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Intercomparison of firn core and meteorological data

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Abstract: High resolution firn core records of the oxygen isotope ratio ($\delta^{18}O$) and trace chemical species were extracted from a high accumulation site on Law Dome, East Antarctica. Inter-core comparisons were conducted and regional events identified in cores 5 km apart. High resolution dating of one of the firn cores was established using a co-located Automatic Weather Station (AWS) equipped with a snow accumulation sensor, allowing dating of individual precipitation events in the firn core record. Variations in the $\delta^{18}O$ and trace chemical records were compared with meteorological conditions at the mesoscale and the synoptic-scale. Particular focus was given to an abrupt change in sea salt concentrations and $\delta^{18}O$ within a depth range that appears from AWS accumulation data to have been deposited over a 24 hour period. The abrupt change in the firn core record was found to be consistent with an abrupt change in meteorological conditions. Direct comparisons between high resolution firn core records and meteorological conditions will greatly facilitate the interpretation of signals preserved in deep ice cores.

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Key words: automatic weather station, firn core, meteorology, oxygen isotope ratios, sea salt ions

Introduction

The aim of deep ice core drilling in polar regions is to extract chemical and physical information that aids in the reconstruction of past atmospheric and climatic conditions. In the face of global climate change, ice core records are powerful tools for understanding atmospheric forcing and potential consequences of climate change. However, our ability to reconstruct climate conditions is limited by difficulties associated with establishing relationships between variations in ice core signals, and changes in atmospheric and meteorological conditions. Previous studies have addressed this issue through the use of high resolution firn core, snow pit and aerosol measurements (e.g. Mayewski *et al.* 1990, Bergin *et al.* 1998, McConnell *et al.* 1998, Minikin *et al.* 1998). More recent research has begun to directly compare firn core and snow pit records with variations in observed meteorological conditions (e.g. Kottmeier & Fay 1998, Hardy *et al.* 1998, Vuille *et al.* 1998).

The firn cores analysed in this research were retrieved from near the Dome Summit South (DSS) site at Law Dome, Antarctica (Fig. 1). The DSS site is the location of a deep ice-coring project which recovered an ice core climate record covering 80 kyr (Morgan *et al.* 1997). Law Dome is situated at the edge of the main East Antarctic ice sheet and projects into the predominantly easterly atmospheric circulation produced by the quasi-stationary cyclone located to the north-east of Law Dome (Bromwich 1988). Cyclonic depressions frequently pass to the north of Law Dome producing high accumulation rates of *c.* 0.7 ma^{-1} ice equivalent (IE) for sites near the summit of the Dome (Morgan *et al.* 1997). This high annual accumulation leads to the deposition of thick annual layers, allowing the extraction of glaciochemical records with sub-annual resolution. The absence of high wind gusts at Law Dome (Adams 1996) minimize mixing and redistribution of surface snow, and low mean summer temperatures (-12.6°C) (Allison *et al.* 1993) preclude summer melt. These conditions limit disturbance of the chemical archive preserved in the firn.

The characteristics of the synoptic-scale meteorology of the Law Dome region make it an interesting site for examining the impact of meteorology on ice core signals. Jones & Simmonds (1993) identified a seasonal variation in the peak values of cyclogenesis and cyclolysis in the circumpolar trough north of this region of East Antarctica, with a general intensification in cyclone density during the winter months (June–August). A semi-annual variation in atmospheric pressure has also been observed in East Antarctica with low pressure recorded in spring (September–November) and autumn (March–May) (Schwerdtfeger 1984, Allison *et al.* 1993, King & Turner 1997). The frequent intrusion of cyclonic events over Law Dome also provides a mechanism for connections with lower latitudes. Meteorological reanalysis has shown that cyclonic activity, storm tracks and general circumpolar circulation in this region are influenced by atmospheric ridging and blocking from low latitudes in Australasia (Cullather *et al.* 1998, Pook & Cowled 1999, Pook & Gibson 1999). It is expected that high resolution ice cores from Law Dome will track variations in synoptic-scale meteorology.

This paper presents preliminary results from new techniques

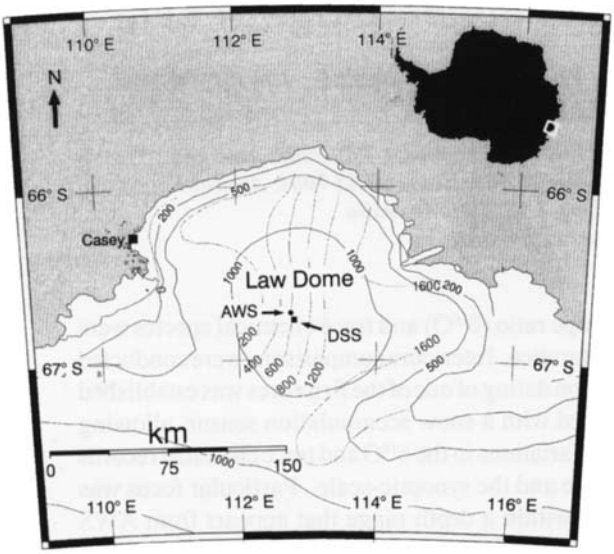

Fig. 1. Location of Law Dome, East Antarctica, showing the location of the AWS (66°44'S, 112°45'E) and DSS (66°46'S, 112°48'E) drilling sites.

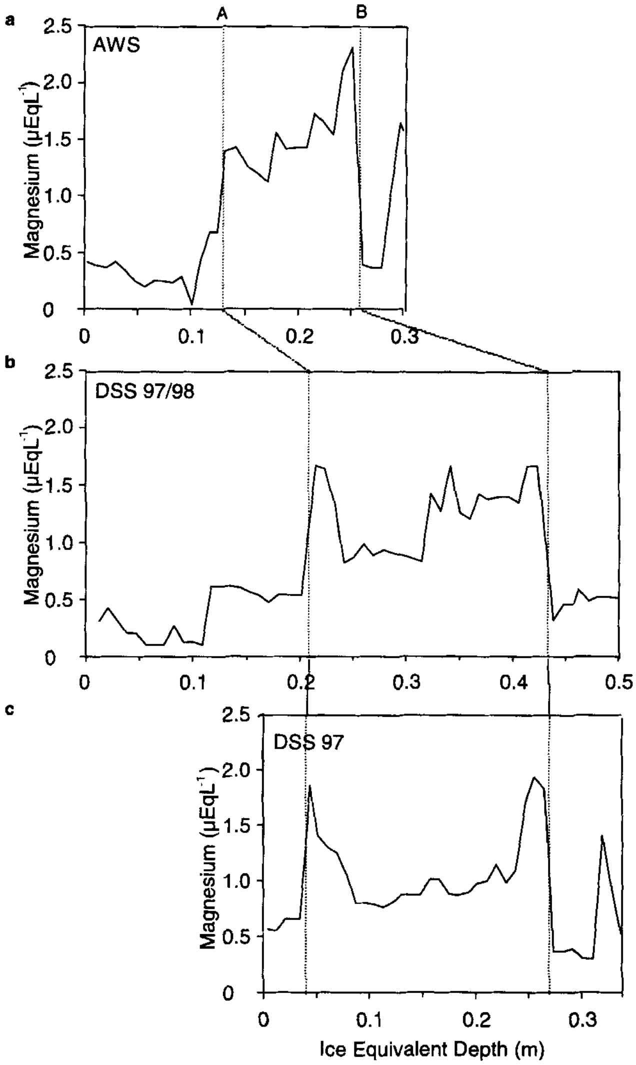

Fig. 2. Intercomparison of magnesium records for three firn cores drilled at Law Dome. **a.** AWS (drilled 04/01/98), **b.** DSS 97/98 (drilled 04/01/98), **c.** DSS 97 (drilled 03/11/97). The offset in the DSS 97 record is due to the earlier drilling date of this core. Regional accumulation events are labelled (A, B).

by which trace chemical and oxygen isotope ratio ($\delta^{18}O$) records in firn cores are directly compared with observed meteorological conditions. Firn cores were analysed for $\delta^{18}O$ and trace cation species (Na^+, K^+, Mg^{2+}, Ca^{2+}). Individual precipitation events were identified and inter-core comparisons used to assess the spatial reproducibility of signals preserved in firn cores. A dating scale was derived using the snow accumulation record from a co-located Automatic Weather Station (AWS 1170). The dated firn core records were compared with meteorological conditions at the mesoscale and synoptic-scale to examine potential source, transport and deposition processes. This present day information is essential to the interpretation of the climate signals contained in the 80 kyr DSS record.

Methods

Firn core analysis

This study draws on material from three shallow firn cores retrieved during the summer of 1997/98: AWS (drilled 4 January 1998), DSS 97/98 (drilled 4 January 1998) and DSS 97 (drilled 3 November 1997) (Fig. 1). The DSS and AWS core sites were 5 km apart and cores were drilled using a hand corer. The core sections cover the eight months that AWS 1170 was operational and were sampled at 2 cm resolution. This equates to approximately 100 and 60 samples per annual layer at DSS and AWS respectively.

$\delta^{18}O$ samples were prepared from outer core sections using a band-saw and analysed by conventional Epstein and Mayeda mass spectrometry (Epstein & Mayeda 1953). The trace cation samples were prepared from inner core sections using the clean preparation techniques described in Curran & Palmer (2001). Trace ions were analysed using a DX500 ion chromatograph equipped with Dionex columns and chemical suppressors (Curran & Palmer 2001).

Inter-core comparisons

Inter-core comparisons were made to examine the spatial reproducibility of firn core signals between drilling sites. The firn core records were converted into an ice equivalent depth scale to account for changes in firn density with depth (Fig. 2). The ice equivalent conversion was developed from an empirical fit to densities from other firn and ice cores retrieved from the DSS drilling site (van Ommen *et al.* 1999). The identification of regional accumulation events that are preserved in all cores is required for comparisons with meteorological conditions.

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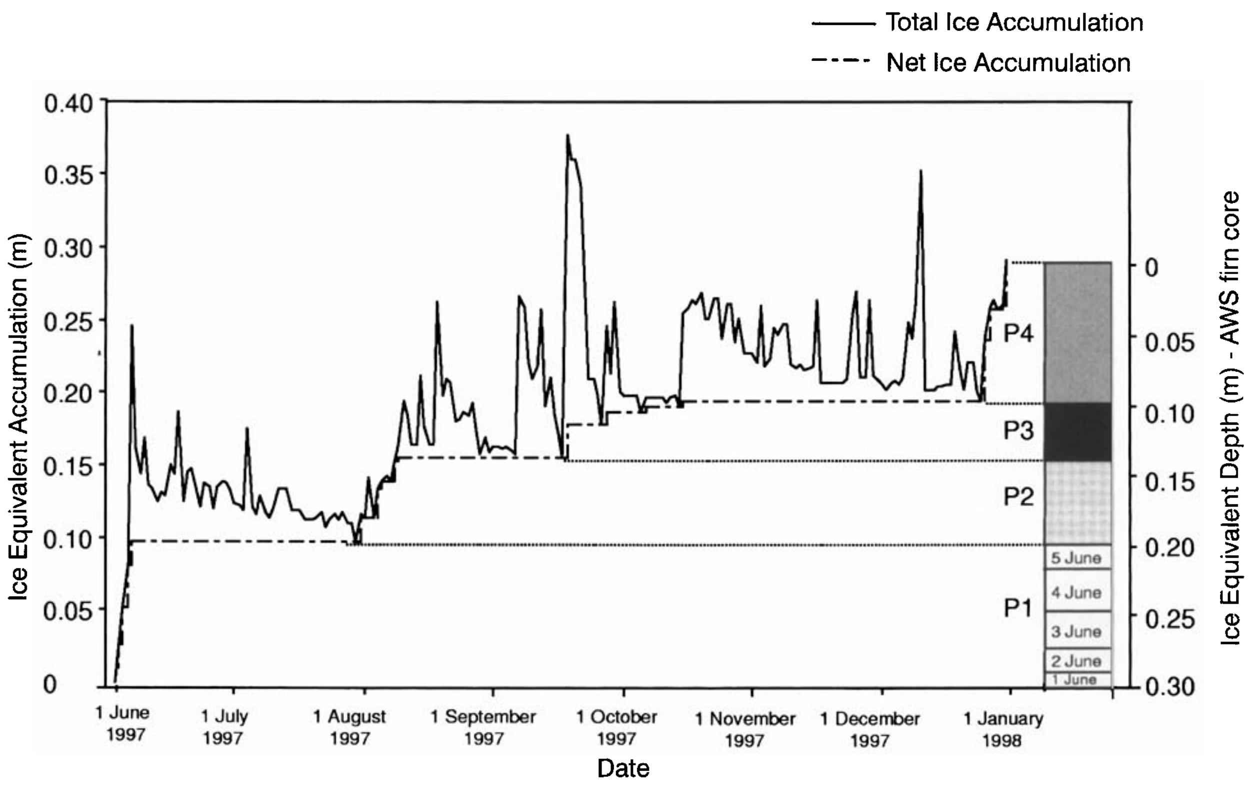

Fig. 3. Total and estimated net accumulation as recorded by AWS 1170 from 1 June–25 December 1997. The 19 net accumulation events are given by the 19 steps on the dashed line (net ice accumulation). These 19 events were grouped into four accumulation periods (P1–P4). The accumulation events comprising P1 are illustrated.

The registration of accumulation events on a common firn core depth scale is influenced by different drilling dates of the cores, accumulation differences between drilling sites, surface irregularity caused by sastrugi and the rapid density changes in the top layers of the snowpack. Despite these factors, regional accumulation events were identified in firn cores 5 km apart (Fig. 2). Abrupt changes in glaciochemical records indicate distinct boundaries between snowfall events, and the reproducibility of abrupt changes in all three firn cores indicate regional events (A, B: Fig. 2). The obvious offset seen in the DSS 97 core compared to the DSS 97/98 and AWS cores is due to the earlier drilling date of this core. The east–west accumulation gradient across Law Dome also has an effect on the registration of events on a depth scale. Accumulation on Law Dome varies from zero to 0.7 ma^{-1} (IE) to the west of the summit, increasing to 1.4 ma^{-1} (IE) 16 km east of the summit (Morgan *et al.* 1997). The AWS drilling site lies 4 km north and 3 km to the west of the DSS drilling site (Fig. 1), and accumulation differences result in a more compressed record preserved at the AWS drilling site (Fig. 2).

Results and discussion

Dating the AWS firn core

High resolution dating of the AWS firn core was established using snow accumulation measured directly over the core site by AWS 1170. AWS 1170 measured snow height at approximately 1000 Univeral Time Coordinated (UTC) every day using an ultrasonic signal, therefore the date of an accumulation event refers to the 24 hours from 1000 UTC the previous day. The accumulation sensor measures surface snow height increments, whereas the firn core records involve sub-surface material subjected to compaction. Snow accumulation was converted to ice equivalent accumulation using the formula:

$$\text{IE Accumulation} = \frac{A_n \times 423.4}{917}$$

where A_n is the snow accumulation on day *n* (m), 423.4 k gm^{-3} is the surface density from an exponential depth–density relationship (Paterson 1994), fit to measured firn densities at the DSS site, and 917 k gm^{-3} is the average density of solid ice. The use of an average density of 423.4 k gm^{-3} gives an estimate of the total accumulated material. Whereas this value is denser than the freshly-fallen material that is deposited and removed over short time scales, it is adopted as a reasonable approximation for the longer time scales applicable to material which is actually compressed and retained.

Figure 3 shows accumulation at the AWS core site from

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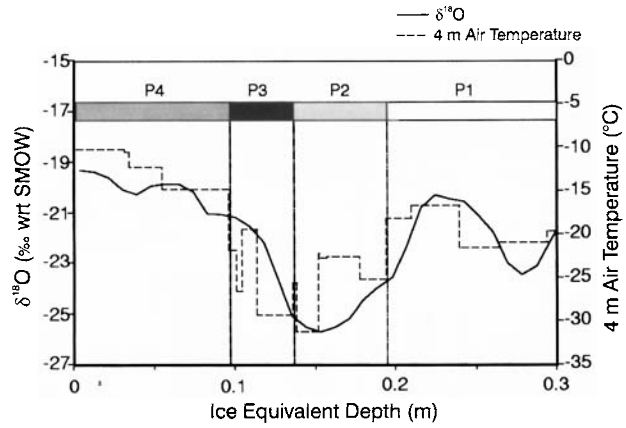

Fig. 4. Comparisons between $\delta^{18}O$ values preserved in the AWS firn core and air temperatures recorded from AWS 1170. Air temperatures correspond to the daily average 4 m temperatures for each of the 19 accumulation events. Accumulation periods are illustrated.

1 June–25 December 1997. Net accumulation of snow is the balance of accumulation events and subsequent snow removal through ablation, wind scouring and a perceived loss through compaction of the snowpack. Winter (June–August) was characterized by a few large accumulation events (5, 16 June, 2 July, 7, 15 August), with little net accumulation on other days. Spring (September–November) and early December featured frequent large accumulation events although snow removal was high. In contrast, accumulation during late December involved numerous small accumulation events with limited snow removal. Net accumulation for the AWS core site was calculated as the difference between snow accumulation and snow removal, as recorded by AWS 1170 (Fig. 3). In this study snow accumulation events resulting in a net increase in the snow surface of 2 cm or more were included in the analysis, and 19 events were identified using this technique, which were grouped into four accumulation periods (P1–P4) (Fig.3).

Temperature and $\delta^{18}O$

The $\delta^{18}O$ record from the AWS core was compared with air temperatures recorded by AWS 1170 during the 19 accumulation events identified in the dating procedure (Fig. 4). The isotopic composition of precipitation is influenced by a number of physical conditions and transport processes, with condensation temperature one of the major influences (Dansgaard 1964). On long time scales site temperatures and $\delta^{18}O$ are well correlated at Law Dome (Morgan & van Ommen 1997), and Fig. 4 shows that this relationship also holds on shorter times scales.

The relationship between $\delta^{18}O$ (δ) and temperature (T), which is required to calibrate the ice core paleothermometer, may be derived from either spatial variability over a region or from temporal variations at a site. A spatially derived slope ($d\delta/dT$) of 0.6–0.7‰/°C has been determined for the Law Dome region (Morgan 1979), and a temporally derived slope of 0.44‰/°C has been calculated from *c.* 700 years of annual cycles of $\delta^{18}O$ at the DSS site (van Ommen & Morgan 1997). Although the short length of the record presented here precludes a robust $\delta^{18}O$ temperature calibration, it is nonetheless interesting to examine the correlation between $\delta^{18}O$ and temperature values on an event-by-event basis. The van Ommen & Morgan (1997) temporal calibration treats the ice core as a continuous recorder, and the comparison here is the first attempt to account for the episodic nature of the record. The temporal relationship between $\delta^{18}O$ and temperature presented here gives a slope of 0.21‰/°C ($r^2 = 0.47$, $n = 15$, $P = 0.002$). The observed slope of temporal calibrations will be influenced by isotopic diffusion in the firn column, which reduces the amplitude of the annual cycle. The degree to which diffusion has affected $\delta^{18}O$ values at the shallow depths examined in this study is not well understood, but may have decreased the amplitude of the $\delta^{18}O$ annual cycle by up to 30%, which is the integrated effect over the full firn column at DSS (van Ommen & Morgan 1997). Therefore, the 0.21‰/°C calibration determined here may be corrected upwards by a corresponding factor, however it is unlikely that the full 30% correction is applicable after 1 year of diffusion. Note that the spatially derived value of 0.6–0.7‰/°C uses long term mean $\delta^{18}O$ values and is unaffected by diffusion (Morgan 1979), and the temporally derived value of 0.44‰/°C has been corrected by van Ommen & Morgan (1997) for diffusion.

The value derived here agrees with the finding that temporally derived calibrations give lower $\delta^{18}O$ temperature slopes than spatially derived calibrations, although the value obtained is considerably lower than the van Ommen & Morgan (1997) value. Whether this difference reflects a genuine consequence of correlating $\delta^{18}O$ and temperature at the event level, or whether it is merely a consequence of the limited data set available here will be answered by further studies similar to the type described here but encompassing longer records.

Table I. Deposition dates and estimated depth of accumulation periods identified in the AWS firn core.

	Date of deposition (1997)	Season of deposition	Number of snowfall days	Estimated ice equivalent depth range in core (m)	Total estimated amount of ice in core (m)
Period 1	1–5 June	winter	5	0.194–0.3	0.106
Period 2	28 July–6 August	winter	6	0.136–0.194	0.058
Period 3	14, 23 September, 2, 11 October	spring	4	0.096–0.136	0.04
Period 4	20–25 December	summer	4	0–0.096	0.096

Winter accumulation Period 1

Uncertainties in the depth registration caused by the use of an average density of surface snow are alleviated in the following analysis by grouping the 19 net accumulation events into four accumulation periods, with three of these accumulation periods characterized by accumulation over a number of days close together in time (Fig. 3, Table I). The following analysis focuses on period 1 (P1), the largest of these accumulation periods, which consisted of events over just a few days and is estimated to have produced approximately 33% of the total material deposited in the 8 month period. Depth-registration uncertainties are much smaller than 33%, allowing material in this depth-range to be reasonably attributed to meteorological events during these few days.

The AWS firn core records of sodium (a sea salt indicator) and $\delta^{18}O$ are shown in Fig. 5. Previous studies for coastal Antarctic sites have found that sea salt concentrations in firn and ice cores are usually higher during the winter months, associated with the increase in cyclonic activity (Curran *et al.* 1998, Wagenbach *et al.* 1998). Since $\delta^{18}O$ values are generally lower during winter due to lower air temperatures an inverse relationship between the sea salt and $\delta^{18}O$ records is expected. This is the case for period 2 (P2), period 3 (P3) and period 4 (P4), however during P1, a period consisting of five consecutive days of accumulation from 1–5 June, sea salt concentrations and $\delta^{18}O$ values are positively related (Fig. 5). Of particular interest during P1 is the abrupt change in firn core signals (sea salts and $\delta^{18}O$) at 0.256 m (IE) (X: Fig. 5), which appears from AWS accumulation data to occur within the 24 hour period prior to 1000 UTC 3 June. This abrupt change was identified in other cores as a regional event (B: Fig. 2).

Examination of the AWS 1170 record during P1 (0000 UTC 1 June–1200 UTC 5 June) reveals a distinct change in the local meteorology during the 24 hour period corresponding with the abrupt change in firn core signals (1000 UTC 2 June–1000 UTC 3 June) (Fig. 6a). Conditions on the previous days (1–2 June) were characterized by low wind speeds (0–2 ms^{-1}), south-easterly wind direction and decreasing air temperatures from 1200 UTC 1 June. During the 3 June wind speed increased (9–16 ms^{-1}), wind direction tended easterly and temperatures increased. The local meteorology at Casey station, 110 km west of Law Dome summit, recorded similar conditions although there is a delay of 24 hours in the onset of strong easterly winds at Casey (Fig. 6b).

Precipitation events at Law Dome are usually caused by the passage of cloud bands, associated with cyclonic systems over the ocean to the north, resulting in strong easterly winds and elevated temperatures at Law Dome (Schwerdtfeger 1984, Callaghan & Betts 1987, Bromwich 1988). Advanced Very High Resolution Radiometer (AVHRR) infrared images confirm the location of an extensive cloud band associated with a well developed cyclonic system to the north of Law Dome on 2 June, which migrated polewards to pass over Law Dome early on 3 June (Fig. 7) (NOAA Satellite Active Archive 2000). The geopotential height (m) of the 850 hPa pressure level for 2 and 3 June, corresponding to an altitude of approximately 1200 m (similar to Law Dome summit), provides further evidence for the deepening and movement of a cyclonic system over Law Dome on 3 June (Fig. 8) (NWS (National Weather Service) 1999). In addition, meridional component winds of the 850 hPa pressure level for 2 and 3 June indicate an increase in the gradient of negative meridional component winds (winds from the north) associated with the poleward circulation of the cyclonic system on 3 June (Fig. 9) (NWS 1999). This indicates rapid advection of air from lower

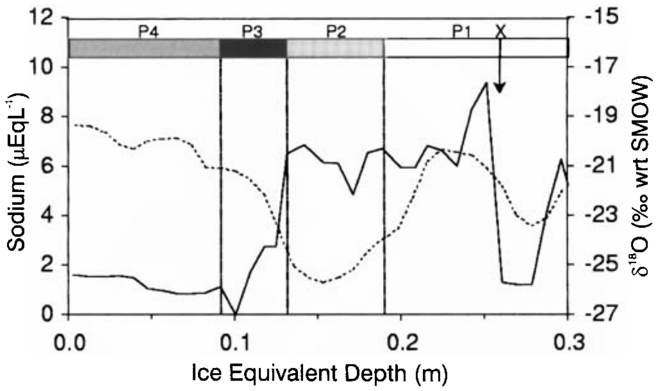

Fig. 5. Sodium and $\delta^{18}O$ records for the AWS firn core. Accumulation periods are illustrated and the abrupt change in firn core signals at 0.256 m (IE) is marked (X).

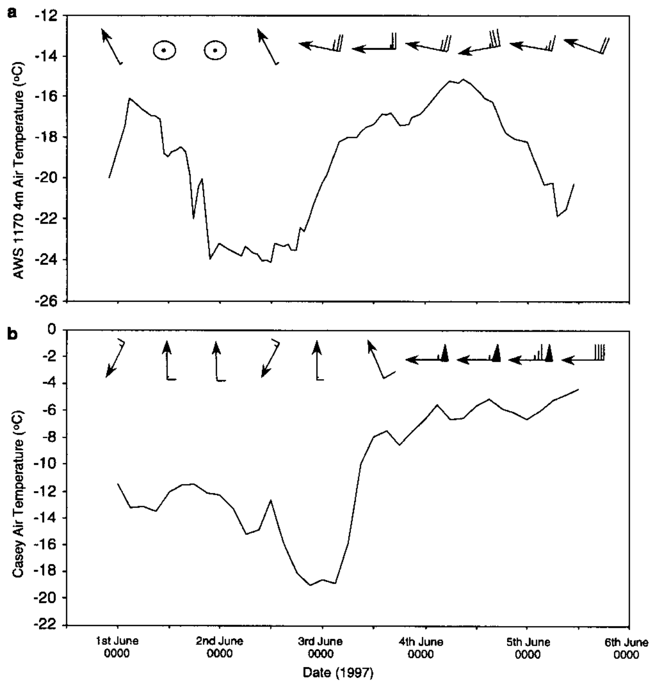

Fig. 6. Meteorological conditions recorded during P1. **a.** AWS 1170, **b.** Casey station. Wind plots indicate speed and direction of wind where flag/barb/half-barb/quarter-barb represent 25/5/2.5/1.25 ms^{-1} respectively, and the circle represents calm conditions.

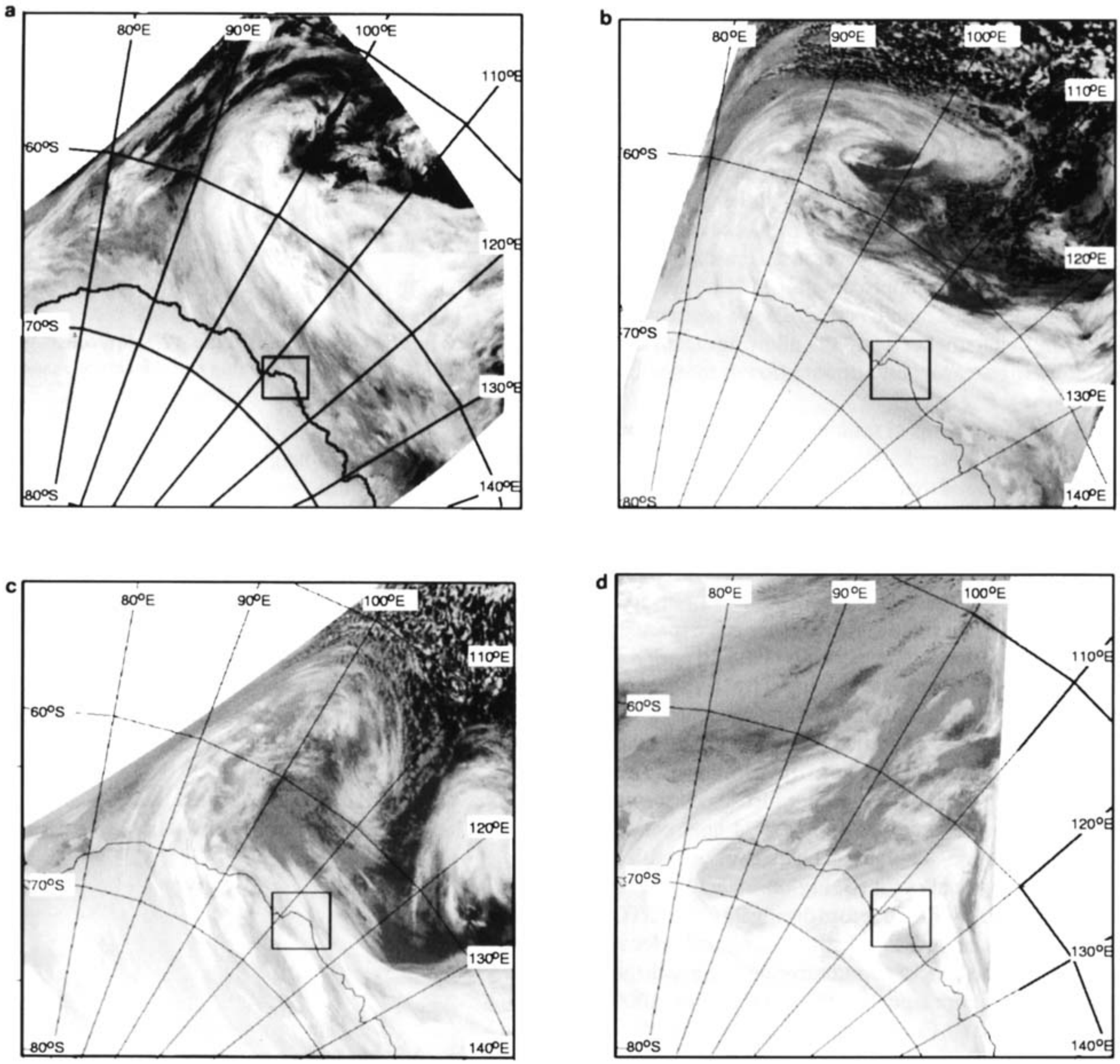

Fig. 7. AVHRR infrared imagery of the East Antarctic region showing the rapid intrusion of a well developed cyclonic system to the north of Law Dome, **a.** 2227–2235 UTC 1 June 1997 NOAA 12 Satellite, **b.** 1118–1304 UTC 2 June 1997 NOAA 14 Satellite, **c.** 2124–2244 UTC 2 June 1997 NOAA 12 Satellite, **d.** 1237–1431 UTC 3 June 1997 NOAA 13 Satellite. Law Dome is indicated by the black box. Images are taken from the NOAA Satellite Active Archive 2000.

latitudes towards Law Dome.

The changes in mesoscale and synoptic-scale meteorological conditions during P1 are consistent with the abrupt variation in firn core signals. The low $\delta^{18}O$ values and low sea salt concentrations preserved in the firn cores are consistent with the "quiet" conditions at Law Dome from 1–2 June. Light south-easterly winds, low temperatures and the absence of major frontal activity at Law Dome summit suggest an intrusion of slow moving air sourced from the Antarctic continent. The intrusion of cold, continental air depleted in sea salts and ^{18}O provides an explanation for the signals preserved in the firn cores. In addition, the slow moving air mass facilitates fractionation of both $\delta^{18}O$ and sea salts, resulting in low $\delta^{18}O$ and sea salt concentrations in the firn cores.

In contrast, abrupt increases in sea salt concentrations and $\delta^{18}O$ values in the firn core are consistent with the swift approach of a well developed cyclonic system towards Law Dome. Rapid advection of warm air from lower latitudes, as indicated in the synoptic-scale circulation, and reflected by the increase in temperatures at Law Dome summit and Casey station, dominate the $\delta^{18}O$ signal in precipitation from 3–5 June. Isotopic fractionation is limited during rapid transport of warm air masses, and this provides an explanation for the elevated $\delta^{18}O$ values preserved in the firn cores. The

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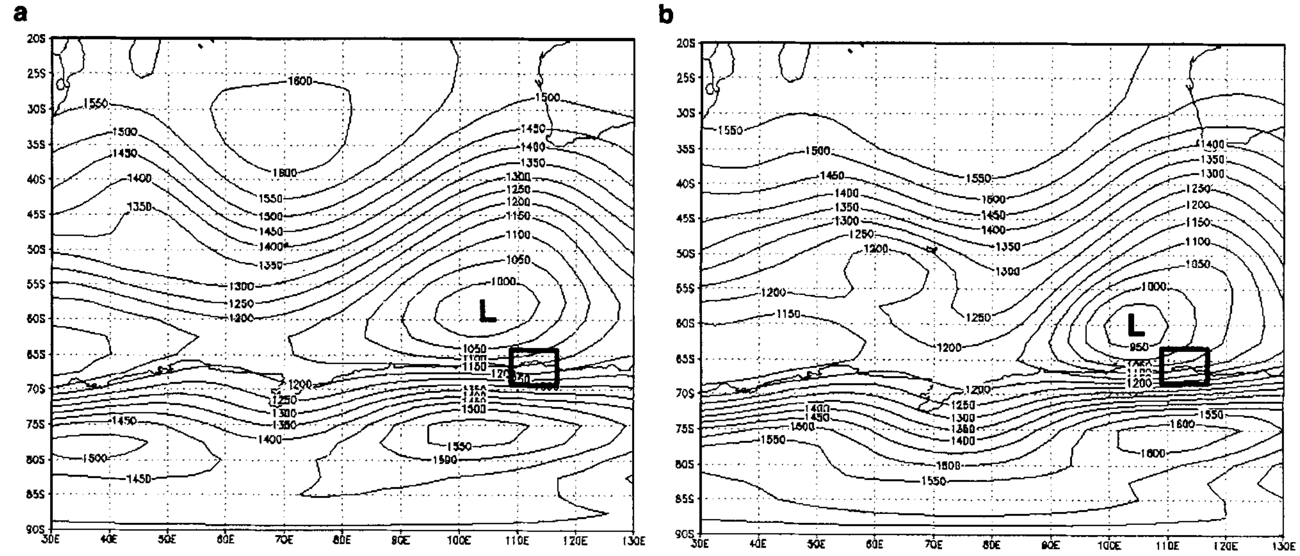

Fig. 8. Geopotential height (m) of the 850hPa pressure level for **a.** 2 June 1997, **b.** 3 June 1997. Law Dome is indicated by the black box. Figures are taken from the National Centre for Environmental Prediction (NCEP)/National Centre for Atmospheric Research (NCAR) 40-Year Reanalysis Project (NWS 1999).

increase in sea salt concentrations during this period is the result of the intrusion of marine air onto Law Dome through the easterly component of the cyclonic system. The deepening of the cyclonic system on its approach to Law Dome and associated higher oceanic wind speeds provides the mechanism for increased sea salt aerosol production.

Conclusions and future directions

Stronger quantification of links between ice core signals and climate conditions is important for interpretation of ice core paleoclimate records. The identification of individual precipitation events in an ice core record, and an understanding of their transport and deposition properties is a key step towards interpretation of information contained in deeper records. The new analysis technique described in this manuscript aimed to facilitate direct comparisons of ice core signals and contemporaneous meteorological conditions. The location of an AWS equipped with a snow accumulation sensor at the drilling site enabled high resolution dating of the firn core record. The identification of 19 accumulation events that comprise the record reveals the episodic nature of

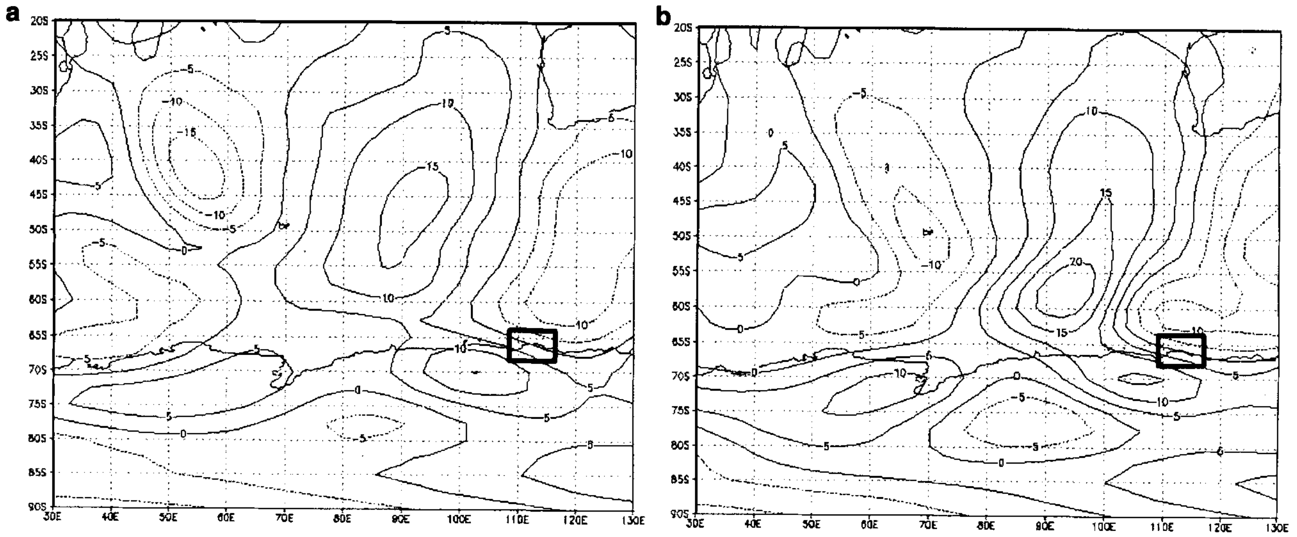

Fig. 9. Meridional component winds (ms^{-1}) of the 850hPa pressure level for **a.** 2 June 1997, **b.** 3 June 1997. Law Dome is indicated by the black box. Figures are taken from the National Centre for Environmental Prediction (NCEP)/National Centre for Atmospheric Research (NCAR) 40-Year Reanalysis Project (NWS 1999).

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accumulation, and has clear implications for assumptions of uniform accumulation throughout the year. Once regional accumulation events were identified from inter-core comparisons, a number of tools were used to compare the firn core signals with meteorological conditions. These included local meteorology recorded by AWS 1170, regional meteorology recorded at Casey station, and synoptic-scale meteorology observed through AVHRR infrared satellite orbits and National Center for Environmental Predication (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis datasets. A particular unique accumulation period was targeted for detailed examination and comparisons with meteorological conditions. The variations in firn signals through the period were found to be consistent with changing meteorological conditions. An abrupt change in firn core signal was explained by an abrupt change in meteorological conditions (over a 24 hour period).

These results indicate that even with uncertainties with firn densification, it is possible to use this technique to identify individual accumulation events preserved in firn cores. The technique appears to be particularly useful for identifying large events, or those with dramatic changes in source characteristics. The results of the application of the novel technique presented here provides some insight into the source, transport and deposition mechanisms influencing a particular winter accumulation period, and will enhance our understanding of similar signals observed in deeper ice core records at Law Dome. In addition, the successful application of the technique allows further applications to longer, more detailed snow pit and firn core records. Current research on longer term snow pit and firn core records aims to develop these techniques further and apply the dating procedure to extensive snow pit records (covering two years) and deeper firn core records (covering six years). This will allow a more detailed investigation of the impact of meteorological conditions on Law Dome ice core climate records and improve our understanding of the relationship between ice core signals and atmospheric conditions. A multi-species approach to future research, including the analysis of a full suite of trace ions, $\delta^{18}O$ and hydrogen peroxide, will greatly improve the interpretative significance of results from the application of the dating technique and add to the findings presented here.

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