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Atmospheric boundary layer characteristics and land−atmosphere energy transfer in the Third Pole area

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Abstract The Tibetan Plateau and nearby surrounding area (the Third Pole area) dramatically impacts the world's environment and especially controls climatic and environmental changes in China, Asia and even in the Northern Hemisphere. Supported by the Chinese Academy of Sciences (CAS) and some international organizations, the Third Pole Environment (TPE) Programme is now under way. First, the background of the establishment of the TPE, the establishment and monitoring plans on long-term for the TPE and six comprehensive observation and study stations are introduced. Then the preliminary observational analysis results on atmosphere−land interaction are presented. The study on the regional distribution of land surface heat fluxes is of paramount importance over the heterogeneous landscape of the Third Pole area. A parameterization methodology based on satellite and *in situ* data is described and tested for deriving the regional surface heat fluxes (net radiation flux, soil heat flux, sensible heat flux and latent heat flux) over the heterogeneous landscape. As a case study, the methodology was applied to the whole Tibetan Plateau area. Eight images of MODIS data and four images of AVHRR data were used for the comparison among winter, spring, summer and autumn, and the annual variation analyses. The derived results were also validated by using the ''ground truth'' measured in the stations of the TPE. The results show that the derived surface heat fluxes in the four different seasons over the Tibetan Plateau area are in good agreement with the ground measurements. The results from AVHRR were also in agreement with MODIS. It is therefore concluded that the proposed methodology is successful for the retrieval of surface heat fluxes using the MODIS data, AVHRR data and *in situ* data over the Tibetan Plateau area.

Key words atmospheric boundary layer characteristics; land−atmosphere energy transfer; Third Pole; TPE

INTRODUCTION

The Third Pole area (the Tibetan Plateau and nearby surrounding areas; Qiu, 2008) is drawing increased attention among the international academic community. It is centred on the Tibetan Plateau, stretching from the Pamir Plateau and Hindu-Kush on the west to the Hengduan Mountains on the east, and from the Kunlun and Qilian mountains in the north to the Himalayas in the south, covering over 5 000 000 km^2 in total and with an average elevation surpassing 4000 m. Because of topographic character of the Tibetan Plateau, its surface absorbs a large amount of solar radiation energy, and undergoes dramatic seasonal changes of surface heat and water fluxes (Ye and Gao, 1979; Ye and Wu, 1998; Ma *et al*., 2006, 2011). The Third Pole region is also home to thousands of glaciers in the tropical/sub-tropical region that exert a direct influence on social and economic development in the surrounding regions of China, India, Nepal, Tajikistan, Pakistan, Afghanistan and Bhutan. It is subject to influences from multiple climatic systems, the complicated geomorphology and various internal and external geological impacts. The result is a region with unique interactions between the atmosphere, cryosphere, hydrosphere and biosphere. In particular, the special atmospheric processes and active hydrological processes formed by glaciers, permafrost and persistent snow are especially influential, as are the ecosystem processes acting at multiple scales. These processes compose the fundamental basis for the unique geographical unit of the Third Pole area. The area demonstrates considerable feedbacks to global environmental changes, while interacting with and affecting each other in response to global environmental variations.

Supported by the Chinese Academy of Sciences (CAS) and some domestic and international organizations, the Third Pole Environment (TPE) Programme is now being implemented. The general goal of the TPE is to attract relevant research institutions and academic talent to focus on a theme of water–ice–air–ecosystem–human interaction in the TPE, to reveal the environmental change processes and mechanisms of the Third Pole and their influences and regional responses to global changes, especially of monsoon systems, and thus to serve the enhancement of human adaptation to the changing environment and realization of human–nature harmony.

The study on atmosphere–land interaction is one of the most important parts in the TPE. Therefore, in this paper the establishment and monitoring plan for the long-term scale of the TPE and six comprehensive atmosphere–land interaction stations will be introduced first. Then the preliminary observational analysis results of atmosphere–land interaction will also be presented. The study on the regional distribution of land surface heat fluxes is of paramount importance over heterogeneous landscape of the Third Pole region. A parameterization methodology based on satellite and *in situ* data will also be described and tested for deriving the regional surface heat fluxes over the heterogeneous landscape of the Tibetan Plateau.

ATMOSPHERE–LAND INTERACTION OBSERVATIONS IN THE TPE

There will be 23 comprehensive observation and research stations in the TPE (Fig. 1). Eleven of them will be managed by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITP/CAS). They will be configured for the study of atmosphere–land interaction. The six constructed stations are: Nam Co Station for Multi-sphere Observation and Research (NAMORS, 30.46°N, 90.59°E; elevation: 4730 m; land-cover: sparse meadow), Qomolangma Station for Atmospheric and Environmental Observation and Research (QOMS, 28.21°N, 86.56°E; elevation: 4276 m; land-cover: sparse grass-Gobi), Southeast Tibet Station for Alpine Environment Observation and Research (SETS, 29.77°N, 94.73°E; elevation: 3326 m; land-cover: grass land), Ngari Desert Observation and Research Station (NADORS, 33.39°N, 79.70°E; elevation: 4270 m land-cover: grassland), Muztagh Ata Westerly Observation and Research Station (MAWORS, 38.41°N, 75.05°E; elevation: 3650 m; land-cover: sparse grass-Gobi desert**)** and Naqu Station (Naqu, 31.37°N, 91.90°E; elevation:4509 m; land-cover: sparse meadow). Qangtang Plateau Station, Metog Station, Sino-Tajikistan joint station, Sino-Pakistan joint station and the Sino-Nepal joint station will be established by ITP/CAS by the end of 2017.

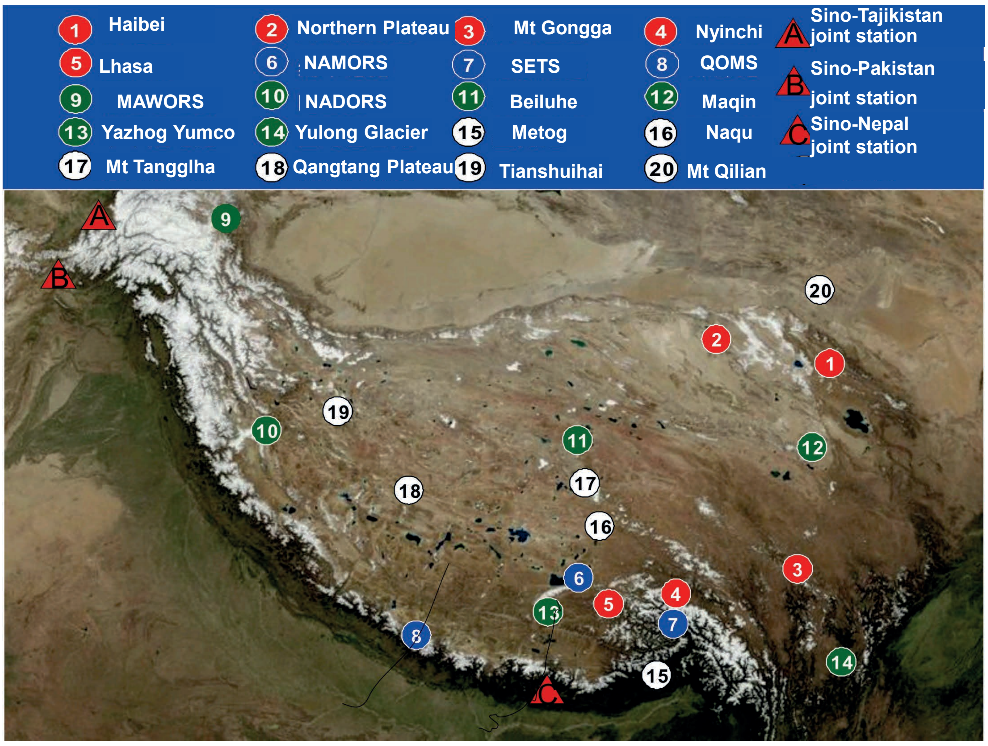

Fig. 1 The station layout in the TPE Programme.

The instruments and parameters measured at the six constructed stations of ITP/CAS in the TPE (NAMORS, QOMS, SETS, NADORS, MAWORS and Naqu) are shown in Table 1. The data collected by the TPE stations will be archived by the TPE data centre at the ITP/CAS. The archived data will be available to the scientific community all over the world. Scientists can submit a proposal to the data centre (http://www.tpedatabase.cn) to apply to use data.

PRELIMINARY RESULTS ON ATMOSPHERIC BOUNDARY LAYER

The characteristics of the land surface heat fluxes, the structure of the atmospheric boundary layer (ABL) and the characteristics of the atmospheric turbulent structure over the Tibetan Plateau area were derived using *in situ* data observed from the TPE in 2010. The results show that:

(1) The diurnal variations of radiation fluxes (downward and upward shortwave radiation and upward long-wave radiation) and surface heat fluxes (net radiation flux, soil heat flux, sensible heat flux and latent heat flux) over the Tibetan Plateau area are very clear, and the downward shortwave radiation is obviously larger than that in other areas due to the higher elevation and clear atmosphere over the Tibetan Plateau area. The sensible heat flux and latent heat flux play different roles in the partition of net radiation flux in different months in the Tibetan Plateau. In other words, the sensible heat flux plays the main role in winter and latent heat flux plays the main role in summer and autumn.

(2) The excess resistance to heat transfer, kB^{-1}, has obvious diurnal variation over the land surfaces of QOMS, NAMORS and SETS of the TPE. In other words, the kB^{-1} values derived by other researchers in other areas cannot be used directly in the numerical solutions and the procedures of satellite remote sensing parameterization over the Tibetan Plateau area; the different values of kB^{-1} should be used for different times of a day.

(3) The radiosonde data observed in the western Tibetan Plateau on a typical sunny day were analysed for the diurnal variations in the structure of a very high convective atmospheric boundary layer (CBL). A surface-based inversion was formed by 07:00, and had disappeared by 13:00. In the sounding at 07:00 we observed a 500-m deep cool and stable layer near the surface, and a residual layer above it with a depth of 1700 m and nearly constant potential temperature. After sunrise at approximately 09:00, the net radiation (R_n) increased very rapidly, resulting in surface heating. As a consequence, by 13:00 a mixing layer (ML) had grown to 3600 m, eroding both the surface and residual layers, and by 19:00 this growing layer was 4780 m deep (9195 m a.m.s.l. at the observing site). During this fast development of the ML, the water vapour content (WV) and wind speed were well mixed by turbulence. The growth of the CABL favoured the entrainment of relatively dry air from above, driving a decrease in the average WV content of the ML from 01:00 to 19:00. The WV content in the ML also decreased slightly with increases in height, due to surface evaporation. All of these phenomena suggested an ML dominated by buoyant turbulence. The horizontal wind shear in the troposphere for this day was weaker than on other days, and the effect of the horizontal mechanical turbulence on the development of the CABL was negligible. We therefore conclude that for the studied day the development of the CABL was primarily caused by underlying surface heating. It was observed that above 9300 m a.m.s.l. the wind speed increased very rapidly and WV dropped quickly. These high-gradient layers could be taken as the top of the CABL (well-mixed layers existed below this height), or as an indication of the upper troposphere and the lowermost stratosphere (UTLS). The top of the CABL at 19:00 was at a height of 9195 m a.m.s.l., and the tropopause was at 9455 m a.m.s.l.

THE REGIONAL DISTRIBUTION OF LAND SURFACE HEAT FLUXES

The study of the regional distribution of land surface heat fluxes over heterogeneous landscape of the Third Pole area is of paramount importance. Based on satellite and *in situ* data the regional surface heat fluxes (net radiation flux, soil heat flux, sensible and latent heat flux) over heterogeneous landscapes can be estimated (Ma *et al*., 2006, 2011). The land surface heat fluxes

Table 1 The instruments and parameters measured in the six constructed stations of ITP/CAS in the TPE (NAMORS, QOMS, SETS, NADORS, MAWORS and Naqu).

Station	Observation item
NAMORS, QOMS, SETS, Naqu	● 20 m ABL tower (MILOS520, Vaisala Co.): wind speed, wind direction, air temperature and humidity (height (m): 1.0, 2.0, 4.0, 10.0 and 20.0), surface temperature, soil heat flux (depth (cm):-10 and –20), air pressure, rain intensity. ● Radiation measurement system (CNR-1, Kipp & Zonen Co.): short wave radiation (downward and upward), long wave radiation (downward and upward). ● Soil moisture and soil temperature measurement system (SMTMS): Soil moisture (Trime EZ, Imko Co.) (depth (cm): -10, -20, -40, -80, -160); Soil temperature (Pt100, Data mark Co.) (depth (cm): -10, -20, -40, -80, -160). ● GPS radio-sonde system (MW21 DigiCORA III, Vaisala Co.): Profile of air pressure, air temperature, relative humidity, wind speed and direction.(This system is only set up in QOMS and Naqu) ● Wind Profiler and RASS (LAP3000, Vaisala Co.): Profile of air temperature, wind speed and direction. (This system is only set up in QOMS and Naqu) ● Sonic turbulent measurement system (CSAT3, Campbell Co.) and CO_2/H_2O flux measurement system (LI7500, Campbell Co.): wind speed, wind direction, air temperature, relative humidity, the characteristic length scales of surface layer, sensible heat flux, latent heat flux, CO_2/H_2O flux, stability parameter.
NADORS, MAWORS	● 3 m Automatic Weather Station (AWS) (MILOS520, Vaisala Co.): wind speed, wind direction, air temperature and humidity at one level, surface temperature, soil heat flux (depth (cm):-10 and –20), air pressure, rain intensity, and snow depth. ● Radiation measurement system (CNR-1, Kipp & Zonen Co.): short wave radiation (downward and upward), long wave radiation (downward and upward). ● Soil moisture and soil temperature measurement system (SMTMS): Soil moisture (Trime EZ, Imko Co.) (depth (cm): -10, -20, -40, -80, -160); Soil temperature (Pt100, Data mark Co.) (depth (cm): -10, -20, -40, -80, -160). ● Sonic turbulent measurement system (CSAT3, Campbell Co.) and CO_2/H_2O flux measurement system (LI7500, Campbell Co.): wind speed, wind direction, air temperature, relative humidity, the characteristic length scales of surface layer, sensible heat flux, latent heat flux, CO_2/H_2O flux, stability parameter.

over the whole Tibetan plateau area are estimated using Ma’s method (Ma *et al*., 2011),the MODIS (eight images) and AVHRR data (four images) and *in situ* data observed from the stations of the TPE. The results show that:

(1) The derived surface heat fluxes (net radiation flux, soil heat flux, sensible and latent heat flux) in four different months over the Tibetan Plateau area are in good accordance with the land surface status. Most derived regional land surface heat fluxes have *APD* (absolute percent difference) less than 10.0% at validation sites (Stations) in the Tibetan Plateau, and are in good agreement with field measurements. The Tibetan Plateau includes a variety of land surfaces such as a large area of grassy marshland, some desertification grassland areas, sparse grass-Gobi, sparse meadow, many small rivers and lakes, snow (glacier) mountains, forest, and farmland. Therefore, these derived surface heat fluxes show a wide range due to the strong contrast of surface features over the whole Tibetan Plateau (Fig. 2).

(2) The derived pixel values (Fig. 2) of latent heat fluxes in summer (1 August 2007 and 23 July 2003) and autumn (25 October 2007 and 16 October 2003) are higher than that in winter (30 January 2007 and 17 January 2003) and spring (15 April 2007 and14 April 2003). It means that there is much more evapotranspiration (ET) in summer and autumn than in winter and spring in the Tibetan Plateau area. The reason is that most of the land surface is wet and covered by green grass and growing vegetation in summer and autumn, but is dry and most the mountain ranges are covered by snow and ice during winter and spring on the Tibetan Plateau area. Hence, sensible heat and latent heat fluxes play different roles in the partition of net radiation flux in different months in the Tibetan Plateau: sensible heat flux plays the main role in winter and spring, and latent heat flux plays the main role in summer and autumn.

(3) Because the land surface cover and properties in spring (April) are very complex (there are ice, snow, seasonal and long-living permafrost, grassland and lakes etc. present in this month), the latent heat fluxes distribution in this month is also complicated (Fig. 2).

(4) The mean latent heat flux over the Tibetan Plateau area increases from January to April and July, then decreases from October (Fig. 2). They were 161.8, 237.5, 380.4 and 219.1 W m^{-2}, respectively, for AVHRR data in 2003, and 170.9, 243.6, 395.0 and 225.8 Wm^{-2} for MODIS data in 2003.

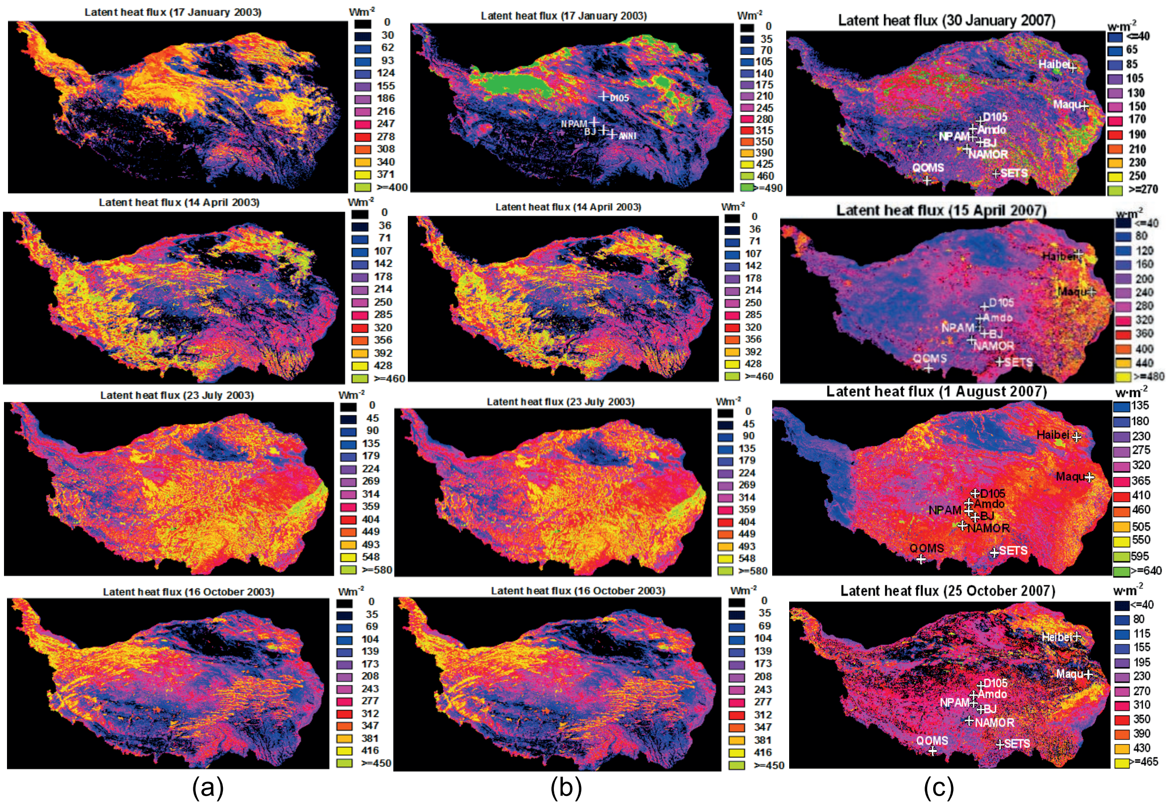

Fig. 2 Distribution maps of latent heat flux over the Tibetan Plateau area: (a) AVHRR-2003; (b) MODIS-2003; and (c) MODIS-2007.

CONCLUDING REMARKS

In this paper, the Third Pole Environment (TPE) Programme and the research issue of atmosphere–land interaction are introduced and some preliminary observational results, such as the characteristics of land surface heat fluxes partitioning, the ABL structure and the turbulence characteristics are shown by using the *in situ* data observed at the stations of the TPE. The regional distribution of surface heat fluxes (net radiation, soil heat flux, sensible heat flux and latent heat flux) derived from satellite remote sensing data are also shown by using MODIS and AVHRR data. The results are in good agreement with the surface conditions of the Tibetan Plateau. Hence, the regional land surface heat fluxes over a heterogeneous landscape can be determined by using satellite remote sensing and the atmospheric boundary layer observations.

All the analysis and results shown in this paper are just preliminary. In order to understand the impact of the Tibetan Plateau on the weather forecast and climatic change prediction over China, eastern Asia and even the globe, deep *in situ* data analysis has to be done in the future research. All the results in this paper were acquired from the datasets observed in the Tibetan Plateau. To extend them to a broader perspective, the results from the Tibetan Plateau need to be compared to those over similar landscape types, i.e. arctic, sub-arctic and alpine. The satellite remote sensing parameterization methodology used should also be improved to determine the regional land surface heat fluxes over whole Third Pole region. All these researches will have to be done by using the *in situ* data observed from the TPE in the days to come.

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