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Synchronicity of Kuroshio Current and climate system variability since the Last Glacial Maximum

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A B S T R A C T

The Kuroshio Current (KC) is the northward branch of the North Pacific subtropical gyre (NPG) and exerts influence on the exchange of physical, chemical, and biological properties of downstream regions in the Pacific Ocean. Resolving long-term changes in the flow of the KC water masses is, therefore, crucial for advancing our understanding of the Pacific's role in global ocean and climate variability. Here, we reconstruct changes in KC dynamics over the past 20 ka based on grain-size spectra, clay mineral, and Sr–Nd isotope constraints of sediments from the northern Okinawa Trough. Combined with published sediment records surrounding the NPG, we suggest that the KC remained in the Okinawa Trough throughout the Last Glacial Maximum. Together with Earth-System-Model simulations, our results additionally indicate that KC intensified considerably during the early Holocene (EH). The synchronous establishment of the KC "water barrier" and the modern circulation pattern during the EH highstand shaped the sediment transport patterns. This is ascribed to the precession-induced increase in the occurrence of La Niña-like state and the strength of the East Asian summer monsoon. The synchronicity of the shifts in the intensity of the KC, Kuroshio extension, and El Niño/La Niña-Southern Oscillation (ENSO) variability may further indicate that the western branch of the NPG has been subject to basin-scale changes in wind stress curl over the North Pacific in response to low-latitude insolation. Superimposed on this long-term trend are high-amplitude, large century, and millennial-scale variations during last 5 ka, which are ascribed to the advent of modern ENSO when the equatorial oceans experienced stronger insolation during the boreal winter.

1. Introduction

The Kuroshio Current (KC), known as a strong western boundary current in the North Pacific Ocean, transports warm, highly saline waters from low to middle latitudes at relatively high speed (Hu et al., 2015). Variations in the KC's flow intensity and path have a substantial impact on the regional climate of East Asia (Hu et al., 2015), and characterize hydrographic and biogeochemical features in downstream regions, e.g., the East China Sea (ECS), south of Japan, and the East Sea (Sea of Japan) (Guo et al., 2012).

On seasonal and inter-annual scales, the intensity of the KC is affected by the East Asian monsoon and El Niño/La Niña-Southern Oscillation (ENSO) (Hu et al., 2015). These climate variations lead to basin-scale changes in surface winds over the North Pacific, which, in turn, modulate the southward transport of water mass in the inner ocean based on the Sverdrup theory (Eq. (1)) and the intensity of the northward flow of the KC at the western boundary (Hu et al., 2015). However, the teleconnection between KC dynam-

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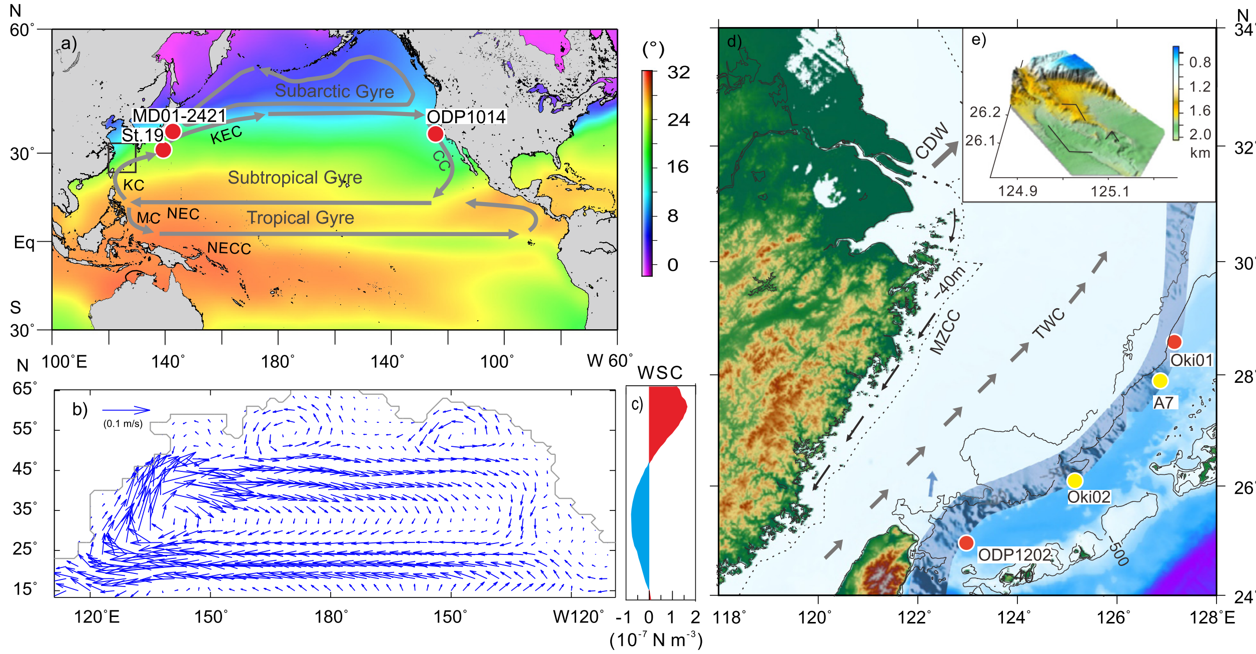

Fig. 1. The current system (small grey arrow lines) and sea surface temperature distribution of the Pacific Ocean during: a) La Niña (January, 1999). b) ocean currents (m/s) at 0∼300 m depth at the Late Holocene, as simulated in the COSMOS Model. c) Pacific zonally averaged wind stress curl at present (Hu et al., 2015). d) a schematic map, enlargement of the black square in a), for the topography and current system in the East China Sea (ECS), cores referred. **KC** = Kuroshio Current; **MZCC** = Min-Zhe Coastal Current; **TWC** = Taiwan Warm Current; **CDW** = Changjiang Diluted Water in summer. The dashed line represents −40 m isobath. The cores with yellow color were analyzed in this study. The red color is that referred. e) The Chiwei Island submarine canyon system from which core Oki02 was retrieved. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ics and the millennial to orbital timescale tropical climate state, which have been proposed to have changed with the precession cycle (Clement et al., 1999; Schneider et al., 2014), remains elusive.

$$M_y = \frac{1}{\beta}(\nabla \times \tau)_k \tag{1}$$

The route of the KC exhibits meandering in the mid-latitude, central Pacific Ocean, especially to the south of Japan. As the meandering path of the KC can migrate spatially, a useful way to index the KC path has proven to be difficult. Although meandering is also observed along the density front of the KC in the Okinawa Trough, the main body of the KC is relatively stable due to topographic constraints (Andres et al., 2015). The high sedimentation rate, advantageous topography condition in the Okinawa Trough, and tight connection with low latitude climate make the Okinawa Trough an ideal location to reconstruct the history of the KC and its link to low latitude climate.

The present day KC enters the southern Okinawa Trough, flows along the outer shelf of the ECS, and exits through Tokara Strait (Fig. 1). However, a debate exists regarding the main pathway of the KC in the past. It has been argued that the KC was deflected to the east part of the Okinawa Trough during the Last Glacial Maximum (LGM) and has reentered the Okinawa Trough since around 7.1 ka (Dou et al., 2010; Jian et al., 2000). For instance, clay mineral and geochemical indices in the middle and northern Okinawa Trough revealed that the increased contribution of sediment from Taiwan Island between ∼8.4 and 14 ka is an indicator of the reentrance of the KC into the Okinawa Trough (Dou et al., 2010, 2012; Li et al., 2015). Studies based on similar methods have, however, suggested that the KC was present in the Okinawa Trough during the LGM lowstand, and intensified during the early Holocene (EH) (Chen et al., 2011; Wang et al., 2015; Zheng et al., 2011). An increase in the pollen of Podocarpus at the topmost part of core DGKS9602 reveals that the KC may have been reinforced in the Holocene (Zheng et al., 2011), agreeing with sedimentological studies (Wang et al., 2015). However, as these proxies are integrations of multiple transport mechanisms and may produce non-unique solutions, a relatively independent KC index is needed to resolve the aforementioned ambiguities.

In order to better examine the past variability of KC intensity and route, and the connections between the KC and low latitude climate systems since the LGM, sediment core A7 situated in the path of the KC, retrieved from the northern Okinawa Trough (Fig. 1), was subject of this study. Varimax Principal Component Analyses (V-PCA) was applied to the complex grain-size matrix to isolate independent grain-size components related to the KC. This method has also been applied to nearby core Oki02, and revealed the East Asian winter monsoon history during the Holocene (Zheng et al., 2014). Sr–Nd isotopic analyses were utilized to constrain the provenance of the KC grain-size spectrum and will verify our conclusions. For a more expanded view of the connections of the current system in this study (Fig. 1), we combined our data with those of core Oki02, two Ocean Drilling Program cores, and one Marion Dufresne core from the high latitude North Pacific to elucidate the relationships between the middle latitude KC and low latitude Pacific climate systems. Moreover, we also reanalyzed the Earth-System-Model simulations for the LGM, 9 ka (a representative for the Early Holocene), and Pre-industrial condition (a representative for the Late Holocene) to assist in understanding the proxy-indicated LGM to Holocene anomalies in the KC.

2. Study area

The climate and oceanography in the Okinawa Trough is significantly influenced by the KC and the East Asian monsoon (Lee and Chao, 2003). Moreover, the KC is the most striking feature of the Okinawa Trough hydrography and constitutes a link between low- and mid-latitudes (Hu et al., 2015). Mooring and float observations revealed that the KC penetrates to greater depths as it progresses downstream. Specifically, it extends to the seafloor at the 1200 m isobath in the middle of the Okinawa Trough at the PN line (0.7 m/s), and is found even deeper at the 1500 to 2000 m isobaths south of Japan (Andres et al., 2015).