

Barbara Delmonte · Jean Robert Petit
Gerhard Krinner · Valter Maggi · Jean Jouzel
Roberto Udisti

Ice core evidence for secular variability and 200-year dipolar oscillations in atmospheric circulation over East Antarctica during the Holocene

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Abstract Two Holocene ice core records from East Antarctica (Vostok and EPICA-Dome C) were analysed for dust concentration and size distribution at a temporal resolution of 1 sample per ~ 50 years. A series of volcanic markers randomly distributed over the common part of the ice cores (from 9.8 to 3.5 kyear BP) ensures accurate relative dating (± 33 years). Dust-size records from the two sites display oscillations structured in cycles with sub-millennial and secular scale frequencies that are apparently asynchronous. The power spectra of the composite sum (Σ) of the two dust-size records display spectral energy mostly for 150- to 500-year periodicities. On the other hand, the 200-year band is common to both records and the 200 year components of the two sites are out-of-phase (100-year lead or lag) over ~ 5.5 kyear, a phenomenon also reflected by a significant ($> 99\%$ conf. lev.) band in the power spectra

of the composite difference (Δ) of the two size records. During long-range transport, mineral dust originating from the Southern Hemisphere continents is graded to a variable extent depending on the altitude and duration of atmospheric transport. Relatively coarse dust is associated with air mass penetration from the middle-lower troposphere and conversely relatively fine dust with upper troposphere air masses or the influence of subsidence over the Antarctic plateau, a hypothesis already proposed for the changes that occurred during the Last Glacial Maximum to Holocene transition (Delmonte et al. 2004b). Moreover, we assume that the overall fluctuation of air mass advection over Antarctica depends on the meridional pressure gradient with respect to low latitudes, i.e. the Antarctic Oscillation (AAO). We therefore suggest a regional variability in atmospheric circulation over East Antarctica. The 150–500 year power spectrum of the composite (Σ) parameter represents the long term variability of the AAO, imprinted by secular internal oscillations probably related to the southern ocean-climatic system. On the other hand, the Δ dust composite parameter suggests a persistent atmospheric dipole over East Antarctica delivering coarser (finer) dust particles alternatively to Vostok and Dome C regions with a bi-centennial periodicity. Indeed, a seesaw phenomenon in dust size distribution was already observed at three East Antarctic sites during the last deglaciation (Delmonte et al. 2004b) and was interpreted as a progressive reduction of the eccentricity of the polar vortex with respect to the geographic south pole. Interestingly, the Δ parameter shows a pronounced 200-year oscillation mode, throwing new light on the unresolved question of a possible relationship between climate and solar activity.

B. Delmonte (✉) · J. R. Petit · G. Krinner
Laboratoire de Glaciologie et de Géophysique de l'Environnement (LGGE-CNRS), BP96, 38402 Saint Martin d'Hères, France
E-mail: petit@lgge.obs.ujf-grenoble.fr
E-mail: krinner@lgge.obs.ujf-grenoble.fr

V. Maggi · B. Delmonte
Department of Environmental Sciences, University
Milano-Bicocca - DISAT, Piazza della Scienza 1,
20126 Milano, Italy
E-mail: valter.maggi@unimib.it

B. Delmonte
Department of geological sciences, University of Siena, Via del
Laterino 8, 53100 Siena, Italy
E-mail: bdelmonte@nest.it
Tel.: + 39-2-64482874
Fax: + 39-2-64482895

J. Jouzel
Laboratoire des Sciences du Climat et de l'Environnement,
Institut Pierre Simon Laplace, UMR CEA-CNRS 1572, CE Saclay,
Orme des Merisiers, 91191 Gif-sur-Yvette, France

R. Udisti
Chemistry Department, Analytical Chemistry Sect., Scientific Pole,
University of Florence, Via della Lastruccia 3, 50019
Sesto Fiorentino (Florence), Italy
E-mail: udisti@unifi.it

1 Introduction

The investigation of Holocene climatic variability over decadal and secular timescales is essential to the

comprehension of present-day climatic trends and to distinguish between natural and anthropogenic contributions to climate change (IPCC 2001). Terrestrial and marine records in polar settings provide important information on the timescales and magnitude of climate variability, useful for climate models aimed at investigating physical processes, interactions, amplifications and for estimating climate sensitivity to either external or internal forcing.

Over the Holocene epoch, a number of marine sediment cores from the North Atlantic (e.g. Bond et al. 1997; Marchitto et al. 1998; Bianchi and McCave 1999), Indian Ocean (e.g. Sakar et al. 2000) and Southeast Pacific (e.g. Lamy et al. 2001; 2002) as well as atmospheric proxies from tropical latitudes (Moy et al. 2002) and northern polar areas (Mayewski et al. 1997) have shown that a prominent millennial-scale oceanic circulation variability mode characterises the present interglacial period. At high latitudes of the Southern Hemisphere, secular-scale periodicities (200 and 400 year band) were detected from 7,000 year long biogeochemical sediment records from the Antarctic Peninsula (Leventer et al. 1996; Domack et al. 1993, 2001; Domack and Mayewski 1999). This was interpreted in terms of local changes in upper ocean conditions such as sea ice extent and wind stress. Recently, an ice core dust record from East Antarctica covering the period from 13,000 BP to 2,000 BP indicated a pronounced variability of particle size at millennial and multi-centennial timescales, linked to atmospheric circulation changes in the Antarctic and circum-Antarctic regions (Delmonte et al. 2002a).

Further investigations at a high temporal resolution (Bond et al. 2001) pointed out that the structured millennial-scale oscillations evident in North Atlantic deep-sea sediment records (e.g. Bond et al. 1997) are actually made up of shorter oscillations (~ 200 – 500 years) with periodicities close to those of solar activity. Several climatic records (Bard et al. 1997; Paterson et al. 1991), especially from tropical latitudes (e.g. Neff et al. 2001), also display such modes of variability during the Holocene and, in particular, in the late Holocene (Hodell et al. 2001; DeMenocal et al. 2002). However, the mechanisms linking faint solar forcing to climate at millennial and secular periodicities are not yet understood.

The southern ocean connects the world's three ocean basins and constitutes an important system for the modulation of long-term climatic changes within Antarctica and the circumpolar region. Deepwater formation and the extent and distribution of sea ice vary greatly along with the climatological position of the atmospheric centres of influence (ridges and troughs). Such a climatic system coupling continental, oceanic and atmospheric influences possesses its own dynamic internal oscillations and interacts with external forcing factors. The impurities emitted from oceans and continents are preserved in the ice layers of the ice sheet. Atmospheric tracers such as insoluble mineral dust

subject to long range transport from Southern Hemisphere continents to the Antarctic can therefore potentially be used to document atmospheric exchanges and the variability of the southern climatic system.

The total dust concentration of mineral dust deflated from continental landmasses and transported to the polar plateau depends on a number of factors such as the aggradation of the source(s), the hydrological cycle and the strength of atmospheric circulation (e.g. Basile et al. 1997). On the other hand, the grain size is an interesting atmospheric circulation indicator sensitive to the grading occurring during transport (e.g. Ruth et al. 2003; Delmonte et al. 2004b). From ice records in East Antarctic sites, Delmonte et al. (2004b) showed that total dust concentration and size distribution are not simply correlated. In particular, the authors pointed out that the drastic decline of total dust concentration during Termination I was associated to a dust-size increase in the Dome C and Komsomskaya regions and to a particle-size decrease at Dome B and Vostok.

Dust is exclusively of aeolian origin and its size distribution is a parameter mostly sensitive to the atmospheric circulation variability. Here, we present two aeolian dust records from European Project for Ice Coring in Antarctica (EPICA)-Dome C and Vostok ice cores (East Antarctica), spanning a large part of the Holocene and analysed with a resolution of ~ 50 years. The paper focuses, in particular, on the variability of the two dust-size records, which are also analysed for their

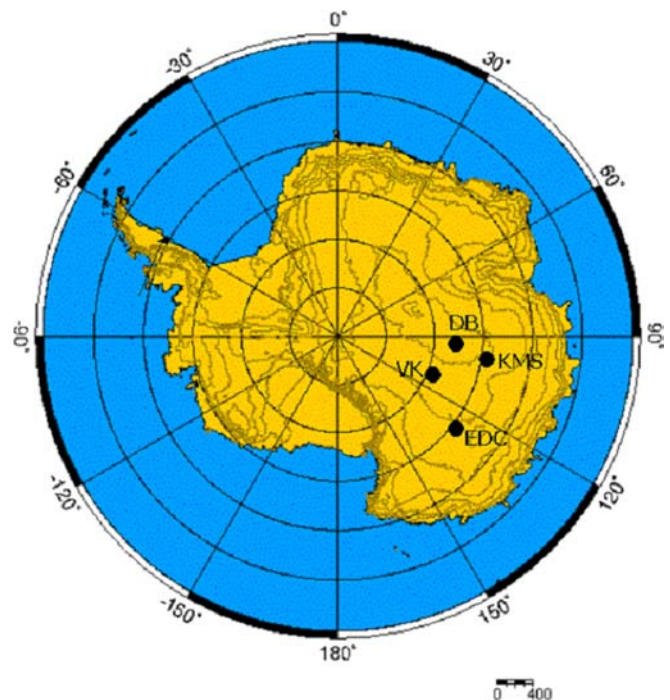


Fig. 1 Antarctic map with ice core drilling location. Map of Antarctica with the locations of the ice coring drilling sites cited in the text (*EDC* EPICA-Dome C; *VK* Vostok; *DB* Dome B; *KMS* Komsomolskaya)

periodic components. The two drilling sites are ~600 km apart and it was possible to determine the relative chronology of the two records by stratigraphic links based on a number of volcanic markers.

2 Analytical methods and results

2.1 Analytical techniques

The EPICA-Dome C ice core (hereinafter EDC, 75°06'S 123°21'E, Epica community members 2004) and an ice core from Vostok (Vostok-BH7, 78°28'S, 106°48'E) were studied. The two sites (Fig. 1) are located 600 km apart

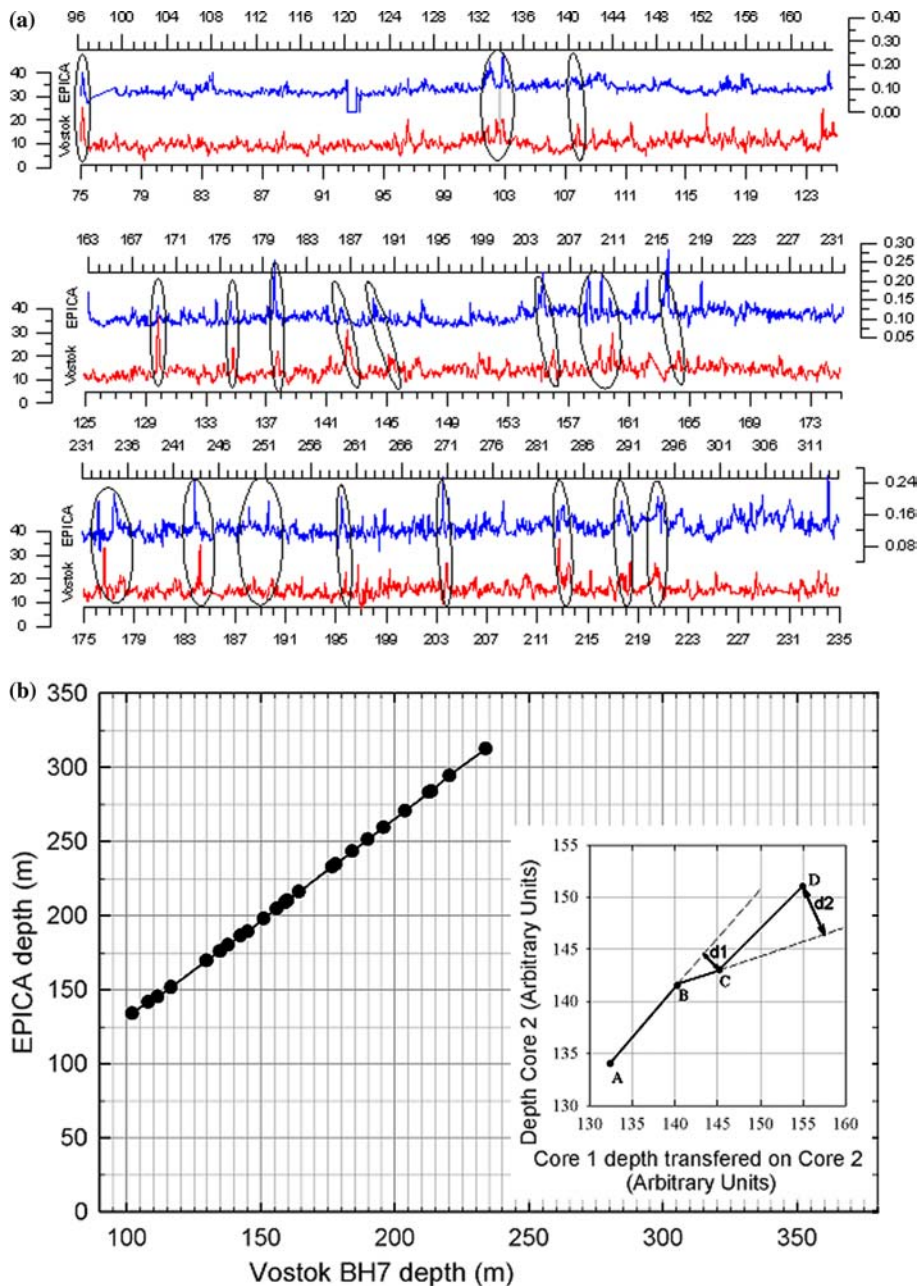
on the East Antarctic plateau. They have similar altitudes (3,233 m a.s.l. and 3,480 m a.s.l., respectively) and climatic characteristics (mean annual temperature -54.5°C and -55.4°C, accumulation rate 2.9 g cm⁻² a⁻¹ and 2.2 g cm⁻² a⁻¹ for EDC and Vostok, respectively). The EDC ice core was analysed from 100 m to 400 m, corresponding to an 11,000-year period from 2,000 BP to 13,000 BP, encompassing the end of the last climatic transition and the Holocene (Jouzel et al. 2001). The Vostok ice core (Vostok-BH7) was drilled in 1996 and was analysed from 104 m to 236 m, corresponding to the period from 3,600 BP to 9,800 BP.

A total of 280 samples from EDC and 130 samples from Vostok ice cores were selected and decontaminated

Fig. 2 Stratigraphic links between ice cores.

a Comparison of ECM records (in relative units) from EDC and VK-BH7 ice cores. The most evident events common to both sites and used as stratigraphic markers are surrounded by an ellipse. The *thick line* at 134 m in EDC and 102.1 m in VK-BH7 records indicates the ash layer (see text). EDC data are from Wolff et al. 1999.

b Depth-to-depth relationship between EDC and Vostok-BH7 ice cores obtained from volcanic markers and indication of the tephra layer (see text). The *insert on the right hand side* is a sketch showing the principle use to estimate the error due to the variability in ice accumulation rate. The error is represented by the mean misalignment of successive markers (exaggerated scale). Distances (d1, d2,...) are calculated as the orthogonal distance to the line linking two successive markers (*bold line*)



using a washing procedure. To avoid contamination, we discarded the porous firn (i.e. the first ~ 100 m) and fractured ice samples. All ice samples (6–10 cm long) correspond to ~ 3 –4 years of accumulation and were

selected every ~ 1 m giving a resolution of about 1 sample per 40 years for EDC and 1 per 50 years for Vostok, respectively. Dust mass concentration (assuming a dust density of 2.5 g cm^{-3}) and size distribution

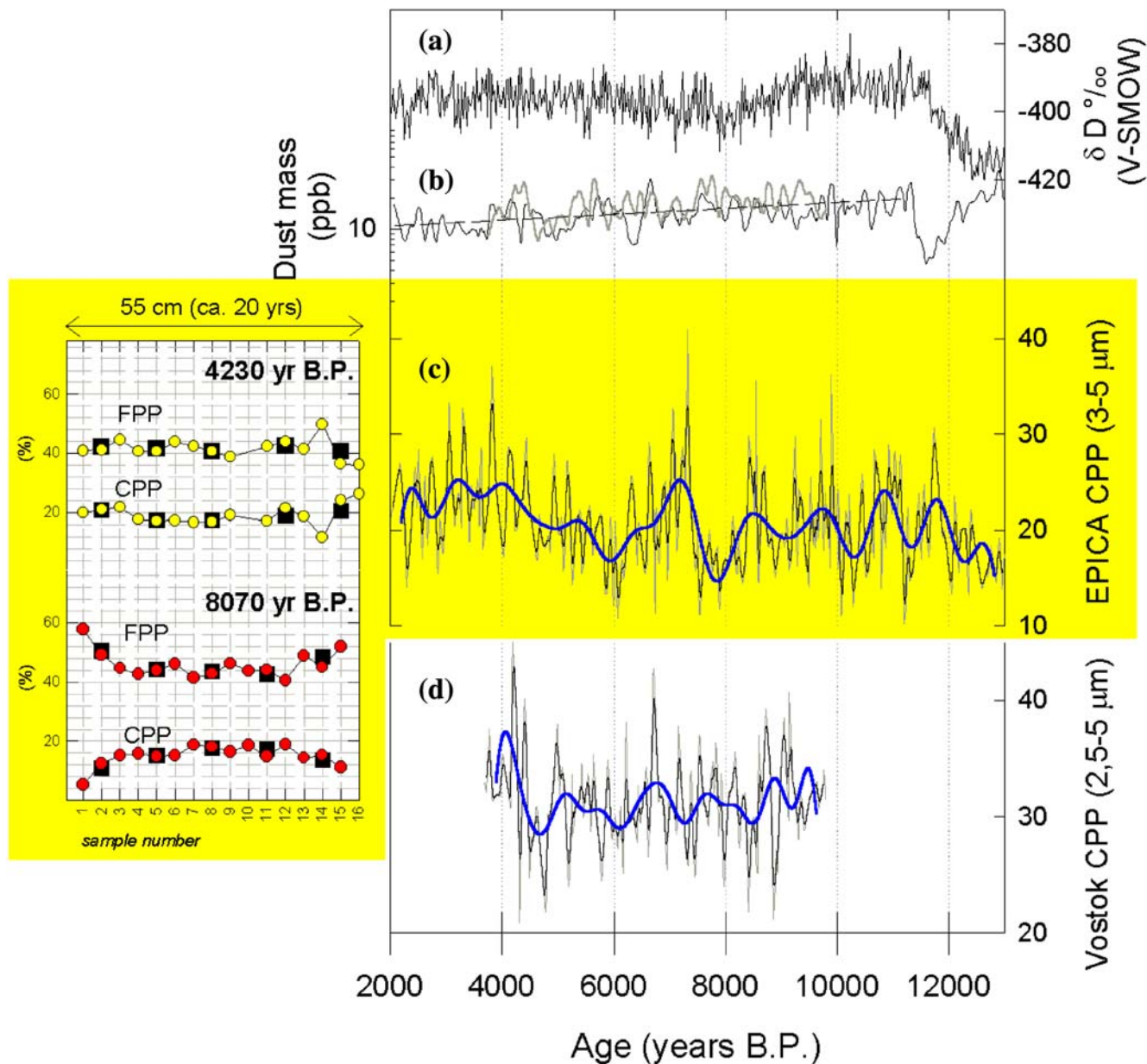


Fig. 3 EPICA Dome C and Vostok Holocene records. **a** Deuterium record (δD expressed in ‰ with respect to Vienna-SMOW) from the EDC ice core, from Jouzel et al. 2001. **b** Total dust mass concentration (ppb or 10^{-9} g/g) for EDC (black line) and Vostok (grey line) ice cores (moving average over 70 years). **c** EDC-CPP record (%), representing the percentage of particles between $3 \mu\text{m}$ and $5 \mu\text{m}$ with respect to the total dust mass of each sample. Raw (grey line) and 70-year average data (black thin line) are shown along with the long-term trend of changes (thick line, lowpass filtered periodicities higher than 1,000 years). **d** Vostok-CPP (2.5–

$5 \mu\text{m}$) record (%). Raw (grey line) and 70-year average data (black thin line) are shown along with the long-term trend of changes (thick line, lowpass filtered periodicities higher than 1,000 years). The two boxes on the left-hand side report two examples of yearly measurements (2–3 cm per sample) performed on 55-cm continuous sections of the EDC ice core (the examples refer to two sections from ca. 4,230 BP and 8,070 BP). Circles indicate CPP and FPP yearly data and black squares the 3-year equivalent samples (averaged over three samples)

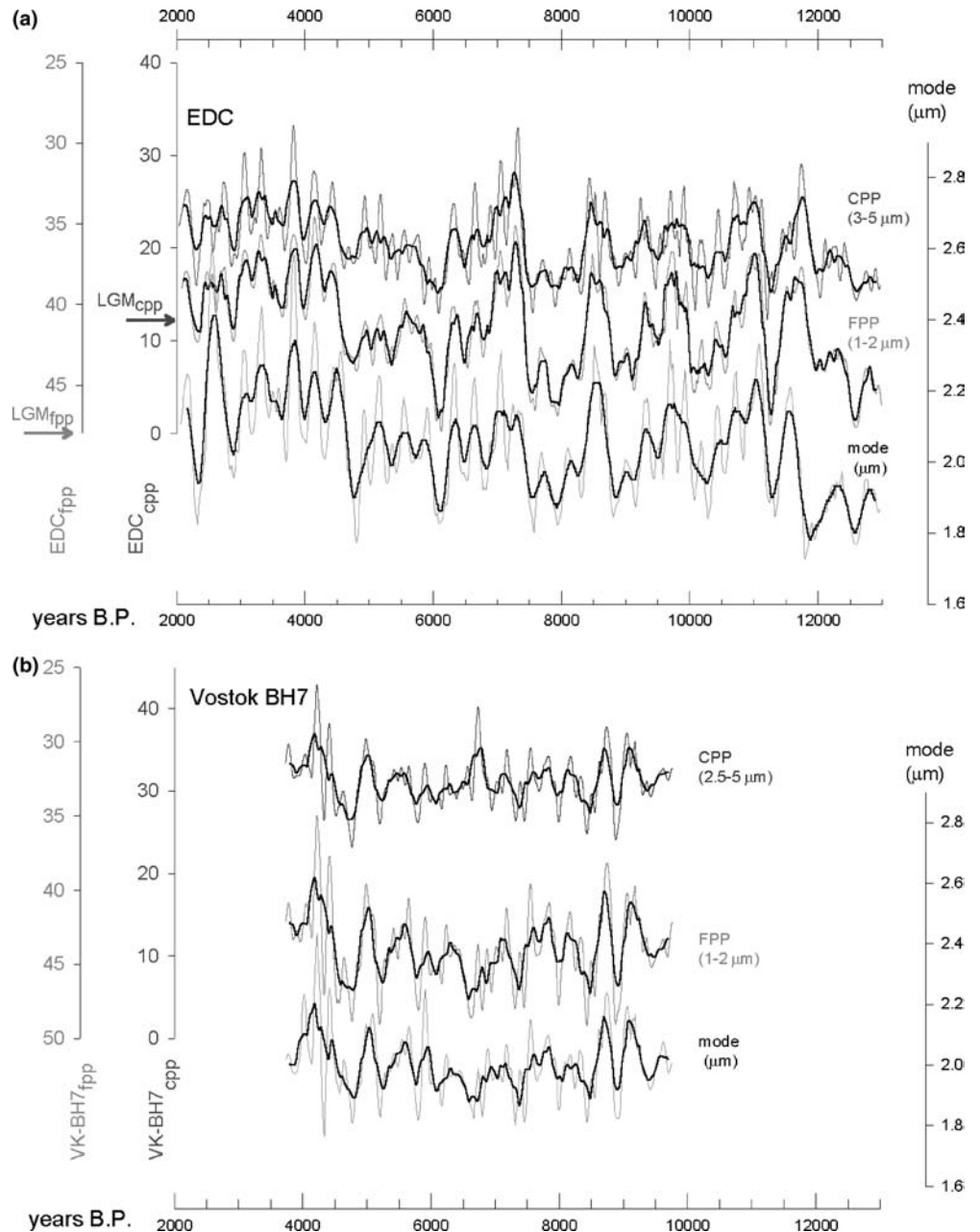
measurements were performed using a 256-channel Coulter Counter. The detailed analytical procedure is described elsewhere (Delmonte et al. 2002b). Samples were processed in random order and the calibration of the particle Counter was checked carefully to avoid instrumental bias.

2.2 Stratigraphic link between the two ice cores and accuracy of the relative chronology

The EDC and Vostok cores can be linked chronologically by the major H₂SO₄ fallout from volcanic events, detected from continuous electrical conductivity

measurements (ECM, Fig. 1a, Wolff et al. 1999) and ion chromatography (Udsiti et al. 2004). The EDC timescale from Schwander et al. (2001) was adopted as a reference. The electrical profiles provided the inventory of volcanic events that are used as stratigraphic markers. A tight depth-to-depth correspondence between the two records was set for the 7,000-year common period using 24 volcanic events (Fig. 2a, b), yielding an average of one marker every ~300 years. To prevent cumulative errors, peak-to-peak matching was not carried out from top to bottom but rather by first establishing a general stratigraphic relationship through the major climatic events, such as the end of the climatic transition (ca. 12,000 BP) and by comparison of the deuterium profiles.

Fig. 4 Holocene variability of dust-size parameters for EDC **a** and Vostok **b** ice cores. Comparison of different dust-size indicators: *CPP* coarse particle percentage, *FPP* fine particle percentage and modal value of a lognormal function fitting the raw mass (volume) size distribution of samples. Average LGM CPP and FPP levels are also indicated



Moreover, the EDC ice core was examined to locate the equivalent of a 2-cm thick tephra layer found at 102.1 m depth in the Vostok-BH7 ice core, an event from the South Sandwich islands (Basile et al. 2001) and lying between two major ECM peaks. The corresponding ECM ice section event did not show visible ash layers. However, continuous Coulter Counter analyses (1 sample per 2–3 cm) and electron microscope observations revealed the presence of a highly concentrated dust layer with large (10–20 μm) glass shards at 132.60 m depth, in-between two ECM peaks. Taking into account the general trend of the depth-to-depth relationship, all the other 23 events were identified from the EDC-Vostok ECM comparison. The main markers made it possible to refine the relationship and to select secondary and then intermediate events.

The accuracy of such matching was estimated. Since the average EDC/Vostok accumulation ratio is ~ 1.33 for the considered period (Udisti et al. 2004), all Vostok depths were first normalised by multiplying by this factor. Assuming correct stratigraphic correspondence (and dating), the relative variation of snow accumulation rate between the two sites was calculated on the normalised depth-to-depth plot. The error can be defined as the orthogonal distance of a marker from the extrapolated line passing through the previous pair of markers (insert in Fig. 2b). The mean (squared) misalignment of all markers gives the mean (squared) distance and error. For EDC and Vostok cores, we calculated a mean distance of about ± 1 m, representing ± 33 years (taking 2.9 cm year^{-1} as the mean ice accumulation rate for EDC).

2.3 Dust-size distribution parameters

The continental dust reaching the high East Antarctic plateau is well sorted: the average particle diameter is generally around $2 \mu\text{m}$ and generally smaller than $\sim 5 \mu\text{m}$ (Delmonte et al. 2002a, 2002b, 2004b). Larger dust (up to $\sim 20 \mu\text{m}$ in diameter) is typically associated with rare ash layers (Basile et al. 2001). To characterise the dust-size distribution, the modal value (mode) of the volume-size distribution obtained from the lognormal fit of the raw data or the proportion of dust within arbitrarily-selected size intervals can be used (Delmonte et al. 2002a, 2004b). In order to define the percentage of fine particles (Fine Particle Percent or FPP), we choose the interval between $1 \mu\text{m}$ and $2 \mu\text{m}$ with respect to the total dust mass spectrum (0.7- to $5\text{-}\mu\text{m}$ interval); the percentage of coarse particles (Coarse Particle Percent or CPP), on the other hand, was defined in the interval $3\text{--}5 \mu\text{m}$ for EDC and $2.5\text{--}5 \mu\text{m}$ for VK-BH7, since dust in the Vostok ice core is slightly smaller than in the EDC ice core (see below).

Each dust sample represents $\sim 3\text{--}4$ years of accumulation. We tested the variability and significance of each

point by analysing a set of seven 55 cm sections of the EDC ice core with annual resolution (~ 1 sample per year, i.e. 1 sample every 2–3 cm) selected at different depths. The FPP and CPP parameters of two of them (corresponding to ca. 4,230 BP and 8,070 BP) are shown in the insert of Fig. 3 both as yearly values and as ~ 3 -year equivalent values (unweighted average of 3 adjacent samples). The variability (standard deviation) calculated on the yearly samples is $\sim 4.6\%$ both for CPP and FPP and it decreases to 2.9% and 2.6% for CPP and FPP, respectively when the 3-year samples are considered. For the sake of comparison, the Holocene standard deviation is about 5.2% for CPP, suggesting that the variations are significant, even for single measurements. Moreover, we averaged the data using a resampling procedure that also improves the significance of the variations.

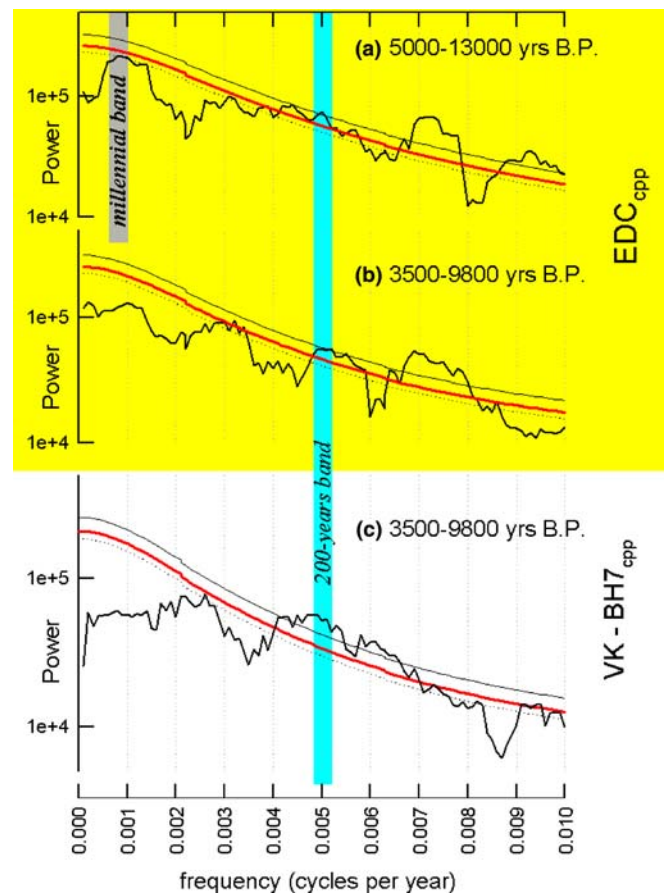


Fig. 5 Spectral analysis of the dust CPP records. MTM method (Dettinger et al. 1995) was performed on the raw data series re-sampled at regular intervals of time through linear interpolation. All MTM spectral analyses were performed using a bandwidth parameter of 4 and 7 tapers. **a** Power spectrum of EPICA CPP dust record from 13 kyear to 5 kyear BP. **b** Power spectrum of EPICA CPP record from 9.8 kyear to 3.5 kyear BP. **c** Power spectrum of Vostok-BH7 CPP record from 9.8 kyear to 3.5 kyear BP. The smoothed curves indicate the 90% (dotted line), 95% (solid thick line) and 99% (solid thin line) confidence levels with respect to a red noise signal

2.4 The EPICA and Vostok records

The EDC deuterium profile, proxy of the surface temperature (Jouzel et al. 2001) is reported in Fig. 3a along with the two records of total dust concentration for EDC and Vostok ice cores (Fig. 3b). Both dust records display a short-term variability superposed on a main long-term Holocene decreasing trend. The EDC record from 13,000 BP to 2,000 BP encompasses the end of the Antarctic Cold Reversal dust event ($\sim 13,000$ BP) and the 800–1,000 year pre-Holocene dust minimum, culminating at $\sim 11,500$ BP (DelMonte et al. 2002).

The proportion of coarse particles (CPP) is reported in Fig. 3c, d for EDC and Vostok ice cores, respectively (raw data, moving average over 70 years and lowpass filtered series for periodicities longer than 1,000 years). A visual observation of the CPP records highlights that EDC dust-size variations clearly overcome the amplitude variation of the stable isotope record for multi-secular to sub-millennial periodicities (Fig. 3a, c). Moreover, EDC and Vostok dust-size profiles display evident dissimilarities at sub-millennial periodicities (Fig. 3c, d). The visual comparison does not make it possible to determine a clear correlation and several sub-millennial oscillations appear to be at least asynchronous, if not totally opposite (Fig. 2c, d). For example, from 13,000 BP to 4,500 BP, the EDC profile suggests short-term (secular-scale) variations structured in apparent multi-secular and millennial-scale cycles, while these are less pronounced in the Vostok record.

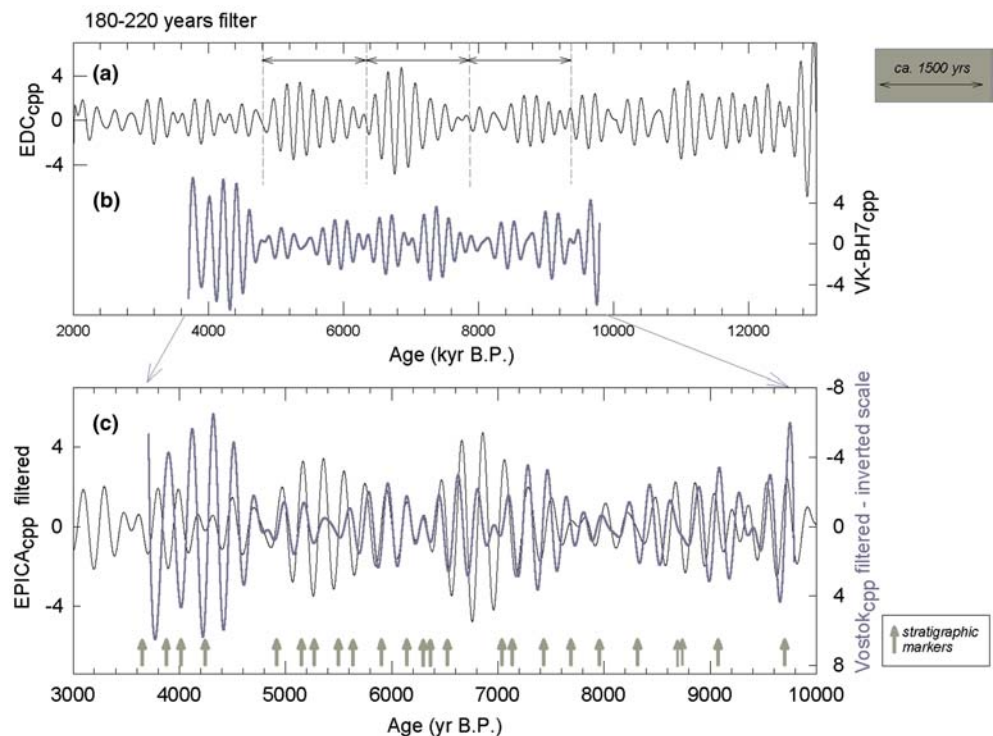
The different dust-size indicators (FPP, CPP and the modal value of the log-normal function fitting the raw

dust mass-size distribution) reported in Fig. 4 consistently capture the overall pattern of dust-size variability and therefore can be used interchangeably. An increase of $\sim 0.50 \mu\text{m}$ in the mode corresponds to a ~ 10 – 15% increase (decrease) in CPP (FPP). Obviously, with respect to FPP variations, the mode and CPP variations are opposite. The average FPP value is $44 \pm 3\%$ for Vostok and $41 \pm 4\%$ for EDC, respectively and Vostok dust is slightly more graded than EDC dust over the common time period. Compared to value obtained for the last glacial climate (ca. 20,000 BP, Delmonte et al. 2002b), the size of EDC dust never returned to the extreme values of the LGM: CPP always represents more than $\sim 20\%$ and FPP more than $\sim 41\%$ of the total mass, while LGM values are about 12.5% and 48%, respectively (see Fig. 4a).

2.5 Spectral analysis of dust-size records

Spectral analyses were performed on the dust records using the Multitaper Method (or MTM, bandwidth parameter of 4 and 7 tapers, Dettinger et al. 1995). For the time period common to the two series (9,800–3,500 BP), the CPP power spectrum of EDC indicates that the energy is mostly spread between ~ 120 and ~ 330 years while two significant ($>95\%$ conf. lev.) secular-scale bands (Fig. 5b) corresponding to periodicities arise around 130–150 years and 180–210 years. Depending on the time series considered, power may be carried by millennial-scale periodicities ($>90\%$ conf. lev.) as shown by the EDC series analysed from 13,000 BP to

Fig. 6 EDC and Vostok CPP records after band pass filtering (180–220 year window). **a** EDC CPP record, **b** Vostok CPP record, **c** Zoom on overlap of the two records (Vostok scale inverted). Thin black line EDC; thick grey line Vostok. Grey arrows indicate the stratigraphic location of the volcanic markers



5,000 BP (Fig. 5a). The power spectrum of Vostok CPP series also indicates a rather wide frequency window (~ 120 – 400 years) while one band (significant $>99\%$ conf. lev.) corresponds to 150- to 230-year periodicities and another band peaks ($>90\%$) at around 380 years (Fig. 5c).

Interestingly, the dust-size distribution records from both sites share a common significant frequency band around ~ 200 years. Filtering the two CPP series in the 180–220 year window (Fig. 5) gives rise to a modulation, likely reflecting a combination of very close secular periodicities. Such modulation is clearly apparent in the EDC record from 9,500 BP to 4,500 BP and the distance between the nodes again suggests a millennial-scale periodicity. Focusing on the 200 year component, the two signals are opposite in phase for most of the Holocene (Fig. 6c) and a matching of the two records is possible with 25 cycles from a total of 29, encompassing about a 5,500-year period (from 9,800 BP to 4,200 BP). Such phase opposition is confirmed by consistency calculations and phase analyses performed on the two records (not reported) but also from the power spectra of the composite (difference between the two records) dust signal (see below).

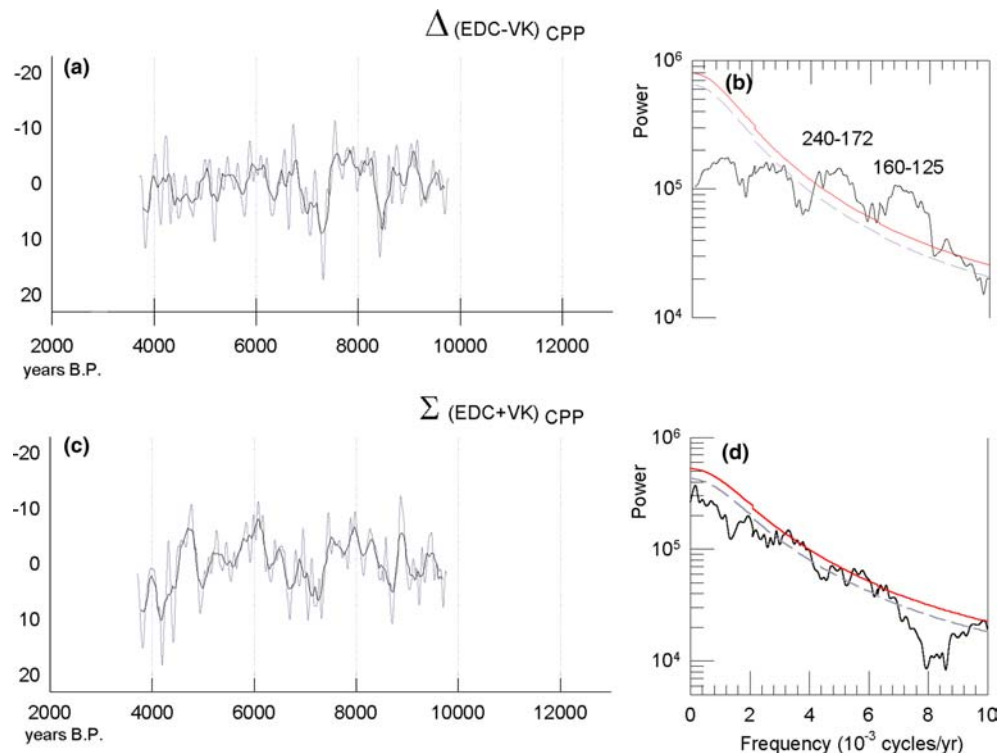
The ~ 100 year lead or lag between the EDC and Vostok dust-size indicators may correspond to a systematic shift in depth between the two ice cores by ~ 3 m. Yet, this is unlikely because the depth-to-depth matching, is accurately determined by volcanic events randomly distributed along the two profiles (Fig. 6) and, in particular, by a number of clear double peaks and the ash layer.

As additional tests on the non-random character of the variability of the two dust-size parameter records, we constructed two composite indicators from a simple linear combination: one is given by the EDC and Vostok CPP difference (Δ , Fig. 7a) and the other is by the EDC and Vostok CPP sum (Σ , Fig. 7c). EDC and Vostok CPP data (re-sampled every 50 years, through linear interpolation) are expressed as normalised differences with respect to the mean, giving the same weight to both records. The MTM spectrum of Δ (Fig. 7b) shows pronounced secular-scale variability. Two significant ($>99\%$ conf. lev.) bands are observed, one around 200 years (170–240 years) and the other corresponding to the 125- to 160-year interval. The increased power in the 200 year band of this composite spectrum, with respect to EDC or Vostok spectra taken alone, give confidence to the dust-size signal and its variability, which is unlikely to result from two independent random processes. The spectrum of the Σ record (Fig. 7d) is slightly different, appearing smoother and containing a continuum of periodicities spread from 140 years to 500 years ($>90\%$ conf. Lev.).

3 Discussion

We will first discuss the meaning of the dust-size signal in terms of indicators of the atmospheric circulation patterns over Antarctica. Then we will assess the possible origin of the secular and multi-secular oscillations, taking into account the main characteristics of the southern climatic system and exchanges with the

Fig. 7 Composite dust records and power spectra. **a** Δ is the difference of EDC minus Vostok (normalised) CPP records re-sampled at regular intervals of time through linear interpolation; **b** MTM spectral analysis (bandwidth parameter of 4 and 7 tapers) of Δ with indication of the 95% (solid thick line) and 99% (solid thin line) confidence levels with respect to a red noise signal. **c** Σ is the sum of EDC plus Vostok CPP normalised records, re-sampled at regular intervals of time through linear interpolation; **d** MTM spectral analysis (bandwidth parameter of 4 and 7 tapers) of Σ with confidence levels indicated as in **b**. The grey line is the 50-year moving average and the black line the 200-year moving average



Southern Ocean. We will also discuss the meaning of the composite Σ and Δ records and the kind of information that can be extracted from them. Finally, given the presence of a persistent 200 year oscillation mode in the Δ record over a large part of the Holocene, the existence of a possible relationship between Antarctic climate and solar variability will be discussed.

3.1 Dust-size changes as an indicator of atmospheric transport pathways

First, let us look at why the salient changes in atmospheric circulation suggested by dust-size records are not so clearly expressed in other climatic proxies such as the stable isotope composition of ice. In fact, the Deuterium or Oxygen 18 record for EDC (Fig. 3a), and similarly for other sites from the east Antarctic plateau, displays a very low temporal variability during the Holocene. Only weak secular and sub-millennial periodicities were found in stacked ice core isotopic records by Masson et al. (2000). However, while isotope sources are extensive, the narrow and geographically fixed location of the main source areas for mineral dust (see below) as well as their relative long distance from Antarctica are good reasons to use this proxy as a tracer for air mass exchanges and variability between middle and high latitude in the southern hemisphere. Insoluble mineral aerosols reaching East Antarctica must be transported at high altitudes (middle to high troposphere) and precipitate exclusively by dry deposition (Legrand and Mayewski 1997). Therefore, the slight size fractionation that we observe is likely insensitive to air temperature or water saturation pressure and should depend mostly on transport time. This likely gives the dust-size parameter a greater sensitivity than other climatic proxies to the variability of atmospheric circulation around Antarctica.

A dominant southern South American provenance for aeolian dust reaching EDC and Vostok sites during the cold periods of the late Quaternary was suggested by Grousset et al. (1992), Basile et al. (1997) and recently by Delmonte et al. (2004a). Preliminary isotopic investigations (Basile 1997; Delmonte 2003) on samples from interglacial periods have suggested that the two sites probably share common dust sources also during warm epochs, although the geographic location is not yet well established.

Over the last 220 kyear, the EDC and Vostok sites show an overall homogeneity of dust flux (Delmonte et al. 2004a); the same conclusion was drawn by Delmonte et al. (2004b) for the last climatic transition (20 kyear to 10 kyear BP) based on three independent ice core dust records from the 90°E–125°E sector of East Antarctica (EDC, Dome B, located 77°05' S, 94°55'E and Komsomolskaya, located 74°05'S, 97°29'E, see Fig. 1). Therefore, the overall agreement between EDC and Vostok dust concentration records reported in Fig 2b confirms that the first-order similarity of mineral dust input also holds for the Holocene.

Indeed, the total concentration depends on several parameters influencing the dust cycle from the continental sources to the snow layers. Among them, we can cite the environmental conditions at the source regions, transport conditions, the hydrological cycle and local snow accumulation rate on the ice sheet. On the other hand, particle grading depends mainly on the transport conditions (Delmonte et al. 2004b) and can be used as an indicator for atmospheric circulation over the Antarctic and circum-Antarctic regions. While the total dust concentration profile is quite homogenous and uniform between sites, the dust-size records can be very dissimilar and sometimes the regional trends are opposite (asymmetric). During the last climatic transition, a significant increase in particle size was observed at EDC site (Delmonte et al. 2002b), while opposite changes were observed on other East Antarctic ice cores from the 90°E–125°E sector of the plateau (Delmonte et al. 2004b). Moreover, asynchronous short-term dust-size oscillations of secular to millennial-scale duration are present in all the records. The authors attributed the *temporal* variability observed in the records to changes in atmospheric circulation and dust transport patterns modulating advection to the East Antarctic plateau and pointed out that the response to this phenomenon can be regionally different.

The progressive seesaw pattern of the dust-size changes observed between the EDC-Komsomolskaya region and the Dome B-Vostok region during the last climatic transition is a clear expression of geo-diversity and regional differences over the East Antarctic plateau (Delmonte et al. 2004b). The authors proposed a conceptual scenario in which the relatively coarser (finer) dust is associated with the penetration of air masses from lower (higher) altitudes and/or through shorter (longer) paths. Indeed, the observed changes in size distribution of dust during a volcanic event recorded in ice supports this interpretation: while the coarse glass shards from the eruption are transported first to the site by a rapid and almost direct pathway through the lower troposphere, the subsequent sulphate compound formed within the stratosphere peaks later in the ice record and is escorted by fine and very fine particles which have transited through the upper troposphere (Delmonte et al. 2004b).

The dust-size changes observed during the Holocene at EDC and Vostok sites are less pronounced than the glacial-to-Holocene differences. As the dust source regions were not constrained yet for the interglacial periods, two possibilities must be considered. Assuming a common source for dust to Vostok and EDC during the Holocene, different transport paths are required to explain the asynchronous grain-size variations. A second possibility is that two or more sources are involved and influence alternatively the two sites. Nevertheless, this would imply an atmospheric circulation and dust transport variability. Therefore, the short-term and asynchronous dust-size oscillations we observe in the records likely represent the continuation during the

Holocene of those observed in the EDC, Dome B and Komsomolskaya ice cores during Termination I and superposed on the main trend of the changes. In other terms, our records suggest that a multi-secular to millennial-scale modulation of lower or higher air-mass penetration onto the polar plateau was taking place over Antarctica for at least 20 kyr.

Despite the relatively short distance between the two ice-coring sites, the climatic and atmospheric regime over East Antarctica is far from uniform. The EDC and Vostok sites are located at similar altitudes (3,233 m a.s.l. and 3,480 m a.s.l., respectively) and distances from the coast (1,100 km and 1,410 km), they have similar mean annual temperatures (-54.5°C and -55.4°C) and probably share the same dust sources.

However, there is evidence of regional differences in atmospheric circulation inside the East Antarctic plateau. The variability of the isotopic composition of snow at a ~ 100 km scale along the 6,000 km transect of the Trans-Antarctic route (Dahe et al. 1994) is a good example of regional differences. The deuterium value for Vostok is the lowest of the whole series ($\delta D \sim -440\text{‰}$) for present-day climate. This is consistent with the gradual trend and the isotope-temperature relationship over more than $\sim 2,500$ km from the Weddell Sea through the South Pole to Vostok. North of Vostok, however, there is a steady gradient ($+7\text{‰}$ per 100 km) and ~ 300 km away a second isotope-temperature relationship occurs, with a 20‰ shift with respect to the previous one. Such variability was believed to be associated with a topographic effect (Dahe et al. 1994), making the Vostok Antarctic site subject to the strongest continental influence. This effect, however, was not reproduced by GCM experiments. However, the isotope content of precipitation is linked to the cloud history and the less depleted isotopic content of EDC ($\delta D \sim -390\text{‰}$) with respect to Vostok ($\sim -440\text{‰}$) can be attributed to different pathways of air masses and to a more oceanic influence. The same conclusion is supported by the Holocene values of deuterium excess, a proxy for the sea surface temperature indicative of water source constraining the atmospheric pathway (Vimeux et al. 2001).

3.2 Possible origin of secular oscillations in atmospheric circulation: influence of the Southern Ocean

Atmospheric circulation at high latitudes of the southern hemisphere is dominated by the circumpolar Westerly winds, reaching their maximum close to 50°S at surface level. The Westerlies can be embedded at any time with disturbances taking the form of cyclonic waves and eddies controlling the daily weather (e.g. King and Turner 1997 and references therein). Beside transient disturbances, present-day climatological data from the Antarctic region show that large-scale semi-stationary waves can maintain a similar location and amplitude all year round. In the analysis of zonal standing waves, low

disturbance levels are generally associated with longer waves (wavenumbers 2 and 3) while intense disturbances are generally associated with shorter waves (higher wavenumbers) and to a more meridional circulation pattern. Planetary long waves can influence the atmospheric circulation of the high troposphere (500–300 hPa) and can be contained and propagated by the jet stream. Wavenumber 1 corresponds to the eccentricity of the Polar vortex, i.e. the distance of the centre of the vortex from the geographic South Pole.

Atmospheric circulation at high latitudes of the Southern Hemisphere is highly related to the Southern Ocean conditions. For example, the present-day eastward propagation of the Antarctic Circumpolar Wave (ACW, White and Peterson 1996) shows that sea ice extent, sea surface temperature and surface wind stress anomalies do exist in the southern polar region and that they are highly interrelated on an interannual (4–5 years) timescale. Changes in the position of storm tracks are thought to affect the amount of sea ice versus open water on an annual basis (see King and Turner 1997 and references therein). Furthermore, high-pressure systems influence the dynamics of sea ice distribution by moving ice and by leading to new ice formation (e.g. Venegas and Drinkwater 2001). Sea ice, in turn, can affect the positions of the major climatological centres influencing the circum-Antarctic, the atmospheric circulation pattern and the cyclonic activity on a variety of timescales (Carleton 1989).

On secular and multi-secular timescales, the annular mode appears to be the dominant atmospheric circulation structure around Antarctica and the zonally symmetric fluctuations of atmospheric masses driven by the overall pressure gradient between polar and lower latitudes characterise the Antarctic oscillation (AAO). The Southern Ocean plays a major role in long-term climate change trends. It potentially influences atmospheric circulation at high latitudes of the Southern Hemisphere through the slow changes in sea ice concentration and distribution around Antarctica and constitutes a key buffer for heat and mass exchanges within the global ocean. The Drake passage allows exchanges with the Pacific ocean, while the Southern circum-Antarctic region is an important crossing for ocean currents including the North Atlantic deep water (NADW) current from the global thermohaline circulation. Due to the geometry of the Atlantic basin, the forcing of surface currents by atmospheric circulation and the density properties of seawater, the system is capable of generating internal oscillations at secular frequencies. Indeed, an ocean–atmosphere experiment performed by Mikolajewicz and Maier-Reimer (1990) suggests internal oscillations in the ~ 50 – 500 year-band for the Southern Atlantic Ocean. In the conducted experiment, the model was forced by a stochastic surface wind at 40°S . Results show that the southward flux of NADW (and heat) through 30°S into the circum-Antarctic current is not continuous but pulsed and appears opposite to the flux of fresh water through the Drake passage. After inte-

gration over $\sim 1,500$ years, the model of the South Atlantic Ocean indicated a mean oscillation mode of about ~ 320 years.

It could be therefore speculated the Southern Ocean resembles a secular *pseudo-oscillator* capable of influencing the atmospheric circulation through surface temperature, sea ice extent, position of the centres of atmospheric influence, atmospheric circulation patterns and meridional air exchanges with Antarctica. In this conjuncture, the variability of the overall atmospheric response or the resulting secular variability of the AAO should have a spectrum similar to that of the Southern Ocean. It is interesting to point out that the spectrum of the composite dust indicator Σ (Fig. 7d), which is representative of the general atmospheric circulation regime (enhanced or reduced subsidence) over the east Antarctic sector (approximately 100°E – 125°E), displays energy over a wide band of periodicities from 150 years to 500 years (confidence $>90\%$), consistent with the cited model results. We therefore speculate that the Southern Ocean modes of oscillations are reflected in the atmospheric circulation and expressed in the sub-millennial and secular-scale pervasive oscillations.

3.3 Sketch of the principal modes of variability of atmospheric circulation over east Antarctica: AAO and an atmospheric dipole oscillation

The influence of air masses from different altitudes suggested by the dust-size variations can be associated with the strength of subsidence over Antarctica, the latter being maximum close to the overall centre of the polar vortex (King and Turner 1997). Actually, the climatological centre of upper cyclonic vorticity is generally zonally asymmetric with respect to the geographic south pole. Among indicators of its variable eccentricity is the Trans Polar Index (TPI, pressure difference between Hobart and Stanley, Pittock 1980), that can be also interpreted as an index of the sea-level pressure wavenumber 1 component of southern Hemisphere circulation. The TPI record shows that the eccentricity of the polar vortex has changed over the last two centuries (Villalba et al. 1997) and it is reasonable to assume that it may have changed in the Quaternary over a variety of timescales. Through this argument, it was suggested (Delmonte et al. 2004b) that the general reorganisation of the atmospheric circulation that occurred during the last glacial/interglacial transition, linked also to Southern Ocean conditions, led to a gradual change in the eccentricity of the polar vortex (centre of relatively higher subsidence) from lower to higher latitudes (e.g. from $\sim 75^{\circ}\text{S}$ over the Dome C region to $\sim 79^{\circ}\text{S}$ over the Vostok region).

In our interpretation, we associate the CPP parameter to the poleward advection of air from the lower troposphere and conversely, the FPP parameter to the influence of the high level and subsidence. The composite sum parameter (Σ) likely characterises the sym-

metric mode of influence of advection/subsidence over the east Antarctic plateau and it could also be an indicator of the AAO strength. On the other hand, the composite difference parameter (Δ) could be associated with the relative difference of air influence over the two sites (Vostok and Dome C), or an asymmetric advection/subsidence regime or in other terms, an atmospheric *dipole* over east Antarctica.

Figure 8 shows the Vostok and EDC CPP dust parameters on the x and y axis, respectively. The two composite indicators (Σ and Δ) are represented by the first and second diagonals. The Σ axis (*symmetric mode*) is associated with the AAO domain. The two sites are under the same influence at any given time (e.g. CPP is low (high), FPP is high (low) and dust mode indicates smaller (coarser) particles size). The power spectrum of Σ contains energy from 150 years to 500 years, which is thought to reflect the internal oscillations of the southern ocean climatic system. Along the Δ axis (*asymmetric mode*), the two sites are under opposite influence: when Vostok is subject to relatively high subsidence (i.e. CPP low, FPP high, small particle size), the EDC site is subject to air advection from the lower troposphere (i.e. CCP high, FPP low, and coarse particle size) and vice versa. Over the studied period, the power spectra of Δ display a significant band of energy centred around 150 and 220 years, suggesting a prominent oscillation mode centred on a 200 year band.

3.4 Is there a link between east Antarctic dipole oscillations and 200 year solar activity?

Our study points out that a 200-year oscillation mode characterises the atmospheric dipole over the east Antarctica during the Holocene. This periodicity is of particular interest since it is typically associated with the variability of solar activity (205-year so-called *DeVries* solar cycle), constituting the most prominent periodicity in the $\Delta^{14}\text{C}$ record during the Holocene (Damon and Sonett 1991), and also imprinted in the ^{10}Be record of polar ice (e.g. Beer et al. 1991). However, a direct comparison with ^{10}Be is not yet possible from the same sample we studied for dust since EDC and Vostok measurements are still in progress (G. M. Raisbeck, personal communication). In spite of this, we can already discuss some facts in the context of our scenario suggesting a possible link with solar activity.

From present-day atmospheric data, a significant statistical relationship between the 11-year sunspot cycle and geopotential heights was reported (Labitzke and Van Loon 1997) with the highest correlation for the subtropics. Also, a model study of modern climate (Shindell et al. 2001) suggests that an external forcing factor such as solar activity can induce significant changes in the intensity of the Westerlies. In fact, an amplification of the faint solar forcing would be required and amongst scenarios, Broecker et al. (1990, 1999) suggest a possible coupling with the ocean system. Sec-

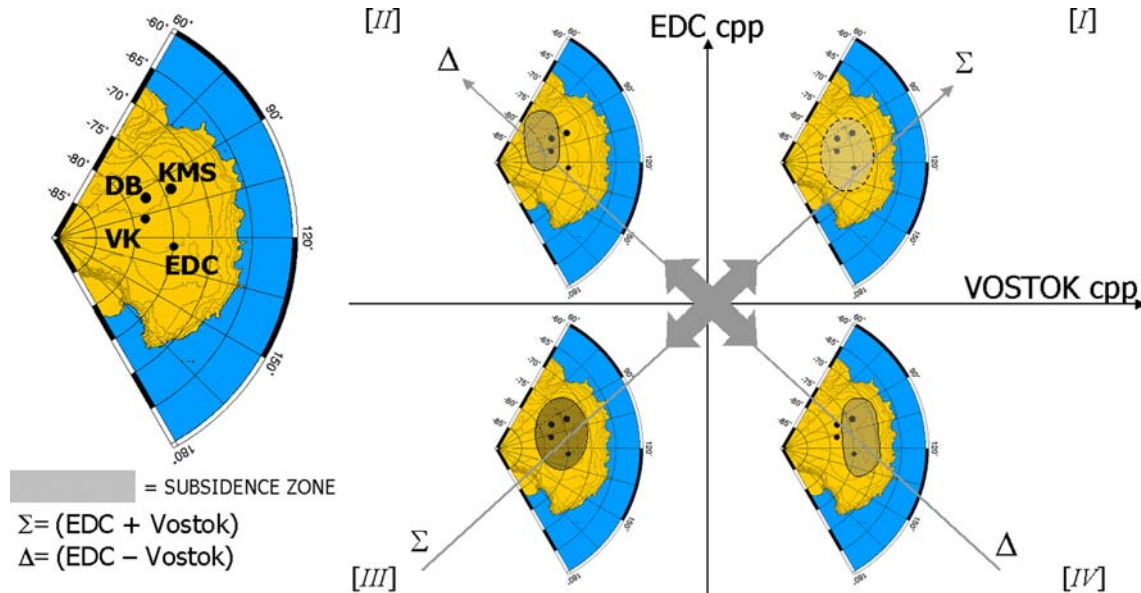


Fig. 8 Sketch of the variability mode of atmospheric circulation over Antarctica. *Left* zoom on the 60°E–180°E sector of the East Antarctic plateau with location of drilling sites. *Right* Vostok CPP and EDC CPP dust parameters are represented by the x and y axis respectively. Σ (sum) and Δ (difference) composite dust parameters are represented by the first and second diagonals. The centre of subsidence over East Antarctica is represented by an arbitrary rounded area that we associate to the fallout area of small-sized dust. We also assume that the Dome B and Komsomorskaya areas are associated with the Vostok and EDC regions, respectively, as they appeared during the last deglaciation period (Delmonte et al.

2004b). Along the Σ axis, a symmetric mode of variation is associated with the AAO variability (see text). Subsidence influence varies from high (quadrant III, area with *bold* boundary) to low (quadrant I, area with *dashed* boundary). Along the Δ axis, an asymmetric mode of variation is proposed and the two sites are under opposite influence. The area of subsidence varies from an eccentric location (quadrant IV) to a more poleward position (quadrant II). This may correspond to an atmospheric dipole over East Antarctica having a power spectra (Fig. 7b) with a significant oscillation mode in the 200 year band

ular-scale changes in sea surface conditions (sea ice extent and wind stress) were also shown to characterise the Holocene climate of the Antarctic Peninsula (e.g. Domack et al. 2001; Domack and Mayewski 1999) and may be linked to the oscillation of the circum-Antarctic trough probably modulated by solar activity. Recently, a marine core record of sea ice presence and summer sea surface temperature from the eastern South Atlantic ocean (Nielsen et al. 2004) also revealed a centennial and millennial-scale variability mode (1,220, 1,070, 400 and 150 years). The authors linked the centennial-scale changes observed in the records to atmospheric changes probably related to solar activity.

From the Atlantic ocean simulation cited above (Mikolajewicz and Maier-Reimer 1990), the ~ 50 –500 year band oscillation of the system introduces the possibility of resonance and amplification of external secular frequencies. The expected response will vary according to the area and time delay. It could be speculated therefore that the Southern Ocean pseudo-oscillator can integrate, amplify and embed into its internal variability mode a possible external (solar-induced) forcing. The 200-year band of variability, which is so strongly imprinted in our atmospheric records might therefore be the final expression of an ocean–atmosphere amplification of solar forcing at these timescales, influencing the sea surface temperature, sea ice extent and

climatological position of highs and lows and likely also expressed in the atmospheric dipole of East Antarctica.

However, the presence of the southern ocean and sea ice cover likely introduces a certain amount of thermal inertia in the system. The expected climatic response over Antarctica or on the East Antarctic dipole may not be direct and is more likely slurred and delayed with respect to solar forcing. At this stage, while speculating on possible links, we can only say that our data from East Antarctic records shows variability at solar band periodicities. Indeed, in addition to model studies of atmosphere–ocean–sea ice interactions along with the study of the regional impacts of solar forcing, ^{10}Be concentration measurements from Vostok or EDC ice core samples will be very helpful to document this relationship and refine such speculations.

4 Conclusions

The dust in East Antarctic ice cores represents a useful tool to trace the variability of atmospheric circulation and exchanges with Antarctica. The size distribution parameters are taken as indicators of atmospheric transport pathway. We assume that fine dust is associated with upper air advection and sinking and/or longer trajectories, while coarser dust indicates advection from

air masses from low levels in the troposphere. Our study shows that atmospheric circulation over East Antarctica contains secular and sub-millennial variations characterising the Holocene epoch similar to those observed for the last climatic transition.

The two Holocene dust-size records analysed at high temporal resolution show a clear secular-scale variability mode for atmospheric circulation over Antarctica at the two sites. A composite dust-size parameter (sum) is associated with the strength of the Antarctic oscillation. Its power spectrum is imprinted by secular scale oscillations that we interpret as internal to the southern ocean climate system, likely playing a buffering role and imposing its internal secular and sub-millennial oscillations to the AAO and to the meridional atmospheric transport of dust toward Antarctica.

The tight stratigraphic link between the two ice cores also makes it possible to show the existence of an atmospheric dipole over east Antarctica during the Holocene, i.e. a mesoscale asymmetric (seesaw) variability mode of atmospheric circulation between Vostok and EDC. Data show pervasive oscillations of the dipole around the 200 year band over $\sim 5,500$ years and suggest a possible link with solar activity, likely through amplification by the Southern Ocean climatic system.

On going ^{10}Be measurements on EDC or Vostok ice cores are expected to bring clues to the solar-climate relationship at secular periodicities by comparison with the dust-size profiles we presented here. In addition, model studies of atmosphere-ocean-sea ice interactions could be used to test the secular time scale behaviour of the southern climate system as well as the regional sensitivity of Antarctic climate to solar forcing.

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