CLIMATE AND CLIMATE CHANGE IN THE SUB-ANTARCTIC

by S. F. Pendlebury and I. P. Barnes-Keoghan

(with 12 text-figures and one table)

Pendlebury, S.F. & Barnes-Keoghan, I.P. 2007 (23:xi): Climate and climate change in the sub-Antarctic. *Papers and Proceedings of the Royal Society of Tasmania* 141(1): 67–82. https://doi.org/10.26749/rstpp.141.1.67 ISSN 0080-4703. Bureau of Meteorology, GPO Box 727, Hobart, Tasmania 7001, Australia. Email: s.pendlebury@bom.gov.au (SFP*, IBK). *Author for correspondence.

Meteorologically, the sub-Antarctic is sparsely represented in the climate literature. Drawing on a variety of sources that are either directly or indirectly linked to the sub-Antarctic, an overview of the climate of the sub-Antarctic is presented. In doing so, we note that, for the most part, the sub-Antarctic climate is more or less fixed to mean monthly air temperatures between –5°C and +15°C. Brief discussion explores the roles of teleconnections that appear to affect the sub-Antarctic climate, focusing on the Southern Hemisphere Annular Mode (SAM). We report on meteorological evidence of climate change that has occurred in the recent history of the sub-Antarctic and note that rainfall climate-change signals from Marion and Macquarie islands are consistent with trends associated with the SAM index. We report that modelling suggests that the climate of the sub-Antarctic will continue to change through the twenty-first century in line with twentieth-century trends. The need for more research into the climate of the sub-Antarctic, underpinned by a robust databank of quality controlled sub-Antarctic meteorological data, is noted.

Key Words: climate, climate change, Marion Island, Macquarie Island, Southern Annular Mode, sub-Antarctic, teleconnections.

INTRODUCTION

Despite its importance as part of the global climate system, and the sensitivity of many of its biological systems to climate change, there is remarkably little published information on either climate or climate change in the sub-Antarctic. Much of the limited discussion that is available in the literature appears to represent the sub-Antarctic through reference to the climate at individual locations; figure 1 shows most of the stations and geographical features referred to here. Smith (2002), for example, discussed climate change in the sub-Antarctic using recent changes on Marion Island as an illustration, while Whinam & Copson (2006) used Macquarie Island as their reference point. These two papers also have climate change impacts on biota as the underlying reason for presentation of the work, which may reflect a dearth of purely meteorologically-based discussion on climate and climate change in the sub-Antarctic. Even the largely meteorological paper of Rouault *et al.* (2005) is mostly confined to considering climate changes evident around Marion Island. There is some discussion of Antarctic climate that has some relevance to the sub-Antarctic; for example Turner & Pendlebury (2004) reported on climate and weather forecasting aspects at various stations in the sub-Antarctic though their focus is on the Antarctic itself.

Drawing on a variety of sources that are either directly or indirectly linked to the sub-Antarctic, the current paper seeks to give an overview of the climate and climate change of the sub-Antarctic as a whole. We start by briefly describing the role of ocean currents and the geographical extent of the sub-Antarctic within our purview; we then discuss the broad features of the surface climate of the sub-Antarctic. The paper then provides a brief discussion on a few of the important teleconnections which appear to affect sub-Antarctic climate. Finally, we report on meteorological evidence of climate change that has occurred in the recent history of the sub-Antarctic, and on modelling of that which might occur over the twenty-first century.

OCEANS AND THE SUB-ANTARCTIC

Ocean currents affect climates, arguably none more so than the climate of the sub-Antarctic. Ocean currents are often bordered by marine frontal surfaces (or convergences): narrow regions of relatively rapid transition in water temperature and salinity. Figure 1 shows the main Southern Hemisphere marine fronts, adopting the scheme of Belkin & Gordon (1996). Key features are a Polar Frontal Zone between the sub-Antarctic Front and the more southern Polar Front, and an Antarctic Zone south of the Polar Front. The Subtropical Frontal Zone has, as its northern boundary, the North Subtropical Front and as its southern boundary the South Subtropical Front. These two fronts merge into a single Subtropical Front south of Australia. Another subtropical-type front is the Agulhas Front in the southwest Indian Ocean. North of the Îles Kerguelen area the subtropical, sub-Antarctic and Antarctic Polar fronts become almost indistinguishable. Similarly, the sub-Antarctic and Polar fronts almost blend in the far southwest Atlantic Ocean, while north of the Marion Island–Îles Crozet region the sub-Antarctic Front comes very close to the South Subtropical Front. Elsewhere the sub-Antarctic Front is quite separate from its more northern counterparts.

The Antarctic Circumpolar Current (ACC) flows eastward around Antarctica over the latitude band 40–65°S (King & Turner 1997) associated with the complex structure of fronts outlined above. Fyfe & Saenko (2005, p. 3068) stated that "the ACC profoundly influences, and is influenced by, the regional and global climate". The ACC carries more water than any of Earth's other ocean currents, and 75% of this flow occurs between the Antarctic Polar Front and the sub-Antarctic Front (American Meteorological Society 2000). Following the King & Turner (1997) representation, figure 2 is a sketch of a typical slice of the waters that surround Antarctica south of the South Subtropical Front. The figure gives a sense of the gradients in surface temperature and current velocities. King & Turner (1997) equated the sub-Antarctic Front with the Subtropical Convergence (Subtropical Front): this can be reconciled with the Belkin & Gordon description by assuming the King & Turner

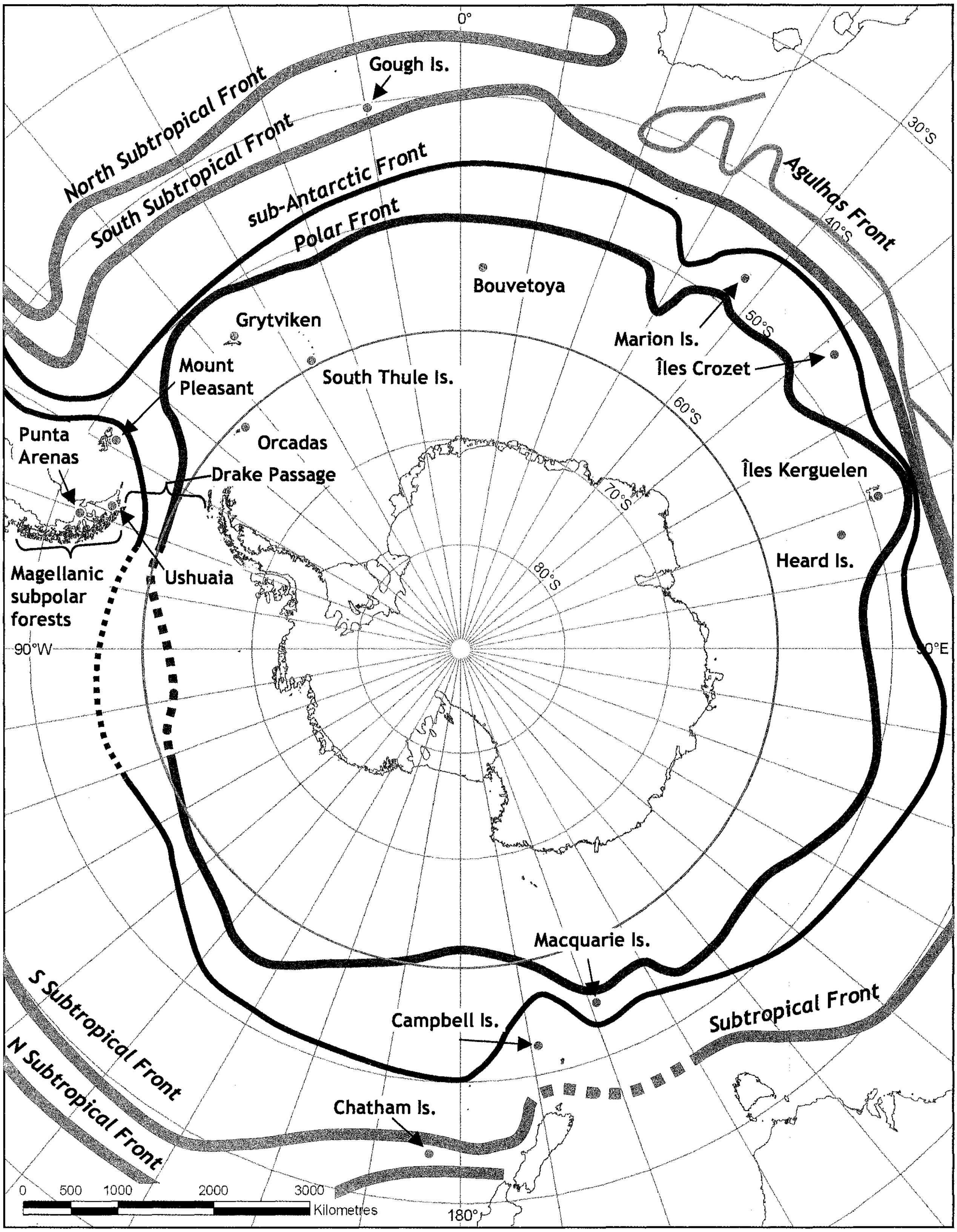

FIG. 1 — Sketch of the locations of key high-latitude oceanic "fronts" and of many of the places referred to in the text. The frontal positions are from Belkin & Gordon (1996). The base map was produced by the Australian Antarctic Data Centre.

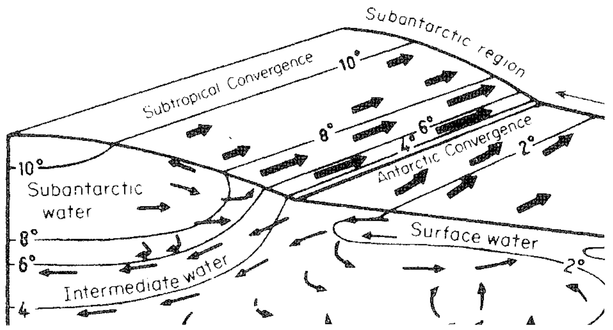

FIG. 2 — Sketch of the locations of key high-latitude oceanic "fronts" and typical winter-time surface isotherms (°C). Adapted from King & Turner (1997).

(1997) Subtropical Convergence is the equivalent of the Belkin & Gordon (1996) South Subtropical Front.

Not only are ocean currents and fronts key components of the climate system; they can be used to delineate the sub-Antarctic. For the purposes of this paper the sub-Antarctic is considered to extend northwards from the northern limit of the Antarctic, which, according to the Antarctic Treaty System, is at 60°S (Antarctic Treaty Secretariat 2007) to include oceanic areas south of the North Subtropical Front, plus adjacent land areas which have monthly mean temperatures less than about +15°C. This comprises a band of about 25° of latitude spanning the southern Atlantic, Indian and Pacific oceans. The landmasses of Africa and Australia constrain the sub-Antarctic to be south of these continents, although the most southern parts of South America are within the sub-Antarctic.

A common criterion for the identification of the South Subtropical Front involves temperatures from the surface to 200 m depth in the order of +10°C (see fig. 2), although some definitions allow the northern edge of the South Subtropical Front surface water temperature to be as high as around +18.5°C over summer (Belkin & Gordon 1996). This criterion makes the above geographical boundaries of the sub-Antarctic consistent with the maritime/taiga land climate of Stern *et al.* (2000). However, while the polar maritime air mass of Stern *et al.* (2000) is characterised by mean monthly temperatures representative of areas south of the tree line, there is a very strong case for the Magellanic subpolar forests (which include, for example, *Nothofagus antarctica* (G.Forster)Oerst.) of far southern Chile and Argentina to be considered as being in the sub-Antarctic. A similar case may be made for the forests on Auckland and Snare islands in the New Zealand sub-Antarctic island-group (United Nations Environment Programme 1998).

THE SURFACE CLIMATE OF THE SUB-ANTARCTIC

Existing studies into the climate of the sub-Antarctic are largely derived from observations at individual land-based stations. An attraction of using meteorological data taken at individual stations to characterise the climate of the sub-Antarctic is that the data would seem to be unambiguous. Strictly, such data apply only to the station itself and only give an approximation to the surrounding land or ocean. Southern South America aside, the land in the sub-Antarctic consists of isolated islands, and with only limited reason for shipping, there are little in the way of "conventional" observations. However, the increasing availability of remotely-sensed observations should gradually allow more detailed analyses of the climate of the entire sub-Antarctic.

As with all climate studies, the homogeneity of data used to describe sub-Antarctic climates must be considered. Changes to instrument type, siting, surrounds or reading practice can have significant effects on the observations even from what appears to be a single, stable station. Conventional homogeneity testing often relies on the existence of data series from neighbouring sites to provide a baseline; as most of the sub-Antarctic stations are remote, such baselines are often difficult to construct. There is no widely available set of meteorological data for sub-Antarctic stations of the high quality similar to the Antarctic data compiled by the Scientific Committee on Antarctic Research (SCAR) Reference Antarctic Data for Environmental Research (READER) project (Turner *et al.* 2004).

Table 1 gives some basic information for most of the meteorological stations in or near the sub-Antarctic. The data were obtained from a number of different sources, as noted with the table. The World Meteorological Organization (WMO) recommends the use of the period from 1961–1990 to calculate "climatological standard normals" for reference and comparison purposes (WMO 1988). For predictive purposes, such as the conditions most likely to be experienced, a more recent and shorter period (as little as 10 years) can provide adequate data (WMO 2007). In either case, the homogeneity of the observations is important, and the calculated statistics will only truly apply at the site where the observations were made. For the current study, complete data were not obtained from either the standard 1961–1990 period or a shorter period; there was not a chance to test the homogeneity of the data; and there are known to be marked topographic influences, with many of the meteorological stations located close to sea level in relatively protected areas. For these reasons, the climate statistics (mean temperatures of the coldest and warmest month and the average annual precipitation) are intentionally shown in table 1 to only a low precision. The presented values should thus be considered indicative only, and more precise values can be derived only after a detailed study.

Surface air temperatures of the sub-Antarctic

The sub-Antarctic climate is more or less fixed to mean monthly air temperatures between about –5°C and +15°C. As mentioned, this is a slightly wider band than that proposed by Stern *et al.* (2000), but allows for inclusion of the relatively mild islands such as Île Amsterdam, and also of contrasting below zero mean winter temperatures near 60°S. Figure 3 shows the annual mean surface temperature across the globe, synthesised from a variety of sources. The 60°S and 40°S latitudes are shown on this figure to highlight that the strongest meridional sea-level surface temperature gradients in the Southern Hemisphere occur in the sub-Antarctic (although the strongest topographical surface temperature gradients are located in the latitude band 80°S to 60°S by virtue of the very high terrain of the Antarctic Continent).

Orcadas, located just south of 60°S and strictly not part of the sub-Antarctic, is nonetheless useful in providing

TABLE 1
Basic climate statistics from locations within or near the sub-Antarctic

Location	Latitude	Longitude	Elevation	Mean temperature of coolest month	Mean temperature of warmest month	Mean annual precipitation	Source	Years used
Marion Island	47°S	38°E	22	+4	+8	2400	SAWS	1961–1990
Îles Crozet (Alfred Faure)	46°S	51°E	146	+3	+8	2200	MF	1980–2006
Îles Kerguelen (Port-aux-Français)	49°S	70°E	29	+2	+9	700	MF	1980–2006
Heard Island (Atlas Cove)	51°S	73°E	3	0	+4		ABOM	1997–2007
Île Amsterdam (Martin-de-Viviès)	38°S	78°E	27	+11	+18	1100	MF	1980–2006
Macquarie Island	54°S	159°E	6	+3	+7	900	ABOM	1961–1990
Campbell Island	53°S	169°E	19	+5	+10	1300	NIWA	1961–1990
Chatham Island	44°S	177°E	29	+8	+15	850	NIWA	1961–1990
Punta Arenas (Carlos Ibañez)	53°S	70°W	37	+1	+11	350	DMC	1961–1990
Ushuaia	55°S	68°W	16	+1	+10	500	SMN	1961–1986
Falkland Islands (Mt Pleasant)	51°S	59°W	74	+2	+11	600	UKMO	1989–2006
South Orkney Islands (Orcadas)	60°S	45°W	6	–10	+1	650	SMN	1961–1982
South Georgia (Grytviken)	51°S	37°W	3	–2	+5	1600	BAS	1951–1980
South Sandwich Islands (South Thule)	59°S	27°W	78	~ –5	~ +1		TT	1995–2005
Gough Island (Transvaal Bay)	40°S	10°W	54	+9	+15	3200	SAWS	1961–1990

Elevation in metres above sea level. Temperature in °C. Precipitation in millimetres. See text for details and discussion.
Data sources: ABOM–Australian Bureau of Meteorology; BAS–British Antarctic Survey; DMC–Dirección Meteorológica de Chile; MF–Meteo France; NIWA–New Zealand National Institute of Water and Atmospheric Research; SAWS–South African Weather Service; SMN–Servicio Meteorológico Nacional (Argentina); TT–TuTiempo (2007), note that data are very limited; UKMO–United Kingdom Met Office.

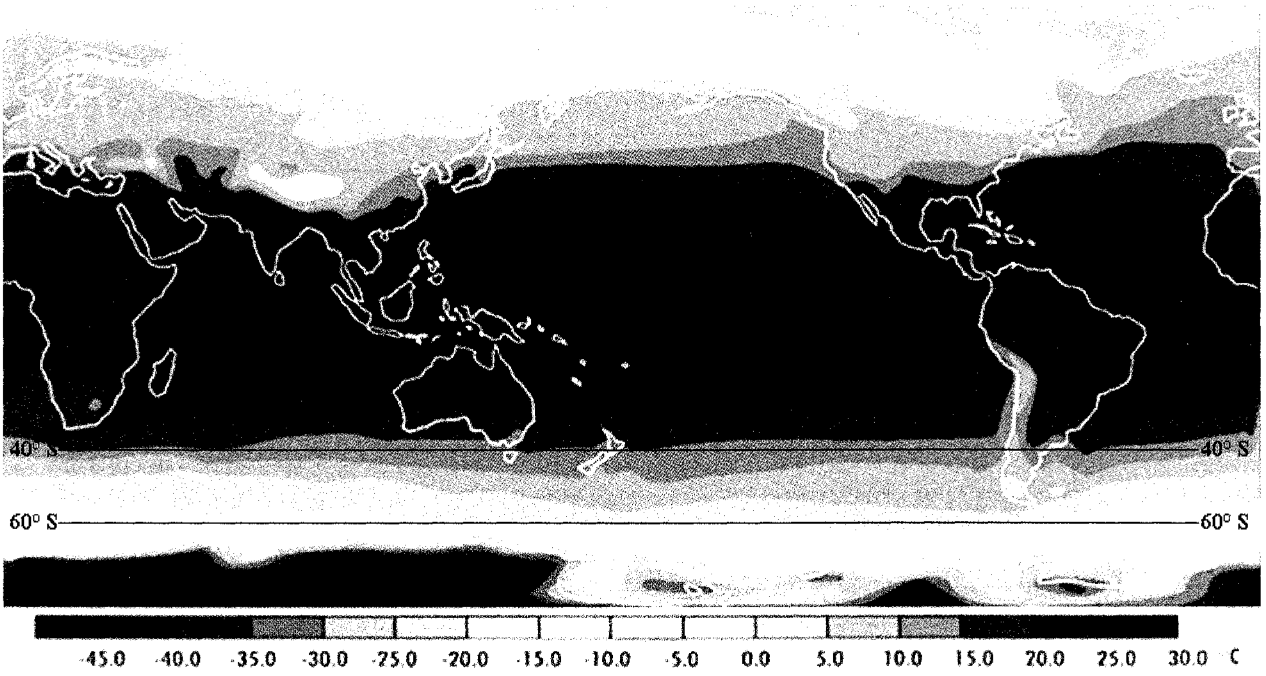

FIG. 3 — Thirty-year (1961–1990) annual mean surface temperature. Adapted from the Australian Bureau of Meteorology (2003).

observations at the southern edge of the region and on the eastern side of Drake Passage. Mean monthly air temperatures range from about −10°C in July to +1°C in February (table 1). Grytviken, on South Georgia, could be considered more typical of the colder areas of the sub-Antarctic, with mean monthly air temperatures ranging between about −2°C and +5°C. Îles Crozet is typical of more moderate sub-Antarctic areas with mean monthly air temperatures between about +3°C and +8°C.

On Chatham Island, mean monthly air temperatures range between about +8°C and +15°C (table 1), placing it within the bounds of the sub-Antarctic climate considered here, although New Zealand does not consider it to be sub-Antarctic (Department of Conservation 2007). At a latitude of around 37°S, the sub-Antarctic island (SCAR 2007) of Île Amsterdam's mean monthly air temperature in February is as high as +18°C; indeed Guinet *et al.* (1994) referred to Île Amsterdam as "subtropical". However, with Île Amsterdam's August mean monthly temperatures close to +11°C, it would seem likely that the islands north of the South Subtropical Front are in a regime that derives its sub-Antarctic status from a combination of meteorological considerations and sub-Antarctic-dependent fauna and flora species. For example, Guinard *et al.* (1998) refer to an increase in the population of Sub-Antarctic Fur Seals (*Arctocephalus tropicalis* (J.E. Gray, 1872)) on the island coincident with a significant decrease in mean sea surface temperature in the area.

Surface wind and waves of the sub-Antarctic

Describing the characteristics of the wind field of a geographical area as large as the sub-Antarctic from land-based point observations has challenges. In particular, the positioning of the wind-measuring equipment relative to the topography of the surrounding features is crucial. For example, Beggs *et al.* (2004, p. 295) reported "considerable spatial variability" in wind speed direction on Heard Island.

Remote sensing from satellites presents the opportunity of a more homogenous view. For example, Young & Holland (1996) produced an atlas of wind and wave height data based on data from satellites; an extract is shown as figure 4. The annual median wave height generally exceeds 2 m south of the North Subtropical Front and 2.5 m south of the South Subtropical Front. The sub-Antarctic is characterised by appreciable sea wave activity: the peak in annual median wave height is over 4 m, in the southeast Indian Ocean, while a substantial part of the oceans of the sub-Antarctic have median annual wave heights over 3.5 m (fig. 4A).

Driving these waves are the winds known as the "Roaring Forties" and the "Furious Fifties". These show up clearly in figure 4B, with annual median wind speeds exceeding 8 m/s for most of the sub-Antarctic. The strongest wind speeds occur over the southern Indian Ocean, with secondary maxima over the southern Pacific Ocean and the lightest speeds in the lee of the southern South American, and to a lesser degree, over the central southern Pacific Ocean. Figure 4B, whilst depicting annual data, is also representative of many individual months.

The Young & Holland (1996) data also show a clear seasonal cycle in wind speeds over the sub-Antarctic. The lightest winds occur in January with most wind speeds in the range 6–12 m/s, while the strongest winds occur during the July–August period when speeds exceed 10 m/s for the majority of the sub-Antarctic region and when mean speeds in the order of 15 m/s are more prevalent. The spring and autumn periods are transitional between the relatively light winds of summer and the winter storms. Mean winds tend to be stronger in spring than in autumn, presumably due to the enhanced thermal gradient in spring when the sea-ice sheet surrounding the Antarctic continent reaches its maximum extent and the continental land masses of Australia, South Africa and South America are beginning to warm.

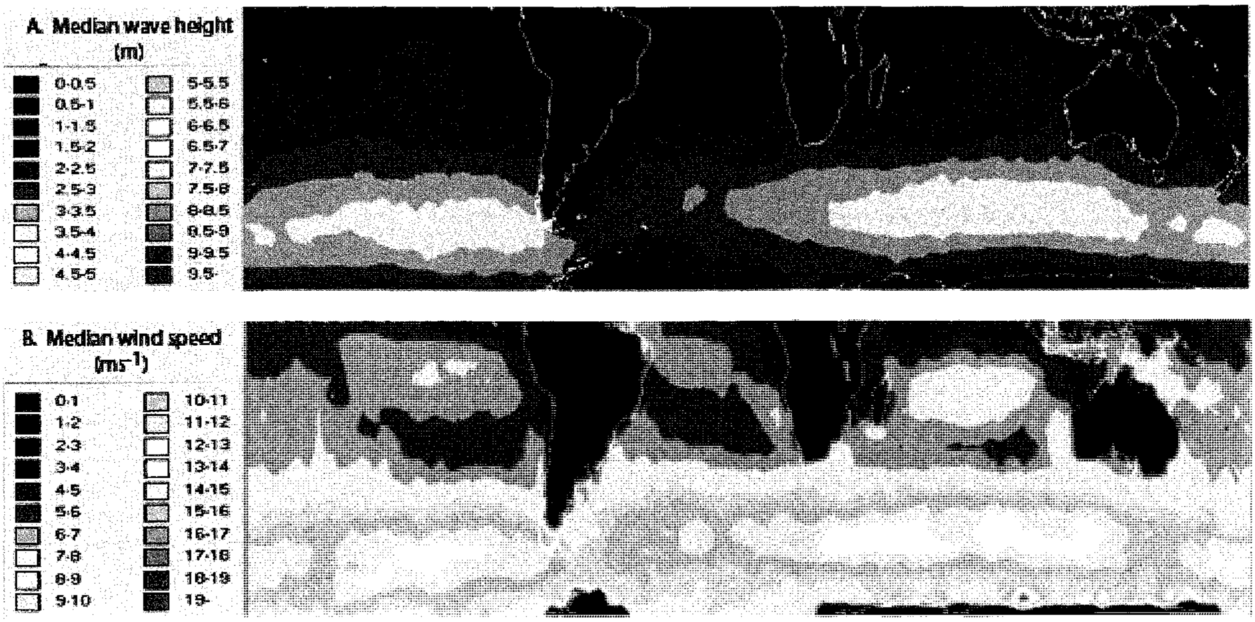

FIG. 4 — (A) Annual median wave heights; (B) annual median wind speeds (bottom) for the Southern Hemisphere. Adapted from Young & Holland (1996).

Precipitation over the sub-Antarctic

As with wind, characterising the precipitation regime of the sub-Antarctic is problematical. Precipitation measurement itself is not straightforward, especially where the water can fall as liquid (rain, mist, etc.) or solid (snow and hail), or a combination of both phases, all in a windy environment. Not only is it difficult to separate free-falling precipitation from that which is wind-blown (e.g., raised snow) but the performance rain gauges is complex and variable in these circumstances (Yang *et al.* 1998). Given these difficulties, and that the precipitation gauges in the sub-Antarctic are confined to the small amount of land, satellite measurements probably hold the most promise for reliable region-wide estimates. Therefore the data presented here should be considered indicative only, and a more definitive description may need to await the outcome of initiatives such as the US National Aeronautics and Space Administration (NASA) Global Precipitation Measurement mission (NASA 2007).

Conventional land-based and satellite techniques give an annual average precipitation for most of the sub-Antarctic in the range of 750 to 1500 mm (fig. 5). The persistent westerly winds ensure the west coasts of the landmasses tend to have higher precipitation than either the eastern coasts or the surrounding ocean. A clear example is the west coast of southern South America, but a similar effect appears even on small land masses: the precipitation on Marion Island in table 1 exceeds that for the nearby ocean in figure 5.

Not evident in figure 5 are the various precipitation types common to the sub-Antarctic, and thus the attendant measurement difficulties. For example, Bouvetøya is 93% glaciated (TheFreeDictionary 2007) while 80% of Heard Island is permanently covered by snow and ice (Australian Government 2007). This is indicative of the mostly frozen nature of precipitation at high-latitude parts of the sub-Antarctic especially during the colder months, the orographic nature of these particular islands and their location south of the Antarctic Polar Front (fig. 1). Macquarie Island, at a similar latitude to Bouvetøya and Heard islands, is of much lower average elevation (200–350 m above sea level (Australian Antarctic Division 2007)); it is also located north of the Polar Front (fig. 1). Macquarie Island has no permanent snow cover although frozen precipitation does occur at the observation station (6 m elevation).

Whilst each location in the sub-Antarctic will have its own precipitation regime, Macquarie Island would be arguably representative of many areas between the Polar and sub-Antarctic fronts and so it is worth noting the following extracts from the Australian Bureau of Meteorology (2007):

- *Rain and Drizzle*: Mean annual precipitation is 954 mm, and the median value is not much different at 958 mm. Autumn is slightly wetter than winter or spring, but all months receive rain. Heavy rain is quite rare, with only about one day in the average year receiving more than 25 mm. The wettest single day was in March 2001, with 52.8 mm. Such heavy rain has been known to trigger landslides on the island. The driest month on record was December 1959, with 16 mm, whilst the wettest was March 1988 with 181 mm. Measurable precipitation is recorded on an average of 313 days per year, or almost six days out of seven. This is fairly consistent across the year.
- *Snow and Hail:* Snowfall can occur at any time of the year, happening on about 80 days on average at sea level. It is least likely in January (less than one day on average) and most likely in September (almost eight days). A typical year would see up to half a dozen falls of around 10 cm depth at sea level. In most years the upper part of the plateau is covered in wet snow much of the time, particularly from May–October, with depths in level areas between one-half and one metre by the

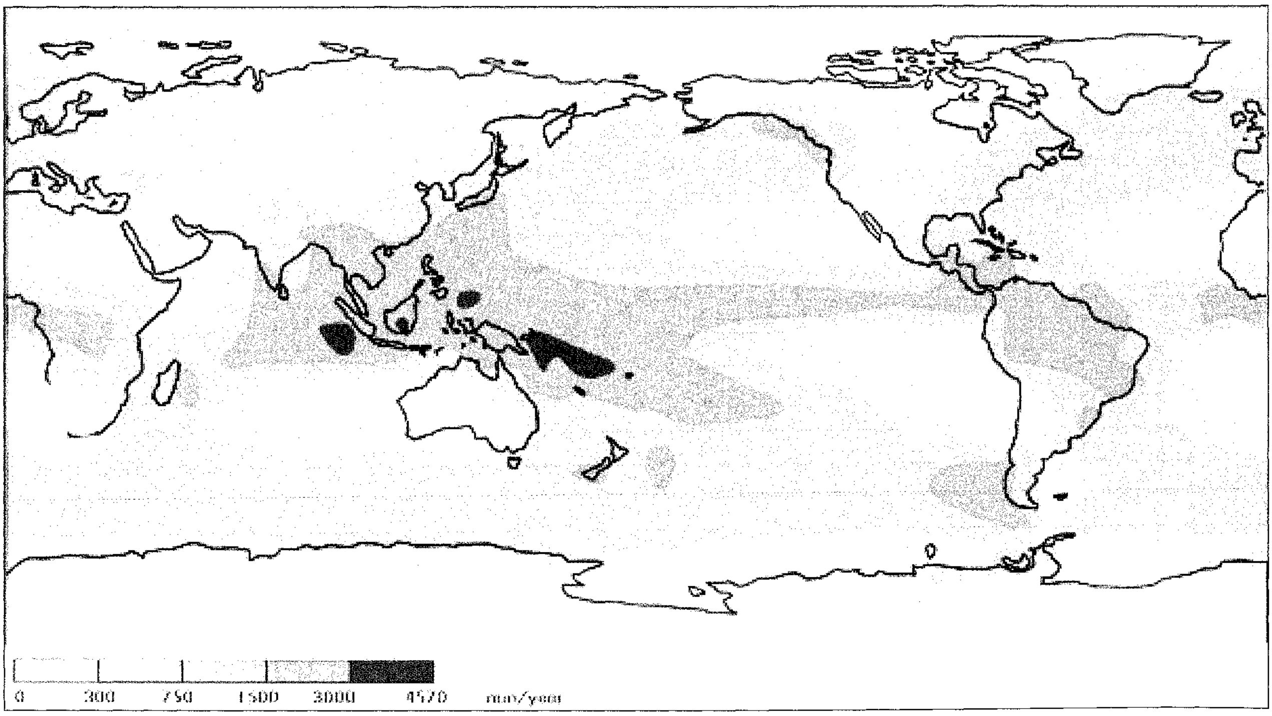

FIG. 5 — Thirty–year (1961–1990) annual precipitation (mm). From the Australian Bureau of Meteorology (2003).

end of the season. Hail, normally small in size, is also relatively common on the island, occurring on about 65 days a year on average. It is most likely in October and least likely in January. Thunderstorms are rare but do occur, averaging about 1 per year at the station.

Sub-Antarctic locations north of the sub-Antarctic Front will likely receive higher precipitation amounts as they are in a relatively warmer environment with more available precipitable water (Amenu & Kumar 2005), although they will still experience frozen precipitation forms. For example, as inferred from data reported by Turner & Pendlebury (2004), Transvaal Bay Station on Gough Island (just south of 40°S and 54 m above sea level) receives approximately three times the precipitation each year of Macquarie Island (just south of 54°S and 6 m above sea level), yet also annually experiences around 11 days of hail and about eight days of snow.

TELECONNECTIONS AND THE SUB-ANTARCTIC

The American Meteorological Society (2000, p. 759) defined a teleconnection as "a linkage between weather changes occurring in widely separated regions of the globe". Carleton (2003) summarised nine teleconnections which he considets to have important roles in the Southern Hemisphere, and some other important teleconnections have also been identified (for example, the Pacific Decadal Oscillation is discussed by Pezza *et al.* (2007)). El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) appear to be the most important teleconnections affecting the sub-Antarctic.

Tropical effects on the sub-Antarctic

There are several studies relating ENSO events to the Antarctic, and Turner (2004) provided an excellent overview of many of these, but none is devoted to the sub-Antarctic. Yuan (2004) discussed physical mechanisms by which the El Niño and La Niña phenomena are thought to influence the "Antarctic Dipole" through effects on the regional Hadley Cell and the resulting jet streams. During an El Niño event the far southeast Pacific Ocean and adjacent Southern Ocean is colder with more storms and more sea ice, whilst the far southwest Atlantic Ocean/adjacent Southern Ocean is warmer with fewer storms and less sea ice. This dipole effect is reversed during La Niña events. To illustrate these effects, figure 6 is adapted from Yuan (2004) and shows conditions averaged over five El Niño events, particularly as they are manifested over the area of the Antarctic Dipole.

As may be inferred from Yuan (2004), the key driver of Antarctic Dipole characteristics in El Niño events is the positive sea surface temperature (SST) anomaly in the equatorial Pacific Ocean east of Colombia, Ecuador and Peru. This leads to several reinforcing factors: the meridional SST gradient increases which, together with increased vertical motion over the warmer equatorial waters, leads to a regional Hadley Cell that is stronger and more compact than average, with the Subtropical jet stream perturbed northwards over the central southern Pacific Ocean. A large-scale atmospheric wave pattern is set up by the vertical motions resulting from this SST anomaly, with the ascending air over the eastern equatorial Pacific perturbing the planetary-scale atmospheric waves. This leads to relatively high surface air pressure over the Bellingshausen Sea area ("H" in fig. 6). Moreover, the increased subsidence associated with the southern descending arm of the Hadley Cell circulation induces a stronger than average Ferrell Cell to the south: the low-level northerly airflow associated with the strengthened Ferrell Cell leads to warm air advection over the adjacent sub-Antarctic and higher southern latitudes and thus a decrease in sea ice in the Southern Ocean.

To the west of the Bellingshausen Sea (the region marked "Less Storms" in fig. 6), an increase in storm activity is likely as lows over sub-Antarctic waters are steered

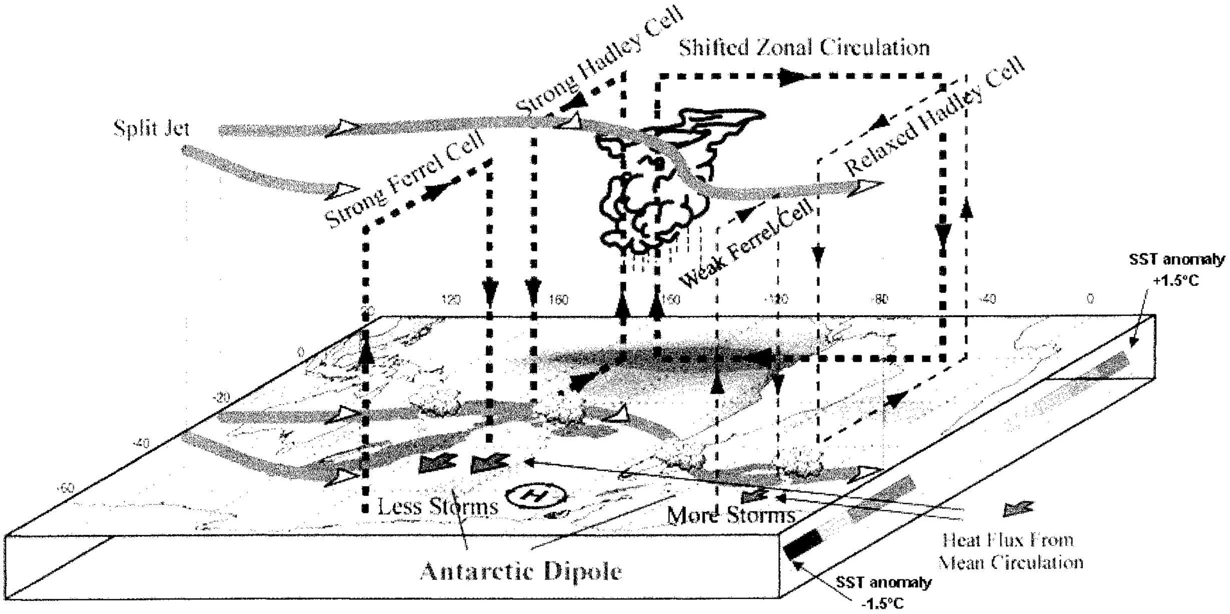

FIG. 6 — A schematic of mean conditions for five El Niño events as they impact on the Antarctic Dipole. Adapted from Yuan (2004).

southeastwards on the western side of the area of high pressure. Massom *et al.* (2004) describe a similar situation in East Antarctica.

The tropical Indian Ocean also has at least an indirect effect on the sub-Antarctic. The Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon characterised by SST cooling in the southeastern equatorial Indian Ocean and SST warming in the western equatorial Indian Ocean (or the converse). The IOD is an area of active research, including not only its direct effects but also links it has to other teleconnections such as ENSO. Behera & Yamagata (2003), for example, report on statistically significant associations with the IOD and sea-level pressure evolution from the western tropical Indian Ocean to the western tropical Pacific region.

Another example of the influence of the tropical Indian Ocean on high southern latitudes is the Madden-Julian Oscillation (MJO) which manifests itself in the atmosphere as a slow (order of one to two months) eastward propagation of disturbances (such as tropical convection/precipitation) with maximum amplitudes in the eastern Indian Ocean (Madden & Julian 1971, 1994). Lau & Chan (1986) noted that the MJO "is the strongest signal so far found in the intraseasonal variability of the tropical atmosphere" while the ENSO is "known to be the single most prominent signal in the interannual variability of the earth's climate". There is evidence that both the IOD and the MJO indirectly affect the sub-Antarctic, via their associations with ENSO.

Matthews & Meredith (2004) reported on a more direct link with the MJO and high southern latitudes. They show that during the southern winter, about seven days after the MJO convection peaks over the equatorial Indian Ocean, there is a peak in the surface westerly wind flow over high southern latitudes, including roughly the southern half of the sub-Antarctic. This is followed three days later by a maximum in the Antarctic circumpolar (ocean) transport. The physical mechanisms driving this response have similarities with the ENSO impacts on the Antarctic Dipole referred to earlier: upward vertical motion over the equatorial tropics disturbs the atmosphere to the south.

Southern Annular Mode

While ENSO is the most famous teleconnection, there has been increasing interest in examining the characteristics of "annular modes". Thompson (2007) had a web site devoted to the topic. The Southern Annular Mode, alternatively known as the Southern Hemisphere Annular Mode, the Antarctic Oscillation (Gong & Wang 1999) or the High-Latitude Mode (Kidson & Watterson 1999), refers to atmospheric mass exchange between middle and high latitudes as weather systems evolve on weekly to monthly timescales. Thompson & Solomon (2002, p. 896) described the SAM as "a large-scale pattern of variability that dominates the SH extratropical circulation on week-to-week and month-to-month timescales". The anomalies in mass tend to occur in zonal or annular bands; Marshall (2003, p. 4134) noted the SAM is "essentially a zonally symmetric or annular structure, with synchronous anomalies of opposite signs in Antarctica and the midlatitudes".

Indices of SAM tend to be constructed to reflect anomalies on monthly, seasonal or annual timescales, with various methods of indexing the related mass exchange. Gong & Wang (1999) described an "Antarctic Oscillation Index", using USA National Center for Atmospheric Research (NCAR)/ National Centers for Environmental Prediction (NCEP) (Kalnay *et al.* 1996) modelled reanalysis data at 40°S and 65°S. Marshall (2003) followed Gong & Wang (1999) but calculated a SAM index (here denoted SAM*i*) using observed mean sea level pressure (MSLP) data from stations located around, or very close to, each of the 40°S and 65°S latitude bands, as:

$$SAMi = P^{*}40^{o}S - P^{*}65^{o}S$$

where P* is the normalised (and unitless) mean monthly, seasonal, or annual zonal MSLP.

Marshall (2007) maintained an observations-based SAM index web site from which the locations of the 12 stations used to define his index (six at 40°S and six at 65°S) may be obtained, along with the normalised SAM*i* data and various monthly, seasonal and annual figures (see fig. 7) showing trends in SAM*i*.

In a low-index phase (negative values of SAM*i*), there is anomalously high pressure at 65°S and anomalously high pressure at 40°S, while a high-index phase (positive values of SAM*i*) has anomalously high pressure at 40°S and anomalously low pressure at 60°S. Matthews & Meredith's (2004) work on the MJO is an example of the forcing of the high-index state of SAM resulting in above average westerly winds over the sub-Antarctic. Further discussion on the role of the Southern Hemisphere Annual Mode in the climate of the sub-Antarctic is deferred until the next section where it may be inferred that a high-index state SAM is associated with relatively dry conditions over some northern parts of the sub-Antarctic, and wetter, windier conditions towards more southern parts.

EVIDENCE OF CLIMATE CHANGE IN THE SUB-ANTARCTIC

There seems little doubt that the climate of the sub-Antarctic is changing, at least in the short to medium term. Glacial retreat on sub-Antarctic islands is an indicator of such change (Budd 2000, Hall 2002). For example, Thost (2005, p. 34) reported, "Research has shown that Brown Glacier on sub-Antarctic Heard Island is retreating rapidly. It suggests that local climatic conditions are continuing to change rather

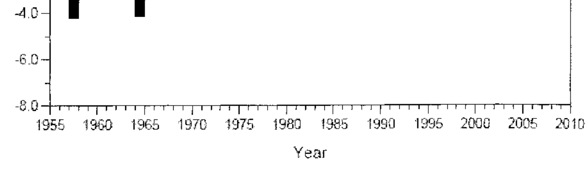

FIG. 7 — Annual SAMi for the period 1957–2006. Adapted from Marshall (2007).

than stabilise". Thost attributes the retreat of this glacier (at an average annual rate of 21 m) to an increase of (local) temperatures of about 1°C since 1950.

Jacka *et al.* (2004) reported on surface temperature changes over the period 1949–2002 for a selection of Southern Hemisphere stations, most of which are located in the Antarctic or in the non-tropical oceans, including 13 which are in, or very close to, the sub-Antarctic. Of these 13 stations, all but Punta Arenas had reported an increase in mean annual surface air temperature over the period examined. The surface air temperature trends for Marion and Gough islands are given by Jacka *et al.* (2004) as 2.8 and 0.4°C per 100 years respectively. These trends are broadly consistent with the SST trends presented by Mélice *et al.* (2003), which show warmings of about 3.0°C per 100 years in the waters surrounding Marion Island and 1.0°C per 100 years near Gough Island.

Bindoff *et al.* (2007, p. 401) noted that "The upper ocean in the [Southern Hemisphere] has warmed since the 1960s, dominated by changes in the thick near-surface layers ... just north of the Antarcric Circumpolar Current". Gille (2002) presented evidence that, within observational error, the surface warming reported by Jacka *et al.* (2004) matches warming which has occurred in middle depths (700–1100 m) of the mid- to high-latitude southern oceans, with the most rapid mid-depth ocean warming being within the sub-Antarctic Front. Thus, not only is there evidence of air and sea-surface temperature warming in the sub-Antarctic, but the warming extends to considerable depths of the sub-Antarctic oceans.

SAM and sub-Antarctic climate change

Figure 7, adapted from the annual SAM*i* data of Marshall (2007), shows a marked change from generally negative values up to the mid-1970s to generally positive values from the mid-1990s. That is, there has been an increase in atmospheric mass around 40°S relative to that at 65°S. This shift in mass, and the implied circulation changes, appear to have had direct effects on the climate of the sub-Antarctic.

Goodwin *et al.* (2004) presented ice core data, with monthly resolution spanning the years from 1300 to 1995. By linking May-June-July sodium concentrations with the SAM for the same period, they were able to create a proxy SAM index spanning almost 700 years. They suggested that the SAM was in a more negative index state prior to 1600, and that the very recent trend towards a positive index state is "part of multi-decadal variability that characterises the past 700 years"; that is, the trend of the past few decades was part of natural variability.

Marshall *et al.* (2004), however, noted that since 1964 statistically significant positive trends in SAM only occur in the annual, summer (December–January–February), and autumn (March–April–May) series. Figure 8 shows the Marshall (2007) SAM*i* for the four seasons, with little trend evident in winter or spring. Moreover, Marshall *et al.* (2004) presented data from a 1000-year climate model run, and separately, four runs from 1860 with varying sources of external forcing. These authors reported that the post-1965 trends in SAM exceed the natural model climate variability, and that "non-linear combination of anthropogenic and

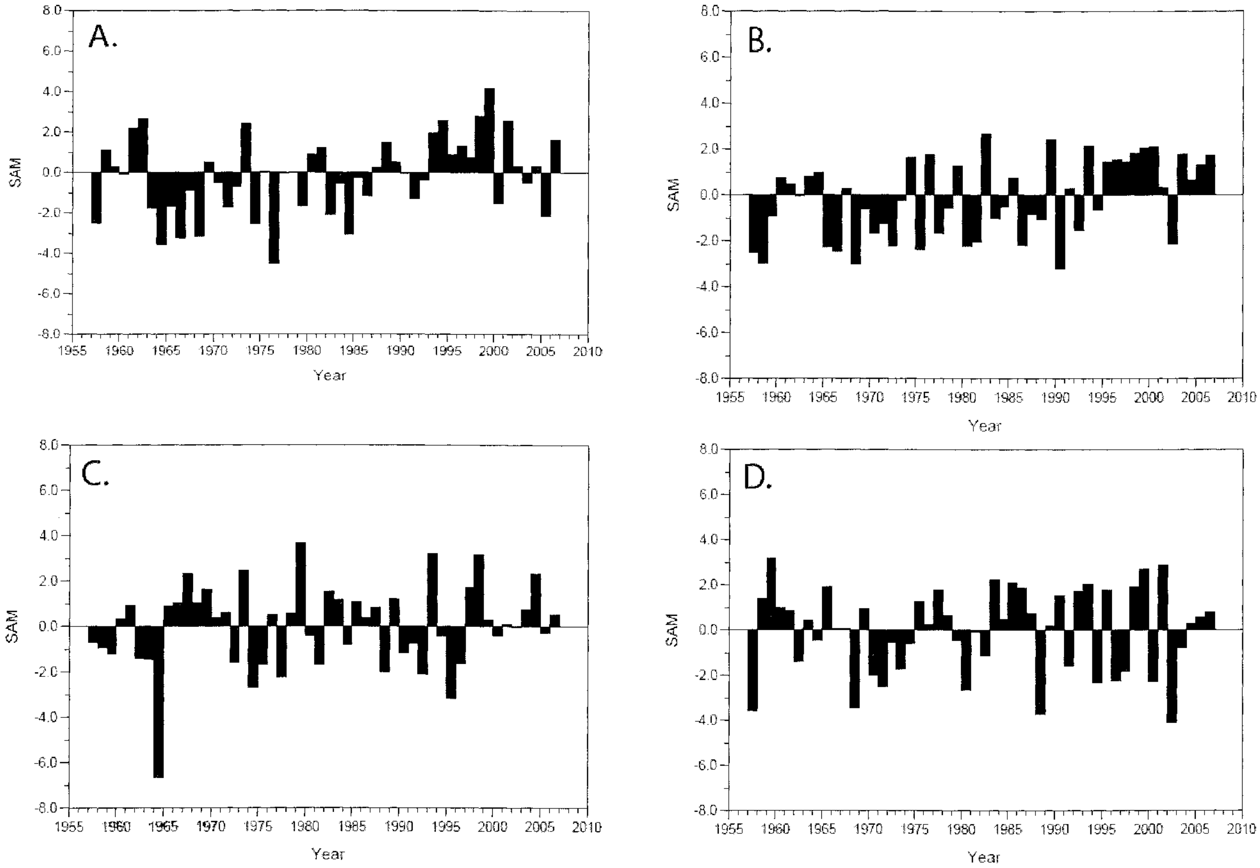

FIG. 8 — Seasonal SAMi for the period 1957–2006: (A) Summer (Dec, Jan, Feb); (B) Autumn (Mar, Apr, May); (C) Winter (Jun, Jul, Aug); (D) Spring (Sept, Oct, Nov). Adapted from Marshall (2007).

natural forcings is responsible for the observed changes in the SAM since the mid-1960s" (Marshall *et al.* 2004).

Recent trends at high latitudes were attributed by Thompson & Solomon (2002) to the effects on SAM of stratospheric ozone depletion. Figure 9A shows recent changes in surface air temperatures and 925 hPa winds in the austral summer and autumn, and figure 9B shows how much these changes can be attributed to changes in SAM. The focus of Thompson & Solomon (2002) was Antarctica and, in particular, the Antarctic Peninsula, so temperature data are not shown for sub-Antarctic stations away from these areas. Nevertheless, it is evident that increased low-level westerly airflow has occurred over the sub-Antarctic and that part of the sub-Antarctic near Drake Passage has warmed in summer and autumn in line with increases in SAM*i*. They concluded around 50% of the increase in surface air temperature observed at the tip of the Antarctic Peninsula could be explained by changes in SAM, and that a high-index state of SAM is consistent with observed ozone depletion. They also noted that this implies that there are other "climate change mechanisms" operating over this region.

Fyfe (2003) provided further evidence that changes have occurred in the sub-Antarctic and the Southern Ocean, using NCEP/NCAR reanalysis data from 1960–1999. In this period, he found: a shift southwards of the baroclinicity of the mid- to high-latitude atmosphere; a decrease in the number of cyclones over the sub-Antarctic ocean (and an increase over the Southern Ocean); and a decrease in the mean depth of cyclones but with numbers of "shallow" cyclones decreasing more than the numbers of deeper cyclones.

Climate change on Marion Island and Macquarie Island

Smith (2002) has demonstrated how the climate of Marion Island has changed since records began on the island in 1949: he reported that simple linear fits to the data show a 0.04°C per year increase in annual mean temperature over the period 1969–1999; an increase of 3.3 hours of bright sunshine per year over 1951–1999; and a decrease of 25 mm per year in annual total precipitation.

There is also evidence (Adamson *et al.* 1988, Jacka *et al.* 2004) of climate change on Macquarie Island, from where continuous weather records are available since 1948. The Macquarie Island data indicate that the surface air temperature has increased, although perhaps not in the past two decades; but rainfall has markedly trended upwards: 2005 was the wettest year on record at the station.

Figure 10 shows the mean annual temperature anomalies (compared to 1961–1990 normals) for both Marion and Macquarie islands. Also shown is a smoothed line produced using a "loess" (local estimator) smoother with an effective span of 20 years (R Development Core Team 2006). Care must be taken in interpreting the shape of the line at each end, but it gives a good overall indication of underlying trends in the data. The warming at the Marion Island station is quite clear, whereas at the Macquarie Island station the trend since about 1980 is more ambiguous, with a number of relatively cold years observed.

Recent trends in precipitation for these two island stations are clearly opposite to each other. Figure 11 shows, for each station, the fraction of annual rainfall compared to the 1961–1990 normals. Marion Island station has become drier whilst Macquarie Island station has become wetter. One possible explanation for the changes at the two islands is the southward shift in tropospheric baroclinicity reported by Fyfe (2003) — his figure 3 shows analysed and projected southward displacement of the maximum in 500 hPa temperature gradient averaged on a decadal basis and zonally around the Southern Hemisphere. The 500-year

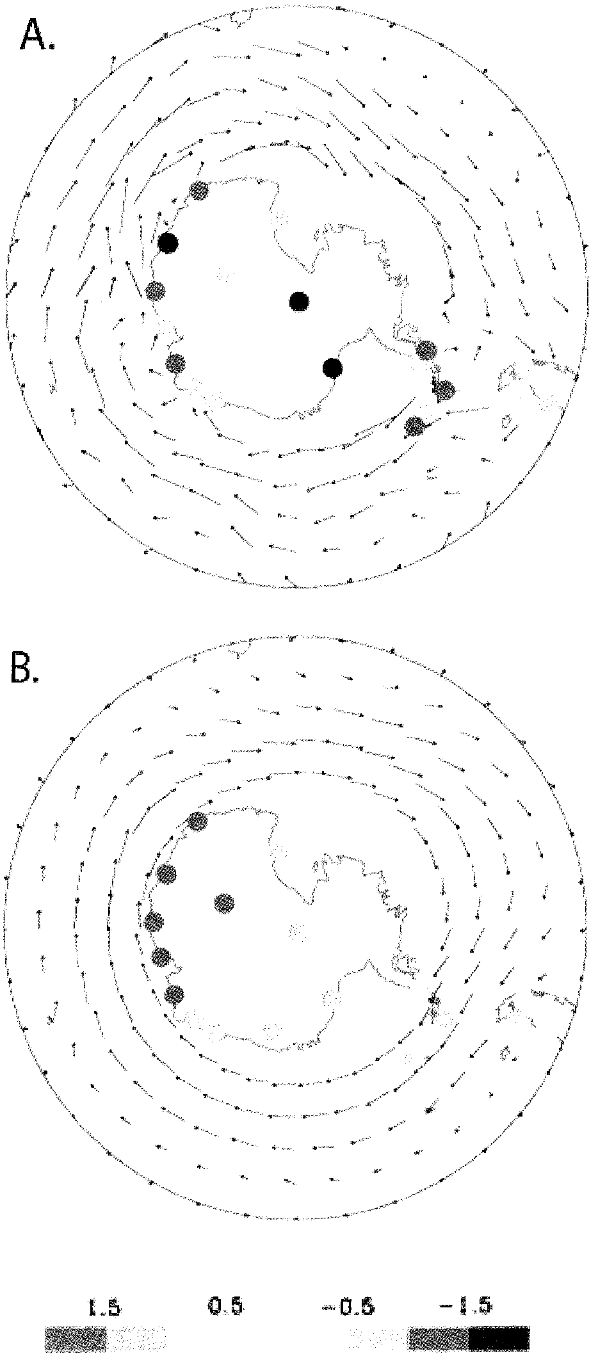

FIG. 9 — (A) Observed December–May trends in surface temperature over the period 1969–2000 and 925 hPa winds over the period 1979–2000; (B) the contribution of SAM to the observed trends in (A). The key (middle) is temperature change in °C per 30 years. The longest vector in (A) and (B) represents 4 m/s. After Thompson & Solomon (2002).

control simulation used by Fyfe (2003) had the maximum in this parameter at approximately 47°S. By inference, this may have seen the latitude of peak intensity of rain-bearing systems moving away from latitudes typical of Marion Island (at around 47°S) towards latitudes represented by Macquarie Island (around 54°S). Another possible explanation, at least for Marion Island, is the suggestion by Rouault *et al.* (2005) that the local changes on that island are due to a phase shift in the semi-annual oscillation in the Southern Hemisphere circa 1980.

However, the SAM may be also implicated. Figure 12 is adapted from Thompson & Wallace (2000) and shows mean zonal flow anomalies and mean meridional circulation anomaly vectors regressed on SAM for November based on monthly data from 1958 to 1997. This is a November case, but it serves as an analogy for high-index state of SAM, showing Marion Island in a region of nett subsidence while Macquarie Island is in a region of increasing westerly winds (potentially bringing more moisture).

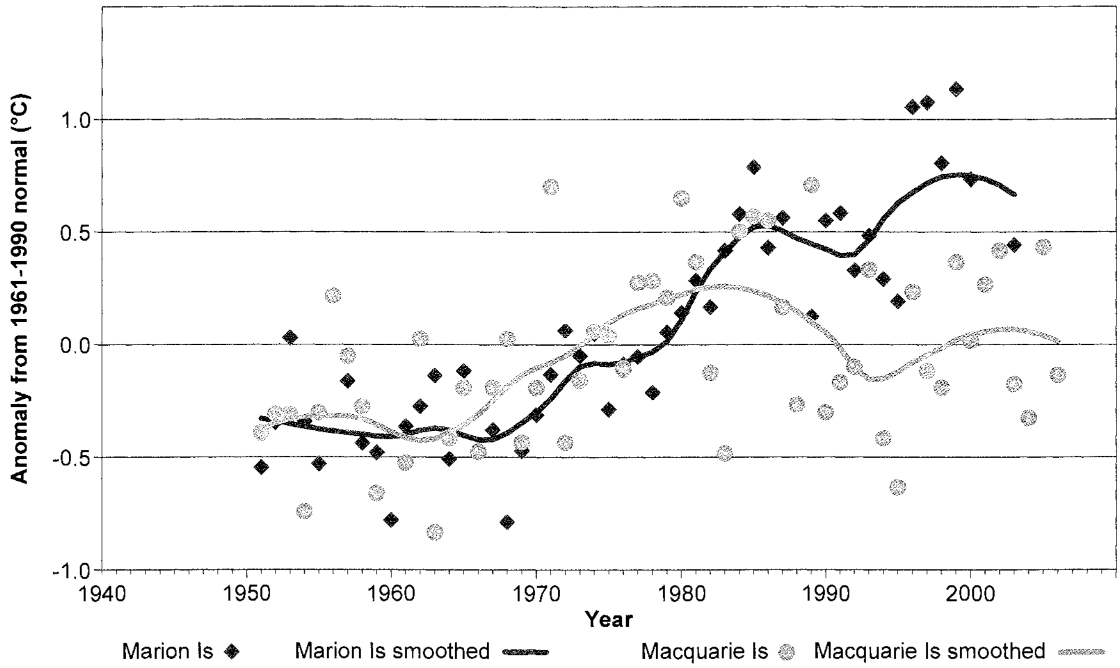

FIG. 10 — Observed mean annual temperature anomalies at Marion and Macquarie islands, relative to the 1961–1990 normals. The dots are the observed values for each year, with the smoothed lines produced using a "loess" smoother with an effective span of 20 years.

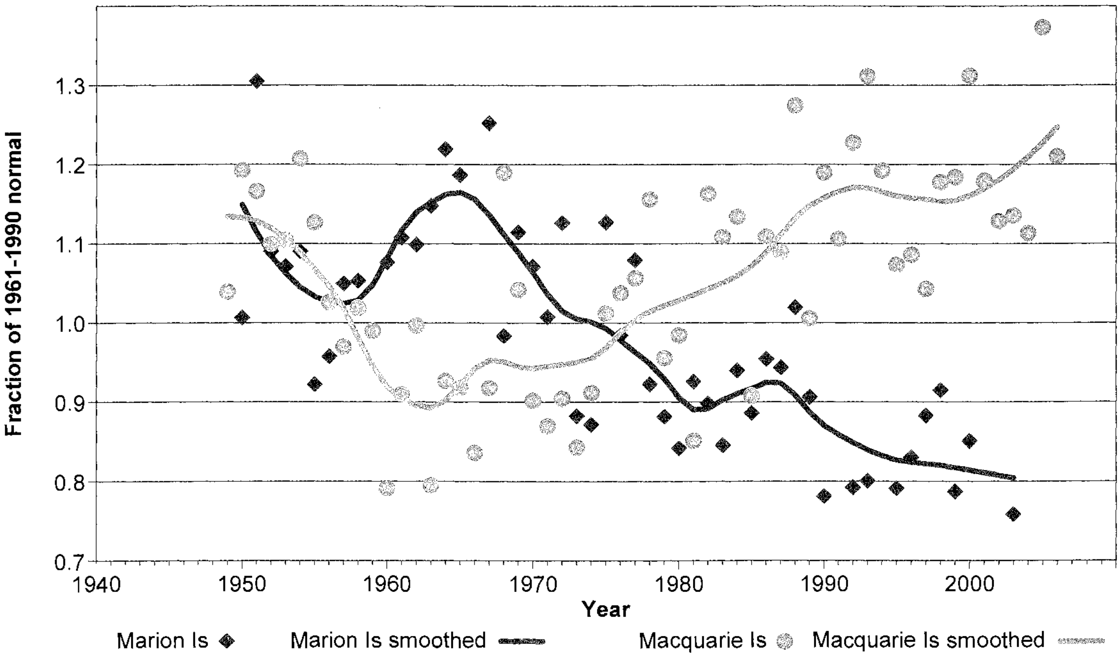

FIG. 11 — Observed total annual precipitation at Marion and Macquarie islands, as fractions of the 1961–1990 normals. The dots are the observed values for each year, with the smoothed lines produced using a "loess" smoother with an effective span of 20 years.

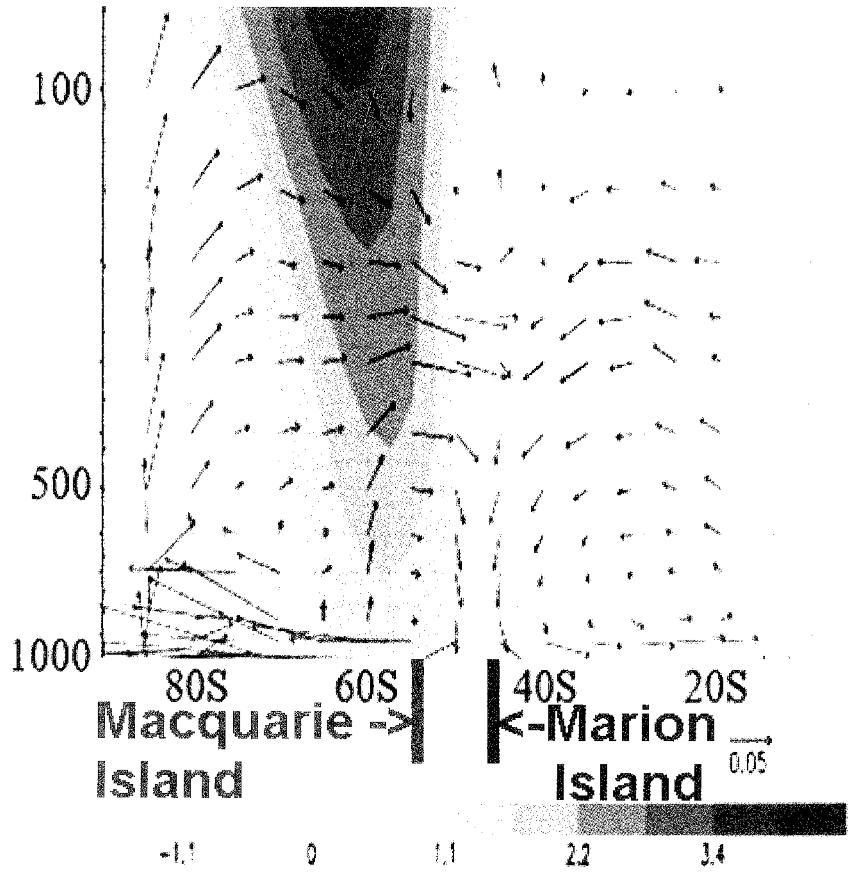

FIG. 12 — Mean cross-section (height scale in hPa) for the Southern Hemisphere of zonal–mean zonal flow anomalies (red represents westerly anomalies and the blue easterly anomalies in m/s) and mean meridional circulation anomalies (vectors: cm/s) regressed on SAM for November based on monthly data from 1958 to 1997. Adapted from Thompson & Wallace (2000).

Whinam & Copson (2006) implicated climate change on Macquarie Island in the decline, through desiccation of the island's sphagnum moss. They inferred that increasing wind speeds, rising surface temperatures and decreased rainfall will continue to place stress on this moss species. It is clear from the data presented in the current paper that mean annual temperatures on Macquarie Island appear to have little trend in recent decades, whilst annual precipitation at the station has actually increased in recent decades. Wind speeds may be slightly increasing over Macquarie Island due to an increasing SAM (figs 9 and 12, for example), so it is possible that there has been an increase in evapotranspiration. Alternatively, there may have been marked changes in the timing or severity of individual weather systems, which has increased stresses on the moss.

THE SUB-ANTARCTIC INTO THE TWENTY-FIRST CENTURY

At time of writing, the Intergovernmental Panel on Climate Change (IPCC) was finalising its Fourth Assessment Report "Climate Change 2007", also referred to as AR4 (and here termed IPCC-AR4). The IPCC Working Group 1 has released its report on the physical basis upon which AR4 is based (Solomon *et al.* 2007). The earlier allusion to observed warming in the upper levels of the oceans of the Southern Hemisphere being dominated by sub-Antarctic Mode Water (Bindoff *et al.* 2007) is one of the few direct references to the sub-Antarctic in Solomon *et al.* (2007). Nonetheless, inferences may be made from the global climate and regional climate projections in that report.

The bases for IPCC-AR4 Global Climate Projections are given in Meehl *et al.* (2007) with IPCC-AR4 Regional Climate Projections being discussed by Christensen *et al.* (2007) these being Chapters 10 and 11 of Solomon *et al.* (2007) respectively. Inferences on pattern changes in the twenty-first-century sub-Antarctic zonally averaged atmospheric and oceanic temperatures, surface temperature, precipitation, sea level air pressure and cloud cover may be obtained from Meehl *et al.* (2007). Slightly more detailed information on precipitation changes may be obtained from Christensen *et al.* (2007). Given that the projections are based on a subset of the IPCC Special Report on Emission Scenarios (Nakicenovic & Swart, 2000) the reader is encouraged to refer to the original references for the nuances behind the various scenarios modelling. However, it would seem that the overall trends for each parameter are similar for each scenario, varying in amount as projections extend forward in time through the twenty-first century.

Inferences of note (relative to a 1980–1999 reference period) are:

- If zonally-averaged, a steady warming seems likely in the sub-Antarctic oceans over most depths, but particularly to a depth of 1000 m, where, in the A1B scenario, the 2080–2099 sub-Antarctic oceans will be 0.5–1.5°C warmer (Meehl *et al.* 2007, their fig. 10.7).
- Over the sub-Antarctic as a whole, and for all three scenarios, surface air temperature changes of 0.0–1.0°C warmer are indicated by the period 2011–2030. However, for the periods 2046–2065 and 2080–2099 while the results for the three scenarios show similar trends, the magnitudes of the changes diverge more widely, with the "low" emission scenario indicating

conditions being 0.5–1.5°C warmer by the period 2046–2065 but the "medium" and "high" scenarios (combined) indicate warming in the range 1.0–3.0°C by the period 2080–2099 (Meehl *et al.* 2007, their fig. 10.8).

- In the "medium" scenario (A1B), by the end of the twenty-first century, south of about 40–45°S latitude austral winter precipitation increases by fractions of a millimetre per day, although a slight drying is indicated on the eastern side (lee in the predominant westerlies) of the south of South America. Sub-Antarctic areas north of about 40–45°S are generally drier in the period 2080–2099 compared to 1980–1999 (Meehl *et al.* 2007, their fig. 10.9; Christensen *et al.* 2007, their fig. 2).
- Austral summer precipitation projections for the A1B scenario and the same timeframes suggests that the area of drying extends southwards towards 50°S, and significantly, over much of the land areas of the sub-Antarctic, with the exception perhaps of Macquarie Island and the sub-Antarctic islands of New Zealand (Meehl *et al.* 2007, their fig. 10.9; Christensen *et al.* 2007, their fig. 2).
- For the A1B scenario, a steady increase in the positive phase of the SAM is indicated with, by 2080–2099, higher sea-level pressures over the sub-Antarctic north of about 45–55°S and lower sea level pressures south of this latitude band.

As may be inferred from the literature such as that of Whinam & Copson (2006), these changes may have major effects on the biology of the sub-Antarctic islands. Impacts might also be expected on sub-Antarctic parts of South America. Vera *et al.* (2006) noted some inconsistencies in the models used for the IPCC-AR4, but there is a consensus for decreased precipitation along the southern Andes for all seasons. There may well be effects on human activity in the area too, not least on the shipping which plies Drake Passage serving Antarctic tourism. The Antarctic and Southern Ocean Coalition & United Nations Environment Programme (2005) reported that 90% of the Antarctic tourist shipping departs for the Antarctic Peninsula from (sub-Antarctic) Ushuaia. As noted above, the positive phase of the SAM is expected to increase: this implies increased westerly winds which may well impact on shipping. Moreover, Meehl *et al.* (2007, p. 751) noted that "Model projections show fewer mid-latitude storms averaged over each hemisphere, associated with the poleward shift of the storm tracks that is particularly notable in the Southern Hemisphere, with lower central pressures for these poleward-shifted storms. The increased wind speeds result in more extreme wave heights in those regions."

Fyfe (2003) included a run of a global climate model for the period 1850–2100 using an ensemble of three transient climate change simulations, and post-1990 the IS92a ("business-as-usual") scenario (the Canadian Centre for Climate Modelling and Analysis (2006) provided a succinct comparison of the IS92a scenario and the IPCC A2 scenario). The results were generally consistent with those seen in Fyfe's findings in the NCEP/NCAR re-analysis data from 1961–1990: a southward shift in baroclinicity, and a decrease in sub-Antarctic cyclone activity.

Similarly, Yin (2005) discussed the output of 15 different coupled general circulation models run in experiments for IPCC-AR4 and reports that, for the Southern Hemisphere, the model consensus for the twenty-first century is that the following seems likely:

- consistent poleward shift in storm tracks
- poleward shift of midlatitude baroclinicity
- increase in meridional surface temperature gradient
- poleward shifts in wind stress and precipitation
- shift towards high-index SAM.

It is salient to note that several of the significant projections presented by IPCC-AR4 are consistent with observed trends recounted here. Increasing surface and submarine temperatures, changes in precipitation, and a high-index state of the SAM, all suggest that the projected climate changes of the twenty-first century are already under way for much of the sub-Antarctic.

CONCLUSION

By any measure the sub-Antarctic is an important region of the world. It is host to the Antarctic Circumpolar Current and a large portion of the extra-tropical atmospheric mass oscillation represented by the Southern Annular Mode.

There is clear evidence that the climate of the sub-Antarctic is changing, at least in the short term, and that human-induced greenhouse gases and ozone depletion are part of the cause (Fyfe & Saenko 2005). However, researchers are yet unambiguously to provide physical mechanisms for the changes observed.

Many studies into the sub-Antarctic climate are primarily interested in biology, with meteorology of importance only in its effects on the local flora and fauna. Without further research into the full extent of climate change and variability in the sub-Antarctic, many of the climatic impacts on biological systems will remain poorly understood. Underpinning this research will be the need for the creation of a robust databank of quality controlled sub-Antarctic meteorological data.

ACKNOWLEDGEMENTS

The organisers of the sub-Antarctic Forum held in Hobart, Australia, in July 2006 are to be congratulated on providing the impetus for preparation of this paper. The paper was substantially improved by adopting suggestions made by reviewer P.J. Beggs and by an anonymous reviewer. The following people were very helpful in providing various data: Jorge Carrasco of Dirección Meteorológica de Chile for data for Puntas Arenas; Ian Hunter and Glenda Swart of the South African Weather Service for data and information on Gough, Marion and South Thule islands; Keith Hymas of the United Kingdom Meteorological Office for data for Mount Pleasant (Falkland Islands); Christian Lafayne of Meteo France for data for Amsterdam, Crozet and Kerguelen islands; Gareth Marshall of the British Antarctic Survey for providing advice on the Internet access to his real-time SAM data; Kevin McGill of National Institute of Water and Atmospheric Research (New Zealand) for data for Campbell and Chatham islands; Jonathan Shanklin of the British Antarctic Survey for data for Grytviken; and Hector Sosa of Servicio Meteorológico Nacional (Argentina) for data for Ushuaia and Orcadas.

REFERENCES

Adamson, D.A., Whetton, P. & Selkirk, P.M. 1988: An analysis of air temperature records for Macquarie Island: decadal warming, ENSO cooling and Southern Hemisphere circulation patterns. *Papers and Proceedings of the Royal Society of Tasmania* **122**(1): 107–112.

Amenu, G.G. & Kumar, P. 2005: NVAP and Reanalysis-2 Global precipitable water products – intercomparison and variability studies. *Bulletin of the American Meteorological Society* **86**(2): 245–256.

American Meteorological Society 2000: *Glossary of Meteorology, Second Edition.* American Meteorological Society, Boston: xii + 855 pp.

Antarctic and Southern Ocean Coalition & United Nations Environment Programme 2005: *Antarctic Tourism Graphics – An Overview of Tourism Activities in the Antarctic Treaty Area.* Information Paper No. 119 submitted to the XXVIII ATCM, by the Antarctic and Southern Ocean Coalition and the United Nations Environment Programme, Stockholm, May 2005: 18 pp.

Australian Antarctic Division 2007: *Macquarie Island.* Retrieved 29 July 2007 from www.aad.gov.au/default.asp?casid=1978.

Australian Bureau of Meteorology 2003: *The Greenhouse Effect and Climate Change.* Australian Bureau of Meteorology, Melbourne: ii + 73 pp.

Australian Bureau of Meteorology 2007: *Climate of Macquarie Island.* Retrieved 29 July 2007 from www.bom.gov.au/weather/tas/macquarie/climate.shtml.

Australian Government 2007: *Heard and McDonald Islands.* Retrieved on 29 July 2007 from www.environment.gov.au/heritage/worldheritage/sites/antarct/index.html.

Antarctic Treaty Secretariat 2007: *The Antarctic Treaty.* Retrieved 25 July 2007 from www.ats.aq.

Beggs, P.J., Selkirk, P.M. & Kingdom, D.L. 2004: Identification of von Karman Vortices in the surface winds of Heard Island. *Boundary-Layer Meteorology* **113**: 287–297.

Behera, S.K. & Yamagata, T. 2003: Influence of the Indian Ocean Dipole on the Southern Oscillation. *Journal of the Meteorological Society of Japan* **8**(1): 169–177.

Belkin, I.M. & Gordon, A.L. 1996: Southern Ocean fronts from the Greenwich meridian to Tasmania. *Journal of Geophysical Research* **101**(C2): 3676–3696.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D. & Unnikrishnan, A. 2007: Observations: oceanic climate change and sea level. *In* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (eds): *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom & New York: x + 996 pp.

Budd, G.M. 2000: Changes in Heard Island glaciers, king penguins and fur seals since 1947. *Papers and Proceedings of the Royal Society of Tasmania* **133**(2): 47–60.

Canadian Centre for Climate Modelling and Analysis 2006: *CGCM Runs Forcing Equivalent CO_2 concentrations used in CCCma coupled global climate model simulations.* Retrieved 26 January 2007 from www.cccma.ec.gc.ca/data/cgcm/cgcm_forcing.shtml.

Carleton, A.M. 2003: Atmospheric teleconnections involving the Southern Ocean. *Journal of Geophysical Research* **108**(C4) 8080: doi:10.1029/2000JC000379.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A. & Whetton, P. 2007: Regional climate projections. *In* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (eds): *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom & New York: x + 996 pp.

Department of Conservation 2007: *Southland.* Retrieved 9 September 2007 from www.doc.govt.nz/templates/PlaceProfile.aspx?id=35670.

Fyfe, J.C. 2003: Extratropical Southern Hemisphere cyclones: harbingers of climate change? *Journal of Climate* **16**: 2801–2805.

Fyfe, J.C. & Saenko, O.A. 2005: Human-induced change in the Antarctic Circumpolar Current. *Journal of Climate* **18**: 3068–3073.

Gille, S.T. 2002: Warming of the Southern Ocean since the 1950s. *Science* **295**: 1275–1277.

Gong, D. & Wang, S. 1999: Definition of Antarctic oscillation index. *Geophysical Research Letters* **26**(4): 459–462.

Goodwin, I.D., van Ommen, T.D., Curran, M.A.J. & Mayewski, P.A. 2004: Mid latitude winter climate variabilty in the South Indian and southwest Pacific regions since 1300 AD. *Climate Dynamics* **22**: 783–794.

Guinard, E., Weimerskirch, H. & Jouventin, P. 1998: Population changes and demography of the Northern Rockhopper Penguin on Amsterdam and Saint Paul Islands. *Colonial Waterbirds* **21**(2): 222–228.

Guinet, C., Jouventin, P. & Georges, J-Y. 1994: Long term population changes of fur seals *Arctocephalus gazella* and *Arctocephalus tropicalis* on subantarctic (Crozet) and subtropical (St. Paul and Amsterdam) islands and their possible relationship to El Niño southern oscillation. *Antarctic Science* **6**: 473-478.

Hall, K. 2002: Review of Present and Quaternary periglacial processes and landforms of the maritime and sub-Antarctic region. *Research Letters: South African Journal of Science* **98**: 71–81.

Jacka, T.H., Budd, W.F. & Holder, A. 2004: A further assessment of surface temperature changes at stations in the Antarctic and Southern Ocean, 1949–2002. *Annals of Glaciology* **39**: 331–338.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne R. & Joseph, D. 1996: The NCEP/NCAR 40–year reanalysis project. *Bulletin of the American Meteorological Society* **77**: 437–470.

Kidson, J.W. & Watterson, I.G. 1999: The structure and predictability of the "High–Latitude Mode" in the CSIRO9 General Circulation Model. *Journal of Atmospheric Sciences* **56**: 3859–3873.

King, J.C. & Turner, J. 1997: *Antarctic Meteorology and Climatology.* Cambridge University Press, Cambridge: xii + 409 pp.

Lau, K.M. & Chan, P.H. 1986: The 40–50 Day Oscillation and the El Niño/Southern Oscillation: a new perspective. *Bulletin American Meteorological Society* **67**(5): 533–534.

Madden, R.A. & Julian, P.R. 1971: Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *Journal of Atmospheric Sciences* **28**(5): 702–708.

Madden, R.A. & Julian, P.R. 1994: Observations of the 40–50 day tropical oscillation: A review. *Monthly Weather Review* **122**(5): 814–837.

Marshall, G. 2003: Trends in the Southern Annular Mode from observations and reanalyses. *Journal of Climate* **16**: 4134–4143.

Marshall, G. 2007: *An observation-based Southern Hemisphere Annular Mode Index.* Retrieved 31 July 2007 from www.antarctica.ac.uk/met/gjma/sam.html.

Marshall, G.J., Stott, P.A., Turner, J., Connolley, W.M., King,

J.C. & Lachlan-Cope, T.A., 2004: Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. *Geophysical Research Letters* **31**: L14205, doi:10.1029/2004GL019952.

Massom, R.A., Pook, M.J., Comiso, J.C., Adams, N., Turner, J., Lachlan-Cope, T. & Gibson, T. 2004: Precipitation over the Interior East Antarctic Ice Sheet related to midlatitude blocking-high activity. *Journal of Climate* **17**: 1914–1928.

Matthews, A.J. & Meredith, M.P. 2004: Variability of Antarctic circumpolar transport and the Southern Annular Mode associated with the Madden–Julian Oscillation. *Geophysical Research Letters* **31**: L24312, doi:10.1029/2004GL021666.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M, Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J. & Zhao, Z.-C. 2007: Global climate projections. *In* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (eds): *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom & New York: x + 996 pp.

Mélice, J-L., Lutjeharms, J.R.E., Rouault, M. & Ansorge, I.J. 2003: Sea-surface temperatures at the sub-Antarctic islands Marion and Gough during the past 50 years. *Research Letters: South African Journal of Science* **99**: 363–366.

Nakicenovic, N. & Swart, R. (eds) 2000: *Special Report on Emissions Scenarios.* A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York: 599 pp.

NASA 2007: Global Precipitation Measurement brochure. Retrieved 8 September 2007 from http://gpm.gsfc.nasa.gov/images/091905GPMBrochure.pdf.

Pezza, A.B., Simmonds, I. & Renwick, J.A. 2007: Southern Hemisphere cyclones and anticyclones: recent trends and links with the Pacific Decadal Oscillation. *International Journal of Climatology.* doi 10.1002/joc.1477.

R Development Core Team 2006: *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria: xxiv + 1507 pp.

Rouault, M., Mélice, J.–L., Reason, C.J.C. &. Lutjeharms, J.R.E. 2005: Climate variability at Marion Island, Southern Ocean, since 1960. *Journal of Geophysical Research* **110**: C05007, doi:10.1029/2004JC002492.

SCAR 2007: *History of SCAR (Scientific Committee on Antarctic Research).* Retrieved 21 January 2007 from www.scar.org/about/history/.

Smith, V.R. 2002: Climate change in the sub-Antarctic: an illustration from Marion Island. *Climatic Change* **52**: 345–357.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (eds) 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom & New York: x + 996 pp.

Stern, H., de Hoedt, G. & Ernst, J. 2000: Objective classification of Australian climates. *Australian Meteorological Magazine* **49**: 87–96.

TheFreeDictionary 2007: *Bouvet Island.* Retrieved 29 July 2007 from http://encyclopedia.thefreedictionary.com/Bouvetoya.

Thompson, D.W.J. 2007: *Annular Modes.* Retrieved 17 January 2007 from http://ao.atmos.colostate.edu

Thompson, D.W.J. & Solomon, S. 2002: Interpretation of Recent Southern Hemisphere Climate Change. *Science* **296**: 895–899.

Thompson, D.W.J. & Wallace, J.M. 2000: Annular modes in the extratropical circulation. Part I: month-to-month variability. *Journal of Climate* **13**: 1000–1016.

Thost, D. 2005: Glacial retreat heralds changing Antarctic climate. *ECOS* **2005**: 34–34. doi:10.1071/EC125p34.

Turner, J. 2004: Review: the El Niño–Southern Oscillation and Antarctica. *International Journal of Climatology* **24**: 1–31.

Turner, J., Colwell, S.R., Marshall, G.J., Lachlan–Cope, T.A., Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A. & Iagovkina, S. 2004: The SCAR READER Project: toward a high-quality database of mean Antarctic meteorological observations. *Journal of Climate* **17**(14): 2890–2898.

Turner, J. & Pendlebury, S.F. 2004: *The International Antarctic Weather Forecasting Handbook.* British Antarctic Survey, Cambridge: xviii + 663 pp.

Tu Tiempo 2007: *Historical weather: South Thule Island, South Georgia and the South Sandwich Islands.* Retrieved 26 January 2007 from www.tutiempo.net/en/climate/south thule island/889860.htm

United Nations Environment Programme 1998: Protected Areas and World Heritage: country – New Zealand. Retrieved 26 January 2007 fromwww.unep-wcmc.org/sites/wh/subantar.htm.

Vera, C., Silvestri, G., Liebmann, B. & González, P. 2006: Climate change scenarios for seasonal precipitation in South America from IPCC–AR4 models. *Geophysical Research Letters* **33**: L13707, doi:10.1029/2006GL025759.

Whinam, J. & Copson, G. 2006: *Sphagnum* moss: an indicator of climate change in the sub-Antarctic. *Polar Record* **42**(220): 43–49.

WMO 1988: *Technical Regulations* (WMO No. 49). Secretariat of the World Meteorological Organization, Geneva (loose leaf).

WMO 2007: *The Role of Climatological Normals in a Changing Climate* (WDCMP-No. 61, WMO-TD No. 1377). World Meteorological Organization, Geneva: 34pp.

Yang, D., Goodison, B.E., Metcalfe, J.R., Golubev, V.S., Bates, R., Pangburn, T. & Hanson, C.L. 1998: Accuracy of NWS 8" Standard Nonrecording Precipitation Gauge: results and application of WMO Intercomparison. Journal of Atmospheric Oceanic Technoogy 15: 54–68.

Yin, J.H. 2005: A consistent poleward shift of the storm tracks in simulations of twenty-first century climate. *Geophysical Research Letters* **32**: L18701, doi:10.1029/2005GL023684.

Young, I.R. & Holland, G.J. (eds) 1996: *Atlas of the Ocean: Wind and Wave Climate.* Elsevier Science, Oxford: xvi + 241 pp.

Yuan, X. 2004: ENSO-related impacts on Antarctic sea ice: a synthesis of phenomenon and mechanisms. *Antarctic Science* **16**(4): 415–425.

(accepted 24 September 2007)