Annals of Arid Zone 45(2): 129-138, 2006

CCM2 Modeling of the Effect of Tibetan Plateau on the Distribution of Arid and Semi-arid Areas and their Vegetation in East Asia

Xiongwen Chen[1,2] and Xin-Shi Zhang[2]

[1] *Center for Forestry & Ecology, PO Box 1927, Alabama A & M University, Normal, AL 35762, USA*

[2] *Laboratory of Quantitative Vegetation Ecology, Institute of Botany, Chinese Academy of Sciences, Beijing, 100093, P.R. China*

Abstract: Studying the causes for the unique distribution of arid and semi-arid areas in East Asia is important for land management and environmental restoration in this region. The distribution of arid and semi-arid areas and their associated vegetation in East Asia (15°N-60°N, 60°E-150°E) were constructed by Geographic Information System and the climatic data set produced by the CCM2 of NCAR with Tibetan Plateau and without Tibetan Plateau (the elevation was assumed to decrease to 1000 m and equal to its surroundings). If there were no Tibetan Plateau, the distribution of arid and semi-arid areas and their vegetation in East Asia would change significantly. The moist and semi-moist areas would increase by about 3.53% and 0.86%, respectively; but the semi-arid and arid areas would decrease by about 2.01% and 2.39%, respectively. The areas of Tropical Thorn Woodland, Warm Temperate Meadow, Subtropical Desert and Warm Temperate Desert would decrease dramatically. The area of Savannah (subtropical grass and scrub) would increase by about 139.7%. Tibetan Plateau has deeply influenced the distribution of arid and semi-arid areas in many surrounding countries. Western China and Mongolia would be less dry if there were no Tibetan Plateau.

Key words: Tibetan Plateau, arid and semi-arid areas, vegetation, East Asia.

The distribution of arid and semi-arid areas in East Asia is different in comparison to those in North America and North Africa (Hou, 1960; Troll, 1968). For example, in East Asia the arid and semi-arid areas are mainly situated at the latitude between 40°N and 45°N; however, it is distributed between 25°N and 35°N in North America and North Africa. In China the arid and semi-arid areas cover about 38.3% of the country area, and may expand under global climate change (Ci, 1994). Currently Western Developing Project is being carried out in arid and semi-arid regions (Jiang, 2000). It is, therefore, necessary to study the formation and evolution of this area. A previous research proposed that the unique distribution of arid and semi-arid areas in East Asia were mainly due to the rising of Qinghai-Xizhang (Tibetan) Plateau since 40 Ma (Zhang, 1998). It is true that the altitude of the Himalayas and the Tibetan Plateau influence many of the Earth's physical processes, including the South Asian monsoon (Weeks *et al.*, 1997; Thompson *et al.*, 2000). Although recent modeling study indicated that Tibetan Plateau had deep impact on the vegetation distribution in East Asia (Chen *et al.*, 2005), there is limited research on the arid and semi-arid areas in East Asia. The present study was carried out to find out the changes in the distribution of arid and semi-arid areas and their vegetation in East Asia in the absence of Tibetan Plateau (the elevation of the Tibetan Plateau was assumed to be 1000 m and equal to its surroundings). For the study a CCM2 (Community Climate Model II) of NCAR (National Center for Atmospheric Research) (Dickinson *et al.*, 1993; Hack *et al.*, 1993; Hack, 1994) was used to produce the climate data set with and without Tibetan Plateau. After that, the distribution of arid and semi-arid areas and their vegetation in East Asia based on climate indices (Hou, 1960) and the modified Holdridge life zone system was constructed (Li *et al.*, 1994; Zhang and Liu, 1994; Zhang *et al.*, 1996), and output produced by GIS.

Methods

Study area

The study area is within the latitude of 15°N to 60°N, and the longitude of 60°E to 150°E, covering about 37,514,840 km^2 area. About 20 countries are located in the region.

CCM2 of NCAR

The NCAR CCM2 was a primitive general circulation model in which variables are solved by the spectral method. In this model the spectral truncation is triangular, allowing 42 wave numbers in both horizontal dimensions. It corresponds to a grid increment of approximately 2.8 longitude by 2.8 latitude (128 by 64 points in the horizontal). There are 18 vertical levels in a hybrid sigma coordinate system, where sigma levels are used near the surface and blend into a pressure coordinate above. The top level is at air pressure of 2.917 hPa. The world surface temperatures are initial input into the model. The CCM2 includes a diurnal as well as a radiation cycle (Briegleb, 1992). Short wave radiation calculations use a delta Eddington approximation. The cloud fraction is calculated as a function of relative humidity, vertical motion, static stability, and convective precipitation rate. The parameterization of the planetary boundary layer (PBL) in CCM2 accounts for dry convection by adjusting non-local transport in the boundary layer (Holtslag and Boville, 1993). The parameterization calculates the PBL height, diffusion profiles and turbulent transport. A mass flux moist convective scheme is included in the model (Hack, 1994). The details of CCM2 can be found in Hack *et al.* (1993) and Bath *et al.* (1992). Briegleb (1992) discussed its sensitivity in radiation parameterizations, Hack (1994) on the convection scheme, Holtslag and Boville (1993) on boundary-layer diffusion, and Williamson and Rasch (1994) on semi-Lagrangian transport scheme. Various aspects of the simulated climate with prescribed climatological sea surface temperatures are described by Kiehl *et al.* (1994), cloud radiation forcings and feedbacks by Lee *et al.* (1997) and formulation for cloud liquid water by Hack (1998). In this study the time step is 20 minutes and the main parameters are listed in Table 1. After the elevation of Tibetan Plateau was decreased to 1000 m, the model continued to simulate for additional five years when the climate in the area reached almost static. The average climatic conditions during these five years were considered as the normal condition in this area without Tibetan Plateau.

Table 1. Main CCM2 field list (adapted from Bath et al., 1992)

Name	Description
PHIS	Surface geopotential
PS	Surface pressure
T	Temperature
U	Zonal wind component
V	Meridional wind component
Q	Specific humidity
TA01	Total advection of q
VD01	Q diffusion tendency
DC01	Q tendency from adjustment physics
DTH	T horizontal diffusion tendency
ORO	Surface type flag
WET	Surface wetness
SNOWH	Water equivalent snow depth
PRECL	Large-scale, stable precipitation
PRECC	Convective precipitation
SHFLX	Surface sensible heat flux
LHFLX	Surface latent heat flux
QFLX	Surface water flux
PBLH	PBL height
USTAR	Surface friction velocity
TPERT	PBL plume temperature perturbation
QPERT	PBL plume moisture perturbation
DTV	T vertical diffusion tendency
FSNS	Net solar flux at surface
FLNS	Net long wave flux at top
FSNT	Net solar flux at top
CLOUD	Cloud fraction
EFFCLD	Effective cloud fraction
FLNTC	Net clear-sky lon gwave flux at top
FSNTC	Net clear-sky solar flux at top
FLNSC	Net clear-sky longwave flux at surface
OMEGA	Vertical pressure velocity
DQP	Q tendency from rainout
TAUX	Zonal surface stress
TAUY	Meridional surface stress
SRFRAD	Net surface radiative flux
QRS	Solar heating rate
QRL	Longwave heating rate
CLDTOT	Total cloud cover
CLDLOW	Low cloud cover
CLDMED	Mid-cloud cover
CLDHGH	High cloud cover
TS1	Surface temperature (level 1)
TS2	Sub-surface temperature (level 2)
TS3	Sub-surface temperature (level 3)
TS4	Sub-surface temperature (level 4)
SOLIN	Solar insulation
UTGW	Gravity wave drag u tendency
VTGW	Gravity wave drag v tendency
TAUGWX	Gravity wave drag zonal surface stress
TAUGWY	Gravity wave drag meridional surface stress
DTCOND	T tendency from adjustment physics
CMFDT	T tendency from moist convection
CMFDQ	Q tendency from moist convection
CMFMC	Total convective mass flux
CMFSL	Convective static energy flux
CMFLQ	Convective total water flux
CNVCLD	Convective cloud fraction
TG	Soil surface temperature at 00z
TGA	Soil surface temperature averaged over history
TSW	Total soil water (upper three layers) at 00z (3000 over ocean)
RSW	Root zone soil water (upper two layers) at 00z (3000 over ocean)
SSW	Water in upper soil layer at 00z (30 over ocean)
LDEW	Depth of water on foliage at 00z
IRCP	Rate of precipitation intercepted by foliage minus dew drop, averaged over history
SAG	Snow-aging factor at 00z
RNO	Total runoff averaged over history
RNOS	Surface runoff averaged over history
SCV2	Water equivalent snow cover at 00z
EVPR	Latent heat flux upward from surface, averaged over history

RH2O	Ratio of excess moisture in total soil above wilting point to the field capacity of the root zone soil layer at 00z (0.2 over ocean)
SKIN	Skin temperature averaged over history
FLUX1	Heat flux from subsurface to surface soil layer
FLUX2	Heat flux from permafrost to second soil layer
TSA	1.5 m height air temperature averaged over history
TLEAF	Leaf temperature averaged over history
SENT	Sensible heat flux upward from surface, averaged over history
TMAX	Maximum 1.5 height air temperature over history
TMIN	Minimum 1.5 m height air temperature over history
SLWD	Surface downward long wave flux

Classification of moist and arid areas

The whole area was divided into four typical areas (Table 2) according to the climate conditions (Hou, 1960). Annual potential evapotranspiration ratio (PER) is the first factor to consider.

Holdridge Life Zone system

Holdridge held that the natural vegetation in a large area could be determined objectively by local climate (Holdridge, 1947; 1967). He defined 39 life zones using three climatic parameters: biotemperature (Bt), mean annual precipitation and PER.

Table 2. Climate indices of moist and arid areas in East Asia

Classification	Annual precipitation (mm)	Annual PER
Moist area	>500	<1.0
Semi-moist area	350-500	1.0-1.5
Semi-arid area	150-350	1.5-4.0
Arid area	<150	>4.0

Biotemperature was defined as the mean of monthly (or daily) positive temperature (t). PER was the ratio of evapotranspiration to mean annual precipitation (P). The equations were listed as follows.

$$Bt = 1/12\sum t \qquad (t>0)$$

$$PER = 58.93 \times Bt/P$$

To improve the agreement between the map modeled by Holdridge Life Zones system and the real distribution of arid and semi-arid areas in China, the Holdridge Life Zone was modified and aggregated into 7 large units (Table 3) (Li *et al.*, 1994; Zhang and Liu, 1994; Zhang *et al.*, 1996).

Simulation procedure

(i) CCM2 of NCAR was used to produce climate data set including mean monthly air temperature, precipitation, etc., at resolution of 0.5° latitude x 0.5° longitude with the current elevation of Tibetan Plateau.

(ii) The above climate data set was used to produce the distribution of arid and semi-arid areas and their vegetation in the study area by climate indices and the modified Holdridge Life Zone system, respectively. The final maps were taken out by ARC/INFO 8.1.

(iii) Comparison between the modeled vegetation distribution in the arid and semi-arid areas by the modified Holdridge Life Zone system and the real distribution in the region from world vegetation map (The Times Atlas of the World Comprehensive Edition, 1977) was made by Kappa statistic (Monserud and Leemans, 1992).

Table 3. The scheme for aggregating the Holdridge Life Zones in the arid and semi-arid areas used in this study

Vegetation	Annual PER	Biotemperature
Tropical Thorn Woodland	3.0-12.0	24.0-36.0
Savannah (Grass and Scrub)	1.5-12.0	17.0-26.0
Warm Temperate Meadow	3.0-16.0	3.0-17.0
Tropical Desert	12.0-32.0	24.0-36.0
Subtropical Desert	3.6-16.0	17.0-27.6
Warm Temperate Desert	1.7-16.0	3.0-17.0
Cold Desert	1.0-2.0	1.5-3.0

(iv) CCM2 of NCAR was used to produce climate data set at 0.5° latitude x 0.5° longitude, with the elevation of 1000 m for the whole Tibetan Plateau.

(v) The climate data of (iv) was used to produce the distribution of arid and semi-arid areas and their vegetation without Tibetan Plateau.

(vi) The change of the modeled distribution of arid and semi-arid areas and their vegetation without Tibetan Plateau was assessed.

Results

Change in arid and semi-arid areas

Without Tibetan Plateau (or when its elevation is reduced to only 1000 m) the moist and semi-moist areas would increase by about 3.53% and 0.86% (Table 4), respectively. However, the semi-arid and arid areas would decrease by about 2.01% and 2.39%, respectively. The arid and semi-arid areas located at about 45°N and between 80°E and 105°E would be replaced by moist area (Figs. 1 and 2). The arid and semi-arid areas located at 15°N-30°N, 75°E-90°E and 30°N-50°N, 60°E-75°E would decrease. However, the arid and semi-arid areas would increase between 30°N and 45°N and in 75°E to 90°E.

Agreement between the modeled vegetation map in arid and semi-arid areas and the current vegetation distribution

Kappa statistic was used to test the agreement between modeled vegetation map of arid and semi-arid areas with the real elevation of Tibetan Plateau (Fig. 3) and the world vegetation map in the study area.

Table 4. The coverage and its change for the area of moist and arid land with and without Tibetan Plateau

Classification	Percentage of whole area with the original elevation	Percentage of whole area without the Tibetan Plateau	Increased percentage
Moist area	53.22	56.76	3.53
Semi-moist area	5.26	6.11	0.86
Semi-arid area	9.01	7.00	-2.01
Arid area	2.87	0.48	-2.39

Table 5. Area change of different vegetation of arid and semi-arid areas in East Asia if without Tibetan Plateau

Vegetation	Vegetation area with the Tibetan Plateau (km^2)	Vegetation area without Tibetan Plateau (km^2)	Increased ratio (%)
Tropical Thorn Woodland	249268	7789.626	-96.9
Savannah (subtropical grass and scrub)	451798.3	1082758	139.7
Warm Temperate Meadow	373902	7789.626	-97.9
Tropical Desert	0*	0*	0*
Subtropical Desert	786752.2	225899.2	-71.3
Warm Temperate Desert	1246340	654328.6	-47.5
Cold Desert	0*	0*	0*

* Limited area having resolution of 0.5° latitude x 0.5° longitude.

Kappa coefficient was 0.488, and the degree of agreement was fair (Monserud and Leemans, 1992).

Area change of different vegetation types

Without Tibetan Plateau (or when its elevation was 1000 m) the area of Tropical Thorn Woodland, Warm Temperate Meadow, Subtropical Desert and Warm Temperate Desert would decrease dramatically (Table 5). However, the area of Savannah (subtropical grass and scrub) would increase by about 139.7%.

Distribution change

Without the Tibetan Plateau (or when its elevation is 1000 m) the Warm Temperate Desert and Warm Temperate Meadow situated at 40°N-45°N, 70°E- 105°E and 30°N-40°N, 60°E-75°E would disappear (Figs. 3 and 4), but the area of Warm Temperate Desert would enlarge at 30°N-40°N and 75°E-90°E. The Subtropical Desert at 15°N-30°N and 60°E-75°E would be partially replaced by Savannah, which would enlarge in this area. Tibetan Plateau would affect the vegetation distribution in arid and semi-arid areas in many countries of East Asia.

Discussion

There are many definitions of arid and semi-arid areas (e.g., Hou, 1960; INCD, 1994), but generally arid areas must have more evapotranspiration than precipitation. Therefore, the simple annual potential evapotranspiration ratio (annual potential evapotranspiration/precipitation) is used in the research studies.

Without Tibetan Plateau the moist and semi-moist areas would increase, but the semi-arid and arid areas would decrease in East Asia. Tibetan Plateau has indeed influenced the general circulation, such as the western flow and South Asia Monsoon (Zeitle *et al.*, 1993; Zhang, 1998), and is crucial to the formation of arid and semi-arid areas in China, Mongolia, India, Pakistan, Nepal and several countries in Middle Asia. Without the Tibetan Plateau the annual precipitation at Baotou (40.40°N, 109.51°E) of Inner-Mongolia Auto- government State and Kelamayi (45.36°N, 84.51°E) of Xingjiang Auto-government State in

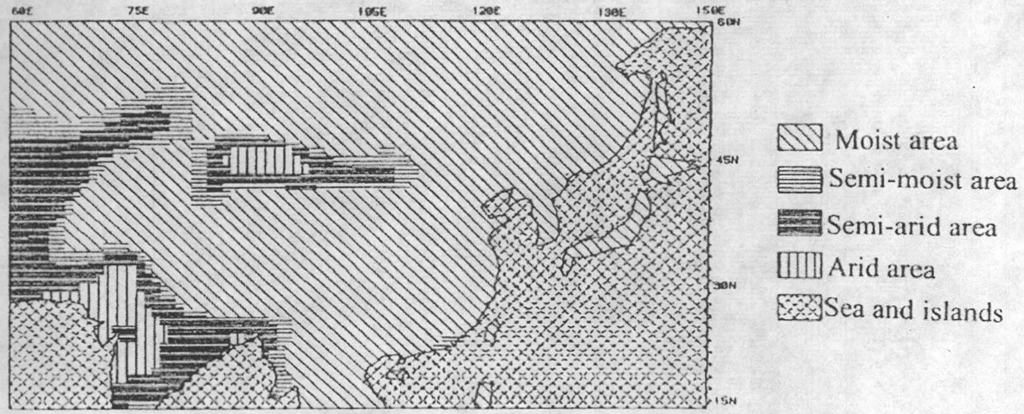

Fig. 1. Distribution of moist and arid areas in East Asia with original elevation of Tibetan Plateau.

western China would increase from about 686 mm to 1082 mm and from 451 mm to 789 mm, respectively.

It is necessary to validate the modeled vegetation map with the real vegetation map in the study area. We assumed that the vegetation map from The Times Atlas of the World could effectively represent the real vegetation map in this area. Since vegetation classification in later map has slight difference from the former one, we modified the later according to the Holdridge Life Zone system and its geographical position. The Kappa statistic was used to test the agreement between the two maps. After calculation of the Kappa coefficient, the degree of agreement for the modeled

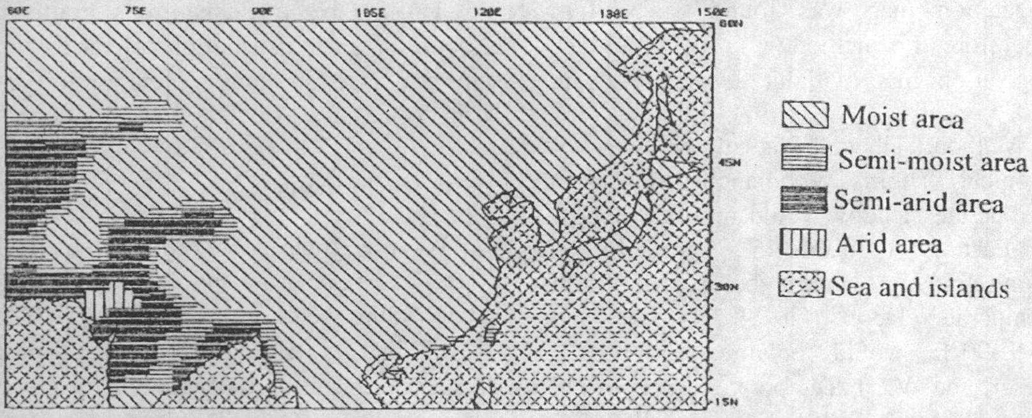

Fig. 2. Distribution of moist and arid areas in East Asia without Tibetan Plateau (the elevation of Tibetan Plateau were 1000 m).

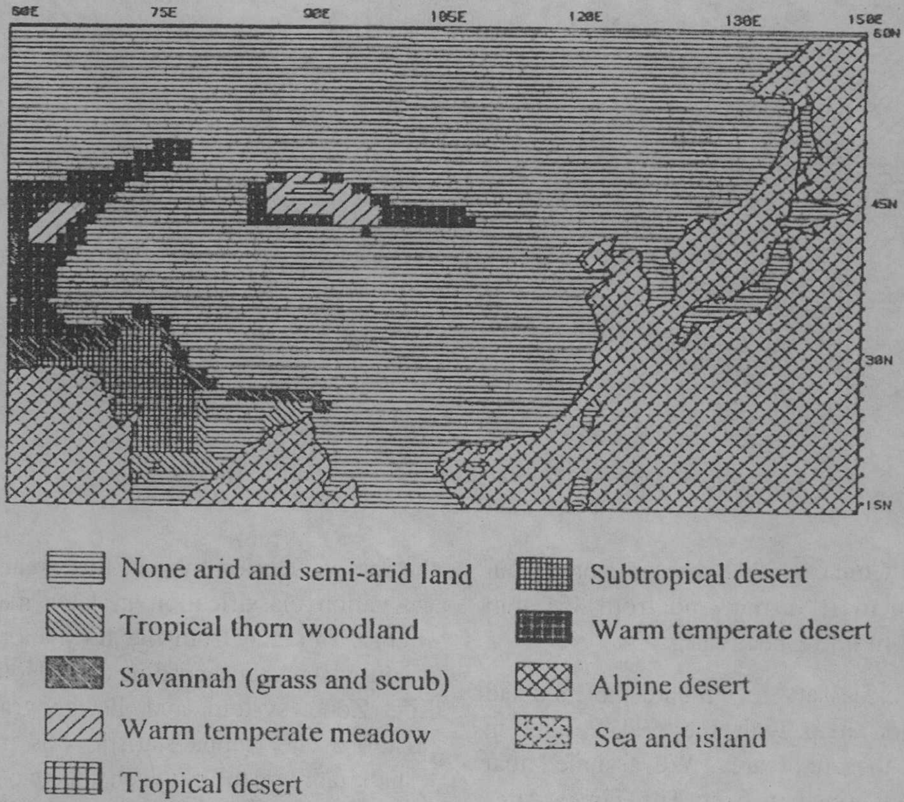

Fig. 3. Modeled distribution of vegetation in arid and semi-arid areas of East Asia with the original elevation of Tibetan Plateau.

vegetation map was found to be fair. Therefore, this method was used to produce vegetation map without Tibetan Plateau.

Without Tibetan Plateau the areas of Tropical Thorn Woodland and Warm Temperate Meadow would almost disappear in East Asia (Table 5), especially in Mongolia (Fig. 4). But the area of Warm Temperate Desert at 30°N-40°N and 75°E-90°E would enlarge. Subtropical Desert and Warm Temperate Desert would decrease dramatically. However, the area of Savannah (Subtropical Grass and Scrub) would increase by about 139.7%, especially in India and Pakistan.

Thus, Tibetan Plateau has dramatic effects on the distribution of arid and semi-arid areas and their vegetation in East Asia.

Acknowledgments

We are grateful to Professor Zongci Zhao, Dr. Yong Luo and Yanhong Dang for providing the climate data set of NCAR CCM2 and Dr. B-L Li for suggestions. This research was partially funded by China National Key Basic Research Program (G1999043507), Key Project of the Chinese Academy of Sciences (K2951-B1-108), and the School of Agricultural and

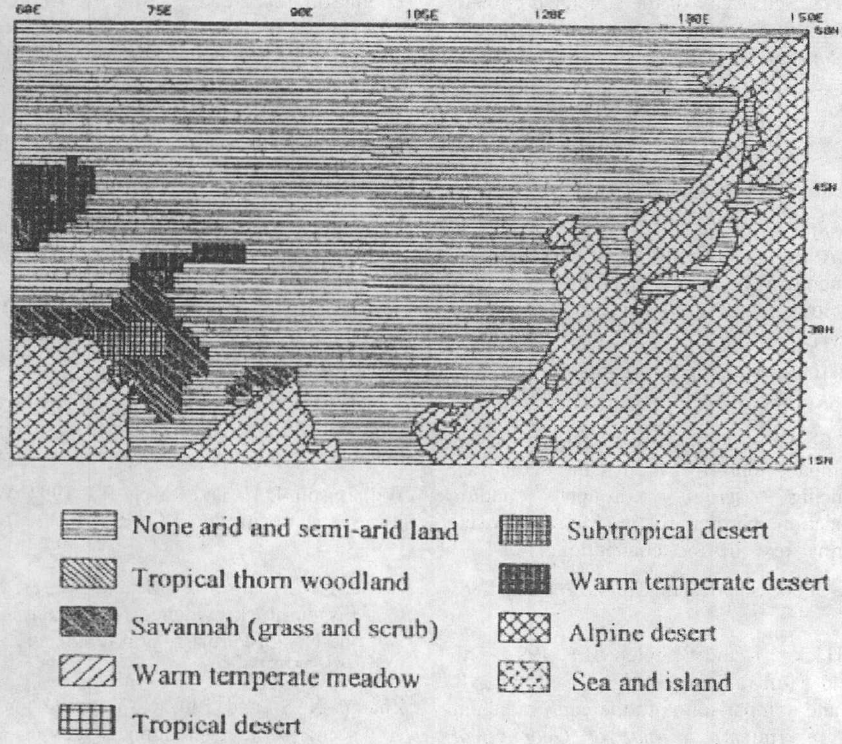

Fig. 4. Modeled distribution of vegetation in arid and semi-arid areas of East Asia without Tibetan Plateau (the elevation of Tibetan Plateau was 1000 m).

Environmental Sciences of Alabama A & M University.

References

Bath, L.M., Rosinski, J. and Olson, J. 1992. User's guide to NCAR CCM2. NCAR Tech. Note NCAR/TN-379+IA. National Center for Atmospheric Research, Boulder, CO, 156 pp.

Briegleb, B.P. 1992. Delta-Eddington approximation for solar radiation in the NCAR Community Climate Model. *Journal of Geophysical Research* 97: 7603-7612.

Chen, X., Zhang, X.-S. and Li, B.-L. 2005. Influence of Tibetan Plateau on vegetation distributions in East Asia: a modeling perspective. *Ecological Modelling* 181: 79-86.

Ci, L.J. 1994. The impact of global change on desertification in China. *Chinese Journal of Natural Resources* 9: 289-303.

Dickinson, R.E., Henderson, S.A. and Kennedy, P.J. 1993. Biosphere atmosphere transfer scheme (BATS) version 1e as coupled to the NCAR Community Climate Model. NCAR Tech. Note, NCAR/TN387+STR. National Center for Atmosphere Research, Boulder, Colorado.

Hack, J.J. 1994. Parameterizations of moist convection in the National Center for Atmospheric Research community climate model (CCM2). *Journal of Geophysical Research* 99: 5551-5568.

Hack, J.J., Boville, B., Briegleb, B., Kiehl, J., Rasch, P. and Williamson, D. 1993. *Description of the NCAR Community Climate Model* (CCM2). NCAR Tech. Note, NCAR/TN-382+STR. National Center for Atmosphere Research, Boulder, Colorado.

Hack, J.J. 1998. Sensitivity of the simulated climate to a diagnostic formulation for cloud liquid water. *Journal of Climate* 11: 1497-1515.

Holdridge, L.R. 1947. Determination of world plant formations from simple climatic data. *Science* 105: 367-368.

Holdridge, L.R. 1967. *Life Zone Ecology*. Tropical Science Center, San Jose, Costa Rica.

Holtslag, A.A.M. and Boville, B.A. 1993. Local versus nonlocal boundary layer diffusion in a global climate model. *Journal of Climate* 6: 1825-1841.

Hou, X.-Y. 1960. *Vegetation of China*. People's Education Press, Beijing, China.

INCD 1994. Elaboration of international convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in Africa. Revised negotiating text of the convention.

Jiang, Z.-M. 2000. Science in China. *Science* 288: 2317.

Kiehl, J.T., Hack, J.J. and Briegleb, B.P. 1994. The simulated earth radiation budget of the NCAR CCM2 and comparison with the earth radiation budget experiment. *Journal of Geophysical Research* 99: 20815-20827.

Lee, W.-H., Iacobellis, S.F. and Somerville, R.C.J. 1997. Cloud radiation forcings and feedbacks: general circulation model tests and observational validation. *Journal of Climate* 10: 2479-2496.

Li, X., Zhang, X.-S. and Yang, D.-A. 1994. Modeling Chinese vegetation response to global change applying Holdridge's Life Zones system. In *Global Change and Ecosystems* (Ed. X.-S. Zhang), pp. 1-16. The Printing House of Shanghai Science and Technology, Shanghai, China.

Monserud, R.A. and Leemans. R. 1992. Comparing global vegetation maps with the Kappa statistic. *Ecological Modelling* 62: 275-293.

The Times Atlas of the World Comprehensive Edition. 1977. Times Books in collaboration with John Batholomew & Son Limited. Plate 5.

Thompson, L.G., Yao, T., Mosley, T.E., Davis, M.E., Henderson, K.A. and Lin, P.-N. 2000. A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores. *Science* 289: 1916.

Troll, C. 1968. The Cordilleras of the tropical Americas. Aspects of climatic, physiogeographical and agrarian ecology. Colloquium Geographicum. Band 9. In *Geoecology of the Mountains Regions of the tropical Americas* (Ed. C. Troll), pp. 15-56. Proceedings of the UNESCO Mexico Symposium 1966.

Weeks, E.R, Tian, Y., Urbach, J.S., Ide, K., Swinney, H.L. and Ghil, M. 1997. Transitions between blocked and zonal flows in a rotating annulus with topography. *Science* 278: 1598.

Williamson, D.L., and Rasch, P.J. 1994. Water vapor transport in the NCAR CCM2. *Tellus* 46A: 34-51.

Zeitle, P.K., Johnson, N.M. and Naeser, C.W. 1993. Fission-track evidence for Quaternary uplift of the Nanga Parbat region, Pakistan. *Nature* 298: 255-257.

Zhang, X.-S. and Liu, C.-Y. 1994. A predictive scenario of vegetation changes on the Tibetan Plateau under global change conditions. In *Global Change and Ecosystems* (Ed. X.-S. Zhang), pp. 17-26. The Printing House of Shanghai Science and Technology, Shanghai, China.

Zhang, X.-S., Yang, D.-A., Zhou, G.-S., Liu, C.-Y. and Zhang, J. 1996. Model expection of impacts of global climate change on biomes of the Tibetan Plateau. In *Climate Change and Plants in East Asia* (Eds. K. Omass, K. Kai, H. Taoda, Z. Uchijima and M. Yoshino), pp. 25-38. Springer-Verlag, Tokyo.

Zhang, X.-S. 1998. The rising of Tibetan Plateau and the difference of vegetation distribution in Asia. In *Formation, Evolution and Development of Qinghai-Xizang (Tibetan) Plateau* (Eds. M.-C. Tang, G.-D. Cheng and Z.-Y. Lin), pp. 213-230. Guangdong Science & Technology Press, Guangzhou, China.