Westward Extension of North Pacific Subtropical High in Summer

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Abstract

The basic features of the North Pacific subtropical anticyclone in summer are studied using the European Centre for Medium Range Weather Forecasts (ECMWF) Re-Analysis data for the period (1979–1993). It has been shown that the North Pacific subtropical high displays substantial interannual variability at its western edge. Further analysis indicates a significant relationship between the zonal variation of the subtropical high, and the variation in the intensity of atmospheric convection over the warm pool. The stronger (weaker) convection over the warm pool is associated with more eastward (westward) position of the western Pacific subtropical high.

The UK Universities' Global Atmospheric Modelling Programme General Circulation Model (UGAMP GCM) is used to examine the influence of the local SST anomalies, and the associated anomalous convection over the tropical western Pacific warm pool on the zonal displacement of the North Pacific subtropical high. The model results show that the suppressed atmospheric convection caused by lower SSTs in the warm pool results in anomalous anticyclonic circulation in lower level over the subtropical western Pacific, and westward extension of the subtropical high. The results are consistent with the composite results based on the reanalysis data, and imply the SST anomalies off-equator over the western Pacific play an important role in the zonal shift of the North Pacific subtropical high in summer. Despite the fact of good agreements in many aspects between the model simulations and composite analyses based on observation, there are some differences between the two especially in terms of upper-level extratropical circulation anomalies over East Asia.

1. Introduction

The East Asian summer monsoon system includes the monsoon trough over the South China Sea and the western Pacific warm pool, western part of the Northwest Pacific subtropical high (hereafter NPSH), upper-level northeasterly return flows, the quasi-stationary frontal zones, and the disturbances in the middle latitudes (Tao and Chen 1987). The lower-level jet at the northwestern edge of the NPSH transports a large amount of water vapor into East Asia (e.g., Ninomiya and Kobayashi 1998, 1999). It has been well known that the northward shifts of the NPSH are closely associated with the onset and retreat of the East Asian summer monsoon. In June the NPSH shifts northwards, and the rainy season starts in the Yangtze River Valley, South Korea and Japan. In July, or sometimes in August, the NPSH shifts poleward further and the rainy season ends in the above-mentioned areas. The position, shape and strength of the NPSH dominate the large-scale quasi-stationary
frontal zones.

The shifts of the NPSH not only in meridional, but also in zonal direction, play a crucial role in the East Asian summer monsoon. Previously, great attentions were paid on the poleward shifts of the NPSH (e.g., Kurihara and Kawahara 1986; Nitta 1987; Kurihara and Tsuyuki 1987). Generally speaking, the zonal shifts of the NPSH may greatly influence the transports of water vapour into East Asia and resultant rainfall, since East Asia is located at the western edge of the NPSH. Lu (2001) found that the westward extension of the NPSH is associated with more rainfall in the East Asian monsoon region.

The influence of the thermal state of the western Pacific warm pool on the variations of the atmospheric circulation and precipitation over East Asia has been extensively studied. Nitta et al. (1986) showed that at lower levels there is a cyclonic circulation along the heat source centre around 20°N, and there is an anticyclonic circulation to the north of about 25°N. The studies by Huang and Li (1987), Nitta (1987), and Kurihara and Tsuyuki (1987) suggest that an atmospheric Rossby wave is generated by anomalous convective activities over the tropical western Pacific, and propagates from tropics to extratropics. From then on, there have been many studies on the physical mechanism and intraseasonal variations of this Rossby wave (Kurihara 1989; Huang and Sun 1992; Ueda and Yasunari 1996; Tanaka 1997). Kawamura et al. (1998) explained the decadal scale amplitude modulation of interannual variations near Japan by the concept of such a Rossby wave. Analysis of observation data by Lu (2001), identified the existence of a significant relation between the zonal displacement of the NPSH, and convection over the tropical western Pacific. This relation again shows the important roles of the thermal states in the warm pool area on the East Asian summer monsoon.

Recently, there were a few modelling studies on the effects of the off-equatorial SST anomalies in the western Pacific (Ose 1998; Wang et al. 2000). These studies, however, have not studied particularly the effects of the SST anomalies in the tropical western Pacific warm pool in summer. For example, Ose (1998) simulated the effects of the enhanced convection in the whole western Pacific, which includes both the tropical western Pacific warm pool, and the East Asian summer monsoon region. From his results, we could not specify the role of the warm pool. On the other hand, Wang et al. (2000) did simulate the effects of the SST anomalies in the tropical western Pacific. However, since they focused on the mature phase of ENSO, their simulated season is the boreal winter rather than summer.

In summary, the potentially important effects of the off-equatorial SST anomalies in the western Pacific during boreal summer have not properly, and thoroughly, simulated yet. The off-equatorial thermal states in the tropical western Pacific may bridge the gap between the SST anomalies in the equatorial eastern Pacific and the East Asian summer monsoon (Zhang et al. 1996; Wang et al. 2000). Therefore, the simulation on the effects of SST anomalies in the warm pool may provide a better understanding of the linkages of the East Asian summer monsoon to ENSO.

Because of the considerable consistency of the annual monsoon cycle, the seasonal evolution processes are of great importance and significance in the monsoon system (Murakami and Matsumoto 1994; Ueda and Yasunari 1996). The anomalous seasonal evolutions cause frequently anomalous summers (Park and Schubert 1997). Nevertheless, substantial interannual variability in intensity of monsoon makes the seasonal evolution seriously difficult to be well understood. Some studies showed that Asian monsoon fluctuations within a season and within different years have a common dominant mode of variability (Ferranti et al. 1997; Sperber et al. 2000). Comparison between the studies on the intraseasonal (Murakami and Matsumoto 1994; Ueda and Yasunari 1996; Tanaka 1997) and interannual variability (Nitta et al. 1986; Nitta 1987; Kurihara 1989; Huang and Sun 1992) suggests that the atmospheric convection over the tropical western Pacific influences the East Asian summer monsoon in both scales by an approximately common mode—teleconnection pattern caused by a Rossby wave. Particularly regarding the NPSH, and convection over the warm pool, Lu (2001) showed such a connection between the interannual variation and seasonal evolution. Therefore, an understanding of the mechanism of interannual variability may be helpful in better understanding seasonal evolution, as well as being crucial to successful seasonal and long-term forecast.

In this study, we focus on the zonal shift and variability of the NPSH on the interannual time scale in summer. The results based on the ECMWF reanalysis are presented in Section 2. The results of a sensitivity experiment using an Atmospheric Gen-
eral Circulation Model (AGCM) are described in Section 3. Discussions and conclusions are made in Sections 4 and 5, respectively.

2. Main features of the NPSH in observation

2.1 Observation data

The primary dataset used is the European Centre for Medium Range Weather Forecasts (ECMWF) global atmospheric Re-Analysis (ERA) dataset covering a 15-year period from 1979 to 1993. A detailed description of the data assimilation system, that produces this dataset, is given by Gibson et al. (1997). A variety of diagnostics have been computed by the Centre for Global Atmospheric Modelling (CGAM) from the model level data (Berrisford et al. 1998), and in this study the monthly mean data are used.

2.2 The NPSH in observation

In summer, the NPSH shifts poleward with time as the season advances. This is clearly illustrated in Fig. 1a, which shows 15 year mean June, July, and August (JJA) geopotential height at 850 hPa and 1480 lines in June, July, and August, respectively. The contour line of 1480 is located south to Japan in June. It shifts poleward and is located over central Japan in July. In August, the contour line of 1480 continues the poleward shift to North Japan. At the meantime, the western edge of the NPSH shown by this contour line shifts considerably eastwards.

The NPSH is often considered as an integrated feature, as appeared in the fields of geopotential height and horizontal winds. However, it is not the decent which dominates the whole anticyclone. The vertical velocity is quite different over different regions of the anticyclone, as indicated in Fig. 2. A mid-level ascent flow accompanies the lower-level southerly winds over the Northwest Pacific, while a mid-level descent flow accompanies the lower-level northerly winds over the Northeast Pacific. The correspondences between the vertical and meridional flows are consistent with the Sverdrup balance of vorticity in the lower troposphere (e.g., Hoskins 1996).

2.3 Interannual variability

Figure 1b shows the year-to-year standard deviation of geopotential height at 850 hPa during 15 years from 1979 to 1993. Comparing with those over the other places at the same latitudes, the variability of geopotential height is considerably greater over the western Pacific. Therefore, the NPSH shows a remarkable variability not only in seasonal march, but also on interannual scale over
the western Pacific. Here, an index, defined as the mean geopotential height at 850 hPa in JJA averaged over the west edge (110°-140°E, 10°-30°N) where the interannual variability has a local maximum, is introduced. The interannual variation of this index anomalies is shown in Fig. 3. We classified the NPSH of a particular year as a high (low) case if the index anomaly exceeds +0.5 (-0.5) of one standard deviation (7.7 m). According to this criterion, years with a greater positive index are 1979, 1980, 1983, 1987, 1988 and 1993, and years with a greater negative index are 1981, 1982, 1984, 1985, 1986 and 1990. These results are in the line with Lu (2001) by using the NCEP-NCAR reanalysis data as it is expected. In the next subsection, the composite analysis is performed to show the associated atmospheric anomalies, and attempt to explore the physical mechanisms that are responsible for the NPSH variability.

2.4 Composite analysis

Figure 4 shows the composite geopotential height at 850 hPa in JJA for the high index case and low index case (Fig. 4a) and the anomalies between them (Fig. 4b). It indicates that the NPSH extends westward (contracts eastward) remarkably over the western Pacific when the index anomaly is positive (negative). Therefore, the index defined in this study describes the zonal shifts of the NPSH over the western Pacific. As a result of this zonal shift, there are significantly positive anomalies over the subtropical western Pacific in higher index case relative to lower index case. The anomalies occur not only over the averaged area (110°-140°E, 10°-30°N), but also extend westward into the Bay of Bengal and eastward into the central tropical Pacific. There are slightly negative anomalies over central Japan.

Being consistent with the distribution of geopotential height anomalies, the wind anomalies at 850 hPa show that there is a strong anticyclonic anomaly over the subtropical western Pacific and a relatively weak cyclonic anomaly over Korea and Japan (Fig. 5a). The anticyclonic and cyclonic anomalies together cause a stronger lower-level southwesterly jet at the northwest edge of the NPSH. The anomalous anticyclonic and cyclonic circulation over the western Pacific in lower level appears to be associated with anomalous anticy-
clonic and cyclonic circulation in upper level, respectively (Fig. 5b). This correspondence is roughly barotropic, but with a slight poleward tilt with height. Similar tilt over East Asia was also mentioned by Yamazaki and Chen (1993), Kodama (1999) and Lu (2001). The upper-level cyclonic anomaly over Japan is associated with the equatorward displacement of the East Asian westerly jet, which is generally located along 40°N in summer and is a crucial factor influencing the East Asian summer monsoon. Over the tropical western Pacific (around 10°N), the wind anomalies exhibit a baroclinic structure, with significant easterly anomaly in lower level and westerly anomaly in upper level. Over the Indian Ocean, the Bay of Bengal and the South China Sea, there are easterly anomalies at the lower levels and westerly anomalies at the higher levels, an indication of weakened Indian summer monsoon.

The baroclinic circulation anomalies over the tropical western Pacific correspond to locally suppressed atmospheric convection that appears to extend into the tropical eastern Pacific (Fig. 5c). There is enhanced convection over Korea and Japan. Along the equator, the convection is also enhanced, but the significance is low. To delineate in more detail the relationship between the zonal shift of the NPSH and the convection over the warm pool, we introduce an Outgoing Longwave Radiation (OLR) index, which is defined as the area averaged OLR over the region (110–160°E, 10–20°N). The interannual variation of the OLR index anomalies is also shown in Fig. 3. It suggests that there is a remarkably good relationship between the NPSH index and OLR index. The correlation coefficient of 0.92 between the two indices is statistically significant at 99% confidence level. This result based on the ERA data is consistent with that based on the NCEP–NCAR reanalysis data (Lu 2001).

The anomalous lower level southwesterly, provides more water vapor into East Asia and cause more precipitation in the East Asian monsoon region, especially in south Japan (Fig. 6).

![Fig. 5. The composite difference (stronger subtropical high index case minus weaker index case) in JJA. (a) Horizontal winds at 850 hPa (m s⁻¹), (b) horizontal winds at 200 hPa (m s⁻¹), and (c) OLR (W m⁻²) with positive anomalies in full lines and negative anomalies in dotted lines. The shading indicates the difference is significant at 95% level using Student’s t-test.](image)

![Fig. 6. As in Fig. 5, but for the composite precipitation difference (mm day⁻¹) in JJA. Precipitation data (CAMS–OPI) are obtained from a merge of rain gauge observation and satellite-derived precipitation estimates (Janowiak and Xie 1999).](image)
also positive anomalies around the equatorial Indian Ocean. In the warm pool region there is a significantly less precipitation directly related to suppressed local convection. This distribution of precipitation anomalies may be explained qualitatively by the composite SST anomalies (not shown, readers refer to Lu (2001)), which exhibit an El Niño pattern, being positive in the equatorial eastern Pacific, tropical Indian Ocean, the Bay of Bengal and South China Sea, and being negative in the tropical western Pacific. This distribution of SST anomalies may hinder the northward march of the Inter-tropical Convergence Zone (ITCZ) and produce the precipitation anomalies similar to those in Fig. 6. Further discussion on the effect of SST anomalies on the ITCZ is made in Section 4.

A question arisen here is what caused the zonal variation of the NPSH, and variation of convection over the warm pool region. One possibility is that these variations arose simply through random internal fluctuations of the atmosphere. If this is the case, it implies these variations are not predictable. Another possibility is that they arose as a response of atmosphere to anomalous lower boundary forcing, for example, SST anomalies. If the latter is the case, it implies their variations are potentially predictable. In next section, we present some numerical experiments to show that anomalous SSTs in the warm pool region play an important role in zonal variation of the subtropical high. In addition, the numerical simulations may be also helpful for better understanding of the linkages of the East Asian summer monsoon to other systems, such as the El Niño SST warming and the mid-latitude disturbances.

3. Results from numerical experiments

3.1 Model and experiment design

The model used in this study is UK Universities' Global Atmospheric Modelling Programme General Circulation Model (UGAMP GCM), which is based on the forecast model of the European Centre for Medium Range Weather Forecasts (ECMWF). It is a special model with a hybrid coordinate in the vertical, using a triangular truncation at wavenumber 42 (T42). The physical parameterizations in the model are described in Slingo et al. (1994). 5 of 19 vertical levels of the model are within the lowest 150 hPa of the atmosphere.

The land surface temperature and moisture content are calculated using a three-layer diffusive model. A no-flux boundary condition, which allows the surface temperature and soil moisture to respond fully to the forcing, rather than being tied to the imposed climatology, is used at the bottom of the soil model. The use of the no-flux boundary condition improves the simulations on the climatological and interannual variability of the Asian summer monsoon circulation (Dong and Valdes 1998).

The control simulation is with the AMIP climatological SST, averaged over 10 years (1979–1988). The last 10 years, in total 11 years of integration, are used as the model control climatology. The anomalous simulations are performed with negative SST anomalies of 1°C off-equator over the western Pacific (10°-20°N, 110°-160°E). This region is the same as the region where the OLR index is defined in Section 2. There are six independent 6-month integrations from April 1 to September 30 with initial data from March 27 to April 1 of the 11th year in the control simulation, respectively. The response to SST anomalies is estimated as the difference between the ensemble mean and the control experiment.

3.2 Basic features of subtropical high in the control simulation

UGAMP GCM captures the main characteristics of the NPSH (Fig. 7). Comparison with the observation (Fig. 1a) suggests that the model has a good ability in simulating the mean position of the NPSH. However, the seasonal poleward advancement of 1480 line is not very well simulated. It should be noted that because the control simulation is with the climatological SSTs, there would

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Fig. 7. Climatological geopotential heights (m) at 850 hPa in JJA for the model control simulations with the AMIP (1979–1988) climatological SSTs. Thin, medium, and thick dashed lines are 1480 m contours in June, July and August, respectively, and full thick line is 1480 m contour in JJA.
be some extra differences between the simulation and observation. Given the fact that the NPSH is well simulated in JJA seasonal mean, the poor simulation of its seasonal advancement is not expected to be crucial for the purpose here since we will investigate the response of the NPSH in JJA to the prescribed SST anomalies.

3.3 Impact of anomalous SST in the warm pool

Figure 8 shows the geopotential height at 850 hPa in JJA for the control and sensitivity experiments, and the difference between the two. The NPSH extends remarkably westward over the western Pacific in the sensitivity experiment, in comparison with the control experiment. The simulated results indicate a relationship between the zonal shift of the NPSH, and SST anomalies over the warm pool. Associated with cold SST anomalies over the

![Image](image_url)

Fig. 8. (a) The geopotential height (m) at 850 hPa in JJA for the model control simulation (dotted lines) and for the sensitivity simulation (full lines) with 1480 m contours highlighted by thick line, and (b) their difference (sensitivity minus control) with positive anomalies in full lines and negative anomalies in dotted lines. The shading in (b) indicates the difference is significant at 95% level using Student's t-test. The box shows the region where SST anomalies were applied in the sensitivity experiment.

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Fig. 9. The mean difference (sensitivity minus control) in JJA. (a) horizontal winds at 850 hPa (m s⁻¹), (b) horizontal winds at 200 hPa (m s⁻¹), and (c) OLR (W m⁻²) with positive anomalies in full lines and negative anomalies in dotted lines. The shading indicates the difference is significant at 95% level using Student's t-test. The box shows the region where SST anomalies were applied in the sensitivity experiment.
Due to the lower SSTs in the warm pool, there are significant changes in the atmospheric circulation over the subtropical western Pacific. The positive lower-level height anomalies over the subtropical western Pacific (Fig. 8b) are associated with anomalous anticyclonic circulation (Fig. 9a) at lower levels. A baroclinic structure appears over the region of anomalous SSTs, i.e., an anomalous easterly in lower level and anomalous westerly in upper level (Figs. 9a and b). North of this region, i.e., over the subtropical western Pacific, there is also a similar baroclinic structure with anomalous anticyclonic and cyclonic circulation in lower and upper levels, respectively. Northeastwards, i.e., over the mid-latitude central Pacific, a relatively weaker cyclonic anomaly appears at both lower and upper levels, exhibiting a barotropic structure. These simulated baroclinic and barotropic structures bear some similarity with those of Wang et al. (2000) based on the observation data.

These simulated circulation anomalies, in both lower and upper levels, show differences with the composite differences between high and low NPSH index cases shown in Section 2. These differences will be discussed in detail in Section 4.

Both convection and precipitation are significantly changed over the warm pool region due to the lower SSTs (Figs. 9c and 10). The suppressed convection and deduced precipitation have not confined over the region of lower SSTs, but shift slightly northeastwards with a tendency of extensively zonally-oriented extension westward into the Arabian Sea and eastward into the tropical eastern Pacific, alone the latitudes of 10°–20°N. An accompanying zonally-oriented zone of enhanced convection and precipitation occurs to the south, extending westward into tropical Indian Ocean and eastward into eastern Pacific. These dipole patterns of changes in both the OLR and precipitation suggest that the ITCZ shifts southward with cold SST anomalies over the subtropical west Pacific. These precipitation anomalies bear some similarities to the composite anomalies (Fig. 6), implying that in both composite based on the observation and the model simulation, there are extra heating anomalies along the equator. These extra heating anomalies, however, seem not to cause significant circulation anomalies even in situ, and most of the simulated results discussed here also appear to be basically explained by the negative SST anomalies in the warm pool.

4. Discussion

In this study, the composite analyses using ECMWF re-analysis data and numerical simulations confirm that there is a close relationship between the zonal shift of the NPSH and the atmospheric convection off-equator over the western Pacific (indicated by OLR), and show that the SST anomalies over the western Pacific influence the zonal shift of the NPSH significantly. The lower SSTs in the western Pacific lead to suppressed convection in situ, and anomalous anticyclonic circulation northwestwards in lower levels, which results in the westward extension of the NPSH. The prescribed SST anomalies produce the tropical heating anomalies, which is indicated by OLR and precipitation, similar to the composite ones based on observation. The remarkably consistence between the composite results based on observation, and those simulated by the model, suggests that the SST anomalies off-equator over the warm pool play an important role in the zonal shift of the NPSH over the western Pacific.

It is expected that the warmer SSTs provide a favourite condition for a stronger atmospheric convection above. This is especially true in the tropical western Pacific, where the SSTs are very high. In this study, we have shown that the changed convection over the warm pool associated with the SST anomalies results in large scale atmospheric circulation changes. The results bear similar characteristics as those in simple model studies (e.g., Webster 1982; Kasahara and Silva Dias 1986; Jin and Hoskins 1995; Ose 1998).

The direct response of atmosphere to diabatic heating has been investigated in a number of studies using simple primitive equation models with prescribed heating (e.g., Webster 1982; Kasahara and Silva Dias 1986; Jin and Hoskins 1995; Hoskins...
and Rodwell (1995; Ose 1998). In their experiments, the Gill-type response was seen both in lower and upper troposphere. However, their prescribed heatings are different to the heating caused by specified SST anomalies in the present study in locations, scales or seasonality. For instance, Jin and Hoskins (1995) examined the effects of heatings on the equator at different longitudes on a resting basic state and in a winter flow. For summer case, Hoskins and Rodwell (1995) reproduced many features of the global circulation in their model by using the June–August global heating, which is basically concentrated in the tropics and subtropics, especially over Asian monsoon regions. Among these studies, some prescribed heatings in Ose (1998) (extended South Asia and the western Pacific) are somewhat similar to the specified SST anomalies in the present study in locations and scopes. These heatings, however, occupy much wider areas and thus probably include the effects of the South Asian monsoon and East Asian monsoon. On the other hand, aforementioned studies are on the effects of heat sources in the climatological senses, whereas the main purpose of this study is on interannual variations.

Despite the many aspects of differences in heating between the present study and the aforementioned studies, there is general consistency in the lower-level circulation between the present GCM results and previous results by simple models. Such a consistency gives more confidence in our conclusion on the effects of the SST anomalies in the western Pacific on the NPSH.

For better understanding the simulated results, in the following we discuss the differences between the composite results based on observation, and those simulated by the model. The similarity between them has been mentioned in the preceding section. In observation, the meridional displacement of the upper-level westerly jet is associated with the zonal shift of the NPSH, and the disturbances exhibit a barotropic structure in the middle latitudes (Figs. 5a and b). However, in the simulation, the upper-level westerly jet does not exhibit a meridional displacement, and the disturbances do not exhibit a barotropic structure in the middle latitudes (Figs. 9a and b). Particularly, over East Asia, the disturbances show a barotropic structure in observation, but a baroclinic structure in simulation. Generally, the differences between observation and simulation dominate in the upper level rather than the lower level.

In lower levels, the simulated wind anomalies (Fig. 9a) are located 5-degree polewards, comparing with the observation (Fig. 5a), although they are basically similar. This difference is likely due to the poor simulation of the southward displacement of the upper-level East Asian jet (Figs. 9b and 5b), which may result in an equatorward displacement of the NPSH over the western Pacific through vertical coupling. Other factors which may be also responsible for the differences between the simulation and observation are SST anomalies over other regions.

**Fig. 11.** The seasonal tendency of precipitation (a) between July and June, and (b) between August and July (mm day$^{-1}$), and (c) sector averaged sea surface temperature (1961–1990 climatology) (Reynolds and Smith 1994) in the western Pacific (110–160°E) in June, July, and August (°C).
Over East Asia, there is more precipitation in both observation and simulation (Figs. 6 and 10). Unlike the results in observation (Fig. 6), however, the change in precipitation over East Asia is not significant in simulation (Fig. 10), likely due to poor simulated East Asian jet and the poleward bias of lower-level circulation anomalies.

The lower SSTs in the tropical western Pacific seem to hinder the seasonal evolution of in situ circulation and of ITCZ. The present study is consistent with that of Lu (2001), who showed that the slower evolution of the NPSH is closely associated with the westward extending of seasonal average. Numaguti (1995) suggested that an abrupt jump of the precipitation peak is observed, when the latitude of the SST peak becomes high enough (about 15°N). Therefore, provided the SST peak is around 15°N (it is exactly so for the boreal summer), any changes in SSTs around the peak leads to great change in the meridional distribution of precipitation.

Figure 11 shows the seasonal tendency of precipitation and SSTs averaged in the tropical western Pacific (110°–160°E). The changes in precipitation during JJA (Fig. 11a and b) are very similar to the precipitation anomalies in both Figs. 5 and 10, but with opposite signs. Corresponding to these changes in precipitation, the peak of SSTs averaged over 110°–160°E reaches 20°N in July and August from 2.5°N in June (Fig. 11c). The zonal mean surface temperature (not shown) also exhibits a similar change in peak latitude with the SSTs averaged over 110°–160°E. Thus, the theory of Numaguti (1995) may be used to explain the delay of the poleward march of ITCZ.

The results from both the re-analysis and numerical simulations are consistent with previous studies in the tropics and subtropics (Nitta et al. 1986; Murakami and Matsumoto 1994; Ueda and Yasunari 1996; Tanaka 1997; Kawamura et al. 1998). All these studies—including this study—showed that there is an anticyclonic circulation anomaly at the lower levels over the Northwest Pacific when the atmospheric convection is suppressed, within a season and within different years. For example, Tanaka (1997) analysed the spatial patterns of the sea-level pressure and the GMS high-cloud amounts for July 20–29 during the La Niña years, and during the El Niño years. The difference between the El Niño and the La Niña years shows the largest pressure difference near (140°E, 25°N), and a weaker convection near (150°E, 20°N). The results of the present study are consistent with his results with a slight difference in spatial location.

Comparison between this study and the studies on the intraseasonal variability (Nitta 1987; Kurihara 1989; Murakami and Matsumoto 1994; Ueda and Yasunari 1996; Tanaka 1997) suggests that the East Asian monsoon fluctuations both within a season and within different years have a common dominant mode of variability. Murakami and Matsumoto (1994) analysed the seasonal march of the western North Pacific summer monsoon (WNPM). It is interesting that the region where we applied SST anomalies in this study is almost exactly identical to the region of WNPM during August 19–23 (Fig. 15 of their paper).

In the experiment of this study, the prescribed lower SSTs correspond well to the locally suppressed convection. In real, however, the relationship between the atmospheric convection and SSTs is complex and far from being well understood. Lu (2001) constructed the SST difference between the years with westward extended and eastward contracted NPSH. There is slightly significant negative SST anomaly in the tropical western Pacific, while the significant positive SST anomalies appear in the Indian Ocean, the Bay of Bengal, South China Sea, subtropical western Pacific, and in the equatorial eastern Pacific. This implies that the atmospheric convection over the warm pool is influenced by the SST anomalies not only in situ, but also in the remote regions. The positive SST anomalies in these regions may change large-scale atmospheric circulation in the tropics and thus suppress the atmospheric convection over the warm pool. For instance, weaker convection accompanies higher SST in the tropical western Pacific in JJA of 1998. Although SST was above normal in the western Pacific in JJA of 1998, the largest SST anomalies (more than 1.0°C) are over the maritime continent. This resulted in much enhanced convection over the maritime continent, and reduced convection over the western Pacific (Lu 2000). A similar situation happens in JJA of 1988 (Nitta 1990). These results imply that the changes in SST gradient are responsible for the anomalous convection. By an ensemble simulation, Kawamura et al. (1998) suggested that the presence of strong east–west gradient of SST anomalies across the Philippines is responsible for the convective activity around the Philippines.
5. Conclusions

This paper provides both observational and numerical modelling studies focusing on the year-to-year variability of the western North Pacific subtropical high (NPSH) in summer. Observational study based on ECMWF reanalysis suggests that there is a strong correlation between the westward extension of the NPSH and the convection activity over the northwestern Pacific. The stronger (weaker) convection over the warm pool is associated with more eastward (westward) position of the NPSH. These relationships are in agreement with the study by Lu (2001) using the NCEP-NCAR reanalysis data as one expects. The suppressed convection over the warm pool is associated with lower-level anomalous anticyclonic circulation northwest of the suppressed convection. This anticyclonic circulation anomaly results in the westward extension of the NPSH and strengthens the lower-level jet at the northwest edge of the NPSH. The strengthened lower-level jet is associated with a stronger ascent motion and more summer monsoon precipitation in East Asia.

Numerical experiment using an atmospheric general circulation experiment indicates that the SST anomalies off-equator in the western Pacific play an important role in the zonal variation of the NPSH. When the SSTs are below normal in the warm pool, the suppressed convection leads to an anomalous lower-level anticyclonic circulation northwest of the suppressed convection. This is what is expected to be associated with a diabatic cooling according to the theory of Gill (1980). The anomalous anticyclonic circulation is associated with a westward extension of the NPSH. The similarity between the composite anomalies based on the observation and the anomalies induced by cold SST anomalies implies that the off-equator SST anomalies are at least one of the main factors responsible for zonal variation of the NPSH. These results imply that the variation of the NPSH both in its intensity, and zonal displacement over the western Pacific, may be predictable provided that the SSTs are accurately forecasted.

The similarities between observation and simulation appear mainly in lower levels, suggesting that the SST anomalies in the warm pool play a dominant role in influencing the lower-level atmospheric circulation. In particular, the anomalous anticyclonic circulation over the subtropical western Pacific exhibits a similar feature between observation and simulation. In upper level, however, there are many differences between observation and simulation, particularly regarding the East Asian jet stream. In simulation, the poleward displacement of the lower-level circulation anomalies over East Asia, comparing with the composite anomalies based on observation, is likely due to the poor simulation on the equatorward displacement of upper-level East Asian jet, which may influence the lower-level circulation through vertical coupling. Besides the SST anomalies off-equator in the western Pacific, there are other factors that may be responsible for the extratropical circulation anomalies in the composite based on the observation.

The SST anomalies in the tropical western Pacific influence atmospheric circulation and precipitation not only in situ, but also in remote areas. They even appear to influence the meridional displacement of ITCZ over the tropical eastern Pacific. The SST and convection in the tropical western Pacific seem to influence the seasonal march of ITCZ and East Asian summer monsoon.

According to the variability of SST in the western Pacific warm pool area, Ailikun and Yasunari (2001) proposed a concept of summer persistence barrier over the western Pacific. This concept suggests that the persistence in SST anomalies from the previous winter to the following May is destroyed once the new summer monsoon season starts. They showed that there are many differences in the correlation pattern between Asian summer monsoon, and ENSO in July–August–September compared with that in June. In this study, however, we did not examine the differences in the effects of SST anomalies in the western Pacific warm pool between these two periods, which should be studied in the future.

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