West Pacific subtropical high double ridges and intraseasonal variability of the South China Sea summer monsoon

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Abstract In this study, the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data from 1979 to 2005 is used to investigate the possible impact of IntraSeasonal Oscillation (ISO) of the South China Sea (SCS) monsoon on the West Pacific Subtropical High (WPSH) double ridges. Three WPSH modes are defined as the 3/6 mode, the 1/2 mode and the dual mode, for the amplitude of the 30–60-day oscillation of SCS summer monsoon which is larger, smaller and comparable to the 10–20-day oscillation, respectively. The results show that there are no double ridges of WPSH present during 3/6 mode, but a weak process can be found during 1/2 mode. However, a powerful double-ridge structure of WPSH is present in several phases of the dual mode during both the 10–20-day oscillation and the 30–60-day oscillation. Then two typical WPSH double ridge cases in 1999, a special year of the dual mode, are chosen to further discuss this interesting phenomenon. Case 1 (24 July–27 July) is much weaker, and in this case the southern ridge disappears after several days, while during case 2 (3 August–11 August), the southern ridge finally replaces the northern ridge. The

double ridges are much stronger compared to case 1. The ISO evolution feature is different between case 1 and case 2. The anomalous circulation of 10–20-day oscillation is anticyclonic over the southern ridge during both case 1 and case 2. However, the anomalous circulation of 30–60-day oscillation is cyclonic during case 1 and anticyclonic during case 2. It is this difference that leads to the double ridges being more powerful in case 2 than in case 1. This indicates that the 10–20-day oscillation of the SCS summer monsoon plays a key role in the WPSH double-ridge formation, while the 30–60-day oscillation provides a favorable background for it.

1 Introduction

The West Pacific subtropical high (WPSH), as an important member of the Asia monsoon system (Tao and Chen 1987), is closely related to the ISO. Using the CEOF (Complex Empirical Orthogonal Function) method, Luo and Yu (1995) found that the mid-range abnormality of the WPSH was connected with the activity of ISO in an area from South China Sea (SCS) to the West Pacific. Li and Yu (1996) pointed out that during the intraseasonal continuous abnormal period of the WPSH, the ISO from the eastern Pacific and the high latitude of East Asia were combined in the western Pacific region. Using the numerical simulation method, Duan and Yu (1997) also found the generation of anomaly geopotential waves assembled in the western Pacific area during the mid-range abnormal period of the WPSH.

It is well known that Madden and Julian (1972) found the 40–50-day oscillation when they studied the zonal wind in the tropics. Krishnamurti and Bhalme (1976) stated that there exists a 10–20-day oscillation in the South Asian and

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India monsoon system. He also proved that the two kinds of Intraseasonal Oscillations (ISO) were global scale phenomena. Since then the ISO is closely linked with both long-range weather variation and short-range climate abnormality.

The previous studies show that during boreal summer the 30–60-day oscillation appears to migrate northward and is linked to monsoon onsets and breaks (Krishnamurti and Subrahmanyam 1982; Lorence 1984; Murakami et al. 1984a, b; Murakami and Nakazawa 1985; Lau and Peng 1987; He and Chen 1988). Chen and Chen (1993), Chen and Chen (1995) investigated the ISO in the 1979 summer monsoon over India and the SCS successively. They reported that the 10–20-day monsoon oscillation exhibits a double-cell (either double high or double low) structure, both of which propagate coherently westward along the India monsoon trough and along the equator. They further suggested that the SCS summer monsoon in 1979 was adjusted by the northward-propagation of the 30–60-day monsoon trough-ridge, and the SCS summer monsoon break occurred simultaneously with a phase lock in the northern SCS between the 30–60-day oscillation and the 10–20-day oscillation. According to the data from South China Sea Monsoon Experiment, Chan et al. (2002) examined the evolution of the SCS summer monsoon in 1998 and found that the maintenance and break of the SCS summer monsoon in that year were controlled by the 30–60-day oscillation, and were further modified by the 10–20-day oscillation.

In most years, these two intraseasonal oscillations can explain a large percentage of the total variance, which suggests that these two intraseasonal oscillations are the essential oscillations that control the activity of the SCS summer monsoon activity (Li 1996). However, Mao and Chan (2005) indicated that the amplitudes of these two oscillations vary from year to year. The different oscillation dominates in different years. In some years, the amplitude of 30–60-day oscillation is greater than that of the 10–20-day such as 1979, which is defined as 3/6 mode. In some other years, the spectral values at the 30–60-day oscillation are much smaller than that of 10–20-day oscillation, for example, in 1980, which is defined as 1/2 mode. However, in another year such as 1999, which is called as dual mode, they are much comparable. Mao and Chan (2005) explored the intraseasonal variability of the SCS summer monsoon in terms of its structure and propagation during 3/6 mode and 1/2 mode. However, the dual mode is of no concern. As we know, there is an obvious interaction between the 10–20-day oscillation and the 30–60-day oscillation during the dual mode, which plays an important role in general circulation and climate change. Therefore, it is necessary to detect the ISO features during dual mode, as well as its possible effect on WPSH.

A brief description of the data and methodology is presented in the next section, while the subsequent section presents a new conception of the WPSH, that is, the WPSH double ridges. An investigation of the structure and propagation of ISO, as well as its possible effects on the WPSH in the 1/2 mode, the 3/6 mode and the dual mode are described after that, followed by a discussion of the potential mechanism of the WPSH double ridges in terms of ISO. The last section is a summary and discussion.

2 Data and methodology

2.1 Data

The data of the daily variable fields for the period of 1979–2005 from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-DOE) reanalysis (Kanamitsu et al. 2002) are used in this work. These data are at 12-level standard isobaric surface with the resolution of $2.5^\circ \times 2.5^\circ$. The ISO reaches its maximum intensity during July to September. So we focus on the period from July to September for every year.

2.2 Interannual variability of ISO

We apply the same methodology as the work of Mao and Chan (2005) to the averaged zonal wind over the South China Sea monsoon region (SCS), which is located between $10\text{--}15^\circ\text{N}$ and $115\text{--}120^\circ\text{E}$. More details can be found in Mao and Chan (2005). Based on this classification, the years can be grouped as follows:

- 3/6 mode: 1979, 1987, 1990, 1991, 1996, 1997, 1998, 2000
- 1/2 mode: 1980, 1982, 1984, 1986, 1988, 1989, 1992, 1993, 2002, 2003
- Dual mode: 1981, 1983, 1985, 1994, 1995, 1999, 2001, 2004, 2005

The category is different from that of Mao and Chan (2005). This is because we use different variability over different SCS domains during different seasons.

2.3 Compositing technique

In the same way, an ISO cycle can be defined as one with a positive and negative anomaly (or an active and an inactive period), both of which must have peak amplitude that is greater than the standard deviation with the value of 1. Based on this selection criterion, 8 cycles are isolated for 3/6 mode, and 33 cycles for 1/2 mode, as well as 9 cycles of the 30–60-day oscillation and 32

cycles of the 10–20-day oscillation selected for dual mode during the period of 1979–2005. Then, each cycle is grouped into several different phases for composition, as in Chan et al. (2002). That is, phase 3 is the peak of the active period, while phase 7 is the peak of inactive period. Compositions are then made of various meteorological quantities for those cases.

3 WPSH double ridges

3.1 Definition of the WPSH double ridges

The West Pacific subtropical high is one of the most important components of the East Asian monsoon system (Tao and Chen 1987). Its meridian shift has a large impact on the location and the intensity of the large-scale summer monsoon rainfall over East Asia, which is identified as Meiyu or Plum rain in China, Baiu in Japan, and Changma in Korea (Tao and Chen 1987; Ding 1994; Ninomiya 2004; Ha et al. 2005; Ha and Sun-Seon 2007). Generally the WPSH jumps northwards twice from winter to summer in one year (Huang and Tang 1962; Krishnamurti 1979), while the movement of the WPSH is quite complicated due to its unusual activities in summer such as abrupt jumps, stable persistence or backwards movement from the north. For most of the years, these unexpected activities of the WPSH play an important role in the generation of the droughts and floods in the east of the Asian regions (Ninomiya 1984; Tao and Chen 1987; Wang et al. 2005). There can be seen as evidence supporting the idea that not only the circulation patterns in the mid-latitude and the high latitudes (Tao and Zhu 1964), but also the tropical convection, the typhoons, and the equatorial anticyclones (Fujita et al. 1969; Sadler 1971;

Kurihara 1989; Huang et al. 2004) could have an effect on the WPSH meridian shift.

The single ridge of the WPSH has been emphasized in most of the previous studies, while the double-ridge receives less attention as an interesting phenomenon. As early as 20 years ago, Sadler (1975) found, in a climatological study of the upper troposphere, that there was a double-ridge over the North Pacific and the North Atlantic at 200 hPa. However, further analysis shows that this double-ridge phenomenon could also occur over other regions. For example, during the interval between the first and second Meiyu periods of 1998 summer, two ridges are clearly presented at 500 hPa over the area covered the East Asia–West Pacific subtropical latitudes with one ridge located at the north (30°N) and the other one in the south (15°N; Fig. 1; Zhan et al. 2004, 2008). It is defined as a double-ridge process (Qi et al. 2006) which was an improvement of the double ridges definition by Sadler (1975). During this double-ridge process, the original ridge in the northern WPSH weakens and disappears, while the new-born ridge in the south maintains and develops into a single ridge of WPSH after the process ends. This process contributes to the stagnancy of the WPSH at the south in the middle July and is different from the former ridge in the view of the sudden southward displacement of the original WPSH ridge (Zhan et al. 2004, 2008). It provides the foresignal for sudden variations of the WPSH and the onset of Meiyu. However, another double-ridge process during the second Meiyu period in 1962 summer (Qi et al. 2006) represents a different process, as the newly born ridge in the southern WPSH vanishes after several days' development, and the northern ridge (the original one) remains with a small shift toward the north. This process leads to an end of the second Meiyu period. Consequently, the double-ridge process plays an important role in the discontinuous movement

Fig. 1 500 hPa stream field on 11 July 1998. The *thick solid lines* denote the ridges of subtropical high (SH) (Zhan et al. 2008)

toward the north and backward the south of the WPSH, and further in the sudden onset or end of second Meiyu period over the middle and lower reach of Yangtze River.

We also notice, using the NCEP/NCAR reanalysis data and the European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis data (Zhan et al. 2005, 2008), that the double-ridge phenomenon appears in almost every year. Statistical investigation of the double-ridge system over the subtropics of North Hemisphere shows that it occurs with significant phase-locking and geographic preference; that is, the majority of WPSH double ridges form more over the eastern North India Ocean-Western Pacific as well as the central North Pacific than other areas in the period from mid-July to mid-September (Zhan et al. 2005). Especially over the western Pacific subtropics, the subtropical high double-ridge events are extremely active. This phase-locking and geographic preference results in the similar behavior on a climatology basis (Qi et al. 2008a, b). These processes are found to be closely related with the 10-day oscillation of SCS summer monsoon.

How does the WPSH response to the strong year-to-year variability in SCS summer monsoon ISO? That is, is there any double ridges during the 3/6 mode, the 1/2 mode or the dual mode? What is the role of the 30–60-day oscillation and the 10–20-day oscillation in contributing to the double ridges formation relatively? The objective of this paper is, therefore, to explore the possible effects of the ISOs on the WPSH double ridges formation.

3.2 Indicators for WPSH double ridges

The quasi-geostrophic equilibrium relation is a fundamental property of the large-scale atmospheric motions over extratropics. However, it is shown from the data diagnosis that the large-scale atmospheric motion at lower latitude outside 5°S–5°N also meets the needs of an approximately balanced geostrophic relation between Coriolis and pressure forces at great precision, i.e., a semi-geostrophic relation (Li and Chou 1998). As a consequence, over the subtropics, the change in position of an easterly–westerly separating line which satisfies $u=0$ and $\partial u/\partial y > 0$ indicates the displacement in the location of the high ridge well (Zhan et al. 2005, 2008).

Based on this definition of high ridge, Qi et al. (2006) has advanced the indicator for the WPSH double ridges as follows:

1. The lines satisfying $u=0$ and $\partial u/\partial y > 0$ can be defined as high ridges.
2. The process locates in West Pacific subtropical region (5–40°N, 100–160°E).

3. Both ridges must lie inside a WPSH domain which is bounded by a certain character isohypse (such as 5,850 geopotential meter isohypse).

4 Possible effect of the ISO on the WPSH double ridges

4.1 1/2 mode

Composite evolution of the 10–20-day oscillation for the 1/2 mode (Figs omitted) is similar to that of Mao and Chan (2005), and is characterized by westward propagation. The corresponding 500 hPa stream field of the 1/2 mode is shown in Fig. 2. It is found that as the SCS summer monsoon 10–20-day oscillation becomes active in the westerly phase, the monsoon trough will enhance, and shift northward, and further intrude the WPSH unit, which leads to the WPSH distorting a little. During phase 2, there is a new ridge born in the southern WPSH, short and weak. In phase 3, the southern ridge develops and becomes enhanced with the length span being about 15°, while at the same time the northern ridge weakens. The SCS summer monsoon is the weakest in phase 7, and the trough retreats to the west of 100°E. Meanwhile, the southern ridge weakens. By phase 8, the WPSH resumes to the single-ridge structure; and, accordingly, there is a weak double ridge during the 1/2 mode.

4.2 3/6 mode

During the 3/6 mode the anomaly circulation propagates northwestward from tropical middle Pacific to the SCS, along with the enhanced/suppressed convection over the anomaly cyclone/anticyclone (Mao and Chan 2005). The corresponding 500 hPa stream field evolution during the 3/6 mode (Fig. 3) suggests that the WPSH maintains a single ridge structure during the whole ISO cycle. Along with the 30–60-day oscillation from the inactive phase to the active phase, the monsoon trough enhances and extends eastward, which reaches to 130°E by phase 3. However, the monsoon trough locates to the south of the WPSH, having no effect on the WPSH distortion. According to the indicators of the WPSH double ridges, there are no double ridges during the whole 3/6 mode.

Based on the comparison with the 1/2 mode (Fig. 2), it is shown that the WPSH is the single ridge structure when there does not exist a 10–20-day oscillation over the SCS. However, when the SCS only has the oscillation of 10–20 days, there are weak double ridges over the WPSH (Fig. 2). That is, the 10–20-day oscillation may play the key roles in the WPSH double ridges formation. It is not convenient for the WPSH double ridges formation when there is only 30–60-day oscillation over the SCS. However, is there any WPSH double ridges when the SCS has both

Fig. 2 Composite evolution during an ISO cycle for 1/2 mode of 500 hPa stream field. Thick dashed lines stand for WPSH ridges

Fig. 3 Same as Fig. 2, except for the 3/6 mode category

Fig. 4 Same as Fig. 2, except for the 30–60-day oscillation of dual mode category

Fig. 5 Same as in Fig. 2, except for the 10–20-day oscillation of the dual mode category

10–20-day and 30–60-day oscillations? How dose the WPSH respond to the strong interactions with ISOs ?

4.3 Dual mode

As mentioned above, there is both a 10–20-day oscillation and 30–60-day oscillation in the dual mode. According to the 30–60-day oscillation of the dual mode, the composited 500 hPa stream field is shown in Fig. 4. The most significant feature is that there is a clear double-ridge structure of the WPSH. On phase 1 the WPSH has been represented as the double ridges. The northern ridge locates near 30°N with two closed anticyclone centers. The southern ridge lies in 12°N, 140–160°E and there is an inverted trough between two ridges. The SCS monsoon trough only locates at the west of 100°E. By phase 2, the SCS monsoon trough has connected with the inverted trough and the WPSH unit is seriously distorted. The southern ridge shifts westward to 130–150°E. The double-center-structure over the northern ridge disappears with the anticyclone center locating around 140°E. In phase 3 the southern ridge disappears, while during phase 4 the WPSH falls together with the anticyclone over Philippines, forming the southern ridge again, which extends from 120 to 160°E. This southern ridge maintains itself until phase 6. In phase 7 the southern ridge disappears again while the northern ridge remains in maintenance and the WPSH returns to a single-ridge structure.

However, 500 hPa stream field of the 10–20-day oscillation also shows the remarkable double-ridge phenomena (Fig. 5). In phase 1 there are already two ridges over the WPSH with the northern ridge located at 25–30°N, while the southern one is located at 10°N. Along with the SCS monsoon trough developing and extending eastward, the southern ridge enhances and shifts eastward. By phase 2 it lies in 120–140°E. The SCS monsoon trough continues to propagate northward and leads to the northern ridge weakened, which locates at the east of 120°E by phase 4. During phase 5, the west part of the northern ridge disappears, while the eastern part conjoins with the southern ridge.

Consequently, the powerful double-ridge events have been detected during both the 10–20-day oscillation and the 30–60-day oscillation of the dual mode. As mentioned already, the intensity of the 10–20-day oscillation and the 30–60-day oscillation are more comparable during the dual mode, and the strong interaction between them is also present. It is this potential interaction that leads to the powerful double ridges during the dual mode compared with the 1/2 mode or the 3/6 mode.

5 Potential mechanism of the WPSH double ridges

Several studies (Qi et al. 2008a, b) have suggested that the 10-day oscillation is responsible for the WPSH double ridges in a climatic basis. Moreover, the above analysis also

Fig. 6 Evolution of the 10–20-day filtered 500 hPa stream field during July in 1999. The shading stands for anticyclonic vorticity of a 30–60-day oscillation

indicates that the 10–20-day oscillation may play key roles in the WPSH double ridges formation. Because these studies are based on composition analysis, it may be more meaningful to compare the results with an individual WPSH double-ridge case. Two WPSH double-ridge cases of 1999 are chosen to make the comparison because 1999 is a distinct year for the dual mode.

During case 1 (Fig. 6), a new ridge was formed in the southern WPSH on 24 July. We call it as the southern ridge. It was overlapped with an anomalous anticyclone of a 10–20-day oscillation, where there was an anomalous cyclone of a 30–60-day oscillation. The southern ridge was weak with a narrow common longitude range that was the same as the northern ridge (the original one). The double-ridge phenomenon maintained the same intensity till 27 July. During the whole process, the southern ridge always layed over the anomalous anticyclone of the 10–20-day oscillation.

tion, even going through the center on 26 and 27 July. However, the southern ridge was located on the anomalous cyclone of the 30–60-day oscillation all the time. Therefore, during case 1, the 30–60-day oscillation is not favorable for the southern ridge maintenance.

Another case took place during the early August of 1999. This progress was more powerful with longer persisting and broader common longitude range between the northern ridge and the southern ridge than that of case 1. This is different from the first case and the corresponding evolution of the ISO (Fig. 7) is also different. During the whole progress, the southern ridge was located on an anomalous anticyclone of a 10–20-day oscillation. Sometimes the southern ridge went through the center of the anomalous anticyclone of the 10–20-day oscillation. Moreover, the anomalous circulation of the 30–60-day oscillation over the southern ridge is anticyclonic. Accordingly, the

Fig. 7 Evolution of the 10–20-day filtered 500 hPa stream field during August of 1999. The shading stands for anticyclonic vorticity of a 30–60-day oscillation

anomalous circulations of the 10–20-day and the 30–60-day oscillation are all in favor of the southern ridge maintenance.

Different features between these two cases further confirmed these results. Thus, the WPSH double ridge is closely related to the 10–20-day oscillation. The same anomalous circulations of the 30–60-day oscillation with that of the 10–20-day under the dual mode will strengthen the WPSH double ridges structure; however, the involved dynamic mechanism is more complicated and needs future systematic research.

6 Summary and discussion

NCEP-NCAR reanalysis data from 1979 to 2005 are used to discuss the potential impact of the intraseasonal oscillation in the SCS summer monsoon on the variations of the WPSH double ridges. It is well known that the oscillations of the 30–60-day and the 10–20-day are the important oscillations that control the activity of the SCS monsoon. However, the amplitudes of these two oscillations vary remarkably from year to year (Mao and Chan 2005). The amplitude of the 30–60-day oscillation is bigger than that of the 10–20-day in some years, which is defined as the 3/6 mode. Meanwhile, the amplitude value of the 30–60-day oscillation is much smaller than that of the 10–20-day oscillation in other years, which is defined as the 1/2 mode. The years with a similar amplitude value for both these two oscillations are defined as the dual mode (Mao and Chan 2005).

The formation of the WPSH double ridges on a climatic basis is closely related to the 10-day oscillation in the SCS monsoon. Therefore, the corresponding stream fields on 500 hPa during the years of the 1/2 mode, and the 3/6 mode as well as the dual mode are composed respectively to find the potential impact of the ISOs on the WPSH double ridges. The interesting result shows that there are no double ridges presented during the 3/6 mode, while it is presented as a weak process during the 1/2 mode. However, during the dual mode, the WPSH presents as a powerful double-ridge structure for several phases during both the 10–20-day oscillation and the 30–60-day oscillation. The simulated results based on the 30–60-day oscillation show clearly that the WPSH always has double ridges except in phases 3, 7 and 8, whereas the composition results corresponding to the 10–20-day oscillation also indicate the double ridges of the WPSH during phase 1 to 4, which may indicate that the 10–20-day oscillation of the SCS summer monsoon plays a key role in the WPSH double-ridge formation, with a favorable background from the 30–60-day oscillation.

Two WPSH double ridge cases in 1999 are chosen to further discuss this interesting phenomenon. As 1999 is a special year of the dual mode, having case 1 (24–27 July) is

much weaker with a narrow common longitude range between the southern ridge and the northern ridge. During this case, the southern ridge disappears after several days. However, case 2 (3–11 August) is presented in that the southern ridge finally replaces the northern ridge. The double ridges in this case are much stronger than those in case 1 with much broader common longitude range and longer duration. The ISO evolution feature is different between case 1 and case 2. The anomalous circulation of 10–20-day oscillation is anticyclonic over the southern ridge during both case 1 and case 2. However, the anomalous circulation of 30–60-day oscillation is cyclonic during case 1 and anticyclonic during case 2. It might be this difference that leads to the double ridges in case 2 as being more powerful than that in case 1. So, when the anomalous circulation of the 30–60-day oscillation is in the same phase with that of the 10–20-day, the WPSH double ridge structure is strengthened. However, it is necessary to point out that the involved dynamic mechanism is very complicated and further investigation is needed.

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