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Implications for the interpretation of ice-core isotope data from analysis of modelled Antarctic precipitation

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ABSTRACT. By consideration of model-generated atmospheric data, dominant anomalies in the synoptic circulation patterns are observed under conditions of high Antarctic precipitation. This is associated with strong moisture advection of marine origin. Examining precipitation at individual locations reveals a strong relationship between local surface temperature and precipitation amount. Days with >5 mm of precipitation (which, on average, corresponds to about 8% of days over Antarctica) have surface temperatures that are around 10°C warmer than the mean. This bias suggest that abnormal conditions are captured in the ice-core record and that interpretation or reconstruction of palaeotemperatures will succeed only under the possibly flawed assumption that similar abnormal conditions existed at the time of deposition. Although isotopic analysis of Antarctic ice cores has been used successfully in palaeoclimate studies, a complete understanding of the underlying processes affecting the deposition of the core remains to be found. It is reasoned that by obtaining such an understanding, it may be possible to reconstruct the synoptic conditions under which accumulation occurred.

INTRODUCTION

The work of Dansgaard (1964) on the behaviour of stable water isotopes in precipitation has prompted many studies of palaeoclimates from ice-core data. It is generally accepted that the high correlation between the annual D/H or $^{18}O/^{16}O$ ratios and mean ambient temperature can be used directly to infer palaeoclimatic temperatures from ice-core samples (e.g. Johnsen and others, 1995; Jouzel and others, 1996). Jones and others (1993) point out, however, that large-scale temperature trends cannot be extrapolated much beyond the locality of the drill-site.

This empirical approach relies solely on the observational data rather than the physical processes involved. An understanding of the role of atmospheric circulation in influencing the isotopic signature revealed in Antarctic drill cores is crucial to the interpretation of the core data. Without such knowledge, conclusions regarding palaeoenvironments from any type of proxy data could be seriously misleading (Taylor and others, 1995). The key to understanding and interpreting the isotopic signals in ice cores over time is two-fold. First, we must consider the atmospheric processes that transport water from a region of evaporation to the place of precipitation, and secondly, we need to understand the processes governing the isotope concentration of the accumulated water. We would expect, for example, that days with precipitation would have greater than average cloud cover and stronger thermal advection from lower latitudes. This would influence the local surface temperature. Such conditions are by definition anomalous and perhaps not fully representative of mean temperature. While this has been appreciated for some time in principle (e.g. Kato, 1978; Aristarain and others, 1986), little attempt has been made to explain or quantify the uncertainties to which the interpretation of the isotope–temperature relationship is subject.

To highlight the important aspects of interpretation of the palaeoclimatic signal at a given locality, we examine here some of the processes involved in deposition of water at the drill-site. To perform such an analysis, we need high-resolution (both spatial and temporal) data. Measurements of daily precipitation and other atmospheric parameters are unavailable from the observational network. Therefore, to perform this analysis, we must make use of output from a global climate model with a complex physical representation of the atmosphere. The implications that a comprehensive understanding of the synoptic processes influencing the isotopic signature has for existing palaeotemperature reconstructions, and for successfully estimating the synoptic variability of palaeoclimate systems from the ice-core data, are discussed.

OVERVIEW OF THE NUMERICAL MODEL

The Melbourne University general circulation model (GCM) is a non-linear, physically based, spectral, primitive equation model and is discussed in detail elsewhere (Simmonds, 1985; Simmonds and others, 1988; Simmonds and Law, 1995). The spatial resolution is defined by truncation of the spectral series at wavenumber 21, roughly corresponding to a 5.6° × 3.3° grid. In the vertical, there are nine discrete levels in the terrain following "sigma" coordinates, with the lowest level about 75 m above the surface. For the model run at this resolution there are approximately 350 points over the Antarctic continent. Many physical processes not governed by the primitive equations are included via appropriate parameterisations. These include the radiation scheme of Fels and Schwarzkopf (1975) and Schwarzkopf and Fels (1991), the convective scheme suggested by

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Manabe and others (1965), a soil hydrology scheme following Deardorff's (1977) model and a parameterisation of heat fluxes over sea ice applied by Simmonds and Budd (1990).

Clouds are included interactively at three levels (Argete and Simmonds, 1996) to affect the radiation, and snow cover is prescribed as the climatology from passive-microwave observations by the Nimbus 7 satellite. The topography originates from continental heights of Smith and others (1966) and there is forcing at the lower boundary from the sea-surface temperatures of Reynolds (1988).

Although modelling Antarctic moisture is a difficult task in practice, Simmonds (1990) showed that the model-generated accumulation rates over the Antarctic are representative of the accumulation estimated from stake measurements in both amount and spatial distribution. As such, it is thought that the Antarctic precipitation is modelled with sufficient accuracy and is appropriate for use in this study. The model results from the second decade of a 20 year control integration are used in this study.

SYNOPTIC CONDITIONS

Precipitation is obviously an integral part of ice-core analysis through accumulation at a drill-site. To determine what synoptic conditions lead to precipitation, we examine the mean sea-level pressure (MSLP) anomalies for each day in the model dataset. One calculates the anomalies by subtracting, from the given pattern, the monthly climatology temporally interpolated to the appropriate calendar day. A subset of the anomalies is chosen and averaged for the days on which more than a specified amount of precipitation fell at a given grid location. The amount chosen here is 5 mm d^{-1}, as it represents high-precipitation conditions and occurs on roughly one in ten days at coastal locations. This fraction varies depending on precisely which gridpoint is considered. Further, even the most arid points (e.g. Vostok) show a number of totals over 5 mm because model data are used.

Figure 1 shows the averaged MSLP anomaly pattern for the coastal point near Casey base (67.7° S, 112.5° E) and the inland Vostok base (77.6° S, 106.9° E). Coastal sites (e.g. Casey) commonly show a local feature associated with the approach of a "cyclonic system". This dipolar structure, seen clearly in Figure 1a, suggests a northerly air stream which would advect relatively warm, moist marine air over the site. Upon cooling, this air would easily become saturated and condense into the modelled precipitation and release latent heat at the site. For inland cases (e.g. Fig. 1b), such a dipolar feature is not usually present, and indeed it is more common for a single cyclonic feature to be present. This low-pressure anomaly is probably associated with precipitation formed by ascending air associated with surface convergence.

Kinematic trajectories were generated in three dimensions for the 6 days prior to arrival at the site under consideration, for each day on which more than 5mm of precipitation occurred. Figure 2 shows the density of the origin of air parcels 6 days prior to precipitation, together with the calculated mean trajectory path. This trajectory reveals that indeed the air is of marine origin for the coastal site. The direction of approach deviates from that suggested by the geostrophic assumption as the driving winds from the GCM include the effects of katabatic flow. Few of the individual trajectories penetrate the region of the circumpolar

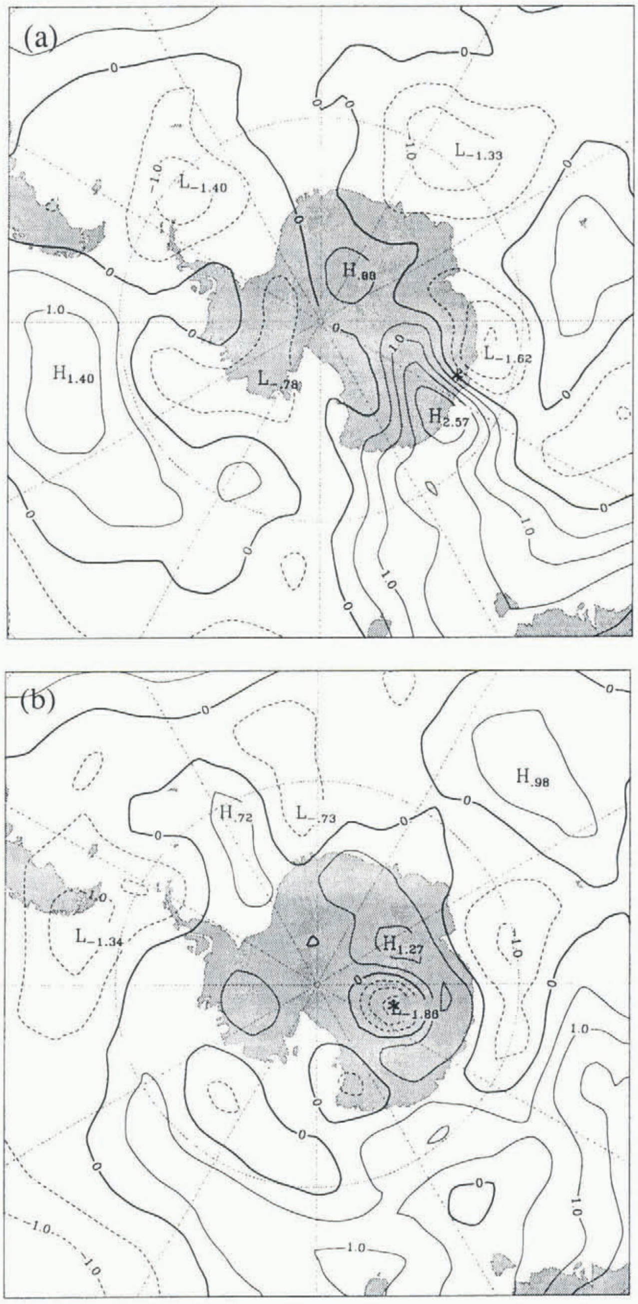

Fig. 1. MSLP anomaly on days with > 5 mm precipitation for (a) Casey and (b) Vostok locations. The contour interval is 0.5 hPa and the zero contour is shown in bold.

trough. The MSLP anomalies and the trajectory analysis suggest that there are active links between the precipitation and the local synoptic conditions on any given day.

Analysis of precipitation

We now turn to consider the precipitation over the Antarctic continent in more detail by examining the daily precipitation totals at the 350 model points located over Antarctica. Although more precipitation events tended to occur in winter months, individual precipitation events with high totals occurred throughout the year. These data revealed that about half of the days showed no or negligible precipitation. From the same 10 year model dataset, we also extract the surface temperatures. For each model point, we calculate the surface-temperature anomaly as the difference between the daily temperature at the site and the climatolo-

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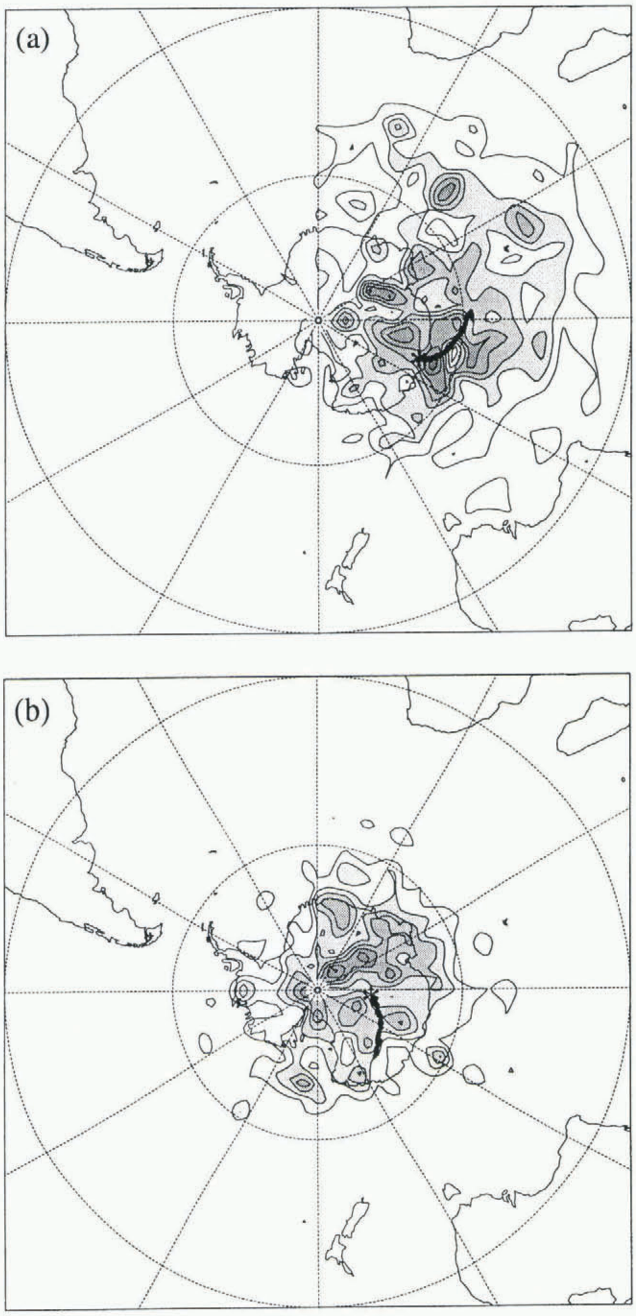

Fig. 2. Average trajectory paths and density of trajectory origins for the 6 days prior to precipitation at (a) Casey and (b) Vostok locations. Dark regions show higher density in arbitrary units of trajectory origins per unit area. An asterisk marks model locations.

gical mean interpolated to the appropriate time of the year. Thus, for each of the 350 Antarctic points, a 10 year time series of both the precipitation and surface temperature was available.

Ordering the precipitation totals at each point by amount from lowest to highest shows a distribution of an exponential nature, common in precipitation data (e.g. Noone and Stern, 1995). This highlights the fact that only a small percentage of precipitation events have high precipitation totals. The shaded region of Figure 3 shows the average of these distributions. We plot the surface-temperature anomaly corresponding to the precipitation amounts and then average across the 350 points.

Figure 3a shows a clear monotonic trend in the associated surface-temperature anomalies. We see that the wettest days are warmer than the average by up to 15°C, and days with over 5 mm of precipitation (around 8% of days) are over 10°C warmer. If the dataset is broken down seasonally (Fig. 3b), we find that the trend is stronger in autumn and winter (up to 20° and 18°C, respectively) than in summer and spring (5° and 12°C). The gradient of this trend is also slightly larger if only coastal locations are considered. A similar trend is found at other model temperature fields although it is not as pronounced. For example, the lowest atmospheric level in the model (sigma level 0.991) displays warm tendencies up to 2°C.

During precipitation events warm air is advected from the north, and the coastal regions of the continent are subject to greater cloud cover. Hence, it is not clear a priori whether the warm surface conditions of high-rainfall days are associated more closely with the extra southward sensible-heat transport or the additional trapping of longwave

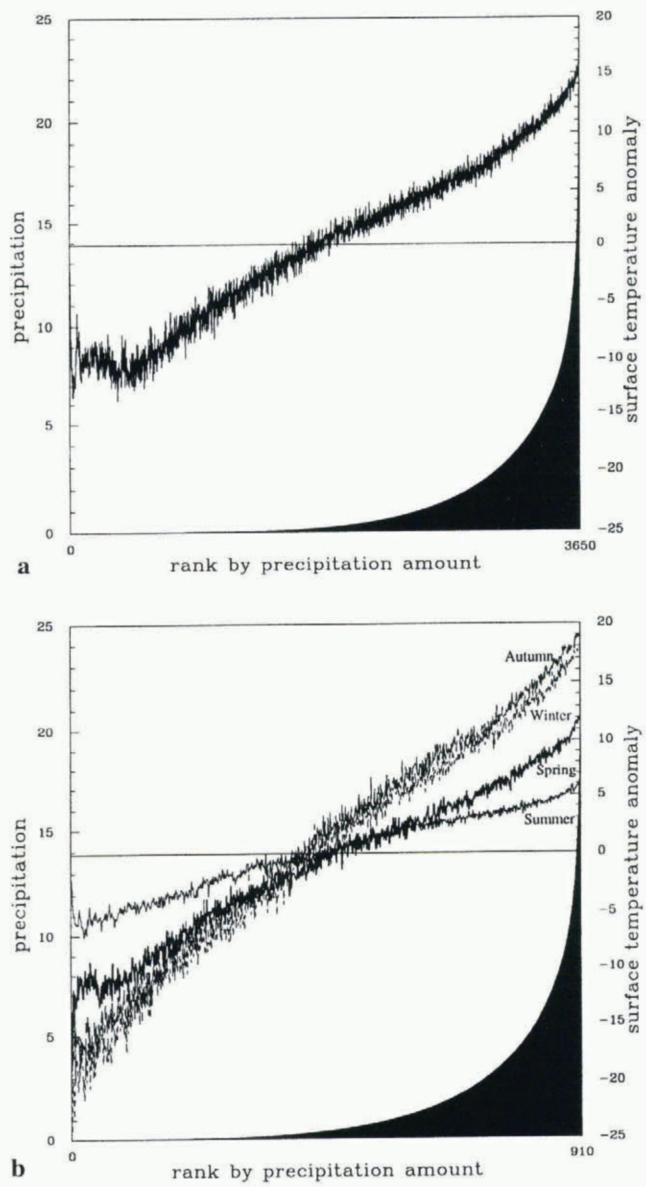

Fig. 3. Mean precipitation amount (shaded region) and corresponding mean surface-temperature anomaly (curve). The x axis is ranked by precipitation amount from lowest to highest for (a) all data (3650 days) and (b) seasonal comparison (910 days). Surface-temperature anomaly is marked on the right axis in °C, and precipitation is on the left axis in mm d^{-1}.

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radiation by the changed cloud conditions. This question can be answered simply by performing experiments in a GCM in which we prescribe cloud cover of given amounts. Specifically, we set the cloud concentration at all three cloud levels to have, first, 100% and, second, 0% and perform a 3 year integration. The close similarity in the temperature trends resulting from these two runs (not shown) suggests that indeed the underlying mechanism is warm advection rather than radiation associated with greater cloud amounts. This conclusion is supported by the earlier result that days with precipitation have a predominant northerly air stream advecting moisture to the precipitation site. Similarly, the reduction in the temperature trend for inland sites results from both weaker advection and a drier air mass.

The trend seen in Figure 3 has an obvious consequence for recreating palaeoclimates from ice-core records. Specifically, as it is the days with high-precipitation events which are recorded in the ice cores, and these days are shown to have significantly higher than average temperatures, the core isotope data will reflect these warmer temperatures.

DISCUSSION

The naive interpretation of the above result suggests that any reconstruction of palaeoclimates from core isotope data will overestimate the temperatures if one does not include this warm bias. However, the relationship between the isotope concentration and temperature is determined by empirical means for a given site or area. Therefore, the bias on any given day has already been included in the regression. We note that such a method focuses on the annual mean temperature, and that daily information associated with individual precipitation events is lost.

The appropriate interpretation is that the core data represent conditions that are in some way abnormal. This is true in the simple case of surface temperature and in the more complex case of the synoptic situation as seen above with the example of MSLP anomalies. That is, the ice-core signal will reflect a circulation regime that is significantly different from the mean conditions.

An important consideration that follows from this is the temporal variation of the bias. We saw in Figure 3b that the temperature anomalies on precipitation days in the autumn and winter differ significantly from those in the warmer summer and spring months. We attribute this difference to more intense baroclinic activity leading to stronger northerly advection of warm, moist air during autumn and winter. As very little is known about the circulation conditions of various palaeoclimates, it is difficult to say whether such a seasonal variation would prevail. Similarly, it is likely that the strength of circulation was different from that of today. This is important insomuch as we cannot be sure that the conditions under which accumulation can occur have the same bias over time.

P. Valdes and others (personal communication, 1997) indicate from simulations with a GCM that there is a reduction in strength of polar baroclinicity during the Last Glacial Maximum. Following the above argument, we would expect a reduced slope in the temperature bias. This would result in an underestimate of palaeotemperatures from the regression relation derived from experimental data collected under today's conditions. This scenario is incomplete, in that altering the circulation strength will also induce changes in other complex atmospheric processes like evaporation, transport and precipitation.

It may be possible to quantify, to some extent, the differences between various global circulation regimes by considering the variation in accumulation rates in ice cores. One could focus on times when there is a shift from glacial to interglacial periods. If there is a particular period of change that is temporally consistent over a large geographical domain, it is possible there was a significant change in the circulation regime and that empirical temperature reconstruction would be less reliable.

To obtain detailed information about the variations in isotopic content from an ice core on short time-scales would be very difficult, and indeed may be impossible. The use of modelling techniques, instead of observational data, may yield a valuable approach. Running an ensemble of simulations that represent a number of palaeoclimate systems would give an indication of the range of circulation regimes that may exist. Incorporating a hydrological cycle that allows for the stable-isotopic forms of water would then give an indication of the spatial and temporal variations in the isotopic concentrations, along with estimates for accumulation rates. This would provide a useful tool in linking the measured isotope data in ice cores to the synoptic conditions via the precipitation signal. This would allow one to gain more information than is given simply by the mean conditions.

CONCLUDING REMARKS

It is of great importance to obtain a complete understanding of the precipitation processes leading to accumulation before analyzing ice-core data. The example shown here highlights how, without such knowledge, the regression techniques commonly used to reconstruct palaeotemperatures are questionable, in that the assumed relationship may be different under a palaeoclimatic regime.

Through precipitation, it is possible to associate the measurements in the ^{18}O record with the prevailing synoptic conditions of the day. As there is only one day in ten that exhibits a high-precipitation event leading to significant accumulation, there will be a bias in the ice-core composition toward conditions that are in some way abnormal. In the results given here, these conditions are warmer. The increased synoptic activity shown in the MSLP anomalies is also not representative of the "average" conditions around any single Antarctic site.

An extension of the argument of bias in ice-core records presented assumes a similar bias would have been evident in a dataset representing the circulation patterns of palaeoclimate systems. Specifically, one can infer from the ice-core measurements only the conditions of the abnormal synoptic situation that lead to precipitation. Nonetheless, it may be possible to assess the expected variability of various palaeoclimates by considering the extreme conditions expected during precipitation. GCM experiments that recreate these extreme conditions of precipitation will also contain information about daily circulation that does not result in precipitation. The difference between these two conditions will give an indication of the atmospheric variability on a daily time-scale present under a given palaeoclimatic circulation regime. By consideration of a range of palaeoclimates a comprehensive understanding of the processes underlying

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the isotopic deposition could be obtained. Palaeoclimate reconstructions could then include estimates of the temporal differences in the variability of the global atmospheric circulation, as well as the mean conditions that are currently reported in the literature.

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