A new climate scenario for assessing the climate change impacts on soil moisture over the Huang–Huai–Hai Plain region of China

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ABSTRACT
To assess the impacts of temperature and precipitation changes on surface soil moisture (SSM) in the Huang–Huai–Hai Plain (3H) region of China, the approach of conditional nonlinear optimal perturbation related to parameters (CNOP-P) and the Common Land Model are employed. Based on the CNOP-P method and climate change projections derived from 22 global climate models from CMIP5 under a moderate emissions scenario (RCP4.5), a new climate change scenario that leads to the maximal change magnitudes of SSM is acquired, referred to as the CNOP-P type temperature or precipitation change scenario. Different from the hypothesized climate change scenario, the CNOP-P-type scenario considers the variation of the temperature or precipitation variability. Under the CNOP-P-type temperature change, the SSM changes in the last year of the study period mainly fluctuate in the range from $-0.014$ to $+0.012$ m$^3$ m$^{-3}$ ($-5.0\%$ to $+10.0\%$), and from $+0.005$ to $+0.018$ m$^3$ m$^{-3}$ ($+1.5\%$ to $+9.6\%$) under the CNOP-P-type precipitation change scenario. By analyzing the difference of the SSM changes between different types of climate change scenarios, it is found that this difference associated with SSM is obvious only when precipitation changes are considered. Besides, the greater difference mainly occurs in north of 35°N, where the semi-arid zone is mainly situated. It demonstrates that, in the semi-arid region, SSM is more sensitive to the precipitation variability. Compared with precipitation variability, temperature variability seems to play little role in the variations of SSM.

1. Introduction
Owing to the increases in greenhouse gas emissions, climate changes have been occurring and continuing from global to regional scales. According to the IPCC AR5 (Kirtman et al. \textit{2013}), in the near-term period 2016–2035, the projected increase in global mean surface air temperature is likely to fall in the range of 0.3–0.7 °C, relative to 1986–2005. In China, compared with the 30-year average of 1961–1990, the country-averaged annual mean temperature is projected to increase by 1.5–2.1 °C by 2020, 2.3–3.3 °C by 2050, and 3.9–6.0 °C by 2100, under various emissions scenarios (special report on emissions scenarios A2 and B2) (Ding et al. \textit{2007}). By the end of the twenty-first century, annual precipitation for the whole of China will increase by 6%–16% under three future emissions scenarios (RCP2.6, 4.5, and 8.5), and the greatest increases are projected to occur over the Tibetan Plateau and eastern China in summer (Chen and Frauenfeld \textit{2014}). These projected changes in temperature and precipitation will inevitably lead to variations in the hydrological cycle (including streamflow, evapotranspiration, and soil moisture).

Many studies have focused on the hydrological impacts of climate change in China (Dan et al. \textit{2012}; Jiang et al. \textit{2007}; Wang et al. \textit{2011, 2013}; Xu, Taylor, and Xu \textit{2011}). For example,
be provided in this paper by employing the Conditional Nonlinear Optimal Perturbation related to model parameters (CNOP-P) approach (Mu et al. 2010). In addition, this kind of scenario could be used to assess the maximal impacts of climate change. Here, only impacts of climate change on soil moisture in the top 10 cm (i.e. surface soil moisture; SSM for short), a key component of the hydrological cycle, are analyzed, in a region (30°–40°N, 110°–120°E) located in North China. To date, the CNOP-P approach has been applied to investigate the influences of climate change on soil carbon and net primary production in China (Sun and Mu 2012, 2013, 2014), screen the most important and sensitive parameter combinations in numerical models (Sun and Mu 2016), and so on.

2. Methods

2.1. Study region

Wang et al. (2011) used the Variable Infiltration Capacity (VIC) model and climate change scenarios from a regional climate model to evaluate the runoff changes in China under global warming, and reported that annual runoff over China as a whole would probably increase by approximately 3%–10% by 2050. Dan et al. (2012) conducted hydrological projections in the Huang–Huai–Hai Plain (3H) region by employing hypothesized climate change scenarios and the VIC model. Wang et al. (2013) used a snowmelt-based water balance model to discuss the impact of climate change on runoff in a typical river catchment of the Loess Plateau with both climate scenarios derived from climate models and hypothetical climate change scenarios. They found that the Kuye River catchment will likely undergo more flooding in the 2020s, and global warming will probably shorten the main flood season in the catchment, with greater discharge occurring in August.

In general, for studies on the hydrological impacts of climate change, there are two critical aspects: climate change scenarios and the responses of hydrological processes. For simulating the changes of hydrological processes, hydrological models are important tools. To produce climate change scenarios, two methods are generally used. One is to apply the outputs from GCMs (Aich et al. 2014; Chen, Xu, and Guo 2012). However, differences exist in the climate scenarios derived from different GCMs under various emissions scenarios, thus leading to significant uncertainty in the projected hydrological changes (Aich et al. 2014; Xu, Taylor, and Xu 2011). Another methodology is to use hypothetical climate change scenarios (Dan et al. 2012; Singh and Bengtsson 2004), in which a constant change is added to the reference climate condition. But this kind of scenario only considers the change in climatology, and doesn’t consider the change in climate variability.

To investigate the impacts of the changes in climatology and climate variability on the hydrological cycle, a new kind of climate change scenario based on projections under a moderate emissions scenario (RCP4.5) will

2.2. The common land model

The Common Land Model (CoLM) is a sophisticated model developed by Dai et al. (2003). It comprehensively considers biophysical, biochemical, ecological, and hydrological processes. The energy and water transmission among soil, vegetation, snow, and atmosphere is well described. This model has undergone extensive offline tests through using a large amount of observational data, the results of which have suggested that CoLM is able to capture different land surface processes reasonably well (e.g. Luo et al. 2008; Meng and Fu 2009).
For a specified time $T$ and norm, the parameter perturbation $\mathbf{p}$, is called a CNOP-P with the constraint condition $\mathbf{p} \in \Omega$, if, and only if,

$$J(\mathbf{p}_0) = \max_{\mathbf{p} \in \Omega} J(\mathbf{p}),$$

(2)

where

$$J(\mathbf{p}) = \| \mathbf{u}(T) \| = \| M_{t}(\mathbf{U}_0, \mathbf{P} + \mathbf{p}) - M_{t}(\mathbf{U}_0, \mathbf{P}) \|.$$  

(3)

$\mathbf{P}$ is a reference state of parameters and generally represents the standard parameter values in a numerical model. $\mathbf{p}$ is the perturbation to the parameter reference state and stands for parameter errors. The CNOP-P stands for a kind of parameter perturbation that satisfies certain constraints and brings about the maximal departure of the studied state variable from its reference state, at the time $T$.

In this paper, $\mathbf{P}$ is taken as the forcing parameters associated with temperature or precipitation, and $\mathbf{p}$ can be regarded as the changes in temperature or precipitation. For our study, the CNOP-P is regarded as a kind of temperature or precipitation perturbation, and can lead to the maximal variation magnitudes of SSM.

### 2.4. Experimental design

Many studies have evaluated the hydrological impacts of climate change. Among these studies (e.g. Dan et al. 2012; Jiang et al. 2007), hypothesized climate change scenarios have been employed, in which a constant (percentage) change was added to the reference climate condition. For this kind of scenario, the way of adding perturbations to the reference temperature or precipitation condition can be characterized by Equation (4) or (5), as follows:

$$\sum_{i=1}^{y} \sum_{j=1}^{12} \sum_{m=1}^{r} \sum_{n=1}^{r} (P_{i,j,m,n} + \delta_i) \times \frac{\sum_{j=1}^{y} \sum_{i=1}^{12} d(i,j)}{\sum_{j=1}^{y} \sum_{i=1}^{12} d(i,j)} = \sum_{i=1}^{y} \sum_{j=1}^{12} \sum_{m=1}^{r} \sum_{n=1}^{r} P_{i,j,m,n} \times \left(1 + \frac{\mathbf{p}}{100}\right),$$

(4)

$$\sum_{i=1}^{y} \sum_{j=1}^{12} \sum_{m=1}^{r} \sum_{n=1}^{r} \left(P_{i,j,m,n} \times \left(1 + \frac{\mathbf{p}}{100}\right) \right) \times \frac{\sum_{j=1}^{y} \sum_{i=1}^{12} d(i,j)}{\sum_{j=1}^{y} \sum_{i=1}^{12} d(i,j)}.$$

(5)

Here, the subscripts $i$, $j$, and $m$ represent the year, month, and day, respectively; $y$ is the number of years during the study period; $d(i,j)$ is the number of days in a month; $n$ stands for the time when a measurement is taken on a particular day; $r$ represents the number of measurements carried.

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**Table 1.** Projections of changes in temperature and precipitation averaged in the 3H (Huang–Hui–Hai Plain) region from the reference period (1991–2000) to the projection period (2011–2020, 2031–2040, 2051–2060, 2071–2080, and 2091–20100), based on 22 GCMs from CMIP5 and a moderate emissions scenario (RCP 4.5). The values in parentheses are the minimum and maximum change derived from all GCMs.

| Decade       | Temperature (°C) | Precipitation (%) |
|--------------|------------------|-------------------|
| 2011–2020    | 0.73 (0.20 to 1.44) | 2.57 (−9.89 to 11.53) |
| 2031–2040    | 1.53 (0.68 to 2.24) | 6.44 (−2.14 to 18.85) |
| 2051–2060    | 2.16 (1.31 to 3.22) | 9.75 (−0.98 to 21.08) |
| 2071–2080    | 2.55 (1.34 to 3.49) | 11.52 (−0.05 to 35.01) |
| 2091–20100   | 2.71 (1.08 to 3.99) | 11.37 (−7.20 to 36.11) |

In CoLM, the total soil column has a depth of 3.43 m, and the thickness of the first three layers is 9.06 cm in total (1.75, 2.76, and 4.55 cm, respectively). As a result, SSM is calculated as the weighted average of soil moisture in the first three soil layers based on soil layer thicknesses, i.e.

$$SSM = \frac{1.75 \times SM_{\text{first layer}} + 2.76 \times SM_{\text{second layer}} + 4.55 \times SM_{\text{third layer}}}{9.06}.$$
out in a day, which depends on the temporal resolution of the forcing data-set. For example, \( r = 48 \) corresponds to a temporal resolution of half an hour. Moreover, \( P_r \) stands for the forcing parameters related to temperature, and \( P_p \) for the forcing parameters associated with precipitation. \( \delta \) and \( p \) are both constants, denoting the temperature change and percentage change in precipitation relative to the reference climate condition, respectively. Both are generally derived from the climate change projections in the region of interest. For the above-mentioned scenario, a \( \delta \) change in the temperature climatology or a \( p \) percentage change of the precipitation climatology is considered. However, this kind of hypothesized scenario does not induce the variability of temperature or precipitation denoted by the standard deviation in comparison with the reference climate condition. To explore the influence of the change in temperature or precipitation variability on SSM, a new type of climate change scenario is proposed in the following by introducing different perturbations to the annual temperature or annual total precipitation time series in the study period.

As forcing parameters of CoLM, both temperature and precipitation are time-dependent. In our study, perturbations to the annual temperature or annual total precipitation are investigated. For temperature, the perturbations \( p_{ij} \) do not alter within a year and satisfy the following equations:

\[
\sum_{i=1}^{y} \sum_{j=1}^{12} \sum_{m=1}^{r} \sum_{n=1}^{\delta} \left( p_{ij,m,n} + p_{ij} \right) \frac{r \times \sum_{i=1}^{y} \sum_{j=1}^{12} d(i,j)}{r \times \sum_{i=1}^{y} \sum_{j=1}^{12} d(i,j)} = \sum_{i=1}^{y} \sum_{j=1}^{12} \sum_{m=1}^{r} \sum_{n=1}^{\delta} p_{ij,m,n} + \delta_{r} + \delta_{t} \tag{6}
\]

The perturbations \( p_{ij} \) to annual total precipitation in each year satisfy the equations as follows:

\[
\sum_{i=1}^{y} \sum_{j=1}^{12} p_{ij} = \sum_{i=1}^{y} \sum_{j=1}^{12} \sum_{m=1}^{r} \sum_{n=1}^{\delta} p_{ij,m,n} \frac{p_{ij}}{y} \times \frac{100}{\sigma_{p}} \tag{8}
\]

The percentage change \( pp_{ip} \) of precipitation, which is unchanged in the same year, is calculated by the below formulation:

\[
pp_{ip} = \frac{p_{ip}}{\sum_{j=1}^{12} \sum_{m=1}^{r} \sum_{n=1}^{\delta} p_{ij,m,n}} \times 100. \tag{10}
\]

In short, the introduced approach of precipitation perturbations in each time step of CoLM can be illustrated by the following equation:

\[
\frac{y \sum_{i=1}^{y} \sum_{j=1}^{12} \sum_{m=1}^{r} \sum_{n=1}^{\delta} \left( p_{ij,m,n} \times (1 + \frac{pp_{ij}}{100}) \right)}{y \sum_{i=1}^{y} \sum_{j=1}^{12} \sum_{m=1}^{r} \sum_{n=1}^{\delta} p_{ij,m,n}} = \frac{y \sum_{i=1}^{y} \sum_{j=1}^{12} \sum_{m=1}^{r} p_{ij,m,n} \times (1 + \frac{p_{ij}}{100})}{y} \tag{11}
\]

The above approach supplies a possible temperature or precipitation change scenario, which is different from the hypothetical one represented by Equation (4) or (5). Due to different perturbations between years, this kind of scenario probably causes the variation in the temperature or precipitation variability, meanwhile keeping the change of temperature or precipitation climatology the same as that of the hypothesized scenario. Moreover, the perturbation superposed on annual temperature or precipitation is bounded. The upper bound is \( \sigma_t \) for temperature and \( \sigma_p \) for precipitation, describing the maximum increase in the annual temperature and annual total precipitation, respectively.

In the CNOP-P approach, SSM is considered as a variable of the cost function, and the annual temperature or annual total precipitation time series during the study period 1991–2000 (i.e. the reference climate condition) are regarded as the reference parameter vectors. For this study, when temperature (precipitation) perturbation is added, precipitation (temperature) is kept unchanged. Many temperature or precipitation change scenarios satisfy the constraints expressed by Equations (6) and (7) or (8) and (9). By employing the CNOP-P method, a temperature or precipitation change scenario that induces the maximal SSM change magnitude can be acquired, in which the variations of both climatology and climate variability are included. This kind of scenario, only related with temperature change, is referred to as the ‘CNOP-P-type temperature change scenario’. And the scenario only associated with precipitation change is denoted as the ‘CNOP-P-type precipitation change scenario’.

To obtain the CNOP-P-type temperature or precipitation change scenario, the parameters \((\delta_{r}, \sigma_t, \sigma_p)\) need to be firstly determined. The two parameter groups describe the constraints on temperature and precipitation perturbations, respectively. Based on 22 GCMs from CMIP5, and the moderate emissions scenario RCP4.5 (Taylor, Stouffer, and Meehl 2012), the future temperature and precipitation changes in the 3H region relative to the study period 1991–2000 are analyzed, as shown in Table 1. Multi-model ensemble averages indicate that temperature will increase by about 2 °C in the middle of the twenty-first century, and 3 °C by the end of the twenty-first century. For precipitation, it will increase by 2%–15% in
the twenty-first century. Consequently, the two parameter groups to restrain the temperature and precipitation changes are chosen as 

\[ (\delta_1 = 2, \sigma_1 = 3) \text{ and } (p = 15, \sigma_p = \max_{i=1}^{12} \sum_{j=1}^{12} \sum_{m=1}^{12} \sum_{n=1}^{12} p_{i,j,m,n} \times 15\%) . \]

That is to say, a 2 °C increase in the climatology of temperature \( \delta_1 = 2 \) and a 15% increase in the climatology of precipitation \( p = 15 \) during the study period are hypothesized to obtain the CNOP-P-type temperature change scenario, respectively. Besides, the perturbation to annual temperature is less than 3 °C (i.e. \( \sigma_1 = 3 \) and the maximal perturbation to annual total precipitation is 15% of the maximal annual total precipitation in the study period, i.e.

\[ \sigma_p = \max_{i=1}^{12} \left( \sum_{j=1}^{12} \sum_{m=1}^{12} \sum_{n=1}^{12} p_{i,j,m,n} \right) \times 15\% . \]

As the cost function, Equation (3), regarding parameters may be non-differentiable, the Differential Evolution (DE) algorithm (Storn and Price 1997) – a derivative-free method – is employed in calculating CNOP-Ps to obtain the CNOP-P-type temperature or precipitation change scenario. Recently, Sun and Mu (2012, 2013, 2014) adopted the DE algorithm to compute CNOP-Ps for investigating the variations in soil carbon and net primary production under changing climate.

In conclusion, the CNOP-P-type climate change scenario is the CNOP-P associated with the forcing parameters of temperature or precipitation. Furthermore, the CNOP-P-type climate change scenario only related with temperature change is referred to as the ‘CNOP-P-type temperature change scenario’, and the one merely associated with precipitation change is denoted as the ‘CNOP-P-type precipitation change scenario’. Under the CNOP-P-type climate change scenario, the added temperature or precipitation change is time-invariant and only changes in climatology are considered. As a result, it is the CNOP-P-type scenario rather than the hypothesized scenario that could be applied to investigate the impacts of changes in climate variability on SSM. Besides, through the optimization procedure of the CNOP-P method, the CNOP-P-type scenario induces the maximal SSM change magnitudes, which could indicate the maximal responses of SSM to future temperature or precipitation change.

3. Results and analysis

3.1. The impacts of the CNOP-P-type temperature change scenario on SSM

In this part, the maximal impacts of temperature change on SSM are revealed by employing the CNOP-P approach with reasonable assumptions based on potential temperature change under the RCP4.5 scenario. Due to the CNOP-P-type temperature change scenario \( (\delta_1 = 2, \sigma_1 = 3, \sigma_p = 15\%) \), the SSM changes in the last year of the study period show spatial variability in the 3H region (Figure 3(a1)). North of 36°N, the SSM is increased due to the melting of surface soil ice (Figure 3(b1)) and reduced in the south owing to the enhanced ET (Figure 3(c1)). Generally, the SSM changes vary in the range from −0.014 to +0.012 m3 m−3 (−5.0% to +10.0%).

By way of comparison, the hypothesized temperature change scenario, in which temperature is added by 2 °C and precipitation is kept unchanged, is also applied. Under this kind of scenario, similar changes in SSM occur (Figure 3(a2)). SSM in the last year of the study period increases north of 36°N and reduces in the remaining region. And the SSM changes mainly fluctuate in the range from −0.010 to +0.009 m3 m−3 (−3.7% to +7.1%). Because of the similar
increased precipitation leads to more water into the surface soil layer, causing the increases of SSM in the last year of the study period across the whole study region. In general, the SSM changes vary in the range from $+0.005$ to $+0.018$ m$^3$ m$^{-3}$ ($+1.5\%$ to $+9.6\%$).

For the hypothesized precipitation change scenario, in which precipitation is increased by 15% and temperature is kept unchanged, it also induces the increase of SSM in the last year of the study period (Figure 4(a2)); however, in terms of magnitude, the SSM changes are smaller than those

$$ p = 15, \quad \sigma_p = \max_{i=1,y} \sum_{j=1}^{12} \sum_{m=1}^{r} P_{p,ij,m,n} \times 15\%,$$

variations in soil ice, as well as ET and Rsur (Figure 3(b3), (c3), and (d3)), little difference exists between the magnitudes of the SSM changes under the two types of temperature change scenarios (Figure 3(a3)).

### 3.2. The impacts of the CNOP-P-type precipitation change scenarios on SSM

Besides temperature, the maximal responses of SSM to precipitation change are also discussed, by employing the CNOP-P approach with reasonable assumptions on potential precipitation change under the RCP4.5 scenario, as shown in Figure 4(a1). Under the CNOP-P-type precipitation change scenario (Figure 2(b)), i.e.
35°N in the study region is mainly semi-arid. Therefore, in this semi-arid region, SSM is more sensitive to the precipitation variability. In the whole study region, temperature variability is likely to have little effect on the SSM changes.

4. Summary and discussion

In this study, CoLM and the CNOP-P approach are used to evaluate the maximal impacts of temperature or precipitation change derived from a moderate emissions scenario (RCP4.5) on SSM in the 3H region. By means of the CNOP-P approach, a new kind of climate change scenario that induces the maximal change magnitudes of SSM can be obtained, denoted as the CNOP-P-type temperature or precipitation change scenario. Different from the hypothesized scenario, especially north of 35°N (Figure 4(a3)). And in this northern region, the difference associated with SSM changes can be primarily attributed to the different precipitation and ET changes between the two scenarios (Figures 2(b) and 4(c3)). Due to this hypothesized scenario, the SSM changes mainly fluctuate in the range from +0.004 to +0.013 m^3 m^{-3} (+1.3% to +6.8%).

As stated in Section 2.4, the difference between the two types of temperature (precipitation) scenarios is whether the variation of the temperature (precipitation) variability is taken into account. From the above analyses, it is apparent that only when precipitation changes are considered is the difference of the SSM changes between the two types of scenarios obvious, especially north of 35°N in the 3H region. According to Ma and Fu (2005), the area north of 35°N in the study region is mainly semi-arid. Therefore, in this semi-arid region, SSM is more sensitive to the precipitation variability. In the whole study region, temperature variability is likely to have little effect on the SSM changes.

Figure 4. The variations of SSM (surface soil moisture, units: m^3 m^{-3}), soil ice (units: m^3 m^{-3}), ET (evapotranspiration, units: mm d^{-1}), and Rsur (surface runoff, units: mm d^{-1}) in the last year of the study period under the CNOP-P-type (left panels) and hypothesized (middle panels) precipitation change scenarios (CNOP-P stands for ‘conditional nonlinear optimal perturbation related to parameters’), and the difference between the variation magnitudes of each variable under the two types of scenarios in the same year (right panels): the CNOP-P-type scenario minus the hypothesized scenario.
climate change scenario, the CNOP-P-type scenario causes the variation of the temperature or precipitation variability. In the last year of the study period, the SSM changes mainly vary in the range from $-0.014$ to $+0.012$ m$^{-3}$ ($-5.0\%$ to $+10.0\%$) due to the CNOP-P-type temperature change, and from $+0.005$ to $0.018$ m$^{-3}$ ($+1.5\%$ to $+9.6\%$) due to the CNOP-P-type precipitation change scenario.

By analyzing the difference of the SSM changes between different types of climate change scenarios, it is revealed that this difference regarding SSM is obvious only when precipitation changes are considered; and the greater difference is mainly distributed in the area north of $35^\circ$N in the 3H region, which is largely characterized as a semi-arid zone. This demonstrates that, in this semi-arid region, SSM is more sensitive to the precipitation variability. Compared with precipitation variability, temperature variability seems to play little role in the variations of SSM.

It is important to note that, here, only projected temperature or precipitation changes under the RCP4.5 scenario from CMIP5 have been employed to acquire the CNOP-P-type temperature or precipitation change scenario. When other RCP scenarios (e.g., RCP2.6 or 8.5) are considered, the future temperature or precipitation change obtained, along with its uncertainty extent, will alter, which will inevitably result in variations in the calculated CNOP-Ps (i.e., the CNOP-P-type temperature or precipitation change scenario). This could induce other spatial patterns of SSM changes in the study region. For comprehensively evaluating the potential changes of SSM, climate changes under other RCP scenarios should therefore be included in further study. In addition, the impacts of temperature and precipitation change on SSM have been assessed separately in this research. In future, temperature and precipitation changes should be taken into account simultaneously. Besides, other hydrological models should be applied to interpret the impacts of model errors on the simulated SSM changes under changing climate.

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