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Effects of sea level change on the upstream Kuroshio Current through the Okinawa Trough

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[1] Sea-level effects on the Kuroshio Current (KC) in the Okinawa Trough (OT) are examined using a 3-D ocean model. When the sea level is −135 m (for the Last Glacial Maximum), topographic high at the southernmost OT partially blocks the KC throughflow, resulting in a 43% reduction of KC inflow. Meanwhile, meandering is enhanced and deepwater ventilation is reduced. However, the KC does not migrate to the east off the OT as suggested previously. When sea level is −40 m (for the beginning of Holocene), the modeled flow pattern resembled present KC in terms of flow path and volume transport. Sea level fluctuation may act as a major control altering the KC course in the OT, leading to significant changes in horizontal and vertical water exchange. It may alter surface water properties, biogeochemistry in both water column and sediments below, potentially, downstream KC and climate over the northeast Asia. **Citation:** Kao, S. J., C.-R. Wu, Y.-C. Hsin, and M. Dai (2006), Effects of sea level change on the upstream Kuroshio Current through the Okinawa Trough, *Geophys. Res. Lett.*, *33*, L16604, doi:10.1029/2006GL026822.

1. Introduction

[2] The Kuroshio Current (KC), a major western boundary current of the Pacific, carries abundant heat from equator to mid-latitudes and strongly influences climate in the northwestern Pacific region [*Barkley*, 1970]. The present KC enters the southern Okinawa Trough (OT), flows along the outer edge of the East China Sea continental shelf, and eventually turns eastward through the Tokara Strait. Portions of KC branch into the Yellow Sea and Japan Sea (Figure 1). However, during the Last Glacial Maximum (LGM) the KC was suspected to have migrated to the east of the Ryukyu Islands (Figure 1) [*Ujiié et al.*, 1991, 2003] and strength of the KC probably differed from the present strength due to sea level fall and/or the emergence of a hypothetical Ryukyu-Taiwan land bridge [*Ujiié et al.*, 1991, 2003; *Ijiri et al.*, 2005].

[3] Evolution history of the KC intensity and flow path in the OT has been inferred from temporal and spatial differences in assemblages, abundances and isotopic compositions of planktonic foraminifera, which are intrinsically affected by surface water hydrology [*Li et al.*, 1997; *Xu and Oda*, 1999; *Ujiié and Ujiié*, 1999; *Jian et al.*, 2000; *Ujiié et al.*, 2003]. The spatio-temporal variation of water property had been attributed to or used to discuss (1) changes in the strength of the KC itself, (2) shifts of the main axis of the KC, (3) the variation of monsoon forcing and (4) freshwater inputs. Recently, sedimentary biogeochemical evidences further revealed that surface KC dynamics might have driven the deepwater ventilation and altered sedimentary diagenesis in the OT [*Kao et al.*, 2005, 2006].

[4] Unfortunately, no modeling work has been done on the flow path and volume transport of the KC at the northwestern Pacific boundary in term of paleoceanographic perspective. Here we use a 3-D ocean model to probe how the KC in the OT and around the Ryukyu Island responds to geomorphic configuration change induced by sea level fluctuation. This modeling work is particularly important since the mid-latitude KC extension and circulation in the Japan Sea are closely related to the KC around the study area. Modeling results offer physical oceanographic evidences benefiting future paleo-studies on biogeography, sediment transportation and biogeochemistry in sediment cores under fluctuating sea levels.

2. Numerical Model

[5] The East Asian Marginal Seas (EAMS, domain in 99–140°E and 0–42°N) model used in this study was based on the Princeton Ocean Model (POM) with realistic topography and forcing at a horizontal resolution of 1/8° embedded in an expanded domain. The EAMS is a sigma-coordinate version of the *Blumberg and Mellor* [1987] hydrodynamic model. The three-dimensional, free surface model solves the primitive equations for momentum, salt and heat. It includes a 2.5-level turbulence closure submodel developed by *Mellor and Yamada* [1982] and the Smagorinsky formulation for horizontal mixing [*Oey et al.*, 1985]. On the open boundaries, the EAMS model derives its boundary condition from a larger-scale North Pacific Ocean (NPO) model. The NPO model domain covers the entire Northern Pacific ranging from 99°E to 77°W in longitude, and from 16°S to 60°N in latitude with a horizontal resolution of 1/4°. The EAMS model was forced by climatological mean wind stress from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data. Additional information on the EAMS model was given by *Wu and Hsin* [2005].

[6] Its predictive capability in simulating 3-D seasonal circulations in the studied domain had been validated with

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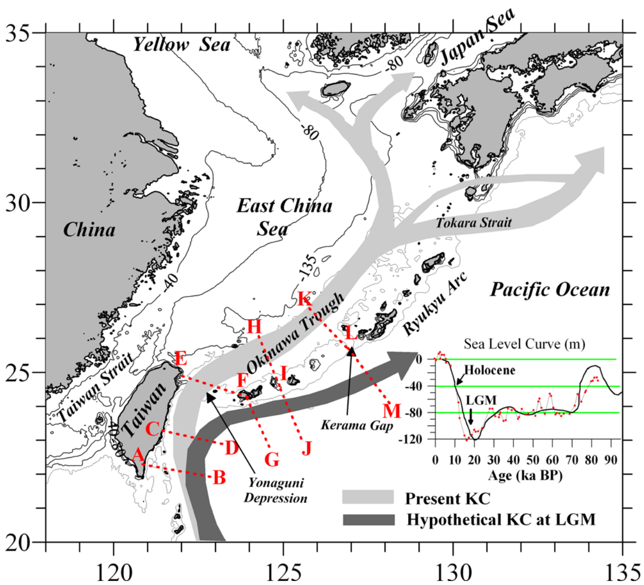

Figure 1. Geographic and topographic features in the study area. Present Kuroshio and hypothetic Kuroshio are in gray and darker gray, respectively. Five cross sections are marked (in red letters; see text). Sea level curves are shown in lower right panel. The red-dot curve and the continuous curve represent data digitized, respectively, from *Saito et al.* [1998] and *Culter et al.* [2003]. Green solid lines stand for the four sea level heights conditioned in the EAMS model.

seasonal data of observed temperature and salinity in the SCS [*Tseng et al.*, 2005] and corroborated with 11 discrete seasonal transports and 2-month continuous field monitoring from both bottom-mounted and shipboard Acoustic Doppler Current Profiler (ADCP) in the Taiwan Strait [*Wu and Hsin*, 2005].

[7] During the LGM, the sea level was about 135 m lower than today in the East China Sea Shelf [*Wang*, 1992; *Wei*, 2006]. Thus we set the lowest sea level case at −135 m, the other three cases are at −80 m, −40 m and 0 m (sea level curve can be seen in Figure 1). The −80 m case is set for the period of 30 through 70 ka BP (thousand years before AD 1950), during which sea level was relatively low and stable over time. The −40 m case is set for the very beginning of Holocene at 10 ka BP, when the KC was suggested to reenter the OT and/or strengthen based on a significant increase in proportions of the warm-water foraminiferal species, calcareous nannofossils and the isotope-derived sea surface temperature [*Li et al.*, 1997; *Xu and Oda*, 1999; *Ujiié et al.*, 2003; *Wei*, 2006]. The present sea level of 0 m is set for comparison. In this paper, we focus on the topographic effects of sea level change on the Kuroshio Current, rather than hydrographic changes in the OT that might be induced by the influence of sea-level change on the land-sea thermal gradients (e.g., monsoons) and freshwater inflow are not taken into consideration.

3. Results and Discussion

[8] The model results indicate that topographic change due to sea level fluctuations has significant effects on the KC circulation pattern and velocity (mean of the upper 100 m). The flow path in the −40 m case (Figure 2b) resembles that of present days (Figure 2a), flowing along the outer edge of the East China Sea continental shelf, branching into the Japan Sea and flowing out of the OT through Tokara Strait. Meanwhile, limited throughflow is found in the shallow Taiwan Strait to the west due to sea level drop. The flow velocity higher than 1 m/s shows higher spatial coverage in −40 m case compared to the 0 m case. This higher velocity is attributable to the reducing cross section of the KC entrance (Yonaguni Depression). As for the −80 and −135 m cases, the path of the KC changes considerably. In addition, the meander is enhanced as the sea level is lowered (Figures 2c and 2d). The much shallower Yonaguni Depression at lower sea level forms a topographic high preventing the KC inflow. A notable fraction of inflow branches toward the southeast before entering the OT to maintain the vorticity balance. At −80 and −135 m conditions, the main outlet for the KC throughflow switches from the Tokara Strait to the Karama Gap (Figures 2c and 2d). The KC course changes very likely affect surface water properties surrounding the OT that foraminifera had relied on. Potential surface water property change induced by sea level fluctuations should be carefully reconsidered before retrieving paleo-information from places upholding significantly different circulations when sea level moves. Meanwhile, sea level, a single factor, is sufficient to manipulate the surface circulation of the KC.

[9] Annual mean volume transports integrated for the upper 800 m through 5 cross sections (Figure 1) are calculated to investigate the sea level effects on volume transport. Sections A-B and C-D represent the KC upstream off the east coast of Taiwan. E-F, H-I and K-L are located in the OT. To envelope the branched KC off the Ryukyu Arc,

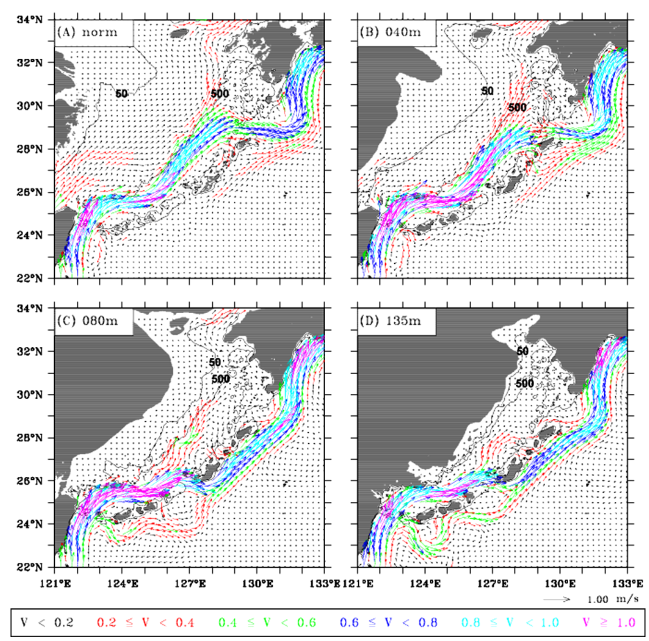

Figure 2. Annual mean flow pattern of the upper 100 m under various sea levels: (a) 0 m, (b) −40 m, (c) −80 m, and (d) −135 m cases. Arrows point to the flow direction and colors represent velocity categories.

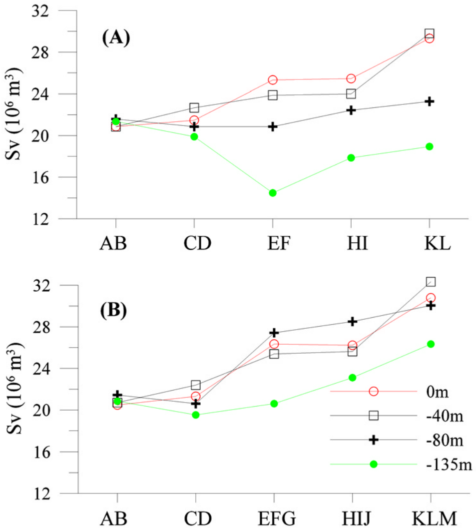

Figure 3. Annual mean volume transport (in 10^6 m^3/s) through the 5 (a) cross sections and (b) extended cross sections (see Figure 1). Colored dots are for different cases.

we have further extended section E-F-G, H-I-J and K-L-M for comparison. The volume transports through the section A-B in the four simulated cases are relatively constant (Figure 3a), yet, transports through the four downstream sections show significantly different patterns.

[10] The mean value of 21 Sv (1 Sv = 10^6 m^3/s) at the section A-B resembles the annual mean (22 ± 1.5 Sv) obtained from 34 cruises (1992 through 2001) for the surface 800 m KC off southeastern Taiwan [*Gilson and Roemmich*, 2002]. Around this region, our modeled flow velocity ranges 90–100 cm/s that is also close to their observation (90 cm/s).

[11] As for the downstream transport along the KC flow path, values for the −135 m case are always the lowest (Figure 3a). The downstream transports for 0 m and −40 m cases increase as the KC flows northeastward. In the −80 m condition, by contrast, transport remains relatively unchanged and −135 m case even gives a decreasing trend in transport along the downstream direction. At the C-D section off east Taiwan, model result reveals small yet notable differences on volume transport that lower transports are found for −80 and −135 m cases. However, at the Section E-F (passage at the Yonaguni Depression), much dramatic decrease appears that the −80 m and −135 m cases seized only 20 and 14 Sv, respectively. The two values are 25% and 43% lower compared to that (24.5 Sv) at the same cross section in present sea level condition. During the low sea level situation, apparently, the Yonaguni Depression efficiently blocks the KC throughflow to the OT. The fluctuation of inflow might subsequently affect the material exchange between the East China Sea and the Pacific Ocean, the surface ocean property and water column biogeochemistry (e.g., primary production). Unlike the previous hypothesis that the KC migrated to the east off the Ryukyu Arc during the LGM our result indicates even if the sea level is at −135 m the KC can still enter the OT, yet with significantly reduced volume transport.

[12] In those extended sections, differences among 0 m, −40 m and −80 m cases are small in terms of volume transports. The meandering flows off the Ryukyu Arc apparently account for the deficits for the three cases. However, −135 m case illustrates significantly lower volume transport all the way downstream. Since the KC plays an important role in conveying heat to mid-latitudes, such a significant transport reduction induced by glacial sea level drop might act as a negative feedback on the cooling at the north western Pacific region.

[13] The present model provides 3-D hydrodynamics; hereby, rate of vertical velocity can be derived even though we use sigma coordination in the vertical scale with low resolution in the deep. We interpolate vertical velocity at different depths basing on rates at 26 sigma levels. Here we set a horizontal plane at 1500 m depth below the present sea level. The upward and downward mass fluxes must be balanced theoretically since the space below the plane is fixed. At this depth, we estimate the area average rate (both positive and negative) of vertical velocity. The magnitude of areal average rate may thus reflect the degree of bottom ventilation below 1500 m. Values of positive mean are 0.0029, 0.0027, 0.0027 and 0.0019 cm/s, respectively, for 0, −40, −80 and −135 m cases. Those numbers are consistent with that model simulation and field observations reported by *Liu et al.* [1992]. The uncertainty of this estimation is hard to evaluate; yet, significant difference appears between 0 m and −135 m cases. The vertical velocity likely decreases for lower sea level, suggesting poor ventilation at low sea level stand. Vertical velocity, therefore, is reduced for a lower KC volume transport.

[14] Vertical velocity change in deepwater may affect redox condition in sediments. By using the relationship among carbon, sulfur and iron, *Kao et al.* [2006] presented a comparatively high degree of pyritization (DOP), which reflects relatively reducing sedimentary environments, when sea level was low during the Last Glacial Maximum (LGM). An obvious mirror image (inverse correlation) was found between the DOP variation and the sea level curve (except the period around 80 ka BP; see below) indicating sea-level height is closely correlated to redox state in depositional environment. This phenomenon agrees well with model results. Based on sedimentary magnetic fabric data *Kao et al.* [2005] suggested an enhancement of deepwater circulation since the beginning of the Holocene (10 ka BP) when sea level was up to −40 m during deglaciation. At the same time, primary production was enhanced due to synchronously increased upwelling (revealed by Ba/Al ratios [*Kao et al.*, 2005]). Biogeochemical and geophysical evidences suggested the tight linkage among sea level fluctuation, deepwater hydrodynamics and subsequent alteration in biogeochemistry in depositional environments; moreover, sea level fluctuation is likely the first control on the sedimentary redox state in the OT when comparing with enhanced organic inputs induced by either monsoon or upwelling indicated by *Kao et al.* [2006]. Our model results lend support to the suggested inter-relationship among sea level height, KC throughflow and upwelling.

[15] The evolution of the KC flow path and variations of the volume transport are particularly important to discuss factors influencing the climate change over the region of

northeastern Asia. A recent sedimentological study [*Huang et al.*, 2005] on the 400-m ODP core 1202 (water depth 1274 m) from the southwestern corner of the OT revealed a massive turbidite layer (150 m in thickness). Since this core is located at downstream region of the KC entrance (the Yonaguni Depression) this major mass wasting sequence recorded between ~65 and 35 ka BP was suggested as evidence of the passage opening. Before this passage opening, unexpected reducing condition had occurred during the previous sea level highstand (~80 ka BP) thus *Kao et al.* [2006] suggested that a topographic barrier had existed at the Yonaguni Depression effectively preventing KC throughflow before 65 ka BP. Our model reveals that sea level is the primary control manipulating hydrodynamic differences in the OT. If no other proper factors account for the redox differences between the two highstands tectonic-induced hydrodynamic change is very likely.

[16] Our modeling study suggests that the sea-level-drop-induced reduction in volume transport and meandering of the KC are substantial. These changes in sea level may have affected deepwater redox conditions in the OT via their deepwater ventilation and upwelling. Notably, our results suggest that the KC still influenced the OT during the LGM, consistent with a recent study [*Sun et al.*, 2005]. It is likely that the reconstructed changes in the KC path and strength due to sea level alone influenced the surface properties of the OT. This study lays the foundation for quantifying the influence of sea level on OT surface properties relative to the influence of climatological factors (e.g., monsoons). Furthermore, the reduction of the KC transport may affect the heat exchange farther downstream and the flow path of the Kuroshio Extension. Recently, based on pollen and spores transport data from the Hess Rise in the north Central Pacific, *Kawahata and Ohshima* [2002] concluded a small latitudinal shift (<3° southward) for the Kuroshio Extension during the glacial periods. This implies the pattern of the Kuroshio Extension is not profoundly affected by the sea-level-drop-induced upstream KC reduction. More studies are needed to examine whether and to what extent the topographic change (due to sea level or tectonic rifting) at the southern end of the Ryukyu Arc can have remote effects on the downstream western boundary current, therefore, the climate over Japan and North America [*Behl and Kennett*, 1996]. Other factors that might vary both due to sea level change and independently, such as monsoon and freshwater inputs, should also be incorporated in future modeling works.

4. Conclusion

[17] This model study advances our knowledge on the possible evolution of the KC in the Okinawa Trough and offers hydrodynamic interpretations of biogeography, biogeochemical and sedimentological clues retrieved from sediment cores. Sea-level effects on the KC around the OT are significant. During the Last Glacial Maximum, the KC inflow and deepwater vertical velocity might have been reduced while meandering was enhanced. Yet, the KC can still enter the OT. On the other hand, physical model supports the existence of topographic barrier at the Yonaguni Depression before 60 ka BP. Further studies are needed to examine to what extent the alteration in the KC influenced surface properties of the OT and whether changes in the KC induced either by sea level change or tectonic rifting influence heat exchange farther downstream, migration of the Kuroshio Extension, and consequently climate over Japan and North America.

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