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Impact of the Kuroshio large meander on local atmospheric circulation and precipitation in winter



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Abstract

The Kuroshio, which flows to the south of Japan, typically takes two paths on decadal timescales; the straight path and the large meander path, or the so-called Kuroshio large meander. This phenomenon is characterized by the presence of the cyclonic cold-core eddy located south of Japan, which leads to both negative and positive sea surface temperature (SST) anomalies along the southeastern coast of Japan. To clarify the atmospheric response to these SST anomalies in winter, we conducted a control experiment employing a regional atmospheric model with observed SSTs and two sensitivity experiments in which the SST boundary conditions were substituted with those corresponding to the periods of for the Kuroshio large meander and the straight path. The differences in these two sensitivity experiments showed that the surface wind response to the SST anomalies associated with the Kuroshio large meander was not only characterized by wind divergence over the cyclonic cold-core eddy, as reported previously but also wind convergence along the southeastern coast of Japan. Interestingly, this wind anomaly blew into the positive SST anomaly along the east coast of Japan at around 36°N. Similar wind anomalies along the east coast of Japan were observed in a reanalysis product. The results of the model simulation and the reanalysis product showed that during the Kuroshio large meander period, the number of rainy days increased significantly over the warm SST anomaly, while the precipitation and the number of rainy days decreased over the cyclonic cold-core eddy. Moisture budget analysis revealed that the observed decrease in precipitation was attributed to the disparity between the reduced evaporation and the anomalous horizontal moisture convergence in a region where the surface winds were divergent. This moisture convergence was mainly induced by a decrease in specific humidity, implying this change in specific humidity effectively mitigated the variation in precipitation.

Keywords Kuroshio, Large meander, Air-sea interaction, Precipitation, Regional atmospheric model

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1 Introduction

The Kuroshio, which is the western boundary current of the subtropical gyre in the North Pacific, exhibits two characteristic paths around the south of the Japanese mainland on decadal timescales (e.g., Kawabe 1980, 1995; Kida et al. 2015). One path is referred to as the straight path, or non-large meander path (Fig. 1a), and the other is the large-meander path (Fig. 1b). The most recent Kuroshio large meander event started in August 2017 (e.g., Qiu et al. 2023). These Kuroshio large meander events exert a significant influence on oceanic states, such as oceanic temperature (e.g., Sugimoto et al. 2020) and coastal sea level (e.g., Kawabe 1985; Usui and Ogawa 2022). In addition, changes in the parameters such as sea



height **a** in 2012 (straight path) and **b** in 2018 (large meander path). The contour interval is 0.1 m. The data are downloaded from the Copernicus Marine Service

surface temperatures (SSTs) associated with the Kuroshio large meander also impact the overlying atmosphere, as will be mentioned in the next paragraph.

Along with the Gulf Stream region in the midlatitude oceans, the Kuroshio region exerts a significant influence on the atmosphere (e.g., Nonaka and Xie 2003; Sasaki et al. 2012; Parfitt and Seo 2018; Seo et al. 2023). In particular, the warm SST associated with the Kuroshio and its variability markedly affects surface winds, sea level pressure (SLP), and precipitation (e.g., Xie et al. 2002; Xu et al. 2011; Iizuka et al. 2013; Kuwano-Yoshida and Minobe 2017; Sasaki and Yamada 2018; Hirata et al. 2021). Furthermore, the variability in the path of the Kuroshio south of Japan on decadal timescales induces marked SST fluctuations; the large meander causes a positive SST anomaly along the southeastern coast of Japan and a large negative SST anomaly associated with a cold-core eddy (Fig. 2). Recently, Sugimoto et al. (2020) reported that the development of the positive SST anomaly is caused by the westward current associated with the Kuroshio. In the present study, the positive SST anomaly along the southern coast of Japan is referred to as the warm SST tongue, and the negative SST anomaly further south is referred to as the cool SST pool. Numerous studies have examined the atmospheric responses to changes in the SST associated with the Kuroshio large meander. For example, the path and intensity of the extratropical cyclones in winter were observed to change over the Kuroshio large meander (e.g., Nakamura et al. 2012; Hayasaki et al. 2013; Tochimoto and Iizuka 2022). However, relatively few studies have focused on the wintertime mean atmospheric response to the Kuroshio large meander. Xu et al. (2010) investigated the atmospheric responses to the Kuroshio large meander event from the summer of 2004 to the summer of 2005, especially in the winter of 2005. They observed that precipitation decreased over the cool SST pool and showed the existence of a positive SLP anomaly over the cool SST pool using regional atmospheric model experiments. Murazaki et al. (2015) also used a regional atmospheric model to examine the atmospheric response to the Kuroshio large meander in winter, but the SST conditions used in the model were estimated from the long-term integration of the regional ocean model. Based on their atmospheric model results, they reported that the frequency of intense precipitation decreased over and around the negative SST anomaly. Sugimoto et al (2021) reported that the southeastern coastal region of Japan becomes hot and humid in response to the effect of the warm SST tongue on the atmosphere in summer. However, the atmospheric response of the mean winter state to the warm SST tongue has not yet been reported. In addition, as mentioned above, decreases in both precipitation and



Fig. 2 Difference in SST between the LM periods and the NLM periods in winter from the OISST dataset. The contours indicate the regions where the difference is statistically significant at the 95% confidence level. The gray inset indicates the regions where the SST of the WRF simulation was replaced. The LM and NLM periods are defined in Sect. 2. The regions indicated by the blue box (33.5°N–34.5°N, 136.5°E–138.5°E) and indicated by the red box (32.5°N–33.5°N, 136°E–138°E) are used to define the Kuroshio large meander index (see Sect. 2)

the frequency of intense precipitation in winter over the south of Japan have been reported, but the causes of these decreases have not been discussed from the viewpoint of the moisture budget. Given that these previous studies focused mainly on the atmospheric response around the cyclonic eddy, the horizontal and vertical extents of these atmospheric responses to the cool SST pool and the warm SST tongue remain unclear. Therefore, the purpose of this study was to clarify the wintertime atmospheric response to the cool SST pool and the warm SST tongue.

The present study is organized as follows. In Sect. 2, we describe the regional atmospheric model and the settings used to investigate the atmospheric response to the Kuroshio large meander. The model results of the atmospheric responses are described in Sect. 3. We focused on surface wind changes and changes in precipitation in Sects. 3.1 and 3.2, respectively. A summary and discussion are presented in Sect. 4.

2 Data and model

We employed the Weather Research and Forecasting (WRF: Skamarock et al. 2019) model, which solves the equations over terrain-following hydrostatic-pressure coordinates. The model domain covers East Asia to the western North Pacific, and a geographical scope that is considerably larger than the spatial scale of the Kuroshio large meander (Fig. 3). The model grid consists of 240 meridional×420 zonal grid points with a horizontal resolution of 20 km and comprises 37 σ -levels. For convective parameterization and boundary layers processes, we used a modified version of the Kain-Fritsch scheme (Kain and Fritsch 1990), the Yonsei University planetary boundary layer scheme (Hong et al. 2006). The schemes employed for longwave and shortwave radiations are the Rapid Radiative Transfer Model (Mlawer et al. 1997) and the Goddard shortwave scheme (Chou and Suarez 1994), respectively. Initial and lateral boundary conditions were the 6-hourly product of the National Centers for Environmental Prediction Climate Forecast System Reanalysis (NCEP-CFSR) product (Saha et al. 2010). The SST condition is the daily product of version 2 of the optimum interpolation SST (OISST; Reynolds et al. 2007) provided by the National Oceanic and Atmospheric Administration (NOAA), which has a $0.25^{\circ} \times 0.25^{\circ}$ horizontal resolution and incorporates both in situ and Advanced Very High-Resolution Radiometer SST data. The simulation period using these forcing data is from November 30 to March 1 from 2001 to 2010. This run is referred to as the CTL run. The model output is at 3-hourly intervals, and the analysis focuses on its wintertime mean (December to February).

In addition to the CTL run, two sensitivity runs were performed to clarify the atmospheric responses to the SST variability associated with the Kuroshio large meander. In these sensitivity runs, the SST boundary conditions within the area indicated by the gray box in Fig. 2 were substituted with the daily SST composites corresponding to the large meander (LM run) and nonlarge meander (NLM run) periods of the OISST dataset. To select these periods, we employed the time series of the southernmost latitude of the Kuroshio south of Japan provided by the Japan Meteorological Agency (JMA) based on the ship observations from 1982 to 2019. However, as this time series contains several missing values, we also used the time series of the coastal sea level difference between Kushimoto and Uragami, also provided by JMA. First, we calculated the wintertime mean of these two time series. After normalization by standard deviation and subtraction of the mean value, we estimated the mean values of these two time series. Based on this time series, the smallest 10 events (1982, 1983, 1984, 1987, 1988, 1990, 1991, 2005, 2018, and 2019) and the largest 10 events (1992, 1993, 1994, 1995, 2002, 2003, 2006, 2007, 2008, and 2012) were identified as the Kuroshio large meander and the non-large meander periods, respectively. Using these classifications, we estimated the daily composite of SST and used these as the boundary forcing for the WRF simulation in the area indicated by the gray box in Fig. 2. Figure 2



Fig. 3 The domain and its topography of the WRF model

shows the SST differences between the LM periods and the NLM periods. The statistical significance of these SST differences was estimated using Student's t test, assuming that each winter season is independent. Three large SST anomalies are aligned in a north–south direction to the south of Japan. As mentioned in the Introduction, a warm SST tongue to the south of Japan was reported by Sugimoto et al. (2020). The amplitude of the negative SST anomaly associated with the cool SST pool is several times larger than that of the positive SST anomaly of the warm SST tongue. Except for these SST anomalies, several statistically significant SST signals were observed, such as the negative SST anomaly in the Kuroshio Extension region, but these anomalies were not included in our simulation.

To compare the simulated atmospheric responses to observations, we used the ECMWF Reanalysis v5 (ERA5) product for winter from 1982 to 2019 (Hersbach et al. 2020). To obtain atmospheric responses to the Kuroshio large meander using this dataset, we define the Kuroshio large meander index as the difference in the SST of the OISST dataset averaged over the region indicated by the blue box (33.5°N-34.5°N, 136.5°E-138.5°E) minus the red box (32.5°N-33.5°N, 136°E-138°E) in Figs. 2 and 7, where both time series were normalized before the subtraction. The former region and the latter region correspond to the warm SST tongue and the cool SST pool, respectively. We performed correlation and regression analyses using this index and the ERA5 dataset. An advantage of using this index is that the role of the SST in the warm SST tongue and the cool SST pool regions could be investigated, separately. The correlation coefficients between this index and the time series of the southernmost latitude of the Kuroshio, the coastal sea level difference between Kushimoto and Uragami provided by JMA, and the aforementioned mean values of the two time series were -0.73, -0.55, and -0.59, respectively.

3 Results

Before presenting the results of the sensitivity experiments, we compared the climatology of the atmospheric state around Japan in winter between the CTL run and the ERA5 dataset (Fig. 4). The WRF simulation well reproduced the mean northwesterly winds and SLP pattern in winter, that is, high and low SLPs in the west and east of Japan, respectively. In addition, the model efficiently simulated the mean precipitation distribution, such as the large precipitation along the western coast of Japan and over the Kuroshio Extension, although it slightly underestimated them. Both ERA5 and WRF showed that the large precipitation over the Kuroshio Extension extended to the Kuroshio south of Japan. Thus, these results show that the WRF simulation effectively reproduced the wintertime mean atmospheric state around Japan.



Fig. 4 Winter mean precipitation (color), sea level pressure (contour) and 10-m wind (vector) averaged from the years 2001 to 2010. **a** ERA5 reanalysis data, and **b** the CTL run of the WRF model

3.1 Wind response

In this subsection, we focused on the surface wind response to the Kuroshio large meander. To this end, we showed the differences between the LM runs minus NLM runs. The simulated changes of the surface wind and its divergence showed the surface wind divergence over the cool SST pool (Fig. 5). This wind divergence was collocated with the positive SLP anomaly (not shown). These wind divergence and positive SLP anomaly responses over the cool SST pool have been reported previously (Xu et al. 2010; Murazaki et al. 2015). They also showed that the relation between the negative SST anomaly and the positive SLP anomaly was consistent with the pressure adjustment mechanism (e.g., Lindzen and Nigam 1987) with thermal advection by the prevailing northeasterly (Small et al. 2003; Xu et al. 2010). On the other hand, the surface wind convergences were located over the two positive SST anomalies associated with the Kuroshio large meander (Figs. 2, 5b). In particular, the amplitude of the wind convergence over the warm SST tongue was comparable to the wind divergence over the cool SST pool. These two surface wind convergences are likely associated with the positive SST anomalies through the pressure adjustment mechanism. These wind convergences were not explicitly described in previous studies, although Murazaki et al. (2015) showed similar convergence to the south of Japan.

A closer look at the statistically significant wind changes showed that the air outflow over the cool SST pool was prominent (Fig. 5a). That is, the southerly and northeasterly wind anomalies were located to the north and south of the cool SST pool, respectively. Interestingly, the northeasterly surface wind anomaly converging to the warm SST tongue extended far to the east of the Japanese coast at around 36°N. This spatial extent of the surface wind response cannot be simply explained by the pressure adjustment mechanism, because the SST anomaly does not extend there. This northeasterly anomaly extended vertically from the surface to 950 hPa (not shown). Note that this northeasterly wind anomaly is collocated with the reduction in meridional wind variance (not shown). This result might imply some relation between this northeasterly wind anomaly and weather disturbances, such as extratropical cyclones.

How far does the vertical structure of the surface wind convergence and divergence over the SST anomalies extend? Figure 6b shows the simulated vertical velocity change along 138°E. A statistically significant downwelling wind anomaly was located over the cool SST pool and extended to 700 hPa. This downwelling wind anomaly was consistent with the surface wind divergence in this region (Fig. 5). In contrast, the upward wind anomaly



Fig. 5 Difference of **a** 10-m wind and **b** the corresponding divergence over the ocean between the LM runs minus NLM runs. In **a**, the black (gray) vectors indicate the regions where the difference of zonal or (and) meridional wind is (not) statistically significant at the 95% confidence level. Red and blue contours indicate the SST difference of \pm 0.5 °C and \pm 0.5 °C, respectively, between the LM runs minus NLM runs (see Fig. 2). In **b**, the contour indicates the regions where the difference is statistically significant at the 95% confidence level

was observed over the warm SST tongue, although its vertical extension was shallower than the downwelling. These vertical extents in the upward/downward winds were shallower than those over the Gulf Stream in winter, which have been reported to reach the upper troposphere (Minobe et al. 2010).





Fig. 6 a Regression coefficients of upward pressure velocity along 138°E based on the ERA5 dataset onto the Kuroshio large meander index from 1982 to 2019. The contour interval is 0.005 Pa s⁻¹. **b** Difference of the vertical velocity of the model along 138°E between the LM runs minus the NLM runs. The contour interval is 0.2 cm s⁻¹. In **a**, **b**, gray shading indicates regions where the corresponding correlation coefficients and the difference are statistically significant at the 95% confidence level, respectively

To confirm whether a similar atmospheric response could be observed, we performed correlation and regression analyses using the Kuroshio large meander index (see Sect. 2) and the ERA5 product from 1982 to 2019. To emphasize atmospheric signals with spatial scales similar to the Kuroshio large meander, the area average over $25^{\circ}-45^{\circ}$ N, $120^{\circ}-150^{\circ}$ E was subtracted from zonal and meridional wind data before these calculations. The surface wind change in the ERA5 product confirmed the divergence over the cool SST pool and convergence over the warm SST tongue (Fig. 7). Associated with these



Fig. 7 Regression coefficients of the 10-m wind as derived from the ERA5 dataset onto the Kuroshio large meander index from 1982 to 2019. This index is defined by the difference in the observed SST averaged over the region indicated by the blue box (33.5°N–34.5°N, 136.5°E–138.5°E) minus the region indicated by the red box (32.5°N–33.5°N, 136°E–138°E). The black (gray) vectors indicate the regions where the corresponding correlation coefficients for either of zonal or (and) meridional wind are (not) statistically significant at the 95% confidence level

wind convergence and divergence dynamics, the vertical velocity anomaly extended to 700 hPa (Fig. 6a), which was consistent with the simulation result. In addition, the northeasterly wind anomaly east of the Japanese coast was also observed. In contrast, the wind convergence over the positive SST anomaly to the south of the cool SST pool was not prominent in the ERA5 dataset, likely because the positive SST anomaly of the ERA5 product in this region is weaker than that of the OISST dataset (not shown).

It is important to clarify the roles of the warm SST tongue and the cool SST pool in inducing the northeasterly wind anomaly. To this end, we separately estimated the regression coefficients of the surface wind using the SST averaged over the warm SST tongue and the cool SST pool regions. The results showed that the northeasterly wind was correlated significantly with the SST averaged over the warm SST tongue region, but not with the SST averaged over the cool SST pool region (Fig. 8). The warm SST tongue was thus mainly related to northeasterly and easterly wind anomalies (Fig. 8a) that blows over the warm SST tongue. These wind anomalies can be seen in the wind anomalies associated with the Kuroshio large meander index (Fig. 7). On the other hand, the SST variability in the cold SST pool region was related to the local



Fig. 8 As for Fig. 7, but for the regression coefficients of the 10-m wind as derived from the ERA5 dataset onto the SST of the OISST dataset averaged **a** over the region indicated by the blue box in Fig. 7 and **b** over the region indicated by the red box in Fig. 7. The sign of the vectors of **b** is reversed for ease of comparison

divergence wind. These results suggest that the warm SST tongue plays an important role in the anomalous northeasterly wind along the east of the Japanese coast around 36°N.

3.2 Precipitation response

In this subsection, we examined the precipitation response to the SST anomalies associated with the Kuroshio large meander. In addition, we clarified the moisture budget of the precipitation change. The basic equation of the moisture budget is as follows (e.g., Seager et al. 2010; Kuwano-Yoshida et al. 2010):

$$\int_{p_{\rm s}}^{p_{\rm T}} \frac{\partial q}{\partial t} dp / \rho_{\rm w} g = -\int_{p_{\rm s}}^{p_{\rm T}} \nabla \cdot (q \mathbf{u}) dp / \rho_{\rm w} g + E - P, \quad (1)$$

where q is specific humidity, u is the horizontal wind vector, p is pressure, p_s is surface pressure, E is evaporation, P is precipitation, g is gravitational acceleration, and ρ_w is water density. Here, we set p_T as 500 hPa and ignore the moisture above this pressure level. Due to the small magnitude of the left hand side of Eq. (1) (not shown), we restricted our analysis to the three terms on the right hand side, that is, horizontal moisture convergence, evaporation, and precipitation, using the 3-hourly model outputs. For each term, we present the difference between the LM and NLM runs (Fig. 9). For example, the difference in the horizontal moisture convergence term can be written as follows:

$$-\int_{p_{\rm s}}^{p_{\rm T}} \nabla \cdot (q_{\rm LM} \mathbf{u}_{\rm LM}) dp_{\rm LM} + \int_{p_{\rm s}}^{p_{\rm T}} \nabla \cdot (q_{\rm NLM} \mathbf{u}_{\rm NLM}) dp_{\rm NLM}$$

where the subscripts LM and NLM denote the valuables in the LM run and the NLM run, respectively.

Since the only difference between the LM and NLM runs was the SST boundary conditions, the evaporation change was considered as the forcing. Thus, we first examined the difference in evaporation between the LM run minus the NLM run (Fig. 9b). The finding showed that evaporation decreased over the cool SST pool, but increased over the warm SST tongue and to the south of the cool SST pool during the LM periods, which was consistent with the SST anomalies. Like the SST anomalies, the evaporation anomaly over the cool SST pool was several times larger than that over the warm SST tongue.

Compared to the evaporation changes, the precipitation response has different characteristic spatial patterns (Fig. 9a). The negative precipitation anomaly was seen over the cool SST pool, consistent with the previous studies (Xu et al. 2010; Murazaki et al. 2015). This is also consistent with the expectation that the cool SST pool would reduce the evaporation in that region and is accompanied by the presence of surface wind divergence aloft (Fig. 5b). However, the amplitude of the negative precipitation anomaly over the cool SST pool was smaller than the corresponding changes in evaporation. In addition, the geographical locations at which the peak changes occurred also differed between precipitation anomaly was observed to the south of the cool SST pool, but not



◄ Fig. 9 Difference in a precipitation, b evaporation and c horizontal moisture convergence over the ocean between the LM minus NLM runs. Solid and dashed contours indicate the SST difference of + 0.5 °C and −0.5 °C, respectively, between the LM runs minus NLM runs (see Fig. 2). In a, the gray contours indicate the regions where the corresponding correlation coefficients are statistically significant at the 95% confidence level

over the warm SST tongue, even though evaporation is enhanced in that region. These results indicate that the response of precipitation to changes in evaporation is not straightforward.

The imbalances between the changes in precipitation and evaporation resulted from changes in the horizontal moisture convergence (Fig. 9c). Interestingly, the positive moisture convergence anomaly was located over the cool SST pool, which contrasted with the surface wind divergence observed in the region (Fig. 5). The amplitude of this moisture convergence was comparable to that of the precipitation change, but the sign is opposite. Since the change in evaporation is considered as the forcing mechanism, the decrease in evaporation was offset by the sum of the decrease in precipitation and the horizontal moisture convergence. Similarly, horizontal moisture divergence was located over the warm SST tongue, which is also inconsistent with the surface wind convergence in that region (Fig. 5b). As a result of this horizontal moisture divergence, the increase in precipitation is limited (Fig. 9a). Conversely, the horizontal moisture convergence was almost zero over the positive evaporation anomaly located to the south of the cool SST pool. In this region, the enhanced evaporation associated with the positive SST anomaly was balanced by enhanced rainfall. Therefore, the dynamics of moisture convergence are considered to be important for the precipitation response to the Kuroshio large meander.

Are there any similarities in the imbalances between the precipitation and evaporation changes over the cool SST pool and the warm SST tongue as observed in the ERA5 dataset? The ERA5 dataset also displayed negative anomalies in both precipitation and evaporation over the cool SST pool (Fig. 10). The amplitude of the evaporation anomaly over the cool SST pool was larger than that of the precipitation anomaly, which is consistent with the WRF simulation results (Fig. 9). These findings imply that horizontal moisture convergence over the cool SST pool is likely necessary to balance the moisture budget, although we did not examine this term



Fig. 10 Regression coefficients of **a** precipitation and **b** evaporation in the ERA5 dataset onto the Kuroshio large meander index from 1982 to 2019. Contours indicate the regions where the corresponding correlation coefficients are statistically significant at the 95% confidence level

 p_{T}

 p_{T}

in the context of the ERA5 dataset. Furthermore, evaporation was also enhanced over the warm SST tongue, but precipitation did not increase in the region (Fig. 10). These findings are consistent with the results of the WRF simulation.

To better clarify the role of horizontal moisture convergence and divergence in the WRF simulation, the moisture convergence term can be separated into two terms, as follows:

$$-\int_{p_{s}}^{p_{T}} \nabla \cdot (q\mathbf{u}) dp = -\int_{p_{s}}^{p_{T}} \mathbf{u} \cdot \nabla q dp - \int_{p_{s}}^{p_{T}} q \nabla \cdot \mathbf{u} dp, \quad (2)$$

where $\rho_w g$ in the denominator is omitted for simplicity (see Eq. 1). The first term and the second term on the right hand side are referred to as the moisture convergence resulting from horizontal moisture advection and the moisture convergence attributed to the wind convergence, respectively. Using this separation, we found that the change in the moisture convergence resulting from horizontal moisture advection (Fig. 11b) was opposite to and larger than the moisture convergence attributed to the wind convergence over the cool SST pool (Fig. 11a). Thus, the moisture convergence resulting from horizontal moisture advection is considered to play an important role in the horizontal moisture convergence in that region. The negative anomaly in the moisture convergence attributed to the wind convergence over the cool SST pool (Fig. 11a) is consistent with the surface wind divergence in that region (Fig. 5b). Conversely, the difference observed in the moisture convergence resulting from horizontal moisture advection is negative over the warm SST tongue (Fig. 11b), whereas the difference in moisture convergence attributed to wind convergence is small (Fig. 11a). Therefore, alternations in the moisture convergence resulting from horizontal moisture advection attenuate changes in precipitation.

To further clarify the role of the moisture convergence resulting from horizontal moisture advection, the term can be separated as follows:

$$-\int_{p_{s}} \mathbf{u}_{LM} \cdot \nabla q_{LM} dp_{LM} + \int_{p_{s}} \mathbf{u}_{NLM} \cdot \nabla q_{NLM} dp_{NLM} \approx$$

$$-\int_{p_{s}}^{p_{T}} (\mathbf{u}_{LM} - \mathbf{u}_{NLM}) \cdot \nabla q_{LM} dp_{LM} - \int_{p_{s}}^{p_{T}} \mathbf{u}_{LM} \cdot \nabla (q_{LM} - q_{NLM}) dp_{LM} + \int_{p_{s}}^{p_{T}} (\mathbf{u}_{LM} - \mathbf{u}_{NLM}) \cdot \nabla (q_{LM} - q_{NLM}) dp_{LM}$$
(3)



Fig. 11 As for Fig. 9, but showing the difference in **a** the moisture convergence attributed to wind convergence and **b** the moisture convergence resulting from horizontal moisture advection

In this equation, the left hand side is not equal to the right hand side, but the residual is small. We checked the three terms on the right hand side and found that the second term is considerably larger than the first and third terms (not shown). Even if the wind field of the second term is replaced with the wind of the NLM run, the result is robust. This second term is moisture convergence due to the horizontal moisture advection caused by changes in the specific humidity. As shown in Fig. 12, the change in moisture convergence due to the horizontal moisture advection caused by changes in the specific humidity is similar to the changes associated with the moisture advection (Fig. 11b), namely, the positive difference over the cool



Fig. 12 As for Fig. 9, but showing the difference in moisture convergence due to horizontal moisture advection caused by the difference in specific humidity between the LM run and the NLM runs

SST pool and the negative difference over the warm SST tongue. These findings suggest that the Kuroshio large meander influences the horizontal moisture convergence mainly via changes in the horizontal gradient of the specific humidity in the lower troposphere (Fig. 13). A



Fig. 13 As for Fig. 9, but showing the difference in specific humidity (color; g kg⁻¹) and the mean wind (vector) at 900 hPa. Solid and dashed contours indicate the SST difference of +0.5 °C and -0.5 °C, respectively, between the LM runs minus NLM runs



Fig. 14 a Regression coefficients for the number of rainy days in the ERA5 dataset onto the Kuroshio large meander index from 1982 to 2019. **b** Difference in the number of rainy days between the LM runs minus NLM runs. In **a**, **b**, contours indicate regions where the corresponding correlation coefficients and the difference are statistically significant at the 95% confidence level, respectively. Rainy days were defined using a 1.0 mm day⁻¹ threshold

decrease (increase) in the evaporation over the cool SST pool (warm SST tongue) induces the negative (positive) specific humidity anomaly in the lower troposphere.

It is worth noting that the amount of precipitation was not increased, but rather, the number of rainy days $(>1.0 \text{ mm day}^{-1})$ was increased significantly over the warm SST tongue in both the WRF and ERA5 results (Fig. 14). Similarly, the number of rainy days was

decreased over the cool SST pool. Murazaki et al. (2015) reported a decrease in the frequency of intense precipitation (>1 mm /3 h) over and around the cool SST pool based on their model results, and here we found a decrease in the weak precipitation over the cool SST pool or an increase in the frequency of the rainfall over the warm SST tongue. When we employed a threshold of 0.5 mm day⁻¹ to define a rainy day, a similar spatial pattern was obtained. However, when a threshold of 5.0 mm day⁻¹ was applied, the area of the positive anomaly over the warm SST tongue decreased (not shown), implying that only the frequency of weak precipitation increased over the warm SST tongue. These findings appear to be consistent with the observation that the amount of precipitation in that region is relatively unchanged (Fig. 9a). As in the case of the surface wind shown in Fig. 8, we calculated the correlation coefficients of the number of rainy days from the ERA5 product using the SST averaged over the warm SST tongue and the cool SST pool, separately. The results show that the SST in the warm SST tongue region (in the cool SST pool region) is correlated with the positive (negative) anomaly of the number of rainy days in that region (not shown). Over the warm SST tongue, the enhanced evaporation (Fig. 9b) and sensible heat release, which induce the vertically unstable condition, and the upwind associated with the surface wind convergence are favorable for the enhanced precipitation (Fig. 14). However, because the anomalous horizontal moisture divergence acts to reduce the moisture, the number of weak rainy days increased over the warm SST tongue (Fig. 9a).

4 Summary and discussion

The wintertime atmospheric responses to the Kuroshio large meander to the south of Japan, especially the cool SST pool and the warm SST tongue (Fig. 2), were investigated using the ERA5 dataset and a set of WRF simulations. The results of sensitivity experiments conducted using the WRF showed that the surface wind responses to the SST anomalies associated with the Kuroshio large meander were not solely characterized by the wind divergence over the cool SST pool, as has been reported previously, but also by the wind convergence over the warm SST tongue (Fig. 5). These wind divergence and convergence were accompanied by downward and upward wind reaching 700 and 800 hPa, respectively (Fig. 6a). Interestingly, during the Kuroshio large meander periods, a northeasterly wind anomaly blew into the positive SST anomaly was observed along the east coast of Japan at around 36°N (Fig. 5). Analyses using the ERA5 product corroborated the presence of similar northeasterly wind anomalies (Fig. 7) and underscored the importance of the

warm SST tongue in contributing to these wind anomalies (Fig. 8).

The response of precipitation to the Kuroshio large meander was also prominent. During the period of the Kuroshio large meander, the number of rainy days significantly increased and decreased over the warm SST tongue and the cool SST pool (Fig. 14), respectively, which was consistent with both the WRF simulation and the reanalysis product. However, changes in the quantity of precipitation were only observed over the cool SST pool (Fig. 9a). The moisture budget analysis revealed that the decrease in precipitation over the cool SST pool resulted from the interplay between the decrease in the evaporation (Fig. 9b) and the anomalous horizontal moisture convergence (Fig. 9c). Interestingly, the anomalous horizontal moisture convergence (divergence) observed over the cool SST pool (the warm SST tongue) was mainly induced by a decrease in the specific humidity (Figs. 12, 13), despite concurrent surface wind divergence (convergence) (Fig. 9c). These changes acted to mitigate changes in precipitation.

In this study, we found that the surface wind response to the Kuroshio large meander extends along the east of the Japanese coast (Figs. 5, 7). This gives rise to an interesting question concerning the oceanic response to this anomalous wind. For example, these surface wind anomalies have the potential to induce positive sea level anomalies along the Japanese coast via Ekman advection. These sea level anomalies could then propagate clockwise along the Japanese coast and potentially influence the Kuroshio to the south of Japan. To our knowledge, no studies have reported on the potential existence of such a feedback loop in this region. A regional atmosphere-ocean coupled model would provide helpful insights into this topic, particularly since coastal sea level variability around Japan is primarily driven by other processes, such as westward propagating Rossby waves (Sasaki et al. 2014) or alterations to the path of the Kuroshio to the south of Japan (Usui and Ogawa 2022).

Abbreviations

JMA	Japan Meteorological Agency
LM	Large-meander
NCEP-CFSR	National Centers for Environmental Prediction Climate Forecast
	System Reanalysis
NLM	Non-large meander
NOAA	National Oceanic and Atmospheric Administration
OISST	Optimum interpolation sea surface temperature
SLP	Sea level pressure
SST	Sea surface temperature
WRF	Weather research and forecasting model

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Author contributions

YNS and RI proposed the topic and designed the study. RI carried out the model experiments. YNS and RI analyzed the simulation and reanalysis data. YNS wrote the first draft of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The JMA data were obtained from https://www.data.jma.go.jp/kaiyou/data/ shindan/b_2/kuroshio_stream/kuroshio_stream.html. The ERA5 product was obtained from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reana lysis-era5-pressure-levels-monthly-means?tab=overview and https://cds.clima te.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overv iew. The OISST product was obtained from https://www.ncei.noaa.gov/data/ sea-surface-temperature-optimum-interpolation/v2/access/. The NCEP-CFSR product was obtained from https://www.ncei.noaa.gov/data/climate-forec ast-system/access/. The outputs from the WRF model are available from Yoshi N. Sasaki on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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References

- Chou M-D, Suarez MJ (1994) An efficient thermal infrared radiation parameterization for use in general circulation models. NASA Tech Memo, TM-104606, vol. 3, 84 pp
- Hayasaki M, Kawamura R, Mori M, Watanabe M (2013) Response of extratropical cyclone activity to the Kuroshio large meander in northern winter. Geophys Res Lett 40:2851–2855. https://doi.org/10.1002/grl.50546
- Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, Nicolas J, Peubey C, Radu R, Schepers D, Simmons A, Soci C, Abdalla S, Abellan X, Balsamo G, Bechtold P, Biavati G, Bidlot J, Bonavita M, De Chiara G, Dahlgren P, Dee D, Diamantakis M, Dragani R, Flemming J, Forbes R, Fuentes M, Geer A, Haimberger L, Healy S et al (2020) The ERA5 global reanalysis. Q J R Meteorol S 146:1999–2049
- Hirata H, Kawamura R, Nonaka M, Tsuboki K (2021) Kuroshio-enhanced convective rainband associated with an extratropical cyclone in the cold season. J Meteorol Soc Jpn 99:899–912. https://doi.org/10.2151/jmsj. 2021-043
- Hong S-Y, Noh Y, Dudhia J (2006) A new vertical diffusion package with an explicit treatment of entrainment processes. Mon Weather Rev 134:2318–2341
- lizuka S, Shiota M, Kawamura R, Hatsushika H (2013) Influence of the monsoon variability and sea surface temperature front on the explosive cyclone activity in the vicinity of Japan during northern winter. SOLA 9:1–4
- Kain JS, Fritsch JM (1990) A one-dimensional entraining/detraining plume model and its application in convective parameterization. J Atmos Sci 47:2784–2802. https://doi.org/10.1175/1520-0469
- Kawabe M (1980) Sea level variations along the south coast of Japan and the large meander in the Kuroshio. J Oceanogr Soc Jpn 36:97–104
- Kawabe M (1985) Sea level changes south of Japan associated with the nonlarge-meander path of the Kuroshio. J Oceanogr Soc Jpn 45:181–189
- Kawabe M (1995) Variations of current path, velocity, and volume transport of the Kuroshio in relation with the large meander. J Phys Oceanogr 25:3103–3117
- Kida S, Mitsudera H, Aoki S, Guo X, Ito SI, Kobashi F, Komori N, Kubokawa A, Miyama T, Morie R, Nakamura H, Nakamura T, Nakano H, Nishigaki H, Nonaka M, Sasaki H, Sasaki YN, Suga T, Sugimoto S, Taguchi B, Takaya

K, Tozuka T, Tsujino H, Usui N (2015) Oceanic fronts and jets around Japan—a review. J Oceanogr 71:469–497. https://doi.org/10.1007/s10872-015-0283-7

- Kuwano-Yoshida A, Minobe S (2017) Storm-track response to SST fronts in the northwestern Pacific region in an AGCM. J Clim 30:1081–1102. https:// doi.org/10.1175/JCLI-D-16-0331.1
- Kuwano-Yoshida A, Minobe S, Xie S-P (2010) Precipitation response to the Gulf Stream in an atmospheric GCM. J Clim 23:3676–3698
- Lindzen RS, Nigam S (1987) On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics. J Atmos Sci 44:2418–2436
- Minobe S, Miyashita M, Kuwano-Yoshida A, Tokinaga H, Xie S-P (2010) Atmospheric response to the Gulf Stream: seasonal variations. J Clim 23:3699–3719
- Mlawer EJ, Taubman SJ, Brown PD, Iacono MJ, Clough SA (1997) Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. J Geophys Res 102:16663–16682. https://doi. org/10.1029/97JD00237
- Murazaki K, Tsujino H, Motoi T, Kurihara K (2015) Influence of the Kuroshio large meander on the climate around Japan based on a regional climate model. J Meteorol Soc Jpn Ser II 93(2):161–179. https://doi.org/10.2151/ jmsi.2015-009
- Nakamura H, Nishina A, Minobe S (2012) Response of storm tracks to bimodal Kuroshio path states south of Japan. J Clim 25:7772–7779
- Nonaka M, Xie S-P (2003) Covariations of sea surface temperature and wind over the Kuroshio and its extension: evidence for ocean-to-atmosphere feedback. J Clim 16:1404–1413
- Parfitt R, Seo H (2018) A new framework for near-surface wind convergence over the Kuroshio extension and Gulf Stream in wintertime: the role of atmospheric fronts. Geophys Res Lett 45:9909–9918. https://doi.org/10. 1029/2018GL080135
- Qiu B, Chen S, Oka E (2023) Why did the 2017 Kuroshio large meander event become the longest in the past 70 years? Geophys Res Lett 50:e2023GL103548. https://doi.org/10.1029/2023GL103548
- Reynolds RW, Smith TM, Liu C, Chelton DB, Casey KS, Schlax MG (2007) Daily high-resolution-blended analyses for sea surface temperature. J Clim 20:5473–5496
- Saha S et al (2010) The NCEP climate forecast system reanalysis. Bull Am Meteorol Soc 91:1015–1057. https://doi.org/10.1175/2010bams3001.1
- Sasaki YN, Yamada Y (2018) Atmospheric response to interannual variability of sea surface temperature front in the East China Sea in early summer. Clim Dyn 51(7):2509–2522. https://doi.org/10.1007/s00382-017-4025-y
- Sasaki YN, Minobe S, Asai T, Inatsu M (2012) Influence of the Kuroshio in the East China Sea on the early summer (Baiu) rain. J Clim 25:6627–6645

Sasaki YN, Minobe S, Miura Y (2014) Decadal sea level variability along the coast of Japan in response to ocean circulation changes. J Geophys Res (oceans). https://doi.org/10.1002/2013JC009327

Seager R, Naik N, Vecchi GA (2010) Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming. J Clim 23:4651–4668. https://doi.org/10.1175/2010JCLI3655.1

- Seo H, O'Neill LW, Bourassa MA, Czaja A, Drushka K, Edson JB, Fox-Kemper B, Frenger I, Gille ST, Kirtman BP, Minobe S, Pendergrass AG, Penault L, Roberts MJ, Schneider N, Small RJ, Stoffelen A, Wang Q (2023) Ocean mesoscale and frontal-scale ocean-atmosphere interactions and influence on large-scale climate: a review. J Clim 36:1981–2013. https://doi. org/10.1175/JCLI-D-21-0982.1
- Skamarock WC, Klemp JB, Dudhia J, Gill DO, Liu Z, Berner J, Wang W, Powers JG, Duda MG, Barker D, Huang X (2019) A description of the advanced research wrf model version 4.3. NCAR Technical Note. https://doi.org/10. 5065/1dfh-6p97
- Small RJ, Xie SP, Wang Y (2003) Numerical simulation of atmospheric response to Pacific tropical instability waves. J Clim 16:3722–3737
- Sugimoto S, Qiu B, Kojima A (2020) Marked coastal warming off Tokai attributable to Kuroshio large meander. J Oceanogr 76:141–154. https://doi.org/ 10.1007/s10872-019-00531-8
- Sugimoto S, Qiu B, Schneider N (2021) Local atmospheric response to the Kuroshio large meander path in summer and its remote influence on the climate of Japan. J Clim 34:3571–3589. https://doi.org/10.1175/ JCLI-D-20-0387.1

- Tochimoto E, lizuka S (2022) Impact of warm sea surface temperature over a Kuroshio large meander on extreme heavy rainfall caused by an extratropical cyclone. Atmos Sci Lett. https://doi.org/10.1002/asl.1135
- Usui N, Ogawa K (2022) Sea level variability along the Japanese coast forced by the Kuroshio and its extension. J Oceanogr. https://doi.org/10.1007/ s10872-022-00657-2
- Xie S-P, Hafner J, Tanimoto Y, Liu WT, Tokinaga H, Xu H (2002) Bathymetric effect on the winter sea surface temperature and climate of the Yellow and East China Seas. Geophys Res Lett 29:2228. https://doi.org/10.1029/ 2002GL015884
- Xu H, Tokinaga H, Xie S-P (2010) Atmospheric effects of the Kuroshio large meander during 2004–05. J Clim 23:4704–4715
- Xu H, Xu M, Xie S-P, Wang Y (2011) Deep atmospheric response to the spring Kuroshio over the East China Sea. J Clim 24:4959–4972

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