

Mechanisms of an extraordinary East Asian summer monsoon event in July 2011

Kyong-Hwan Seo,¹ Jun-Hyeok Son,¹ Seung-Eon Lee,¹ Tomohiko Tomita,² and Hyo-Seok Park³

Received 16 November 2011; revised 20 January 2012; accepted 23 January 2012; published 15 March 2012.

[1] Previous studies have demonstrated that the strong East Asian summer monsoon results mainly from the westward intensification of the North Pacific subtropical high (NPSH), or equivalently, the enhancement of the western North Pacific subtropical high. However, during early July in 2011 a strong southerly or southeasterly moist flow gave rise to a large amount of precipitation over southwestern Japan and Korea and anomalous dry conditions over central China because of the extraordinary intensification of the NPSH to the north. The formation of the anomalous high that occurred to the east of central Japan during early July is very rare, and its physical mechanisms are investigated in this study. The regressed circulation anomalies and wave-activity flux vectors for July 2011 and data from the previous 32 years show that two teleconnection patterns due to Rossby wave trains are the most important mechanisms: Rossby wave propagation from the eastern North Atlantic and western Europe to East Asia following the North Eurasian jet and East Asian jet in the upper level, and northward propagation of Rossby waves forced by diabatic heating over the western North Pacific (WNP) region in the lower level. This simultaneous forcing of a significant negative phase of the summertime North Atlantic Oscillation in the higher latitudes and enhanced diabatic heating over the subtropical WNP is found to be the cause of the abnormal development of the anomalous high to the east of central Japan, resulting in extremely wet conditions in Korea and southern Japan and dry conditions in southern China. **Citation:** Seo, K.-H., J.-H. Son, S.-E. Lee, T. Tomita, and H.-S. Park (2012), Mechanisms of an extraordinary East Asian summer monsoon event in July 2011, *Geophys. Res. Lett.*, 39, L05704, doi:10.1029/2011GL050378.

1. Introduction

[2] The East Asian summer monsoon (EASM) is a distinctive component of the Asian weather and climate that produces a particularly large amount of precipitation from the East Asia subtropical front [*Chen and Chang, 1980; Wang et al., 2009*]. The frontal rain in the summer season is called Meiyu in China, Changma in Korea, and Baiu in Japan. The maximum rainfall zone associated with this front gradually advances northward from southern China to Korea

and Japan from late May to late July [*LinHo and Wang, 2002*]. Substantial interannual and intraseasonal variability in the EASM has been observed, but the precise mechanisms of such variations have not been clearly elucidated. The westward intensification/expansion of the North Pacific subtropical high (NPSH), or equivalently, the enhancement of the western North Pacific subtropical high (WNPSH), over the area [110°–150°E, 10°–30°N] has been considered as one of main reasons for the development of a strong EASM not only on interannual time scale but also intraseasonal time scale (see Figure S1 in the auxiliary material).¹ The strengthened low-level southwesterly jet plays a key role in producing heavy rainfall over much of East Asia. Other reasons for a strong EASM include the effect of cold sea surface temperature (SST) anomalies over the western North Pacific (WNP), which tend to induce suppressed convection around the Philippine Sea and subsequent poleward teleconnection patterns emanating from the WNP [*Nitta, 1987; Wang et al., 2001*]. The northward-propagating wave train induces an anomalous cyclonic circulation, and thus causes heavy rainfall over central China, Korea, and Japan [e.g., *Yun et al., 2008*].

[3] During early July in 2011, however, a large amount of precipitation occurred over southwestern Japan and Korea, together with anomalous dry conditions over southern China. In particular, in just two days (July 8 and 9), Korea received 135 mm of precipitation on average, which amounts to about 50% of the average climatological total precipitation for July. This was due to an extraordinary intensification of the NPSH to the north rather than to the west. The abrupt northward intensification of the NPSH in early July is very rare (less than 10% out of the July days for 32 years), and its physical mechanisms cannot readily be imagined, since many previous studies have focused on the mechanisms of the enhancement of the WNPSH. Moreover, previous studies have examined the interannual variations in the EASM using seasonal (June–July–August) or monthly mean data. However, here we show that the variations in the NPSH during July 2011 took place on a submonthly time scale. The aim of the current study is to investigate the physical mechanisms that lead to the anomalous northward expansion of the NPSH.

2. Data

[4] In this study, the National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) Global Reanalysis (R2) data (June 1979–July 2011), the outgoing longwave radiation (OLR) interpolated data of the National

¹Department of Atmospheric Sciences, Division of Earth Environmental Systems, Pusan National University, Pusan, South Korea.

²Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan.

³Environmental Science and Engineering, California Institute of Technology, Pasadena, California, USA.

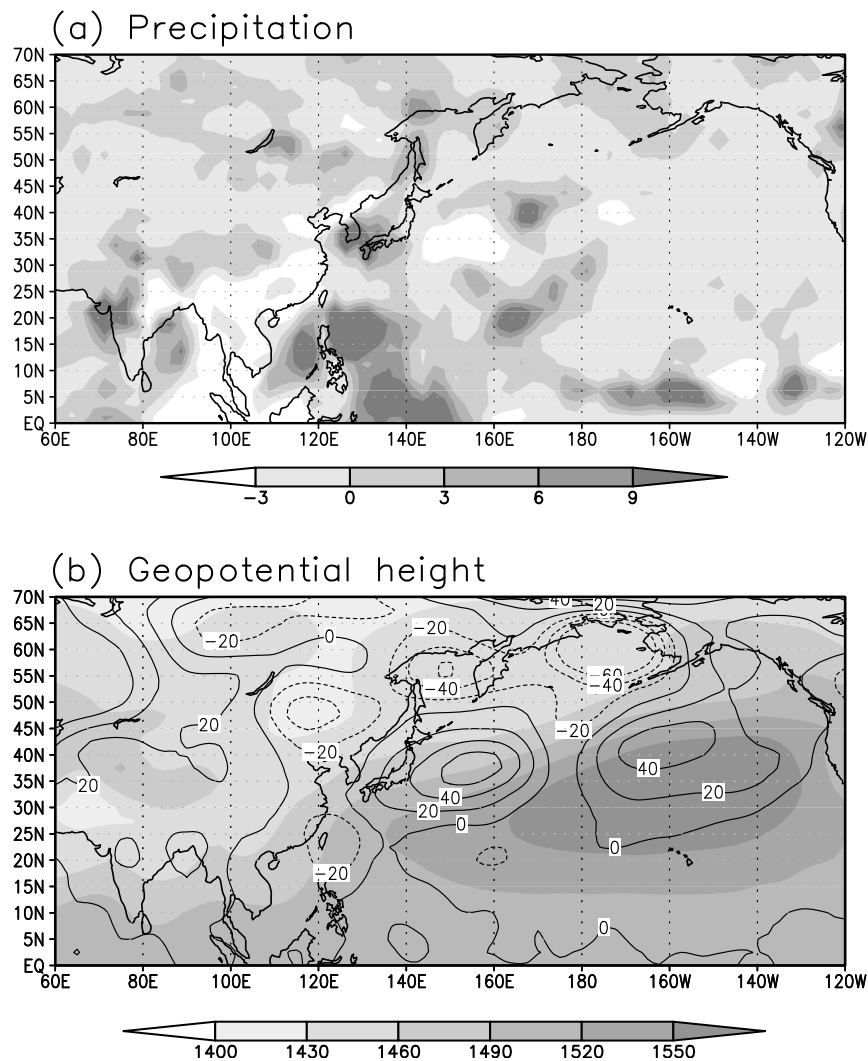


Figure 1. Averaged fields in the period July 6–10, 2011 for (a) GPCP precipitation anomaly (mm day^{-1}), and (b) geopotential height anomaly at 850 hPa (contour, gpm). The shading is the climatological mean (1979–2010) 850-hPa geopotential height. In early July of 2011, the NPSH intensified to the north (east of central Japan). A large amount of precipitation occurred in southwestern Japan and Korea, while southern China experienced dry conditions.

Oceanic and Atmospheric Administration (NOAA) data (June 1974–July 16, 2011), and the Global Precipitation Climatology Project (GPCP) data (1997–2008) are used. The GPCP daily data are not available after 2009, so we used pentad data for the analysis of the year 2011. The R2 and OLR data are on a $2.5^\circ \times 2.5^\circ$ horizontal grid, but the GPCP data has $1^\circ \times 1^\circ$ horizontal resolution. Anomalies are calculated by subtracting the climatological seasonal cycle from raw data.

[5] For the estimation of the propagation of Rossby waves, the wave activity flux (WAF) was calculated according to the method presented by Takaya and Nakamura [2001]. The WAF is an efficient diagnostic tool for viewing a snapshot of Rossby wave propagation under a quasi-geostrophic assumption [e.g., Sato and Takahashi, 2006; Hsu and Lin, 2007].

3. Extraordinary Submonthly Variations in the EASM in July 2011

[6] In early July of the year 2011, the NPSH anomalously expanded to the north rather than to the west, so the 850-hPa

geopotential height anomaly was located to the east of central Japan (i.e., $35^\circ\text{--}45^\circ\text{N}$, $140^\circ\text{--}160^\circ\text{E}$) (Figure 1a). The climatological NPSH was centered at around 30°N , as shown by the shading in the figure. In general, it is thought that when the NPSH intensifies and expands westward, the East Asia regions experience a large amount of precipitation through southwesterly or south-southwesterly moist flows. However, the abnormal northward expansion of the NPSH in 2011 set up another large-scale environment for inducing heavy precipitation in southwestern Japan and Korea: strong southerly or southeasterly flow with abundant moisture from the ocean along the western flank of the NPSH. In particular, in the 34th pentad (from July 6 to 10), southern Japan and Korea experienced a huge amount of rainfall, while southern China had dry conditions (Figure 1a). The anomalous anticyclone east of central Japan is considered to be a major cause of this special rainfall event.

[7] Then what is responsible for the formation of the anomalous anticyclone? To find the answer, the circulation anomalies in the upper and lower troposphere were regressed against the time series indices representing the geopotential

height variations over the anomalous anticyclone region [140°–155°E, 35°–45°N] for the period July 1–15, 2011. The time series are constructed for each level (i.e., 300- and 850-hPa levels). As the Rossby wave requires a propagation time to reach this anomalous anticyclone region, the regressed 300- and 850-hPa geopotential height anomaly fields averaged over –2 and –1 lagged days are shown in Figure 2. The changes in the averaged lag days do not show significant differences. In the upper-level field (Figure 2a), a wave-train-like teleconnection pattern emerges from the eastern North Atlantic and western Europe (Figure 2a). The Rossby wave energy disperses along the waveguides following the jet streams across the Eurasian continent into East Asia, providing a favorable environment for inducing or intensifying the anomalous anticyclone with a barotropic structure. A similar teleconnection pattern was found by *Enomoto et al.* [2003] and *Hsu and Lin* [2007]. In fact, the significant anomaly center appearing in the eastern North Atlantic is associated with the North Atlantic Oscillation (NAO) during the boreal summer (hereafter referred to as SNAO). Although it is well known that the wintertime NAO exerts an influence on East Asia through a modification of the Asian jet waveguide [*Branstator*, 2002; *Yang et al.*, 2002], the summertime teleconnection pattern associated with the NAO has received little attention because of its weak amplitude compared to its winter counterpart. Recently, however, the SNAO has also been treated as an initial forcing of the wave train connecting the eastern North Atlantic and Europe to East Asia [*Wu et al.*, 2009, 2011]. One of the reasons for this is a decadal change. For example, *Sun et al.* [2008] suggested that the center of the SNAO has shifted eastward, and thus a strong connection has been evident between the weather and climate over Korea and Japan and the geopotential oscillation over the eastern North Atlantic since the late 1970s. The negative geopotential anomaly over the eastern North Atlantic is the southern component of the SNAO (its definition will be described in the next section). Therefore, the variation of SNAO needs to be investigated.

[8] In the lower level (Figure 2b), however, such a zonally dominant teleconnection pattern is not as clear as in the upper level. A cyclonic circulation pattern still remains around the United Kingdom because the SNAO has a barotropic structure. More interestingly, a poleward-propagating wave train shows up from the Philippine Sea, passing through the region east of Japan up to the central North Pacific. This teleconnection pattern is closely related to diabatic heating by enhanced convection over the WNP in this period (not shown, but enhanced heating in this region has been verified). An experiment with the GFDL dynamical core model showed a similar teleconnection pattern with low-level cyclonic and anticyclonic circulation anomalies formed over the WNP and to the east of central Japan, respectively (not shown). Therefore, these two different teleconnection patterns may work together to develop and intensify the low-level anomalous high. This means that to understand the variations in mid-latitude climate phenomena such as the EASM, we should consider both the natural variability in the polar region and diabatic forcing in the subtropics.

4. Combined Effect of SNAO and WNP Diabatic Forcing: July 2011 and Climatology

[9] The two major factors in the establishment of the anomalous high to the east of central Japan have been shown

to be the SNAO and WNP diabatic forcing. We now examine how these factors vary with time in the year 2011. The SNAO index is calculated by the sea-level pressure (SLP) difference between [5°–0°W, 55°–65°N] and [10°–15°E, 80°–85°N] [*Yamamura and Tomita*, 2011]. The WNP diabatic forcing index is calculated by the OLR anomaly averaged over the WNP region [120°–130°E, 10°–20°N] [*Hsu and Lin*, 2007]. The time series of these two indices are presented in Figure 3, where the thick line represents the SNAO and the dotted line indicates the OLR index. Both the SNAO and OLR indices show submonthly variations, with minima around July 8 and 9, 2011, the time of the major heavy rainfall event. Therefore, we can infer that the above two factors are very significant in inducing the anomalous high to the north of the climatological NPSH.

[10] Interestingly, however, these two factors do not individually affect the peculiar northward intensification of the NPSH. For example, a composite map with the SNAO index below –1.0 standard deviation during the month of July from 1979 to 2010 showed that the center of the low-level anticyclonic circulation was formed over Japan (around 135°E and 40°N) (Figure S2a), which is much more west than in our case. Also, a composite map of the 850-hPa geopotential height anomaly against the OLR index below –1.0 standard deviation during the same 32 years exhibited the peculiar Pacific–Japan teleconnection pattern with an anticyclonic circulation anomaly over Korea (centered at 122.5°E and 40°N) (Figure S2b). Thus, the separate effects of each factor do not support the formation of the anomalous low-level anticyclone to the east of central Japan.

[11] Therefore, we need to examine the composite circulation fields when both factors are significantly at work. Figure 4 shows the composite fields of the 850-hPa geopotential height and wind anomalies (for the same 32-year period) and GPCP precipitation anomaly (for the period 1997–2008). The composite was constructed for the cases where both the SNAO and WNP OLR indices had standard deviations of less than –1.0. Only 12 days out of all the July days in 32 years satisfied these criteria, demonstrating how rare this northward intensification of the NPSH was during the peak phase of the EASM. Nonetheless, the composite circulation fields grossly resemble the case of July 2011, with an anomalous high located to the east of Japan, but slightly shifted to the northeast (i.e., centered at 160°E and 45°N). Similarly to the 2011 case (Figure 2b), a cyclonic circulation exists around the WNP. A region of heavy rainfall appeared along the line at 130°E from the subtropics to the mid-latitudes, with a general structure similar to that in Figure 1a. In particular, as in our case, heavy precipitation over Korea and southwestern Japan and dry conditions in southern China are prominent. A similar composite analysis was performed for the 500-hPa streamfunction anomaly and the WAF (Figure 5). The WAF vectors are parallel to the wave's group velocity, thus indicating the direction and strength of the energy propagation of the stationary Rossby waves. The vectors tend to be directed to the locally largest horizontal gradient of geopotential height anomalies. In Figure 5, the strong eastward-pointing WAF vector appeared over the eastern North Atlantic; this was associated with the cyclonic circulation anomaly and was directed to the downstream region of western Europe along the North Eurasian jet. The wave-flux vector points southeastward at around 60°E because of a deceleration of the westerly jet

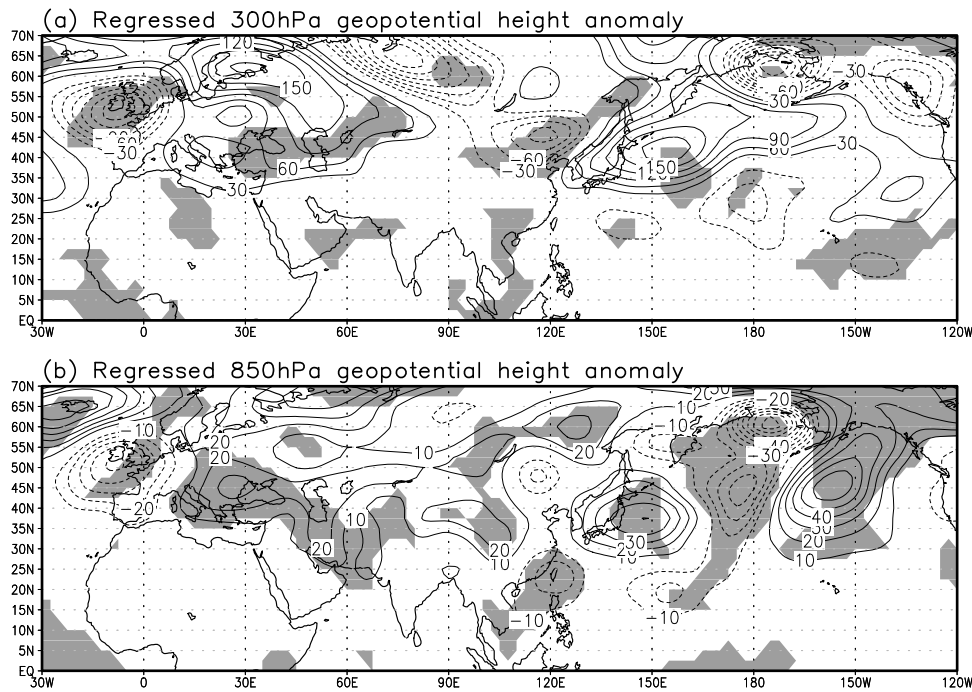


Figure 2. Geopotential height anomalies at (a) 300 hPa (contour intervals of 30 gpm) and (b) 850 hPa (contour intervals of 10 gpm) regressed against the time series indices constructed from their respective geopotential height anomalies averaged over [140°–155°E, 35°–45°N] in the period July 1–15, 2011. The regressed fields are averaged for lag days –2 and –1. Shading indicates statistically significant region at the 90% confidence level based on Student’s *t*-test.

there, and then points to East Asia. The Rossby wave formed an anticyclonic circulation anomaly east of central Japan and north of the climatological NPSH with an equivalent barotropic vertical structure. In addition, the wave-activity flux propagated northeastward from the WNP region to the anomalous high region. Both wave propagations resemble the case of July 2011. Consequently, these two climate

variations (one from higher latitudes, way upstream of East Asia, and the other from the subtropical region) combine to develop the anomalous high to the east of central Japan. Therefore, it is concluded that the simultaneous occurrence of the significant negative SNAO phase and the enhanced diabatic heating over the WNP can cause the abnormal development of this anomalous high to the east of central

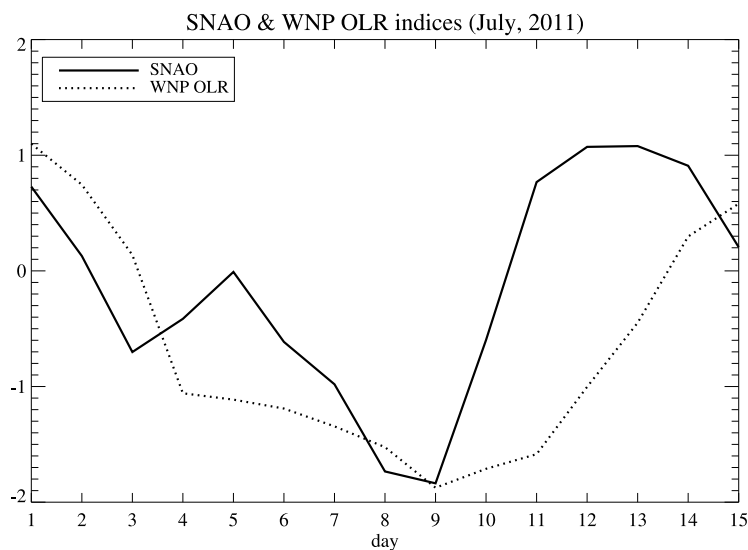


Figure 3. SNAO index (thick line) and OLR index over the WNP (dotted line) in the period July 1–15, 2011. The SNAO index is the sea-level pressure difference between the two regions at [5°–0°W, 55°–65°N] and [10°–15°E, 80°–85°N]. The OLR index is averaged over [120°–130°E, 10°–20°N]. Both indices are normalized by their respective standard deviations.

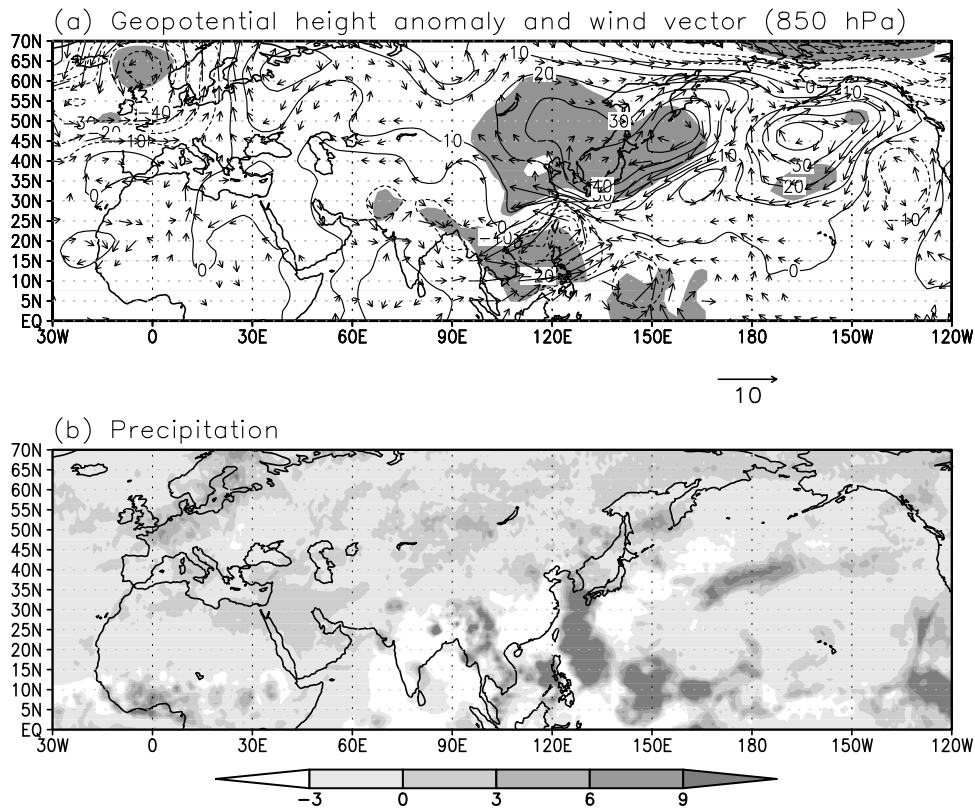


Figure 4. Composite fields of (a) 850-hPa geopotential height anomaly (gpm) and wind vector (m s^{-1}) in July for the climatological period from 1979 to 2010, and (b) precipitation anomaly (mm day^{-1}) in July for the period from 1997 to 2008. Only days with SNAO and OLR indices with standard deviations below -1.0 are selected. In Figure 4a, only wind vectors with magnitudes greater than 5 m s^{-1} are shown. The shading in Figure 4a indicates the statistically significant region at the 90% confidence level based on Student's t -test.

Japan through the Rossby wave train. This then results in extremely wet conditions in Korea and southern Japan and dry conditions in southern China.

5. Summary and Discussion

[12] Previous studies demonstrated that the strong EASM results mainly from the westward intensification of the NPSH or the enhancement of the WNPSH. During early July in 2011, however, a strong southerly or southeasterly flow with abundant moisture from the ocean along the western

flank of the NPSH produced a large amount of precipitation over southwestern Japan and Korea, together with anomalous dry conditions over eastern China, because of an extraordinary intensification of the NPSH to the north instead of to the west. This abrupt northward intensification of the NPSH in early July is very rare, and its physical mechanisms have been investigated in this study.

[13] The regressed geopotential height anomalies and WAF vectors for July 2011 and data from the previous 32 years demonstrate that two teleconnection patterns due to

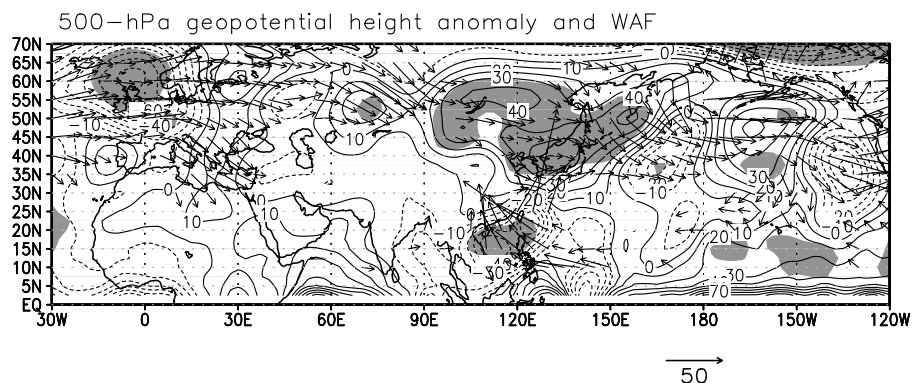


Figure 5. Same as Figure 4a, but for the 500-hPa geopotential height anomaly (contour, intervals of 10 gpm) and the wave activity flux (WAF) (vector, units of $\text{m}^2 \text{ s}^{-2}$). Only WAF vectors with amplitudes greater than $10 \text{ m}^2 \text{ s}^{-2}$ are plotted.

Rossby wave trains are the most important mechanisms for the development of the anomalous high to the east of central Japan: one is the Rossby wave propagation from the eastern North Atlantic and western Europe to East Asia in the upper level following the North Eurasian jet and East Asian jet, and the other is the poleward-propagating Rossby wave forced by diabatic heating over the WNP region in the lower level. The simultaneous forcing of the significant negative SNAO in the higher latitudes and enhanced diabatic heating over the subtropical WNP region caused the abnormal development of the anomalous high located to the east of central Japan, resulting in extremely wet conditions in southwestern Japan and Korea and dry conditions in southern China.

[14] There are many potential factors other than the abovementioned ones that need to be examined in terms of the interannual and intraseasonal variations in the EASM. In the case of early July in 2011, the following climate variability might have played little part in the development of the anomalous high to the east of Japan: the Madden-Julian oscillation (its magnitude far less than 1 standard deviation), Indian dipole-mode forcing (its magnitude less than 0.3), and Indian summer monsoon (nearly normal strength). Other factors including Tibetan heat forcing, Eurasian snow cover, and global SST anomalies need to be investigated.

[15] **Acknowledgments.** This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MEST) (2011-0021927) and the Korea Meteorological Administration Research and Development Program under grant CATER 2012-3071. We would like to thank the two anonymous reviewers for their helpful comments.

[16] The Editor thanks the two anonymous reviewers for their assistance in evaluating this paper.

References

- Branstator, G. (2002), Circumglobal teleconnections, the jet stream waveguide, and the North Atlantic Oscillation, *J. Clim.*, *15*, 1893–1910, doi:10.1175/1520-0442(2002)015<1893:CTTJSW>2.0.CO;2.
- Chen, G. T. J., and C. P. Chang (1980), The structure and vorticity budget of an early summer monsoon trough (Mei-Yu) over southeastern China and Japan, *Mon. Weather Rev.*, *108*, 942–953, doi:10.1175/1520-0493(1980)108<0942:TSAVBO>2.0.CO;2.
- Enomoto, T., B. J. Hoskins, and Y. Matsuda (2003), The formation mechanism of the Bonin high in August, *Q. J. R. Meteorol. Soc.*, *129*, 157–178, doi:10.1256/qj.01.211.
- Hsu, H.-H., and S.-S. Lin (2007), Asymmetry of the tripole rainfall pattern during the East Asian summer, *J. Clim.*, *20*, 4443–4458, doi:10.1175/JCLI4246.1.
- LinHo and B. Wang (2002), The time-space structure of the Asian-Pacific summer monsoon: A fast annual cycle view, *J. Clim.*, *15*, 2001–2019, doi:10.1175/1520-0442(2002)015<2001:TTSSOT>2.0.CO;2.
- Nitta, T. (1987), Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation, *J. Meteorol. Soc. Jpn.*, *65*, 373–390.
- Sato, N., and M. Takahashi (2006), Dynamical processes related to the appearance of quasi-stationary waves on the subtropical jet in the midsummer Northern Hemisphere, *J. Clim.*, *19*, 1531–1544, doi:10.1175/JCLI3697.1.
- Sun, J., H. Wang, and W. Yuan (2008), Decadal variations of the relationship between the summer North Atlantic Oscillation and middle East Asian air temperature, *J. Geophys. Res.*, *113*, D15107, doi:10.1029/2007JD009626.
- Takaya, K., and H. Nakamura (2001), A formulation of a phase independent wave-activity flux for stationary and migratory quasi-geostrophic eddies on a zonally varying basic flow, *J. Atmos. Sci.*, *58*, 608–627, doi:10.1175/1520-0469(2001)058<0608:AFOAPI>2.0.CO;2.
- Wang, B., R. Wu, and K.-M. Lau (2001), Interannual variability of the Asian summer monsoon: Contrasts between the Indian and the western North Pacific-East Asian monsoons, *J. Clim.*, *14*, 4073–4090, doi:10.1175/1520-0442(2001)014<4073:IVOTAS>2.0.CO;2.
- Wang, B., J. Liu, J. Yang, T. Zhou, and Z. Wu (2009), Distinct principal modes of early and late summer rainfall anomalies in East Asia, *J. Clim.*, *22*, 3864–3875, doi:10.1175/2009JCLI2850.1.
- Wu, R., S. Yang, S. Liu, L. Sun, Y. Lian, and Z. Gao (2011), Northeast China summer temperature and North Atlantic SST, *J. Geophys. Res.*, *116*, D16116, doi:10.1029/2011JD015779.
- Wu, Z., B. Wang, J. Li, and F.-F. Jin (2009), An empirical seasonal prediction model of the East Asian summer monsoon using ENSO and NAO, *J. Geophys. Res.*, *114*, D18120, doi:10.1029/2009JD011733.
- Yamamura, T., and T. Tomita (2011), Spatiotemporal differences in the interannual variability of Baiu frontal activity in June, *Int. J. Climatol.*, *31*, 57–71, doi:10.1002/joc.2058.
- Yang, S., K.-M. Lau, and K.-M. Kim (2002), Variations of the East Asian jet stream and Asian-Pacific-American winter climate anomalies, *J. Clim.*, *15*, 306–325, doi:10.1175/1520-0442(2002)015<0306:VOTEAJ>2.0.CO;2.
- Yun, K.-S., K.-H. Seo, and K.-J. Ha (2008), Relationship between ENSO and northward propagating ISO in the East Asian summer monsoon system, *J. Geophys. Res.*, *113*, D14120, doi:10.1029/2008JD009901.
- S.-E. Lee, K.-H. Seo, and J.-H. Son, Department of Atmospheric Sciences, Division of Earth Environmental Systems, Pusan National University, Keumjeong-Gu, Jangjeon-Dong, Pusan 609-735, South Korea. (khseo@pusan.ac.kr)
- H.-S. Park, Environmental Science and Engineering, California Institute of Technology, Mail Code 131-24, Pasadena, CA 91125, USA.
- T. Tomita, Graduate School of Science and Technology, Kumamoto University, Kurokami 2-39-1, Kumamoto 860-8555, Japan.