Influence of land evapotranspiration on climate variations

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Abstract A coupled numerical model of the global atmosphere with a qualified biosphere (GOALS/LASG) has been used to assess the nature of the physical mechanisms for land-atmosphere interactions, and the impacts of the Asian/North American land-surface evapotranspiration on the regional and global climate. This sensitivity study suggests that the simulated climate would be relatively sensitive to land surface evapotranspiration, especially over the Asian regions. The removal of evapotranspiration in Asia would create a warmer and drier climate to a certain degree. Furthermore, the surface evapotranspiration anomalies would make a substantial contribution to the formation and variation of subtropical anticyclones through the changes in monsoon precipitation and the β-effect, but also make a large contribution to the variations of the atmospheric circulation in the Northern Hemisphere and even the globe. Therefore, besides the traditional perception that we have generally emphasized on the influence of subtropical anticyclones activities on the boreal summer precipitation over the regions of eastern China, the surface evapotranspiration anomalies, however, also have substantial impacts on the subtropical anticyclones through the changes in monsoon precipitation. For this reason, the variation in the internal heating sources of the atmosphere caused by the land surface evapotranspiration and the vapor phase change during the boreal summer is an important external factor forcing the weather and climate.

Keywords: land-surface evapotranspiration, land-atmosphere interactions, climate change.

Spatial heterogeneities of the land-surface heat source directly affect the formation of climate. Among these diabatic heating components, the underlying latent heat flux is one of the much more important external heat sources for the atmospheric circulation. On a global average, the latent heat flux accounts for about 50% of the emitted energy away from the surface to the atmosphere[1]. The land-surface evapotranspiration takes up 15% of the global precipitation and 65% of the land surface precipitation. The evapotranspiration would modulate climate as well by reducing the transport of sensible heating away from the radiation energy, enhancing the air humidity, increasing the minimum air temperature and decreasing the maximum air temperature. The initial AGCM sensitivity experiment conducted by Shukla et al.[2] demonstrated that global land-surface evapotranspiration could have important impacts on both the precipitation and the atmospheric circulation. However, early AGCMs incorporated very simply specified surface parameters (e. g.

albedo, roughness and soil moisture availability) and largely data-free algorithms over the continents to improve the exchanges of the evapotranspiration and sensible heating, the conservation of the moisture and convective precipitation. The experiment was relatively unrealistic because the exchanges of moisture and energy from the land surface were treated as independently pure physical processes. Although these surface attributes have profound impacts on the fluxes across the land-surface interface, the climatic effects are still not far more understood quantitatively. Recently, the biophysical land surface processes models[3–6] (LSMs) have been implemented to AGCMs to provide a consistent description of the energy exchanges and the evapotranspiration by plants, thereby making land-atmosphere interactions even more interactive. For example, Sun et al.'s[7] experiments show that GOALS/LASG with realistically biophysical LSM (e.g. SSiB) has conspicuously improved early land surface hydrological parameterizations and reproduced reasonably good climatology, particularly over the continents even at this relatively low resolution.

A scientifically based assessment and understanding of the hydrological cycle for large-scale land-atmosphere systems and credible representation of the physical processes of complex land-atmosphere interactions have become possible only with the advent of realistic LSMs. That is also a new growing point as advances in dynamical climate theory. In this regard, the sensitivity experiments are performed to further study the effects of regional land-surface evapotranspiration on climate by use of GOALS/LASG model and reveal its feedback mechanisms for atmospheric circulation.

1 Model and experimental design

The model used for this study is the coupled global ocean-atmosphere-land system (GOALS) model[8] developed by IAP/LASG which is a modified version of L9R15 global spectral AGCM[9]. Sub-grid scale physical parameterizations include mainly an effective K-distribution radiation scheme[1)], the horizontal and vertical diffusion of momentum, heat and moisture, the convective adjustment scheme (Manabe et al., 1965) and land surface processes, which is Xue et al.'s[6] version of the simplified simple biosphere model (SSiB). The SSiB model has one vegetation canopy layer and three soil layers. The new observed global vegetation distribution provided by Xue (personal communication, 1997) is used. We will de-couple the ocean and polar ice models here. The prescribed seasonally varying climatological sea surface temperatures from 1979 to 1988 obtained from the Atmospheric Model Intercomparision Project (AMIP) datasets are used as a boundary condition for all the integrations described here, i.e. the coupled atmosphere-biosphere model.

In this paper, we have designed control and anomaly experiments respectively. The control case (hereafter called CTL) uses 10-year integration produced with the GOALS/LASG, which stands for the principal large-scale features of the climate systems, while the anomaly case as-

1) Shi, G. Y., An accurate calculation and representation of the infrared transmission function of the atmospheric constituents, Ph.D. Thesis, Dept. of Sci., Tokyo University of Japan, 1981, 191.

sumes that all the evapotranspiration rates over the Asian (hereafter called ANLH) or North American (hereafter called NANLH) continent respectively across the land-atmosphere interface from the moisture prognostic equation are set to zero at each time integration step. Except for this difference, all other initial and prescribed boundary conditions are kept identical in both integrations as described in the corresponding control case. Control and anomaly integrations are conducted for ten years each. Therefore, only the difference between the control and anomaly multi-year integrations of each pair respectively (i.e. CTL minus ANLH, CTL minus NANLH) could be interpreted as the effects of anomalous land-surface evapotranspiration on climate.

2 Results and discussion

In this section, we will focus on the impacts of the evapotranspiration over Asian or North American continent on the regional and Northern Hemisphere model-produced climate in July respectively.

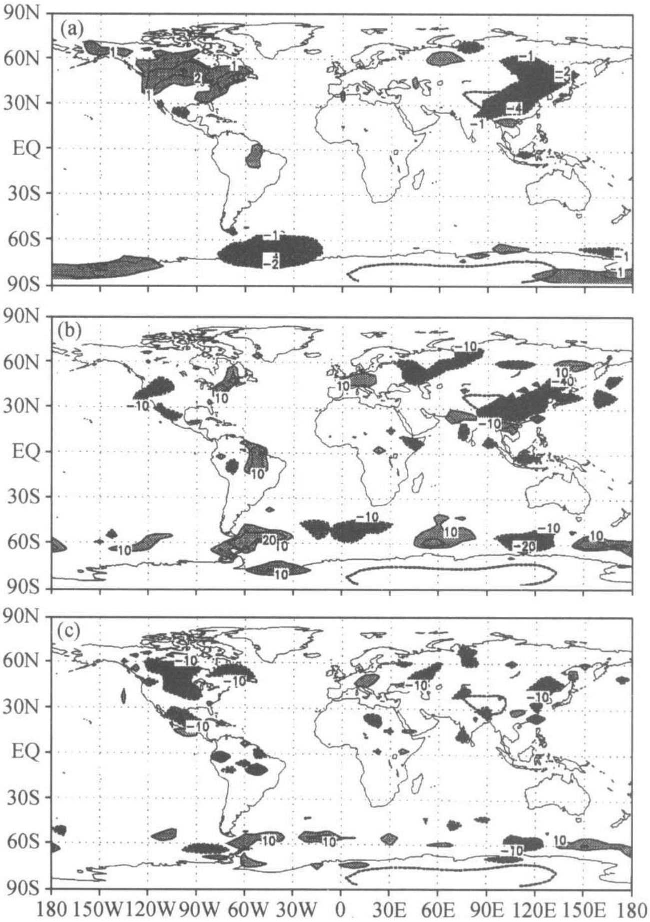

Fig. 1. July mean difference field in surface effective temperature (a), surface sensible heat flux (b) (W/m^2) as calculated by CTL and ANLH run, and surface sensible heat flux (c) (W/m^2) as calculated by CTL and NANLH run. Dashed isohyets are negative. Dark dashed curves indicate the elevation of higher than 3 km on the Tibetan Plateau.

2.1 Impact on the air temperature

The most outstanding difference (CTL minus ANLH) in the surface effective temperature over most of Asian humid regions is given in fig.1 (a). The largest negative anomaly can be as low as −7℃ over the upper and middle reaches of the Yangtze River. There are also large negative differences in surface effective temperature which becomes as low as −2℃ over land regions of eastern China. This could be partly due to much heating escaping the ground for transpiration by plants and evapiration by soil in the evapotranspiration case, in particular due to much higher precipitation rate produced by large evapotranspiration in the East Asian continent. Consequently, higher surface soil wetness (not shown) and a larger heat capacity in that area in the CTL run resulted in lower surface temperature. Nevertheless, it should be pointed out that these significant negative anomalies in the surface temperature are accompanied by a corresponding reduction in the surface sensible heat flux. For example, the maximum surface sensible heat fluxes over the upper and middle reaches of the Yangtze River in the CTL run are $-120\mathrm{W/m^2}$ lower than those obtained in the ANLH run (fig.1 (b)). This indicates that the land-surface evapotranspiration makes a contribution to the large changes in partitioning energy between surface sensible and latent heat flux, thereby leading to a significant decrease in the surface sensible heat flux from the absorbed net radiation flux at the surface in the CTL run.

The strong response in the land surface evapotranspiration is clear in the upper air temperature. Fig. 2 shows the mean 200-hPa air temperature and the differences in the CTL and ANLH run respectively. As compared with the ANLH experiment, the most striking feature in the CTL simulation is that two air temperature maxima are substantially enhanced in the Northern Hemisphere over the subtropical regions, most notably over the Asian and African continents, which are matched closely by the dramatically increased South Asian high seen in the next section. From the differences (CTL minus ANLH), there are positive air temperature anomalies of 3℃ over the Qinghai-Tibetan Plateau, Mongolia and northeastern China. Indeed, the maximum difference can be as high as 4℃ in the Northern Hemisphere over the subtropical ocean. In fact, positive temperature anomalies also appear over much of the Earth. This is associated mostly with the considerable increased precipitable water and condensed moisture in consequence of large evapotranspiration rate over the Asian monsoon regions and consequently the heating of the tropospheric atmosphere. Similarly, in the NANLH simulation, only 2℃ increases in the air temperature occur within the test area as well as over subtropical oceans of the Western Hemisphere because the North American continents occupy a relatively small area. It is inferred, therefore, that land-surface evapo-

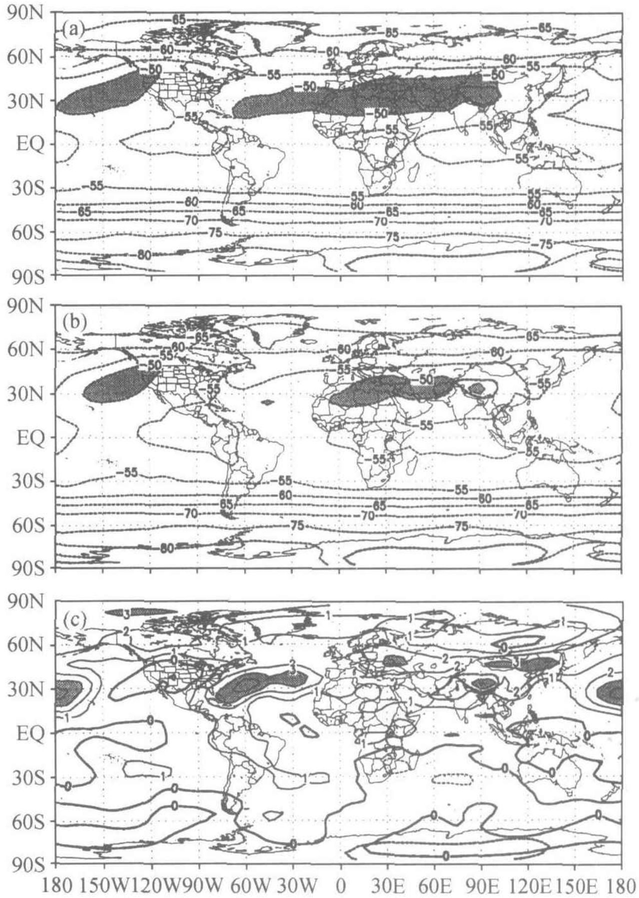

Fig. 2. Simulated July mean air temperature at 200 hPa for CTL run (a), ANLH run (b) and differences (CTL minus ANLH) (c). Dark dashed curves correspond to those in fig. 1.

transpiration during the boreal summer is an important factor controlling the changes in surface temperature and air temperature.

2.2 Impact on the rainfall

Fig. 3 shows that precipitation is generally augmented by 50%—90% over the East China but reduced to the south of the Indo-China Peninsula in the CTL minus ANLH difference (fig. 3(a)). Particularly the largest positive precipitation anomaly which becomes as high as +18.0 mm/d exhibits in the central and eastern part of the Qinghai-Tibetan Plateau. It also represents that these precipitation positive/negative anomalies are consistent with circulation variations (not shown), and correspondingly with the significant changes in the vertically integrated moisture flux convergence/ divergence (fig. 4). Similarly, in the SPCZ to the north of South America (fig. 3(b)), there is a noticeable positive precipitation anomaly with the maximum rate exceeding +10.0mm/d for the CTL run as compared with the NANLH run. In other words, the increased land-surface evapotranspiration transferring the large moisture to the atmosphere apparently contributed to this change; consequently, it exerted a pronounced impact on the hydrological budget and caused the surrounding circulation changes that led to changes in rainfall. From fig. 3(b) we can notice that the evapotranspiration anomaly over North American continents tremendously influenced the monsoon precipitation rate over the South Asia as well.

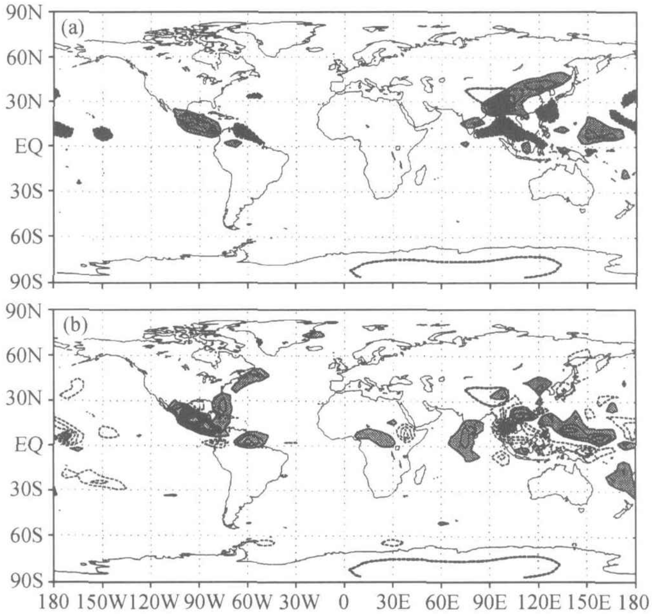

Fig. 3. July mean difference in precipitation as calculated by CTL minus ANLH (a) and CTL minus NANLH run (b), respectively. (a) Contour interval is 2 mm/d with light and heavy shades over 2 mm/d and below –2 mm/d, (b) 1 mm/d with light and heavy shades over 1 mm/d and below – 4 mm/d.

The results discussed above suggest that land-surface evapotranspiration changes are responsible for the summer monsoon rainbelt changes. Most notably over the massive Asian

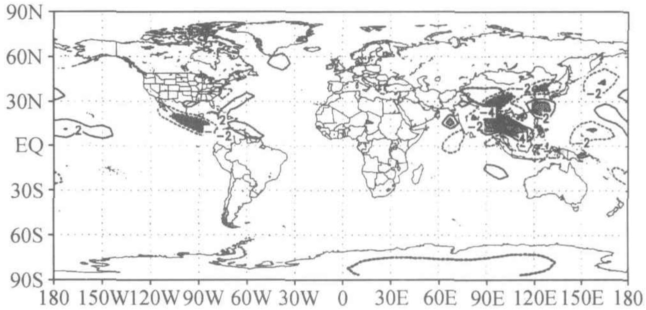

Fig. 4. July mean difference in vertically integrated moisture flux divergence for CTL minus ANLH. Dashed isohyets and dark dashed curves correspond to those in fig. 1. Interval in 2 mm/d. Light and dark shades show regions greater than 4 and below – 4 mm/d respectively.

continental area, the surface evapotranspiration plays a highly important role in the maintenance of the normal southwesterlies over the Indian subcontinent, thereby making the enhanced rainbelt stay over the Asian regions, especially over the most eastern part of China. Meanwhile, the Asian monsoon precipitation is also influenced by the evapotranspiration variations over North America and *vice versa*.

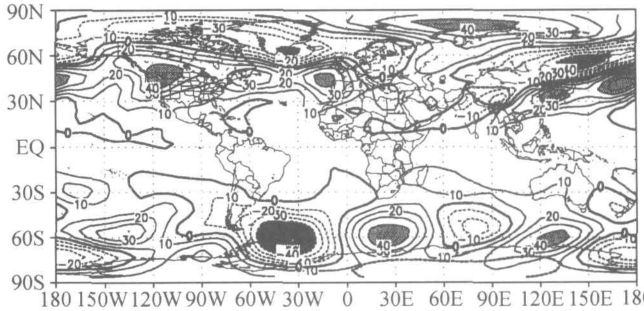

Fig. 5. July mean difference in geopotential height (in gpm) at 500 hPa for CTL minus ANLH run. Dark dashes correspond to those in fig. 1.

2.3 Impact on the subtropical high

The land-surface evapotranspiration has a profound impact on the variations in the subtropical anticyclones of the Northern Hemisphere, most notably over the Asian regions. If surface evapotranspiration over Asia has been cut off in the ANLH run, both the 500 hPa subtropical high in the western Pacific Ocean and 200 hPa South Asian high are reduced dramatically (figs. 5, 6(b)), with the minimum height anomalies as low as –40.0 and –80.0 gpm respectively (not shown). Wu et al.[10] examined the effects of the spatially heterogeneous heating on the formation of the subtropical high and found that vertically heterogeneous heating has at least one magnitude order larger than that of horizontally heterogeneous heating, and among these diabatic heating components, the latent heating ($\frac{\partial Q_{LH}}{\partial z}$) released by the deeply convective monsoon rainfall forces the South Asian high at 200 hPa on the western side of the heating centre and the western Pacific subtropical high at 500 hPa on the eastern side of the centre. Fig. 7(a)—(c) show the vertical cross-section of condensation

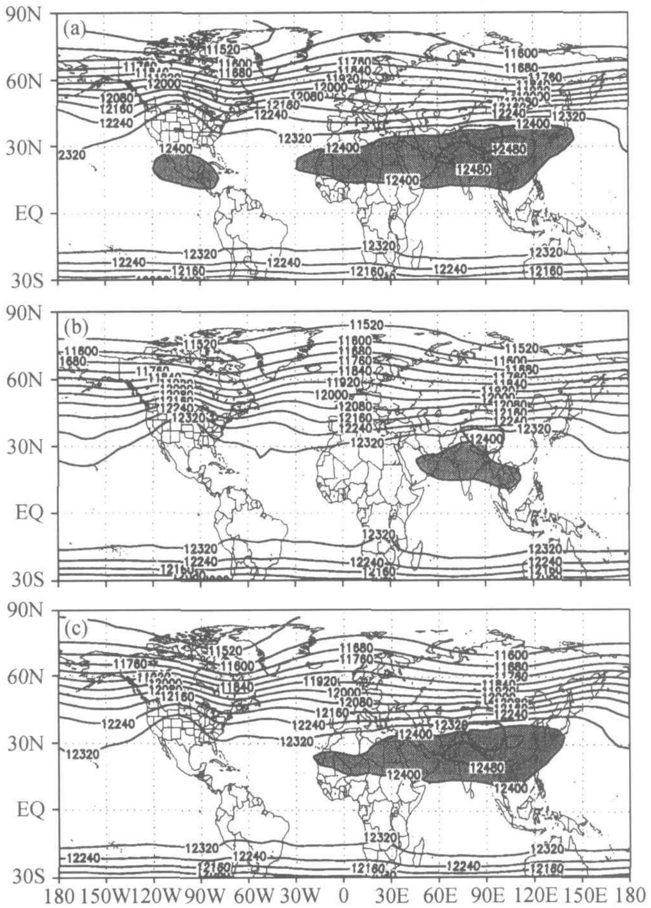

Fig. 6. Simulated July mean geopotential height (in gpm) at 200 hPa for CTL (a), ANLH (b) and NANLH run (c). Dark dashes correspond to those in fig. 1.

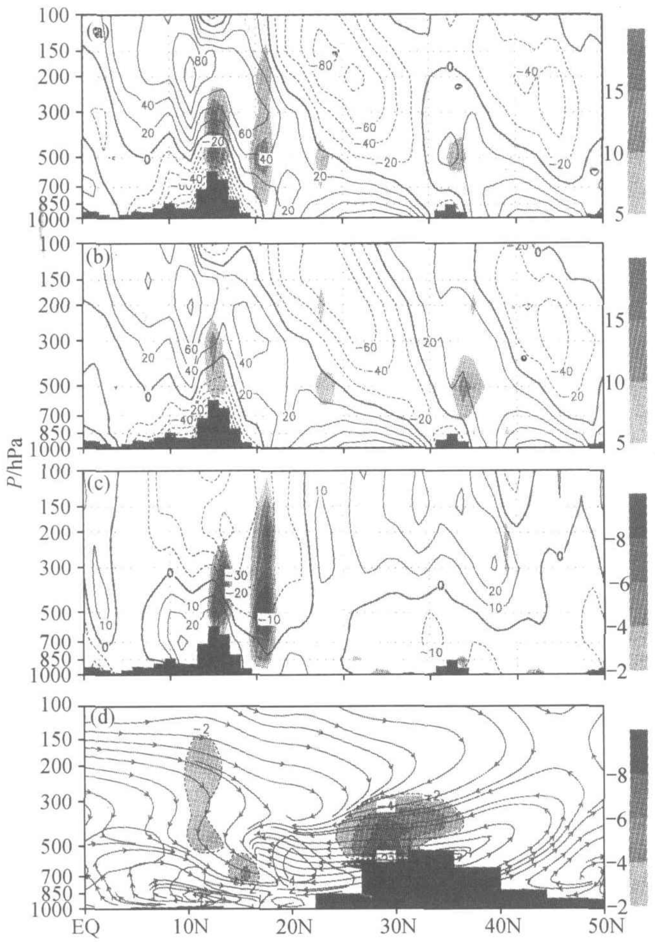

Fig. 7. July mean longitude-height cross-sections of zonally deviated geopotential height (in gpm) along 30°N for CTL (a), ANLH run (b) respectively, (c) the differences (ANLH minus CTL) and (d) the latitude-height cross-sections of the difference in the meridional mean cell along 90° E—105° E. Light, medium and dark shades are condensation heating rates (K/d) respectively. The black bar means orographic height along 30° N in (a)—(c) and along 90° E in (d).

heating and zonally deviated geopotential height along 30° N for the CTL and ANLH run and the difference (ANLH minus CTL) respectively. And fig. 7 (d) shows the vertical differences (ANLH minus CTL) in deep condensation heating along 90° N and the meridional mean cell along 90° E—105° E respectively. The vertical condensation heating rates are shaded in fig. 7. From the figure we see that the rainfall over East Asia regions was conspicuously reduced largely due to no land-surface evapotranspiration over the Asian land masses where the main heating sources for the global atmosphere are located. Correspondingly, much condensation heating released from the middle and upper levels is also substantially curtailed, i.e. $\frac{\partial Q_{LH}}{\partial z}$ was weakened. Therefore, the low (upper) level heating centre induced the reduction in the deviated southerlies (northerlies) (fig. 7(d)) and consequently the subtropical high due to the β-effect (fig. 7(c)). Meanwhile, in the case without evapotranspiration over Asia, both the 200 hPa and 500 hPa subtropical high over North America are also reduced apparently. These major changes reveal an equivalent- baratropic feature. This is presumably related to the propagation of Rossby waves and will not be further discussed in this paper beyond the reach of the aforementioned study.

In the case of no evapotranspiration over North America continent, the significant reductions in the Mexican high at 200 hPa are largely confined to the Western Hemisphere and slight changes in South Asian high compared to ANLH run because there is less condensation heating pertinent to the deeply convective monsoon rainfall over the North American regions than over the Asian monoon regions (fig. 6(c)).

Another most noteworthy feature demonstrated by fig. 8 is that the North Atlantic subtropical high at 1000 hPa was affected by the land-surface evapotranspiration over both Asia and North America, but largely opposite differences occurred for these two continents. The intensity of the subtropical high over the North Atlantic Ocean, for instance, was significantly weakened, and the maximum area was also reduced by about 25% in the ANLH run. This may be in large part related to a significant increase in the surface sensible heat flux along the eastern coast area of the North America and a concomitant decrease in the anticyclone circulation over the Pacific Ocean in consequence of the enhanced northerlies off the coast. Both the maximum area and intensity of the subtropical high in the North Atlantic Ocean, however, are augmented in the NANLH run mainly due to the substantial reduction in the surface sensible heat flux just on the eastern side of the North America (fig. 1 (c)).

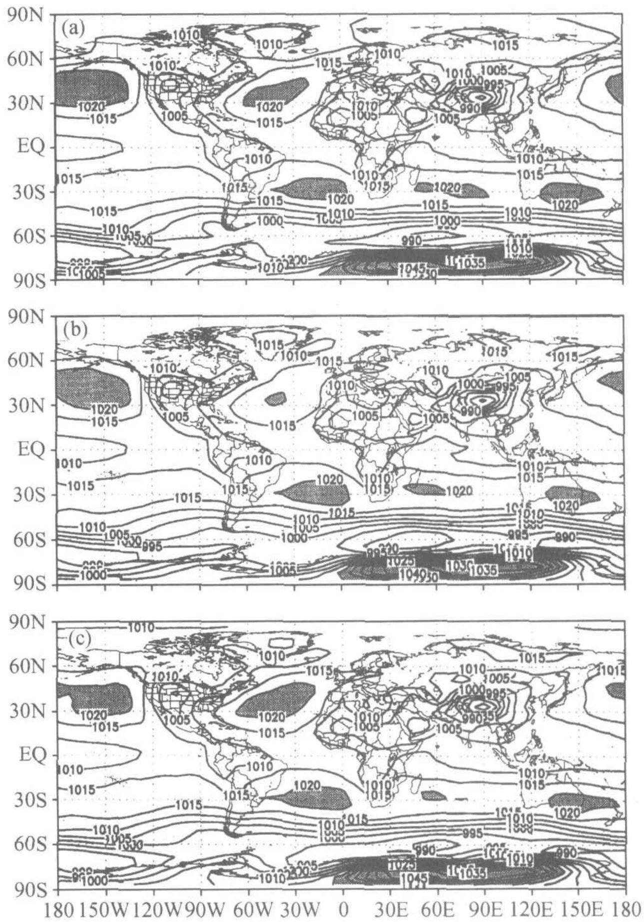

Fig. 8. Simulated July mean sea level pressure (hPa) for CTL (a), ANLH (b) and NANLH run (c). Dark dashes correspond to those in fig. 1.

3 Summary and conclusions

This is a sensitivity study to examine the effect on climate of the land surface evapotranspiration over Asian or North American continent using an atmosphere-biosphere model with realistic land surface processes (SSiB). All of these experiments reveal that the regional variation in land-surface evapotranspiration during the boreal summer had the largest impact on the precipitation, temperature and stream field and thus vindicate that the simulated climate had relatively large sensitivity to the land-surface evapotranspiration. The variations in the regional evapotranspiration at land surface would lead to significant effect on climate. Especially over the massive Asian continent, we have found that the removal of the land-surface evapotranspiration would bring about a significant increase in the surface temperature and sensible heat flux over much of the monsoon region and a decrease in the upper air temperature. Negative air temperature anomalies in the upper are not limited to the test region, but are dispersed on most of the Earth as well. This verified that main heating sources for global atmosphere lie in the Asian monsoon regions.

Meanwhile, the most intriguing feature is the tempiral and spatial variations in the precipitation rate. The precipitation decreases substantially over eastern China continent, where the rainbelt displays a zonal tendency, but increases over the Indo-China Peninsula and the eastern mainland in China. However, as compared with the ANLH simulation, the NANLH simulation represents corresponding, but not entirely counteracting, drops in the precipitation rates of the ITCZ and SPCZ over the north of the South America and the Indo-China Peninsula respectively. This suggests that climate would become warmer and drier to a certain degree. In addition, land surface evapotranspiration would exert considerable impacts on the formation and variation of subtropical anticyclones in the Northern Hemisphere. Particularly over the Asian continent, land surface evapotranspiration during boreal summer would produce reduction in the surface pressure and maintenance of the upper strong South Asian high at 200 hPa and the western Pacific subtropical high at 500 hPa through latent heating released by deeply convective monsoon precipitation as well as β-effect. This further confirmed the theoretical distribution of the effects of the spatially heterogeneous heating on the formation and variation of subtropical high[10]. Historically, we have generally emphasized on the influence of the subtropical anticyclones activities on the summer precipitation rates over the land regions of eastern China. However, we can infer from the experiments that the surface evapotranspiration anomalies would also exert noticeable impacts on the subtropical anticyclones through the changes in the monsoon precipitation, and thus cause the substantial variations in the atmospheric circulation over the Northern and even global Hemisphere.

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References

1. Peixoto, J. , Oort, A. H., Physics of Climate, Am. Inst. of Phys., New York: Woodbury, 1992, 520.
2. Shukla, J., Mintz, Y., The influence of land surface evapotranspiration on Earth's climate, Science, 1982, 215: 1498—1501.
3. Dickinson, R. E, Henderson-Sellers, A., Kennedy, P. J. et al., Biosphere-atmosphere transfer scheme (BATS) for the NCAR community climate model, Boulder, Colorado, NCAR/TN-275+STR, 1986, 69.
4. Dickinson, R. E., Henderson-Sellers, A., Kennedy, P. J., Biosphere-atmosphere transfer scheme (BATS1e) version 1e as coupled to the NCAR community climate model, NCAR Tech. Note NCAR/TN-387+STR, 1993, 72.
5. Sellers, P. J., Mintz, Y., Sud, Y. C. et al., A simple biosphere model (SiB) for use within general circulation models, J. Atmos. Sci., 1986, 43 (6): 505—531.
6. Xue, Y. K., Sellers, P. J., Kinter, J. L. et al., A simplified biosphere model for global climate studies, J. Clim., 1991, 4: 345—364.
7. Sun Lan, Wu Guoxiong , Sun Shufen, Numerical simulations of effects of land surface processes on climate—— Implementing of SSiB in IAP/LASG AGCM and its Performance, Acta Meteorologica Sinica (in Chinese), 2000, 58 (2): 179—193.
8. Wu Guoxiong , Zhang Huehong, Liu Hui et al., Global ocean-atmosphere-land system model of LASG (GOALS/LASG) and its performance in simulation study, Quarterly Journal of Applied Meteorology (in Chinese), 1997, 8 (Suppl.): 15—28.
9. Wu Guoxiong, Liu Hui, Zhao Y. C. et al, A nine-layer atmospheric general circulation model and its performance, Advanced in Atmospheric Sciences, 1996, 13 (1): 1—18.
10. Wu Guoxiong, Liu Yimin, Liu Ping, The effect of spatially nonuniform heating on the formation and variation of subtropical high I. scale analysis, Acta Meteorologica Sinica (in Chinese), 1999, 57(3): 257—263.