Simulated impacts of land cover change on summer climate in the Tibetan Plateau

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Received 17 December 2009
Accepted for publication 17 February 2010
Published 22 March 2010
Online at stacks.iop.org/ERL/5/015102

Abstract

The Tibetan Plateau (TP) is a key region of land–atmosphere interactions with severe eco-environment degradation. This study uses an atmospheric general circulation model, NCEP GCM/SSiB, to present the major TP summer climate features for six selected ENSO years and preliminarily assess the possible impact of land cover change on the summer circulation over the TP. Compared to Reanalysis II data, the GCM using satellite derived vegetation properties generally reproduces the main 6-year-mean TP summer circulation features despite some discrepancies in intensity and geographic locations of some climate features. Two existing vegetation maps with very different land cover conditions over the TP, one with bare ground and one with vegetation cover, derived from satellite derived data, are tested and produce clearer climate signals due to land cover change.

It shows that land cover change from vegetated land to bare ground decreases the radiation absorbed by the surface and results in weaker surface thermal effects, which lead to lower atmospheric temperature, as well as weaker vertical ascending motion, low-layer cyclonic, upper level anticyclonic, and summer monsoon circulation. These changes in circulation cause a decrease in the precipitation in the southeastern TP.

Keywords: land cover change, Tibetan Plateau, summer climate features, NCEP GCM/SSiB, land–atmosphere interaction

1. Introduction

With the most prominent and complicated terrain on the globe, the Tibetan Plateau (TP) is often called the ‘Third Pole’ because its geographic significance is akin to that of Antarctica and the Arctic (Qiu 2008). As a unique geomorphic unit, the TP plays an important role in forming and inducing variations of regional weather and climate in east and south Asia, as well as the Northern Hemisphere atmospheric circulation in general (e.g., Yeh and Gao 1979). The influence of the TP on climate has been extensively investigated using data from the First Global Atmospheric Research Program Global Experiment (FGEE), the Chinese Qinghai-Xizang (Tibet) Meteorological Experiment, Reanalyses data, and satellite data (e.g., Yanai et al 1992, Yanai and Wu 2006).

Evidence has recently indicated that there is serious land degradation caused by human induced land use changes in the TP (Jian 2000, Zou et al 2002). Alpine grassland occupies about 50% of the TP and the alpine grassland ecosystem has degraded significantly in association with global warming (IPCC 1996). Over the last 30 years, livestock numbers across the TP have increased more than 200% due to inappropriate land management practices (Du et al 2004). Zou et al (2002) found that desertified land was about 17.03% of the Tibet Autonomous Region’s total land, and was mainly over densely populated areas. The TP land degradation problem will influence the global climate changes, natural ecosystem, and human living environment (Yang et al 2005).
The impact of land cover change (LCC) on the regional and global climate has been extensively investigated by using the general circulation model (GCM) and regional climate model (RCM) coupled with land surface parameterization schemes (e.g., Xue and Schukla 1993, Pan et al 1999, Suh and Lee 2004). Land degradation in East Asia has significant impact on the local circulation and monsoon system (Xue 1996, Xue et al 2004, Cui et al 2006). For example, Xue et al (2004) found that land degradation could cause delayed monsoon onset.

However, quantitative evaluation of climate changes by LCC over the TP is a challenging task. Land cover data sets for the past are not available and realistic land surface data including land cover maps, vegetation phenology, and soil properties are very limited, which is more serious in eastern Asia than for any other region (Suh and Lee 2004). The only GCM study investigating the impact of the TP LCC thus far (Cui et al 2006) compared the results from a satellite derived vegetation map and a hypothetical non-anthropogenically-influenced vegetation cover. Nevertheless, Cui et al’s study indicated the important continental scale response due to a hypothetical LCC of the TP and demonstrated the necessity for further study.

In this study, we test two existing vegetation maps, with very different land cover conditions, over the TP: one specifies the TP as bare ground and the other as vegetation covered land. The idea is that if such a dramatic change in land cover does not produce any significant impact on the TP climate, then further investigation with more realistic data would be in vain. We also expect results from this study to provide useful guidance for future TP LCC studies, including the impact of future climate projection. This type of approach has yielded useful information in the Amazon (e.g. Shukla et al 1990), Sahel (e.g., Xue and Schukla 1993), and previous East Asian LCC studies (e.g. Yatagai and Yasumari 1995, Xue 1996, Fu 2003). Meanwhile, differently from Cui et al’s study (2006), our focus is mostly on the important TP climate features on the regional scale and the impact of LCC on them, which has never been the focus of a previous modeling study on TP land effect and is very relevant to this special issue.

To have a reasonable assessment of the LCC impact, reasonable TP climate simulation is a necessity. Due to the scarcity of vegetation data over the TP at both spatial and temporal scales, very coarse or even unrealistic vegetation conditions are used in many models, which would result in unrealistic energy and water transfer between the land and near-surface atmosphere (Friend and Kiang 2005).

With the development of remote sensing and retrieval methodology, we have more land data, such as satellite derived data, available for climate research (Kang et al 2007). They provide useful information for evaluating land surface characteristics and assessing the effect of land surface condition and its change on the climate. Buermann et al (2001) found that the usage of satellite derived LAI (referred to as RSLAI hereafter) in the National Center for Atmospheric Research (NCAR) GCM leads to an improvement in the near-surface temperature and precipitation simulations over certain regions. Kang et al (2007) used the RSLAI and other satellite derived land surface products in the NCEP GCM. Experimental results showed substantial improvements in the simulation of near-surface climate in the East Asian summer monsoon areas compared to the control experiment that used LAI extrapolated from limited ground surveys. The study of Yang and Toshio (2008) also shows that a satellite data-based system has a high potential for the reliable estimation of the regional surface energy budget over the Plateau.

The purposes of this letter are (1) to evaluate the state-of-the-art National Center for Environmental Prediction (NCEP) GCM’s ability to produce basic Tibetan climate features for the summer by using satellite derived vegetation products, which provide TP climate and state-of-the-art TP climate modeling information, a useful aspect of this special issue, and (2) to preliminarily assess the effects of LCC from the vegetated surface to bare ground (i.e., land degradation) in the TP and North China on the major Tibetan climate features in summer. The evaluation in the first part should provide a meaningful base for the assessment discussed in the second part.

In this letter, section 2 describes the GCM used in this study and the experimental design. The simulation results are discussed in section 3, including how LCC affects the summer climate features over the TP. Finally, concluding remarks are given in section 4.

2. Model description and experimental design

In this study, the NCEP GCM (Kalnay et al 1990, Kanamitsu et al 2002b) coupled with the Simplified Simple Biosphere Model (SSiB, Xue et al 1991) (NCEP GCM/SSiB) is used with 28 vertical levels and T62 (∼2°) horizontal resolution. SSiB provides fluxes of momentum, sensible, and latent heat, radiative skin temperature, and visible and near-infrared albedo for both direct and diffuse radiation to the GCM.

In NCEP GCM/SSiB, several vegetation properties are derived by using the satellite derived vegetation products—Fourier Adjusted, Sensor and Solar Zenith Angle Corrected, Interpolated, Reconstructed NDVI (FASIR-NDVI) for 17 years from 1982 to 1998 (Los et al 2000). This data set provides leaf area index (LAI), vegetation cover fraction (VCF), green leaf fraction, and surface roughness length. Meanwhile, the datasets explicitly account for atmospheric constituents and cloud frequency (Los et al 2000). Other parameters are provided by a vegetation table, which is derived from ground survey and satellite products (Dorman and Sellers 1989, Xue et al 1996). The simulation period of each experiment is 20 months starting on 1 January and ending on 31 August of the next year for 3 El Niño (1982/83, 1987/88, 1997/98) and 3 La Niña (1984/85, 1988/89, 1995/96) cases, which include many climate anomaly events on some continents. We use FASIR-NDVI datasets for the six specific cases after interpolation from 1° resolution to model grids. This letter presents the ensemble average of the second summer season (hereafter JJA) of the 6 yr cases, which is consistent with the results from the first JJA period but with clearer climatic signals. This experiment is referred to as the FASIR experiment. This global experiment has been reported by Kang et al (2007). We apply part of the results from simulations of this experiment for this TP
study. Kang et al (2007) pointed out that the FASIR-LAI was consistent with the field measurements, and the simulation of summer precipitation by GCM with FASIR have been improved in East Asia in general, compared to that of the GCM without application of satellite products. We expect the FASIR experiment to produce more accurate summer circulation over the TP. It should be pointed out some parts of the TP have snow cover all year (e.g. Pu et al 2007). Los et al (2000) and Tian et al (2004) have pointed out large errors would exist over snow cover regions when comparing AVHRR data with measurements at available sites. It has been identified that proper retrieval algorithms and the atmospheric corrections are crucial for obtaining an accurate land cover map (e.g. Gutman 1999). This study focuses on the TP warm season (from June–August) when snow cover is in its minimum over the TP.

To make a meaningful assessment of LCC impact, we have to evaluate the model’s performance first. Observed precipitation data as well as the NCEP/DOE (Department of Energy) Reanalysis II data (Reanalysis II) (Kanamitsu et al 2002a) are applied for this purpose. Observed precipitation was obtained from Asian Precipitation–Highly-Resolved Observational Data Integration Towards Evaluation of the Water Resources (APHRODITE’s Water Resources) (V0902) with 0.25° × 0.25° spatial resolution (http://www.chikyu.ac.jp/precip/index.html). The datasets are created primarily with data obtained from a rain-gauge observation network.

To assess the effects of TP land degradation on the major Tibetan summer climate features, two vegetation classification maps were used to provide the land surface conditions required by NCEP GCM/SSiB for comparison. Since we have no reliable land cover degradation information over that area, an idealized experiment was conducted and its rationale is discussed in section 1. In one experiment (referred to as
Case S1) a vegetation map is originally derived from a 1 km² spatial resolution global land cover map, which uses data for 1992–1993 from the Advanced Very High Resolution Radiometer (AVHRR) using a decision tree approach (Hansen et al 2000) (referred to as Satellite MAP). The vegetation map was aggregated to the GCM grid system by grouping the cover types into the 12 SSiB vegetation types (Xue et al 2001) and selecting the dominant type in each T62 cell (figure 1(a)). In another experiment (referred to as Case S2), the land cover classes were based on the vegetation and historical information regarding climate, biomes, ecoregions, and life zones and is presumed to represent potential vegetation (Kuchler 1983) and the land use database of Matthews (1984, 1985) (referred to as Kuchler MAP, figure 1(b))⁴.

There are significant differences between Satellite MAP and Kuchler MAP over the TP and North China. The Kuchler map classifies the area as desert, while the Satellite MAP identifies the central plateau as grasslands, needleleaf evergreen trees in the southeast plateau, and desert in part of the north-northwest plateau, which is more close to the real land condition (Chang 1981, Shi and Smith 1992). The change of surface vegetation types leads to changes in surface parameters, such as the LAI, albedo, the roughness length, vegetation root distribution, stomatal resistance, soil property, soil depth, and other variables (table 1).

In this LCC experiment, the GCM simulations consist of five month-long integrations from May to September with three different initial conditions. The results of NCEP GCM/SSiB runs with three different initial conditions were averaged to obtain ensemble means.

3. Impacts of LCC on summer circulation over the Tibetan Plateau

This section first evaluates the performance of NCEP GCM/SSiB, and then compares the climate features between Cases S1 and S2. A number of diagnostic and numerical studies have reported the major circulation features as well as heating in different seasons over the TP (e.g., Yeh 1950, Flohn 1957, Yeh et al 1957, Chen et al 1985, Yanai et al 1992, Yanai and Wu 2006). Sensible heat and latent heat release as well as radiation effects make the Tibetan Plateau a significant elevated heat source in summer, when a heat low dominates the planetary boundary layer and a large anticyclone is located in the upper troposphere over the plateau. During the summer three months (June–August), precipitation over the TP is characterized as weak and frequent (Ueno et al 2001).
Figure 3. JJA of 6 yr mean pressure vertical velocity ($10^{-2}$ Pa s$^{-1}$) (zonal mean removed) at 200 hPa (left) and 500 hPa (right). (a), (d) Reanalysis 2; (b), (e) NCEP GCM/SSiB; (c), (f) the difference between NCEP GCM/SSiB and Reanalysis 2.

Table 1. Major vegetation and soil parameters for three land surface classification types.

| Type            | Mean surface albedo | Roughness length (m) | Total soil depth (m) | Vegetation cover | Mean leaf area index |
|-----------------|---------------------|----------------------|----------------------|------------------|---------------------|
| Bare soil       | 0.32                | 0.01                 | 0.49                 | 0                | 0                   |
| Grass           | 0.23                | 0.07                 | 1.49                 | 0.9              | 3.0                 |
| Needleleaf trees| 0.15                | 1.10                 | 3.5                  | 0.75             | 6.0                 |

3.1. Evaluation of NCEP GCM/SSiB

Evaluation of the NCEP GCM/SSiB over the TP is focused on features at 500 hPa and 200 hPa, which represent the Tibetan circulation features at near-surface and upper levels, respectively. NCEP GCM/SSiB with satellite derived vegetation properties reproduces the major summer (JJA) meteorological features: compared to the same elevation above sea level, there is a high temperature center over the Tibetan Plateau in summer at both 200 and 500 hPa (figures 2(a), (b), (d) and (e)); the zonal geopotential height anomaly fields also show a high center at 200 hPa over the TP (figures 2(a) and (b)), consistent with the atmospheric temperature anomaly field, and a low center at 500 hPa (figures 2(d) and (e)) because there is a low surface temperature center over the TP due to its high altitude; there is wide-spreading ascending motion over the TP (figures 3(a), (b), (d) and (e))$^5$; at the upper level, the northern plateau is a westerlies region and the southern part is an easterlies region and a strong anticyclone exists (figures 4(a), (b), (d) and (e)). As the altitude decreases, the influence of lower layer cyclonic currents near the Indian Ocean increases gradually (not shown). At 500 hPa, a wide cyclone band extends from the central to west TP (figures 4(d) and (e)). Meanwhile, a negative vorticity center to the north of the anticyclone band is evident. There are two prime meridional circulation cells that move upward from the Tibetan Plateau in the summer (figures 5(a), (b), (d) and (e)): one is the cross-equatorial monsoon circulation cell subsiding at the Southern Hemisphere and the other is a smaller circulation cell subsiding at the north side of the Plateau.

There are, however, discrepancies between the simulation results and Reanalysis II data. The model results indicate that over the eastern TP the thermal heating effect is weaker (figures 4(c) and (f)), which could be caused by insufficient convective activity in the modeling process and/or upward

$^5$ Please note that the negative $P$-velocity indicates upward motion.
transportation of heat by mean upward currents to maintain high temperature and geopotential height. In the vast central and eastern TP, the modeling results show weaker ascending motion at 500 hPa than in the Reanalysis data (figure 3(f)). The stronger vertical ascending motion in the northwest of the plateau at 500 hPa, where water vapor concentration is high (not shown), enhances the upward heat transportation processes, resulting in larger latent heat release at middle levels and then higher geopotential height at lower and high levels (figures 2(c) and (f)). This plus the weaker ascending motion over the central and eastern TP result in the shift of the centers of simulated high temperature and geopotential height, as discussed above (figures 2(b) and (d)). As for the vorticity field, the NCEP GCM/SSiB simulates the anticyclonic center shifts to the northwest at about 80°E and 33°N (figure 4(b)). At the upper level, the model results show stronger zonal wind in the western TP and weaker zonal wind in the eastern part (figures 4(a) and (c)), consistent with the difference in the anticyclone center positions between GCM and Reanalysis II.

APHRODITE and NCEP GCM/SSiB show similar precipitation extent over the eastern part of the TP (figure 6). Both show no precipitation at 80°E and the northern TP boundary. However, APHRODITE shows no strong precipitation center within the TP; its precipitation gradient is much smaller than that of NCEP GCM/SSiB, which has a precipitation center in the southern TP, consistent with moisture convergence. In fact, Himalayan precipitation bands occur in the night due to the coupling of meso-scale circulation and monsoon flows, and it is apparent that GCM cannot reproduce those cloud formation process. The precipitation should be investigated further by RCMs with more a realistic meso-scale process. As to the precipitation center over the northwest TP, since this is a remote area lacking observational data, and latest observations reveal there may be an important moisture pathway (personal communication with Professor Tandong Yao of the Institute of Tibetan Plateau, Chinese Academy of Sciences, 2009), more observations are necessary for model validation on these aspects.

3.2. Impacts of LCC on the summer climate over TP

The possible impact of vegetation cover change is examined by a comparison of Case S2, using Kuchler MAP, and Case S1, using Satellite MAP (figure 1). Because the NCEP GCM/SSiB-simulated TP climate features have been discussed in a previous section, the following analysis focuses on the difference between Cases S1 and S2.

After changing the vegetation map and surface variables, the surface albedo is changed. Figure 7 shows that Case 2 has higher albedo, by 0.07 in the central TP and more than

![Figure 4](https://example.com/figure4.png)

**Figure 4.** JJA of 6 yr mean vorticity \(10^{-5} \text{s}^{-1}\) and wind \(\text{m s}^{-1}\) (zonal mean removed) at 200 hPa (left) and 500 hPa (right). (a), (d) Reanalysis 2; (b), (e) NCEP GCM/SSiB; (c), (f) the difference between NCEP GCM/SSiB and Reanalysis 2.
0.09 in the southeast part. The higher surface albedo in Case S2 decreases the net surface shortwave radiation. Changes in land surface conditions also alter the turbulence transfer between land surface and atmosphere and, thus, the surface water and energy balances. A substantial difference between Cases S2 and S1 is the lower surface sensible heat flux, by about 20–30 W m\(^{-2}\) in the central TP and by over 40 W m\(^{-2}\) in the southeast plateau (figure 8), consistent with lower net radiation. Sensible heat change has been shown to have substantial impact on the East Asian circulation. For instance, Xue et al (2004) shows that the vegetation induced sensible heat flux causes low level circulation turning and a jump of East Asian summer monsoon. Wu et al (2007) found that sensible heating on the sloping lateral surfaces appears to be the major driving source in regulating the surface Asian monsoon flow. Since the atmospheric circulations in summer over the TP are closely related to surface thermal forcing, in the following discussions, we further analyze the difference of summer circulation between Cases S1 and S2 caused by surface heating change due to vegetation cover change.

Figure 9 shows the difference of temperature and the mean geopotential height at 500 hPa (figure 9(a)) and 200 hPa (figure 9(b)) between Cases S1 and S2. The weaker surface heating in Case S2 over the TP results in lower temperature at 500 hPa than in Case S1. The strong cooling to the north of the TP is caused by the net radiation and evaporation change. The cold anomaly in Case S2 results in a negative geopotential height anomaly at 200 hPa (figure 9(b)) and weaker ascending motion (figures 9(c) and (d)) over the southeastern plateau. It should be pointed out that all the centers with large changes in temperature and vertical motion at 500 hPa (figures 9(a) and (c)) are located around 32°N and 95°E, which corresponds to the location of the large sensible heat flux difference between the two cases (figure 8) and substantial land cover and large albedo changes in the TP in Case S2 (figures 1(b) and 7(b)). Based on TP major climate features that we
discussed in previous sections, these consistencies indicate that the circulation changes over the TP in Case S2 are closely associated to the LCC over the TP. This phenomenon also illustrates the significant contribution of surface heating to the summer atmospheric circulation over the TP.

These anomalies in temperature and vertical motion weaken the low-layer cyclonic (figure 10(a)) and upper level anticyclonic circulations (figure 10(b)) over the southeastern TP in Case S2. The westerlies in the north of the eastern TP and the easterlies in the south of the eastern TP at upper levels are also weaker compared to those in Case S1 (figure 10(c)).

Both cases show similar meridional circulation patterns (figure 11). Here, we choose the circulation at 90°E as an example to illustrate the differences. For example, the two-cell type monsoon circulation and the small circulation cell that ascend at the TP and subside at its north side (90°E) are shown clearly in both cases (figure 11). The results at other longitudes are similar. But the strength of the monsoon circulation cell can be distinguished by the shaded area in the figure. The ascending currents greater than 10 m s⁻¹ at the southern plateau can reach up to 400 hPa in Case S1 (figure 11(a)), but only to 600 hPa in Case S2 (figure 11(b)).

The stronger ascending motion at the southern plateau in Case S1 can also be seen at different longitudes. At the lower levels (850 hPa) from 85°E to 105°E, the southerly wind blowing to the southern TP is also weaker in Case S2 than in Case S1 (figure 11). Such circulation differences favor a decrease in rainfall in summer over the central-southeastern TP in Case S2 (figure 12). LCC (from the present vegetated surface to bare ground) over the TP would result in a weaker summer monsoon circulation and lower precipitation.

4. Discussion and conclusions

The TP is a key region of land–atmosphere interactions (Yanai and Wu 2006, Xue et al. 2009). This study presents the major TP summer climate features and evaluates the possible effects of LCC from vegetated land to bare ground (i.e., land degradation) on the major Tibetan climate features in summer using NCEP GCM/SSiB with the application of satellite derived vegetation products.

The model reproduces the main circulation features in summer over the TP, compared to Reanalysis II data: the high temperature and ascending motion centers at both lower and upper atmosphere; the high geopotential height center and negative vorticity center at upper atmosphere and low
Figure 8. JJA difference of surface sensible heat flux (W m$^{-2}$) between Cases S2 and S1 in the TP.

Figure 9. JJA differences between Cases S2 and S1 over the TP in temperature ($^\circ$C) and geopotential height (gpm) at (a) 500 hPa; (b) 200 hPa; in vertical velocity ($10^{-2}$ Pa s$^{-1}$) at (c) 500 hPa; (d) 200 hPa.

diff.Temp and Geopotential Height of (Case S2–Case S1) (500hpa)

diff.Temp and Geopotential Height of (Case S2–Case S1) (200hpa)

diff vertical velocity of (Case S2–Case S1) (500hpa)

diff vertical velocity of (Case S2–Case S1) (200hpa)

The analyses reveal that the plateau acts as a heat source in the summer. In particular, the strong surface heating makes the air stratification very unstable and produces a cyclonic circulation, accompanied by strong air convergence.
and subsequent upward motion over the TP in the lower troposphere, and an anticyclonic circulation remains in the higher layers. There are, however, discrepancies between the model simulation and observation/Reanalysis II data, in the intensity and positions of these anomaly centers.

The effects of idealized land degradation on the TP summer circulation are preliminarily assessed by comparing Case S1 (Satellite MAP) and Case S2 (Kuchler MAP). It can be seen from the experiments that when grassland over the central TP and needleleaf evergreen trees in the southeastern TP have been dramatically degraded to desert, the surface albedo would be greatly increased by 7%–9%, which results in lower net radiation. Lower atmospheric temperature and sensible heat flux make the heat source weaker and the low level cycle also becomes weaker, leading to weaker vertical motion in the southern and eastern TP and weaker monsoon circulation. Therefore, precipitation decreases substantially in the central-southeastern TP. When more observed LCC data are available, further studies on the change of TP surface water and energy budget due to LCC should advance our understanding of LCC effect on the climate system in the TP and East Asia. The result in this study demonstrates that the impact on the major TP climate features could be substantial and provides useful reference for future more realistic studies. In addition, more observational data from large-scale field experiments, such as CEOP, along with satellite data should also help more realistic TP climate simulations.

It should be pointed out that the meso-scale feature is an important phenomenon over the TP. Xu et al (2001) and Wang et al (2003) suggested that the TP be an important source of convective cloud systems. GCM resolution...
is too poor to reproduce these local climate conditions, especially for the precipitation system. Regional or meso-scale models embedded within GCMs may be able to assess more realistically the consequences of LCC on local scales, especially when those occur with high spatial heterogeneity (Cui et al 2004). It is, however, also recognized that the final quality of the results from nested RCMs depends in part on the reality of the large-scale forcing provided by GCMs, because the RCM needs to impose the lateral boundary condition from GCM. Therefore, it is important to assess GCM’s ability and weakness in simulating the circulation features at regional and continental scales. Besides, the improper land model parameterization presented in models should also be further investigated when applying GCM and RCM over the TP (e.g., Takayabu et al 2001, Yang et al 2009).

Acknowledgments

This research was supported by (1) the US National Science Foundation grant NSF-ATM-0353606; (2) National Natural Science Foundation of China (Grant No. 40905039); (3) the National Basic Research Program of China Grant No. 2009CB421405; and (4) the National Natural Science Foundation of China (Grant No. 40730952)

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