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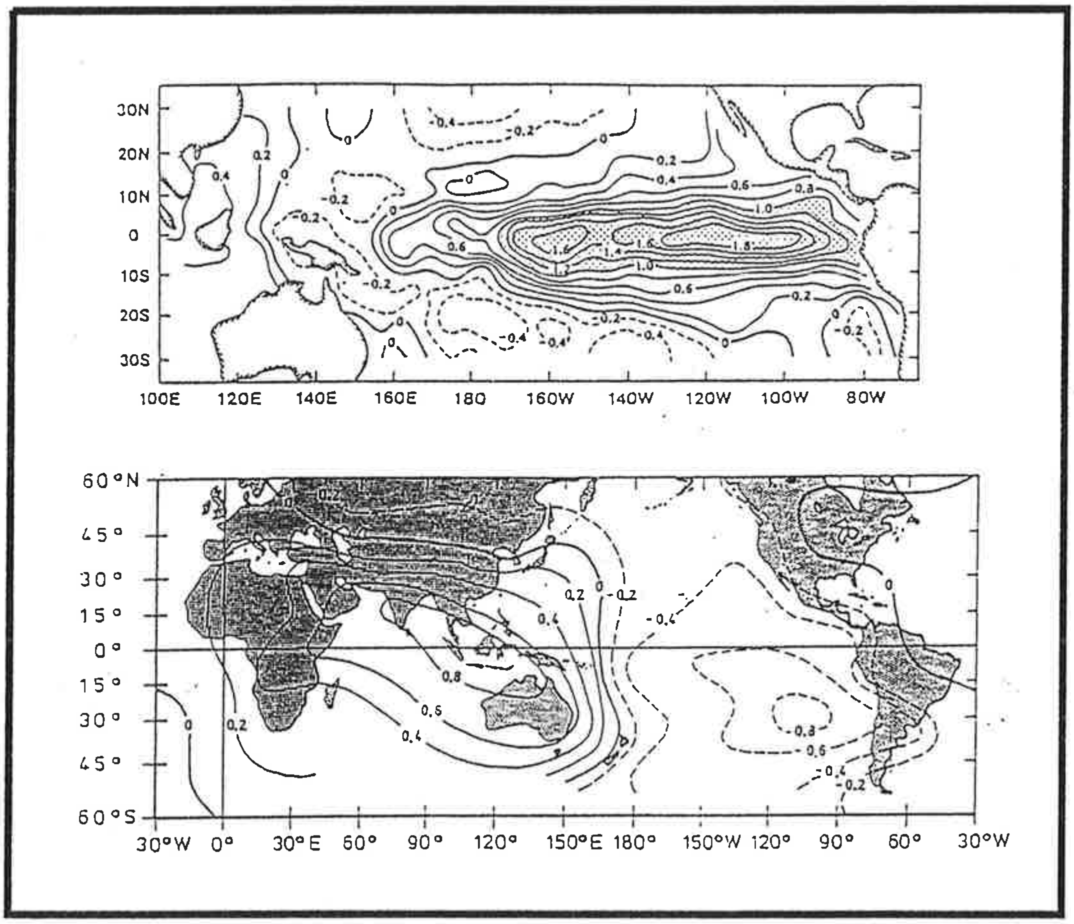

EL NIÑO/SOUTHERN OSCILLATION

by

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El Niño/Southern Oscillation

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1. Introduction

The El Niño/Southern Oscillation (ENSO) phenomenon is the strongest natural climate fluctuation on the short-range climatic time scale from a few months to several years. Although ENSO originates in the tropical Pacific, it influences not only regional but also global climate. Furthermore, ENSO has a significant impact on the ecosystems in the tropics and the economies of several countries (e.g., Oceanus 1984, Glantz et al. 1992). The understanding of ENSO and its successful prediction are therefore not only of scientific but also of enormous public interest.

The term "El Niño" was originally used by Peruvian fisherman at the end of the last century to describe the seasonal warming of the surface waters off the coast of Peru which occurred around Christmas time ("El Niño", Span: the

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Christmas child), marking the end of the fishing season. Today, El Niño is used to refer to the large-scale warming of the entire tropical Pacific (Fig. 1a) which occurs every four years on the average (e.g., Rasmusson and Carpenter 1982). During such events, the surface waters in the tropical Pacific warm by typically 2°C. The interannual variations in sea surface temperature (SST), however, show a pronounced oscillatory behaviour, with positive and negative swings (Fig. 1c). In analogy to the term El Niño, the cold phases are sometimes referred to as "La Niña".

The Southern Oscillation has also long been recognized, originally by Walker 1923 who was studying rainfall variations over India. The Southern Oscillation can be described as a seasaw in the global sea level pressure field, with opposite changes in the western and eastern hemispheres (Fig. 1b). Bjerknes 1969 was the first to hypothesize that the two phenomena El Niño and Southern Oscillation are closely related to each other, representing just different aspects of the same coupled mode in the ocean-atmosphere system. Anomalous warm SSTs in the tropical Pacific, for instance, coincide with negative swings in the "Southern Oscillation Index" (SOI) and vice versa (Fig. 1c). Since the SOI measures the pressure difference between the two centres of action of the Southern Oscillation, anomalies in the SOI are associated with changes in the strength of the Pacific trade winds. Bjerknes realized that the variations in the trade wind field are crucial in the generation of large-scale SST anomalies in the Pacific, and that local air-sea heat exchange is of minor importance.

ENSO is accompanied by global climate anomalies. ENSO-related variations in major rainfall systems, for instance, are well documented (Ropelewski and Halpert 1987). Droughts are frequently observed in Southeast Asia and parts of

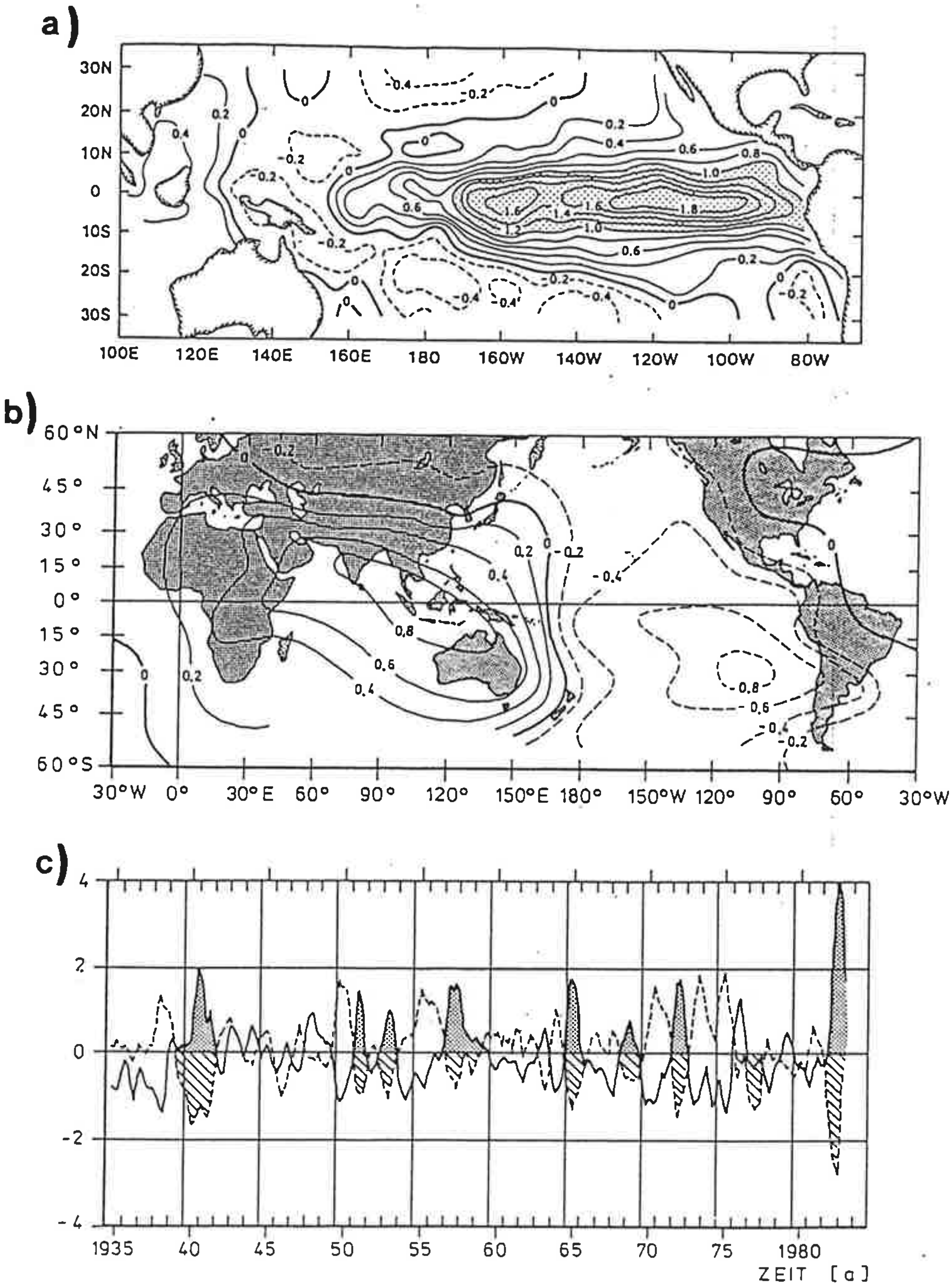

Figure 1: a) Typical anomaly pattern in tropical Pacific sea surface temperature associated with the El Niño phenomenon. The countour interval is 0.2°C. After Ramusson and Carpenter, 1982. b) Spatial structure of the Southern Oscillation. Shown is the correlation of annual pressure anomalies at Djakarta (Indonesia) with all other locations. Note the global-scale nature of the Southern Oscillation. The contour interval is 0.2. After Berlage, 1957. c) Time series of the Southern Oscillation Index (SOI) which measures the atmospheric sea level pressure gradient across the tropical Pacific basin (dashed line), and anomalous sea surface temperature (SST) at Puerto Chicama (Peru) (solid line). Both time series are normalized by their standard deviation. Shading indicates major ENSO warm phases (high SST, low SOI). After Rasmusson, 1984.

Australia during the El Niño phase of ENSO. On the other side of the Pacific, excessive rainfall and flooding are experienced over parts of South America during such periods. Further, connections of ENSO with the strength of the Indian Summer Monsoon and interannual variations in Sahel rainfall have been demonstrated (e.g., Shukla and Paolino 1983, Folland et al. 1986). The extra-tropical atmospheric circulation is also influenced by ENSO, primarily during winter (e.g., Shukla and Wallace 1983). A characteristic teleconnection pattern, the Pacific/North America pattern, describing the response of the atmospheric winter circulation associated with the extremes of the ENSO cycle, has been identified (Wallace and Gutzler 1981) and exploited for short-range climate predictions for the North Pacific/North American region (Barnett and Preisendorfer 1987). Some impact of ENSO was found even over Europe. Fraedrich and Müller 1992 have studied this teleconnection and found a significant (although weak) response.

ENSO has attracted many observationalists, theoreticians, and numerical modelers who worked together very successfully during the last several years within the international TOGA (Tropical Ocean Global Atmosphere) project (1985-1995) to understand ENSO and develop coupled ocean-atmosphere models which can be used for ENSO predictions. A brief description of the current ENSO theory is presented in section two. The state of the art in ENSO modeling is presented in section three, while the issue of ENSO predictability is addressed in section four. A discussion of the outlook for this field concludes the paper.

2. Theory

A thorough description of the ENSO theory is beyond the scope of this paper, and an only brief outline is given here. The interested reader is referred to the review paper by Neelin et al. 1994 for further details. Current theory regards ENSO as originating through an instability of the coupled ocean-atmosphere system in the tropical Pacific in a slightly more complex version of the interactions envisioned by Bjerknes. The climatological SST along the equator in the Pacific is characterized by a strong gradient, with temperatures of about 20°C in the eastern and about 30°C in the western Pacific. This temperature contrast introduces a direct atmospheric circulation cell parallel to the equator which Bjerknes named the "Walker Circulation" in honour to the discoverer of the Southern Oscillation. Within the Walker Circulation, the air flows westward in the surface layers as part of the trade wind system where it is heated and supplied by moisture. The air rises over the warm western Pacific where deep convection and heavy rainfall is observed. The air returns at upper levels and descends over the relatively cold eastern Pacific which completes the Walker Circulation.

The westward wind stress at the ocean's surface has a strong impact on the equatorial ocean circulation. Water mass is piled up in the west and a sea level gradient of about 40 cm across the Pacific is established. This gradient is compensated by a slope in the thermocline (the interface that separates the well-mixed warm surface waters from the cold waters at deeper levels) which tilts upward in the east. The change of sign of the Coriolis force (due to the earth's rotation) at the equator dictates that the associated surface currents at the equator are divergent. This drives a narrow band of equatorial upwelling. The combination of upwelling and shallow thermocline produces the relatively cold surface temperatures in the eastern Pacific, while the deep thermocline in the west is associated with warm SST.

A perturbation in either the equatorial SST or the Walker Circulation can be amplified by unstable air-sea interactions. Consider, for instance, a positive SST anomaly in the eastern equatorial Pacific. This anomaly reduces the east-west SST gradient and hence the strength of the Walker Circulation, resulting in weaker trade winds at the equator. This leeds to a deeper thermocline and reduced currents and upwelling, producing higher SSTs in the eastern Pacific and further reducing the SST gradient in a positive feedback which can lead to instability of the climatological mean state via ocean-atmosphere interactions.

The phase differences to maintain an oscillation exist between SST and wind stress on the one hand and upper ocean heat content on the other. The ocean is not in equilibrium with the atmosphere and carries information associated with past winds that permits continuous oscillation (Cane and Sarachik 1981; Chao and Philander 1992). The phase differences can be seen clearly in Fig. 2 which shows the evolution of equatorial SST and upper ocean heat content as function of longitude and time, as derived from ten years of observations. While the SST is dominated by a standing component, the characteristic signature of the subsurface memory is seen by the lead of heat content anomalies in the western part relative to the eastern part. This behaviour is particularly clear during the latter half of the record during which the number of observations increased considerably due to the TOGA project.

The subsurface memory of the system can be related to ocean wave dynamics. A

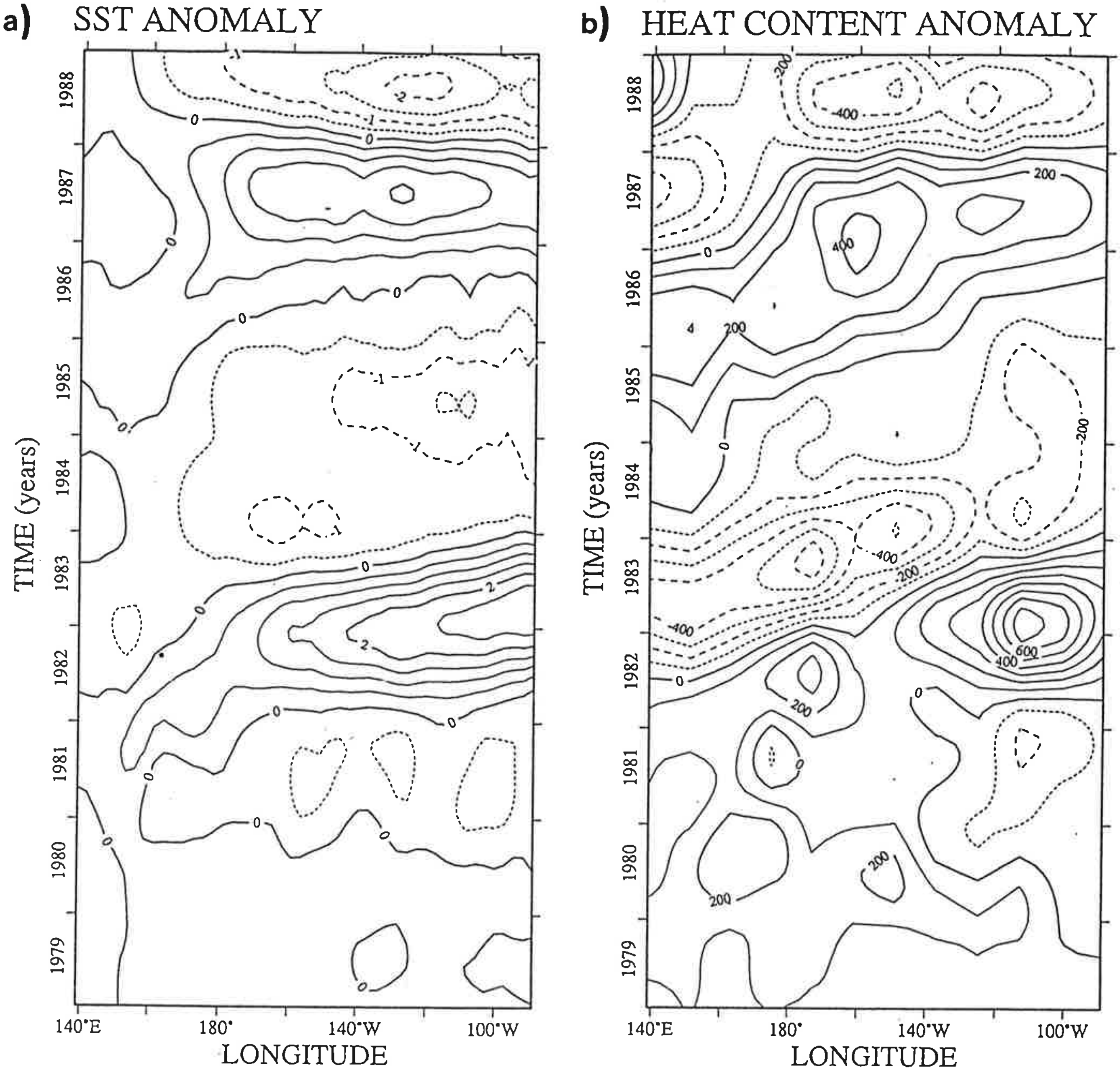

Figure 2: Time-longitude plot of observed anomalies along the equator during the period 1979 to 1988. Left) SST, contour interval is 0.5°C. Right) Heat content integrated above 275m, contour interval is 100°Cm. The data have been low-pass filtered to remove variability on time scales smaller than 17 months. From Neelin et al., 1994.

conceptual model that provides a simple analog for this is referred to as the "delayed action oscillator" (Schopf and Suarez 1988' Suarez and Schopf 1988, Graham and White 1988, Battisti and Hirst 1989). It clearly illustrates the role played by the propagation of equatorial waves and their reflection at meridional boundaries (Fig. 3). Suppose unstable air-sea interactions produce growing warm SST anomalies in the eastern Pacific with eastward wind anomalies to the west of the SST anomalies. The effect of the eastward wind anomalies is to deepen the thermocline in the eastern part of the basin through downwelling "Kelvin" waves which strengthen the El Niño warming. At the same time, the eastward winds force upwelling signals at the western edge of the wind anomalies and these signals propagate westward as "Rossby" waves. The upwelling signal propagates to the western boundary, reflects as an upwelling signal propagating eastward as a "Kelvin" wave packet, and reaches the growing warm SST anomaly in the eastern basin after some "delay" time. Note that the SST is not affected in the western Pacific because of the deep thermocline there. The warm SST anomaly is now affected both by local processes tending to make it grow and by remote processes tending to oppose the growth. Eventually, the remote processes dominate and the warm anomaly stops growing, starts cooling, and the sequence of events is repeated but with reversed signs and the system moves into the cold (La Niña) phase of the ENSO cycle. According to this, ENSO is based on self-sustained oscillations and its attractor can be described by a "limit cycle", a periodic orbit in phase space (Fig. 4).

However, as discussed by Neelin et al. 1994, the "delayed action oscillator" scenario represents just one (although useful) limit in parameter space. The most "realistic" regime includes also other processes independent from ocean wave dynamics, as those described by Hirst 1986 and 1988, Neelin 1991, and Barnett et al. 1991. Further, the real system is less regular than the

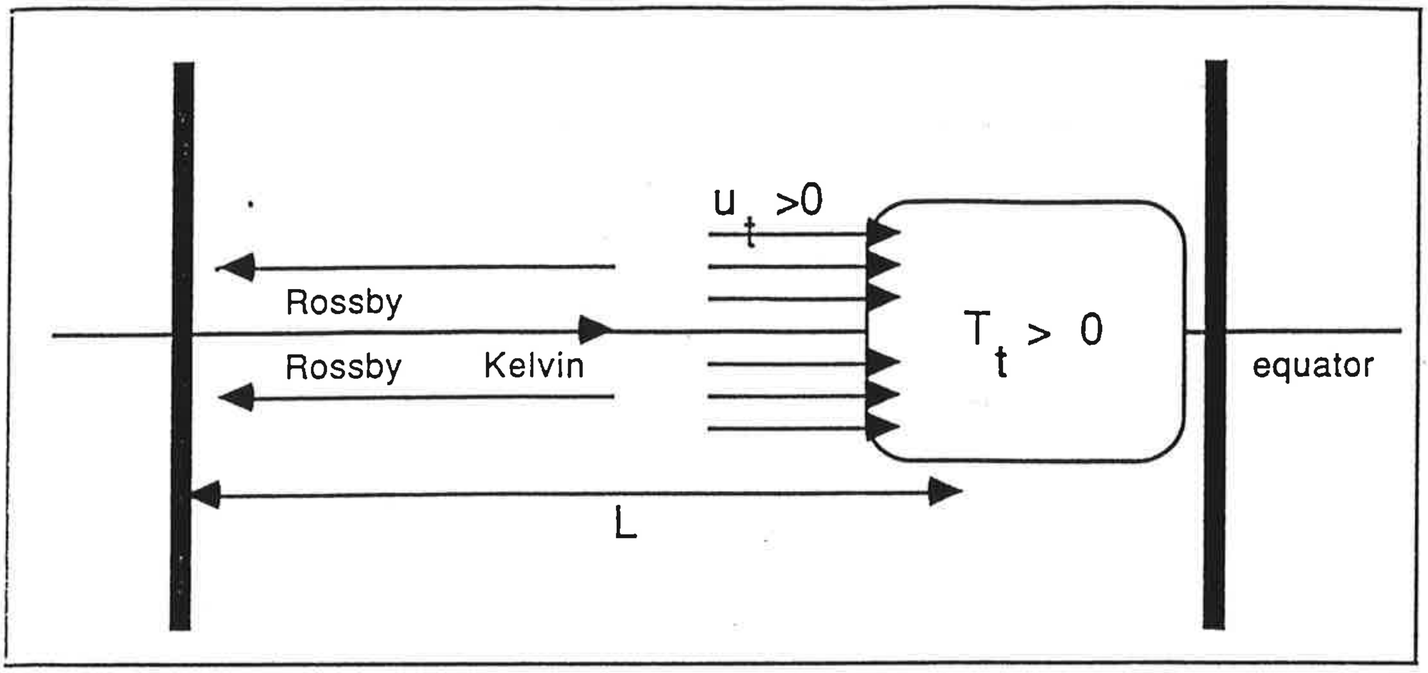

Figure 3: Schematic diagram of the "delayed action oscillator" scenario. Shown are the conditions during the warm (El Niño) phase of ENSO in the eastern Pacific ($T_t > 0$). As the SST anomaly grows, eastward winds (arrows) at the western edge of the SST anomaly excite an upwelling signal which propagates westward as a "Rossby" wave packet, reflects at the western boundary, and returns as a "Kelvin" wave packet. The resulting oscillation period is a result of the superposition of many free and forced wave modes. From Sarachik, 1990.

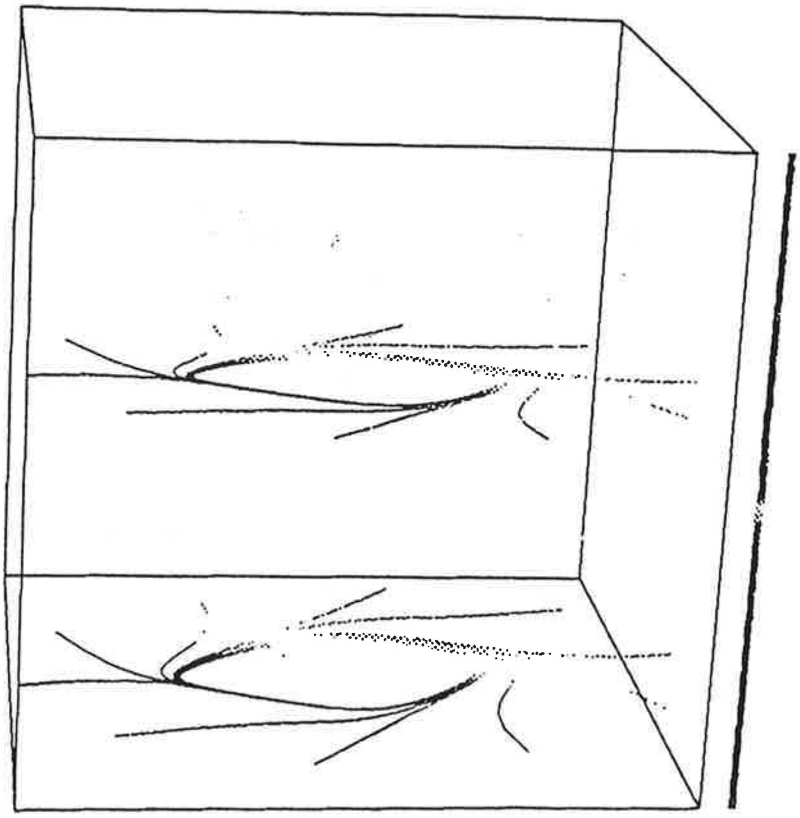

Figure 4: The ENSO attractor displayed in a low-dimensional phase space, as derived from twenty years of tropical Pacific surface and subsurface temperatures and zonal wind stresses. Shown are ten phase space trajectories which converge all onto a limit cycle attractor (upper figure). The curves at the bottom of the box show just a projection (a "shadow") on a plane. From Grieger and Latif, 1994.

theroretical models (Fig. 1c). The inclusion of random forcing to account for the non-modelled high-frequency internal atmospheric variability or nonlinear interactions between different time scales (especially between the annual cycle and the ENSO mode) are possible candidates to obtain more irregular behaviour (e.g., Latif and Flügel 1991, Jin et al. 1994, Tzippermann et al. 1994).

3. Coupled ocean-atmosphere models

A hierarchy of coupled ocean-atmosphere models has been developed to study the dynamics of ENSO. These coupled models can be categorized roughly into three classes (McCreary and Anderson, 1991): conceptual and simple models, intermediate models, and coupled general circulation models (CGCMs). Conceptual and simple models (like the "delayed action oscillator" model) are useful in gaining some insight into the fundamental dynamics of the coupled system, but they cannot be verified rigorously by observations. The intermediate coupled models consist generally of a sophisticated ocean model which is coupled to a simple atmosphere model. These models are realistic enough to be compared to observations, but are still simple enough to trace the basic physical mechanisms. Intermediate models aim usually only to simulate anomalies from a prescribed climatological state. One of the most successful intermediate models is that of Zebiak and Cane 1987 which has been used extensively to simulate and forecast ENSO. Coupled general circulation models are the most complex models based on a rather complete set of physical equations and designed to simulate both the climatological mean state and the variability about it. CGCMs should be compared closely to observations, but they often suffer from "climate drift", i.e., the departure of the model climatology from the observed (e.g., Neelin et al. 1992).

Nevertheless, considerable progress has been made recently in CGCM modeling. Figure 5 provides an example of interannual variability from one of the first CGCMs (Philander et al. 1992). This coupled model consists of a high-resolution ocean model coupled to a coarse-resolution atmosphere model. High resolution in the ocean is required to simulate ENSO realistically. This is due to the rather small meridional scale of equatorial waves which contribute significantly to the oceanic memory, as described above. While the spectrum of interannual time scales may not exactly match that observed, the spatial form, with dominant standing oscillations in SST and with subsurface phase lags, is reasonably close to the observed form. Other CGCMs yield similar results, but with some variation on the spatial form (e.g., Nagai et al. 1992, Latif et al. 1993).

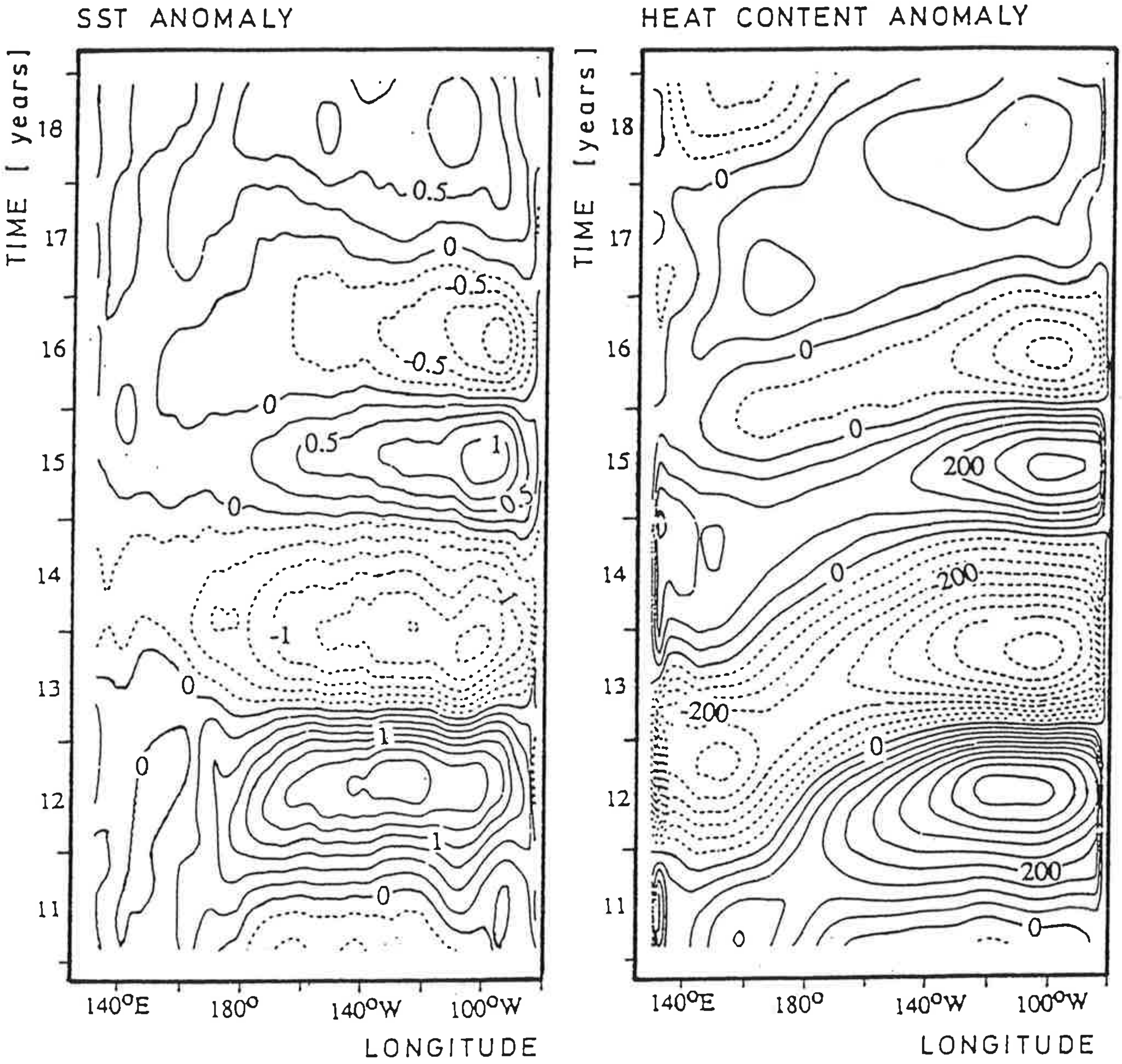

Figure 5: Time-longitude plot of anomalies along the equator from the Philander et al., 1992 coupled general circulation model. Left) SST, contour interval is 0.25°C. Right) Heat content integrated above 275m, contour interval is 50°Cm. The data have been low-pass filtered to remove variability on time scales smaller than 24 months. From Neelin et al., 1994.

4. ENSO predictability

The quasi-periodic nature of ENSO and the above theoretical considerations imply a good deal of ENSO predictability. Several ENSO prediction schemes have been developed, including statistical and physical models (the reader is referred for details on the various schemes to the review papers of Barnett et al. 1988 and Latif et al. 1994). The most successful schemes, the coupled ocean-atmosphere models, show significant skill in predicting ENSO even at lead times beyond one year. Figure 6 shows the anomaly correlation of the observed with the predicted SST anomalies averaged over the eastern equatorial Pacific for the intermediate coupled model of Zebiak and Cane 1987, the first coupled model used for ENSO forecasts.

Most coupled models used in ENSO forecasts such as the coupled model of Zebiak and Cane 1987 are limited-domain models which cover only the tropical Pacific region. They can therefore not be used directly to study the predictability of non-Pacific or extra-tropical climate anomalies. However, the forecasted tropical Pacific SSTs can be used to "nowcast" the associated atmospheric response by feeding them into global atmospheric models. Barnett et al 1993 used such a "two-tiered" approach and obtained encouraging global forecasts. Forecasts were restricted to the winter season and major ENSO extremes. In Fig. 7, we display the correlation of the observed 500 hPa height anomalies with those forecasted two seasons ahead. Significant correlations are found not only in the tropical but also in the extra-tropical regions. Currently, global coupled ocean-atmosphere models are developed at different institutions worldwide which can be used to forecast simultaneously tropical and extra-tropical climate anomalies.

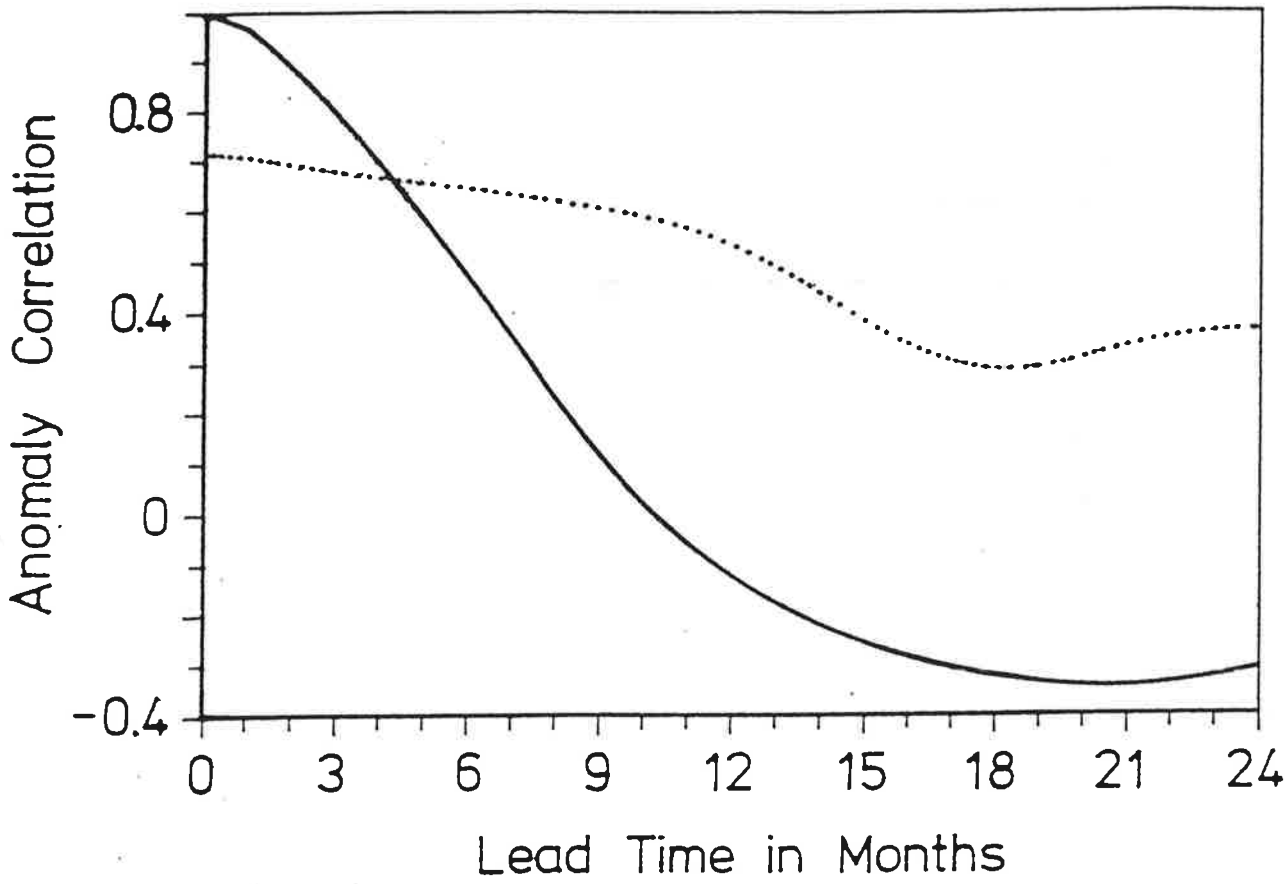

Figure 6: Skill scores of prediction ensembles as function of lead time for forecasts by the Zebiak and Cane, 1987 intermediate coupled model (dotted curve), compared with skill obtained by assuming persistence of anomalies (solid curve). The measure is correlation of predicted and observed SST averaged over the region of largest ENSO anomalies (5°N-5°S, 90°W-150°W) during the period 1972 to 1991. From Neelin et al., 1994.

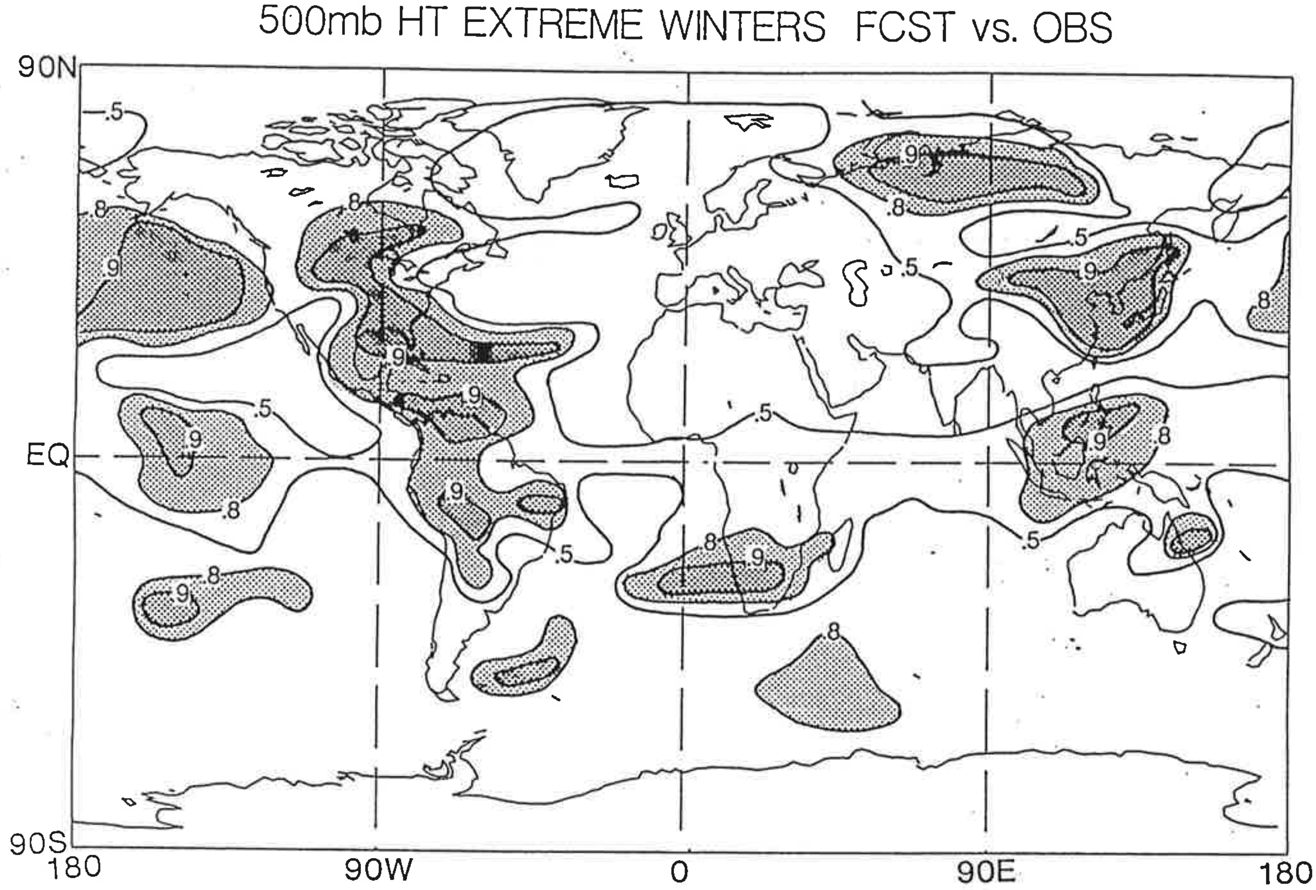

Figure 7: Skill scores in predicting global 500 hPa height anomalies during seven extreme winters (1970-71, 1972-73, 1974-75, 1982-83, 1987-88, 1988-1989, 1991-92). The measure is correlation of predicted and observed height anomalies. Light shading indicates correlations larger than 0.8, while heavy shading indicates correlations larger than 0.9.

At lead times of a few months, the coupled models do not beat the persistence forecast, i.e., the forecast that assumes that the SST anomalies remain constant throughout the forecast period (Fig. 6). This is due to the fact that up to present no ocean observations are used in the initialization of the coupled models. Instead, the observed wind stresses are used to initialize the ocean component. Errors in the forcing and the model formulation thus manifest themselves as considerable errors in the initial SST anomaly fields. Significant improvement of the forecasts at small lead times can be expected by assimilating in situ observations (e. g. Leetmaa and Ji 1989) which are becoming increasingly available, and/or observations from space.

5. Outlook

The El Niño/Southern Oscillation (ENSO) phenomenon has been very influential in climate research. This natural climate fluctuation was a challenge to observationalists, modelers, theoreticians, meteorologists, and oceanographers, and the fruitful international collaboration between these groups led to a reasonably advanced understanding of ENSO. It stimulated the development of coupled ocean-atmosphere models and provides a suitable testbed for these models which is also relevant to the greenhouse warming problem. Furthermore, ENSO forecasts are the first successful examples of short-range climate forecasting. Routine ENSO forecasts are currently conducted at several institutions which are already used by governments of several countries.

However, much remains to be done. ENSO shows, for instance, pronounced variability on interdecadal time scales which still needs to be explained and might be related to variations in the global ocean circulation. Further, particular past time periods have been turned out to be "unpredictable". The reasons need to be explored, and theoretical predictability limits should be determined. A better understanding of the interactions between ENSO and other phenomena and time scales is also needed. Although it is well established, for instance, that ENSO affects the Asian Monsoon, it is still unclear whether the Asian Monsoon feedbacks on ENSO. Another interesting question is whether ENSO is affected by anthropogenic climate change such as a potential greenhouse warming or tropical deforestation. Finally, the ENSO forecasting systems are still at a rather low level relative to Numerical Weather Prediction models. The initialization problem especially needs to be addressed more carefully.

There are other related problems which should be addressed in the near future. The role of SST anomalies in the other tropical oceans (Atlantic and Indian Ocean) in forcing tropical and extra-tropical climate anomalies must be better understood. There is, for instance, some evidence that tropical Atlantic SST anomalies have a significant impact on Brazilian rainfall, but the role of Indian Ocean SST anomalies is still unclear. Further, a systematic assessment of the predictability of mid-latitudinal climate anomalies is pending, although the situation in mid-latitudes is less favourable relative to the tropics because of the high "noise" level in mid-latitudes. The role of mid-latitudinal SST anomalies in forcing regional and global climate anomalies is still a controversial issue. Experimentation with coupled ocean-atmosphere models will provide further insight into this problem. Likewise, the impact of variations in the other atmospheric boundary conditions such as soil moisture and sea ice needs to be investigated. Most of the problems described above will be investigated within the international CLIVAR project (WCRP 1992) which will start in 1995 and last for fifteen years.

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