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学 位 論 文 要 旨
Dissertation Summary

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論 文 名: Changes in the Kuroshio and North Equatorial Current during the last 35,000 years
(Dissertation Title)

The northward flowing Kuroshio Current (KC) is the western boundary current in the North Pacific subtropical gyre, and it is bifurcated from the North Equatorial Current (NEC) east of the Philippines, playing an important role in the water and heat transport to the extratropic. The NEC intensity and the location of its bifurcation have an influence on the Kuroshio transport and determine the water distribution proportion of the NEC between the tropic and subtropic in the North Pacific. There are dramatic changes in climate and sea level during the Last Glacial Maximum (LGM, ~ 21 ka BP). However, because of the insufficiency of the previous model domain and the limitation of the observations in spatial and temporal resolutions, the location and intensity of the paleo-Kuroshio and paleo-NEC remain poorly understood since the last glacial period.

In this study, based on the meteorological and oceanic data provided by the Model for Interdisciplinary Research on Climate (MIROC4m) and other 9 climate models from Paleoclimate Modelling Intercomparison Project Phase 3/4 (PMIP3/4), we introduced the paleo changes in the sea level, air-sea heat flux, and wind stresses into an eddy-resolving ocean general circulation model for the Pacific Ocean to explored the ensemble mean of changes in the Kuroshio region during the LGM and carried out a preliminary evaluation of these models with the available sea surface temperature (SST) proxy observations. The ensemble mean of the 10 LGM models confirmed the enhancement of NEC and that the Kuroshio axis migrates slightly seaward with an increase in volume transport in the East China Sea (ECS) (Figure 1). Although the southward shift (0.2 ± 0.8°) of the zero wind-stress curl is insignificant, the Kuroshio Extension at section 146°E shifts southward by 0.8°–3.1° in 10 models with an average value of 2.0 ± 0.7° relative to the present position.

We compared the zonally integrated volume transport at 137° E with the corresponding wind-driven Sverdrup transport and suggested that the subtropical gyre during the LGM became stronger and migrated southward due to the wind-stress curl in the North Pacific,

especially from 14.6 to 31° N. Furthermore, the ensemble of the zero wind-stress curl from 10 models revealed a southward shift of 0.5°, corresponding to the southward movement of NEC bifurcation at the surface (0.7°) and 500 m (2.5°). However, the zero wind-stress curl exhibited large differences in latitudinal shift for different LGM models. It appears that the latitudinal shift of the NEC bifurcation at the surface does not fully correspond to the location of the zero wind-stress curl.

The spatial distribution of ΔSSTs showed a cooling of 1.9 ± 0.5°C in 15° S–15° N latitude band at LGM. In the ECS, there was a significant cooling exceeding 5°C on the nearshore side along the KC axis and a cooling of 1–2°C on the offshore side. The SST in the northern Okinawa Trough appeared to be intensely cooled at the LGM, up to 4–5°C. Additionally, the SST cooling at LGM exceeded 6° in the Japan Sea and the Kuroshio–Oyashio confluence region at 40° N, with large standard deviations. To evaluate the 10 LGM model simulations, available ΔSSTs derived from $U_{37}^{K'}$, oxygen isotopes, and Mg/Ca ratios were compared to the respective simulated values in the Kuroshio region (0–38° N, 100°–180° E). The Goddard Institute for Space Studies (GISS-E2-R) in PMIP3 performed best in simulating ΔSSTs, with the highest correlation coefficient and lowest normalized centered root-mean-square difference. In contrast, MIROC-ES2L in PMIP4 performed the poorest, with the largest difference from the observations, especially for the summer ΔSSTs.

The LGM results in MIROC4m were comparable to the ensemble mean results of ten climate models in terms of black current path, intensity, and ΔSST; therefore, we further investigated the changes in the Kuroshio system from 35 ka BP to the present using MIROC4m data for different paleo-ages (6 ka BP, LGM, 30 ka BP, and 35 ka BP).Relative to the present, the KC during the last glacial period travels the same path with higher surface velocity in the ECS but migrates northward south of Japan and southward in the Kuroshio Extension (KE) region, respectively. The northern limit of the KE axis at 6 ka BP, LGM, 30 and 35 ka BP exhibits southward migration of 1.1, 1.9, 2.0, and 2.4°, respectively. It was found that the southward migrations of the KE axes are likely closely related to the zero wind-stress curl position, which migrates southward by 0.2, 1.1, 0.9, and 1.1° at 6 ka BP, LGM, 30, and 35 ka BP, respectively.

The upper 1000 m depth-integrated volume transport stream function was calculated from the annual mean velocity and displayed that the North Pacific subtropical gyre in the glacial period becomes stronger and shifts southward. Compared to the wind-driven Sverdrup transport, the enhanced subtropical gyre can be explained by the stronger wind-stress curl and trade winds from 13 to 25°N. To a certain extent, stronger glacial trade winds enhanced the NEC. Consequently, Kuroshio transport increased in the southern and middle Okinawa Trough.

NEC bifurcation divides the NEC into KC and Mindanao Current (MC), affecting the intensity of the KC. The NEC bifurcations at 0 ka BP are located at 13.3°N and 17.3°N at the surface and 500 m, respectively. The position of the bifurcation shifts poleward with increasing depth, which also occurs in the paleo-ocean. Moreover, compared to the modern location of NEC bifurcation, the bifurcation latitude at the surface (500 m) moves southward by about 0.1° (0), 0.9° (2.9°), 1.0° (3.0°), and 0.7° (2.4°) at 6 ka BP, LGM, 30 and 35 ka BP, respectively. Modern oceanic studies have found that the southward shift of NEC corresponds to the enhancement of Kuroshio, and the volume transport of both NEC and Kuroshio are positively correlated. Accordingly, the enhancement of the glacial Kuroshio and the southward shift of the glacial NEC bifurcation location are consistent with our current understanding.

Additionally, the zero-wind stress curl line shifts southward by 0.2°, 1.2°, 1.4°, and 1.0° at 6 ka BP, LGM, 30, and 35 ka BP, respectively, in agreement with the shift of the NEC bifurcation at the surface. However, the bifurcation latitude slope is not completely determined by the ratio of wind stress curl intensity of the subtropical gyre to the tropical gyre, which differs from the results in the modern ocean.

Because many paleo-oceanography studies use different proxies to derive the change in water temperature, we also examined it in our model results of five ages. Our model demonstrated that the SST in the North Pacific subtropical region becomes cooler in the western area and slightly warmer in the eastern band-like area at 6 ka BP. Such SST cooling was most significant at LGM. Moreover, the SST cooling east of the Ryukyu Islands is up to 0.5°C at 6 ka BP, 2~3°C at LGM, and 1~2°C at 30 and 35 ka BP relative to the present SST. In the ECS, along the Kuroshio path, the SST cooling is greater on the nearshore side than on the offshore side. In the northern ECS, the SST cooling is significant, reaching 4~5 ℃ at LGM and 3~4 ℃ at 30 ka and 35 ka BP. In addition, the modeled SSTs were used to confirm that the horizontal gradient of the subsurface temperature, rather than the upper-ocean vertical thermal gradient, is a good indicator of the surface current speed.

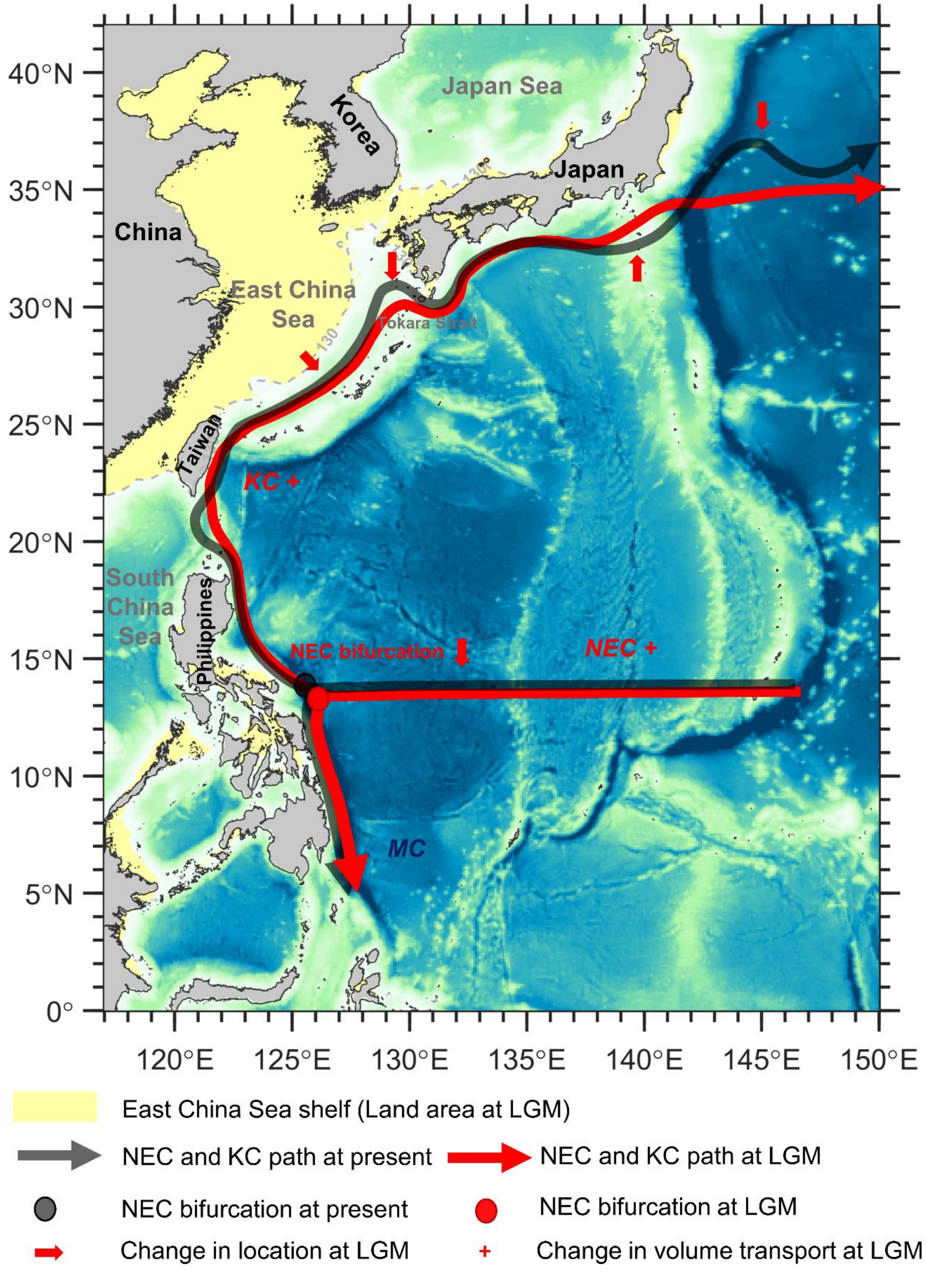

Figure 1 The NEC and KC paths at present and during the LGM. Red arrows indicate the migration of the axis at LGM relative to the present. Red + denotes an increase in the volume transport at LGM.