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The Antarctic climate of the UKMO Unified Model

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Abstract: We examine some aspects of the performance of the United Kingdom Meteorological Office's new climate model over Antarctica. Pressure and temperature fields are presented as a basic check on the model climate. The gradient of pressure between mid-latitudes and high southern latitudes is too great, resulting in an Antarctic trough that is too deep by 4–6 hPa. Temperature is well modelled though the interior is slightly too cold in winter. Precipitation is interesting because of its relevance to mass balance and therefore changes in sea level. The simulation of the pattern of accumulation is good despite somewhat high values at places in the coastal areas, with an areally-averaged value of 182 mm y^{-1}. We also look at the phenomena of the coreless winter and the katabatic winds which are a consequence of the intense radiative cooling. These two effects may provide a useful diagnostic of the model performance.

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Introduction

General Circulation Models (GCMs) are an important tool for studying the world's climate and for simulating possible climate change. However there are deficiencies in current models which do not produce reliable predictions at a regional scale. Only limited verification of model climate over Antarctica has been carried out to date. The first comprehensive discussion of the Antarctic climatology of a GCM was given by Herman & Johnson (1980) who analysed the performance of the Goddard Laboratory for Atmospheric Science model. More recently Schlesinger (1986) compared the summer and winter southern hemisphere climates simulated by nine atmospheric GCMs with observed climatology. Simmonds (1990) reviewed the improvements in GCM performance in simulating Antarctic climate that occurred in the 1980's.

The United Kingdom Meteorological Office (UKMO) has recently rewritten its atmospheric GCM and this paper presents a look at the Antarctic climate of this new "Unified Model" (UM). The Antarctic climate of the previous UKMO model was reported by Mitchell & Senior (1989) in the context of winter sea-ice anomaly experiments and by Roberts & Cattle (1990) for a simulation with the previous UKMO model coupled to a deep ocean model. In climate mode the UM has the same horizontal resolution as the old model but is very different otherwise, with rewritten dynamics and new parametrizations.

The UM is a finite difference GCM designed to run as either a numerical weather prediction (NWP) model or, at a lower resolution, as a climate model. Cullen (1993) provides an overview of the model in both NWP and climate mode, together with details of the model not given here. The model uses a conservative split-explicit integration scheme with fourth order horizontal advection (Cullen & Davies 1991) which, in climate mode, is run on a 2.5° by 3.75° latitude-longitude grid. A 'hybrid' 19-level vertical coordinate system is used which changes from terrain-following ('sigma') coordinates near the ground to pressure coordinates in the upper atmosphere. The levels are spaced to give improved resolution in the boundary layer and near the tropopause; the lowest model level is at sigma =0.997. Details are given in Cullen (1993). Seasonal and diurnal cycles are included. Cloud cover and cloud liquid water and ice content are predicted via the explicit cloud liquid water scheme of Smith (1990). The model also includes amongst its physical parametrizations a 4-layer soil model, short and longwave radiation schemes (Ingram 1990), the convective parametrization scheme of Gregory & Rowntree (1990) modified by inclusion of a parametrization of convective downdraughts (Gregory, personal communication) and the gravity wave drag scheme of Palmer *et al.* (1986). Poleward of 50° (the exact latitude depends on the maximum wind speed) points are Fourier-filtered in longitude to avoid instability. The climate version can be run coupled to simple slab or deep-ocean models. Here we present atmosphere-only runs in which the sea surface temperature and sea ice extents are prescribed from climatology.

In the run considered here sea ice concentration is taken as 100%, with the ice thickness around Antarctica specified as 1 m. Sea ice albedo takes the value of 0.8 for ice surface temperature less than -5°C, linearly decreasing with temperature to a value of 0.5 between -5°C and 0°C. Albedo over the Antarctic continent and other regions of permanent land ice is set to a constant 0.8. Over other land areas the albedo, following the scheme of Hansen *et al.* (1983), varies

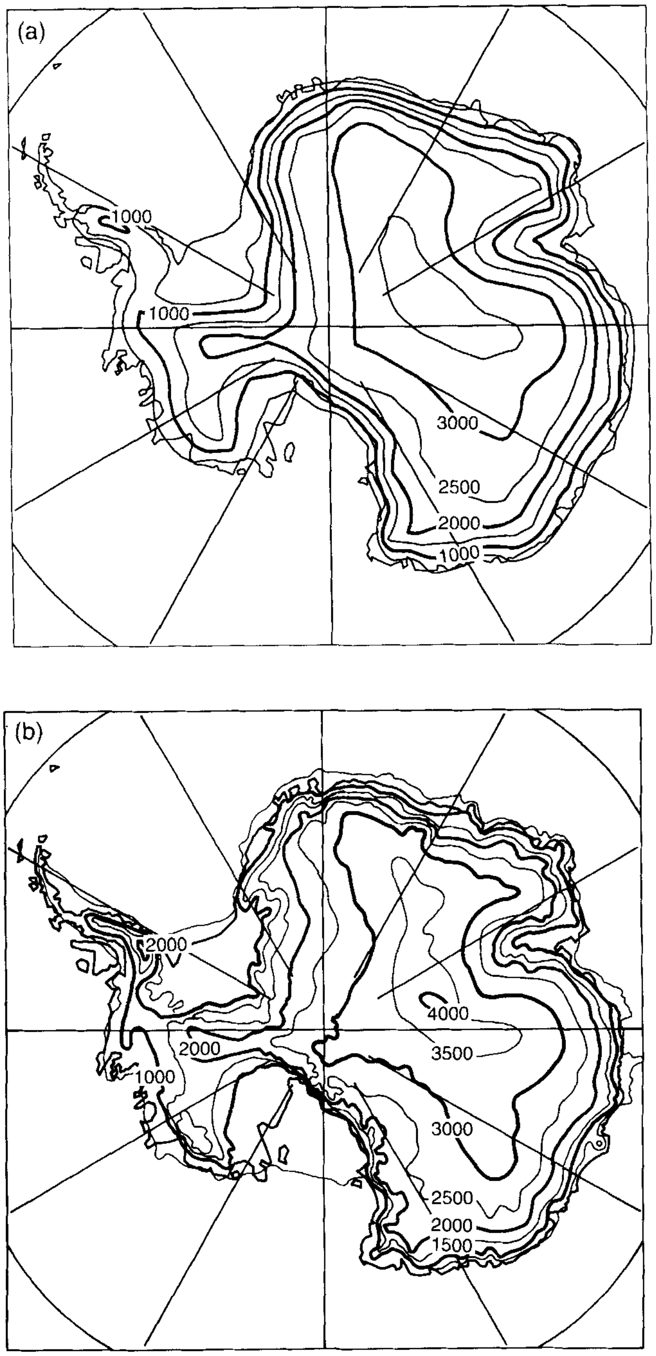

Fig. 1. a. Model topography. **b.** Detailed observed topography (Drewry 1983). The contour interval is 500 m.

between the snow-free albedo and a deep snow albedo for the temperature and vegetation type, according to the thickness of the snow cover (which itself can change from snow accumulation and melt and sublimation or deposition). A simple temperature-dependent representation of snow aging, which causes the snow albedo to vary close to the melting point in a similar fashion to that of sea ice, is also included. Fig. 1 shows the model topography over Antarctica, together with the more detailed observed topography. Unified model data used in this paper are 10–year averages taken from a control run of the "frozen" version of the model carried out in early 1993.

The bane of the Antarctic modeller's life is the sparsity of verification data. Schlesinger (1986), Jones & Wigley (1988) and Simmonds (1990) mention the problems of datasets over this region. Data from routine numerical weather prediction analyses are largely dependent on the model used, which will have changed substantially over the period of accumulation of the climatology. The reanalysis projects planned by the US National Meteorological Centre and the European Centre for Medium-Range Weather Forecasts will help to overcome the latter problem. There is also a certain circularity in verifying a GCM from model data which are rather poorly constrained by observations. Therefore, where possible, we prefer datasets synthesised from surface observations. For continent-scale temperature, we use the Radok *et al.* (1987) data of 10 m borehole temperatures. Reliable time series of surface temperature in the interior are available for a few points and are reported in Schwerdtfeger (1984). For accumulation, Giovinetto & Bull (1987) give a large number of widely varying accumulation composites although the more recent examples have tended to converge. We have chosen one from this set (Giovinetto & Bentley 1985) that seems to be of high quality.

Verification of the pressure and temperature

Fig. 2 shows the mean sea level pressure (MSLP) fields for winter (June–July–August, JJA) and summer (December–January–February, DJF) seasons, from the model and from analyses. The analyses are 10 year means produced from the data assimilation scheme of the previous UKMO NWP model and so are relatively independent of the UM and therefore have little bias towards it. Whilst there is a good representation of the Antarctic trough the pressure as a whole is too low by 4–6 hPa and in DJF the longitudinal positions of the climatological lows is rather poor. We can compare the zonal averages with the results reported by Boer *et al.* (1992a), who compare the climatology of 14 different GCMs with National Meteorological Center (NMC) analyses. The latitude of the UM pressure minimum agrees with the NMC

Table I. Comparison of sea-level zonal average pressures between UM, UKMO analyses, and NMC analyses (as reported in Boer *et al.* 1992a).

		Pressure (hPa)	Latitude (S)
DJF	UM	980.6	65
	UKMO analyses	986.5	66.25
	NMC analyses	987	66
JJA	UM	982.3	70.0
	UKMO analyses	985.5	68.75
	NMC analyses	986	68

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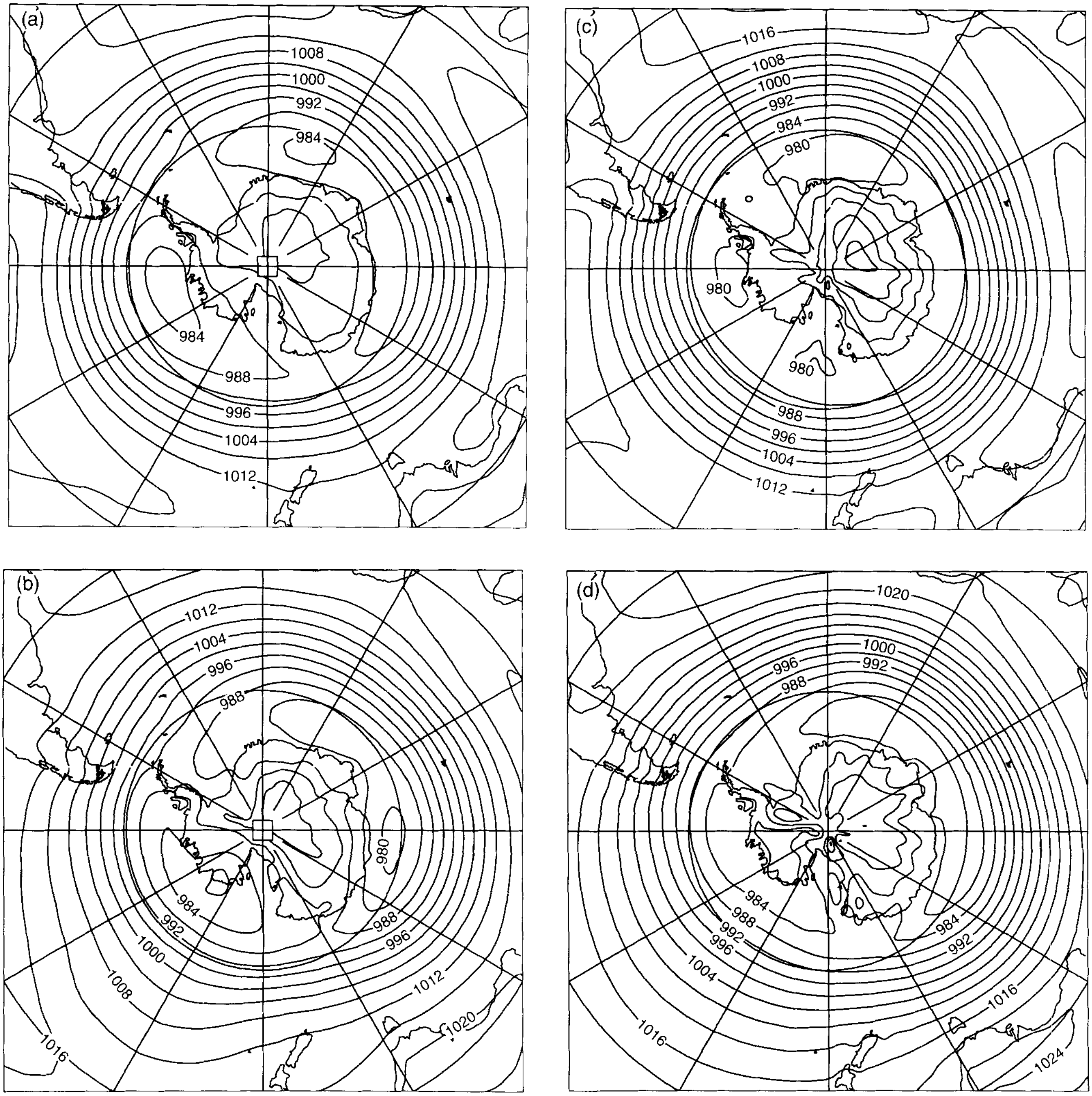

Fig. 2. Climatological and modelled sea level pressure. **a.** Observed climatology for DJF. **b.** Observed climatology for JJA. **c.** Unified Model simulations for DJF. **d.** Unified Model simulations for JJA. The contour interval is 4 hPa.

analyses in DJF but is too southerly by a grid point in JJA, although the trough is rather broad in this season. The UM pressure is lower than both analyses and at the lower end of the range of model results presented in Boer *et al.* Table I summarizes the latitude and depth of the minimum of the zonally-averaged pressure.

Turning now to the temperature field, it should be remembered that in the model both sea-surface temperature and sea-ice cover are prescribed from climatology. Fig. 3 shows the annual average surface temperature from the model and that deduced from 10 m ice temperatures by Radok *et al.* (1987). There is reasonable agreement between the two (closer than the agreement between some climatologies), dominated of course by the effects of orography. The minimum of the annual-average temperature, which occurs at the highest part of the East Antarctic plateau, is too low by about 5 °C in the model simulation. A comparison with station data from Vostok (location 78.5S, 106.9E) shows that this is not

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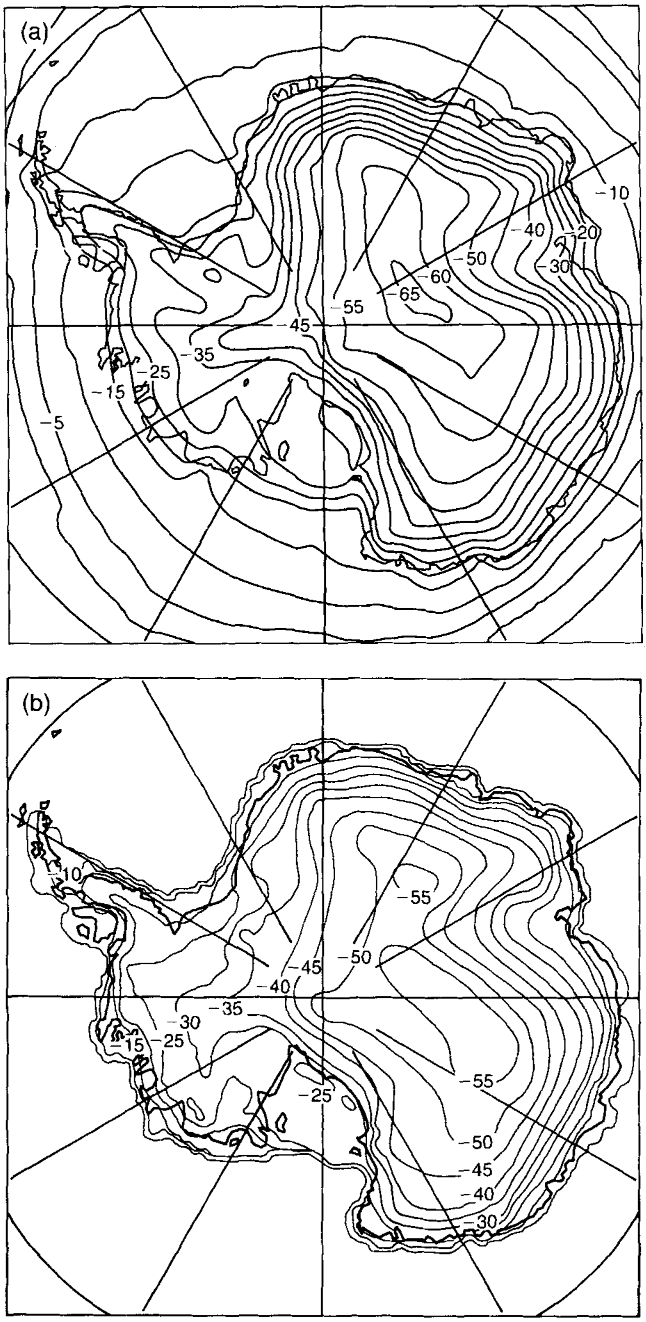

Fig. 3. Annual temperature from **a.** the Unified Model and **b.** deduced from 10m borehole temperatures (redrawn from Radok *et al.* 1987). The contour interval is 5°C.

constant throughout the year: in summer temperatures are approximately correct, but in winter they are too low by about 5 °C. Seasonal variation for two selected locations is discussed in section 5. Around the coasts of East Antarctica, temperatures are around -15°C, in agreement with Radok, and with temperatures from stations reported in Schwerdtfeger (1984). Both the model and the Radok data show a cold area over the Ross ice shelf.

Precipitation

The current mass balance of Antarctica is not known, even to the extent of sign (Houghton *et al.* 1990). In a warmer world two competing changes may be postulated – more glacial discharge, and more precipitation since warmer air can hold more moisture. This latter effect can be crudely predicted by parametrizing accumulation in terms of temperature, height, continentality, etc. (Fortuin & Oerlemans 1990). More accurate predictions can only come from a GCM because of the many possible circulation changes that could also occur. Fig. 4 shows precipitation minus evaporation as predicted by the UM, by its predecessor the fifth annual cycle (5AC) model and that derived from glaciological study by Giovinetto & Bentley (1985) (the 5AC is the version of the UKMO 11 layer model which is essentially that described by Smith (1990). Data used from the 5AC are 5-year averages). Over land, modelled precipitation is in general much larger than evaporation so their difference – accumulation – mostly reflects snowfall patterns.

The most notable features – the central "desert" area (where accumulation is less than 50 mm y^{-1}), the ring of precipitation around the coasts, and the high precipitation on the Antarctic Peninsula – are present in both models. In the UM, the area of and accumulation rate in the central desert are rather good. Coastal high precipitation is probably too high in the UM and underdone in the 5AC. Both produce high precipitation over the peninsula, which is (in reality) an area of complex topography and very spatially variable snowfall. Because of the smoothing necessary to represent the height of the peninsula in the model (see Fig. 1) we cannot expect an accurate accumulation value for this area. Giovinetto & Bentley (1985) give an areally averaged accumulation rate for the whole of Antarctica excluding the peninsula but including ice shelves of 143 mm y^{-1} which Frolich (1992) increases to 154 mm y^{-1} to include the peninsula. We include the ice shelves because the model represents most of them, and certainly the largest, the Ross and the Ronne-Filchner, as land-ice areas. The average annual accumulation for the whole of Antarctica is 182 mm y^{-1} for the UM and 100 mm y^{-1} for the 5AC. If the peninsula is excluded from the calculation for the UM, the rate becomes 170 mm y^{-1}. Although the UM value is higher than that of Giovinetto & Bentley/Frolich it is within the range of values presented in Giovinetto & Bull (1987) and more realistic than the value of 498 mm y^{-1} reported by Boer *et al.* (1992b) for the Canadian Climate Centre GCMII. We are investigating the very high values of snowfall that occur at a few coastal points (e.g. at 55°E).

Katabatic winds

The katabatic, or drainage, winds are generated by the radiative cooling processes which cause surface inversions over much of Antarctica. Information about the inversion structure in winter over the interior is very sparse but the

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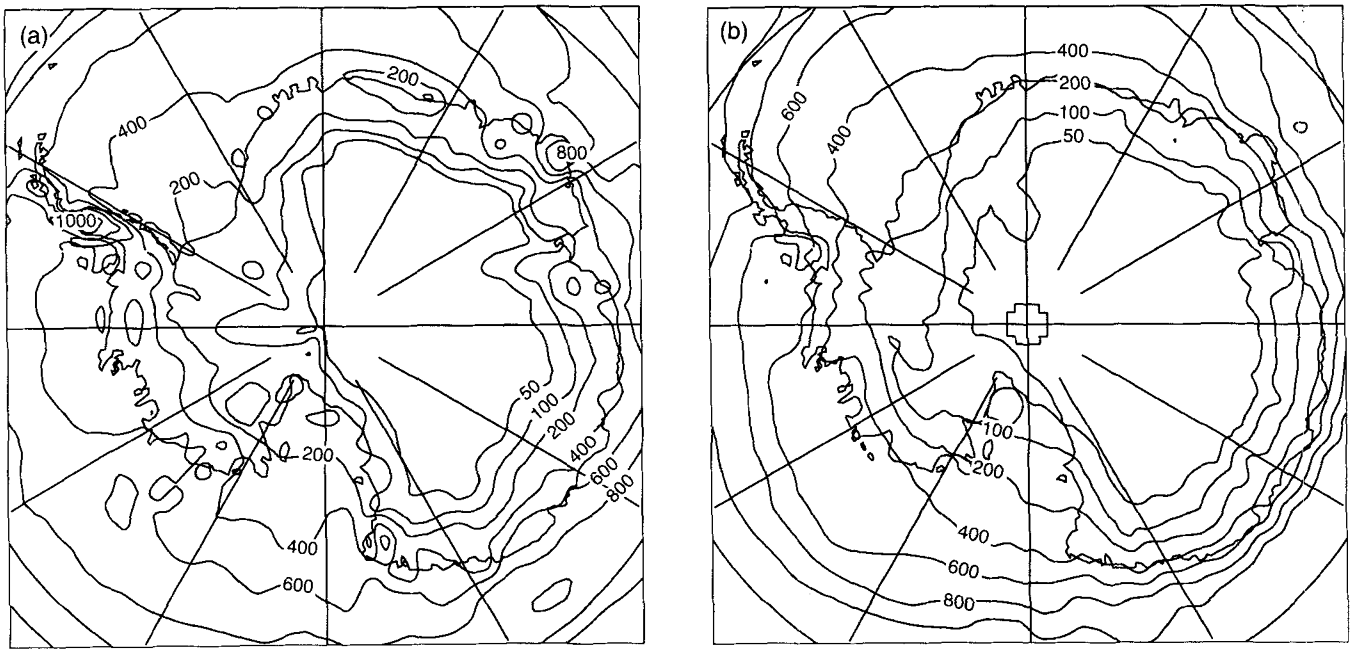
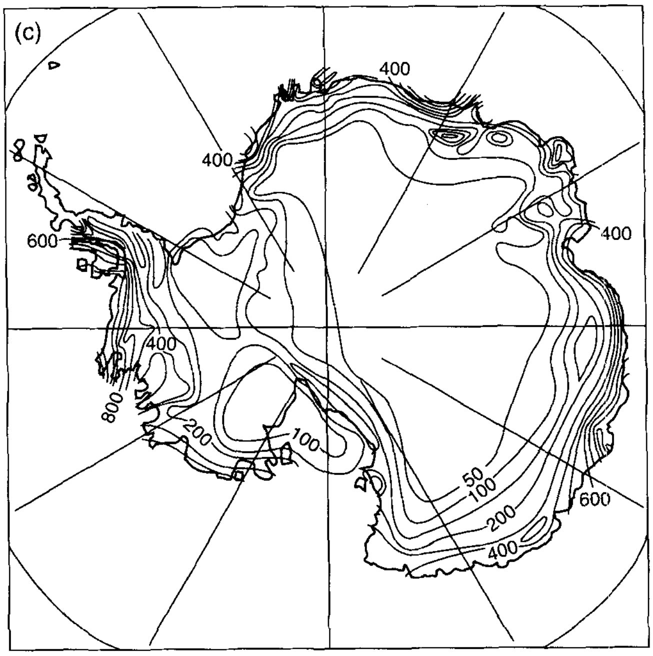


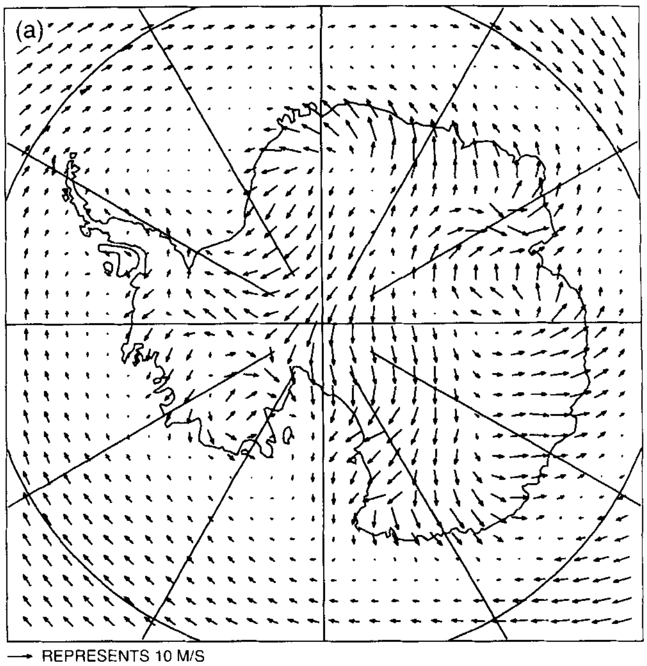
Fig. 4. Net accumulation from a. Unified Model b. Fifth Annual Cycle and c. Giovinetto and Bentley 1985. The contours are at 50, 100, 200, 400, 600 and 1000 mm y^{-1}.



radiosonde database used in Connolley & King (1993) shows that the strength of these inversions at the two remaining interior stations (Amundsen-Scott and Vostok) is on average about 15°C in the lowest 500 m of the atmosphere. Cold air flows northwards off the Antarctic plateau and is given an easterly component by Coriolis forces (Schwerdtfeger 1984 and James 1989). The surface cooling, and hence the katabatic wind regime, is more pronounced in the sunless months. All the results in this section are for the winter period June–July–August. The model cannot resolve individual valleys and so model output should be compared to the general speeds at the coast which are of 5–10 ms^{-1} (Schwerdtfeger 1984) and not to the very high wind speeds that occur locally when valleys cause the winds to converge (e.g. at Port Denison which has an annual average wind speed of 19 ms^{-1}). Fig. 5 compares the winds at 10 m diagnosed by the model with surface winds deduced from stations and traverse records by Mather & Miller (1967) and the continental-scale model of Parish & Bromwich (1991) (lowest level 125 m). The wind pattern from the UM is good on the large scale, showing the expected katabatic flow with easterly deflection, making an angle of 30–45° with the fall-line near the coasts. The wind pattern is in better agreement with Mather & Miller than was the previous UKMO model as reported in Mitchell & Senior (1989), and the wind speeds are up to twice as high, again in better agreement with surface observations from Schwerdtfeger. This improvement is probably due to the increased vertical resolution of the new model, the lowest level now being about 25 m above the surface as opposed to 200 m in the 5AC. As a possible topic for further investigation we note that rather than compare surface winds a more interesting comparison could be made between the mass flux within the inversion layer in different models and in reality, which is probably a more dynamically significant quantity than the surface wind.

Coreless winter

The Antarctic plateau experiences the remarkable phenomenon of the "coreless winter": the multi-annual



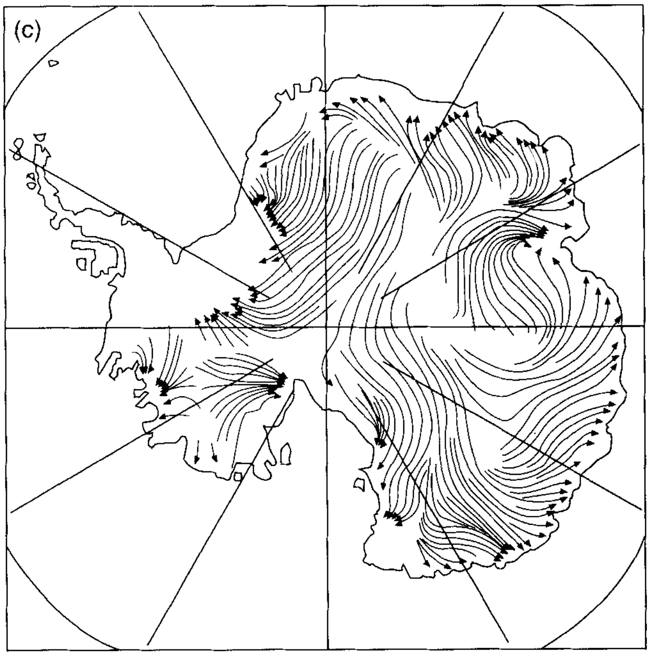
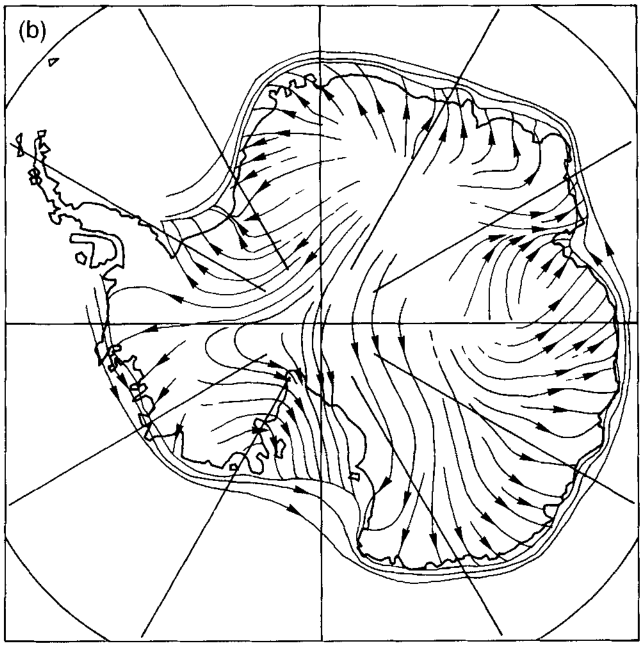


Fig. 5. Low levels winds in m s^{-1}. **a.** Unified Model diagnosed 10m winds for JJA. **b.** Mather & Miller (1967) surface data. **c.** Parish & Bromwich (1991) "winter" conditions.



monthly mean air temperature at 1.5 m remains roughly constant for the 5 months between mid-April and mid-September. During the coreless winter heat loss by radiation from the ground is balanced by sensible heat transfer and downwards radiation from the air above, whose temperature is sustained by air advected from low latitudes. The relative importance in maintaining the temperature profile of the atmosphere during the coreless winter between radiation and adiabatic heating is not yet known. Fig. 6 shows the 1.5 m temperature climatology averaged over 25 years for Vostok and Amundsen-Scott (dashed line) and that produced by the UM run. The Vostok UM data are for the point 77.5°S, 105°E (Vostok is at 78.5°S, 106.9°E), and at approximately the correct height. The Amundsen-Scott UM data are for the grid point at 90.0°S which has an average height of 2708 m, 100 m lower than Amundsen-Scott. Accordingly the UM values for Amundsen-Scott have been reduced by 1°C to account for the height difference between station and model grid points.

The UM reproduces the coreless winter well. The fit for Amundsen-Scott is remarkably good and the rate of change in spring and autumn is accurate. At both stations summer temperatures are correct whilst winter temperatures are too low, by only a few degrees at Amundsen-Scott and by up to 5°C at Vostok. At Vostok the coreless feature is present, but spring decline and autumn increase is too rapid. Because clouds are one of the most uncertain features of climate models we suspect that underprediction of the cloud cover/thickness, which would tend to cool the surface, may explain the too low winter temperatures at Vostok. A further factor is the exchange of heat between the relatively warm ocean and cold air, which is suppressed over sea ice. In an earlier run with (amongst other differences) more extensive sea ice winter temperatures at Vostok were up to 5°C colder, in agreement with the observational study of Weatherly *et al.* (1991) which showed a negative correlation between temperature and ice extent.

Conclusions

The Antarctic climate of the UKMO Unified Model is generally realistic and shows significant improvements over

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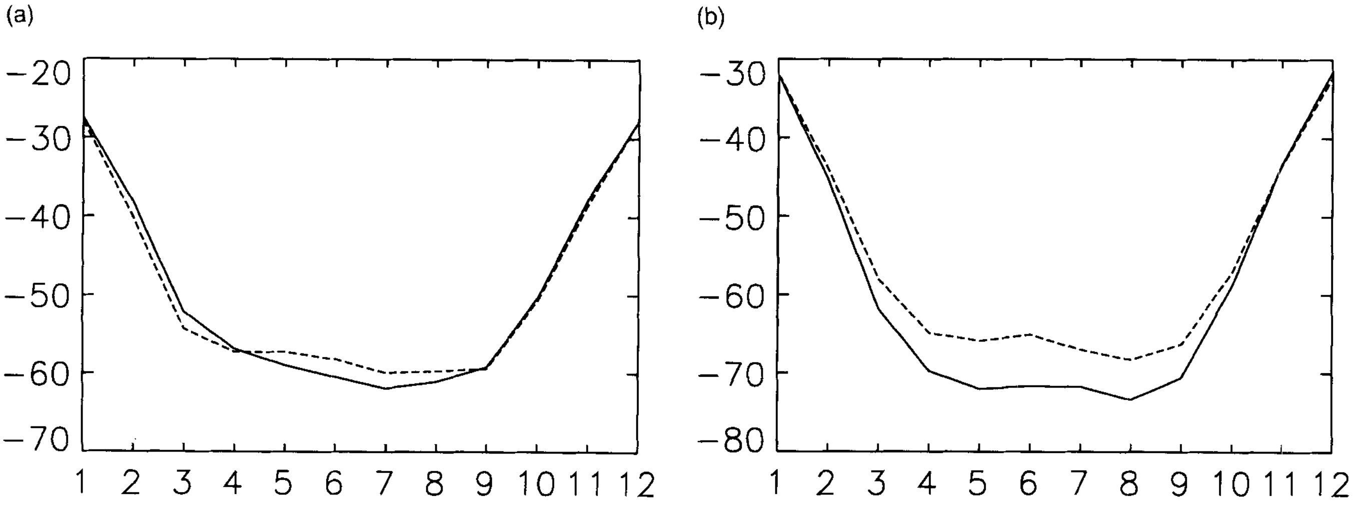

Fig. 6. Series of monthly 1.5 m temperatures (°C) for **a.** Amundsen-Scott and **b.** Vostok. Dashed line: 25-year climatology from Schwerdtfeger (1984); solid line: 10-year averages from the Unified Model. Note the change of vertical axis between **a.** and **b.**

earlier models. The general circulation pattern is acceptably simulated, although the pressure around Antarctica is too low by 4–6 hPa. Annual average temperatures over the continent are plausible and well within the range of observations, although the seasonal variation shows a rather cold winter on the high Antarctic plateau. The low-level wind field is as accurate as can be expected given the resolution of the model. The snow accumulation has the correct general features, although the modelled coastal snowfall appears too high, and the modelled interior snowfall is good.

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