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# Climatological Evolution of the Okinawa Baiu and Differences in Large-Scale Features during May and June

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## ABSTRACT

The Okinawa baiu (summer rainy season) starts in early May and ends in late June, preceding the baiu in mainland Japan by approximately 1 month. This study investigates the time evolution of the large-scale circulation associated with the Okinawa baiu using 10-yr (1997–2006) climatologies of precipitation and meteorological fields, with particular focus on temperature advection at 500 hPa. The onset of the Okinawa baiu occurs in early May and is followed by an initial peak in precipitation during mid-May. The baiu rainband then moves southeastward, leading to a short break in baiu precipitation during late May. The rainband returns to Okinawa in early June, and a second peak in precipitation occurs during mid-June. The baiu rainband withdraws northward in late June. The mid-May precipitation peak is associated with warm advection at 500 hPa, mainly due to the meridional temperature gradient and the prevailing southerly winds. This warm advection coincides with upward motion near Okinawa; however, the warm advection is insufficient to explain the peak precipitation amount. Enhancement of precipitation by a transient disturbance probably contributes to the peak amount. The break period during late May coincides with the peak of South China Sea monsoon. Warm advection at 500 hPa strengthens again in June because of the strong zonal thermal contrast between the warm Tibetan Plateau and cold Pacific. This warm advection is able to adequately explain both the upward motion and precipitation. These results indicate that the large-scale meteorological characteristics are different during the first and second peaks.

## 1. Introduction

Between May and July, East Asia experiences a rainy season that is known as the mei-yu in China and as the baiu in Japan. Okinawa is located southwest of mainland Japan on the eastern fringe of the East China Sea, and consists of numerous small islands (see Fig. 1). In this study, we define the “Okinawa region” as the region within 23°–28°N, 123°–129°E. The Okinawa baiu starts in May when the baiu rainband, which is first observed in late April as a band of enhanced cloudiness along a polar front near 30°N, shifts southward to approximately 20°–25°N (Tanaka 1992). Tian and Yasunari (1998) examined the occurrence of persistent rains over central

China during spring (March and April), and showed that this area of precipitation moves southward in May. The baiu rainband moves rapidly northward in June. This rapid northward shift leads to quasi-stationary precipitation and the onset of the mei-yu–baiu season over a broad region of East Asia, from southern China to mainland Japan (Kato 1985; Tanaka 1992). The baiu front continues to move northward, withdrawing from mainland Japan in mid-July. This continued northward movement is associated with the concurrent northward shift of the upper-level jet. Ueda et al. (1995) suggested that abrupt changes in convective activity over the northwestern Pacific during late July are associated with the northward withdrawal of the baiu front.

The baiu front is elongated in the east–west direction. This front takes on different features to the east and west of 120°–130°E. To the east, the temperature gradient across the front is strong; to the west, the temperature gradient is weaker but the moisture gradient is stronger

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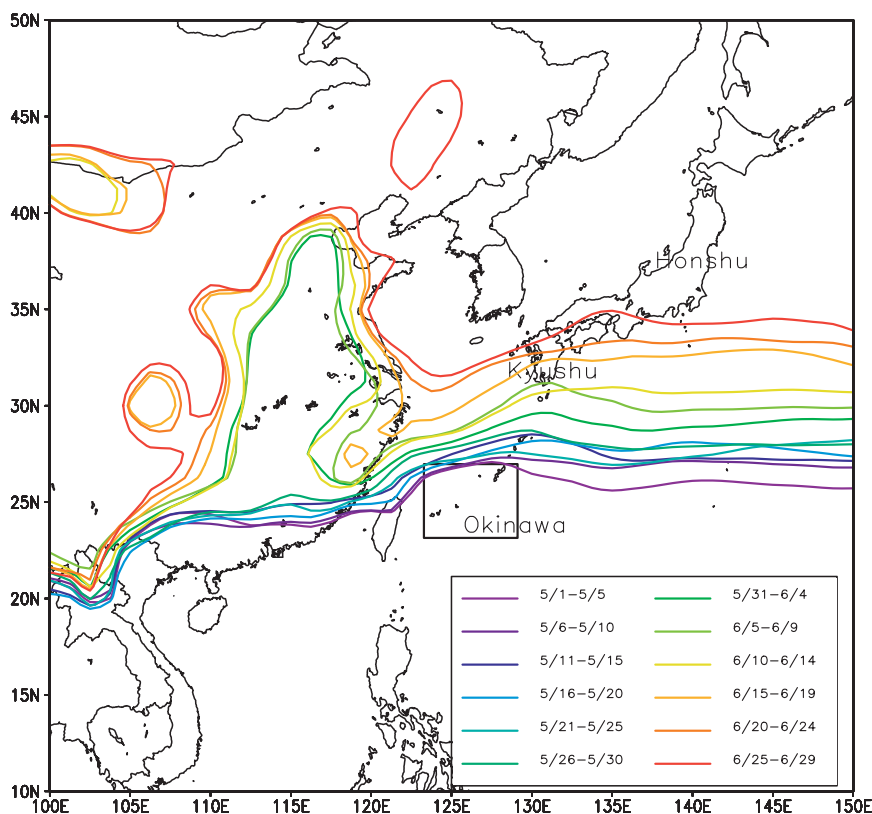


FIG. 1. Contour lines indicate the location of the 297-K surface temperature isotherm for successive pentads during May and June. The solid rectangle in the map indicates the Okinawa region, and the legend is shown at the bottom right.

(Matsumoto et al. 1971; Kato 1985; Ninomiya and Muraki 1986; Ninomiya and Akiyama 1992). Eastward of  $120^{\circ}$ – $130^{\circ}$ E, the baiu front describes the boundary between a warm subtropical air mass to the south and a cold subpolar air mass to the north. To the west, over China, the front describes the boundary between a humid tropical air mass to the south and a dry subpolar air mass to the north (Tanaka 2007). Okinawa is located at  $123^{\circ}$ – $129^{\circ}$ E, within the transitional zone between the temperature-gradient front region (to the east) and the moisture-gradient front region (to the west).

Figure 1 shows the May–June evolution of the 297-K isotherm in surface air temperature as a series of 5-day averages. During May, the 297-K isotherm is located just north of Okinawa and is oriented roughly east–west, running from southern China to the Pacific Ocean. In early June, an abrupt warming occurs over China and a more gradual warming occurs eastward of  $120^{\circ}$ – $125^{\circ}$ E. This distribution of warming leads to the formation of a zonal temperature contrast between continental China and the East China Sea.

Figure 2 shows the time evolution of climatological north–south gradients in potential temperature and

specific humidity at 925 hPa averaged over the longitudinal range that contains Okinawa ( $123^{\circ}$ – $129^{\circ}$ E). The meridional temperature gradient near Okinawa is strong throughout boreal winter (not shown before mid-April). The strongest temperature gradient in this longitudinal range is located near  $24^{\circ}$ – $29^{\circ}$ N until mid-June, although its magnitude weakens slightly during June (Fig. 2a). The strongest moisture gradient is also located at approximately  $25^{\circ}$ – $30^{\circ}$ N until mid-June, when it moves northward (Fig. 2b). The Okinawa baiu front is characterized by strong gradients in both temperature and moisture.

Sampe and Xie (2010) explained the large-scale dynamics of the baiu rainband from the perspective of temperature advection in the midtroposphere. Warm advection implies upward motion in adiabatic flow. During the baiu season in East Asia, the zonal contrast of temperature in the midtroposphere is enhanced due to warming of the Asian continent, especially that of the Tibetan Plateau. The prevailing westerly wind is also relatively strong, which promotes strong warm advection toward East Asia. This region of strong warm advection corresponds well to the region of upward motion

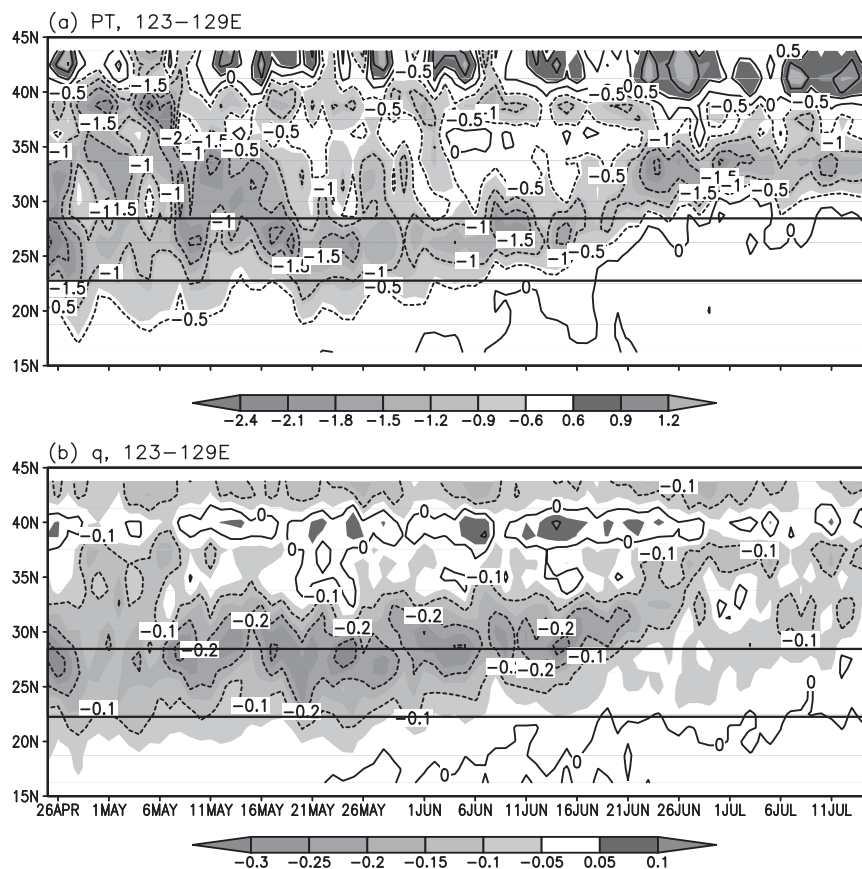


FIG. 2. Time-latitude plots of meridional gradients in (a) potential temperature (K) and (b) specific humidity ( $\text{kg kg}^{-1}$ ) at 925 hPa averaged over the longitudinal range  $123^{\circ}\text{--}129^{\circ}\text{E}$ . The black horizontal lines indicate the boundaries of the Okinawa region.

along the baiu front. In this paper, we apply the methods proposed by Sampe and Xie (2010) to the Okinawa baiu.

The evolution of the Okinawa baiu precedes the evolution of the baiu in mainland Japan by approximately one month, with onset in early May and withdrawal in late June (climatological values from the Japan Meteorological Agency indicate an average onset date of 8 May and an average withdrawal date of 23 June). In early May, Okinawa is usually located at the southern edge of a moving high pressure system. The spring rainy season, which extends from mid-March to early May, is caused by extratropical cyclones and frontal systems in the Japanese Nansei-Shotou (southwest islands) (Matsumoto and Yamamoto 2009). The onset of the Okinawa baiu takes place when the east–west front associated with the moving high pressure system becomes stationary. The westerly winds are still strong at this time; accordingly, moist air intrusions and precipitation events are intermittent during May, and the amount of rainfall is relatively small (Ishigaki 1982). A cloud zone appears over subtropical East Asia at approximately the same time (Hirasawa

et al. 1995). Precipitation amounts increase in June, corresponding to the duration of the baiu from mid-May to mid-June (Matsumoto and Yamamoto 2009). The Okinawa baiu ends in late June with the northward shift of the baiu front.

Although the evolution of the baiu over mainland Japan has been extensively studied, few studies have examined the evolution of the Okinawa baiu. Previous analyses of the Okinawa baiu (e.g., Ishigaki 1982) have been based on monthly averages; its evolution has not yet been studied using daily data. In this study, we provide a detailed examination of the climatological evolution of the Okinawa baiu, with particular focus on temperature advection at 500 hPa.

## 2. Data

We use meteorological data from the Japanese 25-yr Reanalysis (JRA-25) (Takahashi et al. 2006; Onogi et al. 2007; Watarai and Tanaka 2007) and precipitation data from the Global Precipitation Climatology Project

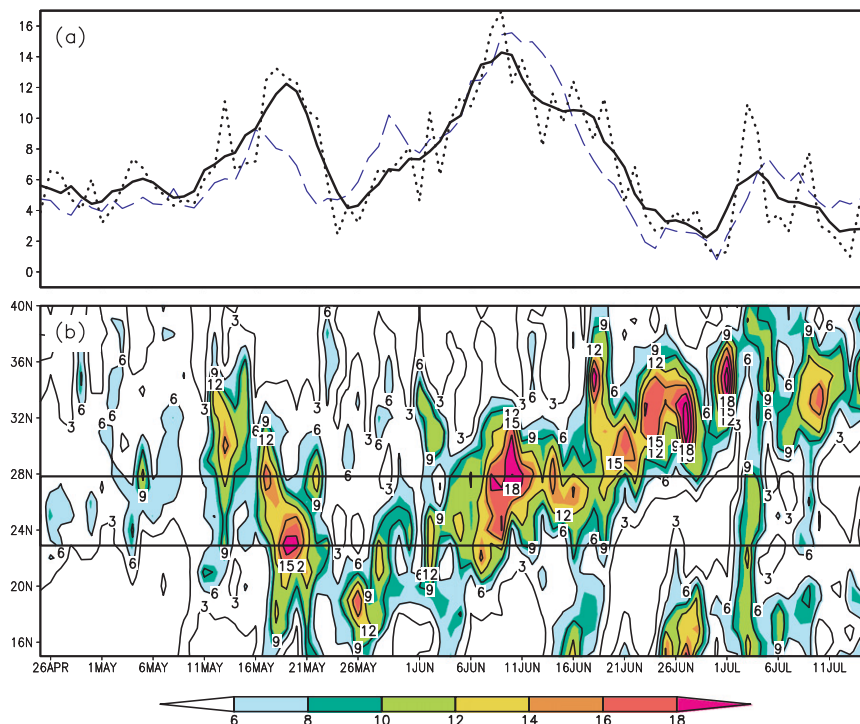


FIG. 3. Temporal evolution of precipitation in the Okinawa region. (a) Time series of precipitation ( $\text{mm day}^{-1}$ ) over the Okinawa region ( $23^{\circ}$ – $28^{\circ}\text{N}$ ,  $123^{\circ}$ – $129^{\circ}\text{E}$ ) from 25 April to 15 July based on 10-yr climatologies from GPCP (dotted line) and APHRODITE (blue dashed line). The black solid line is derived by twice applying a 5-day running mean to smooth the GPCP data. (b) Time–latitude variation of GPCP precipitation averaged over the longitudinal range  $123^{\circ}$ – $129^{\circ}\text{E}$  with a contour interval of  $3 \text{ mm day}^{-1}$ . The black horizontal lines indicate the boundaries of the Okinawa region.

(GPCP; Huffman et al. 2001) for the 10 years from 1997 through 2006. The JRA-25 dataset is provided 6-hourly at a horizontal resolution of  $1.25^{\circ} \times 1.25^{\circ}$  (longitude  $\times$  latitude). The GPCP data is provided daily at a horizontal resolution of  $1^{\circ} \times 1^{\circ}$ . We use the Asian Precipitation Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE) precipitation dataset (Yatagai et al. 2009) to supplement the GPCP data. The APHRODITE data is based solely on rain gauge observations, and is therefore only available over land. This dataset is provided daily at a horizontal resolution of  $0.5^{\circ} \times 0.5^{\circ}$ . We use sea surface temperatures from the National Oceanic and Atmospheric Administration (NOAA)  $\frac{1}{4}^{\circ}$  daily optimum interpolation sea surface temperature (OISST) dataset (Reynolds et al. 2007; [http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.OISST/.version2/.dataset\\_documentation.html](http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.OISST/.version2/.dataset_documentation.html)). The OISST data is provided daily at a horizontal resolution of  $0.25^{\circ} \times 0.25^{\circ}$ . We define the Okinawa region as the region within  $23^{\circ}$ – $28^{\circ}\text{N}$ ,  $123^{\circ}$ – $129^{\circ}\text{E}$ . All results shown in this paper are 10-yr means over the period 1997–2006.

### 3. Evolution of precipitation and sea level pressure fields

The climatological onset date of the Okinawa baiu is 8 May, and the climatological withdrawal date is 23 June (climatological values based on the 30-yr period from 1971 through 2000 as reported by the Japan Meteorological Agency). The average onset and withdrawal dates for the 10-yr period analyzed in this paper match these climatological values: the average onset date is 8 May and the average withdrawal date is 23 June. Figure 3a shows the temporal evolution from 26 April to 15 July of GPCP and APHRODITE precipitation averaged over the Okinawa region. According to GPCP, precipitation starts to increase around 10 May, reaching a peak of approximately  $12 \text{ mm day}^{-1}$  around 18 May. Precipitation decreases following this mid-May peak, reaching a minimum of approximately  $4 \text{ mm day}^{-1}$  around 26 May, after which it increases again. Precipitation reaches a seasonal maximum of approximately  $13 \text{ mm day}^{-1}$  between 6 and 12 June. This seasonal maximum is both larger and longer lasting than the initial peak in mid-May. Precipitation

decreases following the peak in mid-June, and the Okinawa baiu ends around 23 June. APHRODITE data indicates that the mid-May precipitation peak is slightly earlier (around 15 May) and smaller (approximately  $10 \text{ mm day}^{-1}$ ). The subsequent minimum ( $4 \text{ mm day}^{-1}$ ) also occurs earlier, around 22 May. The secondary peak in June is somewhat stronger than that indicated by GPCP, with a maximum of approximately  $15 \text{ mm day}^{-1}$ . The APHRODITE data indicates that the Okinawa baiu ends around 21 June. The evolution of precipitation is generally similar in the GPCP and APHRODITE datasets, despite slight differences in key dates and precipitation amounts. Such differences are unavoidable because the APHRODITE data is only available over land. The land area of the Okinawa islands is much smaller than the area of the Okinawa analysis region defined above. In summary, the Okinawa baiu has two periods of peak precipitation: one in mid-May and the other in mid-June. A short break period occurs during late May, between the two peak periods.

The time–latitude evolution of precipitation averaged over the longitudinal range  $123^{\circ}$ – $129^{\circ}\text{E}$  is shown in Fig. 3b. Precipitation amounts near  $27^{\circ}\text{N}$  increase gradually during early May, as the region of high precipitation moves southward over Okinawa. This region of high precipitation continues southward during late May, leading to a short break in the Okinawa baiu. In June, the precipitation zone moves northward and precipitation amounts increase. The region of high precipitation reaches  $30^{\circ}$ – $35^{\circ}\text{N}$  in late June, at which point it becomes nearly stationary. Based on these observations of the evolution of the Okinawa baiu, we divide the May–June period into 5-day increments (pentads). The following figures show horizontal distributions of a variety of meteorological fields during successive pentads.

Figure 4 shows the distribution of pentad-mean precipitation and sea level pressure (SLP) for each pentad during the evolution of the Okinawa baiu. In early May (preonset), the largest precipitation is observed near the equator, with weak precipitation south of the Yangtze River valley in China ( $\sim 28^{\circ}\text{N}$ ; Figs. 4a,b). The axis of the North Pacific subtropical high (NPSH) is located near  $30^{\circ}\text{N}$  and extends westward to China.

In mid-May, an area of high precipitation forms that extends from the Yangtze River valley in the west through Kyushu island and the Okinawa region in the east (Fig. 4c). Precipitation is also significantly enhanced over the Bay of Bengal (BOB;  $85^{\circ}$ – $95^{\circ}\text{E}$ ). A precipitation zone forms in mid-May that extends from southern China to the east of Japan, corresponding to the onset of the Okinawa baiu (Fig. 4d). Monsoon onset occurs over the Indochina Peninsula ( $\sim 105^{\circ}\text{E}$ ) during

this first period of peak precipitation. The NPSH retreats eastward and the ridge of the NPSH is oriented southwest–northeast. The main precipitation zone is located along the northwestern side of this ridge.

In late May, the NPSH continues its eastward retreat and the precipitation moves southward over the South China Sea (SCS;  $110^{\circ}$ – $120^{\circ}\text{E}$ ; Figs. 4e,f). This southeastward migration of the precipitation area corresponds to monsoon onset over the SCS and causes a short break in the Okinawa baiu at the end of May (Figs. 3 and 4f). Fujibe (2006) found that a short dry period precedes baiu onset over Honshu–Kyushu, and suggested that Okinawa may experience a similar short break in precipitation during late April. We instead find that this short break occurs during late May. In their examination of the baiu front in May 1979, Kato and Kodama (1992) showed that the front moved southeastward from Okinawa in late May (see their Fig. 15). This southeastward migration during late May is consistent with our results (Figs. 3 and 4).

The precipitation zone returns to the Okinawa region in early June as part of a precipitation belt that is oriented southwest–northeast and extends from the northern SCS to the east of Honshu Island (Figs. 4g,h). The maximum precipitation amounts along this belt are located between Okinawa and Kyushu Island. Precipitation increases gradually over the BOB (Figs. 4g–j) and along the west coast of India (not shown) during this period. Using 27-yr (1979–2006) climatological pentad-mean rain rates, Ueda et al. (2009) explained this stepwise evolution of precipitation in Asia as the seasonal progression of precipitation along the  $10^{\circ}$ – $20^{\circ}\text{N}$  latitudinal band. Matsumoto (1997) also showed this stepwise evolution of precipitation over Indochina and the adjacent monsoon region using pentad-mean observations of outgoing longwave radiation (OLR).

The Okinawa baiu withdraws in late June (Figs. 4k,l). The precipitation zone, which was located over Okinawa during the previous period, shifts northward, so that the areas of peak precipitation are centered over the Yangtze River basin and Kyushu islands. This northward shift is associated with the westward expansion of the NPSH into the Okinawa region (Figs. 4k,l). Precipitation increases southward of the NPSH (near  $5^{\circ}$ – $10^{\circ}\text{N}$ ) during this period.

#### 4. Moisture flux and precipitable water

Low-level water vapor transport into the frontal zone by monsoon winds is essential to the formation of baiu precipitation (Ninomiya and Akiyama 1992; Tanaka 2007). Figure 5 shows the spatial distributions of moisture flux integrated from the surface to 200 hPa

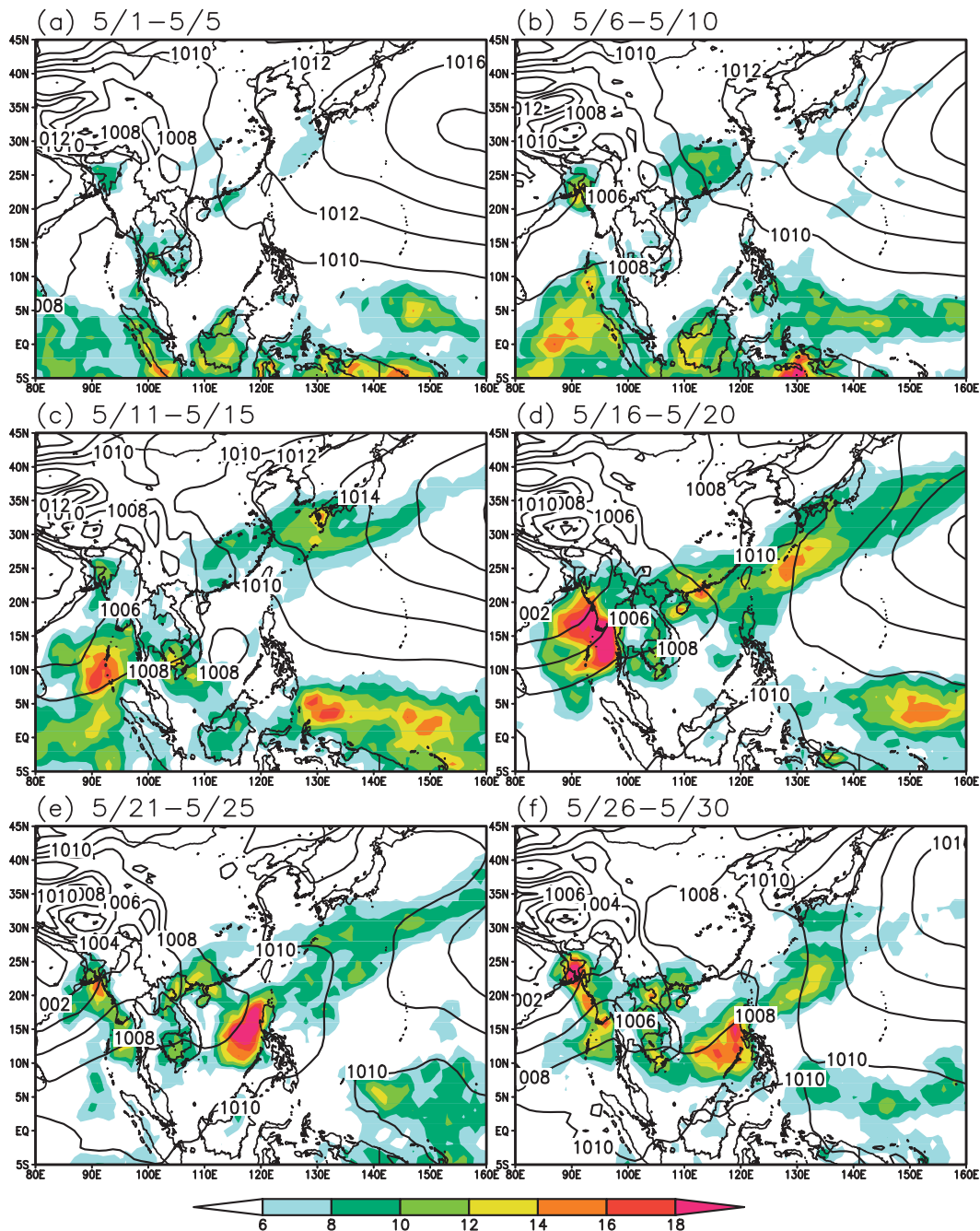


FIG. 4. Average precipitation (color shading; mm day<sup>-1</sup>) and sea level pressure (SLP) (solid contours; hPa) for individual pentads during the Okinawa baiu: (a) 1–5 May, (b) 6–10 May, (c) 11–15 May, (d) 16–20 May, (e) 21–25 May, (f) 26–30 May, (g) 31 May–4 June, (h) 5–9 June, (i) 10–14 June, (j) 15–19 June, (k) 20–24 June, and (l) 25–29 June. Scale for color shading is as in Fig. 3b.

(arrows), moisture flux convergence (color shading), and precipitable water (contours). Although the moisture flux is integrated throughout the troposphere, water vapor is most abundant in the lower troposphere. The direction of the flux therefore primarily reflects low-level moisture transport.

The moisture flux is southwesterly over southern China and regions to its east during early May (Fig. 5a), with areas of weak moisture flux convergence in southern China. The moisture flux is easterly from the northwestern subtropical Pacific to the SCS.

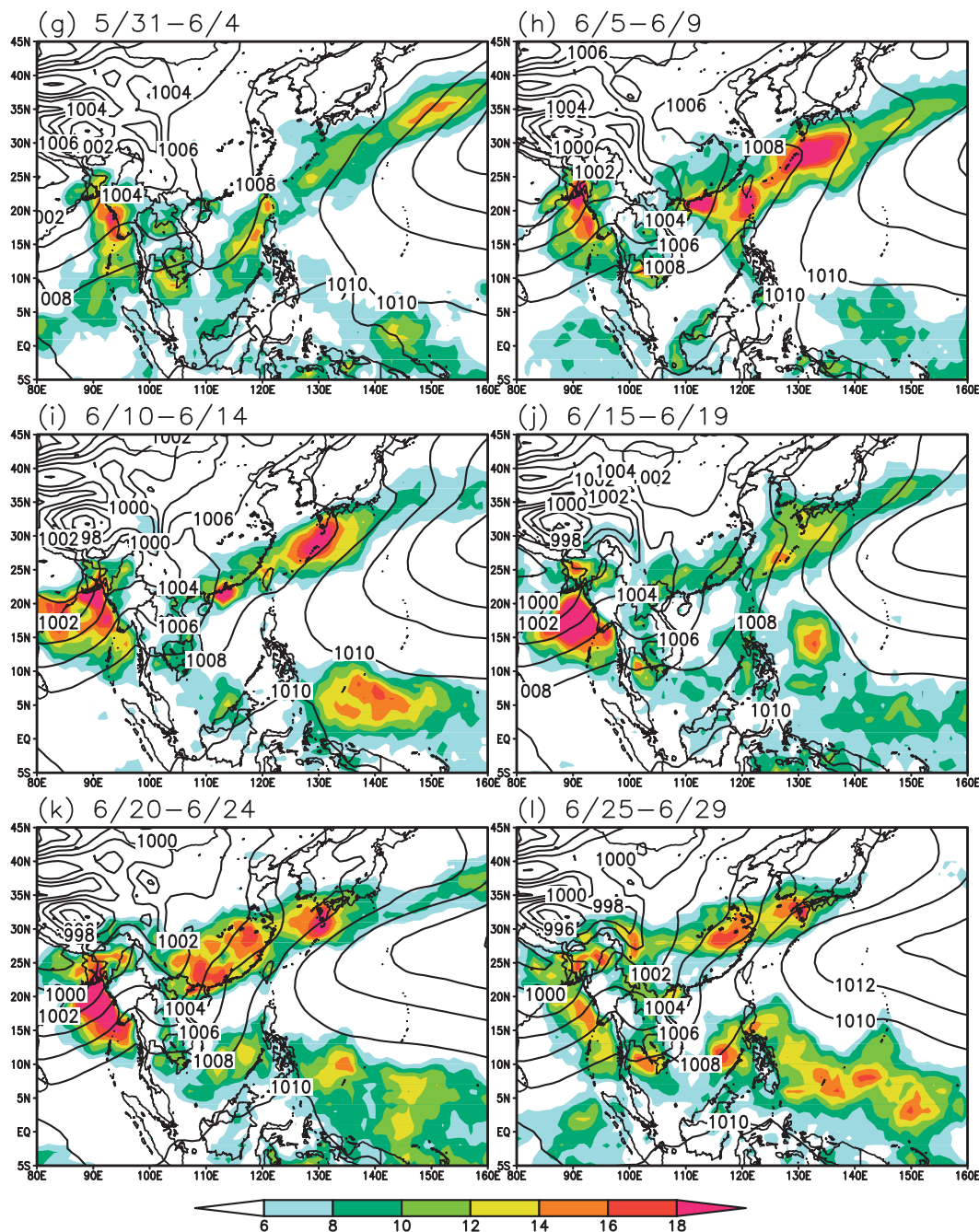


FIG. 4. (Continued)

Westward fluxes continue to prevail over the northwestern subtropical Pacific through mid-May (Fig. 5b). These westward fluxes are directed toward the Indochina Peninsula along the southern periphery of the NPSH. A weak northward flux prevails over the SCS, with moisture flux convergence to the east of the Philippines. In mid-May, coincident with the first peak in Okinawa baiu precipitation, a southwesterly moisture flux develops over the BOB. This southwesterly moisture flux connects

with southwesterly fluxes over southern China and Okinawa. Areas of moisture flux convergence are observed over Indochina and southern China; these areas extend toward Okinawa.

During the Okinawa baiu break period (late May), precipitable water exceeds 50 mm over an area that extends across the northern SCS from southern China along 20°–25°N (Fig. 5c). Precipitation is suppressed to the south of this humid band, along the ridge axis of the

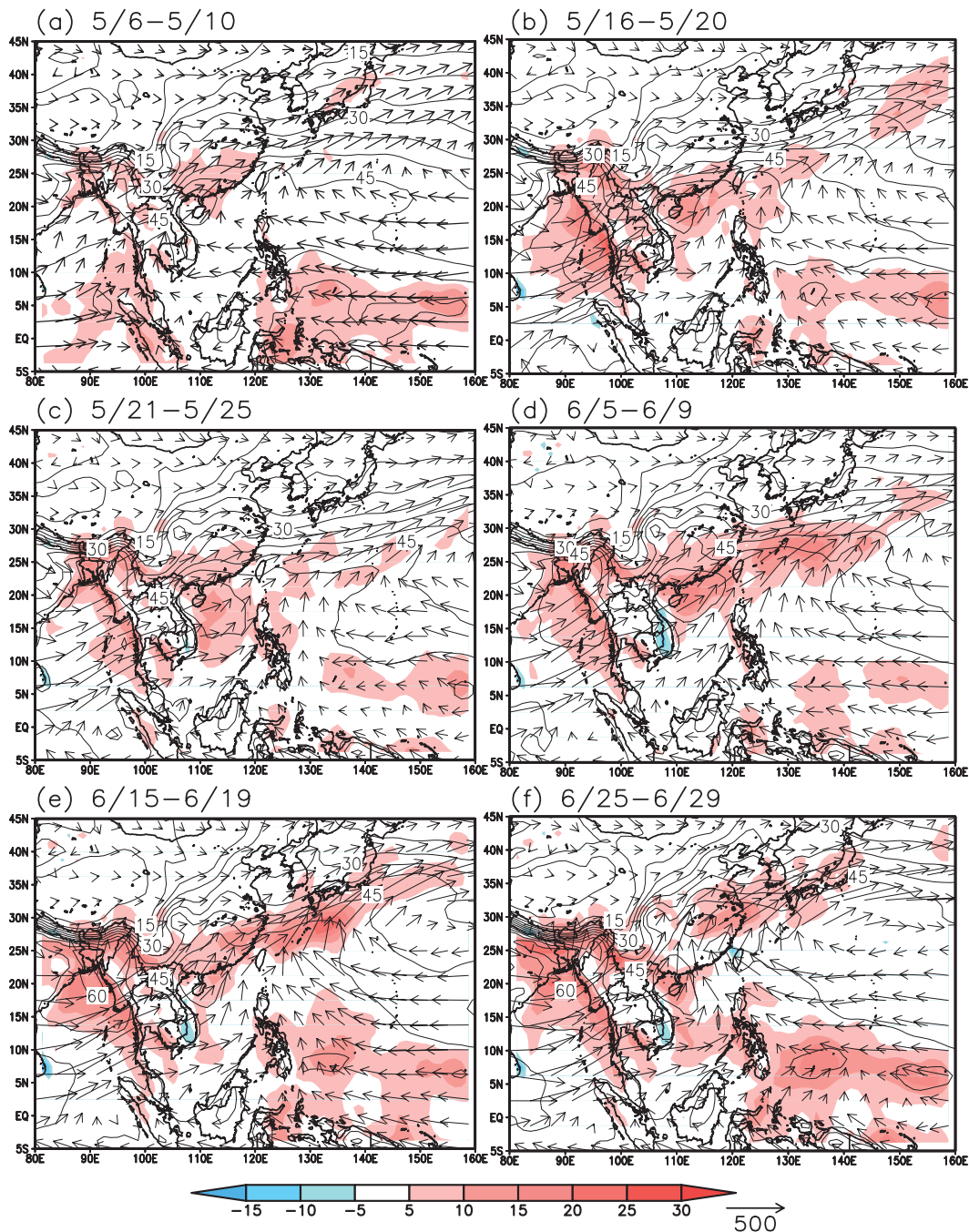


FIG. 5. Moisture flux (arrows;  $\text{kg m}^{-1} \text{ day}^{-1}$ ), moisture flux convergence (shading;  $\text{kg m}^{-2} \text{ day}^{-1}$ ), and precipitable water (solid contours; mm) for selected pentads during the Okinawa baiu: (a) 6–10 May, (b) 16–20 May, (c) 21–25 May, (d) 5–9 June, (e) 15–19 June, and (f) 25–29 June. Moisture fluxes are vertically integrated from the surface to 200 hPa.

NPSH ( $15^{\circ}$ – $25^{\circ}\text{N}$ ). The westerly moisture flux over the SCS strengthens at this time and the SCS monsoon becomes strong (Chan et al. 2000). Wang et al. (2004) showed that the mean 850-hPa westerly wind over the central SCS ( $5^{\circ}$ – $15^{\circ}\text{N}$ ,  $110^{\circ}$ – $120^{\circ}\text{E}$ ;  $U_{\text{SCS}}$ ) strengthens at the onset of the SCS monsoon. They used this information

to define SCS monsoon onset as the first pentad after 25 April that satisfies the following two criteria:  $U_{\text{SCS}}$  is positive in the onset pentad and at least two of the following three pentads, and  $U_{\text{SCS}}$  averaged over the four pentads exceeds  $1 \text{ m s}^{-1}$ . According to this definition, SCS monsoon onset typically occurs around 15 May

during our analysis period.  $U_{SCS}$  peaks at approximately 25 May (not shown). We also find that the break period of the Okinawa baiu occurs simultaneously with the peak of the SCS monsoon. The moisture flux southeast of Okinawa is directed toward the northeast, leading to moisture convergence and an eastward extension of the region of high precipitable water (Fig. 5c).

The westerly moisture flux over the SCS shifts to southwesterly during early June (Figs. 5d,e). This southwesterly moisture flux provides an abundant supply of water vapor and promotes precipitation in the Okinawa region. Moisture convergence along the baiu front increases substantially and the front moves slowly northward as the monsoon circulation in Southeast Asia gradually strengthens during early and mid-June (Fig. 5e). This northward movement continues into late June, resulting in the end of the Okinawa baiu (Fig. 5f). The zone of strong moisture convergence over China shifts northward into central China. The areas of moisture convergence (Fig. 5) correspond approximately to areas of precipitation (Fig. 4) throughout May and June.

## 5. Horizontal temperature advection

Throughout the rainy season, mean ascending motion along the baiu front corresponds well to a band of warm horizontal temperature advection in the midtroposphere (Sampe and Xie 2010). The response of the large-scale atmospheric circulation to diabatic heating from condensation is generally baroclinic; as a result, the midtropospheric circulation is not strongly affected by this heating. Sampe and Xie (2010) examined temperature advection at the 500-hPa level and found good correlations between warm advection and precipitation during the baiu season. We now examine in detail whether this relationship applies to the Okinawa baiu.

Figure 6 shows the 500-hPa horizontal temperature advection (contours) and upward vertical pressure velocity  $-\omega$  (color shading). Warm advection roughly corresponds to ascending motion outside of the tropics. The transient term of temperature advection has only small effects on the Okinawa baiu. Figure 7 shows the temporal evolution of upward vertical velocity and horizontal temperature advection at 500 hPa near Okinawa. Variations in ascending motion and warm advection correspond reasonably well to variations in areas of precipitation associated with the Okinawa baiu (cf. Figs. 3 and 7b). In particular, the region of warm advection shifts southeastward during the short break in the baiu during late May (Figs. 6c and 7b). At around the same time, the cold advection located to the north extends southward to cover the north of Okinawa. During the second peak in baiu precipitation, the temperature

advection over the Okinawa region increases only slightly (from approximately  $0.3 \text{ K day}^{-1}$  to approximately  $0.4 \text{ K day}^{-1}$ ), while the upward pressure velocity increases by a factor of 1.5. Decreases in static stability (see section 6) and increases in diabatic heating due to condensation likely contribute to the relatively large increase in vertical pressure velocity during mid-June relative to that during May. On the other hand, in May, magnitudes of warm advection and vertical  $p$  velocity are insufficient to explain the precipitation peak.

Sampe and Xie (2010) showed that the westerly jet stream across the zonal temperature gradient contributes to ascending motion and the formation of the baiu front. Figure 8 shows horizontal wind, temperature, and temperature advection at 500 hPa. During early May, the warmest temperatures are located over the BOB. This region moves northward as the season progresses, so that it is located over the Tibetan Plateau in late June. Matsumoto (1992) showed that warming over the Tibetan Plateau influences the seasonal transitions that occur over Japan during mid-May and mid-June. The meridional temperature gradient near Okinawa is large during May, so that the southerly component of wind contributes to temperature advection even though it is relatively weak (Fig. 8a). Cold advection associated with the trough near Korea prevails in the area north of Okinawa (Figs. 8b,c). The zonal temperature contrast near Okinawa strengthens during June, as does temperature advection associated with westerly wind (Figs. 8d,e). The region of warm temperature advection shifts northward from Okinawa during late June when the Okinawa baiu withdraws (Fig. 8f). Warm advection and upward motion both approach zero at this point (Fig. 7).

We divide temperature advection into its zonal and meridional terms according to

$$-\mathbf{v} \cdot \nabla T = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y}. \quad (1)$$

Figure 9 shows the zonal term of temperature advection  $-u \partial T / \partial x$  along with its component parts, the zonal temperature gradient  $\partial T / \partial x$  and the zonal wind  $u$ . In May, the zonal term of temperature advection is small near Okinawa (Fig. 9a) because the local zonal temperature gradient is small (Fig. 9b). The zonal term of temperature advection around Okinawa grows during early June due to the persistence of moderate zonal winds in the presence of an increasing zonal temperature gradient (Fig. 9c). The zonal wind speed weakens after mid-June, and the region of strong zonal temperature advection shifts northward from Okinawa. Zonal temperature advection near Okinawa approaches zero at this stage.

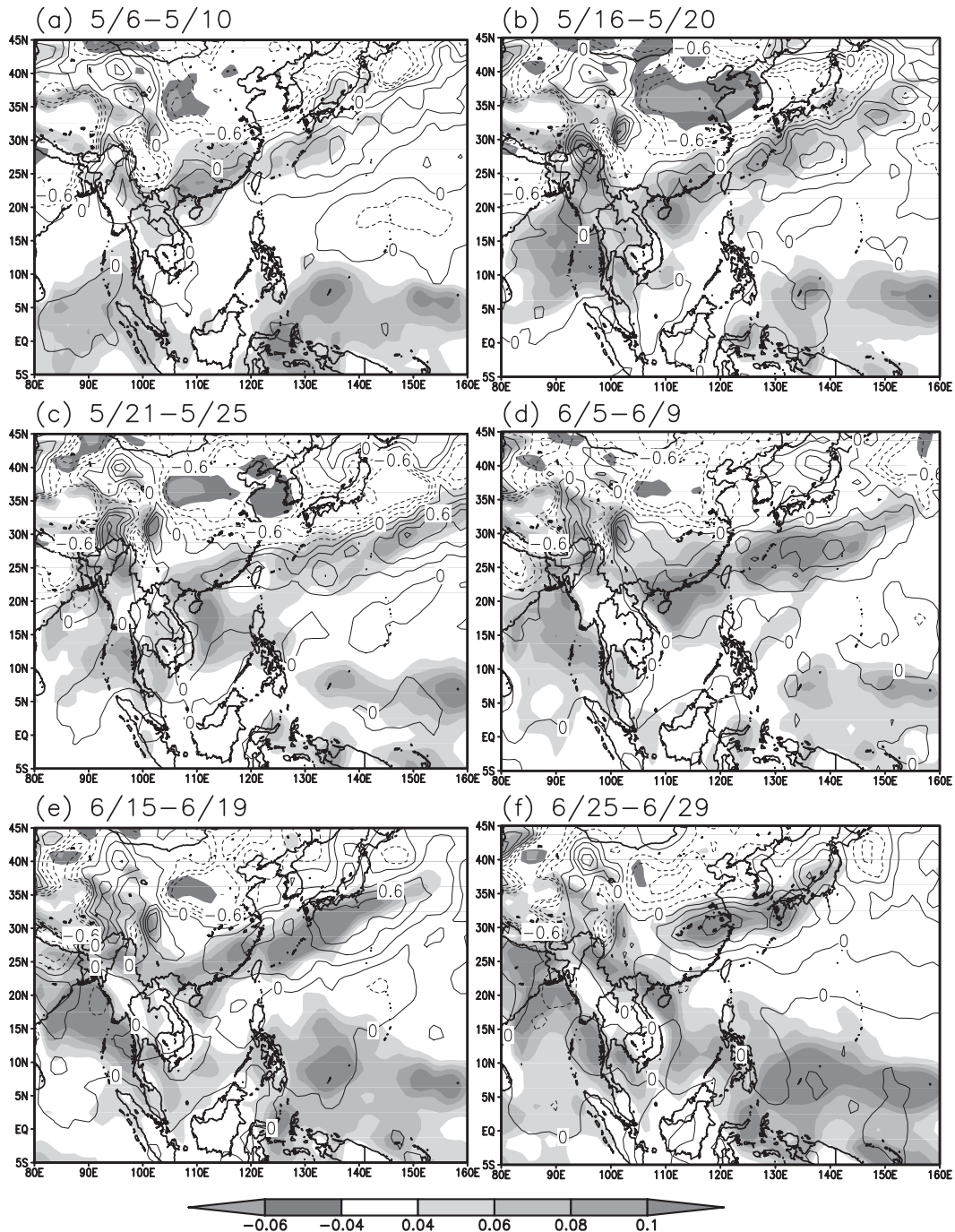


FIG. 6. Horizontal temperature advection (solid contours; contour interval  $0.2 \text{ K day}^{-1}$ ) and upward vertical pressure velocity  $-\omega$  (shading;  $\text{Pa s}^{-1}$ ) at 500 hPa for selected pentads during the Okinawa baiu: (a) 6–10 May, (b) 16–20 May, (c) 21–25 May, (d) 5–9 June, (e) 15–19 June, and (f) 25–29 June. Contours of horizontal temperature advection less than  $-0.6 \text{ K day}^{-1}$  are omitted.

Figure 10 shows the meridional term of temperature advection  $-v\partial T/\partial y$  and its component parts. The meridional term of temperature advection is large near Okinawa in mid-May (Fig. 10a) because the meridional temperature gradient is strong (Fig. 10b) and meridional

winds are moderate and southerly (Fig. 10c). The meridional temperature gradient weakens after mid-May, and the meridional term of temperature advection remains small throughout June even as the meridional wind strengthens. The occurrence of the baiu front over

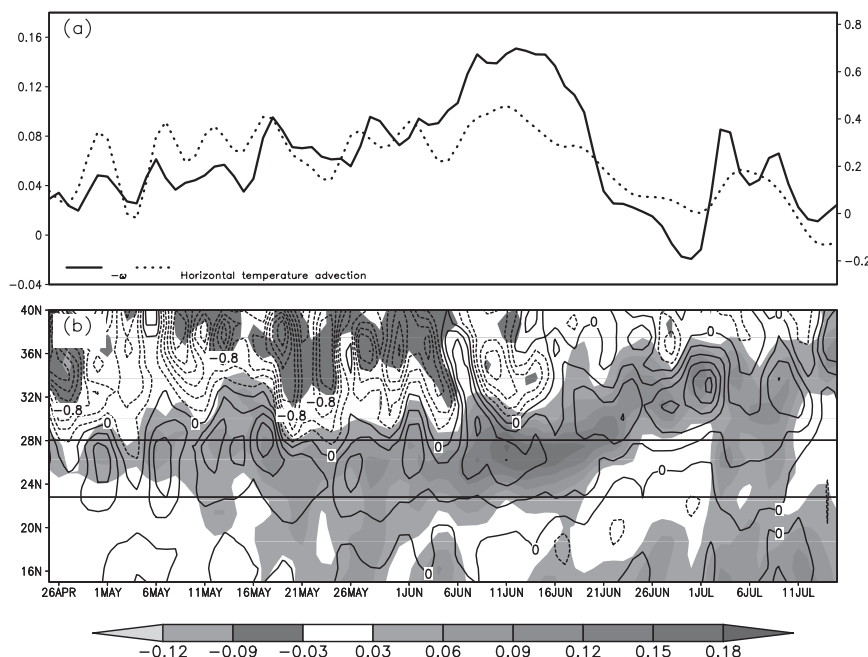


FIG. 7. (a) Time series of  $-\omega$  at 500 hPa (solid line; left axis;  $\text{Pa s}^{-1}$ ) and horizontal temperature advection at 500 hPa (dotted line; right axis;  $\text{K day}^{-1}$ ) averaged over the Okinawa region. Three-day running means are applied for smoothing. (b) Time-latitude plots of  $-\omega$  (shading) and 500-hPa horizontal temperature advection (solid contours; contour interval  $0.2 \text{ K day}^{-1}$ ) averaged over the longitudinal range  $123^{\circ}$ – $129^{\circ}\text{E}$ . Positive values denote upward vertical velocity and warm advection; negative values denote downward vertical velocity and cold advection. The black horizontal lines indicate the boundaries of the Okinawa region.

Okinawa in mid-May is due mainly to southerly winds in the presence of a north–south temperature contrast, while the baiu front over Okinawa in early and mid-June is due mainly to westerly winds in the presence of an east–west temperature contrast.

The warm advection mechanism proposed by Sampe and Xie (2010), in which westerly winds and an east–west temperature contrast combine to enhance warm advection and generate strong upward motion, can be used to explain the Okinawa baiu during June. This mechanism cannot explain the Okinawa baiu during May, as the warm advection during May is primarily due to the combination of southerly winds and a north–south temperature contrast.

## 6. Convective instability

In this section, we investigate the evolution of convective stability and its relationship with the Okinawa baiu. We calculate convective instability as the difference in moist static energy between 925 and 600 hPa. Large positive values indicate an unstable atmosphere. Convective instability is greater in the southern part of the Okinawa region, where SSTs are relatively

warm, than in the northern part, where SSTs are relatively cool.

The Okinawa region is weakly unstable to convection during May, when convective activity over the East China Sea is weak (Figs. 11a–c and 4a–f). Weak convective instability over the Okinawa region during mid-May becomes weakly stable conditions during late May (Fig. 11c). The region of convective instability then extends northward to approximately  $35^{\circ}\text{N}$  during June (Figs. 11d–f). This northward extension of the unstable region is associated with a northward extension of relatively warm SSTs. Convective instability remains high in the Okinawa region into late June, following the northward withdrawal of the Okinawa baiu. The evolution of convective instability is therefore unable to explain the full evolution of the Okinawa baiu season; by contrast, horizontal temperature advection offers a more consistent explanation from onset to withdrawal. Transient weather disturbances may also play a role.

## 7. Role of transient weather disturbances

In this section, we examine the role of transient disturbances such as synoptic-scale low pressure

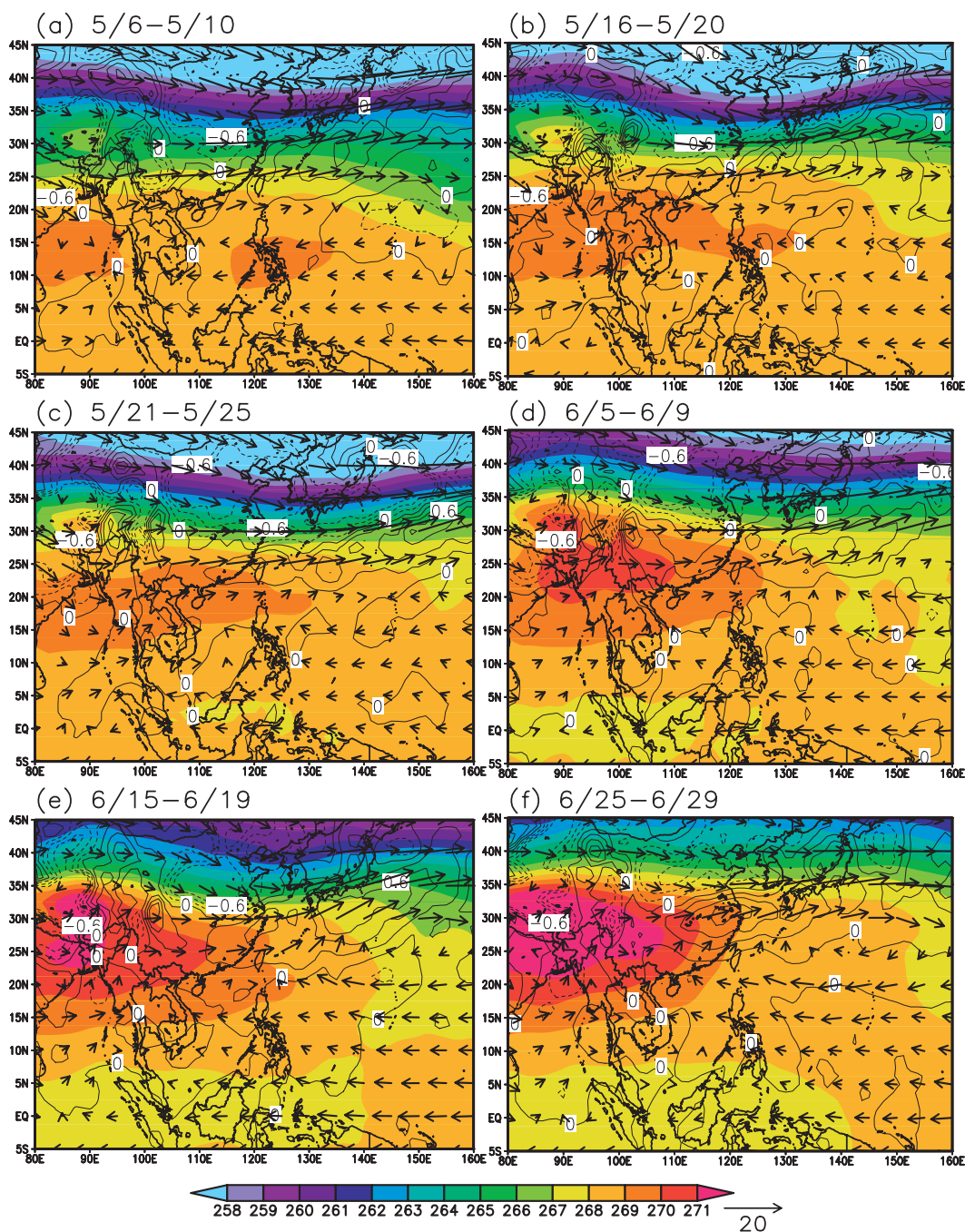


FIG. 8. Mean horizontal wind (arrows;  $\text{m s}^{-1}$ ), horizontal temperature advection (solid contours;  $0.2 \text{ K day}^{-1}$ ), and temperature (color shading; K) at 500 hPa for selected pentads during the Okinawa baiu: (a) 6–10 May, (b) 16–20 May, (c) 21–25 May, (d) 5–9 June, (e) 15–19 June, and (f) 25–29 June.

systems and typhoons in the evolution of the Okinawa baiu. Figure 12 shows transient eddy activity as measured by the standard deviations of selected meteorological variables during three distinct phases of Okinawa baiu development (initial peak in mid-May, short break in late May, and second peak in

June). We apply a high-pass filter with a cutoff period of 7 days.

Active disturbances in the meridional wind occur along the westerly jet stream during all three phases of baiu development (Figs. 12a–c). The region of active disturbances shifts southward toward Kyushu ( $30^{\circ}$ – $35^{\circ}\text{N}$ ,

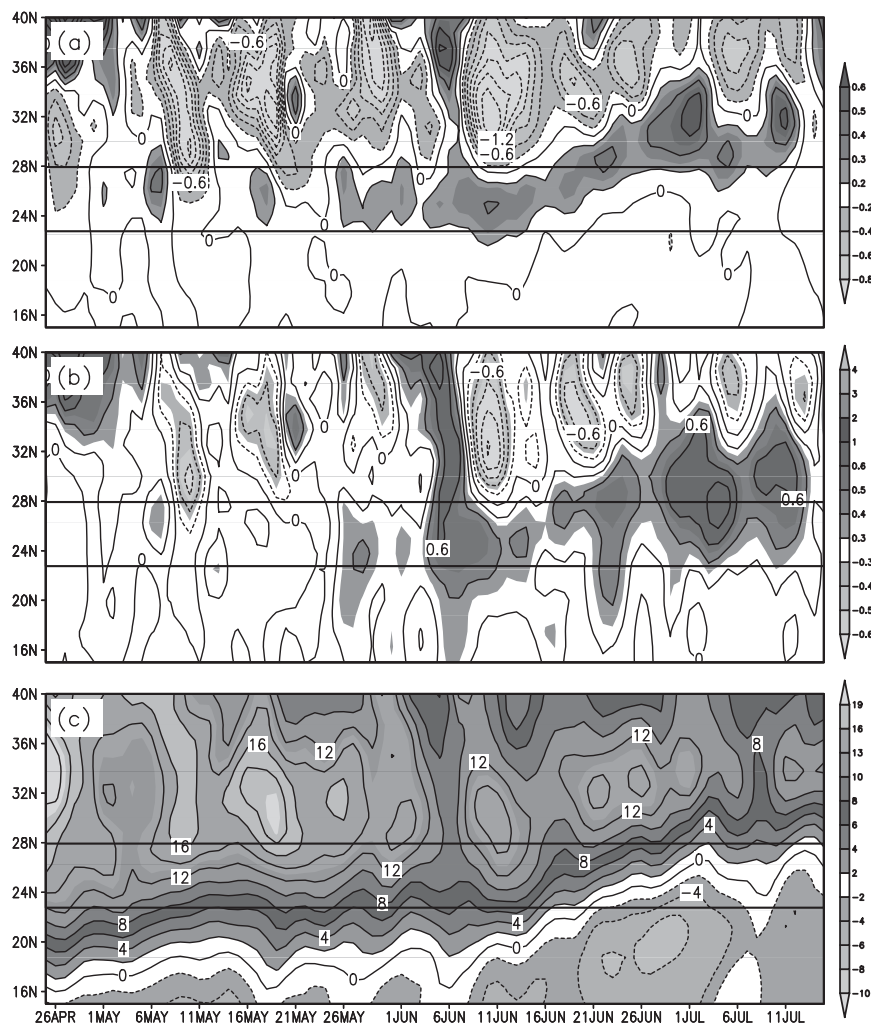


FIG. 9. Time-latitude plots of (a) zonal horizontal temperature advection (contour interval  $0.2 \text{ K day}^{-1}$ ), (b) zonal temperature gradient (contour interval  $0.2 \times 10^{-5} \text{ K m}^{-1}$ ), and (c) zonal wind (contour interval  $2 \text{ m s}^{-1}$ ). In (a)–(c) values are shown at 500 hPa averaged over the longitudinal band  $123^{\circ}$ – $129^{\circ}\text{E}$ . Three-day running means are applied for smoothing. The black horizontal lines indicate the boundaries of the Okinawa region.

$130^{\circ}\text{E}$ ) during the short break in the Okinawa baiu in late May (Fig. 12b), while it is situated over Okinawa during June (Fig. 12c). Transient variability in 500-hPa temperature is large northward of  $30^{\circ}\text{N}$  (Figs. 12d–f), and also shifts southward during the late May break in the Okinawa baiu (Fig. 12e). Fluctuations in low-level specific humidity in precipitation areas are large during the Okinawa baiu (Figs. 4d and 12g–i). As with meridional wind disturbances (Fig. 12b) and temperature variability (Fig. 12e), these fluctuations in specific humidity shift southward during the break period in late May (Fig. 12h). All three variables indicate that transient weather activity decreases in the Okinawa region during late June, when the Okinawa baiu withdraws (not shown). The seasonal evolution of precipitation in

the Okinawa region is generally consistent with that of transient weather disturbances as Sampe and Xie (2010). Relative to mid-June, the mid-May Okinawa baiu is more heavily affected by transient weather disturbances. This result is consistent with the intermittent nature of baiu precipitation events during May (Ishigaki 1982).

## 8. Summary and discussion

We have investigated the detailed climatological evolution of the Okinawa baiu. The Okinawa baiu season spans May and June, with an initial peak in precipitation during mid-May (Fig. 3a). This initial peak is explained by a strong north–south temperature gradient at 500 hPa and northward winds in the vicinity of Okinawa. These

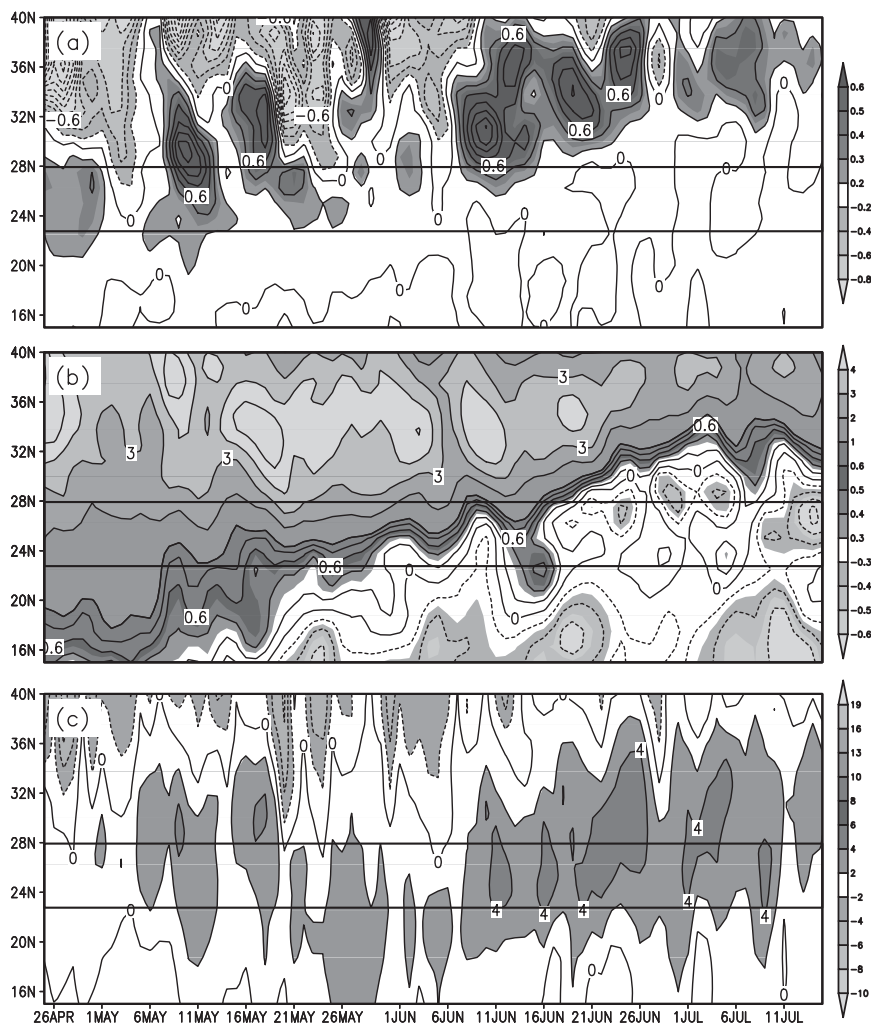


FIG. 10. As in Fig. 9, but for (a) meridional horizontal temperature advection (contour interval  $0.2 \text{ K day}^{-1}$ ), (b) meridional temperature gradient (contour interval  $0.2 \times 10^{-5} \text{ K m}^{-1}$ ), and (c) meridional wind (contour interval  $2 \text{ m s}^{-1}$ ).

two factors together produce warm advection and upward motion over Okinawa during mid-May (Fig. 10). Precipitation over Okinawa is reduced during late May when the baiu front shifts southeastward (Figs. 3 and 4c–d). A region of cold advection from the north shifts southward to cover the northern part of Okinawa during this period (Fig. 6c). We suggest a possibility that the southward migration of this region of cold advection causes a short break in the Okinawa baiu that coincides with the onset of the South China Sea (SCS) monsoon. Another possibility is that the SCS monsoon affects the Okinawa baiu, which will be discussed later. A strong east–west temperature gradient develops at 500 hPa during June. Together with westerly winds, this east–west temperature gradient leads to strong warm advection in the zonal direction (Fig. 9). This warm advection induces the baiu rainband to return to the Okinawa region. The

region of strong warm advection shifts northward from Okinawa in late June, and the Okinawa baiu withdraws.

Our results are broadly consistent with the warm temperature advection mechanism proposed by Sampe and Xie (2010). The behavior of the baiu rainband in the Okinawa region can be explained by seasonal variations in horizontal temperature advection at 500 hPa. The second peak of Okinawa baiu precipitation in June represents a southward extension of the mainland Japan baiu, which withdraws in late June when the region of strong warm advection shifts northward (Figs. 3b and 7b).

The behavior of the Okinawa baiu during May cannot be explained solely by warm advection. One factor that remains to be explored is the possible contribution of typhoons. Typhoons develop in the more uniform tropical atmosphere and are not related to large-scale warm

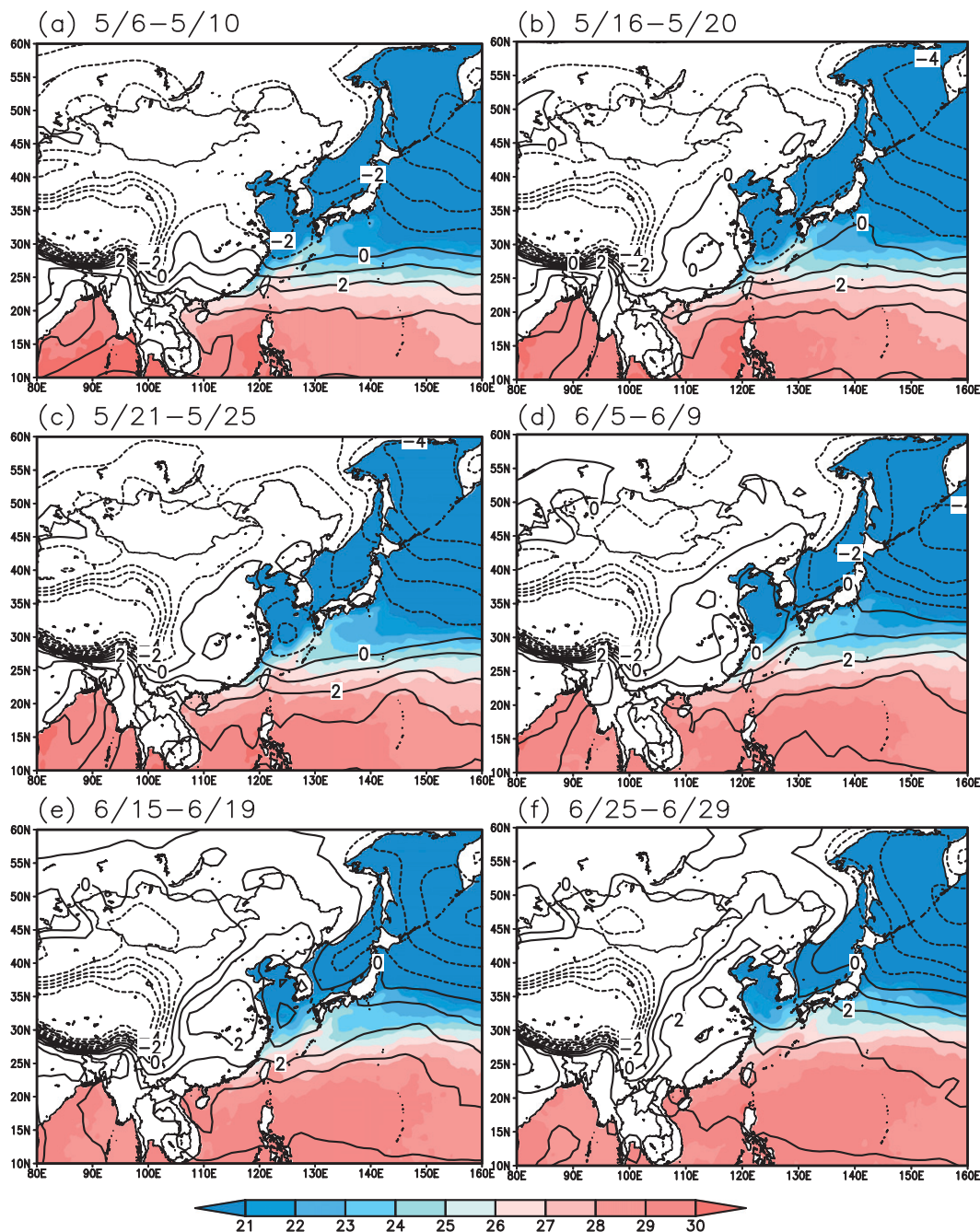


FIG. 11. Vertical gradients of moist static energy between 925 and 600 hPa divided by the specific heat at constant pressure [solid lines; contour interval  $1 \text{ K } (100 \text{ hPa})^{-1}$ ; large positive values indicate an unstable atmosphere] and SST (color shading,  $^{\circ}\text{C}$ ) for selected pentads during the Okinawa baiu: (a) 6–10 May, (b) 16–20 May, (c) 21–25 May, (d) 5–9 June, (e) 15–19 June, and (f) 25–29 June.

advection; therefore, the mechanism proposed by Sampe and Xie (2010) for baiu formation and maintenance does not apply. Typhoons sometimes make landfall in Okinawa during the May–June period. We select 5 years during which no typhoons approached to within 300 km of Okinawa for further study (1998, 1999, 2002, 2005, and

2006). The mid-May peak in mean precipitation amount over these 5 yr is  $7 \text{ mm day}^{-1}$ , approximately 60% of the 10-yr mean; however, the peak in mean precipitation amount during June changes little relative to the 10-yr mean. The latitude–time diagram of precipitation for this 5-yr subset (not shown) is qualitatively similar to

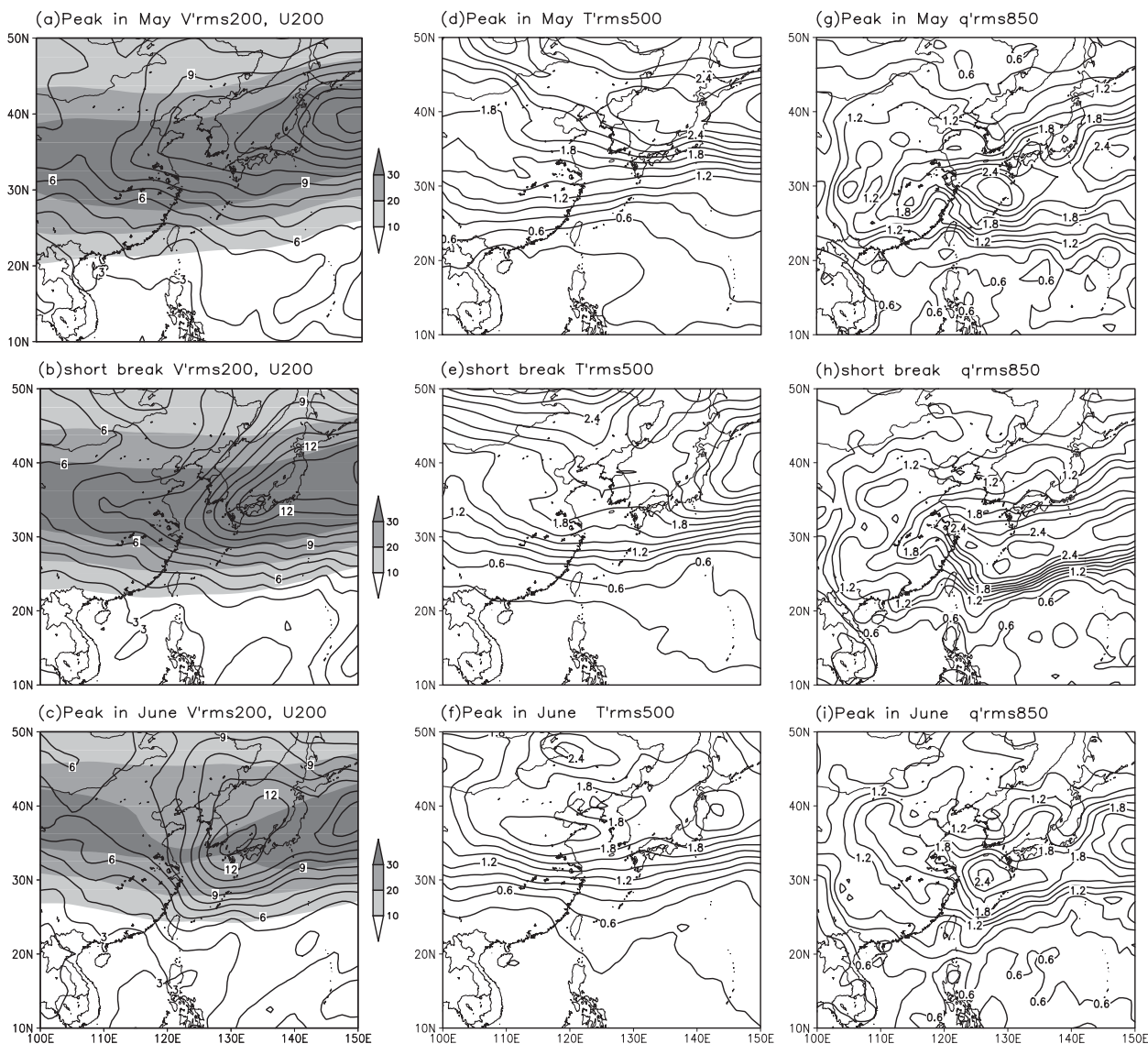


FIG. 12. Mean root-mean-square (rms) of high-pass-filtered (a)–(c) 200-hPa meridional wind (contours; contour interval  $1 \text{ m s}^{-1}$ ) and 200-hPa zonal wind speed (shading;  $\text{m s}^{-1}$ ), (d)–(f) 500-hPa temperature (contours; contour interval  $0.2 \text{ K}$ ), and (g)–(i) 850-hPa specific humidity (contours; contour interval  $0.2 \times 10^{-3} \text{ kg kg}^{-1}$ ) for selected pentads during the Okinawa baiu: (a), (d), (g) 16–20 May; (b), (e), (h) 21–25 May; and (c), (f), (i) 5–9 June.

the diagram for the full 10 years (Fig. 3). This result suggests that the 10-yr mean of mid-May precipitation is enhanced by typhoon activity, which brings convective rainfall but is not related to the large-scale frontal system.

We have also investigated the evolution of transient eddy disturbances during the May–June period. Typhoon is one of transient disturbances. In general, the evolution of transient eddy activity corresponds well to the evolution of the Okinawa baiu. Transient eddy activity is stronger during May than during June, and probably contributes to the peak in precipitation in mid-May.

We have investigated the response of the atmospheric circulation to convective heating under climatological mean conditions for May using the linear baroclinic model (LBM; Watanabe and Kimoto 2000), with particular focus on the relationship between the Okinawa baiu and the SCS monsoon. The introduction of an idealized heat source to the west of the Philippines ( $15^{\circ}\text{N}$ ,  $110^{\circ}\text{E}$ ) induces a low-level cyclonic circulation westward of  $115^{\circ}\text{E}$  and a low-level anticyclonic circulation eastward of  $115^{\circ}\text{E}$  (not shown; N. Kayaba 2012, personal communication). The latter includes the Okinawa region. This result suggests that convection over the

SCS acts to suppress precipitation over Okinawa and to the east of the Philippines, and supports our conclusion that the short break in the Okinawa baiu during late May is related to the onset of the SCS monsoon. This explanation cannot explain the southeastward shift in the precipitation area near Okinawa, however. Changes in the distribution of transient disturbances probably play a role in this southeastward shift (section 7).

Finally, we have investigated interannual variations in the Okinawa baiu using JRA-25 data over a longer time period (1979–2008). Precipitation in May is correlated with 500-hPa cold advection to the north of Okinawa, while precipitation in June is correlated with 500-hPa warm advection to the southeast of Okinawa. These results support our interpretations of differences between large-scale features associated with the Okinawa baiu in May and those associated with the Okinawa baiu in June. In this paper, we have focused solely on the climatological evolution of the Okinawa baiu; interannual variations are beyond the scope of this paper and will be presented separately.

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