Effects of Land Surface Schemes on WRF-Simulated Geopotential Heights over China in Summer 2003*

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ABSTRACT

To quantify and explain effects of different land surface schemes (LSSs) on simulated geopotential height (GPH) fields, we performed simulations over China for the summer of 2003 using 12-member ensembles with the Weather Research and Forecasting (WRF) Model, version 3. The results show that while the model can generally simulate the seasonal and monthly mean GPH patterns, the effects of the LSS choice on simulated GPH fields are substantial, with the LSS-induced differences exceeding 10 gpm over a large area (especially the northwest) of China, which is very large compared with climate anomalies and forecast errors. In terms of the assessment measures for the four LSS ensembles [namely, the five-layer thermal diffusion scheme (SLAB), the Noah LSS (NOAH), the Rapid Update Cycle LSS (RUC), and the Pleim–Xiu LSS (PLEX)] in the WRF, the PLEX ensemble is the best, followed by the NOAH, RUC, and SLAB ensembles. The sensitivity of the simulated 850-hPa GPH is more significant than that of the 500-hPa GPH, with the 500-hPa GPH difference fields generally characterized by two large areas with opposite signs due to the smoothly varying nature of GPHs. LSS-induced GPH sensitivity is found to be higher than the GPH sensitivity induced by atmospheric boundary layer schemes. Moreover, theoretical analyses show that the LSS-induced GPH sensitivity is mainly caused by changes in surface fluxes (in particular, sensible heat flux), which further modify atmospheric temperature and pressure fields. The temperature and pressure fields generally have opposite contributions to changes in the GPH. This study emphasizes the importance of choosing and improving LSSs for simulating seasonal and monthly GPHs using regional climate models.

1. Introduction

Geopotential height (GPH) is one of the most fundamental variables considered in meteorological and climatological research and applications. Because of its

close relationship with air pressure, GPH is also an important variable for characterizing general atmospheric circulation. In an earlier work on numerical forecasting, Phillips (1957) proposed a sigma coordinate system in which GPH was used as the dependent variable when depicting general atmospheric circulation from the hydrostatic equation. Following the work of Phillips (1957), several researchers have used GPH as a major variable to assess model performances for weather and climate modeling and prediction. For example, to evaluate the performance of the ensemble prediction system operationally used at the European Centre for Medium-Range Weather Forecasts (ECMWF), Chessa and Lalaurette (2001) applied some basic measures of skill

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to a probabilistic forecast of four regimes for the 700-hPa GPH. Moreover, some investigators focused on predicting the 500-hPa GPH [e.g., [Zheng and Frederiksen \(2007\)](#) applied a variance decomposition approach to predict seasonal 500-hPa geopotential height anomalies in the Southern Hemisphere]. Although GPH is not a forecast variable of the atmospheric model in the dynamical seasonal prediction system at the National Centers for Environmental Prediction (NCEP; [Kanamitsu 1989](#)), the GPH anomaly is a major quantity in the assessment of general atmospheric circulation patterns in the NCEP Dynamical Seasonal Forecast System 2000 ([Kanamitsu et al. 2002](#)) and NCEP Climate Forecast System ([Saha et al. 2006](#)). In addition, many investigators have found that the GPH field can be considered as a key predictor, particularly when downscaling regional/local climate. For instance, [Yang et al. \(2012\)](#) suggested that the 2-m maximum and minimum temperatures are closely related with the 850-hPa GPH, which can be considered as a useful predictor for temperatures in China. All of the above-mentioned studies have demonstrated the crucial role of GPH in research and its applications at weather and climate time scales.

The climate over continental China is characterized by its large time–space variability and is closely associated with the general atmospheric circulation, which is commonly shown by the GPH field. For instance, around mid-May the rain belt near the equator suddenly moves northward and merges with the southern China rain belt. Next, the East Asian summer monsoon advances northward and northeastward in a distinct stepwise manner ([Ding and Chan 2005](#)). This sudden onset of the monsoon season in the South China Sea has been well documented by several researchers based on large-scale wind, GPH, rainfall, and OLR patterns ([Lau and Yang 1997](#); [Wang and Lin 2002](#)) and can be explained by changes in the temperature gradient (as well as the GPH gradient) over continental China ([Wu and Wang 2001](#); [Zhang et al. 2004](#)). In addition, numerical studies of the monsoon system, which contain some major synoptic systems over China (e.g., the western Pacific subtropical high, as characterized by the 500-hPa GPH field), were also carried out (e.g., [Chen et al. 2010](#)).

Currently, general circulation models (GCMs) are very useful for simulating and predicting large-scale general circulation. However, when used for climate research and applications at regional scales, GCMs are unable to capture some regional features (e.g., complex topography and local circulation dynamics) and have large computational costs with greater spatial resolution (e.g., [Dickinson et al. 1989](#); [Giorgi and Mearns 1999](#); [Argüeso et al. 2011](#)). To partially overcome these deficiencies, regional climate models (RCMs) have been

widely employed for climate simulation and prediction during the last three decades (e.g., [Giorgi and Mearns 1999](#); [Chen and Xie 2012](#)). Thus, when assessing RCM simulations over China, two questions should be asked: 1) How well do the commonly used RCMs reproduce the GPH field over continental China? and 2) To what extent is the simulated GPH field sensitive to different physical parameterizations?

The first question might be important to model users who are interested in the overall performance of state-of-the-art RCMs (e.g., [Wang et al. 2004](#); [Findell et al. 2006](#); [Seneviratne et al. 2006](#); [Walther et al. 2013](#); [Akkermans et al. 2014](#)) and is an important issue regarding the application of forecast GPH fields, as stated above. Unlike modeled precipitation and temperature sensitivities to physical options, which have drawn significant attention (e.g., [Giorgi 1991](#); [Argüeso et al. 2011](#)), the sensitivities of GPH fields to different physical parameterizations have rarely been investigated by focusing on GPHs. In addition, the second question is of interest because the uncertainty of the simulated GPH field can be shown because of the complexity of the physical parameterizations while benefiting the development and application of numerical models. Previously, several sensitivity studies were carried out to determine the effects of simulated regional climate on different parameterizations. For instance, using the Fourth-generation Pennsylvania State University (PSU)–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM4), [Giorgi and Marinucci \(1991\)](#) analyzed the sensitivity of the climate model over Europe to selected physical parameterizations (e.g., explicit moisture scheme) and lower boundary conditions (e.g., initial soil moisture and snow cover). When simulating the North American monsoon system using the Fifth-generation PSU–NCAR Mesoscale Model (MM5), [Gochis et al. \(2002\)](#) found that substantial differences in precipitation, surface climate, and atmospheric stability occurred because of different convection parameterizations. More recently, [Argüeso et al. \(2011\)](#) evaluated the sensitivity of the Weather Research and Forecasting (WRF) Model to eight different combinations of cumulus, microphysics, and planetary boundary layer schemes (PBLSS) over a topographically complex region in southern Spain and found that both cumulus and PBLSS affect precipitation descriptions, while no noticeable differences were observed between the microphysics options. Similar to [Argüeso et al. \(2011\)](#), [Crétat et al. \(2012\)](#) quantified the uncertainties associated with some physical parameterizations for the core of a summer rainy season over southern Africa. All of these investigations have generally emphasized the importance of choosing physical schemes,

especially cumulus schemes, in RCMs for use in different regions worldwide.

While several sensitivity studies have been performed using WRF, few, if any, have been performed to determine the GPH sensitivities to land surface schemes (LSSs) when using WRF models over continental China. As a key component of the climate system, the land surface transfers momentum, moisture, and heat to the overlaying atmosphere and modifies the climate states at the global and regional scales (e.g., Shukla and Mintz 1982; Xue 1997; Zeng et al. 2003; Chen and Xie 2012). Thus, the aim of this study is to quantify and explain the sensitivity of WRF-simulated GPH to different LSS models for continental China by using a case study.

Therefore, this paper is arranged as follows. In section 2, we describe the WRF Model, the experimental design, datasets, and relevant methods for analysis. Detailed quantitative data regarding the sensitivities of WRF-simulated GPH to different LSSs are presented in section 3, while a mechanistic explanation for the sensitivity is addressed in section 4. In the final section, we summarize and provide a discussion of the study.

2. Methodology

a. Model and experimental design

Here, we applied the Advanced Research version of WRF (ARW), version 3 (Skamarock et al. 2008). The WRF Model is a next-generation mesoscale model that has been jointly developed by many scientific research and operational agencies and widely applied in various research and operational forecasting studies. WRF contains many advanced physical parameterization schemes. This paper uses nearly the same physical options for all simulations, that is, the Rapid Radiative Transfer Model (RRTM) longwave scheme (Mlawer et al. 1997), the MM5 shortwave scheme (Dudhia 1989), the modified version of the Kain–Fritsch scheme (Kain 2004), and the WRF single-moment 5-class (WSM5) microphysics scheme (Hong et al. 2004; Hong and Lim 2006).

The following four LSSs are used in the model:

- 1) The five-layer thermal diffusion scheme (SLAB; Dudhia 1996) uses the force–restore method to solve the thermal diffusion equation for soil temperature in the five soil layers with thicknesses of 1, 2, 4, 8, and 16 cm, whereas soil moisture values are determined using a season-dependent function of land use.
- 2) The Noah LSS (NOAH; Chen and Dudhia 2001; Ek et al. 2003) simulates soil variables (i.e., temperatures and moistures) for four layers with thicknesses of 10, 30, 60, and 100 cm by using the force–restore method. The LSS accounts for detailed physical

vegetation and soil hydrology processes and urbanization treatment.

- 3) The Rapid Update Cycle LSS (RUC; Smirnova et al. 1997, 2000) is characterized by a layer method for solving energy and moisture budget equations for soil variables and fluxes, which include soil, snow cover, and vegetation processes at six soil levels: 0, 5, 20, 40, 160, and 300 cm.
- 4) The Pleim–Xiu LSS (PLEX; Xiu and Pleim 2001) forecasts soil temperature, soil moisture, and canopy moisture for the two layers with thicknesses of 1 and 99 cm, where three pathways for moisture fluxes are considered: evapotranspiration, bare soil evaporation, and wet-leaf evaporation.

Among the four LSSs, SLAB is the simplest in both structure and process physics, while NOAH, RUC, and PLEX are more sophisticated (e.g., the latter three LSSs include the sophisticated snow, soil, and vegetation physics). Moreover, the LSSs consider different soil layering schemes, which could affect the solutions.

The four LSSs in the WRF are used to investigate the sensitivity of the simulated height fields to the LSS choice for 12-member ensembles of simulations. In the next sections, the differences among the SLAB, NOAH, RUC, and PLEX simulations are compared. Because of the important role of soil moisture in land–atmosphere coupling (e.g., Koster et al. 2004) and according to Zeng et al. (2014), simulations are also performed using PLEX with initial soil moisture contents reduced by 25% (but with a 12-member ensemble as the additional simulations for further discussion here), which are termed the PXsm simulations, with the abbreviations “PX” for the Pleim–Xiu LSS and “sm” for soil moisture.

Using different PBLSSs, the other four-ensemble experiments are also carried out to compare the height sensitivity to the LSSs choice and that to the PBLSSs. Four PBLSSs in the WRF are employed here, that is, the Yonsei University scheme (YSUbl; where “bl” denotes boundary layer; Hong et al. 2006); the modified Mellor–Yamada scheme (MYJbl; Mellor and Yamada 1982; Janjić 2001); the quasi-normal scale elimination model (QNSEbl; Sukoriansky et al. 2006); and the PBLSS of the asymmetric convective model, version 2 (ACM2bl; Pleim 2007).

All of the above-mentioned simulations employ the default land surface datasets of the WRF modeling system. However, these data may need updating for simulations. For example, the surface albedo and green vegetation fraction (GVF) were retrieved from the images of the Advanced Very High Resolution Radiometer (AVHRR) about 20 years ago (e.g., Gutman and Ignatov 1998). We updated the monthly surface albedo and GVF data and incorporate them into the WRF

preprocessing system for the simulations with the Noah and Pleim–Xiu LSSs, which are termed the NHag and PXag simulations, respectively (e.g., the “a” and “g” denote albedo and GVF, respectively), to examine to what extent the simulated GPHs are affected by the updated data.

In summary, SLAB, NOAH, RUC, and PLEX (without the lowercase letters in naming) are investigated for comparisons among different LSSs, which is the focus of this study; PXsm and PXag (NHag) use the Pleim–Xiu (Noah) LSS and newly prescribed initial values for soil moisture, surface albedo, and GVF to compare with original PLEX (NOAH) results so as to investigate the effect of the related quantities; YSUbl, MYJbl, QNSEbl, and ACM2bl are used for simulations with different PBL schemes. Therefore, in total, 11×12 seasonal simulations are performed for the 11 ensembles in this study. In the following sections, the coupled-model simulations/ensembles are referred to by the names of the schemes used, while for a specific LSS, a slightly complex expression is applied, such as “the SLAB LSS.” Table 1 summarizes the physical options used in the 11 ensembles, and additional details regarding schemes are described by Skamarock et al. (2008) or in the above-mentioned references.

In this study, the simulation area (Fig. 1) is centered at (37°N, 103°E), with 144×116 grid points at a horizontal resolution of 30 km. A vertical resolution of 28 uneven levels was set with the top prescribed at 50 hPa. We choose three subareas in the investigations, that is, D_{tb} , D_{sc} , and D_{ec} included in Tibet, southern China, and eastern China with cold and high plateau, humid, and semihumid climates, respectively. We use the summer of 2003 as the simulation period, during which a prolonged, extremely heavy rainfall event and a persistent super heat wave occurred in eastern China (Zeng et al. 2012, 2014). All of these simulations were carried out for the approximate period from 1 May through 1 September 2003, and each simulation is a slightly perturbed, 12-member ensemble with initial conditions chosen at 0000, 0600, 1200, and 1800 UTC 1–3 May 2003 to make the simulation results more robust. The 4-month (May–August) integrations were performed using the first-month integration as a model spinup, and we used the June–August (JJA) results for analysis. Because the physical options of the simulations are nearly the same, except for the LSSs (or the PBLs), the differences observed between the simulations result from the different LSSs (or the PBLs).

b. Datasets

For the initial and boundary conditions of the simulations, the NCEP $1^\circ \times 1^\circ$ Final (FNL) analysis data are

TABLE 1. Physical options used in the experiments.

Expt	Land surface	Boundary layer	Cumulus	Microphysics	Radiation
SLAB	Five-layer thermal diffusion scheme (Dudhia 1996)	As in NOAH	As in NOAH	As in NOAH	As in NOAH
NOAH/NHag/YSUbl	Noah scheme (Chen and Dudhia 2001; Ek et al. 2003)	Yonsei University scheme (Hong et al. 2006)	Modified Kain–Fritsch scheme (Kain 2004)	WSM5 microphysics (Hong et al. 2004; Hong and Lim 2006)	RRTM longwave (Mlawer et al. 1997); MM5 shortwave (Dudhia 1989)
RUC	Rapid Update Cycle scheme (Smirnova et al. 1997, 2000)	As in NOAH	As in NOAH	As in NOAH	As in NOAH
PLEX/PXsm/PXag	Pleim–Xiu scheme (Xiu and Pleim 2001)	As in NOAH	As in NOAH	As in NOAH	As in NOAH
MYJbl	As in NOAH	Mellor–Yamada–Janjić (Mellor and Yamada 1982; Janjić 2001)	As in NOAH	As in NOAH	As in NOAH
QNSEbl	As in NOAH	Quasi-normal scale elimination model (Sukoriansky et al. 2006)	As in NOAH	As in NOAH	As in NOAH
ACM2bl	As in NOAH	Asymmetric convective model, version 2 (Pleim 2007)	As in NOAH	As in NOAH	As in NOAH

FIG. 1. Topographic elevations (m) and spatial distribution of selected observational stations within the model domain. The subareas denoted as D_{tb} (28°–35°N, 86°–93°E), D_{sc} (25°–32°N, 108°–115°E), and D_{ec} (32°–38°N, 115°–120°E) are used in section 4.

used. Because the horizontal resolution of 30 km in this study is much higher, the 38-km NCEP Climate Forecast System Reanalysis (CFSR) data (<http://cfs.ncep.noaa.gov/cfsr/>) are also employed for the comparison.

Conventional radiosonde GPH data (available at 0000 and 1200 UTC each day during the summer of 2003) are used for validation. Considering the smoothly varying nature of GPH fields, which has been indicated by previous researchers (e.g., Reichler and Roads 2004), 161 meteorological stations with radiosonde data are assessed, which cover the domain area of continental China and the surrounding regions (Fig. 1).

For the PXag and NHag simulations, following Meng et al. (2014), we employ MODIS global 16-day 0.05° bidirectional reflectance distribution function (BRDF)/albedo data (i.e., black-sky albedo from MCD43C3 dataset), which were downloaded from the Land Processes Distributed Active Archive Center (LP DAAC) for the period from 1 May to 29 August 2003 to obtain monthly mean values. In addition, the GVF data were constructed following Jiang et al. (2010), with global MODIS vegetation indices (i.e., MOD13C2 data from LP DAAC) provided monthly as a level-3 product projected on a 0.05° geographic Climate Modeling Grid (CMG) (<http://lpdaac.usgs.gov>).

c. Assessment measures

To assess the performance of the model and investigate the sensitivity of the GPH simulations to different LSSs, we use monthly or seasonal-mean model bias (BIAS), root-mean-square error (RMSE), standard deviation (STD; STD_M and STD_O for simulations and observations, respectively), and correlation coefficient (CORR), which are computed as follows:

$$BIAS = \overline{M} - \overline{O}, \quad (1)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (M_i - O_i)^2}, \quad (2)$$

$$STD_M = \sqrt{\frac{\sum_{i=1}^N (M_i - \overline{M})^2}{N}}, \quad (3)$$

$$STD_O = \sqrt{\frac{\sum_{i=1}^N (O_i - \overline{O})^2}{N}}, \quad (4)$$

and

$$CORR = \frac{\sum_{i=1}^N (M_i - \overline{M})(O_i - \overline{O})}{\sqrt{\sum_{i=1}^N (M_i - \overline{M})^2} \sqrt{\sum_{i=1}^N (O_i - \overline{O})^2}}, \quad (5)$$

where N is the total number of the stations, M and O represent the simulated and observed values of the quantity (i.e., GPH), respectively, the overbar denotes the mean values, and the subscript i is for relevant stations.

d. Atmospheric equation for GPH change

Different land surface processes lead to different land surface fluxes, which cause changes in basic meteorological quantities, such as air pressure, temperature, and wind speed. Given an isolated column of air without horizontal divergence, higher heat fluxes can result in greater surface temperature and enhance the heights of the pressure levels under air mass conservation constraints. Theoretically, the specific mechanism of the LSS-induced effect on simulated GPHs can be explained as follows.

To simulate the domain at the seasonal or monthly scale, the following hydrostatic equation can be used:

$$\frac{\partial p}{\partial H} = -\rho g^*, \quad (6)$$

where p , H , ρ , and g^* stand for the air pressure, GPH, air density, and acceleration due to gravity (constant value), respectively. Using the equation of state for air

$$p = \rho RT, \quad (7)$$

where R and T are the gas constant and temperature, respectively. The following equation is obtained by integrating the above equation from the surface to 850 hPa with the mean value theorem:

$$\int_{p_s}^{p_{850}} \frac{dp}{p} = - \int_{H_s}^{H_{850}} \frac{g^*}{RT} dH, \quad (8)$$

where $p_{850} = 850$ hPa, $H_s = \text{constant}$, and H_{850} and p_s are temporal variables:

$$\ln \frac{p_{850}}{p_s} = -\frac{g^*}{RT} (H_{850} - H_s), \quad (9)$$

where $\bar{T}$ is the mean temperature value of the air column between H_s and H_{850} . Equation (9) indicates that H_{850} is a function of the two atmospheric variables for a given location, that is, p_s and $\bar{T}$. With respect to the function and variables, the differential form of (9) over a given area (e.g., eastern China) is obtained as follows:

$$d \left[\ln \left(\ln \frac{p_s}{p_{850}} \right) \right] = d \left[\ln \left(\frac{g^*}{R\bar{T}} H_{850} \right) \right], \quad (10)$$

or

$$\frac{1}{\ln \frac{p_s}{p_{850}}} \left(\frac{dp_s}{p_s} \right) = \frac{dH_{850}}{H_{850}} - \frac{d\bar{T}}{\bar{T}}. \quad (11)$$

Generally, p_s varies little over the given area (e.g., for eastern China, $p_s \approx 1000$ hPa). Thus,

$$\frac{dH_{850}}{H_{850}} \approx \frac{d\bar{T}}{\bar{T}} + 6.15 \frac{dp_s}{p_s}. \quad (12)$$

The finite differential form of (12) can be rewritten as follows:

$$\delta H_{850} \approx H_{850} \frac{\delta \bar{T}}{\bar{T}} + 6.15 H_{850} \frac{\delta p_s}{p_s}. \quad (13)$$

Similarly, for the 500-hPa GPH over the area,

$$\delta H_{500} \approx H_{500} \frac{\delta \bar{T}}{\bar{T}} + 1.44 H_{500} \frac{\delta p_s}{p_s}. \quad (14)$$

In this study, the finite differential values in (13) and (14) can be regarded as the perturbations induced by the LSSs, and the contributions to the GPH changes from the changes in air temperature and surface pressure can be obtained.

3. Simulation results

Because of the complex, nonlinear, diurnal variations of GPH, we present the simulated GPHs for both 0000 and 1200 UTC, which is consistent with the radiosonde GPH data available. In addition, because LSSs mainly influence simulations from the lower to midtroposphere (see next section), we only provide results for the 850- and 500-hPa levels.

a. Summer means

Because of the same lateral-boundary forcings, the LSS-simulated GPH fields are generally in agreement with analysis data (e.g., Giorgi and Mearns 1999). Figures 2 and 3 depict the simulated ensemble-mean seasonal (JJA)-mean 0000 UTC GPH fields and the CFSR fields at 500 and 850 hPa, respectively. For the 0000 UTC 500-hPa GPH, the PLEX analysis fields show generally consistent spatial results compared with the CFSR fields, for example, high GPH values in southern China and low values in the north with maximum values in the southeastern corner of the model domain, where the western Pacific subtropical high persists. However, the GPH values are generally approximately 20 gpm higher than CFSR (Figs. 2a,b). In addition, the 850-hPa PLEX GPH pattern is similar to the analysis field [Figs. 3a,b; it is noteworthy that, because of high elevations and low air pressure at the surface of the Tibetan Plateau and part of inner Mongolia (Fig. 1), no GPH output is given for 850 hPa over the area], except for the values in the eastern part of the domain, which are generally lower than those from reanalysis data. Meanwhile, apparently systematic differences between different schemes can be observed. As shown in Fig. 2c for 500 hPa, the PLEX GPH is consistently higher than the SLAB GPH over most continental areas of China to the west of $\sim 110^\circ\text{E}$, with a large total area of differences of more than 6 gpm in western China. In southeastern China, the Korean Peninsula, and over the East China Sea, SLAB provides obviously higher values than PLEX. These values of LSS-induced differences are very large compared with those of Shabbar et al. (1990), who provided a 500-hPa summer GPH anomaly (with a value of ~ 7 gpm for the largest anomaly amplitude over a relatively small area in continental China) when analyzing the Northern Hemisphere GPHs from 1946 to 1985. It can be concluded that because different LSSs produce different surface fluxes that further affect simulated atmospheric states, GPH fields (even over ocean) can be substantially modified as PLEX is used instead of SLAB. The NOAA GPH is relatively similar to PLEX (Fig. 2d). Compared with PLEX, RUC results in obviously higher simulated values over most of the north (north of 30°N), with a large total area of GPH differences of more than 10 gpm around northern China, and provides slightly lower values south of 30°N (Fig. 2e). At 850 hPa, SLAB simulates significantly higher values than PLEX, with differences of more than 10 gpm over most areas of eastern China (Fig. 3c). In addition, as shown in Fig. 3d (Fig. 3e), the NOAA (RUC) 850-hPa GPHs are slightly higher (lower) than the PLEX results. Furthermore, in the comparisons among SLAB, NOAA,

FIG. 2. Ensemble- and seasonal-mean GPH distributions at 500 hPa for 0000 UTC (gpm), where regions with significant LSS-induced differences are marked with gray and black dots. Specifically, gray (black) dots indicate the ensemble-mean GPH differences that are significant at the 5% (10%) level, according to the Student's *t* test for the time series of daily GPH values of the study period.

and RUC, large 500-hPa differences between SLAB and NOAA (RUC and SLAB/NOAH) are found over southwestern (northwestern) China (Figs. 2f–h), with even larger differences at 850 hPa (Figs. 3f–h).

Because of the higher level of 500 hPa in comparison with 850 hPa, the GPH difference fields at 500 hPa are more systematically distributed. In addition, the fields are

generally characterized by two large areas with opposite signs (e.g., Figs. 2c–h). This finding suggests that LSS-induced GPH difference fields generally show spatially large-scale features, which are produced by the simulations with a relatively high resolution (i.e., 30 km) in this study.

Additionally, Figs. 2 and 3 also present the Student's *t*-test results of different LSS-simulated ensemble-mean

FIG. 3. As in Fig. 2, but for 850 hPa.

GPH fields and show that GPH differences can be significant at the 5% and 10% levels for very large areas over continental China, especially at 850 hPa, which corresponds with the above results. For instance, although at 500 hPa the total area with the significantly large SLAB–PLEX differences is relatively small (Fig. 2c), it is much larger at 850 hPa (Fig. 3c), which agrees well with the distributions of the GPH difference fields. In addition, the largest differences occur between SLAB and RUC over northwestern China at 500 hPa and over most of the

simulation domain at 850 hPa according to the Student's *t* tests (Figs. 2g, 3g). Considering the high elevations and low air pressure at the surface of the Tibetan Plateau and in part of inner Mongolia (Fig. 1), the largest differences occupy most of the areas, with surface pressures of more than 850 hPa.

Figure 4 is similar to Figs. 2 and 3 but for the differences in ensemble maximum and minimum, where the ensemble maximum (minimum) is the simulation with the highest (lowest) GPH seasonal-mean value from one

FIG. 4. As in Fig. 2, but for differences in ensemble max and min at 500 and 850 hPa, where the ensemble max (min) has the highest (lowest) GPH seasonal-mean value from one of the 12 members in an ensemble.

of the 12 members in an ensemble. Rather than the differences in ensemble mean (Figs. 2 and 3), the differences in ensemble maximum and minimum are statistically significant over much larger areas. This result indicates that the simulations of extreme values are very sensitive to the LSS choice.

As shown in Fig. 5a for BIAS, the effects of the LSSs on the GPH results depend on the characteristic

pressure levels. As indicated by Zhuang et al. (2006), 0000 UTC GPH fields show forecast errors that are similar to those of 1200 UTC GPH fields from 14 May to 14 July 2003. This study confirms that the 0000 UTC BIASs are similar to those at 1200 UTC when using different models. At 500 hPa, the four LSS ensembles provide higher ensemble-mean seasonal GPHs than the observed values (e.g., the RUC ensemble-mean

FIG. 5. Ensemble results of (a) BIAS, (b) RMSE, (c) GPH BIAS profiles at Zhengzhou station (34.72°N, 113.65°E), and (d) the difference of the std dev of the summer-mean GPHs over China at 500 and 850 hPa for 0000 and 1200 UTC, where the “Ave,” “Max,” and “Min” levels in the shaded bars denote the 12-member ensemble mean, max, and min, respectively.

seasonal GPHs for 0000 and 1200 UTC are higher than those observed for 17.4 and 17.5 gpm, respectively). The 500-hPa BIAS differences among the LSS ensembles are generally lower than 5 gpm, and the PLEX GPHs are generally the most similar to the observations. However, for ensemble means at 850 hPa, obvious BIAS differences are produced among the LSS ensembles, in which the PLEX BIAS values are the lowest in amplitude, followed by NOAH, RUC, and SLAB (e.g., when comparing the seasonal-mean 1200 UTC GPHs with the observations, SLAB and NOAH are 8.4 and 4.1 gpm higher, respectively, while RUC and PLEX are 5.0 and 1.2 gpm lower), and large differences were observed among the LSS ensembles. Particularly, the RUC–SLAB difference is approximately 13 gpm and approximately 260% of the RUC BIAS. These LSS-induced BIAS differences also represent the LSS-induced GPH differences. In addition, these values are area averaged over the entire model domain, and larger and much larger values exist over part of continental China, as shown in the above LSS-induced difference fields (Figs. 2c,e,g). Relative to SLAB, the other ensembles can significantly improve the 850-hPa GPH simulation, and the low-level GPH simulation is sensitive to the LSS choice. Moreover, the 500- and 850-hPa GPH BIAS values from SLAB are

both very large, while the BIAS values from the other ensembles are reduced as the pressure decreases (Fig. 5a). Among the LSS ensembles, RUC produces the lowest height and results in a difference of more than 20 gpm (e.g., the 1200 UTC RUC BIAS difference between 500 and 850 hPa).

Regarding the ensemble- and seasonal-mean RMSE (Fig. 5b) at 500 hPa, both 0000 and 1200 UTC values are near 18 gpm, which shows no large LSS-induced differences. At 850 hPa, some large differences are produced, with the maximum RMSE occurring for SLAB and lower, similar values occurring for the other LSS ensembles (e.g., compared to SLAB, the PLEX RMSE is reduced by over 50%). Overall, these RMSEs agree well with those of BIAS. The area-averaged BIAS and RMSE values both generally increase as the pressure level increases over most of the simulation area (Figs. 5a,b) because the height fields are, in the context of hydrostatics, computed from temperature, moisture, surface height, and surface pressure, and lower-level errors are accumulated and added to the upper-level errors. However, for more localized regions, the GPH profiles are quite complex (e.g., Fig. 5c for Zhengzhou station), as is explained in section 4. In addition, the variations (with pressure level) and amplitudes of the

RMSE and BIAS values are consistent with the GCM results of Xu et al. (2001), who used standard deviations to forecast errors in height and suggested that LSS-induced errors could substantially influence GPH forecasts.

Simulation standard deviations (i.e., STD_M) closer to the observation standard deviation (i.e., STD_O) correspond with better LSS simulations of the spatial GPH variability. Compared with the ensemble-mean STD_M and STD_O values of ~ 60 gpm, both the 500-hPa $STD_M - STD_O$ values are small, with the PLEX STD_M values closer to the observed values (Fig. 5d). At 850 hPa, the schemes have little STD_M difference (generally lower than 3 gpm), and all of the LSS ensembles slightly overestimate the spatial variability, with SLAB providing the best performance. All of the LSS ensembles appear to simulate the GPH spatial variability well, and the variability is only slightly sensitive to the LSS choice.

The 12-member ensemble spread (i.e., the standard deviation with respect to the ensemble mean; not shown) is very low for the above 12-member BIAS, RMSE, and $STD_M - STD_O$ results. For instance, SLAB gives the largest spread (1.65 gpm) for 500-hPa 0000 UTC BIAS, which is much lower than the ensemble mean (~ 15 gpm) and is consistent with the range of BIAS change (Fig. 5a). All of these results confirm the robustness of the conclusions addressed above.

Generally, the LSS ensembles can produce general seasonal-mean GPH patterns. While the performances of the ensembles when simulating the 500-hPa GPH field are not noticeably different over the entire domain, the LSS-induced differences are likely substantial at subregional scales (e.g., northwestern China). In addition, at 850 hPa, the overall performances can be substantially different, which indicates that the simulated GPH field is even more sensitive to the LSS choice in the lower troposphere than in the midtroposphere. For GPH fields at 500 hPa, all of the LSS simulations produce large ensemble-mean BIAS values, while the values from the LSS ensembles, except for SLAB, are reduced at 850 hPa. Overall, PLEX performs the best, followed by NOAH and RUC and SLAB. In addition, SLAB presents the largest ranges (or ensemble spread values) of BIAS, RMSE, and $STD_M - STD_O$, which suggests the largest uncertainty induced by the scheme. The worst performance of SLAB may largely occur because among the four LSSs, the five-layer thermal diffusion scheme (i.e., SLAB) is the simplest in complexity. Thus, the SLAB LSS poorly reflects the actual land surface characteristics and therefore decreases the computational precision of the surface fluxes. For instance, unlike the other LSSs in the WRF, SLAB does not calculate soil moisture. Instead, SLAB considers soil moisture as a seasonally varying function of land-cover

type and does not explicitly consider the effects of vegetation (Dudhia 1996).

The above-mentioned GPH differences are directly caused by changes in the surface fluxes of the LSSs. As an example of how well the LSSs reproduce surface fluxes, Fig. 6 displays LSS-simulated evapotranspiration fields and an observation-based field (Miralles et al. 2013). These results show that while LSSs can reasonably simulate fields with high correlations (Table 2), some large differences are also clearly presented [e.g., SLAB (PLEX) gives apparently higher values for northwestern (eastern) China].

The results show that simulated higher evaporation leads to lower GPH fields in a given area. For instance, compared with SLAB, PLEX simulates higher evaporation (Fig. 6a vs Fig. 6d) and lower sensible heat flux (not shown) throughout most of southeastern continental China, which directly results in lower PLEX surface temperatures in the area. This lower temperature (colder air) reduces the pressure levels under the hydrodynamic balance, for example, PLEX provides lower GPHs than SLAB over most of the southeast (Fig. 3c). Overall, higher simulated evaporation generally reduces pressure levels and vice versa (further discussion is given in section 4).

Compared with the observations, PLEX presents much higher evaporation (Fig. 6d vs Fig. 6f) over the southeast. However, the overall PLEX 850-hPa GPH field is nearly unbiased (Fig. 5a). This result indicates the complexity of the behaviors by the LSSs in the context of the GPH simulation, as is in agreement with previous studies; for example, Jerez et al. (2013) showed that no single ensemble member can present results better than the others in every situation by a multiphysics ensemble of regional climate simulations. This finding suggests that even if an LSS ensemble presents a “perfect” GPH field, the simulated surface fluxes might be biased with large amplitudes. In addition, unbiased simulated surface fluxes do not necessarily result in well-simulated GPH fields when using a coupled model.

Additional PXsm simulations with reduced soil moisture contents show that the simulated evaporation is still higher than the observations (Fig. 6f) even when the initial soil moisture content is decreased by 25%. Because the initial soil moisture content is generally not negatively biased by 25% over all of continental China [e.g., compared with results by Zhang et al. (2008)], biased PLEX evaporation likely results from parameterizations other than the initial values. Based on the above result with a consideration of previous investigations that have highlighted the importance of initial land states (e.g., Guo et al. 2011), it is suggested that improving land initialization is inadequate for achieving better model performance for

FIG. 6. (a)–(e) LSS-simulated ensemble-mean summer evapotranspiration fields (mm day^{-1}) and (f) the observation-based evapotranspiration field (mm day^{-1}), which has a resolution of 0.25° over land and was obtained from [Miralles et al. \(2013\)](#).

continental China in seasonal simulations/forecasts using coupled models. However, the parameterizations should be improved simultaneously.

Furthermore, both the NHag and PXag results (see supplemental material) are shown to be only slightly

different from the NOAH and PLEX results, respectively, which demonstrates that the BIASs are caused by different land parameterizations rather than the use of the satellite data (i.e., surface albedo and GVF).

TABLE 2. Ensemble-mean seasonal CORR, BIAS, RMSE, STD_M , and $\text{STD}_M - \text{STD}_O$ for the LSS-simulated evapotranspiration over land, where observations are from [Miralles et al. \(2013\)](#) and $\text{STD}_O = 0.87 \text{ mm day}^{-1}$.

	CORR	BIAS (mm day^{-1})	RMSE (mm day^{-1})	STD_M (mm day^{-1})	$\text{STD}_M - \text{STD}_O$ (mm day^{-1})
SLAB	0.51	0.17	1.19	1.35	0.48
NOAH	0.73	−0.03	0.85	1.24	0.37
RUC	0.55	−0.43	0.97	0.94	0.07
PLEX	0.70	0.68	1.24	1.45	0.58
PXsm	0.61	0.56	1.13	1.31	0.44
PXag	0.71	0.71	1.25	1.46	0.59
NHag	0.74	0.08	0.84	1.26	0.39

FIG. 7. Ensemble-mean monthly GPH differences between SLAB and the other LSSs for 0000 UTC in July (gpm).

b. Monthly means

In addition to the consistency of the ensemble-mean monthly GPH fields with the corresponding NCEP reanalysis (not shown), large differences are induced by the LSS choice, which is more apparent in the lower layer. Figure 7 provides the mean GPH difference fields for 0000 UTC in July among the SLAB and other LSSs. For 850 hPa, the monthly GPH field is generally more sensitive to the LSSs than at the seasonal scale (e.g., Figs. 3f,g vs Figs. 7b,d, respectively), which is the most obvious for eastern China; for example, RUC-SLAB differences of more than 20 gpm cover a large total area in the region (not shown).

As shown in Fig. 8a for 0000 UTC, the ensemble-mean monthly GPH values from the four LSSs are higher than observations at 500 hPa, which is consistent with the above-mentioned results for the seasonal scale. However, very large BIAS differences are observed between

the monthly and seasonal results that are higher than the differences in the seasonal-mean BIAS (Fig. 5a).

In addition, at the monthly scale, the low-level GPH simulation is more sensitive to LSS choice than at the upper level (e.g., all of the 500-hPa ensemble means of monthly BIAS are positive with relatively small differences, while the 850-hPa ensemble means of monthly BIAS can change from positive to negative values with large amplitudes). Generally, lower 850-hPa BIAS and RMSE values can be clearly identified (Figs. 8a,b); the mean values of RMSE and those of $STD_M - STD_O$ increase with time at the monthly scale (Figs. 8b,c).

Because of differences among the LSSs, the monthly variations of the ensemble-mean BIAS also differ complexly. For instance, among the values by different LSSs for 0000 UTC at 500 hPa (Fig. 8a), the SLAB BIAS values are 12.8, 19.4, and 8.2 gpm, which basically correspond to the minimum, maximum, and minimum for June,

FIG. 8. Ensemble monthly 500- and 850-hPa results of (a) BIAS, (b) RMSE, and (c) $STD_M - STD_O$ for 0000 UTC, where shaded bars are the same as those shown in Fig. 5.

July, and August, respectively. This clearly indicates that SLAB presents the most apparent monthly variation in the 500-hPa BIAS. Relatively, BIAS changes from the other LSSs are more moderate, with RUC being the most stable. Similarly, large differences appear at 850 hPa. In this case, NOAH results in the BIAS with the least change, while RUC produces the largest variations in BIAS (e.g., the RUC BIAS at 0000 UTC changes from -9.8 gpm in June to 2.2 gpm in August).

c. Comparison of sensitivity: LSSs versus PBLs

Because of the substantial influences of boundary layer processes on the climate system, several researchers have emphasized the role of PBL on climate. For example, Flaounas et al. (2011) examined the sensitivity of the 2006 West African monsoon simulation to convection and PBL parameterization using WRF, while Solman and Pessacg (2012) performed several 3-month MM5 simulations using different cumulus schemes and PBLs to define the optimal combination of physical parameterizations over South America. As indicated by Garratt (1993), intercomparisons of PBLs and LSSs are needed for climate models. In this context, it is useful to compare

the relative importance of LSSs and PBLs in GPH simulations.

We suggest that the comparison should be made between the largest LSS-induced differences and the largest PBL-induced differences for 500 and 850 hPa, separately. Figure 9 presents the seasonal-mean difference fields with the PBLs (listed in Table 1) at 500 and 850 hPa for 0000 UTC. Looking back at the difference fields induced by the LSSs (e.g., Figs. 2, 3), the LSS-induced GPH difference fields are larger than those induced by the PBLs when considering the total area with large difference values and maximum values. For instance, over most of northwestern China, the 500-hPa RUC–SLAB and ACM2bl–QNSEbl differences both exceed 10 gpm, where the LSS-induced differences can be substantially larger (Fig. 2g vs Fig. 9c). At 850 hPa over eastern China and in the neighboring areas, the RUC–SLAB and ACM2bl–QNSEbl differences are both greater than 6 gpm where the LSS-induced differences are still much larger (Fig. 3g vs Fig. 9d). Moreover, all of the Student's t -test results confirm the larger LSS-induced sensitivity: only two out of six comparisons show statistical significance for 500 hPa (i.e., the ACM2bl–QNSEbl and YSubl–QNSEbl differences out of the differences among the four PBLs), and for 850 hPa, no large areas with statistical significance appear for the differences induced by the PBLs.

Considering the results from both the LSSs and PBLs, the regions with significant differences detected using the Student's t test are generally consistent with and somewhat different from those determined by merely subtracting the ensemble means (e.g., Figs. 2g, 9c). These results suggest that the Student's t -test results provide an additional inspection of significant differences and do not contradict the subtraction results (e.g., because of the large variances of the inspected time series, the two time series in the Student's t test might not be significantly different, although their average values are very different).

Similar to the LSS-induced difference fields, the 500-hPa difference fields caused by the PBLs are generally characterized by a few large-difference regions, such as the region covering the larger part of China for the 500-hPa QNSEbl–ACM2bl differences (Fig. 9c). Additionally, although no significant differences in ensemble mean might be identified, the differences in ensemble maximum and minimum would generally be statistically significant (e.g., Figs. 9g–j).

Figure 10 presents the ensemble seasonal-mean GPH BIAS and RMSE using different PBLs. When considering the BIAS and RMSE, the LSS-induced GPH errors are generally equivalent to those induced by the PBLs (Fig. 5 vs Fig. 10) and the LSS-induced errors are slightly larger at 850 hPa. This result is consistent with

FIG. 9. As in Figs. 2–4, but for PBLS-induced simulations.

FIG. 10. As in Fig. 5, but for PBLs-simulated GPH fields.

the above-mentioned difference field results. Moreover, the LSS ensemble spread values are generally larger than those of the PBLs simulations, which is consistent with the ranges of the measures, such as BIAS and RMSE (Figs. 5, 10). All of these results demonstrate that the GPH sensitivity to the LSSs is generally equivalent to or above that of the PBLs, which confirms the importance of the LSS choice when simulating the GPHs of regional climate.

4. Explanation of GPH change

The LSSs regulate the GPHs through modifying the surface fluxes. In fact, there are some further intermediate processes between surface energy transfer and the GPHs: land surface fluxes need to take effect by acting on some thermal quantities such as air temperature and pressure via thermodynamical processes in the atmosphere. Therefore, the processes that occur in more interior atmosphere other than surface turbulent transfer are also important in modifying the GPHs.

Figure 11 shows the seasonal-mean differences in sensible heat flux, surface air temperature (SAT), and surface pressure among the SLAB and other schemes for an investigated subarea with relatively low elevation in eastern China (denoted as D_{ec} in Fig. 1). These results suggest that although higher sensible heat flux does not necessarily result in a higher SAT over different areas

from a given LSS ensemble [e.g., over the area (32° – 34° N, 116° – 118° E), the SLAB-simulated higher sensible heat flux corresponds to a lower SAT; Fig. 11a vs Fig. 11e], the increased sensible heat flux resulting from different LSSs generally heats the air directly and results in a generally higher SAT for the study area (e.g., Figs. 11b–d vs Figs. 11f–h, respectively). Meanwhile, at low levels near the land surface, the heated air arises, which results in the horizontal convergence of the air mass over the region. Because of hydrostatic balance, a lower surface air pressure is generally induced into the air column (e.g., Figs. 11j–l). This is consistent with results reported previously; for example, Jerez et al. (2012) investigated the LSS role for climate change projections and indicated that the enhanced warming implies a strengthening of the Iberian thermal low and the cyclonic circulation.

Figure 12 depicts the LSS-induced surface fluxes, air temperature, and air pressure that are associated with the GPH changes for the three investigated subareas (Fig. 1). It shows that although the net radiation at the surface has a slight LSS-induced change, generally, the increase in sensible heat flux corresponds to the decrease in latent heat flux and the SAT is positively correlated with sensible heat flux (Figs. 12a,c,e). Additionally, the SAT is negatively correlated with surface pressure, and the surface pressure is positively correlated with the 850- and 500-hPa GPH BIASs (Figs. 12b,d,f), which further suggests that the GPH

FIG. 11. Ensemble-mean seasonal SLAB means and differences between SLAB and the other LSSs. (a) SLAB sensible heat flux (W m^{-2}). (b) Difference in sensible heat flux between NOAH and SLAB ($\text{NOAH} - \text{SLAB}$). (c) As in (b), but for $\text{RUC} - \text{SLAB}$. (d) As in (b), but for $\text{PLEX} - \text{SLAB}$. (e)–(h) As in (a)–(d), but for SLAB SAT ($^{\circ}\text{C}$). (i)–(l) As in (a)–(d), but for SLAB surface pressure (hPa).

BIASs are caused by the changes in air temperature and pressure.

Figures 12g and 12h depict the GPH differences in (13) and (14) between the SLAB and other LSSs due to changes in temperature and pressure and the total LSS-induced GPH difference for the D_{ec} subarea. All three terms, total difference D_h , difference due to temperature change D_t , and difference due to pressure change D_p , are directly calculated from simulated GPH fields and pressure and temperature fields rather than from (13) and (14). Because the air column has no exchange with the environment, the increase in the lower-level temperature will directly result in an increase in the pressure level (i.e., D_h and D_t have the same sign). However, at the regional scale, the impact of the environment on the air column cannot be ignored. As shown in Figs. 12g and 12h, D_h and D_t have opposite signs, while D_h and D_p have the same sign.

Thus, the lower atmospheric warming of the regional air column is accompanied by a reduced GPH at the isobaric surface, which plays a leading role in the surface pressure change in modifying the heights of the pressure levels (compared with the secondary role of the temperature change), especially for the 850-hPa level in this study. The GPH differences calculated by the simulation results rather than by (13) and (14) suggest that D_h is basically balanced by D_t and D_p , which are consistent with the theoretical results from (13) and (14). At 500 hPa across the region (Fig. 12g), the ensemble-mean D_h is less than 5 gpm, which shows that the simulated seasonal-mean GPH is not sensitive to the LSS choice. However, at the monthly scale (e.g., July), D_h can reach more than 10 gpm, which suggests a substantial sensitivity that is much higher than at the seasonal scale. At 850 hPa (Fig. 12h), the seasonal-mean D_h reaches approximately

FIG. 12. Ensemble LSS-induced means for the three subareas (Fig. 1): (a) sensible heat flux (SHF), land heat flux (LHF), the sum of SHF and LHF, and SAT for D_{ec} ; (b) 850- and 500-hPa GPH BIASs and surface air pressure for D_{ec} ; (c) as in (a), but for D_{sc} ; (d) as in (b), but for D_{sc} ; (e) as in (a), but for D_{tb} ; (f) as in (b), but for D_{tb} ; (g) 500-hPa GPH differences, where $D_h = \delta H_{500}$, $D_t = H_{500} \delta T / T$, and $D_p = 1.44 H_{500} \delta p_s / p_s$; and (h) 850-hPa GPH differences, where $D_h = \delta H_{850}$, $D_t = H_{850} \delta T / T$, and $D_p = 6.15 H_{850} \delta p_s / p_s$ (gpm).

18 gpm and shows a pronounced LSS-induced difference. At the monthly scale (e.g., July), D_h exceeds 20 gpm, which also displays a higher sensitivity for the D_{ec} area.

It is noteworthy that (13) and (14) are theoretically derived from the hydrostatic equilibrium equation,

which is different from the WRF formulations that use the nonhydrostatic dynamical framework. We suggest the derived equations confirm and explain, theoretically, the GPH changes due to the changes in air temperature and surface pressure over quite a large area (e.g., D_{ec}). The reasons are as follows:

- 1) The D_h , D_t , and D_p are directly calculated from simulated GPH fields, and there is a good balance among the three terms. This confirms our derived equations quantitatively. Additionally, it suggests that although the WRF uses the nonhydrostatic dynamical framework, over quite a large area (e.g., D_{ec}), the hydrostatic equilibrium equation is still satisfied.
- 2) The balance of the three terms suggests qualitatively that the LSS-induced GPH changes are caused by the changes in air temperature and surface pressure under the hydrostatic equilibrium over a given area. This is why, generally, the D_t and D_p terms have opposite signs.

Given that the 850- and 500-hPa BIASs are two special forms of δH_{850} and δH_{500} in (13) and (14), respectively, and that the effect of pressure change on GPH is generally dominant over and opposite to the effect of temperature change (Figs. 12g,h), the coefficient (i.e., $6.15H_{850}$) of the pressure-change term on the right-hand side of (13) is generally larger than that (i.e., $1.44H_{500}$) of (14), which suggests that the amplitude of the 850-hPa BIAS is generally larger than that at 500 hPa for localized regions (Fig. 5c).

Compared with latent heat flux, sensible heat flux more directly heats the SAT, affects surface pressure, and hence more directly leads to the GPH changes. However, latent heat flux is also important because of the following reasons:

- 1) Given a certain net radiation at the surface, the amount of the net radiation is basically partitioned between sensible and heat fluxes. Latent heat flux then acts on the GPH via sensible heat flux in the partitioning, and in this context, the effect of latent heat flux is equivalent to the effect of sensible heat flux on the GPH.
- 2) Latent heat flux means evapotranspiration from the land surface becomes a portion of water vapor in the atmosphere and can change surface net radiation because of the effect of the greenhouse gas. In addition, the added water vapor can also condense in the atmosphere (e.g., via convection), release latent heat, and further change the atmospheric state. However, because the LSS-induced change in water vapor contributes little to the total precipitable water, the effect induced by the greenhouse gas and the latent heat release is suggested to be minor compared to the first reason.

Note that latent heat flux is highly relevant to soil moisture (e.g., latent heat flux is proportional to evapotranspiration, and the evapotranspiration difference between PXsm and PLEX is shown in Fig. 5). We suggest that soil moisture also plays an important role in

the GPH change for areas with a humid or semihumid climate (e.g., the climate transient zone of northern China); however, in areas with an arid climate (e.g., the deserts that widely cover northwestern China), latent heat flux (and soil moisture) has little effect on the GPH.

Considering that at the land surface the net surface radiation is basically partitioned between latent and sensible heat fluxes, both latent and sensible heat fluxes are equally important, whereas in the lower troposphere, sensible heat flux directly affects the SAT (and hence pressure) while latent heat flux shows little effect, as is explained in the equation for SAT change (Zeng et al. 2014, 2015). Additionally, because the GPH is an atmospheric parameter that land surface processes can act on indirectly, we can conclude that, generally, the LSS-induced change in sensible heat flux is mainly responsible for the LSS-induced GPH sensitivity via affecting air temperature and pressure.

5. Summary and discussion

In this paper, we investigated the effects of the land surface schemes (LSSs) on simulated geopotential heights (GPHs) over continental China during the summer of 2003 using the 12-member ensembles with ARW, version 3. Although the model can generally reproduce the GPH patterns over China, the simulated GPH fields are sensitive to the coupled-model ensembles using different LSSs.

At the seasonal scale, obvious systematic distribution differences occur between different LSS-ensemble GPHs, which indicate that the simulated GPHs are sensitive to different LSS ensembles over continental China. Particularly, 500-hPa GPH differences of more than 10 gpm between the ensemble means (e.g., the RUC-SLAB mean difference) occurred over northwestern China. These differences potentially occurred because northwestern China is located in a dry climate region where lower soil thermal inertia values exist; thus, LSS-induced perturbed atmospheric conditions would have a larger impact on the land surface than elsewhere, and the land surface would amplify the GPH changes in the region. These differences can be very large compared with the multiyear GPH anomalies given by Shabbar et al. (1990) and the forecast errors provided by Xu et al. (2001). Because of the slowly varying nature of GPH, the LSS-induced 500-hPa GPH difference fields are generally characterized by two large areas with opposite signs over continental China and its surrounding regions.

At 850 hPa, the sensitivity of simulated GPH to different LSS ensembles is found to be higher than that of 500-hPa GPH because the LSS choice largely influences the simulated GPH fields directly by modifying surface

fluxes in the lower atmosphere rather than in the upper atmosphere. Among the four LSS ensembles, RUC-simulated GPHs significantly change with the pressure level.

It appears that simulated monthly GPHs are more sensitive to the LSS choice than simulated seasonal GPHs. Even if the ensemble-mean seasonal spatial variability of GPH is only slightly sensitive to the LSS choice, the spatial variability shows quite high sensitivity at the monthly scale.

Considering the overall behavior of the measures, PLEX behaved the best, followed by NOAH, RUC, and SLAB for the GPH simulations. Although large LSS-induced differences appear, the largest difference generally exists between SLAB and other schemes, which demonstrates that more detailed parameterizations in soil moisture and vegetation physiology are needed. Additionally, good performance of the coupled model in simulating surface fluxes may not necessarily result in a good GPH simulation. All of these suggest the complexity of the land-atmosphere coupled-model performances and the need to improve both the land and the atmospheric components of the model.

The GPH sensitivity to the LSS choice is shown to be generally equivalent to or higher than the sensitivity to the PBLSSs, particularly at 850 hPa. Previous studies have demonstrated that the PBLSSs can significantly affect the model climatology, including precipitation, temperature, and moisture (e.g., Giorgi et al. 1993). This study demonstrates the substantial impacts of different LSSs and PBLSSs on GPH climatology simulations.

The result of soil-moisture-induced differences implies that refining the LSS parameterizations should be the first step rather than land initializations for state-of-the-art LSSs (given the land-cover types) when coupled-model simulations are performed, for example, for LSS studies during the second phase of GLACE.

Different LSS choice can result in large simulated GPH differences, which mainly result from different surface sensible heat fluxes induced by different LSSs, thereby causing further surface pressure and average temperature variations between the pressure levels. The theoretical analysis shows that the LSS-induced GPH change at a given pressure level is balanced by two terms, one based on temperature change and one with the opposite sign and based on surface pressure change, which could dominate the total GPH change. Thus, LSS-enhanced sensible heat leads to higher low-level temperature, which is accompanied by the rise of air, the horizontal convergence of the air mass, and a reduction in the low-level pressure. This result is further confirmed by the ensemble simulation results.

In this study, we focus on the LSS-induced sensitivity of the GPH simulations. In fact, state-of-the-art LSSs

are generally very sophisticated in complexity, and many factors may contribute to model (both coupled and off-line) errors. For example, Koster et al. (2004) highlighted the importance of soil moisture in land-atmosphere coupling over some “hot spot” regions in summer; Zeng et al. (2015) showed the sensitivity of simulated SAT to initial soil moisture, which is comparable with the sensitivity induced by the LSS choice in the medium-range weather in eastern China; and Zheng et al. (2012) found a large and cold bias in simulated surface skin temperature over the arid western continental United States during the daytime due to the formulations of roughness lengths. In this paper, we have paid less attention to what causes model biases except for soil moisture. The experiments of this study are performed using nearly the same model area settings and lateral-boundary conditions, and the effects of the different LSSs on the simulated GPHs are generally associated with the domain size, spatial resolutions, and physical options of the models (e.g., Marsigli et al. 2014), which suggest some uncertainty of the results in the present regional model study. Additional experiments should be designed to further test the model performance and determine the effects of different LSS choice on GPH simulation.

Notably, the results of the coupled-model ensemble simulations might not reasonably reflect the offline LSS performances. However, the coupled-model simulations would, more or less, produce some features of each LSS as the land component of the coupled model (e.g., Zeng et al. 2015). This study presents the ensemble results of simulated GPHs, which clearly show systematic features for each LSS ensemble (e.g., the performance in the context of BIAS). These features may help modelers (meteorologists) in GPH simulations (forecasts) by choosing a proper LSS. Because these LSS simulations are performed using the coupled mode, the results also suggest the deficiencies in the coupling strategy or the offline LSS behavior (e.g., few offline LSS simulations had been conducted for validation against observations over a large area with a broad range of land-cover types before the LSSs were incorporated into the WRF), which are left for further investigations. Additionally, the BIASs at 500 hPa indicate the overall GPH overestimation for all of the LSSs, which implies that the deficiency may probably lie in the atmospheric (rather than land surface) component of the WRF and that adequate validation for the atmospheric component is also needed before land-atmosphere coupling for the modeling system.

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