# A Theoretical Analysis on the Local Climate Change Induced by the Change of Landuse [1]

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ABSTRACT

The local climate change induced by the change of landuse, i.e., the degeneration of vegetation is studied by the consideration of the equilibrium among radiation, phase change and convection in an air column and the energy balance condition on the ground surface. The result shows that the increase of ground albedo and the change of the surface heat flux as well as the decrease of the surface roughness length may induce the decrease of precipitation and the increase of temperature in the northern China, similar to the numerical simulation. Considering advection, this conclusion is also true except the amounts of the decrease of precipitation and the increase of temperature are changed. The decrease of precipitation and the increase of temperature will be more serious in case of global warming.

**Key words:** Climate change, Albedo, Landuse

## 1. Introduction

Human activity is an important factor affecting climate change, besides the increasing release of carbon dioxide, the change of ground surface or landuse is one of these important factors. The deforestation and the degenerations of agricultural land and grass land change the albedo and the roughness length of the ground, then change the energy equilibrium at the surface, as a result, the local and atmospheric circulations will be affected, hence, the local climate will also be changed. A typical example is the local climate variation induced by Amazon tropical deforestation which has attracted the attention of many investigators; the research method is usually numerical, such as Sellers et al. (1993), Lean and Rowntree (1993), Sud et al. (1996), Zhang and Sellers (1996), Zhang et al. (1996) etc., a large part of research results showed that the deforestation would induce the decrease of precipitation and the increase of temperature, the method is mainly to use the land process model nested in GCM model. This method is also used to research the impact of other surface ground on the climate such as Sahel Desert (Xue and Shukla, 1993; 1996). On the other hand, there was theoretical method to research the effects of the change of land surface on radiation, convection and circulation, finally, on local climate, such as Charney (1975)'s research on Sahel draught; Eltahir and Bras (1993) studied the response of atmosphere to Amazon deforestation by dynamical method; Zeng and Neelin (1999) studied the effect of Amazon deforestation on atmosphere based on the viewpoint of increasing albedo by the method of energy and moisture equilibrium in an air column, they also reached the conclusion of decreasing precipitation and slightly increasing temperature. The advantage of the theoretical analysis works is that it can clearly

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and analytically express the roles played by different factors, and the shortcoming is that it cannot consider the roles of all factors completely and simultaneously like the numerical model, for instance, some assumptions of Zeng and Neelin (1999) are suitable only in tropical region, not general: in addition, some simplifications were made in their work based on the characteristics of the atmospheric motion in tropical region, however, their results still can reflect the main process that surface ground affects atmosphere. The aridification in northern China is an important climate problem which is being investigated, the change of the surface should be one of the causes. Xue (1996)'s numerical research proved that the deforestation in Inner Mongolia can induce the decrease of precipitation, Zheng (2000) studied the climate change induced by the change of vegetation from regional climate model, he also obtained the conclusion that the damage of vegetation can decrease precipitation and deteriorate climate The aim of this paper is to analytically study the impact of the changes of the surface parameters (mainly, the albedo) which are caused by the change of the landuse on the local climate in the northern China by the method of energy equilibrium in an air column through the couple of atmospheric motion equations and the land surface process equations. The main conclusion is that the degeneration of agricultural land or deforestation will induce the decrease of precipitation accompanying with the increase of temperature, expressing that the change of the surface ground may be one of the causes of aridification in northern China, and to increase vegetation or forestation can improve the local climate.

## 2. The energy equilibrium in air column

The atmospheric thermodynamic and the moisture conservation equations may be written as

$$c_p\left(\frac{\partial T}{\partial t}+\vec{V}\cdot\nabla_h T\right)+\frac{\partial(c_p T+gz)}{\partial z}w=Q_c+Q_R-\frac{\partial F_T}{\rho\partial z}\ . \qquad (1)$$

$$L\left(\frac{\partial q}{\partial t}+\vec{V}_h\cdot\nabla_h q\right)+L\frac{\partial q}{\partial z}w=-Q_c-\frac{\partial F_q}{\rho\partial z}\ . \qquad (2)$$

where $L$ is evaporation latent heat, $q$ the specific humidity, $Q_c$ and $Q_R$ the convective (condensation) and radiative heating rates, $F_T$ and $F_q$ are the eddy sensible and latent heat fluxes respectively, which boundary values are the surface sensible and latent heat fluxes respectively. Zeng and Neelin (1999) neglected the advection terms in Eqs.(1) and (2) for tropical area. We will first neglect the advection terms, then take it into account. We also neglect the time derivatives because the annual mean climate state, i.e., the equilibrium state is discussed in this paper. Eqs.(1) and (2) neglecting advection terms may be changed as

$$\frac{\partial(c_p T+gz)}{\partial z}w=Q_c+Q_R-\frac{\partial F_T}{\rho\partial z}\ , \qquad (3)$$

$$wL\frac{\partial q}{\partial z}=-Q_c-\frac{\partial F_q}{\rho\partial z}\ . \qquad (4)$$

Similar to Zeng and Neelin (1999)'s treatment, we assume

$$w=\Omega(z)\nabla\cdot\vec{V}_1(x,y)\ . \qquad (5)$$

$\nabla\cdot\vec{V}$ may be seen as the mean divergence of the air column, $\Omega(z)$ represents the variation of

$w$ with height. Vertically integrating Eqs.(3) and (4) in the whole air column which top is $Z$, after applying Eq.(5), we get the equilibrium equations for the heat and moisture in the air column as

$$\int_0^Z \frac{\partial(c_p T + gz)}{\partial z} \Omega \nabla \cdot \vec{V}_1 \rho dz = \hat{Q}_c + \hat{Q}_R + H \, . \tag{6}$$

$$\int_0^Z L \frac{\partial q}{\partial z} \Omega \nabla \cdot \vec{V}_1 \rho dz = - \hat{Q}_c + E \, . \tag{7}$$

where

$$(\hat{x}) = \int_0^Z \rho x dz \, ,$$

$H$, $E$ are the sensible and latent heat fluxes at the surface respectively. Putting

$$M_s = \int_0^Z \frac{\partial(c_p T + gz)}{\partial z} \Omega \rho dz \, ,$$

$$M_q = \int_0^Z - L \frac{\partial q}{\partial z} \Omega \rho dz \, ,$$

then (6) and (7) become

$$M_s \nabla \cdot \vec{V}_1 = \hat{Q}_c + \hat{Q}_R + H \, , \tag{8}$$

$$- M_q \nabla \cdot \vec{V}_1 = - \hat{Q}_c + E \, . \tag{9}$$

let $C = M_q \nabla \cdot \vec{V}_1$ be the vertically integrating moisture convergence, then Eq.(9) become

$$- C = - P + E \, . \tag{10}$$

$P$ is the total latent heat release in the air column due to condensation, i.e., the rainfall amount in energy unit. Combining Eq.(8) with Eq.(9), we have

$$mC = \hat{Q}_R + E + H \, , \tag{11}$$

where $m = (M_s - M_q) / M_q$, the net downward heat fluxes at the top of atmosphere and surface are as follows

$$R_t = S_0 - S_t^{\uparrow} - L_t^{\uparrow} \, , \tag{12}$$

$$F_s = S_s^{\downarrow} - S_s^{\uparrow} + L_s^{\downarrow} - L_s^{\uparrow} - E - H \, . \tag{13}$$

$S$, $L$ are the short and long wave radiation fluxes respectively, the subscript $t$ represents the top, $s$ represents the surface, $S_0$ the short wave flux out of the atmosphere. Eq.(11) may also be written as

$$mC = R_t - F_s \, , \tag{14}$$

because

$$\hat{Q}_R = S_0 - S_t^{\uparrow} - S_s^{\downarrow} + S_s^{\uparrow} - L_s^{\downarrow} + L_s^{\uparrow} - L_t^{\uparrow} .$$

For the annual mean state, the net heat flux at surface can be set to be zero (Zeng and Neelin, 1999). Eq.(14) then becomes

$$mC = R_t \ . \tag{15}$$

## 3. The climate response due to the change of the albedo of surface

The downward short wave energy at the surface is

$$S_s^{\downarrow} = (1 - \alpha)(1 - a)S_0 \ . \tag{16}$$

where $S_0$ varies with time and space, we will take its mean value in a year because we investigate the annual mean state here. We study two cases corresponding to Ningxia and Hebei Provinces in northern China which values of $S_0$ are set to be identical because their latitudes are similar. $a$ and $\alpha$ are the sum of the absorptive coefficient and albedo of the cloud and atmosphere respectively. The upward short wave energy at the surface is

$$S_s^{\uparrow} = (1 - a)(1 - \alpha)AS_0 \ . \tag{17}$$

where $A$ is the surface albedo. At the top of atmosphere, we have

$$S_t^{\uparrow} = [(1 - a)^2(1 - \alpha)^2 A + \alpha]S_0 \ . \tag{18}$$

The albedo of the cloud may be considered as proportional to the cloud cover (Yi and Wu, 1994 ), then the sum of the albedo of cloud and atmosphere may be written as

$$\alpha = \alpha_0 + \alpha_n \sigma_n \ , \tag{19}$$

where $\alpha_0$, $\alpha_n$ are the albedos of atmosphere and cloud respectively, $\sigma_n$ the cloud cover.

The outward long wave flux at the top of atmosphere can be computed by Budyko's formula (Tang, 1989)

$$L_t^{\uparrow} = a_1 + b_1 T_g - (a_2 + b_2 T_g)\sigma_n \ . \tag{20}$$

$T_g$ is the surface temperature in Centigrade, $a_1$ = 226.8 W / m$^2$, $b_1$ = 2.668 W / (°C m$^2$), $a_2$ = 47.68 W / m$^2$, $b_2$ = 1.62 W / °C m$^2$, the upward long wave flux at the surface can be found from the well-known Stefan formula

$$L_s^{\uparrow} = \delta\sigma(T_g + 273)^4 \ . \tag{21}$$

$\delta$ is set to be 1, the downward long wave flux at the surface may be calculated by the following equation (Yi and Wu, 1994):

$$L_s^{\downarrow} = \varepsilon(a_3 + b_3 T_g) \ , \tag{22}$$

$a_3 = 273^4\sigma$, $b_3 = 4\times 273^3\sigma$, and

$$\varepsilon = \varepsilon_0 + \varepsilon_c + \varepsilon_1 T_g - \varepsilon_n \sigma_n^2 \ . \tag{23}$$

$\varepsilon_0$ = 0.1917, $\varepsilon_c$ = 0.0235ln[$CO_2$]+0.0537, $\varepsilon_1$ −0.004915 (°C)$^{-1}$, $\varepsilon_n$ = 2.159 × 10$^{-2}$, [$CO_2$] may set to be constant 330 ppm.

When atmospheric state changes due to the change of ground surface parameters, $T_g$, $\sigma_n$, rainfall, radiation fluxes, heat fluxes all are changed. Zeng and Neelin (1999) assumed that $\sigma_n$ is proportional to the rainfall for the tropical precipitation, based on the analysis of the data observed at the meteorological stations Shijiazhuang and Yinchuan located in Hebei and Ningxia provinces respectively, we take

$$\sigma_n = \sigma_p P + b_4 \ , \tag{24}$$

where $P$ is the rainfall (mm), constants $\sigma_P$, $b_4$ are different for different stations, the values of $\sigma_P$ found from the statistical method are listed in Table 1. The variations of different meteorological quantities induced by the change of the surface albedo $A'$ can be found from Eqs.(17)–(24) as follows:

$$S_s^{*'} = \theta_{SA} A' S_0 \ , \tag{25}$$

$$S_s^{\downarrow'} = -\theta_{S\alpha} \alpha' S_0 \ , \tag{26}$$

where

$$\theta_{SA} = (1-\alpha)(1-a), \quad \theta_{S\alpha} = 1-a \ ,$$

$$S_t^{\uparrow'} = S_0(\theta_{tA} A' + \alpha') \ , \tag{27}$$

where

$$\theta_{tA} = (1-\alpha)^2(1-a)^2 \ ,$$
$$\alpha' = \alpha_n \sigma'_n \ , \tag{28}$$

$$L_t^{\uparrow'} = (b_1 - b_2\sigma_n)T_g' - (a_2 + b_2 T_g)\sigma_n' \ , \tag{29}$$

$$L_s^{\uparrow'} = \varepsilon_s T_g' \ , \tag{30}$$

where

$$\varepsilon_s = 4\delta\sigma(T_g + 273)^3 \ ,$$

$$L_s^{\downarrow'} = \varepsilon b_3 T'_g + (a_3 + b_3 T_g)(\varepsilon_1 T_g' - 2\varepsilon_n \sigma_n \sigma_n') \ , \tag{31}$$

$$\sigma_n' = \sigma_P P' \ . \tag{32}$$

From Eqs.(15), (12), (18), (20), and (31), we obtain the change of $C$

$$mC' = -S_t^{\uparrow'} - L_t^{\uparrow'} = -S_0(\theta_{tA} A' + \alpha_n \sigma_P' P') - (b - b_2\sigma_n)T_g' + (a_2 + b_2 T_g)\sigma_P P' \ , \tag{33}$$

the perturbed state of the heat balance equation for surface satisfies the following equation due to $F_s = 0$:

$$S_t' - S_s^{\uparrow'} + L_s^{\downarrow'} - L_s^{\uparrow'} - E' - H' = 0 \ . \tag{34}$$

Similar to Zeng and Neelin (1999), we may assume that there is a relation between perturbed latent heat flux and perturbed precipitation amount in energy unit:

$$E' = eP' , \tag{35}$$

we may find $e$ from land surface process model (see Appendix). The sensible heat flux and its perturbation in Eq.(34) can be found from bulk formula (Zeng and Neelin, 1999)

$$H = C_D c_p \rho V (T_g - T) ,$$

and

$$H' = \zeta T'_g , \tag{36}$$

where

$$\zeta = C_D c_p \rho V = \frac{k^2 \rho V c_p}{(\ln \frac{z}{z_0})^2} , \tag{37}$$

the surface roughness $z_0$ has been included from the surface layer meteorology in order to introduce the effect of roughness, the height $z$ in Eq.(37) may be set to be 10 m.

From Eqs.(34), (25), (26), (30), (31), (35) and (36), we have

$$- \lambda P' - \theta_{SA} S_0 A' + \mu T'_g = 0 . \tag{38}$$

where

$$\lambda = S_0 \theta_{S\alpha} \alpha_n \sigma_p + 2\sigma_n (a_3 + b_3 T_g) \varepsilon_n \sigma_p + e ,$$

$$\mu = (a_3 + b_3 T_g) \varepsilon_1 - \varepsilon_s + \varepsilon b_3 - \zeta .$$

Eq.(33) may be written as

$$mC' = - \eta A' - \nu P' - \xi T'_g , \tag{39}$$

where

$$\eta = S_0 \theta_{tA} , \quad \nu = S_0 \alpha_n \sigma_p - (a_2 + b_2 T_g) \sigma_p , \quad \xi = b_1 - b_2 \sigma_n .$$

Combining (10) with (35) yields

$$- C' = - P' + E' = (e - 1) P' . \tag{40}$$

From Eqs.(38), (39), and (40), we can find $T'_g$, $P'$ from known $A'$ and $C'$ may be computed from (40)

$$T'_g = \frac{- \eta \lambda + [m(1-e) + \nu] \theta_{SA} S_0}{\xi \lambda + [m(1-e) + \nu] \mu} A' , \tag{41}$$

$$P' = \frac{- \theta_{SA} S_0 A' + \mu T'_g}{\lambda} . \tag{42}$$

Now consider the change of surface albedo, the albedo increases when the soil becomes drier or the vegetation degenerates because the albedo of vegetation is lower than that of bare soil. Let $A_s$ and $A_f$ be the albedos for the bare soil and vegetation respectively, $\sigma_f$ is the vegetation cover, then

$$A = (1 - \sigma_f) A_s + \sigma_f A_f . \tag{43}$$

According to the land surface process model BATS (Dickinson et al., 1993), we can compute the variation of $A_s$ with the humidity of the soil

$$A_s = 0.11 + 0.01(11 - 40w) , \tag{44}$$

here the albedo of the dry soil has been set to be 0.22, $w$ is the water content of the water in the soil, i.e., the water volume in a unit volume soil, the change of either $w$ or $\sigma_f$ may induce the variation of $A$, and further cause the changes of $T_g$ and $P$, we mainly research the effects of $\sigma_f$ as well as $w$.

## 4. The computational results

The parameters are set as follows: the value of $S_0$ is set to be the mean value of the solar radiation out of the atmosphere after considering its diurnal and annual variations, $T_g$, $P$, $V$ and $\sigma_n$ are obtained from annual mean meteorological data. For Hebei and Ningxia areas, the soil parameters are chosen as that values corresponding to Nos. and 5 in BATS, the former corresponds to the loam, the latter is more sandy compared with the former. The water content is estimated from concerned reference (You and Wang, 1996). Table 1 lists various parameters, in which the precipitation amount is the annual mean, $\alpha_0$ is taken from Lu and Gao (1987 ), $\alpha_n$ from Yi and Wu (1994), $A_f$ corresponds to the crop or high grass in BATS, $z_0$ is also from BATS, the absorptive coefficient is from Zeng and Neelin (1999).

**Table 1.** The parameter values

| $S_0$ (W m$^{-2}$) | $T_g$ (°C) | $V$ (m s$^{-1}$) | $\sigma_n$ | $\alpha_0$ | $\alpha_n$ | $\sigma_p$ | $\sigma_f$ | $w$ | $A_f$ | $z_0$ (m) | $a$ | $P$ (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 350 | 14.3 (Hebei) | 3 | 0.48 (Hebei) | 0.09 | 0.5 | $1.69 \times 10^{-3}$ (Hebei) | 0.8 | 0.2 (Hebei) | 0.08 | 0.06 | 0.28 | 600 (Hebei) |
| | 11 (Ningxia) | | 0.4 (Ningxia) | | | $6.14 \times 10^{-3}$ (Ningxia) | | 0.15 (Ningxia) | | | | 200 (Ningxia) |

According to the definitions of $m$, $M_s$ and $M_q$ in Section 2, which computation needs the values of $\partial T / \partial z$ and $\partial q / \partial z$, the former may set to be $-0.6$°C / 100 m, the latter can be found its mean value in an air column from the $q$ at the surface and the value 0 at the top of atmosphere, so which is different for Hebei and Ningxia, the values of $m$ are 0.13 and 0.2 for these two areas.

We first perform the experiments of decreasing $\sigma_f$, when $\sigma_f$ decreases from 0.8 to 0, the changes of precipitation and ground temperature are shown in Figs. 1 and 2, the precipitation decreases and temperature increases both for Hebei and Ningxia areas, in agreement with observation. The precipitation decreases and temperature increases more seriously with the decrease of the value of $\sigma_f$, the precipitation amount decreases almost 40%–50% when $\sigma_f$ becomes 0. Zheng (2000)'s numerical research proved that the precipitation may decrease up to 60% in case of vegetation degeneration, which is similar to our results. From the viewpoint of climate response to the energy equilibrium in an air column studied in this paper, the reason of the change of local climate induced by surface albedo is that when the albedo increases, the net downward radiation at the top of atmosphere decreases, which enables to decrease the convergence of the moisture in an air column, as a result, the precipitation decreases, meanwhile, the evaporation amount decreases due to the decrease of precipitation, which further decreases the precipitation. On the other hand, the increase of the albedo should decrease the

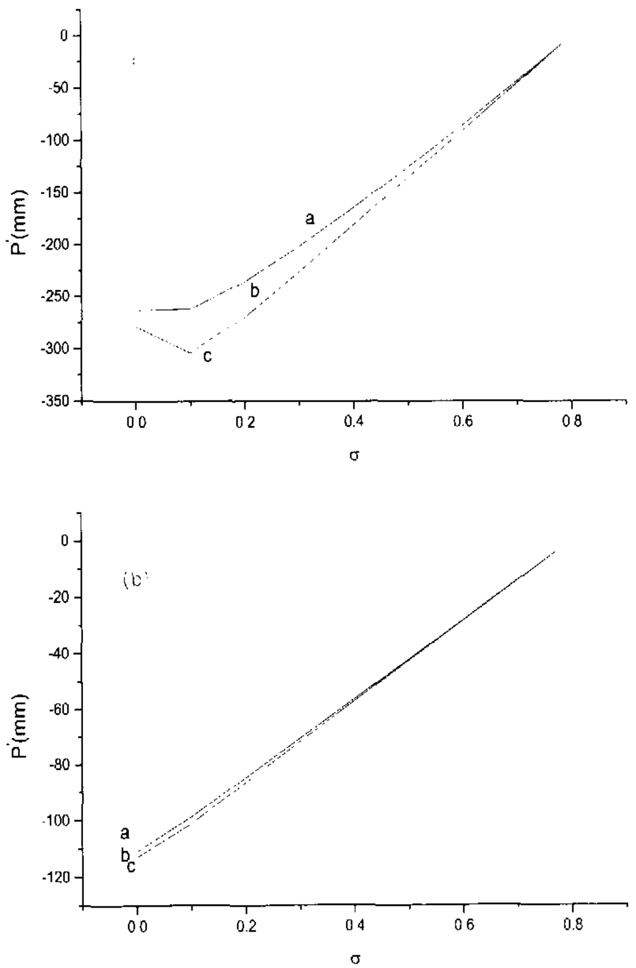



Fig. 1. The change of precipitation induced by the change of $\sigma_f$, (a) is for Hebei, (b) for Ningxia, curve $a$ does not consider the variation of $z_0$, $b$ includes the varying roughness, $c$ corresponds to the case that $T_g$ increases 1 degree Centigrade (varying rughness), the $\sigma$ marked in the abscissas represents $\sigma_f$.

surface temperature, however, the decreases of evaporation and latent heat flux make the temperature increase, at the same time, the decrease of cloud cover increases the short wave energy at the surface, also increases the surface temperature, the increased temperature results in increased outward long wave flux which makes surface temperature decrease. The total effect of above different factors enables the surface temperature to increase slightly which is shown in Figs. 1 and 2. The results here do not include all causes increasing the surface temperature because only changes of albedo and heat flux are considered in this paper. Here we only research the case that the vegetation is substituted by bare soil, in reality, the vegetation may also be substituted by desert, for which the albedo may change more, the numerical

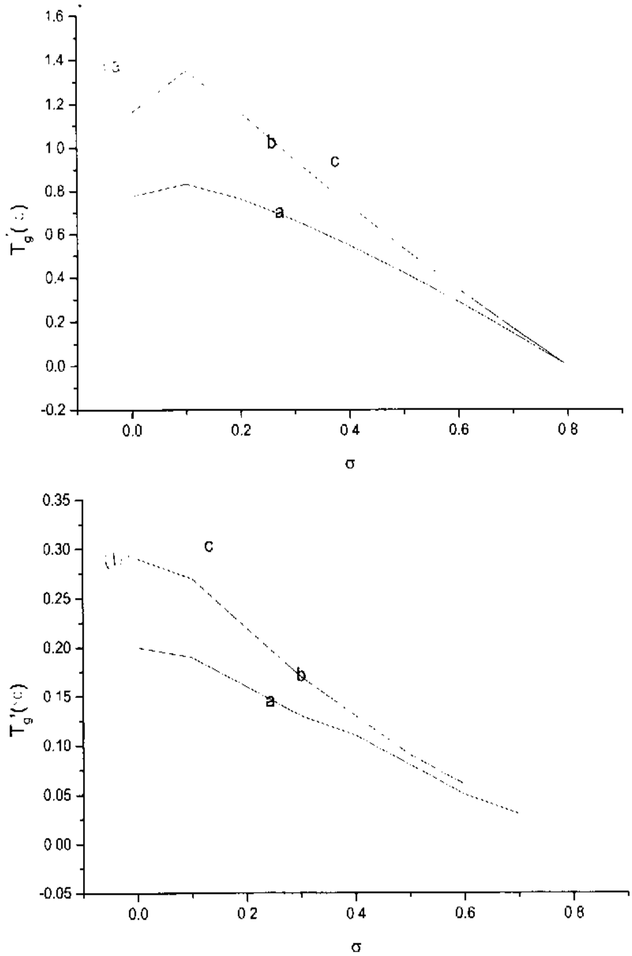


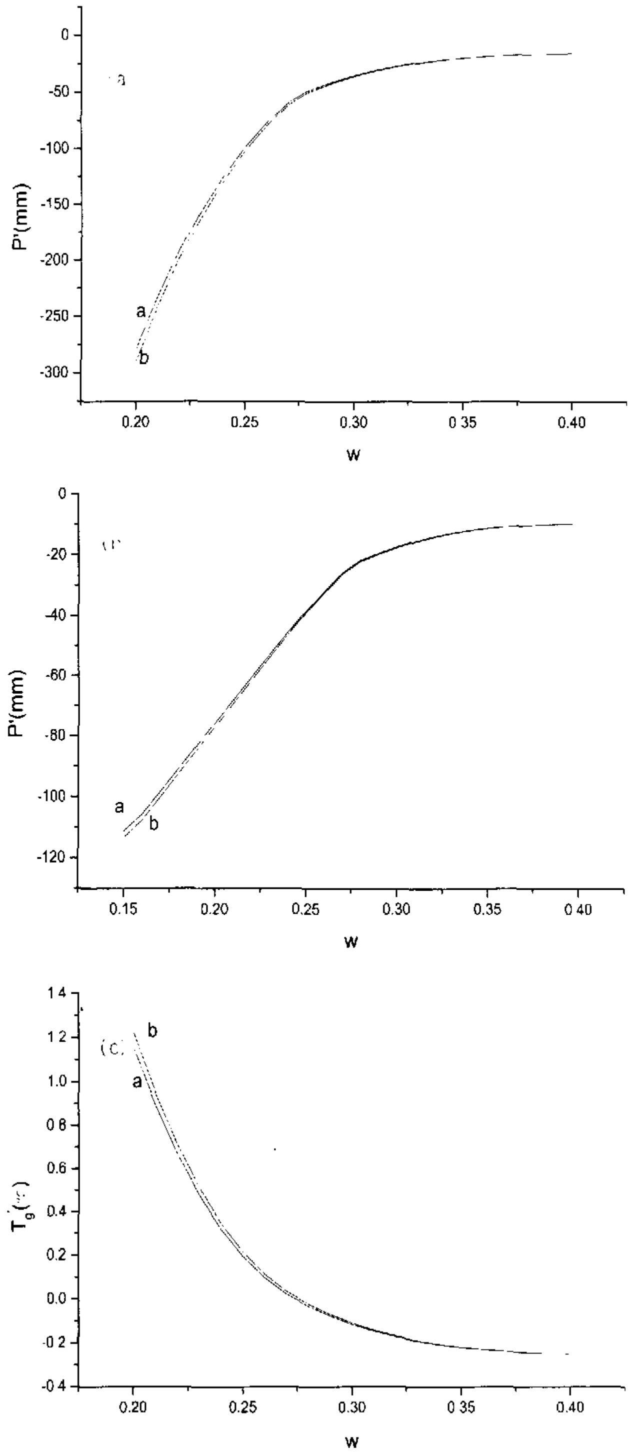

Fig. 2. The change of ground temperature induced by the change of $\sigma_f$, the legend is identical to Fig. 1, the meanings of curves $a$, $b$, $c$ are also identical to Fig. 1.

results in this paper will also be changed.

In case of vegetation degeneration, the roughness will also change besides albedo, we use

$$z_0 = (1 - \sigma_f) z_{0s} + \sigma_f z_{0f}$$

to compute the value of roughness after $\sigma_f$ changes, $z_{0s} = 0.02$ m represents the roughness of soil, $z_{0f}$ is the roughness of vegetation shown in Table 1, the decrease of $z_0$ will affect the sensible and latent heat fluxes by affecting the value of $C_D$ through Eq.(37), the decrease of precipitation and the increase of temperature after considering the change of $z_0$ are also shown in Figs. 1a and 2a, it can be seen that after the decrease of roughness is taken into account, the more decrease of precipitation the more increase of temperature appear, which is in agreement with Zheng's (2000) numerical results. We also can see from this case study that the decrease of precipitation and the increase of temperature induced by the change of roughness


P'(mm)
w
a
b
P'(mm)
w
a
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(c)
$T_g'$
w
a
b

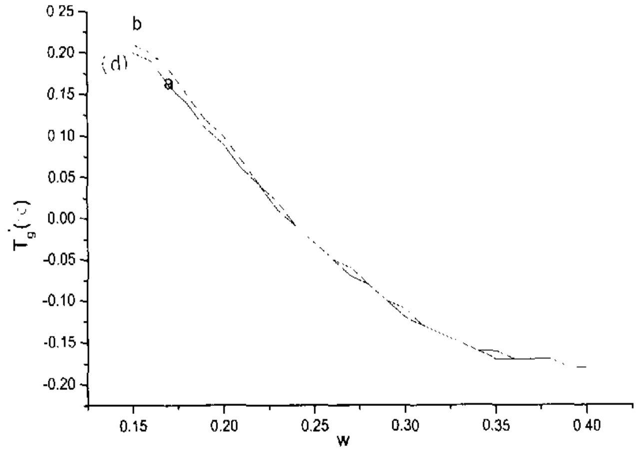


Fig. 3 The effect of soil humidity on the precipitation and surface temperature when $\sigma_f$ decreases. Precipitation: (a) is for Hebei, (b) for Ningxia, surface temperature, (c) is for Hebei, (d) is for Ningxia.

are not great, i.e., when both albedo and roughness are taken into account, the effect of albedo is more important. The physical reason of the effect of roughness is that the decrease of roughness decreases the sensible and latent heat fluxes from surface, and results in the increase of surface temperature due to the heat equilibrium at the surface, meanwhile, the decrease of evaporation decreases the precipitation. A more complex reason is that the change of the heat balance at surface certainly will influence the energy equilibrium in an air column, changing the precipitation and temperature, this impact will be much greater in case of great change of roughness, for example, the forest is substituted by bare soil.

The curves $c$ in Figs. 1 and 2 are the results when the surface temperature increases 1 degree Centigrade in order to investigate the impact of the degeneration of vegetation in case of global warming.

We have also investigated the role of soil moisture when $\sigma_f$ changes, assume different soil water content $w$, let $\sigma_f$ change from 0.8 to 0 to study the effect of $w$ on the precipitation and temperature, the variation of $w$ changes both albedo and evaporation, in this case the roughness for soil is applied. Fig. 3 is the computational results for Hebei and Ningxia areas. The figure shows that when $w$ increases the decrease of precipitation and the increase of temperature are weakened, even the tendency of the variation becomes reverse, which means that the soil moisture greatly alleviates the impact of the degeneration of vegetation on the climate. Here we cannot find the evolution of the soil moisture induced by the change of vegetation because this is not a numerical research, hence the results of this paper have limited meaning only, however, the significant role played by the soil moisture is convincible. It may also be seen that the effect of $\sigma_f$ has become small in case of great $w$. Curve $b$ is the result corresponding to one degree increase of temperature which shows more decrease of precipitation and more increase of temperature in case of global warming.

## 5. The effect of advection

If advection is taken into account, Eqs.(3) and (4) become

$$c_p(\vec{V}\cdot\nabla_h T)+\frac{\partial(c_p T+gz)}{\partial z}w=Q_c+Q_R-\frac{\partial F_t}{\rho\partial z}\ . \tag{45}$$

$$L(\vec{V}_h\cdot\nabla_h q)+wL\frac{\partial q}{\partial z}=-Q_c-\frac{\partial F_q}{\rho\partial z}\ . \tag{46}$$

The magnitude of the horizontal advection terms is determined by the distributions of temperature, humidity and wind fields in a large domain, obviously which cannot be found from the air column model, so that we will assume their values to study their effect on precipitation and temperature, i.e., study its sensitivity to the local climate.

Let $A_t$ and $A_q$ represent the annual mean of the advection terms in Eqs.(45) and (46), suppose that their perturbations $A'_t$ and $A'_q$ are known, for this case, Eq.(34) or Eq.(38) needs not to change, but Eq.(33) or Eq.(39) is changed to be

$$A'_t+A'_q+mC'=-\eta A'-\nu P'-\xi T'_g\ . \tag{47}$$

Eq.(40) becomes

$$-C'=-P'+E'-A'_q=(e-1)P'-A'_q\ . \tag{48}$$

The solutions for $P'$, $T'_g$, $C'$ can be found from (38), (47) and (48)

$$T'_g=\frac{\{-\eta\lambda+[m(1-e)+\nu]\theta_{SA}S_0\}A'-(mA'_q+A'_q+A'_t)\lambda}{\xi\lambda+[m(1-e)+\nu]\mu}\ . \tag{49}$$

$$P'=\frac{-\theta_{SA}S_0A'+\mu T'_g}{\lambda}\ . \tag{50}$$

$$C'=\frac{-\eta A'-\nu P'-\xi T'_g-A'_q-A'_t}{m}\ . \tag{51}$$

Eqs.(49) and (50) show that when $A'_t$ and $A'_q$ are positive, $T'_g$ increases (original $T'_g$ is larger than 0) because the denominator of (49) is negative and $|P'|$ also increases (original $P'$ is negative, i.e., the precipitation decreases more), and vice versa. The reason is that when $A'_q>0$, i.e., the perturbed value of the first term in Eq.(46) is larger than 0, meaning a net lost of water vapor, the moisture in the air column decreases, meanwhile, from (47) and (51), $A'_t>0$ and $A'_q>0$ enable $C'$ to be more negative, i.e., the degree of convergence decreases because $C$ represents convergence, which results in much less precipitation and evaporation, correspondently, the surface temperature increases further, this is the conclusion when the advection is included in the energy balance in an air column.

According to the climatological computation (Lu and Gao, 1987), there is a net positive flux for the water vapor, i.e., there is import of annual mean water vapor in the Hebei area, i.e., $A_q<0$; however, Ningxia is a more closed area, few water vapor can be exchanged with external area, where we may set $A'_q=0$, i.e., the perturbation of the advection of water vapor may not be considered. From Lu and Gao (1987), we may estimate approximately the annual mean value of $A_q$ for Hebei which is about −300 mm or −25 W / m$^2$, then we can assume

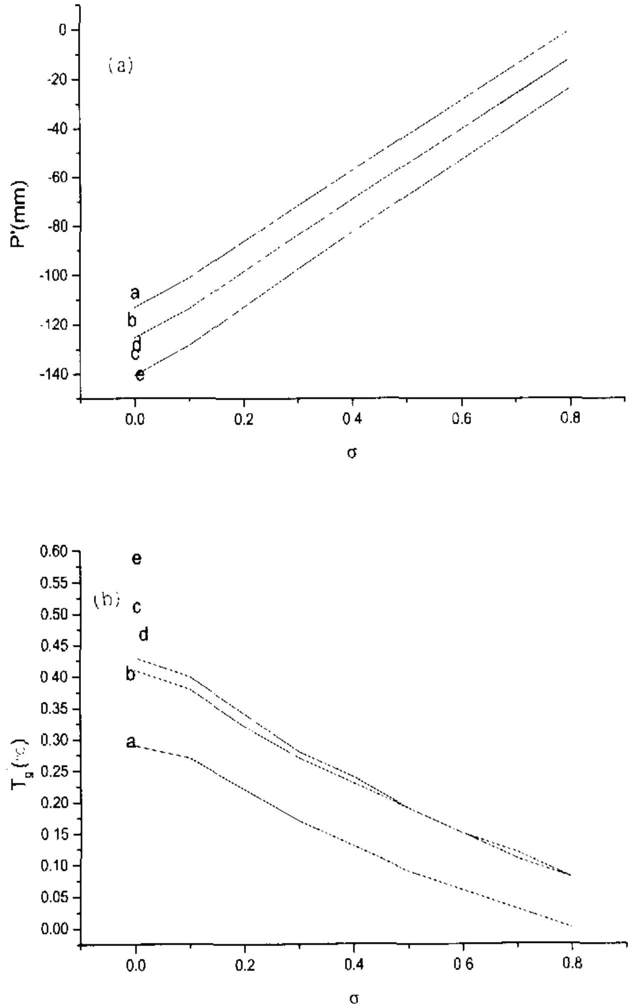


Fig. 4. The impact of $A'_t$ on $P'$ and $T'_g$ for Ningxia. (a) is for $P'$, (b) for $T'_g$, curve a is for $A'_t = 0$, *b* for $A'_t = 0.5$ W / m², *c* for $A'_t = 1$ W / m², *d* is the same as *b*, but $T_g$ increases 1 degree, *e* is the same as *c*, but $T_g$ increases 1 degree.

different values for $A'_q$. Unfortunately there are no data about $A_t$, but we may estimate the mean net heat flux along longitude between 30°–40°N over the whole earth which is about 10–20 W / m² (Lu and Gao, 1987), and is the net heat export, we will approximately assume $A_t$ to be about 1020 W / m², then to give different values for $A'_t$.

Fig. 4 shows the variations of precipitation and surface temperature with $\sigma_f$ for some values of $A'_t$ for Ningxia area, in which the change of roughness has been considered, we can see that when $A'_t$ increases, $|P'|$ also increases, i.e., precipitation decreases more, at the same time, $T'_g$ increases, however, the effect of the advection is relatively not great due to the drier climate in Ningxia, for example, the difference between $P'$ and its corresponding value with

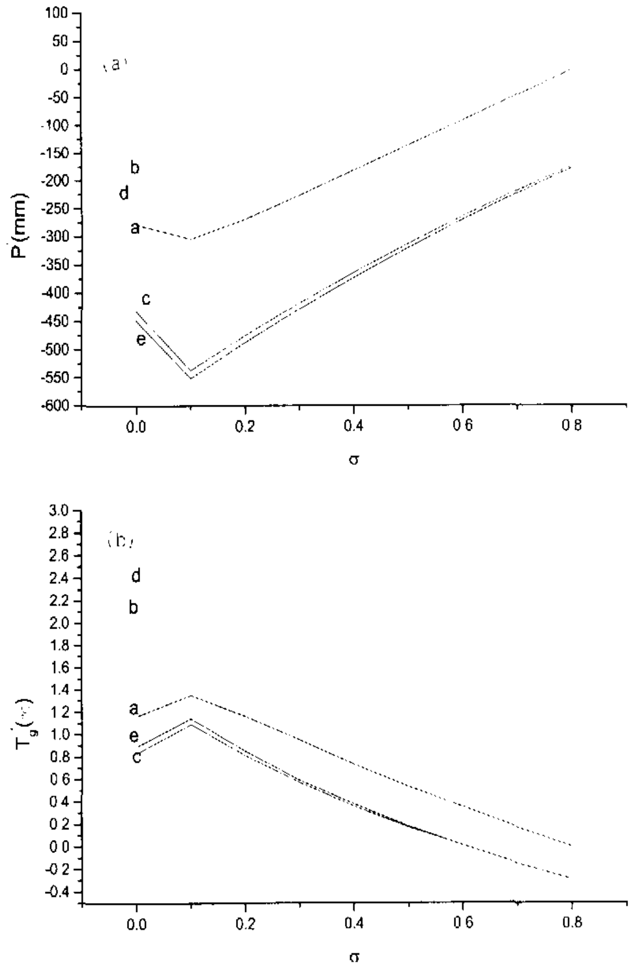


Fig. 5. The impact of advection on $P'$ and $T'_g$ for Hebei. (a) is for $P'$, (b) for $T'_g$. Curve $a$ is for $A'_t = A'_q = 0$, $b$ for $A'_q = -2$ W/m², $A'_t = 4$ W/m², $c$ for $A'_q = -1$ W/m², $A'_t = 4$ W/m², $d$ and $e$ are the same as in Fig. 4.

no advection is about 20–30 mm (for the $A'_t$ values shown in the figure).

Fig. 5 is the variations of $P'$ and $T'_g$ with $\sigma_f$ for some combinations of $A'_t$ and $A'_q$ for Hebei, on account of the selected $A'_q < 0$, $A'_t > 0$, their effect on $P'$ and $T'_g$ is opposite, the results are that $P'$ are more negative compared with no advection for some cases, but are reverse for other cases. Because from Eq.(49) we can see that the effect of $A'_t$ and $A'_q$ is opposite and complex when their signs are opposite. The effect of advection is greater for Hebei than that for Ningxia due to the greater $|P'|$, from Figs. 4 and 5 we also can see that the characteristics of the decrease of precipitation and the increase of temperature in case of global warming are similar to that no advection case, i.e., more serious, the amplitude of decrease

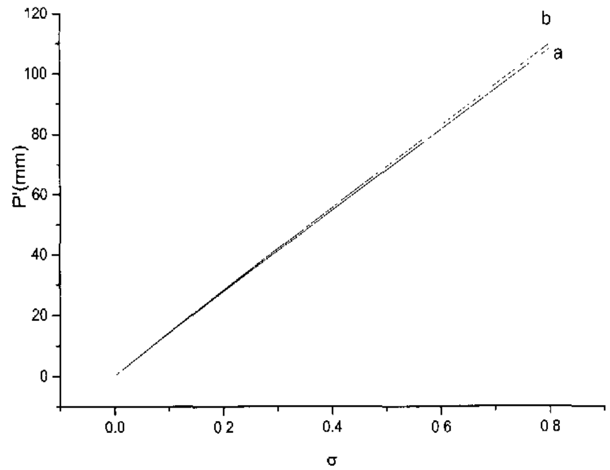


Fig. 6. The $P'$ after forestation for Ningxia, curve $a$ does not consider global warming. Curve $b$ is for considering global warming, $T_g$ increases 1 degree.

or increase is almost the same compared with no advection case.

## 6. The experiment of increasing vegetation cover

The above experiments are all about vegetation degeneration, what result will be if the bare soil is changed by vegetation? We study the Ningxia case, first take the parameters in Table 1, then let $\sigma_f$ increase from 0, the vegetation is forest which $z_0$ is 1 m, the precipitation may increase 108 mm when $\sigma_f$ is 0.8 (see Fig. 6), the surface temperature decreases slightly, the result proves that the forestation can increase precipitation, improve the climate. In case of global warming, the increase of precipitation becomes slightly stronger, i.e., global warming will strength the impact of vegetation on climate, however, this conclusion does not include the effect of vegetation on soil moisture, hence is limited, but the qualitative conclusion is convincible.

## 7. Conclusions and discussion

The energy equilibrium model for air column is used to study the local climate change caused by the changes of albedo and sensible and latent heat fluxes at ground surface which is induced by vegetation change, cases for northern China are studied. The results show that the degeneration of vegetation can induce the decrease of precipitation and the increase of temperature, especially, in case of global warming, it may be one of the reasons of the aridification of northern China. To increase the vegetation can increase precipitation and improve climate. The simple air column model in this paper contains clear physical process, however, cannot obtain continuous variation temporally and spatially by combining the physical processes in atmosphere, vegetation and soil like numerical model. For the annual mean state, the conclusions in this paper reflect realistic physical feature. The change of vegetation is only one of the causes of climate change, so the conclusion in this paper cannot be applied to discuss all the features of climate change. One of the shortcomings of the air column model is that which is an analytic model, cannot find the variation of the soil moisture induced by the variation of vegetation. On the other hand, the model needs further improvements, for example, the parameters about soil moisture are estimated from concerned references on account of lacking accurate soil and vegetation data. We find that the results are very sensitive to the saturated water content in some soil moisture parameters, when a value less than that we have chosen above is taken, the absolute values of $P'$ and $T'_g$ will also be less, but main conclusions are the same. There are some uncertainties for some parameters such as the constants $a_i$, $b_i$ in Budyko's formula and the atmospheric albedo $\alpha_0$. Further, the determination of some parameters, for example $\sigma_p$, is estimated from the data in some years, which may be different for the data in other years, all of these enable the conclusions in this paper to be limited, however, that the degeneration of vegetation induces decrease of precipitation and increase of temperature is certain, the magnitudes obtained in this paper are also reasonable (in recent 20 years, the mean decrease of precipitation is about 200–300 mm in Hebei and 100 mm in Ningxia, the increase of temperature is about 1 degree in Hebei and slightly smaller than 1 degree in Ningxia). The conclusion may be more convincible if more precise data and method determining parameter are applied.

## APPENDIX

### The evaporation in land surface model

In order to find $e$ in Eq.(35), we use some land surface models, the precipitation and evaporation in the following will not use energy unit, the equation for the soil moisture may be written

$$\frac{\partial W}{\partial t} = P - E_I - R_s - R_g - E_T\sigma_f - F_q(1-\sigma_f) . \tag{A1}$$

$P$ is the precipitation amount, $E_I$ the interception water, $R_s$ and $R_g$ are the runoff over and under ground respectively, $F_q$ is the evaporation over land, $E_T$ the transpiration over vegetation, $W$ the water content in soil (equivalent water depth), there are many formulas for interception water, we choose that in Seller's land surface model (Sellers and Mintz, 1986), which is

$$E_I = \begin{cases} \sigma_f P(1-e^{-kL}) , & \text{when } E_I < \max \\ 0, & \text{when } E_I > \max, \end{cases} \tag{A2}$$

$k = 0.5$, 3 is set for leaf area density $L$, the value of $E_I$ may be larger or less than the maximum value in a year, we will multiply a factor $\varphi$ in Eq.(A2) to consider this problem in an annual mean model, and first we will set $\varphi = 0.5$, our experiment shows that the result is not sensitive to the value of $\varphi$, there is no obvious difference for $\varphi = 0.5$ or 1 because of the drier climate. For $R_s$ and $R_g$, we use the formulas in BATS

$$R_s = \left(\frac{w}{w_0}\right)^4 (P - E_I) , \tag{A3}$$

$$R_g = K_{sa}\left(\frac{w}{w_0}\right)^{2B+3} . \tag{A4}$$

$w_0$ is the saturated value of $w$. $K_{w0} = 8.9 \times 10^{-7}$ m / s, set $B = 4$ corresponding to the selected soil parameters, the evaporation over bare soil applies

$$F_q = \rho C_E V(q_g - q_a) \ . \tag{A5}$$

The value of $C_E$ in (A5) is set to be $C_D$, the $q$ at surface is computed as follows (Bosilovich and Sun, 1998)

$$q_g = 0.5\left[1 - \cos\left(\frac{\pi w}{w_1}\right)\right] q_{sat} \ . \tag{A6}$$

$q_{sat}$ is the saturated specific humidity at corresponding temperature, $w_1$ is the field water content, for convenience, the transpiration is evaluated as the formula in Kan et al. (1994)

$$ET_{0i} = 1.6\left(\frac{10T_i}{I}\right)^a \ , \qquad \text{(mm / day)} \tag{A7}$$

$ET_{0i}$ is the referred transpiration for $i$-th month, $T_i$ is the monthly mean air temperature and

$$I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514} \ ,$$

there is a regression formula on $I$ for the exponent $a$ (Kan et al., 1994). The transpiration is calculated as follows:

$$ET_a = f_2(S) K_c ET_0 \ , \tag{A8}$$

$ET_0$ is the mean of $ET_{0i}$, $K_c = 1$,

$$f_2 = \begin{cases} c\left(\dfrac{w - w_p}{w_j - w_p}\right)^d \ , & \text{when} \quad w < w_j \\ 1 \ , & \text{when} \quad w > w_j \end{cases}$$

$c = 1$, $d = 0.7$, $w_p$ the wilt water content, according to the surface type for Hebei and Ningxia and the parameters in BATS, 0.16 and 0.13 are chosen for it in Hebei and Ningxia respectively, $w_j = 0.28$ is the critical water content (Kan et al., 1994). From (A1) we obtain the equation for the perturbed state

$$\frac{dW'}{dt} + \left[\left(\frac{\partial R_s}{\partial w} + \frac{\partial R_g}{\partial w} + \frac{\partial E_T}{\partial w}\sigma_f + \frac{\partial F_q}{\partial w}(1 - \sigma_f)\right]w'$$
$$= -\frac{\partial R_s}{\partial P}\left(1 - \frac{\partial E_l}{\partial P}\right)P' + \left(1 - \frac{\partial E_l}{\partial P}\right)P' = \left(1 - \frac{\partial E_l}{\partial P}\right)\left(1 - \frac{\partial R_s}{\partial P}\right)P' \ .$$

Setting $dW' / dt = 0$, we have

$$w' = \frac{\left(1 - \dfrac{\partial E_l}{\partial P}\right)\left(1 - \dfrac{\partial R_s}{\partial P}\right)P'}{\dfrac{\partial R_s}{\partial w} + \dfrac{\partial R_g}{\partial w} + \dfrac{\partial E_T}{\partial w}\sigma_f + \dfrac{\partial F_q}{\partial w}(1 - \sigma_f)} \ , \tag{A9}$$

the variation of total evaporation and transpiration is

$$E' = E'_l + E'_T\sigma_f + F'_q(1 - \sigma_f) = eP' \ ,$$

after applying (A9), we get

$$e=\frac{\partial E'_l}{\partial P'}+\frac{\partial E'_T}{\partial P'}\sigma_f+\frac{\partial F'_g}{\partial P'}(1-\sigma_f)=\frac{\partial E'_l}{\partial P'}+\left[\frac{\partial E'_T}{\partial w'}\sigma_f+\frac{\partial F'_g}{\partial w}(1-\sigma_f)\right]\frac{\partial w'}{\partial P'}$$

$$=\frac{\partial E_l}{\partial P}+\frac{\left[\frac{\partial E_T}{\partial w}\sigma_f+\frac{\partial F_g}{\partial w}(1-\sigma_f)\right]\left(1-\frac{\partial E_l}{\partial P}\right)\left(1-\frac{\partial R_s}{\partial P}\right)}{\frac{\partial R_s}{\partial w}+\frac{\partial R_g}{\partial w}+\frac{\partial E_T}{\partial w}\sigma_f+\frac{\partial F_g}{\partial w}(1-\sigma_f)}. \qquad (A10)$$

the different partial derivatives in the r.h.s. of (A10) may be found from (A2), (A8), (A5), (A3), and (A4), $e$ may then be found from (A10).

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# 下垫面改变导致局地气候变化的理论分析

赵 鸣 曾新民

**摘 要**

运用气柱内辐射、相变、对流间的平衡及地表能量平衡条件研究了由于地表状况改变，即植被退化所造成的局地气候变化，结果表明地表反射率的加大及地面热通量的变化造成中国北方降水量的减少和温度的增加。粗糙度的减少也能造成降水量减少和温度增加，这些结果与数值模拟一致。考虑平流作用以后，上述特征不变，但降水及温度改变量发生变化。在全球增暖背景下，降水减少和温度增加要更剧烈些。

**关键词**：气候变化，反射率，土地利用

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From 2002, the Co–Chief Editors of Advances in Atmospheric Sciences will be changed. Prof. Wang Mingxing will be no more the co–chief editor, instead, Prof. Wang Huijun, director of Institute of Atmospheric Physics, will take his place. We appreciate the effort Prof. Wang Minxing has made during his tenure of office in the past two years. We would like to thank him for his great supports to our journal *Advances in Atmospheric Sciences*.

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