Forcing and feedback mechanisms of suborbital-scale climate variability during interglacials

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Abstract

Suborbital climate variability during the last glacial period is suggested to have involved a 1,500-year pacing cycle, but the expression and spatial distribution of the ~1,500-year oscillation during interglacials remain unclear. The alkenone sea-surface temperature record in the northwestern Pacific off central Japan during the Holocene indicates that the mean latitude of the Kuroshio Extension has varied on 1,500-year cycle. The regular pacing at 1,500-year intervals seen throughout both the Holocene and the last glacial period suggests that the oscillation was a response to external forcing (Isono et al., 2009). The origin of 1,500-year cycle still remains a question, and the future investigation is necessary to solve this question by drilling the region sensitive to climate changes such as oceanic frontal zones.

Persistent suborbital-scale cycles in glacial and interglacial modes

The last glacial period was characterized by the recurrence of abrupt climate changes, the Dansgaard-Oeschger (DO) events, observed in the Greenland ice cores (Dansgaard et al., 1993). Greenland Ice Sheet Project 2 (GISP2) oxygen isotope records have revealed a spectral density peak with 1,470-year periodicity (Grootes and Stuiver, 1997). However, the significance of this periodicity remains under debate, with researchers questioning whether DO events reflect a precise clock (Schulz, 2002; Rahmstorf, 2003) or are noise induced (Ditlevsen et al., 2007).

The ~1,500-paced variation during the Holocene was first reported by Bond et al. (1997) based on the ice-rafted hematite-stained grain (HSG) record in North Atlantic cores. Although spectral analysis did not indicate a 1,500-year period, the average interval of HSG maxima (Bond events) was ~1,500 years (Bond et al., 2001). High HSG content was interpreted to express a reduced North Atlantic deep water (NADW) formation event (Bond event; Bond et al., 1997, 2001). However, few climate records have shown a clear 1,500-year periodicity in the Holocene.

If the ~1,500-year variation was expressed during both glacial and interglacial climate modes, then such a regular variation could be considered a response to a periodic external forcing rather than an internal oscillation in the climate system (Bond et al., 1997; Rahmstorf, 2003). To clarify this issue, we must find a significant 1,500-year periodicity in Holocene records.

Isono et al. (2009) demonstrated that the detrended SST variation at the Japan margin in the northwestern Pacific during the Holocene showed a statistically significant spectral peak with a periodicity of 1,470 years (Fig. 1). The 400-year running average of detrended SST shows this periodic change more clearly (Fig. 2B). The timing of warming events is defined as the time when the 400-year running-mean curve is halfway (at the mid-point) between the maximum and minimum. The standard deviation of the last seven warming events in the Holocene is nearly equal to that of glacial Dansgaard-Oeschger (DO) events (130 years; DO 0 to DO 12, DO 9 omitted, GISP2 timescale; Grootes and Stuiver, 1997; Schulz, 2002; Rahmstorf, 2003). The stability is distinguishable from noise above a 90% confidence level (Ditlevsen et al., 2007). The phase of the last seven warming events is consistent with that of DO events; the former lagged the latter by only 56 years on average (Fig. 1B). This correspondence suggests the existence of a persistent 1,470-year cycle during both the Holocene and the last glacial period.

What is the origin of 1,500-year cycle?

A persistent 1,500-year cycle in glacial and interglacial modes suggests that such a regular cycle is a response to a periodic external forcing rather than an internal oscillation in the climate system (Rahmstorf, 2003). Solar output variations (equivalent to sunspot numbers estimated from variations in tree ring $\Delta^{14}C$ variation; Solanki et al., 2004) do not match the Japan-margin SST variation (Figs. 2A and 2F). Only in the Little Ice Age did low temperatures at the Japan margin correspond to low solar output; such a correlation is not evident at other times. Spectral analysis of solar radiation variation does not show ~1,500-year periodicity (Stuiver and Braziunas, 1993). Braun et al. (2005) suggested that a nonlinear response of freshwater input into the North Atlantic Ocean to the solar DeVries-Suess and Gleissberg cycles (210- and 87-year periodicities, respectively) is a candidate mechanism for the 1,500-year cycle. Their modeling study suggested that some non-linear process might be producing a 1,500-year cycle. Further study is needed to understand which nonlinear process might induce a regular 1,500-year cycle in the climate system, and not only in the North Atlantic.

Modern oceanographic patterns indicate that the SST at the study site reflects variation in the North Pacific gyre system, i.e., PDO and NPGO (e.g., Qiu and Chen, 2005; Di Lorenzo et al., 2008). If such patterns have been expressed over millennia, then the 1,500-year temperature variation at the Japan margin implies that the North Pacific gyre circulation is involved in 1,500-year cycles. At the northern California margin, $U^{K'}_{37}$-derived SSTs (Fig. 2E; Barron et al., 2003) indicated a broad peak of spectral density with periodicity of ~1,470–1820 years. Because of uncertain carbon reservoir ages for age determination, it is not clear whether the SST variations at the Japan and California margins are in-phase or out-of-phase. If the variations are anti-phase, the pattern is consistent with a SST pattern induced by PDO and NPGO (Mantua et al., 1997; Di Lorenzo et al., 2008).

Jian et al. (2000) generated SST records for the northern and southern Okinawa Trough (sites B-3GC and 255) based on planktonic foraminiferal assemblages and claimed that the variation in the SST difference between these two sites showed a 1,500-year periodicity. The SST minimal events 1, 2, and 4 at the study site were correlated with ΔSST maxima at the Okinawa Trough (Fig. 2D); but the records did not fully correlate. The ΔSST maxima were interpreted as a function of either winter monsoon intensity or the position of the Kuroshio Current axis (Jian et al., 2000). The latter interpretation is consistent with the interpretation for our study site.

The SST minima at the study site were correlated with Bond events 2, 5, and 7 and partly with events 0, 1, and 3 (Fig. 2C). Although the correlation is not perfect, this correspondence suggests that the southward shift of the KE jet in the northwestern

Pacific was often synchronous with a decrease in the degree of NADW formation. A partial correspondence between the Japan margin SST and Bond events suggests a possible linkage between the North Pacific gyre system and the North Atlantic thermohaline circulation (THC) through a non-linear process. More regular periodicity in the Japan margin SST record than in the North Atlantic HSG record suggests that the North Pacific gyre system has been involved in propagating or generating 1,500-year oscillation in the Earth climate system. Future investigation in the North Pacific is necessary to clarify this issue.

Future targets

Investigation on the periodicity and spatial distribution of suborbital-scale climate variability in interglacials contributes to the understanding of the forcing and feedback mechanisms. In particular, comparing the periodicity and phase of climate variability between glacials and interglacials benefits for understanding the role of northern hemisphere ice sheets in amplifying climatic responses on suborbital timescale. The weak signals of climate variability in interglacials are often not detected. Oceanic frontal zones are sensitive to climate changes. For examples, the sea surface temperature in the mid-latitudes of the North Pacific are sensitive to changes in subtropical and subarctic gyre circulations which are linked with the strength and the position of the westerly jet as well as the El Niño-Southern Oscillation and the Arctic Oscillation. Oceanic frontal zones are major drilling targets in detecting weak suborbital-scale climate signals in interglacials.

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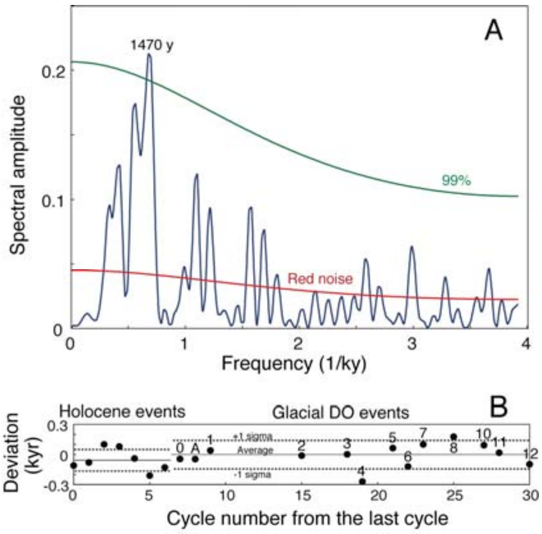

Figure 1. (A) Power spectrum of SST from cores at site MD01-2421, Japan margin, during the last 10.8 ky, theoretical red noise spectrum (lower curve), and false alarm level for 99% significance (upper curve). The spectrum was obtained by a REDFIT software package (Schulz and Mudelsee, 2002). The bandwidth was 0.11. The number of Welch-overlapped-segment-averaging segments is one. (B) Time deviations for the mid-point of warming events at the study site during the Holocene and those at GISP2 during the last glacial period from the 1,470-year template of glacial DO events

(Rahmstorf, 2003). Numbers in panel B indicate DO interstadial numbers. “A” represents the Allerød period. After Isono et al. (2009).

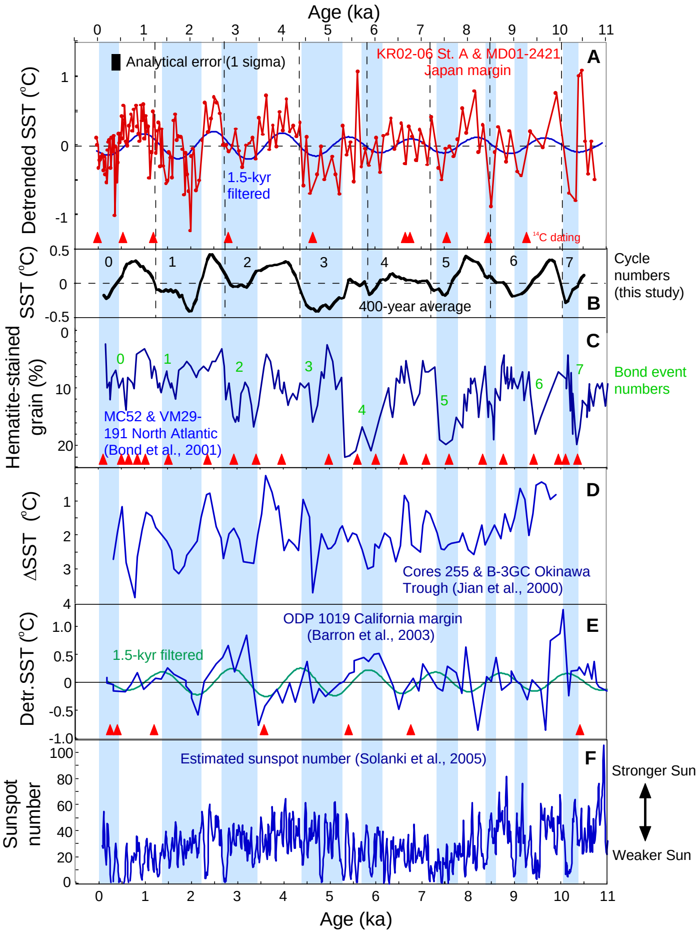

Figure 2. Variations in (A) detrended $U^{K'}_{37}$-derived SST at the study site, (B) its 400-year running mean after the cooling event at 8.5 ka, (C) hematite-stained grain content in a North Atlantic core (Bond et al., 1997), (D) differences in foraminifer-derived SST between cores 255 and B-3GC of the Okinawa Trough (Jian et al., 2000), (E) detrended $U^{K'}_{37}$-derived SST at ODP Site 1019 in the California margin (Barron et al., 2003), and (F) tree-ring $\Delta^{14}C$-based sunspot numbers (Solanki et al., 2004) during the last 11 ky. Blue shading indicates periods of lower SST at the Japan margin. After Isono et al. (2009).