Effect of high-resolution SST on East Asian summer monsoon and tropical cyclone activity in a 60-km AGCM

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Abstract:
This study uses an atmospheric general circulation model (AGCM), with a resolution of 60 km, to investigate the effect of high-horizontal-resolution SST data on simulations of elements of the East Asian summer monsoon (EASM), including the northwestern Pacific subtropical high (NWPSH) and tropical cyclone (TC) genesis. Plotting the result of the fine-resolution (60 km) minus coarse-resolution (300 km) SST AGCM runs shows a low-level anticyclonic anomaly (with suppressed convective activity) over the northwestern Pacific (NWP) following the onset of the NWP monsoon (July–September). In addition, TC frequency and mean TC intensity are controlled by the atmospheric circulation change that is related to the NWPSH. Changes in environmental parameters can partly explain these TC frequency and intensity changes. Based on the similarity between the realistic and idealized SST experiments, the cold SST anomaly around 10–15°N seems to play a key role in the low-level anticyclonic anomaly. Analysis of the ocean circulation and heat budget reveals that advection of cold water from the central Pacific by the westward-flowing North Equatorial Current (NEC) is important for the development of this cold SST anomaly.

KEYWORDS Asian summer monsoon; climate modeling; tropical cyclone

INTRODUCTION

The northwestern Pacific subtropical high (NWPSH) is an important component of climatic variability over East Asia. Its multi-scale variability covers sub-seasonal to inter-decadal timescales and can cause natural disasters as well as affecting water resources. For example, anomalous rainfall in 1998 led to the Yangtze River flood that resulted in 3000 deaths and caused economic losses in China of US$ 24 billion. Previous studies have pointed out that the variability of the NWPSH is a major contributor to flooding and droughts across central China (Chang et al., 2000; He and Zhou, 2015). In addition, forecasting the likely risks and impacts associated with the effect of global warming on the East Asian monsoon remains an important element of recent Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2013).

Since the 1990s, high-resolution observations and numerical simulations have provided new insights into air–sea interactions. For basin-scale studies, western warm boundary currents, such as the Kuroshio Current and the Gulf Stream, play important roles in determining surface wind patterns (Nonaka and Xie, 2003), storm track activity (Nakamura et al., 2004; Hayasaka et al., 2013), and climatological precipitation (Minobe et al., 2010; Sasaki et al., 2012). More recently, Ogata and Kitoh (2014) investigated the effects of sea surface temperature (SST) on snowfall in Japan using a high-resolution 60-km-mesh atmospheric general circulation model (AGCM). The AGCM experiment used high-resolution SST data to simulate snowfall increases over warm-SST regions (along the Tsushima warm current) caused by increased evaporation.

However, the effect of high-resolution SST data on AGCM simulations of the Asian summer monsoon, including the NWPSH, remains to be investigated. The horizontal resolution of recent climate models is generally around 100 km, and this is too coarse to resolve regional topography around East Asia or physical phenomena such as sharp SST fronts and narrow currents. Furthermore, high-resolution AGCMs can capture more realistic tropical cyclone (TC) intensity and distribution patterns (Murakami et al., 2012b) than can models with coarser resolution. On the other hand, AGCMs do not depend on the lateral boundary condition, which is essential to regional downscaling. To resolve the fine-scale SST effect, AGCMs require a high resolution, which is difficult to achieve because of the high computational cost. However, the development of high-performance computing has facilitated the use of such high-resolution AGCMs that can resolve the fine-scale SST effect, although the use of high-resolution CGCMs that incorporate an eddy-resolving OGCM (ca. 10 km resolution) remains challenging. As a first step, in this study we compare the response of the TL319 (60-km-resolution) AGCM to fine- and coarse-resolution SST data. In addition, we consider the importance of the cold SST band over the northwestern Pacific (NWP) and its formation mechanism.

DATA AND MODELS

We used the MRI-AGCM3.2H AGCM (Mizuta et al., 2012), which has a horizontal resolution of 60 km and 64 vertical levels (TL319L64), and employed the high-resolution (ca. 20 km) AMSR-AVHRR-OISST product for the SST boundary condition. In MRI-AGCM3.2, an especially deep convective scheme was changed from a relaxed Arakawa–Schubert scheme to a Tiedtke-like scheme, which is an...
RESULTS

Figure 1a shows the SST anomalies for the fine-SST minus smooth-SST runs during July-September. The seasonal evolution of z850 (850 hPa geopotential height) and rainfall at 135°E (Supplement Figure S2) show a significant anticyclonic z850 anomaly and a decrease in rainfall during the June–September period as a component of the NWP summer monsoon. Figure 1b shows the 850-hPa horizontal wind and rainfall anomalies for the fine-SST minus smooth-SST runs. During July–September (Figure 1b), a significant decrease in rainfall appears in the tropical Pacific (around 10–20°N) and a strong anticyclonic anomaly (NWPSH) appears as a response to this decrease. It should be noted that a weak but significant increase in rainfall over the warm SST band along the Kuroshio also appears southwest of Japan (around 25°N, 130°E), which is probably a local SST response (Sasaki et al., 2012).

The mean circulation anomaly over the northwestern Pacific also affects TC frequency (TCF). Figure 2 shows TC frequency and mean intensity differences between the fine- and smooth-SST runs. Figure 2a shows the difference in the frequency distributions of intense TCs (maximum wind speed > 45 m s⁻¹), between the fine- and smooth-SST runs. Unlike a 20-km-resolution AGCM (Murakami et al., 2012b), the 60-km-resolution AGCM is too coarse to capture realistic C4–C5 extreme TC frequencies (C4 is maximum wind speed > 59 m s⁻¹, C5 is maximum wind speed > 70 m s⁻¹). Therefore, we used the lower criteria for this study. Although the 60-km-resolution AGCM shows a quantitative bias in TC intensity distribution, caused by its coarser resolution, the 20-km and 60-km AGCMs both generated a northward bias in the TC intensity peak (Murakami et al., 2012a). The spatial distribution of intense TCF change (Figure 2a) shows a significant decrease over the NWP (west of 150°E), but a slight TCF increase to the east of 150°E. For all TCs considered (Figure 2b), the spatial distribution of TCF change is generally similar to the intense TC case. Both intense and all TCFs decrease (Figure 2a and 2b) over the northwestern Pacific despite the warm SST anomaly around 20–40°N which is favorable for TC genesis. This implies that atmospheric circulation (e.g., the NWPSH) is more important than SST change for TC genesis. As an additional measure of TC behavior, the mean TC intensity change is shown in Figure 2c. In the South China Sea (SCS), East China Sea (ECS), and south of Japan (west of 140°E), the mean TC intensity weakens in the fine-SST run. On the other hand, to the east of 140°E the mean TC intensity increases in the fine-SST run to the north of 20°N. Around Japan, mean TC intensity becomes stronger (weaker) in the eastern and northern (southwestern) regions. Compared with TCF (Figure 2a and 2b), TC intensity (Figure 2c) is more closely related to the local SST pattern (Figure 1a) although low-level vorticity also seems important (Figure 3b).

Previous studies have reported that TC distribution is controlled by the mean atmospheric condition (Emanuel and Nolan, 2004). For example, Gray (1975) proposed that weak vertical wind shear, cyclonic vorticity in the lower troposphere, and high relative humidity in the mid troposphere are important for TC genesis. For TC intensity, Emanuel (1995) defined maximum potential intensity (MPI) using SST and

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convective available potential energy (CAPE). Furthermore, Emanuel and Nolan (2004) proposed genesis potential index (GPI) for TC genesis using four parameters (relative humidity at 700 hPa, relative vorticity at 850 hPa, MPI, and vertical wind shear). To investigate the differences in simulated TC frequency (Figure 2b), Figure 3 shows environment change (relative humidity at 700 hPa, relative vorticity at 850 hPa, and vertical wind shear) between the fine- and smooth-SST runs. Over the northwestern Pacific (Figure 3a and 3b) a dry (wet) tendency of relative humidity and an anticyclonic (cyclonic) vorticity anomaly appear from the SCS to the south of Japan (from the Yellow Sea and Japan Sea to the central Pacific around 20–40°N, 150–180°E), which favors a decrease (increase) in TC development. Vertical wind shear increases (decreases) over the SCS (25–35°N) (Figure 3c), and this favors a decrease (increase) in TC development. Over the northwestern Pacific, the TCF decrease seen in Figure 2a and 2b seems to be caused mainly by the anticyclonic vorticity associated with the NWPSH and dry environmental air at 700 hPa over the TC genesis region around 10–25°N. On the other hand, the change in mean TC intensity (Figure 2c) seems to result from the relat-
tive humidity change and relative vorticity change, not only over the TC genesis region, but also the central Pacific (north of 20°N). The similarity in the spatial seesaw pattern between mean TC intensity, relative humidity, and relative vorticity changes suggests that the local environmental change (caused partly by the local SST pattern seen in Figure 1a) determines the mean TC intensity.

These results demonstrate that the NWPSH generated by the rainfall decrease around 10–20°N is a dominant response and that such mean climate change also affects TC activity. In Figure 1, the weak and cold SST band around 10°N seems to contribute to the NWPSH, but what causes this cold SST anomaly over the NWP? We used a heat budget analysis of the upper ocean to investigate the importance of ocean dynamics in this regard. Figure 4a shows SST and mean sea surface height (SSH) as a measure of stream function, as derived from an assimilated ocean dataset of ORA-S3 (Balmaseda et al., 2008). At around 10°N the westward current known as the North Equatorial Current (NEC) (Tomczak and Godfrey, 1994) advects cold surface water from the eastern Pacific. North of 20°N, the eastward Subtropical Counter Current (STCC) (Oka and Qiu, 2012) advects warm surface water from the western Pacific. These features indicate that ocean dynamics cause the cold SST anomaly around 10–20°N (and the warm SST anomaly around 20°N).

Figure 4b shows horizontal temperature advection derived from ORA-S3. Cold temperature advection around 10–15°N is consistent with the cold SST band (Figure 4b; also seen in Figure 1a and 4c). The cold advection is stronger to the east of 150°E. To the west of 150°E, temperature advection is weaker because of the weak horizontal SST gradient over the warm pool. Nevertheless, temperature advection seems to enhance the cold SST anomaly in this region. Surface heat flux also tends to cool the ocean to the west of 150°E, but the spatial pattern is much broader compared with the advection term and SST anomaly (data not shown). The results presented in Figure 4 support our proposal that ocean dynamics caused by horizontal advection play an important role in cold SST formation around 10–20°N. For comparison, we conducted an OGCM experiment using the Modular Ocean Model version 3 (MOM3) (Pacanowski and Griffies, 1999). The model covers a near-global domain (65°S to 65°N) and has zonal and meridional resolutions of 2.5° and 0.5°, respectively, and 25 vertical levels (10 m intervals in the upper 100 m). This model has been used in previous studies and is capable of realistic simulations in the tropics (Ogata et al., 2013). The OGCM was spun up for 28 years under the monthly NCEP/NCAR reanalysis (Kalnay et al., 1996) surface climatology. Similar to Figure 4, the OGCM-simulated SST and SSH show a westward NEC and cold SST band around 10°N caused by cold advection (Supplement Figure S3), although the OGCM simulation overestimates the cold SST band along the NEC compared with ORA-S3. These results in Figure 4 and Figure S3 indicate that fine-SST run with high-resolution SST product can resolve the narrow SST band while smooth-SST run with coarse-resolution SST product cannot resolve this, and such SST difference gives a significant impact on the NWPSH and TC activity. Resolution sensitivity of the heat budget in ORA-S3 also exhibits the fact that the cold advection in 60-km resolution (–0.33°C month–1 in fine-SST case at 12°N, 160°E) is larger than in 200-km resolution (–0.17°C month–1 in smooth-SST case)

### SUMMARY AND DISCUSSION

This study investigated the effect of high-resolution SST data on the simulation of elements of the EASM, such as the NWPSH and TC genesis, using a 60-km-resolution AGCM. Subtracting the results of the coarse-resolution-SST run from those obtained by running the AGCM with the fine-resolution SST data showed the development of an anticyclonic anomaly with suppressed convective activity over the NWP after onset of the NWP monsoon (July–September). In addition, TC frequency and mean TC intensity were found to be lower under the NWPSH condition.
be controlled by atmospheric circulation changes caused by the NWPSH. Changes to environmental parameters can partly explain these changes in TC frequency and intensity. Analysis of the ocean circulation and heat budget indicated that cold advection from the central Pacific by the westward NEC is important for the development of the cold SST anomaly around 10°N.

Figures 1 and 4 indicate that the cold SST anomaly around 10°N is important for the formation of the NWPSH in the fine-SST run. To confirm this result, we completed a sensitivity experiment with an idealized SST anomaly (Figure 5a) using a similar 60-km-resolution AGCM (“cNWP run”). The AGCM (cNWP-smth) generated an anticyclonic anomaly of the NWPSH over the northwestern Pacific together with a significant decrease in rainfall around 10–20°N (Figure 5b). A significant increase in rainfall also appeared over central China (around the Yangtze River) as a remote response. Two additional experiments, “fine-TP run” (fine-SST over the tropical Pacific from 20°S to 20°N, and smooth-SST elsewhere) and “fine-NP run” (fine-SST over the north Pacific north of 20°N, and smooth-SST elsewhere), were also performed (Supplement Figure S4a and S4b). The anticyclonic z850 response was significant in the fine-TP run, but was not reproduced in the fine-NP run (Supplement Figure S4c and S4d).

Previous studies have focused mainly on the interannual variability of the NWPSH (Wang et al., 2000; Xie et al., 2009). Our study is similar in the sense that we have investigated the atmospheric response to an imposed SST anomaly. However, we focused on the spatial deviation of the seasonal climatology rather than interannual variability. With respect to the formation mechanism of the SST anomaly (Figure 4), we emphasized the importance of narrow oceanic currents (the NEC and STCC). Comparison of both runs (fine-SST and smooth-SST) and observations (CMAP and GPCP climatology) also suggests that the improvement of SST biases at higher resolution reduces the bias in rainfall amount (excessive rainfall in smooth-SST run) after the monsoon onset around 5–20°N (Supplement Figure S5). This indicates that fine-resolution ocean models are required to generate accurate seasonal and multi-scale interactions, not only for the mid-latitudes (Minobe et al., 2010; Hayasaka et al., 2013) but also for the tropics. Regarding an improved understanding of the EASM, recent studies based on regional coupled models (Zou and Zhou, 2013; Zou et al., 2016) have suggested the importance of atmosphere–ocean coupling. In addition, other studies have found that more realistic extreme TC distributions will require simulations based on 20-km-resolution (or finer) AGCMs (Murakami et al., 2012b).

Ogata et al. (2015) emphasized the importance of realistic atmosphere–ocean coupling in order to simulate the distribution of intense TCs accurately. As a next step, 20-km-resolution AGCM and/or AOGCM experiments will be required to obtain more accurate estimations of atmosphere–ocean coupling under more realistic TC-intensity conditions.

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SUPPLEMENTS

Figure S1. Effectiveness of spatial smoothing between fine- and smooth-SST (filter response functions in Figure S1a and smoothing of SST front in Figure S1b)

Figure S2. Seasonal variations of atmospheric responses (rainfall and z850) as the difference between fine- and smooth-SST runs

Figure S3. Contribution of horizontal heat advection on SST in the OGCM experiment

Figure S4. AGCM responses to tropics (20°S–20°N) and extra-tropics (north of 20°N) origin SST patterns

Figure S5. Comparison between observed (CMAP and GPCP) and AGCM simulated rainfall (fine-SST and smooth-SST runs)