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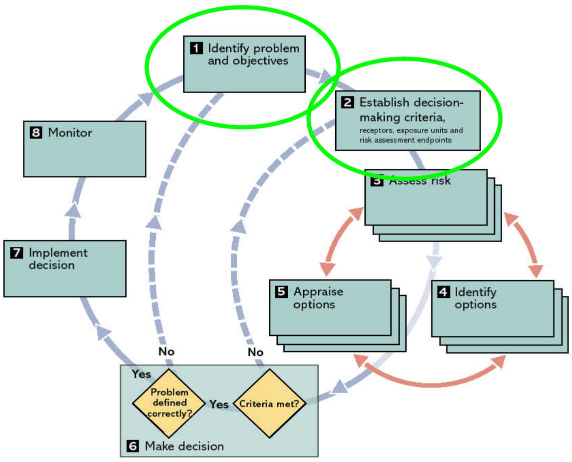
The Isle of Man Climate Change Scoping Study

Technical Paper 3

Climate indicators



Report for
Martin Hall, DLGE, Isle of Man Government

Our reference IOM001

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This report should be referenced as:

Fealy, R., Sweeney, J., Murphy, C., McElwain, L. (2006) The Isle of Man Climate Change Scoping Study: Climate Indicators for acclimatise and the Department of Local Government and the Environment, Isle of Man Government.

CLIMATE CHANGE:

Indicators, Scenarios and Impacts for the Isle of Man

A scoping report prepared for the Isle of Man
on behalf of
acclimatise.

Prepared by

ICARUS
Irish Climate Analysis and Research Units

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Acknowledgements

The authors would like to greatly acknowledge the following for provision of data, help or assistance, and without whom this research would not have been possible.

David Viner, Climate Research Unit
Alan Hisscott, Oik Emshyr Runnysvie, Isle of Man
Theresa Shammon, Port Erin Marine Laboratory
Geoff Jenkins, UK Meteorological Office
Jonathan Lee, Jersey
Laura McElwain, Irish Climate Analysis and Research Units
Robert Clynes, Department of Local Government and the Environment, Isle of Man

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Contents

Climate change: the global context

1.1 Introduction

The current scientific consensus attributes most of the increase in global temperature experienced since the middle of the 20th century, to anthropogenic activities (IPCC, 2001). This increase is associated with increasing atmospheric concentrations of greenhouse gases, primarily CO_2, from pre-Industrial Revolution levels of 280 p.p.m.v. (parts per million volume) to their current levels of over 380 p.p.m.v. The present day concentration of CO_2 is at a level that has not been exceeded during the past 420,000 years and most likely not during the past 20 million years (IPCC, 2001).

The natural greenhouse effect, which results from naturally occurring quantities of greenhouse gases, acts to raise the temperature of the Earth's surface by ~21°C; thereby making the planet habitable. However, as a consequence of the increasing concentrations of these gases in the atmosphere, primarily attributed to human activity such as the burning of fossil fuels, it is likely that global temperatures will increase significantly during the course of the present century.

Records of surface temperatures from the Northern Hemisphere, compiled from various sources and proxy data, suggest that, globally, 1998 was the warmest year of the warmest decade of the warmest century of the last millennium (IPCC, 2001). Indeed eight of the ten warmest years on record have occurred in the last decade (1996-2005) with 2005 being the second warmest year recorded by the UK Met Office. These increases in temperature have been accompanied by decreases in snow cover and retreat of mountain glaciers. As a consequence, a rise in sea level of between 10-20 cm has occurred since 1900. Reductions in the sea-ice thickness of the Arctic and increases in precipitation over the land masses of temperate regions of between 0.5-1.0% have also been observed (IPCC, 2001).

If emissions of greenhouse gases were to continue increasing at current rates, a doubling of atmospheric concentrations of CO_2 is likely to occur by the end of the present century. An increase in effective CO_2 is likely to occur much sooner. Global Climate Model (GCM) simulations of the climate system suggest that increases in global temperature in the order of between 1.4 to 5.8°C by 2100 are likely as a consequence. These temperature increases are unlikely to be uniformly distributed and there is likely to be a large degree of regional variation in the spatial distribution of these increases.

1.2 Past climate

The Earth has undergone repeated glacial and interglacial cycles as a consequence of climatic fluctuations between cold, glacial, and warm, interglacial periods during the Quaternary Period (<2 million years). During glacial periods, approximately one-third of the Earth's surface was covered by ice sheets (Benn and Evans, 1998). These glacial-to-interglacial sequences are primarily driven by changes in solar radiation receipt as a consequence of periodicities inherent in the Earth's orbit around the Sun.

These orbital cycles affect climate by causing variations in the seasonal and latitudinal amount of solar radiation received at the Earth's surface. These variations in turn have a dramatic effect on the global climate system, producing climatic fluctuations between cold, glacial conditions, resulting in the development of ice sheets, and warm, interglacial periods, with a much reduced ice cover.

Terrestrial storage of water as ice and snow had a dramatic effect on global sea levels during glacial periods. Evidence from proxy sources suggest that sea level was approximately 120 metres lower than present during the last glacial maximum (Benn and Evans, 1998). At present, glaciers and ice sheets cover about 10% of the Earth's surface which if melted, could raise present day sea levels by approximately 70 metres (Nesje and Dahl, 2000).

After the last glacial maximum, a cold interstadial occurred around 11-10 kyr ago, after which rapid retreat of the northern hemisphere ice sheets occurred. The onset of this retreat marked the beginning of the present interglacial, known as the Holocene Epoch, and within 1,000 years, the North American Laurentide ice sheet had been reduced to remnants, some of which still exists today on Baffin Island.

Periods of neoglaciation, which refer to the readvance or regrowth of glaciers after attaining their minimum extent during the Holocene (Nesje and Dahl, 2000), occurred as early as 8 kyr ago (Benn and Evans, 1998). The most recent period of neoglacial activity, known as the Little Ice Age, commenced during the late 16th century and continued up until the middle of the 19th century, was marked by temperature reductions of up to 1.0 - 1.5^{o}C, most likely resulting from a reduction in sunspot activity and increased volcanic activity during this time.

1.3 Present climate

Global average surface temperature has increased by 0.6 ±0.2^{o}C over the course of the 20th century (IPCC, 2001). The global temperature record displays a large degree of variability, but does suggest that most of this warming occurred between two specific periods, 1910-1945 and 1970-2000. While the temperature increase experienced during the 1910-1945 was larger than the latter period, the rate of warming during the 1970-2000 has been faster over land than the oceans. In the Northern Hemisphere, the 1990s was the warmest decade and 1998 was the warmest year (IPCC, 2001), followed by 2005, 2002 and 2003 since reliable global instrumental records began in 1861. Proxy records indicate that the temperature increases recorded during the 20th century in the Northern Hemisphere resulted in it being the warmest century in the last millennium. Much of this warming has occurred in the winter, spring and autumn seasons (Jones *et al*., 2001). There is evidence to suggest that this increasing trend in temperatures has accelerated over the past three decades (IPCC, 2001).

In a study of long-term temperature trends in Western Europe over the 20th century, Moses *et al*. (1987) detected a greater magnitude of change at higher latitudes reflecting the sensitivity of high-latitudes to climate change. This increased sensitivity at these latitudes primarily results from ice-albedo feedback mechanisms. The detection of this increased temperature trend at high-latitudes is consistent with current global climate model predictions on global warming.

Sea levels have been rising at approximately 1-2 mm/annum over the course of the 20th century, as a consequence of a number of factors, such as, thermal expansion of the water column and glacial meltwater, released from the ongoing and widespread retreat of mountain glaciers. Decreases in the Arctic sea-ice thickness of up to 40% during the late summer and early autumn, while not contributing to sea-level, does indicate a warming trend in the Arctic regions.

There is evidence to suggest that regional changes in precipitation amounts, intensity and location have likely occurred over the course of the 20th century (IPCC, 2001). Annual precipitation over the 20th century has displayed an increasing trend in the mid- to high-latitudes in the order of approximately 0.5-1.0% per decade (IPCC, 2001), while in the sub-tropical Northern Hemisphere land areas, precipitation has decreased by 0.3% per decade (IPCC, 2001). Associated with these precipitation increases in the mid- to high- latitudes is a tendency towards an increase in the frequency of more intense precipitation events (IPCC, 2001). An increasing frequency of more intense events can occur due to a number of factors, such as, changes in humidity, atmospheric circulation patterns and increased storm activity.

1.4 Projections of future climate

- Globally averaged surface temperature is projected to increase by between 1.4 to 5.8°C, over the 1990 to 2100 period, depending on emissions scenario.

- Precipitation increases are likely by the middle of the present century in the mid to high latitudes in winter, with large year-to-year variations.

- An increase in maximum temperatures and in the frequency of hot days is very likely.

- More intense precipitation events are also very likely over mid to high latitude areas of the Northern Hemisphere

- The present day retreat of mountain glaciers is likely to continue during the course of the 21st century. While Eastern Antarctica is likely to gain mass due to enhanced precipitation, Greenland is likely to lose mass due to a greater increase in runoff over precipitation increases.

- The best estimate for global mean sea-level rise over the present century is 0.48 metres. Sea levels are likely to continue to rise after 2100.

2.1 Primary indicators

2.1.1 Introduction

In order to assess if the global trends described above are occurring at the regional scale of the Isle of Man, this chapter will examine the available meteorological data for any long-term trends, which may have occurred over the period of record. The focus of this examination will be on the two key climatological parameters, that of temperature and precipitation, but additional climate parameters will also be discussed.

2.2 Air temperature indicators in the Isle of Man

A limited observational record exists for the Isle of Man with only two long-term records available. Long term data extends as far back as 1870 for precipitation and to 1878 for temperature at Douglas. Data from Ronaldsway commenced in 1947. These two stations are located on the eastern side of the island and are monitored by the Isle of Man meteorological service.

2.2.1 Global and Isle of Man temperature anomalies

Annual mean temperatures, from both Douglas and Ronaldsway, were used to calculate the mean annual air temperature anomaly for the Isle of Man, relative to the 1961-1990 period (Table 2.1). The 1961-1990 period is considered to be a representative 30-year period for assessing climate change and is the recommended period for assessing change by the World Meteorological Organisation (WMO). The Isle of Man has a mild maritime climate, reflecting its proximity to the Atlantic Ocean. As a consequence, the annual temperature range tends not to experience the large ranges of other countries at similar latitudes. Annual average temperatures on the Isle of Man are between 9ºC - 10ºC.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Douglas	5.0	4.4	5.6	7.4	10.1	12.8	14.4	14.4	12.7	10.6	7.3	5.9	9.2
Ronaldsway	5.4	4.9	5.9	7.5	10.1	12.8	14.4	14.5	13.0	11.0	7.7	6.3	9.5

Table 2.1 Mean monthly temperature for Douglas and Ronaldsway for the 1961-1990 period

Figure 2.1 illustrates the mean annual air temperature anomalies calculated for the Isle of Man, based on the average anomalies for Douglas and Ronaldsway for the 1947-2001 period and the global anomaly for 1890-2004. The global anomaly demonstrates largely decreasing negative anomalies from the start of the records up to the 1940s, with slightly negative anomalies between the 1940-1970 period. After the 1980s, increasing and positive anomalies are evident.

Overall, the trend is one of decreasing negative to increasing positive anomalies over the course of the 20th century.

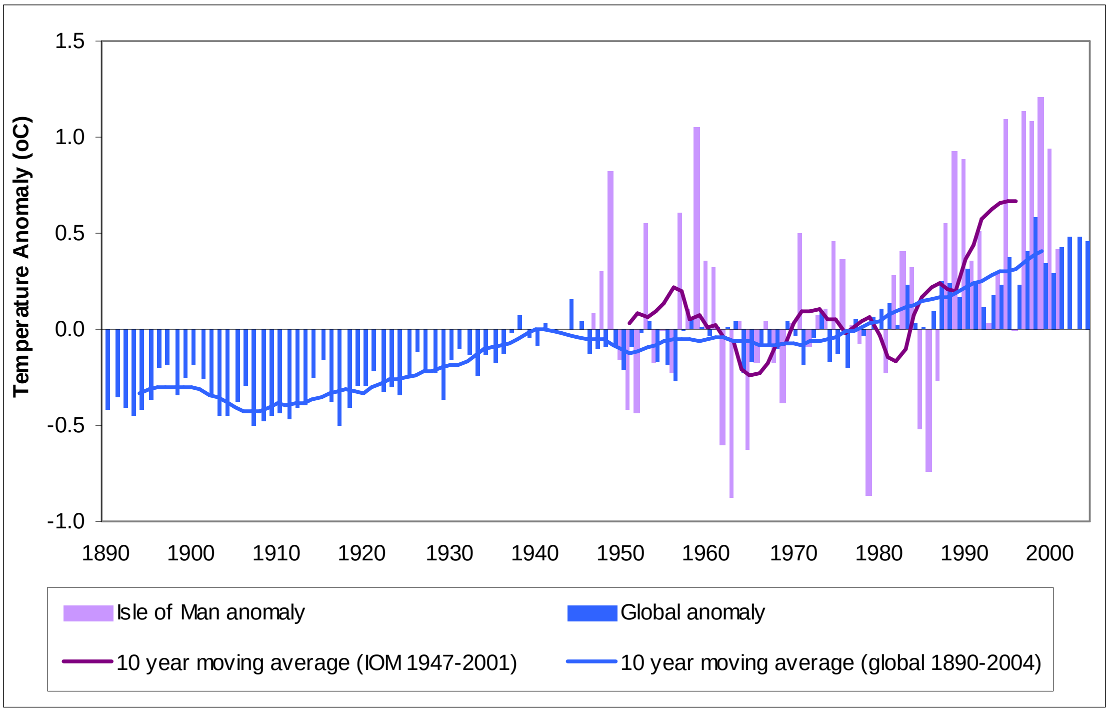

Figure 2.1 Global and Isle of Man temperature anomalies, relative to 1961-1990. (*1999 and 2000 were removed from the Douglas record due to missing monthly values; anomaly values from Ronaldsway are used directly for these years)

The annual temperature anomalies from the Isle of Man demonstrate much greater interannual variability than is evident in the global anomalies. During the 1950s, a number of years with large positive anomalies are evident with departures from the 1961-1990 mean of greater than +0.5°C. Negative departures from the mean, of similar magnitude, are experienced during the 1960s, 1970s and 1980s. However, after 1988, consistent and positive anomalies become evident, with nine years displaying positive anomalies greater than +0.5°C, four of which are greater than +1.0°C above the 1961-1990 average. The warmest year globally was recorded in 1998, with an anomaly of +0.58°C, while the warmest year for the Isle of Man was recorded in 1997 with an annual anomaly of +1.1°C, over the 1947-2001 period of record.

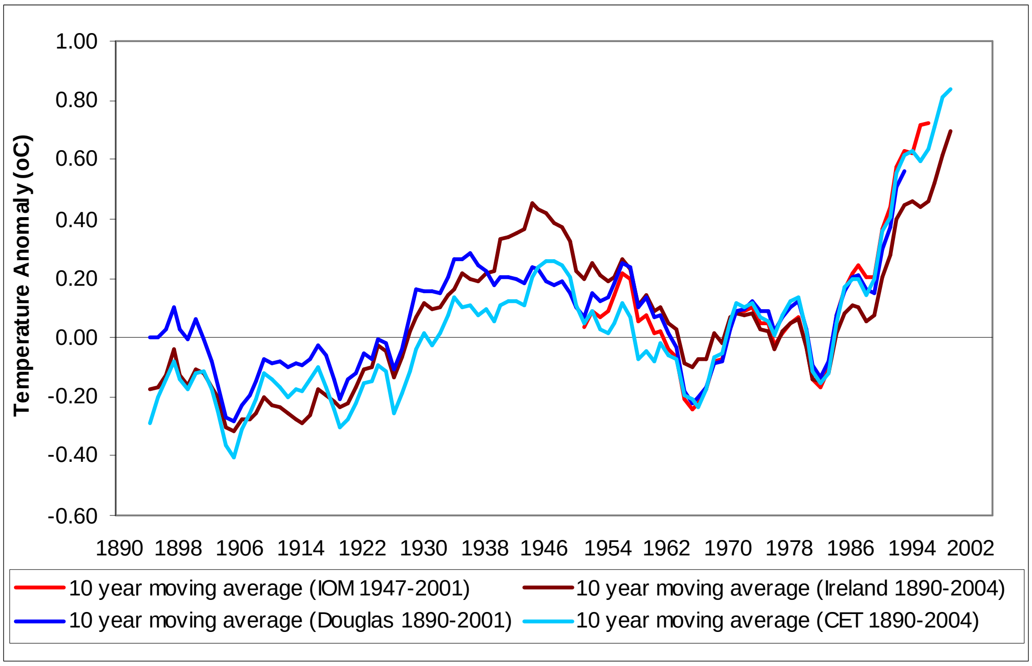

Figure 2.2 10-year moving averages of the regional temperature anomalies for the CET series, Ireland and the Isle of Man, relative to 1961-1990. (*1999 and 2000 were removed from the Douglas record due to missing monthly values)

Figure 2.2 shows the 10-year moving average of the regional temperature anomalies for the Central England Temperature (CET) series, the Irish temperature anomalies, calculated from the Irish synoptic network, and the Isle of Man anomalies. The anomaly series from Douglas was included due to its data record length extending far back in time relative to the Isle of Man only anomaly.

While the Isle of Man anomalies demonstrate a large degree of interannual variability with regards to the global temperature anomaly record, when compared to the CET and Irish anomaly series, they are found to be consistent with both of these anomaly series. Warming occurred from the start of the 20th century to the mid-1940s with cooling occurred thereafter until the 1960s, commonly referred to as mid-century cooling and most likely associated with large-scale circulation changes. Rapid warming then becomes evident from the 1980s to the present. It is evident that at the present the Isle of Man temperatures are increasing faster than the global average, in line with findings from Ireland (Sweeney et al., 2002)

2.2.2 Long-term mean annual air temperature

The mean annual air temperature index (1947-2001) derived from the average of the Douglas and Ronaldsway annual temperature series is illustrated in Figure 2.3. An annual temperature of 10.5^{o}C was recorded in 1997, the warmest year on record for the period 1947-2001. 6 of the 10 warmest years have occurred since 1988 resulting in the 1990s being the warmest decade on record for both stations. Warming in the Isle of Man annual air temperature index was found to be significant at the 0.05 level. All significance levels were derived from the Kendall's tau b significance test.

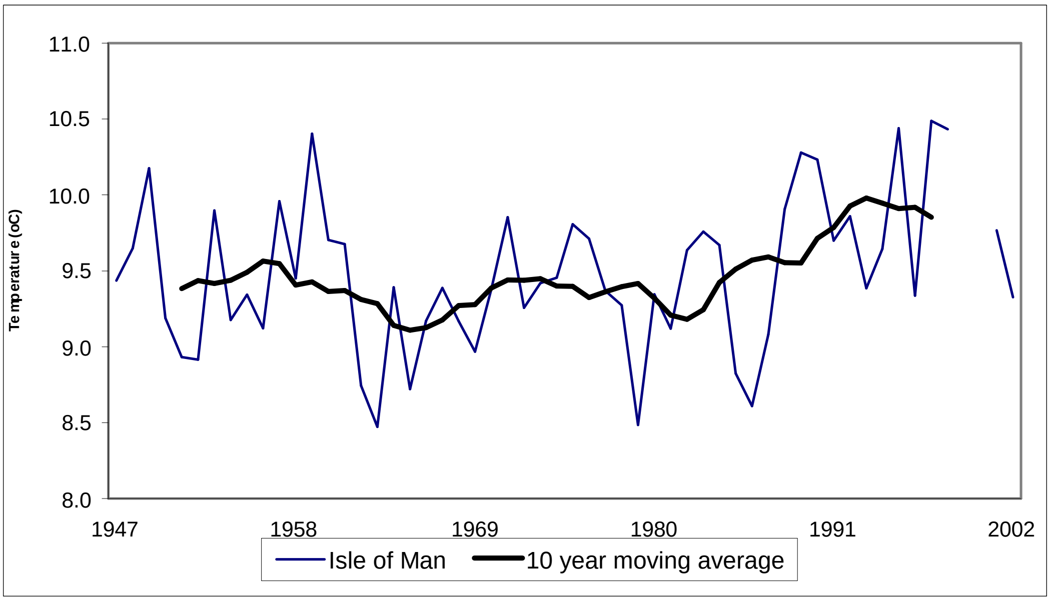

Figure 2.3 Mean annual air temperature index (1947-2001). (*1999 and 2000 were removed from the Douglas record due to missing monthly values).

Warming in both the Douglas (1878-2001) and Ronaldsway (1947-2004) mean annual temperature series was also found to be significant, at the 0.01 level, for their respective periods. Similarly to the Irish records, the warmest month on record was recorded in August 1995, with a mean monthly temperature of 17.9°C at Douglas and 17.8°C at Ronaldsway. A monthly temperature of 16.8°C recorded in August 2003 was the second warmest year on record at Ronaldsway.

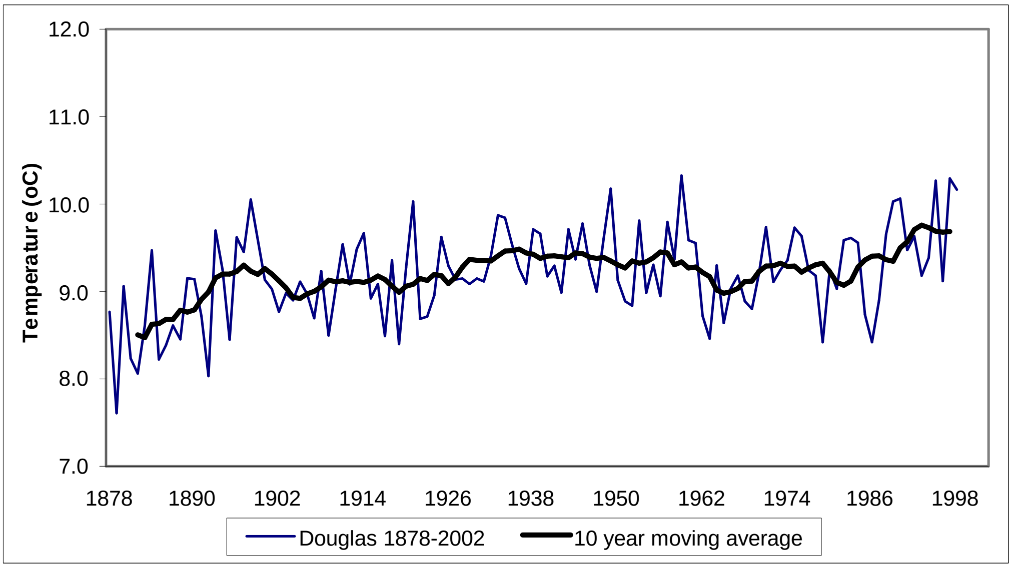

Figure 2.4 Mean annual air temperature for Douglas (1878-2001). (*1999 and 2000 were removed from the Douglas record due to missing monthly values)

The highest maximum monthly temperature recorded at Douglas was 21.6°C in August 1947, while the second highest of 21.3°C was recorded in August, 1995. Records from Ronaldsway only start in September of 1947. While it is likely that

August of that year was very warm, the warmest month on record is again August of 1995, when the mean monthly temperature from this station was 21.6ºC. The coldest minimum temperature recorded at Douglas was in the 19th century, a value of –4.4ºC in December of 1882. While station relocation may explain the fact that 6 of the 8 lowest minimum monthly temperatures at Douglas were recorded before 1900, a possible influence of cooler conditions after the Little Ice Age (LIA), when European temperatures were colder than present, warrants further investigation. At Ronaldsway, the lowest minimum monthly temperature was recorded in February of 1963, associated with a very cold winter across Ireland and the UK.

2.2.3 Seasonal maximum and minimum air temperatures

Globally, minimum temperatures appear to be warming at a faster rate than maximum temperatures (Karl et al., 1993), particularly since the 1950s (IPCC, 2001), possibly associated with a change in cloud cover. Jones et al. (1999) found no significant increase in very warm days in the Central England Temperature series in recent years, but there was a marked decrease in the frequency of very cold days. A decrease in the diurnal temperature range has also been found in Northern and Central Europe (Heino et al., 1999).

	Douglas	Ronaldsway
winter max	0.124	1.160**
spring max	0.000	0.870**
summer max	-0.123	0.928*
autumn max	0.620	0.638
winter min	0.875*	1.829**
spring min	1.240**	1.357**
summer min	1.353**	1.062**
autumn min	2.232**	0.870*

** significant at 0.01 level (2-tailed).
* significant at 0.05 level (2-tailed).

Table 2.2 Increase in seasonal maximum and minimum temperatures for Douglas (1878-2001) and Ronaldsway (1947-2004) derived from linear regression.

Significance determined from Kendall's Tau-b.

Figure 2.5 illustrates the changes in seasonal maximum and minimum temperatures over the period of record for both Douglas and Ronaldsway. The seasons are comprised of the following months: Winter- December, January and February (DJF); Spring- March, April and May (MAM); Summer- June, July and August (JJA); Autumn- September, October and November (SON). Minimum temperatures were found to be increasing at a greater rate than maximum temperatures (Table 2.2). The increasing trends in minimum temperatures for both stations, calculated by fitting a least squares linear regression to the seasonal values, were found to be statistically significant. Increases in the autumn minimum temperature at Douglas were found to display the greatest degree of warming, increasing by 2.2ºC over the period of record, while winter minimum temperatures at Ronaldsway display the greatest increases for this station. For maximum temperature, the only significant trend found at Douglas was in the autumn series. Maximum temperature increases were found to be significant for all seasons at Ronaldsway. The greater increases evident in the autumn and winter periods are consistent with findings from Ireland (Butler et al., 2005).

Between 1950 and 1993, global maximum and minimum temperatures increased by 0.1°C/decade and 0.2°C/decade, respectively. Table 2.3 displays the seasonal increases in maximum and minimum temperature in °C/decade, which are largely consistent with global trends.

°C/decade	Douglas	Ronaldsway
winter max	0.01	*0.2*
spring max		*0.2*
summer max	-0.01	*0.2*
autumn max	0.1	0.1
winter min	*0.1*	*0.3*
spring min	*0.1*	*0.2*
summer min	*0.1*	*0.2*
autumn min	*0.2*	*0.2*

Table 2.3 Rate of warming in seasonal maximum and minimum temperatures for Douglas and Ronaldsway (°C/decade). Significant results are shown in *italics*.

Table 2.4 shows the trend (°C/decade) for changes in the highest daily maximum and lowest daily minimum temperature recorded for all seasons over the period 1947-2004. These findings are consistent with those trends found in the seasonal maximum and minimum series. Again, the significance of the lowest daily minimum temperature demonstrates that increasing minimum temperatures are the predominant driver of temperature changes in the Isle of Man.

	HD	LD
Winter	0.17**	0.53**
Spring	0.04	0.32
Summer	0.09	0.30*
Autumn	0.14	0.35*

** Correlation significant at 0.01 level (2-tailed).
* Correlation significant at 0.05 level (2-tailed).

Table 2.4 Rate of warming in seasonal highest daily maximum (HD) and lowest daily minimum (LD) temperatures for Ronaldsway (1947-2004) (°C/decade) derived from linear regression. Statistical significance derived from Kendall's Tau b.

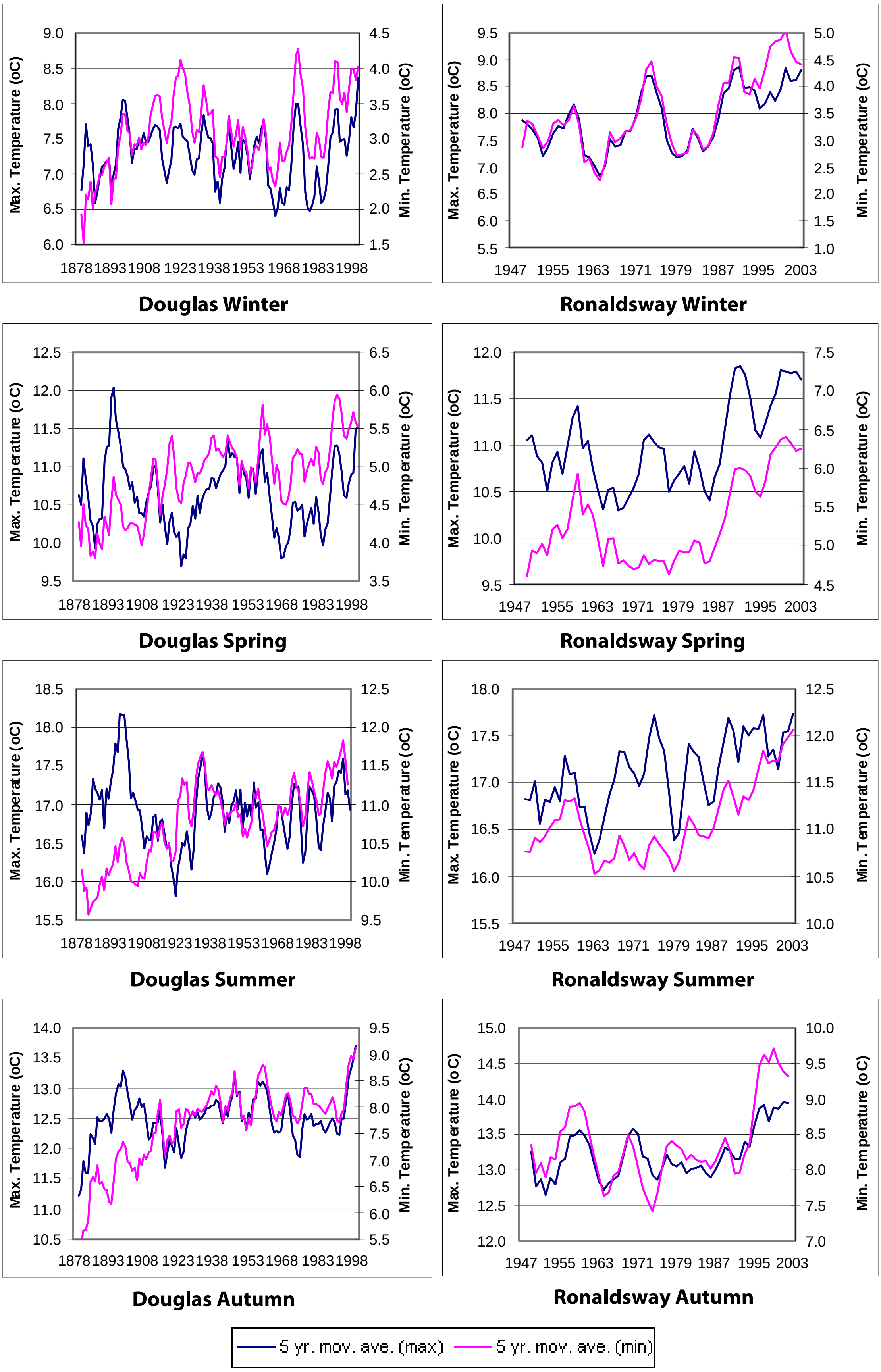

Figure 2.5 5-year moving averages of maximum and minimum temperatures for Douglas (1878-2001) and Ronaldsway (1947-2004)

2.2.4 Annual frequency of days with air frost

Figure 2.6 displays the annual number of days in which frost was recorded at Ronaldsway over the 1947-2004 period. Decadal means for the 1950s-1980s indicate that, on average, greater than 20 days each year recorded days with air frost. However, the decadal average for the 1990s suggest a reduction by approximately half in the number of days with air frost, recording, on average, only 12 days per year in which air frost occurred. As minimum temperatures continue to increase, it is likely that the number of days with air frost will continue to decline resulting in a longer growing season.

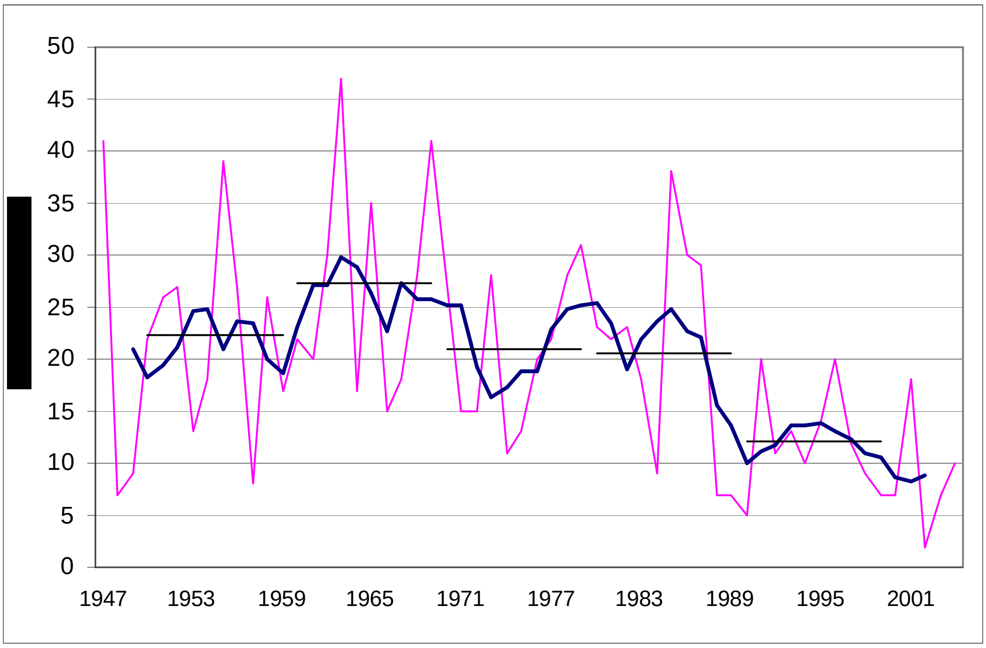

Figure 2.6 Annual number of days on which air frost was recorded at Ronaldsway (1947-2004). 5-year moving average included as a smoothed line. Decadal means are displayed in black.

2.2.5 Sun hours

Changes in the sun's elevation produce large seasonal variations in bright sunshine (Keane and Sheridan, 2004), from a minimum in December, January and February to a maximum in May, June and July (Table 2.5). While no trend exists in the annual series of sun hours, there is large interannual variability apparent in the observed record (Figure 2.7), fluctuating between approximately 1300 hours of annual sunshine in 1958 to approximately 1800 hours in 1955.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Sun hrs	52	71	113	170	216	208	194	180	131	95	64	43	1537

Table 2.5 Mean monthly sun hours from Ronaldsway for the 1961-1990 period

The 10-year smoothed average shows an overall tendency towards decreasing sun hours between the 1950s and the 1970s. This decreasing trend reverses in the early 1980s, with an increasing trend evident until the end of the records in 2004. These changes in annual sun hours are likely to be driven by changes in winter cloud cover. A split sample of winter season sun hours was assessed for a trend. The sample was split into pre-1990 and post-1990 and then both data series were input into a linear regression. A decreasing trend of –0.75 hours per winter season, significant at 0.05, was found in the pre-1990, while, in the post-1990 data (with fourteen cases), a strongly increasing trend of 6.2 hours per winter season was found to be significant at 0.01.

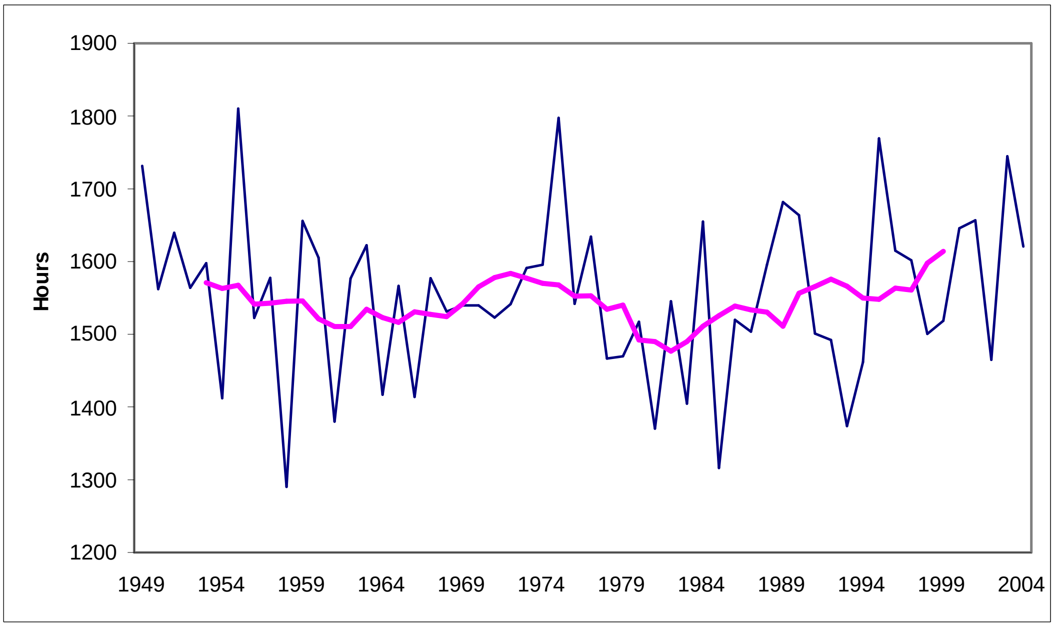

Figure 2.7 Annual sun hours from Ronaldsway 1949-2004. Smoothed line represents the 10-year moving average

Stanhill (2005) in an analysis of global irradiance, the flux in solar radiation of direct and diffuse radiation reaching the earth's surface measured during four years, 1958, 1965, 1975 and 1985, found that large significant reductions had occurred at a number of sites around the world. Gilgen et al. (1998) analysed of global radiation data over the 1964-1993 period also found a decrease, averaging 2% per decade, over large regions of Africa, Asia, Europe and North America. This phenomenon was termed 'Global Dimming' and is likely a consequence of changes in the transmissivity of the earth's atmosphere due to an increased loading of aerosols (Stanhill, 2005) and not necessarily associated with changes in cloud cover. Conversely, as the aerosol loading in the atmosphere is reduced we may find that the warming signal observed thus far has been masked, with the warming signal being greater than previously thought; a concept termed Global Brightening.

2.3 Precipitation Indicators

2.3.1 Long-term precipitation series

An amplification of the hydrological cycle is likely to result from an increase in global temperatures as a consequence of increased evaporation from the surface of the oceans. Over the course of the 20th century, large scale regional changes in precipitation amounts, intensity and location are likely to have occurred (IPCC, 2001), with annual precipitation displaying an increasing trend of approximately 0.5-1.0% per decade in the mid- to high- latitudes over the same period. There has also been an increasing trend towards more intense precipitation events in the order of 2-4% (IPCC, 2001).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean (1870-2002)	110.3	83.0	77.3	65.1	64.9	67.2	75.5	95.1	98.7	122.5	122.1	125.1	1105.1
Max. (mm)	276.6	193.3	199.1	149.2*	166.7	179.6	166.5	202.2	263.7	233.0	281.4	287.3	1598.7
Year	**1948**	**1937**	**1947**	**1961**	**1886**	**1982**	**1888**	**1956**	**1950**	**1903**	**1931**	**1934**	**1872**
Min. (mm)	21.0	2.2	15.7	8.6	5.7	2.8	7.4	7.4	5.8	13.7	6.9	25.1	701.8
Year	**1880**	**1986**	**1953**	**1980**	**1896**	**1925**	**1898**	**1959**	**1986**	**1946**	**1945**	**1963**	**1887**

Table 2.6 Mean, maximum and minimum monthly precipitation data for the period 1870-2002 for Douglas. Year indicates the year in which the greatest or smallest monthly total was recorded.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean (1947-2004)	86.4	60.5	63.8	55.6	49.1	55.1	56.7	68.0	80.2	95.6	97.2	93.9	863.1
Max. (mm)	237.1	139.1	211.1	130	140.9	132.8	139.8	184.3	184	228.6	210.7	213.4	1118.2
Year	**1948**	**1977**	**1947**	**1961**	**1993**	**1982**	**1985**	**1956**	**1950**	**2002**	**2002**	**1978**	**2002**
Min. (mm)	14	1.5	7.6	4.8	10	8.4	9.9	4.1	3.2	18.3	26.9	17.6	683.8
Year	**1997**	**1986**	**1953**	**1980**	**1977**	**1949**	**1989**	**1976**	**1986**	**1951**	**1956**	**1963**	**1995**

Table 2.7 Mean, maximum and minimum monthly precipitation data for the period 1947-2004 for Ronaldsway. Year indicates the year in which the greatest or smallest monthly total was recorded

Tables 2.6-2.7 display the mean monthly precipitation for Douglas and Ronaldsway, along with years in which the highest and lowest monthly falls were recorded. There appears to be no strong seasonality to precipitation receipts at either of these stations. However, there does appear to be large interannual variability (Figure 2.8). Increasing precipitation is evident from the start of the 20th century until the 1930s, after which, a general decline is apparent until the 1970s. Increases in receipts during the late 1970s and early 1980s are followed thereafter by a decline in annual receipts until the end of the records. The 1961-1990 mean rainfall total is 1131 mm for Douglas and 863 mm for Ronaldsway. While receipts for Ronaldsway are lower than Douglas, they follow a similar annual pattern. No significant trend was found in the annual series for either station.

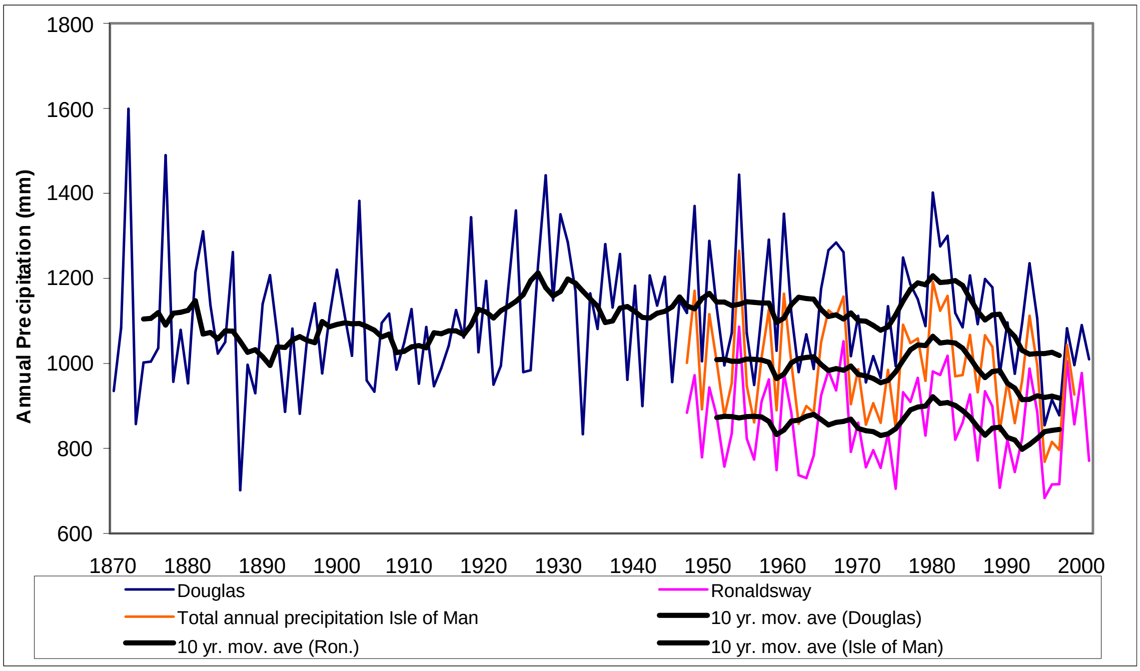

Figure 2.8 Annual precipitation for Douglas (1870-2001), Ronaldsway (1947-2005) and a combined annual precipitation series comprised of both Douglas and Ronaldsway (Annual receipts from Douglas for 2000 removed due to a missing value recorded in November of that year).

A significant trend in seasonal rainfall amounts was only found for increasing spring precipitation at Douglas, significant at the 0.05 level. A decreasing trend at Ronaldsway during the summer months, significant at the 0.05 level was also found. All other seasons displayed no significant trend in terms of changing seasonal precipitation amounts. However, a significant and decreasing trend in the 90^{th} percentile of winter rainfall, over the 1961-2000 period, was found to be occurring on the Isle of Man in research conducted by the STARDEX project (http://www.cru.uea.ac.uk/cru/projects/stardex/) inconsistent with trends occurring in England. A decreasing trend in the maximum 5-day rainfall during winter was also found to be occurring over the 1958-2000 period. Figures 2.9-2.10 display the 10-year moving average of winter and summer amounts, suggest only slight changes in the seasonality of precipitation.

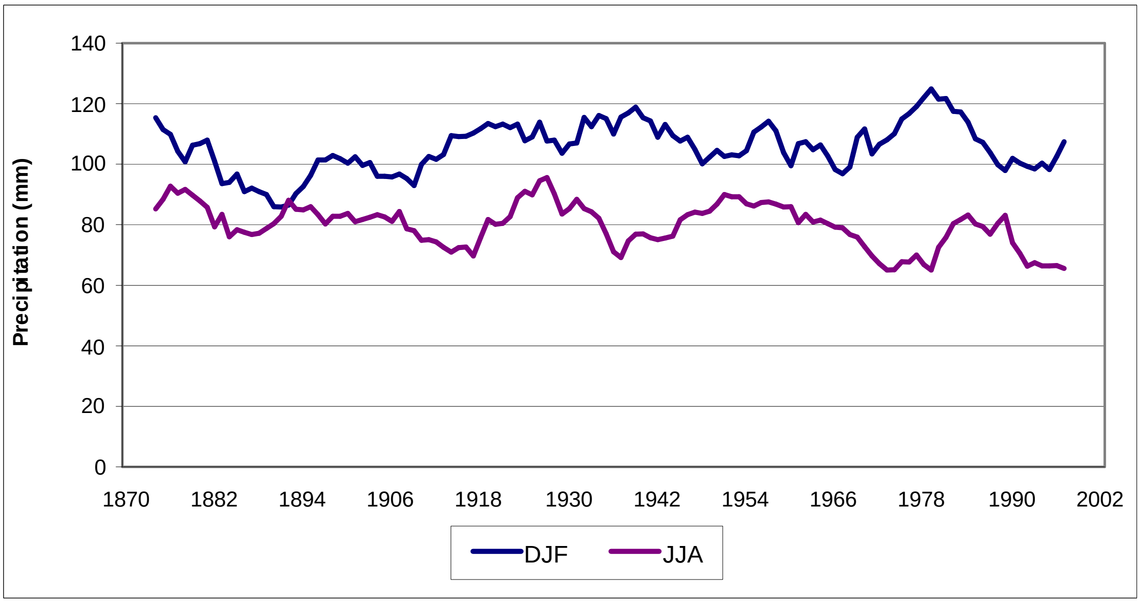

Figure 2.9 10-year moving averages of the winter (djf) and summer (jja) seasonal precipitation receipts for Douglas.

Analysis of the monthly precipitation totals for both stations only displayed statistically significant changes during August, with a decreasing trend precipitation, for both Douglas and Ronaldsway. A decreasing trend of –0.191 mm per year (significance level 0.05) was found for Douglas, while a decrease of –0.488 mm per year (significance level 0.05) was found for Ronaldsway. No significant trends in precipitation were found for the other months.

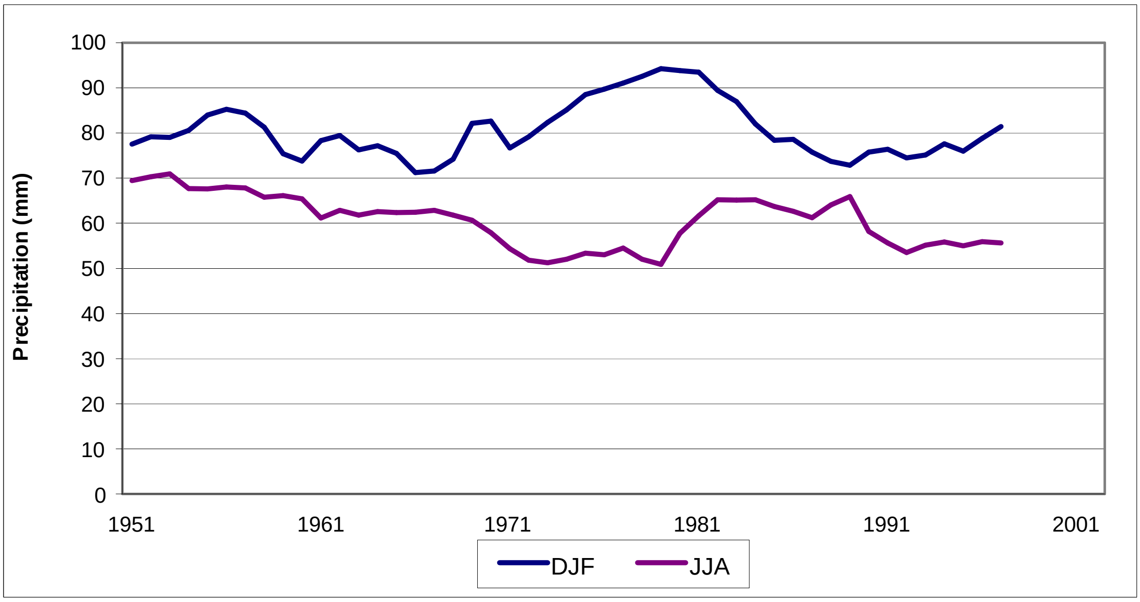

Figure 2.10 10-year moving averages of the winter (djf) and summer (jja) seasonal precipitation receipts for Ronaldsway.

2.3.2 Annual frequency of 'rain' and 'wet' days

No significant trends were found to be occurring in the annual series of raindays or wetdays (Figure 2.11) or in the monthly frequencies of raindays or wetdays at Ronaldsway over the period 1947-2005.

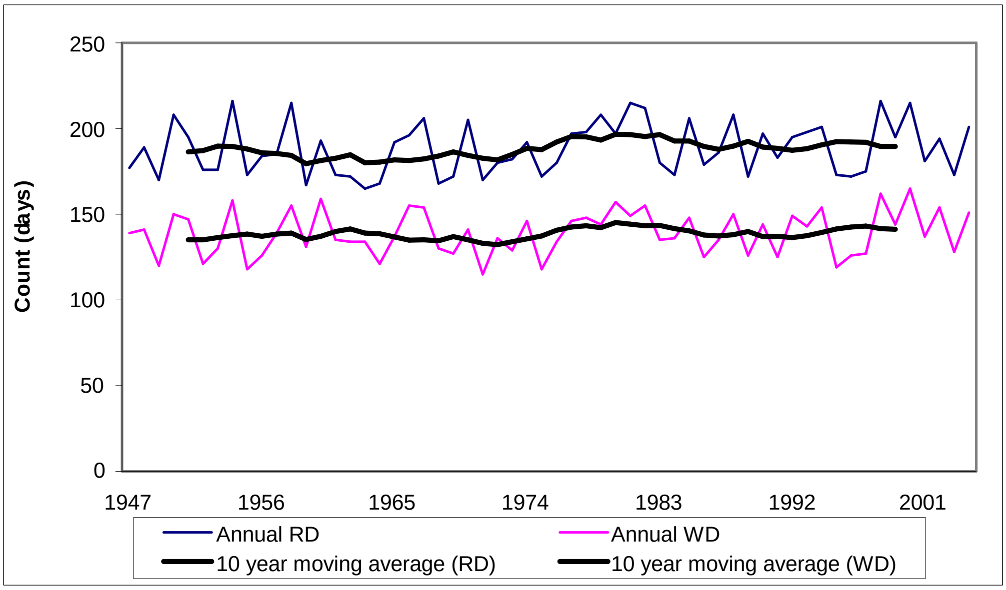

Figure 2.11 Annual frequencies of raindays (>0.1 mm) and wetdays (>0.9 mm).

2.4 Wind Indicators in the Isle of Man

2.4.1 Wind

Mean monthly wind speeds (knots) from Ronaldsway for the period 1961-1990 are displayed in Table 2.8. Wind speeds during the winter months tend to be moderate (11-16 knots), while during the summer months they tend towards more gentle breezes (7-10 knots). Over the 1961-1990 period, January displays the highest mean monthly wind speeds, followed by December and February, while the lowest wind speeds tend to occur during the summer months of June, July and August.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	15.7	15.0	13.8	11.7	10.7	9.8	9.6	10.1	11.7	13.4	14.5	15.3	12.6
Minimum	11.3	8.4	9.3	8.1	7.4	7.8	6.3	7.0	7.4	10.6	10.0	11.9	8.8
Maximum	19.9	22.0	18.5	19.6	15.8	13.3	13.1	14.9	14.7	17.5	20.2	19.6	17.4

Table 2.8 Mean monthly wind speeds (knots) for the Isle of Man from Ronaldsway (1961-1990).

In an analysis of seasonal trends of wind speeds at Ronaldsway over the 1961-2005 period, no significant trend was found to be occurring. Similarly, in an analysis of monthly trends, no significant trends were found to be occurring in windspeeds.

Year	Month	mph	knots
1964	Dec	64	55
1965	Jan	63	55
2005*	Jan	62	54
1961	Oct	61	53
1963	Feb	61	53
1965	Nov	60	52
1966	Dec	60	52
1984	Jan	57	49
1997	Dec	57	49
1998	Dec	57	49

Table 2.9 Highest hourly mean speeds for Ronaldsway (Table compiled by Alan Hisscott, Oik Emshyr Runnysvie, Isle of Man). (* Storm on January 2005).

Significant decreases in the highest hourly wind speeds were also found for a number of months. Decreases in April and September of -0.136 and -0.248 knots per year, respectively were significant at the 0.01 level, while decreases in November of –0.130 knots per year, respectively, were significant at the 0.05 level. The ten highest recorded hourly mean wind speeds are shown in table 2.9. However, site and instrumentation changes also occurred at this station during the period of record, which may also account for the changes found. Further work is required to assess these impacts.

Year	Month	mph	knots
1966	Dec	98	85
1965	Jan	96	83
1998	Dec	95	82
1991	Nov	91	79
2005*	Jan	91	79
1997	Dec	90	78
1961	Oct	89	77
1962	Dec	89	77
1964	Dec	89	77
1983	Mar	89	77

Table 2.10 Highest recorded gusts for Ronaldsway (Table compiled by Alan Hisscott, Isle of Man Oik Emshyr Runnysvie, Isle of Man). (* Storm on January 2005).

Similarly, decreases in the highest monthly gusts were also found for a number of months. Decreases during April (-.134 knots per year), May, (-0.197 knots per year), and November decreased (-0.233 knots per year) were found to be significant at the 0.05 level, while a decrease during September (-0.277 knots per year) was found to be significant at the 0.1 level. Again, caution must be exercised with regards to these results due to changes in site and instrumentation. The ten highest recorded gusts are shown in table 2.10.

2.5 North Atlantic Oscillation

Climate variability in the North Atlantic results from numerous interactions: between the troposphere, stratosphere, ocean, adjacent land masses, the Arctic, the Tropics and remote forcing from the Pacific (Marshall *et al.*, 2001). This variability results primarily from the interaction of three interrelated phenomena; the Tropical Atlantic Variability (TAV), fluctuating tropical Atlantic sea surface temperatures which straddle the intertropical convergence zone (ITCZ), the North Atlantic Oscillation (NAO), which represents fluctuating sea level pressure between the Azores and Iceland, and the Atlantic Meridional Overturning Circulation (MOC) or thermohaline circulation (Marshall *et al.*, 2001). These phenomena interact on a variety of timescales, from interannual to decadal, and over a large spatial area, vertically integrating the ocean and atmosphere.

In the mid-latitudes, the North Atlantic Oscillation accounts for 37% of the variability of the winter 500 hPa heights over the North Atlantic (Marshall *et al.*, 2001). It is the leading mode of climate variability, particularly in winter when it is most pronounced in amplitude (Marshall *et al.*, 2001). The NAO is also linked to the leading annular mode of climate variability in the Northern Hemisphere, the Arctic Oscillation (AO).

The NAO is characterised by a meridional or north-south pressure gradient between the semi-permanent low pressure centred over Iceland (Icelandic Low) and the semi-permanent high pressure centred over the Azores (Azores High). It is instrumental in the large-scale transfer and redistribution of atmospheric mass between the equator and the North Pole and is associated with changes in westerly airflow over the North Atlantic onto Europe (Hurrell, 1995). It is most pronounced during the boreal winter months of December, January and February, when it accounts from more than one-third of the total variance in sea-level pressure (SLP) over the North Atlantic, but is present throughout the whole year (Marshall and Kushnir, 1997; Hurrell and Dickson, 2001).

The NAO fluctuates between positive and negative modes on a decadal to multi-decadal time scale (Figure 2.12). Positive modes are associated with stronger than average westerlies due to a large pressure gradient between the Icelandic Low and Azores High. A positive phase of the NAO results in intensified depressions tracking over Northern Europe due to the increased pressure gradient. Negative modes result from a diminished gradient between Iceland and the Azores. Fluctuations in the NAO have also been found to co-vary with fluctuations in temperature and precipitation.

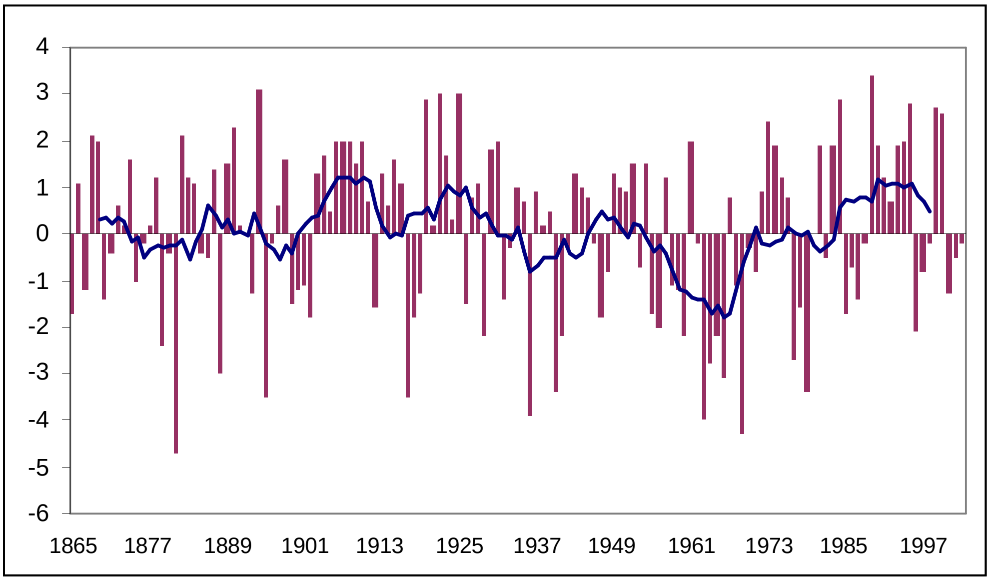

Figure 2.12 Winter time (DJF) North Atlantic Oscillation 1865-2003. Smoothed line represents the 10-year moving average.

2.6 Storminess

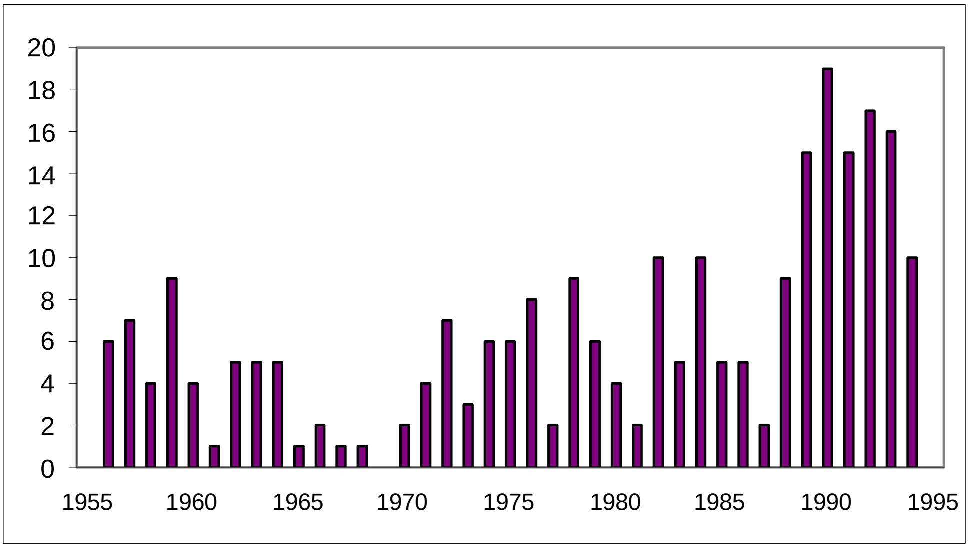

Figure 2.13 Number of North Atlantic low pressure systems with pressure less than 950hPa

(Source: Deutscher Wetterdienst, 1994)

Extra tropical cyclones are low-pressure systems that occur throughout the mid-latitudes of both hemispheres (IPCC, 2001). These low-pressure systems can cause significant damage resulting from increased wind speeds and wind generated waves and flood damage from the frontal systems associated with extra tropical storms, particularly during the winter months when these systems are most active. Analysis of changes in frequency and intensity of extra tropical storms has produced conflicting results. However, evidence for an increase in storm intensity in the North Atlantic during the 1980s and early 1990s has been found by a number of researchers (Figure 2.13) (Stein and Hense, 1994; Kushnir et al., 1997). Jones et al. (1999) in an analysis of severe gales over the United

Kingdom for the period 1881 to 1997 found a higher frequency of severe gales occurring after 1990, which were attributed to an intensification of the NAO during the 1980s and 1990s (Figure 2.12).

However, drawing any conclusions with regards to long-term changes in storm frequency and intensity still remain uncertain. Model projections from the HadCM3 suggest an overall decrease in storm frequency over Northern Europe and the Mediterranean, but an increase in frequency over the British Isles and Ireland. Storm intensity is also predicted to increase substantially as a consequence of enhanced global warming (McDonald et al., 1999).

2.6.1 Case study- January Storm 2005

Between 0000GMT and 1200GMT on the 8th January, 2005, a rapidly deepening area of low pressure moved from western Ireland towards southern Norway with fronts spread south east across the British Isles (Figure 2.13) (http://www.met.rdg.ac.uk/~brugge/diary2005.html). Heavy rain, associated with the fronts, caused widespread flooding, resulting in thousands of people having to be evacuated from their homes. The city of Carlisle suffered its worst flood in over one hundred years. Strong gusts were recorded at many coastal locations across Northern Europe, the most damaging of which were recorded across Northern Ireland, the North of England, Denmark and Southern Sweden.

On the Isle of Man, the strongest winds, from WSW to W, were reached between 0430GMT and 0700GMT. At Ronaldsway, the highest hourly mean wind speed recorded was 54 knots (62mph) and the highest gust reached 79 knots (91mph) (Alan Hisscott, Oik Emshyr Runnysvie, Isle of Man). Maximum gusts on the island reached 112mph at Brandywell, 101mph at Mountain Box, 98 mph at Point of Ayre, 96mph at Douglas Breakwater and 85mph at Peel Breakwater. Based on approximately 45 years of recorded wind data at Ronaldsway, the estimated return period is around 10 years (Alan Hisscott, Oik Emshyr Runnysvie, Isle of Man). Plates 2.1 to 2.3 illustrate some of the damage caused by the high winds on the island (Courtesy of Isle of Man Newspapers).

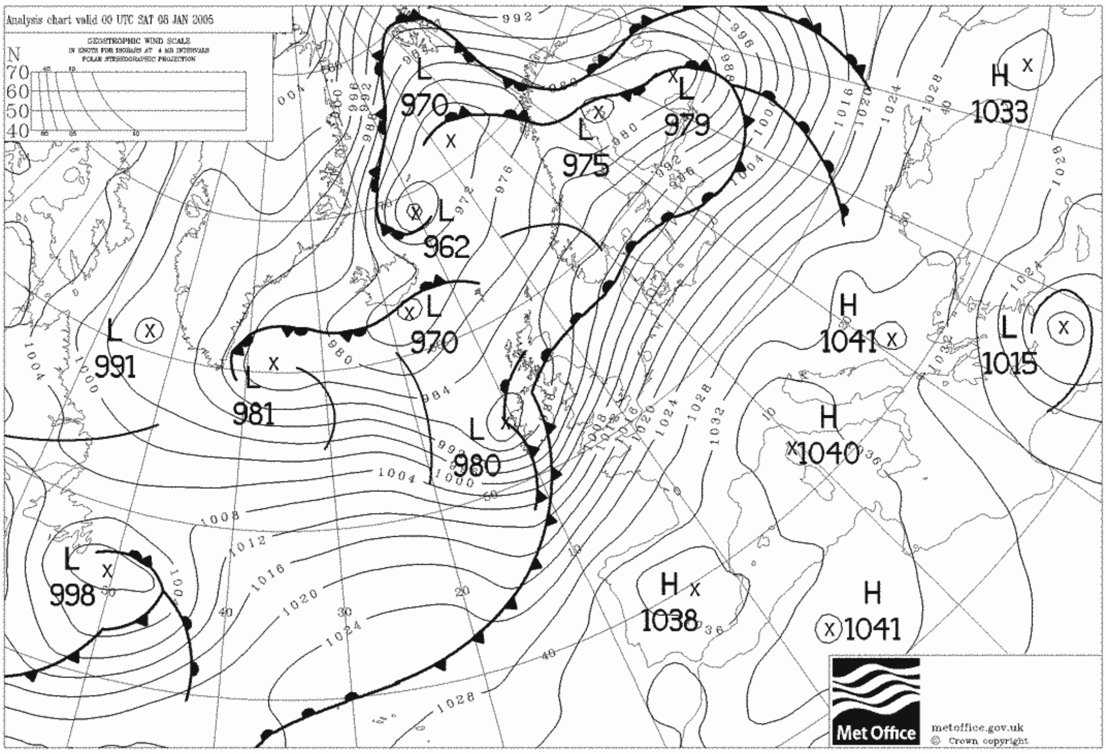

Figure 2.13 Surface pressure chart from 00 UTC on the 8th January 2005 showing the area of low pressure which resulted in widespread flooding in England and high wind speeds over Northern Ireland, Isle of Man, Scotland (Source: http://www.wetterzentrale.de/topkarten/tkfaxbraar.htm).

Plate 2.1 Damage from fallen tree

Plate 2.2 Wind throw of a forest stand

Plate 2.3 Grave stones damaged by fallen tree

2.7 Mean Sea Level

Observational estimates and modelling studies suggest that warming of the oceans, with resultant thermal expansion of the ocean layers, has accounted for a rise in sea level of approximately 0.3-0.7 mm/yr, averaged over the 20th century (IPCC, 2001). Sea surface temperatures from the Isle of Man have increased by 0.7°C throughout their observational period (Figure 2.15). Eleven of the twelve warmest years have occurred in the record over the period 1989-2005. During this period, 1998 was the warmest year with an average annual anomaly of 1.15°C relative to the 1961-1990 period.

Changes in salinity have also been found in the upper layers of the ocean (IPCC, 2001). Melting of glaciers and ice caps, outside of Greenland and Antarctica, indicate a contribution of 0.2 to 0.4 mm/yr over the 20th century. Dyurgerov (2003) estimated that the glacier melt contribution to sea level rise was 0.15 mm/yr or 10% of total sea level rise. However, this contribution increased to 0.41 mm/yr or 27% of total sea level rise between 1988-1998 suggesting that glacier sensitivity to climate warming may be accelerating. Due to increased precipitation over Antarctica during the course of the 20th century, contributions to sea level, estimated from modelling studies, are suggested to be between –0.2 and 0.0 mm/yr (IPCC, 2001). Greenland contributes between 0.0 and 0.1 mm/yr resulting from a change in the balance between increased storage, in the form of precipitation, and increased runoff due to melting (IPCC, 2001).

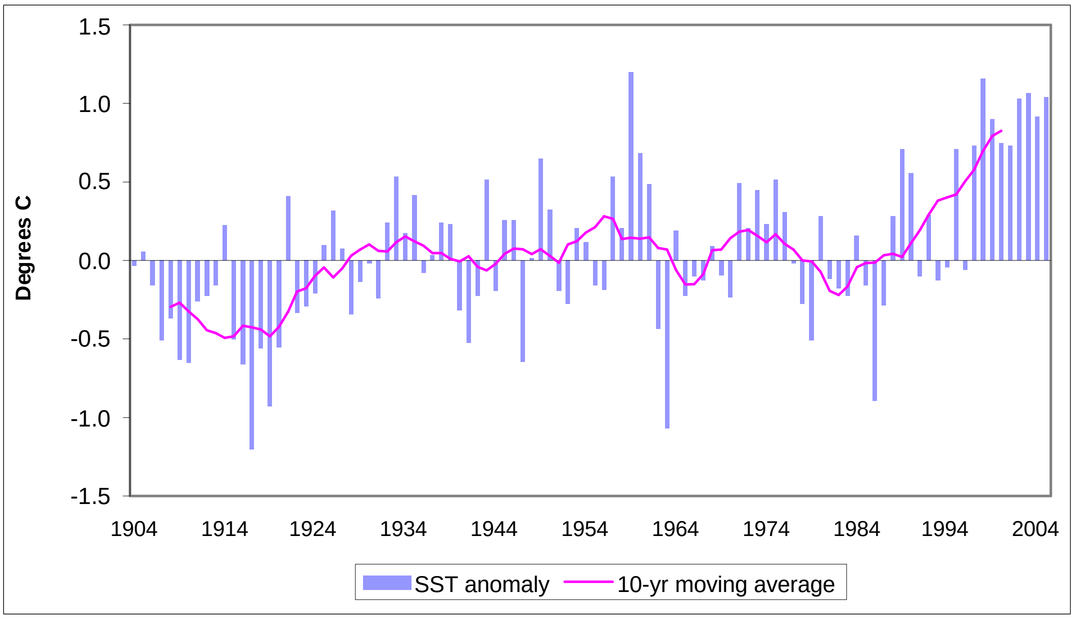

Figure 2.15 Annual average anomalies (1904-2005) of sea surface temperatures from Port Erin, Isle of Man, relative to the 1961-1990 period (Data reproduced with kind permission of Theresa Shammon, Port Erin Marine Laboratory, Isle of Man).

2.7.1 Waves and Storm Surges

Wave heights are determined by the distance of uninterrupted open water over which a wave forming wind can travel, called the fetch. On the Atlantic coast, a south-westerly wind can have a fetch in excess of 5000km, dramatically enhancing wave heights (Lewis, 1971). Wave heights in excess of 24m have been recorded in the Atlantic (Pethick 1984), although these are considered extreme.

Wind waves, or sea waves occur when the wind has a direct influence over a body of water. Swell waves are initially generated by wind but have propagated out from the centre of action where they were initially generated. Wind waves tend to appear as chaotic and less well structured while swell waves appear as structured and regular wave movements. The interaction between both sea and swell waves can enhance wave heights causing unusually high waves.

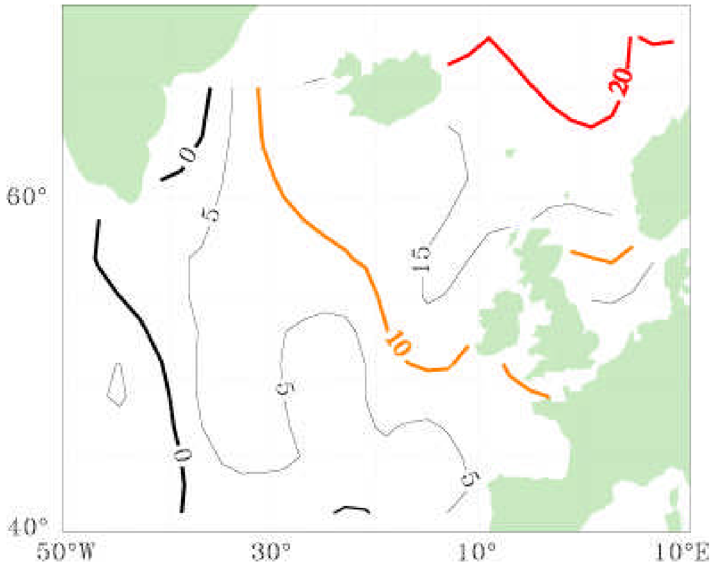

Figure 2.16 Percentage increase in mean winter significant wave height, 1985-89 to 1991-96 from altimeter data (JERICHO) (Cotton et al. 1999)

Bouws et al. (1996) found a trend towards increasing wave heights in the North East Atlantic, with significant wave heights increasing by between 10 and 30 cm decade^{-1} over the1961-1993 period (Gulav and Hasse, 1999). Figure 2.16 illustrates the percentage increase in mean winter significant wave heights between the 1985-1989 and 1991-1996 periods for the North Atlantic.

Research conducted by the Waves and Storms in the North Atlantic group (WASA) (1998) showed that there was no significant long term trend in windiness and cyclonic activity in the North Atlantic but that major variations did exist on decadal time scales (IPCC, 2001). This variability is likely linked to variations in the NAO. Even if there is no significant change in the frequency of storm surge events, return periods are likely to decrease relative to the present day, as a consequence of an increase in sea level, which will act to raise the base water level.

Figures 2.17 and 2.18 show the mean significant wave height and variance for the Atlantic and Irish Sea for the period 1993-1997. Significant wave heights are indicative of significant wave conditions averaged over a particular period of time. Significant wave heights in the Atlantic are in the order of 2.5 to 4 metres, while in the Irish Sea significant wave heights are lower, ranging from 0.5 to 1.5 metres. Figures 2.19 and 2.20 show the seasonal difference between significant wave heights.

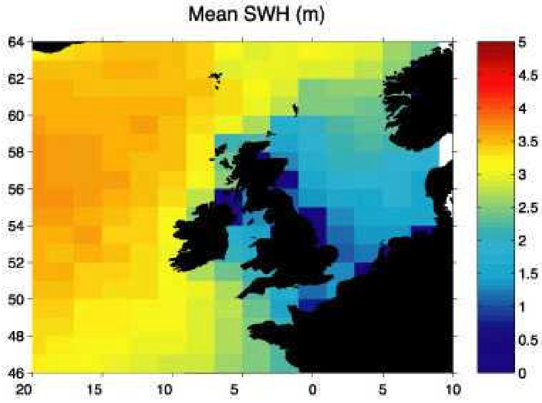

Figure 2.17Mean Significant Wave heights for the period 1993-1997 from altimeter data

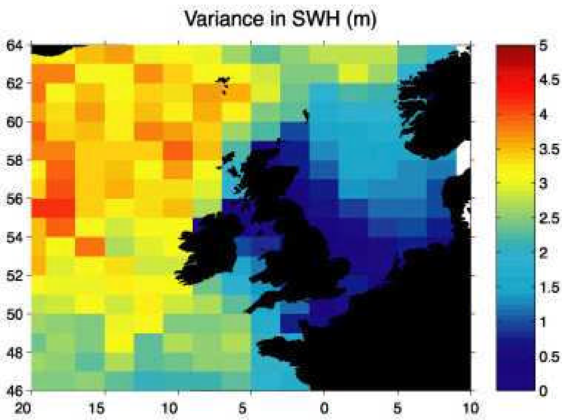

Figure 2.18 Variance in Significant Wave heights for the period 1993-1997 from altimeter data

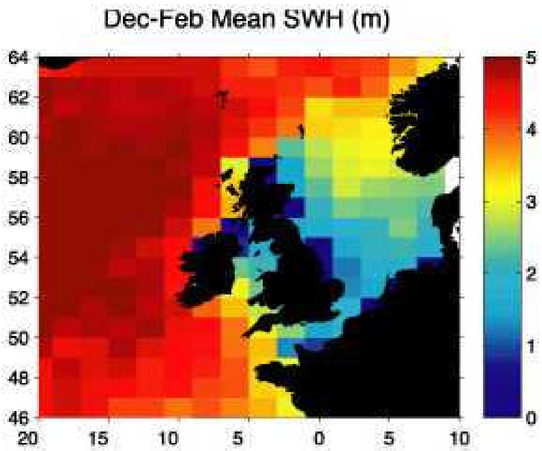

Figure 2.19Mean Winter Sig. Wave Height for the period 1993-1997 from altimeter data

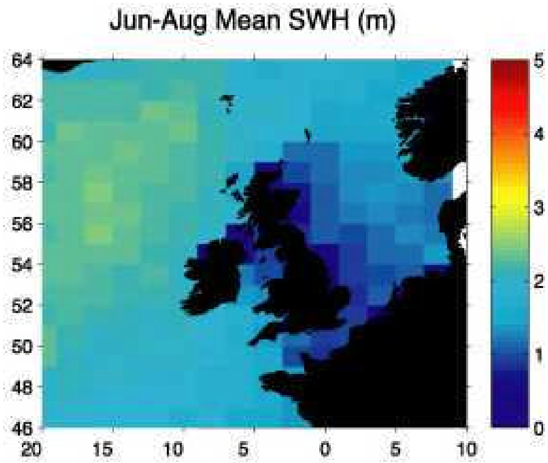

Figure 2.20 Mean Summer Sig. Wave Height for the period 1993-1997 from altimeter data

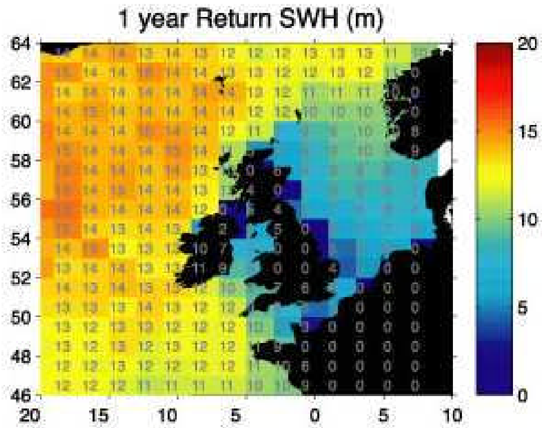

Figure 2.21 1-Year Return Value of Significant Wave Height from altimeter data (JERICHO)

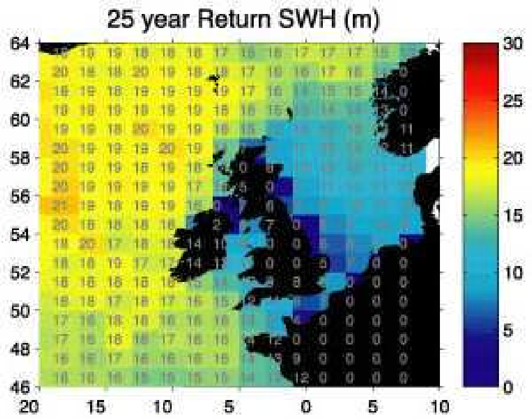

Figure 2.22 25-Year Return Value of Significant Wave Height from altimeter data (JERICHO)

(Figures were produced by Satellite Observing Systems Ltd, as part of the British National Space Centre supported JERICHO project.)

This difference is greatest in the Atlantic, while for the sheltered Irish Sea, the seasonal difference in wave heights tends to be greatly diminished. Figures 2.21 and 2.22 illustrate the significant wave height of waves likely to occur once every year and once every 25 years.

Surges are generated when meteorological variables, such as barometric pressure and winds, depart substantially from average conditions. This can produce negative or positive surge conditions, which are reflected in the difference between actual tidal height and predicted tidal height, based on average conditions, at a location. A decrease of 1hPa in pressure can raise sea level locally by approximately 10mm. An area of extreme low pressure over the ocean associated with a strong wind acts to enhance the resulting storm surge elevation. In Irish Sea waters this can result in significantly increased water levels at the coast (ECOPRO, 1996). Figure 2.23 shows the 50-year surge elevation for the North Eastern Atlantic. The 50-year surge elevation for the Isle of Man is 125cm.

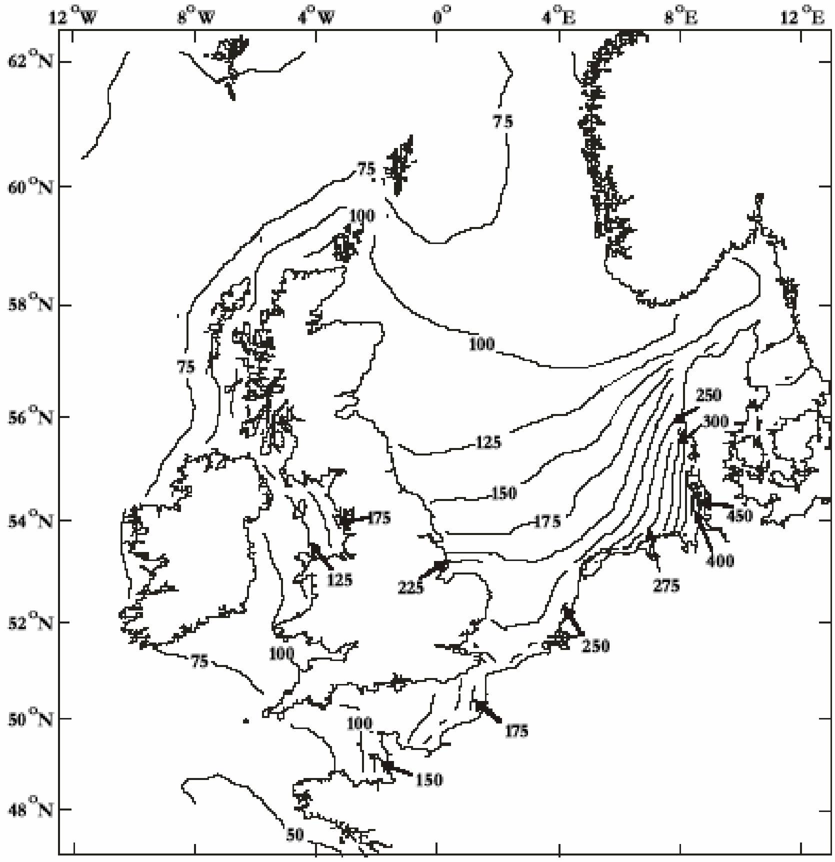

Figure 2.23 Distribution of 50 year surge elevation (cm) based on analysis of model surges (from Flather et al. 1998)

As a depression moves, the generated swell can become coupled with a tidal wave, which results from the gravitational pull of the sun and moon on the oceans, further enhancing the surge elevation. The effects of a storm surge as it moves onshore depends on a number of factors, including local topographical features of the sub-surface, strength and direction of an onshore wind, occurrence with a spring or neap tide and location of the tidal bulge. The elevation of a storm surge can also be greatly enhanced when it becomes coupled with wind waves. The duration of a surge event also has implications that determine its potential for damage

2.7.2 Case Study- Storm Surge Event: 1st February 2002

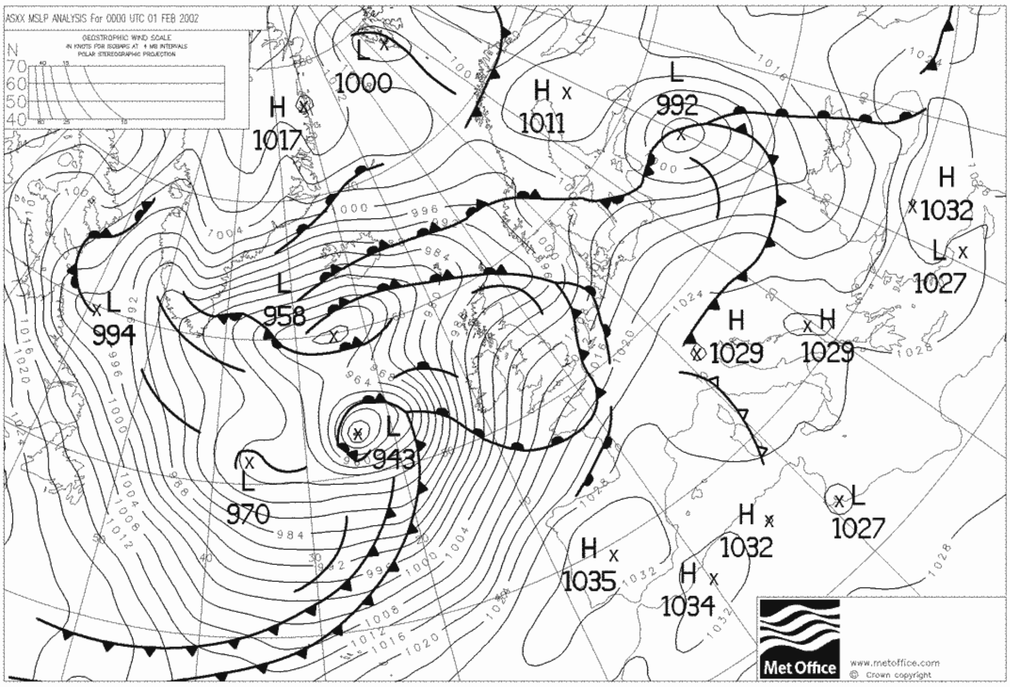

Figure 2.24 Synoptic weather chart from the 1st of February showing a deep depression off the west coast of Ireland ((Source: http://www.wetterzentrale.de/topkarten/tkfaxbraar.htm).

During the 1st February 2002, a combination of several meteorological factors produced a storm surge, which led to significant damage on the Isle of Man. A deepening area of low-pressure in the North Eastern Atlantic, off the West coast of Ireland (Figure 2.24), produced gale force south westerly winds. At Ronaldsway, the hourly wind speed reached nearly 50 mph, with gusts of 70mph. A combination of the sustained winds and the long fetch resulted in increased water levels being forced up the Irish Sea. The resultant storm surge, combined with a large astronomical tidal wave, produced a water level over a metre higher than was expected from astronomical calculations alone. Importantly, for the Isle of Man, a veer in wind direction and a decrease in wind strength, which occurred approximately 2 hours before high tide, diminished the extent of damage caused as a consequence of flooding.

Severe flooding occurred around the islands coastal areas, with seawater encroaching into several towns (Isle of Man Meteorological Office report) (Plates 2.4 to 2.6). Figure 2.25 illustrates the skew surge of the afternoon tide on the 1st February. The skew surge is a modelled height (cm) estimation of the storm surge component by which the actual total water levels exceeded the tidal predictions based on astronomical calculations alone.

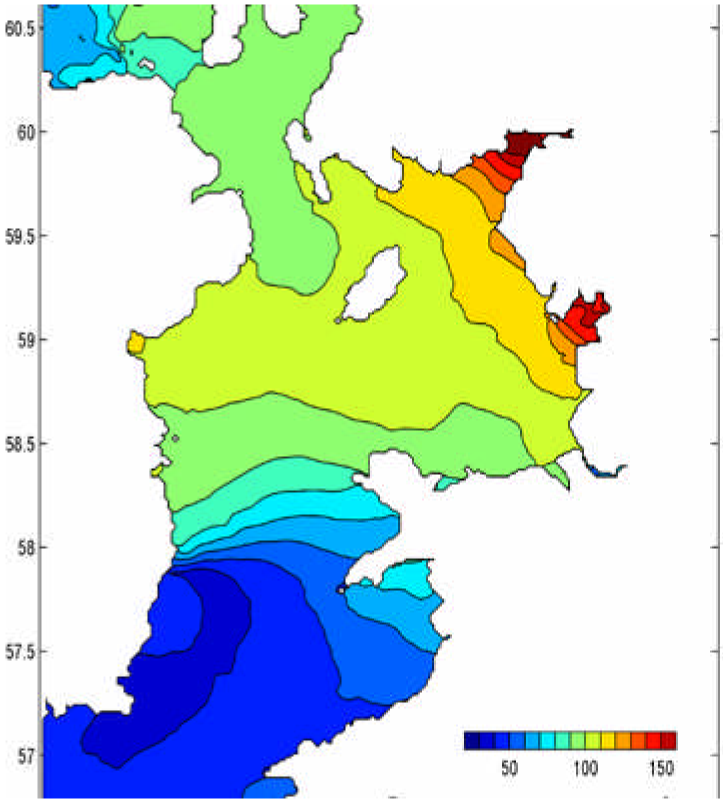

Figure 2.25 Skew surge for the afternoon tide on 1st February 2002 (Source: Proudman Oceanographic Laboratory). The water height, in centimetres, that exceeded the predicted level based on astronomical calculations.

The following warning was issued by the Ronaldsway Meteorological Office–

WARNING Issued By Ronaldsway Meteorological Office
SEVERE GALE, HEAVY RAIN, LARGE HIGH TIDE / TIDAL FLOODING.

It'll stay very windy today and sometimes wet between now & mid afternoon, the spells of rain coming & going, possibly heavy at times & driven hard by the SSW'ly Gale which is reaching Severe Gale force at times at low levels with gusts 55 to 65mph but over the hills it's reaching Storm force indeed the Audi Stn at Brandywell has already recorded gusts over 75mph. Driving conditions are bad, especially for high-sided vehicle & it'll be very dodgy up on the Mountain Rd. -indeed I'd recommend all drivers to avoid using the Mountain Rd.

There's a large high tide at $^1/_4$ to 2 this afternoon & the very rough to high sea is likely to break over along windward promenades & coastal roads, especially Shore Rd. in Rushen, Castletown promenade & parts of Douglas prom as well - leaving quite a lot of sea water & debris. A tidal surge may also cause some problems up into the inner harbour areas with a risk of flooding. However the gales will slowly abate mid to late afternoon as the rain is replaced by showers.

There's likely to be further splash-over on the following high tide overnight (about 10 past 2 tomorrow morning) with a very strong to gale force SSW or S'ly wind and further spells of rain. (Source: Alan Hisscott, Oik Emshyr Runnysvie, Isle of Man)

Plate 2.4 Overtopping at the Douglas Promenade.

Plate 2.5 Flooding on the Douglas Promenade.

Plate 2.6 Flood waters on the Douglas Promenade.

3.0 Conclusions

In this chapter, meteorological data from the Isle of Man were assessed for any changes that may have occurred over the course of the 20th century. Temperature and precipitation, two key climatic parameters, from Douglas and Ronaldsway were examined for trends to determine if, and how, climate on the island is responding to global warming.

Annual temperature anomalies, which displayed a large degree of interannual variability, were found to be largely consistent with global temperature anomalies. However, they display a faster rate of warming from the 1980s onwards than is apparent in the global anomalies. The warming rates evident in the 10 year moving averages of annual anomalies from the Isle of Man were found to be highly consistent with more regional indices, such as the Central England Temperature series and the annual anomalies from the Irish temperature records.

An index of mean annual air temperature demonstrates warming occurring after 1980, with 6 of the 10 warmest years on record occurring after 1988, making the 1990s the warmest decade on record. This warming trend was found to be significant.

Consistent with global trends, minimum temperatures were found to be warming at a greater rate than maximum temperatures, with the greatest warming occurring in minimum temperatures during autumn at Douglas. Winter minimum temperatures displayed the greatest increases at Ronaldsway. Increases in the seasonal minimum temperatures from both stations were found to be significant; maximum temperatures from Ronaldsway were also significant. Seasonal increases in minimum and maximum temperatures per decade are consistent with global trends. Significant increases in the lowest daily temperatures were also found.

While no significant trends were found in the annual frequency of frost days, the decadal average for the 1990s represents a reduction of approximately half in the number of frost days when compared to previous decades. These findings are consistent with the increases found in minimum temperatures.

While no significant trend was found in annual precipitation data, large interannual variability is evident in the series, with a decreasing tendency from the 1980s onwards. However, a significant and increasing trend was found in the spring receipts at Douglas, while a decreasing trend at Ronaldsway during the summer months was also found to be significant. No apparent changes in the annual count of rain days or wet days were found to be occurring.

A significant and increasing trend was found in the number of sun hours during the winter months after 1990, which up to this point had been decreasing. This may reflect changes in cloud cover and extent, and may partially explain the reductions in precipitation after the 1980s.

The trends identified in this chapter are largely consistent with findings from other studies and in line with global trends. Precipitation series require further analysis. Despite the oceanic influence of the Atlantic, seasonal precipitation series were found to be unrelated to the large-scale circulation represented by the North Atlantic Oscillation, results which are inconsistent with findings from both the UK and Ireland and which may explain the decreasing trends found in the 90th percentile of rainfall and 5-day maximum rainfall amounts on the Isle of Man.

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