Antarctic climate variability and change

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Abstract

I review our understanding of the variability of climate in high southern latitudes from interannual to interdecadal timescales. Few climate records from south of 60° S extend back longer than 50 years, while reliable atmospheric reanalyses for the Antarctic are unavailable before 1979. Despite these limitations, it has been possible to produce a reasonable description of recent Antarctic climate variability and to link some of the observed variations to large-scale modes of atmospheric circulation variability. While there is some evidence which suggests that changes in anthropogenic forcing may be contributing to observed change in the Antarctic, current climate models may not represent Antarctic climate sufficiently realistically to allow unequivocal attribution of the observed changes.

1. Introduction

It is now generally recognised that the polar regions are an integral and important part of the climate system. Taken together, the Arctic and Antarctic form the "cold" end of the global heat engine, connected to the rest of the climate system by fluxes of heat carried by the atmosphere and ocean. Both polar regions are important sources of ocean bottom waters which play a major role in driving global ocean circulation. The presence of sea ice on the polar oceans introduces important positive feedbacks into the climate system.

While both polar regions have the potential to contribute to global variability and change through the processes mentioned above, there are a number of unique aspects to the Antarctic climate system that make understanding its behaviour a key priority. Most notably, the Antarctic ice sheets are a huge reservoir of fresh water, with the potential to raise global sea levels by over 60 m if fully melted. While much of this ice is locked up in the East Antarctic Ice sheet, which is believed to be relatively stable, glaciological studies indicate that the smaller West Antarctic Ice sheet may be more vulnerable to relatively small increases in atmospheric and oceanic temperatures and could contribute significantly to sea level rise over the coming centuries. The Southern Ocean also plays an important role in regulating global climate. It is an important sink of both atmospheric heat and CO_2. Changes in Antarctic climate will impact on its effectiveness in these roles.

In order to understand how the Antarctic regions may contribute to change in the global system, it is clearly important to know how Antarctic climate varies, both in response to large-scale change and as a result of local processes. In this paper, I shall review some of what we know about Antarctic climate variability on timescales of years to decades. As observations are central to our understanding, I shall first look at how the observing network has developed in the Antarctic and review the quality of atmospheric analyses and reanalyses derived from these observations. I shall then describe the spatial and temporal patterns of climate variability revealed by these observations and discuss to what extent these can be related to large-scale modes of atmospheric circulation variability. As global models are one of our most important tools for studying the causes of climate variability and change, I shall consider how well current models can reproduce recent observed change and how confident we can be in projections of future Antarctic climate made using such models. Finally, I shall present a list of what I consider to be some of the most important challenges facing Antarctic climate researchers for the forthcoming International Polar Year and beyond.

2. Development of the Antarctic climate observing network

By Northern Hemisphere standards, all Antarctic instrumental climate records are short and this places severe limitations on the study of Antarctic climate variability. It was not until 1903 that a permanent meteorological observatory was founded south of 60°S. In that year, the Scottish National Antarctic Expedition established a station on Laurie Island in the South Orkney Islands. At the conclusion of the expedition, the station was handed over to the Argentine government who have operated it, as Orcadas station, ever since.

Although a number of short climate records were obtained by expeditions visiting Antarctica during the first half of the twentieth century, the next major development of the observing network did not take place until the International Geophysical Year (IGY) of 1957/58. During the IGY, 55 research stations were established in the Antarctic by a variety of nations. While not all of these continued to operate after the IGY, a reasonable number did and these still form the basis of the Antarctic climate observing network. Today, around 30 Antarctic stations produce monthly surface climate reports, of which around 12 also make upper-air observations.

The IGY station network provided a reasonable coverage of observations around the coast of East Antarctica and in the Antarctic Peninsula. However, only two permanent stations (South Pole and Vostok) operated on the high interior of East Antarctica and the Southern Ocean around Antarctica – the major region of genesis of Southern Hemisphere synoptic-scale cyclones - was almost completely devoid of observations. The next major improvements to the Antarctic observing system took place around the time of the First GARP Global Experiment (FGGE) in 1979. FGGE was, in part, motivated by the availability of new satellite observations which greatly improved the quality of atmospheric analyses. In the Antarctic, satellite sounder data helped to fill the great data void over the Southern Ocean, while microwave radiometer observations provided, for the first time, frequent measurements of the extent and concentration of Antarctic sea ice in all seasons. Drifting buoys deployed in the Southern Ocean further improved the observing network while a complementary effort established a network of automatic weather stations to remedy the lack of observations from the interior of the continent. Since FGGE, there has been a reduction in the number of staffed observatories as a result of the closure of some stations operated by the former Soviet Union while the automated observing network has expanded, and improved sources of satellite data have become available. While the IGY stations still form the basis of the Antarctic observing network today, our knowledge of Antarctic climate variability relies heavily on the data that are available from automated platforms and satellites, and from the atmospheric analyses that are based on these data. In the next section I will look at how the quality of atmospheric analyses and reanalyses has been affected by the limited availability of data from this region.

3. The quality of atmospheric analyses in the Antarctic

Although attempts were made to produce hand-drawn analysis charts for the Antarctic covering the IGY period (e.g. Taljaard and van Loon, 1964), the reliability of such products is questionable given the limited amount of data available to the analysts. Global analyses, based on operational numerical weather prediction (NWP) models became available during the 1980s and, in recent years, global atmospheric reanalyses have been carried out, extending back to the IGY or earlier. Such products are potentially of great value in studying Antarctic climate variability but do they give a reliable picture of atmospheric circulation in high southern latitudes?

A number of factors may influence the reliability of analyses and reanalyses in the Antarctic. First, the limited amount of data available for assimilation may not adequately constrain the model. Before large quantities of satellite sounder data became available in the late 1970s, the only observations from the Antarctic were those from the sparse surface and upper-air observing network. Second, if the climatology of the analysis model is biased with respect to the observed climatology, and if observations are sparse, many observations will be rejected by the analysis scheme. Third, errors in ancillary fields, such as sea surface temperature, sea ice concentration, orography and land-sea masks can affect the accuracy of the analysis. While satellite surveys of the Antarctic have greatly improved our ability to specify such fields, operational analyses and reanalyses have not always kept up-to-date with these improvements (see, e.g., Renfrew et al, 2002). Finally, the parametrisations of physical processes used in analysis models may not be well-tuned for some features of the Antarctic atmosphere, such as highly stable boundary layers and mixed-phase clouds (King and Connolley, 1997; Briegleb, 1998; Hines et al., 1999, 2004).

Bromwich and Fogt (2004) investigated how well the NCEP-NCAR and ECMWF 40-year (ERA40) reanalyses represent variability in monthly mean surface pressure at Antarctic stations for which good records were available from the IGY to the present day. Data from these stations were available to both reanalyses and one might thus have anticipated a good fit between observations and reanalysis. This proved true after 1979, when satellite sounder data became available but in the pre-1979 era, the fit of both reanalyses to the observations was rather poor. This suggests that, as a result of some of the problems mentioned above, the reanalyses were not well constrained by the limited amount of Antarctic data available during the “pre-satellite” era. At present we can, therefore, only rely on atmospheric reanalyses as a source of information on atmospheric circulation variability in the Antarctic after 1979. This restriction on the available length of record places limitations on our studies of Antarctic climate variability.

The quality of Antarctic operational analyses and reanalyses in recent years appears to be very good, even over parts of the Southern Ocean where no conventional data are available (King, 2003). Simmons and Hollingsworth (2002) demonstrate that analysis and forecast skill for the Southern Hemisphere in general has improved markedly as additional satellite observations have become available and as analysis schemes have improved the way in which they assimilate such observations. Analyses today appear to be well-constrained by the limited conventional data and plentiful satellite data available for the Antarctic region and provide an accurate picture of the regional atmospheric circulation and its variability, at least on the broad scale.

4. Observed climate variability and change

Short instrumental records and a sparse observing network restrict us to analysing climate variability over the past five decades at a limited number of sites. However, these studies can be put into a broader spatial and temporal context by comparison with proxy records, such as those available from isotopic analysis of ice cores, and through the use of remote sensing (e.g. Comiso, 2000).

Turner et al. (2005) present a comprehensive analysis of recent observed changes in Antarctic surface air temperatures. Figure 1 shows trends in seasonal and annual temperatures at Antarctic stations over the 30 years from 1971 to 2000. Interannual variability of temperature is high at all Antarctic stations so 30-year trends need to be quite large before they become statistically significant. The majority of stations around the coast of East Antarctica (from approximately 30^{o}W to 210^{o}E) show no statistically-significant warming or cooling trends. Trends are also small at the two stations (South Pole and Vostok) on the high interior plateau of East Antarctica but both records show a statistically-significant cooling in autumn (March-May).

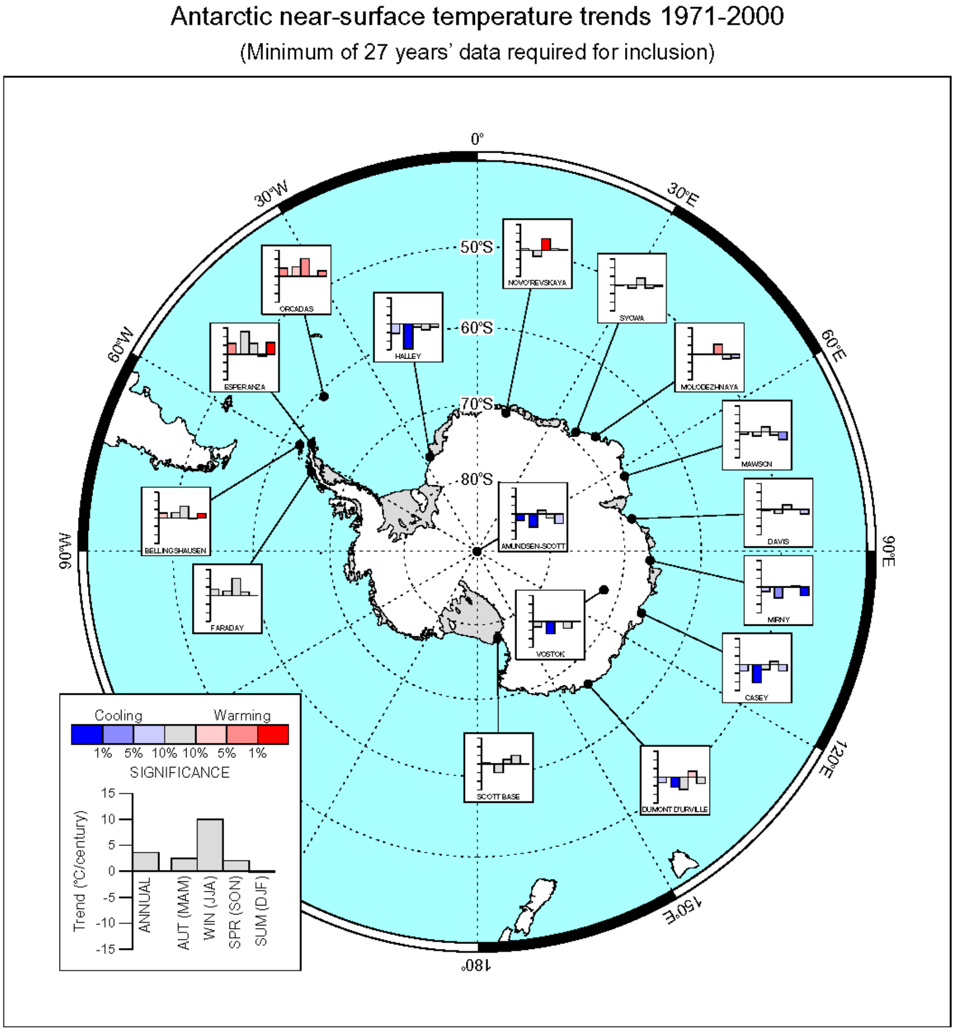

Figure 1. Seasonal trends (°C per century) in Antarctic near-surface air temperatures over 1971-2000. The statistical significance of the trend is indicated by the colour of the bars. A larger version of this figure can be downloaded from http://www.nerc-bas.ac.uk/icd/gjma/temps.html

By contrast, records from the Antarctic Peninsula exhibit strong warming trends in most seasons (King et al., 2004). Fig. 2 shows how annual mean temperatures have varied at Faraday (now Vernadsky) station on the west coast of the Peninsula over the past five decades. Interannual variability is very large but the underlying warming trend is statistically significant. Indeed, the Antarctic Peninsula has been one of the most rapidly-warming regions on Earth over this period (Vaughan et al., 2001). On the west coast of the Peninsula, warming has been most rapid during the winter (June-August) season, reaching over 5 ^{o}C per decade. Winter temperatures here are strongly anticorrelated with sea ice extent to the west of the Peninsula and the large winter warming in this sector may be associated with a decline in sea ice extent. Consistent with the air temperature increase, ocean surface waters to the west of the Peninsula have warmed significantly since the 1950s (Meredith and King, 2005). In northern and eastern parts of the Peninsula, by contrast, significant warming is seen during summer and autumn. The spatial and seasonal complexity of warming patterns seen within this relatively small subregion of the Antarctic suggests that a number of different controlling mechanisms may be at work.

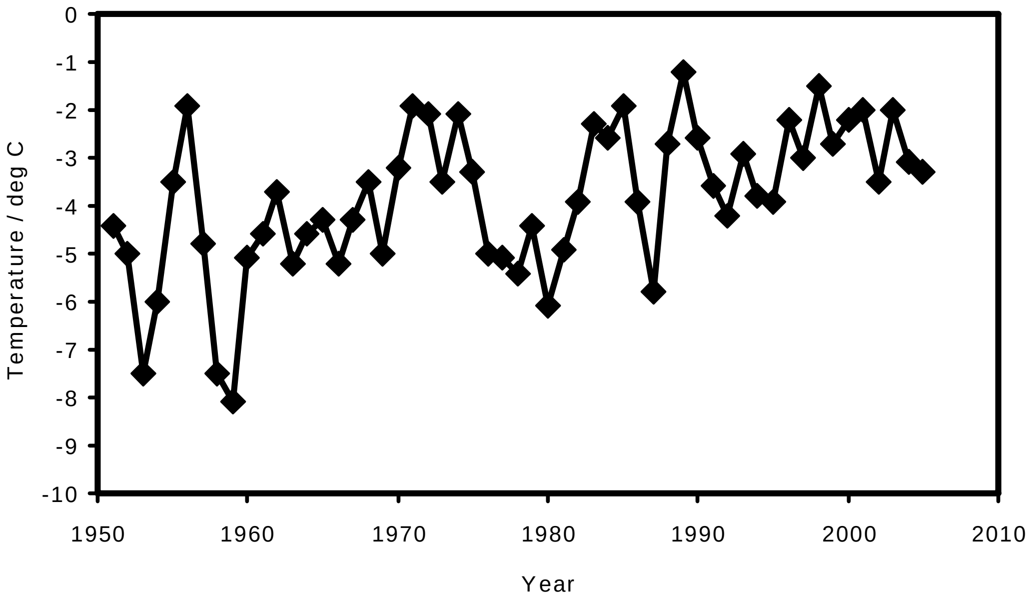

Figure 2. Annual mean temperatures, 1951-2005, at Faraday/Vernadsky station on the west coast of the Antarctic Peninsula.

Significant changes have also been measured in free atmosphere temperatures over Antarctica. Turner at al. (2006a) calculated temperature trends in the troposphere and lower stratosphere at Antarctic radiosonde stations for the period 1971-2003. They found that the variation of temperature trend with height was similar to that seen globally, with warming observed in the middle troposphere and cooling in the lower stratosphere, a “signature” of the influences of both greenhouse gas increases and stratospheric ozone depletion. However, the rate of mid-tropospheric warming at Antarctic stations greatly exceeds that seen elsewhere on Earth. Warming is greatest during the austral winter, when the Antarctic average mid-tropospheric trend reaches 0.7 ^{o}C per decade, compared to a global average of only 0.11 ^{o}C per decade. The reasons for this Antarctic amplification of the tropospheric temperature trend are, at present, unclear. Simulations of 20th-century climate using global models (see below) fail to reproduce the effect.

The contrast between temperature trends at the surface (little change or weak cooling) and in mid-troposphere (strong warming) over East Antarctica is, at first sight, remarkable. However, over much of Antarctica (and particularly during austral winter) these two levels are largely decoupled owing to the presence of strong and persistent surface temperature inversions. Surface temperatures are, therefore, determined by processes that control mixing within the inversion layer (e.g. the strength of near-surface winds) as well as by the temperature of the free atmosphere.

5. Large-scale modes of atmospheric circulation variability and their impact on Antarctic climate

The leading mode of variability in extratropical Southern Hemisphere atmospheric circulation is the Southern Hemisphere Annular Mode (SAM, Thompson and Wallace, 2000), sometimes known as the Antarctic Oscillation or High Latitude Mode. This mode takes the form of synchronous, quasi zonally-symmetric anomalies of pressure and geopotential, of opposite sign, at mid- and high southern latitudes. This pattern of variability explains over 30% of the total variability of Southern Hemisphere atmospheric circulation on timescales from weeks to years. Associated with this pattern of geopotential variability is a strengthening and weakening of the circumpolar westerly winds. The state of the SAM may be described by an index based on the difference between normalised pressure or geopotential anomalies at mid- and high latitudes (Gong and Wang, 1999). By convention, the SAM index is positive when pressure/geopotential is anomalously low over the Antarctic and high over mid-latitudes. A positive SAM index is associated with a strengthening of the circumpolar westerlies, and *vice-versa*.

Using station pressure observations, it is possible to produce a reliable timeseries of the SAM index back to the IGY. This series exhibits a statistically-significant positive trend from the mid-1960s to the present day (Marshall, 2003), with the strongest trends being seen during the summer and autumn. The observed trend is larger than any observed during a 1000-year control run of a coupled climate model (Marshall et al., 2004), suggesting that it cannot be explained by natural variability alone. Experiments with climate models using different combinations of forcings indicate that a combination of stratospheric ozone decrease, greenhouse gas increases and changes in natural forcings (solar variability and volcanic aerosols) are all contributing to the observed trend (Kushner et al., 2001; Gillet and Thompson, 2003; Marshall et al., 2004; Arblaster and Meehl, 2006).

A significant fraction of the variability in surface temperatures described in the previous section can be attributed to changes in the state of the SAM. Figure 3 shows the anomalies of annual mean surface temperatures at Antarctic stations associated with a unit positive anomaly of the SAM index. A spatially-consistent pattern is seen, with a high SAM index associated with anomalously cold temperatures over East Antarctica and warm temperatures over the Antarctic Peninsula (Marshall, 2006). This pattern is confirmed by studies using remotely-sensed surface temperatures (Kwok and Comiso, 2002) and in regional climate model simulations (van den Broeke and van Lipzig, 2003). Given that the SAM has tended to a more positive phase in recent decades, figure 3 is also broadly consistent with the pattern of long-term temperature change shown in figure 1. While the trend in the SAM can explain a large part of the observed temperature trends, there are exceptions. Although summer temperatures in parts of the Antarctic Peninsula are strongly correlated with the SAM index (Marshall et al., 2006), winter temperatures on the west coast of the Peninsula, which have risen rapidly over the last 50 years, show little sensitivity to this mode of variability.

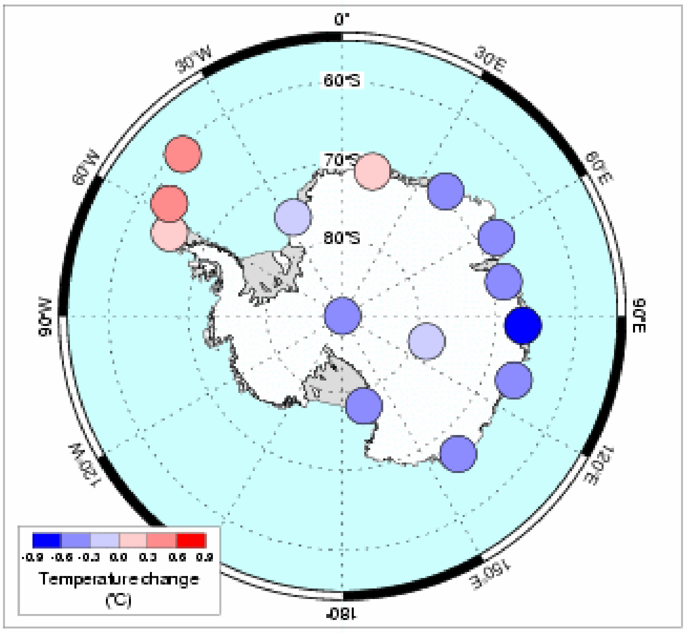

Figure 3. Changes in annual mean near-surface air temperature at Antarctic stations associated with a unit positive change in the SAM index.

In fact, winter temperatures in the western part of the Peninsula appear to be more closely related to another pattern of large-scale variability, the Pacific – South American (PSA) mode (Ghil and Mo, 1991). The PSA pattern takes the form of a standing wave train of geopotential anomalies extending from the tropical Pacific towards the Antarctic Peninsula and through into the Atlantic sector of the Southern Ocean. Forcing of the PSA pattern has been associated with ENSO events in the tropical Pacific, and there is a tendency for warm ENSO events to be associated with blocking to the west of the Peninsula, while cold ENSO events promote enhanced cyclonic activity in this region (Turner, 2004). However, these relationships with ENSO are not highly robust and great variability is seen in the high-latitude response to individual ENSO events. Independent of the state of ENSO, winter temperatures in the west of the Antarctic Peninsula are robustly correlated with the state of the PSA mode (Marshall and King, 1998; see also figure 4) so it would seem likely that the rapid rise in winter temperatures in this region are associated with circulation changes that project strongly onto the PSA mode. It is difficult to test this hypothesis since all of the centres of action of the PSA mode are over data-sparse regions of the ocean, precluding the use of indices based on station data. Studies of trends in the PSA mode are thus restricted to the period after 1979 when reanalyses become reliable and this period is not sufficiently long to determine statistically-significant trends. The observation that there has been an upward trend in the frequency with which precipitation has been reported at Antarctic Peninsula stations (Turner et al., 1997) provides some indirect evidence for a long-term decrease in sea level pressure (associated with increased cyclonic activity) to the west of the Peninsula.

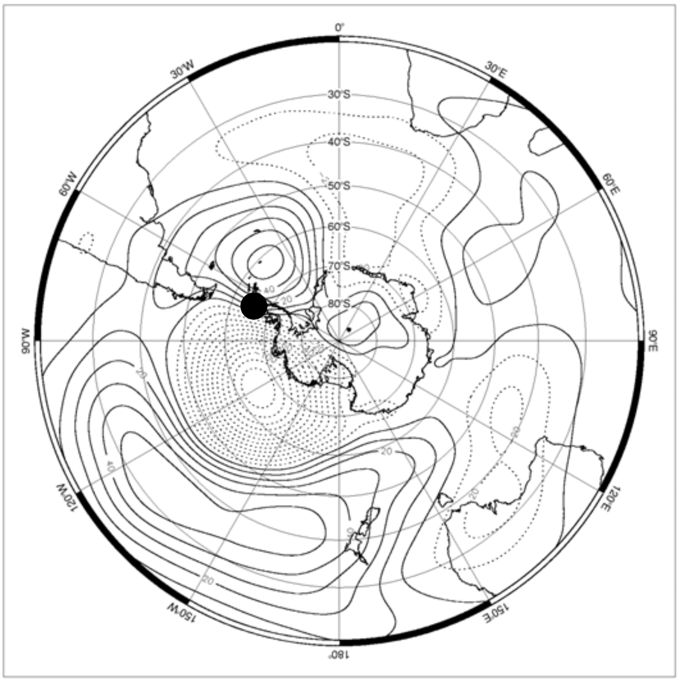

Figure 4. Winter (June-August) mean 500 hPa height for a group of exceptionally warm winters (greater than 1 standard deviation from the long-term mean: 1971, 1983, 1989, 1998, 2000) at Faraday/Vernadsky station minus that for a group of exceptionally cold winters (1969, 1976, 1977,1978, 1980, 1987). The location of the station is shown by the filled circle. Contours are at intervals of 10 geopotential metres, with negative values shown dashed. Data are from the NCEP/NCAR reanalysis. The anomaly pattern shows a striking resemblance to the PSA mode of atmospheric variability.

The impact of the PSA pattern is not restricted to the Antarctic Peninsula. Yuan and Martinson (2001) have shown that this mode is associated with opposing anomalies of sea surface temperature and sea ice concentration in the Pacific and Atlantic sectors of the Southern Ocean, a pattern they call the “Antarctic Dipole”. The existence of this pattern indicates that tropical Pacific variability may, through atmospheric teleconnections, impact on the climate of a significant area of the Antarctic and the Southern Ocean.

6. Modelling Antarctic climate variability and change

Climate change experiments carried out with over 20 different models as part of the IPCC 4th assessment report (AR4, see www.ipcc.ch) are an important resource for the attribution of recent observed change in the Antarctic. A 20th-century climate simulation run is available for each of the AR4 models, in which natural and anthropogenic forcings were varied in accordance with observations. An ensemble average has mixed success in reproducing observed changes in Antarctic climate over the past 50 years. The model ensemble exhibits a trend towards lower pressures over Antarctica, consistent with the observed trend towards a more positive SAM. A large modelled decease in pressure to the west of the Antarctic Peninsula is consistent with the observed warming of this region and the model ensemble does show an enhanced warming trend in the Peninsula region (Walsh and Chapman, 2006). However, the modelled warming of the Peninsula in winter is only about one third of that observed. The model ensemble also fails to reproduce other observed changes, such as the enhanced tropospheric warming and the surface cooling over parts of East Antarctica discussed above.

There is a high degree of variability between the patterns of change simulated by the different models within the ensemble. One interpretation of this variability would be that the response of the Antarctic climate system to changes in forcing over the last 50 years may have been quite small and that the modelled (and observed) changes may thus largely reflect natural variability. This interpretation assumes, however, that all of the models are able simulate the processes that control and vary Antarctic climate with reasonable accuracy. There are serious biases in the Antarctic climate of at least one of the AR4 models (Turner at al., 2006b) and a detailed study of the performance of each model is required before we can confidently use the AR4 ensembles as tools for the attribution and prediction of Antarctic climate change.

7. Future challenges

The International Geophysical Year of 1957/58 and its legacy provided a wealth of new observations that gave us, for the first time, an insight into the workings of the Antarctic climate system and the processes that couple it to the global system. In 2007, an International Polar Year (IPY) will celebrate the achievements of the past 50 years and will provide fresh impetus for research into Antarctic climate. What are our priorities for the IPY and beyond?

Over the past 50 years, climate in the Antarctic has been changing more rapidly than almost anywhere else on Earth. In particular, the rise in winter temperatures in the Antarctic Peninsula and the warming of the mid-troposphere across Antarctica have been exceptional in the global context. As I demonstrated above, neither of these exceptional warmings are reproduced adequately in climate change simulations and the atmospheric analyses currently available do not provide long enough reliable records to study these changes diagnostically. There is thus an urgent requirement to assess the performance of global models in the Antarctic and to correct errors and biases that arise as a result of inadequate representation of Antarctic climate processes or teleconnections between the Antarctic and lower latitudes. Along with this modelling effort, there is a need to reassess the procedures used for the production of atmospheric reanalyses to see if we can extend the period for which reliable products are available for the Antarctic. Given the sparse data available before the development of satellite systems this presents a considerable challenge.

We are now able to describe how Antarctic climate has varied over the past 50 years and we have some understanding of the processes that control that variability. Providing that we can resolve problems with the current generation of climate models, we should soon be able to make reasonable projections of changes over the coming century, together with estimates of uncertainties in those projections. The most important tasks will then be to use those projections to quantify how the Antarctic environment may respond to regional climate change and to determine how those changes will impact on the global system. The mass balance of the Antarctic ice sheets will vary as a result of changes in precipitation and in atmospheric and oceanic temperatures. Can we use predictions from climate models to calculate changes in mass balance and hence improve projections of future sea level rise? Variations in wind stress and atmosphere-ocean heat flux will drive change within the Southern Ocean. How will the production of Antarctic Bottom Water and other water masses of global importance be affected? What will the impact be on Southern Ocean ecosystems and the size of the Southern Ocean carbon sink? These questions are central to the problem of predicting future global climate. Answering them will require ever closer cooperation between Antarctic climate scientists, glaciologists, oceanographers and biologists.

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References

Arblaster, J. M. and G. A. Meehl, 2006: Contributions of external forcings to southern annular mode trends. *J. Climate*, **19,** 2896-2905.

Bromwich, D. H. and R. L. Fogt, 2004: Strong trends in the skill of the ERA-40 and NCEP-NCAR reanalyses in the high and midlatitudes of the southern hemisphere, 1958-2001. *J. Climate,* **17,** 4603-4619.

Briegleb, B. P. and D. H. Bromwich, 1998: Polar radiation budgets of the NCAR CCM3. *J. Climate*, **11,** 1246-1269.

Comiso, J. C., 2000: Variability and trends in Antarctic surface temperatures from in situ and satellite infrared measurements. *J. Climate*, **13,** 1674-1696.

Ghil, M. and K. C. Mo, 1991: Intraseasonal oscillations in the global atmosphere. Part II: Southern Hemisphere. *J.Atmos.Sc.*, **48,** 780-790.

Gillett, N. P. and D. W. J. Thompson, 2003: Simulation of recent Southern Hemisphere climate change. *Science*, **302,** 273-275.

Gong, D. Y. and S. W. Wang, 1999: Definition of Antarctic Oscillation Index. *Geophys, Res. Letters*, **26,** 459-462.

Hines, K. M., R. W. Grumbine, D. H. Bromwich, and R. I. Cullather, 1999: Surface energy balance of the NCEP MRF and NCEP-NCAR reanalysis in Antarctic latitudes during FROST. *Wea. and Forec.*, **14,** 851-866.

Hines, K. M., D. H. Bromwich, P. J. Rasch, and M. J. Iacono, 2004: Antarctic clouds and radiation within the NCAR climate models. *J. Climate*, **17,** 1198-1212.

King, J. C., 2003: Validation of ECMWF sea level pressure analyses over the Bellingshausen Sea, Antarctica. *Wea. and Forec*, **18,** 536-540.

King, J. C. and W. M. Connolley, 1997: Validation of the surface energy balance over the Antarctic ice sheets in the U.K. Meteorological Office Unified Climate Model. *Journal of Climate*, **10,** 1273-1287.

King, J. C., J. Turner, G. J. Marshall, W. M. Connolley, and T. A. Lachlan-Cope, 2004: Antarctic Peninsula Climate Variability And Its Causes As Revealed By Analysis Of Instrumental Records. *Antarctic Peninsula Climate Variability: A historical and Paleoenvironmental Perspective*, E. Domack, A. Burnett, P. Convey, M. Kirby, and R. Bindschadler, Eds., American Geophysical Union, 17-30.

Kushner, P. J., I. M. Held, and T. L. Delworth, 2001: Southern Hemisphere atmospheric circulation response to global warming. *J.Climate*, **14,** 2238-2249.

Kwok, R. and J. Comiso, 2002: Spatial patterns of variability in Antarctic surface temperature: connections to the Southern Hemisphere Annular Mode and the Southern Oscillation. *Geophys.Res.Letters*, **29,** 10.1029/2002GL015415.

Marshall, G. J., 2003: Trends in the southern annular mode from observations and reanalyses. *J.Climate*, **16,** 4134-4143.

Marshall, G.J., 2006; Half-century seasonal relationships between the Southern Annular Mode and Antarctic temperatures. *Int. J. Climatol.*, (in press).

Marshall, G. J. and J. C. King, 1998: Southern Hemisphere circulation anomalies associated with extreme Antarctic Peninsula winter temperatures. *Geophys.Res. Letters*, **25,** 2437-2440.

Marshall, G. J., P. A. Stott, J. Turner, W. M. Connolley, J. C. King, and T. A. Lachlan-Cope, 2004: Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. *Geophys.Res. Letters s*, **31,** L14205, doi:10.1029/2004GL019952.

Marshall, G. J., A. Orr, N. van Lipzig, and J. C. King, 2006: The impact of a changing Southern Hemisphere Annular Mode on Antarctic Peninsula summer temperatures. *J.Climate*, **19,** 5388--5404.

Meredith, M. P. and J. C. King, 2005: Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. *Geophys.Res. Letters*, **32,** L19604, doi:10.1029/2005GL024042.

Renfrew, I. A., J. C. King, and T. Markus, 2002: Coastal polynyas in the southern Weddell Sea: variability of the surface energy budget. *J.Geophys. Res.*, **107,** 16-1 - 16-22.

Simmons, A. J. and A. Hollingsworth, 2002: Some aspects of the improvement in skill of numerical weather prediction. *Q.J.Roy.Meteor.Soc.*, **128,** 647-677.

Taljaard, J. J. and H. van Loon, 1964: Southern Hemisphere weather maps for the International Geophysical Year. *Bull. Americ.Meteor.Soc.*, **45,** 88-94.

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

Turner, J., 2004: The El Nino-Southern Oscillation and Antarctica. *Internat.J.Climatol.*, **24,** 1-31.

Turner, J., S. R. Colwell, and S. Harangozo, 1997: Variability of precipitation over the coastal western Antarctic Peninsula from synoptic observations. *J.Geophys.Res.*, **102,** 13999-14007.

Turner, J., S. R. Colwell, G. J. Marshall, T. A. Lachlan-Cope, A. M. Carleton, P. D. Jones, V. Lagun, P. A. Reid, and S. Iagovkina, 2005: Antarctic climate change during the last 50 years. *Internat.J.Climatol.*, **25,** 279-294.

Turner, J., T. A. Lachlan-Cope, S. Colwell, G. J. Marshall, and W. M. Connolley, 2006a: Significant warming of the Antarctic winter troposphere. *Science*, **311,** 1914-1917.

Turner, J., W. M. Connolley, T. A. Lachlan-Cope, and G. J. Marshall, 2006b: The performance of the Hadley Centre climate model (HADCM3) in high southern latitudes. *Internat.J.Climatol.*, **26,** 91-112.

Van den Broeke, M. and N. van Lipzig, 2003: Response of wintertime Antarctic temperatures to the Antarctic Oscillation: Results of a regional climate model. *Antarctic Peninsula Climate Variability: A Historical and Paleoenvironmental Perspective*, E. Domack, A. Burnett, P. Convey, M. Kirby, and R. Bindschadler, Eds., American Geophysical Union, 43-58.

Vaughan, D. G., G. J. Marshall, W. M. Connolley, J. C. King, and R. Mulvaney, 2001: Climate change - Devil in the detail. *Science*, **293,** 1777-1779.

Walsh, J.E. and W.L. Chapman, 2006: A synthesis of Antarctic temperatures. *J. Climate*, (in press).

Yuan, X. J. and D. G. Martinson, 2001: The Antarctic Dipole and its predictability. *Geophys.Res. Letters*, **28,** 3609-3612.