The fraction of East Asian interannual climate variability explained by SST in different seasons: an estimation based on 12 CMIP5 models

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Abstract

Using the output of 12 models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), this study assessed to what extent is the interannual climate variability over East Asia explained by sea surface temperature (SST). By comparing the atmospheric component model simulations forced by observed interannual varying SST and fixed annual cycle of SST, the fraction of interannual variability explained by SST is estimated. Although SST explains a major fraction of interannual variability of both seasonal mean surface air temperature (SAT) and precipitation over tropical western Pacific, it only explains about 0–30% of the interannual variance over East Asian land. The SST explains a greater fraction of interannual SAT variance in summer, since the SAT variance induced by non-SST factors is relatively small possibly due to the weaker impact by mid-latitude eddy activities. During winter and spring, SAT accounts for a larger fraction of interannual precipitation variability over southern China than in summer and autumn, due to the stronger modulation of El Niño-Southern Oscillation-related SST anomalies through the anomalous anticyclone over western north Pacific from winter to spring.

Keywords: interannual variability; precipitation; surface air temperature; sea surface temperature

1. Introduction

The interannual climate variability is often associated with floods, droughts, heat waves, and cold spells over East Asia (Zhou and Yu, 2005; Hu et al., 2011; Lin et al., 2012; He and Wang, 2016). Much efforts were devoted to understanding and predicting the climate variability, and it was believed that the most important source of predictability originates from the interannual variability of sea surface temperature (SST), especially the SST anomalies related to El Niño-Southern Oscillation (ENSO) (Yang et al., 2008; Zuo et al., 2013). Several key oceanic regions were identified to be responsible for the interannual climate variability over East Asia, such as the equatorial Pacific (Wang et al., 2000; Stuecker et al., 2015), tropical Indian Ocean (Xie et al., 2009; Wu et al., 2010a), and subtropical western North Pacific (Wu et al., 2010a; Wang et al., 2013).

Although great efforts were devoted to identifying the key oceanic regions and the mechanisms how they modulate East Asian climate, up to now it is not very clear how much of the interannual climate variability in East Asia is explained by SST. He et al. (2016a) claimed that SST only accounts for about 18% of the interannual variability of East Asian summer rainfall, but the following two questions are still not well addressed so far. (1) What fraction of the interannual variability in East Asia is explained by SST; for surface air temperature (SAT) and precipitations in different seasons? (2) Does the fraction contributed by SST show seasonality and what may cause the seasonality? Answering these two questions not only helps to obtain an in-depth understanding on East Asian climate variability, but also helps seeking the source of predictability and reasonably evaluating the performance of the strategies for climate prediction.

2. Data and method

A variety of numerical experiments were performed by the models participating the Coupled Model Intercomparison Project Phase 5 (CMIP5), which allows us using multi-model outputs to obtain model-independent results (Taylor et al., 2012). In Atmospheric Model Intercomparison Project (AMIP) experiment, the atmospheric component models were forced by the observed interannual varying SST and were integrated for 30 years from 1979 to 2008. In addition to AMIP experiment, many models also performed SSTClim experiment, in which the atmospheric component models were forced by the fixed annual cycle of SST.
and were integrated for 30 years. The 12 models which performed both AMIP and SSTClim experiments were selected for analyses, and the names of these models can be found in Table 1 of He et al. (2016a). Although the SST in SSTClim experiment does not exactly equal to the climatological SST in AMIP experiment, these two experiments were confirmed to be comparable under the assumption of the weak dependence of atmospheric internal noise on SST mean state (He et al., 2016a).

Following He et al. (2016a), the monthly outputs of the models are first averaged into seasonal means, and an 8-year high-pass filter is applied to the 30-year time series. The interannual variance (IAV) is calculated as the variance of the filtered time series, to measure the amplitude of interannual variability. The total IAV for an atmospheric variable is approximated by its IAV in AMIP simulation \( IAV(\text{Total}) = IAV(\text{AMIP}) \), and the IAV induced by non-SST factors is approximated by the IAV in SSTClim simulation \( IAV(\text{non-SST}) = IAV(\text{SSTClim}) \). Under the assumption of independence between SST-forced and non-SST-induced interannual variabilities which was tested to be valid by Koster et al. (2000), the IAV forced by SST \( IAV(\text{SST}) \) is estimated as \( IAV(\text{AMIP}) - IAV(\text{SSTClim}) \), and the fraction of IAV explained by SST \( IAV(\text{SST})/IAV(\text{Total}) \) is estimated as \( 1 - IAV(\text{SSTClim})/IAV(\text{AMIP}) \). The fractions of SST contribution for the 12 models are calculated separately, and the multi-model median of the 12 models is obtained. We use the median instead of mean value since the median is more robust to outliers (Gleckler et al., 2008).

Some observational datasets were also used. We use monthly precipitation data from the Global Precipitation Climatology Project (Adler et al., 2003) and monthly SST data from the Extended Reconstruction SST version 3 (Smith et al., 2008). The 1979–2008 period of these observational datasets were selected to compare with AMIP simulation.

## 3. Results

Figure 1 shows the fraction of interannual SAT variance explained by SST for the four seasons, including December–January–February (DJF, Figure 1(a)), March–April–May (MAM, Figure 1(b)), June–July–August (JJA, Figure 1(c)), and September–October–November (SON, Figure 1(d)). Results for the East Asia-western Pacific region are shown, to compare East Asian continent with the surrounding ocean. In most parts of tropical western Pacific, the fraction of interannual SAT variance explained by SST is >80% throughout the year, comparable with the fraction of potentially predictable variance estimated by previous studies (Feng et al., 2011; Feng and Houser, 2014). In mid-latitude western Pacific, this value is as high as in tropical western Pacific in summer but lower in winter. The difference in IAV between AMIP and SSTClim simulations is significant at the 95% confidence level.
Figure 2. Same as Figure 1 but for seasonal mean precipitation.

Figure 3. The latitude-season profile (a, c) and longitude-season profile of the fractions of SST contribution to interannual SAT (a, b) and precipitation (c, d) variability. The zonal averages within 105°–120°E are shown in (a, c). The meridional average within 22°–40°N is shown in (b) and the meridional average within 22°–33°N is shown in (d). The x-axis is the latitude/longitude and the y-axis is the season in terms of 3-month average. The stippled region indicates the difference in the IAV between AMIP and SSTClim runs is statistically significant at the 95% confidence level according to $F$-test.

The fraction of SAT variance explained by SST is <30% in most parts of East Asian continent. Over eastern China, the percentage is the highest in summer (Figure 1(c)), followed by autumn (Figure 1(d)), and the lowest in winter and spring (Figures 1(a) and (b)). Figure 2 shows the fraction of interannual precipitation variance explained by SST. Over most parts of East
Asian continent and mid-latitude western Pacific, the fraction of interannual precipitation variance explained by SST is <30% throughout the year, much smaller than in tropical western Pacific where it generally exceeds 50%. The difference in IAV between AMIP and SST-Clim experiments is insignificant at the 95% confidence level based on F-test. The low and insignificant contribution of SST to East Asia precipitation is consistent with previous studies (Ferguson et al., 2010; Feng et al., 2011). The spatial patterns are similar between DJF and MAM (Figures 2(a) and (b)), while the spatial patterns for JJA and SON are similar (Figures 2(c) and (d)). Compared with boreal summer and autumn, the fraction of SST contribution is substantially higher in winter and spring over 10°–20°N from South China Sea to western Pacific, collocating with the anomalous western North Pacific anticyclone (WNPAC) mentioned by many studies (Wang et al., 2000; Stuecker et al., 2015; Zhang et al., 2016). Over southern China, the percentage of precipitation variance explained by SST is also higher in winter and spring than in summer and autumn.

Figure 3(a) shows the 105°–120°E averaged latitude-season profile on the fraction of SST-explained interannual SAT variance, to demonstrate the seasonal cycle clearly. The fraction of SST contribution exceeds 80% throughout the year over the oceanic regions south of 15°N, but is approximately zero north of 45°N. Over eastern China from about 22° to 40°N, the fraction of SST contribution is about 30–40% in summer and early autumn, but approximately 10% in winter (Figure 3(a)). The SST anomalies in tropical Indian Ocean was claimed to have a profound influence on the summertime SAT in eastern China (Wu et al., 2010b; Hu et al., 2011). To examine whether the seasonal cycle in Figure 3(a) is a distinct feature in eastern China, Figure 3(b) shows the longitude-season profile of the 22°–40°N averages. Similar seasonal cycle is seen around the subtropical Northern Hemisphere, with a higher fraction of SST-forced variance in summer compared to winter.

For precipitation (Figure 3(c)), the fraction of contribution by SST generally ranges from 0 to 30% over East Asian continent north of 22°N throughout the year. In southern China, the percentage of interannual precipitation variance explained by SST reaches about 20–30% from winter to spring, higher than in summer and autumn (<20%). Similar seasonal cycle with a peak in winter–spring is also found in South China Sea at about 5°–20°N, but is absent to the north of 35°N. As seen from the longitude-season profile for 22°–33°N (Figure 3(d)), the winter–spring peak in southern China is also evident in the western Pacific but not clear over other subtropical regions.

Since the fraction of SST contribution is regulated by both IAV(SST) and IAV(non-SST), we display the seasonal cycles of IAV(SST) and IAV(non-SST) in Figure 4. For SAT (Figure 4(a)), the magnitude of IAV(SST) over 22°–40°N, 105°–120°E does not exhibit clear seasonal difference, but the magnitude of IAV(non-SST) shows an annual cycle with a peak in winter. The non-SST factors in winter include atmospheric internal modes such as Arctic Oscillation (He and Wang, 2016) and blocking highs (Luo et al., 2016). The atmospheric noise acts to increase the total SAT variability in winter and reduce the fraction of SST contribution. The stronger (weaker) SAT variability induced by non-SST factors in winter (summer) may be explained by the equatorward (poleward) shifted mid-latitude eddies and Hadley cell boundary (Seager et al., 2003; Tao et al., 2016). For precipitation over southern China (Figure 4(b)), the variances resulted from SST and non-SST factors are both higher in summer than in winter, since the more abundant mean state rainfall in summer gives rise to stronger rainfall variability (He et al., 2016b).

In order to understand the seasonality in the fraction of SST-explained precipitation variance over southern China, a southern China precipitation (SCPr) index is defined as the regional averaged rainfall over 22°–33°N, 105°–120°E, and the correlation patterns of the simultaneous Indo-Pacific SST anomalies with SCPr are shown in Figure 5. Although the forcing by global SST does not significantly enhance the IAV of East Asian rainfall based on F-test (Figure 2),
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Figure 5. The correlation coefficients between the SCPr index (22°–33°N, 105°–120°E averaged precipitation) and the simultaneous SST anomalies, based on the observational data (contours) and the multi-model median in the AMIP experiment of the 12 models (shading). The stippled region indicates that the correlation coefficient in AMIP simulation exceeds the 95% confidence level according to Student’s t-test. For the correlation in observation, only the ±0.36 and ±0.46 contours are shown, corresponding to the 95 and 99% confidence levels for correlation (negative contours in dashed line). The vectors are the simultaneous 850hPa wind anomalies regressed onto the SCPr index in the AMIP experiment.

The SCPr is significantly correlated with the SST anomalies over certain regions in winter and spring at the 95% confidence level based on Student’s t-test, including the equatorial central-eastern Pacific, subtropical western north Pacific, and tropical Indian Ocean (Figures 5(a) and (b)). These SST anomalies are related to ENSO (Wang et al., 2000; Xie et al., 2009). In summer and autumn, the correlation patterns are similar to winter and spring but less significant (Figures 5(c) and (d)). The multi-model median of the AMIP experiment (shading) well agrees with those in observation (contours) in Figure 5.

As seen from the 850hPa wind anomalies regressed onto the SCPr index in AMIP experiment (vectors in Figure 5), the anomalous WNPAC connects southern China rainfall with SST anomalies. The regressed WNPAC anomaly is evident from winter to spring (Figures 5(a) and (b)), possibly forced by the warm SST anomaly over the equatorial central-eastern Pacific (Wang et al., 2000). At the eastern flank of the WNPAC, negative SST anomaly is seen, suggesting that the WNPAC may be maintained by the local air-sea interaction under the mean state easterly trade wind (Wang et al., 2000, 2013). The warm SST anomaly over the tropical Indian Ocean may be a passive response to ENSO during winter and spring (Xie et al., 2009). Our pattern of regression is consistent with the schematic diagram in Figure 16 of Wang et al. (2000). In summer and autumn, similar patterns of SST and low-level wind anomalies are identified (Figures 5(c) and (d)), but they are much weaker than in winter and spring. Since the anomalous WNPAC has a profound impact on southern China rainfall through the anomalous water vapor transport on its western flank (Zhou and Yu, 2005; Zhang et al., 2016), we hypothesize that the stronger modulation of the ENSO-related SST anomalies on WNPAC in winter and spring is responsible for the stronger relation of southern China rainfall to SST.

The fraction of the SST contribution to WNPAC variability supports the above hypothesis. Defining a WNPAC intensity index as the regional averaged relative vorticity at 850hPa within 5°–25°N, 110°–150°E (the box in Figures 5(a) and (b)), Figure 6 shows the fraction of SST contribution to the interannual variability of the WNPAC. The fraction of SST contribution to WNPAC variability is about 80% in winter and spring but <70% in other seasons. The variability of WNPAC is more strongly controlled by SST variability in winter and spring, consistent with Zhang et al. (2016). The higher fraction of SST-forced variability of WNPAC explains the higher fraction of SST-forced SCPr variability from winter to spring.

Tropical SST anomalies were claimed to be an important source of predictability on Asian monsoon rainfall in summer (Yang et al., 2008; Zuo et al., 2013), but our results show that the SST contribution to East Asian rainfall is lower in summer and autumn than in winter and spring. The spatial pattern in Figure 2 looks noisy, possibly due to the too small number of models and too short period of integration. Our results
may also be limited by the unsatisfactory performance of the models in simulating ENSO-related anomalies (Hu et al., 2014). Although our numbers of percentage may be not precise due to the limited sample size and model bias, our estimated fraction of SST contribution to rainfall and its seasonality is consistent with previous studies. Figure 3 of Feng et al. (2011) showed insignificant potential predictability on precipitation in East Asia and a relatively higher potential predictability in winter. Our result is also consistent with the seasonality of ENSO-forced WNPAC variability (Stuecker et al., 2015). Meanwhile, it should be noted that a substantial part of the rainfall over southern China in summer and autumn are related to tropical cyclones (Li and Zhou, 2015), and the location and intensity of the rainfall related to tropical cyclones are largely stochastic.

4. Summary

Using the output of 12 CMIP5 models, we addressed how much of the interannual variability in SAT and precipitation over East Asia can be explained by SST in different seasons, by comparing the atmospheric model simulations forced by observational interannual varying SST and fixed annual cycle of SST. Although the fraction of SST contribution is generally >80% for SAT and >50% for precipitation over most parts of tropical western Pacific, it is <30% for both SAT and precipitation in most parts of East Asia throughout the year.

The fractions of SST contribution to SAT and precipitation show distinct seasonality. Like most subtropical regions, the fraction of SAT variance explained by SST is higher in summer (30–40%) than in winter (about 10%) over East Asia, since the SAT variability induced by non-SST factors is weaker in summer possibly due to the poleward shift of the mid-latitude eddy activities. Over southern China, the SST accounts for about 30% of the interannual precipitation variance in winter and spring but <20% in summer and autumn. In winter and spring, the anomalous WNPAC is more strongly modulated by ENSO-related SST anomalies, and the WNPAC modulates the rainfall in southern China, giving rise to a relatively stronger connection of southern China rainfall to ENSO-related SST anomalies.

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