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Atmospheric and Oceanic Science Letters

ISSN: 1674-2834 (Print) 2376-6123 (Online) Journal homepage: http://www.tandfonline.com/loi/taos20

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To cite this article: Mei Shuang-Li, Chen Wen & Chen Shang-Feng (2015) On the Relationship between the Northern Limit of Southerly Wind and Summer Precipitation over East China, Atmospheric and Oceanic Science Letters, 8:1, 52-56

To link to this article: https://doi.org/10.3878/AOSL20140078

Published online: 12 Aug 2015.

ATMOSPHERIC AND OCEANIC SCIENCE LETTERS, 2015, VOL. 8, NO. 1, 52–56

On the Relationship between the Northern Limit of Southerly Wind and Summer Precipitation over East China

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Received 19 September 2014; revised 4 November 2014; accepted 21 November 2014; published 16 January 2015

Abstract The relationship between the summer northernmost position of southerly wind and precipitation over East China is investigated. The northern limit of summer southerly wind index (I_{NLSSW}) over East China is defined as the latitude where the zonal-averaged (105–120°E) low-level meridional wind is equal to zero. Results show that there is a significant negative (positive) correlation between I_{NLSSW} and summer precipitation over the Yangtze River (North China) region. Thus, the proposed I_{NLSSW} may have implications for the prediction of summer precipitation anomalies in these regions. In positive I_{NLSSW} years, a cyclonic circulation anomaly is observed over the tropical western North Pacific and an anticyclonic circulation anomaly is seen over the subtropics of East China, accompanied by southerly anomalies over East China. This leads to above-normal moisture penetrating into the northern part of East China. In addition, significant upward (downward) motion anomalies can be found over the North China (Yangtze River) region. As a result, there are significant positive (negative) precipitation anomalies over the North China (Yangtze River) region. Further examination shows that sea surface temperature anomalies over the tropical eastern Pacific and Indian Ocean both contribute to the formation of I_{NLSSW}-related circulation anomalies over the tropical western North Pacific.

Keywords: northern limit of southerly wind, precipitation, Yangtze River, North China

Citation: Mei, S.-L., W. Chen, and S.-F. Chen, 2015: On the relationship between the northern limit of southerly wind and summer precipitation over East China, *Atmos. Oceanic Sci. Lett.*, **8**, 52–56, doi:10.3878/AOSL20140078.

1 Introduction

The East Asia summer monsoon (EASM) is one of the most important climate systems over East Asia (Wang et al., 1999; Lau et al., 2000; Wang et al., 2001). Interannual variability of the EASM can have substantial effects on social and economic activity in the East Asian region. Hence, it is of great importance to predict the interannual variation of the EASM (Lau and Li, 1984; Ninomiya and Murakami, 1987; Tao and Chen, 1987).

In the EASM region, many researchers have devoted themselves to identifying an index that adequately represents the strength of the EASM. The mei-yu rainfall is often considered representative of the EASM (Tanaka, 1997; Chang et al., 2000a, b; Huang et al., 2004). However, since rainfall has complex structures, circulation parameters are utilized instead of rainfall to define the monsoon. The definitions of different EASM indices are summarized in the work of Wang et al. (2008).

For the representation of the northernmost location of the boundary of the EASM, one category of indices is defined based on air masses, i.e., the northern edge of the interaction between warm/wet air masses from the tropical low latitudes and cold/dry air masses from the westerly wind belt in East Asia (Tu and Huang, 1944). Another category is based on the seasonal northward shift of the EASM rain belt (Tao and Chen, 1987; Wang and Lin, 2002). More recently, Hu and Qian (2007) proposed a new method that integrates both the air mass and rainfall perspectives. However, although the study about the definition of the EASM indices has made great progress, consensus has not yet to be reached regarding the definition of indices that adequately represent the strength and northernmost location of the EASM. In particular, much more research on the northern boundary of the EASM is needed.

A number of studies have advanced our understanding of the relationship between summer monsoon and rainfall in China. Wang et al. (2008) mentioned that a strong summer monsoon can reach farther north in China, and the northern limit of the southerly penetration was emphasized. At the moment, it corresponds to increased rainfall in northern China and deficient mei-yu rainfall. Ding and Chan (2005) suggested that the strength of the Chinese summer monsoon emphasizes the rainfall in northern, since the conventional concept of a strong summer monsoon used by Chinese meteorologists implies a weak mei-yu period. Ding (2004) suggested that if the summer monsoon is too weak to reach northern China or has a very short duration, below-normal rainfall anomalies are observed over northern China and droughts often arise, and vice versa. However, most of the above- mentioned studies focused on the strength of the summer monsoon, and there have been few studies conducted from the viewpoint of the limit of southerly wind.

The present study examines the relationships among the northernmost position, strength and precipitation of the summer monsoon in East China, and explains the causes that are contributed to these relationships. The paper begins by defining the northernmost limit of sum-

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mer southerly winds over East China, based on the meridional wind component. Then, indices representing the East China summer monsoon and rainfall strength are defined. The interannual relationships between the EASM and rainfall strength indices and the northern limit of summer southerly winds are examined. In addition, the possible mechanisms responsible for these relationships are analyzed. The paper is structured as follows: section 2 describes the data used in the study; section 3 presents the definition of the northern limit of summer southerly winds over East China (NLSSW), analyzes the relationships among NLSSW index (I_{NLSSW}), precipitation and EASM strength over East China, and illustrates the atmospheric circulation and SST anomalies associated with I_{NLSSW}; section 4 concludes the study.

2 Data description

This study uses the monthly mean horizontal winds from the National Centers for Environmental Precipitation/National Center for Atmospheric Research (NCEP/NCAR) reanalysis from 1948 to present (Kalnay et al., 1996), and the European Centre for Medium-Range Weather Forecasts 40-yr reanalysis dataset (ERA40) from 1958 to 2001 (Uppala et al., 2005). The horizontal winds are available on 2.5° × 2.5° grids for both datasets. We also use monthly mean precipitation from 160 Chinese weather stations for the period from 1951 to present, provided by the China Meteorological Administration. In addition, the monthly mean SST used in this study are from the Hadley Centre Sea-ice and Sea-surface Temperature Data Set Version 1 (HadSSTI). The HadSSTI dataset has a horizontal resolution of 1° × 1° and covers the period from 1870 to present. Considering the time periods covered by each of the datasets, the study period adopted in this study, i.e., the period that all datasets have in common, is 1958–2001. Note that the horizontal wind data presented in this study are the ensemble mean of the NCEP/NCAR and ERA40 reanalysis data.

3 Results

3.1 Definition of the northern limit of summer southerly winds over East China

In this section, we first discuss the definition of the northern limit of summer (June-July-August-averaged; JJA) southerly I_{NLSSW}. The I_{NLSSW} is defined as the latitude where low-level (averaged between 925 hPa and 850 hPa) meridional wind averaged between 105°E and 120°E (the definition of East China in this study) is equal to zero. On the one hand, 105°E could be considered as the dividing line between the EASM and the South Asian summer monsoon, and the southwest monsoon flow northward to the east of the Tibetan plateau. On the other hand, this range is the dominant region of summer monsoon and precipitation over East Asia. Figure 1 displays the detrended and normalized time series of I_{NLSSW}. From Fig. 1, significant interannual variability of I_{NLSSW} can be observed.

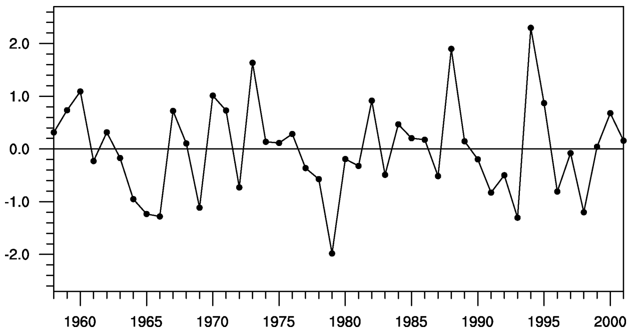

Figure 1 Normalized and detrended time series of the northern limit of summer (June-July-August-averaged; JJA) southerly wind index (I_{NLSSW}).

3.2 Relationships of I_{NLSSW} with precipitation and the EASM

In this subsection, we investigate the relationships of I_{NLSSW} with EASM index and precipitation anomalies averaged over different regions in China. Detailed information on the definition of these indices is provided in Table 1. Note that the selection of northern China (36–42°N), the Yangtze River (27–35°N), and southern China (20–26°N) follows the study of Wang et al. (2008).

The limit of southerly wind has a significant positive (negative) correlation with the rainfall in the Yangtze River (North China) region. The correlation coefficient between I_{NLSSW} (detail definition is provided in Table 1) and rainfall in the Yangtze River (North China) region is –0.32 (0.28), exceeding the 95% (90%) confidence level (Table 2), which indicates that the precipitation in the Yangtze River (North China) region decreases (increases)

Table 1 The description of indices.

Abbreviation	Description	Region
I_{NLSSW}	Northern limit of summer southerly wind index	105–120°E
I_{CP}	China region precipitation index	20–50°N, 105–120°E
I_{SP}	Southern China precipitation index	20–26°N, 105–120°E
I_{YP}	Yangtze River precipitation index	27–35°N, 105–120°E
I_{NP}	Northern China precipitation index	36–42°N, 105–120°E
I_{V1}	The southerly strength index over Region1	20–26°N, 105–120°E
I_{V2}	The southerly strength index over Region2	27–35°N, 105–120°E
I_{V3}	The southerly strength index over Region3	36–42°N, 105–120°E
I_{U1}	The westerly strength index over Region1	20–26°N, 105–120°E
I_{U2}	The westerly strength index over Region2	27–35°N, 105–120°E
I_{U3}	The westerly strength index over Region3	36–42°N, 105–120°E
I_{WF}	Wang and Fan (1999) index	5–32.5°N, 90–140°E
I_{ZTC}	Wang et al. (1998) index	10–35°N, 100–150°E
I_{WDJ}	Wang et al. (1998) index	5–15°N, 90–130°E
I_{LZ}	Li and Zeng (2002) index	10–40°N, 110–140°E

Table 2 Correlation coefficients between the limit of southerly wind and precipitation and monsoon strength indices in summer over China for the period 1958–2001: statistically at the *90%, **95%, and ***99% confidence level.

	I_{CP}	I_{SP}	I_{YP}	I_{NP}	I_{V1}	I_{V2}	I_{V3}
I_{NLSSW}	−0.001	0.12	−0.32**	0.28*	0.12	0.42***	0.56***
	I_{U1}	I_{U2}	I_{U3}	I_{LZ}	I_{WDJ}	I_{ZTC}	I_{WF}
I_{NLSSW}	−0.02	−0.2	−0.09	0.29*	0.29*	0.18	0.19

when extensive southerlies penetrate inland to farther north in China. However, the correlation of I_{NLSSW} and precipitation anomalies over southern China is statistically insignificant and weak (Table 2). To further confirm the relationship between I_{NLSSW} and rainfall in summer over China, Fig. 2 shows the precipitation anomalies in the simultaneous summer (JJA) obtained by regression on the I_{NLSSW}. Significant and positive (negative) precipitation anomalies are observed over the northern (central) part of East China. Over the southern part of East China, precipitation anomalies are not significant at the 95% confidence level.

To study the relationships between I_{NLSSW} and monsoon strength, the I_{NLSSW} and the strength of the *u*- and *v*-component of wind are examined. The correlation coefficients between I_{NLSSW} and I_{V2} and I_{V3} (definitions are provided in Table 1) are 0.42 and 0.56, both exceeding the 99% confidence level. The I_{NLSSW} has an insignificant correlation with the strength of I_{U1}, I_{U2}, and I_{U3} (definitions are provided in Table 1) in China (Table 2).

A number of summer monsoon indices were summarized in the work of Wang et al. (2008). To assess whether the I_{NLSSW} defined in the study has a close correlation with these previously defined EASM indices, we perform comparative analyses. Four EASM indices defined by (1) Wang et al. (1998), (2) Wang and Fan (1999), (3) Li and Zeng (2002), and Zhang et al. (2003) were selected. Detailed definitions of these four selected EASM indices can be found in the study of Wang et al. (2008). Table 2 shows that the correlation coefficients

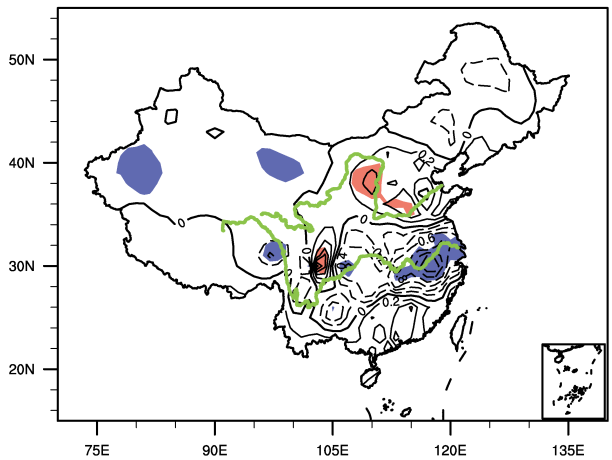

Figure 2 Anomalies of precipitation in JJA regressed on the I_{NLSSW} during 1958–2001. Red (Blue) shading denotes positive (negative) anomalies that are significantly different from zero at the 95% confidence level. Contour interval is 0.2 mm.

between I_{NLSSW} and the EASM defined by I_{ZTC} (0.18), I_{WF} (0.19), I_{LZ} (0.29) (definitions are provided in Table 1), and I_{WDJ} (0.29) are less than the 95% confidence level. This indicates that the I_{NLSSW} defined in this study is independent of the EASM indices defined in previous studies (Wang et al., 2008).

3.3 Atmospheric circulation and sea surface temperature anomalies in association with I_{NLSSW}

To explain the above-mentioned relationships between I_{NLSSW} and precipitation anomalies, we show the anomalies of vertical velocity at 500 hPa obtained by regression on the I_{NLSSW} in Fig. 3. The results indicate that negative (positive) precipitation anomalies over the central (northern) part of East China correspond to downward (upward) motion anomalies.

We further discuss the atmospheric circulation and SST anomalies to help understand the interannual variability of I_{NLSSW}. Figure 4 displays the JJA 850 hPa wind anomalies obtained by regression on the I_{NLSSW}. To help explain the winds anomalies in association with

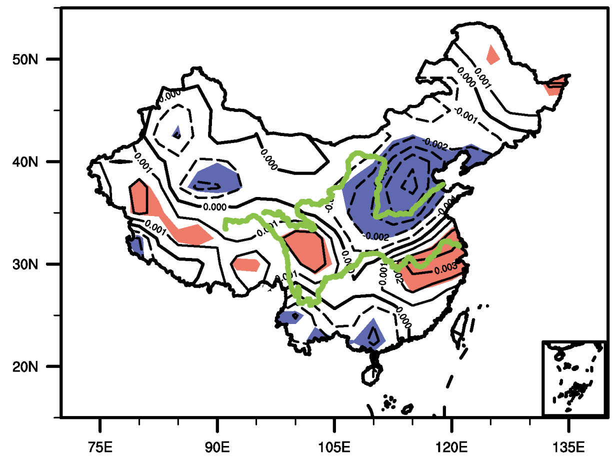

Figure 3 Anomalies of vertical velocity at 500 hPa in JJA regressed on the I_{NLSSW} during 1958–2001. Red (Blue) shading denotes positive (negative) anomalies that are significantly different from zero at the 95% confidence level. Contour interval is 0.001 Pa s^{-1}. Note that positive (negative) values of vertical velocity represent downward (upward) motion.

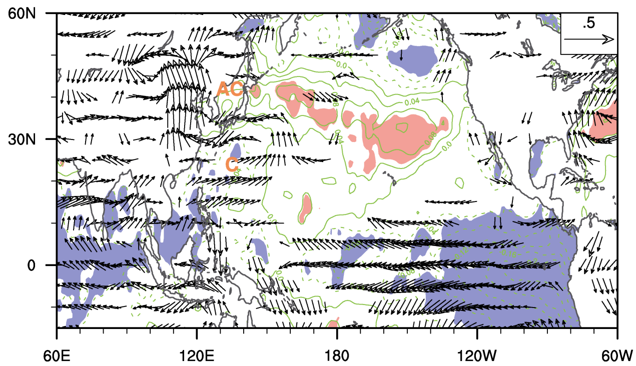

Figure 4 Anomalies of JJA SST (contours) and winds at 850 hPa (vectors) regressed on the I_{NLSSW} during 1958–2001. Red (Blue) shading denotes positive (negative) SST anomalies that are significantly different from zero at the 95% confidence level. Contour interval is 0.04°C. The wind vector scale is shown in the top-right corner (units: m s^{-1}).

I_{NLSSW}, the JJA SST anomalies are also shown in Fig. 4. A cyclonic circulation anomaly is observed to the northwest of the Philippines and an anticyclonic circulation over East China. Southerly wind anomalies over East China, extending from the southern to the northern part of East China indicate that southerly winds can penetrate farther north. In addition, southerly wind anomalies transport more moisture northward and result in above- normal precipitation over North China (Fig. 2). Westerly wind anomalies can be observed over the North Indian Ocean, indicating a stronger EASM (Wang et al., 2008). In the presence of westerly wind over the Indian Ocean in summer, westerly wind anomalies would enhance the climatological wind speed and lead to negative SST anomalies in the Indian Ocean via the enhancement of upward latent heat flux. In the tropical eastern Pacific, easterly wind anomalies are accompanied by negative SST anomalies. Previous studies (Wang et al., 2000) have demonstrated that an anticyclonic circulation anomaly can be observed over the tropical western Pacific when the central and eastern Pacific is covered by positive SST anomalies. The anticyclonic circulation anomaly persists into the following summer via local air-sea interaction. Note that significant negative SST anomalies in the Indian Ocean may also be important for the persistence of La Niña-associated cyclonic circulation anomalies over the tropical western Pacific. Xie et al. (2009) demonstrated tropical Indian Ocean warming emanates a baroclinic Kelvin wave into the Pacific. In the northwestern Pacific, this equatorial Kelvin wave induces suppressed convection and the anomalous anticyclone. It should be mentioned that significant negative precipitation anomalies can be observed over the Indian Ocean (figures not shown). Therefore, SST anomalies in the tropical eastern Pacific and Indian Ocean may both be important for the existence of cyclonic circulation anomalies in association with the I_{NLSSW} over the tropical western North Pacific. In addition, the anticyclonic circulation anomalies are likely a Rossby wave response to the cyclonic circulation anomalies in the tropical North Pacific, resembling the East Asia-Pacific or Pacific-Japan pattern identified in previous studies (Nitta, 1987; Huang and Wu, 1989).

To compare the lead-lag relationship of I_{NLSSW} and different EASM indices with the SST anomalies over the Indian Ocean and eastern Pacific Ocean, Fig. 5 displays the lead-lag correlation coefficients of the I_{NLSSW}, and the EASM defined by Wang and Fan (1999), Li and Zeng (2002), Wang et al. (1998), and Zhang et al. (2003) with the SST anomalies over the Indian Ocean (averaged over the region (5°S–10°N, 50–90°E)) and the eastern Pacific Ocean (averaged over the region (10°S–10°N, 80–130°W)). These regions are selected based on the larger SST anomalies shown in Fig. 4. Figure 5 indicates that the correlation of I_{NLSSW} with SST anomalies over the Indian Ocean and eastern Pacific Ocean are larger than those between the EASM indices and SST anomalies. The I_{NLSSW} has significant negative correlations with the SST anomalies over the Indian Ocean from January to December. For comparison, the EASM indices have significant negative correlations with the SST anomalies from the previous December to July. Meanwhile, the I_{NLSSW} has significant negative correlations with the SST anomalies over the eastern Pacific Ocean from February to November. However, the EASM indices have significant negative correlations with the SST anomalies from the previous December to August. In addition, the correlation between the I_{NLSSW} and SST anomalies is larger than that between the EASM indices and SST anomalies in JJA. Over both the Indian Ocean and eastern Pacific Ocean, I_{NLSSW} has a closer correlation with later SST anomalies from August to December.

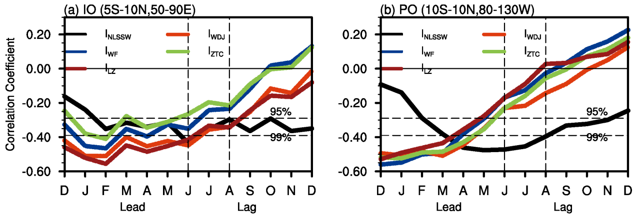

Figure 5 Lead-lag relationship between I_{NLSSW} (black line), I_{WF} (blue line), I_{LZ} (brown line), I_{WDJ} (red line), I_{ZTC} (green line), and the SST anomalies averaged over the (a) Indian Ocean (5°S–10°N, 50–90°E) and (b) East Pacific Ocean (10°S–10°N, 80–130°W).

4 Conclusion

This paper examines the relationship between summer monsoon and precipitation in East China using NCEP/NCAR, ERA40, and Chinese 160 station data for the period 1958–2001. A representation of the northernmost location of the East China summer monsoon in JJA, which is defined as the latitude where the zonal-averaged (105–120°E) low-level (averaged between 925 hPa and 850 hPa) meridional wind is equal to zero, is given. The results show that there is a significant negative (positive) correlation between the limit of the southerly wind and the precipitation in summer over the Yangtze River (North China) region, and significant positive correlation between the limit of southerly wind and the strength of *v*-wind over Region2 (27–35°N, 100–120°E) and Region3 (36–42°N, 100–120°E). The proposed I_{NLSSW} may provide a new method for predicting summer monsoon strength and precipitation anomalies over the northern (central) part of East China.

In positive (negative) I_{NLSSW} years, a cyclonic (anticyclonic) circulation anomaly is observed over the tropical western North Pacific and an anticyclonic (cyclonic) circulation anomaly over most parts of East China, accompanied by southerly (northerly) anomalies over East China, leading to more (less) moisture in North China. In addition, significant upward (downward) motion anomalies are observed over North China, and significant downward (upward) motion anomalies over the central part of East China. As a result, there are significant positive (negative) precipitation anomalies over the northern part of East China and negative (positive) precipitation anomalies over the central part of East China. Further results show that negative (positive) SST anomalies over the tropical eastern Pacific and Indian Ocean both contribute to the formation of I_{NLSSW}-related circulation anomalies over the tropical western North Pacific and East China.

It should be emphasized that the I_{NLSSW} defined in this study is independent of the EASM indices used in previous studies. We also compare the lead-lag relationship of the I_{NLSSW} and different EASM indices with SST anomalies over the Indian Ocean and eastern Pacific Ocean regions. Results show that the correlations of the I_{NLSSW} with SST anomalies over the Indian Ocean and eastern Pacific Ocean are larger than those between the SST anomalies and the EASM indices used in previous studies. Hence, the I_{NLSSW} defined in this study could be used as an effective predictor of summer precipitation anomalies in the Yangtze River and North China regions.

Acknowledgments. We wish to express our sincere gratitude to Prof. Tim LI of the University of Hawaii for his insightful suggestions, and also thank the two anonymous reviewers for their valuable comments and suggestions, which helped to improve the paper. This study was supported by the National Natural Science Foundation of China (Grant No. 41230527).

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