Note

Data include previously published diatom-derived sea-ice reconstruction (Crosta et al., 2004; www.sciencedirect.com/science/journal/03778398) and EPICA Dome C ssNa+ flux and D data (NOAA Paleoclimatology website www.ncdc.noaa.gov/paleo/paleo.html).

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Accurate chronology for Antarctic ice cores on orbital timescales

KENJI KAWAMURA

National Institute of Polar Research, Research Organization of Information and Systems, Tokyo, Japan; kawamura@nipr.ac.jp

An accurate chronology of Dome Fuji and Vostok ice core records, with dating accuracy better than ~2 kyr, has been established for the past 400 kyr and is consistent with the Milankovitch theory for the sequence of 100-kyr climatic cycles.

Deep ice cores from Antarctica have provided key records of past climate, including local temperature, atmospheric greenhouse gases and aerosols (e.g., Petit et al., 1999; Kawamura et al., 2007; Lüthi et al., 2008), over several glacial-interglacial cycles. In particular, the records have revealed a strong correlation between Antarctic temperature and greenhouse gas concentrations. In order to understand further the roles of both orbital and greenhouse gas forcings on climate changes, and to test Milankovitch forcing as the driver for the 100-kyr cycles seen in the ice core proxies, one would need paleoclimate chronologies with accuracy better than ~2 kyr (~10% of a precession cycle). A brief review is presented here on recent progress in improving the chronology of Antarctic ice cores for ~80 kyr BP and older, by orbital tuning of the record of oxygen-to-nitrogen concentration ratio (O_2/N_2) in trapped air with the local summertime insolation (Kawamura et al., 2007; Suwa and Bender, 2008). The implications for our understanding of the mechanisms of glacial cycles is also discussed.

Orbital tuning using O_2/N_2

Dating of the Antarctic deep ice cores involves models of past snow accumulation rates and ice flow (to account for thinning) whose parameters are constrained by depth-age control points with associated uncertainties (typically 2-6 kyr for MIS 5 and older periods). The error of the glaciological chronology may be large (>10 kyr) especially deeper in cores (>~2000 m, e.g., GT4 of Vostok and EDC2 of Dome C chronologies) because the real ice flow and/or accumulation histories do not follow the models' simple assumptions. Orbital tuning utilizes the known relationship between a measured parameter in the ice and an insolation curve to correct the glaciological chronology. Conventional orbital tuning uses global climate proxies, such as atmospheric CH_4 or $\delta^{18}O$ of O_2, which are matched to proximal insolation forcing (Dreyfus et al., 2007; Ruddiman and Raymo, 2003). This has brought great improvement over the glaciological chronology (e.g., EDC3 over EDC2 for the Dome C core; Parrenin et al., 2007) but the error is still up to ~6 kyr because the actual phasing between these gas proxies and orbital variations is variable.

New orbital tuning using O_2/N_2 has been developed for the Dome Fuji and Vostok cores covering 80-400 kyr BP (Kawamura et al., 2007; Suwa and Bender, 2008) (Fig. 1, A-C). O_2/N_2 in these cores is depleted relative to the atmospheric ratio because of physical fractionation during air-bubble formation at ~100 m depth (Severinghaus and Battle, 2006). The magnitude of this depletion is controlled by the magnitude of snow metamorphism, driven by local summer insolation when the layer was originally at the surface (Bender, 2002).Although the exact mechanisms are currently not well understood, empirical evidence indicates that the O_2/N_2 variation is probably phase-locked to the local summer solstice insolation, with negligible climatic influences (Kawamura et al., 2007). The independent Dome Fuji and Vostok O_2/N_2 chronologies agree within 1 kyr, indicating robustness of the method. The accuracy of the chronology (and thus the assumption of using the solstice insolation as the target) is validated through comparison with several age markers (a volcanic ash layer and CH_4/monsoon abrupt events) whose radiometric ages are accurate to within ~2 kyr for the last ~200 kyr, and which agree within 2 kyr (Kawamura et al., 2007; Suwa and Bender, 2008; Wang et al., 2008). Suwa and Bender (2008) developed a nearly identical O_2/N_2-tuned chronology for the Vostok core (100-400 kyr BP), with the addition of new O_2/N_2 data and using a slightly different method for the matching. Another local insolation proxy is air content (used for EDC3), although it gives less accurate age control (with an error of ±4 kyr) partly because of climatic influences (Raynaud et al., 2007).

Climatic implications

The new chronology permits comparisons between parameters measured in Antarctic ice cores (such as temperature and atmospheric greenhouse gases) and orbital variations, thus providing the possibility to separate the respective contributions to past global climate and sea level changes. The 340-kyr-long Dome Fuji temperature record on the new chronology closely follows boreal summer insolation, possibly with a slight lag behind solstice insolation (Fig. 1D). Thus, the previous arguments of early Antarctic warming following the southern summer insolation to trigger northern deglaciation is not supported by the new chronology. Further, the onset of the last four Antarctic terminations are found to lag behind the minima of insolation by 2-7 kyr, and the entire duration of the warming events fit within the rising phase of June solstice insolation at 65°N. For the last three glacial inceptions, Antarctica cooled in phase with the decrease in northern summer insolation and before significant decreases seen in CO_2 and sea level (Fig. 1, D-F) curves.

The above timings are fully consistent with the view that high northern latitude summer insolation drives the 100-kyr glacial cycles by changing summertime temperature and thus long-term glacial mass balance (Raymo, 1997; Denton et al., 2006), with large amplification by albedo and CO_2 feedbacks. This view is supported by the recent analysis of marine sediment data by Bintanja and van de Wal (2008), which

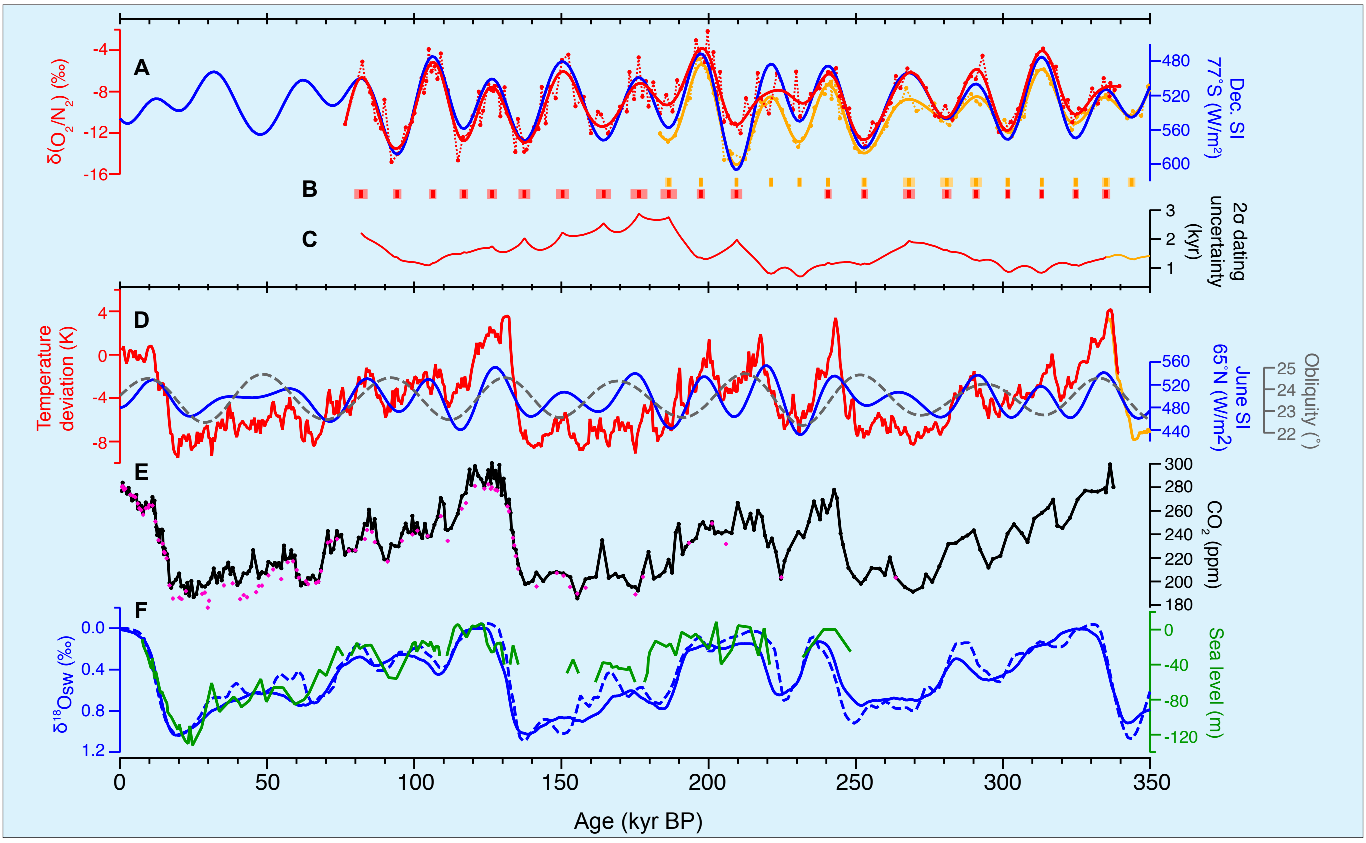

Figure 1: Accurately dated Antarctic ice core records and comparison with sea level proxies (Kawamura et al., 2007). ***A)*** *Orbital tuning of O_2/N_2 in the Dome Fuji (red) and Vostok (orange) cores with local summer insolation (SI; blue).* ***B)*** *Tuning tie points with 2σ error bars due to O_2/N_2 data noise.* ***C)*** *2σ dating uncertainty by combining those of the tie points and interpolation procedure.* ***D)*** *Dome Fuji temperature (red), Vostok temperature (orange), northern hemisphere summer insolation (SI; blue) and obliquity (gray).* ***E)*** *Dome Fuji CO_2 concentration by wet (black) and dry (purple) extraction. Note: wet values are too high at LGM and dry values too low in MIS 3, due to artifacts during extractions.* ***F)*** *Sea level reconstructions using radiometrically dated corals (green; Thompson and Goldstein, 2005) and orbitally tuned $\delta^{18}O$ of seawater, based on marine sediment records through ice sheet modeling (blue solid line; Bintanja et al., 2005) and regression analyses (blue dashed line; Waelbroeck et al., 2002). Records are plotted on their own chronologies.*

shows that the decrease in ice volume did not lag behind the increase of air temperature at the 100-kyr terminations after ~700 kyr BP. This suggests that the huge northern hemisphere ice sheets were actively involved in terminating the 100-kyr glacial periods.

For the last termination, the onset of sea level rise (at 19 kyr BP) may have triggered the Antarctic warming (and CO_2 rise, which is in phase with the Antarctic temperature within 1 kyr) through the bipolar seesaw mechanism (Clark et al., 2004). Assuming that the same mechanism worked during the older terminations, the onset of sea level rise for the older terminations is predicted to be slightly earlier than the onset of the Antarctic warming. There is an alternative view that Antarctic temperature is independent of northern climate and is controlled by the duration of the Antarctic summer, which shows a nearly identical pattern to the northern summer insolation (intensity) (Huybers and Denton, 2008). However, the tight bipolar coupling seems to apply also to orbitally driven warming events (A4 and A7 events in Blunier and Brook, 2001; see also EPICA, 2006). Thus the contribution of the local (Antarctic) orbital forcing could actually be small. A global climate modeling approach would be required to quantitatively estimate the contributions of local and distant orbital forcings to the Antarctic temperature (and CO_2) changes.

Summer insolation intensity (June solstice, mid July, mean July, JJA average, etc.) is dominated by the precession signal, whose amplitude is modulated by eccentricity. However, the obliquity signal becomes stronger if longer periods (e.g., half-year average) or summer energy (time-integrated insolation over the days where daily insolation exceeds a certain threshold) (Huybers, 2006) is taken into consideration. The last four terminations actually started when obliquity was relatively large (Huybers and Wunsch, 2005; Suwa and Bender, 2008). With regard to the relative importance of precession and obliquity, termination III (~245 kyr BP) is interesting because the precession (as in northern summer insolation) and obliquity were out of phase just before the termination. Here, the pattern of temperature evolution from the termination to the next glacial inception is similar to northern summer insolation, while obliquity is decreasing from the previous peak. A longer ice core record with the O_2/N_2 chronology is certainly needed to investigate further terminations before this problem can be resolved.

Outlook

It is very important to extend the O_2/N_2 chronology further back in time. The second drilling at Dome Fuji reached 3035 m in depth (~720 kyr BP according to EDC3 chronology; Motoyama, 2007) and the measurement of gas records is underway. The extended chronology will permit statistical testing of the phase stability of terminations with respect to both precession and obliquity (Huybers and Wunsch, 2005). It will also help clarify the true duration of Marine Isotope Stage 11 and how the climate evolution around this interglacial period might serve as an analog to the Holocene and future climate.

Note

Data used in this article are available from the World Data Center at www.ncdc.noaa.gov/paleo/icecore/antarctica/domefuji/domefuji.html

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