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Application of a "Big-Tree" model to regional climate modeling: a sensitivity study

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With 7 Figures

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Summary

In order to better understand land-atmosphere interactions and increase the predictability of climate models, it is important to investigate the role of forest representation in climate modeling. Corresponding to the "big-leaf" model commonly employed in land surface schemes to represent the effects of a forest, a so called "big-tree" model, which uses multi-layer vegetation to represent the vertical canopy heterogeneity, was introduced and incorporated into the National Center for Atmospheric Research (NCAR) regional climate model RegCM2, to make the vegetation model more physically based. Using this augmented RegCM2 and station data for China during 1991 Meiyu season, we performed 10 experiments to investigate the effects of the application of the "big-tree" model on the summer monsoon climate.

With the "big-tree" model incorporated into the regional climate model, some climate characteristics, e.g. the 3-month-mean surface temperature, circulation, and precipitation, are significantly and systematically changed over the model domain, and the change of the characteristics differs depending on the area. Due to the better representation of the shading effect in the "big-tree" model, the temperature of the lower layer atmosphere above the plant canopy is increased, which further influences the 850 hPa temperature. In addition, there are significant decreases in the mean latent heat fluxes (within 20–30 W/m^2) in the three areas of the model domain.

The application of the "big-tree" model influences not only the simulated climate of the forested area, but also that of the whole model domain, and its impact is greater on the lower atmosphere than on the upper atmosphere. The simulated rainfall and surface temperature deviate from the originally simulated result and are (or seem to be) closer to the observations, which implies that an appropriate representation of the "big-tree" model may improve the simulation of the summer monsoon climate.

We also find that the simulated climate is sensitive to some "big-tree" parameter values and schemes, such as the shape, height, zero-plane displacement height and mixing-length scheme. The simulated local/grid differences may be very large although the simulated areal-average differences may be much lower. The area-average differences in the monthly-mean surface temperature and heat fluxes can amount to ~0.5 °C and ~4 W/m^2, respectively, which correspond to maximum local/grid differences of ~3.0 °C and ~40 W/m^2 respectively. It seems that the simulated climate is most sensitive to the parameter of the zero-plane displacement among the parameters studied.

1. Introduction

Global change has been receiving a lot of attention worldwide. The interactions between the ecosystem and other subsystems of global change (e.g. the atmosphere and land hydrosphere), which can significantly influence the surface climate as well as the hydrological cycle and soil characteristics, are particularly emphasized. In this respect, forest-climate interaction is very important to local climate, which further influences the climate around the forested region due to the unity of the climate system. Therefore, studies with the inclusion of detailed descriptions of land surface physical processes and plant-growth physiological processes are necessary in regional climate modeling, e.g. in the context of assessing the uncertainty of regional climate modeling.

Since the so called "big-leaf" theory was first introduced into a meteorological model (Deardorff, 1978), state-of-the-art land surface schemes accounting for vegetation effects have been developed (e.g. Wood et al., 1998), of which BATS (Dickinson et al., 1986, 1993) and SiB (Sellers et al., 1986) are two typical examples. All the above schemes are based on the "big-leaf" theory that considers generally one layer or less than three layers of vegetation with no or very little inclusion of vertical canopy heterogeneity. The theory is not included at all in some atmospheric boundary-layer schemes considering the effect of trees (e.g. Wilson and Shaw, 1977; Yamada, 1982; Gross, 1987, 1988; Schilling, 1991; Zeng et al., 1999). These boundary-layer schemes can reproduce distributions of the meteorological characteristics in and around the forested region which are consistent with observations. Due to the inclusion of vertical heterogeneity (i.e. multi-layer representation for forests) in these atmospheric boundary layer schemes, the physical realism in the forest physics is increased. However, these schemes have seldom been coupled to general circulation models or regional climate models for climate investigations, and they do not include a detailed description of land surface processes, which is of great importance for the representation of soil-vegetation-atmosphere interactions in climate models.

The objective of this paper is to investigate the sensitivity of regional climate modeling to the multi-layer representation of forests. Therefore, a boundary-layer model, which considers multi-layer heterogeneous vegetation and explicitly computes the characteristics in and above the plant canopy (Zeng et al., 1999), is introduced and incorporated into the NCAR regional climate model RegCM2 (Giorgi et al., 1993a, b), and treated as an option in the regional climate model. Therefore, the augmented version of RegCM2 includes not only a sophisticated description of land surface processes (BATS, Dickinson et al., 1993), but also a detailed boundary-layer scheme, in which the forested-region climate is modeled. For the locations or model grid cells where the land cover is not dominated by trees, the same physics as used in the original RegCM2 is used in the augmented model. Thus, as for the treatment of vegetation, the "big-leaf" theory is just one component of the augmented regional model, i.e. the "big-leaf" model is replaced by the "big-tree" model when the climate of the forested-region is simulated.

This paper describes a multi-layer heterogeneous-vegetation model in section two, section three presents the experimental design, section four addresses the analysis of the experiments, and the summary and discussion are given in the final section.

2. The "Big-Tree" model

2.1 Background to the model

Deardorff (1978) introduced the "big-leaf" concept and assumed the vegetation within a grid cell to be a single leaf, which is homogeneously distributed without vertical structure and has a uniform temperature and so influences the atmosphere via the radiative transfer and turbulent transportation of momentum and sensible and latent heat fluxes. The subsequent land surface schemes, BATS (Dickinson et al., 1986, 1993) and SiB2 (Sellers et al., 1996) consider a single leaf. SiB (Sellers et al., 1986) includes two leaves, one for trees and shrubs, and the other for grasses and other herbaceous plants. Though there are other developments, as well as the successes in modeling the evapotranspiration from the surfaces covered by grasses or crops, the essence of the "big-leaf" theory does not change when the forested-region meteorology/climate is modeled. It is natural for us to suggest that there are large limitations to the "big-leaf" theory in accounting for forest effects in climate models. The limitations are mainly because the "big-leaf" theory cannot represent the geometric heterogeneity of forests, especially the vertical heterogeneity, and therefore the dynamic and thermodynamic effects are not taken into account in a detailed manner. In order to make the modeling of the forested-region climate firmly and physically based, we introduce here a "big-tree" model, corresponding to the "big-leaf" model.

In short, as a conceptual model, the "big-tree" model is based on the assumption that the forest part within a whole grid cell is a "big-tree" (e.g. Yamada, 1982; Gross, 1987, 1988; Zeng et al., 1999). The heterogeneities of forest characteristics and physics (e.g. the leaf-area-index distribution, wind profile, and turbulent and radiative transfers above and within the plant canopy) are all considered and therefore the model is more physically based.

2.2 Brief description of a "Big-Tree" model

Following previous studies (e.g. Gross, 1988; Schilling, 1991), Zeng et al. (1999) developed a boundary-layer model which considers a multi-layer heterogeneous vegetation (i.e. tree) and explicitly computes the characteristics in and above the plant canopy. By assuming hydrostatic, incompressible conditions with no consideration of water-phase change, the governing equations are obtained:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial z}\left(k_m \frac{\partial u}{\partial z}\right) + f(v - v_g) - n_t c_d b_t W u, \quad (1)$$

$$\frac{\partial v}{\partial t} = \frac{\partial}{\partial z}\left(k_m \frac{\partial v}{\partial z}\right) - f(u - u_g) - n_t c_d b_t W v, \quad (2)$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(k_h \frac{\partial \theta}{\partial z}\right) + \frac{1}{\rho c_p}\left[(1 - n_s - n_t)\frac{\partial R_{nb}}{\partial z} + n_t\left(\frac{\partial R_{nt}}{\partial z} - \rho l_v p_v\right) + n_s \frac{\partial R_{ns}}{\partial z}\right], \quad (3)$$

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z}\left(k_q \frac{\partial q}{\partial z}\right) + n_t p_v, \quad (4)$$

$$\frac{\partial E}{\partial t} = \frac{\partial}{\partial z}\left(k_m \frac{\partial E}{\partial z}\right) + k_m\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] - k_h \frac{g}{\theta}\frac{\partial \theta}{\partial z} - c_e \frac{\phi}{l} E^{3/2} - n_t c_d b_t W^3, \quad (5)$$

where t is the time, u and v denote the mean velocity components in the x- and y-directions, corresponding to the geostrophic windspeeds u_g and v_g, respectively, $W = (u^2 + v^2)^{1/2}$ the mean windspeed, f the geostrophic parameter, ρ the air density, c_p the specific heat at constant pressure, b_t the leaf area density of trees, n_t and n_s the fractional coverages for trees and grasses, respectively, c_d the drag coefficient, R_{nb}, R_{nt} and R_{ns} the net radiation-fluxes over bare soil, trees and grassland respectively, θ the potential temperature, E the turbulent kinetic energy (TKE), k_m, k_h and k_q the eddy exchange coefficients for momentum, heat and water vapor in the z direction, respectively, g the acceleration of gravity, l the mean mixing-length over the fractions of bare soil, woodland, and grassland, and $c_e = 0.2$ is assumed. The evapotranspiration flux p_v is computed at each level within the plant canopy.

In the above equations, the leaf area index at the reference height z, $LAI(z)$, is calculated by using the leaf area density b_t (m^2/m^3):

$$LAI(z) = \int_z^{h^t} b_t(z)dz, \quad (6)$$

where h^t is the height of the tree top. It should be noted that l (mean mixing length) is assumed to be a function of b_t (leaf area density) in Zeng et al. (1999).

All the terms describing the influence of trees are computed at different model levels by including n_t and b_t in the equations. Through the equations, the wind, temperature, water vapor profiles, as well as the TKE in and above the canopy can be simulated.

Corresponding to the "big-leaf" model, the above boundary-layer multi-layer vegetation model, which can represent the mean status of forested regions, is referred to as the "big-tree" model. It differs from the "big-leaf" model in its explicit computations of the characteristics in and above the plant canopy. While in a "big-leaf" model (e.g. BATS), the characteristics in the plant canopy are simple and uniform, calculated only through diagnostic equations.

Conceptually, the "big-leaf" model is a 2-dimensional "plane" model, while the "big-tree" model is a 3-dimensional one, which has

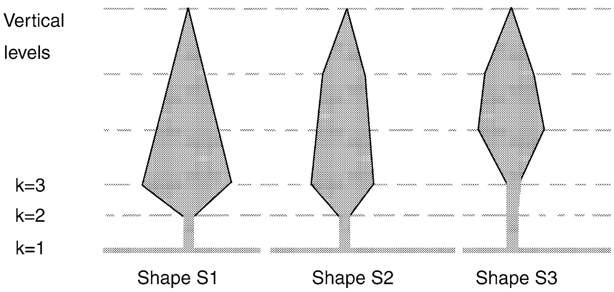

Fig. 1. Schematic of the big-tree model. The three big-tree shapes (i.e. Shapes 1, 2 and 3) are applied in the sensitivity experiments

a geometric structure within the plant canopy (Fig. 1). Through the parameters such as the fractional coverage and leaf area density, the conceptual "big-tree" model can be synthesized.

3. Experimental design

3.1 Incorporation of the "Big-Tree" model into RegCM2

Here we incorporate the multi-layer heterogeneous vegetation model (the "big-tree" model) into the regional climate model RegCM2 (Giorgi et al., 1993a, b). The "big-tree" model is only used for the forested regions corresponding to the vegetation of Types 3, 4, 5 and 6 in BATS, i.e. the evergreen needle-leaf, deciduous needle-leaf, evergreen-broadleaf and deciduous broadleaf forests. Thus in the augmented RegCM2 the momentum, sensible and latent heat fluxes from the forested area to the lower atmosphere are computed with the "big-tree" model, while for grid cells that are not dominated by the above forest types the simulation of fluxes is performed with the original-RegCM2 scheme.

The fluxes in the soil, vegetation and atmosphere can be computed more accurately by the vegetation boundary layer model in the surface layer below the height H, which is the lowest level of the atmospheric component of RegCM2. At the beginning of each time step, the meteorological quantities at the level H from the original atmospheric component of RegCM2, i.e., the downward radiation, pressure, wind, temperature and water vapor, and the relevant surface characteristic quantities predicted from BATS, are used as the boundary conditions to run the "big-tree" model and to obtain the meteorological quantities at each level below H. Then, as the fluxes in the surface layer (i.e. the momentum, sensible and latent heat fluxes at the canopy top) are computed, they feed back to the atmospheric component of the augmented RegCM2 for the integration of the next time step. We can see that the "big-tree" model does not substitute the original boundary layer model in RegCM2 except the values of the fluxes from the vegetation and soil to the atmosphere in the forested regions. Because the atmospheric component of the original RegCM2 needs fluxes from the surface to the overlying atmosphere from BATS, it is reasonable to apply a different atmospheric boundary layer scheme in neighboring grid cells within the atmospheric component of the augmented RegCM2.

Due to the smaller temporal and spatial scales used the "big-tree" model, a smaller time step is used e.g. 20 s, about 1/10 of the value for the atmospheric model in RegCM2. The stagger scheme is chosen for the "big-tree" model for the sake of computational stability. Wind speed, temperature and specific humidity are defined at the integer levels, while the eddy energy, mixing length and eddy-exchange coefficients are calculated at half levels.

The initial values at each level below H are obtained by linear interpolation and they are adjusted by the prognostic equations before the integration of the model to ensure computational stability. In the stage of the integration with small time steps within the large time step, the boundary values linearly approach the corresponding values predicted in the large time step.

3.2 Model domain and resolution

The model domain is centered at 117.00° E/32.00° N, covering an area within 24.7–45.7° N, and 100.88–133.12° E. The horizontal resolution is 60 km, while the vertical levels include 11 integer levels (i.e. $\sigma = 0.0$, 0.15, 0.30, 0.45, 0.60, 0.75, 0.85, 0.93, 0.97, 0.99, 1.00) and 10 half levels within the integer levels. The output quantities at the half-levels are all the variables except vertical velocity.

In the "big-tree" model, 10 vertical levels are set between 0-H, which are 0, 1, 2, 4, 7, 10, 14, 21, 28 and H(m) if the canopy top is 10 m from the characteristic values given by BATS, and are

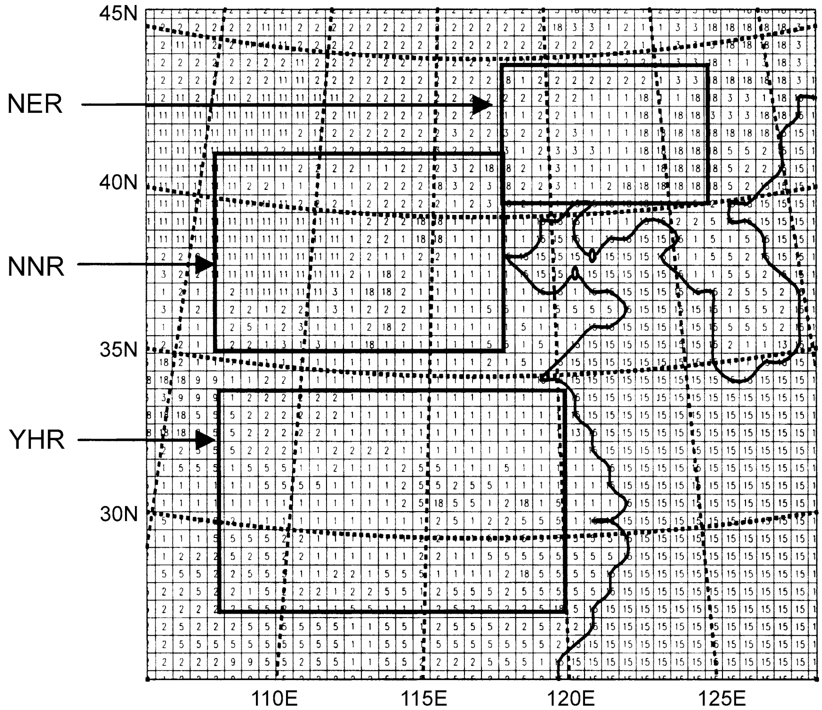

Fig. 2. Land-cover types in the model domain. The lower, middle and upper rectangles denote the YHR, NNR and NER areas, respectively, and land cover types are set according to BATS (*1* crop; *2* short grass; *3* evergreen needleleaf tree; *4* deciduous needleleaf tree; *5* deciduous broadleaf tree; *6* evergreen broadleaf tree; *7* tall grass; *8* desert; *9* tundra; *10* irrigated crop; *11* semi-desert; *15* ocean; *18* mixed woodland)

0, 2, 4, 7, 11, 15, 20, 25, 30 and H(m) if the canopy top is 20 m. The height H is computed from the atmospheric model (corresponding to $\sigma = 0.995$).

Figure 2 gives the vegetation cover in the model domain. The forests in China mainly include the needle-leaf, deciduous broadleaf and evergreen broadleaf forests in different climate zones. For the simulations we choose three sub-regions: NER for the northeast part of China; NNR for the northern part of China; and YHR for the Yangtse-Huaihe region, based on the distributed characteristics of the forests (Ye and Chen, 1992).

3.3 Options for experimental design

Station data in the Meiyu season during summer 1991 are taken as the initial and boundary conditions. In order to investigate the sensitivity of the short-term summer monsoon climate to different representations of forest effects and to compare them, the same options for all the physical processes are employed in all the experiments, including the one with the original RegCM2. For example, Holtslag's high resolution scheme is chosen for the boundary-layer parameterization (Holtslag, 1990, 1993), the modified Kuo's scheme is applied for the cumulus parameterization (Anthes et al., 1987), the time-dependent nudging technique is used for the lateral boundary conditions, etc.

We have designed 10 experiments (EXP1–EXP10) in five groups. The time intervals for the experiments are two months from 00GMT May 1 to 00GMT July 1, 1991 except Group 1 whose period is the three months from 00GMT May 1 to 00GMT August 1. Because extremely heavy rainfall mainly occurred in June in the 1991 summer, only the results for June are taken to analyze the groups, apart from Group 1, which is used for the overall analysis. The first group, including EXP1 and EXP2, is designed to simulate the 3-month changes in the major characteristics of the model's climatology due to the application of the "big-tree" model; the second group, including EXP3 and EXP4, is to study the effects of the improvement in the mixing-length scheme in the "big-tree" model on the simulated climate; the third group, including EXP3, EXP5 and EXP6, is used to study the sensitivity of the simulated climate to the zero-plane displacement in the "big-tree" model; the fourth group, including EXP3, EXP7 and EXP8, is designed to study the influence of the shape and structure of the "big-tree" model on the simulated climate;

Table 1. Prescription in the experiments. The symbol 'O' represents the original mixing-length scheme, 'N' the improved mixing-length scheme, '*DR*' means the ratio of zero-plane displacement to the big-tree height, while S1, S2 and S3 correspond to the tree shapes S1, S2 and S3 in Fig. 1, respectively, 'L' and 'H' mean 10 m and 15 m of the big-tree height, respectively

a

Experiment	Simulated month	Mixing length scheme	*DR*	Shape	Height	Experiment	Simulated month	Mixing length scheme	*DR*	Shape	Height
EXP1	5–7	–	0.9	–	L	EXP6	6	N	0.8	S1	L
EXP2	5–7	N	0.9	S1	L	EXP7	6	N	0.9	S2	L
EXP3	6	N	0.9	S1	L	EXP8	6	N	0.9	S3	L
EXP4	6	O	0.9	S1	L	EXP9	6	N	0.9	S1	H
EXP5	6	N	0.85	S1	L	EXP10	6	N	0.9	S2	H

b

GROUP \ EXP	1	2	3	4	5	6	7	8	9	10	Aim: to study
1	×	×									general change due to big tree
2			×	×							mixing length
3			×		×	×					DR
4			×				×	×			big-tree shape
5			×				×		×	×	big-tree top height

the fifth group, including EXP3, EXP7, EXP9 and EXP10, is to investigate the sensitivity of the simulated climate to the "big-tree" top height. Table 1 lists the specific prescriptions for each experiment.

4. Simulation and analysis

In this section, the preliminary analyses of the "big-tree" model application are given first, and then the sensitivity of the model's climatology to different schemes is discussed.

4.1 Preliminary analyses of the "Big-Tree" model application

Two experiments, EXP1 with the original RegCM2 and EXP2 with the adapted version in Group 1, are analyzed to study the changes in general characteristics due to the application of the "big-tree" model. The basic patterns of the simulated temperature and stream fields for EXP2 are in good agreement with the observations, although some small differences exist (not shown here) due to the same lateral forcing and almost the same model physics (Giorgi et al., 1999). Hence, the following analyses (including Subsection 4.2) will focus on the differences between the experiments.

Figure 3 shows the differences between EXP1 and EXP2, there is a large area in Fig. 3a with an absolute value of the 3-month-mean surface-temperature difference greater than 0.5 °C (e.g. for the NNR region), the surface temperature is obviously reduced by inclusion of the "big-tree" model, and the maximum difference in surface temperature may be up to 3.0 °C. These differences of surface temperature are very large compared with the increase of about 0.5 °C of the global mean temperature during the last century (Houlton, 1997). It is also found that the original RegCM2 has a bias of overestimating near-surface air temperature (2 m-level air temperature) for the continental areas of the model domain (i.e. the simulated temperatures in EXP1 are generally 1–2 °C warmer than the observed temperatures over land in the model domain; not shown). This is generally consistent with Liu et al. (1996) who evaluated the performance of RegCM2 for simulating the 1991 east Asia flood. However, the simulated values for near-surface air temperature from EXP2 are generally more consistent with the observations after the inclusion of the "big-tree" model (not shown), as is confirmed by the surface temperatures listed in Table 2. The surface temperatures in the NER, NNR and YHR areas are decreased by 0.2, 0.8 and 0.0 °C respectively, after the "big-tree" model is taken into account.

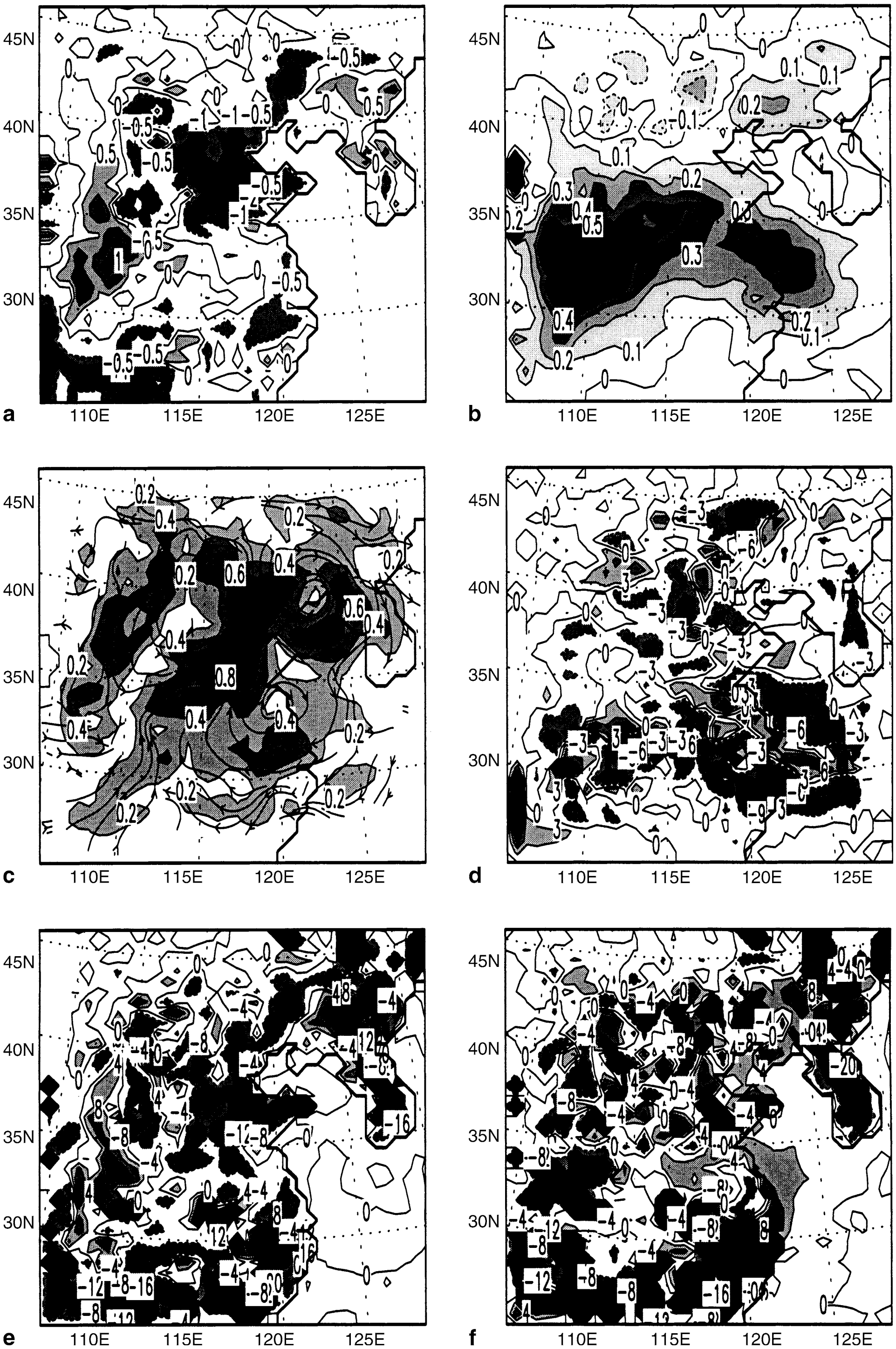

Fig. 3. Differences between EXP1 and EXP2 (the former minus the latter). **a** The 3-month-mean surface temperature (contour interval is 0.5 K); **b** the 3-month-mean 850 hPa temperature (contour interval is 0.1 K); **c** the 3-month-mean 850 hPa wind vector (contour interval is 0.2 m/s); **d** monthly-accumulated precipitation for June (contour interval is 3 cm); **e** the 3-month-mean sensible heat flux and **f** the 3-month-mean latent heat flux (contour intervals are $4\,W/m^2$). Areas with large absolute values of differences, which are greater than 0.5 K in Fig. 3a, 0.1 K in Fig. 3b, 0.2 m/s in Fig. 3c, 3 cm in Fig. 3d, and $4\,W/m^2$ in Figs. 3e and 3f, are shaded, respectively

Correspondingly, at 850 hPa there is a large and systematic increase over the larger part of the domain (Fig. 3b), and very interestingly, the area with high difference in temperature extends over the marine region, which is different to what is presented in Fig. 3a. This implies that the

Table 2. Results in the experiments. NER, NNR and YHR represent the 3 sub-regions in the model domain (Fig. 2). Except the accumulated characteristic of the maximum grid rainfall for June, the other results are area-averaging mean characteristics (i.e. 3-month mean in EXP1 and EXP2, and monthly mean in the other experiments). For surface fluxes, the results are the mean values at the level of canopy top for the experiments except that they are at the 'big-leaf' level in EXP1

	Surface temperature (K)			850 hPa temperature (K)			Sensible heat flux (W/m^2)			Latent heat flux (W/m^2)			Maximum rainfall for June (mm)
	NER	NNR	YHR	NER	NNR	YHR	NER	NNR	YHR	NER	NNR	YHR	
EXP1	292.2	297.5	300.2	286.7	291.0	292.4	25.6	22.8	7.04	99.4	98.1	91.4	615
EXP2	292.0	296.7	300.2	286.8	291.1	292.7	24.7	17.3	7.25	74.6	85.2	66.0	519
EXP3	298.7	303.0	304.9	292.0	296.3	297.9	35.8	21.9	4.79	82.3	98.5	72.2	501
EXP4	298.6	303.0	304.8	292.1	296.4	297.9	34.4	22.0	4.55	75.3	94.7	71.0	672
EXP5	298.7	303.2	304.8	292.1	296.5	298.1	33.7	22.8	4.96	77.3	95.8	70.9	673
EXP6	298.6	303.3	304.9	292.1	296.5	298.1	33.3	24.3	5.79	72.0	96.7	74.0	549
EXP7	298.6	303.1	304.8	292.0	296.4	297.9	33.3	22.0	4.87	82.5	96.1	70.4	518
EXP8	298.6	303.3	304.8	292.0	296.4	297.8	33.6	24.1	5.14	83.4	93.9	68.9	593
EXP9	298.5	303.2	304.8	292.0	296.4	297.9	34.6	23.1	5.23	78.5	94.8	68.8	573
EXP10	298.7	302.7	304.8	292.1	296.2	297.8	34.8	20.9	5.08	77.0	99.2	71.7	545

application of a "big-tree" model affects not only the climate in the forested area but also the climate over the whole domain. From all these analyses of temperature in the experiments a conclusion can be drawn that the surface and low-level air temperatures can be significantly influenced by the "big-tree" model.

Figure 3c displays a large wind difference at 850 hPa due to the effects of the model. Wind-speed differences as large as 0.8 m/s can be seen over a large area, in which the relative difference in wind speed can amount to 147.4%.

Figure 3d shows the precipitation difference for June, when during the 1991 summer monsoon, extremely heavy rainfall mainly occurred. EXP2 successfully simulates the rainfall pattern for June, and generally precipitation in EXP2 is less than that in EXP1 (e.g. there is a large area with negative differences in Fig. 3d) and closer to the observations. Table 2 shows the simulated maximum precipitation in the YHR area, 519 mm, is very close to the observed precipitation, 478 mm, and is also better than 615 mm from EXP1. In the two experiments, the local/grid difference (difference on the scale of the grid cell) in precipitation may reach up to 250 mm and results in precipitation differences in each area. The analysis for a shorter time scale shows that when the "big-tree" model is applied (not shown) the precipitation variation in the NNR area is larger than in the YHR area, and is also larger than in NER area. It is this shorter time-scale variation that leads to large differences in the monthly-accumulated precipitation.

Figure 3e and 3f present the differences in the 3-month-mean sensible and latent heat fluxes, respectively. Due to the inclusion of the model there are large areas where the absolute values of the differences in surface heat flux are greater than 4 W/m^2. Considering the Earth's surface flux balance of CO_2 doubling which would reduce the thermal radiation flux by about 4 W/m^2 (Houlton, 1997), we suggest therefore that these differences in surface fluxes are very large. Correspondingly, from Table 2, we can see that the latent heat fluxes are reduced considerably in the three areas (i.e. 24.8, 12.9, and 25.4 W/m^2 for the NER, NNR and YHR areas, respectively). Although the mean sensible heat fluxes do not change by such large amounts, quite large differences in the surface temperature are induced by inclusion of the "big-tree" model (e.g. a decrease of 0.8 °C for the NNR area) and further influences also occur on the near surface and higher level air temperatures (e.g. an increase of 0.3 °C for 850 hPa temperature in the YHR area). The quite large decrease in latent heat flux does not induce the increase of surface temperature in summer especially in the NER and NNR areas with large areas of forest. The reason for this is that the shading effect of the forest canopy can be expressed better by the "big-tree" model which enables the temperature stratification in the forest canopy to differ from temperatures above the canopy (Hosker et al., 1974; Gross, 1987, 1988; Yamada, 1982). Therefore, the diurnal temperature variation in the canopy layer may be stronger than at the surface and the quite large decrease in latent heat flux induces the increase in temperature at the top of the canopy, which can be seen from the 850 hPa-temperature difference (shown in Table 2, the temperature in EXP2 is slightly higher than in EXP1). Hence application of the "big-tree" model can produce systematic and very large differences in surface heat flux fields which would systematically cause change in the distribution of temperature, circulation, precipitation, etc. The impact of the model is larger on the lower atmosphere than on the upper atmosphere, e.g. for the NNR area, a temperature decrease of 0.8 °C at 850 hPa corresponds to a decrease of 0.1 °C at 500 hPa (not shown).

In short, through analysis of the two experiments it can be concluded that application of the "big-tree" model may simulate more realistic intraseasonal climate and that the climate over the whole of the model domain is very sensitive to the inclusion of the "big-tree" model.

4.2 Analysis of sensitivity experiments

Four groups of experiments are designed to study the sensitivity of the simulated regional climate to different mixing length schemes and different parameters in the "big-tree" model.

4.2.1 Mixing length

Based on observations Zeng et al. (1999) proposed an improved mixing-length scheme, which uses an offline multi-layer vegetation model, and showed that the two different schemes (original and improved) may cause about 30% of the difference in momentum flux for neutral stratification. If we apply the "big-tree" model in the regional climate model and use the different mixing length schemes, to what extent will the model's climatology be altered? The second experiment group including EXP3 (improved mixing length scheme) and EXP4 (original mixing length scheme) is designed to study the effects of the two mixing length schemes (Zeng et al., 1999) in the "big-tree" model on the simulated climate.

Figure 4a illustrates the difference between the monthly-mean surface temperature in EXP3 and that in EXP4. Differences greater than 0.5 °C can still be identified over quite a large area, especially in the NNR region, and the maximum difference can amount to 2.7 °C. This shows that the local/grid differences in surface temperature can be very large, though the area-average differences are not large (Table 2).

Figure 4b shows the difference between the monthly-mean surface latent heat flux in EXP3 and EXP4. The differences remain larger than $4\,W/m^2$ over the larger part of the domain. According to the statistical results the maximum local/grid difference in the sensible and latent heat fluxes can be as large as $33.6\,W/m^2$ and

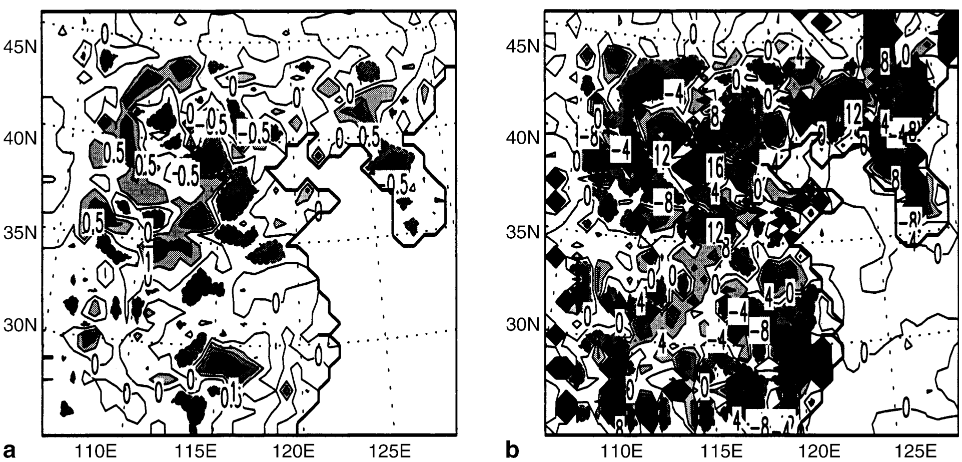

Fig. 4. Differences between EXP3 and EXP4 (the former minus the latter). **a** The monthly-mean surface temperature (contour interval is 0.5 K); **b** the monthly-mean latent heat flux (contour interval is $4\,W/m^2$)

60.8 W/m^2, respectively. As with the difference in monthly-mean surface temperature, the area-average differences in the monthly-mean heat fluxes are not as large as the local/grid differences, e.g. the maximum area-average latent heat difference is only 7 W/m^2, which exists in the NER area (Table 2).

As for the monthly precipitation, it can be seen that the maximum difference between EXP3 and EXP4 is 299 mm and there is also a quite large difference over a large area of the East Sea region (not shown). This means that the effect of the "big-tree" model is not confined to the forest area. The simulated area-average precipitation in the YHR area is 147 mm in EXP3 and 152 mm in EXP4. Table 2 shows that the maximum local rainfall in EXP4 is 672 mm, while the amount in EXP3 (501 mm) is closer to the observation (478 mm).

In summary, improvement of the mixing length in the "big-tree" model has a large impact on the simulated climate so that the simulated climate is quite sensitive to different schemes of mixing length.

4.2.2 Zero-plane displacement height

In the forested area the logarithmic law for the wind profile in the surface layer must be modified by introducing the zero-plane displacement height. In previous studies, different authors gave different values of displacement (e.g. Baldocchi et al., 1987; Baldocchi et al., 1988; Amiro et al., 1990). A larger zero-plane displacement means a larger wind shear near the top of the canopy layer when the height of the canopy layer and the wind speed above the canopy layer are given. This gives a larger value of *DR*, defined as the ratio of the zero-plane displacement height to the canopy top, and may result in a stronger upward turbulent transfer near the canopy top, and therefore further induces changes in climate in the forested area. Usually, the *DR* value ranges from 0.7 to 0.9, and 0.9 is adopted in the original RegCM2. Until now there have been few investigations concerning how large the effect of different *DR* values is on model climatology (simulated by a regional climate model or general circulation model) in the forested area. Our third group of experiments, including EXP3 ($DR = 0.9$), EXP5 ($DR = 0.85$) and EXP6 ($DR = 0.8$), is designed to investigate the sensitivity of the simulated climate to different values of the zero-plane displacement in the "big-tree" model.

Figure 5a illustrates the difference in monthly-mean surface temperature between EXP3 and EXP6. There is a large area with high absolute values of monthly-mean surface-temperature difference around the NNR area. Surface temperature is increased by 0.3 °C after the value of *DR* is changed from 0.9 to 0.8 (Table 2). In addition, the maximum difference in surface temperature may be up to 2.6 °C, correspondingly, there is a very large area with large systematic differences in the 850 hPa temperature (Fig. 5b), with the maximum difference amounting to 0.73 °C. The pattern in Fig. 5b is similar to that in Fig. 3b, which further shows that the inclusion of the "big-tree" model can influence areas outside of the forested regions.

Figure 5c displays large difference in the 850 hPa-wind field. Due to change in the zero-plane displacement, the windspeed difference can be as large as 0.6 m/s over quite a large area, in which the maximum difference can amount to 1.2 m/s. These results show that change in *DR* can greatly alter circulations across the model domain.

The difference in the monthly-mean sensible heat flux is shown in Fig. 5d. There is a large area where the absolute differences in the surface heat flux are greater than 4 W/m^2. The difference in the monthly mean latent heat flux is also similar (not shown). Table 2 shows that the latent heat fluxes are altered to different degrees in the three areas (i.e. the decreases of 10.3, 1.8, and -1.8 W/m^2 for the NER, NNR and YHR areas, respectively) as *DR* decreases. Since the differences are heterogeneously distributed, the local differences can be much larger. This shows that change in *DR* can greatly affect the surface turbulent transfer.

The differences in some variables between EXP5 and EXP3 are also large, even though the *DR* difference between EXP5 and EXP3 is not as large as between EXP6 and EXP3. For example, the maximum precipitation for June is 673 mm in Exp5, but it is 501 mm in EXP3. For the simulated temperatures at 850 hPa in EXP5 and EXP3 the area with a difference of more than 0.2 °C occupies more than half of the domain, and the maximum difference can amount to 0.51 °C (not shown).

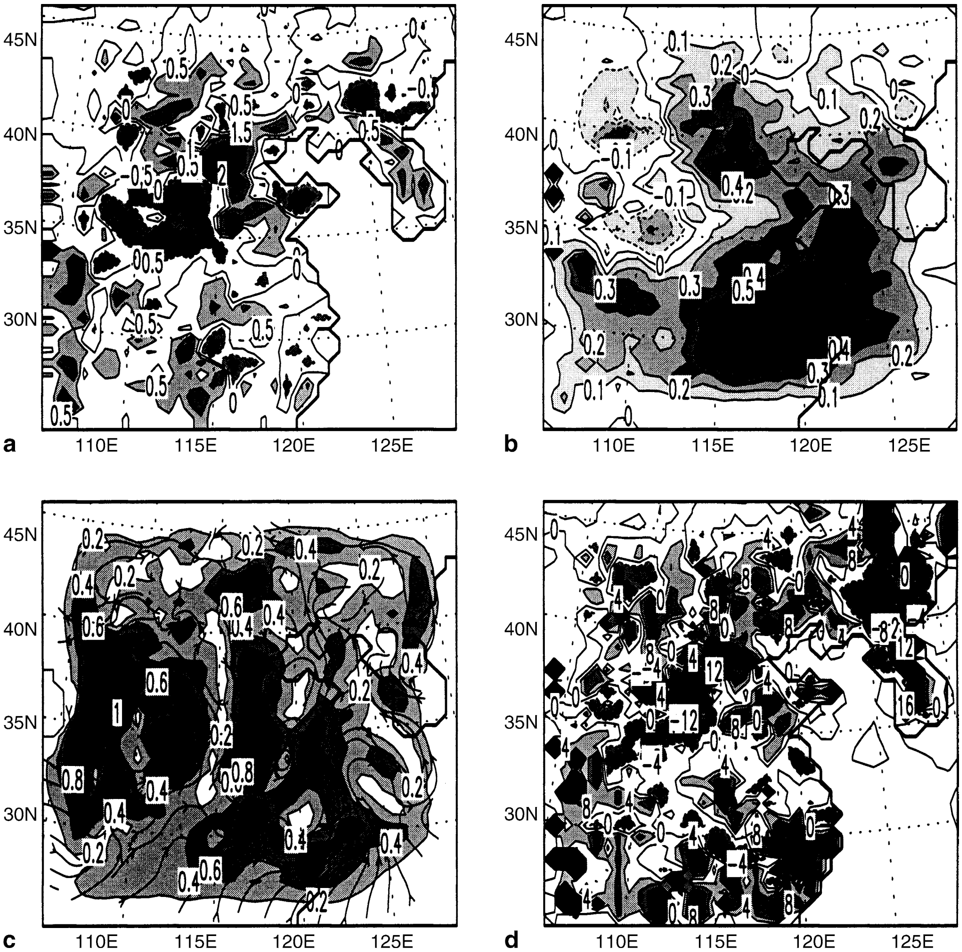

Fig. 5. Differences between EXP3 and EXP6 (the former minus the latter). **a** The monthly-mean surface temperature (contour interval is 0.5 K); **b** the monthly-mean 850 hPa temperature (contour interval is 0.1 K); **c** the monthly-mean 850 hPa wind vector (contour interval is 0.2 m/s); **d** the monthly-mean sensible heat flux (contour interval is 4 W/m^2)

In general, we conclude that change in the zero-plane displacement in the "big-tree" model can produce very different regional climates.

4.2.3 Shape of the "Big Tree"

The shape of the 'big tree' can be described by parameters such as the vegetation fractional coverage and leaf area density. Obviously, the larger the vegetation cover, the bigger the "tree"; the larger the leaf area density at a certain level, the more leaves are at that level. Observations show that there is stronger turbulent intensity within the plant canopy (e.g. Baldocchi et al., 1987, 1988; Amiro et al., 1990). Similar to the improvement in the mixing length (Zeng et al., 1999), we suggest that the greater turbulence should be associated with characteristic quantities such as the leaf area density. Different leaf area densities at different levels (or different shapes of the "big tree") will influence the turbulent transfer in and near the canopy layer, and further affect the forested-area climate. The total leaf area index and stem area index are two characteristic quantities related to the "big-leaf" in the original RegCM2. As for the treatment of the "big-tree" model, based on the tree shapes shown in Fig. 1 and the leaf area index in BATS, the leaf area densities at different levels are derived through Eq. (6). The fourth group of experiments, including EXP3, EXP7 and EXP8, is designed to study the effect of the "big-tree" shape on the simulated climate. EXP3, EXP7 and EXP8 correspond to the three shapes, S1, S2 and S3 in Fig. 1, respectively.

Figure 6a displays the difference in the monthly-mean surface temperature between EXP3 and EXP8. Due to the difference in the

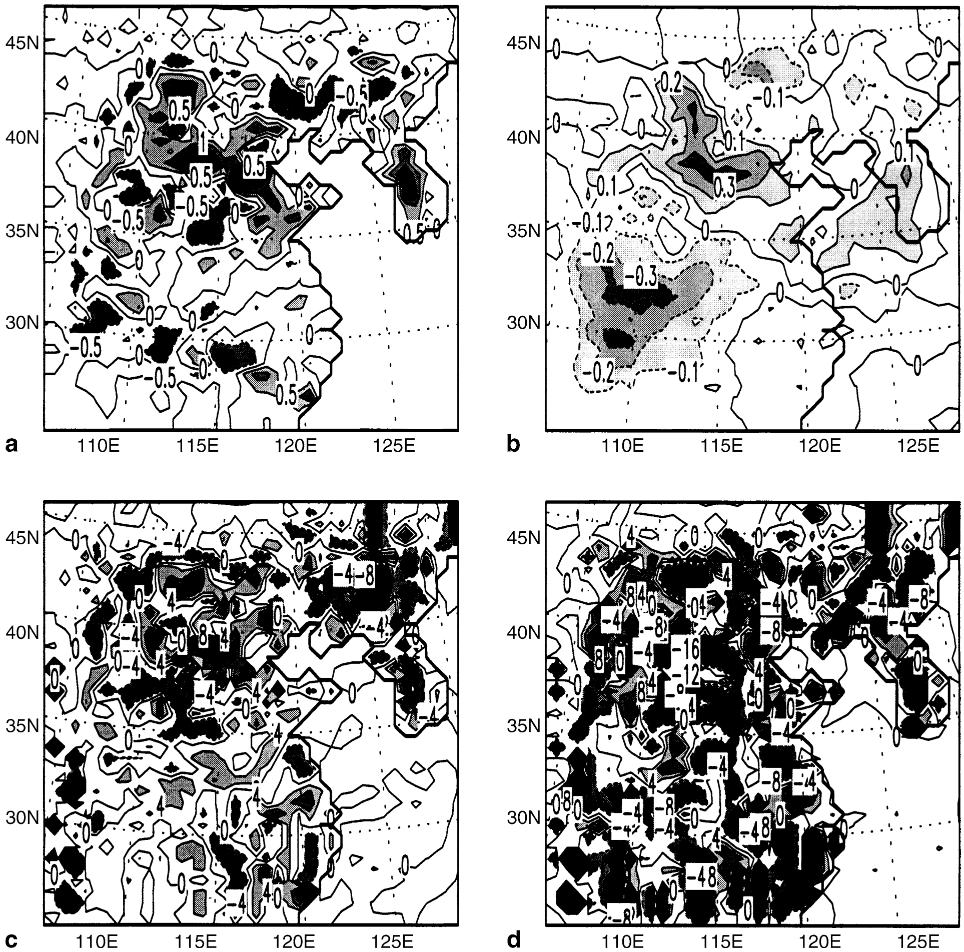

Fig. 6. Differences between EXP3 and EXP8 (the former minus the latter). **a** The monthly-mean surface temperature (contour interval is 0.5 K); **b** the monthly-mean 850 hPa temperature (contour interval is 0.1 K); **c** the monthly-mean sensible heat flux; **d** the monthly-mean latent heat flux (contour interval is 4 W/m^2)

"big-tree" shape there is a large area with high absolute values of temperature difference around the NNR region. As shown in Table 2, it seems that the NNR area is the most significantly affected among the three areas, with a surface-temperature increase of 0.3 °C. In addition, the maximum difference in surface temperature can amount to 3.6 °C. Correspondingly in the lower-layer atmosphere there is a very large aggregated area with parse differences in temperature (Fig. 6b), and the maximum difference can reach 0.41 °C.

Figure 6c and 6d show the difference in the monthly-mean sensible and latent heat fluxes, respectively. Owing to the tree-shape difference, large differences in the heat fluxes are very obvious. As for the latent-heat-flux difference, the area-average values are 4.6 W/m^2 and 3.3 W/m^2 for the NNR and YHR areas, respectively (Table 2). The maximum local/grid differences are 48.6, 45.4 W/m^2 and 45.4 W/m^2 for the three areas, respectively.

Table 2 lists differences between EXP7 and EXP8, e.g., as for the monthly-mean surface temperature in the NNR area, the values are 303.1 K and 303.3 K; as for the monthly-accumulated precipitation, the local/grid maximum values are 518 mm and 593 mm, respectively. Thus, the conclusion can be drawn from these results that the model's climate is also sensitive to the shape of the "big-tree".

4.2.4 Height of the "Big Tree"

In China, some needle-leaf forests in the temperate zone are often 10–25 m high, while the height of deciduous broadleaf forests in northern China usually range within 10–15 m, and those

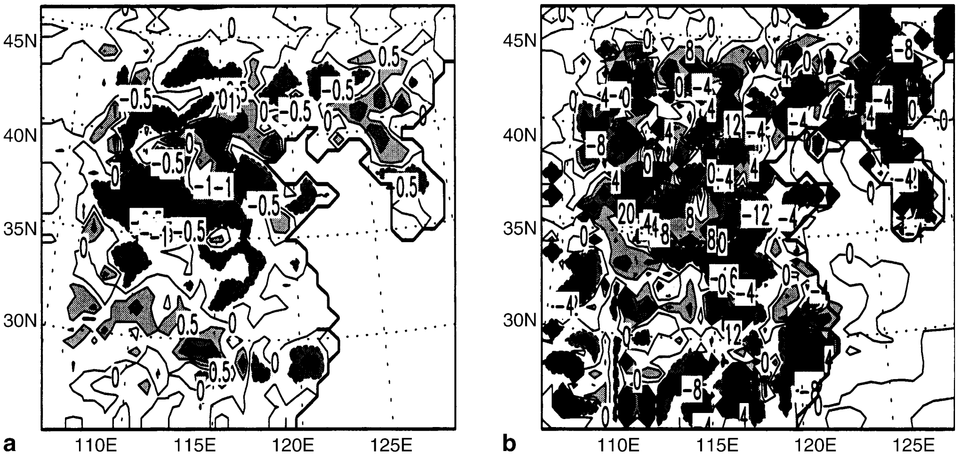

Fig. 7. Differences between EXP3 and EXP9 (the former minus the latter). **a** The monthly-mean surface temperature (contour interval is 0.5 K); **b** the monthly-mean latent heat flux (contour interval is $4\,W/m^2$)

of the evergreen broadleaf forests in sub-tropic region are usually 10–30 m high. The characteristic values of the forests in the vegetation classification adopted in the original RegCM2 may not reflect the reality in China, which will affect the simulated climate in the forested area. We therefore design the fifth group of the experiments (i.e. EXP3 vs. EXP9, and EXP7 vs. EXP10) to assess the sensitivity of the climate to the height of the tree top in the "big-tree" model.

Figure 7a presents the difference in the monthly-mean surface temperature between EXP3 and EXP9. There is a large area with high absolute values of temperature difference and the maximum local/grid difference in surface temperature can amount to 3.3 °C. As for the monthly-mean latent heat flux, large differences can still be seen (Fig. 7b) with the maximum local/grid difference of $59.1\,W/m^2$. Table 2 shows the monthly-mean latent heat fluxes are 82.3, 98.5 and $72.2\,W/m^2$ for the NER, NNR and YHR areas in EXP3, respectively, corresponding to 78.5, 94.8 and $68.8\,W/m^2$ in EXP9. All these display quite large differences.

In addition, there are also quite large differences between EXP7 and EXP10 (not shown). Some large differences can still identified from Table 2, e.g. the monthly-mean surface temperature for the NNR area is 303.1 K in EXP7, and is 302.7 K in EXP10; the monthly-mean latent heat flux for the NER area is $82.5\,W/m^2$ in EXP7, and is $77.0\,W/m^2$ in EXP10.

Therefore, it can be concluded that the simulated climate may be greatly altered by change in the height of the 'big tree'.

5. Summary and conclusions

Corresponding to the "big-leaf" model that considers little vertical heterogeneity for vegetation, the boundary-layer model, which considers this heterogeneity and in which the characteristics are explicitly computed for different levels of forest canopy (Yamada, 1982; Gross, 1987, 1988; Zeng et al., 1999), is here referred to as the "big-tree" model. The "big-tree" models are characterized by their detailed descriptions of tree features and processes, such as the geometric heterogeneities of trees, as well as the profiles and turbulent and radiative processes in and above the canopy. Generally, 'big tree' models are implemented for studies on characteristic profiles or for studies of short-term weather. In this paper, a "big-tree" model (Zeng et al., 1999) is intended to replace the currently-used "big-leaf" model for investigation of short-term climate. We have incorporated the "big-tree" model into the NCAR regional climate model RegCM2 (Giorgi et al., 1993), so as to make the vegetation model more physically based and to investigate some of the uncertainties in regional climate modeling. It is expected that the forest climate produced by the "big-tree" model should be more realistic.

Using the augmented version of RegCM2 we have applied the station data in the Meiyu season, during the 1991 summer monsoon, as the initial and boundary conditions and performed ten experiments to investigate the effects of application of the "big-tree" model.

With the "big-tree" model incorporated into the regional climate model, some climate characteristics, e.g. the 3-month-mean surface temperature, circulation, and precipitation, are systematically and significantly changed in the domain, e.g. the 3-month-mean surface temperature is decreased by 0.8 °C in the NNR area, with a maximum local/grid difference of about 3 °C. Due to the better representation of shading effects with the "big-tree" model, the air temperature just above the plant canopy is increased, which further influences the 850 hPa temperature (Fig. 3b). As for surface heat fluxes, although no great change occurs in the mean sensible heat fluxes, there are significant decreases in the mean latent heat fluxes (within 20–30 W/m^2) in the three areas of the model domain.

Changes in the climate characteristics differ in different areas of the domain and the application of the "big-tree" model influences not only the simulated climate for the forested area, but also that for the whole domain. Its impact is greater on the lower atmosphere than that on the upper atmosphere.

After the incorporation of the "big-tree" model, the simulated precipitation and surface temperature differ from the original model and are (or seem to be) closer to the observations. This implies that appropriate representations of the "big-tree" model may improve the simulation of the summer monsoon climate.

The experiments conducted for different parameters/schemes of the "big-tree" model show that the simulated climate is sensitive to some parameters, such as the shape, height, zero-plane displacement height. Different mixing-length schemes can also lead to quite large differences in climate characteristics.

In the sensitivity tests some systematic large differences can be caused by different parameters/schemes. The local/grid differences may be very large although the area-average differences may be much smaller. The area-average differences in the monthly-mean surface temperature and heat fluxes can amount to ~0.5 °C and ~4 W/m^2, respectively. These correspond to the maximum local/grid differences of ~3.0 °C and ~40 W/m^2. Moreover, judging from differences which result from different values of the "big-tree" model parameters in the present study, the simulated climate is most sensitive to the zero-plane displacement. Figure 5 shows the differences in the surface and 850 hPa temperatures, as well as in the windspeed, are generally larger than other parameters, e.g. the shape of the "big tree" whose effects are shown in Fig. 6. Different displacements may induce different climate features and produce greater influences on the circulation, temperature, surface fluxes, etc.

Additionally, from the results and conclusions of the set of experiments with different applications of the "big-tree" model, it can be shown that:

(i) The regional climate is sensitive to many factors. In other words, there are many uncertainties in the regional climate modeling. This paper provides some results concerning the uncertainties when a "big-leaf" model is applied. Through some formulations of more realistic physical processes in the "big-tree" model (e.g. the turbulent and radiative transfer schemes are more physically based), some uncertainties are reduced. Yet uncertainties remain, e.g. the choice of the values for the "big-tree" model. It is expected that developments of remote sensing and theoretical studies will provide possibilities to reduce these uncertainties, and via these developments, a more realistic model for the representation of vegetation will be derived. Decrease in uncertainties due to the application of the "big-tree" model suggests that the "big-tree" model might play an important role in regional climate modeling. Although this increases computer requirements, improvements in the computational resources and numerical schemes may solve this problem.

(ii) Simulated precipitation after application of the "big-tree" model is systematically overestimated in all the experiments conducted (e.g. the maximum grid precipitation for June in each experiment is larger than the observations, 478 mm), which implies that there are still limitations in the regional climate model even after land surface processes are improved. For land surface heterogeneities, Giorgi and Avissar (1997) and Zeng et al. (2002, 2003) showed the importance of including land surface horizontal heterogeneities, other than the vertical heterogeneities of the "big-tree" model used in this study, in climate models.

(iii) The differences in the results due to the "big-tree" model seem to be dependent on the current weather, e.g. the magnitude of the mean sensible and latent heat fluxes appear to be dependent on the current "wet" climate, there was an extremely anomalous flood in 1991 over east Asia, while for some "dry" climates, the magnitudes might be very different. For example, the changes in the latent heat flux for the three areas are larger than those in the sensible heat flux in the present "wet" climate due to the application of the "big-tree" model, while for some "dry" climates, the changes might be reversed. These considerations, as well as the changes over shorter time scales (e.g. how the differences change from day to day?), remain for follow-up studies.

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