Dynamic millennial-scale climate changes in the northwestern Pacific over the past 40,000 years

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[1] Ice core records of polar temperatures and greenhouse gases document abrupt millennial-scale oscillations that suggest the reduction or shutdown of thermohaline Circulation (THC) in the North Atlantic Ocean may induce the abrupt cooling in the northern hemisphere. It remains unknown, however, whether the sea surface temperature (SST) is cooling or warming in the Kuroshio of the Northwestern Pacific during the cooling event. Here we present an AMS ^{14}C-dated foraminiferal Mg/Ca SST record from the central Okinawa Trough and document that the SST variations exhibit two steps of warming since 21 ka — at 14.7 ka and 12.8 ka, and a cooling (~1.5°C) during the interval of the Younger Dryas. By contrast, we observed no SST change or oceanic warming (~1.5–2°C) during the episodes of Northern Hemisphere cooling between ~21–40 ka. We therefore suggest that the "Antarctic-like" timing and amplitude of millennial-scale SST variations in the subtropical Northwestern Pacific between 20–40 ka may have been determined by rapid ocean adjustment processes in response to abrupt wind stress and meridional temperature gradient changes in the North Pacific.

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1. Introduction

[2] The accumulated evidence on millennial-scale variations in high latitude air temperatures, greenhouse gas concentrations, monsoon precipitation, and tropical sea surface temperatures (SST) and salinity (SSS) [*Barbante et al.*, 2006; *Lea et al.*, 2006; *Andersen et al.*, 2004; *Wang et al.*, 2008] during the last glacial period suggests that the processes underlying millennial-scale climate changes can effectively transfer signals almost globally. These observed global millennial-scale changes could be due to climatic impacts from the North Atlantic through atmospheric, or "bipolar see-saw" thermohaline circulation (THC) changes. More spatially distributed, precisely dated high-resolution records as well as some model works are essential for understanding what climatic processes have been responsible for these global climate impacts over millennial time scales. It is generally accepted that the reduction or shutdown of THC in the North Atlantic is responsible for the abrupt cooling in the northern hemisphere via atmospheric teleconnection [*Wu et al.*, 2008]. The atmospheric cold advection from high latitudes cool the SST and cause the "North Atlantic" timing of millennial climate changes in some regions of the tropics [*Oppo et al.*, 2003; *Oppo and Sun*, 2005; *Wang et al.*, 2008] and high latitude north Pacific [*Kotilainen and Shackleton*, 1995]. One key uncertainty in identifying millennial-scale climatic forcing mechanisms is the role of ocean currents, which transport heat signals and affect the SST variability. A recent study showed that the heat transport by north Brazil current contributes to the surface warming in the tropical Atlantic Ocean during the abrupt cooling events [*Chang et al.*, 2008]. Considering the huge heat transport by the Kuroshio, SST in the Northwestern Pacific Ocean may respond differently on millennial-scales than the more Northern Pacific [*Kiefer and Kienast*, 2005].

2. Data and Methods

[3] Here we present a millennial-scale study of a marine record (core MD012404, see Text S1 of the auxiliary material) of the past 40,000 years from the Okinawa Trough (Figure 1).[1] The Kuroshio is the western boundary current of the North Pacific subtropical gyre, and is responsible for poleward heat and salt transport in the North Pacific. A main stream of the Kuroshio intrudes annually into the Okinawa Trough. We focused on the top 22 m of the core, which is dated with 19 accelerator mass spectrometer (AMS) ^{14}C dates that are reservoir-corrected and calibrated into calendar year ages (see Figure 2a and auxiliary material). Our record has ample high-precision ^{14}C age controls which are optimal enough to compare with NGRIP and Hulu Cave records that have been developed by independent, very high-precision time scales. Moreover, our age model is corroborated two independent tie points ("K-Ah" and "AT" tephra layers; Figure 2a; Figure S3). However, we notice that the uncertainty range of our ^{14}C dates is relatively larger (~0.4–2.5k, $\pm 1\sigma$) in 30–40 ka interval (Figure 2d), which makes our correlation of millennial-scale climate events in this interval tentative. Mg/Ca data measured on the calcite shells of

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL045202.

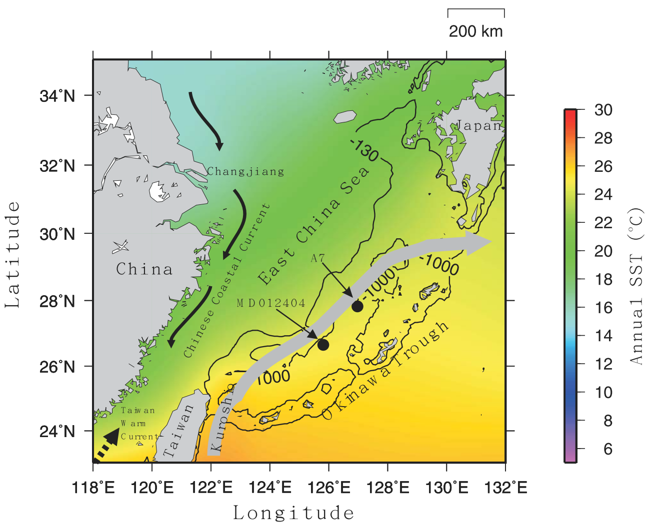

Figure 1. MD012404 core location and the Kuroshio. Sampling location of sediment core MD012404 (26°38.84′N, 125°48.75′E, water depth 1,397 m) in the central Okinawa Trough (OT) and annual mean SST in the East China Sea. The core was taken during an International Marine Past Global Change (IMAGES) cruise in 2001, near a small topographic low on the western edge of the OT. Modern SST ranges from 21.2°C (Jan.) to 28.3°C (July), and SSS varies from 34.1 (July) to 34.6 (Jan.) [*Levitus and Boyer*, 1994]. The gray line represents the general path of the Kuroshio which intrudes from the northeastern Taiwan offshore area in which a sill depth (~300–600 m) at Yonaguni Depression near Ryukyu Island is indicated. The location of core A7 previously studied is also shown [*Sun et al.*, 2005].

Globgerinoides ruber (white, *sensu stricto* (s.s.) morphotype) from core MD012404 provide a SST record in this region [*Steinke et al.*, 2005].

3. Results: Millennial-Scale Variability

[4] Our Mg/Ca SST record from core MD012404 indicates a ~6°C warming since the last deglaciation from 21 ka to 10 ka, and exhibits two steps of warming at 14.7 ka and 12.8 ka, both with a magnitude of ~2°C (Figure 2d). This "two-step" warming indicates a response of SST variations in the northwestern Pacific to climate changes in the North Atlantic / northern high latitudes (Figure 2a). However, our data suggest only weak cooling (~0.5°C) across the first Heinrich (H1) interval, but no temperature change or warming during H2 and H3 events. Moreover, although the cooling during the Younger Dryas (YD) interval appears to be larger (~1.5°C) than during H1, the warming at 12.8 ka may slightly lead (~200–300 years, within the dating uncertainty) the high latitude cold shown in the North Greenland Ice Core Project (NGRIP) ice core. The warming subsequent to the oceanic cooling at the initial phase of the YD also shows a gradual warming with a duration of ~1000 years. The foraminiferal Mg/Ca SST record from core A7 [*Sun et al.*, 2005], which is ~150 km north of site MD012404, shows a deglacial pattern similar to MD012404. Moreover, the A7 SST record shows an average ~1°C relative cooling, and maintains a latitudinal gradient with MD012404 SST (see auxiliary materail).

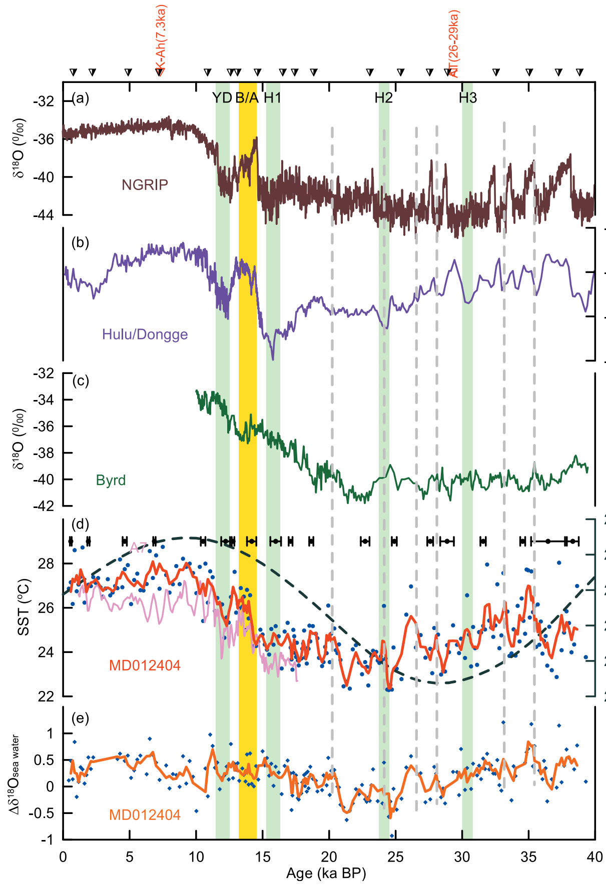

Figure 2. Millennial-scale paleoclimatic records during 0–40 ka. Shown in comparison of (a) Greenland air temperature based on North Greenland Ice Core Project (NGRIP) δ^{18}O data [*Andersen et al.*, 2004]. The age scales of the ice core record are based on CH_4 synchronized GICC05 [*Barbante et al.*, 2006], (b) East Asian summer monsoon proxy based on stalagmite δ^{18}O from Hulu and Dongge Caves [*Wang et al.*, 2008], China, (c) Antarctic temperature record based on Byrd ice core δ^{18}O (GISP2 time scale) [*Blunier and Brook*, 2001], (d) subtropical northwestern Pacific SST based on Mg/Ca ratios from planktic foraminifers *G. ruber* in core MD012404, and (e) MD012404 $\Delta\delta^{18}O_{sea\ water}$ estimates based on δ^{18}O values of planktic foraminifers measured from the same depth of the core, after correcting for ice volume effects on changing δ^{18}O compositions in sea water, and a temperature effect on changing the δ^{18}O composition in foraminifer calcite calcification [the resulting $\Delta\delta^{18}O_{sea\ water}$ data are reported here as proxies for sea surface salinity (SSS) changes]. MD012404 SST and $\Delta\delta^{18}O_{sea\ water}$ (SSS) data (blue dots) and three-point moving averages (red and orange curves) are presented. A *G. ruber* Mg/Ca SST (pink curve) from nearby core A7 [*Sun et al.*, 2005] is shown. Triangles are the calibrated 19 AMS ^{14}C dates by CALIB 6.0, and the uncertainty ranges of the dating are given on the top of the Mg/Ca SST curve. Shaded bars show intervals of Younger Dryas cooling (YD) from 12.8 to 11.4 ka, Bølling-Ållerød warming (B/A) from 15.4 to 12.9 ka, and Heinrich events (H1 at 16 ka, H2 at 24 ka, H3 at 31 ka. Intervals of Antarctic-like warming are indicated by dashed lines.

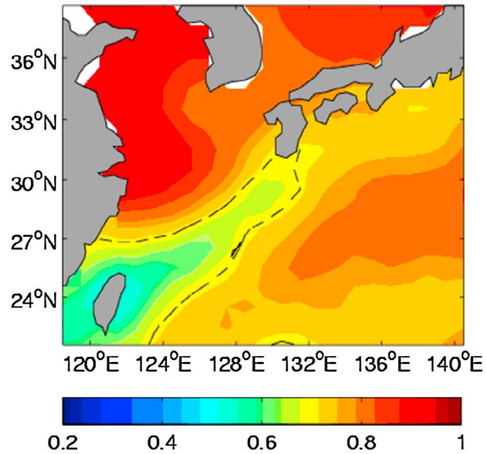

Figure 3. The correlation between the *dSST* and Q_{net} from monthly climatology of OAFlux+ISCCP data. This dataset includes the air-sea heat flux (Q_{net}) and SST based on the satellite observations from 1984–2007. The correlation coefficient between the SST variability (*dSST*, the SST change between the adjacent months) and Q_{net} (hereafter denoted as $\langle dSST, Q_{net}\rangle$) is shown. The correlation coefficient higher than 0.7 is significant at 99% confidence level. Values of 0.7 are denoted by dashed black contours.

[5] Millennial-scale variations in our SST record prior to the LGM (~21 to 40 ka) (Figure 2d) show relatively larger amplitudes (~3°C) that indicate substantial climate and oceanographic changes in the subtropical Western Pacific during this time interval. The larger amplitude millennial warming events in this portion of the record appear to be coeval with the Antarctic climate changes. We can easily identify counterparts of Antarctic-like warming in our record at ~20, 24.5, 26.5, 28, 33.5, 34.5 and 36 ka (Figures 2c and 2d). The timing of the increased SST appears to be in-phase with millennial Antarctic warming, and out-of-phase with cold events in northern high latitudes (Figure 2a).

[6] We have attempted to estimate sea surface salinity (SSS) variations by calculating the δ^{18}O residual ($\Delta\delta^{18}O_{\text{sea water}}$) of planktic foraminifer from the same core, after removing the contributions of SST and global ice volume (estimated from global sea levels, see auxiliary material) to the δ^{18}O data (Figure 2e). On a millennial-scale, our $\Delta\delta^{18}O_{\text{sea water}}$ record suggests a range from only slight increases to no significant change during northern high latitude cold events. The $\Delta\delta^{18}O_{\text{sea water}}$ (SSS) increases with a relatively large amplitude (0.5‰ ≈2.0) during the interval of YD, but the $\Delta\delta^{18}O_{\text{sea water}}$ shows only slightly increase (≤0.25‰ ≈1.0) or no change during the H1, H2 and H3. The amplitude of the $\Delta\delta^{18}O_{\text{sea water}}$ increases appears to be much larger during the millennial-scale oceanic warming (cooling in northern high latitudes) shown in our record at ~20, 24.5, 26.5, 28, 33.5, 34.5 and 36 ka, suggesting the existence of warm and saline conditions in the subtropical western Pacific during the episodes.

4. Discussion: Atlantic Versus "Antarctic" Signals

[7] The competition between the atmospheric process and the oceanic process controls the SST variability. High latitude "North Atlantic" processes have been proposed to explain the SST variability since the last glacial in the tropics and mid-latitude by atmospheric process from the Atlantic to the Pacific associated with a reduction of the THC [*Wu et al.*, 2008; *Zhang and Delworth*, 2005], intensification by an albedo feedback [*Kutzbach and Geutter*, 1986], and latitudinal displacement of Intertropical Convergence Zone [*Chiang and Bitz*, 2005] and a stronger winter East Asian Monsoon (EAM) [*Oppo et al.*, 2003; *Oppo and Sun*, 2005; *Wang et al.*, 2008] (Figure 2b). In the Western Pacific, this climate linkage appears to be well expressed in the South China Sea during the time interval of the last deglaciation [*Kiefer and Kienast*, 2005], due to stronger influences from the continental climate to the marginal sea areas. On the other hand, the "Antarctic" timing-related change emerges as a more regional feature in the western tropical Pacific [*Kiefer and Kienast*, 2005; *Rosenthal et al.*, 2003]. However, in our studied area, it may seem physically implausible that the ocean transmits the Antarctic temperature signals to the Kuroshio, because completing the large scale "heat loop" would require a cross-equatorial mechanism in thermocline water, which has not yet been identified in modern observations. This implies that the oceanic processes in the Northern Hemisphere may be important for setting the "Antarctic-like" SST signals in the Kuroshio region.

[8] In order to understand the possible dynamic role of the oceanic process like Kuroshio heat advection in determining the SST variability, we use the newly developed Objectively Analyzed air-sea Fluxes project and the International Satellite Cloud Climatology Project (OAFlux+ISCCP) datasets [*Yu and Weller*, 2007] (Figure 3). The Q_{net} in the marginal seas out of Kuroshio is highly correlated with *dSST*, which shows the dominant role of the atmospheric forcing to the seasonal SST variability in these regions. The fast warming in the East China Sea in the past 100 years is believed to be related to the Kuroshio heat transport [*Liu et al.*, 2005; *Zhang et al.*, 2010].

[9] Our studies provide new data that document first that an "Antarctic-like" record of warm and saline surface water in the subtropical northwestern Pacific, and second that the "Antarctic-like" variation appears to be more robust from 21 to 40 ka. Based on the observations from this portion of our SST and SSS ($\Delta\delta^{18}O_{\text{sea water}}$) records, we raise the possibility that from 21–40 ka, ocean processes such as adjustment of subtropical Pacific gyre or change of heat transport in the Kuroshio may play more dynamic roles in the abrupt millennial climate events, effectively competing with the atmospheric teleconnections from the northern high latitudes. This evidence highlights a dynamic Kuroshio system in abrupt climate changes [*Sawada and Handa*, 1998]. Furthermore, our SSTs appear to remain stable or even to increase during stronger winter EAM intervals (Figure 2, except for possibly the YD), which imply that processes other than atmospheric cooling may contribute to the SST variability. This raises an interesting question about how the Kuroshio and EAM systems have interacted on millennial time scales. Finally, since the Kuroshio is an important component of poleward heat transport in the North Pacific, our study may shed light on how poleward heat fluxes in the North Pacific have changed through time during abrupt cooling in northern high latitudes. Our evidence suggests that increased SSTs are confined to subtropical Northwestern Pacific Ocean in millennial North Atlantic cooling events (with the possible exception of the YD).

[10] Strong cooling in the North Atlantic with a significant reduction of THC is thought to generate intensified westerlies and trade wind in the North Pacific [*Wu et al.*, 2008; *Zhang and Delworth*, 2005]. If we accept this scenario, we would expect increased wind stress curl in the subtropical North Pacific strengthens the circulation of the subtropical gyre with an intensification of the Kuroshio (see auxiliary material). Our SST and SSS ($\Delta\delta^{18}O_{\mathrm{sea\ water}}$) data do indicate significant increases during strong North Atlantic cooling events, and therefore support the possibility of increased heat and salt transport by the Kuroshio.

[11] The different climate boundary conditions before and after 21 ka may lead to the more obvious "Antarctic-like" warming in the Northwest Pacific during 21–40 ka. The Kuroshio heat transport to the northwestern Pacific Ocean is determined not only by the volume transport but also the temperature gradient between low and high latitudes. The large extent of ice sheet, strong north hemisphere forcing and relatively low obliquity during 21–40 ka may set up a background condition that helped amplify the meridional temperature gradient and thus promote a more dynamic role of the Kuroshio in the northwestern Pacific SST variability during the time interval.

[12] Though the current ocean-atmosphere coupled modeling studies [*Zhang and Delworth*, 2005;*Wu et al.*, 2008; *Okumura et al.*, 2009] do not simulate a warming during the reduction of THC in Kuroshio area, we could identify a weak cooling tongue in the modeled SST anomalies along the Kuroshio pathway. Considering the enhanced atmospheric cooling in the Kuroshio region after the reduction of THC in their model results [*Wu et al.*, 2008; *Okumura et al.*, 2009], the weaker SST decrease compared with the interior Pacific Ocean also confirms the dynamic role of Kuroshio heat transport. In fact, these models usually use the modern boundary conditions and have a very coarse spatial resolution, which always produce a weak but broad Kuroshio pathway (see auxiliary material). This may be the reason why these models cannot simulate the significant increases of SSTs indicated by our paleo-Kuroshio record during the interval of THC reduction.

5. Implications and Conclusions

[13] Our data suggest that the millennial-scale climate variations in the subtropical Western Pacific may have been determined by basin-scale patterns of atmospheric and oceanic circulation in the North Pacific, and indicate a need to improve current modeling to understand the underlying dynamics of SST and SSS changes in the Kuroshio region. We conclude that our single site reconstruction of "North Atlantic" and "Antarctic-like" types of millennial SST patterns in the subtropical western Pacific provides a useful target for future modeling studies of the Kuroshio may respond to events of THC reduction and will stimulate additional regional and higher resolution data/model analyses.

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