Cloud Response to the Meandering Kuroshio Extension Front^{*,†}

HIROYUKI TOMITA

Hydrospheric Atmospheric Research Center, Nagoya University, Nagoya, Japan

SHANG-PING XIE

Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, and International Pacific Research Center, University of Hawai'i at Mānoa, Honolulu, Hawaii

HIROKI TOKINAGA

International Pacific Research Center, University of Hawai'i at Mānoa, Honolulu, Hawaii

YOSHIMI KAWAI

Research Institute for Global Change, Japan Agency for Marine and Earth Science Technology, Yokosuka, Japan

(Manuscript received 7 March 2013, in final form 26 June 2013)

ABSTRACT

A unique set of observations on board research vessel (R/V) *Mirai* in April 2010 captured a striking cloud hole over a cold meander of the Kuroshio Extension (KE) east of Japan as corroborated by atmospheric soundings, ceilometer, shipboard radiation data, and satellite cloud images. Distinct differences were also observed between the warm meander farther to the north and warm water south of the KE. The atmosphere is highly unstable over the warm meander, promoting a well-mixed marine atmospheric boundary layer (MABL) and a layer of solid stratocumulus clouds capped by a strong inversion. Over the warm water south of the KE, MABL deepens and is decoupled from the ocean surface. Scattered cumulus clouds develop as captured by rapid variations in ceilometer-derived cloud base. The results show that the meandering KE front affects the entire MABL and the clouds. Such atmospheric response can potentially intensify the baroclinicity in the lower atmosphere.

1. Introduction

Sharp sea surface temperature (SST) fronts and intense heat release to the atmosphere are defining features of the Kuroshio–Oyashio Extension (KOE), with significant climatic impacts over the North Pacific (e.g. Nakamura et al. 1997). A steep thermal contrast across the SST front intensifies the near-surface baroclinicity, anchoring the

storm track and zonally elongated rainfall/cloudiness band (Nakamura et al. 2004; Taguchi et al. 2009; Tokinaga et al. 2009). Such association between the oceanic frontal zone and atmospheric circulations is robustly observed not only in the time-mean fields but also on interannual-to-decadal time scales (Tanimoto et al. 2003; Taguchi et al. 2012). Detecting the KOE influence on synoptic time scales is hampered, however, by strong weather disturbances and poorly sampled in situ and satellite measurements (Tokinaga et al. 2006). As a result, few observational studies provide direct evidence that the KOE SST plays a role in synoptic weather system, limiting the physical understanding of high-frequency air–sea interaction processes over this region. Given the SST influence on the extratropical cyclones traveling basinwide, it remains an important task to identify observational evidence for and explore how the SST fronts interact with the overlying atmosphere on synoptic time scales.

*Supplemental information related to this paper is available at the Journals Online website: <http://dx.doi.org/10.1175/JCLI-D-13-00133.s1>.

†International Pacific Research Center Contribution Number 1008 and School of Ocean and Earth Science and Technology Contribution Number 9000.

Corresponding author address: Hiroyuki Tomita, Hydrospheric Atmospheric Research Center, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan.
E-mail: tomita@hyarc.nagoya-u.ac.jp

Previous studies have focused on the climatological or long-term-mean fields over the KOE after suppressing the weather noise with temporal averaging (Nonaka and Xie 2003; Liu and Xie 2008; Tokinaga et al. 2009; Tanimoto et al. 2011). The present study rather shows a “snapshot” to investigate quick atmospheric response to SST fronts on daily time scales. Although there is a few pioneer observational studies that attempted to observe quick atmospheric response to SST fronts (Tokinaga et al. 2006; Tanimoto et al. 2009), here we present a suite of unique shipboard observations from radiosonde soundings, ceilometer, and surface radiative and turbulent heat fluxes during a 1.5-day cruise survey by research vessel (R/V) *Mirai* of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in a different season. To our knowledge, this observational campaign is the first to capture a clear signature of the Kuroshio Extension (KE) front’s imprint on clouds and the marine atmospheric boundary layer (MABL) under less influence from weather disturbances.

2. Field observations

The shipboard survey was conducted over the KE and its recirculation on board R/V *Mirai* during 8–9 April 2010. All observations were performed along a ship track connecting between two Kuroshio Extension Observatory (KEO) buoy sites: one operated by National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory (32.4°N, 144.6°E; Cronin et al. 2008) and another operated by JAMSTEC (JKEO; 38°N, 146.5°E; Konda et al. 2010) (Fig. 1). R/V *Mirai* sailed southward from the JKEO site at 0730 UTC 8 April, passed across the main KE front at 0100 UTC 9 April, and reached the KEO site at 1730 UTC 9 April 2010. A total of 18 global positioning system (GPS) radiosondes were launched along the ship track at 0.25°–0.5° latitude intervals (~1.5-h intervals) within the 1.5-day cruise. R/V *Mirai* also provides continuous, along-track measurements of SST, surface air temperature T_a , humidity, surface wind, cloud-base height (by a ceilometer), and surface radiation with high temporal resolutions, enabling us to study cross-frontal variations of surface heat flux and vertical development of MABL.

These in situ measurements are compared with four satellite-based datasets: a visible image from the Multifunctional Transport Satellite (MTSAT); SST from the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) (Wentz and Meissner 2000); sea surface height (SSH) from the Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) (Ducet et al. 2000); and surface wind from the Cross-Calibrated Multiplatform (CCMP) surface vector

FIG. 1. Synoptic conditions of ocean and atmosphere during the cruise, 8–9 Apr 2010: SSH (color shading in cm) from satellite altimeter product of AVISO; and SLP (contours at 1-hPa intervals) from the NCEP–NCAR reanalysis. Locations of KEO–JKEO buoys (red circles) and radiosonde sounding sites (arrowheads) are superimposed.

wind product (Atlas et al. 2008). Sea level pressure (SLP) from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) is also used.

3. Results

a. Near-surface changes

Figure 1 displays SSH from satellite altimeters and SLP from NCEP–NCAR reanalysis during the cruise, overviewing the synoptic condition of the ocean and atmosphere. Against the climatological field in April characterized by weak westerly or southwesterly winds, an atmospheric high pressure system appears east of Japan, leading to stable weather conditions and moderate northeasterly to southeasterly winds over the KOE region during the cruise. Even the observations were conducted over a short period (1.5 days); the surface high pressure propagates eastward. As a result, synoptic surface wind changes from northeasterly to southwesterly during the cruise period. From the oceanic viewpoint, SSH observations reveal a rich structure of the meandering KE front. Reaching to the JKEO site, a warm meander branches northwestward from the main stream of KE current. The warm recirculation gyre is centered at 33.5°N, 144.5°E, encircling the KEO site. Sandwiched by the two warm regions, the cold water intrudes from the northwest, forming a SSH minimum around 35°N, 145.5°E. This mesoscale SSH tripole suggests a warm–cold–warm SST pattern along the ship track.

The three distinct oceanic regimes are actually identified by the continuous SST measurement by R/V *Mirai* (Fig. 2a). The sharp KE front is observed between 34.8° and 34.6°N with a SST gradient exceeding 5°C per 30 km. The T_a also shows a local maximum of meridional gradient near the KE front but increases southward more smoothly than SST, a gradual change almost like a function of latitude. As a result, a near-surface stability, measured by air–sea temperature difference, is relatively stronger over the cold meander than over warm SST regions. This KE-induced stability change is important for the atmospheric vertical mixing, possibly playing a role in surface wind divergence and convergence (Chelton et al. 2004; Xie 2004).

Air–sea turbulent flux is a key parameter to mediate the interaction between the KE and MABL. From the synoptic weather pattern during the cruise, it is expected that northeasterly transports cold air mass from north to south across the oceanic front and it tends to enhance surface upward flux. The warm meander and northeasterly induced cold advection enhance upward turbulent heat flux [$\sim(300\text{--}600)\text{ W m}^{-2}$] over the warm meander north of the KE front, as well as large variance of high-frequency fluctuations due to the unstable near surface (Fig. 2b). Over the cold meander, on the other hand, the turbulent heat flux decreases to 200 W m^{-2} with suppressed high-frequency variance. And then, it sharply increases southward by about 300 W m^{-2} across the KE front, strengthening a meridional contrast in surface heating.

b. Cloud response

Figure 3a shows the latitude–height section of potential temperature θ and relative humidity (RH) from radiosonde soundings along the ship track. Overall, a well-defined MABL, characterized by vertically uniform θ , develops up to 1.5–2 km deep capped by a strong temperature inversion, consistent with previous observational studies (Tokinaga et al. 2006, 2009). RH reaches 100% below the temperature inversion, suggesting a cloud layer between 1 and 1.5 km.

Besides the overall features, ceilometer and radiosonde soundings exhibit distinct changes in vertical MABL structure in response to the different oceanic regimes (Figs. 3a,b). Over the warm meander north of 35°N, the well-mixed MABL is capped by a relatively thin cloud layer with a thickness of a few hundred meters. Over the warm recirculation region south of the KE front, by contrast, a decoupled MABL with shallow convection and cumulus is observed. Between the surface mixed layer and inversion, significant vertical gradients develop in θ (Figs. 3 and supplemental Fig.S1). The cloud base derived from the ceilometer jumps rapidly between 1.0 and 1.8 km in this decoupled layer: the variability is indicative of convective cumulus.

FIG. 2. Along-track sections of (a) SST and surface air temperature T_a , (b) air–sea turbulent heat flux, and (c) downward short and long wave radiations. Arrows in (a),(b) indicate synoptic surface wind vectors from NCEP–NCAR reanalysis.

The most striking is a cloud hole over the cold meander with a horizontal scale of 50 km, sandwiched between cloudy regions over the warm SSTs. The ceilometer shows no backscatter from the cloud base in 34.6°–35°N (Fig. 3b), supported by radiosonde soundings showing RH less than 80% at 1.2–1.5 km high in the same region (Fig. 3a). Superimposed on the diurnal cycle, the short-wave radiation drastically increases near the cloud hole

FIG. 3. Along-track vertical sections of (a) relative humidity (color shading in %) from radiosonde soundings and (b) backscatter from cloud base [color shading in $(1000 \text{ srad km}^{-1})$] from ceilometer. Potential temperature (contours at 1-K intervals) from radiosonde soundings is superimposed on both panels. Locations of radiosonde soundings are indicated as triangles. Cloud-base heights detected by ceilometer are indicated as black dots in (a).

(Fig. 2c). Although the most part of the increase may be due to the diurnal cycle, it appears to be influenced by the cloud hole because it drastically decreases to the north and south because of cloudy regimes over the warm SSTs. The downward longwave radiation, which is mostly radiated from cloud base, also shows a sharp drop under the cloud hole, consistent with the ceilometer and radiosonde observations.

MTSAT clearly captured a visible image of this cloud hole around 35°N, 145°E at 0000 UTC 9 April 2010 (H1 in Fig. 4). As observed by radiosonde soundings, stratocumulus dominates north of the cloud hole while scattered cumulus to the south. Another larger cloud hole is found around 35.5°N, 148°E (H2 in Fig. 4), sandwiched by stratocumulus regions to the west and east. Interestingly, the pattern of cloud patches closely resembles the shape of the KE meander observed by AMSR-E 3-day-mean SST field. Although the spatial structures of the KE meander may be smoothed by the limit of spatial and temporal resolutions, a closer look shows that both cloud holes, H1 and H2, form slightly downwind of the cold meander, where the SST gradient shows a local maximum. Indeed, the meridional gradient of θ locally intensifies in the entire MABL underneath

the H1 cloud hole, suggesting the KE front influence there (Fig. 3). These cloud holes developed at the almost same locations from 2300 UTC 8 April to 0200 UTC 9 April 2010 (not shown), implying their formation mechanism localized by the relatively persistent KE front.

c. Possible mechanism for cloud holes

As illustrated in previous studies (Chelton et al. 2001, 2004; O'Neill et al. 2003, 2005; Chelton and Xie 2010), the meandering SST front generates patches of surface wind divergence and convergence as an ocean imprint. When the easterly winds blow across the cold-to-warm (warm-to-cold) SST front, the longitudinal acceleration (deceleration) leads to surface wind divergence (convergence) through enhanced (suppressed) atmospheric vertical mixing over the warm (cold) SST (Sweet et al. 1981; Wallace et al. 1989). As illustrated in previous studies, in our case, surface wind divergence and convergence calculated from the CCMP surface vector wind data also reveal the oceanic frontal change. The H1 cloud hole is clearly accompanied by surface wind divergence over the downwind cold-to-warm SST gradient that possibly brings dry air from above the MABL (see supplemental Fig. S2). The H2 cloud hole is also observed

FIG. 4. Satellite visible image of MTSAT at 0000 UTC 9 Apr 2010. The 3-day-mean AMSR-E SST (orange contours of 17°, 17.5°, 18°, and 18.5°C) is superimposed. The locations of R/V *Mirai* (triangle) and its cruise track (dashed line) connecting JKEO and KEO (circles) are also indicated. The green lines labeled H1 and H2 point to the cloud holes.

over surface wind divergence while slightly displaced to the east (Fig. S2). Likewise, the well-organized stratocumulus deck north of the H1 cloud hole may be in part explained by strong surface wind convergence over the downwind warm-to-cold SST gradient.

4. Summary and discussion

The present study has presented a successful case capturing the quick response of clouds and MABL to the meandering KE front. Distinct oceanic and atmospheric changes were robustly observed over the KE and its recirculation by a unique set of in situ measurements including radiosonde soundings and continuous air–sea flux variables and cloud base by ceilometer on board R/V *Mirai*. Over the warm meander north of the KE front, upward turbulent heat flux enhanced and the well-mixed MABL developed up to 1.5 km high, capped by a deck of stratocumulus a few hundred meters thick. Over the warm recirculation, by contrast, the deepened MABL was decoupled from the ocean surface, with scattered convective cumulus clouds. This decoupled feature in MABL might be related to both of an active surface heating and a forming of the mixed layer over

the warm recirculation. Over the cold meander, a striking cloud hole developed with a width of 50 km, suggesting a descending flow of dry air locally generated by the KE front.

The cloud hole (H1), as well as another one farther to the east (H2), possibly resulted from surface wind divergence slightly west of the cold meander. We speculate from a series of observations that cross-frontal changes in atmospheric vertical mixing may be responsible for the surface wind divergence. On one hand, the SLP adjustment may be an alternative mechanism (Lindzen and Nigam 1987). Small et al. (2003) with a regional atmospheric model simulation suggest that easterly induced horizontal advection leads to the occurrence of high and low SLP downwind of the cold and warm SST patches, respectively. Such advection effects may similarly cause surface wind divergence above the cold-to-warm downwind SST gradient. Moreover, in contrast to the geostrophic adjustment process, an ageostrophic process with secondary vertical flow may be noted. Further observations and simulations would be needed for clarifying which mechanism dominates, but both mechanisms underline the importance of the sharp SST front.

Our results have implications for the development of extratropical cyclones along the KE front. Nakamura et al. (2004) proposed an “oceanic baroclinic adjustment” over the subarctic frontal zone, in which meridional contrast in surface heating can effectively restore the Ta gradient toward the underlying SST gradient and thus intensify atmospheric baroclinicity in the lower atmosphere. While their mechanism emphasizes a direct heating by surface sensible heat flux, the quick cloud response presented in this study suggests that ocean controls a strong latent heating by a cloud forming–deforming at the top of MABL across the KE front. Such cloud response to the KE front may play an additional role in restoring the atmospheric baroclinicity and developing the extratropical cyclones.

Acknowledgments. We thank Mr. Wataru Tokunaga and Mr. Ryo Kimura in Global Ocean Development Inc. for obtaining and processing observational data from R/V *Mirai*. MTSAT data were obtained from the Center for Environmental Remote Sensing, Chiba University. Satellite-derived sea surface height data were obtained from Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO).

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