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; Arístarain 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, 1983; Simmonds and others, 1988; Simmonds and Law, 1995). The spatial resolution is defined by truncation of the spectral series at wave number 21, roughly corresponding to a $0.56° \times 3.3°$ 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 (Argente 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 grid point 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 5 mm 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 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-
test 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 season­
ally (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 sub­
ject to greater cloud cover. Hence, it is not clear a priori
whether the warm surface conditions of high­rainfall days
are associated more closely with the extra southward sensi­
ble­heat transport or the additional trapping of longwave
conclude 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 palaeoclimatic 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 δ18O 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
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.

REFERENCES


