SIDEBAR. Illuminating the Past to See the Future of Western Boundary Currents

MICROPALEONTOLOGICAL INVESTIGATIONS OF THE KUROSHIO CURRENT EXTENSION

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The most prominent features of the marine circulation system, the western boundary currents (WBCs), flow along the western edges of the major ocean basins. These fast-moving, deep, and narrow wind-driven surface currents rim the subpolar and subtropical ocean gyres. WBCs of subtropical gyres transport heat, moisture, salt, and gases from the tropical ocean poleward, creating ocean-atmosphere interactions that impact regional weather patterns. Subtropical WBCs meet their subpolar WBC counterparts in the mid-latitudes, leading to sharp temperature and nutrient gradients (Figure 1a). Mixing of subpolar and subtropical water masses creates an ecotone, a region of overlap between biological communities. The WBC ecotones support rich ecosystems that contain some of the highest biodiversity in today's world ocean (Tittensor et al., 2010), making them regions of significant biologic importance. Due to their high biological abundance and diversity, these currents are vastly important resources for countries with robust fishing industries. Currently, fish stocks are declining in some of these areas, with decreases mostly attributed to the increase in WBC sea surface temperatures (Noto and Yasuda, 2011). Thus, understanding how these complex systems have responded to past warming and will respond to anthropogenic climate change scenarios has significant implications for predicting and mitigating future impacts on weather patterns, local biodiversity, and the human food supply.

Long-term observational and modeling studies confirm that the effects of anthropogenic climate change are significant within WBC systems. Over the past half century, these currents have intensified and shifted poleward, with the surface ocean in WBCs warming two to three times faster than the globally averaged sea surface temperature (Wu et al., 2012). Projections of WBC behavior under increasing CO_2 scenarios mostly forecast continued and increasing intensification, warming, and transport due to strengthening of near-surface winds (with the exception of the Gulf Stream; Yang et al., 2016). However, most WBCs lack long-term monitoring data needed to effectively assess how they behave beyond decadal timescales. One way we can improve our understanding of the response of WBCs to climate change is by examining the behavior of these systems through the lens of the geologic, and especially the paleontological, records. For example, our research on the Kuroshio Current (KC) and its Extension (KCE) using plankton proxies reveals its behavior during periods of prolonged global warmth and climatic transition. This research, then, also has implications for the behavior of regional zooplankton populations (specifically, planktic foraminifera), whose domain lies near the base of the oceanic food web.

The KC and KCE in the Northwest Pacific Ocean, a leg of the North Pacific Subtropical Gyre (Figure 1a), is one of the most prominent WBCs in the world ocean. The KC is sourced from the western equatorial Pacific and flows north along the eastern Japanese coast. At approximately 36°N, 141°E, the current turns east and flows into the Pacific as the KCE, with volume transport reaching 130 Sv. The KCE meets the south-flowing Oyashio Current, the WBC of the North Pacific Subpolar Gyre (Figure 1a). The world's highest latitude coral reefs are found within the KCE region at 33°N, and the KCE, along with the KC, serve as a dispersal corridor for some fish species, supporting the large diversity (including planktic foraminifera) and biomass of marine life in the area.

We have characterized the behavior of the KCE using micropaleontological methods, specifically biostratigraphy and paleobiogeography of planktic foraminifera, to better evaluate how this current system responded to prominent tectonic and climate perturbations through the late Neogene and Quaternary periods (~7–0 million years ago). This time interval includes the closure of the Central American Seaway between North and South America (~3.8–2.5 million years ago); the mid-Piacenzian Warm Period (mPWP; 3.2–2.9 million years ago) when global temperatures were >2°C above pre-industrial levels; and the last major climate reorganization, the Mid-Pleistocene Transition (MPT; ~1.2–0.6 million years ago). We analyze deep-sea sediment cores recovered by the Ocean Drilling Program that cross the KCE (Figure 1a) to provide a multi-dimensional view of the current across these important time intervals.

Our research indicates the KCE and the North Pacific Subtropical Gyre expanded and contracted in response to tectonic and climate events. From planktic foraminiferal diversity curves calculated at the three deep-sea sites (Figure 1a), we infer that the KCE was likely a prominent feature through the late Neogene and Quaternary, as foraminifera diversity remained highest on the northern edge of the current, more so than tropical foraminiferal diversity (Lam and Leckie, 2020a). Paleobiogeographic analyses also indicate that throughout the entire time interval, the KCE was used as a corridor for species dispersal into the Northwest Pacific region. The timing and pattern of dispersals varied, but many species reveal a diachronous dispersal pattern from the cooler northern edge of the KCE to the warmer southern edge (Lam and Leckie,

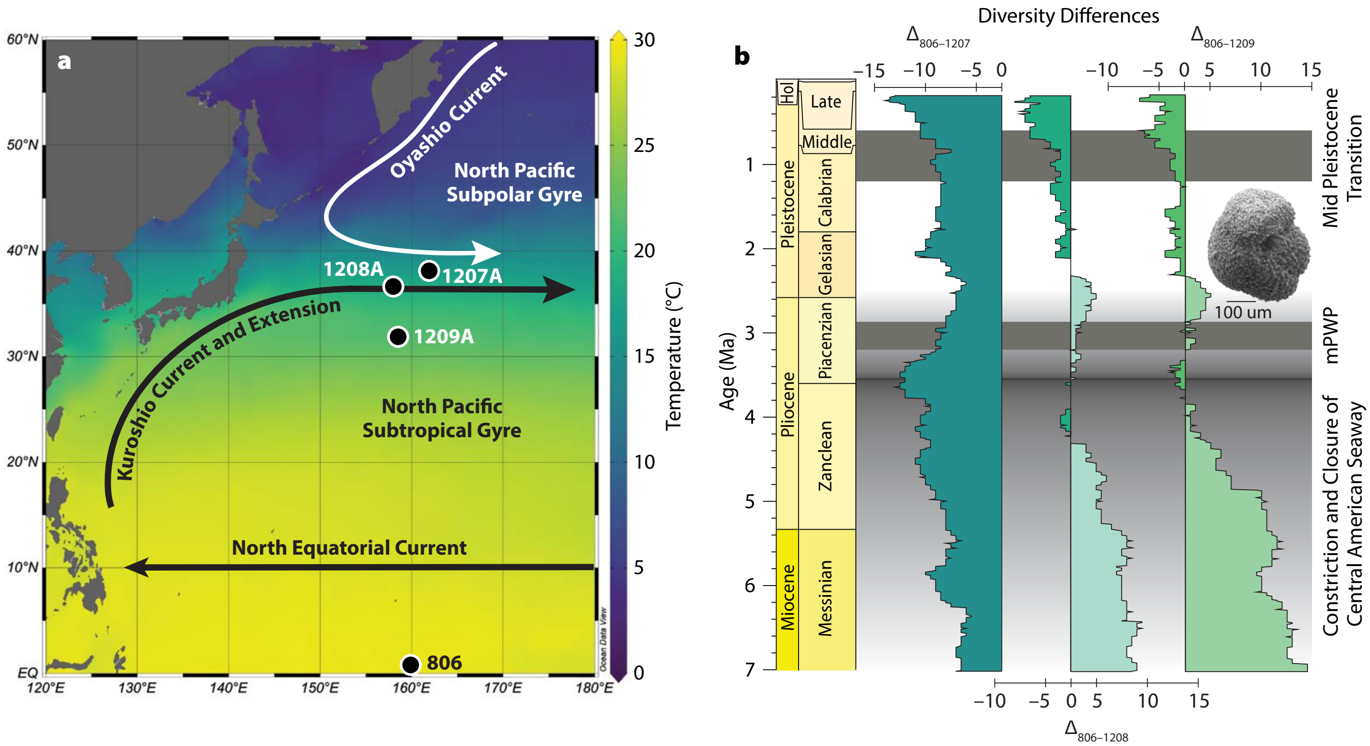

FIGURE 1. (a) Modern sea surface temperature map of the Northwest Pacific region characterized by two western boundary currents, the Kuroshio Current and its Extension (KCE) as part of the North Pacific Subtropical Gyre, and the Oyashio Current as part of the North Pacific Subpolar Gyre. The black dots denote Ocean Drilling Program (ODP) site locations discussed in the text. *Image modified from Lam and Leckie (2020a) under the CC BY 4.0 license (https://creativecommons.org/licenses/by/4.0/)* (b) Diversity differences of planktic foraminifera between ODP Site 806 in the western equatorial Pacific and ODP sites in the Northwest Pacific that cross the KCE. Negative values and darker colors indicate higher diversity within the KCE region relative to the western equatorial Pacific, with significant tectonic and paleoclimate events highlighted against the geologic timescale. Note that the difference in diversity between Site 806 in the western equatorial Pacific and Sites 1209 and 1208 on Shatsky Rise is tightly coupled with the effective closure of the Central American Seaway by ~4 million years ago. The scanning electron image is of *Globoconella puncticulata*, a common Pliocene KCE species.

2020b), indicating perhaps that differing water mass properties (e.g., temperature, salinity, nutrients) controlled the timing of species dispersals across the current.

Plankton diversity gradually increased during the final phases of the constriction of the Central American Seaway (~3.8–2.5 million years ago), reaching a diversity apex at the northernmost site (Figure 1b) when surface water exchange was shut off between the Atlantic and Pacific basins. Diversity at the other two sites increased to levels observed in the western equatorial Pacific. We interpret these results to indicate a spin-up and strengthening of the North Pacific Subtropical Gyre, in which warmer waters were brought further north by more vigorous circulation as this important ocean gateway closed. Turnover rates increased within the KCE during final seaway constriction and closure (~5–3 million years ago; Lam and Leckie, 2020b), indicating this tectonic event had profound effects on plankton populations in response to gyre spin-up.

During the mPWP (~3.2–2.9 million years ago), the KCE was incredibly sensitive to warming and cooling. With global warming during the mPWP, the North Pacific Subtropical Gyre and subtropical waters expanded poleward, with potentially steepened temperature and salinity gradients across the current (Lam, 2020). Planktic foraminiferal data indicate decreasing diversity on the northern edge of the KCE after seaway closure, with a slight uptick in diversity during the mPWP interval (Figure 1b; Lam and Leckie, 2020a). This may indicate another short-lived intensification of the gyre and the KCE in response to warming. During the MPT (~1.2–0.6 million years ago), plankton diversity again increased within the KCE at all three sites (Figure 1b; Lam and Leckie, 2020a), in parallel with long-term cooling over the last 800,000 years and another potential equatorward shift of the KCE.

Micropaleontological data indicate that the KCE was a dynamic feature in the geologic past. It responded to relatively small changes in global mean temperature, with current activity directly influencing the foraminiferal community and biodiversity within the region. Our data support other geologic studies focused on the more recent past (reviewed in Gallagher et al., 2015), observational and modeling studies that show the KCE shifts north and intensifies during warmer periods and shifts south during cooler periods.

As we show here, studies of plankton diversity and paleobiogeography are excellent ways of establishing past KCE behavior and can be used to better assess WBCs and illuminate the response of these systems to climate perturbations. Additional geochemical and X-ray fluorescence data sets utilizing these sedimentary sequences from the Northwest Pacific are underway to expand upon the hypotheses presented here. It is our hope that these studies can test, refine, and generalize findings from the KCE in order to provide a deeper understanding of these currents that can help set a baseline for understanding marine food web dynamics, the extent of WBC sea surface warming, and the latitudinal extent of WBC shifts associated with anthropogenic warming.

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