Combined impact of in-phase and out-of-phase variation between the northern East Asian low and western North Pacific subtropical high on East Asian summer rainfall

DU Meng-Xing, LIN Zhong-Da and LU Ri-Yu

State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; College of Earth Science, University of Chinese Academy of Sciences, Beijing, China

ABSTRACT

East Asian summer rainfall is affected by both the continental northern East Asian low (NEAL) and the western North Pacific subtropical high (WNPSH) in the lower troposphere. This study investigates the joint effect of the two circulation factors on East Asian summer rainfall. It is found that the rainfall in East Asia behaves differently in the years with in-phase and out-of-phase variation between the NEAL and WNPSH. When the NEAL and WNPSH vary in phase, i.e. when they are both stronger, the rainfall anomaly shows a dipole pattern in East Asia and displays opposite changes between north and south of 30°N. When the two circulation factors vary out of phase, the rainfall anomaly is concentrated in the Yangtze River valley.

1. Introduction

East Asian summer monsoons and rainfall are affected by the land-sea thermal contrast between continental East Asia and the North Pacific Ocean (Guo 1983; Shi and Zhu 1996; Zhao and Zhou 2005; Zhu et al. 2005). The thermal contrast is characterized by a continental low pressure system that is centered over northern East Asia (NEAL) and a subtropical high over the western North Pacific (WNPSH) in the lower troposphere (Figure 1(a)). Previous studies have found that the WNPSH and NEAL both have a crucial role in affecting East Asian summer rainfall (e.g. Chang, Zhang, and Li 2000a, 2000b; Lu 2001; Lu and Dong 2001; Gong and Ho 2002; Wu et al. 2010; Shen et al. 2011; Ren, Yang, and Sun 2013; Lin 2014; Huangfu, Huang, and Chen 2015; Lin and Wang 2016). For example, Chang, Zhang, and Li (2000a, 2000b) showed that a westwardly extended WNPSH can cause heavier rainfall along the Yangtze River valley and droughts in southeast China in May and June. Lin and Wang (2016) found that an enhanced NEAL can increase the rainfall in northern East Asia and shift the subtropical East Asian rain belt northward.

However, the relationship between the NEAL and WNPSH and their joint impact on East Asian summer rainfall have yet to be well studied. This study tries to explore this issue by investigating the impact of in-phase and out-of-phase variation between the NEAL and WNPSH on East Asian summer rainfall. The arrangement of the text is as follows. Section 2 introduces the data and methods used in this study. Section 3 presents the results, and the key findings are summarized in Section 4.

2. Data and method

The monthly geopotential height data used in this study are derived from the National Centers for Environmental Prediction/National Center for Atmospheric Research...
(NCEP/NCAR) reanalysis datasets (Kalnay et al. 1996) at a resolution of 2.5° × 2.5°. The monthly precipitation data used include the TS3.22 data-set provided by the Climatic Research Unit (CRU), the University of East Anglia, UK, with a spatial resolution of 0.5° × 0.5° (Harris et al. 2014) and the 160-station observed rainfall for continental China provided by the National Climate Center of the China Meteorological Administration. All of the data used are from the period 1968–2013.

In this study, to obtain the interannual variability, both the long-term trends and decadal variations have been removed by eliminating the components with periods larger than eight years using Fourier harmonic analysis. Student’s t-test is used to determine statistical significance.

3. Results

3.1. In-phase and out-of-phase variation between the NEAL and WNPSH

To depict the interannual variations of the NEAL and WNPSH, we define the NEAL and WNPSH indices using the 850-hPa geopotential height ($H_{850}$) following previous studies (Lu 2002; Lin and Wang 2016). The NEAL index (NEALI) is defined as the reversed $H_{850}$ anomaly averaged over the region (45°–60°N, 110°–130°E) and $H_{850}$ anomaly over the region (10°–30°N, 110°–150°E) for the WNPSH index (WNPSHI). The two core regions are depicted by the two boxes in Figure 1(a). The NEAL enhances when the

![Figure 1](image-url)  
Figure 1. (a) Climatological summer mean of the geopotential height at 850 hPa ($H_{850}$; units: gpm) during 1968–2013; and (b) time series of the northern East Asian low index (NEAL, blue line) and the western North Pacific subtropical high index (WNPSH, red line). Note: The two boxes in (a) depict the regions used to define the two indices.

![Figure 2](image-url)  
Figure 2. The scatter plot of the NEALI (X-axis) and WNPSHI (Y-axis).

| Phase | Year                  |
|-------|-----------------------|
| Phase 1 | 1969, 1971, 1975, 1976, 1987, 1988, 1995, 2003, 2005, 2006, 2013 |
| Phase 2 | 1970, 1973, 1979, 1980, 1983, 1989, 1993, 1996, 1998, 2008, 2010 |
| Phase 3 | 1968, 1974, 1982, 1986, 1992, 1994, 2001, 2002, 2004 |
| Phase 4 | 1972, 1977, 1978, 1981, 1984, 1985, 1990, 1991, 1997, 1999, 2000, 2007, 2009, 2011, 2012 |

Table 1. Years of the four phases classified based on the NEALI and WNPSHI.
NEALI is positive and weakens when the NEALI is negative. The WNPSH is enhanced and shifts westward when the WNPSHI is positive, whereas it weakens and retreats eastward when the WNPSHI is negative. The time series of the two indices are presented in Figure 1(b). The NEALI and WNPSH both show strong interannual variability. The correlation coefficient between the indices is $-0.22$ during 1968–2013 and is insignificant at the 90% confidence level.

To investigate the combined effect of the two circulation factors, we classify the NEAL and WNPSH into four types according to the two indices (Figure 2). Phases 1 and 3 represent the in-phase variation (simultaneous enhancement...
or weakening) of the NEAL and WNPSH; Phases 2 and 4 represent the out-of-phase change (one enhancing, the other weakening) of the NEAL and WNPSH. The years included in each of the four phases are presented in Table 1. During 1968–2013, there are 11 and 9 years in Phases 1 and 3, and 11 and 15 years in Phases 2 and 4, respectively. The number of out-of-phase years (26) is slightly larger than that of in-phase years (20), which is consistent with the weak and negative correlation coefficient (−0.22) between the NEALI and WNPSHI. We also chose the cases based on the criterion of the NEALI and WNPSHI anomalies being stronger than ±0.5 times the standard deviations and obtained similar results (not shown).

Figure 3 shows the spatial distribution of the composited $H850$ for the four phases. In Phase 1 (Figure 3(a)), a negative $H850$ anomaly over continental northern East Asia and a positive $H850$ anomaly over the western North Pacific Ocean are identified, enhancing the NEAL and WNPSH, respectively. The enhanced NEAL and WNPSH can also be indicated by a southward expansion of the $H850$ contour of 1432 gpm (solid blue line) and a westward extension of the $H850$ contour of 1510 gpm (solid orange line), compared with the climatology (dashed lines). The pattern in Phase 3 is in opposition to Phase 1, with both the NEAL and WNPSH weakened (Figure 3(b)). The $H850$ difference between Phases 1 and 3 shows a significant negative anomaly centered over continental northern East Asia and a positive anomaly over the western North Pacific Ocean (Figure 3(e)). That is, Phases 1 and 3 depict an in-phase change of the NEAL and WNPSH, in which the NEAL and WNPSH simultaneously enhance in Phase 1 and weaken in Phase 3.

**Figure 4.** Difference of rainfall anomalies in Phase 1 and Phase 3 based on (a) CRU and (c) station data. (b) and (d) as in (a) and (c), but for Phase 2 and Phase 4.

Note: Shadings in (a) and (b) and dots in (c) and (d) illustrate regions of significance at the 0.1 level.
Similarly, the $H850$ anomalies in Phases 2 and 4 are shown in Figure 3(d) and (e), respectively. In Phase 2 (Figure 3(d)), the NEAL weakens and the WNPSH is enhanced, indicated by a northward retreat of the 1432 gpm contour over continental northern East Asia and a westward extension of the 1510 gpm contour over the western North Pacific Ocean in comparison with the climatology (dashed lines), which is consistent with two strong positive $H850$ anomalies over the two regions. The $H850$ anomalies in Phase 4 are opposite to that in Phase 2, so the NEAL is enhanced while the WNPSH weakens. Their differences (Phase 2 minus Phase 4) show two significant positive anomalies over the two core regions (Figure 3(f)). Therefore, Phases 2 and 4 depict an out-of-phase change of the NEAL and WNPSH; i.e. the WNPSH is enhanced when the NEAL weakens in Phase 2, and the WNPSH weakens when the NEAL is enhanced in Phase 4.

### 3.2. Effect on the East Asian summer rainfall

Corresponding to different circulation patterns of the WNPSH and NEAL during in-phase and out-of-phase years, East Asian summer rainfall behaves differently (Figure 4). When the NEAL and WNPSH are both enhanced (Phase 1 minus Phase 3), the rainfall anomaly shows a dipole pattern over East Asia: rainfall increases north of 30°N and decreases to the south, similar to the second leading mode of summer rain in eastern China (e.g. Huang, Chen, and Huang 2007; Ye and Lu 2012). The dipole pattern is found using both the CRU (Figure 4(a)) and station (Figure 4(c)) rainfall data. In the out-of-phase years, rainfall increases significantly along the Yangtze River valley in response to the enhanced WNPSH and weakened NEAL (Phase 2 minus Phase 4) based on the CRU (Figure 4(b)) and station (Figure 4(d)) rainfall data.

These rainfall anomalies are consistent with the circulation anomalies. When the NEAL and WNPSH are both enhanced, the lower-tropospheric southerlies over eastern China would be stronger and extend northward into North China (estimated from Figure 3(c)), enhancing rainfall in North China and suppressing rainfall in the Yangtze River valley. In contrast, when the WNPSH is enhanced and the NEAL weakens, the lower-tropospheric southerlies would be stronger south of the Yangtze River valley but could not extend into North China (estimated from Figure 3(f)), leading to an increase of rainfall in the Yangtze River valley.

The out-of-phase variation of the NEAL and WNPSH corresponds well to the rainfall anomalies along the Yangtze River valley, which are well documented to be associated with the circulation anomalies characterized by the East Asia-Pacific pattern (Huang and Sun 1992) or Japan-Pacific pattern (Nitta 1987). We analyzed the circulation anomalies associated with the out-of-phase variation of the NEAL and WNPSH, and confirmed that they are manifested by the East Asia-Pacific pattern (not shown).

Therefore, we here focus on the impact of the in-phase variation between the NEAL and WNPSH. Based on the composite rainfall anomalies during the in-phase years, a rainfall dipole index is defined as the rainfall anomaly averaged over the region to the north of the Yangtze River (30°–40°N, 100°–120°E) minus that over the region to the south of the Yangtze River (20°–30°N, 100°–120°E). The regression of $H850$ anomalies on the rainfall dipole index shows a similar spatial pattern to the composite in-phase result (Figure 3(c)). The similarity confirms the combined effect of the in-phase change of the enhanced NEAL and WNPSH on the rainfall dipole pattern identified in Figure 4(a) and (c). The possible mechanism is that the increased geopotential height gradient caused by the enhanced NEAL and WNPSH leads to a stronger southwest wind,

**Figure 5.** Regressions of $H850$ anomalies with respect to the rainfall dipole index calculated using the (a) CRU and (b) station rainfall data.

Note: The correlation coefficients statistically significant at the 0.1 level are shaded.
which delivers more moisture transported northward and brings more rainfall to north of the Yangtze River (Figure 5).

We examined the sea surface temperature (SST) anomalies and found that the SST anomalies in in-phase years were relatively weaker from the preceding winter to simultaneous summer than those in out-of-phase years (not shown). The SST anomalies in out-of-phase years showed a quick decaying of El Niño, similar to the result shown by Chen et al. (2012).

4. Conclusion and discussion

This study investigates the joint effect of the NEAL and WNPSH on East Asian summer rainfall. When the NEAL and WNPSH vary in phase, the rain anomaly in East Asia shows a dipole pattern, displaying opposite variation between north and south of the Yangtze River. That is, when both the NEAL and WNPSH are strong, rainfall increases north of the Yangtze River and decreases south of the Yangtze River. The opposite rainfall anomaly occurs when both circulation systems are weak. When the NEAL and WNPSH vary out of phase, the rainfall anomaly is concentrated in the Yangtze River valley. The rainfall over the region of the Yangtze River increases as the WNPSH is enhanced and the NEAL weakens but decreases when the WNPSH weakens and NEAL is enhanced.

The mean sea level pressure (MSLP) has been widely used to depict the land-sea thermal contrast between continental East Asia and the North Pacific Ocean. Therefore, we examined the MSLP anomalies during in-phase years, and found that they are very similar to the H850 anomalies shown in Figure 3(c). This result is different to the well-known land-sea thermal contrast between East Asia and the North Pacific (e.g., Zhao and Zhou 2005), suggesting that the present results highlight the land-sea thermal contrast in the north-south direction, while the zonal contrast has been previously highlighted.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was supported by the National Natural Science Foundation of China [grant number 41375086].

References

Chang, C. P., Y. Zhang, and T. Li. 2000a. “Interannual and Interdecadal Variations of the East Asian Summer Monsoon and Tropical Pacific SSTs. Part I: Roles of the Subtropical Ridge.” Journal of Climate 13 (24): 4310–4325. doi:10.1175/1520-0442(2000)013<4310:IAIVOT>2.0.CO;2.

Chang, C. P., Y. Zhang, and T. Li. 2000b. “Interannual and Interdecadal Variations of the East Asian Summer Monsoon and Tropical Pacific SSTs. Part II: Meridional Structure of the Monsoon.” Journal of Climate 13 (24): 4326–4340. doi:10.1175/1520-0442(2000)013<4326:IAIVOT>2.0.CO;2.

Chen, W., J. K. Park, B. W. Dong, R. Y. Lu, and W. S. Jung. 2012. “The Relationship between El Niño and the Western North Pacific Summer Climate in a Coupled GCM: Role of the Transition of El Niño Decaying Phases.” Journal of Geophysical Research 117: D12111. doi:10.1029/2011JD017385.

Gong, D. Y., and C. H. Ho. 2002. “Shift in the Summer Rainfall over the Yangtze River Valley in the Late 1970s.” Geophysical Research Letters 29 (10): 781–784. doi:10.1029/2001GL014523.

Guo, Q. Y. 1983. “The Summer Monsoon Intensity Index in East Asia and Its Variation (in Chinese).” Acta Geographica Sinica 38 (3): 207–217.

Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister. 2014. “Updated High-resolution Grids of Monthly Climatic Observations – The CRU TS3.10 Dataset.” International Journal of Climatology 34 (3): 623–642. doi:10.1002/joc.3711.

Huang, R. H., and F. Y. Sun. 1992. “Impacts of the Tropical Western Pacific on the East Asia Summer Monsoon.” Journal of the Meteorological Society of Japan 70 (1B): 243–256.

Huang, R. H., J. L. Chen, and G. Huang. 2007. “Characteristics and Variations of the East Asian Monsoon Systems and Its Impacts on Climate Disasters in China.” Advances in Atmospheric Sciences 24 (6): 993–1023. doi:10.1007/s00376-007-0993-x.

Huangfu, J. L., R. H. Huang, and W. Chen. 2015. “Influence of Tropical Western Pacific Warm Pool Thermal State on the Interdecadal Change of the Onset of the South China Sea Summer Monsoon in the Late-1990s.” Atmospheric and Oceanic Science Letters 8 (2): 95–99. doi:10.3878/AOSL201500002.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, et al. 1996. “The NCEP/NCAR 40-year Reanalysis Project.” Bulletin of American Meteorological Society 77 (3): 437–471. doi:10.1175/1520-0477(1996)077<0437:TNRP>2.0.CO;2.

Lin, Z. D. 2014. “Intercomparison of Impacts of Four Summer Teleconnections over Eurasia on East Asian Rainfall.” Advances in Atmospheric Sciences 31 (6): 1366–1376. doi:10.1007/s00376-014-3171-y.

Lin, Z. D., and B. Wang. 2016. “Northern East Asian Low and Its Impact on the Interannual Variation of East Asian Summer Rainfall.” Climate Dynamics 46 (1): 83–97. doi:10.1007/s00382-015-2570-9.

Lu, R. Y. 2001. “Interannual 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 (3): 771–783. doi:10.2151/jmsj.79.771.

Lu, R. Y. 2002. “Indices of the Summertime Western North Pacific Subtropical High.” Advances in Atmospheric Sciences 19 (6): 1004–1028. doi:10.1007/s00376-002-0061-5.

Lu, R. Y., and B. W. Dong. 2001. “Westward Extension of North Pacific Subtropical High in Summer.” Journal of the Meteorological Society of Japan 79 (6): 1229–1241. doi:10.2151/jmsj.79.1229.

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 (3): 373–390.
Ren, X. J., X. Q. Yang, and X. G. Sun. 2013. “Zonal Oscillation of Western Pacific Subtropical High and Subseasonal SST Variations during Yangtze Persistent Heavy Rainfall Events.” *Journal of Climate* 26 (22): 8929–8946. doi:10.1175/JCLI-D-12-00861.1.

Shen, B. Z., Z. D. Lin, R. Y. Lu, and Y. Lian. 2011. “Circulation Anomalies Associated with Interannual Variation of Early- and Late-summer Precipitation in Northeast China.” *Science China Earth Sciences* 54 (7): 1095–1104. doi:10.1007/s11430-011-4173-6.

Shi, N., and Q. G. Zhu. 1996. “An Abrupt Change in the Intensity of the East Asian Summer Monsoon Index and Its Relationship with Temperature and Precipitation over East China.” *International Journal of Climatology* 16 (7): 757–764. doi:10.1002/(SICI)1097-0088(199607)16:7<757::AID-JOC50>3.0.CO;2-S.

Wu, R. G., Z. P. Wen, S. Yang, and Y. Q. Li. 2010. “An Interdecadal Change in Southern China Summer Rainfall around 1992/93.” *Journal of Climate* 23 (9): 2389–2403.

Ye, H., and R. Y. Lu. 2012. “Dominant Patterns of Summer Rainfall Anomalies in East China during 1951–2006.” *Advances in Atmospheric Sciences* 29 (4): 695–704. doi:10.1007/s00376-012-1153-5.

Zhao, P., and Z. J. Zhou. 2005. “East Asian Subtropical Summer Monsoon Index and Its Relationships to Rainfall (in Chinese).” *Acta Meteorologica Sinica* 63 (6): 933–941.

Shen, B. Z., Z. D. Lin, R. Y. Lu, and Y. Lian. 2011. “Circulation Anomalies Associated with Interannual Variation of Early- and Late-summer Precipitation in Northeast China.” *Science China Earth Sciences* 54 (7): 1095–1104. doi:10.1007/s11430-011-4173-6.

Shi, N., and Q. G. Zhu. 1996. “An Abrupt Change in the Intensity of the East Asian Summer Monsoon Index and Its Relationship with Temperature and Precipitation over East China.” *International Journal of Climatology* 16 (7): 757–764. doi:10.1002/(SICI)1097-0088(199607)16:7<757::AID-JOC50>3.0.CO;2-S.

Wu, R. G., Z. P. Wen, S. Yang, and Y. Q. Li. 2010. “An Interdecadal Change in Southern China Summer Rainfall around 1992/93.” *Journal of Climate* 23 (9): 2389–2403.

Ye, H., and R. Y. Lu. 2012. “Dominant Patterns of Summer Rainfall Anomalies in East China during 1951–2006.” *Advances in Atmospheric Sciences* 29 (4): 695–704. doi:10.1007/s00376-012-1153-5.

Zhao, P., and Z. J. Zhou. 2005. “East Asian Subtropical Summer Monsoon Index and Its Relationships to Rainfall (in Chinese).” *Acta Meteorologica Sinica* 63 (6): 933–941.

Zhu, C. W., W. S. Lee, H. W. Kang, and C. K. Park. 2005. “A Proper Monsoon Index for Seasonal and Interannual Variations of the East Asian Monsoon.” *Geophysical Research Letters* 32 (2): L02811. doi:10.1029/2004GL021295.