Two anomalous convective systems in the tropical western Pacific and their influences on the East Asian summer monsoon

XUE Feng, DONG Xiao and LIN Ren-Ping

International Center for Climate and Environmental Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

ABSTRACT

By decomposing outgoing longwave radiation through empirical orthogonal function (EOF) analysis, the authors identify two anomalous convective systems in the tropical western Pacific. Besides the classical convective system near the Philippines (PC), there is another convective system near the Federated States of Micronesia (MC). As the first EOF component in this region, the variance explained by MC is higher than that by PC. Both MC and PC are regulated by the tropical sea surface temperature (SST) anomalies. While PC is associated with an El Niño event, MC is correlated with SST anomalies in the central and eastern Pacific during summer. It is also found that the East Asian summer monsoon (EASM) is influenced by these two convective systems. In general, enhanced (suppressed) convection corresponds to an eastwards (westwards) western Pacific subtropical high with weak (strong) intensity. Besides, the summer monsoon rainfall from the Yangtze River basin to Japan tends to increase (decrease) when PC is suppressed (enhanced). By comparison, the influence of MC is generally weak, with vague signals in the East Asian continent. Moreover, the influence of suppressed convection on the EASM is more significant than that of enhanced convection.

1. Introduction

During boreal summer, convective clouds appear in the tropical western Pacific, which play an important role in East Asian climate. In particular, the influence of convection near the Philippines (PC) on the East Asian summer monsoon (EASM) has been emphasized. Nitta (1987) noted that, when sea surface temperature (SST) is warmer than normal, Rossby waves are generated by PC associated with typhoons and tropical depressions, and high pressure anomalies appear in East Asia and the northwestern Pacific. He then referred to the teleconnection between PC and the EASM as the Pacific-Japan (PJ) pattern. Ueda, Yasunari, and Kawamura (1995) further indicated that the large-scale convective activity near (20°N, 150°E) enhances suddenly and shifts northwards in late July, resulting in an anomalous anticyclone to its north and the termination of baiu in Japan. As a dominant mode of the EASM intraseasonal variation, the northward jump of the western Pacific subtropical high (WPSE) is related to the enhancement of warm pool convection (Su and Xue 2011). On the interannual timescale, the WPSE is also affected by PC. Lu (2001a) demonstrated that, when PC is enhanced (suppressed), there is a low-level cyclonic (anticyclonic) anomaly in the subtropical western Pacific, leading to an eastward (westward) movement of the WPSE. The collective evidence presented above indicates that PC and the associated PJ pattern play a crucial role in EASM variability.

The original work by Nitta (1987) focused on enhanced PC and its teleconnection with the EASM, which usually occurs in La Niña years (Xue and Zhao 2017). Later, it was demonstrated that PC provides a crucial link between the El Niño—Southern Oscillation (ENSO) and EASM (Huang...
Recent studies show that this link is associated with a basin-wide warming over the tropical Indian Ocean following an El Niño event. The warming acts like a capacitor sustaining atmospheric anomalies over the Indo-western Pacific Ocean, prolonging the influence of El Niño after its decay. By emanating a baroclinic Kelvin wave into the western Pacific, it induces suppressed PC and an anomalous anticyclone over the subtropical western Pacific, resulting in summer rainfall anomalies in East Asia (Yang et al. 2007; Xie et al. 2009).

While the SST is relatively homogeneous in the tropical western Pacific, the convective systems, especially deep convection, are generally confined to particular regions owing to the complex geography and the influence of atmospheric circulation. Although PC and its influence are well recognized, other systems are rarely mentioned in the literature thus far. For this purpose, in the present study, we conduct an empirical orthogonal function (EOF) analysis in the tropical western Pacific and identify an independent component near the Federated States of Micronesia, which we refer to as Micronesian convection (MC). In addition, we compare the influences of MC and PC on the EASM.

2. Data and methods

Outgoing longwave radiation (OLR) data, used as a proxy for tropical convection, are obtained from the National Oceanic and Atmospheric Administration (NOAA) (Liebmann and Smith 1996). Other datasets used in this study include: atmospheric circulation data from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (Kanamitsu et al. 2002); precipitation data from the Global Precipitation Climatology Project (Huffman et al. 1997); and SST data from NOAA (Smith et al. 2008). The horizontal resolution of the SST data is 2.0° × 2.0°, while that of the other datasets is 2.5° × 2.5°. For convenience, all datasets are taken as the 35-yr period from 1979 to 2013, to match with the availability of the OLR data.

In order to identify the distribution of anomalous convection in the tropical western Pacific, we decompose the OLR anomaly using EOF analysis. Besides, the influence of major components on the EASM is also analyzed. All results are tested using the Student’s t-test.

3. Results

Focusing on convection near the Philippines, Lu (2001b) defined warm pool convection as the regional mean OLR within (10°–20°N, 110°–180°E), based on the interannual variability of OLR. To build a complete picture of convection, we further extend the region into the tropical western Pacific in the Northern Hemisphere (0°–30°N, 110°–180°E).

Figure 1 shows the spatial distribution of the first two EOF components of OLR, i.e. EOF1 and EOF2, with the explained variances reaching 27% and 24%, respectively. The variance of EOF3 is only 9% and not shown here. Besides, the eigenvalue difference between EOF1 and EOF2 (53.5) is larger than the corresponding eigenvalue error (37.3). Based on the rule proposed by North, Bell, and Cahalan (1982), the two modes can be distinguished statistically.

The distribution of EOF1 shows that there is an anomalous convective system near the Federated States of Micronesia, i.e. MC (Figure 1(a)). The enhanced MC (negative OLR) corresponds to suppressed convection near Indonesia and the subtropical region to the north of MC. The distribution of EOF2 agrees well with the classical PC, with the largest value to the east of the Philippines (Lu 2001b). Therefore, PC is not the only convective system in the tropical western Pacific, although it is relatively stronger. Also of note is that both MC and PC are stable and less related to the selected regions. If we extend the region to 10°S, for instance, the two systems are still evident. Besides, a robust interannual variability is evident in the corresponding time series, as shown in Figure 2.

The two convective systems are associated with the tropical SST, and the correlation exhibits a clear seasonal variation (Figure 3). The correlation between MC and SST is not so significant in winter, and only a negative correlation is found in parts of the tropical Indian Ocean and western Pacific (Figure 3(a)). In summer, the correlation is significantly enhanced, with a positive correlation in the central and eastern Pacific and a negative one in the western Pacific (Figure 3(b)). Different from MC, the correlation of PC with the winter SST exhibits a negative correlation.
in the central and eastern Pacific and a positive one in the western Pacific; this typical horseshoe pattern indicates an influence of El Niño (Figure 3(c)). With the decay of the El Niño signal in summer, the correlation in the Pacific is greatly weakened (Figure 3(d)). Instead, a negative correlation appears in the tropical Indian Ocean. The result agrees well with previous studies showing a warmer SST in the Indian Ocean tending to suppress PC in the subsequent summer following El Niño (e.g. Xie et al. 2009). On the other hand, the significant discrepancy of the correlation between MC and PC further demonstrates that the two systems are mutually independent. While PC is closely related to El Niño, it seems that MC is directly driven by the SST in the central and eastern Pacific.

In order to illustrate the influence of the two systems on the EASM, we perform a composite analysis by selecting the years with an anomaly over 0.8, based on the time series of EOF1 and EOF2 in Figure 2. As shown in Table 1, there are 8 years with a positive anomaly and 7 years with a negative anomaly. Among the selected 15 years, only one overlapping year with a positive anomaly for the two systems is found (in 2004), and one with a negative anomaly (in 1998), indicating that the two systems are generally independent.

Figure 4 shows the composite 500-hPa geopotential height anomaly in the selected years listed in Table 1. The significant anomaly for MC is mainly located in northeastern Asia to the north of Japan, while the major significant anomaly for PC is found in the tropics. In the meantime, the anomaly in the positive years is obviously smaller than that in the negative years, and the anomaly for PC positive years near Japan cannot reach the 95% confidence level (Figure 4(c)). The antisymmetric aspects between the positive and negative years are clearly related to a larger absolute mean value in the negative years listed in Table 1. In other words, the EASM is more significantly influenced by suppressed tropical convection.

### Table 1. Selected years with an anomaly over 0.8 for the first and second EOF components (EOF1 and EOF2).

| EOF component | Anomaly | Selected years | Mean value |
|---------------|---------|----------------|------------|
| EOF1          | Positive| 1980, 1982, 1987, 1991, 1993, 1997, 2002, 2004 | 1.21       |
|               | Negative| 1984, 1988, 1996, 1998, 2008, 2010, 2013 | −1.27      |
| EOF2          | Positive| 1981, 1984, 1985, 1986, 1990, 2001, 2004, 2012 | 1.00       |
|               | Negative| 1980, 1982, 1983, 1987, 1993, 1995, 1998 | −1.27      |
As a major circulation system for the EASM, the WPSH exhibits an evident anomaly following geopotential height change over East Asia. Note that the significant anomaly is located in high latitudes to the north of 40°N with an enhanced MC (Figure 4(a)), and the WPSH remains almost unchanged (Figure 5(a)). When the MC is suppressed, however, the significant anomaly extends further to subtropical East Asia (Figure 4(b)). Accordingly, the WPSH tends to intensify and extend westwards (Figure 5(a)). In agreement with previous studies (Lu 2001a; Xue and Fan 2016), the WPSH exhibits a zonal displacement with anomalous PC (Figure 5(b)). Corresponding to suppressed (enhanced) PC, the WPSH tends to extend westwards (retreat eastwards). In comparison with MC, PC exerts a more significant effect on the WPSH. This is because PC is nearer than MC to the WPSH. At the same time, the significant anomaly in northern Japan caused by MC is also far from the WPSH (Figure 4). In addition, the antisymmetric feature between the enhanced and suppressed convection is also evident for the WPSH, as found in Figure 4.

The rainfall distribution in East Asia is largely controlled by the WPSH. Following the anomalous WPSH in Figure 5, rainfall in East Asia and the western Pacific exhibits an evident anomaly (Figure 6). Different from geopotential height, the influence of MC on rainfall is generally confined to the tropics (Figure 6(a) and (b)). Enhanced

Figure 4. Composite 500-hPa geopotential height anomaly in selected years (units: gpm): (a) positive years for the first EOF component (EOF1+); (b) negative years for EOF1 (EOF1−); (c) positive years for the second EOF component (EOF2+); (d) negative years for EOF2 (EOF2−). Note: Regions above the 95% confidence level are shaded.

Figure 5. The western Pacific subtropical high in summer (units: gpm): (a) the first EOF component (EOF1); (b) the second EOF component (EOF2). Note: The long-dashed, short-dashed, and solid contours represent the positive years, negative years, and climatological mean, respectively.
In general, the WPSH tends to extend westwards in association with suppressed convection, while an opposite trend is found with enhanced convection. Also of note is that the response of the EASM to suppressed convection is much more pronounced. Besides, the summer rainfall anomaly in East Asia is affected by PC. More rainfall from the Yangtze River basin to Japan typically coincides with suppressed PC, and vice versa. By contrast, the influence of MC is confined to the tropics, with only a vague signal in the East Asian continent. Nevertheless, the MC signal may provide some useful information for EASM prediction, especially when PC is anomalously weak.

It should be pointed out that a more significant influence of PC on the EASM is not only related to the tropical SST anomaly, but also to the tropical circulation in summer. As is well known, southwest summer monsoon circulation exists from the tropical Indian Ocean to the western Pacific, and East Asia is located in the downstream of this monsoon. Since PC is closely related to El Niño (Figure 3), the result agrees with the influence of El Niño on the EASM, as noted in several previous studies (e.g. Xue and Liu 2008; Zhao et al. 2016).

4. Summary

By decomposing OLR data using EOF analysis, we identify two anomalous convective systems in the tropical western Pacific, which are represented as the first and second EOF components. Besides the classical convective system near the Philippines (PC), there is another system with a larger variance near the Federated States of Micronesia (MC). Both systems are related to the SST anomalies in the tropical Pacific. While PC is closely correlated with El Niño, MC is significantly correlated with the summer SST anomaly in the central Pacific. The seasonal difference of the correlation pattern also indicates that the two systems are generally independent.

Composite analysis in selected years yields well-defined rainfall and circulation signals in East Asia and the western Pacific that are closely linked to anomalous MC and PC. In general, the WPSH tends to extend westwards in association with suppressed convection, while an opposite trend is found with enhanced convection. Also of note is that the response of the EASM to suppressed convection is much more pronounced. Besides, the summer rainfall anomaly in East Asia is affected by PC. More rainfall from the Yangtze River basin to Japan typically coincides with suppressed PC, and vice versa. By contrast, the influence of MC is confined to the tropics, with only a vague signal in the East Asian continent. Nevertheless, the MC signal may provide some useful information for EASM prediction, especially when PC is anomalously weak.

It should be pointed out that a more significant influence of PC on the EASM is not only related to the tropical SST anomaly, but also to the tropical circulation in summer. As is well known, southwest summer monsoon circulation exists from the tropical Indian Ocean to the western Pacific, and East Asia is located in the downstream of this monsoon. Since PC is significantly correlated with the Indian Ocean SST, it shows a more pronounced influence on the EASM. By comparison, MC is correlated with the SST in the tropical central and eastern Pacific, where the trade wind prevails. Hence, the influence of MC is relatively weaker than that of PC.

MC exhibits a significant correlation with the summer SST in the tropical Pacific, with a positive correlation in the central and eastern Pacific and a negative one in the western Pacific. This correlation pattern is related to, but somewhat different from, the SST anomaly during a central Pacific El Niño event, which shows a typical tripolar distribution (Kao and Yu 2009; Sun, Xue, and Zhou 2013).
Therefore, further study through numerical experiments is needed to reveal the physical mechanism responsible for anomalous MC, especially the relationship with the two types of El Niño. A better understanding of these mechanisms will advance our ability in forecasting the EASM.

Acknowledgements

The authors appreciate the comments and suggestions from the two anonymous reviewers.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by the National Natural Science Foundation of China [grant number 41475052].

References

Huang, R. H., and Y. F. Wu. 1989. “The Influence of ENSO on the Summer Climate Change in China and Its Mechanism.” *Advances in Atmospheric Sciences* 6: 21–32.

Huffman, G. J., R. F. Adler, P. Arkin, A. Chang, R. Ferraro, A. Gruber, J. Janowiak, A. McNab, B. Rudolf, and U. Schneider. 1997. “The Global Precipitation Climatology Project (GPCP) Combined Precipitation Datasets.” *Bulletin of the American Meteorological Society* 78: 5–20.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter. 2002. “NCEP-DOE AMIP-II Reanalysis (R-2).” *Bulletin of the American Meteorological Society* 83: 1631–1643.

Kao, H. Y., and J. Y. Yu. 2009. “Contrasting Eastern-Pacific and Central-Pacific Types of ENSO.” *Journal of Climate* 22: 615–632.

Liebmann, B., and C. A. Smith. 1996. “Description of a Complete (Interpolated) Outgoing Longwave Radiation Dataset.” *Bulletin of the American Meteorological Society* 77: 1275–1277.

Lu, R. 2001a. “Interrannual Variability of the summertime North Pacific Subtropical High and Its Relation to Atmospheric Convection over the Warm Pool.” *Journal of the Meteorological Society of Japan* 79: 771–783.

Lu, R. 2001b. “Atmospheric Circulations and Sea Surface Temperatures Related to the Convection over the Western Pacific Warm Pool on the Interannual Scale.” *Advances in Atmospheric Sciences* 18: 270–282.

Nitta, T. 1987. “Convective Activities in the Tropical Western Pacific and Their Impact on the Northern Hemisphere Summer Circulation.” *Journal of the Meteorological Society of Japan* 65: 373–390.

North, G. R., T. L. Bell, and R. F. Cahalan. 1982. “Sampling Errors in the Estimation of Empirical Orthogonal Functions.” *Monthly Weather Review* 110: 699–706.

Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore. 2008. “Improvements to NOAA’s Historical Merged Land–Ocean Surface Temperature Analysis (1880–2006).” *Journal of Climate* 21: 2283–2296.

Su, T. H., and F. Xue. 2011. “Two Northward Jumps of the Summertime Western Pacific Subtropical High and Their Associations with the Tropical SST Anomalies.” *Atmospheric Oceanic Science Letters* 4: 98–102.

Sun, D., F. Xue, and T. J. Zhou. 2013. “Impacts of Two Types of El Niño Events on the Atmospheric Circulation in the Southern Hemisphere.” *Advances in Atmospheric Sciences* 30: 1732–1742.

Ueda, T., T. Yasunari, and R. Kawamura. 1995. “Abrupt Change of Large-scale Convective Activity over the Western Pacific in the Northern Summer.” *Journal of the Meteorological Society of Japan* 73: 795–809.

Xie, S.-P., K. Hu, J. Hafner, H. Tokinaga, Y. Du, G. Huang, and T. Sampe. 2009. “Indian Ocean Capacitor Effect on Indo–Western Pacific Climate during the Summer following El Niño.” *Journal of Climate* 22: 730–747.

Xue, F., and F. X. Fan. 2016. “Anomalous Western Pacific Subtropical High during Late Summer in a Weak La Niña Year: Contrast between 1981 and 2013.” *Advances in Atmospheric Sciences* 33: 1351–1360.

Xue, F., and C. Z. Liu. 2008. “The Influence of Moderate ENSO on Summer Rainfall in Eastern China and Its Comparison with Strong ENSO.” *Chinese Science Bulletin* 53: 791–800.

Xue, F., and J. J. Zhao. 2017. “Intraseasonal Variation of the East Asian Summer Monsoon in La Niña Years.” *Atmospheric Oceanic Science Letters* 10: 156–161.

Yang, J., Q. Liu, S.-P. Xie, Z. Liu, and L. Wu. 2007. “Impact of the Indian Ocean SST Basin Mode on the Asian Summer Monsoon.” *Geophysical Research Letters* 34: L02708. doi: 10.1029/2006GL028571.

Zhao, J. J., F. Xue, W. T. Lin, and A. M. Duan. 2016. “The El Niño Influence on Intra-seasonal Variations of East Asian Summer Monsoon and Summer Rainfall.” *Climatic and Environmental Research* 21: 678–686. (in Chinese).