Atmospheric Circulations and Sea Surface Temperatures Related to the Convection over the Western Pacific Warm Pool on the Interannual Scale①

Lu Riyu (陆日宇)

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100080

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ABSTRACT

The difference is examined in atmospheric circulation and Sea Surface Temperatures (SSTs) in the tropics and subtropics between weak and strong convection over the tropical western Pacific warm pool (signified as WPWP). The WPWP is chosen as the region (110–160°E, 10–20°N), where the Outgoing Longwave Radiation (OLR) shows a great year–to–year variance. A composite study was carried out to examine the differences in atmospheric circulation and SSTs between weak and strong convection over WPWP. First, NCEP/NCAR re–analysis data and satellite–observed OLR data are used to examine the differences. ERA data, in which the OLR data are calculated, are then used for re–examination.

The composite results show that the differences are remarkably similar in these two sets of data. The difference in circulations between weak and strong convection over WPWP is significantly associated with westward extension of the North Pacific subtropical anticyclone and stronger westerlies at the northwestern edge of the subtropical anticyclone. It also corresponds with the significant easterly anomaly and the descent anomaly in situ, i.e., over the WPWP. The most prominent characteristics of the difference of SSTs between weak and strong convection over the WPWP are the significant positive SST anomalies in the Indian Ocean, the Bay of Bengal and the South China Sea. In WPWP, however, there are only weak negative SST anomalies. Thus, the anomaly of OLR over WPWP is weakly associated with the SST anomalies in situ, while closely associated with the SST anomalies west of WPWP.

Key words: Convection over the western Pacific warm pool, Northwest Pacific subtropical high, Sea surface temperatures

1. Introduction

The influence of the thermal state, including the atmospheric convection and sea surface temperatures (SSTs), of the western Pacific warm pool (WPWP) on the variations of the atmospheric circulation and climate over East Asia has been extensively studied (Nitta et al., 1986; Nitta, 1987; Huang and Li, 1987; Huang and Sun, 1992; Ueda and Yasunari, 1996; Murakami and Matsumoto, 1994; Tanaka, 1997; Kawamura et al., 1998). These studies suggested that an atmospheric Rossby wave is generated by anomalous heating over the tropical western Pacific and propagates from the tropics to the extratropics in the Northern Hemisphere. Such a Rossby wave influences the meridional shift of the Northwest Pacific

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subtropical anticyclone and the climate in East Asia.

In general, suppressed convection corresponds to a negative anomaly of SST in the tropics. In the summers of 1998 and 1988, however, there are slightly above normal SSTs in the tropical western Pacific, with suppressed convection over there (Nitta, 1990; Lu, 2000). The warmer SSTs–enhanced convection relationship is broken in the tropical western Pacific in these two summers due to the large–scale circulation in the tropics, which is supposed to be driven by the warmer SST in the tropical Indian Ocean. However, it is difficult to draw any a definite conclusion on the relationship between convection and SST from only these two case studies.

Lau et al. (1997) showed that the relationship among the large–sale atmospheric circulation, atmospheric convection, and SSTs in the tropics is complex and far from clearly understood. They argued that the warmer SSTs–enhanced convection relationship may break down due to the large–scale atmospheric circulation in the tropics. Their study does not pay special attention to WPWP.

In this study, we will focus on the atmospheric circulation and SSTs associated with the convection over WPWP in summer on the interannual scale. The three–dimensional structure of atmospheric circulations is emphasized. A description of data is given in Section 2. In Section 3, the interannual variability of the convection over WPWP is examined by use of observed data and ERA data. Based on the interannual variations of the convection over WPWP, a composite study is performed on the large–scale atmospheric circulation anomalies in the tropics and subtropics in Section 4. Another composite study is performed on the SSTs in the tropics and subtropics in Section 5. A summary is presented in Section 6.

2. Data

In this study, two sets of reanalysis data were used. The first set is the European Centre for Medium Range Weather Forecasts (ECMWF) Re–Analysis (ERA) data for 15–year period from 1979 to 1993. Gibson et al. (1997) gave a comprehensive description of the assimilation scheme, forecast model used in ERA. It comprises T106 spectral resolution in the horizontal with 31 hybrid model levels in the vertical, Optimal Interpolation intermittent statistical analysis with 6–hour cycling and diabatic non–linear normal mode initialization. The outgoing longwave radiation (OLR) in ERA is calculated.

The other set is National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP / NCAR) Re–analysis data for 19–year period from 1979 to 1997. Kalnay et al. (1996) gave a full description of the re–analysis project. The model is run at T62 spectral resolution in the horizontal with 28 levels in the vertical.

Slightly different SSTs are used in ERA and NCEP / NCAR re–analysis. During 1979, both re–analyses employed version 2.2 of the Global Sea Ice and Sea Surface Temperature (GISST 2.2), while during 1982–1995 the optimum interpolated SSTs of Reynolds and Smith (1994) were used. Difference in SSTs appears during 1980–1982, ERA using GISST 1.1 while NCEP / NCAR using GISST 2.2.

Differences between ERA and NCEP / NCAR re–analysis were given in more details by Annamalai et al. (1999). Annamalai et al. (1999) performed a comparison between ERA and NCEP / NCAR re–analysis. They used ERA and NCEP / NCAR data both during 17–year period from 1979 to 1995, while in this study, we used ERA data during 15–year period from 1979 to 1993 and NCEP / NCAR data for 19–year period from 1979 to 1997. Despite of the difference in periods of data, their results provide help to this study. They showed that there are inconsistencies in the definition of weak and strong monsoon years based on typical monsoon indices such as dynamical monsoon index between ERA and NCEP / NCAR re-analysis. Therefore, re-examination by ERA data may provide extra evidences to the examination by NCEP / NCAR re-analysis.

Beside the calculated OLR data of ERA, we also used satellite-observed OLR data for 19-year period from 1979 to 1997, same as NCEP / NCAR data used in this study.

3. Interannual variations of convection over WPWP

The convection anomalies over WPWP result in an atmospheric Rossby wave that propagates from the tropics to the extratropics in the Northern Hemisphere and influence the atmospheric circulation and climate over East Asia (Nitta et al., 1986; Nitta, 1987; Huang and Li, 1987; Huang and Sun, 1992; Ueda and Yasunari, 1996; Murakami and Matsumoto, 1994; Tanaka, 1997; Kawamura et al., 1998). Figure 1 shows the year-to-year variances of JJA mean OLR during 19 years from 1979 to 1997, obtained by use of the observed data. The atmospheric convection shows a great interannual variability over WPWP, over Indonesia and along the equatorial Pacific. Over these three regions, the climatological intensity of the atmospheric convection is also very strong. Over South Asia, the year-to-year variance is relatively smaller, although the climatological convection is considerably strong. A great interannual variability of convection means a great change in heating and may be a source for some other changes.

In the following, we will examine the interannual variations of the JJA mean convection averaged over WPWP. By the year-to-year variance in Fig. 1, and concerning the results of previous studies on the relationship between the convection over WPWP and East Asian summer monsoon (for example, Nitta et al., 1986; Nitta, 1987; Huang and Li, 1987; Huang and Sun, 1992; Kawamura et al., 1998), we chose the averaged area, i.e., the region of WPWP, as (110–160°E, 10–20°N). Figure 2 shows the interannual variations of JJA mean OLR averaged over the region in the observed data and in ERA data, i.e., calculated data,

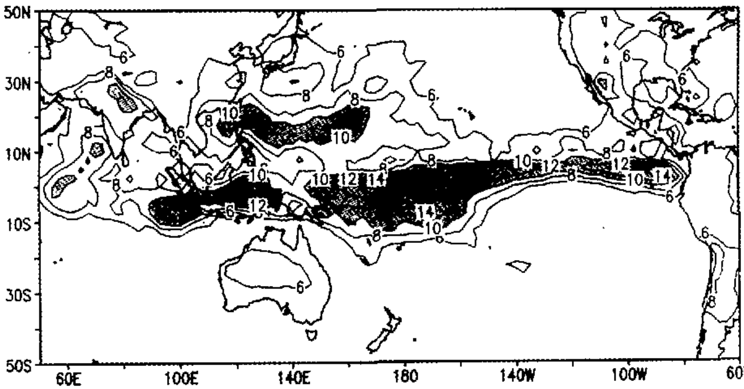

Fig. 1. Year-to-year variances of June-July-August (JJA) mean OLR during 19 years from 1979 to 1997 by use of the observed OLR data. Contour interval is 2, and values lower than 6 are not shown for the sake of clarity. The shaded areas illustrate the values greater than 10.

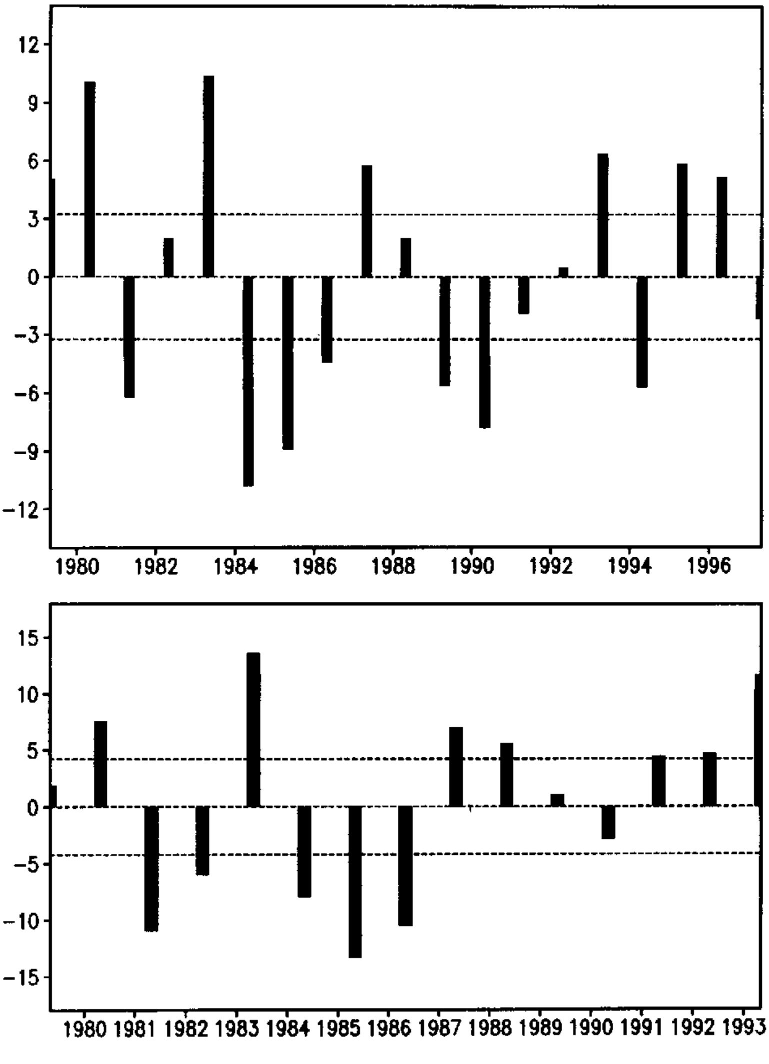

Fig. 2 Interannual variations of JJA mean OLR averaged over WPWP (110–160°E, 10–20°N). Upper panel is by the observed data in 19 years and lower panel by the ERA data in 15 years, i.e., calculated data.

respectively. The variances of the interannual variations of OLR are 6.5 and 8.48 W m^{-2} in the observed data and in ERA data, respectively. We chose the years in which the absolute values of the OLR anomalies are greater than half of the variances, and performed a composite study based on these years. In the observed OLR data, the years with a greater OLR (weak convection) are 1979, 1980, 1983, 1987, 1993, 1995 and 1996 (7 years), and the years with a less OLR (strong convection) are 1981, 1984, 1985, 1986, 1989, 1990 and 1994 (7 years). In ERA data, the years with a greater OLR (weak convection) are 1980, 1983, 1987,

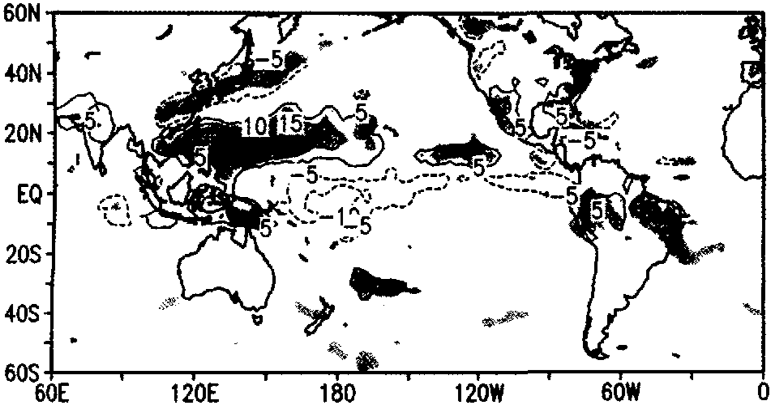

Fig. 3. Composite difference in OLR between the weak and strong convection by use of observed data. Zero contour is not shown for the sake of clarity. The shaded areas illustrate the significance of the differences at 95% level determined from a Student's t-test.

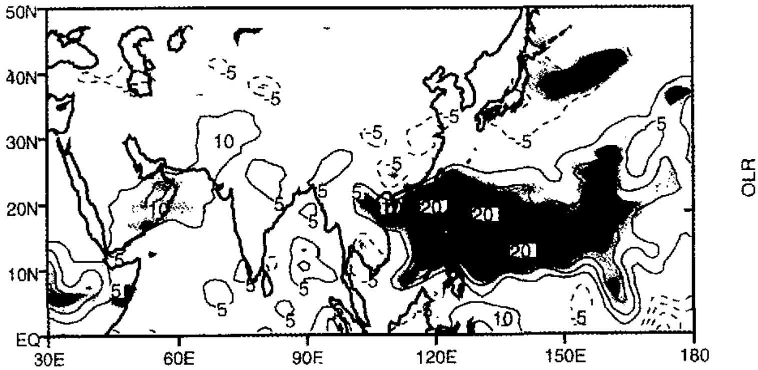

Fig. 4. Composite difference in OLR between the weak and strong convection by use of ERA data. Zero contour is not shown for the sake of clarity. The shaded areas illustrate the significance of the differences at 90% level (light shaded) and 95% level (dark shaded) determined from a Student's t-test.

1988, 1991, 1992 and 1993 (7 years), and the years with a less OLR (strong convection) are 1981, 1982, 1984, 1985 and 1986 (5 years). Besides the difference in periods, there is a slight difference in the chosen years in the observed OLR data and in ERA data, such as that year 1979 is chosen in the observed data but not in ERA data, and that year 1991 is chosen in ERA data but not in the observed data. However, the years that are chosen as weak (strong) convection year in one dataset do not appear as strong (weak) convection year in the other dataset.

Figures 3 and 4 show the composite difference in OLR between the weak and strong convection by use of observed data and ERA data, respectively. In Fig. 3, there are significantly positive anomalies over WPWP, almost exactly the same as the averaged area but with a slight bias in direction. The OLR difference appears actually in a shape of Southwest–Northeast. There are significantly negative anomalies over the Meiyu zone, i.e., a region occupying the Yangtze River basin in China, South Korea and southern Japan. Figure 4 shows a similar distribution to Fig. 3, with slight differences in the shapes of significantly positive anomalies over WPWP and significantly negative anomalies over the Meiyu zone. In Fig. 4, the shape of significantly positive anomalies appears in a zonal direction over WPWP, and the negative anomalies are relatively weaker over the Meiyu zone. Both Figs. 3 and 4 exhibit a close relation between the Meiyu and the convection over WPWP.

4. Atmospheric circulation anomalies related to the convection anomalies over WPWP

The convection over WPWP is related to the atmospheric circulation and SSTs in the tropics (Lau et al., 1997), although the relationship is far from clearly understood. The relationship between the convection over WPWP and SST anomaly in the tropics and subtropics will be examined in the next section. In this section, a composite study will be performed on the relationship between the convection over WPWP and atmospheric circulation in the tropics and subtropics. We will examine the vertical velocity, horizontal winds, geopotential heights, and velocity potential, respectively, by use of NCEP / NCAR re–analysis data and the satellite–observed OLR data.

a. *Vertical velocity*

In the tropics, adiabatic cooling and warming are associated with ascent and descent, and tend to balance the diabatic warming and cooling, respectively. Thence, the distributions of the OLR anomaly, which is closely related to latent heat release in the atmospheric column, should be in a fairly good agreement with that of vertical velocity. Fig. 5 shows the composite difference of vertical velocity (*dp / dt*) at 500 hPa between weak and strong convection over WPWP. Corresponding to the weak convection, a descent anomaly appears over the WPWP. The composite difference distribution for vertical velocity is considerably similar to that for OLR (Fig. 3), especially over WPWP. The dissimilarity is mainly exhibited as the difference in the level of statistical significance at several regions, such as the Meiyu zone and the tropical eastern Pacific.

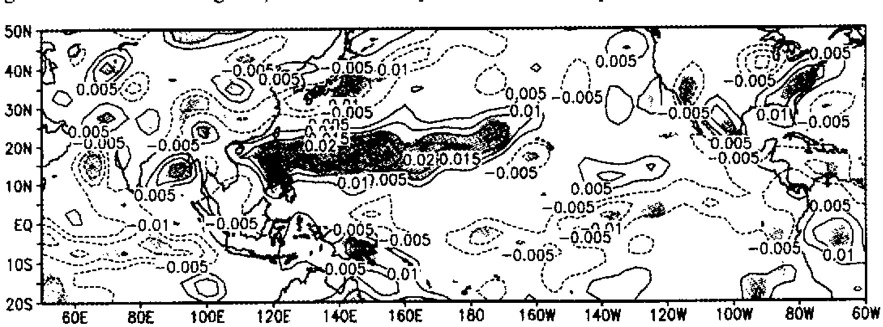

Fig. 5. Composite difference of vertical velocity (*dp / dt*) at 500 hPa between weak and strong convection over WPWP, by use of observed OLR and NCAR / NCEP reanalysis data. Units are in Pa / s. Interval is 0.005, and zero contour is not shown for the sake of clarity. The shaded areas illustrate the significance of the differences at 95% level. Solid lines are for positive values and dashed for negative values.

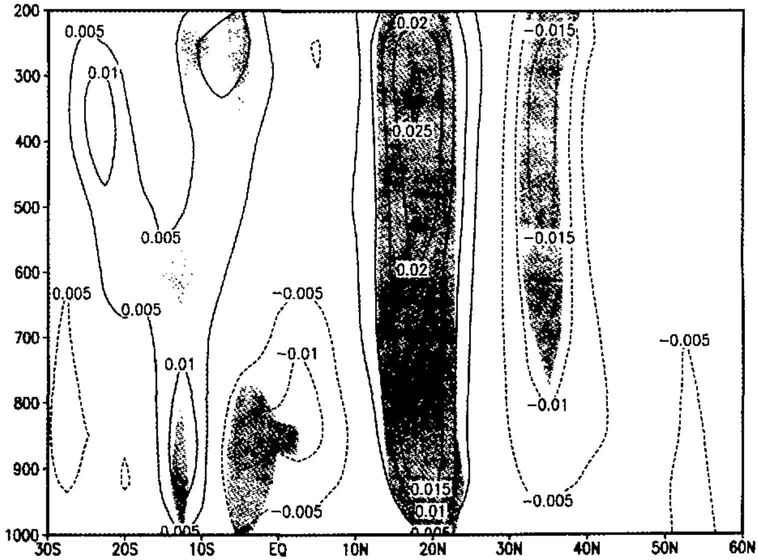

Fig. 6. Composite difference of vertical velocity (dp / dt) along 140°E between weak and strong convection over WPWP, by use of observed OLR and NCAR / NCEP reanalysis data. Units are in Pa / s. Interval is 0.005, and zero contour is not shown for the sake of clarity. The shaded areas illustrate the significance of the differences at 95% level.

Such an anomaly of vertical velocity appears at all levels in the troposphere between WPWP and the Meiyu zone, i.e., over the subtropical western Pacific, and reaches its largest values between 300 and 400 hPa (Fig. 6). Usually, the ascent flow reaches its largest value at the middle troposphere (500 hPa). The fact that the ascent anomaly reaches 95% statistical significance over the Meiyu zone suggests that the Meiyu is significantly related to the convection over WPWP.

b. *Zonal winds*

The differences in horizontal winds related to the convection over WPWP were examined. The meridional velocity, however, does not show any significant difference. Thus, we will focus on the difference in the zonal velocity. Fig. 7 shows the composite difference of the zonal velocity at 850 hPa between weak and strong convection over WPWP. Significant easterly difference appears exactly over WPWP and extends westwards into the Arabian Sea. This fact suggests that the South Asian monsoon, which is closely associated with the zonal winds at the lower levels, is possibly related to the convection over WPWP. Another significant difference is the westerly difference over the Meiyu zone, which is located in a direction of Southwest–Northeast. The co–appearance of easterly difference over WPWP and westerly difference over the Meiyu zone indicates a westward shift of the Northwest Pacific subtropical high (see also geopotential height difference in the following). The westerly difference may transport more water vapour into the Meyu zone and favour the convection and precipitation over there.

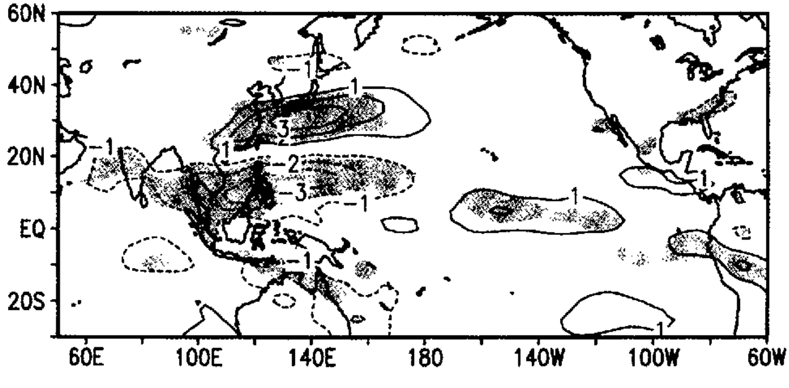

Fig. 7. Composite difference of zonal velocity at 850 hPa between the weak and strong convection over WPWP. Units are in m / s. Contour interval is 1, and zero contour is not shown. The shaded areas illustrate the significance of the differences at 95% level.

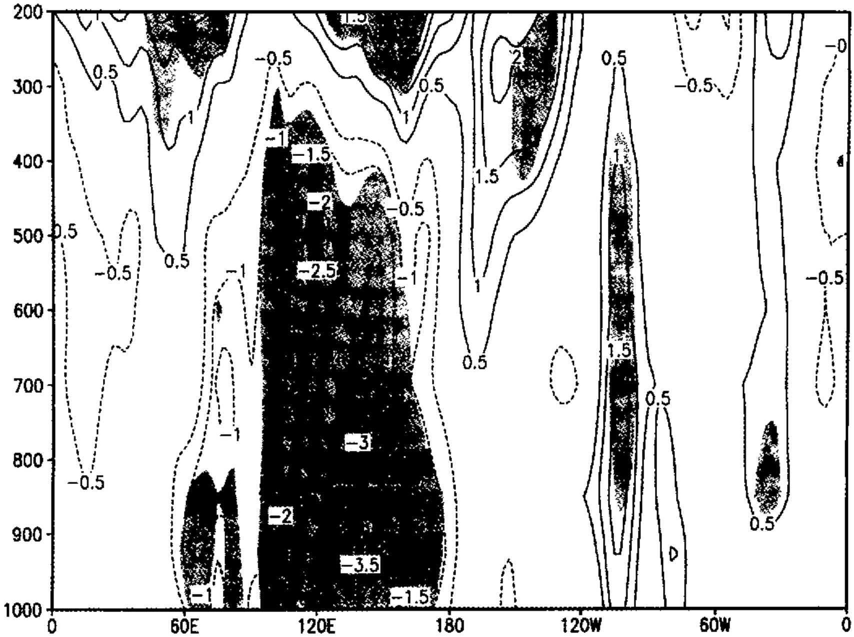

Fig. 8. Composite difference of zonal velocity along 15°N between the weak and strong convection over WPWP. Units are in m / s. Contour interval is 1, and zero contour is not shown. The shaded areas illustrate the significance of the differences at 95% level.

Along the latitude of the central WPWP (15°N), the easterly difference appears from the surface upwards into around 300 hPa (Fig. 8). Above 300 hPa, westerly differences appear. Such a vertical distribution of the easterly difference is in agreement with the increase of vertical velocity with height.

c. Geopotential heights

The co–appearance of easterly difference over WPWP and westerly difference over the Meiyu zone suggests that there would be an anticyclonic anomaly between WPWP and the Meiyu zone. The composite difference of geopotential height at 850 hPa (Fig. 9b) shows that

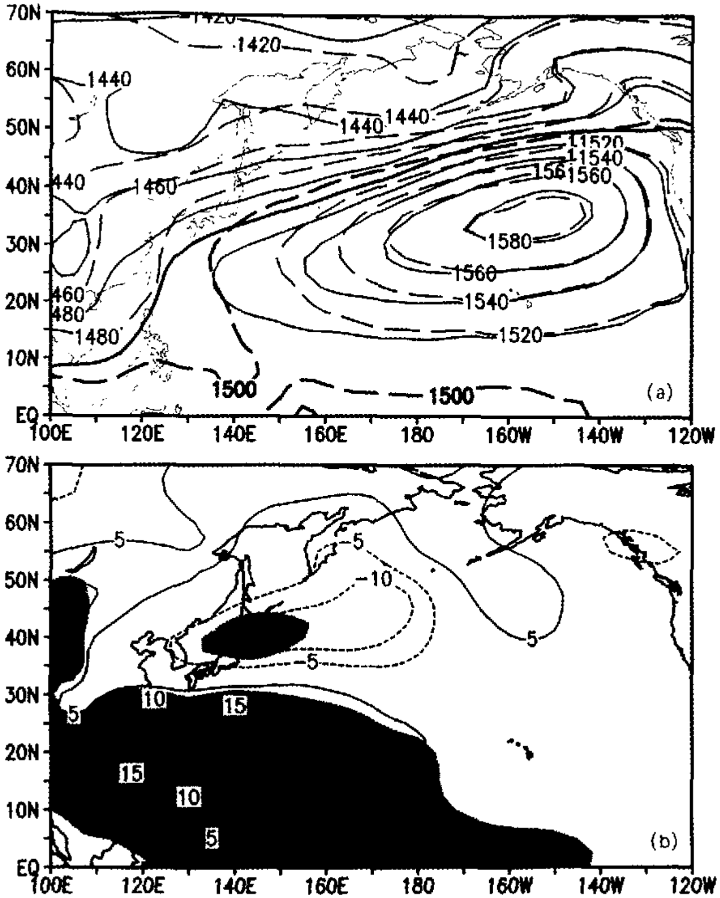

Fig. 9. Composite geopotential heights at 850 hPa for weak and strong convection over WPWP (a) and their difference (b). In (a), the solid lines are for weak convection, and dashed lines for strong convection. The contour lines of 1500 are thickened. In (b), the shaded areas illustrate the significance of the differences at 95% level.

a positive difference actually appears over the region, and a weak negative difference over the region east to Japan. The positive difference, however, is not limited over the region. The area with statistical significance is much larger than the above–mentioned region, extending south to Australia and east to the central equatorial Pacific. Such a height difference is associated with the remarkable change in the shape of the Northwest Pacific subtropical high (Fig. 9a). The Northwest Pacific subtropical high extends westwards for weak convection over WPWP, and retreats eastwards for strong convection. For example, the contour line of 1480 is located over South China for weak convection, but over the East China Sea for strong convection, indicating a great difference in the zonal location of the Northwest Pacific subtropical high. On the other hand, the same contour line appears over the south edge of Korean peninsula for both weak and strong convection, indicating a similarity in the meridional location of the Northwest Pacific subtropical high.

We re–examined the above relationship by use of ERA data, and found remarkably similar results (not shown).

5. SSTs in the tropics and subtropics related to convection over WPWP

The warmer SSTs provide a favourite condition for a stronger atmospheric convection above. However, the warmer SSTs may correspond to a weaker convection sometimes, due to the large–scale atmospheric circulation in the tropics (Lau et al., 1997; Nitta, 1990; Lu, 2000).

In this section, we examined the difference in SSTs between the different years with weaker and stronger convection, by the SSTs in NCEP / NCAR re–analysis and observed OLR data. We also chose the years in which the absolute values of the OLR anomalies are greater than half of the year–to–year variance, and performed a composite study based on these years. The approach is the same as in Section 4.

Figure 10 shows the composite difference in SSTs between weak and strong convection over WPWP. There are slightly significant negative SST anomalies in WPWP, somewhat eastward comparing with the averaged area (110–160°E, 10–20°N). The most prominent feature is the significant positive SST anomalies in the Indian Ocean, the Bay of Bengal and the South China Sea. There are also significant positive SST anomalies in the equatorial eastern Pacific and the subtropical western Pacific. The anomaly of OLR over WPWP is weakly associated with the SST anomalies in situ, while closely associated with the SST anomalies in remote regions.

The positive SST anomalies in the Indian Ocean, the Bay of Bengal and the South China Sea may change large–scale atmospheric circulation in the tropics and thus suppress the atmospheric convection over WPWP. The significant positive SST anomaly in the subtropical western Pacific in Fig. 10 may be the effect of the anomaly of atmospheric circulation, instead of the cause. The weak convection over WPWP causes westward extension of the North Pacific subtropical high, and the southwesterly is strengthened at the northwest edge of the high. The strengthened southwesterly would transport warmer seawater into the subtropical western Pacific and finally result in higher SSTs. The higher SSTs are not apparently related to the anomalous net solar radiation flux at the surface. The composite difference of the net solar radiation flux at the surface (not shown) does not show any significantly more flux into sea at the subtropical western Pacific.

Figure 11 shows the composite difference in SSTs by use of ERA data. Generally, it is considerably similar to that obtained by use of observed OLR and NCEP / NCAR re–analysis data (Fig. 10). The most prominent feature is also significant positive SST anomalies

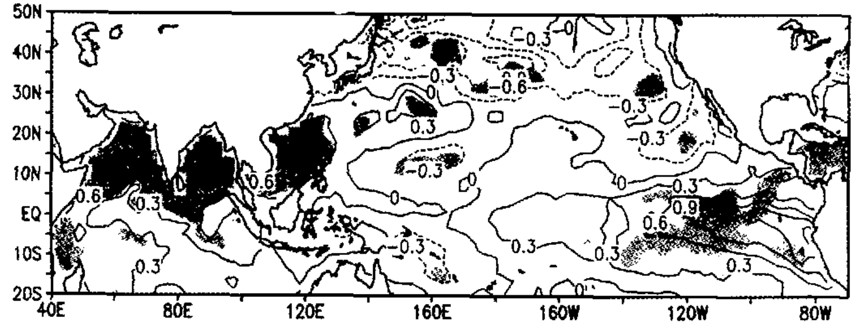

Fig. 10. Composite difference in SSTs between weak and strong convection over WPWP. Units are in °C. Contour interval is 0.3. The shaded areas illustrate the significance of the differences at 95% level.

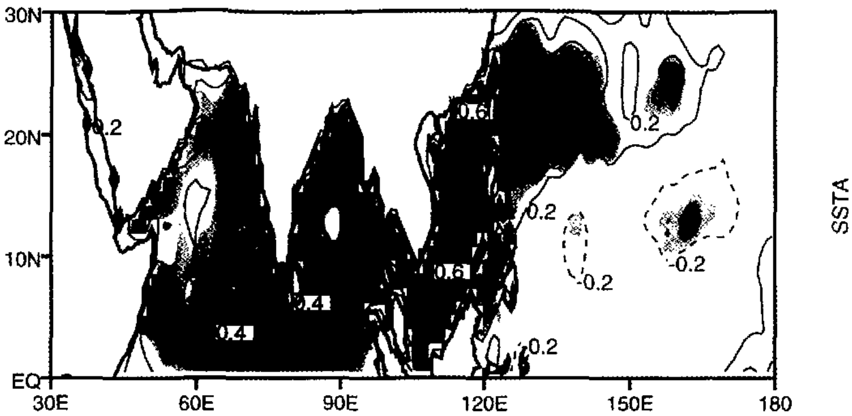

Fig. 11. Composite difference in SSTs between weak and strong convection over WPWP. Units are in °C. Contour interval is 0.2, and zero contour is not shown. The shaded areas illustrate the significance of the differences at 90% level (light shaded) and 95% level (dark shaded).

occupied also in the Indian Ocean, the Bay of Bengal and the South China Sea. The SST differences appear to be less significant in the equatorial eastern Pacific and more significant in the subtropical North Pacific in Fig. 11, compared to that in Fig. 10.

6. Summary

In this study, we examined the differences in atmospheric circulation and SSTs in the tropics and subtropics between weak and strong convection over the tropical western Pacific warm pool (signified as WPWP). We investigated the composite differences first by use of NCEP/NCAR re-analysis data and satellite-observed OLR data, and performed a re-examination by use of ERA data, in which the OLR data are calculated by a numerical model, It was found that the composite differences are remarkably similar in these two datasets.

The difference between weak and strong convection over WPWP is significantly associated with westward extension of the North Pacific subtropical anticyclone and stronger westerlies at the northwestern edge of the subtropical anticyclone. It also corresponds with significant easterly anomaly and descent anomaly in situ. The anticyclonic anomaly over the subtropical western Pacific can be explained by the theory of Gill (1980), while the easterly anomaly in situ and wider height anomaly, however, cannot be explained well by the theory.

The most prominent characteristics of the difference in SSTs between weak and strong convection over WPWP are the significant positive SST anomalies in the Indian Ocean, the Bay of Bengal and the South China Sea. Positive SST anomalies also appear less significantly in the equatorial eastern Pacific and the subtropical western Pacific. In WPWP, however, there are negative SST anomalies with only a slight significance. Thus, the anomaly of OLR over WPWP is weakly associated with the SST anomalies in situ, while closely associated with the SST anomalies west of WPWP.

The atmospheric circulation anomalies, however, do not show any possible linkage between the anomalous SSTs west of WPWP and the anomalous convection over WPWP. We could not find any significant change in Walker circulation or Hadley circulation associated with the anomalous SSTs west of WPWP and anomalous convection over WPWP.

Finally, it should be noted that it is difficult to draw a definite conclusion due to the decadal–scale amplitude modulation of interannual variations (Kawamura et al., 1998) and the short period of OLR observation.

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与西太平洋暖池上空对流年际变化相关联的大气环流和海温

陆日宇

摘　要

诊断分析了热带西太平洋暖池上空对流弱和强的情况下，大气环流和海温所表现出来的差异。本文中西太平洋暖池是指(110–160°E, 10–20°N)地区，向外射出长波辐射(OLR)在该地区具有明显的年际变率。对西太平洋暖池对流弱和强之间大气环流和海温的差别进行了合成分析。首先，利用 NCEP／NCAP 再分析资料和卫星观测的 OLR 资料进行了分析。之后，利用欧洲中期天气预报中心再分析资料和再分析计算而得的 OLR 资料重复进行了合成分析。合成结果表明由这两套资料所分析得到的结果非常相象。与西太平洋暖池上空弱(强)对流显著对应的大气环流表现为北太平洋副热带高压的西伸(东退)，以及副高西北侧更强(弱)的西风。此外，在局地(即暖池)上空，还显著对应着东(西)风异常和下沉(上升)气流异常。对应于西太平洋暖池对流强弱，最为显著的海温差别(对流弱减去对流强)为印度洋、孟加拉湾和南海的正海温异常。也就是说，西太洋暖池上空的对流与局地海温异常只有微弱的联系，而与其西部的海温异常密切相关。

关键词：西太平洋暖池上空对流，西北太平洋副高，海温