Understanding the Predictability of East Asian Summer Monsoon from the Reproduction of Land–Sea Thermal Contrast Change in AMIP-Type Simulation

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ABSTRACT

Previous studies on the predictability of East Asian summer monsoon circulation based on SST-constrained Atmospheric Model Intercomparison Project (AMIP)-type simulations show that this phenomenon is reproduced with lower skill than other monsoon patterns. The authors examine the reason in terms of the predictability of land–sea thermal contrast change. In the observation, a stronger monsoon circulation is dominated by a tropospheric warming over East Asian continent and a cooling over the tropical western Pacific and North Pacific, indicating an enhancement of the summertime “warmer land–colder ocean” mean state. The tropospheric cooling over the tropical western Pacific and North Pacific, and the tropospheric warming over East Asian continent are reproducible in AMIP-type simulations, although there are biases over both the North Pacific and East Asia. The tropospheric temperature responses in the model indicate a reasonable predictability of the meridional land–sea thermal contrast; the zonal land–sea thermal contrast change is also predictable but shows bias over the region north to 25°N in North Pacific. The reproducibility of the meridional thermal contrast is higher than that of the zonal thermal contrast. An examination of the predictability of two commonly used monsoon indices reveals far different skills. The index defined as zonal wind shear between 850 and 200 hPa averaged over East Asia is highly predictable. The skill comes from the predictability of the meridional land–sea thermal contrast. Although the zonal thermal contrast change is mostly predictable except for the biases over the North Pacific, the monsoon index defined as zonal sea level pressure (SLP) difference across the East Asian continent and the North Pacific is unpredictable. The low skill is related to the index definition, which attaches more importance to the land SLP change. The limitation of the index in measuring the land SLP change reduces the model skill. Although regional features of monsoon precipitation changes remain a challenge for current climate models, the predictable land–sea thermal contrast change sheds light on monsoon circulation prediction.

1. Introduction

East Asia (EA) is one of the most populated regions of the world. Both the economy and society of the region rely heavily on the regular onset and retreat of monsoon rainfall. The East Asian monsoon prediction has historically been of crucial importance. However, understanding the physical processes that determine the monsoon phenomena and performing accurate predictions have posed remarkable challenges (see reviews by Wang 2006; Zhou et al. 2009a). Climate models are useful tools in understanding the mechanisms involved in monsoon processes and their prediction.

Numerical model prediction has developed from the concept that variation in atmospheric conditions is potentially predictable based on slowly varying lower boundary conditions, especially the anomalous sea surface temperature (SST) as well as land surface forcing (Charney and Shukla 1981). Substantial efforts have been devoted to the study of monsoon predictability by conducting Atmospheric Model Intercomparison Project–type experiments in which an atmospheric general circulation model (AGCM) is constrained by realistic SST and sea ice from 1979 to near present (Gates et al. 1999). The AMIP-type simulation has been subsequently
extended to the preindustrial era by the Climate Variability and Predictability (CLIVAR) International Climate of the Twentieth Century Project (C20C), with the intent of determining the extent to which observed climate anomalies in the past century, or longer, can be attributed to variations in SST (Folland et al. 2002). Analysis of the output of C20C experiments demonstrates encouraging performance of AMIP-type simulations in reproducing some major twentieth-century climate events, such as the globally rapid land surface warming occurring since the 1970s, Southern Oscillation variability, part of the Sahel drought, and the long-term variability of South Asian monsoon rainfall (Scaife et al. 2009; Kucharski et al. 2009). However, disappointing performance is found in the simulation of East Asian summer monsoon (EASM) variability. Identifying the priority of different components of Asian–Australian monsoon circulations in terms of reproducibility reveals that, while the South Asian monsoon, Australian monsoon, and western North Pacific monsoon circulations are highly predictable with specified SST, the EASM circulation variation is poorly modeled (Zhou et al. 2009b). Previous studies also show controversial results on the predictability of the EASM by AMIP-type integration. For example, while Han and Wang (2007) indicated that interdecadal variability of the EASM is a natural variability and cannot be explained by historical global SST and sea ice evolution, Li et al. (2010) argued that interdecadal variability of the EASM circulation is partially predictable owing to the tropical ocean warming. The predictability of the EASM remains inconclusive.

The difficulty of AMIP-type experiments in reproducing the variation of Asian monsoon rainfall has been well documented. For example, the AMIP1 models show a large bias in simulation of the annual cycle of eastern China monsoon rainfall, and the biases are concurrently reflected in planetary circulation (Liang et al. 2001). The Indian monsoon rainfall variation during 1979–88 is poorly simulated by AMIP1 models due to the mean state bias (Sperber and Palmer 1996). Although the subseasonal mode of monsoon precipitation may be distinguished from the seasonal mean mode (Kim et al. 2008), the skill of summer precipitation simulation in the Asian–Australian monsoon region is considerably lower than its counterpart in the tropical central-eastern Pacific region (Kang et al. 2002; Wang et al. 2004). The AMIP2 models show barely any skill in the simulation of interannual variability of summer precipitation over the extratropical western North Pacific and South China Sea (Zhou et al. 2009c). Low skill is also seen in the simulation of long-term precipitation changes over the EA land area in an AMIP-type integration covering the period from 1950 to 2000 (Zhou et al. 2008). While the unsatisfactory rainfall simulation may be partly attributed to neglect of local air–sea feedback in the AMIP-type simulation (Wang et al. 2005; Wu et al. 2006; Wu and Kirtman 2007), the climate modeling community is puzzled about previously reported low skill of EASM circulation prediction since the dominance of remote tropical ocean forcing on the EASM circulation should produce better predictive skills than actually observed (Wang et al. 2000; Wu et al. 2003). Until now, the reason for the low skill of AMIP-type experiment in simulation of EASM circulation change remains unknown. Given the fact that the monsoon is a result of land–sea thermal contrast (Guo 1983), the main motivation of this study is to examine the predictability of the EASM circulation from the perspective of land–sea thermal contrast change. Discussions on this issue will improve our understanding of the physical processes that determine monsoon variability and should serve as a useful reference for monsoon prediction.

The rest of the paper is organized as follows. Section 2 details the model data used and the methods, and section 3 presents the results. The conclusions are given in section 4 along with a discussion.

2. Model, data, and analysis method

The climate model used in this study is the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM3) (Collins et al. 2006), which employs an Eulerian dynamic core on a T85 (~1.4°) grid and 26 vertical levels. The model was forced by historical global SSTs covering the period from 1958 to 2000. The SST dataset was a blended version of the HadISST and Reynolds dataset (Hurrell et al. 2008). An ensemble simulation with four realizations was done by the climate variability group of NCAR. Our forthcoming analysis is based on the ensemble mean of four realizations.

The verification datasets include: 1) The European Centre for Medium-range Weather Forecasts (ECMWF) 40-yr Reanalysis (ERA-40) data (Uppala et al. 2005). The 2.5° × 2.5° monthly temperature and wind at different vertical levels and sea level pressure (SLP) data were used. 2) The monthly Hadley Centre Climate Research Unit version 3 (HadCRUT3) combined land (Climate Research Unit land temperature dataset) and marine [sea surface temperature anomalies from the Hadley Centre’s sea ice and SST data set version 2 (HadSST2), see Rayner et al. 2006] temperature anomalies on a 5° × 5° grid (Brohan et al. 2006). 3) The monthly precipitation dataset for 1958–2005 created by collecting observational data of 700 rain gauges across continental China. The data was provided by the National Meteorological Information Center of China Meteorological Administration. Since the observational data, reanalysis data, and model output were available on different horizontal resolutions, all data
were regridded to a common 2.5° × 2.5° grid box in order to facilitate comparison. The results are shown on a 2.5° × 2.5° grid basis.

We use the ERA-40 as observational evidence because the quality of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data (hereafter NCEP data) (Kalnay et al. 1996) before 1970s was questionable (Inoue and Matsumoto 2004; Wu et al. 2005; Greatbatch and Rong 2006). The EASM has experienced a strong interdecadal variability, which is evident in both independent station observations and the reanalysis data [see Zhou et al. (2009a) for a review]. Although the NCEP and ERA-40 reanalysis data qualitatively exhibit agreement in quantifying the weakening tendency of the EASM circulation starting from the end of 1970s, the change derived from the NCEP data is stronger than that derived from the ERA-40 data (Li et al. 2010) and the Hadley Centre’s sea level pressure (HadSLP) dataset (Zhou et al. 2009a).

Although it is difficult to measure the EASM with only one index owing to its complex space and time structures encompassing tropics, subtropics, and midlatitudes (Wang et al. 2008b), we employ two frequently used dynamical EASM circulation indices in our model evaluation:

1) The traditional SLP index defined by Guo (1983, hereafter Guo index), which is the summation of June–August (JJA) SLP difference (ΔSLP) from 10°N to 50°N between 110°E and 160°E. The ΔSLP shows the pressure gradient between land (110°E) and sea (160°E). Integrating the ΔSLP emphasizes the general intensity of the summer monsoon. The time series was divided by its climate mean value. So, a stronger East Asian summer monsoon corresponds to a higher Guo index and stronger lower-tropospheric southerly wind. The Guo index reflects the east–west thermal contrast.

2) The zonal wind shear index of Han and Wang (2007, hereafter Han index), which is defined as the normalized zonal wind shear (or difference) between 850 and 200 hPa averaged over 20°–40°N, 110°–140°E. The Han index reflects the north–south thermal contrast.

The traditional Chinese meaning of a strong EASM corresponds to a deficient mei-yu that is associated with its abnormal northward extension of southerly winds over northern China (Wang et al. 2008b; Zhou et al. 2009a). Both Guo and Han indices belong in the category of the traditional Chinese definition, where a stronger index means a weaker mei-yu along the Yangtze River valley (30°N) but excessive rainfall in north China (35°–40°N).

The monsoon indices derived from the reanalysis data are termed observed indices in the following discussion.

3. Results

a. Monsoon indices and related surface climate

The performance of the CAM3 model in simulating the EASM has been assessed by Chen et al. (2010). The major climate mean states and seasonal features of the EASM circulation system are well simulated except for the bias in monsoon rainfall (Chen et al. 2010). As shown in Fig. 1, the prominent features of the EASM circulation are reasonably simulated, except that the western Pacific subtropical high (WPSH) in the middle and lower troposphere shifts northward. This bias is also evident in earlier version of CAM3 (Zhou et al. 2009b) and may have impacts on the water vapor transport of monsoon circulation (Zhou and Yu 2005).
The summertime (JJA) mean SLP field features the WPSH in the Pacific Ocean and relatively lower pressure systems over the East Asian continent (Fig. 1), so clearly the Guo index is a measure of the zonal pressure gradient. The monsoon circulation over the East Asian continent on the surface features a prominent southwestern flow; the Han index reflects the surface southwesterly flow (Fig. 1) and the upper-level subtropical westerly jet around 200 hPa (Zhang et al. 2006).

The monsoon indices derived from the ERA-40 reanalysis are shown in Figs. 2a and 2c. Variation of the EASM in the past 43 years is characterized by distinct events of above and below normal conditions. The monsoon was stronger than normal prior to the 1970s. Starting from the mid-1970s, a weakened monsoon was witnessed. The interdecadal shift of the monsoon circulation is more evident in the Han index. Interannual variability was also robust along with low-frequency interdecadal variation. The above features have been well-documented in previous studies (Hu 1997; Hu et al. 2003; see also Zhou et al. 2009a for a review). The correlation coefficient between the two indices is 0.48, which is statistically significant at the 5% level.

The monsoon indices derived from the simulation are shown in Figs. 2b and 2d. Variations of the EASM measured by the Han index is partially reproduced in the simulation. The correlation coefficient between the simulation and the observation is −0.02. Predictability of the two indices with specified identical SST is different.

Precipitation is the most direct and important measurement of a monsoon. To depict the precipitation pattern, Fig. 3 presents correlation coefficient patterns of precipitation anomalies with two monsoon indices. In the observation (Figs. 3a,c), strong phases of the two monsoon indices are associated with excessive precipitation in north China (35°–40°N) and deficient precipitation in middle China along the Yangtze River valley (30°N). The structure of the simulation is not well shaped, and no resemblance to the observation is seen (Figs. 3b,d). While the specified SST forcing can partly reproduce the monsoon circulation changes measured by the Han index, it does not show significant skill in precipitation anomalies. This result is consistent with previous studies and may be related to the relatively low resolution of the global AGCM (Yu et al. 2000; Zhou and Li 2002; Zhou et al. 2009b,c; Li et al. 2010) and the bias of climate mean precipitation in CAM3 (Chen et al. 2010). This is another reason why our analysis focuses on the monsoon circulation.

The traditional meaning of a monsoon is a seasonal reversal of wind. To determine the surface circulation fields associated with monsoon indices, the observed monsoon time series are regressed upon the 850-hPa wind fields derived from both the reanalysis and the simulation. Regression coefficients for the meridional and zonal wind components are shown as vectors in Fig. 4.
In the reanalysis (Fig. 4a), East Asia is dominated by an anticyclonic circulation over northern China and a cyclonic circulation over southern China. The circulation pattern is consistent with the corresponding rainfall anomalies. North China is dominated by northward wind anomalies and excessive rainfall associated with a stronger phase of the Guo index (Fig. 3a). Thereby the Guo index highlights the monsoon strength over northern China. The 850-hPa wind associated with the Han index features an anticyclonic circulation over the East Asian continent and western North Pacific (Fig. 4c). Thereby the Han index highlights the monsoon circulation over a broader scale.

In the simulation, the northward wind anomalies are partially reproduced but with much weaker magnitudes (Figs. 4b,d). While the surface wind anomalies for the Han index are consistent with the indices shown in Fig. 2d, the wind anomaly in the Guo index is surprising (Fig. 4b). Although the Guo index derived from the reanalysis is poorly modeled (Fig. 2b), the surface wind field still exhibits some useful skill. This raises an issue about an apparent paradox between the surface wind and the monsoon index. This paradox will be explained by the index definition in the following discussion.

Variations in SLP are closely related to wind vectors. The correlation maps of SLP anomalies with two monsoon indices are shown in Figs. 5a,c for the reanalysis. The SLP fields feature negative anomalies over the East Asian continent, which is consistent with the cyclonic circulations shown in Figs. 4a,c. For the Guo index, significant positive SLP anomalies are seen over the tropical and extratropical North Pacific east to 130°E (Fig. 5a). For the Han index, significant positive anomalies are seen over the western Pacific around the Philippine Sea. The SLP pattern indicates a pressure gradient in the zonal direction associated with a stronger phase of the Guo index, but a pressure gradient in the meridional direction associated with a stronger phase of the Han index.
In the simulation, negative SLP anomalies associated with the Guo index are also evident over East Asia but with a weaker magnitude and narrower zonal extent (Fig. 5b). Responses of SLP fields in the model are consistent with those of surface wind, which appear as northward wind anomalies over northern China (Fig. 4b). The narrower zonal extent of negative SLP results in a weak signal eastward to 110°E, which may further impact the predictability of the Guo index. In the meantime, a discrepancy is also seen over the North Pacific, where the simulated positive SLP anomalies are far weaker than in the reanalysis. For the Han index (Fig. 5d), the meridional SLP contrast is partly reproduced except with weaker amplitude, in particular over the East Asian land area. The tropical positive SLP anomalies are constrained south of 20°N, which is about 5° south to the reanalysis. This deficiency is consistent with the wind fields shown in Fig. 4d.

We note the consistency between negative SLP over East Asia and the northward wind anomaly over land...
The meridional wind is a direct response to SLP change. Since the Guo index is defined as the SLP gradient between 110°E and 160°E, the weak negative land SLP along 110°E, together with the weak oceanic positive SLP across 10°–50°N along 160°E, result in the low skill in simulation of the Guo index (Fig. 5b). This partially explains the paradox between the surface wind and the monsoon index as noted above.

In summary, the AMIP-type simulation shows some significant skills in the simulation of EASM circulation variability, depending on the type of monsoon index employed. The strength and weakness for two monsoon indices are also evident in the related surface climate fields. Thus, these preliminary remarks prompt a further look into the driving mechanisms. Because the primary cause of the monsoon circulation is the gradient of atmospheric diabatic heating between the ocean and land (Li and Yanai 1996), an examination of the land–sea thermal contrast should help us understand the physical and dynamical processes that determine monsoon variability in the AMIP-type simulation. This is the issue to be discussed in the following section.

b. Land–sea thermal contrast: Spatial structure

We feature the land–sea thermal contrast change in the reanalysis by presenting the tropospheric mean (200–500 hPa) temperature anomalies correlated with the monsoon index (Figs. 6a,c). In the reanalysis, the spatial structure exhibits significant tropospheric warming over East Asia. Cooling temperature anomalies are evident in the tropical western Pacific and extratropical North Pacific. The correlation coefficients exceed 0.60 over East Asia and are lower than −0.60 over the ocean. Since the mean state of summertime tropospheric mean temperature features a “warm land–cold ocean” condition, the “warmer land–colder ocean” anomaly pattern favors a stronger summer monsoon circulation.

Contrary to the Indian monsoon, which is primarily caused by the meridional temperature gradient between

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**FIG. 5.** Patterns of correlation coefficients between JJA mean residual SLP anomalies and time series of (a),(b) the Guo index and (c),(d) the Han index from (a),(c) the ERA-40 reanalysis and (b),(d) the CAM3 simulation. The residual is defined as the local value minus the domain average. The anomalies are calculated relative to the climate mean for 1958–2000. The contour indicates the threshold of the regions that are statistically significant at the 5% level.
the Indian Ocean and South Asia, the EASM is caused by a combination of zonal thermal contrasts between East Asia and the North Pacific and meridional thermal contrasts between East Asia and the tropical western Pacific (Figs. 6a,c). This is consistent with previous findings that the EASM is composed of tropical and extratropical systems, where both meridional and zonal land–sea thermal contrast play pronounced roles, as first noted by Zhu et al. (1986) and later emphasized by Zhu et al. (2005) and many others.

The spatial structures of warm temperature anomalies associated with two monsoon indices are consistent over the East Asian continent. The cold temperature associated with the Guo index extends from the equator to 40°N in the extratropical North Pacific, while that associated with the Han index is confined to the tropical western Pacific, suggesting that it is closely linked to the convective activity over the western Pacific. The Guo index highlights the zonal land–sea thermal contrast part, while the Han index mainly reflects the meridional thermal contrast part.

The simulated meridional land–sea thermal contrast is generally better than the zonal land–sea thermal contrast (Figs. 6b,d). For the Guo index, the simulation reproduces the tropospheric cooling over the tropical ocean, but the cold anomalies extend northward to 30°N over the East Asian continent, thus the simulated East Asian tropospheric warming is confined to the region north to 30°N (Fig. 6b). The warm temperature over land also erroneously extends eastward to the extratropical North Pacific, leading to low skill in that region. For the Han index, while the tropical cooling is reasonably well simulated, the warming over East Asian continent is weaker than in the reanalysis, and the warming over the midlatitude North Pacific is too strong (Fig. 6d).

This comparison demonstrates that the AMIP-type simulation is able to reproduce the observed tropospheric mean temperature changes over the East Asian continent, tropical and extratropical North Pacific. Thereby both meridional and zonal land–sea thermal contrast change is greatly predictable with specified SST forcing, with the former being better reproduced than the latter. The weakness of AMIP-type simulation is that the tropospheric warming over the East Asian continent is weaker than in the reanalysis, leading to a zonal thermal contrast weaker than the reanalysis.

Maps of the corresponding structure of land–sea thermal contrast at various vertical levels (Fig. 7 and Fig. 8) help clarify the nature of vertical mean patterns. The Guo index highlights the zonal land–sea thermal contrast (Fig. 7). In the reanalysis, the signature of “warmer land–colder ocean” is evident with maximum warming
over East Asia extending from 20° to 50°N, 90° to 125°E. Maximum cooling is seen over the ocean area eastward to 140°E (Fig. 7, left column). Both warmer anomalies over East Asia and colder anomalies over the ocean show deep vertical structure and penetrate throughout the upper troposphere from 500 to 200 hPa. Both the warmer and colder centers exhibit the maximum magnitude in the upper troposphere above 300 hPa. The above feature fits the definition of the Guo index, which focuses on the measure of zonal land–sea thermal contrast change.

An encouraging result is seen in the simulation of the zonal land–sea thermal contrast change (Fig. 7, right column). The observed “warmer land–colder ocean” structure is also evident in the simulation. The model also shows several weaknesses. The spatial coverage of
the colder anomalies over the ocean is wider than for the reanalysis below 300 hPa, while the reproduced upper-tropospheric warming over the East Asian continent is narrower in the meridional extent. In the reanalysis the warm anomalies over East Asia extend from 50°N southward to 10°N along 110°E, but in the simulation the warm anomalies are confined to the north of 30°N. The AMIP-type simulation is able to reproduce the zonal land–sea thermal contrast change across East Asia and the North Pacific. But the meridional coverage of warmer air over East Asia and the colder air over the ocean show biases. The deficiency may influence the regional averages of warmer air over the land and colder air over the ocean, and thereby the zonal land–sea thermal contrast change.

The Han index highlights the meridional land–sea thermal contrast, the meridional signature of “warmer land–colder ocean” is evident in the reanalysis, with maximum warming around 300 hPa over East Asian land extending from 20° to 50°N (Fig. 8, left column). The cold anomalies over the western Pacific are evident throughout the upper troposphere. The meridional land–sea thermal contrast change associated with the Han index partly resembles that associated with the Guo index, but clearly highlights the tropical western Pacific Ocean.

The encouraging aspect of the simulation is that the meridional “warmer land–colder ocean” structure associated with the Han index has been largely reproduced (Fig. 8, right column), although in comparison to the reanalysis, the simulated warmer temperature over East Asian land is weaker in magnitude and narrower in the meridional extent. In the reanalysis, the warmer anomaly is confined to west of the date line but in the simulation it extends eastward across the date line. From 500 to 200 hPa, the colder ocean structure is reasonably simulated, with a magnitude comparable to the reanalysis. The well-shaped “warmer north–colder south” structures in both the reanalysis and the simulation indicate high predictability of the meridional land–sea thermal contrast.

In addition, there are also some studies that simply measure the land–sea thermal contrast change by surface air temperature (SAT) (Zhang et al. 2002). The correlation coefficients of SAT anomalies with two monsoon indices in the observations are shown in Figs. 9a,c. A stronger phase is associated with a warmer land and colder ocean. For the Guo index cool conditions prevail over the tropical western Pacific and extend westward to the tropical Indian Ocean. A weak insignificant cooling center is also evident over the extratropical North Pacific. Comparable warmth appears over the Tibetan Plateau and central eastern China along 30°N. For the Han index, the warming center over East Asia extends eastward to the North Pacific. The cooling signature is most significant over the Maritime Continent.

In the simulation (Figs. 9b,d), colder temperature anomalies prevail over the Maritime Continent and the tropical Indian Ocean, in particular for the Guo index, such that warmth over the East Asian continent is weak. Positions of the warm centers are also different from the observations. The warm signature over the Tibetan Plateau is weak in the simulation. The center associated with the Han index shifts eastward to the coastal area.

In the observation, the emphasis of land–sea thermal contrast as measured by SAT is the meridional temperature gradient. The AMIP-type experiment is useful in simulating the SAT change over the tropical ocean, but is a far weaker predictor over East Asian land. In comparison with the pattern of SAT shown in Fig. 9, the well-organized structures of tropospheric mean temperature changes shown in Figs. 6–8 imply that they are better indicators of land–sea thermal contrast change than the SAT.

A demonstration of the land–sea thermal contrast effect is the narrow and strong westerly jet over subtropical East Asia, which is usually referred to as the East Asian subtropical westerly jet (EASWJ) (Zhang et al. 2006). The meridional shift of the westerly jet center is closely related to the interannual variability of the East Asian summer monsoon (Lau et al. 1988; Liang and Wang 1998) and Asian–Pacific climate (Yang et al. 2002). The zonal wind at 200 hPa is a reasonable measure of the EASWJ. Changes of the zonal wind at 200 hPa, associated with stronger monsoon indices, are shown in Figs. 10a,c for the reanalysis. A stronger monsoon index is associated with a weakened (intensified) westerly south (north) to the jet axis, as revealed by many previous studies and generally accompanied by deficient (excessive) rainfall in central (northern) China along the Yangtze (Yellow) River valley (Liang and Wang 1998; Zhou and Yu 2005). The meridional shift of the westerly jet is reasonably reproduced (Figs. 10b,d), although the enhanced zonal wind northward to the jet axis is weaker than the reanalysis in amplitude. Given the reasonable performance of the model in reproducing the meridional land–sea thermal contrast (Fig. 8), this result is expected. Whereas the zonal wind at 200 hPa was used in the calculation of the Han index, the resemblance of Fig. 10d to Fig. 10c also confirms the significant correlations of the simulated and observed Han indices. The principle of thermal wind tells us that the variation of zonal wind with altitude depends on the meridional gradient of air temperature. If the air temperature increases poleward, the westerly would weaken (Zhang et al. 2006).
The correspondence between the temperature gradient and westerly jet in the model responses is well explained.

c. Land–sea thermal contrast: Time series

In the reanalysis, an intensified monsoon features a warmer center over East Asia (region A of Fig. 6c; 30°–55°N, 95°–130°E) and two cold centers over the North Pacific (region B of Fig. 6a; 5°–30°N, 135°–200°E) and the tropical western Pacific (region C of Fig. 6c: 0°–25°N, 110°–170°E). We further examine the predictability of land–sea thermal contrast in terms of the 200–500 hPa thickness mean temperature averaged within the three boxes. An overlapping area exists between boxes B and C. Boxes A and B (A and C) are used to measure the Guo (Han) index.

The time series derived from the reanalysis are shown in Figs. 11a–c. The simulated climate mean temperature
over the East Asian land area is comparable to the reanalysis (−31.8°C versus −31.4°C), but there is a discrepancy in the time evolution of the indices (Fig. 11a). The simulated year-by-year variability of the index is weaker than the reanalysis in amplitude with a standard deviation of 0.31°C versus 0.61°C. The correlation coefficient between the index derived from the reanalysis and that derived from the simulation is 0.35, which is statistically significant at the 5% level. The negative SLP anomalies over the East Asian continent may be partly explained as a surface response to tropospheric warming. The tropospheric warming-induced mass change may be reduced in the lower troposphere—especially the surface pressure—resulting in an anomalous cyclone beneath the upper tropospheric warming and, thereby, an enhanced southerly flow over East Asian continent. A similar mechanism has been used to explain the interdecadal variability of the EASM (Yu et al. 2004; Yu and Zhou 2007). Note that, since the Indian thermal low is shallow and has little consistency with upper-troposphere temperature, caution is needed when using a monsoon index based on single SLP in Indian monsoon studies.

A high predictability is seen for the temperature index averaged within region B (Fig. 11b). The simulation is closely similar to the reanalysis in climate mean value (−28.7°C versus −30.2°C), amplitude (0.42°C versus 0.34°C in standard deviation), and phase relationship of year-by-year variability. The correlation coefficient between the two time series is 0.72, which is statistically significant at the 1% level.

The tropical western Pacific temperature index (region C) is also highly reproducible (Fig. 11c). The simulation exhibits a close resemblance to the reanalysis in year-by-year variation, having a correlation coefficient of 0.63, which is statistically significant at the 1% level. One defect of the simulation is the stronger upward trend after the early 1990s. The standard deviation of the simulation is 0.45°C, which is stronger than the observed value of 0.27°C.

Among the temperature indices averaged respectively over three boxes, the indices measuring the temperature changes over regions B and C in the western Pacific are highly predictable, whereas that measuring the temperature changes over the East Asian continent is partly
predictable, as evidenced by the lower but still statistically significant (at the 5% level) correlation coefficient.

d. Discussion of the paradox of monsoon predictability measured by different indices

In conjunction with previous studies (Han and Wang 2007; Zhou et al. 2009b; Li et al. 2010), our results shown in Fig. 2 reveal a paradox of monsoon predictability in terms of different indices. To explore the reason for the paradox, we further examine the predictability of different components used in constructing the index. We begin the discussion with the conventional Guo index, which has been widely used in Chinese literature and also highlighted by the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report (AR4) (Trenberth et al. 2007). The Guo index is defined as a zonal SLP difference between the land and the ocean, the skills of the land and ocean components (i.e., the meridional summation of SLP anomalies from 10° to 50°N along 110°E and 160°E, respectively) are examined.

If we consider the simulation as a first-order approximation of the observation, we construct the simulated Guo index in two ways. First, supposing that the model has a perfect reproduction of land SLP, we compute the Guo index based on the observed land SLP and simulated ocean SLP. This index is called the perfect-land index.

Second, supposing that the model has a perfect reproduction of ocean SLP, we compute the Guo index based on the simulated land SLP and observed ocean SLP. This index is called the perfect-ocean index.

The correlations of the perfect-land and perfect-ocean indices with the observational Guo index are computed. As shown in Fig. 12a, the correlation coefficient of the perfect-land (ocean) index with the observation is 0.53 (0.39), which is statistically significant at the 5% level. Both the perfect-ocean and the perfect-land assumption significantly improve the model skill, but the improvement due to the perfect-land assumption is larger. The low skill in the prediction of the Guo index is largely a result from the land component.

Why does the land component of the Guo index show such lower predictability? Recall that the land component of the Guo index is the summation of SLP anomalies along 110°E from 10°N to 50°N. Inspection of Fig. 5b indicates that the 110°E longitude is located at the eastern edge of the regions with significant negative correlation coefficients. The negative SLP anomaly along 110°E in the simulation is weaker in amplitude than in the reanalysis. The northward penetration of tropical positive SLP anomaly to 20°N along the East
Asian continental boundary also partially cancels the weak negative SLP anomalies over the land. These two limitation aspects explain why the variation of land component of the Guo index is poorly simulated. The contrasting skill difference between the perfect-land and the perfect-ocean indices also indicates the larger contribution of the land component of the Guo index. We verify this by estimating the contribution of land and ocean components to the Guo index. In the reanalysis, the standard deviation of SLP anomaly is 12.58 hPa for the land component and 11.75 hPa for the ocean component. The correlation coefficient of land (ocean) component with Guo index is 0.53 (-0.42), indicating that the variance accounted by the land component is about 10.5% larger than that accounted by the ocean component. Therefore, the Guo index is dominated primarily by the land SLP change over East Asia and secondarily by the ocean SLP changes over the western Pacific.

A similar method is employed for the Han index with the motivation of estimating the contribution of different components. For the Han index defined as the zonal wind shear between 850 and 200 hPa, a perfect 850-hPa index is computed based on the observed (simulated) zonal wind at 850 hPa and a corresponding perfect 200-hPa index is computed based on simulated (observed) zonal wind at 850 hPa. As shown in Fig. 12b, the correlation coefficients of the perfect 850-hPa and perfect 200-hPa indices with the observed Han index are 0.69 and 0.61, respectively, and both are statistically significant at the 5% level. Therefore, the model shows comparable skills in reproducing zonal wind variability at 850 and 200 hPa, with the former being slightly higher. There is also a hint that the zonal wind at 850 and 200 hPa has comparable contributions to the variability of the Han index. This is further confirmed by a comparison of the variances of Han index
accounted for by two different components. The correlation coefficient of the 850 hPa (200 hPa) component with the Han index is 0.53 (~0.53), indicating an equal percentage variance of 28.9%.

4. Summary and discussion

a. Summary

Understanding the physical processes that determine specific climate variability phenomena and performing climate predictions heavily requires reliance on the response of AGCM to specified SST forcing. The skill of this kind of SST-constrained AGCM simulation in the East Asian monsoon region is generally lower than that in other monsoon regions. Given that the monsoon circulation is dominated by land–sea thermal contrast, the reproducibility of the EASM circulation is studied from the perspective of changes in land–sea thermal contrast simulation. The main results are summarized below:

1) The observational change of the EASM circulation is dominated by a combination of meridional and zonal land–sea thermal contrast changes. A stronger phase of monsoon circulation follows a tropospheric warming over the East Asian continent, a cooling over the tropical western Pacific and extratropical North Pacific, indicating enhancement of the summertime “warmer land–colder ocean” mean state. The land–sea thermal contrast measured by tropospheric mean temperature is a better indicator than that measured by surface air temperature.

2) The AMIP-type simulation shows significant skills in reproducing the tropospheric cooling over the tropical and extratropical western Pacific. The observed tropospheric warming over the East Asian continent is reasonably reproduced, as evidenced by the statistically significant correlation coefficient at the 5% level. The tropospheric temperature responses in the model indicate that both meridional and zonal land–sea thermal contrasts are predictable, but the meridional thermal contrast is better reproduced than the zonal thermal contrast.

3) The predictability of two frequently used monsoon indices is examined. The meridional land–sea thermal contrast monsoon index (i.e., Han index)—defined as the normalized zonal wind shear between 850 and 200 hPa averaged within 20°–40°N, 110°–140°E—is highly predictable as indicated by the statistically significant correlation coefficient at the 5% level between the simulation and the reanalysis. Another index (i.e., the Guo index)—defined as the zonal sea level pressure difference between 110° and 160°E—is unpredictable based on the result of CAM3 simulation.

4) The skill of the predictable wind shear monsoon index comes from the predictability of meridional land–sea thermal contrast. Evidence is also seen in the successful simulation of changes in the subtropical westerly jet over East Asia, which is a representative of meridional land–sea thermal contrast.

5) With regard to the lower predictability of monsoon index defined as the zonal SLP difference across the land and ocean (i.e., the Guo index), the primary reason is related to the definition of the index, which attaches great importance to land SLP change. In the model’s response, the weaker SLP signal along 110°E over the land together with a cancellation of positive ocean SLP anomalies owing to the northward penetration of a tropical signal, results in the low skill of predictability. The model also shows significant skills in reproducing the zonal land–sea thermal contrast change, albeit with clear bias; the potential skill of the Guo index should be higher than that we observed.

6) In comparison with the predictable monsoon circulation change, the regional features of monsoon precipitation anomalies are still unpredictable. In the observation, a stronger phase of monsoon circulation is associated with a warmer surface air temperature over East Asian continent and a colder surface air temperature over the tropical ocean, highlighting a meridional land–sea thermal contrast. The model shows significant skill over the tropical ocean but lower skill over East Asia. A realistic reproduction of surface air temperature and precipitation anomalies over East Asia remains a challenge.

b. Discussion

Previous studies on the EASM predictability show controversial results. Our analysis has elaborated the confusion in terms of the first-order driving mechanism of monsoon circulations. The high predictability of meridional land–sea thermal contrast and also the reasonable skill of zonal land–sea thermal contrast, and thereby the monsoon circulation, sheds light on monsoon prediction. Previous analyses of multimodel ensemble two-tier prediction systems found very poor precipitation correlation skill over the Asian monsoon region (Kang and Shukla 2006). Since the relationship between monsoon rainbands (and surface air temperature) and monsoon circulation has been well established in observations, the predictability of monsoon circulation may allow us to construct rainfall (as well as surface air temperature) anomalies based on this statistical relationship. In addition, the challenge that we are facing in realistic monsoon rainfall prediction may be partially due to the
low model resolution, which is unable to correctly simulate the narrow monsoon rainfall front. The dependence of rainfall interannual predictability on the annual cycle has been discussed (Liang et al. 2002). Whether high-resolution climate models can improve the skill of monsoon rainfall predictability deserves further study.

Theoretically, ocean–atmosphere coupled models should be more suitable tools in monsoon rainfall prediction since air–sea feedback processes are included (Wang et al. 2005; Wu et al. 2006; Wu and Kirtman 2007). However, an evaluation of the performance of a seven coupled-model ensemble, retrospective of seasonal predictions (1980–2004), found nearly zero predictive skill in surface temperature and rainfall over East Asian land area (Wang et al. 2008a). The coupled NCEP climate forecast system also performs poorly in capturing interannual variability of the EASM circulation index (Yang et al. 2008). The predictability skill may be compromised by model bias in the mean state. Coupled model SST biases could interfere with the benefits deriving from an active air–sea coupling (Cherchi and Navarra 2007). An improvement in an ocean–atmosphere coupled model’s mean state can lead to a realistic simulation of ENSO–monsoon connection (Lau and Nath 2000; Turner et al. 2005). Given limitations of current state-of-the-art coupled models, the two-tier prediction system and AMIP-type simulations should still serve as a useful tool in the field of monsoon prediction and related studies, which aim to understand the physical processes related to monsoon variability.

The predictability of the meridional land–sea thermal contrast is dominated by tropical ocean forcing. Tropical SST anomalies are primary sources of atmospheric climate variability (Wang et al. 2008a; Yang et al. 2008). The theory of how the tropical ocean forces the atmosphere has been well addressed (Bjerknes 1969; Trenberth et al. 1998). In the simulation, the tropospheric temperature change over the extratropical North Pacific northward to 30°N is poorly simulated, this may be attributed to the experimental design in which the atmosphere is forced to respond to the specified SSTs, while in nature SSTs are partially forced by the atmosphere (Lau 1997; Alexander et al. 2002).

Although both meridional and zonal land–sea thermal contrast change is significantly predictable, the skill over the land is far lower than its counterpart over the ocean. For example, the model accounts for 51.8% of the variance of the observed western Pacific tropospheric temperature anomaly (i.e., the temperature anomaly averaged within region B), but only explains about 12.3% of its counterpart over region A of the East Asian continent (Fig. 11). Land-surface processes have significant feedbacks on the East Asian monsoon (Yang and Lau 1998; Xue 2004; Yasunari 2007). The limitation of land SLP simulation may be also partly due to the influence of lower troposphere and surface conditions, which is hard to reproduce in simulations. Since the land surface was not constrained to the observational data in the AMIP-type simulation, there is potential for further improvement of land–sea thermal contrast change prediction by including the land surface forcing. The impacts of land surface on the prediction skill of land–sea thermal contrast, especially the land component, should be assessed in future studies.

Analysis on the monsoon index, which is defined as the zonal SLP gradient across East Asia and the western Pacific, reveals some aspects of the index’s limitations. The summation of SLP anomalies along only the 110°E longitude may not be a good representative of SLP anomalies over the East Asian land area. For example, our analysis reveals a weak but statistically significant SLP anomaly over East Asia (Figs. 5b,d) because 110°E is located at the eastern edge of regions with significant signals, and a summation of SLP anomalies along this single longitude underestimates the model’s skill. Because the instrumental record of SLP data has a far longer history than any other variable, one unique merit of the SLP-based monsoon index is its long time coverage. An examination into possible ways to improve the SLP-based monsoon index deserves further study.

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