GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L20809, doi:10.1029/2010GL044931, 2010

Impacts of tropical ocean warming on East Asian summer climate

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Received 30 July 2010; revised 31 August 2010; accepted 14 September 2010; published 26 October 2010.

[1] The impacts of eastern Pacific (EP) and Indian Ocean (IO) warming after the late 1970s on the East Asian climate in July and August were investigated, to understand the distinct impacts of the abovementioned warming on differences in sub-seasonal characteristics. The EP warming induced a strong Pacific-Japan (PJ)-like (tropics-related meridional) pattern during July, but the IO warming preferred a Eurasian (EU)-like wave (extratropics-related zonal) pattern during August. The former is weaker in August and the latter in July. Additionally, the results of perpetual July and August model experiments revealed that these distinct atmospheric responses to the EP and IO warming during July and August, respectively, were caused by different mean thermal states. The difference in the mean thermal states was mainly derived from (1) a warmer ocean and cooler continent in August than in July and (2) a warmer tropics and cooler extratropics in July than in August. **Citation:** Yun, K.-S., K.-J. Ha, and B. Wang (2010), Impacts of tropical ocean warming on East Asian summer climate, *Geophys. Res. Lett.*, *37*, L20809, doi:10.1029/2010GL044931.

1. Introduction

[2] Sub-seasonal variability, one of the most predominant aspects of climate variability, has a significant effect on the active and break cycles of the monsoon and leads to intensification of severe floods and droughts [*Chen and Chen*, 1995; *Yang and Li*, 2003]. In earlier studies [*Wang et al.*, 2007; *Ha et al.*, 2009], it has been revealed that the East Asian climate shows different interannual and interdecadal variabilities on a sub-seasonal time scale. It is reported that the monsoon rainfall over East Asia experiences different interdecadal changes after the late 1970s, between July and August [*Ha et al.*, 2009; *Lee et al.*, 2010]. Figures 1a and 1b present the distinct interdecadal rainfall changes during July and August, respectively: an insignificant change in the rainfall in July, but an evident increase in the rainfall in August.

[3] *Lee et al.* [2010] investigated the cause of this distinct interdecadal change between July and August. They demonstrated that after the late 1970s, the Indian Ocean (IO) sea surface temperature (SST) anomaly altered the western North Pacific (WNP) subtropical high anomaly, particularly during La Niña years and at the decay phase of major El Niño years [*Yang et al.*, 2007; *Xie et al.*, 2009; *Du et al.*, 2009]. This changed impact of the IO thereby weakened the relationship between the East Asian rainfall in August and El Niño/Southern Oscillation (ENSO). This result implied that after the late 1970s, the summer extratropical circulation response caused by the IO SST is remarkably different from that caused by ENSO (or the tropical eastern Pacific (EP) SST). Our primary objective is to investigate different impacts of the simultaneous EP and IO warming between July and August, in relation to the sub-seasonally different interdecadal change over East Asia.

[4] The EP warming during the El Niño winter initiates warming of the IO and East Asian marginal seas [*Klein et al.*, 1999]. This warming of the IO and East Asian marginal seas persists throughout the ensuing summer and may play an important role in modulating the East Asian circulation [*Xie et al.*, 2009; *Du et al.*, 2009]. In particular, the interdecadal EP and IO warming after the late 1970s [*Wang*, 1995] has placed great emphasis on these distinct impacts of EP and IO. In this study, we examine the distinctive impacts of the interdecadal EP and IO SST warming on the East Asian climate in July and August. The different circulation responses between July and August are mainly shown in relation to the mean thermal state. To demonstrate the influences of the difference in the mean thermal states between July and August, we perform perpetual July and August model experiments with the interdecadal EP and IO SST warming, by using an atmospheric general circulation model (AGCM).

2. Data and Model Experiment

[5] For a composite and regression analysis of the East Asian climate during July and August, the European Centre for Medium-range Weather Forecasts (ECMWF) Reanalysis (ERA-40) data [*Uppala et al.*, 2005] from 1958 to 2001 (44-yr) were used. The SST data were obtained from the British Atmospheric Data Centre (BADC) HadISST (Hadley Centre Sea Ice and Sea Surface Temperature data set) [*Rayner et al.*, 2003] for the period 1958 to 2001. Since the transition year in the interdecadal change around the late 1970s is often referred as 1979/80 [*Wang et al.*, 2008], the main results of the present study are shown for two periods, before and after 1979/80. Figures 1c and 1d display the interdecadal change in the SST (1980–2001 minus 1958–1979). Significant warming in the EP, IO, and the tropical WNP was observed during both July and August. The subtropical and mid-latitude North Pacific SST anomaly (~30–45°N) has experienced cooling state since 1980. Despite the analogous forcing during both July and August, why do sub-seasonally different interdecadal changes over East Asia matter? For individual assessment of the tropical EP and IO SST anomalies, the EP and IO SST were identified by the anomaly area-averaged over the EP region [15°S–15°N, 180–100°W] and the IO region [15°S–15°N, 50–100°E].

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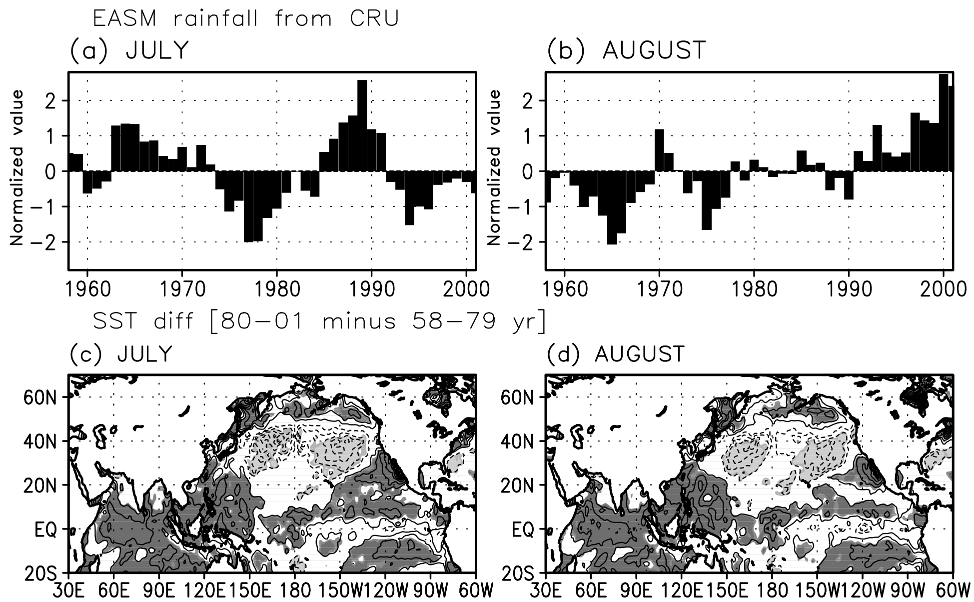

Figure 1. The 5-year running averaged East Asian rainfall over [125–130°E, 34–38°N] obtained from Climate Research Unit (CRU) during (a) July and (b) August. Composite difference in the SST anomaly between two periods: 1980–2001 and 1958–1979 during (c) July and (d) August. Heavy (light) shading indicates the positive (negative) anomaly significant at the 95% confidence level. The contour interval is 0.2K and the zero line is omitted.

[6] To examine the impact of the interdecadal EP and IO SST forcing on the East Asian climate during July and August, an AGCM experiment was performed using the ECHAM4.6 model from the Max Planck Institute for Meteorology, Hamburg, Germany, which was built on the weather forecast model of the ECMWF. This ECHAM4.6 is a global spectral model, with triangular truncation at wave number 42 and a 19-level hybrid sigma-pressure coordinate system. A detailed description of this model is provided by *Roeckner et al.* [1996]. After a 30-year integration, the results from the last 25 years of the simulation were considered. The EP and IO SST warming forcing were specified by doubling the observed interdecadal change in the SST (i.e., 1980–2001 minus 1958–1979) to the climatological SST (from 1958 to 2001), in the domain of EP and IO. The experiment designs are presented in Table 1. For the purpose of demonstrating the mean states different between July and August, the annual cycle was switched off and the mean state in the model was perpetually sustained for July or August conditions, respectively (i.e., the fixed Sun and other boundary conditions for July or August).

3. Effect of Tropical EP and IO SST Warming

[7] The interdecadal change in the tropical SST is notably characterized by the EP and IO SST warming. Prior to examining the impact of the interdecadal SST warming to locate the impacts of the EP and IO warming on the July and August extratropical circulation after the late 1970s, we have regressed the observed 500hPa geopotential height anomaly against the EP and IO SST anomalies during 1980–2001 years (Figure 2). The regression result confirms that the effects of EP and IO warming are distinctly different from each other. If the patterns in Figures 2 and 3 are similar, then the interdecadal SST warming in EP and IO seems to be a primary source in inducing the interannual anomalies. Note that the link between the EP and IO SST is weak during July and August (r ~ 0.3), unlike the strong correlation between wintertime EP and IO SST (r ~ 0.71). During July, it is found that the EP warming corresponds to a clear Pacific-Japan (PJ)-like wave pattern along the East Asian coast, whereas the IO warming shows a PJ-like wave pattern elongated to the east (Figures 2a and 2b). During August, the EP warming still seems a consequence of the PJ-like pattern, although the amplitude becomes somewhat weak (Figure 2c). However, the IO warming is rather associated with the Eurasian (EU)-like wave pattern (Figure 2d). The center of the EU-like pattern is slightly shifted to ~15°E, as compared to the EU index suggested by *Wallace and Gutzler* [1981]. Thus, to quantify the EU-like pattern associated with the IO warming, we redefine the EU analog index (i.e., EUAI) using the definition of *Wallace and Gutzler* [1981] but shifted in longitude 15°E, as follows:

$$EUAI = -0.25 \times Z^*(55^\circ N, 35^\circ E) + 0.5 \times Z^*(55^\circ N, 95^\circ E) - 0.25 \times Z^*(40^\circ N, 160^\circ E) \quad (1)$$

where Z* indicates the 500-hPa geopotential height anomaly. The regressed field against the EUAI (Figure 2f)

Table 1. Explanation of the Model Experiment Design by ECHAM4.6

Experiment	Month for the Perpetual Run	SST Forcing
CTL_JUL	July	N/A
CTL_AUG	August	N/A
EXP_EP_JUL	July	EP warming (15°S–15°N, 180–100°W)
EXP_EP_AUG	August	EP warming (15°S–15°N, 180–100°W)
EXP_IO_JUL	July	IO warming (15°S–15°N, 50–100°E)
EXP_IO_AUG	August	IO warming (15°S–15°N, 50–100°E)

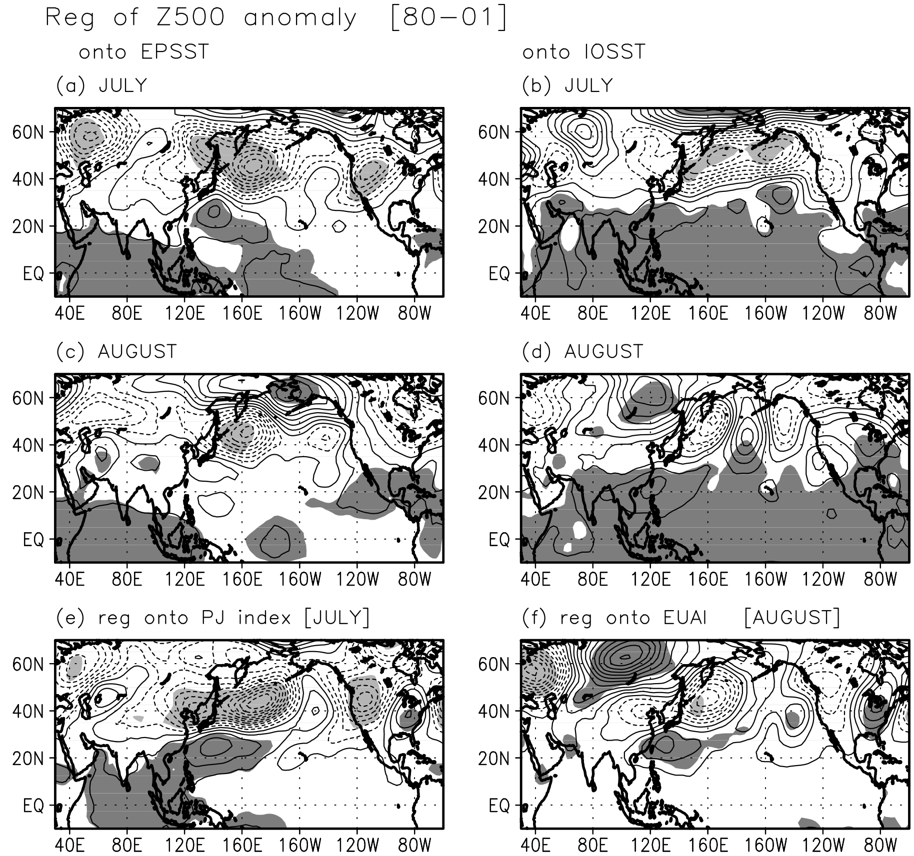

Figure 2. Regression of the (a) July and (c) August 500hPa geopotential height anomaly against the July (Figure 2a) and August (Figure 2c) EP SST anomaly during the period 1980–2001. (b, d) Same as Figures 2a and 2c, but for the IO SST anomaly. Regression of (e) the July 500hPa geopotential height anomaly against the July PJ index and (f) the August 500hPa geopotential height anomaly against the August EUAI during 1980–2001 years. Heavy (light) shading indicates the positive (negative) value significant at the 95% confidence level. The contour interval is 3gpm and the zero line is omitted.

exhibits a similar extratropical circulation anomaly to that against the IO SST anomaly during August (see Figure 2d). The August IO SST anomaly is significantly associated with the August EUAI, with a significant correlation coefficient ($r \sim 0.40$) at the 90% confidence level. On the other hand, the July EP SST anomaly is strongly correlated ($r \sim 0.58$) with the July PJ index, whereas the weak relationship between the July IO SST and PJ index ($r \sim 0.24$). The regressed field against the July PJ index (Figure 2e) is also similar to the regressed pattern against the July EP SST anomaly (see Figure 2a). In the previous epoch (1958–1979), such preferences for the EP and IO warming did not emerge (not shown). Here, the PJ index is identified as the difference in the OLR anomaly between [16–20°N, 142–150°E] and [32–38°N, 134–142°E], based on the definition of *Nitta* [1987]. The rest of the cases (e.g., July IO SST versus PJ, July EP SST versus EUAI, and August IO SST versus PJ) show no statistically significant relationships.

4. Sub-seasonal Mean Thermal State Effect

[8] The key question here is why the July PJ pattern is related to the EP warming, while the August EU-like pattern is related to the IO warming. Could these preferences be induced by the interdecadal SST change (because in the previous epoch, such preferences did not exist)? Could the mean thermal state differences between July and August partly account for the sub-seasonal preferences? To examine the different impacts of the mean thermal state between July and August on the interdecadal EP and IO warming, we have performed perpetual experiments with the observed EP and IO SST forcing, using ECHAM4.6 AGCM. As shown in the 500hPa circulation response (Figures 3a–3d); the PJ pattern is preferred in July, but the EP warming induces a stronger PJ-like pattern (Figures 3a and 3c). In August, the EP warming favors a meridional dipole pattern in the central eastern North Pacific (Figure 3b), but the IO warming produces an EU-like wave pattern and a strong response in the tropical western Pacific (Figure 3d), which does not exactly resemble the pattern in Figure 2d. Even though some differences are observed during the comparison of Figures 2 and 3, the experimental results suggest that the difference in the mean thermal states between July and August favors the EP-related PJ-like pattern during July and the IO-related EU-like pattern during August.

[9] If so, how does the sub-seasonal difference in the mean thermal states induce the different extratropical response? In relation to this question, we present the differences in

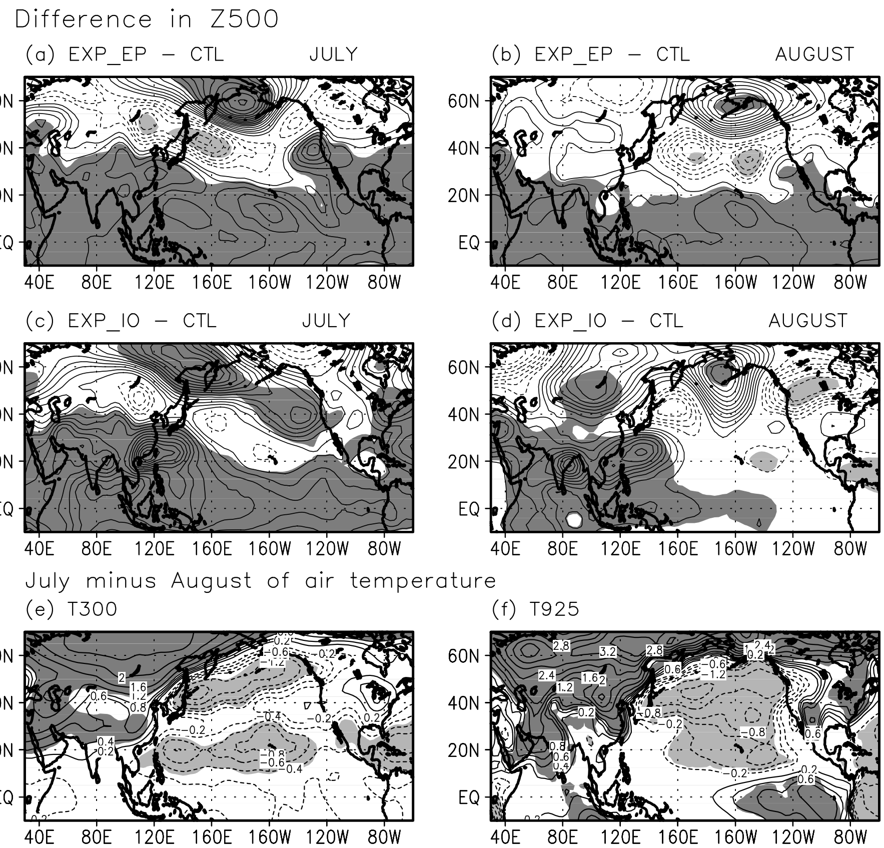

Figure 3. The difference in the 500hPa geopotential height anomaly between (a) CTL_JUL and EXP_EP_JUL, (b) CTL_AUG and EXP_EP_AUG, (c) CTL_JUL and EXP_IO_JUL, and (d) CTL_AUG and EXP_IO_AUG (e.g., CTL_JUL indicates the control experiment given by the climatological SST in the July perpetual run, while EXP_IO_AUG and EXP_EP_AUG means the experiment forced by the doubled IO and EP SST warming in the August perpetual run, respectively). The contour interval is 1gpm and the zero line is omitted. Difference in (e) 300hPa and (f) 925hPa air temperature between July and August (i.e., July minus August) during the period 1980–2001. Heavy (light) shading indicates the positive (negative) anomaly significant at the 95% confidence level.

the thermal structure (i.e., 300hPa and 925hPa air temperature) between July and August (Figures 3e and 3f). At the upper level (Figure 3e), the land-sea contrast is notably apparent, resulting in a warmer Eurasian continent and cooler surrounding ocean including IO in July than in August. It is due to the difference in the land ocean thermal inertia (rapid cooling over the land and delayed warming in the ocean). At the lower level (Figure 3f), outside of the land-sea contrast, a warmer tropics and cooler extratropics is marked in July compared to August. This is because the thermal condition at the lower level is primarily affected by the fact that increases in the SST with latitudinal variations follow solar insolation.

[10] Note that the wave activity of PJ pattern is propagated to the north only in the lower troposphere [*Kosaka and Nakamura*, 2006], implying the importance of the lower level thermal state. Consequently, in relation to a warmer tropical warming during July compared to August, the EP warming produces a stronger enhanced convection over the central Pacific and in turn stronger suppressed convection over the WNP, than that during August (Figures 4a and 4c). It results in the PJ-like Rossby wave pattern during July, consistent with the observed PJ-related convection structure (Figure 4e). On the other hand, the EU-like pattern is primarily affected by the upper-level jet flow. The zonal wind anomalies regressed against the EU-like pattern (Figure 4f) are closely associated with the meridional modulation of the westerly flow (i.e., the increase south of westerly jet stream but the decrease north). During August, the IO warming generates a stronger meridional modulation of the upper-level westerly flow than that during July (Figures 4b and 4d). It may be contributed that a warmer ocean to the south and cooler land (i.e., Eurasian continent) to the north during August (as opposed to during July), which provide the mean thermal condition for a stronger meridional temperature gradient. Finally, it induces a stronger change in the upper-level westerly flow via the thermal wind balance.

5. Discussion and Conclusion

[11] We have investigated the distinct extratropical circulation responses between July and August associated with EP and IO SST warming, respectively, after the late 1970s. The EP warming induces a significant PJ-like pattern during July, while the IO warming is somewhat responsible for the upper level EU-like wave pattern during August. The difference in the responses to the EP and IO warming between

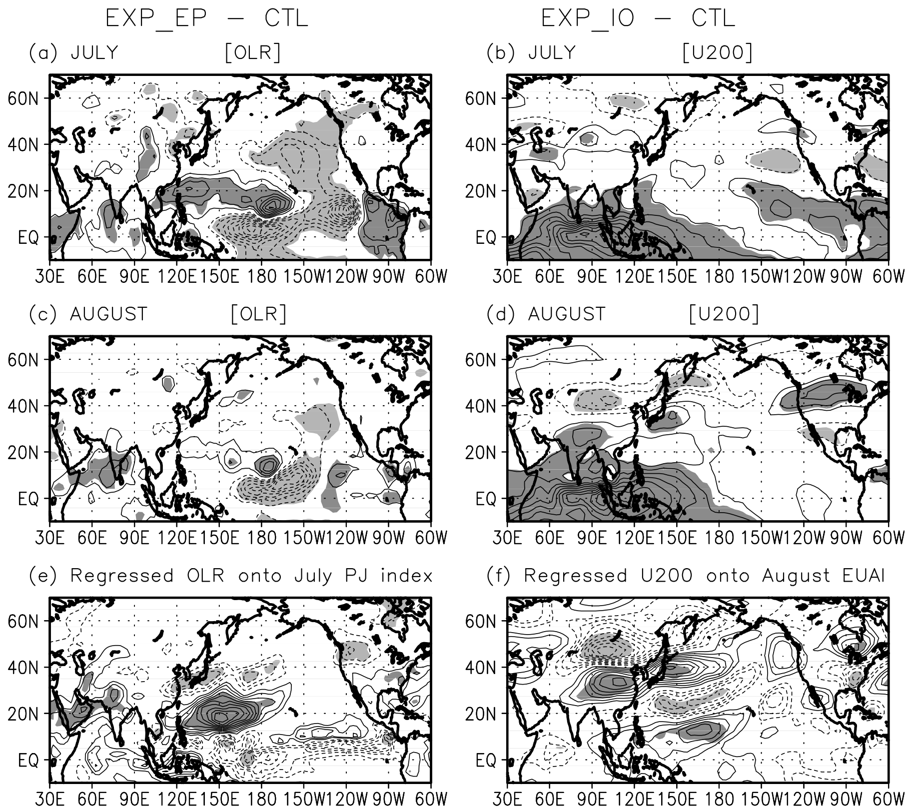

Figure 4. The difference in OLR and 200hPa zonal wind anomaly between (a) CTL_JUL and EXP_EP_JUL, (b) CTL_JUL and EXP_IO_JUL, (c) CTL_AUG and EXP_EP_AUG, and (d) CTL_AUG and EXP_IO_AUG. The regression of the simultaneous (e) OLR anomaly against the July PJ index and (f) 200hPa zonal wind anomaly against the August EUAI. Heavy (light) shading indicates the positive (negative) value significant at the 95% confidence level. The contour interval is 2.0 Wm^{-2} in Figures 4a, 4c, and 4e and 0.5 ms^{-1} in Figures 4b, 4d, and 4f and the zero line is omitted.

July and August may be mainly due to the differences in the mean thermal states: (1) a warmer ocean and cooler continent in August compared to July and (2) a warmer lower level tropics and cooler extratropics in July compared to August. To verify these hypotheses, we conducted perpetual model experiments on the observed tropical EP and IO warming in July and August, respectively. The experimental results support the aforementioned distinct impacts on East Asian circulation.

[12] These distinct sub-seasonal responses to the EP and IO warming supports the results of *Ha et al.* [2009], according to which the monsoon rainfall in July is strongly influenced by the PJ-like pattern, whereas the August rainfall is strongly related to the EU-like pattern. These differences may contribute to the predominance of the PJ-like (tropics-related) pattern during July and the EU-like (extratropics-related) pattern during August and hence to the sub-seasonally different interdecadal change of East Asian rainfall. However, it is difficult to confirm the detailed dynamical process on the sub-seasonal preferences, which will be investigated in a future study. In addition, the impacts of the EP and IO SST anomalies may be different with the developing/decaying El Niño or La Niña phases, which should be discussed in detail in a future study. Understanding the sub-seasonally different impacts of the EP and IO warming is expected to help in a more accurate prediction of the East Asian monsoon.

[13] **Acknowledgments.** This work was supported by the Ministry of Environment as "The Eco-technopia 21 project."

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