October, 22-26.

Holland, G.J., 1993: Ready Reckoner. In: Global Guide to Tropical Forecasting (Ed. G.J. Holland). WMO/TC-No. 560, Report No. TCP-31, World Meteorologiocal Organisation, Geneva, Switzerland, 9.1-9.32.

Holland, G.J., 1995: Scale interaction in the western Pacific monsoon. *Meteor. Atmos. Phys.*, **56**, 57-79.

Holland, G.J., 1997: The maximum potential intensity of tropical cyclones. *J. Atmos. Sci.*, **54**, 2519-2541.

Hope, J.R. and C.J. Neumann, 1969: Climatology of Atlantic tropical cyclones by two and one-half degree latitude-longitude boxes. ESSA Technical Memorandum WBTM-SR-44, Environmental Science Services Administration, Fort Worth, Texas, 50 pp.

Horsfall, F. and M. DeMaria, 2000: Climatological analysis of tropical cyclogenesis in the North Atlantic and eastern North Pacific basins. 24th conference on hurricanes and tropical meteorology, Fort Lauderdale, American Meteorological Society, 53-54.

Hoyt, D.V. and Schatten, K.H., 1997: The Role of the Sun in Climate Change. Oxford University Press, Oxford, 279 pp.

Idso, S.B., R.C. Balling, Jr. and R.S. Cerveny, 1990: Carbon dioxide and hurricanes: implications of Northern Hemisphere warming for Atlantic/Caribbean storms. *Meteorol. Atmos. Phys.*, **42**, 259-263.

IPCC (Intergovernmental Panel on Climate Change), 1996: Summary for policy makers, In: Climate Change 1995: The Science of Climate Change (Eds. J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell). Cambridge University Press, Cambridge, 1-7.

Irwin III, R.P. and R.E. Davis, 1999: The relationship between the Southern Oscillation Index and tropical cyclone tracks in the eastern North Pacific. *Geophys. Res. Lett.*, **26**, 2251-2254.

Jarque, C.M. and A.K. Bera, 1980: Efficient tests for normality, homoscedasticity and serial independence of regression residuals. *Economic letters*, **6**, 255-259.

Jarvinen, B.R., C.J. Neumann and M.A.S. Davis, 1984: A tropical cyclone data tape for the North Atlantic basin, 1886-1983: Contents, limitations, and uses. NOAA Technical Memorandum NWS NHC, **22**, Miami, 22pp.

Kalnay, E., and collaborators, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull.*

Am. Meteor. Soc., **77**, 437-471.

Kaplan, J., and M. DeMaria, 1995: A simple empirical model for predicting the decay of tropical cyclone winds after landfall. *J. Appl. Meteor.*, **34**, 2499-2512.

Kashiwabara, T., 1987: On the recent winter cooling of the North Pacific. *Tenki*, **34**, 777-781 (in Japanese).

Keim, B.D. and J.F. Cruise, 1998: A technique to measure trends in the frequency of discrete random events. *J. Clim.*, **11**, 849-855.

Kimberlain, T.B., and J.B. Elsner, 1998: The 1995 and 1996 North Atlantic hurricane seasons: a return of the tropical only hurricane. *J. Clim.*, **11**, 2062-2069.

Kimberlain, T.B., 1999: The effects of ENSO on North Pacific and North Atlantic tropical cyclone activity. 23rd conference on hurricanes and tropical meteorology, Dallas, American Meteorological Society, 250-253.

Kistler, R., and coauthors, 2001: The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation. *Bull. Am. Met. Soc.*, **82**, 247-267.

Klein, S.A., B.J. Soden, and N.C. Lau, (1999) Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge. *J. Clim.*, **12**, 917-932.

Knaff, J.A., 1993: Evidence of stratospheric QBO modulation of tropical convection. Colorado State University, Atmospheric Science Paper No. 520, 91pp.

Knaff, J.A. 1997: Implications of summertime sea level pressure anomalies in the tropical Atlantic region. *J. Clim.*, **10**, 789-804.

Knutson, T.R. and R.E. Tuleya, 1999: Increased hurricane intensities with CO_2-induced warming as simulated using the GFDL hurricane prediction system. 23rd conference on hurricanes and tropical meteorology, Dallas, American Meteorological Society, 1069-1072.

Kriner, S., 2000: Another ominous rainy season draws near; Mozambique still recovering from floods. www.disasterrelief.org, Fri, 27 September, 2000.

Lander, M.A. and C.P. Guard, 1998: A look at global tropical cyclone activity during 1995: contrasting high Atlantic activity with low activity in other basins. *Mon. Wea. Rev.*, **126**, 1163-1173.

Landsea, C.W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.*, **121**, 1703-1713.

Landsea, C.W., 2000: El Niño-Southern Oscillation and the seasonal predictability of tropical cyclones. In: El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts (Eds. H. F. Diaz and V. Markgraf). Cambridge University Press, Cambridge, 149-181.

Landsea, C.W. and W.M. Gray, 1989: Low-frequency and seasonal variability within ocean basins: Northeastern Pacific Ocean. Report of WG 6.2 (Northeast Pacific Ocean) of IWTC -II, WMO, Geneva, 315-330.

Landsea, C.W. and W.M. Gray, 1992: The strong association between western Sahel monsoon rainfall and intense Atlantic hurricanes. *J. Clim.*, **5**, 435-453.

Landsea, C.W., N. Nicholls, W.M. Gray and L.A. Avila, 1996: Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophys. Res. Lett.*, **23**, 1697-1700.

Landsea, C.W., G.D. Bell, W.M. Gray and S.B. Goldenberg, 1998: The extremely active 1995 Atlantic hurricane season: Environmental conditions and verification of seasonal forecasts. *Mon. Wea. Rev.*, **126**, 1174-1193.

Landsea, C.W., R.A. Peilke, A.M. Mestas-Nuñez and J.A. Knaff, 1999: Atlantic basin hurricanes: indices of climatic changes. *Climate Change*, **42**, 89-129.

Latif, M., D. Anderson, T. Barnett, M. Cane, R. Kleeman, A. Leetmaa, J. O' Brien, A. Rosati and E. Schneider, 1998: a review of the predictability and prediction of ENSO. *J. Geophys. Res.*, **103**, 14375-14393.

Liebmann, B and C.A. Smith, 1996. Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Amer. Meteor. Soc*, **77**, 1275-1277.

Lighthill, J., G. Holland, W. Gray, C. Landsea, G. Craig, J. Evans, Y. Kurihara, and C. Guard, 1994: Global climate change and tropical cyclones. *Bull. Am. Meteorol. Soc.*, **75**, 2147-2157.

Madden, R.A. and P.R. Julian, 1994: Observations of the 40-50 day tropical oscillation - a review. *Mon. Wea. Rev.*, **122**, 814-837.

Maloney, E.D. and D.L. Hartmann, 1998: Frictional moisture convergence in a composite lifecycle of the Madden-Julian Oscillation, *J. Clim.*, **11**, 2387-2403.

Maloney, E.D. and D.L. Hartmann, 2000: Modulation of eastern North Pacific hurricanes by the Madden-Julian Oscillation. *J. Clim.*, **13**, 1451-1460.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteor. Soc.*, **78**, 1069-1079.

Mayfield, M. and E.N. Rappaport, 1998: Eastern North Pacific hurricane season of 1996, *Mon. Wea. Rev.*, **126**, 3068-3076.

McBride, J.L., 1981a: Observational analysis of tropical cyclone formation. Part i: Basic description of data sets. *J. Atmos. Sci.*, **38**, 1117-1131.

McBride, J.L., 1981b: Observational analysis of tropical cyclone formation. Part iii: Budget analysis. *J. Atmos. Sci.*, **38**, 1152-1166.

McCullagh, P. and J.A. Nelder, 1989: Generalised Linear Models (2nd edition). Chapman and Hall. London, 511pp.

McDonald, R.E., D.G. Bleaken, D.R. Cresswell, V.D. Pope and C.A. Senior, 2001: Tropical storms: representation and diagnosis in climate models and the impacts of climate change. PMSR Report. Hadley Centre for Climate Prediction and Research.

McGregor, G.R., and S. Nieuwolt, 1998: Tropical Climatology. Wiley and Sons, New York, 339pp.

McIlveen, R., 1992: Fundamentals of Weather and Climate. Stanley Thornes (Publishers) Ltd, Cheltenham, 497pp.

Meldrum, C., 1872: On a periodicity in the frequency of cyclones in the Indian Ocean south of the equator. *Nature*, **6**, 357-358.

Met. Office, 1995: Principles of Tropical Meteorology. Meteorological Office College, Reading, 9pp.

Met. Office, 1999: Tropical Meteorology, Tropical Cyclones. Meteorological Office College, Reading, 14pp.

Molinari, J., D. Knight, M. Dickinson, D. Vollaro, and S. Skubis, 1997. Potential vorticity, easterly waves, and eastern Pacific tropical cyclogenesis. *Mon. Wea. Rev.*, **125**, 2699-2708.

Molinari, J., D. Vollaro, S. Skubis, and M. Dickinson, 2000: Origins and mechanisms of eastern Pacific tropical cyclogenesis: A case study. *Mon. Wea. Rev.*, **128**, 125-139.

Montgomery, M.T. and B.F. Farrell, 1993. Tropical cyclone formation. *J. Atmos. Sci.*, **50**, 285-310.

Mozer, J.B. and J.A. Zehnder, 1996: Lee vorticity production by large-scale tropical mountain ranges. Part 1: Eastern North Pacific tropical cyclogenesis. *J. Atmos. Sci.*, **53**, 521-538.

Mull, M.W., 1962: Tropical cyclones in the Eastern North Pacific, 1961. *Mariners Weather Log*, **6**, 44-46.

Munich Re., 2000: Natural Catastrophes - The Current Position. Munich, Germany, 126pp.

Murakami, T., T. Nakazawa, and J. He, 1984: On the 40-50 day oscillations during the 1979 Northern Hemisphere summer. *J. Meteor. Soc. Japan*, **62**, 440-468.

Namias, J., 1954: Long range factors affecting the genesis and paths of tropical cyclones. Proceedings of the UNESCO symposium on typhoons, 213-219.

Namias, J., 1955: Secular Fluctuations in vulnerability to tropical cyclones in and off New England. *Mon. Wea. Rev.*, **83**, 155-162.

Namias, J., 1968: On the cause of the small number of Atlantic hurricanes in 1968. *Mon. Wea. Rev.*, **96**, 346-348.

Namias, J., X. Yuan and D.R. Cayan, 1988: Persistence of North Pacific sea surface temperature and atmospheric flow patterns. *J. Clim.*, **1**, 682-703.

Neumann, C.J., 1993: Global Overview. In: Global Guide to Tropical Cyclone Forecasting (Ed. G.J. Holland). WMO/TC-No. 560, Report No. TCP-31, World Meteorologiocal Organisation, Geneva, Switzerland, 1.1-1.56.

Nicholls, N., 1995: Long term climate monitoring and extreme events. *Climate Change*, **31**, 231-245.

Nicholls, N., C.W. Landsea and J. Gill, 1998: Recent trends in Australian region tropical

cyclone activity. *Meteorol. Atmos. Phys.*, **65**, 197-205.

Nitta, T. and S. Yamada, 1989: Recent warming of tropical sea surface temperature and the relationship to the Northern Hemisphere Circulation. *J. Meteor. Soc. Japan*, **67**, 375-383.

Novlan, D.J. and W.M. Gray, 1974: Hurricane-spawned tornadoes. *Mon. Wea. Rev.*, **102**, 476-488.

Palmén, E., 1948: On the formation and structure of tropical hurricanes. *Geophysica*, **3**, 26-38.

Palmén, E., 1956: Formation and development of tropical cyclones. Proceedings of the tropical cyclone symposium. Brisbane, 213-232.

Palmén, E., and C.W. Newton, 1969. Atmospheric Circulation Systems. Academic Press, New York, 603 pp.

Philander, S.G. 1989. El Niño, La Niña, and the Southern Oscillation. Academic Press, New York, 293pp.

Pielke, Jr., R.A., 1995: Hurricane Andrew in South Florida: Mesoscale weather and societal responses. National Center for Atmospheric research, 56pp.

Pielke, Jr., R.A. and C.W. Landsea, 1998: Normalised hurricane damages in the United States: 1925-1997. *Wea. Forecasting*, **13**, 621-631.

Poey, M.A., 1873: Sur les rapports entre les taches solaires et les ourages des Antilles de l'Atlantique-nord et de l'Ocean Indien sud. *Comptes Rendus*, **77**, 1223-1226.

Ramage, C.S., 1995. Forecasters Guide to Tropical Meteorology. AWS TR **240** Updated. AWS/TR-95/001. Air Weather Service.

Raper, S.C.B., 1993: Observational data on the relationships between climatic change and the frequency and magnitude of severe tropical storms. In: Climate and Sea Level Change (Eds. R.A. Warrick, E.M. Barrow and T.M.L. Wigley). Cambridge University Press, Cambridge, 192-212.

Rappaport, E.N., 2000: Loss of life in the United States associated with recent Atlantic tropical cyclones. *Bull. Amer. Meteor. Soc.*, **81**, 2065-2073.

Ray, C.L., 1935: Relation of tropical cyclone frequency to summer pressure and ocean surface water temperatures. *Mon. Wea. Rev.*, **63**, 10-12.

Renard, R.J. and W.N. Bowman, 1976. The climatology and forecasting of eastern North Pacific ocean. Technical paper no. 7-76. Naval Environmental Predictions Facility. Monterey, California.

Riehl, H., 1954: Tropical Meteorology. McGraw-Hill, New York, 392pp.

RPI, 1997: Tropical cyclones and climate variability: a research agenda for the next century. Risk Prediction Initiative, Bermuda Biological Station for Research Inc., Ferry Reach, St. George's GE 01, Bermuda.

Royer, J.F., Chauvin, F., Timbal, B., Araspin, P. and D. Grimal, 1998: A GCM study of

the impact of greenhouse gas increase on the frequency of occurrence of tropical cyclones. *Climate Change*, **38**, 307-343.

Ryan, B.F., I.G. Watterson and J.L. Evans, 1992: Tropical cyclone frequencies inferred from Gray's yearly genesis parameter: validation of GCM tropical climates. *Geophys. Res. Lett.*, **19**, 1831-1834.

Saunders, M.A. and A.R. Harris, 1997: Statistical evidence links exceptional 1995 Atlantic hurricane season to record sea warming. *Geophys. Res. Lett.*, **24**, 1255-1258.

Schonwiese, C.D. and J. Rapp, 1997. Climate trend atlas of Europe - based on observations 1891-1990. Kluwer Academic Publishers. Dordrecht. 228pp.

Serra, S.C., 1971: Hurricanes and tropical storms of the west coast of Mexico. *Mon. Wea. Rev.*, **99**, 302-308.

Shea, D.J., S.J. Worley, I.R. Stern and T.J. Hoar, 1996: An introduction to atmospheric and oceanographic datasets. NCAR Technical Note 404+IA. Boulder, Colorado.

Shapiro, L.J., 1982: Hurricane climate fluctuations. Part 1: Patterns and cycles. *Mon.Wea. Rev.*, **110**, 1007-1013.

Shapiro, L.J. and S.B. Goldenberg, 1998: Atlantic sea surface temperatures and tropical cyclone formation. *J. Clim.*, **11**,578-590.

Simpson, R.H., N. Frank, D. Shideler, and H.M. Johnson, 1969: Atlantic tropical disturbances of 1968. *Mon. Wea. Rev.*, **97**, 240-255.

Slingo, J.M., D.P. Rowell, K.R. Sperber, and F. Nortley, 1999: On the predictability of the interannual behavior of the Madden-Julian oscillation and its relationship with El Niño. *Quart. J. Roy. Meteor. Soc.*, **125**, 583-610.

Stephens, G.L., 1990: On the relationship between water vapor over the oceans and the sea surface temperature. *J. Clim.*, **3**, 634-645.

Stephens, G.L., A. Slingo, M.J. Webb, P.J. Minnett, P.H. Daum, L. Kleinman, I. Wittmeyer, and D.A. Randall, 1994: Observations of the earth's radiation budget in relation to atmospheric hydrology. 4: Atmospheric column radiative cooling over the world's oceans. *J. Geophys. Res.*, **99**, 18585-18604.

Stewart, J., 1991: Econometrics. Philip Alan. New York, 331pp.

Tai, K.S. and Y. Ogura, 1987: An observational study of easterly waves over the eastern Pacific in the northern summer using FGGE data. *J. Atmos. Sci.*, **44**, 339-361.

Thompson, R.D., 1998: Atmospheric Processes and Systems. Routledge, New York, 194pp.

Tonkin, H., G.J. Holland, N. Holbrook and A. Henderson-Sellers, 2000: An evaluation of thermodynamic estimates of climatological maximum potential tropical cyclone intensity. *Mon. Wea. Rev.*, **128**, 746-762.

TPC, Northeast Pacific tropical cyclone best-track file, 2000: [online computer file], 1886-(updated annually). NOAA/NWS/Tropical Prediction Center, Miami, Florida. Available: ftp server: ftp.nhc.noaa.gov/pub/tracks/tracks.epa

Trenberth, K.E., 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc.*, **78**, 2771-2777.

Trenberth, K.E. and Stepaniak, 2001: Indices of El Niño evolution. *J. Clim*, **14**, 1697-1701.

Tulich, S.A. and T.B. Kimberlain, 1999: Relationships between deep convective cloud, precipitation, and North Atlantic tropical cyclone climatologies. 23rd conference on hurricanes and tropical meteorology, Dallas, American Meteorological Society, 266-269.

Van Loon, H. and K. Labitzke, 1988: When the wind blows. *New Scientist*, **119**, 58-60.

Waliser, D.E. and W. Zhou, 1997: Removing satellite equatorial crossing time biases from the OLR and HRC data sets. *J. Clim.*, **10**, 2125-2146.

Ward, G.F.A., 1995. Prediction of tropical cyclone formation in terms of sea-surface temperature, vorticity and vertical wind shear. *Australian Meteorological Magazine*, **44**, 61-70.

Weisberg, R.H. and C. Wang, 1997: Slow variability in the equatorial West-Central Pacific in relation to ENSO. *J. Clim.*, **10**, 1998-2017.

Wells, N., 1997: The Atmosphere and Ocean. Wiley and Sons, New York. 394pp.

Whitney, L.D. and J.S. Hobgood, 1997: The Relationship between sea surface temperature and maximum intensities of tropical cyclones in the Eastern North Pacific Ocean. *J. Clim.*, **10**, 2921-2930.

Whittingham, H.E., 1958: The Bathurst Bay Hurricane and associated storm surge. *Aust. Met. Mag.*, **23**, 14-36.

Wolter, K., 1987: The Southern Oscillation in surface circulation and climate over the tropical Atlantic, Eastern Pacific, and Indian oceans as captured by cluster analysis, *J. Climate Appl. Meteor.*, **26**, 540-558.

WMO, 1989: World Meteorological Organisation, World Weather Watch: Fourteenth Status Repport on Implementation, WMO 714.

Yanai, M., 1961: A detailed analysis of typhoon formation. *J. Meteor. Soc. Japan.* Series II, **39**, 187-213.

Zehnder, J.A., 1991: The interaction of planetary scale tropical easterly waves with topography: A mechanism for the initiation of tropical cyclones. *J Atmos. Sci.*, **48**, 1217-1230.

Zehr, R.M., 1992: Tropical cyclogenesis in the western North Pacific. NOAA Tech. Rep. NESDIS 61, 181pp. [Available from National Technical Information Service, U.S. Dept. of Commerce. Sills Building, 5285 Port Royal Rd., Springfield, VA 22161.]

Zhang, C and J. Gottschalck, 2002: SST anomalies of ENSO and the Madden-Julian oscillation in the equatorial Pacific. Submitted (and revised) to *J. Clim.*

Zhong, W., R.L. Gall, and J.A. Zehnder, 1993: Interannual variability of Tropospheric waves in the Tropics: a possible link with tropical cyclogenesis. *J. Atmos. Sci.*, **50**, 333-341.