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Review
Improvements in General Circulation Model performance in simulating Antarctic climate

IAN SIMMONDS

Department of Meteorology, University of Melbourne, Parkville, Victoria 3052, Australia

Abstract: Increasingly, many aspects of the study of Antarctica and the high southern latitudes are being aided by various types of numerical models. Among these are the General Circulation Models (GCMs), which are powerful tools that can be used to understand the maintenance of present atmospheric climate and determine its sensitivity to imposed changes. The changes in the ability of GCMs used over the last two decades to simulate aspects of atmospheric climate at high southern latitudes are traced and it is concluded there has been a steady improvement in model products. The task of assessing model climates in high southern latitudes is made difficult by the uncertainties in the data used for the climatological statistics. It is suggested that the quality of the climates produced by most modern GCMs in many aspects cannot be said to be poor, especially considering the uncertainties in 'observed' climate. There is obviously need for improvements in both modelling and observations. Finally, some topics are highlighted in which the formulation of models could be improved, with special reference to better treatment of physical processes at high southern latitudes.

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Introduction

The high southern latitudes, including Antarctica, play a very important part in determining the balances which establish climate over a large fraction of the earth's surface. Antarctica is the largest sink for energy in the global circulation and this role may be thought of as just as important as that played by the tropical energy source regions. The ice cover over the continent offers a stabilising influence on shorter time scales (but possibly destabilising on longer scales) and its surrounding sea ice cover is very dynamic. These features suggest that the high southern latitudes assume a large role in influencing global climate variability and change. It is becoming clear that the balances that result in the present climate are rather sensitive in this region. This is exemplified by the reduction of stratospheric ozone which was first observed over the continent and by the important role that the Antarctic environs are expected to play in climatic changes induced by 'greenhouse' gases. Not surprisingly then, increasing world-wide attention is being paid to gaining a greater understanding of the Antarctic environment. The aim of this paper is to indicate briefly the improvements that have been made in the modelling of the present Antarctic climate and to show some examples of how well the present generation of models can simulate some of the climatic features of most general interest.

The climate system is one of immense complexity as a glance at the interactions represented in a 'spaghetti diagram' of the system (e.g. Robock 1985) makes abundantly clear. One of its characteristics is the presence of a myriad of feedback processes (both positive and negative) and compensatory mechanisms. A number of these feedbacks are of relevance only at high latitudes and are associated with the presence of sea ice. These are much stronger in the Southern Hemisphere (SH) due predominantly to the fact that the sea ice distribution and its temporal evolution is much less constrained by land masses than in the north. The human mind has trouble understanding the quasi-stationary balances and estimating the net effect of small changes in even simple coupled systems, let alone those we are discussing here. To gain insight into what is going on resort must be made to mathematical techniques.

An additional and independent difficulty in understanding the atmosphere is that it is highly nonlinear. Apart from posing difficulties for our intuition this means that most of the classical mathematical techniques may be of limited use in explaining certain aspects of the atmospheric system. A way of addressing this dilemma is by the use of numerical models of the atmosphere in which we are able to consider the various equations of the system in their entirety, without having to neglect the effect of processes that are 'mathematically inconvenient'. The most comprehensive models we have of the large-scale climate system are the General Circulation Models (GCMs). These are based on the mathematical equations expressing the laws of physics of the atmosphere as we know them: the statements of the

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conservation of momentum, energy and mass. (In the longer term these models will need ultimately to be coupled with ocean and sea ice models to more closely approximate nature.) Of necessity, the domain of interest in these models must be broken up into a finite number of 'grid points', and the basic parameters of interest e.g, wind and temperature defined only at these points. It is a consequence of the nonlinearity of the system that processes, such as convection, that occur below the scale of grid point separation (a few hundreds of kilometers in most GCMs) cannot be neglected as their effects are eventually felt at all scales. Hence one must try to represent at least the statistical effects of these processes on the larger scale. This is what is referred to as the 'parameterization' of these processes, in which their effect is approximated in terms of what *is* known, viz., the values at the grid points. Addressing the problems of parameterization raised here requires mathematical expertise, physical intuition and detailed observations on appropriate scales. It is in these very important areas of model structure that the models differ most. The structure and philosophy of modern GCMs has been outlined in the monograph of Washington & Parkinson (1986).

The immense value of using GCMs in climate research derives from the fact that all aspects of both the forcing and the physics are under the control of the researcher. For example, if one wants to determine the climatic effects of a reduction in solar radiation or of modifying or eliminating the interactions between atmosphere and sea ice these can be done in an unambiguous way. As already pointed out, the basic equations need to be approximated in various ways before they can be assembled as a GCM, but the error characteristics of many of the approximations (e.g. those associated with the 'finite-difference' approximations on our finite grid) are known as are the requirements to obtain more accurate schemes. The important point is that in a given model we know what physics have been included, which have been omitted and which may be treated only approximately.

The philosophy of constructing and using GCMs is that in understanding climate and its variability emphasis should be placed on the dynamics and physics operating. An aspect of this view was raised by Pittock (1988) who pointed out that seasonal predictions based on lag correlations and teleconnections appear to work in some locations and seasons, but may not apply in an era of rapidly changing climate. Research conducted with GCMs, based on the (unchanging!) laws of physics, is not subject to this level of uncertainty. It should be mentioned, however, that to some extent the model parameterizations of sub-grid scale physics are tuned to present conditions. As Hall (1985) has cautioned, ' ... there is always the danger that precisely those parts of the model that are most highly approximated have been adjusted to produce a good simulation of a subset of the variables of the contemporary climate, and that these variables are the only ones that the model simulates well'. The level of this potential problem is reduced accordingly when the parameterizations can be based on sound physical principles.

This paper addresses the question of how well the current generation of GCMs simulate the basic aspects of climate of special interest in the Antarctic. In the past relatively few of the general circulation modelling simulations have specifically addressed the questions of performance in this polar region. Features of particular relevance in this context are considered, such as inversion strength, surface wind, and net accumulation as simulated by models over Antarctica and the high latitude pressure distribution.

The assessment of examples of GCM performance

The initial concept and development of GCMs came from US scientists some 25 years ago. Since that time the number of research groups developing and using these models has undergone an almost monotonic increase up to the present time, but the vast majority of these groups are resident in the Northern Hemisphere (NH). A consequence of this concentration had been that modellers took great pains to assess the quality of their global simulations in the NH, but paid less attention to the product in the other hemisphere, perhaps because the quality of the product was so low there. As an example of some early simulations we reproduce results obtained by the National Center for Atmospheric Research and by the Geophysical Fluid Dynamics Laboratory, two of the leading climate modelling groups. The climate variable presented here is the mean sea level pressure, being probably the single most important variable indicating the state of the atmosphere. The observed high southern latitude distributions (from Schutz & Gates 1971, 1972) of this variable for December–February and June–August are shown in Fig. 1, while the summer simulations of Kasahara & Washington (1971) and Manabe *et al.* (1975) appear in Fig. 2. It is clear that the simulations of this parameter in the SH were poor: the subtropical ridge is either badly located or non-existent and it is difficult to find any semblance of the midlatitude westerlies.

The improvement in model simulations in this region since these experiments in the 1970s are considered below. However, just as there are a number of models which produce different climates, there are also a number of climatologies which differ considerably amongst themselves. Which data set should modern GCMs be verified against? Aspects of this question are also considered.

Quality of modern models

Since the time that the studies cited above were published, the quality of GCM products on a global scale has improved considerably. However, few studies have assessed modelled climates in the mid to high latitudes of the SH. Many reports of model investigations display global plan maps, but these are usually on an equally-spaced latitude projection, which

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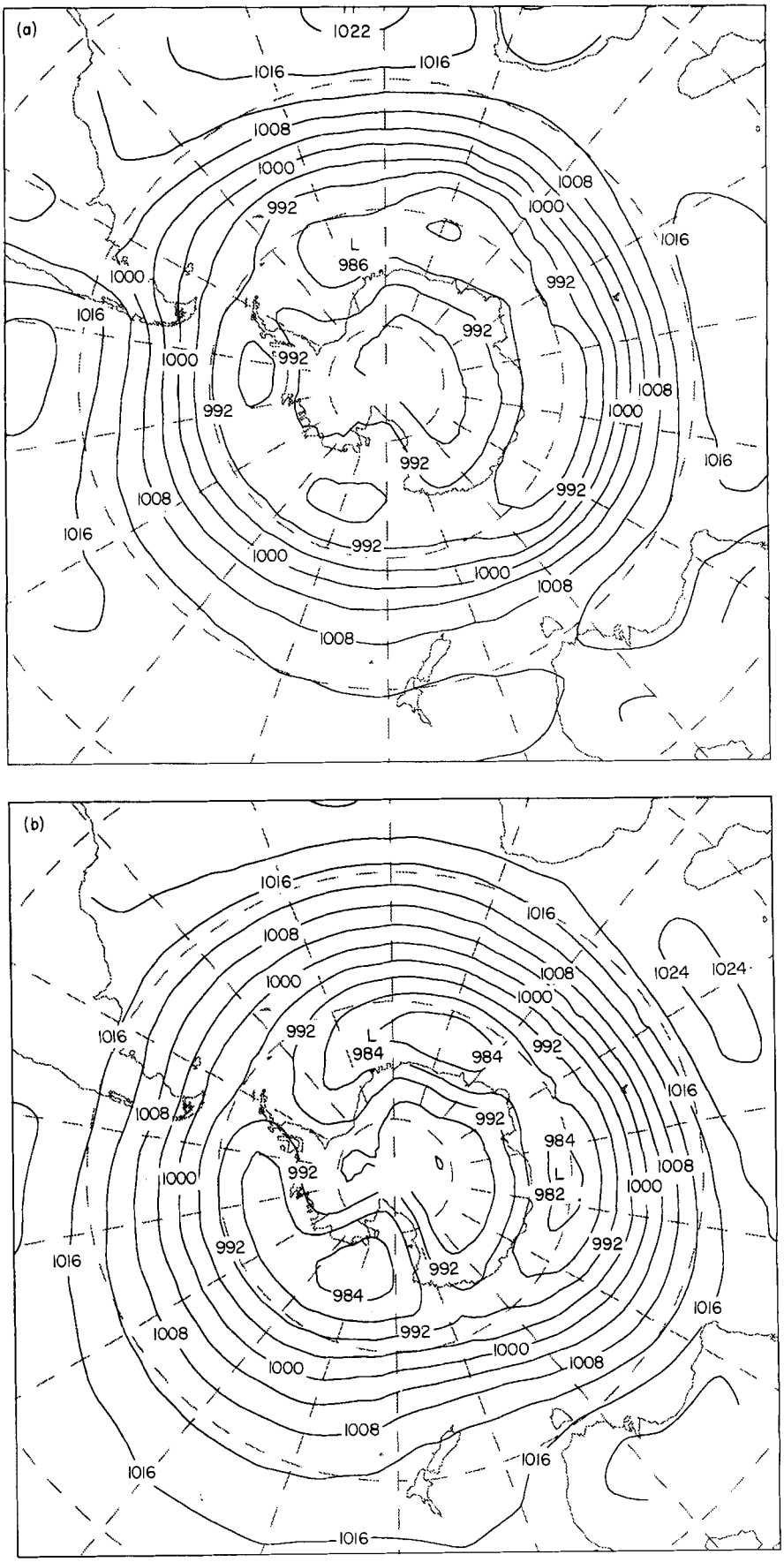


Fig. 1. Mean sea level pressure observed for (a) December–February (Schutz & Gates 1971) and (b) June–August (Schutz & Gates 1972). The contour interval is 4 hPa.

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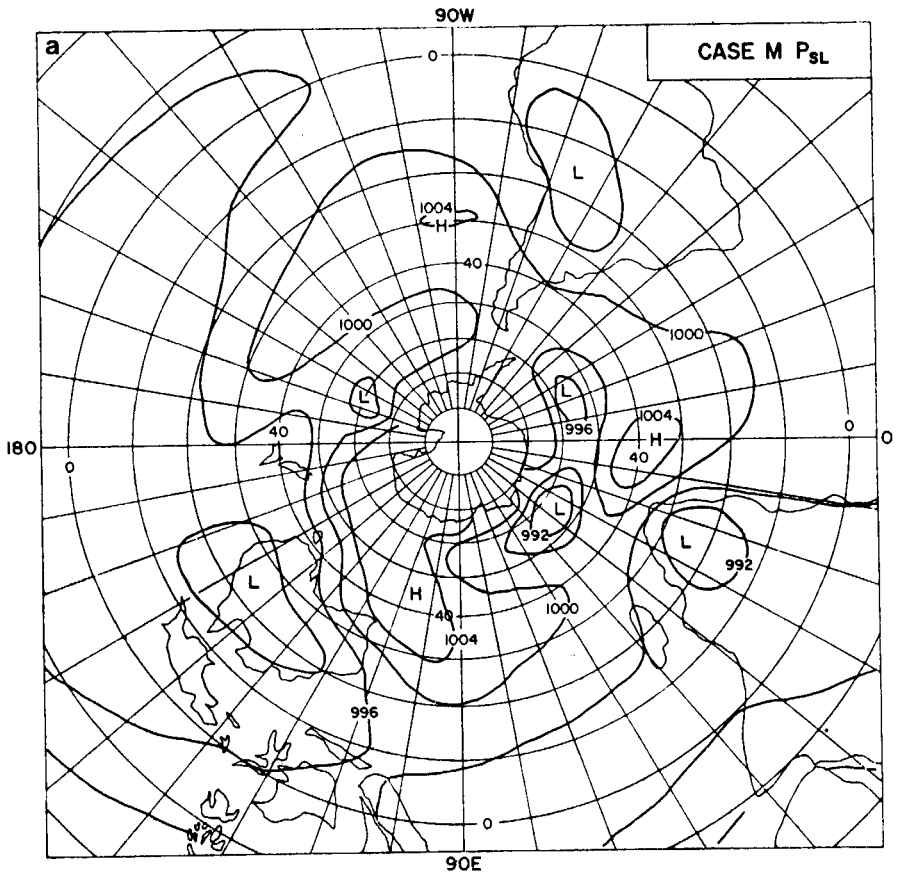


Fig. 2. Mean sea level pressure for January for the simulations of (a) Kasahara & Washington (1971) and (b) Manabe *et al.* (1975). The contour interval is 4 hPa.

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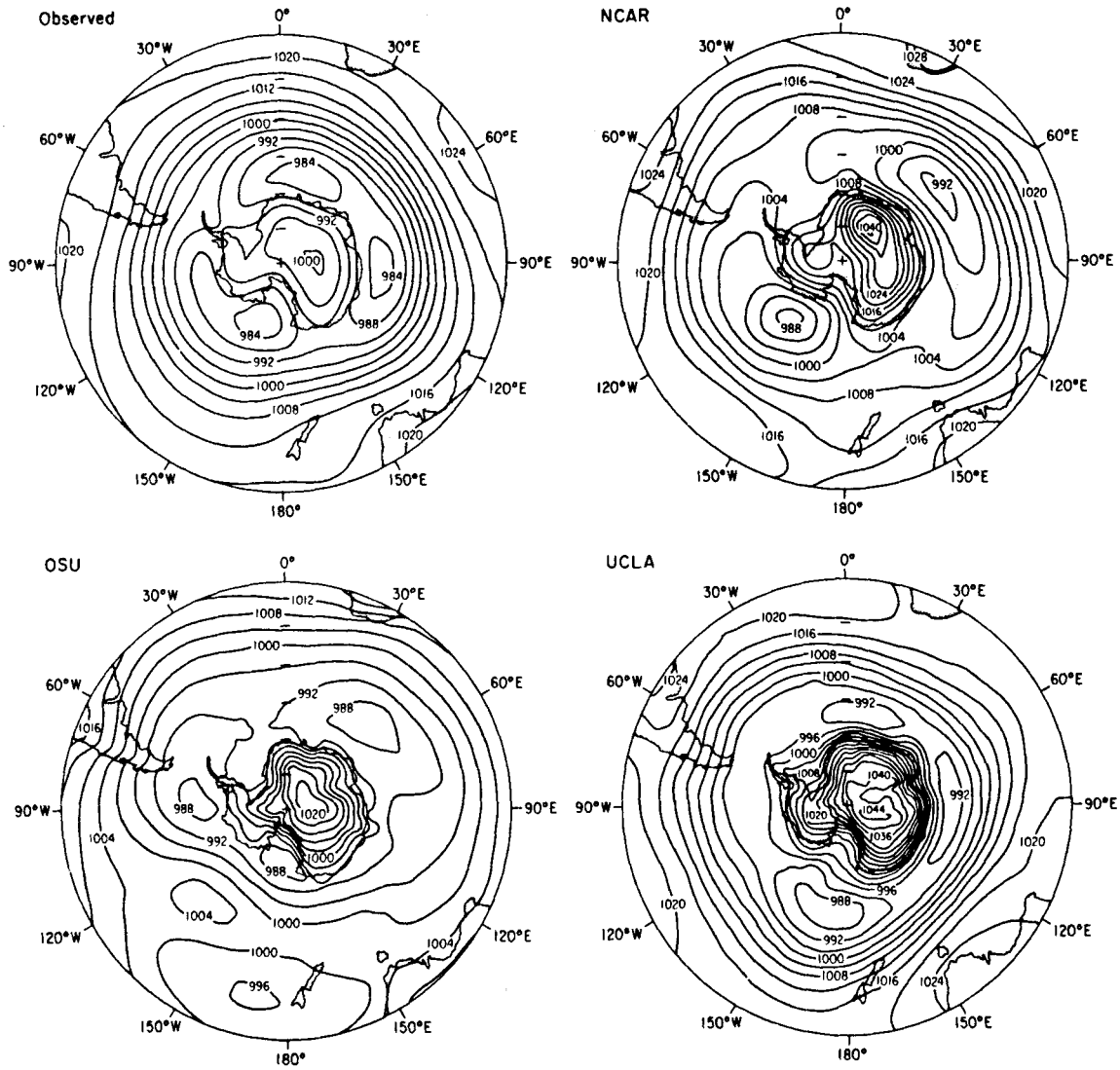


Fig. 3. Mean sea level pressure for June–August or July for observed and the NCAR, OSU and UCLA models. The contour interval is 4 hPa. (From Schlesinger 1984)

distorts the high latitudes, and particularly Antarctica, so that they are of limited use for present purposes. Schlesinger (1984, 1986) employed a SH polar stereo projection to compare the simulations of various GCMs of the early 1980s with reality. Fig. 3 shows a comparison taken from Schlesinger (1984) of the winter distribution of mean sea level pressure produced by some of the models he surveyed. Note that over most of the continent the 'mean sea level pressure' is an extrapolated quantity and has limited meaning. Its structure should be ignored over the very high elevations. It is clear from this parameter (and most aspects of modelled climate) that by the early 1980s the quality of climate simulations in high southern latitudes had increased greatly, but that they were still far from adequate.

The veracity of GCM performance in high southern latitudes has continued to improve through to the end of the 1980s. Evidence for this is in the studies (with prescribed climatological sea surface temperatures and sea ice) of Mitchell & Hills (1986), Simmonds & Dix (1987), Cattle & Roberts (1988) and Xu *et al.* (1990), which have shown some of the results on a polar projection centered on the South Pole. Figs 4 & 5 illustrate the mean sea level pressure distribution in the simulations of Simmonds *et al.* (1988) (July) and Mitchell & Senior (1989) (July–September). It is clear from these publications and Figures that the quality of the simulation of this parameter in most GCMs is continuing to improve to the present time. This implies a corresponding improvement in modelling the lower tropospheric winds over the region.

There are other examples of GCM performance which are of relevance to a wide range of studies. Three such examples

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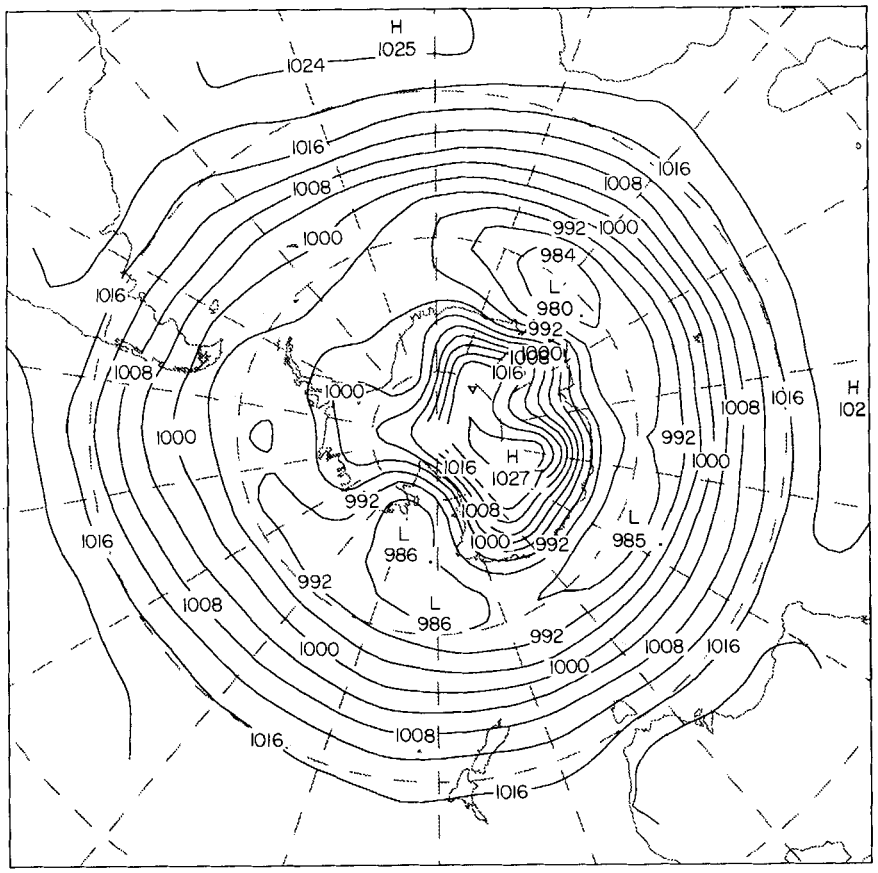


Fig. 4. Mean sea level pressure for July for the simulation of Simmonds *et al.* (1988). The contour interval is 4 hPa.

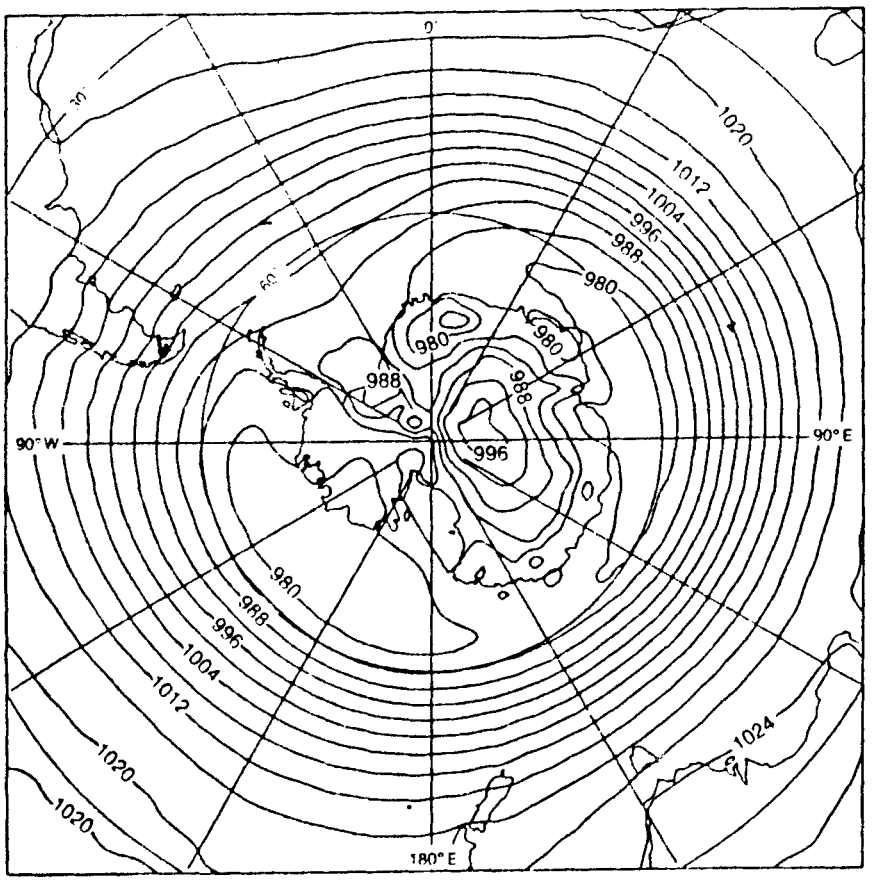
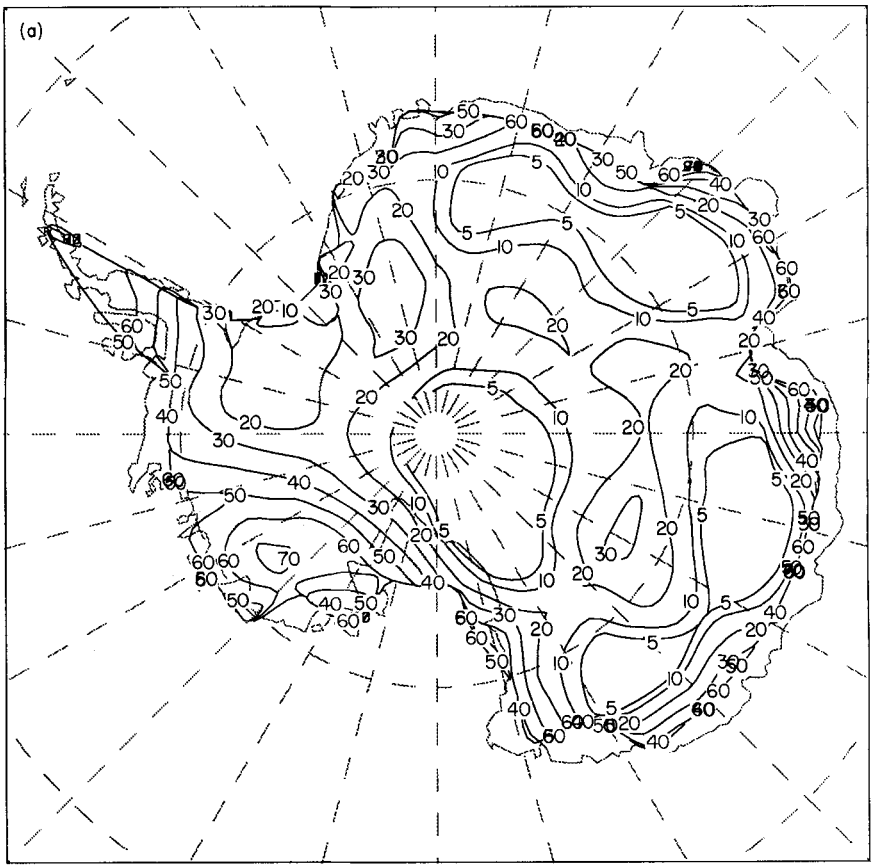


Fig. 5. Mean sea level pressure for July-September for the simulation of Mitchell & Senior (1989). The contour interval is 4 hPa.

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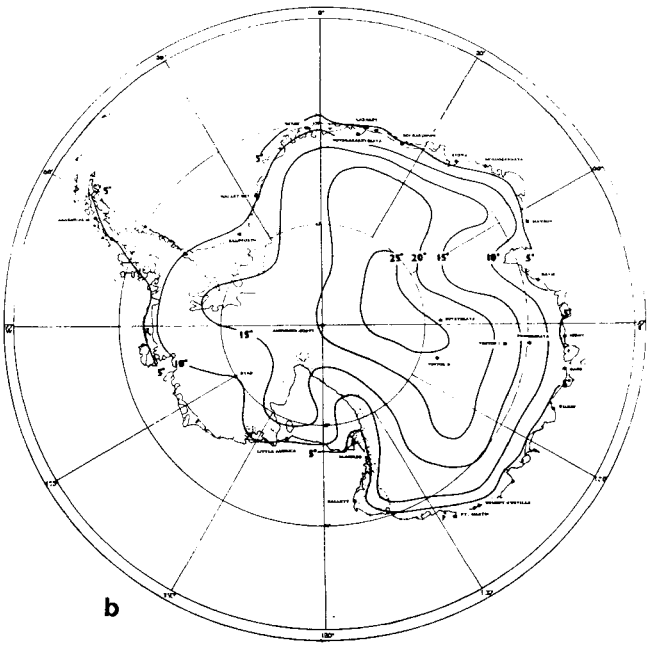


Fig. 6. Average strength of the surface temperature inversion from (a) the July simulation of Simmonds *et al.* (1988) and (b) observed for June–August (Phillpot & Zillman 1970). The contour interval is 5K.

have been chosen from the results of Simmonds *et al.* (1988). The basic form of the model is described in Simmonds (1985) and its performance compared with climate statistics in Simmonds *et al.* (1988), Simmonds & Dix (1989) and Simmonds *et al.* (1990). In the model, the horizontal distribution of most variables is represented in terms of spherical harmonic series rhomboidally truncated at wave number 21. The variables are represented at nine 'sigma' levels in the vertical. The input to the radiation scheme is the diurnally averaged solar radiation for the selected month. The scheme allows for interaction with specified climatological distributions of ozone, clouds and carbon dioxide (functions of latitude and height only) and with water vapour which is predicted by the model. The model was run in 'perpetual' month mode, with prescribed global distributions of sea surface temperature taken from the atlas of Levitus (1982) (after some weak space smoothing). The statistics presented here are taken from 600-day simulations.

One of the most important aspects of Antarctic climate is the low surface temperature in winter and the strong surface inversion in the lower boundary layer. The first example examines the simulation of this surface temperature inversion (the difference between surface air temperature and surface temperature), which is very strong over Antarctica and its surrounding sea ice in the winter months. This inversion is understood to be a factor contributing to the Antarctic katabatic winds. Fig. 6(a) shows the mean inversion strength in the July model simulation, defined as the difference between the temperatures at the lowest level in the model ($\sigma = 0.991$ or about 65 m above the surface) and the surface. Fig. 6(b) displays the June–August data of Phillpot & Zillman (1970). The direct comparison of these is complicated by the

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fact that they are calculated over different inversion depths. Schwerdtfeger (1984) has pointed out that the question "how high is the inversion?" is really not a good question at all. He refers to pronounced surface inversions below 150 m. Schwerdtfeger (1970) notes that widely scattered values for the depth of the surface inversion, anywhere between 100 and 1000 m, can be found in the literature. Phillpot & Zillman (1970) state that the *mean* temperature inversion over the continent is usually some 300–700 m deep. However, aside from the difficulties in interpretation, it is clear that the model has sufficient vertical resolution to adequately resolve the inversion. The agreement between the model and the observed is very good, with both showing a trend to stronger inversions at higher elevations reaching in excess of 25K in the region of the highest Antarctic elevation. Both display inversion strengths of about 5K at the coast. (The zero contour in part (a) corresponds to the edge of the sea ice surrounding Antarctica in the model.) In the model time mean there is an inversion over all the sea ice, but its strength is only 0-5K, much weaker than that over the continent. It is of interest to note that to the north of the ice the inversion strength is negative, particularly in a narrow latitude belt adjacent to the edge. That is to say, in that region the water is warmer than the overlaying air. This is due to the occurrence of winds with southerly components advecting cold air from off the sea ice to over relatively warm water, as discussed by Simmonds & Budd (1990). To put this in context it should be realized that in the version of the model under consideration here the sea ice is prescribed as a continuous slab. The allowance for the effect of open water in the ice (e.g., Simmonds & Budd 1990) lessens the difference both over the sea ice and to the north but has little effect over the continent.

The second feature of interest is the simulation of the mean surface wind regime over the continent. Fig. 7 (a) shows the vector wind distribution at the lowest model level in July and 7(b) displays the averaged pattern inferred by Mather & Miller (1967). The overall structure of the modelled winter low-level wind field agrees quite well with the observed. Because of the relative coarseness of the representation of topography in the model, however, the fine structure in individual valleys cannot be simulated. Higher resolution surface windfields have been well depicted by Parish & Bromwich (1987, unpublished) and show greater topographic channelling.

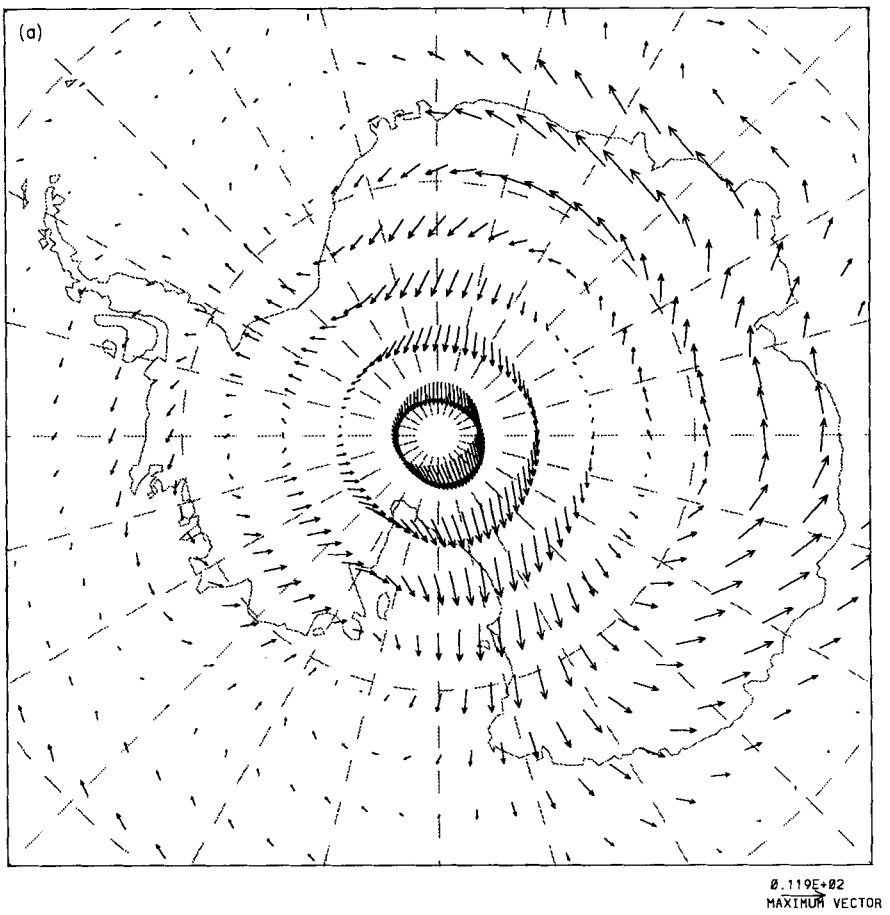
The third parameter displayed, which is of particular interest for the Antarctic mass budget, is the net accumulation (i.e., precipitation minus evaporation) over the Antarctic continent. This parameter is probably one of the most difficult to simulate accurately, particularly at high latitudes over elevated surfaces. However it is of considerable importance in terms of its possible changes under global warming conditions, which in turn have implications for changes in sea level. The annual accumulation rate has been estimated by averaging the rates obtained in a January and a July model simulation. The estimation of an annual amount by this method probably introduces bias into the model value. For example the data compiled by Rusin (1964, Table 56) for coastal and interior stations implies that this approximation underestimates the annual precipitation rate by about 10%. This rate is displayed Fig. 8 with a climatological estimate, in this case from the Scott Polar Research Institute and presented by Robin (1983). It should be noted that there have been a considerable range of representations of the observed field from still relatively sparse data compiled over the years, as shown by Giovinetto & Bull (1987). The modelled accumulation shows serious discrepancies from those observed but there are a number of common features on the large scale which are well simulated. For example, both maps exhibit values of less than 5 cm year^{-1} in the centre of the continent and in excess of 60 cm yr^{-1} at a number of coastal locations. The Antarctic mean (excluding the Peninsula) of the modelled accumulation is 20.8 cm yr^{-1}, only slightly larger than the 16.0 cm yr^{-1} of the Scott Polar map (Giovinetto & Bull 1987). However, it should be made clear that in spectral models of the sort used here the topography of a given area will generally not be matched exactly to the actual heights. By the spectral process the topography is somewhat smoothed and the elevation of the higher regions reduced, resulting in an appreciable positive bias for precipitation. Giovinetto *et al.* (1990) have recently discussed the dependence of the Antarctic mass balance on elevation.

The above discussion is not to suggest that the models are performing to the level of skill we would like but the stage has been reached where the uncertainties in the observed fields need also to be assessed. For example, the simulation of surface air temperature over the Antarctic continent and sea ice leaves room for improvement, particularly in winter. Grotch (1988) compared this parameter simulated in four models of mid-1980s vintage with the data of Oort (1983) and found that at high southern latitudes the models tend to be too warm. However, it is accepted that the models are improving and that the various improvements have come about not by tuning them to give a closer fit to reality but by a better understanding of the physics of the environment and how to treat it properly. Most of the improvement over this period has resulted from more careful or accurate treatments of various modelled processes. Among those are a better treatment of orography ('silhouette', 'envelope', and 'gravity wave drag'), radiative processes, surface-atmosphere interactions, cloud processes, soil hydrology, numerical techniques, and finer resolution.

Quality of verifying climate

An important reason for treating model comparisons with 'observed' climate with some caution is that the real climate means are not known with a high degree of certainty. This is due to the fact that, firstly, relatively few data are available in the high southern latitudes with which to form climate

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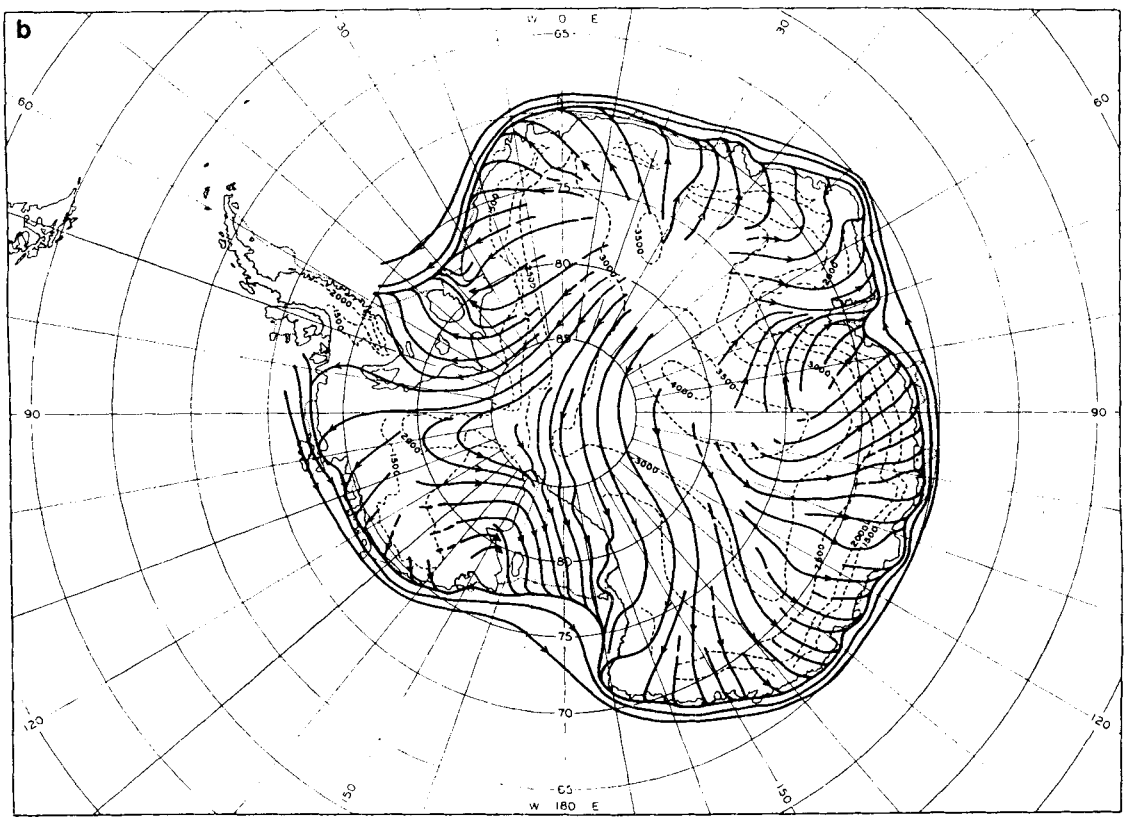


Fig. 7. Low-level wind field from (a) the July simulation of Simmonds *et al.* (1988) and (b) observed (Mather & Miller 1967). The maximum vector length in (a) corresponds to 11.9 ms^{-1}.

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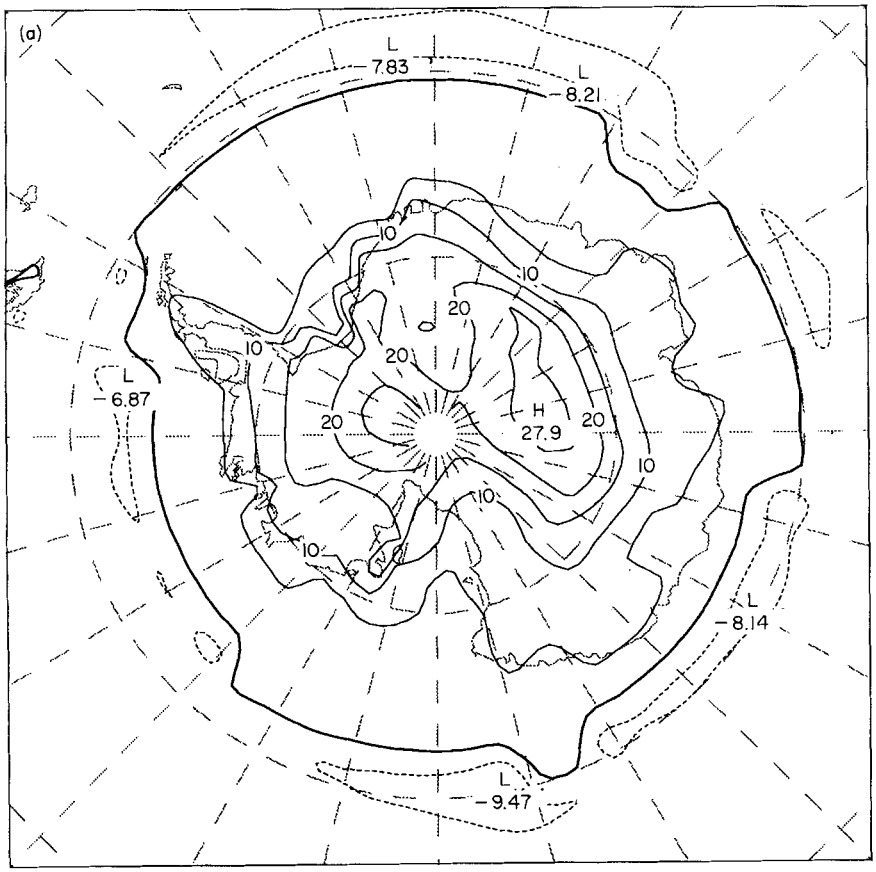
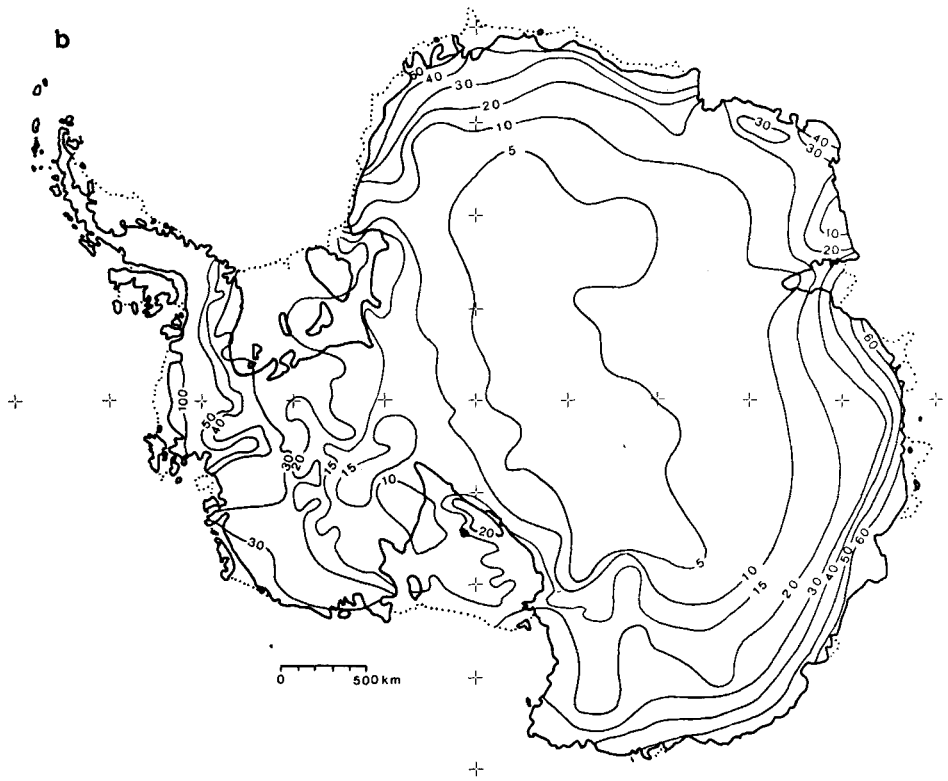


Fig. 8. Annual Antarctic accumulation rate from (a) the mean of the January and July simulations of Simmonds *et al.* (1988) and (b) observed from the Scott Polar Research Institute (Robin 1983). The contour interval is 10 cm yr^{-1} and the 5 cm yr^{-1} contour is also included.



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means. To exacerbate this problem, the atmospheric variability is large near, and to the north of, the Antarctic coast so that reduced confidence can be placed in those means as representative of the climate of the vicinity. Recently Trenberth & Olson (1988) compared global analyses produced by the US National Meteorological Center and by the European Centre for Medium Range Weather Forecasts and found them to differ greatly south of about 30°S, with very large differences apparent over Antarctica. The authors pointed out that a reliable climatology is required for a number of purposes. Such large analysis differences in the southern extra-tropics lead one to question the veracity of a climatology derived from either source. Karoly & Oort (1987) have contrasted many climate statistics of analyses from the Geophysical Fluid Dynamics Laboratory and the Australian Bureau of Meteorology. They found that the differences between the time mean fields in the two analyses were large away from the radiosonde station locations. In a study to simulate the effect of the spatial data gaps Oort (1978) sampled the climate produced by a GCM only at points corresponding to the rawinsonde network existing at that time. Statistics from the analyses performed with these pseudo-observations were then compared with those from the original data. Over the southern extra-tropics he found large root-mean-square differences between the two. Daley & Mayer (1986) performed a similar experiment and found the errors, though smaller than those of Oort, were still large at high southern latitudes, despite an improved observing network in their synthetic experiment.

These problems of accurately defining the climate against which models should be verified extend even to parameters observed at the surface. For example, as pointed out by Schlesinger (1986), the models he assessed simulated surface air temperatures over Antarctica which were 10–15°C *warmer* than the observed of Taljaard *et al.* (1969). However, when compared with the compilation of Oort (1983) the models appeared to be too *cold* by similar amounts. It should be said, however, that the Taljaard *et al.* analyses appear to bear a closer relation to the station observations than do those of Oort. A similar situation applies to precipitation, a parameter that is very difficult to measure over both the Antarctic continent and its surrounding sea ice and ocean. Two sets of precipitation data that have been commonly used in the verification of GCM products at high southern latitudes are Schutz & Gates (1971, 1972) and Jaeger (1976). The zonal averages of these two differ significantly south of about 55°S (by about 2 mm d^{-1} at 60°S in January). There are difficulties associated with measuring precipitation in the Antarctic (Rusin 1964) and this is one of the reasons why net accumulation over the continent has been used for comparison here. A mean sea level pressure dataset against which many models have been assessed is that of Taljaard *et al.* (1969). However, Jones & Wigley (1988) have suggested that this set '... is unreliable over large parts of the region south of 60°S...' and recommended it should not be used in climatological studies.

The difficulties in obtaining reliable climate estimates of higher order quantities are even greater. In examining the eddy statistics of the SH circulation, Trenberth (1984) concluded that '... the model simulations to date are not good'. On this general question of against what should the models be verified, Covey's (1988,1989) recent study of the meridional atmospheric heat transports is of some interest. He found that this transport simulated in the model he used was significantly greater than that implied by the radiosonde network. A similar finding had been made by other groups using different models. The suggestion that the radiosonde-determined transport was too low is supported by independent assessments of ocean heat transport and satellite data. Covey was led to suggest that the atmospheric heat transport is actually better estimated from circulation models than radiosonde data and that in the southern extra-tropics the modelled heat flux is approximately double that of the conventional estimates.

A second example of the idea that the observations of higher order quantities should be treated with some scepticism is provided by the global distribution of ocean-atmosphere heat fluxes. Direct observations of these fluxes (based on measured eddy correlations) are very rarely made and estimates are formed based on profile methods and bulk aerodynamic formulae of varying degrees of sophistication. Among others, Simmonds & Dix (1989) have drawn attention to the large differences between many of the atlases of oceanic heat flux, particularly in the SH. They also pointed out that many of the compilations were constructed from the monthly means of the primary variables near the interface. As a result of the temporal covariances between these variables this procedure does not produce estimates as accurate as averaging the fluxes calculated over short intervals. They found the difference due to the two methods was particularly marked at high southern latitudes as a result of the large covariances, between,for example, the drag coefficient and air-sea temperature difference there . They also made a point analogous to Covey in that the modelled air-sea fluxes may be more reliable than those derived from sparse and inadequate observations. This was because of the points raised above and also the fact that the model data are consistent with the physics of the simulated atmospheric surface layer. On the other hand this may not be the case for observations of the surface ocean temperature and air temperature taken independently, which may have different error characteristics.

Given the difficulty in modelling precipitation it is felt that the broadscale features of the net accumulation over Antarctica have been simulated fairly well although problems still exist in some regions. As indicated above one should also bear in mind the wide variety of estimates of the distribution of observed accumulation over the continent. This variety is reflected in the range of Antarctic-averaged accumulations in the compilations reviewed by Giovinetto & Bull (1987), varying between 12.5 and 21.0 cm yr^{-1}, although two thirds of the estimates surveyed lay between 14

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and 16 cm yr^{-1}. Some recent work has focussed on attempting to reduce this uncertainty in the observed estimates by considering the atmospheric flux of water vapour across the Antarctic coast (e.g. Bromwich 1990) but this approach is not without its difficulties due, for example, to the large spacing between radiosonde stations.

The main point to be made here is that a definitive assessment of all aspects of GCMs' performance at high southern latitudes is extremely difficult as yet in view of the range of estimates and uncertainty in many of the observed features. As far as the atmospheric parameters are concerned, Bengtsson & Shukla (1988) state that 'a decadal or longer time-mean circulation for the earth's atmosphere has never been calculated using a homogeneous data set'. They suggest that four dimensional assimilation with current techniques applied to past data for a 20-year period might provide a more accurate estimate of climate. A complicating issue arises as to what extent dissimilarities in climatologies constructed over different periods are due to real climatic change. Bengtsson and Shukla suggest this could be addressed with the above approach. It is clear that the question of model verification becomes even more difficult when climatic change is occurring.

Discussion

The understanding of the high southern latitude climate system should involve both observational and modelling studies and the intelligent and imaginative analysis of the results of these. The two prongs of this approach are by no means disparate. As implied earlier, the results of observational studies can be used to indicate where the treatment of the appropriate physics in a model needs some modification and conversely the interpretation of certain data (e.g. from Antarctic ice cores) is very difficult without the use of some type of model. The necessity of GCMs playing a central role in our comprehension of the climate system, particularly at high southern latitudes, is now well appreciated (e.g. Budd 1982, Tucker 1988, Mitchell & Senior 1989). In spite of the progress in the quality of GCM simulations, there has been a perception that they perform poorly in the higher latitudes of the SH. For example, Streten (1988) felt that, up to the mid 1980s, there were '...large and scientifically unacceptable deficiencies in all models currently used internationally to represent the ...climate of the Antarctic region'. Improvements since then suggest that the present capability is not as deficient as this statement implies. Indeed, contrary to this perception, the performance of current GCMs in high southern latitudes cannot be said to be poor. This is partly due to the fact that there is little agreement on what is the accepted climate for many parameters. This is not to say that the models cannot and will not be improved. It has been shown that over the last decade or so the quality of climate simulations in high latitudes has increased immensely. There is every reason to believe that this improvement will continue and that numerical schemes based more solidly on the physics of the various processes will reap rewards. There are several areas of model improvement which have had little or scant attention in the past but which are recommended here as having high priority for implementation, particularly in connection with the simulation of the atmosphere, ocean and ice over and in the environs of Antarctica.

The uses to which our climate models are going to be put in the next decade makes it essential that an 'ocean' that is able to respond to atmospheric forcing, and vice versa, be part of the modelling approach. Over the last decade a better appreciation of what form this ocean should take in atmospheric models has stimulated the development of a hierarchy of ocean models for various purposes. It may not be necessary to model the ocean in its full complexity, at least in the immediate future. In the first instance it is important to allow the interaction between subantarctic waters and the atmosphere in a realistic, if simplified, manner.

The treatment of interactive sea ice is related but distinct from the previous point. The Antarctic sea ice and atmosphere are known to be strongly interactive in both dynamic and thermodynamic processes. In the next generation of models these processes must be treated more realistically if they are to be applied to problems of climatic change in the Antarctic.

The treatment of clouds in most models is fairly rudimentary and must be improved, particularly as the GCMs are to play an important role in understanding of climate variability and change. Some models simply prescribe the cloud cover, which may make them of limited use in this context. At present many models generate clouds internally, with varying degrees of success. The cloud generation processes at high southern latitudes are different from those, say, in the tropics. It is important to get this feature right as, for example, the response of surface temperature to a change in cloud cover may have opposite signs in these two regions. It is clear that additional effort must be put into this.

More attention must be paid to improving the treatment of the atmospheric interaction with the high latitudes southern oceans, the sea ice zone and the ice sheet on the continent itself. For example, are the parameterizations of the sensible heat flux, usually developed with data from other regions of the world, appropriate at these high latitudes in the presence of sea ice with open water leads and katabatic winds? There is also a need to develop appropriate large scale observations (by remote sensing, for example) for comparison with model results.

The last few years have seen a considerable development in the improved treatment of the earth's topography. Most of the rationale for this work has come from shortcomings in the models' NH climate. Consequently, some of the techniques may not be the best for the Antarctic dome. More needs to be understood of the dynamic influence of Antarctica and how this is appropriately modelled.

It was suggested earlier that the improvement in the quality of GCM simulations has come about as a result of the

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better treatment of the basic physics and numerics. Most practitioners believe this improvement will continue as a result of advances made in association with some of the topics mentioned above. In this paper the aim has been to show, by way of examples, that present GCMs are of sufficient quality to simulate many of the weather and climate parameters that are of interest to Antarctic scientists with reasonable skill. This means they may be used with some confidence in a wide variety of Antarctic and high southern latitude problems. Among these are the climatological control of the continental mass balance, the interpretation of paleo-climates, and the sensitivity of Antarctica to imposed forcings such as changes in ozone and carbon dioxide.

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