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Impacts of SST configuration on monthly prediction of western North Pacific summer monsoon in coupled and uncoupled models

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Abstract

This study examines the impacts of sea surface temperature (SST) configuration on the monthly prediction of summer monsoon over the western North Pacific (WNP) by conducting several sets of hindcast experiments using the Beijing Climate Center Climate System Model and its atmospheric component model. The results show that the atmosphere-only model exhibits limited skill in predicting the WNP monsoon rainfall and circulation, and this skill can hardly be improved by simply increasing the frequency of prescribed SST observation. Compared to the atmosphere-only model, the coupled model shows much better performance in predicting the WNP monsoon rainfall and circulation, which can be further improved by adopting the observed SST with relatively higher frequency in the model initialization. This indicates that the high frequency of observed SST used is much more important in the coupled model than in the uncoupled model. In addition, the uncoupled model forced by the SST predicted by coupled model tends to produce better prediction of WNP monsoon rainfall and circulation than that forced by the observed SST. Both the coupled model and the atmosphere-only model forced by the coupled model predicted SST can well reproduce the surface latent heat flux and shortwave radiation flux over the WNP, leading to a reasonable SST-monsoon relationship and thus skillful predictions of WNP monsoon. Therefore, although the Tier-1 approach based on coupled model is increasingly popular, the Tier-2 approach based on atmosphere-only model is still feasible for the monthly prediction of WNP summer monsoon despite the lack of air-sea interaction. To obtain more skillful Tier-2 prediction, we recommend seeking for SST forcing that is unrealistic but consistent with the atmospheric model rather than SST forcing with very high accuracy.

Keywords SST forcing · Initial condition · Air-sea interaction · Prediction · WNP monsoon

1 Introduction

The western North Pacific (WNP) summer monsoon is an essential subcomponent of the Asian summer monsoon system (Tao and Chen 1987; Li and Wang 2005). It is featured by multi-scale variability and closely related to main modes of tropical air-sea interaction, such as El Niño-Southern Oscillation (ENSO) and Indian Ocean Basin Mode (Xie et al. 2009; Wu et al. 2010; Lu et al. 2015). The convective activity over the WNP can greatly affect the weather and climate over East Asia (Nitta 1987; Huang and Sun 1992; Wang et al. 2000) and North America (Wang et al. 2001; Lau et al. 2004; Jiang and Lau 2008) via teleconnection. Due to its complex variability and strong influence, the prediction of WNP monsoon beyond several weeks has been an important but challenging task.

Dynamic models are the main tools for short-term climate prediction of monsoon. Over the past decades,

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atmosphere-only models have been widely used with prescribed sea surface temperature (SST) forcing, namely the so-called Tier-2 approach. Although with reasonable skill, the Tier-2 predictions are limited by the surface energetic inconsistency due to the lack of air-sea interaction, especially over the WNP (Barsugli and Battisti 1998; Wang et al. 2004, 2005; Kumar et al. 2005). In contrast, the predictions using coupled ocean-atmosphere model (i.e., the Tier-1 approach) can overcome such limitation (Kug et al. 2008; Wang et al. 2009a; Zhu and Shukla 2013), and thus have gained preference by research and operational sectors for subseasonal and seasonal prediction. For example, in the latest Subseasonal to Seasonal Prediction Project, about two-thirds of the participants are coupled models (Vitart et al. 2017).

For both the prediction by atmosphere-only model and that by coupled model, SST configuration is quite important. The temporal frequency, spatial pattern, and amplitude of the SST field used in model initialization could exert a strong impact on the short-term climate prediction (e.g., Klingaman et al. 2008; Wang et al. 2009b; Zhang et al. 2019). Kim et al. (2008) and Boisséson et al. (2012) found that the subseasonal prediction skill can be obviously enhanced in the atmosphere-only model forced by the daily or weekly SST observation compared to that forced by the monthly SST observation. Wang et al. (2015) indicated that the accurate SST forcing prescribed in the atmosphere-only model prediction is important for reproducing the structure, intensity, and propagation of tropical intraseasonal oscillation. Liu et al. (2016) and Bo et al. (2020) noted that, due to the updated SST initial condition, the subseasonal prediction by coupled model is apparently improved. Zhu et al. (2021) explored that the changes of SST initial condition can modulate the moist static energy associated with the intraseasonal oscillation and further affect the subseasonal climate predictability.

Besides the SST configuration, the air-sea interaction is also an important factor that is responsible for the differences between the coupled and uncoupled predictions. Many previous studies stated that the inclusion of ocean–atmosphere coupling is critical to the monsoon simulation and prediction (e.g., Kug et al. 2008; Wu and Kirtman 2007; Jiang et al. 2013b; Shukla and Zhu 2014). Wu and Kirtman (2005) found that the air-sea interaction significantly contributes to the atmospheric variability over most of the Pacific. Wang et al. (2004, 2005) and Wu et al. (2006) indicated the lack of local negative feedback between atmosphere and ocean in climate model could lead to large deficiencies in simulating the monsoon rainfall over the Indo-Pacific. However, some studies reported that the monsoon prediction is weakly influenced by the air-sea interaction, but largely determined by the SST forcing used in the prediction (e.g., Beraki et al. 2015). Kim and Kang (2008) and Fu et al. (2013) found that the atmosphere-only model and its coupled counterpart with the same SST conditions show comparable skill in the subseasonal prediction. Infanti and Kirtman (2017) obtained similar results for the seasonal prediction. Fu et al. (2013) demonstrated that the atmosphere-only model with actual SST forcing can even outperform the corresponding coupled model in forecasting the tropical intraseasonal oscillation.

Many efforts have been made to understand the impact of SST configuration or sea-air interaction on monsoon prediction. However, few studies have compared the differences of SST's impact between atmosphere-only model forecast and coupled model forecast. Moreover, the relative contributions of SST forcing and air-sea interaction are rarely explored based on an integrated framework with both atmosphere-only model and coupled model. In this study, focusing on the WNP monsoon prediction, we aim to further understand to what extent the SST configuration can influence the uncoupled and coupled model predictions, and which factor is key to determine the skill difference between these two types of model predictions.

The model, experimental design, and validation data are described in Sect. 2. Section 3 explores the impacts of SST configuration on predictions of the atmosphere-only model and coupled model. Section 4 investigates the relative importance of SST forcing and air-sea interaction. The summary and discussion are given in Sect. 5.

2 Model, experimental design, and validation data

2.1 Model

In this study, the atmosphere-only model used for Tier-2 prediction is the Beijing Climate Center (BCC) Atmospheric General Circulation Model version 3 (BCC-AGCM3; Wu et al. 2019). It has a horizontal resolution of T106 (approximately 1.1°), and a vertical resolution of 46 hybrid sigma/pressure layers. The atmosphere-only model is forced by prescribed SST, which is either from observation or from coupled model prediction.

The coupled model used for Tier-1 prediction is the BCC Climate System Model version 2 (BCC-CSM2) at T106 resolution (Wu et al. 2019). The BCC-CSM2 is a fully coupled model with atmosphere, ocean, sea ice, and land components. The atmosphere component is the BCC-AGCM3, which is the same as the model in Tier-2 prediction. The ocean component is the Modular Ocean Model version 4 (MOM4) from the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL; Griffies et al. 2005). In MOM4, the horizontal resolution is nominally 1°, but meridionally increases to 1/3° between 30° S and 30° N; the vertical coordinate is geopotential (z) with 40 layers. The ocean component communicates with the atmosphere component every 30 min without any flux adjustment.

2.2 Experimental design

2.2.1 Atmosphere-only model prediction

To examine the impact of SST configuration on the atmosphere-only model prediction, we carry out three sets of hindcast experiments using BCC-AGCM3 forced by the observed SST with different frequencies (i.e., monthly, weekly, and daily). We also carry out another set of atmosphere-only model predictions forced by the SST predicted by the coupled runs to investigate the role of air-sea interaction. The experiments are listed in Table 1 and the details of experimental design are described as follows.

(1) ATM_MSST (atmosphere-only model prediction forced by monthly mean observed SST): The underlying SST field is prescribed with monthly mean SST observation, which is derived by averaging the daily NOAA Optimum Interpolation Sea Surface Temperature (OISST; Reynolds et al. 2007). The atmosphere initial condition is obtained by a nudging strategy towards the 6-hourly air temperature, humidity, and wind data from the National Center for Environmental Prediction's Final Operational Global Analysis (NCEP-FNL; Kalnay et al. 1996). The hindcasts are initialized on the first day of each month in June–August during 2000–2014, with 1-month forecast integration. Each hindcast case is composed of four ensemble members, using atmosphere initial conditions at a successive 6-h interval starting back from 00:00 UTC of the first forecast day. The initialization scheme and ensemble forecast strategy are similar to those in Liu et al. (2016) and Zhu et al. (2021).

(2) ATM_WSST (atmosphere-only model prediction forced by weekly mean observed SST): The experimental design is similar to that in ATM_MSST, but the SST forcing uses weekly mean SST data, which is also derived by averaging the daily OISST.

(3) ATM_DSST (atmosphere-only model prediction forced by daily mean observed SST): The experimental design is similar to that in ATM_MSST, but the SST forcing is replaced by the daily mean SST from OISST.

(4) ATM_CPLDSST (atmosphere-only model prediction forced by forecasted SST): The experimental design is similar to that in ATM_DSST, but the SST forcing is replaced by forecasted SST output at a 3-h interval from the coupled run (i.e., CPL_DSST described in Sect. 2.2.2). The ATM_CPLDSST uses the same SST condition as that in the coupled model prediction, to objectively isolate the impact of SST forcing or air-sea interaction.

2.2.2 Coupled model prediction

In coupled model, the SST field is not specified but predicted by the model itself. To examine the role of SST initial condition in the coupled model prediction, the following three sets of hindcast experiments (Table 1) are conducted with the BCC-CSM2.

(1) CPL_MSST (coupled model prediction initialized with monthly mean observed SST): The initialization scheme and ensemble forecast strategy are identical to those in ATM_MSST prediction. Briefly, the atmosphere and ocean initial conditions are obtained by nudging towards 6-hourly NCEP-FNL and monthly mean OISST, respectively. The hindcasts are initialized on the first day of each month in June–August during 2000–2014, with an ensemble of four members integrating for 1 month.

(2) CPL_WSST (coupled model prediction initialized with weekly mean observed SST): The experimental design is similar to that in CPL_MSST, but the SST initial

Table 1 Settings of hindcast experiments

Experiment name	Model type[a]	SST
ATM_MSST	A	Forced by observed monthly mean SST
ATM_WSST	A	Forced by observed weekly mean SST
ATM_DSST	A	Forced by observed daily mean SST
CPL_MSST	C	Initialized with observed monthly mean SST
CPL_WSST	C	Initialized with observed weekly mean SST
CPL_DSST	C	Initialized with observed daily mean SST
ATM_CPLDSST	A	Forced by forecasted SST from CPL_DSST

The hindcasts start on the first day of each month in JJA during 2000–2014

[a] A and C denote atmosphere-only model and coupled model, respectively

condition is obtained by nudging towards weekly mean OISST.

(3) CPL_DSST (coupled model prediction initialized with daily mean observed SST): The experimental design is similar to that in CPL_MSST, but the SST initial condition is obtained by nudging towards daily mean OISST.

2.3 Validation data

To validate the model results, this study utilizes the following datasets: (1) the daily precipitation from the Global Precipitation Climatology Project (GPCP; Adler et al. 2003), available at https://www.ncdc.noaa.gov/cdr/atmospheric/precipitation-gpcp-daily; (2) the daily horizontal and meridional winds at 850 hPa, net longwave and shortwave radiation flux at surface, and surface latent and sensible heat flux from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5 (ERA5; Hersbach et al. 2020), provided at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5; (3) the daily SST from the NOAA Optimum Interpolation Sea Surface Temperature (OISST; Reynolds et al. 2007), available at https://www.ncdc.noaa.gov/oisst. These observations or reanalysis cover the period of 2000–2014. All data are interpolated onto a horizontal T106 resolution (~ 110 km) to be consistent with the model resolution.

3 The impacts of SST configuration in uncoupled and coupled predictions

In this section, we explore the impacts of SST configuration on monthly prediction of monsoon over the Asia-Pacific in both the atmosphere-only model and the coupled model. We examine the monthly prediction skills of three sets of uncoupled runs (i.e., ATM_DSST, ATM_WSST, and ATM_MSST) forced by the observed SST with different frequencies (i.e., daily, weekly, and monthly, respectively) and three sets of coupled runs (i.e., CPL_DSST, CPL _WSST, and CPL _MSST) initialized by the observed SST with different frequencies (i.e., daily, weekly, and monthly, respectively).

Figure 1 gives the climatological mean summer (JJA) precipitation and 850-hPa winds in observation and hindcasts. Generally, apparent wet biases appear over the tropical WNP and some coastal regions, such as the west coast of Indo-China Peninsula and the east coast of Maritime Continent. Strong easterly wind biases occur around equatorial WNP and the South China Sea. These rainfall and wind biases in hindcasts are very similar to those in a long-term free run simulation of BCC-CSM2 (see Fig. 3 in Zhu et al. 2021), indicating the presence of systematic errors of the model itself. The three sets of atmosphere-only model hindcasts exhibit tiny differences (Fig. 1b–d), and so do the three sets of coupled model hindcasts (Fig. 1e–g). This suggests that these systematic errors can hardly be reduced by increasing the frequency of SST observation used in either uncoupled model or coupled model. The differences between the two types of hindcasts are also small and only confined over the region from Indo-China Peninsula to Philippine Sea (Fig. 1h–j), implying that such systematic errors may mainly arise from the atmosphere-only model itself.

The rainfall prediction skill, measured by the temporal correlation coefficients (TCCs) of monthly rainfall anomalies between observation and hindcasts, is given in Fig. 2. ATM_MSST, ATM_WSST, and ATM_DSST exhibit similar skills, which are considerably high over the Maritime Continent and tropical central Pacific but quite low over the rest of Asia–Pacific (Fig. 2a–c). Such similarity suggests that the rainfall prediction of atmosphere-only model cannot be improved when driven by more realistic SST observation with higher temporal frequency. This is contrary to the findings of Kim et al. (2008) and Boisséson et al. (2012), which showed improved prediction of tropical intraseasonal oscillation due to higher-frequency SST forcing. However, for the coupled predictions, CPL_DSST and CPL_WSST exhibit higher skills than CPL_MSST. This indicates that the rainfall prediction of coupled model can benefit from the initialization using more realistic SST observation with higher temporal frequency. The advantage of this initialization strategy for subseasonal forecast is also demonstrated by Liu et al. (2016) and Zhu et al. (2021). Moreover, the coupled runs are superior to the uncoupled runs in predicting the rainfall over the tropical WNP (i.e., the box area in Fig. 2i). Such difference is more evident when the SST observation with much higher frequency is used in the initialization process of coupled model. The TCC differences between CPL_MSST and ATM_MSST are very small over most areas in the tropical WNP, whereas those between CPL_WSST and ATM_WSST and between CPL_DSST and ATM_DSST become increasingly apparent. Quantitively, the TCC differences averaged over the tropical WNP (i.e., the box area in Fig. 2i) between the above two types of hindcasts are 0.09, 0.17, and 0.20, respectively.

Figure 3 depicts the prediction skill of 850-hPa zonal wind. The wind field is more predictable than the rainfall, consistent with the findings of previous studies (e.g., Wang et al. 2009a; Lee et al. 2011; Liu et al. 2015). The skill differences among different hindcasts mainly occur over the South China Sea and the Philippine Sea. Over these regions, the TCCs of zonal wind are reduced by up to 0.2 in ATM_DSST and ATM_WSST than those in ATM_MSST (Fig. 3a–c). Conversely, the TCCs are increased by up to 0.1 in CPL_WSST and CPL_DSST compared to those in CPL_MSST (Fig. 3d–f). These results indicate that the use of more realistic SST observation with higher frequency leads to no improvement of low-level wind prediction in

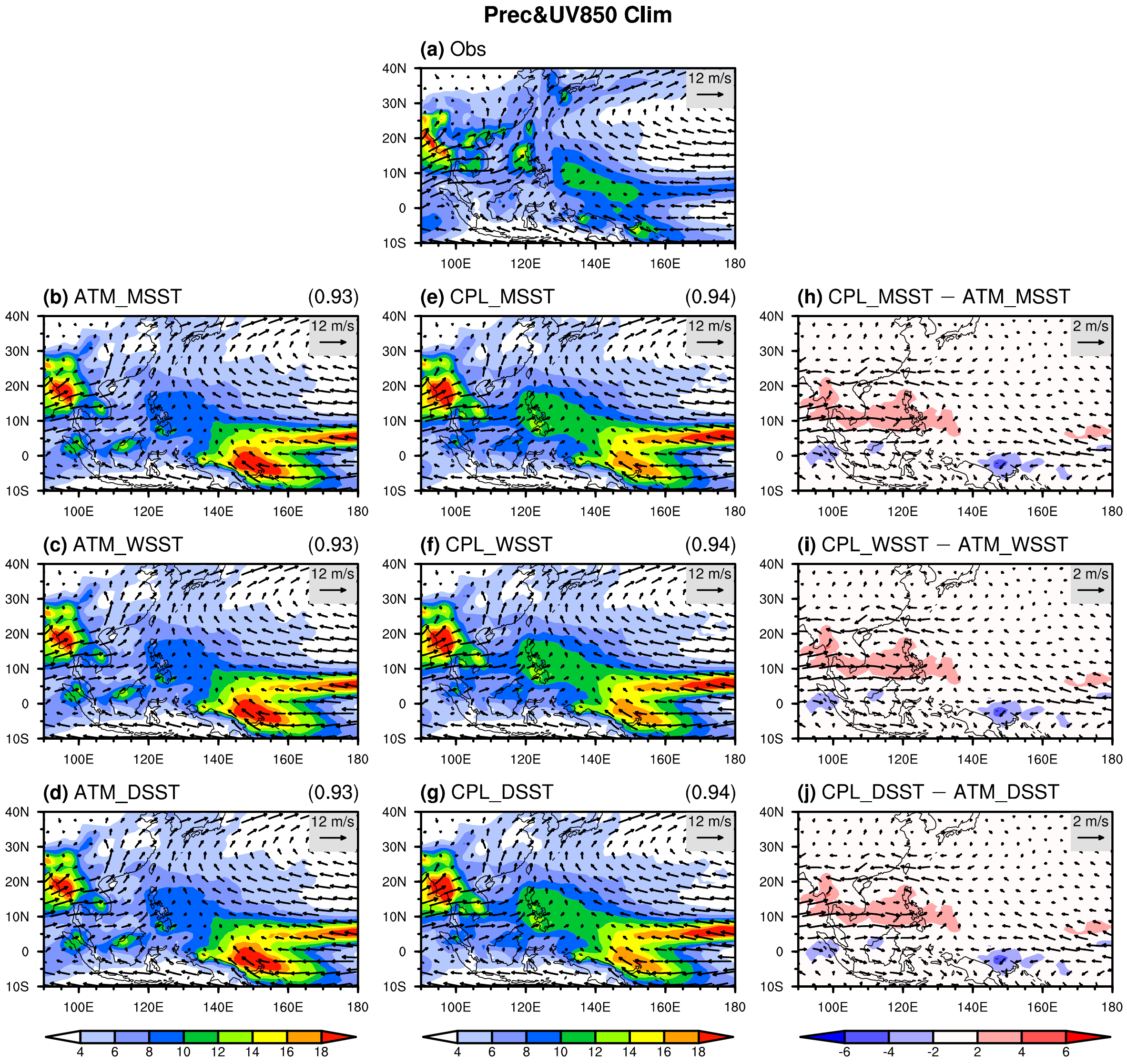

Fig. 1 Climatological mean of summer (JJA) precipitation (unit: mm/day; contour) and 850-hPa winds (unit: m/s; vector) in **a** observation (top panel) and hindcasts of **b**–**d** the atmosphere-only model (left panel) and **e**–**g** the coupled model (middle panel), and **h**–**j** differences between the two types of hindcasts (right panel). The decimals shown in brackets are the pattern correlation coefficients of rainfall between observation and hindcasts over the Asia–Pacific (10° S–40° N, 90°–180° E)

atmosphere-only model, but causes moderate improvement in coupled model. Moreover, CPL_MSST exhibits slightly higher skill than ATM_MSST, with TCC increase of about 0.1 over the WNP (Fig. 3g). The skill differences between CPL_WSST and ATM_WSST and between CPL_DSST and ATM_DSST become more evident, with TCC differences of above 0.2 over the area from the Indo-China Peninsula to the Philippine Sea (Fig. 3h, i). This suggests the superiority of coupled model to atmosphere-only model in the prediction of low-level circulation.

To further examine the prediction skill of summer monsoon over the WNP, Fig. 4 gives the TCCs of two WNP monsoon indices, including the WNP precipitation index and the WNP circulation index. The WNP precipitation index is defined as area-averaged rainfall over (5°–25° N, 120°–160° E), similar to the definition in Wang and Fan (1999) and Lu and Lu (2014). The WNP circulation index is defined as the difference of area-averaged 850-hPa zonal wind between (5°–15° N, 100°–130° E) and (20°–30° N, 110°–140° E), following Wang et al. (2001, 2004). The region of rainfall (zonal wind) used for the monsoon precipitation (circulation) index is indicated by a red box in Fig. 2i (Fig. 3i). The WNP circulation index denotes the intensity of low-level vorticity associated with the convection activity represented by the WNP precipitation index (Wang and Fan 1999; Wang et al. 2001). The two WNP monsoon indices are closely correlated with a correlation coefficient over 0.8 in either observation or hindcasts (figures not shown).

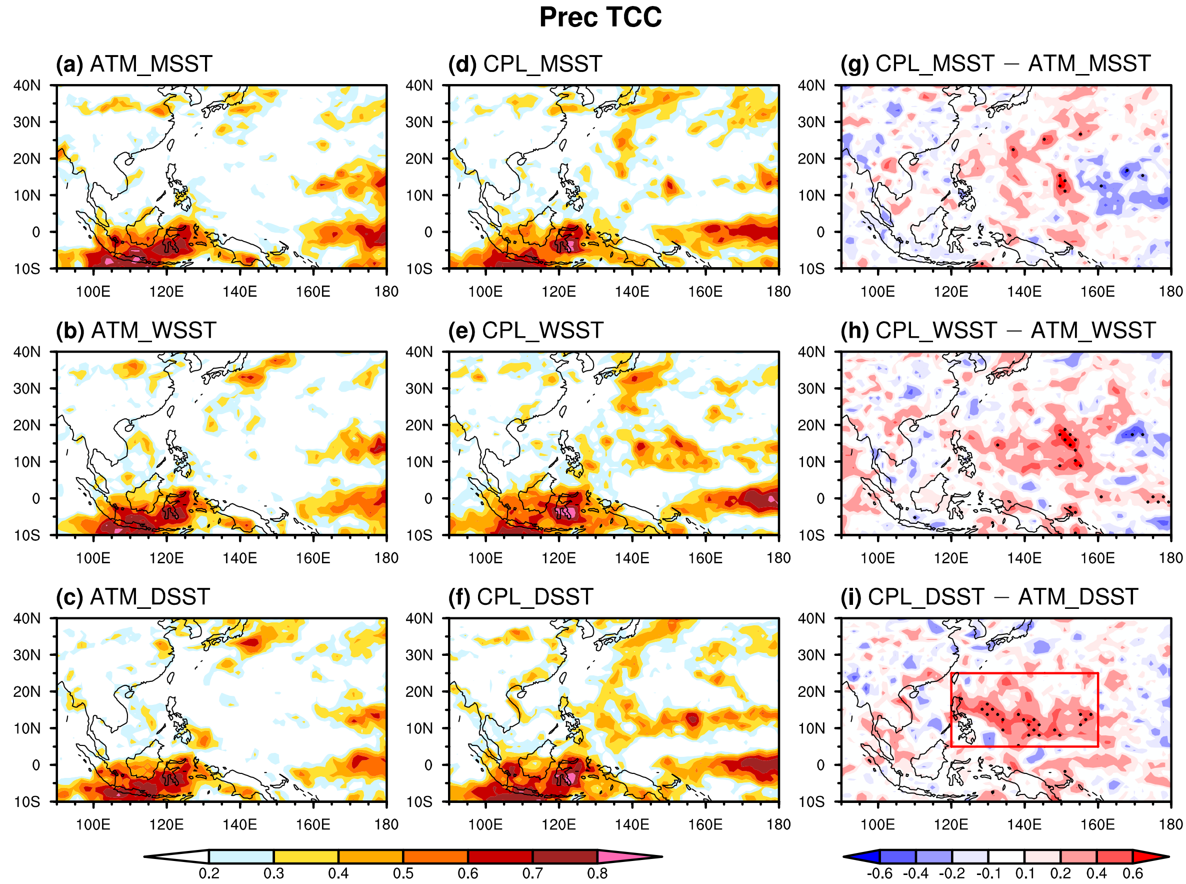

Fig. 2 Temporal correlation coefficients (TCCs) of monthly rainfall anomalies in summer between observation and hindcasts of **a**–**c** the atmosphere-only model (left panel) and **d**–**f** the coupled model (middle panel), and **g**–**i** differences between the two types of hindcasts (right panel). The TCCs larger than 0.29 are significant at the 95% confidence level. Stipplings denote where the TCC differences are significant at the 99% confidence level according to the Steiger's Z test. The red box in (**i**) denotes the region where the rainfall is used to define the WNP monsoon precipitation index

From ATM_MSST to ATM_WSST and ATM_DSST, the TCC of WNP precipitation index remains negative (Fig. 4a), and the TCC of WNP circulation index is even reduced (Fig. 4b). However, from CPL_MSST to CPL_WSST and CPL_DSST, the TCCs of the two WNP monsoon indices are increased (Fig. 4a, b). Especially for the WNP precipitation index, the TCC is enhanced from 0.22 to above 0.42. In addition, the coupled runs are more skillful than the uncoupled runs. Particularly, the TCC of WNP precipitation (circulation) index is only -0.18 (0.14) in ATM_DSST, but is 0.42 (0.59) in CPL_DSST. These are consistent with the results in Figs. 2 and 3.

The above results suggest that, for monthly predictions of summer monsoon rainfall and circulation over the WNP, the use of realistic SST observation may be more necessary for the coupled model prediction than for the atmosphere-only model prediction. Meanwhile, over the WNP, we find that the coupled runs are significantly superior to the uncoupled runs forced by observed SST. Such difference is even more evident when the SST observation with much higher frequency is used in the coupled and uncoupled hindcasts. This stresses the superiority of the Tier-1 approach to the Tier-2 approach for the WNP monsoon prediction. The reason for the skill difference between these two types of predictions will be further investigated in the next section.

4 The relative importance of SST forcing and air-sea interaction

Section 3 shows that for the monthly prediction of WNP summer monsoon, the atmosphere-only model experiments with prescribed observed SST (e.g., ATM_DSST) are significantly inferior to the coupled model experiments that include air-sea coupling process (e.g., CPL_DSST). However, these two types of model predictions differ in the SST fields during the model integration. Thus, to make a strict comparison, we conduct another set of atmosphere-only model hindcast experiments forced by the SST predicted by the CPL_DSST, referred to as ATM_CPLDSST. To

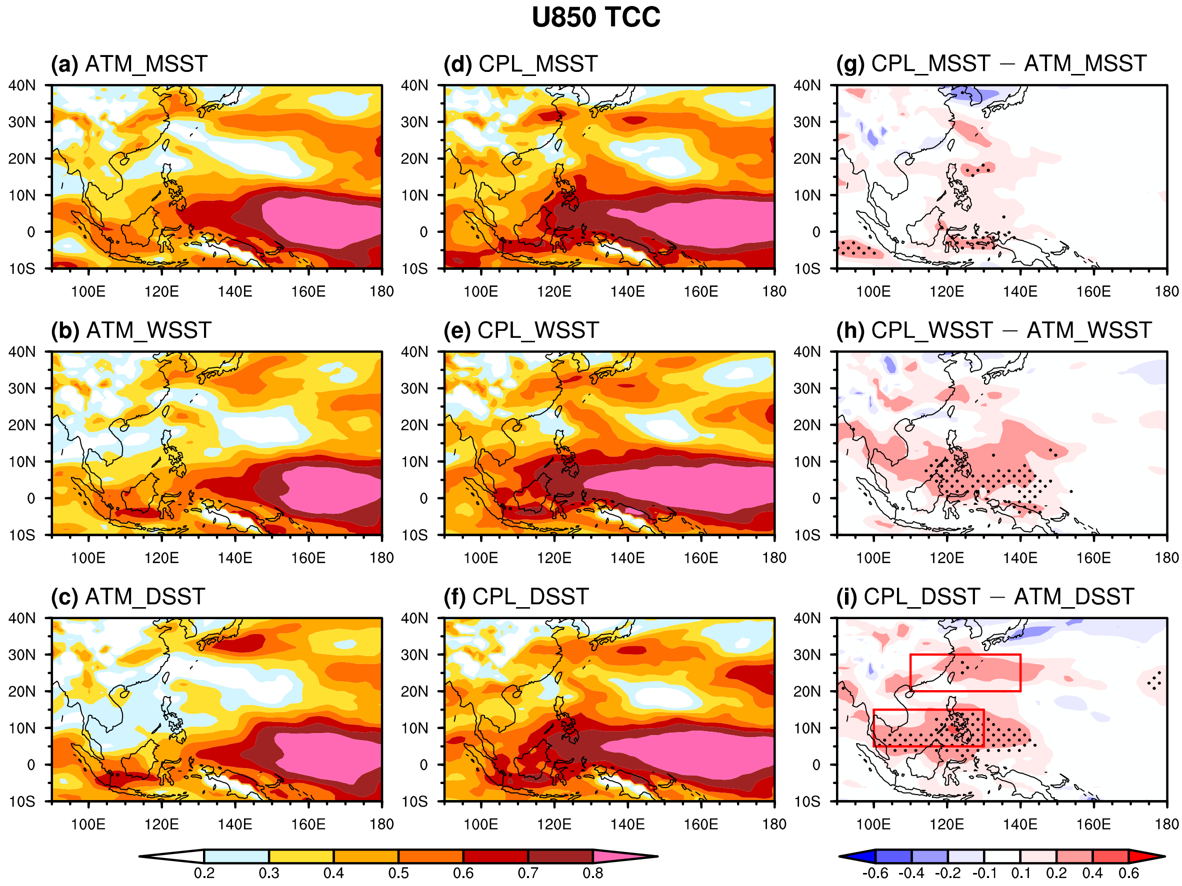

Fig. 3 Same as in Fig. 2, but for TCCs of monthly anomalies of 850-hPa zonal wind. The red boxes in (**i**) denote the regions where the zonal winds are used to define the WNP monsoon circulation index

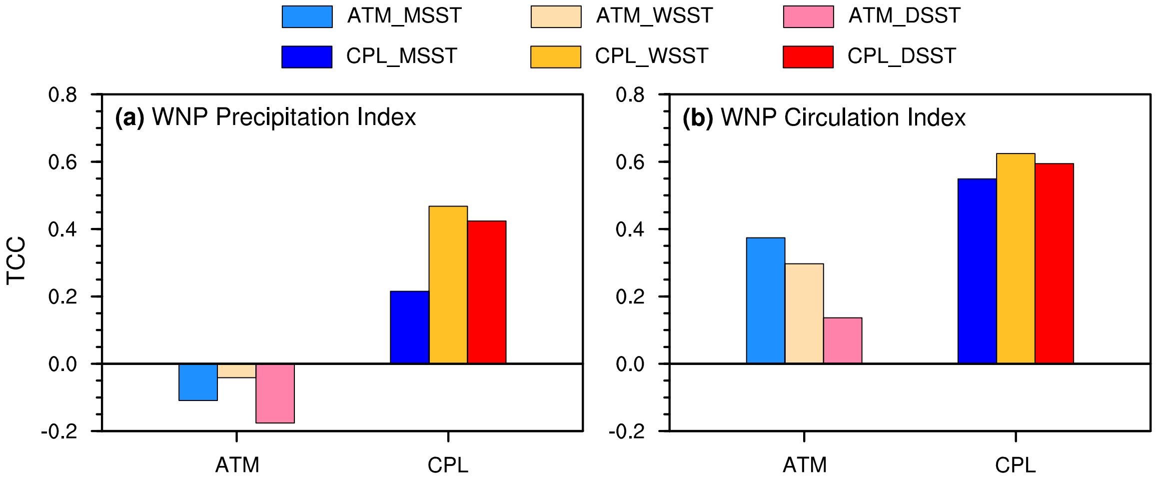

Fig. 4 Temporal correlation coefficients (TCCs) of two WNP monsoon indices between observation and hindcasts of the atmosphere-only model (ATM) and the coupled model (CPL). The monsoon indices include **a** WNP precipitation index and **b** WNP circulation index. The TCCs larger than 0.29 are significant at the 95% confidence level

determine the relative importance of SST forcing and air-sea interaction, in this section we compare the hindcasts of CPL_DSST, ATM_DSST, and ATM_CPLDSST. The comparison between ATM_CPLDSST and CPL_DSST helps to understand the role of air-sea interaction, while the comparison between ATM_CPLDSST and ATM_DSST helps to understand the role of SST forcing (coupled model predicted SST versus observed SST).

The monthly prediction skill of rainfall and low-level zonal wind in ATM_CPLDSST and its difference from CPL_DSST/ATM_DSST are shown in Fig. 5. Compared to CPL_DSST, ATM_CPLDSST exhibits small difference of skill in the prediction of rainfall and circulation, except over several scattered areas. This suggests that the prediction of WNP monsoon may be weakly influenced by the air-sea coupling process. Similar results were obtained by Beraki et al. (2015) and Infanti and Kirtman (2017), which found comparable skill of WNP monsoon prediction between uncoupled runs and coupled runs that share the same SST fields. However, compared to ATM_DSST, ATM_CPLDSST is more skillful in predicting the rainfall over the Philippine Sea, and the 850-hPa zonal wind over a broad belt from Malaysia to the east of Philippines and a narrow belt to the south of Japan. The skill differences between ATM_DSST and ATM_CPLDSST over these regions are more than 0.2 and significant at the 99% confidence level according to the Steiger's Z test (Raghunathan et al. 1996). Similar skill differences are also shown by the comparisons

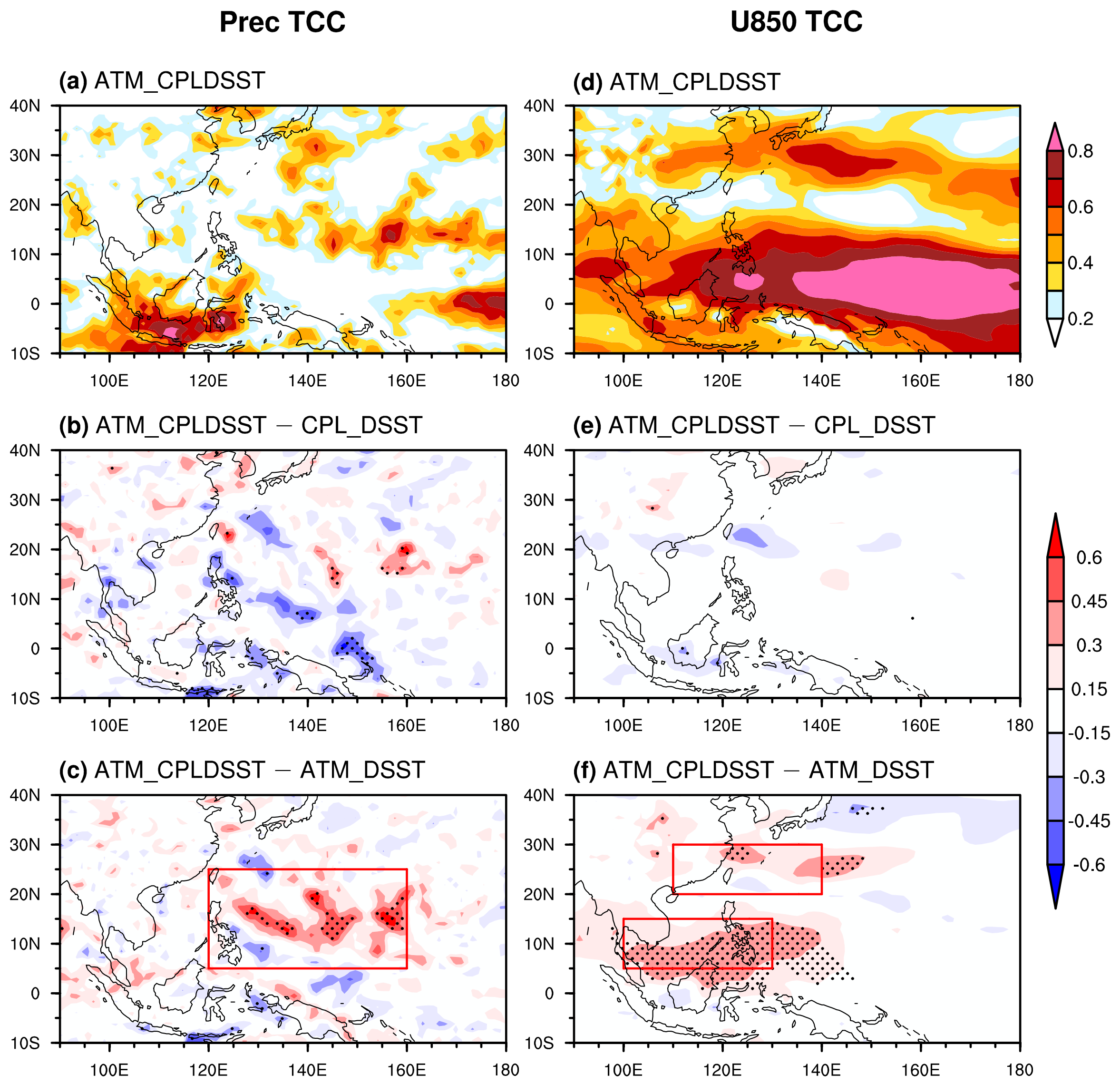

Fig. 5 Temporal correlation coefficients (TCCs) of monthly anomalies of **a** precipitation (top left panel) and **d** 850-hPa zonal wind (top right panel) between observation and hindcasts of ATM_CPLDSST. Also shown are **b**, **e** TCC differences between ATM_CPLDSST and CPL_DSST (middle panel) and **c**, **f** those between ATM_CPLDSST and ATM_DSST (bottom panel). Stipplings denote where the TCC differences are significant at the 99% confidence level according to the Steiger's Z test. The red box in (**c**) [or (**f**)] denotes the region where the rainfall (or zonal wind) is used to define the WNP monsoon rainfall (or circulation) index

among CPL_WSST, ATM_WSST, and the atmosphere-only model hindcasts forced by SST from CPL_WSST (figure not shown). This indicates that the prediction skill of WNP monsoon may be more determined by the SST forcing than the air-sea interaction. It is unexpected that using imperfect forecasted SST as boundary forcing leads to skill improvement compared to using accurate observed SST. This is contrary to the findings of some previous studies (e.g., Fu et al. 2013; Beraki et al. 2015; Infanti and Kirtman 2017), which demonstrated that the subseasonal and seasonal predictions are improved due to the more accurate SST prescribed in the atmosphere-only model.

Figure 6 shows the monthly-to-interannual variation of the WNP precipitation and circulation indices, which are defined in Sect. 3. CPL_DSST and ATM_CPLDSST can well capture the observed variation of WNP precipitation index with TCCs over 0.4. However, ATM_DSST produces negative TCC. Similar results are found for the prediction of WNP circulation index, with relatively higher skills in CPL_DSST and ATM_CPLDSST but lower skill in ATM_DSST. These results are consistent with Fig. 5, suggesting that the SST forcing rather than the air-sea interaction may largely determine the prediction skill of WNP monsoon rainfall and circulation.

To explore the possible link of SST with the WNP monsoon, Fig. 7 gives the spatial distribution of the correlation coefficients between SST and the two WNP monsoon indices. In observation, the WNP precipitation index is significantly negatively correlated with the SST over the tropical WNP region (Fig. 7a), indicating the forcing of atmosphere

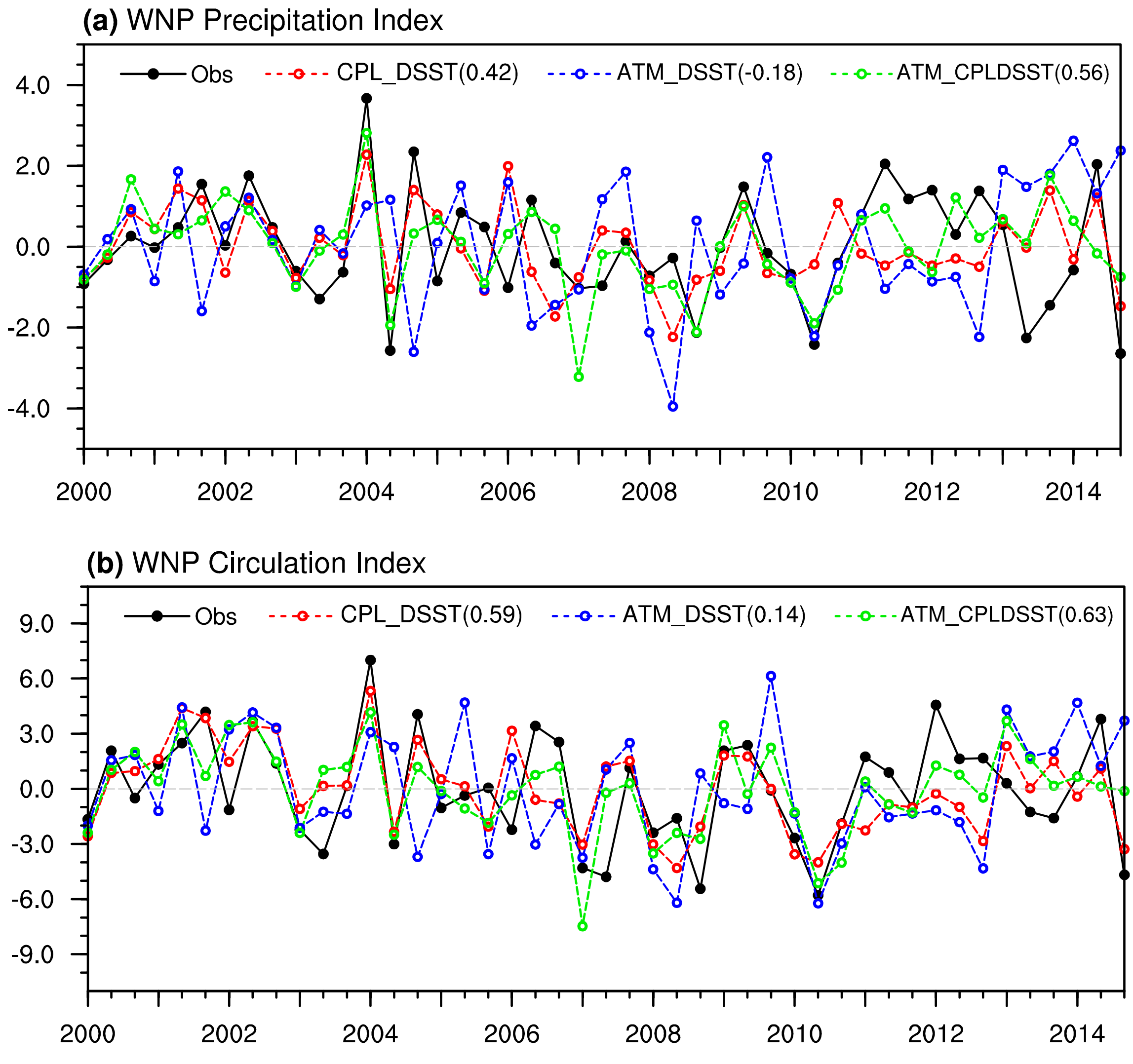

Fig. 6 Time series of monthly anomalies of two WNP monsoon indices in observation and hindcasts during June–August of 2000–2014. The monsoon indices include **a** WNP precipitation index and **b** WNP circulation index. The decimals shown in brackets are temporal correlation coefficients of monsoon indices between observation and hindcasts, and the correlation coefficients larger than 0.29 are significant at the 95% confidence level

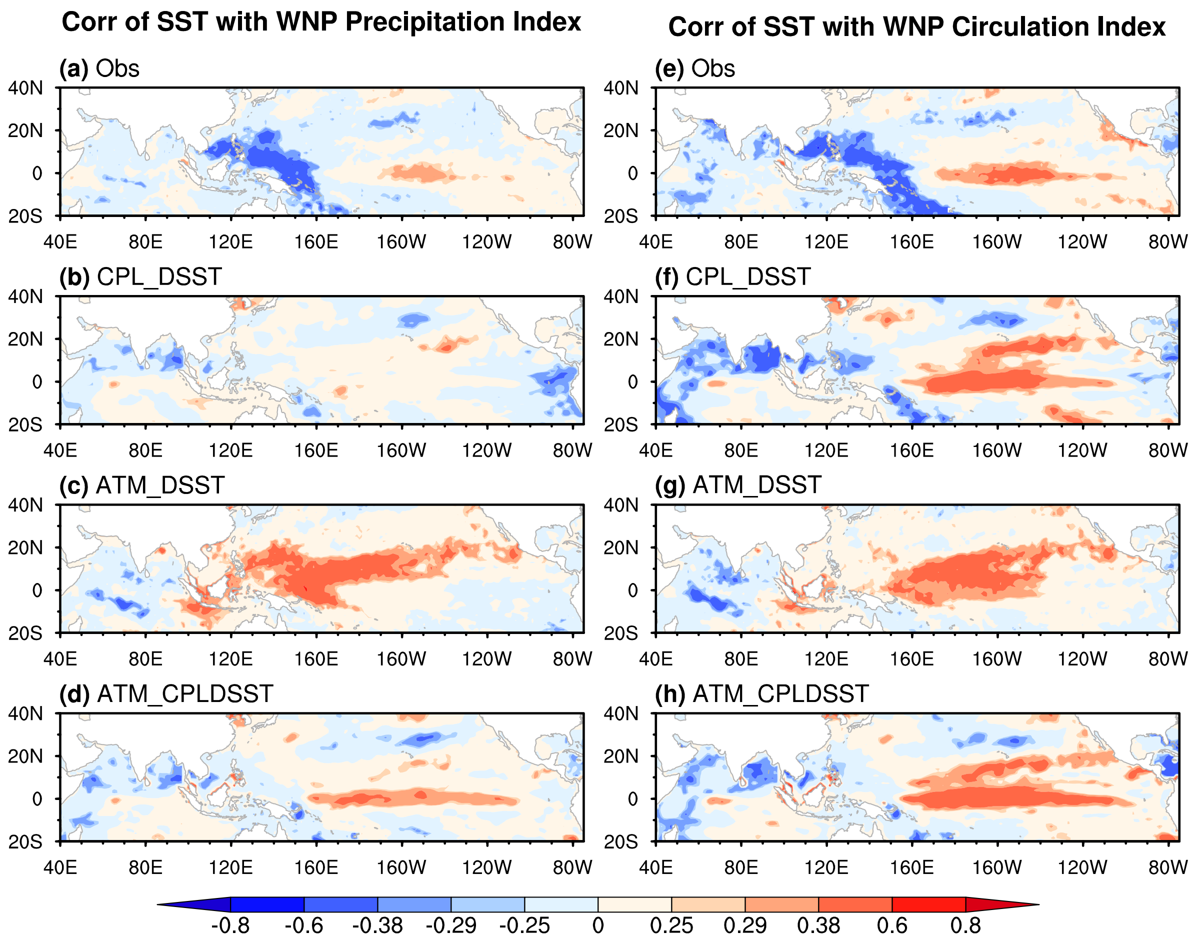

Fig. 7 Spatial distributions of correlations between monthly anomalies of SST and WNP precipitation index (left panel) and between those of SST and WNP circulation index (right panel) in observation and hindcasts. The correlation coefficients larger than 0.25, 0.29, and 0.38 are significant at the 90%, 95% and 99% confidence level, respectively

on the underlying ocean over the WNP (Wu and Kirtman 2007). The WNP precipitation index exhibits a significant positive correlation with the SST over the equatorial central Pacific, suggesting the ENSO's impact on the atmospheric anomalies over the WNP. When the ENSO's impact is removed by a partial correlation analysis as that in Zhang et al. (2016), the negative SST-monsoon correlation over the WNP is still significant. This indicates that the local SST, instead of ENSO, mainly modulates the monthly variability of WNP monsoon during summer. ATM_DSST fails to capture the observed impact of local SST and ENSO on the WNP monsoon. It exhibits an erroneous strong positive correlation of monsoon with SST over a broad area from the Maritime Continent to the tropical central Pacific (Fig. 7a). Such failure was also noticed by Wang et al. (2004, 2005), which found that in the atmosphere-only model simulations and predictions forced by the observed SST, the summer rainfall over the WNP is positively correlated with the local SST on monthly scales. Compared to ATM_DSST, CPL_DSST and ATM_CPLDSST show obvious improvements. They can capture the local negative correlation near the Philippine Sea, although with obviously underestimated magnitude (Fig. 7b, d). Similar results can be seen for the correlation between SST and the WNP circulation index (Fig. 7e–h). Both CPL_DSST and ATM_CPLDSST can more reasonably reproduce the relationship of the WNP monsoon with the tropical SST than ATM_DSST. This is consistent with the results shown in Figs. 5 and 6, further indicating the more importance of the SST forcing than the air-sea interaction in the prediction skill of WNP monsoon.

Given that the differences in SST-monsoon relationship among various hindcasts may be especially obvious in several years, we make a composite analysis of some typical cases. Focusing on the normalized WNP precipitation indices in observation and hindcasts, the typical cases are selected according to two criteria: (1) the observed index is very strong (larger than 0.8 for wet case and smaller than -0.8 for dry case); (2) the forecasted index in CPL_DSST/ATM_CPLDSST is closer to observation than that in ATM_DSST and the absolute difference between CPL_DSST/

ATM_CPLDSST and ATM_DSST is larger than 0.2. The selected typical cases include 6 wet cases and 5 dry cases, in which the WNP precipitation anomalies are strong in observation and the disparities among different experiments are apparent.

The composite anomalies of rainfall and 850-hPa winds for wet and dry cases are shown in Fig. 8. In the observed wet cases, suppressed convection appears over the Maritime Continent, and enhanced convection occurs over the WNP (Fig. 8a). This corresponds to strong westerly anomalies over the equatorial western Pacific and cyclonic wind anomalies over the Philippine Sea. These features are reversed in the observed dry cases (Fig. 8g). For the predictions of both wet and dry cases, CPL_DSST and ATM_CPLDSST can basically capture the precipitation and circulation features over the WNP despite some biases in the amplitude and location

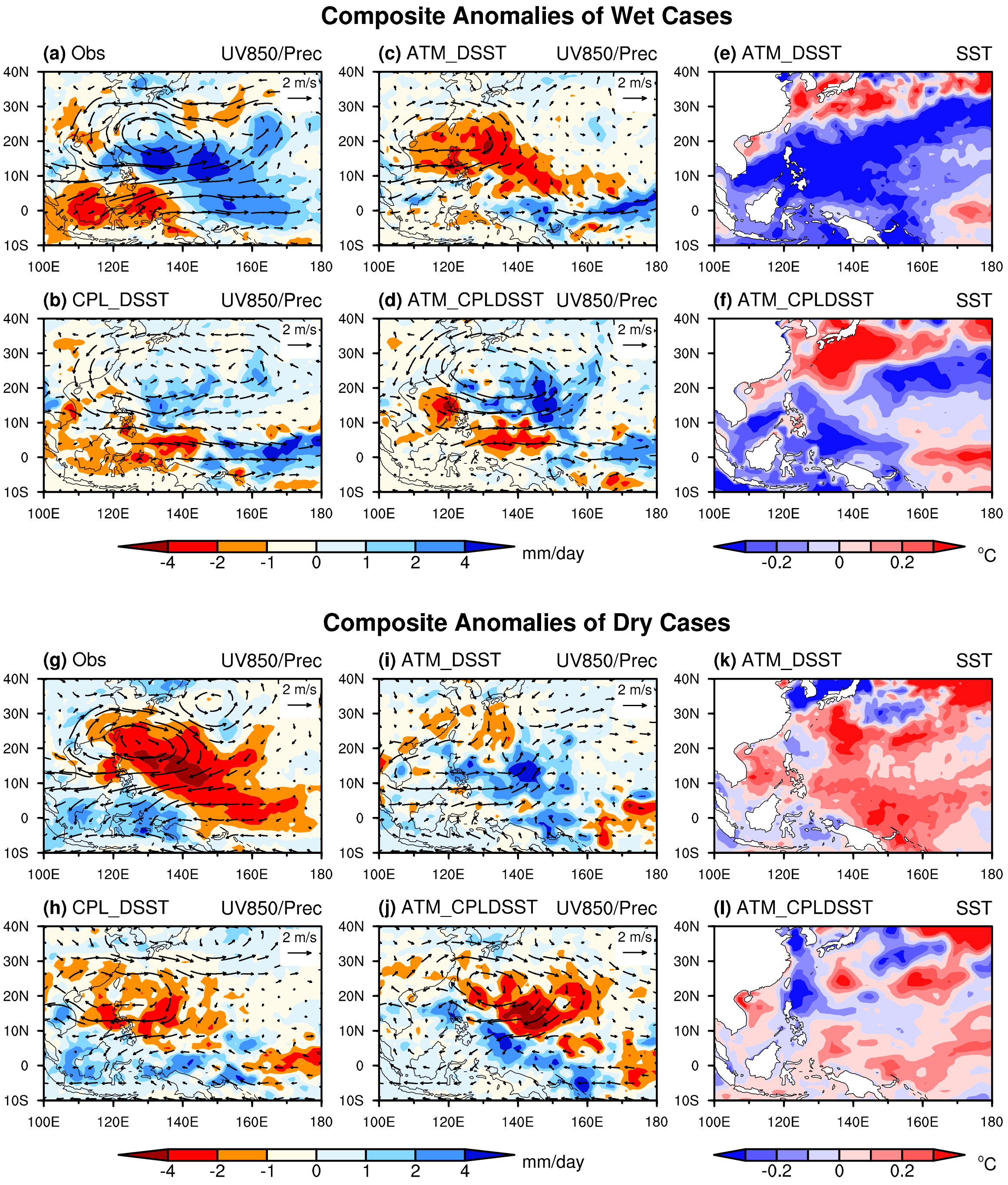

Fig. 8 Composite anomalies of precipitation (unit: mm/day), 850-hPa winds (m/s), and SST fields (°C) in observation and hindcasts for **a**–**f** the wet cases and **g**–**l** the dry cases

of anomaly centers. However, ATM_DSST exhibits an opposite-to-observation feature and is thus extremely unskillful. Note that the SST used in ATM_CPLDSST (Fig. 8f, l) largely deviates from the SST observation prescribed in ATM_DSST (Fig. 8e, k). Specifically, the forecasted SST anomalies to the east of Philippines in the WNP are about 0.2 °C smaller than the observed SST anomalies. This indicates that the atmosphere-only model prediction may be sensitive to the amplitude of prescribed SST anomalies, consistent with the findings of Wang et al. (2009b).

Figure 9 further gives the composite anomalies of surface energy fluxes for the wet cases. The surface energy fluxes include surface latent flux (LH), surface sensible heat flux (SH), surface longwave radiation flux (LW), and surface shortwave radiation flux (SW). In observation, when enhanced convection occurs over the WNP, the net surface flux is upward positive, with large contribution from SW and LH and small contribution from LW and SH (Fig. 9). The upward positive (namely downward negative) SW anomaly over the WNP (Fig. 9m) corresponds to the wet anomaly (Fig. 8a) and cool SST anomaly (Fig. 8e), suggesting that the atmosphere affects the underlying SST through cloud-radiation feedback (Wu and Kirtman 2005, 2007). Specifically, the increased cloudiness associated with enhanced convection can reduce the downward solar radiation into the ocean, leading to the cooling of underlying SST (Wang et al. 2004). Meanwhile, the increased upward LH (Fig. 9a) is associated with strong westerly wind anomalies (Fig. 8a) and cool SST anomalies (Fig. 8e), indicating the atmosphere's impact on the underlying SST through wind-evaporation feedback (Wu and Kirtman 2005, 2007). Specifically, the enhanced winds can result in more surface evaporation and thus lower underlying SST (Wang et al. 2004). CPL_DSST and ATM_CPLDSST can basically reproduce the anomaly centers of LH and SW that dominate the surface energy flux over the WNP. However, the ATM_DSST exhibits negative LH and SW anomalies that are opposite to the features in observation and the other two sets of experiments. These results suggest that the better SST-monsoon relationship over the WNP may be due to the more realistic atmosphere response to underlying ocean state in CPL_DSST and ATM_CPLDSST than in ATM_DSST.

For the dry cases, the composite anomalies of surface energy fluxes are given in Fig. 10. In observation, when the suppressed convection appears over the WNP (Fig. 8), the increased downward SW and reduced upward

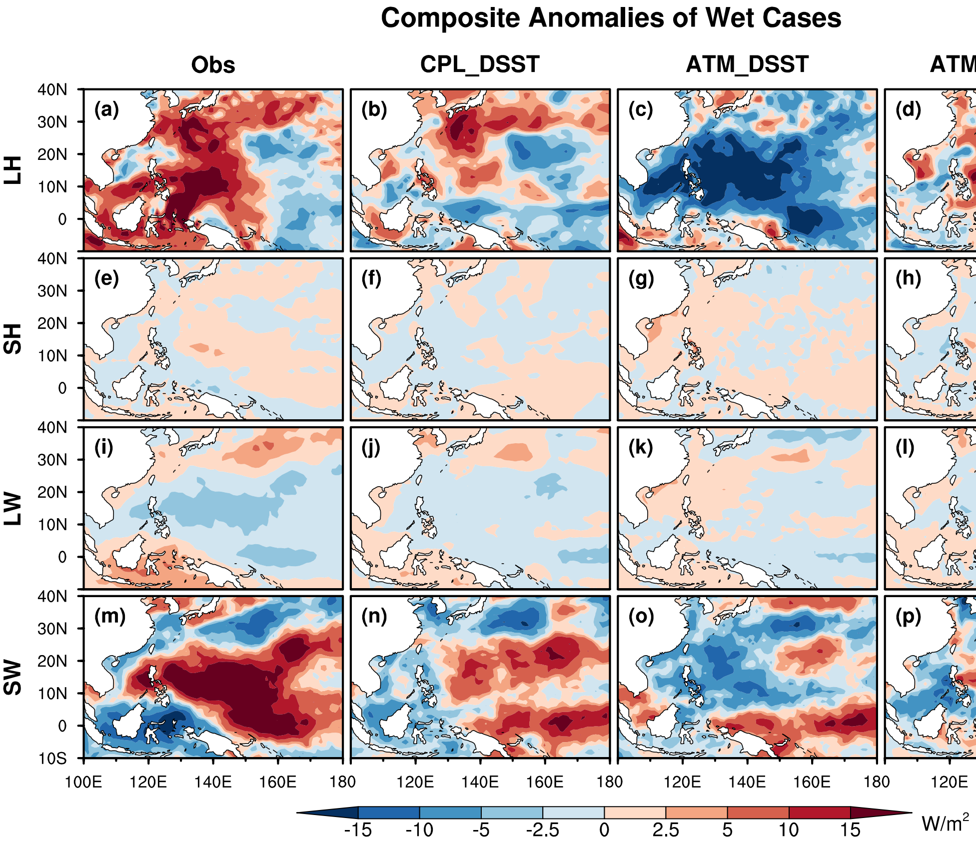

Fig. 9 Composite anomalies of **a–d** surface latent heat flux, **e–h** sensible heat flux, **i–l** longwave radiation flux, and **m–p** shortwave radiation flux (unit: W/m^2) in observation (left panel) and hindcasts (right three panels) for the wet cases. Positive values denote upward flux

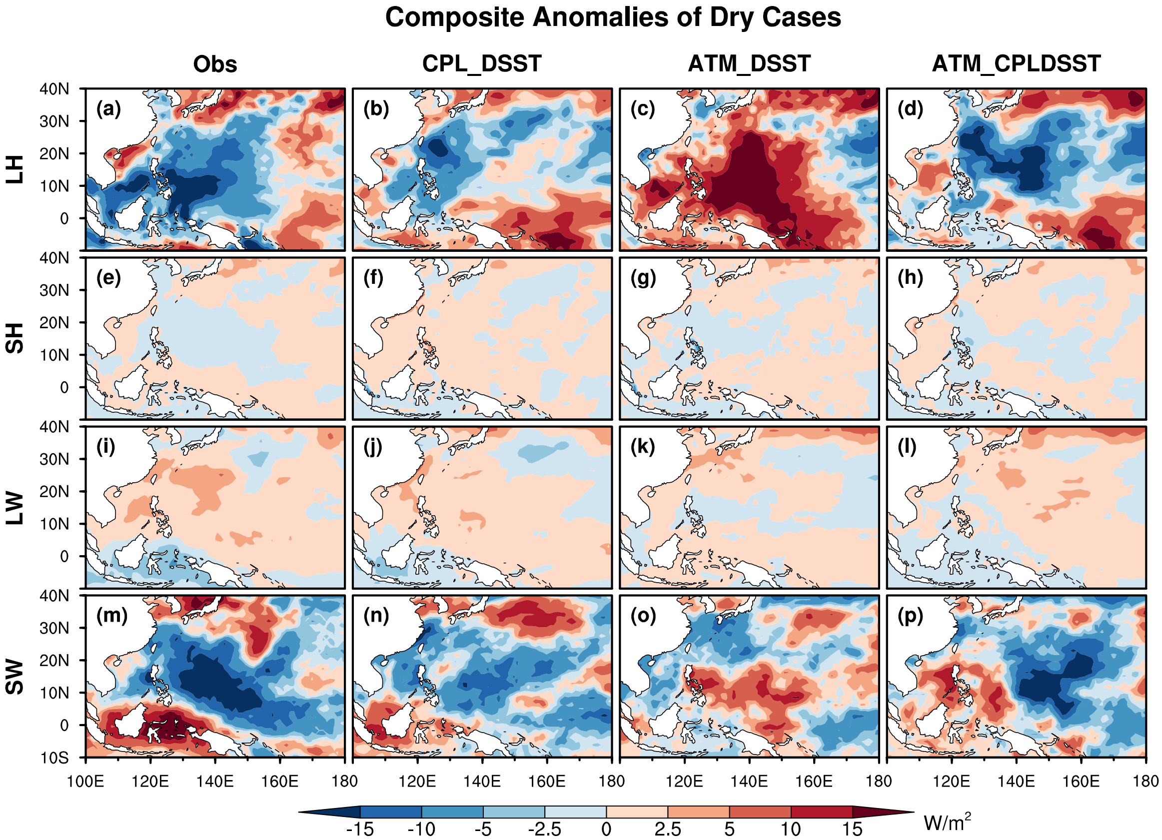

Fig. 10 Same as in Fig. 9, but for the dry cases

LH mainly account for the net downward surface flux (Fig. 10). ATM_DSST fails to capture these features. In contrast, CPL_DSST and ATM_CPLDSST can reasonably reproduce the LH and SW anomalies. This also indicates that CPL_DSST and ATM_CPLDSST can more realistically reproduce the atmosphere response to sea surface state than ATM_DSST, which is consistent with the results of the wet cases.

For the monthly prediction of WNP monsoon, although the coupled model with forecasted SST performs better than the atmosphere-only model prescribed with observed SST (Figs. 2, 3 and 4), in this section we find that the two types of predictions exhibit small differences when the same SST is used during the model forecast integration. This means that the skill difference between the Tier-2 approach and the Tier-1 approach may be largely determined by the SST forcing instead of the air-sea coupling process.

The SST predicted by the coupled model deviates from the observation, but it can result in more skillful prediction when it is used as boundary forcing in the atmosphere-only model. This indicates that the degree of prediction skill largely depends on the characteristics of SST forcing, whose consistency (i.e., suitable to the model itself) is more important than its accuracy (i.e., close to the observation). The improved prediction skill due to the use of coupled-model SST is associated with a more reasonable SST-monsoon relationship, which possibly results from more realistic processes of surface evaporation and solar radiation.

5 Summary and discussion

In this study, the impacts of SST configuration on the monthly prediction of WNP summer monsoon are investigated with both BCC atmosphere-only model and coupled model. Several sets of uncoupled hindcasts and coupled hindcasts are conducted, with 1-month integration starting on the first day of each month during June–August of 2000–2014.

In the prediction of monthly rainfall and 850-hPa circulation anomalies over the WNP, atmosphere-only model experiments forced by the observed SST with different frequencies (i.e., daily, weekly, and monthly) exhibit similar poor performance. The prediction with daily SST forcing is even slightly inferior to that with monthly SST forcing. Conversely, for the coupled model experiments, the use of daily or weekly mean SST observation in the model initialization can enhance the prediction skill than the use of monthly mean SST observation, especially for the monsoon rainfall. Similar results are found for the predictions of monsoon rainfall and circulation indices, suggesting that the use of high-frequency SST observation is much more necessary in the coupled model than in the atmosphere-only model.

The coupled model hindcasts show much better performance than the uncoupled model hindcasts forced by the observed SST in the monthly prediction of WNP summer monsoon. The superiority of coupled model to uncoupled model is more evident with the increase in the frequency of the observed SST used. However, the coupled model and the atmosphere-only model forced by the same SST predicted by coupled model exhibit comparable skills in the monthly prediction of the WNP summer monsoon and its relationship with the underlying SST. Composite analysis of several typical cases further shows that such reasonable prediction in the above two types of model hindcasts with the same SST may be related to the reliable description of surface latent heat flux and shortwave radiation flux over the WNP. These results suggest that the skill difference of WNP monsoon prediction between atmosphere-only model and coupled model may be mainly attributed to the different SST forcing rather than the air-sea interaction itself. For the skill of Tier-2 prediction, the consistency of SST with the atmospheric model is more important than the accuracy of SST.

This study suggests that the coupled model prediction of WNP summer monsoon can benefit from initialization using realistic SST observation with relatively higher frequency. This is consistent with the findings of Liu et al. (2016), Bo et al. (2020), and Zhu et al. (2021), which showed that adopting the observed SST with much higher frequency in the initialization process of coupled model tends to produce more skillful prediction of intraseasonal oscillation. On the contrary, the atmosphere-only model prediction of WNP summer monsoon can hardly be improved and even be degraded by using more accurate SST observation as boundary forcing (e.g., replacing monthly SST observation with daily SST observation). Instead, the atmosphere-only model forced by unrealistic SST condition that is forecasted by the coupled model can produce much more skillful forecast. This is contrary to the findings of some previous studies (e.g., Kim et al. 2008; Boisséson et al. 2012; Fu et al. 2013; Beraki et al. 2015; Infanti and Kirtman 2017), which showed that the atmosphere-only model forecasts are more skillful when driven by more accurate observed SST. The above differences could be partially due to the model dependence (Kug et al. 2008) and the uncertainty of observed SST products (Boisséson et al. 2012; Wang et al. 2015).

Note that the SST anomalies predicted by the coupled model over the tropical WNP are about 0.2 °C weaker than those of observation (Fig. 8f, i), implying that the atmosphere-only model prediction may be considerably sensitive to the amplitude of SST anomalies. Similarly, Wang et al. (2009b) showed that the subseasonal prediction of Indian monsoon can be obviously improved by the forcing of unrealistic SST whose intraseasonal anomalies are 2–3 times larger than the observation. Further investigation is needed to indicate the sensitivity of WNP monsoon prediction to the amplitude of underlying SST anomalies. In addition, the impact of SST configuration may be dependent on target month of forecast. Wu et al. (2010) found that the WNP monsoon is dominated by local SST forcing in June but by remote forcing from Indian Ocean in July and August. Jiang et al. (2013a) further demonstrated that such formation mechanism of WNP monsoon determines its prediction skill, which decreases from June to July and August. Similarly, this study also shows high prediction skill of WNP monsoon in June but low skill in August in ATM_MSST, ATM_WSST, ATM_DSST, and CPL_MSST (figure not shown). Nevertheless, such skill variation feature is absent in CPL_WSST and CPL_DSST, indicating the large uncertainty and complexity of subseasonal prediction. Of course, this result may be uncertain because the number of hindcast experiments for each individual month during summer is limited in this study.

In addition, this study suggests that the Tier-2 approach using atmosphere-only model with prescribed SST can be as effective as the Tier-1 approach using coupled ocean-atmosphere model, at least for the monthly prediction of WNP summer monsoon with the BCC model. Similarly, Infanti and Kirtman (2017) noticed that the skill improvement due to the inclusion of air-sea coupling process is considerably limited. These findings are contrary to the notion that the monsoon (especially the WNP summer monsoon) simulation and prediction greatly require the inclusion of air-sea interaction (e.g., Wang et al. 2004, 2005; Wu and Kirtman 2005, 2007; Wu et al. 2006; Kug et al. 2008). Nevertheless, Zhu and Shukla (2013) stated that the inclusion of air-sea interaction may not be important for the prediction of monsoon variation trend (often measured by temporal correlation) but quite necessary for the prediction of monsoon variation amplitude (often measured by root mean square error). Note that in this study the Tier-2 approach with SST from coupled model is slightly more skillful than the Tier-1 approach for the WNP monsoon prediction (Fig. 6). This is not found in some previous studies (e.g., Zhu and Shukla 2013; Infanti and Kirtman 2017). The differences among the studies mentioned above may be partially due to the different model physics and initializations in various models. For example, compared with the model used in Zhu and Shukla (2013), the coupled model in this study shows more deficiency in reproducing the observed air-sea coupling process over the WNP, considering that the coupled hindcasts and uncoupled hindcasts with the same SST exhibit similar limitation in depicting the relationship between WNP rainfall and local SST (Fig. 7). Moreover, even with the same model configuration and initialization strategy, the impact of air-sea coupling is dependent on the forecast cases, showing distinct regional and seasonal disparities. Therefore, more efforts should be made to fully comprehend the role of air-sea interaction and its dependence on the model, to further improve climate model predictions.

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