The Intraseasonal Oscillation of the Lower-Tropospheric Circulation over the Western Pacific during the 1979 Northern Summer

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Abstract

An effort is made in this study to explore the intraseasonal (30-60 day) oscillation of the lower-tropospheric circulation over the western tropical Pacific. It is found that during the 1979 northern summer, the eastward propagation of the global-scale intraseasonal divergent mode induces quasi-periodic alternations of intraseasonal local divergent and convergent centers over the western Pacific. These alternations of intraseasonal local divergent and convergent centers result in the intraseasonal north-south migrations of the North Pacific Convergence Zone (NPCZ), i.e., the Mei Yu and Baiu fronts combined, and the South Pacific Convergence Zone (SPCZ). The regional circulations associated with the NPCZ and SPCZ also exhibit a coherent intraseasonal oscillation. With the intraseasonal local Hadley circulations and the intraseasonal streamfunction budget analysis of the lower-tropospheric circulation, it is shown that the aforementioned coherent intraseasonal oscillation is a response of the regional lower-tropospheric circulation to the eastward propagation of the global-scale intraseasonal oscillation.

1. Introduction

The most distinct element of the upper-tropospheric summer circulation portrayed by Krishnamurti (1971) over the Pacific Ocean is the mid-oceanic trough north of the equator. In contrast to this oceanic trough, there is also a weaker mid-oceanic trough in the Pacific Ocean south of the equator (Chen and Yen, 1991a). Corresponding to these two mid-oceanic upper-tropospheric troughs, two well-organized lower-tropospheric anticyclones exist in the Pacific north and south of the equator (Fig. 1a). In addition, a well-developed medium-scale anticyclone also appears over the cold landmass of Australia. The trades located between the two Pacific anticyclones transport the moist tropical air across the Pacific toward the westernmost tropical Pacific, the so-called warm pool. The warm moist air over the warm pool may move northward and merge with the warm moist air of the South-Asian monsoon westerlies to form the water vapor source of the North Pacific Convergence Zone (NPCZ), that is, the Mei-Yu and Baiu fronts combined (Chen et al., 1988a). The warm moist air from the warm pool may also flow along the South-Pacific anticyclone southward to meet the midlatitude cold dry air and to form the South Pacific Convergence Zone (SPCZ). As revealed from the precipitation distribution, the warm moist air that converges toward the warm pool maintains cumulus convection there, and the released latent heat maintains the upper-tropospheric divergent center of planetary-scale divergent circulation (Fig. 1b). The Intertropical Convergence Zone (ITCZ), the NPCZ, and the SPCZ radiate out of this divergent center.

It was shown by Chen (1987) that the intensity of the North-Pacific anticyclone and the Indian monsoon trough vary coherently during the northern summer with an intraseasonal time scale. Later, examining convective activities and water vapor transport along the NPCZ, Chen and Murakami (1988) and Chen et al. (1988a) found that the NPCZ undergoes an intraseasonal oscillation in response to the eastward propagation of the global-scale intraseasonal oscillation. These studies mainly focused on the intraseasonal oscillation of the lower-tropospheric circulation of the northwestern Pacific. Recently, Magaña and Yanai (1991) and Chen and Yen (1991a) pointed out that the mid-oceanic upper-tropospheric troughs over both the North and South Pacific exhibit a coherent intraseasonal oscillation during the northern summer. They argued that the intraseasonal oscillations of the two mid-oceanic Pacific troughs are induced by the eastward propagation of the global-scale intraseasonal oscilla-
Salient elements of the lower-tropospheric circulation over the western South Pacific (shown in Fig. 1) are the integrated part of the atmospheric circulation system over the entire Pacific Ocean. The intraseasonal oscillation mode of the divergent circulation that was identified by Lorenc (1984) and Krishnamurti et al. (1985) is global-scale not only longitudinally, but also latitudinally. The upper-tropospheric mid-oceanic troughs over the tropical Pacific (both north and south of the equator) can undergo intraseasonal oscillations induced by the eastward propagation of the global-scale intraseasonal oscillation mode. It is likely that pronounced elements of the lower-tropospheric circulation contain a coherent intraseasonal oscillation in both hemispheres over the western Pacific. However, no attempt has been made so far to explore this possibility. For both hemispheres over the western Pacific, we shall report in this study our finding about the coherent intraseasonal oscillation of some distinct circulation elements in the lower troposphere during the 1979 northern summer. The presentation of this paper is arranged as follows. Section 2 presents a coherent intraseasonal oscillation of the lower troposphere identified in the western Pacific. The synoptic structure of this intraseasonal oscillation, portrayed with streamlines and the divergent circulation associated with the intraseasonal oscillation, is discussed in Sections 3 and 4, respectively. In order to substantiate the hypothesis that this regional intraseasonal oscillation may be a response of the regional lower-tropospheric circulation to the eastward propagation of the global-scale intraseasonal oscillation mode, we construct the vertical cross-sections of intraseasonal local Hadley circulations in Section 5 and analyze the streamfunction budget of the lower-tropospheric circulation over the western Pacific in Section 6. Finally, some concluding remarks are offered in Section 7.

2. Data and intraseasonal oscillation

The data used in this study were derived from two sources: (1) the analyzed grid-point upper-air data and (2) precipitation. The upper-air data of the FGGE (1979) summer were generated by the Global Data Assimilation System (GDAS) of the European Centre for Medium Range Weather Forecasts. The precipitation data were created by a satellite data retrieval scheme designed by J. Susskind of Goddard Laboratory for Atmospheres (GLA) (Susskind and Pfaendtner, 1989). The horizontal resolution of the daily GLA precipitation data is 1°×1°. This data set has been used by Chen and Pfaendtner (1992) to delineate the atmospheric branch of the hydrological cycle during the 1978/79 northern winter and the 1979 northern summer. The daily velocity-potential (\(\chi\)) fields analyzed in this study were prepared by solving the Poisson equation in terms of the spherical harmonics with a 31-wave triangle truncation. To isolate the intraseasonal oscillation of any meteorological variable with a time scale of 30-60 days, the fourth-order Butterworth bandpass filter, introduced by Murakami (1979), is adopted.

Shown in Fig. 2a is the y-t diagram of the 30–60 day bandpass filtered 200-mb velocity potential \(\bar{\chi}\) at 150°E. \(\bar{\chi}\) (200 mb)\(^1\) is superimposed on the P y-t diagram. It is clearly seen in Fig. 2a that there is a coincidence between the divergent (convergent) center of the intraseasonal oscillation, indicated by negative (positive) \(\bar{\chi}\) (200 mb) anomalies over the western Pacific, and the north (south) end of the north-south migration of the precipitation band associated with the NPCZ. The thick solid lines are traced on Fig. 2a to indicate the north-south migration of the NPCZ precipitation band. This north-south migration is relatively consistent with that of the NPCZ cumulus convection band

\(^1\)\(\bar{\chi}\) denotes hereafter the 30–60 day bandpass filtered \(\chi\).
Fig. 2. The y-t diagrams of \( \bar{\chi} \) (200 mb) and precipitation averaged over a 10° longitudinal zone and centered at (a) 150°E and (b) 160°W. The thick solid lines in (a) denote the 30–60 day oscillation of P north of 20°N, while those in (b) indicate the 30–60 day oscillation of P south of 15°S. The positive value of \( \bar{\chi} \) (200 mb) is lightly shaded and precipitation larger than 3 mm day\(^{-1}\) is heavily shaded.

identified by Chen and Murakami (1988).

Following the approach described above, we also construct the y-t diagram of P and \( \bar{\chi} \) (200 mb) at 160°W (Fig. 2b) to illustrate the possible north-south migration of the precipitation band associated with the SPCZ. Thick solid lines indicating this north-south migration are sketched on Fig. 2b. Indeed, there is in fact a relatively regular north-south migration of precipitation associated with the SPCZ in an intraseasonal time scale. Surprisingly, this intraseasonal oscillation coincides with that revealed from the P-\( \bar{\chi} \) (200 mb) y-t diagram at 150°E, except that is has a slight phase lag. Note that the eastward propagation speed of the global-scale intraseasonal oscillation is about 8–10 ms\(^{-1}\). With this speed, it takes about 4–8 days for this low-frequency oscillation to move from 150°E to 160°W. Because of this, there should be a several day phase lag between intraseasonal oscillations shown in the P-\( \bar{\chi} \) (200 mb) y-t diagrams at 150°E and 160°W. Regardless of this slight phase lag, the coherency between intraseasonal oscillations of precipitation associated with the NPCZ and SPCZ implies that these two convergence zones respond coherently to the eastward propagation of the global-scale intraseasonal oscillation.

In view of the intraseasonal oscillation of the NPCZ and SPCZ described above, it is likely that some elements of the lower-tropospheric circulation coupled with these two convergence zones may also contain this low-frequency oscillation. In order to seek for this possibility, the distribution of the summer-mean \( \sqrt{\bar{u}^2 + \bar{v}^2} \) (850 mb)\(^{1/2} \) (=|V (850 mb)|), i.e., the 850-mb isotach, over the Pacific is shown in Fig. 3a. Several regions of significant |V (850 mb)| emerge over the western Pacific. The \( u \) (850 mb) and \( \bar{u} \) (850 mb) time series of two |V (850 mb)| centers associated with the NPCZ and SPCZ are displayed in Figs. 3b and 3c, respectively. Even without imposing the \( \bar{u} \) (850 mb) time series on the \( u \) (850 mb) time series, a distinct intraseasonal oscillation stands out clearly from the latter time series. Note that the two selected locations are separated by a distance of some six thousand kilometers. In spite of this distance, the \( u \) (850 mb) and \( \bar{u} \) (850 mb) time series of these two locations fluctuate coherently with an intraseasonal time scale. In addition, it is also of interest to note that the alternation between westerlies and easterlies of the 850-mb zonal winds at these two locations coincides, respectively, with the north and south end of the NPCZ and SPCZ.

The two examples of the coherent intraseasonal oscillation shown in Figs. 2 and 3 indicate that some elements of the lower-tropospheric circulation over the western Pacific, in both the Northern and Southern Hemispheres, must oscillate coherently with an intraseasonal time scale. However, without illustrations of the synoptic structure of these circulation elements, it is difficult, if not impossible, for us to imagine how this low-frequency oscillation behaves. Therefore, the next two sections are devoted to this purpose.

3. Synoptics of the lower-tropospheric intraseasonal oscillation

In order to illustrate synoptics of those lower-tropospheric circulation elements which contain an intraseasonal oscillation, we adopt the \( \bar{u} \) (850 mb)
Fig. 3. (a) The summer (May-August)-mean \[\bar{u} (850\text{mb})^2 + \bar{v} (850\text{mb})^2\]^{1/2} and time series of \(u (850\text{mb})\) (solid line) and \(u (850\text{mb})\) (dotted line) at (b) (150°E, 25°N) and (c) (170°W, 22.5°S). The contour interval of (a) is 0.25 ms\(^{-1}\) and the values larger than 1.0 ms\(^{-1}\) (1.5 ms\(^{-1}\)) are lightly (heavily) shaded.

Associated with the SPCZ (Fig. 3c) as an index for the selection of proper phases of the oscillation. As revealed from the \(\bar{u} (850\text{mb})\) time series at (170°W, 22.5°S), there are three phases of westerlies and three phases of easterlies. The \(\bar{u} (850\text{mb})\) index shown in Fig. 3 is almost synchronized with the \(\psi (200\text{mb})\) index used by Chen and Yen (1991a, their Fig. 2a) to indicate the intraseasonal oscillation of the uppertropospheric mid-Pacific troughs. The inphase oscillation between the \(\bar{u} (850\text{mb})\) index and Chen and Yen’s \(\psi (200\text{mb})\) index implies that the deepening and filling of the upper-tropospheric mid-Pacific troughs go hand-in-hand with the alternation between the lower-tropospheric easterlies and westerlies associated with the NPCZ and SPCZ at the two selected locations. Accordingly, we select a total of six 5-day phases which are centered at dates when \(\bar{u} (850\text{mb})\) reaches its maximum or minimum values of each \(\bar{u} (850\text{mb})\) cycle: three phases of maximum

\(\bar{u} (850\text{mb})\) (May 5-9, June 18-22, and July 24-28) and three phases of minimum \(\bar{u} (850\text{mb})\) (May 25-29, July 5-9, and August 13-17).

Recall that the summer-mean lower-tropospheric circulation over the Pacific Ocean consists of two major anticyclones located \textit{north} and \textit{south} of the equator. Additionally, a pair of medium-scale anticyclones exists over the westernmost Pacific: (1) a well-developed Australian anticyclone and (2) an ill-organized, inversed -omega high that is north of the former anticyclone. The latter medium-scale high coincides with the warm pool. The summer-mean precipitation mainly occurs along the NPCZ, ITCZ and SPCZ, which radiate out of the warm pool. The precipitation bands associated with the NPCZ and SPCZ are formed because the warm moist air transported from the tropics meets the cold dry air from midlatitudes. For all the six selected phases, streamlines constructed with 5-day-mean V (850 mb) are superimposed on the corresponding 5-day-mean precipitation (P), shown in Fig. 4. The 5-day-mean precipitation of all six selected phases (Fig. 4) is distributed in a way similar to the summer-mean precipitation. It is revealed from the contrast between Figs. 2 and 3 that the precipitation bands of the NPCZ and SPCZ oscillate coherently on an intraseasonal time scale in the north-south direction with the \(u (850\text{mb})\) time series associated with these two convergence zones. Comparing the precipitation y-t diagrams at both 150°E and 160°W (Fig. 2), particularly in the midlatitudes of both hemispheres, with the precipitation bands around the anticyclones in the Pacific (Fig. 4) for different phases of the \(\bar{u} (850\text{mb})\) index, we can see that the north-south migration of the precipitation bands along the NPCZ and SPCZ results from the time evolution of these Pacific anticyclone systems.

During the low \(\bar{u} (850\text{mb})\) index, two anticyclonic gyres appear in the North Pacific (the left column of Fig. 4). The anticyclone to the west has its south branch located close to 25°N. Thus, easterlies emerge in the \(u (850\text{mb})\) time series (Fig. 3b). In the meantime, the north branch of this anticyclone is located around 40°N, and the precipitation band around its northern rim is moved to that latitude. This is why the precipitation band reaches the north end of its north-south migration, as revealed from the P y-t diagram. In the Southern Hemisphere, there is a pair of medium-scale anticyclones in the vicinity of Australia: one exists over the Australian continent and the other over the ocean east of Australia. The northern branch of the latter anticyclone is located around 22.5°S and results in easterlies, shown in the \(u (850\text{mb})\) time series at (170°W, 22.5°S). The precipitation bands attached to the former anticyclone are on its western rim adjacent to the Australian continent and on its northern rim, which is also the north end in the north-south mi-
Fig. 4. The 5-day-mean 850-mb streamlines superimposed on 5-day-mean precipitation for the six selected phases: three low (May 5–9, June 18–22, July 24–28) and three high (May 25–29, July 5–9, August 13–17) \( \bar{u} \) (850 mb) indices. Precipitation larger than 3 (7) mm day\(^{-1} \) is lightly (heavily) shaded.

One may question here what may cause a quasi-periodic variation of the lower-tropospheric circulation over the western Pacific such as that depicted above. To answer this question, let us first understand the contribution of the intraseasonal-oscillation mode to the synoptic change of the lower-tropospheric circulation. The intensity of atmospheric circulation reaches its summer extreme about a month after the summer solstice (e.g. Wiin-Nielsen, 1967). The 5-day-mean streamlines for July 19–23 are shown in Fig. 5a. They are constructed by combining the summer-mean, \( \bar{V} \) (850 mb), and the low-frequency component of \( V \) (850 mb) with a period longer than 60 days and shorter than 123 days (the time span of data analyzed in this study), \( \bar{V} \) (850 mb). The salient features of the lower-tropospheric circulation that are portrayed with \( \bar{V} \) (850 mb) + \( V \) (850 mb) do not differ significantly from those portrayed with \( V \) (850 mb)
Fig. 5. (a) The 5-day (July 19-23) -mean 850-mb streamlines constructed with $V (850 \text{ mb})$ and $V_D (850 \text{ mb})$, and (b) the 5-day (July 19-23) -mean $(\chi + \dot{\chi}, V_D + \dot{V})$ (200 mb). Note that $(\cdot) = \text{summer-mean} (\cdot)$ and $(\cdot) = \text{60-123 day bandpass filtered} (\cdot)$ during summer (May-August). The positive $(\chi + \dot{\chi}) (200 \text{ mb})$ values are shaded and the contour interval of $(\chi + \dot{\chi}) (200 \text{ mb})$ is $2 \times 10^5 \text{ m}^2 \text{s}^{-1}$.

For the three phases of low $\bar{u} (850 \text{ mb})$ index, it is shown in Fig. 6 that two major anticyclones of the intraseasonal-oscillation mode appear in the North Pacific: one circles around Japan and the other is centered south of the Bay of Alaska. The two separate anticyclonic gyres of the North Pacific, shown in Fig. 4 for the three corresponding phases, are mainly formed by the summer-mean North Pacific anticyclone (Fig. 1a) and the two anticyclones of the intraseasonal-oscillation mode shown in Fig. 6. In the South Pacific adjacent to Australia, there is a dipole structure to the intraseasonal-oscillation mode: a cyclonic cell located either east of or over Australia and an anticyclonic cell over the ocean east of Australia. The combination of this dipole with the summer-mean Australian anticyclone and part of the major South-Pacific anticyclone results in the slightly westward shift of the Australian anticyclone and the appearance of the anticyclone east of Australia. During the three phases of low $\bar{u} (850 \text{ mb})$ index, the Japan anticyclone cell of the intraseasonal-oscillation mode has its south branch passed through $(150^\circ \text{E}, 25^\circ \text{N})$, and the oceanic anticyclone cell of the intraseasonal-oscillation mode east of Australia passed through $(170^\circ \text{W}, 22.5^\circ \text{S})$. Thus, the $\bar{u} (850 \text{ mb})$ time series at these two locations reach their minimum values in these three phases.

During the three phases of high $\bar{u} (850 \text{ mb})$ index, the intraseasonal-oscillation components of the lower-tropospheric circulation, depicted above for the three phases of low $\bar{u} (850 \text{ mb})$ index, reverse their directions. The North-Pacific anticyclone shown in Fig. 1 and Fig. 5 is altered in such a way that the flow along its northwest rim is strengthened toward the center of the anticyclonic gyre, and the strong lower-tropospheric flow around Japan is moved southeastward. In the Southern Hemisphere, the intraseasonal anticyclone over Australia intensifies the summer-mean Australian anticyclone, and the cyclonic cell of the intraseasonal-oscillation mode east of Australia weakens the western part of the major South-Pacific anticyclone. For the three phases being discussed, the $\bar{u} (850 \text{ mb})$ time series obtain their maximum values, as indicated by Fig. 3b and 3c, because of the reversal of the intraseasonal oscillation components of the lower-tropospheric circulation from the three opposite phases.

Besides the intraseasonal oscillation of the medium-scale anticyclones described above, a clear alternation emerges in the direction of the basin-scale lower-tropospheric circulation over the Pacific between low and high $\bar{u} (850 \text{ mb})$ indices (Fig. 6). During low $\bar{u} (850 \text{ mb})$ index, the Pacific of each hemisphere is occupied by the basin-scale anticyclonic flow with distinct easterlies across the tropical Pacific. The direction of the 850-mb intraseasonal circulation is reversed to cyclonic during a high $\bar{u} (850 \text{ mb})$ index. Chen and Yen (1991a) pointed out that the upper-tropospheric mid-Pacific troughs and the North-Pacific anticyclones undergo a coherent intraseasonal oscillation. Based upon the comparison of the $\bar{u} (850 \text{ mb})$ and $\bar{v} (200 \text{ mb})$ indices, and upon the alternation in direction of the basin-scale 850-mb intraseasonal oscillation (Fig. 6), we may conclude that a coherent intraseasonal oscillation exists among pronounced elements of the Pacific’s atmospheric circulation in both the upper and lower troposphere.
4. Intraseasonal oscillation of the divergent circulation

It has been pointed out previously that the north-south migration of the NPCZ (Chen and Murakami, 1988) and the intraseasonal oscillation of the Pacific oceanic troughs (Chen and Yen, 1991a) are responses of regional circulation component over the Pacific to the eastward propagation of the global-scale intraseasonal mode. It is likely that the coherently intraseasonal oscillations of the lower-tropospheric circulation systems associated with the NPCZ and SPCZ (described in Section 2) are also responses of regional circulation systems to the eastward propagation of the global-scale intraseasonal mode. Numerous studies (e.g., Lorenc, 1984; Krishnamurti et al., 1985; Chen et al., 1988b, and many others) have shown that velocity potential ($\nabla \chi$) is the most sensitive variable for portraying the global-scale intraseasonal mode. Thus, we shall devote this section to examining how the regional divergent circulation over the Pacific, particularly over the western part, responds to the eastward-propagating intraseasonal mode.

For all six phases determined by the $u$ (850 mb) index, the 5-day-mean divergent circulations, depicted in terms of $\nabla \chi$ (200 mb) and $V_D$ (200 mb) [$= \nabla \chi$ (200 mb)] and superimposed on the 5-day-mean precipitation, are shown in Fig. 7. During the three phases of low $u$ (850 mb) index, the large-scale $\nabla \chi$ (200 mb) pattern is dominated by a significant east-west cellular structure with a major negative center located over the westernmost Pacific and a positive center located over the eastern Pacific. As indicated by $V_D$ (200 mb) vectors, a major divergent center exists around the Taiwan-Philippines region, and a minor divergent center appears in Central America. On the other hand, this large-scale east-west cellular $\nabla \chi$ (200 mb) pattern yields to a north-south structure which has positive values of $\nabla \chi$ (200 mb) in the South Pacific during the three phases of high $u$ (850 mb)
The major divergent center in these three phases migrates somewhat northeastward and is located south of Japan, while the minor divergent center over Central America is intensified. Regardless of their fine structure, the contrast of the $\chi$ (200 mb) fields between low and high $\tilde{u}$ (850 mb) indices alludes to the existence of a systematic east-west alternation of $\chi$ (200 mb) over the Pacific Ocean.

Shown in Fig. 8 are the intraseasonal 200-mb divergent-circulation components for the six selected $u$ (850 mb) phases. The flip-flop alternation of positive and negative $\chi$ (200 mb) is very systematic between the low and high $\tilde{u}$ (850 mb) indices. In the three phases of the former index, a divergent center of $(\tilde{\chi}, \tilde{V}_D)$ (200 mb) is located over the westernmost Pacific (the left column of Fig. 8), and a convergent center is located over either Central America or the eastern Pacific. The reversed situation occurs in the phases of high $\tilde{u}$ (850 mb) index (the right column of Fig. 8). The comparison of $(\chi, V_D)$ (200 mb) (Fig. 7) and $(\chi + \tilde{\chi}, \tilde{V}_D + \tilde{V}_D)$ (200 mb) (Fig. 5b) reveals clearly that the systematic alternation of the divergent circulation over the Pacific basin is not caused by the seasonal-cycle mode. Chen et al. (1988b) showed that both the annual-cycle and intraseasonal modes contribute about 40% each to the total variance of $\chi$ (200 mb) fields during December 1978–November 1979. By contrasting Figs. 7 and 8, we can infer that the systematic alternation of the divergent circulation over the Pacific is attributable to the $\chi$ (200 mb) intraseasonal oscillation. Shown in Fig. 9 are the $\tilde{\chi}$ (200 mb) and $\chi$ (850 mb) x-t diagrams at the equator. Both $\tilde{\chi}$ (200 mb) and $\chi$ (850 mb) exhibits a relatively regular eastward propagation of the intraseasonal mode during the 1979 summer. Apparently, the systematic alternation of the regional divergent circulation over the Pacific results essentially from the eastward propagation of the intraseasonal mode.

It was shown by Chen and Murakami (1988) that the intraseasonal oscillation can profoundly affect cumulus convection and precipitation over the East
Fig. 8. Same as Fig. 6, except for \((\tilde{x}, \tilde{V}_D)\) (200 mb). The contour interval is \(10^6 \text{ m}^2\text{s}^{-1}\).

Fig. 9. The \(x-t\) diagrams of (a) \(\tilde{x}\) (200 mb) and (b) \(\tilde{x}\) (850 mb) at the equator. The contour interval is \(5 \times 10^5 \text{ m}^2\text{s}^{-1}\).

Asian monsoon region. As shown in Fig. 7, there are three precipitation areas during the low \(\tilde{u}\) (850 mb) index: (1) extending northeastward from east China, across Japan, to the ocean adjacent to Japan, (2) covering the warm pool-ITCZ and centering in the ocean east of the Philippines, and (3) extending southeastward from the east coast of Australia to the ocean southeast of the continent. During the three phases of the high \(\tilde{u}\) (850 mb) index, changes occur in the three aforementioned precipitation areas: (1) the precipitation region across Japan disappears because of the eastward migration of this precipitation band; (2) the precipitation region containing part of the warm pool and the ITCZ is weakened; and (3) the precipitation band attached to the east coast of Australia either weakens [in the first phase of the high \(\tilde{u}\) (850 mb) index] or disappears [in the other two phases of the high \(\tilde{u}\) (850 mb) index]. Comparing the intraseasonal divergent circulation \((\tilde{x}, \tilde{V}_D)\) (200 mb) shown in Fig. 8 and the precipitation distribution shown in Fig. 7, one would be surprised to find that the three aforementioned precipitation regions coincide with local divergent centers of \((\tilde{x}, \tilde{V}_D)\) (200 mb) over these regions during the three phases of the low \(\tilde{u}\) (850 mb) index.
These local divergent centers reverse to local convergent centers during the three phases of the high $\bar{u}$ (850 mb) index. According to the water-budget equation, precipitation is primarily maintained by the convergence of water vapor flux. If the phase change does not occur, water vapor is a passive quantity. The convergence and divergence of water vapor flux is determined by the lower-tropospheric divergent circulation. Based upon Fig. 8, water vapor converges (diverges) toward (out of) local upper-level divergent (convergent) centers over the westernmost Pacific during the three low (high) $\bar{u}$ (850 mb) indices. Recall that the major water vapor is transported by the rotational component of water vapor flux. It can be inferred from the contrast between Figs. 6 and 8 that the systematic variations of the $\bar{\psi}$ (850 mb) and $\bar{\chi}$ (200 mb) intraseasonal oscillations are in concert over the Pacific. The appearance of the $\bar{\chi}$ (200 mb) divergent center over the western Pacific during the three phases of the low $\bar{u}$ (850 mb) index takes place when the lower-tropospheric $\bar{\psi}$ (850 mb) circulation transports the warm moist air toward the western Pacific. In contrast, the $\bar{\chi}$ (200 mb) divergent center yields to the $\bar{\chi}$ (200 mb) convergent center during the three phases of high $\bar{u}$ (850 mb) index, and the lower-tropospheric $\bar{\psi}$ (850 mb) circulation transports the warm moist air out of the western tropical Pacific.

In view of the systematic eastward propagation of the intraseasonal oscillation revealed from the equatorial x-t diagrams of $\bar{\chi}$ (200 mb) and $\bar{\chi}$ (850 mb), the coherent variations of $\bar{\chi}$ (200 mb) and $\bar{\psi}$ (850 mb) shown in Figs. 6 and 8 lead us to gather that intraseasonal oscillations of several lower-tropospheric circulation elements over the western Pacific result from the eastward propagation of the global-scale intraseasonal mode.

5. Intraseasonal local hadley circulations

The contrast between the equatorial x-t diagrams of $\bar{\chi}$ (200 mb) and $\bar{\chi}$ (850 mb) that were shown in Fig. 9 suggests that the intraseasonal mode of the global-scale divergent circulation may extend vertically over the entire depth of troposphere. Because of its vertical extent, it is possible that the eastward-propagating intraseasonal mode interacts dynamically with some lower-tropospheric circulation elements. Moreover, it is revealed from the y-t diagrams of $\bar{\chi}$ (200 mb) and precipitation at 150°E (Fig. 2a) and 160°W (Fig. 2b) that both the NPCZ and SPCZ exhibit a coherent north-south migration with an intraseasonal time scale. In order to illustrate the vertical extent of the intraseasonal divergent mode, we construct the intraseasonal local Hadley circulation at these two longitudes in terms of a meridional mass flux function

$$M_D = \int_P^P \bar{v}_D dp$$

for the six selected phases of the $\bar{u}$ (850 mb) index. In Eq. (1), $\bar{v}_D$ is the 30–60 day filtered meridional divergent wind, and $p$ and $p_0$ are pressure at a given level and at 1000 mb, respectively. Of course, the mass flux function of $M_D$ may not be exactly the same as the mass flux function obtained from the continuity equation that included the zonal divergence. However, Chen et al. (1988b) showed that the circulation direction depicted by $M_D$ is relatively consistent with vectors constructed with $(\bar{v}_D, \bar{\theta})$. In order to avoid redundancy and to connect the coherent north-south oscillation between the NPCZ and SPCZ, we shall only present the meridional mass fluxes $M_D$ averaged over the 10° longitudinal zones centered at 150°E and 160°W. The direction convention of the meridional mass flux function is clockwise (counterclockwise) if $M_D \geq 0$ ($\leq 0$).

According to Eq. 8, during the low $\bar{u}$ (850 mb) index the 30°N divergent center of $(\bar{\chi}, \bar{V}_D)$ (200 mb) southeast of Japan and the 30°S convergent center along the east coast of Australia yield to convergent and divergent centers, respectively, in the high $\bar{u}$ (850 mb) index. Because of this reason, we shall use 30°N and 30°S as reference latitudes. Along 150°E (Fig. 10), the 30°N downward branch of the intraseasonal local Hadley circulation during the low $\bar{u}$ (850 mb) index is replaced by an upward branch in the high $\bar{u}$ (850 mb) index. In the meantime, the 30°S upward branch of the intraseasonal local Hadley circulation during the low $\bar{u}$ (850 mb) index becomes downward in the high $\bar{u}$ (850 mb) index. At 160°W (Fig. 11), the 30°S downward branch of the intraseasonal local Hadley circulation during the low $\bar{u}$ (850 mb) index is reversed to be an upward branch during the high $\bar{u}$ (850 mb) index. These downward and upward branches of the intraseasonal local Hadley circulations coincide with the convergent and divergent centers of $(\bar{\chi}, \bar{V}_D)$ (200 mb) shown in Fig. 8, respectively. These systematic alternations between upward and downward motions associated with the intraseasonal local Hadley circulation enhance or suppress cumulus convection at locations of these upward and downward motions and result in the intraseasonal north-south migrations of the NPCZ and SPCZ.

It is also revealed from Figs. 10 and 11 that the intraseasonal local Hadley circulations cover the entire depth of the troposphere. Because of this vertical extent, the eastward-propagating intraseasonal divergent circulation should be able to interact dynamically in some way with the regional lower-tropospheric circulation over the western Pacific (as depicted in Figs. 4 and 6) through the intraseasonal local Hadley circulations.
Fig. 10. The intraseasonal meridional mass flux ($\bar{M}_D$) at 150°E for the six selected phases. The positive values of $\bar{M}_D$ are shaded and the contour interval of $\bar{M}_D$ is 25 m mb s$^{-1}$.

Fig. 11. Same as Fig. 9, except at 160°W.

6. The $\bar{\psi}$ (850 mb) budget analysis

According to the vorticity equation, vorticity, which is the Laplacian of streamfunction, is generated by the vorticity source. In turn, the streamfunction tendency, i.e. the local rate of change of streamfunction, can be induced by the inverse Laplacian $[\nabla^{-2}(\cdot)]$ of vorticity source. Because streamlines function synoptically as streamfunctions, the 850-mb streamline synoptic charts of Fig. 6 can be well represented with the intraseasonal 850-mb streamfunction $\bar{\psi}$ (850 mb). Thus, the interaction between the intraseasonal divergent mode and regional rotational flow can be illustrated diagnostically through the streamfunction budget analysis. For a detailed formulation of the $\bar{\psi}$ budget equation, readers are referred to Chen and Yen (1991a). It is sufficient here to present the final form of the equation:

$$\frac{\partial \bar{\psi}}{\partial t} = -\nabla^{-2} \left[ \bar{\nabla}_\psi \cdot \nabla \zeta + \bar{\nabla}_\psi \cdot \nabla (\bar{\zeta} + f) + \bar{V}_\psi \cdot \nabla \zeta' \right]$$

$$-\nabla^{-2} \left\{ \nabla \cdot \left[ \bar{V}_D \bar{\psi}_x (\bar{\zeta} + f) + \bar{V}_x \bar{\psi} + \bar{V}_D \bar{\psi}_x \right] \right\}_F$$

$$+ \nabla^{-2} \bar{F},$$

where $\bar{\cdot}$ = $\bar{\cdot} - \bar{\cdot}$, i.e., daily ( ) departure from its seasonal mean, and $\bar{\cdot}$ = seasonal-mean ( ). $\bar{\psi}_{AV}$ and $\bar{\psi}_x$ are the $\bar{\psi}$ tendencies induced by horizontal advection associated with rotational flow and by the
vorticity source, respectively. The nonlinear interaction terms, $-\nabla^{-2}(V'\zeta')$ and $-\nabla^{-2}[\nabla \cdot (V'\chi')]$, contain contributions to intraseasonal oscillation from interactions between various time-scale modes. This approach makes the computation of nonlinear interaction terms manageable. Using the residual method, the budget analysis of (2) in our diagnostic computation reveals that $\psi_F$ is generally much smaller in magnitude than either $\psi_{AV}$ or $\psi_X$. Thus, we may approximate (2) as

$$\tilde{\psi}_t \approx \tilde{\psi}_{AV} + \tilde{\psi}_X.$$  

(3)

The time evaluation of $\tilde{\psi}$ is apparently accomplished by the mutual adjustment between physical processes represented by $\psi_{AV}$ and $\psi_X$. Based upon scale analysis and our diagnostic computation, the interaction between $\tilde{\psi}$ and $\chi$ can be established through the following approximated relation:

$$\tilde{\psi}_X \simeq \nabla^{-2} \left[ \nabla \cdot \left( \tilde{V}_D f \right) \right] \equiv \tilde{\psi}_{X1}.$$  

(4)

Because $f$ is a function of latitude only, $\tilde{\psi}_{X1}$ provides a direct channel to revealing the effect of the global-scale $\chi$ mode on the time evolution of the $\psi$ field. Assuming $\psi$ is represented by sinusoidal waves and $\psi_{AV}$ is approximated by linear terms, one may obtain

$$\tilde{\psi}_{AV} \approx -i\tilde{\psi},$$  

(5)

where $i = (-1)^{1/2}$. Equation (5) indicates that a quadrature relationship exists between $\psi$ and $\psi_{AV}$ both in time and in space. If the time variation of $\psi_{X1}$ follows that of $\chi$, and if $\psi_X$ and $\psi_{AV}$ counterbalance each other at all times, the effect of the eastward propagation of the global-scale $\chi$ mode on $\psi$ can be realized through the chain relation $\chi \rightarrow (4) \tilde{\psi}_{X1} \rightarrow (5) \tilde{\psi}$. We shall use the $y$-$t$ diagrams of these quantities of this chain relation at some particular longitudes to illustrate how the interaction between $\chi$ (850 mb) and $\psi$ (850 mb) may result in intraseasonal oscillations of those lower-tropospheric circulation components over the western Pacific.

Shown in Fig. 12 are the 850-mb $y$-$t$ diagrams of $\tilde{\psi}$, $\tilde{\psi}_{AV}$, $\tilde{\psi}_X$, and $\chi$ averaged over two longitudinal zones (145°−150°E and 170°−165°W). These longitudinal zones cut through the 850-mb intraseasonal circulation cells (Fig. 6) east of Japan and Australia. On the two top panels of Fig. 12, the negative (positive) $\psi$ (850 mb) values denote the cyclonic (anticyclonic) flow in the Northern Hemisphere, but this convention is reversed in the Southern Hemisphere. Emerging from these two panels is a systematic north-south alternation of positive and negative $\psi$ across the equator that has a period of about 45 days. This alternation of $\psi$ (850 mb) values means that direction changes of intraseasonal circulations east of Japan and Australia are synchronized. In the two bottom panels of Fig. 12, the $\chi$ (850 mb) $y$-$t$ diagrams also show a very systematic alternation of this variable. This systematic alternation is attributed to the relatively regular eastward propagation of the global-scale intraseasonal $\chi$ (850 mb) model shown in Fig. 9. However, we may wonder here how this eastward-propagating global-scale $\chi$ mode interacts
with the intraseasonal $\psi$ (850 mb) oscillation over the western Pacific.

It was shown in Eq. (4) that $\psi_x \approx \psi_{x1}$. This approximation is confirmed by the resemblance between the y-t diagrams of these two quantities, shown in rows three ($\psi_x$) and four ($\psi_{x1}$) of Fig. 12. Because $\chi$ (850 mb) maintains the same sign over the two hemispheres and Coriolis parameter $f$ changes its sign across the equator, we expect that $\psi_{x1}$ (850 mb) changes its sign as $f$ does across the equator. In fact, this is the case, as revealed by contrasting the $\chi$ (850 mb) and $\psi_{x1}$ (850 mb) y-t diagrams. Thus, the eastward propagation of the intraseasonal $\chi$ (850 mb) oscillation results in the time evolution of $\psi_{x1}$ (850 mb) and in turn that of $\psi_x$ (850 mb).

The y-t diagrams of $\psi_{AV}$ (850 mb) are displayed in row two of Fig. 12. As revealed from this figure, the signs between $\psi_x$ (850 mb) [or $\psi_{x1}$ (850 mb)] and $\psi_{AV}$ (850 mb) are more or less opposite. It is indeed implicated by the opposite signs of these two quantities that the $\psi$ (850 mb) tendencies induced by vorticity source and by horizontal advection associated with rotational flow of intraseasonal oscillation counterbalance each other. Thus, the $\psi$ (850 mb) tendency results primarily from the mutual adjustment between $\psi_x$ (850 mb) and $\psi_{AV}$ (850 mb), as Eq. (3) predicts. Because of the counterbalance between $\psi_{AV}$ (850 mb) and $\psi_x$ (850 mb), the time variation of $\psi_{AV}$ (850 mb) ensures the time variation of $\psi_x$ (850 mb) from the low to high $u$ (850 mb) index or vice versa. Finally it was predicted by Eq. (5) that there is a quadrature relation in time between $\psi$ (850 mb) and $\psi_{AV}$ (850 mb). This theoretical argument is supported by the contrast between the y-t diagrams of $\psi$ (850 mb) and $\psi_{AV}$ (850 mb) shown in Fig. 12. In view of this discussion concerning the $\psi$ (850 mb) budget, the interaction between $\chi$ (850 mb) and $\psi$ (850 mb) can be accomplished by the chain relation $\chi$ (850 mb) $\rightarrow$ $\psi_{x1}$ (850 mb) [or $\psi_x$ (850 mb)] $\rightarrow$ $\psi_{AV}$ (850 mb) $\rightarrow$ $\psi$ (850 mb).

Apparently, intraseasonal oscillations of the lower-tropospheric circulation cells over the western Pacific can respond to the eastward-propagating $\chi$ (850 mb) mode through the aforementioned chain relation.

The y-t diagrams of the $\psi$ (850 mb) budget limit our view about the local response to the eastward propagating $\chi$ intraseasonal oscillation. An overview of this response over the entire Pacific region can only be attained through horizontal charts. Displayed in Fig. 13 are the five-day averaged charts of $\psi$ (850 mb), $\psi_{AV}$ (850 mb), $\psi_x$ (850 mb), and $\psi_{x1}$ (850 mb) for the last selected phases of minimum and maximum and maximum $u$ (850 mb) indices. Recall that $\psi_{x1}$ (850 mb) changes its sign across the equator in its y-t diagrams (Fig. 12). Because the wavenumber-1 structure of $\chi$ (200 mb) is preserved latitudinally from the Southern to the Northern Hemisphere, the sign change of $\psi_{x1}$ (850 mb) across the equator essentially occurs over the entire analysis domain. The resemblance between $\psi_x$ (850 mb) and $\psi_{x1}$ (850 mb) appears not only in the y-t diagrams (Fig. 12), but over the entire Pacific. Here, we also superimpose $\nabla \psi_x$ and $\nabla \psi_{x1}$ vectors on $\psi_x$ and $\psi_{x1}$, respectively, to indicate the source and sink regions of vorticity. These source and sink regions correspond to negative and positive tendencies of $\psi$ (850 mb), respectively. It was revealed from Fig. 12 that $\psi_{AV}$ (850 mb) and $\psi_x$ (850 mb) counterbalance each other. This relation between the two streamfunction tendencies is true over the entire Pacific region, too. Finally, the quadrature relation between $\psi$ (850 mb) and $\psi_{AV}$ (850 mb), as expected by Eq. (5), can be seen by contrasting the $\psi$ (850 mb) and $\psi_{AV}$ (850 mb) shown in Fig. 13 for the two phases of the $\psi$ (850 mb) index.

7. Summary and concluding remarks

As revealed form the summer-mean circulation over the Pacific Ocean, there are two lower-tropospheric Pacific anticyclones corresponding to the mid-oceanic upper-tropospheric Pacific troughs that are located north and south of the equator, respectively. It was shown by our previous studies (Chen and Yen, 1991a) that an intraseasonal (30–60 day) oscillation of the two Pacific troughs is induced by the eastward propagation of the global-scale intraseasonal divergent circulation. Because the lower-tropospheric circulation is an integrated part of the entire atmospheric system, the lower-tropospheric Pacific anticyclone should also undergo an intraseasonal oscillation. Besides the Intertropical Convergence Zone (ITCZ) sandwiched between the two Pacific anticyclones, the two remaining major convergence zones of the Pacific [the North Pacific Convergence Zone (NPCZ) and the South Pacific Convergence (SPCZ)] radiate out of the warm pool along the poleward branches of the Pacific anticyclones. Chen and Murakami (1988) showed that the NPCZ exhibits an intraseasonal oscillation in response to the eastward propagation of the global-scale intraseasonal divergent circulation. Likewise, the SPCZ should undergo an intraseasonal oscillation, as well.

The y-t diagrams of precipitation at 150°E and 160°W show clearly that precipitation bands associated with the NPCZ and SPCZ exhibit a coherent north-south migration with an intraseasonal time scale. Based upon the 850-mb isotherms of the 30–60 day bandpass filtered wind fields, we adopted the 30–60 day filtered zonal wind, $\tilde{u}$ (850 mb), at (170°W, 22.5°S) as an index to indicate the intraseasonal oscillation of the lower-tropospheric circulation over the western Pacific. The time series of $\tilde{u}$
Fig. 13. The 850-mb 5-day-mean synoptic charts of $\bar{\psi}$, $\bar{\psi}_{AV}$, $\bar{\psi}_x$ and $\bar{\psi}_x^1$. The vectors displayed on $\bar{\psi}_x$ and $\bar{\psi}_x^1$ are $\nabla \bar{\psi}_x$ and $\nabla \bar{\psi}_x^1$, respectively, to indicate the $\psi$ tendency induced by a source or sink of vorticity. The positive values of all quantities are shaded, and the contour interval is $10^6 \text{m}^2\text{s}^{-1}$ for $\bar{\psi}$ (850 mb); $20 \text{m}^2\text{s}^{-2}$ for other quantities.

(850 mb) index coincided with the time series of the 30-60 day filtered 200-mb streamfunction, $\bar{\psi}$ (200 mb), averaged over two areas ([25°–30°N, 175°E–175°W]; part of the North-Pacific trough, and [17.5–22.5°S, 150–155°W]; part of the South-Pacific trough) (Chen and Yen's Fig. 2). Apparently, the lower-tropospheric circulation over the western Pacific and the upper-tropospheric mid-oceanic Pacific troughs oscillate coherently with an intraseasonal time scale.

Based upon the streamline synoptic charts of the 30-60 day filtered 850-mb wind, we found that the intensity of the two Pacific anticyclones vary in concert with the intraseasonal oscillation of the mid-Pacific troughs. In addition to the two major Pacific anticyclones, a medium-scale anticyclone appears adjacent to Japan and another one exists in and near Australia. The streamline synoptic charts showed that the former anticyclone oscillates in the northwest-southeast direction and the latter anticyclone is split into two when the $\bar{u}$ (850 mb) index reaches its maximum: One is located over the ocean east of Australia and the other centered in western Australia. It was confirmed with the streamline
Contrasting the seasonal-mean and intraseasonal divergent circulation and midlatitude rotational flow. Chain relation between tropical diabatic heating, diagnosed that the midlatitude-tropical intersection of monsoon life cycle. Chen and Yen (1991a) suggested that these circulations extend over the entire Indian Ocean. Chen (1987) also pointed out that the systematic changes of the Japan and Australia anticyclones are mainly contributed by the intraseasonal mode.

In view of the discussion of this study made so far, it is clear that some pronounced elements of the regional circulation in both the upper and lower troposphere over the western Pacific to the eastward propagation of the global-scale intraseasonal oscillation, as well. To substantiate this argument, we constructed the intraseasonal local Hadley circulations in the western Pacific with intraseasonal mass flux. It was shown that these circulations extend over the entire depth of the troposphere so that a dynamical interaction between the lower-tropospheric circulation and the eastward-propagating global-scale $\chi$ mode is possible. This dynamic interaction is accomplished through the counterbalance between the $\psi$ (850 mb) tendencies induced by the vorticity source and by the horizontal advection of vorticity.

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References


1979年夏季の西太平洋における対流圈下層の季節内変動

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当研究においては西太平洋における対流圈下層の季節内 (30–60 日) 変動についての調査を行なった。1979年夏季の解析期間において、東進する全球規模の季節内変動発散場が、西太平洋における局所的発散収束場の季節内変動的自然周期変動をもたらすことが見いだされた。この局所的発散収束場の変動は、北太平洋収束帯 (NPCZ) 即ち Mei Yu 及び梅雨前線との結合システム、並びに南太平洋収束帯 (SPCZ) の季節内変動的南北移動をもたらす。NPCZ 及び SPCZ に伴う局所大気循環も、一体となった季節内変動を示す。季節内変動的局所ハドレー循環と流線関数の収支解析から、上記の一体となった季節内変動は、東進する全球規模の季節内変動に対する地域的な対流圈下層の大気循環の応答であることが示される。