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Sensitivity of a regional climate model to land surface parameterization schemes for East Asian summer monsoon simulation

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Abstract Land surface processes play an important role in the East Asian Summer Monsoon (EASM) system. Parameterization schemes of land surface processes may cause uncertainties in regional climate model (RCM) studies for the EASM. In this paper, we investigate the sensitivity of a RCM to land surface parameterization (LSP) schemes for long-term simulation of the EASM. The Weather Research and Forecasting (WRF) Model coupled with four different LSP schemes (Noah-MP, CLM4, Pleim–Xiu and SSiB), hereafter referred to as Sim-Noah, Sim-CLM, Sim-PX and Sim-SSiB respectively, have been applied for 22-summer EASM simulations. The 22-summer averaged spatial distributions and strengths of down-scaled large-scale circulation, 2-m temperature and precipitation are comprehensively compared with ERA-Interim reanalysis and dense station observations in China. Results show that the downscaling ability of RCM for the EASM is sensitive to LSP schemes. Furthermore, this study confirms that RCM does add more information to the EASM compared to reanalysis that imposes the lateral boundary conditions (LBC) because it provides 2-m temperature and precipitation that are with higher resolution and more realistic compared to LBC. For 2-m temperature and monsoon precipitation, Sim-PX and Sim-SSiB simulations are more consistent with observation than simulations of Sim-Noah and Sim-CLM. To further explore the physical and

dynamic mechanisms behind the RCM sensitivity to LSP schemes, differences in the surface energy budget between simulations of Ens-Noah-CLM (ensemble mean averaging Sim-Noah and Sim-CLM) and Ens-PX-SSiB (ensemble mean averaging Sim-PX and Sim-SSiB) are investigated and their subsequent impacts on the atmospheric circulation are analyzed. It is found that the intensity of simulated sensible heat flux over Asian continent in Ens-Noah-CLM is stronger than that in Ens-PX-SSiB, which induces a higher tropospheric temperature in Ens-Noah-CLM than in Ens-PX-SSiB over land. The adaptive modulation of geopotential height gradients affects wind field (through geostrophic balance) simulation especially at lower levels, which subsequently affects the simulation of large-scale circulation, 2-m temperature and monsoon precipitation as well as RCM's downscaling ability.

Keywords Regional climate model · East Asian summer monsoon · Dynamical downscaling · Land surface parameterization scheme · Atmosphere-land interaction

1 Introduction

Regional climate models (RCMs) have been applied for climate research since the late 1980s (Dickinson et al. 1989; Giorgi and Bates 1989). One distinct advantage of RCM application is its high horizontal resolution, which enables the RCM to provide additional details beyond global reanalysis or global climate simulations (Liang et al. 2004; Feser et al. 2011) and realistically describe certain critically important climate processes, such as clouds and land-surface processes/features (Leung et al. 2003; Xue et al. 2014; Oaida et al. 2015). As a promising tool, RCMs are now widely applied for dynamic downscaling

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of coarse-resolution gridded data from various reanalysis datasets and/or forecast products of general circulation models (GCMs). RCMs have also been increasingly used to meet the demand of forecast (e.g. Castro et al. 2012; Ratnam et al. 2013; Shukla and Lettenmaier 2013), to conduct sensitivity experiments (e.g. Xue et al. 2012; Barlage et al. 2015; Oaida et al. 2015), to project future climate change scenarios (e.g. Liang et al. 2006; Mearns et al. 2012; Dubois et al. 2012; Rajbhandari et al. 2015) etc., among many other applications.

However, there are large uncertainties in RCMs studies (Fu et al. 2005; Foley 2010; Feser et al. 2011; Mearns et al. 2012; Xue et al. 2014). Several important factors that lead to uncertainties in the dynamic downscaling of RCM studies include errors caused by the poor quality of lateral boundary condition (Mearns et al. 2012; Yang et al. 2012) and/or choice of driving GCM (Déqué et al. 2007). Domain size, location, resolution (Liang et al. 2001; Alexandru et al. 2007; Xue et al. 2007; Hagos et al. 2014), natural variability of the atmospheric circulation (Kjellström et al. 2011), physical parameterization (Fernández et al. 2007; Mooney et al. 2013) etc., also contribute to uncertainties in RCM studies. Among the factors mentioned above, physical parameterizations, including the radiation parameterization scheme (e.g. Mooney et al. 2013), the microphysics scheme (e.g. Fernández et al. 2007), the convective parameterization scheme (e.g. Giorgi and Shields 1999; Gochis et al. 2002; Liang et al. 2006, 2007; Ratna et al. 2014), the planetary boundary layer parameterization scheme (e.g. Flaounas et al. 2011; Güttler et al. 2014; Wang et al. 2014), and land surface parameterization scheme (e.g. Music and Caya 2009; Gianotti et al. 2012; Sato and Xue 2013) exert significant influences on the dynamic downscaling capability of RCMs.

Previous studies have demonstrated that land surface processes play a crucial role in the climate system. In regions where the land–atmosphere coupling is strong, land surface processes, such as soil–precipitation feedback (Schär et al. 1999; Koster et al. 2004; Sörensson et al. 2010), soil moisture initial conditions (Sörensson et al. 2010; Sato and Xue 2013) and vegetation feedbacks (Xue et al. 2010; Lu and Kueppers 2012), have significant impacts on the dynamic downscaling of RCMs.

The East Asian summer monsoon (EASM) is the most distinctive climate feature in China during summertime. The anomaly of EASM could cause floods and droughts (Ding and Chan 2005). A number of studies have explored the roles of land surface processes in the EASM and the mechanisms that govern land surface–atmosphere interactions (Meehl 1994; Douville and Royer 1996; Xue 1996; Texier et al. 2000; Douville et al. 2001; Xue et al. 2004; Gao et al. 2011; Zhang et al. 2011; Wu et al. 2012). Since land–atmosphere interaction plays an important role in the

EASM, land surface parameterization (LSP) schemes significantly affect the dynamic downscaling for the EASM. Sato and Xue (2013) found that different descriptions of land surface processes in various schemes are one major source of uncertainties for the EASM downscaling. Zeng et al. (2011) evaluated the sensitivity of simulated short-range high-temperature weather to LSP schemes by WRF. However, few studies have been done on the evaluation of RCM to multi-LSP schemes for long-term simulation of the EASM comprehensively. The effects of different LSP schemes on large-scale land surface energy balance and the EASM climate are still unclear.

In this study, the sensitivity of RCM to LSP schemes for long-term simulations of the EASM is examined for the purpose to comprehensively understand the role of land surface processes in the RCM simulation of the EASM. Results of the present study will help us to further improve regional climate modeling studies of the EASM. A brief description of the model and experimental design is given in Sect. 2. Verification data is also introduced in this section. The simulated large-scale atmospheric circulation, 2-m temperature and precipitation are compared with reanalysis/observations in Sect. 3. In Sect. 4, we discuss physical processes that greatly affect the RCM performance with different LSP schemes. Conclusions and discussion are given in Sect. 5.

2 Model description, experimental design and verification data

2.1 Model description and experimental design

The RCM used here is the Advanced Weather Research and Forecasting Model (WRF-ARW, version 3.6.1) developed by the National Center for Atmospheric Research (NCAR). The model domain is centered at 35°N and 115°E, covering an area of 9250 km (west–east) × 6350 km (south–north) with a horizontal resolution of 50 km (Fig. 1). There are 28 levels in the vertical.

The WRF is driven by atmospheric and surface forcing data extracted from the National Centers for Environmental Prediction (NCEP)–Department of Energy (DOE) Reanalysis 2 (hereafter, NCEP2; Kanamitsu et al. 2002). The simulation covers 22 summers from 1991 through 2012. The model is initialized on 23 May for each summer simulation and the integration ends on 1 September of the same year, covering the entire EASM period. The first 9 days are for spin-up and the results are discarded. The three-month simulations (JJA, June–July–August) are applied for analysis.

Four ensemble experiments (Sim-Noah, Sim-CLM, Sim-PX and Sim-SSiB) have been conducted with different LSP schemes, including the Noah-MP land surface model

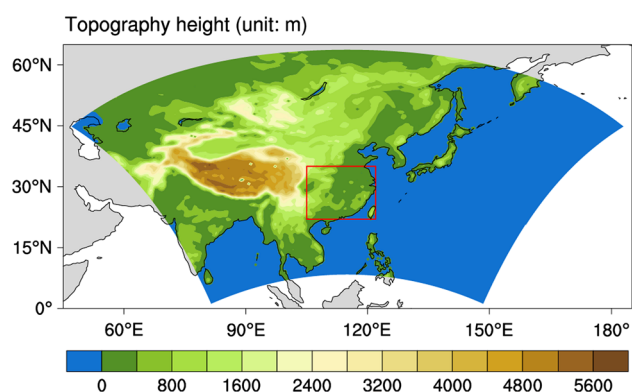


Fig. 1 Topography in this study area and experimental domain. The red rectangle shows sub-domain for southern China

(Niu et al. 2011), the Community Land Model version 4 (CLM4; Lawrence et al. 2011), the Pleim–Xiu land surface model (Pleim and Xiu 1995; Xiu and Pleim 2001), and the Simplified Simple Biosphere (SSiB) land surface model (Xue et al. 1991; Sun and Xue 2001). Table 1 provides the physics configuration of each simulation. All the physics options except for the land surface scheme are the same in these experiments. Important physics options include the WRF single-moment 6-class microphysics scheme (Hong and Lim 2006), NCAR Community Atmosphere Model (CAM 3.0) spectral-band shortwave and longwave radiation schemes (Collins et al. 2004), the Yonsei University planetary boundary layer scheme (Hong et al. 2006), and the Kain–Fritsch convective parameterization scheme (Kain 2004). Differences between these simulations are solely attributed to different parameterizations of land surface processes.

The LSP uses atmospheric information from the boundary layer scheme, radiative forcing from the radiation scheme, and precipitation forcing from the microphysics and convective schemes, together with internal information on the land's state variables and land-surface properties, to provide heat and moisture fluxes over land points (Skamarock et al. 2008). A better parameterization of land surface processes through LSP enhances the ability of dynamic downscaling and reduces the uncertainties. The Noah-MP LSP (Niu et al. 2011) uses soil temperature and moisture at four layers. It contains a separate vegetation canopy

defined by a canopy top and bottom with leaf physical and radiometric properties used in a two-stream canopy radiation transfer scheme that includes shading effects. It also contains a multi-layer snow pack with liquid water storage and melt/refreeze capability and a snow-interception model describing loading/unloading, melt/refreeze, and sublimation of the canopy-intercepted snow. The CLM4 (Lawrence et al. 2011) contains sophisticated treatment of biogeophysics, hydrology, biogeochemistry, and dynamic vegetation. But the last two processes are not included in this study. In CLM4, the land surface in each model grid cell is characterized into five primary sub-grid land cover types. The vegetated sub-grid consists of up to 4 plant functional types (PFTs) that differ in physiology and structure. The CLM4 vertical structure includes a single-layer vegetation canopy, a five-layer snowpack, and a ten-layer soil column. The Pleim–Xiu LSP (Pleim and Xiu 1995; Xiu and Pleim 2001) includes a 2-layer force-restore soil temperature and moisture model. Its top layer is taken to be 1-cm thick, and the lower layer is 99-cm. Grid aggregate vegetation and soil parameters are derived from fractional coverage of land use categories and soil texture types. There are two indirect nudging schemes that correct biases in 2-m air temperature and moisture by dynamic adjustment of soil moisture and deep soil temperature. The SSiB version 3 (Xue et al. 1991; Sun and Xue 2001) is used for this study and is developed for land/atmosphere interaction studies in the climate model. The aerodynamic resistance values in SSiB are determined in terms of vegetation properties, ground conditions and bulk Richardson number according to the modified Monin–Obukhov similarity theory. SSiB-3 includes three snow layers to realistically simulate snow processes, including destructive metamorphism, densification process due to snow load, and snow melting.

2.2 Verification data and method

The downscaled large-scale circulations (including wind, geopotential height and vertical velocity) are verified against ERA-Interim reanalysis based on statistical analysis (hereafter, ERA; Dee et al. 2011). Sato and Xue (2013) evaluated three global reanalysis data, i.e. ERA, JRA-25 (Onogi et al. 2007) and NCEP2, using the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon

Table 1 Physical parameterizations schemes used in four experiments

Simulation name	Land surface	Microphysics	Shortwave radiation	Longwave radiation	Boundary layer	Convective
Sim-Noah	Noah-MP					
Sim-CLM	CLM4	WSM6	CAM	CAM	YSU	Kain–Fritsch
Sim-PX	Pleim–Xiu					
Sim-SSiB	SSiB					

Experiment (GAME) Intensive Observation Period reanalysis (Yamazaki et al. 2003) for June–July–August of 1998. The GAME reanalysis is regarded as the most reliable reanalysis for the East Asian region because it includes additional upper-air sounding conducted during the GAME intensive observing period in 1998 while a high-resolution GCM was used for data assimilation (Yamazaki et al. 2003). Note that the GAME reanalysis covers only the intensive observation period of the warm season in 1998. The results show that the ERA data is more consistent with the GAME reanalysis than others. Therefore, in this study we verify the RCM simulations of large-scale circulations against the ERA.

The downscaled 2-m temperature and precipitation are evaluated based on statistical analysis of model simulations and observations. The high-resolution gridded 2-m temperature and precipitation dataset (China Ground 2-m Temperature and Precipitation $0.5^\circ \times 0.5^\circ$ Grid Dataset, V2.0) produced by the National Meteorological Information Center of the China Meteorological Administration is used in this study. This dataset is derived from 2474 daily gauge observations, which are interpolated to regular latitude-longitude grids using the thin plate spline method. Standard quality controls, mainly including the removal of outliers, the interpolation at points where data is missing, and the check for temporal consistency in time series, have been applied to each rain-gauge dataset before spatial interpolation is conducted. Digital terrestrial height data (Global 30 arc-second elevation) are used to eliminate the impact of terrain on the accuracy of interpolation. The study of Ren et al. (2015) indicated that these gridded rainfall data are highly reliable and can well represent the rainfall over southern China. It is the best available large-scale surface temperature and precipitation data with high resolution at this point.

This study focuses on the multi-year averaged distribution and intensity of several important variables in the RCM simulations. The results are compared with reanalysis/observations. To quantify the downscaling ability of the RCM, three common statistical measures, i.e. the mean bias [BIAS, Eq. (1)], the spatial correlation coefficient [SCC, Eq. (2)], and the root-mean-square error [RMSE, Eq. (3)], are calculated in this study. The equations are written as:

$$BIAS = \frac{\sum (m_i - o_i)}{N}, \quad (1)$$

$$SCC = \frac{\sum (m_i - \bar{m}) \cdot \sum (o_i - \bar{o})}{\sqrt{\sum (m_i - \bar{m})^2 \cdot \sum (o_i - \bar{o})^2}}, \quad (2)$$

$$BIAS = \sqrt{\frac{\sum (m_i - o_i)^2}{N}}, \quad (3)$$

where m_i is the spatially averaged value from model outputs; o_i is the spatially averaged values from reanalysis/observations; and N is the number of grid points. In the following section for the analysis of the large-scale circulation, the statistics are calculated over the entire model domain ($10^\circ\text{--}60^\circ\text{N}$, $70^\circ\text{--}160^\circ\text{E}$). This is because the EASM is influenced not only by the circulation in the EASM region, but also by the atmospheric variability outside the EASM region. For the evaluation of 2-m temperature and precipitation simulations, the area from 22°N – 35°N and 105°E – 122°E is chosen and referred to as the southern China in this paper. This area covers most of the EASM region defined by Wang and LinHo (2002; see their Fig. 9). The observational data have a high density over this area. The climate in southern China is characterized by monsoon rainfall and strong ascending motions, which will be discussed later in this study.

The statistical significance of the BIAS, SCC and RMSE was calculated using the so-called bootstrap method (Efron 1979). Resampling with replacement was applied from 1000 bootstrap to estimate the probability distribution of the multi-year averaged fields. The three statistical measures were calculated for each bootstrap. Then the results are sorted. The 5 % significance intervals are determined from the 2.5 and 97.5 percentiles of the values obtained by 1000 repetitions. Such test does not determine the field significance of the differences between model simulations and observations but can be used as a relative measure of the differences among the four simulations.

3 Simulation results

In this section, the downscaled large-scale circulation, 2-m temperature and precipitation are compared with reanalysis/observations to investigate the sensitivity of the RCM downscaling to LSP schemes.

3.1 Large-scale circulation

The upper-level (200-hPa) summertime zonal mean winds (U200) from simulations and from ERA and NCEP reanalysis are shown in Fig. 2. Long-term mean structures for U200 in the ERA and NCEP2 are very similar. Sim-Noah and Sim-CLM can reproduce the westerly jet core with wind speeds greater than 30 m s^{-1} . However, the jet cores simulated by Sim-Noah and Sim-CLM are located to the north of that in the ERA reanalysis. Sim-PX and Sim-SSiB can accurately simulate the location of the westerly jet core, whereas the intensity of winds along the jet core is weaker than that in the ERA and NCEP2 reanalysis. Table 2 shows the BIASs, SCCs and RMSEs of U200 over the model domain. The SCCs between the NCEP2

Fig. 2 Summer mean zonal wind at 200-hPa (U200, unit: m s^{-1}) during 1991–2012 from **a** ERA; **b** NCEP2; **c** Sim-Noah; **d** Sim-CLM; **e** Sim-PX; **f** Sim-SSiB

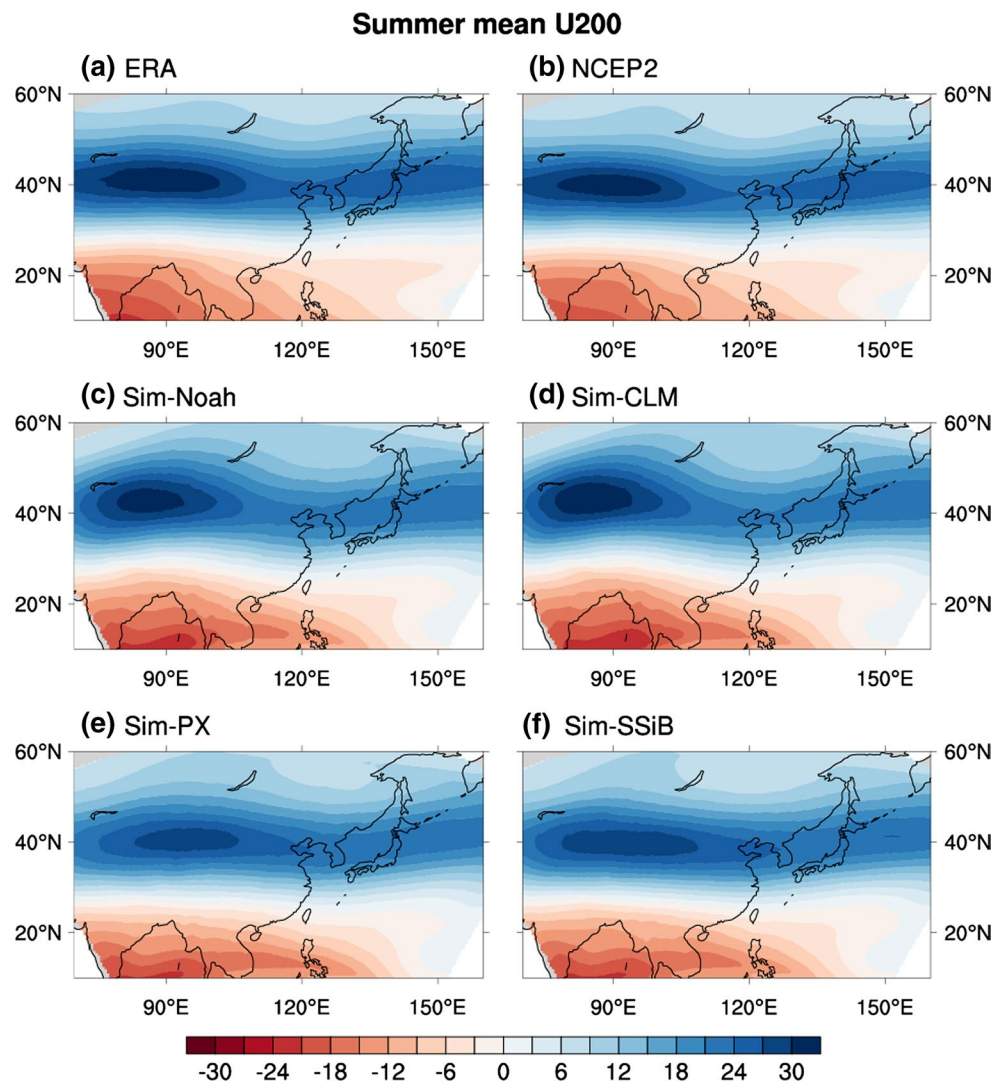


Table 2 Mean bias (BIAS, unit: m s^{-1} or m), spatial correlation coefficient (SCC) and root-mean-square error (RMSE, unit: standard deviation) of summer mean zonal wind at 200-hPa (U200) and geopotential height at 850-hPa (H850) during 1991–2012 in NCEP2 and simulations against ERA over model domain (10–60°N, 70–160°E)

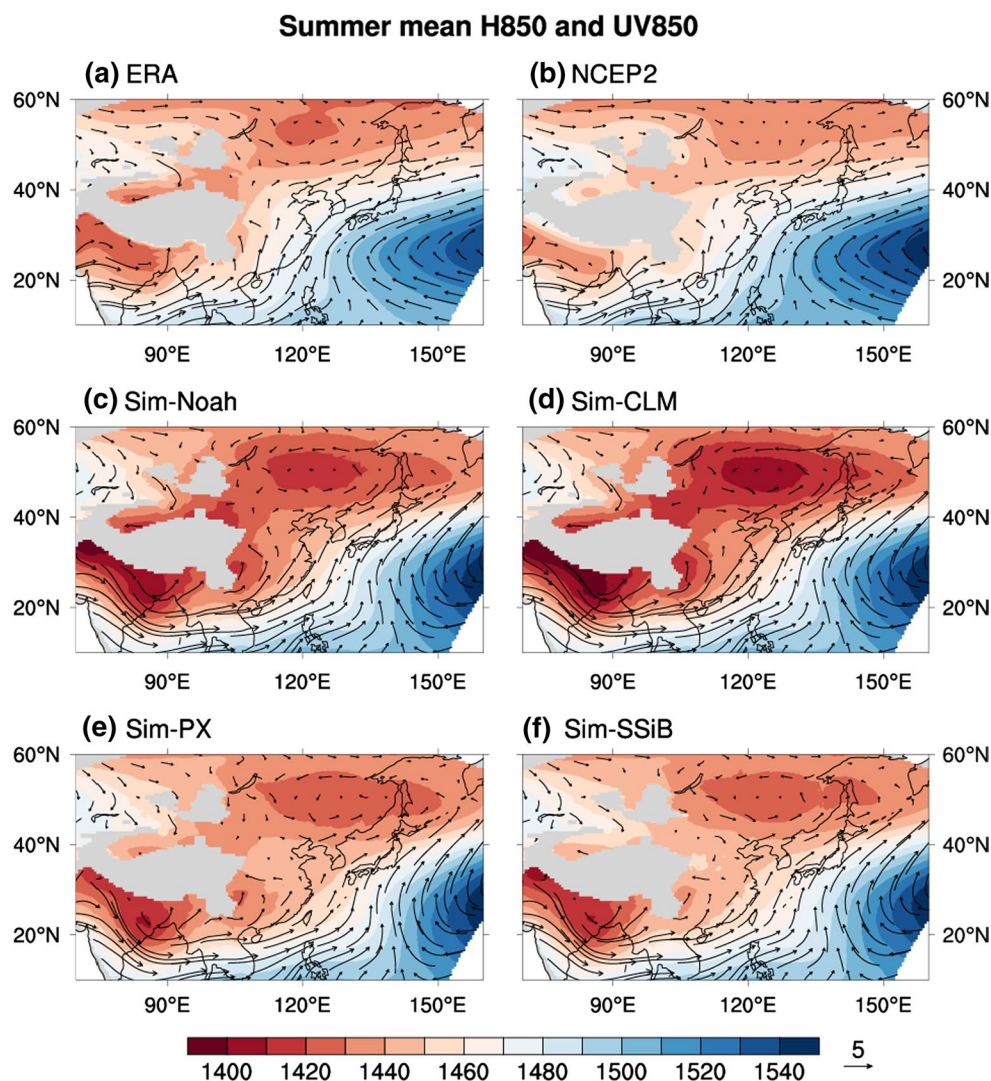
	U200			H850		
	BIAS	SCC	RMSE	BIAS	SCC	RMSE
NCEP2	−0.17 [−0.19, −0.14]	0.99 [0.99, 0.99]	0.11 [0.11, 0.11]	4.13 [4.04, 4.22]	0.98 [0.98, 0.98]	0.19 [0.18, 0.19]
Sim-Noah	−0.20 [−0.25, −0.15]	0.99 [0.99, 0.99]	0.17 [0.17, 0.17]	−10.69 [−10.84, −10.52]	0.95 [0.95, 0.95]	0.32 [0.32, 0.32]
Sim-CLM	−0.23 [−0.29, −0.17]	0.98 [0.98, 0.98]	0.20 [0.20, 0.20]	−13.18 [−13.36, −12.99]	0.94 [0.94, 0.95]	0.33 [0.33, 0.34]
Sim-PX	−0.05 [−0.10, 0.01]	0.99 [0.99, 0.99]	0.16 [0.16, 0.16]	−9.05 [−9.22, −8.87]	0.92 [0.92, 0.93]	0.39 [0.38, 0.39]
Sim-SSiB	−0.05 [−0.10, 0.00]	0.99 [0.99, 0.99]	0.15 [0.15, 0.15]	−6.90 [−7.09, −6.79]	0.94 [0.94, 0.95]	0.33 [0.33, 0.34]

Also shown between brackets are the 5 % significance intervals for the BIAS, SCC and RMSE

and the four experiments are 0.98–0.99. These results indicate that all the four simulations generally well reproduce the spatial pattern of U200. The BIASs and RMSEs reveal

that U200 in Sim-PX and Sim-SSiB simulations are more consistent with reanalysis than that in Sim-Noah and Sim-CLM. Moreover, the BIASs and RMSEs in Sim-PX and

Fig. 3 As in Fig. 2, but for geopotential height (H850; shaded, unit: m) and wind (UV850; vector, unit: m s^{-1}) at 850-hPa



Sim-SSiB are different from that in Sim-Noah and Sim-CLM at the 5 % significance level. Generally, compared to the differences in simulations of lower-level circulation, which will be presented later, the differences in U200 simulations of the four experiments are relatively small. Based on the simulation of U200 jet core and the BIAS of U200 over the model domain, the Sim-Noah produces results are similar to that of Sim-CLM, while Sim-PX simulations are consistent with that of Sim-SSiB.

Figure 3 shows lower-level (850-hPa) geopotential height (H850) and wind vector (UV850) from simulations and from reanalysis. WRF can well reproduce the spatial pattern of circulation at the lower level of 850-hPa. However, large negative biases of H850 are found nearby the Tibetan Plateau in Sim-Noah and Sim-CLM simulations. Meanwhile, the low-level winds over the Bay of Bengal and South China Sea (BOB-SCS) are overestimated in all the four experiments. Such an overestimation of winds over the BOB-SCS influences monsoon precipitation and will be

discussed in Sect. 4. Looking at the differences in UV850 between the four simulations and ERA (not shown), it is found that the overestimation of winds over the BOB-SCS is less severe in Sim-PX and Sim-SSiB than in Sim-Noah and Sim-CLM. Table 2 shows the BIASs, SCCs and RMSEs of H850 averaged over the model domain. The absolute values of BIASs of Sim-PX and Sim-SSiB simulations are smaller than that of Sim-Noah and Sim-CLM similar in the U200 simulation, mainly because of large biases of H850 around the Tibetan Plateau by Sim-Noah and Sim-CLM. Moreover, the BIASs in Sim-PX and Sim-SSiB are different from that in Sim-Noah and Sim-CLM at the 5 % significance level. Similar to the U200 simulations, characteristic spatial patterns and biases of H850 and UV850 simulated in Sim-Noah resemble that in Sim-CLM, while results of Sim-PX resemble that of Sim-SSiB.

Vertical velocity (W) is closely associated with the monsoon precipitation. Figure 4 shows the vertical profiles of area-averaged W over southern China. Note that there is

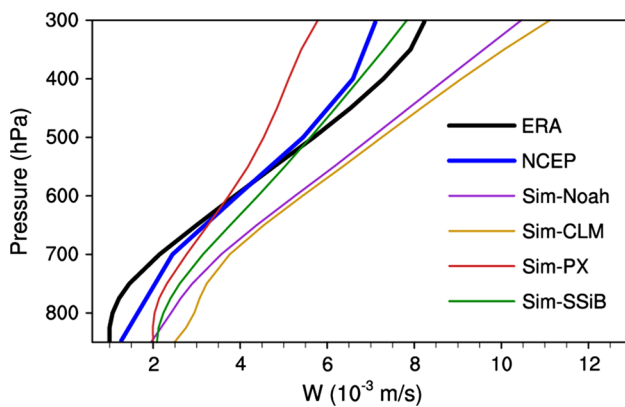


Fig. 4 Summer mean vertical profiles of area averaged mean of vertical velocity (unit: 10^{-3} m s^{-1}) during 1991–2012 over southern China ($22\text{--}35^{\circ}\text{N}$, $105\text{--}122^{\circ}\text{E}$)

little difference in the vertical velocity field between the ERA and NCEP2 reanalysis. Comparing the four RCM simulations with reanalysis, it is found that simulations of Sim-Noah and Sim-CLM are again similar. The vertical velocity is overestimated in both experiments at each pressure level from 850 to 300 hPa. Compared with ERA, the biases of vertically averaged W simulated by Sim-Noah and Sim-CLM are 1.4 and 1.8 mm s^{-1} , respectively. Results of Sim-PX and Sim-SSiB show positive biases below 500-hPa and negative biases above 500-hPa against ERA; the vertically averaged W biases simulated in Sim-PX and Sim-SSiB are -0.4 and 0.4 mm s^{-1} , respectively.

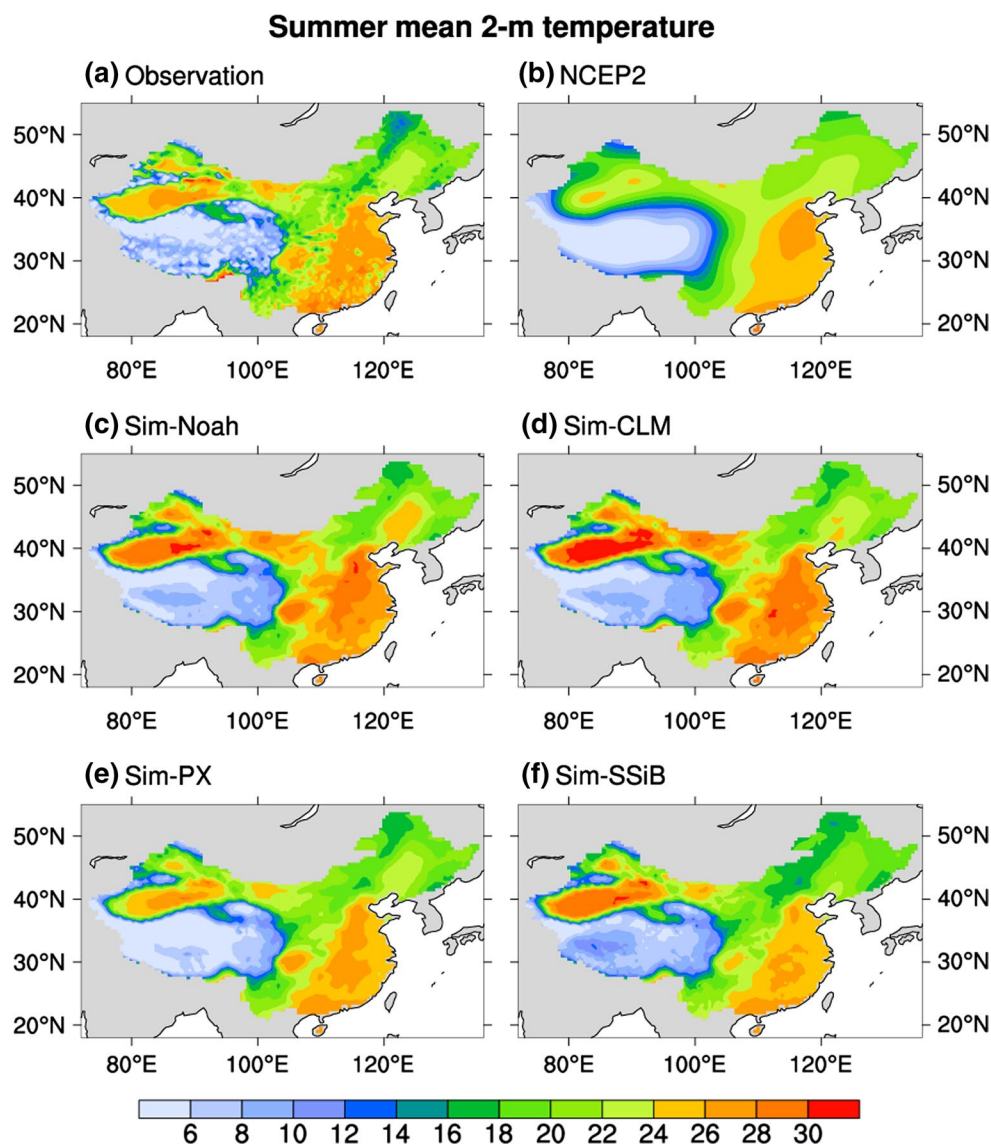
3.2 2-m temperature and precipitation

Consecutive hot days or persistent heat waves during the EASM season are typical disastrous weather events that affect large areas in East Asia (Sheridan and Kalkstein 2004; You et al. 2011). Figure 5 shows the distribution of the observed, NCEP2-derived and simulated 2-m temperature averaged over the summertime for the period of 1991–2012. All the four experiments can well reproduce the general spatial pattern of 2-m temperature, whereas large differences exist among the simulations. In southern China and over the semi-arid region of East Asia, Sim-Noah and Sim-CLM significantly overestimate the 2-m temperature, while results of Sim-PX and Sim-SSiB are relatively consistent with the observations. NCEP2 fails to describe the details of the spatial pattern of 2-m temperature due to its coarse-resolution. Table 3 shows the BIASs, SCCs and RMSEs of 2-m temperature from NCEP2 and from simulations against observations over southern China. The simulated 2-m temperatures in all the four experiments are more consistent with observations than that in NCEP2. For instance, the SCCs/RMSEs in all the four simulations are higher/lower than that in NCEP2. The biases of

the four simulations show large discrepancies. Sim-Noah and Sim-CLM have warm biases, while the Sim-PX and Sim-SSiB show cold biases. The absolute values of BIASs and RMSEs for Sim-PX and Sim-SSiB simulations are smaller than that of Sim-Noah and Sim-CLM. Moreover, the BIASs, SCCs and RMSEs in Sim-PX and Sim-SSiB are different from that in Sim-Noah and Sim-CLM at the 5 % significance level.

Precipitation is a primary meteorological element that is especially important for the monsoon climate simulation. The EASM precipitation is often intense, and can cause disastrous floods in some years, while the lack of precipitation in other years can lead to severe droughts (Wang and LinHo 2002; Ding and Chan 2005). Figure 6 presents distributions of the observed and simulated summertime mean precipitation for the period of 1991–2012. To examine WRF's downscaling ability, the NCEP2 precipitation is also shown. In general, the WRFs can reproduce the spatial pattern of summertime monsoon precipitation over China. The rainfall over the semi-arid region, which is also the northern boundary of EASM (the region between the 2 and 3 mm day^{-1} contours in Fig. 6a), however, is overestimated in all the experiments. The simulated distribution and intensity of summertime precipitation, however, show large differences among the four experiments. In southern China, especially along the coast line and southwestern China centered at about 100°E and 25°N , Sim-Noah and Sim-CLM significantly overestimate the rainfall, while Sim-PX and Sim-SSiB results are relatively consistent with observations. Meanwhile, Sim-Noah and Sim-CLM produces a low precipitation center over the Sichuan Valley centered at about 106°E and 30°N , which does not exist in observations. NCEP2 has the worst results compared to results of the four experiments, probably due to its coarse-resolution. Table 3 shows BIASs, SCCs and RMSEs of precipitation in NCEP2 and in simulations of the four experiments against observation over southern China. The SCCs in all the four simulations are higher than that in NCEP2. Sim-PX and Sim-SSiB have smaller biases than NCEP2. Sim-Noah and Sim-CLM show reduced RMSEs compared with NCEP2, but have larger biases. The BIASs in Sim-PX and Sim-SSiB are smaller than that in Sim-Noah and Sim-CLM at the 5 % significance level. Compared with NCEP2, WRF adds more information to the EASM, despite the fact that NCEP2 actually provides initial condition and lateral forcing for the experiments.

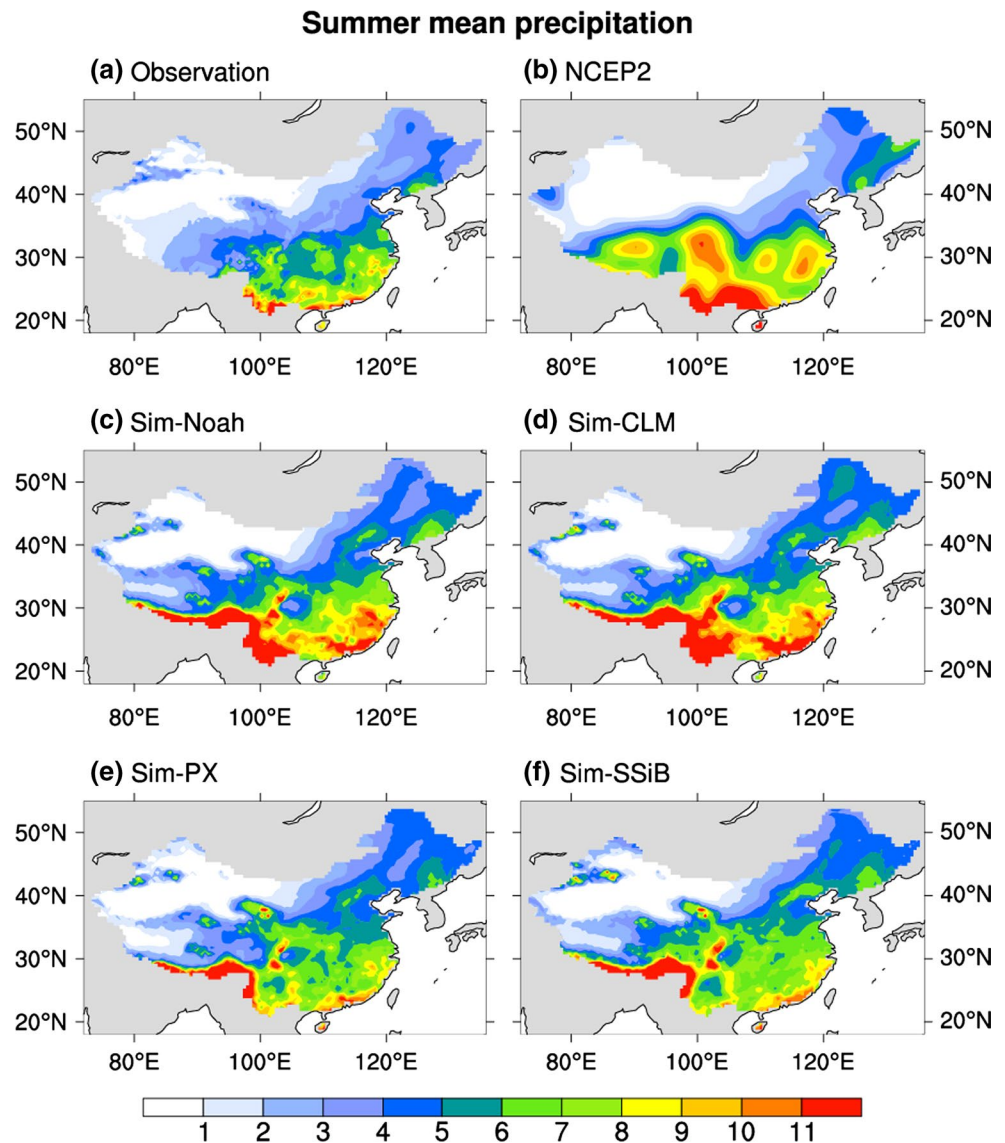
The above comparisons of large-scale circulation, summertime 2-m temperature and precipitation between simulations of the four experiments and that from ERA and NCEP2 reanalysis indicate that the performance of WRF coupled with different LSP schemes are quite different in the EASM simulation, which suggest that the downscaling ability of RCM for EASM is sensitive to the LSP schemes.

Fig. 5 As in Fig. 2, but for 2-m temperature (°C)**Table 3** Mean bias (BIAS, unit: mm day⁻¹ or °C), spatial correlation coefficient (SCC) and root-mean-square error (RMSE, unit: standard deviation) of summer mean 2-m temperature and precipitation during 1991–2012 in NCEP2 and simulations against observation over southern China (22–35°N, 105–122°E)

	2-m temperature			Precipitation		
	BIAS	SCC	RMSE	BIAS	SCC	RMSE
NCEP2	−0.67 [−0.82, −0.52]	0.57 [0.51, 0.62]	0.93 [0.88, 0.99]	1.30 [1.18, 1.42]	0.66 [0.62, 0.69]	0.83 [0.78, 0.88]
Sim-Noah	1.14 [0.99, 1.28]	0.63 [0.58, 0.67]	0.86 [0.81, 0.91]	1.40 [1.30, 1.50]	0.71 [0.68, 0.75]	0.76 [0.71, 0.80]
Sim-CLM	1.74 [1.60, 1.85]	0.72 [0.68, 0.75]	0.75 [0.70, 0.80]	1.68 [1.56, 1.80]	0.71 [0.67, 0.74]	0.76 [0.72, 0.81]
Sim-PX	−0.22 [−0.34, −0.11]	0.77 [0.73, 0.80]	0.68 [0.63, 0.73]	0.54 [0.45, 0.62]	0.68 [0.64, 0.72]	0.79 [0.75, 0.85]
Sim-SSiB	−0.66 [−0.78, −0.54]	0.75 [0.72, 0.79]	0.70 [0.65, 0.75]	0.63 [0.56, 0.71]	0.74 [0.71, 0.77]	0.72 [0.68, 0.76]

Also shown between brackets are the 5 % significance intervals for the BIAS, SCC and RMSE

Fig. 6 As in Fig. 2, but for precipitation (unit: mm day^{-1})



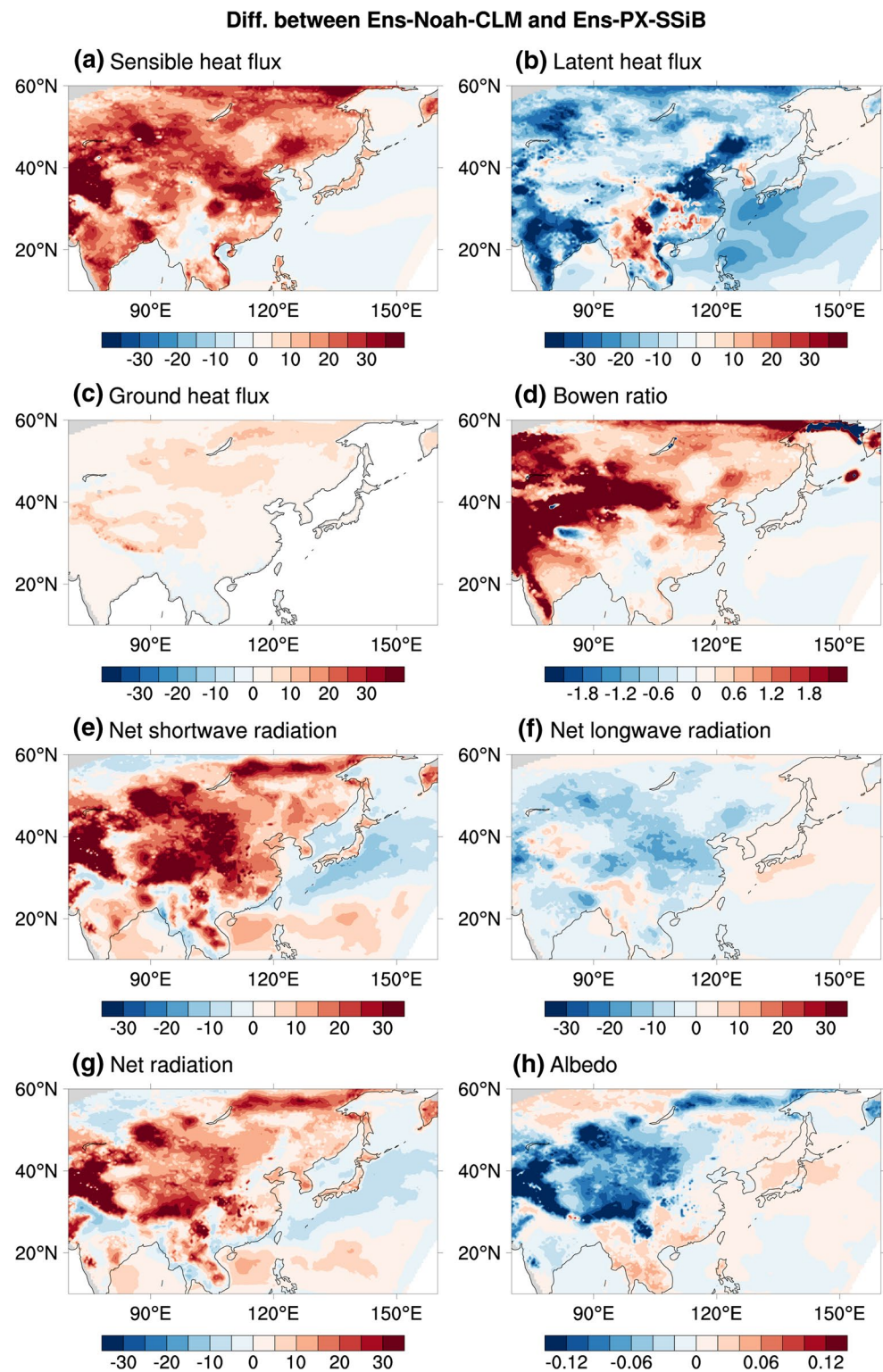
Furthermore, the RCM simulation does add more information to the EASM compared to reanalysis that imposes the LBC because it provides 2-m temperature and precipitation that are with higher resolution and more realistic compared to LBC. The simulated 2-m temperature and precipitation are more consistent with observations in Sim-PX and Sim-SSiB than in Sim-Noah and Sim-CLM.

4 Land surface heating and its atmospheric effects

In Sect. 3, we have shown that the downscaling ability of RCM for the EASM is sensitive to LSP schemes, and results of Sim-Noah are generally similar to results of Sim-CLM, while results of Sim-PX and Sim-SSiB are consistent in the EASM simulations. To further explore the possible

causes for this sensitivity, physical processes related to the LSP scheme is discussed in this section. As described in Sect. 2.1, the differences between the four WRF simulations are solely caused by the different parameterizations of land surface processes. The LSP scheme affects energy balance at the land surface, which subsequently affects atmospheric conditions through land–atmosphere interactions. In WRF, surface sensible heat (SH) and latent heat (LH) fluxes are calculated in the LSP and passed to planetary boundary layer (PBL), affecting the EASM simulation. We compare the differences in the surface energy budgets and their atmospheric effects between results of Ens-Noah-CLM (ensemble mean averaging Sim-Noah and Sim-CLM) and Ens-PX-SSiB (ensemble mean averaging Sim-PX and Sim-SSiB), since the results of two models in each ensemble mean are similar as discussed earlier.

Fig. 7 Summer mean differences of **a** sensible heat flux; **b** latent heat flux; **c** ground heat flux; **d** Bowen ratio; **e** net shortwave radiation; **f** net longwave radiation; **g** net radiation; **h** albedo between Ens-Noah-CLM and Ens-PX-SSiB. Units for fluxes and radiation are W m^{-2}



4.1 Land surface heating

The energy budget differences between Ens-Noah-CLM and Ens-PX-SSiB simulations are shown in Fig. 7 and summarized in Table 4. Because the energy budget differences

over sea/ocean are negligible compared to that over land, only land points are included for Table 4. There are significant differences in SH and LH fluxes (Fig. 7a, b) between the two ensembles. In some areas, the difference can reach up to 35 W m^{-2} . Generally, the simulated SH

Table 4 Summer mean differences of sensible heat flux (SH), latent heat flux (LH), net shortwave radiation (Net SW), net longwave radiation (Net LW), net radiation (Net Rd), albedo and 850-hPa tempera-

ture (T850) between Ens-Noah-CLM and Ens-PX-SSiB over model domain (10–60°N, 70–160°E; only land points)

	SH	LH	Net SW	Net LW	Net Rd	Albedo	T850
Ens-Noah-CLM – Ens-PX-SSiB	19.61	–11.73	13.90	–3.28	10.62	–0.03	1.24

Units for fluxes and radiation are W m^{-2} . Unit for T850 is $^{\circ}\text{C}$

flux in Ens-Noah-CLM is much stronger than that in Ens-PX-SSiB over the land area. The domain average value of SH over the land points is about 20 W m^{-2} higher in Ens-Noah-CLM than in Ens-PX-SSiB (Table 4). The situation is opposite for the LH flux simulation. Domain average LH flux over the land points is about 12 W m^{-2} lower in the Ens-Noah-CLM simulation than in Ens-PX-SSiB result. Compared to the SH and LH fluxes, the differences in ground heat flux are small between the Ens-Noah-CLM and Ens-PX-SSiB simulations (Fig. 7c). Over arid/semiarid areas, the differences in the LH flux are relatively small while the differences in the SH flux are substantially large. The LSP modulates energy partitioning between the SH and LH fluxes (Bowen ratio; Fig. 7d), which has crucial impact on the atmospheric circulation as demonstrated in a number of studies (Betts et al. 1996; Xue et al. 2004, 2006, 2010; Fischer et al. 2007; Berg et al. 2014).

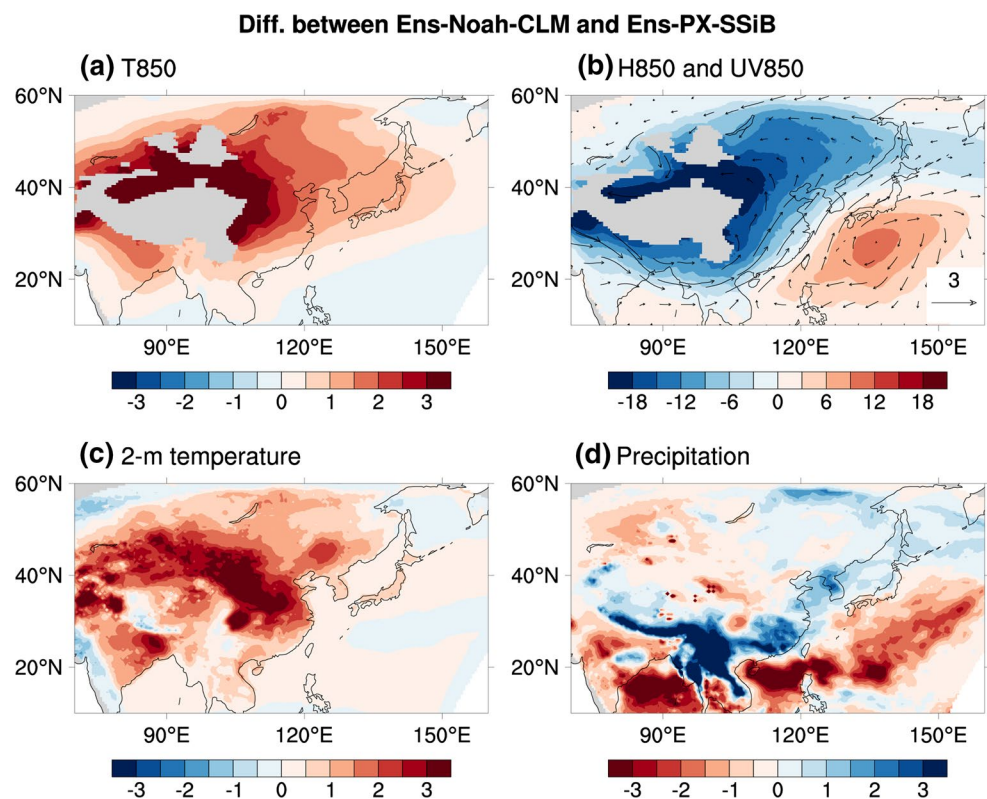
The source of energy for SH and LH fluxes is the absorbed net solar radiation at the land surface. The net radiation consists of longwave (LW) and shortwave (SW) components. The difference in LW radiation is minor compared to that in SW radiation (Fig. 7e, f; Table 4). The difference in net radiation is thus dominated by the difference in net SW radiation (Fig. 7e, g; Table 4). The difference in net shortwave radiation is mainly a result of the difference in surface albedo (Fig. 7h; Table 4), whose distribution is similar to that of net SW radiation. Compared to Ens-PX-SSiB, the lower albedo in Ens-Noah-CLM leads to a higher net shortwave radiation and consequently a higher net radiation on the surface, which partially contributes to the higher sensible heat flux. Table 4 shows that the increased sensible heat flux ($\sim 20 \text{ W m}^{-2}$) is about twice larger than the change in net radiation ($\sim 10 \text{ W m}^{-2}$). Latent heat flux is reduced in Ens-PX-SSiB to balance the surface energy budget. Moreover, the land surface schemes affect greatly the partitioning of the net radiation into SH and LH fluxes (Bowen ratio; Fig. 7d). The LSP affects the surface energy balance not only via modulating the surface radiation balance but also through, for instance, the surface turbulence and transpiration processes among others. Therefore, the surface parameters such as albedo, leaf area index, and aerodynamic and stomatal resistance parameterizations etc. in the LSP schemes play an important role in the energy balance and energy partitioning.

4.2 Impact on atmospheric circulation

Section 4.1 discusses the significant differences in the SH and LH fluxes between Ens-Noah-CLM and Ens-PX-SSiB simulations. LH flux is released when phase changes of atmospheric water vapor, mostly vaporization and condensation, occur. The SH flux directly affects the temperature of the atmosphere. The absolute value of difference in the SH flux between Ens-Noah-CLM and Ens-PX-SSiB is about twice that of the LH flux (Table 4), indicating that the differences in the SH flux dominate the difference in total upward heat flux, and play a key role in the difference in atmospheric temperature simulation between Ens-Noah-CLM and Ens-PX-SSiB. Figure 8a shows the simulated T850 over Asian continent is higher in Ens-Noah-CLM than in Ens-PX-SSiB, with a difference larger than 2°C for most area (Fig. 8a). Domain average T850 is 1.24°C higher in Ens-Noah-CLM than in Ens-PX-SSiB over the land points (Table 4). Compared with ERA, the domain average T850 bias is 1.64°C for Ens-Noah-CLM simulation and 0.40°C for Ens-PX-SSiB simulation. Because the difference over sea/ocean is negligible, such difference over land would substantially affect the land-sea thermal contrast due to the difference of temperature gradient from land to ocean.

Many previous studies have suggested that the land-sea thermal contrast affects monsoon intensity. For example, Li and Yanai (1996) found that strong (weak) Asian summer monsoon are associated with positive (negative) tropospheric temperature anomalies over Asian continent. Compared to Ens-PX-SSiB, Ens-Noah-CLM overestimates the temperature at 850-hPa over Asian continent, leading to an abnormally strong thermal difference between sea and land. As a result, the EASM in Ens-Noah-CLM simulation is more intense than that in Ens-PX-SSiB. The thermal differences lead to differences in geopotential height (GHT) simulation over land between Ens-PX-SSiB and Ens-Noah-CLM (Fig. 8b). At 850-hPa, the considerable difference in GHT covers the entire Asia continent, which is consistent with the distribution of temperature difference shown in Fig. 8a. The differences in GHT as well as associated differences in pressure gradient between simulations of Ens-Noah-CLM and Ens-PX-SSiB result in extensive differences in the simulated geostrophic winds (Fig. 8b).

Fig. 8 As in Fig. 7, but for **a** temperature at 850-hPa (T850; unit: °C); **b** geopotential height (H850; *shaded*, unit: m) and wind (UV850; vector, unit: m s^{-1}) at 850-hPa; **c** 2-m temperature (unit: °C); **d** precipitation (unit: mm day^{-1})



During the summertime, ERA and NCEP2 reanalysis both exhibit a lower-level southwesterly jet over the BOB-SCS region (not shown), which pulls atmospheric moisture from the tropical and subtropical oceans to southern China. Figure 8b clearly indicates that the atmospheric moisture transport in Ens-Noah-CLM simulation is unrealistically intensified. As a result, precipitation over southern China is significantly overestimated in both Sim-Noah and Sim-CLM simulations (Fig. 8d, and also Fig. 6c, d).

Land surface processes have substantial influences on 2-m temperature, and can lead to high-temperature weather during summertime under certain conditions (Fischer et al. 2007; Zhang et al. 2011; Berg et al. 2014). The SH flux directly influences 2-m temperature. Fischer et al. (2007) and Zhang et al. (2011) found that the SH flux is dominantly responsible for 2-m temperature: an enhanced (reduced) SH flux leads to an increased (decreased) 2-m temperature; meanwhile, the LH flux normally changes in opposite direction to the SH flux. This is exactly the case we discuss in this study. In addition, large-scale circulations can also make contribution to changes in 2-m temperature. The enhanced southwesterly wind (Fig. 8b) in Ens-Noah-CLM simulation brings warm air from tropics to East Asian continent. As a result, Ens-Noah-CLM overestimates 2-m temperature in most area of the model domain, whereas no such overestimations are found in Ens-PX-SSiB results (Fig. 8c, and also Fig. 5).

By and large, the strong intensity of the SH flux in Ens-Noah-CLM induces a higher tropospheric temperature over land. Meanwhile, such difference is not discovered over sea/ocean. The land-sea thermal contrast is therefore enhanced because of the higher temperature gradient from land to ocean. The adaptive modulation of GHT gradients affects wind fields (through geostrophic balance), especially at lower levels. As a result, the simulation of large-scale circulation, 2-m temperature and monsoon precipitation are all affected.

5 Conclusion and discussion

This study demonstrates that RCMs are a promising tool for dynamic downscaling, but with certain uncertainties. As the land-atmosphere interaction plays an important role in the EASM, LSP schemes may significantly affect the dynamic downscaling results of the EASM. With few studies focusing on the sensitivity of RCM to the multi-LSP schemes in long-term simulations of the EASM, responses of land surface and atmospheric conditions to different LSP schemes in the EASM simulation are unclear. Taking the advantage of recently available high-resolution surface temperature and precipitation data, in the present study, the sensitivity of the RCM to LSP schemes for the EASM simulation is investigated. The results are obtained by using

WRF coupled with four different LSP schemes (Noah-MP, CLM4, Pleim-Xiu and SSiB).

The 22-summer averaged spatial distribution and intensity of downscaled large-scale circulation pattern, 2-m temperature and precipitation are compared with ERA reanalysis and station observations in China. Results indicate that the downscaling ability of RCM for the EASM is sensitive to LSP schemes. Furthermore, the RCM does add more information to the EASM compared to reanalysis that imposes the LBC because it provides 2-m temperature and precipitation that are with higher resolution and more realistic compared to LBC. Looking at 2-m temperature and monsoon precipitation, Sim-PX and Sim-SSiB simulations are more consistent with observations than Sim-Noah and Sim-CLM results. Generally the performance of Sim-Noah is similar to that of Sim-CLM, while the Sim-PX performance is similar to that of Sim-SSiB.

One important goal of this study is to better understand the mechanisms behind the impact of LSP schemes on RCMs' EASM downscaling. The physical processes involved in the LSP scheme-atmosphere interactions are discussed. The differences in the surface energy budget simulations between Ens-Noah-CLM and Ens-PX-SSiB and their consequent effects on atmospheric circulations are compared. It is found that the intensity of the simulated SH flux over Asian continent is stronger in Ens-Noah-CLM than that in Ens-PX-SSiB, which induces unrealistically high tropospheric temperature simulation in Ens-Noah-CLM over the land area. Meanwhile, such difference is not discovered over sea/ocean. The land-sea thermal contrast is therefore enhanced because of the higher temperature gradient from land to ocean. The adaptive modulation of GHT gradients affects wind fields simulation (through geostrophic balance), especially at lower levels. As a result, the simulation of large-scale circulation, 2-m temperature and monsoon precipitation are all affected.

It is worth noting that the ensemble average results, i.e. results of Ens-PX-SSiB, are better than individual simulations of Sim-PX and Sim-SSiB. This suggests that ensemble could be an effective approach for RCM studies as previous studies have shown (Liang et al. 2012; Mearns et al. 2012). However, it does not mean that we can obtain further in-depth understanding of the atmosphere-land interaction with ensemble RCM studies. RCMs still require more realistic LSP schemes.

It is found that the SH flux plays an important role in downscaling for the EASM. Further investigation is necessary to answer the question whether a better simulation of SH flux at surface is in favor of a better dynamic downscaling for the EASM. Without sufficient observations of SH flux at the surface, it is not easy to directly verify the SH flux simulations in RCM. We expect that station observations, such as data collected in Semi-Arid Climate and

Environment Observatory of Lanzhou University (SACOL, Huang et al. 2008), can be applied to verify RCM simulations in China. In addition, accurate specification of surface boundary conditions is a prerequisite for credible dynamic downscaling, especially since most of the RCM skill enhancement results from surface-atmosphere interactions at regional-local scales (Liang et al. 2012). Other model settings, such as model domain (Liang et al. 2001; Xue et al. 2007) and the combination of parameterizations (Fernández et al. 2007; Flaounas et al. 2011; Mooney et al. 2013) also influence the downscaling ability of the RCM. It is valuable to carry out sensitive experiments with inconsistent specification of surface boundary conditions and other model settings. These will be research topics in our future study.

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