Influence of the Temporal Resolution of Sea Surface Temperature on Winter Precipitation over the Coastal Area of the Sea of Japan

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Abstract

High-frequency variations are excluded in the merged satellite and in-situ data global daily sea surface temperature (MGDSST) used in weather forecasting in Japan Meteorological Agency. We investigated the importance of temporal resolution on sea surface temperature (SST) when predicting winter precipitation using the Non-Hydrostatic Regional Climate Model. We used seven-day temporal smoothing to investigate the influence of temporal resolution on precipitation. The Gaussian filter was used as spatial smoothing for comparison with the influence of spatial resolution. The influence of the temporal resolution of SST on monthly precipitation is smaller than that of spatial resolution. However, the influence of the temporal resolution on daily precipitation is comparable to that of spatial resolution. The temporal resolution of SST greatly affects precipitation, particularly in December, as the variations in SST are largest compared to the rest of the year. Furthermore, the winter monsoon promotes the effect of SST on winter precipitation. Our experiments using seven-day moving average smoothing indicates that the temporal resolution of the SST on precipitation become about 15% K under the winter monsoon.

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1. Introduction

Several studies have investigated the influence of sea surface temperature (SST) range from local-scale to large-scale precipitation. Richter et al. (2012) found that the interannual fluctuations of SST in the eastern part of the equatorial Atlantic Ocean change surface wind and precipitation in the tropical Atlantic, and thereby affect the climate of surrounding continents. Moteki and Manda (2013) found that the seasonal SST warming affects the northward migration of the Baiu Frontal Zone over the East China Sea. There is great interest in the influence of the spatial resolution of SST on the atmosphere. Iizuka et al. (2013) found that high-resolution SST affects the activity of cyclones. Masunaga et al. (2018) revealed that the influence of frontal-scale SST distributions can reach the middle and upper troposphere.

The coastal area of the Sea of Japan experiences the heaviest snowfall worldwide. The winter monsoon characterizes the winter climate along the Sea of Japan coastline (Manabe 1957; Chen et al. 2001; Iizuka et al. 2010). During the winter monsoon, a dry cold air mass from the continent passes over the relatively warm ocean, bringing heat and water vapor, undergoing an air mass transformation. The transformed air mass brings rainfall and snowfall to the coast. Yamamoto et al. (2008) showed that the SST of the Sea of Japan greatly influences atmospheric circulation and precipitation over the sea. Takahashi et al. (2013a) found that precipitation increases by approximately 10% when the SST of the Sea of Japan increases by 1 K. Iizuka et al. (2010) found that the spatial resolution of the SST of the Sea of Japan influences winter precipitation in Japan. Many other studies have been conducted on the influence of SST in the Sea of Japan (such as Sato and Sugimoto 2013; Fujita et al. 2014; Yasunaga and Tomochika 2017).

The merged satellite and in-situ data global daily SST (MGDSST, Kurihara et al. 2006) used for weather forecasting in Japan was created using a merged field of SST of MGDSST is well reproduced, although the MGDSST exclude high-frequency variations by use of the low-pass filter (Iwasaki et al. 2008). Since SST anomalies not only are affected by atmospheric circulations but also has a weak influence on atmospheric circulations (Frankignoul 1985), eliminating high-frequency variations may affect various atmospheric phenomena. The discussions of spatial resolution of SST have already done by previous studies (e.g., Iizuka et al. 2013; Masunaga et al. 2018).

On the other hand, as for the influence of temporal resolution of SST, there is research such as Woolling et al. (2010), but discussion is not enough. In this study, we investigate the influence of the temporal resolution of SST on winter precipitation in the coastal areas of the Sea of Japan, where the SST greatly influences precipitation. We also compare the impact of temporal resolution on winter precipitation with that of spatial resolution.

2. Data and study method

The non-hydrostatic regional climate model (NHRCM, Sasaki et al. 2008) was used to investigate the effect of the temporal resolution of SST on winter precipitation. The horizontal resolution is 5-km, and the number of vertical layers is 60. The initial and lateral boundary conditions were obtained from the 20-km NHRCM downscaled simulations from the Japanese 55-year reanalysis (JRA-55, Kobayashi et al. 2015). The prescribed SST fields were taken from the four-dimensional variational ocean re-analysis for the Western North Pacific over 30 years (FORA-WNP30, Usui et al. 2017). The horizontal resolution of FORA-WNP30 is 0.1° × 0.1°, which is higher than that of MGDSST (0.25° × 0.25°). And, MGDSST cannot resolve the high-frequency variability, because it is based on the satellite observation. On the other hand, as FORA-WNP30 is based on model simulation, it can resolve high-frequency variability less than 10 days. Spectral density of both SST is shown in Fig. S1. The period of simulation was 10 years from the winter of 2005/2006 to that of 2014/2015. The starting date for each year’s numerical integration was 11 November and the ending date was 10 March of the following year.

To investigate the influence of the temporal and spatial resolution of SST, seven-day moving average smoothing was used for temporal smoothing and a Gaussian filter with a 100-km scale was used for spatial smoothing. Hereafter, TSM, SSM, and CTL represent the simulations using temporal smoothing, spatial smoothing, and that without any smoothing, respectively. The difference in SST between SSM and CTL in December is particularly clear around the Kuroshio Current (Fig. 1b). The flows in the center of the warm currents decrease in temperature due to spatial smoothing, and the temperature increases in the periphery of the warm currents. The difference in the monthly SST between TSM and CTL is quite small as the effect of the temporal moving average is diminished by the long-term average (Fig. 1c). Meanwhile, the difference in the daily SST between TSM and CTL is much larger than the monthly average, and shows the daily fluctuations of ocean currents and vortices. (Fig. 1f).
3. Results and discussion

3.1 Influence of the temporal resolution of SST on monthly and daily precipitation

The difference in the 10-year mean precipitation between CTL and TSM is very small in December, and is less than 10 mm at many points (Fig. 2c). SSM has a larger influence on monthly precipitation than TSM, and the monthly precipitation in SSM is larger in the northern side of Kuroshio Current and smaller in the southern side than that in CTL, in response to the differences in the SST. The difference in the 10-year monthly mean SST (Figs. 1b and 1c) is reflected in the monthly precipitation, though, the difference in precipitation (Figs. 2b and 2c) exhibits little signifi-
The differences in precipitation on 1 December 2005 of SSM and TSM from CTL are shown in Fig. 2. The magnitude of the difference for the former is comparable to that for the latter. This suggests that temporal smoothing of SST can affect the daily precipitation in the simulation.

The coastal areas of the Sea of Japan receive a large amount of snowfall during winter and the SST influences precipitation in these areas. To investigate differences in the SST over the Sea of Japan, the days during which the difference in the regional mean SST in the red frame presented in Fig. 1 exceeds 0.1 K are counted. The influence of the temporal smoothing of the SST appears clearly because of the warm Tsushima Current flowing over this area (e.g. Fig. 1f). Hereafter, the SST averaged within the red frame of each experiment is presented as SST<sub>CTL</sub>, SST<sub>TSM</sub>, and SST<sub>SSM</sub>. There was no case where SST<sub>SSM</sub> was larger than SST<sub>CTL</sub> by 0.1 K or more. As the warm Tsushima Current flows through the target area, the regional mean SST is decreased by spatial smoothing. Lower SST decreases precipitation of SSM in the target area (Fig. S2). Although the influence of spatial resolution of SST has been discussed widely, the influence of the temporal resolution of SST has not enough. Therefore, the effect of the SST in this area on daily precipitation was only investigated for TSM.

Table 1 shows the number of days when the difference in SST between TSM and CTL was larger than 0.1 K. Hereafter, DY<sub>LOW01</sub> and DY<sub>HIGH01</sub> represent the days when SST<sub>TSM</sub> is 0.1 K lower and higher than SST<sub>CTL</sub>, respectively. The values of DY<sub>LOW01</sub> and DY<sub>HIGH01</sub> are largest in December. In general, the seasonal march of the SST in the Sea of Japan is largest in December. The standard deviation of SST in the Sea of Japan is larger in December than that in January and February (Figs. 3a, 3b, and 3c). In addition, the latent and sensible heat fluxes over the Sea of Japan are also larger in December (Figs. 3d, 3e, 3f, 3g, 3h, and 3i). The large latent and sensible heat fluxes indicate a large amount of water vapor and heat supplied from the sea to the atmosphere and enhance the influence of SST on precipitation in December.

In all months from December to February, the value of DY<sub>HIGH01</sub> is larger than that of DY<sub>LOW01</sub>. During the winter monsoon, SST<sub>TSM</sub> exceeds SST<sub>CTL</sub>; the latter decreases rapidly whereas the former delays the decrease due to temporal smoothing (Fig. S3). When the cold air outbreak prevails, the temperature difference between atmosphere and sea surface becomes large. This difference drops the SST sharply due to cold and strong northwesterly i.e., the atmospheric forcing. On the other hand, when the cold air outbreak becomes weak, the SST moderately decreases.
3.2 Influence of the temporal resolution of SST on precipitation during the winter monsoon

To investigate the effects of the temporal resolution of SST on daily precipitation in December, DY_LOW and DY_HIGH were composited, which are similar to DY_LOW01 and DY_HIGH01, but are without the 0.1 K threshold. Figures 4a, 4b, 4c, and 4d shows the differences in the composited latent heat flux and precipitation between TSM and CTL in December. The differences in latent heat flux correspond to the differences in SST, i.e., latent heat flux increases when the SST of the Sea of Japan is warmer than that in CTL, and vice versa. The difference of the latent heat flux causes precipitation difference between TSM and CTL. The rate of the difference in precipitation when SSTTSM is higher than SSTCTL is +0.9%, and −1% when SSTTSM is lower than SSTCTL. They are statistically significant differences at the 95% level, according to a Student's t-test. However, the difference in each grid point does not show a statistical significance.

The strong winter monsoon modulates both SST and lower tropospheric humidity over the Sea of Japan, which can affect the precipitation along the coastal areas of the Sea of Japan. The temporal resolution of the SST during the winter monsoon may have a remarkable influence on precipitation in the coastal area of the Sea of Japan. Takahashi et al. (2013b) defined an index of the winter monsoon’s occurrence as the day when the atmospheric pressure difference between Akita and Nagasaki exceeds 5 hPa. This study defines the winter monsoon index as the day when the atmospheric pressure of the Sea of Japan grid point (131°E, 37°N) is higher than the Pacific grid point (142°E, 37°N) by 5 hPa since we can use the atmospheric pressure data at the grid point at the same latitude on the sea.

The precipitation of TSM during the winter monsoon is higher than that of CTL in DY_HIGH, and vice versa in DY_LOW. The precipitation difference is observed over the land as well as the sea (Figs. 4e and 4f). The precipitation difference in Figs. 4e and 4f is clearer than that in Figs. 4c and 4d. The rate of the difference in precipitation is +0.9% in DY_HIGH and −1.4% in DY_LOW, which are statistically significant changes at the 95% level according to a Student’s t-test. However, on the days other than the winter monsoon, there are many places where the difference in precipitation does not correspond to the difference in SST (Figs. 4g and 4h); the rate of the difference in precipitation is +1.0% in DY_HIGH and −0.4% in DY_LOW. These differences are not statistically significant at the 95% level.

Figure 5 shows the relationship between SST and daily precipitation in the red-framed area in Fig. 1. There is almost no relationship between the SST and daily precipitation on all days (both black and red circles in Fig. 5, sample number is 310), and the correlation coefficient is 0.18. The red circle in Fig. 5 shows the relationship between the SST and precipitation on the day when the winter monsoon occurs. The precipitation changes by 15%/K during the winter monsoon in December, and the correlation coefficient is 0.57 (red circle in Fig. 5, sample number is 142). However, when there is no winter monsoon (black circles in Fig. 5, sample number is 168), the correlation coefficient between the SST and precipitation is 0.15. The days that are not influenced by SST, such as when there is a southern wind or the weather is calm, may reduce the correlation coefficient. The rate of change in precipitation is roughly the same as the increase in latent heat flux is 13%/K. Using the winter monsoon index of Takahashi et al. (2013b), the rate of change in precipitation is 13%/K. This value is similar to the results in this work. The rates of change in precipitation 15%/K and 13%/K are larger than 10%/K in Takahashi et al. (2013a), because in this study it was calculated only on winter monsoon day. The temporal resolution of SST can strongly affect precipitation in the coastal area of the Sea of Japan during the winter monsoon.

Figure 6 shows the time series of SST_CTL and SST_TSM, the difference of those SSTs, and the rate of precipitation difference in December 2012 as one of strong winter monsoon years. The precipitation difference (green bars) corresponds to the differences in SST (blue bars) on winter monsoon days (gray shaded areas). In other words, the precipitation increases when SST_TSM is higher.
term averaging process. However, the influence of the temporal resolution of SST on daily precipitation is not negligible in the coastal area of the Sea of Japan in winter, especially in December. In December, the number of SST differences is largest throughout the year due to the seasonal march and large effect of temporal resolution. In addition, the large latent heat flux indicates that the sea supplies a large amount of water vapor to the atmosphere. This water vapor supply modifies the East Asian winter monsoon through the near surface wind speed. As a result, the SST has a great influence on precipitation in the coastal area of the Sea of Japan in the winter monsoon period. It is possible that the temporal resolution of SST affects the winter precipitation in the same way even outside the target area of this study. Since our quantitative results may be influenced by the terms of moving average smoothing, we need to investigate the sensitivity of various temporal resolutions of SST to the atmosphere as a future task.

The SST is an important boundary condition for numerical simulations. Daily weather forecasting by Japan Meteorological Agency uses MGDSST, in which the low-pass filter removes high-frequency variations. Since SST anomalies not only are affected by atmospheric circulations but also has a weak influence on atmospheric circulations, removal of high-frequency variations of SST affects various atmospheric phenomena. This study found that the temporal resolution of SST in the Sea of Japan influences the daily precipitation in winter. In order to further improve the accuracy of numerical simulations, it is necessary to use a high-resolution air-sea coupled model.

4. Conclusion and recommendations

We investigated the influence of the temporal resolution of SST on precipitation. The temporal resolution of the SST had almost no influence on the monthly precipitation due to the long-term averaging process. However, the influence of the temporal resolution of SST on daily precipitation is not negligible in the coastal area of the Sea of Japan in winter, especially in December.

Figure 5. Scatter diagram of the differences in SST and precipitation in December (Black circle: all cases, Red circle: winter monsoon pattern cases, green line: approximate straight line of the red circles).

Fig. 6. Time series of SST CTL (black line), SST TSM (red line), the difference between SST CTL and SST TSM (blue bars), and the rate of the difference in precipitation between CTL and TSM (green bars). The grey shaded areas represent the days when the winter monsoon occurs.

than SST CTL and decreases when SST TSM is lower. Because the high-frequency variation in the FORA-SST is primarily influenced by the atmospheric forcing, i.e. JRA-55, the cold atmospheric influx during the winter monsoon causes a rapid decline in SST. The rapid decline in SST brings about the difference between SST CTL and SST TSM. Therefore, SST CTL decreases sharply due to the cold air outbreaks around the winter monsoon, e.g. 4–12 December 2012.

SST TSM (red line) changes more smoothly than SST CTL due to the temporal smoothing. When the winter monsoon continues, the difference in SST increases and the effect of the temporal resolution of SST increases. In contrast, on days without the winter monsoon, the change in the difference in SST is more moderate than that on days during the winter monsoon. The differences in SST and precipitation do not coincide on some days when the southern wind dominates or the weather is calm.

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Supplement

Figure S1 shows a diagram of spectral density of the SST of FORA-WNP30 and MGDSST.

Figure S2 shows differences in the composited SST (SST SSM–SST CTL) and the differences in the composited precipitation (SSM/CTL) in the case of SST SSM < SST CTL.

Figure S3 shows the difference in the SST variation between TSM and CTL after the winter monsoon.

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