Seasonal Migration of the Baiu Frontal Zone over the East China Sea: Sea Surface Temperature Effect

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Abstract

We propose a new scenario for the seasonal migration of the Baiu frontal zone over the East China Sea in which this migration is affected by variations in the sea surface temperature (SST). Using atmospheric and oceanic objective analysis datasets, a relationship was determined between the seasonal migration of the Baiu frontal zone and the decaying process of the cold high over the East China Sea. Before the middle of June, the cold high, cooled by the low SST, is present over the continental shelf, and the position of the Baiu frontal zone corresponds to that of the Kuroshio Front. After the middle of June, the cold high decays and is shifted northward in association with the warming SST over the shelf. As a result, the Baiu frontal zone migrates northward and ends in the middle of July due to the dissipation of the cold high.

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1. Introduction

The early summer rainy season of East Asia is characterized by a quasi-stationary frontal zone that is formed between the North Pacific sub-tropical high to the south and several cold highs to the north. This frontal zone, called Mei-yu in China, Chang-ma in Korea, and Baiu in Japan, migrates northward from May to July due to the balance between the highs to the south and north (Tomita et al. 2011).

Research regarding the cold highs is considerably scarcer than that on the other factors regulating the seasonal migration of the Baiu frontal zone, namely, the North Pacific sub-tropical high (Miyasaka and Nakamura 2005) and the influence of the upper-level westerly jet (Sampe and Xie 2010). The Okhotsk and Yangtze River highs are well-known cold highs to the north of the Baiu frontal zone. These highs are stationary cold air-masses in the lower atmosphere formed by geographically fixed surface cooling (e.g., Ninomiya and Mizuno 1985).

In this work, we focus on the Yellow Sea high (here abbreviated YSH), which is one of these cold highs. The YSH has been investigated as a major factor in spring fog formation around the eastern coast of China (Zhang et al. 2011). The YSH is a cold dome in the atmospheric boundary layer and is cooled by the low sea surface temperature (SST) over the Yellow-East China Sea. The YSH appears from April to June in the climatology of the sea level pressure (SLP) (Zhang et al. 2009). However, the relationship between the YSH and the migration of the Baiu frontal zone over the East China Sea has yet to be investigated.

The East China Sea is a key region of the Baiu frontal rainfall because the accumulative precipitation for June in the Baiu frontal zone is the largest in Kyushu, which is located at the eastern edge of the East China Sea and regularly suffers heavy rainfall disasters (e.g., Nagata and Ogura 1991; Kato 1998; Kato 2005). During several of these heavy rainfall events, a localized cold high over the Yellow Sea has been confirmed on the surface weather map (Moteki et al. 2004a, 2004b). These authors note that a cold dome originating from the Yellow Sea contributes greatly to the behavior of the Baiu front, which induces rainfall events over Kyushu.

We present here the relationship between the seasonal northward migration of the Baiu frontal zone and the decaying process of the YSH as correlated with the variation of SST. This study proposes a new scenario for the seasonal migration of the Baiu frontal zone over the East China Sea.

2. Data

The atmospheric and oceanic objective analysis datasets of the JCDAS (Japan Meteorological Agency Climate Data Assimilation System, Onogi et al. 2007), the JCOPE2 (Japan Coastal Ocean Predictability Experiment 2, Miyazawa et al. 2009), and the TRMM (Tropical Rainfall Measurement Mission) 3B42 precipitation product (Huffman et al. 2007) are used in this study. The JCDAS is a 6-hourly atmospheric objective analysis with a horizontal resolution of 1.25° and 40 vertical sigma levels. The JCOPE2 is a daily oceanic objective analysis with a horizontal resolution of 0.2° and 28 vertical depth levels. The model for the JCOPE2 was driven by the atmospheric reanalysis with the NCEP/NCAR (National Centers for Environ- mental Prediction/National Center for Atmospheric Research) (Kalney et al. 1996) as the sea surface boundary condition so that it is independent from the JCDAS. The TRMM 3B42 product is derived from the TRMM and other satellite observations on a 3-hourly basis for a 0.25° × 0.25° grid between 50°S and 50°N. This study analyses the 10-year period from 2000−2009, the same period covered by JCOPE2.

3. Seasonal variations of SST, SAT, and SLP

Figure 1 shows the climatology of the SST (sea surface temperature), SAT (surface air temperature), and SLP (sea level pressure) in May, June, and July. In May (Fig. 1a), the features of the YSH are clearly shown in the local maximum of the SLP and the local minimum of the SAT. These values are higher (approximately 0.5 hPa) and lower (2−5°C) than the same variables over China, Korea, and Japan at the same latitude. These features of the YSH are consistent with previous studies (Zhang et al. 2009, 2011). The SLP trough corresponding to the Baiu frontal zone extends from the southwest to the northwest along the Kuroshio Current. The remarkable meridional gradient of the SAT associated with the Baiu frontal zone corresponds to the location of the Kuroshio Front, the most significant SST front at the northern edge of the Kuroshio Current.

In June (Fig. 1b), the features of the YSH become unclear, although the SLP ridge associated with the local minimum of the SAT still remains at approximately 35°N. The Kuroshio Front also becomes unclear due to significant increases of the SST over the southern part of the continental shelf.

In July (Fig. 1c), there is no SLP trough associated with the Baiu frontal zone, and the SLP features of the YSH disappear. The

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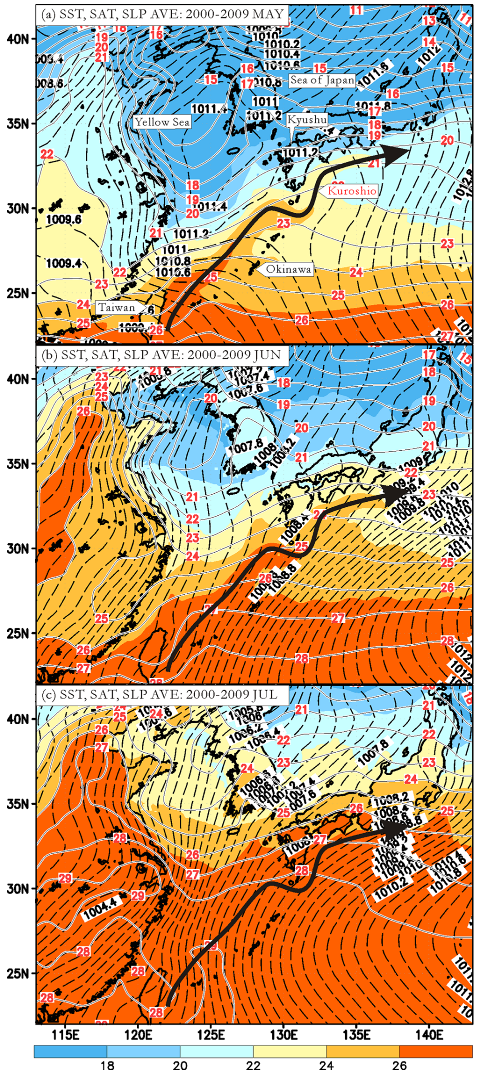

Fig. 1. Climatology of SST (color except for the land), SAT (solid contours every 1°C and color over the land), and SLP (dashed contours every 0.2 hPa) for May, June, and July during 2000−2009. The representative position of the Kuroshio Current is shown by the bold arrow.

local minima of the SAT and SST also disappear by this point, and the meridional contrast of the SAT is clearly separated from the Kuroshio Current.

These features of the SST, SAT, and SLP climatology suggest that there is a unique relationship between the atmospheric and oceanic mixed layers in the Baiu frontal zone over the Yellow-East China Sea. The marine surface layer over the Yellow Sea is well mixed in periods of intense cooling during the winter months due to the strong northerly monsoon. As a result, the SST and SAT over the continental shelf are lower than those of the surrounding areas. The cool SST over the shelf and the warm SST over the Kuroshio Current, however, cause a meridional gradient of the SAT that is larger than that of surrounding areas. The seasonal migration of the Baiu frontal zone over the East China Sea can be characterized by the unique variation of the atmospheric and oceanic mixed layers.

4. Thermal structure of the atmospheric and oceanic mixed layers

Figure 2 shows the vertical structure of the potential temperature and water temperature for May, June, and July. In May (Fig. 2a), the contours of the water temperature are nearly vertical relative to the sea surface over the southern part of the continental shelf. This water temperature structure is consistent with the bathymetric control of the SST proposed by Xie et al. (2002).

Bathymetric control is a mechanism by which the thermal inertia of a water column on the shelf becomes linearly proportional to its bottom depth under intense winter monsoon cooling. Because the water temperature structure of the winter season extends into May, the Kuroshio Front has a large meridional gradient of the water temperature of 1.5°C deg^{-1} (Fig. 3a). The potential temperature structure in the lower atmosphere below 900 hPa appears to be strongly affected by the water temperature: a remarkable cold dome is formed over the shelf. The potential temperature of the cold dome is 16−22°C, corresponding to the water temperatures over the shelf.

The Baiu frontal zone, which has its maximum potential temperature gradient at the southern edge of the cold dome, almost coincides with the Kuroshio Front (Fig. 3a). This correspondence of the positions of the Baiu frontal zone and the Kuroshio Front in May is consistent with several recent studies (Xu et al. 2011; Sasaki et al. 2012; Miyama et al. 2012).

In June and July (Figs. 2b, c), the marine surface layer of 0−50 m over the shelf significantly warms from the south. The cold dome gradually decays and is shifted northward. As a result, the Baiu frontal zone migrates northward in conjunction with the SST front (Figs. 3b, c). In June, two distinct maximum potential temperature gradients are observed independently at approximately 26°N−28°N and 30°N−35°N (Fig. 3b). The SST gradient of the Kuroshio Front becomes smaller than 1.0°C deg^{-1}, and the largest SST gradient appears at approximately 31°N.

In July, the largest SST gradient appears at approximately 32°N (Fig. 3c). A single maximum potential temperature gradient coincides with the SST front at approximately 32°N−35°N. Thus, the Baiu frontal zone is shown to migrate northward in association

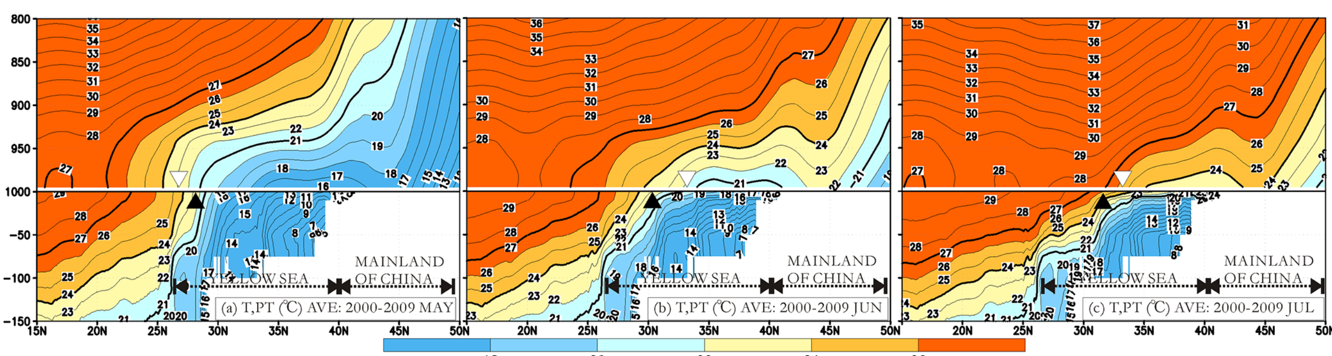

Fig. 2. Climatology of the water temperature and potential temperature averages between 120°E−127°E for (a) May, (b) June, and (c) July during 2000−2009 (colored and contoured every 1°C). The open and closed triangles indicate the representative positions of the Baiu frontal zone and SST front from Fig. 3.

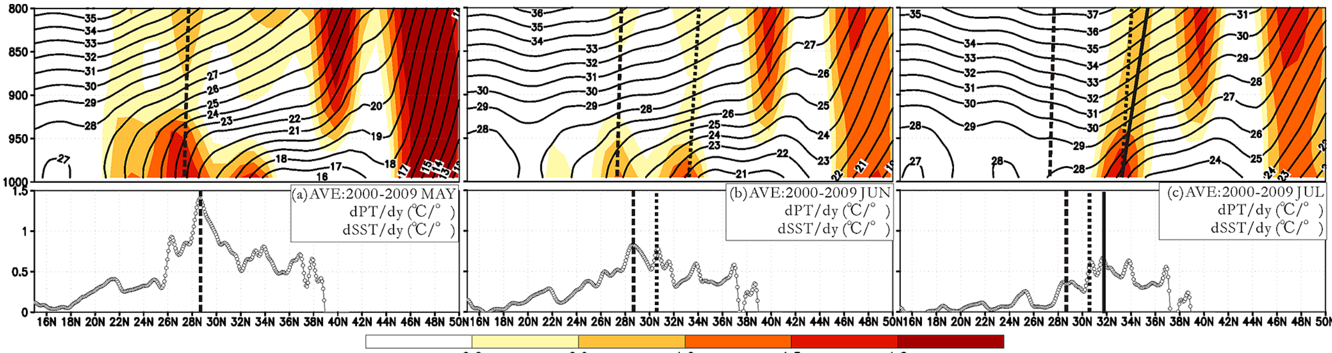

Fig. 3. Climatology of the meridional gradient of the SST and potential temperature averages between 120°E−127°E for (a) May, (b) June, and (c) July during 2000−2009. The dashed, dotted, and solid lines indicate the representative positions of the Baiu frontal zone and SST front in May, June, and July, respectively.

with the SST front, which is separated from the Kuroshio Front.

5. Seasonal variations of the SLP anomaly, rainfall, and SST

Figure 4 shows the seasonal variations of the positive SLP anomaly (SLPA), rainfall, and SST from 1 May to 31 July for the climatological average and 2001, respectively. The SLPA is calculated from the difference between the SLP averages for the 120°E−127°E and 113°E−120°E so that a positive SLPA represents the YSH. To eliminate positive SLPA due to the North Pacific sub-tropical high, the YSH was defined by the SLPA with an SAT of less than 24°C. The threshold of 24°C was determined from the representative SST of the Kuroshio Current in May (Fig. 2a).

Based on the average climatology data for May and the first half of June, the YSH tends to develop between 25°N−40°N (Fig. 4a). The rainfall of the Baiu frontal zone tends to be stagnant at approximately 22°N−28°N, which corresponds to the regions of Taiwan and Okinawa. In the latter half of June and the first half of July, the high SST area (more than 22°C) expands to the north of the Kuroshio Current, and the positive SLPA area shifts northward in conjunction with the high SST. In the latter half of July, after the end of the Baiu season in northern Kyushu, the climatological average rainfall of the Baiu frontal zone becomes quite small. Although the positive SLPA remains at approximately 38°N, there is no isolated YSH after 15 July in the surface weather maps for any of the 10 years of this study.

In 2001, the Baiu frontal zone followed a typical seasonal migration pattern similar to that of the average climatology data. The dotted lines in Figure 4b represent the date of the cold high isolated over the Yellow Sea confirmed by the surface weather map of the JMA (Japan Meteorological Agency). The latitude bands of the positive SLPA accurately correspond to each instance of the YSH confirmed by the surface weather map (Figs. 4c, d). The positive SLPA, except for the isolated YSH, represents a pressure ridge extending from the Sea of Japan to the Yellow Sea, as shown in Fig. 1b.

These features in the average climatology data and the data for 2001 support a scenario in which the northward shift of the YSH, which is affected by the warming of the marine surface layer over the shelf, results in the northward migration of the Baiu frontal zone over the East China Sea. In other words, the variation of the SST over the East China Sea is considered to impact the seasonal migration of the Baiu frontal zone via its influence on the decay of the YSH. While development of the North Pacific sub-tropical high is also an important factor to regulate the migration of the Baiu frontal zone, its strength is not well correlated with the local SST over the shelf (not shown). Because the sub-tropical high is developed in association with the land-sea heating contrast (Miyasaka and Nakamura 2005), its dependency on such local SST is considered to be small.

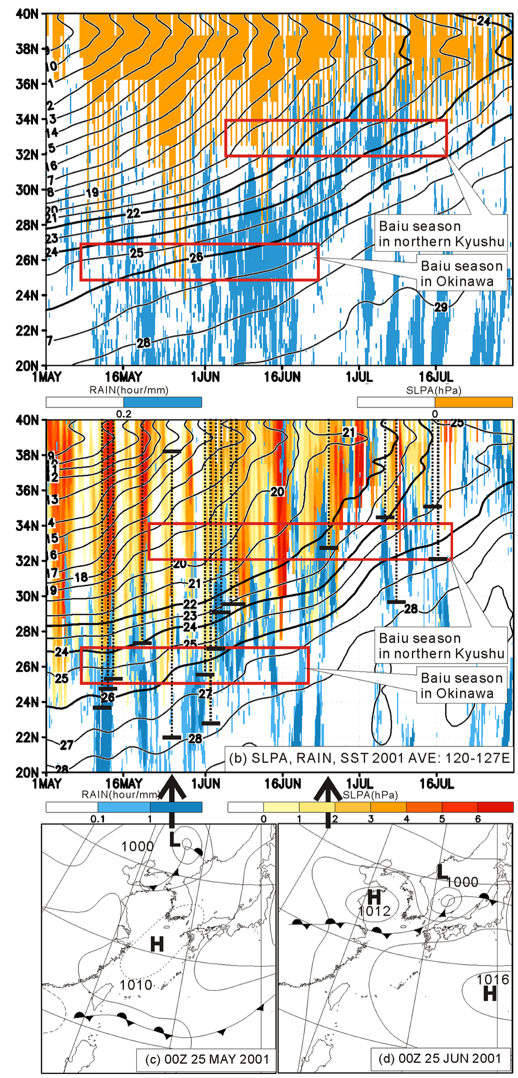

Fig. 4. The time-latitude cross section of the positive SLP anomaly (orange), rainfall (blue) and SST (contoured) from 1 May to 31 July for (a) the climatological average and (b) the 2001 average for 120°E−127°E. The Baiu season in Okinawa (25°N−27°N) and northern Kyushu (32°N−34°N), which is defined by the JMA, are during the red rectangles. The tick mark at the end of the dotted line indicates the meridional position of the front. The weather charts for the representative cases of the YSH on (c) 25 May and (d) 25 June in 2001 are shown. The dotted lines represent cases of the YSH confirmed from the surface weather map as an isolated high over the Yellow Sea, as in (c) and (d).

Previously, the North Pacific sub-tropical high, land surface heating over the continent, the Okhotzk high, and other factors have been implicated in the seasonal migration of the Baiu frontal zone. However, as we show in this study, the decay of the local YSH cold high corresponds with the variation of the SST over the East China Sea and is an important factor for the northward migration of the Baiu frontal zone.

6. Summary

In this study, the seasonal migration of the Baiu frontal zone over the East China Sea is investigated using the atmospheric and oceanic objective analysis datasets of the JCDAS and JCOPE2. We propose the following new scenario for the seasonal migration of the Baiu frontal zone over the East China Sea as affected by the variation of the marine surface layer.

First, the Baiu frontal zone is formed in May between the YSH and the North Pacific sub-tropical high and stagnates along the Kuroshio Front at approximately 22°N−28°N. The SST over the continental shelf area is less than 20°C due to the bathymetric control feature that forms over the winter months. The meridional contrast of the SST between the continental shelf area and the Kuroshio Current is rather large (approximately 1.5°C deg^{-1}) and corresponds with the SAT contrasts in association with the Baiu frontal zone.

Second, the Baiu frontal zone migrates northward to approximately 30°N−35°N as a result of the dissipation of the YSH. The bathymetric control of the SST begins to dissipate due to the warming of the 0−50 m marine surface layer over the shelf. The large SST contrast shifts to the north of the Kuroshio Current. The position of the meridional gradient of the lower atmospheric temperature along the Baiu frontal zone corresponds to the SST contrast at approximately 30°N−35°N.

Third, in July, the YSH disappears, and the cold dome in the atmospheric boundary layer cannot be maintained because the SST over the Yellow Sea warms to 22°C. The position of the large meridional gradient of the air temperature is shifted northward to approximately 32°N−35°N. Although baroclinic wave disturbances easily propagate in the region of the large gradient, the resulting disappearance of the YSH causes the stationary frontal feature to disappear and the rainy season of the Baiu to withdraw.

Thus, this study shows that the seasonal migration of the Baiu frontal zone strongly depends on the warming in the marine surface layer of the Yellow Sea. The Yellow Sea high is one of the important factors regulating the seasonal migration of the Baiu frontal rainfall. This new scenario over the East China Sea suggests that the YSH is one of the keys to understanding the behavior of the Baiu front, not only for climatological seasonal changes but also for individual rainfall events. Additionally, the winter cooling of the marine surface layer over the shelf may influence the seasonal migration of the Baiu frontal zone through its effects on the strength of the YSH.

Numerical experiments to describe the sensitivity of various SST patterns over the East China Sea will be conducted in future report based on the present scenario. Also, future research should explore relationship between this scenario and other large-scale environmental factors (e.g., mid-tropospheric westerly jet and its thermal advection, Sampe and Xie 2012).

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