Local Atmospheric Response to the Kuroshio Large Meander Path in Summer and Its Remote Influence on the Climate of Japan

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ABSTRACT: The Kanto district in Japan, including Tokyo, has 40 million inhabitants and its summer climate is characterized by high temperature and humidity. The Kuroshio that flows off the southern coast of the Kanto district has taken a large meander (LM) path since the summer of 2017 for the first time since the 2004–05 event. Recently developed satellite observations detected marked coastal warming off the Kanto–Tokai district during the LM path period. By conducting regional atmospheric model experiments, it is found that summertime coastal warming increases water vapor in the low-level atmosphere through enhanced evaporation from the ocean and influences near-surface winds via the vertical mixing effect over the warming area. These two changes induce an increase in water vapor in Kanto district, leading to an increase in downward longwave radiation at the surface and then surface warming through a local greenhouse effect. As a result, summer in Kanto district becomes increasingly hot and humid in LM years, with double the number of discomfort days compared with non-LM years. Our simulations and supplementary observational studies reveal the significant impacts of the LM-induced coastal warming on the summertime climate in Japan, which can exceed previously identified atmospheric teleconnections and climate patterns. Our results could improve weather and seasonal climate forecasts in this region.

KEYWORDS: North Pacific Ocean; Atmosphere-ocean interaction; Boundary currents; Summer/warm season; Climate variability; Numerical analysis/modeling

1. Introduction

The Kuroshio is a western boundary current of the North Pacific subtropical gyre, which advects warm water from the tropics and flows northeastward along the continental slope of the East China Sea and southern coast of Japan. It veers off the Japanese coast at around 35°N, forming the eastward jet known as the Kuroshio Extension (KE). The warm Kuroshio/KE releases large amounts of heat and moisture (Bond and Cronin 2008; Kubota et al. 2008) and has a sharp SST front along its poleward flank. Recent high-resolution satellite measurements and numerical simulations have revealed significant impacts of the Kuroshio/KE on the overlying marine atmospheric boundary layer (MABL), such as surface winds and surface air temperature (SAT), through heat and moisture exchanges (Xie et al. 2002; Nonaka and Xie 2003; Tokinaga et al. 2006, 2009; Small et al. 2008; Kelly et al. 2010; Minobe et al. 2010; Xu et al. 2011; Masunaga et al. 2016, 2020; Sugimoto et al. 2017). Responses to the Kuroshio/KE are also detectable in the free atmosphere, precipitation (Miyama et al. 2012; Sasaki et al. 2012; Sasaki and Yamada 2018; Xu et al. 2018), synoptic weather disturbances (Tanimoto et al. 2011; Nakamura et al. 2012; Hayasaki et al. 2013; Kuwano-Yoshida and Minobe 2017; Masunaga et al. 2020), and large-scale atmospheric circulation across the North Pacific (Nakamura et al. 2004; Ma et al. 2015, 2017; Qiu et al. 2014, 2020). Most of these previous studies have investigated the atmospheric responses to the Kuroshio/KE in autumn, winter, and spring, when the SST front becomes stronger and the heat and moisture exchanges become more active. In contrast, there are few studies on the effects of the Kuroshio/KE on the overlying atmospheric field in summer because of the weak SST front and small heat/moisture exchanges.

The Kuroshio south of Honshu, Japan, has remarkable bimodal features (Fig. 1a; Taft 1972; Kawabe 1985); a large meander (LM) path, detouring (i.e., meandering) offshore south of Japan, and a non-LM path, flowing along the southern coast of Japan. Both paths are relatively stable and maintained for several years to a decade once formed (Kawabe 1987). These features are not found in the other western boundary currents, such as the Gulf Stream. In the LM period, a developed cyclonic eddy is present in the onshore region between the Kuroshio and the southern coast of Tokai district (Fig. 1b). It has been recognized that the cool water pool is broadly distributed because of the upwelling and shoaling thermocline inside the cyclonic eddy. The LM-induced cool water pool can affect the overlying atmospheric field, including reduced surface winds in winter (Xu et al. 2010) and decreased precipitation in winter (Xu et al. 2010) and throughout the year (Murazaki et al. 2015). It also induces a significant southward shift of extratropical cyclone tracks in winter (Nakamura et al. 2012; Hayasaki et al. 2013). The cool water pool off Tokai district was considered the prominent feature in the LM path, and numerous air-sea-
coupled studies have been conducted for the cold season (i.e., mainly in winter). A recent study by Sugimoto et al. (2020) showed marked coastal warming off Kanto–Tokai district during LM periods (Fig. 1c), which is attributable to the westward Kuroshio bifurcation that occurred during the LM periods, based on high-resolution satellite-derived data. The detected warming was in sharp contrast to the previous recognition that a cool water pool is distributed broadly in the region between the Kuroshio and the southern coast of Tokai district. Based on statistical analyses of weather station data, Kanto–Tokai district becomes warmer than usual in summer during LM periods, which indicates that LM-induced coastal warming could have an influence on the summertime climate in Japan via coastal air–sea interaction. However, the physical processes responsible for this have not yet been clarified.

It has long been recognized that the summer climate in Japan is largely affected by a combination of the North Pacific high, Bonin high (Ogasawara high), Tibetan high, and Okhotsk high. These highs are closely related to the large-scale atmospheric circulation fluctuations associated with four atmospheric teleconnection patterns: the Europe–Japan patterns (EJ1 and EJ2), which prevail over northern Eurasia and are linked to variations of the Okhotsk high (Wakabayashi and Kawamura 2004); the West Asia–Japan (WJ) pattern, which is characterized by a stationary wave train pattern along the upper-level subtropical jet from West Asia to the central North Pacific (Wakabayashi and Kawamura 2004); and the Pacific–Japan (PJ) pattern, which is a stationary wave train pattern generated by tropical convective activity in the vicinity of the Philippine Sea (e.g., Kurihara and Tsuyuki 1987; Nitta 1987; Kosaka and Nakamura 2010). It has been reported that the WJ pattern influences the surface air temperature in the western part of Japan, and the PJ, EJ1, and EJ2 patterns affect the SAT in the northern part of Japan (Tachibana et al. 2004; Wakabayashi and Kawamura 2004; Kubota et al. 2016). With recent progress in regional atmospheric modeling, it has been shown that the SST around Japan can exert an influence on summer climate (e.g., Takahashi et al. 2015); the northward movement of the SST front to the east of Japan triggers a northward shift of the tropospheric jet (Nakamura and Miyama 2014; Matsumura et al. 2016), resulting in anomalous warming in northern Japan (Nakamura and Yamane 2010; Matsumura et al. 2016); the LM-induced cool water pool off Tokai district induces lower SAT and increased precipitation on the Pacific coast of Japan.

Fig. 1. (a) Typical paths of the Kuroshio (lines) superimposed on bathymetry taken from ETOPO2 (colors). (b) SST on 1 Jul 2018 (shading; °C), when the Kuroshio takes the LM path, which was taken from MURSST (see the text for details). Black contours indicate the satellite-derived sea surface height from the Copernicus Marine Environment Monitoring Service (CMEMS; Mertz et al. 2018), with an interval of 0.2 m. (c) As in (b), but for the SST anomaly (°C). The daily climatology was obtained by applying a 31-day running filter to calendar-day means for the consecutive 11 years of 2006–16, which is equivalent to a non-LM path period. White contours indicate an anomaly of 2°C.
Japan (Murazaki et al. 2015). Most studies have focused on the effects of the open ocean, large-scale SST (>500 km) on the climate of Japan, and our understanding of the smaller-scale SST impacts, such as coastal warming, is still lacking.

It is expected that the coastal warming off Kanto–Tokai attributable to the LM path would exert a significant impact on summer climate, because the southerly wind flow along the periphery of the western Pacific subtropical high (Fig. 2a) is predominant over Japan in summer. In addition, the summertime SST varies considerably off Kanto–Tokai district with coastal warming (Fig. 2b). The purpose of this study is to reveal summertime local atmospheric responses to coastal warming off Kanto–Tokai district, and quantitatively assess its remote effects on the summer climate of Japan via low-level atmospheric processes. We conduct regional atmospheric model experiments using the recently developed SST product on a 1/100° (longitude) × 1/100° (latitude) grid from the NASA Jet Propulsion Laboratory, which adequately captures the coastal warming. In the summer of 2017, the Kuroshio took the LM path for the first time since the summer of 2005, and this event remains ongoing as of January 2021, at the time of writing of this manuscript. Our study is timely and will be helpful for predicting the effects of the ongoing LM event on the summer climate of Japan.

2. Data and model

a. Observations and reanalysis data

We use the daily NASA Jet Propulsion Laboratory multiscale, ultra-high-resolution SST (MURSST) product (Chin et al. 2013) on a 1/100° (longitude) × 1/100° (latitude) grid. This product incorporates SSTs from eight satellites, using both infrared and passive microwave retrievals, along with in situ data. It has been used previously for research on coastal upwelling (Vazquez-Cuervo et al. 2013; Gentemann et al. 2017). Data from this product are available from January 2003 onward.

We use the monthly SAT data at weather stations and the Automated Meteorological Data Acquisition System (AMeDAS) stations operated by the Japan Meteorological Agency (JMA). We also use four atmospheric teleconnection pattern indices, calculated from the JMA Japanese 55-year Reanalysis (JRA-55) data (Kobayashi et al. 2015), based on the definitions of Wakabayashi and Kawamura (2004): P J , W P , E J 1 , and E J 2 . The Niño-3 index (SST anomalies averaged for 5°S–5°N, 150°–90°W), is also used, which is regarded as an indicator of El Niño events.

We examine 18 summers (June–August) from 2003–20, for which the above datasets are available.

Fig. 2. (a) Summertime climatology of the SST (shading; °C), SLP (contours; 1-hPa intervals), and surface winds (arrows), taken from ERA5 (see the text for details). The climatology is for 31 summers (June–August) of 1990–2020. (b) SD of the daily SST anomaly (°C) during 16 summers (June–August) of 2003–20, taken from MURSST (see the text for details). The daily climatology was obtained by applying a 31-day running filter to calendar-day means of 2006–16. (c) Histogram of daily SST anomalies averaged within a coastal area of Kanto–Tokai district [33.5°–35°N, 137°–139°E; white rectangle in (b)] during summer for the latest LM event (August 2017–present). Here the daily climatology is as in (b). Light blue shading indicates a width of ±1 std dev, based on the mean value.
b. Regional atmospheric model experiment

The regional atmospheric model used in this study is the JMA/Meteorological Research Institute (JMA/MRI) nonhydrostatic model (NHM; Saito et al. 2006, 2007). The NHM is designed to serve both weather forecasting and atmospheric research needs, and has been used in a variety of regional climate studies. The model domain covers the Kuroshio south of Japan from 28° to 40°N and from 130° to 145°E in the Lambert projection (Fig. 3a), with 5-km horizontal grid spacing. The model has 51 vertical levels with realistic topography; 19 levels are placed below 2 km in height to finely resolve the MABL. We used the Mellor–Yamada–Nakanishi–Niino level-3 planetary boundary layer scheme (Nakanishi and Niino 2004), the Beljaars–Holtslag flux and bulk coefficient scheme (Beljaars and Holtslag 1991), and the Kain–Fritsch convection parameterization scheme (Kain and Fritsch 1993; Kain 2004) for convective processes.

The coastal warming off Kanto–Tokai district ranges from 1.5° to 3.5°C during the latest LM event (Fig. 2c). In our experiments, we focus on the month of July, when the baiu rainband is located in northern Japan away from the coastal area off Kanto–Tokai district, as compared with June when the rainband is found around southern part of Japan and August when more typhoons approach Japan. To detect the effects of the coastal warming off Kanto–Tokai district on the overlying atmosphere and climate of Japan, we conduct two sets of experiments by imposing different SST boundary conditions. The first is the control (CTRL) run, in which we prescribe daily SSTs from MURSST for 17 June to 31 July 2004, when the Kuroshio takes the LM path, and in a near-neutral phase of natural variability, such as El Niño and the PJ pattern, that affect the summertime atmospheric conditions around Japan. The second experiment (COLD run) is conducted by subtracting the idealized SST anomaly (Fig. 3b), representing the coastal warming, from the daily SST field of the CTRL run. We used the idealized SST because a simple difference in SST between the LM and non-LM periods includes effects that are not related to the Kuroshio LM path, such as eddies. The idealized SST anomaly has a maximum amplitude of about 3°C, which falls within +1 SD of the mean value (Fig. 2c).

This experiment design differs from the traditional method of using SST data and spatially and/or temporally smoothed data as the boundary condition (e.g., Takahashi et al. 2015; Matsumura et al. 2016). In addition, SSTs used as a boundary condition in previous studies do not resolve coastal warming. Our experiment is designed to reveal only the atmospheric response to coastal warming off Kanto–Tokai district.

For the initial and boundary atmospheric conditions, we use the recently released fifth generation of atmospheric reanalysis of the global climate of ECMWF (ERA5; Copernicus Climate Change Service 2017), which is on a 1/4° (longitude) × 1/4° (latitude) grid. The CTRL and COLD experiments consist of seven NHM simulations, in which the initial and boundary conditions were calculated based on the method of Inatsu and Terakura (2012). The period between 17 June and the end of the month is a spinup phase, and then July is analyzed. All results are shown as an average over July and an average over the ensemble. It is worth emphasizing that in this regional modeling approach, the initial and lateral boundary conditions are identical in the two experiments.

3. Local atmospheric response to coastal warming off Kanto–Tokai district

The CTRL run from NHM (Fig. 4b) successfully captures the large-scale features of the summer SAT field in the ERA5 (Fig. 4a). The SAT fields show a gradual westward increase south of 35°N and a sharp meridional front associated with the KE along 35°N east of Japan. Low SATs are detected north of 35°N east of Japan, which reflects the southward cold-water intrusion associated with the Oyashio. Over the islands of Japan, the CTRL run shows higher and lower temperature in some regions, compared with the ERA5, because of the spatially high-resolution topography. The surface winds show a striking
correspondence between ERA5 and the CTRL run; southwesterly winds are dominant south of Japan and blow strongly into Kanto district. These provide confidence that the NHM simulation is capable of successfully reproducing climate features over the Kuroshio south of Honshu, Japan, and Pacific coast cities, such as in Kanto district, in July. However, our simulation may depend on the spatial resolution and parameterization.

a. Air temperature and water vapor response

We explore the local atmospheric responses over the coastal warming off Kanto–Tokai district attributable to the LM path. A comparison between the CTRL and COLD runs shows a local SAT increase off Kanto–Tokai district (Fig. 5a), with the values increasing by 3°C in the CTRL run, which is almost consistent with the SST increase in terms of both location and amplitude (Fig. 3b). We investigate the upward influence of the coastal warming by examining the difference in virtual potential temperature along 34°N, where a marked difference in SAT can be detected, between the two runs (Fig. 5b). Significant warming extends not only into the near surface but also throughout the MABL, reaching the 950-hPa level in the CTRL run.

Numerous studies have noted that the summertime SST anomalies in the western North Pacific are formed by downward solar heating (e.g., Wu and Kinter 2010). In contrast to the basin-scale studies, our recent work (Sugimoto et al. 2020) showed that the SST increase off Kanto–Tokai district is not related to downward solar heating, but is associated with advection of warm Kuroshio water by meander and the resulting enhanced upward heat flux in summer. The upward heat flux occurs predominantly by latent heat flux and, to a lesser extent, by sensible heat flux. Therefore, it is expected that the increase in upward heat fluxes can induce warming of the MABL. Our experiments reveal a collocation of increased SATs and enhanced upward heat release off Kanto–Tokai.

Fig. 4. (a) July-mean air temperature at 2-m height (shading; °C) and horizontal winds at 10-m height (arrows) and (c) horizontal winds at 925-hPa level from ERA5 in 2004. (b),(d) As in (a) and (c), but for air temperature at 1.5-m height from the CTRL run.

(a) SAT/Surface winds (ERA5) (b) SAT/Surface winds (CTRL)

(c) 925 hPa winds (ERA5) (d) 925 hPa winds (CTRL)
The heat flux increase attributable to the coastal warming is about 100 W m$^{-2}$, and the latent heat flux is about 10 times larger than the sensible heat flux. We diagnostically investigate the diabatic heating, following Yanai et al. (1973) and Yanai and Tomita (1998), to detect the effects of the oceanic heat release on the overlying atmosphere. There is a strong diabatic heating rate over the coastal warming area (Fig. 6c), the effect of which extends to the top of the MABL (Fig. 6d). It is evident that the coastal warming off Kanto–Tokai district heats the MABL both directly and locally.

The large latent heat flux (Fig. 6a)—which is enhanced evaporation from the ocean—over the coastal warming area results in an increase in water vapor in the MABL (Figs. 7a,b). It is expected that the large amount of water vapor affects the cloud distribution. Figure 7d shows the difference in cloud amount along 34°N between the two runs, indicating a well-defined seesaw pattern in the vertical direction, with increased cloudiness between the 970- and 920-hPa levels and reduced cloudiness at the near surface. In the upper part, the cloud increases (Fig. 7c) are collocated with the area of enhanced evaporation (Fig. 6a), except for a slight displacement of the cloud maximum downstream of the evaporation, which is consistent with advection by the prevailing southwesterly winds. The lower part implies a fog formation due to the lack of coastal warming during the COLD run (Fig. 7e).

b. Surface wind response

The recent observational study of Schneider (2020) indicated that the ocean mesoscale SST has a significant impact on near-surface winds in the midlatitude ocean. It is expected that the coastal warming off Kanto–Tokai district attributable to the LM path also has an impact on winds. A difference in surface winds between the CTRL and COLD runs (Fig. 8a) clearly shows westerly wind anomalies over the coastal warming area, revealing wind acceleration due to the consistency in wind direction with the mean state (Fig. 4b). In addition, westerly wind anomalies are detected within the MABL and, in contrast, easterly wind anomalies are found above the MABL height (Fig. 8b).

It is important to explore what processes contribute to the surface wind responses to the coastal warming. Two processes have been proposed as effects of SST, at SSTs below the convective threshold (i.e., 26°C–27°C): 1) the pressure adjustment process (Lindzen and Nigam 1987; Minobe et al. 2008), whereby a depression in sea level pressure (SLP) around a positive SST anomaly forms a pressure gradient, resulting in surface wind changes; and 2) the vertical mixing process (Wallace et al. 1989; Tanimoto et al. 2011), which produces surface wind changes due to a decrease in static stability above positive SST anomalies that enhance vertical mixing, and promote momentum transport from above into the lower boundary layer or through equilibrium changes in boundary layer height (Samelson et al. 2006). These processes have been mainly investigated over oceanic western boundary currents with sharp SST fronts, such as the KE and Gulf Stream.

The westerly winds are locally enhanced over the coastal warming area, which is consistent with the vertical mixing process because of the presence of monsoonal westerly winds aloft in summer (Fig. 4). This implies that the pressure adjustment process associated with the negative SLP anomaly around the coastal warming area forms easterly winds to the east of the coastal warming area. The winds shown in Fig. 8a appear to be blowing counterclockwise, which suggests a possible influence from Coriolis forcing. To explore the effects of the above processes on the surface wind responses to the coastal warming, we perform a vertically averaged momentum budget analysis from the 3-hourly simulation output, as follows (e.g., Song et al. 2006; Takatama et al. 2012):
\[
\frac{\partial U}{\partial t} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + f V - \frac{1}{\Delta z} \left( \overline{w w'}_{\Delta z} - \overline{\overline{w w'}}_{\Delta z} \right) - A_x + D_U \quad (1)
\]

and

\[
\frac{\partial V}{\partial t} = -\frac{1}{\rho} \frac{\partial P}{\partial y} - f U - \frac{1}{\Delta z} \left( \overline{w w'}_{\Delta z} - \overline{\overline{w w'}}_{\Delta z} \right) - A_y + D_V \quad (2)
\]

where

\[
\Delta z = z'' - z' \quad (3)
\]

\(U\) and \(V\) are the vertically averaged zonal and meridional winds, \(u'\) and \(v'\) are the turbulent fluctuations of horizontal winds, \(w'\) is the fluctuation associated with the vertical wind, \(P\) is the vertical average of air pressure, \(\rho\) is the air density, \(f\) is the Coriolis parameter, \(A_x\) and \(A_y\) are the horizontal advection, and \(D_U\) and \(D_V\) are the horizontal diffusion. Here, we focus on the first three terms on the right-hand side of Eqs. (1) and (2), because the last two terms are very small compared with the first three terms. These three terms are referred to as the pressure gradient Coriolis and vertical mixing terms, respectively. For the momentum budget calculation, \(z''\) and \(z'\) are respectively set as 20 and 500 m in height to explore the near-surface winds diagnostically. The lower height corresponds to the lowest model level, and the highest height is broadly consistent with the MABL height.

Fig. 6. As in Fig. 5, but for (a) upward latent heat flux difference (W m\(^{-2}\)), (b) sensible heat flux difference (W m\(^{-2}\)), (c) diabatic heating rate difference at 1000-hPa level (K day\(^{-1}\)), and (d) diabatic heating rate difference along 34°N (K day\(^{-1}\)).
Our results reveal that the westerly wind anomalies are dominated by the vertical mixing term (Fig. 9d), which reflects the downward transfer of westerly component momentum owing to the monsoonal westerly component aloft in summer. This results in the acceleration of surface westerly winds. The pressure gradient term is toward the north over the coastal warming area (Fig. 9a), indicating the wind response to the negative SLP anomalies attributable to the coastal warming. In contrast, the Coriolis term is toward the south (Fig. 9b) over the coastal warming area, and acts to cancel the pressure gradient-driven flow because of the identical amplitude compared with the pressure gradient term (Fig. 9c).

4. Kanto district warming linked to the Kuroshio LM path via a local greenhouse effect

A close look at Fig. 10a reveals significant warming on the Pacific coast of Kanto and Tokai districts, which is attributable to the coastal warming off Kanto–Tokai district. Here we...
investigate the remote impact of coastal warming on summer climate in Kanto district, where the megacity Tokyo is located and 40 million people live.

In Kanto district (KD; a land area surrounded by a blue line in Fig. 10a), the SAT in the CTRL run is 0.61°C warmer than in the COLD run. The SAT increase could be attributable to two processes: 1) horizontal temperature advection in the lower troposphere and 2) net radiation heating at the surface. Figure 10b displays the difference in horizontal temperature advection at the surface between the CTRL and COLD runs. Positive anomalies can be observed in the Pacific coastal regions, including Kanto district, but are not significant. We checked that the results were similar at other heights. In contrast, the net radiation at the surface [i.e., the sum of net shortwave radiation flux and net longwave radiation (LWR) flux] shows significant positive anomalies in the Pacific coastal regions, including Kanto district (Fig. 10c), which are collocated with the SAT pattern in Fig. 10a. By comparing the four components of net radiation (Fig. 11), it is found that the downward LWR (Fig. 11a) has the largest amplitude, and which also has a spatial pattern similar to the net radiation, with an amplitude that increases toward the Pacific coast. The downward LWR is responsible for the determination of net radiation. The increase in downward LWR in the KD is 3.3 W m⁻². Previous studies have noted that solar heating has an essential role in the summer SATs over Japan (e.g., Yasunaka and Hanawa 2006), but the solar radiation response to coastal warming is incoherent in our simulation (Fig. 11c), which is consistent with the incoherent cloud responses over Japan to coastal warming (Fig. 7).

Changes in downward LWR at the surface largely reflect cloudiness and water vapor in the atmosphere. The changes in cloudiness were incoherent over Kanto district. Accordingly, we focus on the water vapor [i.e., total precipitable water (TPW)]. A comparison between the CTRL and COLD runs shows significant increases in TPW in Kanto–Tokai district (Fig. 12a), which are more prominent on the Pacific coast side. The increase in TPW in KD is 2.3 mm. These spatial features are very similar to that in the downward LWR difference in Fig. 11a. Qualitatively, it appears that the increase in TPW induces the increase in downward LWR at the surface, resulting in the increase in SATs in Kanto district.

We attempt to quantitatively evaluate the influence of TPW on the downward LWR and SAT based on a diagnosed approach. We adopt the approach for clear sky proposed by Allan et al. (2004) because our simulation showed an incoherent cloudiness response to coastal warming. We confirmed that identical results to Fig. 11a were obtained from the clear-sky LWR in our simulation (not shown). In the diagnostic calculation, July-mean values averaged within the KD in the CTRL run are set as a basic state: SAT = 299 K, TPW = 47.7 mm, and downward LWR at surface = 402.2 W m⁻². Given the TPW difference between the two runs (2.3 mm), the diagnosed increase in downward LWR is about 2.3 W m⁻², and these conditions result in an increase in SAT of about 0.43 K. The diagnosed LWR and SAT responses to the TPW increase are about 60% and 70% of the simulated results (3.3 W m⁻² and 0.61 K), respectively. It is apparent that the TPW is primarily responsible for the SATs in Kanto district.

To assess how is the water vapor (i.e., TPW) is supplied to Kanto district, we calculate the water vapor flux (WVF) from the 3-hourly model output as follows (e.g., Smith et al. 2010):

$$\text{water vapor flux} = \frac{1}{g} \int_{P_{\text{top}}}^{p} q \frac{du}{dp} \, ,$$

where $q$ is the specific humidity, $p$ is the pressure, $P_{\text{top}}$ is the surface pressure, $P_{\text{top}}$ is set as 100 hPa, $u$ is the horizontal wind vector, and $g$ is the acceleration due to gravity. As expected, the WVF converges over Kanto–Tokai district (Fig. 12b), and its spatial features closely resemble that of the water vapor in Fig. 12a. The increase in water vapor in Kanto district results...
from a change in water vapor distribution and/or change in wind circulation. Water vapor transport occurs at various altitudes, and it is expected that the dominant altitude would differ at each location. We try to extract the wind circulation pattern that controls the water vapor transport by adopting a weighted average, as follows (e.g., Ito 2019):

$$v_m = WVF \cdot TPW^{-1},$$  \hspace{1cm} (5) 

where $v_m$ is the mean-transport wind with WVF weighted by the TPW. Equation (5) is represented in each run as follows:

$$(WVF)_{CTRL} = (v_m)_{CTRL} \cdot (TPW)_{CTRL},$$  \hspace{1cm} (6) 

$$(WVF)_{COLD} = (v_m)_{COLD} \cdot (TPW)_{COLD}. \hspace{1cm} (7)$$

Then, by taking the difference between Eqs. (6) and (7) we obtain

![Fig. 9](image-url)
\[
\text{(WVF)} = \text{(WVF)}_{\text{CTRL}} - \text{(WVF)}_{\text{COLD}}
\]
\[
= (\text{TPW})_{\text{CTRL}} \cdot \mathbf{v}_m' + \text{TPW} \cdot (\mathbf{v}_m'_{\text{CTRL}} - \text{TPW} \cdot \mathbf{v}_m'),
\]

where the prime denotes the difference between the CTRL and COLD runs. Equation (8) shows that the WVF difference can be mainly separated into two terms. On the right-hand side, the first term represents a contribution from changes in mean-transport wind circulation, and the second term represents that from changes in water vapor distribution. We refer to these two terms as the wind circulation and water vapor terms, respectively. Here, the third term is negligible since its magnitude is \(O(10^{-2})\). The wind circulation term (Fig. 13a) shows westerly components above the coastal warming area, which blow into Kanto district. In addition, southeasterly components are observed around the east of the coastal warming area. These spatial patterns are similar to the near-surface wind pattern in Fig. 8a. The wind circulation term has a large amplitude off Kanto district. The water vapor term (Fig. 13b) reveals clear southwesterly components attributable to the summertime prevailing winds, showing large values over Kanto district, which are comparable to the wind circulation term; 4.36 kg m\(^{-2}\) s\(^{-1}\) for the water vapor term and 4.21 kg m\(^{-2}\) s\(^{-1}\) for the wind circulation term in KD.

These results indicate that the combination of low-level wind circulation changes and increase in water vapor attributable to the coastal warming off Kanto–Tokai district leads to water vapor convergence over Kanto district. This causes the increase in downward LWR at the surface and the surface air warming in response to a local greenhouse effect.

5. Observational evidence of hot summers in Kanto district attributable to the Kuroshio LM path

a. Large SAT increase in Kanto district attributable to the Kuroshio LM path

Our simulation revealed that the coastal warming off Kanto–Tokai district attributable to the Kuroshio LM path leads to a SAT increase in KD of \(-0.6^\circ\)C. To evaluate the simulated warming, we compare it with the observed anomaly during the present LM event. Figure 14 displays summertime SAT anomalies for the latest LM event. The anomalies are different from mean values during the non-LM period of 2006–16, as in imposed SST in our simulation. During the latest LM event, the summertime climate has been affected by various phenomena. For example, Japan experienced an unprecedented heat wave with record-high the coastal warming region with a SST anomaly > 2°C, which was set in the simulation. Black dots indicate regions exceeding a 90% confidence limit. The gray dashed line indicates a contour of altitude = 1000 m. (b),(c) As in (a), but for horizontal temperature advection at the surface (K s\(^{-1}\)) and downward net radiation flux at the surface (W m\(^{-2}\)), respectively.

\[\text{FIG. 10. (a) Difference in SAT (°C) between the CTRL and COLD runs (CTRL minus COLD; as in Fig. 5a, except the ocean is masked). The area surrounded by the blue line represents Kanto district (KD; the land area bounded by 34.9°–36.0°N, 139.4°–140.8°E). The yellow-colored area indicates} \]

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temperatures in July 2018 (Imada et al. 2019), and record-heavy rainfall and record-low sunshine durations due to the active mei-yu–baiu front in July 2020, resulting in low temperatures (JMA 2020). Nevertheless, the SAT fields during the latest LM path period show large positive anomalies around Kanto district of $0.4^\circ\text{C}$ in KD. This is the same order of amplitude as the simulated LM-induced warming. This indicates that the Kuroshio path can significantly impact the summer climate in Kanto district.

b. Coastal warming versus teleconnection and climate patterns

We revealed the significant impacts of coastal warming off Kanto–Tokai district on summer SATs in Kanto district through SST sensitivity experiments. To verify the model result, we examine its relationship with an observational dataset. Figure 15a displays a map of correlation coefficients between SST off Kanto–Tokai district (green dot in the lower panel in Fig. 15a) and SATs from weather station/AMeDAS data in summer. Significant relationships are concentrated predominantly in the Pacific coast of Kanto and Tokai districts, which is consistent with our simulated results (Fig. 10a). Numerous studies have noted that various atmospheric teleconnection patterns and El Niño events affect the summertime SATs over Japan. We attempt to identify the significance of the oceanic impact on the summer climate of Japan by comparisons with teleconnection patterns and El Niño. The PJ pattern is significantly correlated with the SATs in eastern Japan (Fig. 15b), and El Niño shows a significant relationship in western Japan (Fig. 15f), but these have little effect on the climate in Kanto and Tokai districts. For the WJ, EJ1, and EJ2 patterns, there are hardly any significant signals during this
period (Figs. 15c–e). These observational results highlight us the uniqueness of the Kuroshio path changes on the summertime climate variability on the Pacific coast of Kanto and Tokai districts, which supports our simulation results.

6. Discussion

Our experiments showed that the change in downward LWR at the surface associated with the water vapor change is the dominant influence on the summertime SATs in Kanto district. It is known that the LWR at the surface has diurnal variations, such as upward LWR (radiative cooling) during nighttime. We examine the diurnal sensitivity to the LM-induced coastal warming off Kanto–Tokai district in our experiments. Figure 16 displays the diurnal difference in SATs between the two runs in Kanto district, as a function of Japan standard time (UTC +9 h). A diurnal variation is evident, with a high sensitivity of 0.7°C from midnight to early morning and low sensitivity during the day (0.4°C). This indicates that the daily minimum SAT tends to increase during the LM path.

![Fig. 12](image12.png)

**Fig. 12.** As in Fig. 10, but for (a) TPW (mm) and (b) WVF convergence (mm s⁻¹).

![Fig. 13](image13.png)

**Fig. 13.** (a) Wind circulation term and (b) water vapor term (arrows). The shading denotes its magnitude (kg m⁻¹ s⁻¹). The area surrounded by the yellow line is KD. The orange dashed line indicates a contour of SST difference = 2°C, which was set in the simulation.
periods, which would be caused by the reduced radiative cooling associated with the increased water vapor. The temporal resolution of the SST data used in our experiments is daily, and the effects of diurnal SST variation on the regional climate remains unclear. Some studies denoted that the diurnal SST variation in some coastal regions has a large amplitude [see the review of Kawai and Wada (2007)]. For example, the diurnal SST amplitude is as large as $5.5 \pm 8$ C in Tokyo Bay in summer (Oda and Kanda 2009). Ocean assimilation models have improved and progressed dramatically in recent years, and have a temporal resolution of 30 min and 1 h with a spatial resolution of 1–2 km. These new assimilated SST data should help us in the future to quantitatively assess the influence of LM-induced coastal warming on the regional climate.

7. Summary and concluding remarks

The westward Kuroshio bifurcation induces coastal warming off Kanto–Tokai district during LM periods, with SST anomalies of $1.5^\circ$–$3.5^\circ$C during the latest LM path period of 2017–20, compared with the non-LM path period of 2006–16. We conducted an atmospheric response sensitivity experiment to the idealized SST with a maximum amplitude of $3^\circ$C that represents the coastal warming. Our regional atmospheric model experiments revealed that the summertime coastal warming off Kanto–Tokai district attributable to the Kuroshio LM path heats the MABL both directly and locally through a large upward heat release, which then increases the water vapor in the MABL through enhanced evaporation from the ocean. A momentum budget analysis showed that the coastal warming leads to the acceleration of westerly winds in the near-surface atmosphere via a vertical mixing process, owing to the presence of monsoonal westerly winds aloft in summer, and to the development of easterly/southerly winds blowing into Kanto district due to a combination of a pressure adjustment process and Coriolis force in the east of the warming area. Furthermore, our simulations and supplementary observational studies revealed the significant remote impacts of coastal warming on summertime SATs in Kanto district. The Kanto district was $0.6^\circ$C warmer due to coastal warming, which is similar to the observed SAT anomalies during the latest LM period ($+0.4^\circ$C than the non-LM periods of 2006–16), even though the observations include effects other than the LM. This indicates that the Kuroshio path state has a significant impact on the summer climate in Kanto district. A SAT increase results from a combination of the low-level wind circulation changes and increase in water vapor attributable to coastal warming off Kanto–Tokai district. This leads to the water vapor convergence over Kanto district, resulting in an increase in downward LWR at the surface and then surface air warming due to a local greenhouse effect. Atmospheric teleconnection patterns and El Niño events have no significant impacts on the SATs in Kanto district, which also highlights the uniqueness of the Kuroshio path state on the summertime climate variability in Kanto district.

Kanto district, including Tokyo, is one of the 37 megacities in the world and has 40 million inhabitants. Its summer climate is characterized by high temperature and humidity that lead to discomfort for its inhabitants. Our experiments showed that the climate in Kanto district becomes hotter and more humid because of the Kuroshio LM path. We attempt to provide an additional perspective on the impacts of Kuroshio on the summer climate in Japan in terms of discomfort information. Here, as an indicator of discomfort, we use a modified version for Japanese climate (Kinouchi 2001;
Table 1) of Thom’s index (Thom 1957, 1959), based on the basic environmental parameters SAT and relative humidity. The mean state in the CTRL run yields remarkably high discomfort values in Kanto district (Fig. 18a). To examine the influence of the Kuroshio on the discomfort in further detail, we count the days that the daily maximum discomfort index exceeds 80 (i.e., most inhabitants feel discomfort). As expected, the difference between the two runs is remarkable in Kanto district, and is 13.1 days in the CTRL run, which is 160% greater than that in the COLD run (8.1 days; Fig. 18b). The Kuroshio path state is responsible for the climatic comfort of living in Tokyo, Japan.
In the summer of 2017, the Kuroshio took the LM path, and this event is ongoing as of January 2021. The establishment of a general and regional framework that describes how LM-induced coastal warming drives the atmosphere could greatly improve weather and seasonal forecasting. Our approach is also applicable in other coastal cities worldwide.

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<thead>
<tr>
<th>Condition</th>
<th>DI range</th>
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<tbody>
<tr>
<td>No discomfort</td>
<td>&lt;70</td>
</tr>
<tr>
<td>&lt;50% of the population feels discomfort</td>
<td>70–74</td>
</tr>
<tr>
<td>&gt;50% of the population feels discomfort</td>
<td>75–79</td>
</tr>
<tr>
<td>Most of the population feels discomfort</td>
<td>80–84</td>
</tr>
<tr>
<td>Everyone feels severe stress</td>
<td>&gt;85</td>
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Fig. 18. (a) July-mean discomfort index from the CTRL run. (b) Difference in days of discomfort index &gt; 80 between the CTRL and COLD runs. The area surrounded by the black line represents KD.

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REFERENCES


Kosaka, Y., and H. Nakamura, 2010: Mechanisms of meridional teleconnection observed between a summer monsoon system