Influence of the Kuroshio on Mesoscale Convective Systems in the Baiu Frontal Zone over the East China Sea

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DOI: 10.1175/MWR-D-15-0139.1

ABSTRACT

Two mesoscale convective events in the baiu frontal zone (BFZ) were documented, based on intensive atmospheric soundings and oceanic castings in the East China Sea during May 2011, in addition to continuous surface meteorological observations, satellite products, and objective analyses. These events occurred while the BFZ was nearly stagnant and a mesolow was deepening in the zone. Near-surface southerlies associated with the low-level jet transported a warm, humid air mass from south of the BFZ. Enhanced evaporation, which was mainly attributable to the high sea surface temperature of the Kuroshio, augmented the moisture content of the air mass and helped maintain a convectively unstable stratification in the lower troposphere around the BFZ.

1. Introduction

The baiu frontal zone (BFZ) is a quasi-stationary precipitation band that typically occurs over East Asia and the northwestern Pacific in early summer (e.g., Akiyama 1973; Chen and Chang 1980; Kodama 1992; Yihui and Chan 2005; Ninomiya and Shibagaki 2007). The BFZ provides much needed rainfall that supplies precious water to a broad region of East Asia (Kuwano-Yoshida et al. 2013), but sometimes brings heavy rain that causes local disasters such as floods and mudslides (e.g., Ogura et al. 1985; Kato 1998; Davidson et al. 1998; Manda et al. 2014). Because of its socioeconomic impacts, the BFZ is regarded as one of the most important climatic phenomena in East Asia (Sampe and Xie 2010). The BFZ can be identified by sharp gradients of specific humidity and equivalent potential temperature ($\theta_e$; Ninomiya 1984) and a horizontal wind shear line (Akiyama 1973).

BFZ structures are multiscale, from meso to synoptic, and mutual interactions among structures of various scales are believed to be essential to the development and maintenance of the zone (Moteki et al. 2004a,b, 2006; Ninomiya and Akiyama 1992). Frequent development of mesoscale convection within the BFZ is one of its most important characteristics (Moteki et al. 2004a,b, 2006; Ninomiya and Akiyama 1992; Ninomiya and Shibagaki 2007).

Moteki and Manda (2013) showed a close relationship between seasonal BFZ migrations and sea surface
temperature (SST) in the East China Sea, on both climatological and synoptic time scales. This relationship implies that surface heat fluxes in the East China Sea affect BFZ seasonal migration. In addition, Kuwano-Yoshida et al. (2013) demonstrated by a suite of numerical experiments using global climate models that surface evaporation from the warm ocean is important for maintenance of the quasi-stationary BFZ.

The Kuroshio, one of the most prominent ocean currents in the world, flows along the shelf edge in the East China Sea (e.g., Ichikawa and Beardsley 2002) and carries a vast amount of heat from the tropics to mid-latitudes. It is one of the main controls of SST distribution in the East China Sea. Sasaki et al. (2012) used satellite observations, reanalysis data, and numerical experiments to examine the influence of the Kuroshio on the baiu rainband. They reported that strong surface evaporation and surface wind convergence associated with local SST maxima along the Kuroshio strengthened baiu precipitation over the East China Sea.

Most studies of air–sea interaction in the East China Sea have been based on numerical models, satellite data products, or model-based reanalysis. In situ atmospheric vertical soundings over the East China Sea have been lacking. Models and products should be validated using in situ data. In particular, mesoscale convective systems, structure of the marine atmospheric boundary layer, and detailed SST distributions around the Kuroshio have not been fully resolved by the models and model-assimilated products, or validated by previous studies. Sasaki et al. (2012) concluded that vertically and temporally high-resolution, in situ observations are needed for further understanding of convective processes and resultant adjustment in the marine atmospheric boundary layer.

In the extratropics, because the influence of SST on the marine atmospheric boundary layer is relatively modest compared with internal atmospheric variability, such a relationship is difficult to detect (e.g., Kushnir et al. 2002). To our knowledge, very few studies have made simultaneous high-resolution atmospheric soundings and oceanic castings, such as are necessary to detect the effect of the Kuroshio on the BFZ in the East China Sea (Kunoki et al. 2015). Therefore, during a study cruise from 22 to 23 May 2011, we made simultaneous atmospheric and oceanic measurements along the Kuroshio front in the East China Sea to examine the impact of SST on the marine atmospheric boundary layer and BFZ mesoscale convection. This cruise offered an excellent opportunity to deepen understanding of the effect of the Kuroshio on the BFZ. Minobe et al. (2015) showed that the relatively weak signals of midlatitude air–sea interactions are most detectable in phenomena with spatial scales on the same order as that of the SST front. Therefore, to resolve atmospheric and oceanic phenomena at the horizontal scale of the Kuroshio SST front in the East China Sea (~100 km), we chose a sampling interval of ~20 km. During the period of the cruise, we detected two intense mesoscale convection events along the BFZ. Here, we examine the evolution of these events and show how enhanced evaporation, by increasing the water vapor content of the lower troposphere, helps maintain the convectively unstable stratification in the BFZ.

In section 2 we describe the field campaign and datasets and methods used. In section 3, we present the synoptic atmospheric conditions, and in section 4 we describe the frontal structures and convective events associated with the BFZ during the study period. In section 5, we discuss oceanic influences on the BFZ and, in particular, the importance of evaporation and moisture supply to the lower troposphere. Section 6 is a summary and discussion.

2. Observations, data, and methods

The field campaign on board the training vessel (T/V) Nagasaki-Maru (Nagasaki University, Japan) was conducted in the East China Sea from 21 to 23 May 2011 as part of project “Hot Spot in Climate System: Coupled Ocean-Atmosphere Variability over Monsoonal Asia due to Contiguosity Between Tropical Warmness and Arctic Coolness,” under the leadership of H. Nakamura of the University of Tokyo. During this campaign, we used global positioning system (GPS) sondes (Meisei RS-06G) for atmospheric soundings, and measured seawater temperature from the surface to depth 760 m by castings of expendable bathythermographs (XBTs; Tsurumi T7) (Fig. 1). Surface air temperature (SAT), surface wind velocity, relative humidity, and SST were measured at 1-min intervals. The T/V Nagasaki-Maru sailed from Okinawa Island and cruised northward, traversing the Kuroshio front. During the cruise, GPS sondes were launched and XBTs were cast at 11 stations between 2100 UTC 22 May (station S0) and 0800 UTC 23 May (station S10). Station S0 was in a high-SST region of the Kuroshio, and station S10 was in a low-SST region of cold shelf water (Fig. 1). Atmospheric soundings at stations S1–S9 were made approximately 1 h apart, and the distance between adjacent stations was about one nautical mile (18.5 km). These sampling intervals allowed resolution of atmospheric and oceanic phenomena with the same horizontal scale as the SST front around the Kuroshio (~100 km) (Kunoki et al. 2015).

We supplemented the in situ data with gridded analyses of precipitation derived from Japan Meteorological Agency (JMA) radar data (JMA 2015a), and Tropical Rainfall
Measuring Mission (TRMM) 3B42 v6 data (Goddard Earth Sciences Data and Information Services Center 2015) to portray precipitation in areas lacking radar precipitation data. We also used visible images derived from JMA’s Multifunctional Transport Satellite (MTSAT) observations. We also used objective analysis data produced by a global climate model and JMA operational nonhydrostatic mesoscale model (henceforth referred to as the global and mesoscale analyses, respectively), provided by JMA (2015b). The global analysis data comprised 6-hourly tropospheric wind velocity, temperature, and relative humidity at the surface, 1000-, 925-, 850-, 700-, 600-, 500-, 400-, and 300-hPa levels on a 0.5° latitude × 0.5° longitude grid. The mesoscale analysis data comprised 3-hourly tropospheric wind velocity, temperature, and relative humidity at the surface, 1000-, 975, 950, 925, 900, 800, 700, 600-, and 500-hPa levels on a 0.1° latitude × 0.125° longitude grid. We also used hourly SAT, wind velocity, humidity, and precipitation forecast by the JMA mesoscale model, which was initialized with the 3-hourly mesoscale analysis data. Saito et al. (2006) described the mesoscale model and its evaluation in detail. The mesoscale analysis domain was 20°–50°N, 120°–150°E. Sounding and surface meteorological data from the cruise were not assimilated in the global and mesoscale analyses.

We used a blended daily satellite SST dataset from the JMA called the Merged Satellite and In Situ Data Global Daily SST (MGDSST) (Kurihara et al. 2006) for analyzing SST fields during the campaign. The MGDSST dataset was also used for the bottom boundary condition of the mesoscale model.

To assess thermodynamic forcing and oceanic influence on the atmosphere around the BFZ, we estimated apparent heat sources and moisture sinks using output of the mesoscale analysis following Yanai et al. (1973)

We estimated latent and sensible surface heat fluxes by bulk aerodynamic equations (Kondo 1975).

To assess the origin of air masses flowing into the areas where the two convective events were observed and the influence of evaporation from the Kuroshio region on the development of convective instability, we conducted a backward trajectory analysis using threedimensional wind data from the mesoscale analysis. To track the air parcels, we used the fourth-order Runge–Kutta method with a 10-min time step to numerically integrate the following equations:

\[
\begin{align*}
\frac{d\theta}{dt} &= R_e^{-1} v_x (\theta, \phi, p, t), \\
\frac{d\phi}{dt} &= (R_e \cos \theta)^{-1} u_x (\theta, \phi, p, t), \quad \text{and} \\
\frac{dp}{dt} &= \omega (\theta, \phi, p, t),
\end{align*}
\]

where \(\theta\) is latitude; \(\phi\) is longitude; \(p\) is pressure; \(t\) is time; \(R_e\) is the radius of the earth; \(u_x\) and \(v_x\) are the eastward and northward components of horizontal wind velocity, respectively; and \(\omega\) is pressure velocity. To assess the evolution of lower-tropospheric stratification, we virtually sampled the output of the mesoscale analysis and MGDSST dataset for air temperature, relative humidity, surface wind, and SST along the backward trajectories.

3. Synoptic conditions

In this section, we describe the synoptic weather conditions that characterized the environment around the time of the two mesoscale convective events detected during the cruise. On the surface weather map at 0600 UTC 23 May 2011 (Fig. 2a), the BFZ extends from the north of Taiwan to the North Pacific, and is characterized by an eastward-oriented pressure trough and a mesolow centered at 30.5°N, 129.5°E. The BFZ remained almost stationary, although the mesolow deepened slightly (Fig. 2b). Satellite images (JMA 2015c; Figs. 2c and 2d) show high-level clouds extending from the South China Sea to the North Pacific along the BFZ. These conditions are typical for the baiu rainy season (e.g., Sampe and Xie 2010).
The distribution of geopotential height in the upper troposphere shows that at 1800 UTC 22 May, the upper jet was directed eastward around 40°N (Fig. 3a). A shortwave trough, indicated by a high potential vorticity (PV) anomaly, was near 37°N, 119°E, at the southern periphery of the jet. By 1200 UTC 23 May, this trough had moved eastward to 37°N, 127°E (Fig. 3b). Marking the BFZ was an east–west band with strong gradient of $\theta_e$ in the lower troposphere (850-hPa level), which was accompanied by a relatively strong PV anomaly (Figs. 3c and 3d). Latitude–height sections of PV averaged zonally over 123°–128°E (Figs. 3e and 3f) show that high-PV air protruded from the upper to lower troposphere. This protrusion indicates a coupling of PV anomalies between the upper and lower troposphere, a phenomenon typical of mesolow development in the BFZ (Tagami et al. 2007). The next section describes the mesoscale convection events under these synoptic conditions.

4. Frontal structure and mesoscale convective systems

In this section, we document the spatiotemporal evolution of convective activity and precipitation, which are important components of the BFZ, along with the observed frontal structure. To supplement the observations, we analyzed the output of the mesoscale analysis.

a. Observations

Figure 4 displays in situ observations along the cruise track. Winds were predominantly southerly at 1500 UTC 22 May (S0), but they began to shift around 2100 UTC 22 May (S1) at heights above 1000 m (Fig. 4a). After 0000 UTC 23 May (S2), they were predominantly westerly. In the lower troposphere, wind speed decreased north of S4, and directions were predominantly westerly. The presence of a cold air mass in the lower troposphere (surface to 500 m) indicated a surface front between S4 and S5.
Surface wind speed gradually increased by \( \sim 3 \text{ m s}^{-1} \) from 1500 UTC 22 May (S0) to 0200 UTC 23 May (S4), as the ship was approaching the surface front (Fig. 4c). Speeds declined rapidly after that, when a shift in wind direction was observed in the lower troposphere (Fig. 4a). This directional shift reflects the passage of the ship across the surface front.

In the lower troposphere (surface to 1000 m), a southerly low-level jet (LLJ; Matsumoto et al. 1971) accompanied by warm, humid air dominated at stations south of the BFZ (around S3). Although the wind speed maximized at heights above 300 m, the surface speed exceeded 10 m s\(^{-1}\) below the LLJ (Fig. 4c).

Latent heat flux gradually increased from 2100 UTC 22 May and exhibited a local maximum near S2 (0000 UTC 23 May), after which it decreased rapidly (Fig. 4c). This decrease corresponded to a rapid decline in the difference between saturated specific humidity...
and specific humidity (Fig. 4d). The difference between SST and SAT was slight near station S2 (0000 UTC 23 May). These results indicate that variation of saturation vapor pressure caused by SST change was the dominant factor in altering surface evaporation, with a modest contribution by surface wind speed.

At most stations, $\theta_e$ exhibited large values in the lower troposphere and decreased with height, a condition that favored convection (Fig. 4b). This $\theta_e$ increased northward from station S1 and had a local maximum around station S4, slightly north of the local maximum of latent heat flux. The high $\theta_e$ region...
around the local maximum extended northward around station S6. The mechanism of these features is discussed later.

A warm water mass (temperature ≥24°C) was observed in the upper ocean at stations south of S4 (Fig. 4e). This water mass, which was >60 m thick at stations S0–S3, corresponds to the Kuroshio, indicating that the high SST associated with the Kuroshio intensified the latent heat flux (Figs. 4c and 4e).

JMA radar and TRMM data showed intense precipitation along the BFZ from 0900 to 1200 UTC 23 May (Figs. 5 and 6). The TRMM data revealed another intense precipitation area along the BFZ around 0300 UTC 23 May (Fig. 6c). These data suggest that two events of intense precipitation occurred along the BFZ during the campaign period.

To obtain a more comprehensive view of these events, we analyzed the output of the mesoscale analysis as a proxy for in situ observations. The frontal structure, precipitation, and convective activity from this analysis are described in section 4b.

b. Objective analysis

Figure 7 shows atmospheric and oceanic fields corresponding to observed fields (Fig. 4) obtained by virtual sampling of the mesoscale analysis output and MGDSST dataset. The mesoscale analysis is broadly consistent with the observed frontal structure, capturing most aspects of the in situ observations. The analysis reproduced the wind field along the cruise track reasonably well. The LLJ south of the surface front was well reproduced. However, changes of surface wind speed in the hourly forecast were less sharp than those of the in situ observations. Differences in winds between observation and forecast may be partly attributed to the model’s lack of skill in reproducing the rapid wind shift around the surface front and to differences in temporal resolution of the two datasets. Kunoki et al. (2015) showed that the relatively smooth SST used in the mesoscale analysis affected sharpness of the atmospheric front produced by the mesoscale analysis.

The overall structure of the observed θe field was reproduced by the mesoscale analysis (Fig. 7b). The θe decreased with height at most stations and had a local maximum slightly north of that of the latent heat flux. The high θe region extended northward from the location of the local maximum. The time series of latent heat flux nearly reflected that of the SST, qualitatively consistent with in situ observation (Fig. 7c). However, the latent heat flux was underestimated compared with the in situ observations, which is discussed later.

Horizontal distribution of latent heat flux from the mesoscale analysis and MGDSST (Fig. 8) show that the high latent heat flux area extended all along the tongue of warm water associated with the Kuroshio. As in situ observation suggests, the LLJ below the 900-hPa level transported warm and humid air in the lower troposphere (Figs. 8 and 9). The θe distribution in the in situ observation and mesoscale analysis described above may be explained by transport of this air from the south by the LLJ and enhanced evaporation over the Kuroshio. The LLJ could have advected the warm, humid air mass, whose water vapor content was augmented by enhanced evaporation over the Kuroshio. This characteristic is further examined by the backward trajectory analysis described in a later section.

Overall, observed rainfall features such as horizontal distribution were reproduced in the forecast (Figs. 5, 6, and 10). The intense precipitation events in the BFZ at 0300 and 0900–1200 UTC 23 May were reproduced reasonably well by the mesoscale analysis (Figs. 10 and 11). The intensity of precipitation was however underestimated compared with the radar observation (Figs. 5, 10, and 11). This underestimation is discussed later. Both precipitation events described above were characterized by strong updrafts, a strong apparent heat source, and moisture sink in the midtroposphere (Fig. 12). These features suggest deep convection during these two events.

Some recent studies have stated that evaporation from the sea surface in the Kuroshio region enhances the formation of convectively unstable air masses, which can produce deep convection (Sasaki et al. 2012; Kuwano-Yoshida et al. 2013; Tsuguti and Kato 2014; Manda et al. 2014; Kunoki et al. 2015). It is well known that water vapor content in the lower troposphere affects convective activity in the BFZ, but the influence of evaporation from warm ocean currents on water vapor content has not been fully examined. The surface meteorological data showed that the warm water around the Kuroshio intensified the latent heat flux. Although somewhat underestimated, this was reproduced by the mesoscale analysis. In the next section, we assess the influence of evaporation from the sea surface in the Kuroshio region on lower-tropospheric stability during the two convective events.

5. Influence of enhanced evaporation over the Kuroshio

The results shown in previous sections illustrate the intensified latent heat flux over the warm water in the Kuroshio region. We examined the influence of this region on intensified latent heat flux during the two convective events through a backward trajectory analysis (Fig. 13).
FIG. 5. Hourly precipitation (colors) measured by JMA radars (mm) at 3-h intervals and SST (contours). Contour interval is 1°C and thick contour lines are isotherms of 24°C, which is an approximate boundary between the Kuroshio and surrounding waters. (a)-(g) From 2100 UTC 22 May to 1500 UTC 23 May 2011. Location of the front at each time was subjectively analyzed using $u_e$ and horizontal wind data at 950-hPa level from mesoscale analysis output. Gray shading indicates where precipitation data were unavailable. Area within the box with dashed lines was used to calculate area averages of precipitation. Squares indicate ship locations.
Fig. 6. As in Fig. 5, but for precipitation of TRMM 3B42 dataset.
In this analysis, all parcels were initiated at the 950-hPa level, where high-$\theta_e$ air masses were observed in situ and reproduced by the mesoscale analysis. The initial location of the air parcels for each convective event was determined from the location of the event as reproduced by the mesoscale analysis output (Fig. 11). An ensemble of five parcels was used for each event, to assess uncertainty of parcel trajectory caused by initial parcel location. Parcels in each ensemble did not disperse much during the period of tracking, remaining near the ensemble centroid (Fig. 13). Therefore, uncertainty in air parcel location did not significantly alter the results of the following analyses.

The southwesterly low-level jet transported air parcels for both events southwest–northeast in the lower troposphere, over the tongue of warm water associated with the Kuroshio (Fig. 13). This result supports our inference that the Kuroshio modulated formation of the high-$\theta_e$ air masses in the lower troposphere. Figure 14a shows a warm, humid air mass with high $\theta_e$ in the lower troposphere, along the backward trajectory of a
representative air parcel for the first convective event (orange stars in Fig. 13), which was initiated at 0600 UTC 23 May. This high-$\theta_e$ air was the cause of convectively unstable conditions near the sea surface, as shown in Fig. 9. Latent heat flux along the trajectory showed large values while the high-$\theta_e$ air was forming near the sea surface (Figs. 14a and 14b). In contrast, sensible heat flux was nearly zero during the parcel tracking period. Temporal evolution of latent heat flux corresponded well to the difference between water vapor pressure and saturation vapor pressure of the air.
Fig. 10. As in Fig. 6, but for output of mesoscale analysis.
parcel at the SST (Figs. 14c and 14d). This difference was controlled mainly by saturation vapor pressure at the SST, consistent with in situ observations. The temporal evolution of these parameters during the second event was very similar to that during the first event, although SST was relatively low and latent heat flux relatively weak compared with those during the first event (Fig. 15). These results are consistent with the findings of recent studies, which show that evaporation from the sea surface in the Kuroshio region has a strong influence on the formation of convectively unstable air masses, which promote deep convection (Tsuguti and Kato 2014; Manda et al. 2014; Kunoki et al. 2015).

6. Discussion

High-frequency atmospheric soundings were taken in the East China Sea during 22–23 May 2011 with the objective of analyzing the impact of the Kuroshio on BFZ mesoscale convective systems, together with continuous surface meteorological observations and oceanic castings. Two convective events were detected while the BFZ was nearly stagnant and a mesolow in the BFZ was deepening. The coupling of a high-PV anomaly in the upper troposphere with one in the lower troposphere intensified the mesolow in the lower troposphere. A warm and humid air mass from south of the BFZ associated with a LLJ contributed to convectively unstable stratification in the lower troposphere. Evaporation in the Kuroshio region enhanced moisture content in the warm, humid air mass and helped maintain instability in the lower troposphere.

Although the mesoscale analysis reproduced overall characteristics of observed precipitation and wind fields and thermodynamic structures such as $\theta_v$, there were some discrepancies between observations and analyses. Precipitation intensity in the mesoscale analysis was underestimated relative to the radar observation (Figs. 5, 10, and 11). The TRMM data also underestimated this intensity (Figs. 5, 6, and 11). These findings indicate the need for further validation and improvement of the numerical model used in the mesoscale analysis and retrieval algorithm for the TRMM dataset, although this was beyond the scope of the present study. In addition, latent heat flux was underestimated in the mesoscale analysis compared with in situ data. One of the most important reasons...
for this underestimation is that the satellite data (MGDSST) used in that analysis underestimated SST. This should be explored further in future studies evaluating the effect of the Kuroshio on mesoscale convective events, which would improve understanding of the interaction between the BFZ and Kuroshio.

Acknowledgments. Professor Y. Kodama, who is currently experiencing a serious health problem, substantially contributed to this paper, to the extent that he should have been an author. The authors thank the crew of T/V Nagasaki-Maru and participants in the field campaign. We also thank Dr. Yoshimi Kawai of JAMSTEC, Japan, for providing equipment. This

FIG. 13. (a) Backward trajectories superimposed on MGDSST contours of 22 May 2011. Orange and purple symbols indicate locations of air parcels, initiated at 0600 and 1200 UTC 23 May 2011, respectively, used to examine trajectories of air masses during first and second convective events, respectively. Stars indicate trajectories of representative air parcels during each convective event. Squares, diamonds, triangles, and hexagons represent air parcels whose locations were 0.2° north, west, south, and east of starred parcel when parcels were initiated. (b) Longitude–height section of air parcels.
study would not have been possible without his support. We also thank Dr. Miki Hattori of JAMSTEC for her help with the backward trajectory analysis. Constructive comments provided by Dr. Ron McTaggart-Cowan and three anonymous reviewers greatly improved the manuscript. This work was supported in part by the Japanese Ministry of Education, Culture, Sports, Science and Technology through a Grant-in-Aid for Scientific Research on Innovative Areas 2205 (22106003), by the Japan Society for the Promotion for Science through a Grant-in-Aid for Scientific Research (22244057), and by Nagasaki University major research project “Research Initiative for Adaptation to Future Ocean Change.”

FIG. 14. (a) Time–height diagram of water vapor mixing ratio (color) and $\theta_e$ (contour) from mesoscale analysis, with times and locations of air parcel indicated by orange stars in Fig. 12. (b) Time histories of latent heat flux (orange), sensible heat flux (red), and sum of latent and sensible heat fluxes (black) in W m$^{-2}$, along backward trajectory. (c) Time series of water vapor pressure ($e$; blue), saturated water vapor pressure at SST ($e_s$; red), and their difference ($e_s - e$; black), in hPa. (d) Time series of SST (red), surface air temperature (black), and their difference (blue), in °C. (e) Time series of wind speed in m s$^{-1}$.
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FIG. 15. As in Fig. 14, but for air parcel indicated by purple stars in Fig. 13.


