ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 26, NO. 1, 2009, 101–108

Linkage Between Mei-yu Precipitation and North Atlantic SST on the Decadal Timescale

GU Wei*[1,2] (顾 薇), LI Chongyin[1,3] (李崇银), WANG Xin[1] (王 鑫), ZHOU Wen[4] (周 文), and LI Weijing[2] (李维京)

[1] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[2] *National Climate Center, China Meteorological Administration, Beijing* 100081

[3] *Meteorological College, PLA University of Science and Technology, Nanjing* 211101

[4] *CityU-IAP Laboratory for Atmospheric Sciences, Department of Physics & Materials Science, City University of Hong Kong, Hong Kong*

(Received 3 December 2007; revised 22 April 2008)

ABSTRACT

This paper investigates the relationship between mei-yu and North Atlantic sea surface temperature anomalies (SSTA). Results show that they are significantly associated with each other on the decadal timescale. Both mei-yu precipitation and mei-yu duration are characterized by significant decadal variability. Their decadal components are closely correlated with a triple mode of North Atlantic SSTA in the preceding winter. Regression analysis demonstrates that the wintertime North Atlantic SSTA may impose a delayed impact on East Asia Summer Monsoon (EASM) circulation and mei-yu on the decadal timescale. The persistency of SSTA plays an important role during this course. The triple SSTA mode can persist from winter until late spring. It is suggested that the springtime SSTA may excite a stationary wave-train propagating from west Eurasia to East Asia and exert an impact on mei-yu.

Key words: mei-yu, decadal, North Atlantic SSTA

Citation: Gu, W., C. Y. Li, X. Wang, and W. Zhou, 2009: Linkage between mei-yu precipitation and North Atlantic SST on the decadal timescale. *Adv. Atmos. Sci.*, **26**(1), 101–108, doi: 10.1007/s00376-009-0101-5.

1. Introduction

Studies of East Asian Summer Monsoon (EASM) precipitation have great social and economic importance for the Asian countries. Summer precipitation in the middle and lower reaches of the Yangtze River valley (YRV), known as mei-yu, reflects the second stage of the East Asia summer monsoon (Ding, 2004). So far, many researchers have analyzed the variability of mei-yu and its possible causes, and pointed out that mei-yu may be affected by many factors in the ocean-atmosphere system, such as tropical Pacific sea surface temperature anomalies (SSTA), Indian Ocean SSTA, Eurasian snow, Arctic Oscillation/North Atlantic Oscillation (AO/NAO) etc. (e.g., Huang and Wu, 1989; Wu and Chen, 1998; Li and Mu, 2001; Wu and Wang, 2002; Gong and Ho, 2003; Ju et al., 2005; Gao et al., 2006; Weng et al., 2007).

The ocean-atmospheric systems in the North Atlantic sector exhibit strong variability from seasonal to interdecadal timescales. Previous studies revealed the possible influence of North Atlantic systems on weather and climate in many regions such as Europe, America and Africa (e.g., Marshall et al., 2001). Recently, several studies noticed the close relationship between the North Atlantic Ocean-atmosphere system and summer monsoon climate in East Asia (e.g., Xu et al., 1999; Ogi et al., 2003; Lu et al., 2006; Sung et al., 2006). For example, Sung et al. (2006) demonstrated a significant interannual relationship between December

*Corresponding author: GU Wei, guwei@mail.iap.ac.cn

NAO and summer precipitation in the northern and southern part of East China and postulated a potential influence of NAO on EASM precipitation. Lu et al. (2006) documented a possible impact of the Atlantic Multi-decadal Oscillation on Asian summer monsoon on the interdecadal timescale through model experiments.

Periodicity of mei-yu is examined in this study using the 121-yr mei-yu dataset. Then, the relationship between the decadal variation of mei-yu and SSTA is analyzed. For the close association between mei-yu and North Atlantic triple SSTA mode on the decadal timescale, possible mechanism is suggested through the analyses of the corresponding SSTA and atmospheric situations.

Section 2 describes the datasets and methods used. Section 3 presents the close relationship between mei-yu and North Atlantic SSTA on the decadal timescale. Section 4 analyzes the possible impact of the SSTA on EASM circulation. A summary and discussion are given in section 5.

2. Data and methods

The 121-yr mei-yu dataset from 1885 to 2005 is from the National Climate Center of China Meteorology Administration. It describes the precipitation, duration, start date and end date of mei-yu season. It is constructed by averaging the data at 5 stations, including Shanghai, Nanjing, Wuhu, Jiujiang and Wuhan. The atmospheric data for the period 1948–2006 are from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996). The variables used for this study include 850-hPa winds and 500-hPa geopotential heights. These data have a horizontal resolution of 2.5° × 2.5°. We also use monthly SST data, HadISST, from the Hadley Center of the UK Meteorological Office. HadISST is a unique combination of monthly globally-complete fields of SST and sea ice concentration on a 1 degree latitude-longitude grid from 1870 to date (Rayner et al., 2003).

Power spectrum is used to identify the periodicity of mei-yu. Cross wavelet analysis is performed to examine the relationship between mei-yu and the SSTA index in time-frequency space (Grinsted et al., 2004). Using the Fast Fourier transformation method, band-pass filtering is performed in order to extract the decadal components. Since the data used in this study are band-pass filtered and their corresponding numbers of degree of freedom are greatly reduced, the effective number of degree of freedom (EDOF, Bretherton et al., 1999) is estimated to check the significance

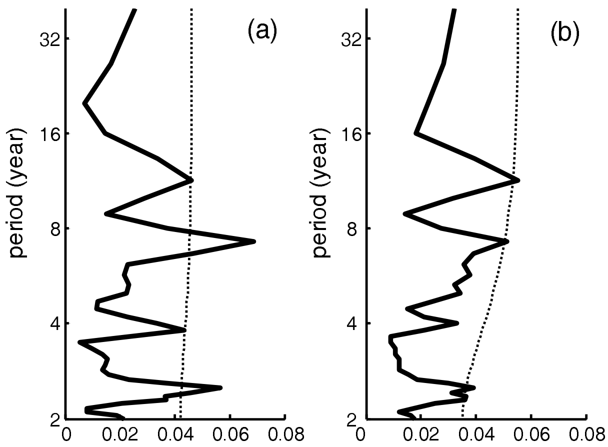

Fig. 1. Power spectra of (a) mei-yu precipitation and (b) mei-yu duration time series, the dotted lines in both figures indicate the 95% significance level.

level throughout this paper. The EDOF is estimated for each pair of time series as:

$$E_{\mathrm{DOF}} = N \times (1 - r_1 \times r_2)/(1 + r_1 \times r_2)$$

where N denotes the length of the time series, and r_1 and r_2 refers to the lag-one autocorrelation of each series, respectively. Seasonal data are used throughout this study and they are constructed by averaging June and July for summer and December, January and February for winter.

3. Relationship between mei-yu and North Atlantic SST on the decadal timescale

3.1 *Periodicity of mei-yu*

Figures 1a and 1b show the power spectrum of the normalized time series of mei-yu precipitation and mei-yu duration, respectively. For both precipitation and duration, it is clear that the 121-yr series is not only characterized by significant interannual variability with a center period of about 3 years and 7 years, but also significant decadal variability with a center period of about 12 years. In order to focus on the decadal variability of mei-yu, we apply a 9–16-yr band-pass filter to the normalized precipitation and duration time series to extract their decadal components (Fig. 2). After filtering, the first and last 8 years are removed to get rid of the edge effect. This decadal component of mei-yu precipitation (duration) explains 13.5% (14.2%) of the total variance and can influence the total behavior of mei-yu to a large extent. If the +1(−1) standard deviation is taken to distinguish the typical dry (wet) mei-yu years, we can easily find that 11 (9) out of 14 (11) typical wet (dry) years occur in

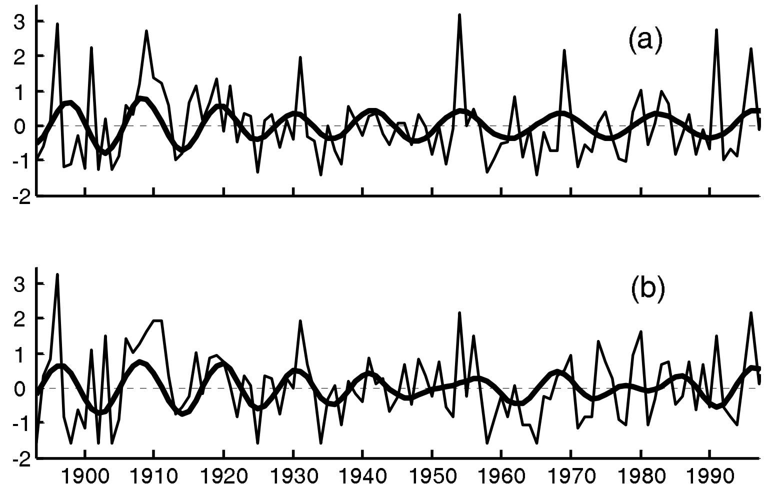

Fig. 2. Normalized (thin line) and 9–16-yr band-pass filtered (thick line) (a) mei-yu precipitation and (b) mei-yu duration.

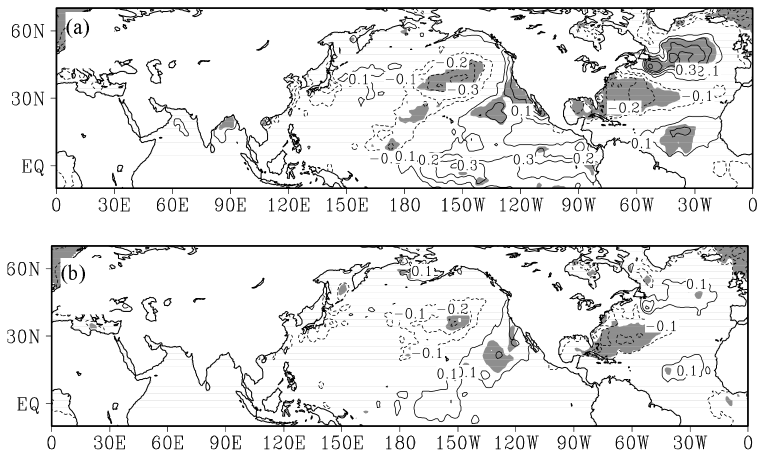

Fig. 3. Difference of wintertime SSTA between positive and negative mei-yu (a) precipitation and (b) duration years. The shading indicates the 95% significance level.

the positive (negative) phases of the decadal component. That is, higher frequency of droughts (floods) during the mei-yu period is associated with the negative (positive) decadal phases. Therefore, it is important to investigate the influencing factors of mei-yu on the decadal timescale.

3.2 *Relationship between mei-yu and North Atlantic SSTA on the decadal timescale*

To examine the relationship between mei-yu and the SSTA on the decadal timescale, we perform composite analyses on the seasonal SSTA according to the 9–16-yr band-pass filtered (hereafter filtered) mei-yu precipitation and duration indices. Taking a standard deviation of 0.3 as the criteria to distinguish abnormal years from normal years, we calculate the differ-

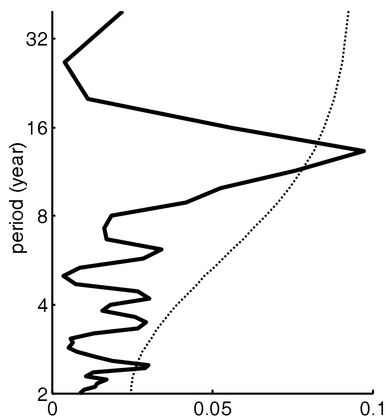

Fig. 4. The same as Fig. 1, but for normalized $I_{\rm NA}$ index.

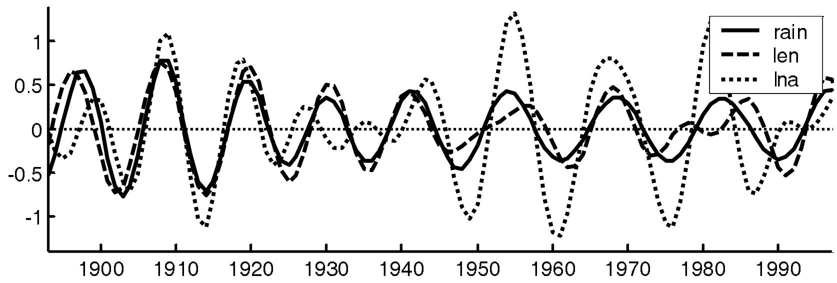

Fig. 5. The 9–16-yr band-pass filtered mei-yu precipitation (solid line), duration (dashed line) and $I_{\rm NA}$ (dotted line) indices.

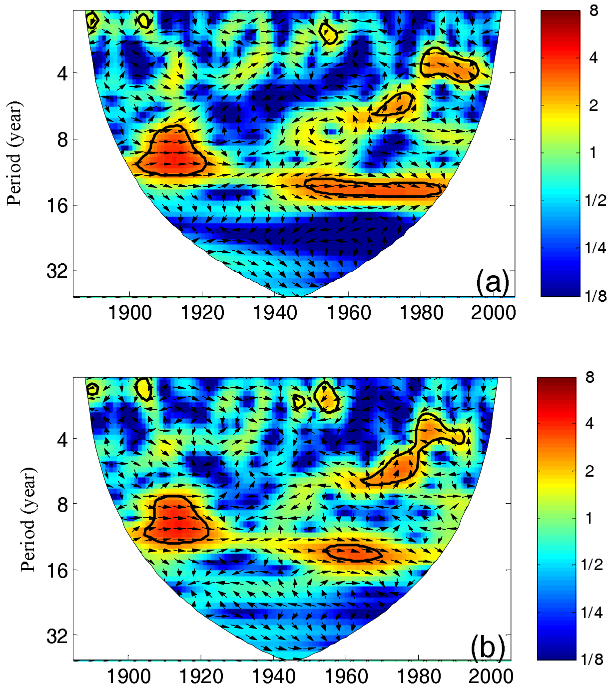

Fig. 6. Cross wavelet transform (a) of the normalized $I_{\rm NA}$ and mei-yu precipitation indices, and (b) of the normalized $I_{\rm NA}$ and mei-yu duration indices (b). The 95% significance level against red noise is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left, and $I_{\rm NA}$ leading MP by 90° pointing straight down, regions outside of the black arcs on either end indicate the "cone of influence", where edge effects become important).

ence of SSTA between positive and negative precipitation/duration years. For both the precipitation and duration, the most significant signal appears as a triple mode in North Atlantic for the preceding winter (Fig. 3). This triple mode constitutes of three zonally elongated centers in the North Atlantic, with two positive centers to the south of Greenland and in the subtropics respectively, and one negative center to the east of the U.S. continent at about 30°N. It is indicated that the decadal variations of both mei-yu precipitation and duration are closely related to wintertime North Atlantic SSTA. This pattern resembles the well-known North Atlantic SSTA triple mode that is associated with the North Atlantic Oscillation. Using the area-averaged SSTA in the two northern centers, which are more significant than the southern one, an index $I_{\rm NA}$ is defined to describe the variation of North Atlantic SSTA, which is closely related with mei-yu on the decadal timescale. $I_{\rm NA}$ is calculated as the difference of the normalized area-averaged SSTA between (40°–55°N, 30°–15°W) and (25°–35°N, 75°–60°W). Power spectrum analysis shows that the most significant period of $I_{\rm NA}$ is around year 14 (Fig. 4). Similarly, the decadal component of $I_{\rm NA}$ is extracted through the 9–16-yr band-pass filter, and is used to represent the decadal variation of the North Atlantic SSTA that is closely related to mei-yu. Figure 5 shows the filtered mei-yu precipitation, duration and $I_{\rm NA}$ indices. The two mei-yu indices are strongly coherent with $I_{\rm NA}$ before the 1930s. During 1930–1940, their decadal variations become weak, and so does their close in-phase relationship. After 1940, they enter into an in-phase relationship again until 1990, after when, their close relationship seem to break down again. It appears the decadal relationship between mei-yu and $I_{\rm NA}$ is not very stable and can change with time. But on the whole, it exhibits a significant in-phase relation during the last century.

Wavelet cross spectra can be used to examine the relationship between two time series in time-frequency space. Using the unfiltered indices, we calculate the wavelet cross spectra between $I_{\rm NA}$ and mei-yu indices (Fig. 6). For mei-yu precipitation (Fig. 6a), the most significant common power appears on the decadal band. That is to say, they are most significantly related to each other on the decadal timescale. There exists an obvious interdecadal transition around the 1930s, with the center period of around 9 years before the 1930s and about 14 years after. For the whole period, the two indices show a stable in-phase relationship on the decadal timescale. For mei-yu duration

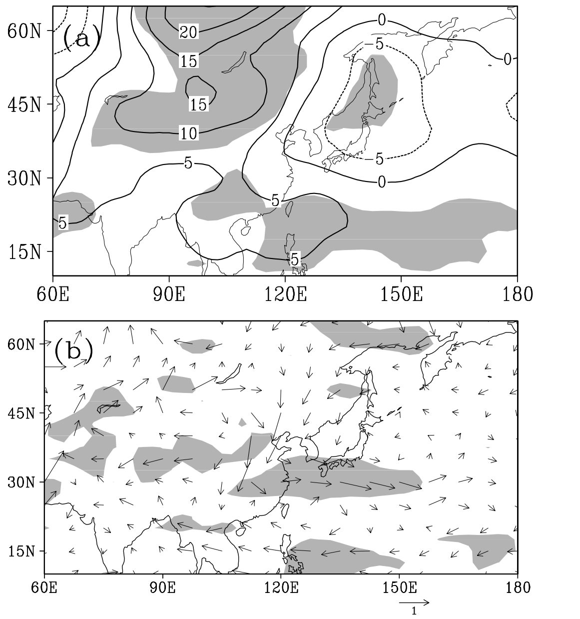

Fig. 7. Regression of summer (a) 500 hPa height and (b) 850 hPa wind anomalies on the filtered I_{NA} during 1956 to 1997. The shading indicates the 90% significance level.

(Fig. 6b), similar results can be obtained. The results are coherent with our previous conclusions that I_{NA} and mei-yu are closely and positively correlated with each other on the decadal timescale.

4. Possible impact of wintertime North Atlantic SST on East Asian summer circulation

4.1 *The relationship between wintertime North Atlantic SST and summer circulation*

Previously in section 3, the close relationships between mei-yu and North Atlantic SST on the decadal timescale are identified. In the following part of this section, we try to explore the possible impact of North Atlantic SSTA of the preceding winter on EASM circulation. Limited by the length of the filtered NCEP circulation data, the period 1948–1997 is chosen for the following analysis.

Figure 7a shows the regression maps of summertime 500 hPa geopotential height and 850hPa wind field on the filtered I_{NA}. In the 500 hPa height field, there is one positive regression center over Siberia and one negative center over Japan. Correspondingly, in the lower troposphere, southward wind anomalies are favored in East Asia (Fig. 7b). Such a situation indicates the weakening of the EASM. In weaker EASM years, the northward propagation of monsoon is limited and a sustained mei-yu front around the YRV tends to be favored (e.g., Zhang and Tao, 2003; Long et al., 2003; Ding and Chan, 2005; He et al., 2007). Thus, for positive I_{NA} phases, a longer mei-yu season and more precipitation are favored in the YRV, and vice visa.

4.2 *The persistency of the wintertime North Atlantic SSTA*

Previous analyses indicate that the wintertime North Atlantic SSTA can have a delayed impact on East Asian circulation in the following summer. However, the atmosphere changes very fast and the persistency of the signal from winter to summer must be realized through some slow-varying systems. Since the SSTA has good persistency and varies very slowly, we examine the persistency of the wintertime triple SSTA mode in the following. Regression of winter, spring and summer SSTA on the filtered I_{NA} index are shown in Fig. 8. The winter SSTA field (Fig. 8a) shows a clear triple mode. During spring (Fig. 8b), this triple mode is still significant, but slightly weaker than in winter. During summer (Fig. 8c), significant SSTA exist only to the south of Greenland, and the triple mode disappears. In order to examine the persistency of the triple SSTA mode more clearly, we calculate the regression of zonally (80°–20°W) averaged monthly SSTA on the filtered wintertime I_{NA} index (Fig. 9). It is clear that the triple mode persists from winter until May. In June and July, the triple mode does not exist any more.

4.3 *The role of the springtime North Atlantic SSTA*

Since the North Atlantic triple SSTA mode can persist well from winter until late spring, in the same manner as how we define the winter I_{NA} index in section 3.2, we calculate the spring I_{NA} index. In order to evaluate the possible impact of spring SSTA on summer circulation, regression of 500 hPa height and wave activity (Plumb, 1985) on the filtered spring I_{NA} index are calculated. Regression of 500 hPa height (Fig. 10) shows significant features in East Asia, similar to the regression map on winter I_{NA} index. Regressed wave activity shows a clear wave-train propagating from West Eurasia to East Asia. It is therefore suggested that the spring triple SSTA mode can excite a stationary Rossby wave-train and exert an impact on East Asian circulation through such a wave-train.

5. Summary and discussion

In this paper, we demonstrate that mei-yu is characterized by a significant decadal variability by analyzing a 121-yr mei-yu dataset from the National Climate

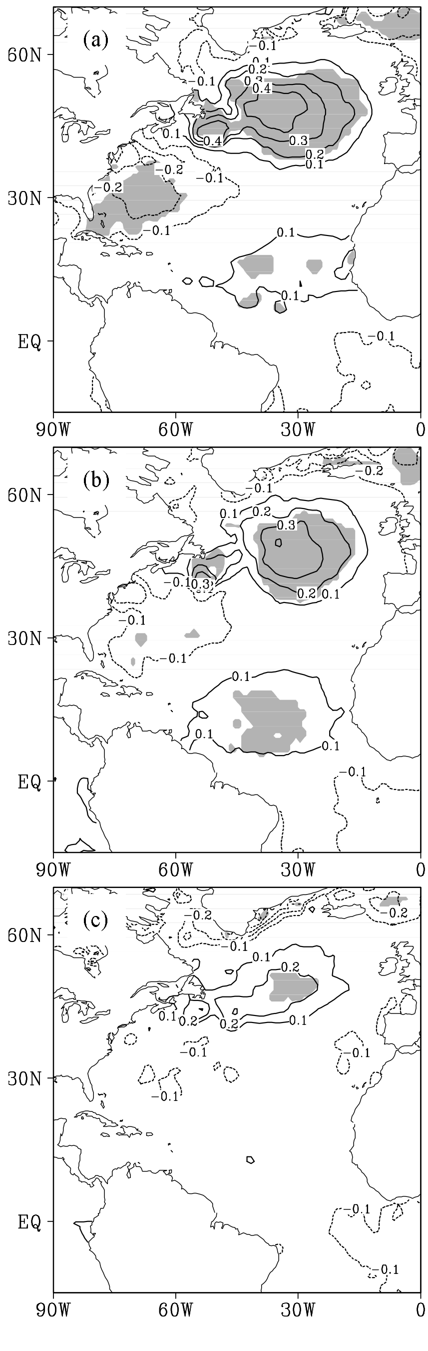

Fig. 8. Regression of (a) winter, (b) spring and (c) summer SSTA on the filtered I_{NA}. The shading indicates the 95% significance level.

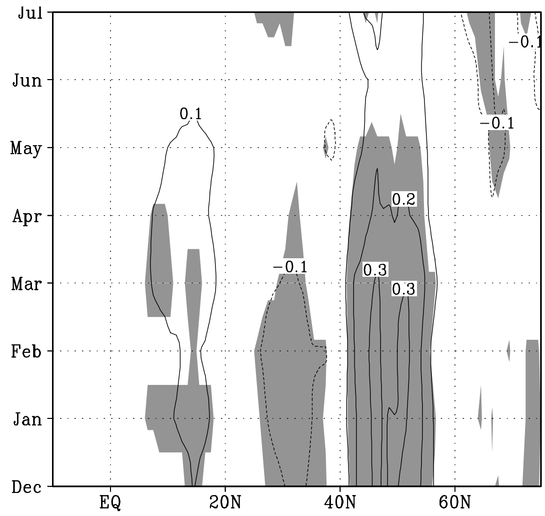

Fig. 9. Regression of monthly SSTA averaged over (80°–20°W) on the filtered I_{NA}.

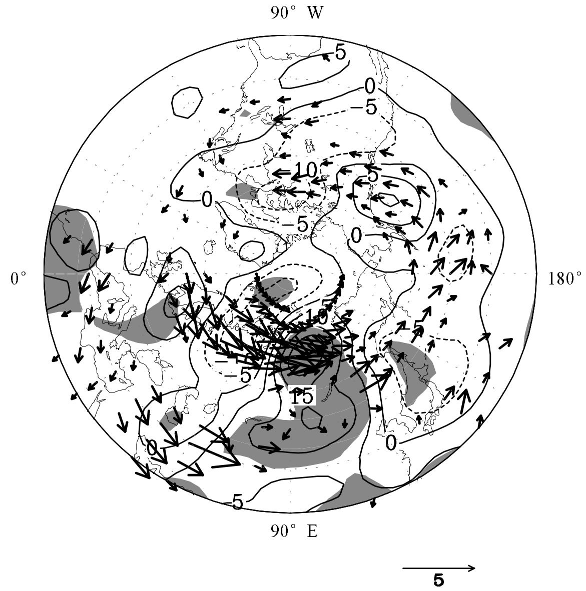

Fig. 10. Regression of summer 500 hPa height anomalies (contours) and wave activity (vectors) on the filtered spring I_{NA}. The shading indicates the 90% significance level.

Center of China Meteorology Administration. On the decadal timescale, both mei-yu precipitation and duration are closely related to a triple mode in the North Atlantic SSTA in the previous winter. The winter triple SSTA mode can persist until late spring, and the spring SSTA may exert an impact on mei-yu by exciting a Rossby wave-train during summer.

Previous studies (e.g., Wu and Liu, 2005) revealed that the wintertime North Atlantic air-sea system is characterized by a significant decadal variability, with the spatial pattern of a triple mode in the SSTA and a NAO-like mode in the atmosphere. It is also suggested in these studies that such variability originates from local or non-local air-sea interaction. It is this strong decadal variability that may exert a delayed impact on mei-yu in East Asia through a stationary Rossby wave-train propagating from West Eurasia to

East Asia during summer. However, how the spring SSTA can excite a Rossby wave-train needs further study.

Besides the SSTA, other factors, such as the Eurasian snow condition, may also exert an influence on the decadal variation of mei-yu. The Eurasian snow condition also exhibits strong decadal variability, which is closely associated with the wintertime triple SSTA mode in the North Atlantic (Ye, 2000). It is indicated in previous studies (Yang and Xu, 1994; Tan et al., 1999; Liu and Yanai, 2002; Ye and Bao, 2005) that the Eurasian snow condition may exert an influence on Asia summer monsoon on the interannual timescales. Therefore, it is possible that the decadal variations of the Eurasia snow condition may also exert an influence on mei-yu. However, more studies are needed to explore the relationship between snow condition and summer monsoon precipitation in East Asia on the decadal timescales.

Acknowledgements. The authors would like to thank Drs. Yihui Ding, Yiwen Yang and Qun Xu for providing the mei-yu data. This research is supported by the research grant KZCX3-SW-226 of the Chinese Academy of Sciences, the National Basic Research Program of China (973 Program, Grant No. 2006CB403600) and CityU Strategic Research Grant 7002231.

REFERENCES

Bretherton, C. S., M. Widmann, V. P. Dymnikov, J. M. Wallace, and I. Blade, 1999: The effective number of spatial degrees of freedom of a time-varying field. *J. Climate*, **12**, 1990–2009.

Ding, Y., 2004: Seasonal march of the east-Asian summer Monsoon. *East Asian Monsoon*, C.-P. Chang, Ed., World Scientific Publishing, 21–22.

Ding, Y., and J. C. L. Chan, 2005: The East Asian summer monsoon: An overview. *Meteorology and Atmospheric Physics*, **89**, 117–142.

Gao, H., Y. Wang, and J. He, 2006: Weakening significance of ENSO as a predictor of summer precipitation in China. *Geophys. Res. Lett.*, **33**, L09807, doi: 10.1029/2005GL025511.

Grinsted, A., J. C. Moore, and S. Jevrejeva, 2004: Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics*, **11**, 561–566.

Gong, D.-Y., and C.-H. Ho, 2003: Arctic oscillation signals in the East Asian summer monsoon. *J. Geophys. Res.*, **108**(D2), 4066, doi: 10.1029/2002JD002193.

He, J.-H., L. Qi, J. Wei, and Y. Z. Chi, 2007: Reinvestigations on the East Asian Subtropical Monsoon and Tropical Monsoon. *Chinese J. Atmos. Scis.*, **31**, 1257–1265. (in Chinese)

Huang, R. H., and Y. Wu, 1989: The influence of ENSO on the summer climate change in China and its mechanism. *Adv. Atmos. Sci.*, **6**, 21–32.

Ju, J. H., J. Cao, and J. Ren, 2005: Possible impacts of the Arctic Oscillation on the interdecadal variation of summer monsoon rainfall in East Asia. *Adv. Atmos. Sci.*, **22**, 39–48.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Li, C. Y., and M. Q. Mu, 2001: Influence of the Indian Ocean Dipole on Asian Monsoon Circulation. *CLIVAR Exchange*, **6**, 11–14.

Long, Z. X., J. Pan, and C. Y. Li, 2003: Influences of anomalous summer monsoon over the South China Sea on climate variation. *Acta Meteorologica Sinica*, **17**, 118–129.

Liu, X., and M. Yanai, 2002: Influence of Eurasian spring snow cover on Asian summer rainfall. *International Journal of Climatology*, **22**, 1075–1089.

Lu, R., B. Dong, and H. Ding, 2006: Impact of the Atlantic Multidecadal Oscillation on the Asian summer monsoon. *Geophys. Res. Lett.*, **33**, L24701, doi: 10.1029/2006GL027655.

Marshall, J., and Coauthors, 2001: North Atlantic climate variability: Phenomena, impacts and mechanisms. *International Journal of Climatology*, **21**, 1863–1898.

Ogi, M., Y. Tachibana, and K. Yamazaki, 2003: Impact of the wintertime North Atlantic Oscillation (NAO) on the summertime atmospheric circulation. *Geophys. Res. Lett.*, **30**, 1704, doi: 10.1029/2003GL017280.

Plumb, R. A., 1985: On the three-dimensional propagation of stationary waves. *J. Atmos. Sci.*, **42**, 217–229.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108**(D14), 4407, doi: 10.1029/2002JD002670.

Sung, M.-K., W. Kwon, H. Back, K. Boo, G. Lim, and J. Kug, 2006: A possible impact of the North Atlantic Oscillation on the east Asian summer monsoon precipitation. *Geophys. Res. Lett.*, **33**, L21713, doi: 10.1029/2006GL027253.

Tan, Y. K., J. H. He, and C. W. Zhu, 1999: Impact of Eurasian winter snow cover on the Northern Hemisphere summer circulation and its possible relation to East Asia pacific teleconnection pattern. *Chinese J. Atmos. Sci.*, **23**, 152–160. (in Chinese)

Weng, H., K. Ashok, S. K. Behera, S. A. Rao, and T. Yamagata, 2007: Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific rim during boreal summer. *Climate Dyn.*, **29**, 113–129.

Wu, L., and Z. Liu, 2005: North Atlantic decadal variability: Air-sea coupling, oceanic memory, and potential Northern Hemisphere Resonance. *J. Climate*, **18**, 331–349

Wu, R., and L. Chen, 1998: Decadal variation of summer rainfall in the Yangtze-Huaihe River valley and its relationship to atmospheric circulation anomalies over

East Asia and western North Pacific. *Adv. Atmos. Sci.*, **15**, 510–522.

Wu, R., and B. Wang, 2002: A contrast of the East Asian summer monsoon-ENSO relationship between 1962–77 and 1978–93. *J. Climate*, **15**, 3266–3279.

Xu, H. M., J. H. He, and Y. H. Yao, 1999: Interannual variability of the mei-yu onset and its association with the atmospheric circulation in the previous winter and possible causes. *Journal of Nanjing Institute of Meteorology*, **22**, 246–253. (in Chinese)

Yang, S., and L. Xu, 1994: Linkage between Eurasian winter snow cover and regional Chinese summer rainfall. *International Journal of Climatology*, **14**, 739–750.

Ye, H., 2000: Decadal variability of Russian winter snow accumulation and its associations with Atlantic sea surface temperature anomalies. *International Journal of Climatology*, **20**, 1709–1728.

Ye, H., and Z. Bao, 2005: Eurasian snow conditions and summer monsoon rainfall over South and Southeast Asia: Assessment and comparison. *Adv. Atmos. Sci.*, **22**, 877–888.

Zhang, Q. Y., and S. Y. Tao, 2003: The anomalous subtropical anticyclone in western Pacific and their association with circulation over East Asia during summer. *Chinese J. Atmos. Sci.*, **127**, 369–380. (in Chinese)