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Holocene Climate Variability in Antarctica Based on 11 Ice-Core Isotopic Records

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A comparison is made of the Holocene records obtained from water isotope measurements along 11 ice cores from coastal and central sites in east Antarctica (Vostok, Dome B, Plateau Remote, Komsomolskaia, Dome C, Taylor Dome, Dominion Range, D47, KM105, and Law Dome) and west Antarctica (Byrd), with temporal resolution from 20 to 50 yr. The long-term trends possibly reflect local ice sheet elevation fluctuations superimposed on common climatic fluctuations. All the records confirm the widespread Antarctic early Holocene optimum between 11,500 and 9000 yr; in the Ross Sea sector, a secondary optimum is identified between 7000 and 5000 yr, whereas all eastern Antarctic sites show a late optimum between 6000 and 3000 yr. Superimposed on the long time trend, all the records exhibit 9 aperiodic millennial-scale oscillations. Climatic optima show a reduced pacing between warm events (typically 800 yr), whereas cooler periods are associated with less-frequent warm events (pacing >1200 yr).

INTRODUCTION

In the context of recent warming, understanding the mechanisms responsible for Holocene fluctuations in Antarctic climate is critical with respect to forecasts of global climate, ice-sheet mass balance, and sea-level change. The Southern Hemisphere atmospheric heat sink located in the Antarctic is of key importance for atmospheric and oceanic circulations. The surrounding floating ice (ice shelves, sea-ice) is a contributor to climate variability, which connects the atmospheric and oceanic components of the climate system (katabatic winds induce downwellings and modify the extent of the sea ice; sea ice formation and ice shelf base melting provide dense ocean waters). On seasonal to decadal timescales, present climatic teleconnections between Antarctica and Southern Hemisphere variability (ENSO) have been shown in atmospheric and oceanic parameters (temperature, sea-level pressure, and sea-ice extent) (e.g., Smith and Stearns, 1993).

Instrumental observations since the 1950s from permanent Antarctic stations and Southern Ocean island stations indicate a warming trend, more pronounced in winter for Antarctic stations and in autumn for the Southern Ocean (Jacka and Budd, 1998). The largest warming trend is documented in areas of the west Antarctic peninsula (+2.5°C/century), where large retreats of ice shelves have been observed in recent years (Rott *et al.*, 1996). It is crucial to put these past 40 yr of instrumental records into perspective with local climate natural variability. Ice-core isotopic analyses have been used for some time to do this on the scale of the last glacial–interglacial cycle, but little focus has been placed on Holocene climate variability (Ciais *et al.*, 1992, 1994; Domack and Mayewski, 1999) due to the small amplitude of the Holocene fluctuations and the requirements of records with good temporal resolution and precise timescales.

In the Northern Hemisphere, Holocene climate variability that is indicated by a wide diversity of available proxies (e.g., pollen, tree-rings, ice-cores, lakes, glaciers) shows regional complexity compared with larger climatic changes, such as glacial to interglacial changes (O'Brien *et al.*, 1995). In particular, temperate regions show an optimum in summer temperatures in the early Holocene, whereas at higher northern latitudes this optimum occurs later, during the middle Holocene. At lower latitudes, more intense monsoons are documented in the early Holocene (e.g., Gasse and Van Campo, 1994). Recently, an abrupt event occurring about 8200 yr ago has been identified at various latitudes (e.g., Stager and Mayewski, 1997; Von Grafenstein *et al.*, 1998). This abrupt early Holocene climate change is explained by a weakening of

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the North Atlantic thermohaline circulation due to a change in freshwater input (possibly from the collapse of the Hudson Bay ice dome and catastrophic drainage of Laurentide lakes); Barber *et al.* (1999). Over the past 7500 yr, declining temperatures in middle and high latitudes and decreasing tropical moisture are punctuated by abrupt and relatively short climatic fluctuations. Millennial-scale oscillations documented in some North Atlantic Holocene records are interpreted as weak Dansgaard-Oeschger cycles, with the 8200-yr event and the Little Ice Age being part of a 1470-yr oscillation that is possibly related to modes of the thermohaline circulation (Bond *et al.*, 1997; Bianchi and McCave, 1999). Similar periodicity is also apparent in records of tropical aridity (Sirocko, 1996), as documented in a succession of arid intervals in tropical lake and pollen records (Lamb *et al.*, 1995). Millennial-scale Holocene variability, therefore, results from a combination of abrupt events (e.g., final ice-sheet collapse) and possible internal oscillations of the climate system.

It is important for understanding the mechanisms responsible for the short-term Holocene climatic events to determine whether events similar to those observed in the Northern Hemisphere occurred in high southern latitudes. Here we compare the Holocene climate as archived in water isotope records from 11 Antarctic ice cores (Fig. 1; Table 1) located on the central plateau (Vostok, Dome B and Dome C, Komsomolskaia, Plateau Remote), at coastal sites of east Antarctica (D47, KM105, Law Dome-DSS), and on both sides of the Ross Shelf (Byrd in west Antarctica, Taylor Dome and Dominion Range in the Transantarctic Mountains). The geographical spread of these cores allows the separation of continental climate change from more regional patterns. In addition to significant high-frequency variability on the centennial scale, we show common millennial-scale aperiodic events and discuss possible mechanisms responsible for fluctuations of Antarctic Holocene climate.

QUANTITATIVE INTERPRETATION OF ISOTOPIC FLUCTUATIONS: ISOTOPIC PALEOTHERMOMETER

In this paper, we focus on multicentennial isotopic fluctuations, which enables us to minimize the noise associated with the various postdeposition processes (Fisher *et al.*, 1985). Assuming that deposition and postdeposition processes have a constant isotopic impact, the isotopic profiles should reflect fluctuations in the isotopic composition of precipitation. This isotopic composition of polar precipitation results from the fractionation history of the water vapor mass and depends on the site condensation temperature, on the moisture trajectory (distillation), and on the initial conditions of evaporation at the ocean surface. The dependency of surface snow isotopic composition on mean surface temperature of a site has long been evidenced in east Antarctica (Lorius and Merlivat, 1977). Our sites are quite representative of Antarctica, as their surface isotopic composition depends on their annual mean surface temperature with a spatial slope of 6.5‰ δD/°C (Fig. 2 and caption). This relationship is the basis for the climatic interpretation of isotopic fluctuations, with a deuterium shift of 10‰ supposed to reflect a change of 1.5°C in surface temperature. The use of the modern spatial isotope–temperature relationship to quantify temporal isotopic fluctuations requires the following assumptions (Jouzel *et al.*, 1997): (1) the annual mean condensation temperature covaries with the annual mean surface temperature, which requires no change in precipitation seasonality and no change in the strength of surface temperature inversion; (2) the evaporation conditions at the oceanic moisture source remain unchanged (constant sea-surface-temperature of the moisture source, constant isotopic composition $\delta^{18}O_{SW}$ of the ocean surface).

Recent modeling studies using atmospheric general circulation models, including the explicit modeling of water stable isotopes, have focused on the temporal isotope–temperature relationships between last glacial maximum (21,000 yr ago) and modern climates (Delaygue *et al.*, 2000). For Greenland, drastic changes in precipitation seasonality account for a factor of two between the spatial and temporal isotope–temperature relationships (Jouzel, 1999). For Antarctica, these modeling studies support the classical assumption that the spatial isotope–temperature relationship can be used to interpret long-term temporal variations (within 30% uncertainty). At the coastal site of Law Dome, an estimation of the seasonal isotope–temperature relationship has led to a slope of 3.5‰ δD/°C (Van Ommen and Morgan, 1997); at Taylor Dome, such an estimation based on borehole temperature measurements over the past 4000 yr is quite close (4‰/°C) (Steig *et al.*, 1998a). However, these small slope values can be partly explained by seasonal or local changes in oceanic moisture sources (Delmotte *et al.*, 2000).

Changes in $\delta^{18}O_{SW}$ of ocean surface waters due to deglaciation are still significant in the early Holocene (0.4‰ at 12,000 yr ago). Both simple isotopic models and GCMs simulate an imprint of ocean isotopic composition into polar precipitation of 5‰ deuterium per 1‰ $\delta^{18}O_{SW}$. As a result, about a third of the early Holocene optimum isotopic amplitude can be attributed to a change in ocean surface isotopic composition. Second, changes in evaporation conditions can be inferred from the second-order isotopic parameter, the deuterium excess. Holocene excess profiles obtained at Dome B, Dome C, Taylor Dome, and Vostok show a small increasing trend in the early Holocene, indicating a warming of the ocean surface, warming the moisture source by a few degrees, thereby partly compensating the impact of the change in ocean isotopic composition on the deuterium profiles (Vimeux *et al.*, in press).

To summarize, we interpret the Holocene isotopic fluctuations in terms of site temperature changes, with a necessary correction due to ocean surface isotopic composition in the early Holocene; we have some indications that changes in evaporation conditions should not play a major role. We are aware that climate changes associated with deposition (seasonality of the precipitation) and/or postdeposition processes

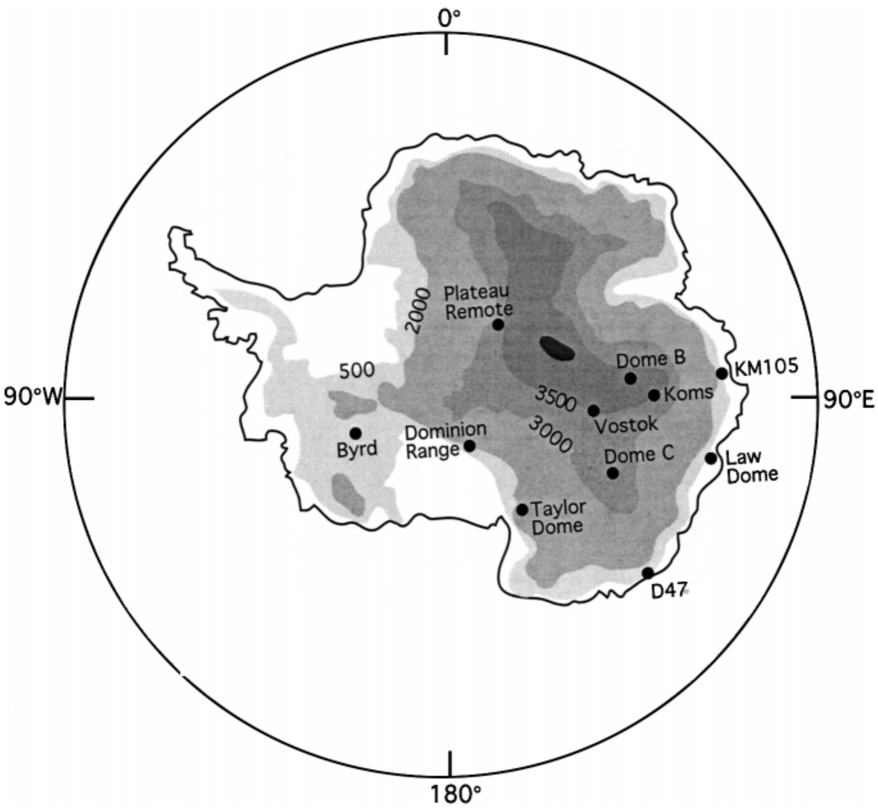

FIG. 1. Map of Antarctica showing drilling sites (elevation in meters).

(wind scouring, sublimation, removal of summer snow layers) may also be responsible for some of the Holocene isotopic fluctuations, but we have no means of quantifying them.

LONG-TERM TRENDS IN ANTARCTIC ISOTOPIC PROFILES: CLIMATE VERSUS ELEVATION CHANGES

The Holocene δD records (Fig. 3) exhibit small but significant isotopic fluctuations (typically 10‰), much larger than the analytical precision (0.5‰ for δD measurements, apart from Dome C and Taylor Dome, 1‰), indicating a remarkable Antarctic climate stability during the past 10,000 yr when compared with the amplitude of glacial–interglacial changes (40‰).

Ice-core isotopic ratios record temperature change arising from climate fluctuations but also from ice sheet dynamics (elevation, ice originating upstream of the core site). Modern isotopic contents along the 11 sites reflect the strong imprint of

TABLE 1
Characteristics of the Drilling Sites

Site	Latitude	Longitude	Altitude (m)	Distance (km)	Accumulation (cm/yr)	Temperature (°C)	δD (‰)	Velocity (m/yr)	Dating	Correlation parameters	Sampling interval (cm)	Resolution (yr)	References
Vostok	78°28′S	106°48′E	3490	1260	2.3	−55.5	−441.6	2	2D	G, Be, D	50	22	Petit *et al.*, 1999
Plateau Remote	84°S	43°E	3330	1370	4	?	−434.9*	?	0D	V	5	1	Mosley-Thompson, 1995
Dome B	77°05′S	94°55′E	3650	1020	3.8	−57.5	−430.4	0	1D	D	100	26	Jouzel *et al.*, 1995
Komsomolskaia	74°05′S	97°27′E	3499	840	6.4	−52.6	−400.6	?	1D		200	31	Nikolaiev *et al.*, 1988
Dome C	74°39′S	124°10′E	3240	870	3.4	−53.5	−393.3	0	1D	Be	200	60	Lorius *et al.*, 1979
Dominion Range	85°15′S	166°10′E	2700	780	3.5	−37	−338.0	?	1D	V	20	6	Mayewski *et al.*, 1995
Taylor Dome	77°48′S	158°43′E	2365	120	5 to 7	−43.0	−315.8	?	2D	G, Be	50	8	Steig *et al.*, 1998a
Byrd	80°01′S	119°31′W	1530	620	10 to 12	−28.0	−263.1*	12.7	LC	G, Be	20	12	Hammer *et al.*, 1994
D47	67°23′S	154°03′E	1550	130	26	−25.4	−219.4	26	2D	D	100	4	Ciais *et al.*, 1992
KM105	67°26′S	93°23′E	1416	85	33.1	−24.5	−231.4	45	1D		50	1.5	Lipenkov *et al.*, 1998
Law Dome	66°46′S	112°48′E	1370	90	70.0	−22.0	−177.2*	1	LC, 1D	L, G	50	0.7	Morgan *et al.*, 1997

Note. Latitude, longitude, altitude, distance from nearest ocean (ice shelves considered as part of the continent), accumulation (water equivalent per year), annual mean surface air temperature, average ice deuterium content (last 1000 yr; *, calculated as $8*\delta^{18}O$ measurements), surface ice velocity, dimensions of the ice flow model used to date the ice core (LC, layer counting), other dating tools (correlations based on G, gas; Be, ^{10}Be; D, dust; V, volcanic ash layers; L, direct estimates of layer thickness).

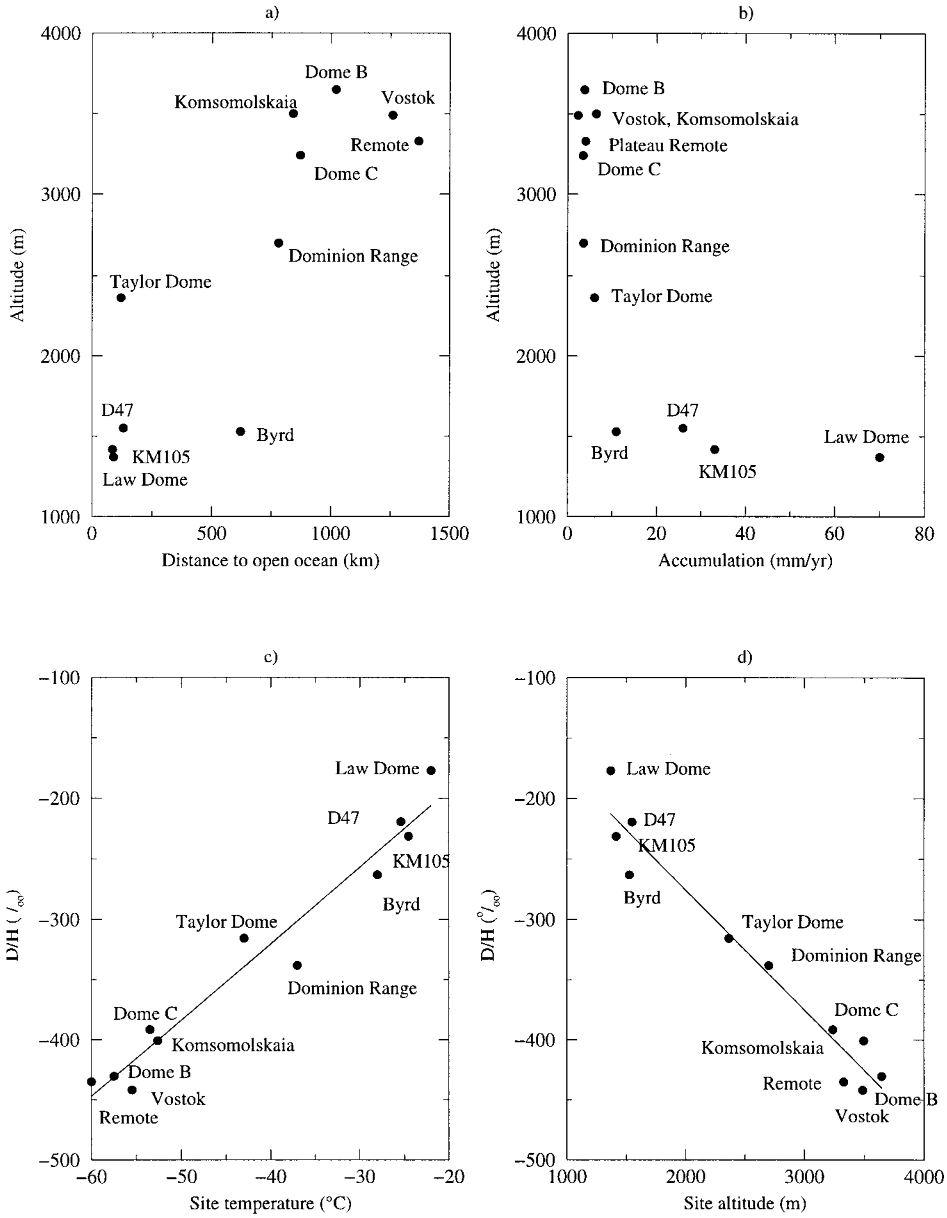

FIG. 2. Characteristics the Antarctic drilling sites relevant to isotopic records. If the spatial isotope/temperature, isotope/elevation, and isotope/distance from ocean relationships hold true in time, which is reasonable for the relatively stable Holocene period, then a change in δD of 10‰ corresponds to a surface temperature fluctuation of 1.5°C, or to a 50-km difference in the distance to the coast, or to 100 m elevation difference. (a) Geographic location as a function of distance to the nearest modern open ocean and elevation. Three groups can be identified (coastal low-elevation sites; sites located around the Ross Sea; central sites). (b) Comparison of modern accumulation as function of elevation. Central and Ross Sea sites have accumulations of <10 cm of ice per year. Coastal sites show a wide range of accumulations, probably related to the local meteorology. As a separate coastal dome, Law Dome summit does not experience katabatic winds and receives a remarkably high modern accumulation. (c) Dependency of modern (past millennium) isotopic composition on site surface temperature. The slope calculated with these 10 points (6.5‰°C) is very close to the relationship obtained from a wider distribution of semicontinental Antarctic surface data (Lorius and Merlivat, 1977). Our sites are thus representative of the spatial distribution of Antarctic isotopic surface snow. (d) Same as (c) but for modern site elevation. The vertical lapse rate calculated from the sites modern temperature and elevation is high (−14.8°C/km). The mean δD decreases when the elevation increases (−9.7‰/100 m) and decreases when the distance from the nearest coast increases (−19.4‰/100 km, not shown).

altitude (9.7‰/100 m, Fig. 2). In order to focus on time scales of ice sheet elevation, the long-term trend deviation to modern values (Fig. 4) was extracted from each ice core isotopic profile (Table 1; Fig. 3) using the first component of a SSA (singular spectrum analysis). Initial time scales were used (Table 1) and the long-term trend was centered to modern levels; the error on the dating is evaluated to about 10% for each record (relative error of ±500 yr at 10,000 yr).

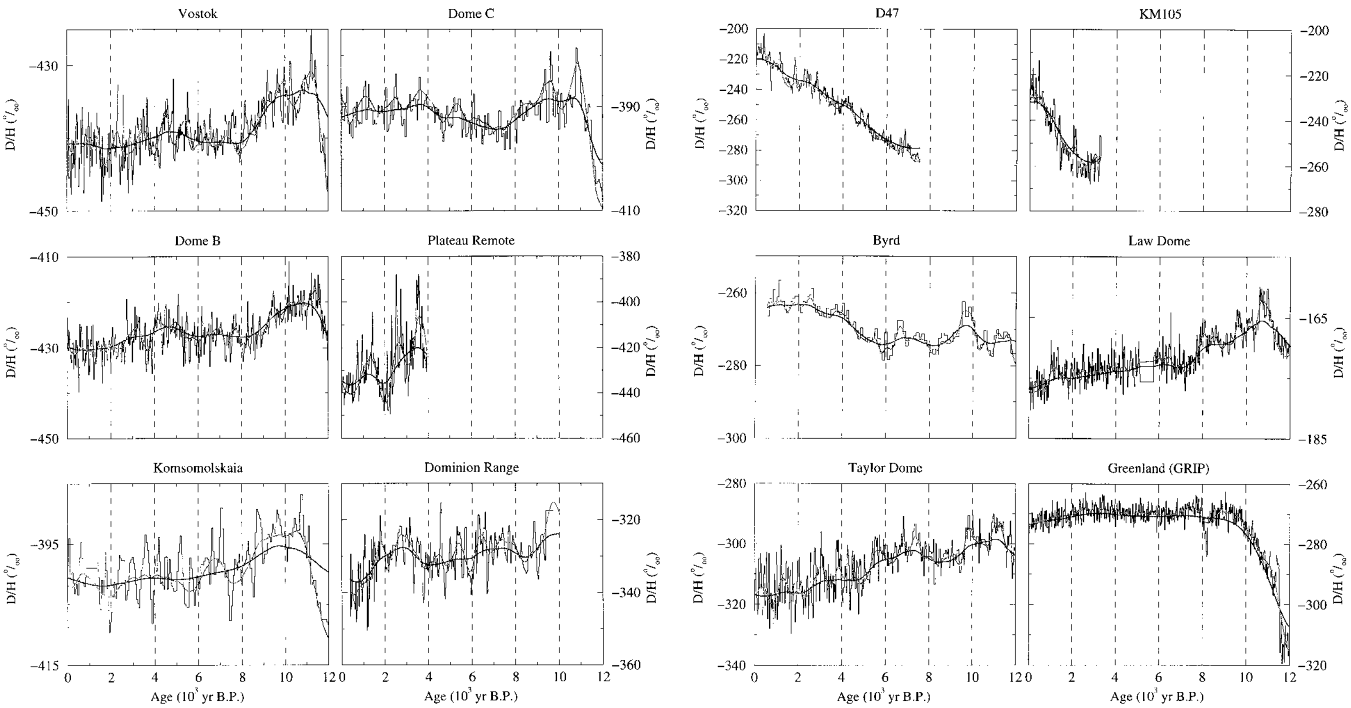

FIG. 3. Initial deuterium profiles (stairs, black); long-term trend (first component of the SSA analysis, black line); millennial scale variability (second and third components of the SSA analysis, gray line).

The two coastal sites where the surface flow velocity is large (KM105, D47) exhibit large increasing isotopic trends (10‰/1000 yr). These trends result from ice flow (change with depth of the initial precipitation elevation) and have no climatic meaning. These records can only be discussed in term of short-term isotopic fluctuations.

At Byrd, in western Antarctica, the ice flow is also large and probably explains the observed Holocene isotopic increasing trend. A study of the total air content of Byrd ice has led to an estimate of 500 m elevation increase during last deglaciation (Jenssen, 1983), ending about 7000–5000 yr ago, and an elevation decrease of about 100 m during the past 5000 yr. We combine these elevation changes with the effect of ice flow (the 10,000-yr-old ice at Byrd arrives from the surface about 40 km upstream, and 60 m higher). Both elevation and ice flow effects indicate that the ice originated about 200 m higher 5000 yr ago, which results in an apparent increase of δD by about 2 to 3‰/1000 yr, assuming the present elevation–isotope spatial relationship (Fig. 2 and caption). This rough estimate is consistent with the observed slope of 2.8‰/1000 yr. It is further supported by ice-flow modeling results constrained by direct evidence in the Executive Committee Range (Hackert *et al.*, 1999). We have therefore corrected the isotopic profile along the past 12,000 yr by adding a 2.5‰/1000-yr trend. The corrected Byrd record (empty circles, Fig. 4) is in fair agreement with the isotopic records from central and east Antarctica; our somewhat arbitrary correction has removed glaciological perturbations, but we may have underestimated the elevation change during the early Holocene. Hereafter, we use the corrected Byrd isotopic record as a climatic proxy for comparison with the other records.

All the records from eastern Antarctica exhibit a clear early Holocene optimum from 11,500 to 9000 yr ago, followed by a secondary minimum about 8000 yr ago. Compared to modern levels, the relative isotopic amplitude of the optimum ranges from 3.5‰ for Dome C to 18.5‰ for Taylor Dome. The amplitude seems larger at coastal locations (Law Dome, Taylor Dome). As 2‰ of the optimum amplitude is attributed to the change in ocean surface isotopic composition, the classical temperature interpretation suggests a warming by 0.2 to 2.5°C, depending on the site. At the end of this optimum, most sites show a clear minimum about 8000 yr ago (apart from Law Dome where it takes place 1000 yr later). The sites located in the Ross Sea sector are characterized by a mid-Holocene optimum 8000 to 6000 yr ago (amplitude 5‰). In east Antarctica (apart from Taylor Dome and Dome C), a weak late Holocene optimum occurs between 6000 and 3000 yr ago (amplitude from 1 to 5‰) and is followed by a negative trend. Some sites (corrected Byrd, Dominion Range, and Dome C) also show a late optimum about 3000 yr ago, possibly related to the maximum in Southern Hemisphere summer insolation at this time.

The early Holocene optimum in Antarctica occurs at the same time as the Northern Hemisphere summer insolation optimum (11,000 yr ago). During the end of the Northern Hemisphere deglaciation, a reduced northern Atlantic thermohaline circulation could contribute to warm conditions in high

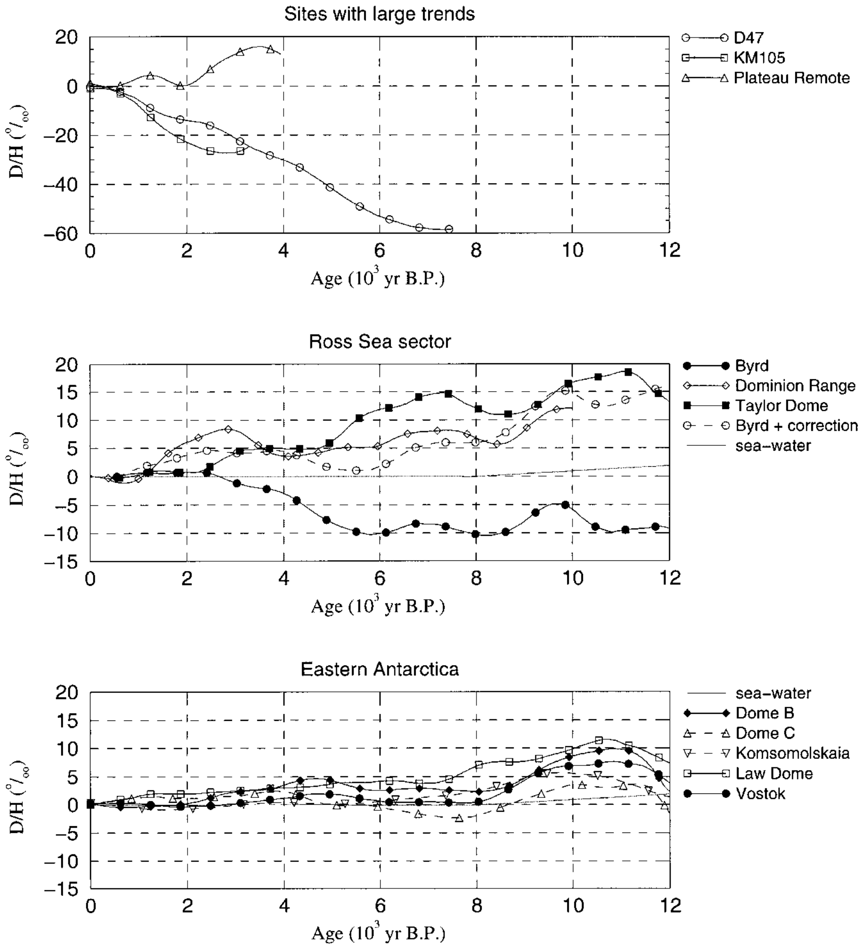

FIG. 4. Centered deuterium trends (first SSA component) extracted from the resampled isotopic profiles using the SSA analysis. For Byrd and Law Dome, the $\delta^{18}O$ profile was converted to deuterium using the meteoritic water line slope of 8. For Byrd, we propose a correction for the ice origin isotopic imprint (dashed line) (25 m per thousand year, i.e., 2.5‰ per thousand year).

southern latitudes, as suggested for the last deglaciation (Blunier *et al.*, 1997). When the northern deglaciation ends, the switch-on of the North Atlantic circulation removes heat from high southern latitudes, therefore ending the early Holocene optimum in Antarctica. This is supported by the $\delta^{13}C$ record from benthic foraminifera in Atlantic core CH69-K09, which shows a maximum North Atlantic influence in the mid-Holocene (8000 to 6000 yr ago). This mechanism would provide an explanation for the end of the Antarctic optimum, when the Northern Hemisphere warms after the last cold episode of deglaciation (8200 yr ago).

The decreasing isotopic values over the past 10,000 yr suggest an overall Holocene increase in elevation of the east Antarctic ice sheet (<50 m), consistent with available indications about ice-sheet elevation changes obtained from geologic observations at the ice-sheet margins (Goodwin, 1998), measurements from total air content in the bubbles trapped in the ice (Martinerie *et al.*, 1994; Delmotte *et al.*, 1999), and three-dimensional ice-sheet modeling (Huybrechts, 1992). The different trend observed at Dome C compared to other east Antarctic sites may reflect a different ice-sheet elevation history. Assuming that climate fluctuations are of similar amplitude at Dome C and central sites, our data suggest that Dome C has undergone a relative elevation decrease of about 75 m in the past 10,000 yr, which is qualitatively consistent with results from three-dimensional ice-sheet models (Huybrechts, 1992). Finally, the large decreasing trend at Taylor Dome (1.5‰/1000 yr, twice as large as in central Antarctica) may reflect a larger elevation increase since the last deglaciation observed in stratigraphic studies (Marchant *et al.*, 1994). This is surprising considering that Taylor Dome has a rapid ice-dynamics response time that tends to balance variations in accumulation (Steig *et al.*, in press).

MILLENNIAL-SCALE AND HIGH-FREQUENCY VARIABILITY

We have extracted the millennial-scale variability from each record (Fig. 3) as reconstructed by the second and third components of the SSA. To highlight the fluctuations possibly common to several sites, we have performed an empirical orthogonal function (EOF) analysis on different subsets of record (sites with large trends, limited to 3500 yr due to the length of Plateau Remote record; sites from the Ross Sea sector; sites from east Antarctica). The first component of the EOF accounts in all cases for more than 65% of the variance and is displayed on Fig. 5. The EOFs exhibit organized fluctuations common to the different sites within the dating uncertainty (less than 500 yr at 11,000 yr B.P.). These events are numbered on the figure (positive anomalies numbered from 1 to 8, negative events A to D).

Several aperiodic 500-yr-long isotopic fluctuations punctuate the long-term trends described previously. These small fluctuations ($<$5‰) have a significantly larger amplitude at coastal locations than in central sites and at Law Dome, in contrast with the common glacial-to-Holocene isotopic increase. The pacing of the warm events (average pacing of 1450 yr for east Antarctica and 1250 yr in the Ross Sea sector) increases during the cold periods ($>$1200 yr) and decreases in the optima ($<$900 yr). The early Holocene optimum results from two warm oscillations at all sites (events 1 and 2); it is followed by minimum A about 8000 yr ago.

The mid-Holocene optimum also corresponds to a succession of warm events (events 3 to 4 in the Ross Sea sector; events 4 to 6 in eastern Antarctica). At 5500 yr ago, the Ross Sea sector shows a second minimum "B" resulting from a long-term decrease superimposed on a more rapid oscillation (Steig *et al.,* 1998b). This period may correspond to the inflow of seawater onto the Ross Shelf (modern bathymetry lower than 5 m) and retreat of the grounded ice sheet (Domack *et al.,* 1999). The decrease in deuterium values is consistent with decreased continentality and a stronger contribution from local moisture sources. This interpretation is further supported by the simultaneous decrease in deuterium excess at Taylor Dome (Vimeux *et al.,* in press), indicating a colder oceanic moisture source.

Superimposed on the past 5000-yr cooling trend common to all records apart from Dome C, two warm events (6 and 7) precede a relative minimum in all the records about 2000 yr ago (C). It is followed by the last warm event (8) about 1000 yr ago and a last cold spell (Antarctic Little Ice Age, D). These recent isotopic fluctuations are associated with observed environmental changes. For instance, the penguin population on the Victoria Land coast (Baroni and Orombelli, 1994) was unusually large about 4000 to 3000 yr ago, corresponding to events 7 and 8 and the end of the mid-Holocene optimum; a second occupation about 1000 yr ago corresponds to warm event 9. In the Antarctic Peninsula, ocean sediments also record warmer climatic conditions before 2500 yr ago (Leventer *et al.*, 1996). Goodwin (1998) argues that the late Holocene optimum may have contributed significantly to the observed recent thickening of the east Antarctic ice sheet.

The spectral properties of the isotopic signal is evaluated with a Monte-Carlo singular spectrum analysis method (MC-SSA) (Dettinger *et al.*, 1995) on the regularily sampled records without correction of the long-term trend. The power spectrum is compared to a red noise spectrum at 97.5% confidence level (Fig. 6). In the analysis, Dome C, Byrd, and Komsomolskaia appear as outliers due to their lower temporal resolution, as well as Dominion Range, KM105, D47, and Plateau Remote due to their shorter length. The low-frequency mode is, in general, not significantly different from the red noise, apart from the trend for some of the records (Law Dome, Dome B, Taylor Dome, Byrd). The millennial-scale fluctuations discussed previously are mostly aperiodic and do not significantly appear in the power spectrum.

All the records show several common intervals of significant periodicities in the multidecadal to centennial mode, as discussed by Yiou *et al.* (1997): about 240, 180, 150 (these three modes do not appear in Law Dome and KM105), 120–110, 100–90, 85, 75, and 70 years. Obviously, the uncertainty of the dating ($\sim$10%) and the initial sampling (20 to 50 yr) strongly limit the interpretation of these periodicities. However, the range of periodicities remains unchanged when the time scale is linearly adjusted by $\pm$5%. Other records, such as Holocene tree-ring ^{14}C fluctuations, show similar significant periodicities (Stuiver and Braziunas, 1993) (206, 148, 87, and 46–49 years). Such periodicities may arise from fluctuations in solar activity and/or be the consequence of changes in thermohaline oceanic circulation.

The succession of millennial warm episodes cannot be explained by low-frequency changes in insolation or Holocene greenhouse gases and may result from internal oscillations of the climate system (possibly amplifying short-term forcings, such as solar activity or volcanic activity). Modes of thermohaline circulation in the North Atlantic are possibly characterized by a millennial-scale periodicity (Bond *et al.,* 1997; Bianchi and McCave, 1999); the Southern Ocean circulation, however, is poorly documented at these timescales. Around Antarctica, historical records document calvings of the Ross Ice Shelf with century-scale periodicities (Keys *et al.,* 1998). Century-scale changes of sea-ice are also documented in the Ross Sea (Leventer and Dunber, 1988) and the Antarctic Peninsula (Leventer *et al.*, 1996). Climate mechanisms responsible for century-scale fluctuations may involve a positive albedo feedback (a cold perturbation leads to more sea-ice formation, which in turn enhances the cooling), and a negative thermohaline feedback (a warm perturbation leads to less sea ice, an increased local hydrological cycle, less stratification of the ocean, and more heat advection, which enhances the initial warming). The dynamics of ice sheet/ice shelves/sea ice growth and decay, involving a combination of temperature and moisture controls, may generate multidecadal- to millennial-scale fluctuations. These coastal mechanisms are consistent with the larger amplitude of isotopic variations at coastal Antarctic sites compared with central sites and with the simulation of Bromwich *et al.* (1998), which removes all sea ice around Antarctica and shows a limited impact in the eastern

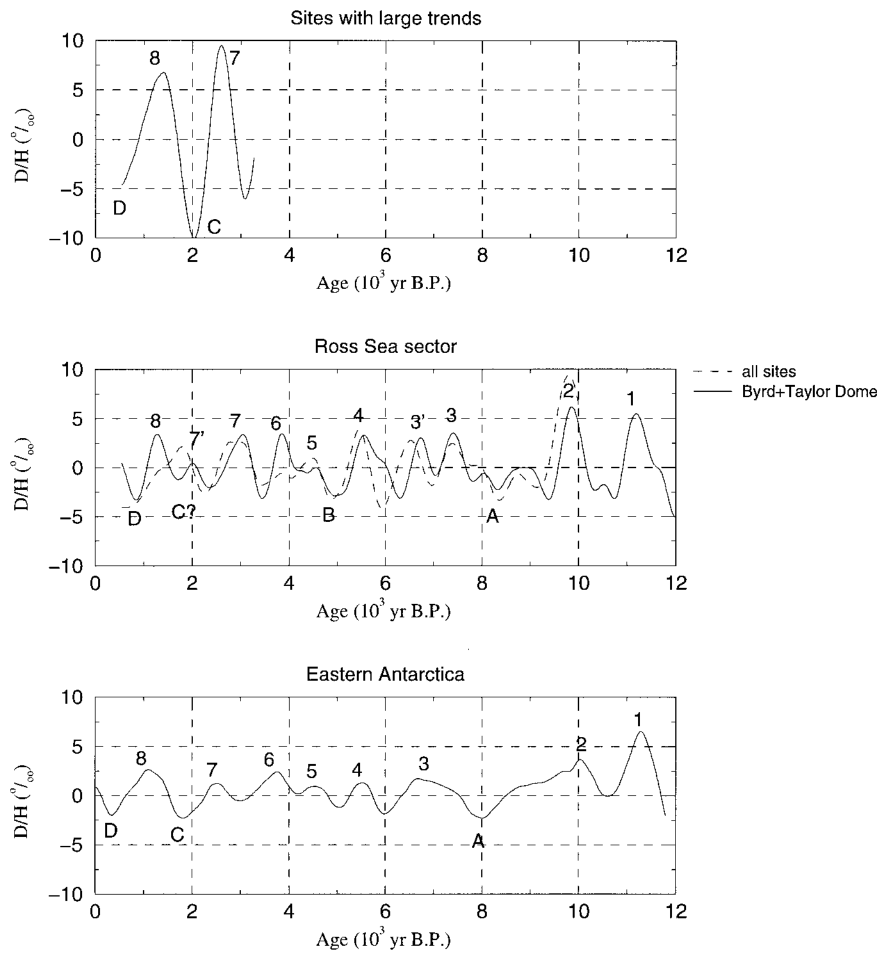

FIG. 5. Common millennial-scale variability in the different sets of records calculated as the first EOF of the detrended isotopic records filtered in the millennial periodicities (second and third components of the SSA). For the Ross Sea, the first EOF calculated from Byrd, Taylor Dome, and Dominion Range accounts for 55% of the variance. The EOF calculated without Dominion Range and covering also the early Holocene accounts for 66% of the variance. For central Antarctica, the first EOF accounts for 67% of the variance.

plateau (+2°C) but a very large impact at coastal locations, especially near Taylor Dome. Interestingly, the most coastal site of Law Dome registers only weak fluctuations and behaves more like inland sites than other coastal sites. This may arise from its constant maritime location, far from ice shelves that may act as amplifiers of climatic fluctuations.

CONCLUSIONS AND PERSPECTIVES

The long-term trends of Antarctic isotopic profiles record a complex combination of temperature and elevation changes, even at the scale of the Holocene. The deconvolution of the two signals will be aided by a detailed comparison with results from long integrations of three-dimensional ice-sheet models forced with different temperature variation scenarios. Our results suggest that Dome C and the sites from the Ross Sea region undergo specific elevation histories that differ from those of the central plateau and Law Dome.

All the long Holocene records combined in this work (including recent profiles from coastal and Ross Sea locations) confirm the widespread Antarctic early Holocene optimum (11,500–9000 yr ago). The mechanism responsible for this optimum may involve a reduced interhemispheric heat transport by the global oceanic thermohaline circulation during the end of Northern Hemisphere deglaciation. Secondary warm periods are observed ca. 8000 to 6000 yr ago in the Ross Sea sector, ca. 6000 to 3000 yr ago at central locations, and ca. 3000 yr at Dome C, Dominion Range, and Byrd.

These warm intervals are always associated with a reduced pacing between aperiodic millennial-scale warm fluctuations (eight warm fluctuations during the Holocene). Within the uncertainties of the timescale, these events appear in phase in all the records and are characterized by a greater amplitude at coastal locations (apart from Law Dome), suggesting positive feedbacks due to sea ice and/or ice shelves. Such oscillations are somewhat similar to the land surface/atmosphere feedback

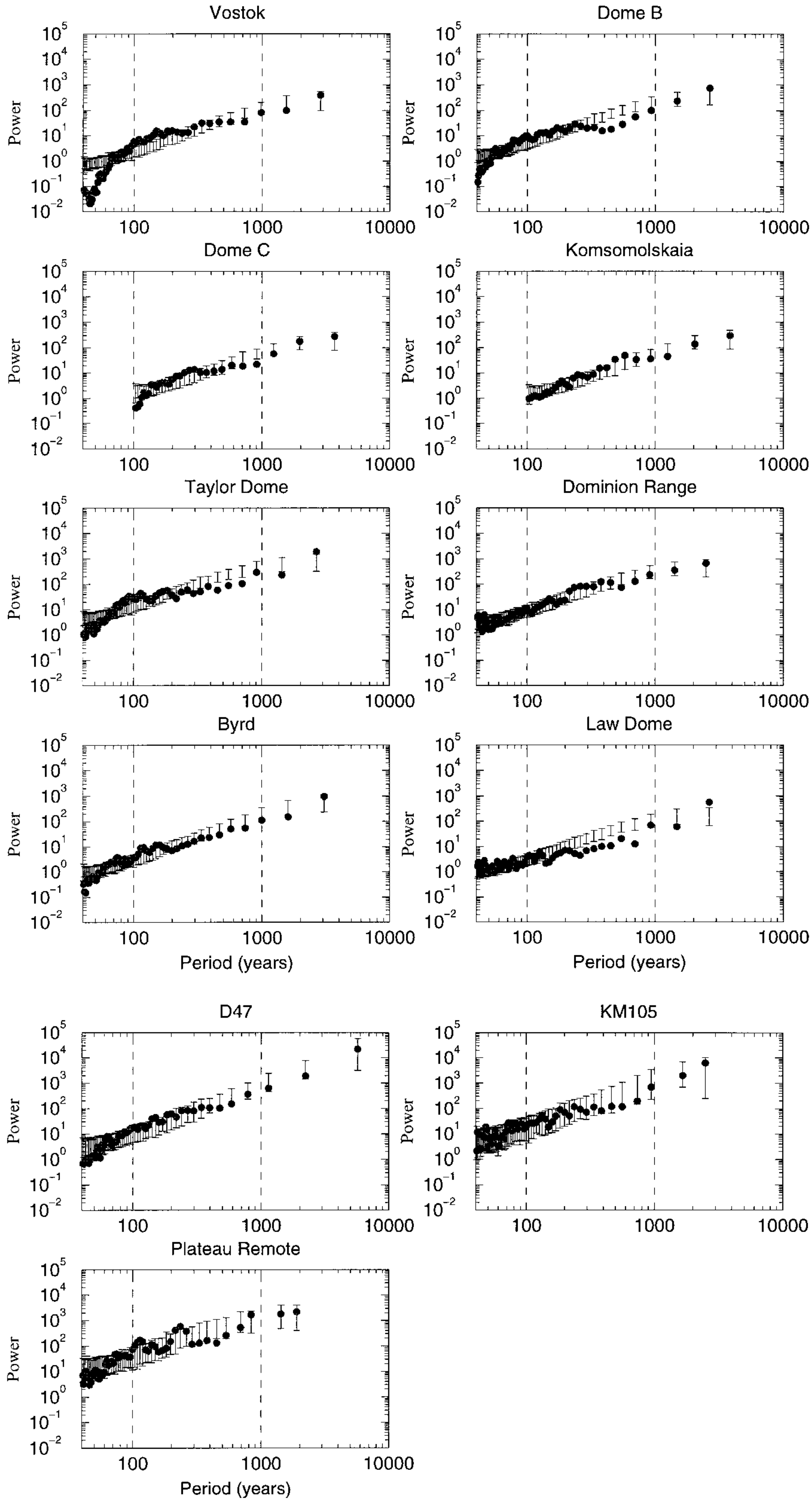

FIG. 6. Power spectra based on resampled isotopic records (without trend correction) and calculated by the SSA (singular spectrum analysis with 8 tapers and a window length of 60 points) spectral analysis, as a function of the logarithm of the period (in years). The 97.5% confidence error bars are estimated from a Monte Carlo significance test.

mechanisms taking place in the tropics, where arid intervals show a millennial rhythm. All the records exhibit a high-frequency variability in the multidecadal mode (70–240 yr) characteristic of internal oscillations of the ocean–ice–atmosphere system.

In order to document the spatial variability of climate fluctuations better, new ice core drilling projects are in progress or planned in east Antarctica (Dome C, EPICA), west Antarctica (Siple Dome), and the Atlantic sector of Antarctica (Dome F, Dronning Maud Land-EPICA). Identifying common volcanic events will be necessary to improve the accuracy of the chronology of Antarctic Holocene isotopic records. Combining isotopic records (including deuterium excess) with paleotemperatures reconstructed from borehole measurements at sites with high accumulation and with detailed chemistry records will permit better understanding of the site temperature signature in the isotopic profiles (deconvolution of site temperature versus seasonality and moisture origin). Obtaining Holocene isotopic records from the Antarctic Peninsula would be of great interest for comparison with the high-resolution glacier and sediment records. Alternatively, high-resolution Holocene records obtained from sediment cores around Antarctica and in the temperate oceanic moisture source regions would give more constraints on the mechanisms responsible for Antarctic climate variability.

Simulating the natural variability in the Antarctic sector presents a challenge for coupled ocean/floating-ice/atmosphere climate models. Long simulations will possibly help in understanding the mechanisms responsible for at least the high-frequency Holocene variability.

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