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A scheme for calculating soil moisture content by using routine weather data

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Abstract

Soil moisture content is one of the most important parameters as input conditions in forecasting model systems of dust storm, but it can not be directly obtained from daily routine weather report. In this paper, a scheme is developed to calculate the surface soil moisture content in China by using both precipitation and evaporation. Precipitation is directly from routine weather report, while evaporation is indirectly calculated by using meteorological elements which are also from routine weather report. According to the formula by Penman, evaporation can be considered as a linear composition of dynamic evaporation and thermodynamic evaporation caused by radiation. First, an equation for calculating daily global radiation within China is given by using regression analysis and the data of global radiation and cloud cover from 116 meteorological stations in China. Then, an equation for calculating evaporation within China is given by using regression analysis and the data of cloud cover, air temperature, precipitation, relative humidity, and wind velocity from 701 meteorological stations. Finally, a scheme for calculating soil moisture content within China is established by using regression analysis and the soil moisture content, precipitation, and evaporation at 79 agro-meteorological stations. Validation results show that the forecasting accuracy of the Chinese dust numerical model can be clearly increased by using this scheme.

1 Introduction

As a key physical factor in land surface processes, soil moisture content is an important parameter to scientists in many related fields. It plays an important role in adjusting and controlling the interactive processes between the ground and the atmosphere. On the one hand, the thermodynamic character of soil moisture determines Bonn ratio of sub grid processes and causes the flux of sensible heat, latent heat, and long wave radiation from the ground to atmosphere to change, thus influencing climatic changes. On the other hand, the change of soil moisture content itself also affects the thermodynamic character of the soil and the hydrological cycle of the land surface, making various physical and biochemical parameters change accordingly, thus further affecting climatic changes. Research results show that in the processes of climatic changes, the effect of soil moisture is only inferior to that of sea-surface temperature, and it also has an important influence on the formation and variation of regional climate (Yeh et al., 1984; Lin et al, 2001).

In the processes of wind erosion and dust storm development, soil moisture content, by affecting the cohesion between soil particles, influences the threshold friction velocity at which dust particles escape from the surface, and thus influences the amount of dust emitted into the atmosphere from the surface. However, in most numerical models, soil moisture content in China is treated as a constant, namely the climatic mean value, because it can not be directly obtained from routine daily weather report. Obviously this is not reasonable.

Up to now, there have been no directly observed data of routine daily soil moisture content, and calculation of soil moisture content is also very difficult. Because of the importance of soil moisture in synoptic, climatic, and environmental studies, some scholars have studied the distribution characteristics of soil moisture content within local areas based on a limited amount of experimental and observational data (Matsuyama et al., 1997; Li et al., 2000). At the present, the methods for estimating soil moisture content can be divided into three types. The first type is based on the relationship between meteorological factors and soil moisture by using statistical analysis (Clapp et al., 1978; Lu, 1989; Wang et al., 1991; Jin et al., 1998; Reichle et al., 2002; Zhang et al., 2004, 2006), but these studies are mostly limited to local areas. The second type is based on the equilibrium equation of soil moisture or hydrodynamic equation (Baier et al., 1966; Campbell et al., 1974; Lei et al., 1988; Pei et al.,1990; Xie et al.,1998, 1999; Entin et al., 1999; Shen et al., 2003; Zhang et al., 2006). But this type needs real-time soil moisture content data of multiple layers as initial values and thus can not be used widely. The third type is based on the retrieval of soil moisture content from satellite remote sensing data (Kerstin et al., 1993; Jackson et al., 1996; Lin et al., 1994; Houser

et al., 1998; Levitt et al., 1998; Liu et al., 1998; Gao et al., 2001; Yao et al., 2004; Qiao et al., 2006; She et al., 2006). This type is good for drought monitoring and the climatic evaluation of soil moisture, but not so good for daily soil moisture content retrieval. Therefore establishing a reasonable scheme for estimating soil moisture content is an important and urgent task in current synoptic and climatic numerical simulation studies (Sellers, 1996).

Research results show that precipitation is the most important of all meteorological factors which influence soil moisture content (Chen et al., 2005), and the influence of precipitation on surface soil moisture content does not last over a month (He et al., 2002). In this paper we use the Penman formula, statistical analysis, and available meteorological data in China to develop a scheme for calculating daily soil moisture content, with the aim to improve the numerical forecasting accuracy of dust storm events.

2 Data and research method

2.1 Data

Data used in this study are as follows: (1) the data of soil moisture content 0 to 10 cm depth, measured by oven drying, from 79 agro-meteorological stations in China between 1981 and 2002; (2) global radiation data from 116 meteorological stations in China between 1961 and 2000; (3) the data of cloud cover, air temperature, precipitation, relative humidity, wind velocity and evaporation from 700 meteorological stations in China between 1961 and 2002.

2.2 Research method

The most important factors affecting soil moisture content are precipitation and evaporation. In geography and climatology, the ratio of annual (or monthly) precipitation to annual (or monthly) evaporation is used to indicate the wetness of soil (Liu et al., 2000).

Based on the same principle, the ratio of daily precipitation to evaporation can also be used to calculate daily soil moisture.

In routine weather report, precipitation is given directly, but not evaporation. However, it can be calculated by using of other meteorological elements. According to the Penman formula (Chen et al., 1993), evaporation can be calculated as follows:

$$E_T = C(E_h + E_m) \tag{1}$$

$$E_h = \frac{\Delta}{\gamma + \Delta}\frac{R_S}{L} \tag{2}$$

$$E_m = \frac{\Delta}{\gamma + \Delta}[0.37(1 + \mathrm{V}/160)](e_s - e_a) \tag{3}$$

$$e_s = e_0 \exp\left(\frac{at}{273.16 + t - b}\right) \tag{4}$$

$$e_a = \mathrm{RH} \cdot e_s \tag{5}$$

$$R_s = (1 - \alpha)Q - F \tag{6}$$

where E_T is total evaporation,E_h is thermodynamic evaporation, E_m is dynamic evaporation, $\Delta = \frac{e_a}{T_a}(\frac{6463}{T_a} - 3.927)$, $\gamma = \frac{C_p P_s}{0.622L}$, Rs is net radiation, L is the latent heat of vaporization per unit mass, V is wind velocity, e_a is actual vapor pressure, e_s is saturation vapor pressure, a, b, and e_0 is constant, t is air temperature, RH is air relative humidity, α is surface albedo, Q is global radiation, and F is effective radiation.

According to Eq. (6), α and F are needed to calculate Rs, but they can't be obtained directly from routine weather report. Generally, effective radiation F is proportional to global radiation, and surface albedo α is proportional to vegetation cover rate and indirectly related to global radiation. In order to simplify the calculation, net radiation R_s can be assumed proportional to global radiation

$$R_s = D_0 + D_1 Q \tag{7}$$

Replacing Eq. (6) with Eq. (7), we get:

$$\begin{aligned} E_T &= C\frac{\Delta}{\gamma + \Delta}[0.37(1 + \mathrm{V}/160)](e_s - e_a) + C\frac{\Delta}{\gamma + \Delta}\frac{D_0 + D_1 Q}{L} \\ &= C\frac{\Delta}{\gamma + \Delta}\frac{D_0}{L} + C\frac{\Delta}{\gamma + \Delta}[0.37(1 + V/160)](e_s - e_a) + C\frac{\Delta}{\gamma + \Delta}\frac{D_1 Q}{L} \end{aligned}$$

Let $B_0 = C\frac{\Delta}{\gamma+\Delta}\frac{D_0}{L}$

$$B_1 = C\frac{\Delta}{\gamma + \Delta}$$

$\mathrm{B}_2 = C\frac{\Delta D_1}{\gamma+\Delta}$

$$E_1 = [0.37(1 + \tfrac{\mathrm{V}}{160})]\,(e_s - e_a) \tag{8}$$

$$E_2 = \frac{\mathrm{Q}}{L} \tag{9}$$

then

$$E_T = B_0 + B_1 E_1 + B_2 E_2 \tag{10}$$

where E_1 can be calculated by ground wind speed, air temperature and air relative humidity, and E_2 can be calculated by global radiation and the latent heat of vaporization per unit mass L. But the value of C, D_0, and D_1 is uncertain . For this reason, B_0, B_1, andB_2 need to be calculated by statistical regression

There are no radiation data at most meteorological stations in China, so we need to calculate global radiation Q. When solar radiation enters into the atmosphere, it is usually weakened by the reflection and absorption due to many meteorological factors, among which cloud is the most important. So global radiation can be calculated as follows:

$$Q = S_0[1 - (A_0 + A_1 C_n + A_2 C_L)] \tag{11}$$

where C_n is total cloud cover, C_L is low cloud cover, and $\mathbf{S}_0$ is astronomical radiation. A_0, A_1 and A_2 can be calculated by statistical regression. S_0 can be calculated as follows (Wen, 1997):

$$S_0 = \int_{-t_0}^{t_0} \frac{I_0}{\rho^2} \sinh_\Theta dt = \int_{-t_0}^{t_0} \frac{I_0}{\rho^2} (\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\varpi) dt \quad (12)$$

where I_0 is the solar constant and is equal to 1367 W/m^2, h_Θ is solar altitude angle, $\frac{1}{\rho^2}$ is the correction to the average sun-earth distance, φ is geographical latitude, δ is declination, ϖ is the azimuth angle of the sun, -t_0 is the time of sunrise, and t_0 is the time of sunset. From Eq. (11) we have:

$$S_0 = \frac{TI_0}{\pi\rho^2} (\varpi_0 \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\varpi_0) \quad (13)$$

where T=86 400 s, $-\varpi_0$ is the azimuth angle of sunrise, and ϖ_0 is the azimuth angle of sunset.

$$\varpi_0 = \arccos(-tg\varphi tg\delta) \quad (14)$$

$\frac{1}{\rho^2}$ and δ can be calculated as follows:

$$\frac{1}{\rho^2} = 1.00011 + 0.03422 \cos\theta_0 + 0.00128 \sin\theta_0 + 0.000719 \cos 2\theta_0 + 0.000077 \sin 2\theta_0 \quad (15)$$

$$\begin{aligned} \delta = {} & 0.006918 - 0.399912 \cos\theta_0 + 0.070257 \sin\theta_0 - 0.006758 \cos 2\theta_0 \\ & + 0.000907 \sin 2\theta_0 - 0.0002697 \cos 3\theta_0 + 0.000148 \sin 3\theta_0 \end{aligned} \quad (16)$$

where θ_0=2π(d_n–1)/365, d_n is the order number of the day, counted from 1 January to 31 December.

To sum up the above discussion, a scheme for calculating soil moisture content in China can be developed according to the following four steps:

First, a method for calculating daily solar radiation Q can be established by using global radiation and cloud data available from some meteorological stations in China.

Second, a method for calculating total evaporation E_T can be set up by using dynamic evaporation E_1 and the thermodynamic evaporation E_2 which can be calculated from routine meteorological elements available from some meteorological stations in China.

Third, a scheme for calculating soil moisture content can be established by using the data of precipitation, total evaporation, and soil moisture content available from some agro-meteorological stations in China.

Fourth, validation of the established scheme.

3 Establishment of the scheme for calculating soil moisture content

3.1 Calculation of global radiation

There are only 116 meteorological stations in China with available global radiation data. By using the data of total cloud cover, low cloud cover and global radiation from the 116 meteorological stations, we get the coefficients A_0, A_1, and A_2 for these stations through statistical regression based on Eq. (11). The results show that the value of the multiple correlation coefficient R of this regression equation is from 0.5715 to 0.8592. All regression equations of the 116 meteorological stations can pass the significance test at the level of α=0.001. The coefficients A_0, A_1, A_2 at the 116 meteorological stations are different from each other, but they are all related to latitude, longitude, elevation, annual mean temperature, annual precipitation, annual mean total cloud cover, and annual mean low cloud cover (denoted by $x_1, x_2, \ldots x_7$, respectively, and the same applies below) from 116 meteorological stations. By using the above parameters as independent variables and A_0, A_1, A_2 as dependent variables, we get a group of regression equations as follows:

$$\begin{aligned}
A_0&=0.17412+0.0010343x_2-0.0000197x_3+0.0055469x_4-0.0000501x_5 \quad R=0.7494\\
A_1&=0.01392-0.0011179x_4+0.0000103x_5+0.0065975x_6-0.0064179x_7 \quad R=0.7840\\
A_2&=0.01810-0.0000015x_3+0.0004412x_4-0.0024786x_6+0.0043320x_7 \quad R=0.7589
\end{aligned} \tag{17}$$

It can be seen clearly that Eq. (17) also passes the significance test at the level of α=0.001. Putting Eq. (17) into Eq. (11), we can calculate daily global radiation in China by using daily cloud cover data.

3.2 Calculation of evaporation

By using the data of daily wind velocity V, air temperature t, and air relative humidity RH from 701 meteorological stations in China, based on Eqs. (4), (5), and (8), we obtain dynamic evaporation E_1 for the 701 meteorological stations.

By using the data of daily cloud cover from 701 meteorological stations in China, based on Eq. (13) to (16), (11), and (9), we obtain daily thermodynamic evaporation E_2 for the 701 meteorological stations.

By using the data of daily observed evaporation, E_1, and E_2 for the 701 meteorological stations, the coefficients B_0, B_1, B_2 and multi-correlation coefficient R of the 701 meteorological stations can be obtained based on Eq. (10) through statistical regression. The value of R ranges from 0.73 to 0.97, so all the regression equations pass the significance test at the level of α=0.001. The coefficients B_0, B_1, B_2 (dependent variables) of the 701 meteorological stations are different from each other, but they are also related to $x_1, x_2, \ldots\ x_7$ (independent variables). By using regression analysis we get a group of regression equations as follows:

$$\begin{aligned}
B_0&= 3.77802-0.063042x_1-0.011743x_2-0.000454x_3-0.085141x_4+0.000552x_5 R=0.7331\\
B_1&= 3.86344-0.056688x_1+0.008792x_2-0.095390x_4-0.000092x_5 \quad R=0.8636\\
B_2&=+0.74944-0.002038x_2+0.008871x_4-0.000068x_5-0.039797x_6 R=0.6656
\end{aligned} \tag{18}$$

It can be seen clearly from Eq. (18) that the equations also pass the significance test at the level of α=0.001. By putting Eq. (18) into Eq. (10), daily total evaporation in

China can be calculated by using daily cloud cover, wind velocity, air temperature, and air relative humidity.

3.3 Calculation of soil moisture

In China there are only 79 agro-meteorological stations with available soil moisture data "non- routine weather report". Based on Eqs. (4) to (5), (13) to (16), (11), (18), and (8) to (10), we can calculate evaporation for the 79 agro-meteorological stations, By using the data of daily cloud cover, wind velocity, air temperature, and air relative humidity from the 79 agro-meteorological stations.

According to the above discussion, soil moisture content can be calculated by using the ratio of daily precipitation to daily evaporation. The influence of precipitation on soil moisture content decreases with time. In other words, the influence of precipitation on the day which is K days ago on soil moisture is related to the sum of evaporation since then. Thus, the combined effect of precipitation and evaporation can be defined as follows:

$$Z_K = \frac{P_K}{\sum\limits_{j=1}^{K} E_{T_J}} \tag{19}$$

whereP_k is precipitation of K days ago, $E_{T\,j}$ is evaporation of j days ago. The compound influence of all the precipitation events and evaporation in the past N days on soil moisture content can be defined as follows:

$$X = \left(\sum_{K=1}^{N} (Z_K)^C \right)^D \tag{20}$$

In order to obtain the best values of N, C, and D, we first take C=0.02, 0.04, 0.06,···,2.0; D=0.02, 0.04, 0.06,···,2.0; and N=1,2,3,···,38; then we calculate the daily value of X for the 79 available agro-meteorological stations in China by using Eq. (20). And then the correlation coefficient between X and soil moisture content is calculated. Calculation results show that when N=16, C=0.64, and D=0.62, the average value of the correlation coefficients of the 79 agro-meteorological stations is the greatest (0.4909) (see Fig. 1)

As a result, Eq. (20) can be concretely expressed as follows:

$$X = \left(\sum_{K=1}^{16} \left(\frac{P_K}{\sum_{j=1}^{K} E_{T_J}} \right)^{0.64} \right)^{0.62} \tag{21}$$

Assuming that soil moisture content has a linear relationship with X, we have

$$S = A + BX \tag{22}$$

where S is soil moisture content, while A and B can be obtained through regression analysis. The values of A and B of the 79 agro-meteorological stations are different from each other, but they are all related to longitude (x_2), annual mean temperature (x_4), and total cloud cover (x_6). By using regression analysis, we can obtain the values of A and B as follows:

$$\begin{aligned} A &= -33.37 + 0.253x_2 - 0.300x_4 + 4.15x_6 R = 0.6229 \\ B &= 6.30 - .038x_2 R = 0.5048 \end{aligned} \tag{23}$$

It can be seen clearly from Eq. (23) that the equations pass the significance test at the level of α=0.001. Based on Eqs. (4) to (5), (13) to (16), (11), (18), (8) to (10), and (21) to (23), the daily soil moisture content in China can be calculated by using the data of daily cloud cover, wind velocity, air temperature, air relative humidity and precipitation from routine weather report.

However, sometimes one or two of the meteorological elements needed for the above calculations is not available in routine weather reports, so simplified schemes

are needed to replace the original scheme. Three kinds of simplified schemes are given as follows:

1. Scheme without cloud data

   When cloud data are absent, only E_1 can be calculated. The compound effect X is given as follows:

$$X = \left(\sum_{K=1}^{12} \left(\frac{P_K}{\sum_{j=1}^{K} E_1 j} \right)^{0.6} \right)^{0.6} \tag{24}$$

$$\begin{aligned} A &= 1.59 - 0.636x_4 + 0.015x_5 + 2.01x_6 R = 0.6157 \\ B &= 3.87 - 0.024x_2 R = 0.5987 \end{aligned} \tag{25}$$

2. Scheme with only cloud cover and precipitation

   If there are only cloud cover and precipitation, only E_2 can be calculated. The compound effect X is given as follows:

$$X = \left(\sum_{K=1}^{16} \left(\frac{P_K}{\sum_{j=1}^{K} E_2 j} \right)^{0.70} \right)^{0.68} \tag{26}$$

$$\begin{aligned} A &= 1.09 - 0.641x_4 + 0.0150x_5 + 0.208x_6 R = 0.6139 \\ B &= 8.47 - 0.049x_2 R = 0.5065 \end{aligned} \tag{27}$$

3. Scheme with only precipitation

   We have to consider evaporation as constant when only precipitation is available. The compound effect X is given as follows:

$$X = \left(\sum_{K=1}^{12} \left(\frac{P_K}{K} \right)^{0.70} \right)^{0.74} \tag{28}$$

$$\begin{aligned} A &= 0.94 - 0.643x_4 + 0.015x_5 + 2.20x_6 R = 0.6280 \\ B &= 3.08 - 0.00186x_2 R = 0.5385 \end{aligned} \tag{29}$$

4 Validation of the scheme for calculating soil moisture content

4.1 Direct validation of the scheme

In order to validate the established scheme for calculating soil moisture, calculated and observed soil moisture content data from 2003 to 2005 are compared for 7 agro-meteorological stations in the east of Gansu Province in China (see Table 1). The results show that the correlation coefficients of 6 stations pass the significance test at the level of α=0.001, but that of the Maqu station only passes the significance test at the level of α=0.01. This demonstrates that the established scheme can be used to calculate ground soil moisture content.

4.2 Indirect validation of the scheme

Soil moisture content is an important parameter in the dust event operational forecasting system(DOFS) of the National Meteorological Center in China, but it is treated as a constant. Figure 2 shows its distribution in China used by the DOFS. It can be seen from Fig. 2 that the soil moisture content in most of China is from 5 to 10%. Obviously, this is unreasonable.

Figure 3 shows the soil moisture content distribution in China on 19 March 2002, calculated based on our scheme. It can be seen from Fig. 3 that soil moisture content increases from the northwest to the southeast, which is much closer to the reality in China.

From 18 to 20 March 2002, a strong dust storm event occurred in Northwest China. Figure 4a shows the simulated dust concentration distribution output by the DOFS, with soil moisture content input as shown in Fig. 2. Figure 4b shows the simulated dust concentration distribution output by the DOFS, but with soil moisture content input calculated according to our scheme as shown in Fig. 3. It can be seen clearly that the distribution of simulated dust concentration shown in Fig. 4b is much closer to the observed intensity distribution of the dust event than that shown in Fig. 4a. Particularly, the two simulated dust storm centers shown in Fig. 4b are much closer to the actually observed ones, but the position and intensity of the simulated dust storm centers as shown in Fig. 4a are much more different from the actually observed situation. The above results show that the forecasting accuracy of the DOFS can be clearly improved by using our scheme.

5 Conclusions

1. The influence of precipitation on surface soil moisture content does not last more than 16 days.
2. The compound effect of the ratio of precipitation to evaporation, which is non-linearly summed, can be used to calculate the surface soil moisture content in China.
3. Direct validation results show that our scheme can be used to calculate soil moisture content in China satisfactorily.
4. Indirect validation results show that the forecasting accuracy of dust storm events in China can be clearly improved by using our soil moisture scheme.

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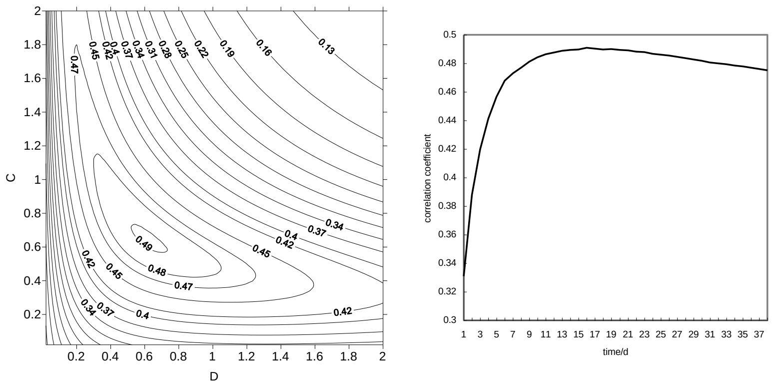
Table 1. Correlation coefficients between estimated and observed soil moisture content at 7 ago-meteorological stations in the east of Gansu.

ago-meteorological station	Dingxi	Huanxian	Xifeng	Tongwei	Maqu	Tianshui	Chengxian
Latitude/(° N)	35.58	36.58	35.73	35.22	34.00	34.57	33.75
Longitude/(° E)	104.62	107.30	107.63	105.23	102.08	105.87	105.72
Correlation coefficient	0.662	0.759	0.800	0.748	0.337	0.688	0.717
Numbers of samples	75	75	75	75	75	75	75



(a) (b)

Fig. 1. Average correlation coefficient of soil moisture content and the compound effect of precipitation and evaporation for the 79 agro-meteorological stations in China (**a**: correlation coefficient distribution with C and D when N=16. **b**: correlation coefficient variation with N when C=0.64, D=0.62).

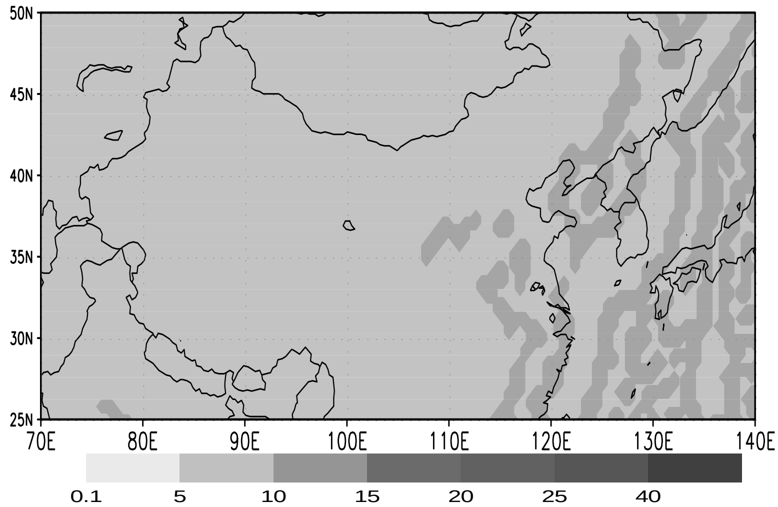


Fig. 2. Soil moisture content distribution used by DOFS.

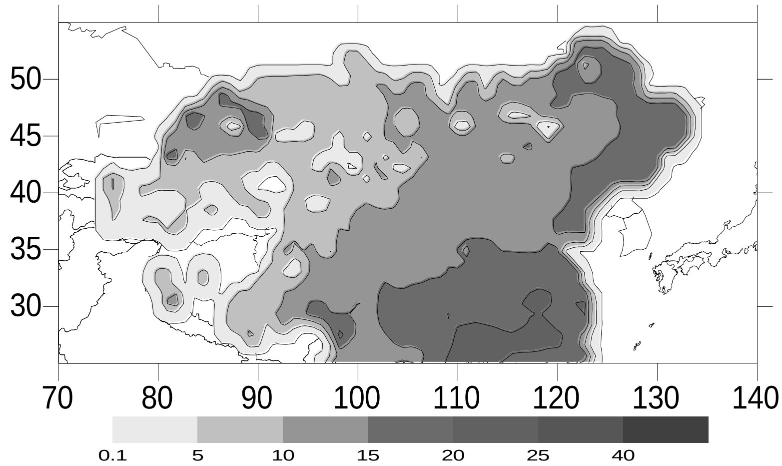


Fig. 3. Soil moisture content distribution in China on 19 March 2002 based on our scheme.

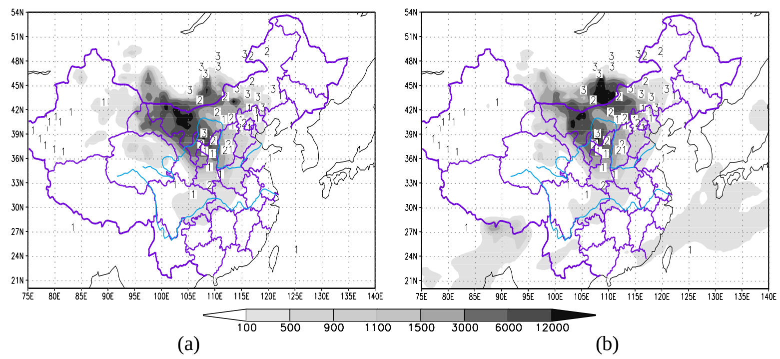


Fig. 4. Comparison of simulated dust concentration distribution (20 March 2002, 03:00 UTC) (**a**: result from the original DOFS; **b**: result from our scheme; 1,2,3 represent actual floating dust, blowing sand and dust storm, respectively; simulated dust concentration is in μg/m^3).