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Gravel Parameterization Scheme and Verification Using BCC_CSM

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Abstract: The soil in China contains an abundance of gravels, but it is poorly described in land surface models. To solve this problem, the Beijing Climate Center Atmosphere–Vegetation Interaction Model (BCC_AVIM), which is a land surface model with the gravel parameterization, is coupled to the Beijing Climate Center System Model (BCC_CSM). The simulation ability of BCC_CSM for China using the gravel parameterization is evaluated by comparing the simulation results using original and new schemes with the observed data. The results show that the annual average surface temperature simulated with the new scheme is more consistent with the observation in terms of the spatial distribution, and the simulation results in Southwest China, Northwest China and the Qinghai-Tibet Plateau are significantly improved, especially in summer. In the perspective of the area-averaged variables, the situation of more precipitation simulated using the original scheme is improved except for summer. The high-level and low-level wind fields simulated by BCC_CSM have a significant improvement in the Qinghai-Tibet Plateau. In general, this gravel parameterization is more suitable for areas with the high gravel content, and it

improves the simulation performance of BCC_CSM in some areas of China.

Keywords: Gravel parameterization; BCC_CSM; Soil temperature and humidity; Air temperature; Precipitation

1. Introduction

The medium-resolution Beijing Climate Center (BCC) Climate System Model version 2 (BCC_CSM2_MR) is a global climate system model coupled with atmosphere, land surface, ocean and sea-ice components, which participated in the Coupled Model Intercomparison Project Phase 6 (CMIP6; Wu et al., 2014). The land surface accounts for about 30% of the global surface area, so the study of land surface models and land-air interactions is far-reaching (Zhang, 1998; Dai, 1996). Coupling land surface models with climate system models by sensitivity tests have verified that different land surfaces have different influences on climate (He et al., 2017). Therefore, optimizing the land surface models and coupling them to the climate models is one of the important ways to improve the climate models (Sun, 2002).

Stony soils are widely distributed in China, with gravels being mainly concentrated in the plateaus as well as northwestern and northern mountainous areas (Fu et al., 2001; Hou, 1993; Chen, 2007; Gao et al., 2011). Gravels firstly affect the physical properties of the soil, such as soil porosity and soil hydraulic conductivity, which in turn change the hydrothermal transport in the soil (Mehuys et al., 1975; Hanson et al., 1979; Poesen et al., 1994). With the rapid development of numerical models, many studies have attempted to simulate the role of gravels on hydrothermal transport processes in the soil. In the Water Erosion Prediction Project (WEPP) model,

for example, for describing the porosity of gravel-containing soils, gravels can be considered non-porous spheres. The presence of gravel reduces the porosity and the available water content of the soil (Alberts et al., 1995). Different models have also been used to simulate the water infiltration in the soils with gravels, and it has been concluded that the water infiltration in soils decreases with the increasing content of gravels (Cousin et al., 2003; Ma et al., 2008). After simulating at a single site (Naqu station) using the CoLM model, Luo et al. (2008) raised that ignoring the gravel component of the soil may cause some biases in the simulation results. Pan et al. (2015) pointed out that the presence of gravels causes changes in the capacity of mixed soils, which alters the thermal conductivity of the soil and ultimately affects the soil temperature. Yi et al. (2013) considered soils as a mixture of fine soils and gravels. They analyzed the process of multi-year permafrost on the Qinghai-Tibet Plateau after adding the impact of gravels on soil hydrothermal properties to a terrestrial ecological model. The simulated soil temperature and humidity were more accurate in the Bei Lu River.

The previous gravel parameterization formula has been revised to form a gravel parameterization scheme suitable for the BCC_AVIM land surface model. The soil hydrothermal process has been simulated using the observations at the Maduo station as the reference data. (Ma et al., 2020a). The results show that the BCC_AVIM land surface model is more accurate after using the gravel parameterization. It is important to evaluate the applicability of this gravel parameterization scheme for China due to the high gravel content in China, and this is of great significance for improving

climate simulations.

2. Model introduction and data

2.1. Model introduction

The atmospheric model component of BCC-CSM2-MR is BCC-AGCM3-MR with a horizontal resolution of T106 ($1.125^{\circ} \times 1.125^{\circ}$), increased vertical stratification of 46 layers, and a model layer top of 1.459 hPa. The description of the model dynamical framework and physical processes and an assessment of the basic model performance can be found in the relevant references (Dong et al., 2009; Guo et al., 2011; Wu, 2012). The land surface model component is BCC_AVIM2.0, an atmosphere–vegetation interaction model with some ability to simulate land surface processes. The BCC_AVIM soil hydraulic property parameterization scheme is based on the studies from Clapp et al. (1978) and Cosby et al. (1984). The soil thermal property parameterization scheme is based on the work of Farouki (1981). AVIM2, a domestically developed dynamic vegetation and soil carbon cycle model, is introduced based on the physical module in community land surface model version 3 (CLM3) of the National Center for Atmospheric Research (NCAR) land surface model (Ji, 1995; Ji et al., 2008). The Modular Ocean Model Version 4, a 40-level ocean model (MOM4_L40), has a horizontal resolution of $1^{\circ} \times 1^{\circ}$ with a longitudinal direction encrypted to $1/3^{\circ}$ in the tropics. The sea ice model, Sea Ice Simulator (SIS), has a horizontal resolution of $1^{\circ} \times 1^{\circ}$ with one snow layer and two sea-ice layers of the same thickness in the vertical direction, and the model has the same horizontal resolution as MOM_L40.

2.2. Data

The current surface data used in BCC-CSM does not include the gravel parameter. To more accurately simulate the effect of gravels on soil hydrothermal properties over a regional area and apply the gravel parameterization scheme to the global climate model BCC_CSM, a new soil dataset with the gravel content needs to be created to input the model. The dataset used in this study is the gravel data with the spatial resolution of 1 km and 10 km from Sun Yat-sen University. This dataset is based on the Global Soil Dataset for use in Earth System Models (GSDE) and other applications. In this study, the gravel data with the 10-km resolution is used. Firstly, the global gravel data is converted into a Gaussian grid surface with a precision of 320×160 in the BCC model. The gravel parameter is created in the surface data of the BCC model. As this global gridded soil dataset has a large number of missing data in deep soils, such as the gravel data in North America and Asia, especially in the layer of 1.383–2.296 m, and it does not adopt the data structure of the soil dataset used in this model but only has eight layers in the vertical direction (0–0.045 m, 0.045–0.091 m, 0.09–0.166 m, 0.166–0.289 m, 0.289–0.493 m, 0.493–0.829 m, 0.829–1.383 m and 1.383–2.296 m), it is crucial to complete and improve the gravel data. To match the ten layers of the data required in the model, the gravel data is interpolated into ten layers (node depths of 0.0071 m, 0.0279 m, 0.0623 m, 0.119 m, 0.212 m, 0.366 m, 0.620 m, 1.038 m, 1.728 m and 2.865 m, using bilinear interpolation method). The data at the first and the tenth layers are determined according to the distribution of gravel content in adjacent layers. At the same time, to reduce the missing data, the

missing data is replaced with the data at the adjacent layer or grid points. However, this method may cause the sum of sand, clay, and gravel contents to be greater than 100% at some point, contrary to the fact. To solve it, the values where the sum of the three exceeds 100% are reduced in the same proportion. Figure 1 shows the improved soil gravel data in China. Compared with the original data, the distribution of gravel content and the location of the large-value areas remain. The gravel content is high and widespread in China, with the large-value center mainly in the Qinghai-Tibet Plateau, where the gravel content increases with the increase of depth. The deep gravel content is even over 50%, and the medium-depth and shallow gravel content is relatively uniform. The areas with high gravel content of the deep layer are mainly in the western Qinghai-Tibet Plateau. The shallow gravel content is low in Northeast China and North China and the gravel content increases with depth.

The gravel-parameterized land surface component—BCC_AVIM is coupled to the BCC_CSM climate system model to simulate global surface air temperature, wind field and precipitation from January of 2000 to December of 2001, and China is selected for analysis. To test the simulation results with the gravel parameterization, the monthly mean wind field data with a horizontal resolution of $2.5^{\circ} \times 2.5^{\circ}$ from National Centers for Environmental Prediction (NCEP) and the gridded surface air temperature and precipitation dataset from the China Meteorological Data Network with a resolution of $0.5^{\circ} \times 0.5^{\circ}$ for the same time period are also used.

Fig. 1. Spatial distribution of the improved gravel content (unit: %) in China.

3. Gravel parameterization schemes

3.1. Impacts of gravel on the soil hydraulic properties

The weathering condition of gravels may have different effects on soil porosity. For less-weathered gravels, the soil porosity is mainly determined by the fine soil content, so we calculate the soil porosity using the equation of Poesen and Lavee (Poesen et al., 1994), and for mixed gravels it is expressed as follows.

$$\theta_{sat,m} = (1 - V_g)\theta_{sat,f} + V_g\theta_{sat,g} \quad (1),$$

where $\theta_{sat,f}(\text{mm}^3 \cdot \text{mm}^{-3})$ is the porosity of fine soil, $\theta_{sat,g}(\text{mm}^3 \cdot \text{mm}^{-3})$ is the porosity of gravel, and V_g is the gravel volume content. In this study, the gravel is not highly weathered, and its porosity is negligible. $\theta_{sat,g}$ is set to zero and $\theta_{sat,f}$ can be calculated based on the sand content of the fine soil.

The presence of gravel alters the soil porosity, increasing the proportion of soil macropores. Therefore, it inevitably affects the soil hydraulic conductivity. Peck and Watson used a homogeneous medium containing a spherical mosaic to calculate the relationship between the saturated hydraulic conductivity of a gravel-free soil and the saturated hydraulic conductivity of a gravel-containing soil (Peck et al., 1979), and it is as follows.

$$k_{sat,m} = k_{sat,f} \left(\frac{2(1-V_g)}{2+V_g} \right) \quad (2),$$

where the $K_{sat,f}(\text{mm} \cdot \text{s}^{-1})$ is the saturated hydraulic conductivity of fine soils which is determined by the soil sand content in BCC_AVIM. It has been shown that the work of Peck and Waston provides a more accurate description of the saturated hydraulic conductivity for the soil with the gravel content below 40% (Beibei et al., 2009).

In BCC_ AVIM, the pore-size distribution coefficient (b_m , unitless) of mineral soils is an important dimensionless parameter for describing the hydraulic properties of soils. The magnitude of b_m is related to the water-holding capacity of the soil. The b_f of fine soils increases with the clay content in the soil. Previous studies have shown that when the soil suction is low, the water-holding capacity of gravels is lower than

that of fine soils. On the contrary, when the soil suction is high, the water-holding capacity of gravels is higher than that of fine soils. In this experiment, due to the effect of the gravel parameterization on b_m , b_g is set to 7.5 (the pore-size distribution coefficient is set to 3 for sandy soils and 12 for clay soils).

$$B_m = b_g V_g + b_f (1 - V_g) \quad (3),$$

In BCC_AVIM, the soil matric potential (mm) of saturated fine soils is related to the soil sand content. The water-holding capacity of fine soils decreases with the sand content. The water-holding capacity of gravels is generally considered low, but studies have found that the higher-weathered the gravels, the higher the effective soil water content. Cousin et al. (2003) have found that if only the gravel volume is considered and its water-holding properties are ignored, the calculated effective water volume is underestimated by 34%. The infiltration volume is overestimated by 15.8%. Considering the role of gravels on soil water-holding properties is therefore essential to accurately model the water transport in gravel-containing soils. The mixed soil matric potential can be calculated using the following equation.

$$\psi_{sat,m} = \psi_{sat,f}^{1-V_g} \psi_{sat,g}^{V_g} \quad (4),$$

where $\psi_{sat,g}$ (mm) is the matric potential of saturated gravels and set to -1.3 mm (Pan et al., 2015).

Soil capacity is an index to measure the soil structure. In practice, the capacity of gravelly soils is not easy to measure directly. Russo (1983) proposed the use of the gravel volume content, gravel capacity, and fine soil capacity to calculate the capacity of gravelly soils.

$$\rho_b = \rho_n (1 - V_g) + 2650 V_g \quad (5),$$

where $\rho_n = 2700 \times (1 - \theta_{sat,f})$ for the capacitance of the fine soil.

3.2. Impact of gravels on the soil thermal properties

In the original parameterization scheme of BCC_AVIM, the soil mineral thermal conductivity is a weighted average of the quartz sand thermal conductivity and the clay thermal conductivity, according to the relative contents of the quartz sand and the clay.

$$\lambda_s = \lambda_q^{f_q} \lambda_0^{f_0} \quad (6).$$

$\lambda_q=7.7$, $\lambda_0=2.0$ are the thermal conductivity of quartz and other minerals, respectively.

λ_q is considered as the sum of the quartz and the gravel in the new scheme.

The calculation of dry-soil thermal conductivity (λ_{dry} , $W \cdot m^{-1} \cdot K^{-1}$) in BCC_AVIM is based on the Farouki and Jonansen scheme and does not consider the effect of different soil compositions on dry-soil thermal conductivity. In the new scheme, the dry-soil thermal conductivity is calculated based on the work of Côté and Konrad (Côté et al., 2005).

$$\lambda_{dry,i} = \chi \times 10^{-\eta \theta_{sat,m}} \quad (7),$$

where χ ($W \cdot m^{-1} \cdot K^{-1}$), η (unitless) are empirical parameters used to calculate the different soil types. In Côté scheme, the values of χ and η for gravels are 1.70 and 1.80, respectively; for natural mineral soils, χ and η are 0.75 and 1.20, respectively; for fibrous soils, χ and η are 0.3 and 0.87, respectively. In this paper, we consider the general application of this scheme for different soils, so χ and η are 0.917 and 1.29, respectively, taken as the average values of the three soils.

Due to the different gravels with different structures and mineral compositions, the heat capacity of gravels will be different. Referring to the modification of thermal melting of gravelly soils by Pan et al. (2015), the thermal melting of gravel-containing soils c_m ($J \cdot m^{-3} \cdot K^{-1}$) is simply expressed as the following equation in this paper.

$$c_m = \left(\frac{2.128V_{sand} + 2.385V_{clay} + 2.2V_g}{V_{sand} + V_{clay} + V_g} \right) \times 10^6 \quad (8),$$

where V_{sand} and V_{clay} are the volume fractions of the sand and the clay, respectively.

Based on the above theory about the effect of gravel on soil hydrothermal properties, the soil scheme in the original model is modified as follows for a new parameterization scheme with the effect of gravels (see Table.1).

Table.1 Gravel parameterization scheme (new scheme) and the original scheme

Parameters	Original Scheme	New Scheme
Soil porosity (Saturated soil water content)	$\theta_{sat,i} = 0.489 - 0.00126(\%sand)_i$	$\theta_{sat,i} = 0.489 - 0.00126(\%sand)_i - 0.00489(\%rock)_i$
Saturated hydraulic conductivity	$K_{sat}[Z_{h,i}] = 0.0070556 \times 10^{-0.884+0.0153(\%sand)_i}$	$K_{sat}[Z_{h,i}] = 0.0070556 \times 10^{-0.884+0.0153(\%sand)_i} \times \frac{2(1-\%rock)}{(2+\%rock)}$
Exponent B	$B_i = 2.41 + 0.129(\%clay)_i$	$B_i = (2.41 + 0.129(\%clay)_i) \times (1 - \%rock) + 0.075(\%rock)$
Soil matric potential	$\psi_{sat,i} = -10.0 \times 10^{1.88-0.0131(\%sand)_i}$	$\psi_{sat,i} = -10.0 \times 10^{1.88-0.0131(\%sand)_i} \times (1 - \%rock) + 1.3(\%rock)$
Soil bulk density	$\rho_{d,i} = 2700(1 - \theta_{sat,i})$	$\rho_{d,i} = 2700(1 - \%rock)(1 - \theta_{sat,i}) + (\%rock) \times \rho_r$
Soil solid thermal conductivity	$\lambda_{s,i} = \frac{8.80(\%sand)_i + 2.92(\%clay)_i}{(\%sand)_i + (\%clay)_i}$	$\lambda_{s,i} = 7.7(\%sand + \%rock) \times 2.0^{[1-(\%sand + \%rock)]}$
Thermal conductivity of dry soil	$\lambda_{dry,i} = \frac{0.135\rho_{d,i} + 64.7}{2700 - 0.947\rho_{d,i}}$	$\lambda_{dry,i} = 0.917 \times 10^{-1.29\theta_{sat,i}}$
Solid soil heat capacity	$c_{s,i} = \left(\frac{2.128(\%sand)_i + 2.385(\%clay)_i}{(\%sand)_i + (\%clay)_i} \right) \times 10^6$	$c_{s,i} = \left(\frac{2.13(\%sand)_i + 2.39(\%clay)_i + 2.20(\%rock)_i}{(\%sand)_i + (\%clay)_i + (\%rock)_i} \right) \times 10^6$

4. Results

4.1. Verification of the surface temperature simulated with the new and original

schemes

BCC_AVIM was coupled to BCC_CSM, and the global surface temperature from January of 2000 to December of 2001 was simulated to verify the simulation performance of this model after adding the gravel parametrization. The global surface temperature was averaged over two years, and the gridded surface temperature dataset was used as the reference data ($0.5^{\circ} \times 0.5^{\circ}$). Since the surface temperature was simulated at the resolution of $1.125^{\circ} \times 1.125^{\circ}$, the simulation results were interpolated to the grid points of the reference data using the bilinear interpolation. China was also divided into eight regions, Northeast China, North China, Jianghuai, Southeast China, Eastern Northwest China, Southwest China, Western Northwest China, and Qinghai-Tibet Plateau, based on climate and vegetation differences in China (Fig. 2). The ability of the model to simulate temperature before and after adding the gravel parameterization was analyzed for the area-averaged variables.

Fig. 2. Eight sub-regions in China: I Northeast China, II North China, III Jianghuai, IV Southeast China, V Eastern Northwest China, VI Southwest China, VII Western Northwest China, and VIII Qinghai-Tibet Plateau.

As it can be seen in Figs. 3 and 4, the model can simulate the spatial distribution

of temperature well compared with the observed data, and the annual mean surface temperature map simulated with the new scheme shown in Fig. 3 is more consistent with the observed spatial distribution than the original scheme, especially in the central and southern China. In winter (Fig. 4d), the minimum temperature in China appears in the northeast, with the average temperature below -20°C ., and the simulated value of the model is lower compared with the observed data (Figs. 4h and 4i). However, the difference between the simulated value with the new scheme and the observed value is significantly reduced after adding the gravel parameterization. The reason is that the soil exerts heat to the outside in winter, and the temperature in the deep soil layer is high, so the heat is transferred to the shallow layer. After adding gravel the thermal conductivity of the soil increases (Ma, 2020a). The heat transfer from the deep soil to the surface layer gets greater, resulting in an increase of the surface soil temperature and making the near-surface temperature higher through interaction between the ground and the atmosphere. As shown in Fig. 4b, the simulated temperature in the central and southern China in summer is $2\text{--}4^{\circ}\text{C}$ higher than the observed data, but it is lower in Northeast China and the Qinghai-Tibet Plateau. The soil absorbs heat from the outside in summer, so the heat is transferred from the surface to the deeper layers of the soil, leading to soil thermal conductivity increasing after adding gravels, and the surface temperature decreases. As shown in Fig. 4j, the simulated value with the new scheme minus the observed value is negative. The simulated surface temperature changes significantly in summer and winter after adding gravels.

Fig. 3. Spatial distribution of average temperature ($^{\circ}\text{C}$) from 2000 to 2001 for (a) original-scheme simulation, (b) new-scheme simulation and (c) observation.

Fig. 4. Spatial distribution of average temperature ($^{\circ}\text{C}$) in (a–i) spring, (b–j) summer, (c–k) autumn and (d–l) winter from 2000 to 2001. Obs indicates observation, ori–obs is the simulation with the original scheme minus observation, and new–obs is the simulation with the new scheme minus observation.

In terms of regional mean temperatures (Fig. 5), the original model simulates higher temperature than the observation in Northeast China and North China but lower or insignificant temperature in the rest sub-regions. Compared with the original scheme, the model with the new scheme has significantly improved in Southwest China, Northwest China and the Qinghai-Tibet Plateau. Especially in summer, they are more consistent with the observed values. The reason is that this gravel

parameterization scheme is more suitable for areas with the high gravel content. Due to the relatively low gravel content and high precipitation in Jianghuai and Southeast China, the corresponding soil water and heat transport process is more complicated. Still, the surface temperature does not change significantly before and after adding the gravel parameterization. The surface temperature in Northeast China and North China tends to decrease after adding the gravel parameterization compared to the simulation with the original scheme, probably because the soil texture and plant types in Northeast China are different from those in Northwest China and Southwest China, and the gravel parameterization scheme only works better in winter.

Fig. 5. The area-averaged surface temperature (°C) in the eight sub-regions.

4.2. Verification of the precipitation simulated with the new and original schemes

The spatial distribution of precipitation and the location of rain-bands are

important indicators for assessing the simulation ability of the model (Wu, 2012). Gravels can alter the thermal and hydraulic conductivity within the soil, affecting soil temperature and humidity, which can alter the simulated results of precipitation by affecting the exchange between ground and air. As shown in Fig. 6, the spatial distribution of the simulated precipitation with the original and new schemes from 2000 to 2001 are consistent with the observation overall. The simulated rainfall in Jianghuai and southeastern coastal regions of China is less than 60 mm on average, while the observed surface precipitation is above 100 mm. The precipitation simulated with the gravel parameterization shown in Fig. 6b increases in Jianghuai, reaching 40 mm above and increasing by 10–20 mm than the original scheme. It is more consistent with the observed values shown in Fig. 6c. The differences between spatial distributions simulated with the original and new schemes are not significant in other areas.

Seen from the distributions of precipitation in different seasons in Fig. 7, compared with the observed data, the model can simulate the seasonal variation and distribution pattern of precipitation in China. The precipitation reaches the maximum in summer, and spatially it shows a decreasing trend from Southeast China to Northwest China. Compared with the observed data, the rain band simulated by the model is weaker in summer, but there is more precipitation in Northwest China. The new scheme improves this problem to some extent. In winter (Fig. 7d), precipitation is concentrated in Jianghuai and Southeast China. The biases of the simulations with the original and new schemes from the observation in these regions are both large. The

simulated values are slightly larger than observed values in Northwest China and Qinghai-Tibetan Plateau. The bias of the simulated precipitation with new scheme from the observation gets less in Northwest China and Qinghai-Tibetan Plateau.

Fig. 6. Spatial distributions of average precipitation from 2000 to 2001 (mm) simulated with (a) the original scheme and (b) the new scheme, as well as (c) the spatial distribution of the corresponding observed precipitation.

Fig. 7. Simulated spatial distribution of precipitation (mm) (a-i) in spring, (b-j) summer, (c-k) autumn and (d-l) winter from 2000 to 2001. Obs indicates observation, ori-obs is the simulation with the original scheme minus the observation and new-obs is the simulation with the new scheme minus the observation.

Seen from the area-averaged precipitation (Fig. 8), compared with the observed data, the precipitation simulated by the BCC model is less in summer but more in winter. The precipitation simulated by the new scheme is less in all seasons except for

summer compared with the precipitation simulated with the original scheme. The main reason is the weak precipitation in these seasons. The soil hydraulic conductivity is the leading cause for changes of soil moisture. The gravel increases the soil hydraulic conductivity, decreases the soil moisture and affects processes such as the evaporative runoff in the surface soil, resulting in a decreasing trend of precipitation. The problem that the simulated precipitation by the original model is more than the observation except for summer is improved. The simulation and trend of the maximum summer precipitation are also more consistent with observation. The precipitation in summer is large, and the change in soil hydraulic conductivity caused by adding gravels is not the most crucial cause for the soil moisture change. The evaporation and runoff processes are more complicated, and the physical processes need to be further explored. The simulation results over the Qinghai-Tibet Plateau show that the new scheme reduces the summer precipitation on the plateau by about 20 mm. The month with the maximum precipitation shifts from July to August, which is more consistent with the observation. The simulated precipitation is locally improved after adding gravels, and the improvement is more obvious in areas with high gravel content.

Fig. 8. The area-averaged precipitation (mm) in eight sub-regions.

4.3. Verification of the wind simulated with the new and original schemes

In this paper, the simulation results in 2000 and 2001 are averaged and compared with NCEP wind field data in four seasons, to test the simulation ability of the model before and after adding gravels. Figs. 9a-9d show the wind fields from the NCEP data at 850 hPa in four seasons. The northwesterly monsoon forms in the northern China under the influence of the Siberian airflow during autumn and winter. It can be simulated well before and after adding gravels. The simulation results in spring are shown in Figs. 9e and 9i. After adding gravels, the bias of the simulated wind speed from the NCEP data over the Qinghai-Tibet Plateau significantly gets smaller compared with that simulated with the original scheme. The wind speed simulated by the BCC_CSM model in summer (Figs. 9f and 9j) is slightly lower than the NCEP

data all over China, and the change is not obvious after adding gravels. As shown in Figs. 9g and 9k, the improvement of the simulated wind speed in the plateau in autumn is obvious, being closer to the NCEP data. The wind speed in China is larger in winter than in other seasons, especially in the Qinghai-Tibet Plateau, where the wind speed is greater than 10 m s^{-1} . The difference between the wind field simulated with the new scheme (Fig. 9l) and the NCEP data, decreases in both the Qinghai-Tibet Plateau and the eastern Northwest China, compared with the original scheme (Fig. 9h). Fig. 10 shows the wind fields at 200 hPa in four seasons, and we can see that the model can reasonably simulate the westerly jets over China and the South Asian High over the plateau in summer. The wind speed over the plateau increases after adding gravels in summer with an average increase of 2-3 m/s, making the location of the South Asian High move by 2-3 latitudes to the north compared with the original scheme. The wind speed simulated with the new scheme in Northeast China is closer to the NCEP data. The problem is also improved that the simulated wind speed in Northeast China region in winter is much larger compared with the NCEP data.

Fig. 9. 850-hPa wind field from 2000 to 2001. (a), (e) and (i) respectively represent NCEP data, BCC_CSM simulation with the original scheme minus NCEP data, and BCC_CSM simulation with the new scheme minus NCEP data in spring; (b), (f) and (j) represent those in summer; (c), (g) and (k) represent those in autumn; and (d), (h), (l) represent those in winter.

Fig. 10. Same as Fig.9, but for 200-hPa wind field

4. Conclusions

Gravel is an important component of soils in China, yet its impacts are poorly

described in current land surface models. In this study, a new gravel parameterization scheme was firstly established, and then BCC_AVIM with this gravel parameterization was coupled to BCC_CSM, finally the impacts of this scheme on the simulation results of meteorological elements in eight sub-regions of China were discussed. The following conclusions are drawn.

Compared with the original scheme, the annual mean surface temperature simulated by the new scheme is more consistent with the observation in terms of the spatial distribution pattern, especially in the central and southern China. The surface temperature changes significantly in summer and winter before and after adding gravels. In terms of the area-averaged temperature, the temperature simulated by the original model in Northeast China and North China is relatively high. At the same time, that in the rest sub-regions is relatively low or nearly equal. Compared with the original scheme, the simulation results of the new scheme have significantly improved in Southwest China, Northwest of China, and the Qinghai-Tibet Plateau. Especially in summer, the simulation results are more consistent with the observed values. The impact is not significant in Southeast China and Jianghuai and the simulation in Northeast China and North China is only improved in winter. This gravel parameterization scheme is more suitable for areas with the high gravel content.

Precipitation shows more significant regional variability than temperature. The mean precipitation simulated with the original scheme throughout the year is lower in the Jianghuai and southeastern coastal regions. In comparison, the precipitation

simulated with the gravel parameterization is more consistent with the observed data. The precipitation simulated by the BCC model is less in summer and more in winter. The new scheme has improved the overall bias of the original simulations except in summer. The maximum values and trends of summer precipitation simulated with the new scheme have improved in some local areas.

For the low-level wind field simulated by BCC_CSM, the simulation in spring and autumn is significantly improved in the plateau region, which is closer to the NCEP data. The bias in winter is reduced in the Qinghai-Tibet Plateau and the eastern Northwest China. The model can reasonably simulate the westerly jets over China at 200 hPa and the South Asian High over the plateau in summer. The wind field over the plateau increases after adding gravels in summer, with an average increase of 2–3m/s, making the South Asian High moves 2–3 degrees north compared to the original scheme. The simulated wind speeds in Northeast China are closer to the NCEP data. The higher wind speed compared to the reference data in Northeast China has been improved in winter as well.

As the climate system model can only be run on mainframes, the simulation time is not long enough. This paper only briefly tests the impact of this gravel parameterization and does not discuss the physical mechanisms. A more in-depth study will be carried out later, based on the sensitivity test.

Declarations

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Gravel content dataset for this research is available in <http://globalchange.bnu.edu.cn/research/data>, Temperature and precipitation data are temporarily unavailable due to website reasons. Precipitation data is available in http://www.nmic.cn/http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_PRE_MON_GRID_0.5.html. Temperature data is available in http://www.nmic.cn/http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_TEM_MON_GRID_0.5.html. Wind field data is available in <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.pressure.html>.

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