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Water Recycling between the Land Surface and Atmosphere on the Northern Tibetan Plateau—A Case Study at Flat Observation Sites

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Abstract

High-resolution soil moisture, temperature, and precipitation data from the northern part of the Tibetan Plateau provide the basis for analyzing the cycling of water between the land surface and atmosphere. Data analyzed come from the Intensive Observation Period (IOP) of the GEWEX (Global Energy and Water Cycle Experiment) Asian Monsoon Experiment (GAME) on the Tibetan Plateau (GAME-Tibet). Observations from July to August 1998 show that evaporation from flat land surfaces was 177 mm on the south side of the Tanggula Mountains, and 73 mm on the north side. These represent about 73% and 58%, respectively, of the precipitation in the same period. Evaporation not only transports considerable water but also considerable energy from the land surface to the atmosphere, which can slow the rising of soil temperatures. Differences in the evaporation between the south and north sides of Tanggula Mountains is mainly caused by differences in precipitation.

Introduction

Many scientists (Liu, 1997; Liu and Sun, 1999; Xing, 1999; Zhang, 1999) have summarized and reported on processes of large-scale water recycling. However, few studies are available regarding water recycling between the land surface and the atmosphere, especially on the Tibetan Plateau. The spatial and temporal distributions of soil temperatures and soil moisture contents reflect soil saturation as well as the soil energy status. Because the soil heat capacity and soil moisture content are large compared to the atmosphere, the temporal and spatial variations in soil temperature and moisture are key components in energy and water recycling in the land-atmosphere system. Soil energy and moisture are not only influenced by the weather but also dramatically affect weather processes (Shukla and Mintz, 1982; Mintz, 1984; Yeh et al., 1984; Dickinson and Henderson-Sellers, 1988; Barnett et al., 1989; Liu et al., 1989; Yasunari et al., 1991; Liu et al., 1992a, 1992b; Vernekar et al., 1995). Evaporation of soil moisture affects weather by transferring the moisture to the atmosphere, where it takes part in the local convective circulation.

Various studies have attempted to show how precipitation on the Tibetan Plateau relates to local convection (Zheng et al., 1997; Yang et al., 1999, 2006a, 2006b). The GEWEX Asian Monsoon Experiment-Tibetan Plateau (GAME-Tibet) Intensive Observation Period (IOP) precipitation and δ^{18}O data from 1998 provide a basis for quantitative estimates of precipitation originating from different water vapor sources (Yang et al., 2006b). The percentage of precipitation derived from vapor in ocean-air-masses near Amdo, central Tibet, did not exceed 32% of the total precipitation from June to September 1998 (Yang et al., 2006b). However, water derived from local evaporation was at least 46% of the total precipitation. As much as 21% of the total precipitation may have been derived from evaporative water vapor transported inland by monsoon circulation. They also point out that precipitation in the middle of the Tibetan Plateau (such as the Amdo area), might have come from water vapor derived from ocean air masses that have experienced several cycles of condensation-precipitation-evaporation under monsoon circulation. Zhang et al. (1997) demonstrated the importance of surface evaporation in hydrological processes. Precipitation in the Dongkemadi River basin (Tanggula Mountains) was about 500 mm from May to September 1993. Of that, 63% formed runoff and 37% evaporated. Although Zhang et al. (1997) addressed the importance of the evaporation, they did not consider the fact that precipitation contributed to the supply of soil moisture. Chahine (1992) concluded that 65% of the precipitation onto the land came from land surface evaporation. Numerical simulation also indicates that around 70% of the precipitation near Nagqu (south of Tanggula Mountains) from June to August comes from land surface evaporation (Numaguti, 1998). However, the evaporated soil moisture was previously supplied by precipitation. This exemplifies the recycling of water between land and atmosphere on the Tibetan Plateau.

One of the key projects of the GEWEX carried out in 1990s by the World Climate Research Program (WCRP) was to examine interactions between the land surface (vegetation) and the atmosphere. Full understanding of water transport in the soil-vegetation-atmosphere system requires additional study. Liu and Sun (1999) explain the importance of more accurately determining the water and energy fluxes at the land surface and understanding

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the processes of water vapor and energy transport across the boundary layer to the interpretation of climate and water cycles. In this paper, GAME-Tibet high-resolution data of soil temperature, soil moisture, and precipitation is examined to study water recycling between land and atmosphere in northern Tibetan Plateau.

Data Collection

Soil temperature and soil moisture observation sites were installed at seven locations, mainly along the Qinghai-Tibet highway (Fig. 1). Yang et al. (2003) provide the longitude, latitude, elevation, and permafrost conditions of these locations. Each soil temperature observation system incorporated 10 platinum (Pt) ground-temperature probes and two data loggers. The depths of the ground temperature probes were 4, 20, 40, 60, 80, 100, 130, 160, and 200 cm and the maximum depth. The maximum depth varied at different observation sites, except for sites D110 and WADD, where the maximum depths were 180 cm and 160 cm, respectively (Yang et al., 2003). Each soil moisture observation system consisted of six time-domain reflectometer (TDR) probes and one data logger. The depths of the TDR probes were 4, 20, 60, 100, and 160 cm, but the maximum depths varied with the observation sites (Yang et al., 2003). Data were collected automatically with an observation interval of 1 h (Beijing Time). The soil moisture content measured by the TDR probes refers to volumetric liquid water content when soil is thawed and to volumetric unfrozen water content when soil is frozen. Therefore, in analysis below, the soil water content refers only to unfrozen water (i.e., ice is not included).

During the GAME-Tibet IOP (May to September, 1998), rain gauges were established at D105, WADD, NODA, AQB, Amdo,

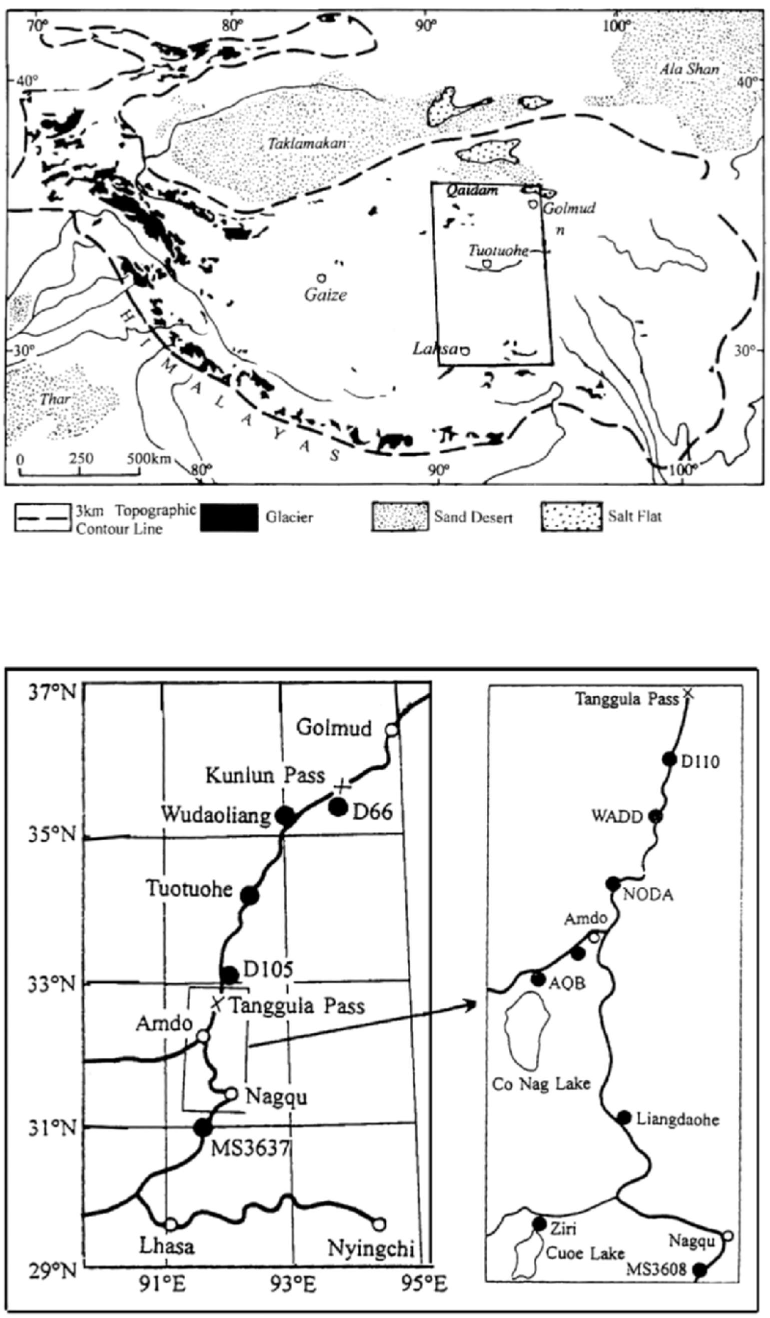

FIGURE 1. (a) Geography of the Qinghai-Xizang (Tibet) Plateau. Box outlines the study area, shown in more detail in lower maps. (b) Qinghai-Tibet highway and observation sites across the Tanggula Mountains. Soil temperature and moisture observation sites are at D66, Tuotuohe, D110, Noda, Amdo, MS3608, and MS3637.

Ziri, Nagqu, and MS3637 (N-PAM). Hourly precipitation was concurrently observed at sites D66, Tuotuohe, D110, and MS3608 (Fig. 1).

Methodology for Estimating Total Soil Moisture

The volumetric soil moisture contents at different depths are identified as V_4, V_{20}, V_{60}, V_{100}, V_{160}, and $V_{deepest}$. Assuming that soil moisture content between two measuring points (probes) varies linearly, the soil moisture content between two depths can be determined as the area of the trapezoid. For example, the volumetric soil moisture content per unit area between 4 cm and 20 cm depth, S_{4-20}, can be computed as

$$S_{4-20} = (20 - 4) \times (V_4 + V_{20})/2 \tag{1}$$

which has units of length. V_0, the soil moisture content at the surface, is calculated by assuming soil moisture varies linearly from 0 to 20 cm (i.e., using the same slope as between 4 and 20 cm). We calculated the total daily mean soil moisture content in the different layers at each site using the above method.

Water Transport from Soil to Atmosphere

The soils thawed to a depth exceeding 160 cm at all of the observation sites in July 1998. Consequently, our calculated soil moisture contents in July and August should represent the total soil moisture contents. We selected the sites D66, Tuotuohe, D110, Amdo, and MS3637, located in flat areas, for detailed analysis. We then assumed that no water percolates beyond 160 cm depth, i.e., the soil moisture in the layer from 0 to 160 cm only exchanges moisture with the atmosphere via the ground surface. Such exchanges are carried out by two processes: the soil loses moisture to the atmosphere through evaporation (including evapotranspiration), and gains moisture through precipitation. Because the four observation sites lie on flat terrain, we assume no surface runoff. Precipitation either infiltrates to the soil and/or evaporates from the surface. If *WS* denotes the water in soil (soil moisture content over the full soil depth, up to 160 cm), then,

$$\Delta WS_{1,2} = WS_{t2} - WS_{t1} \tag{2}$$

WS_{t1} = the soil moisture content at time *t1*, WS_{t2} = the soil moisture content at time *t2*, and $\Delta WS_{1,2}$ = the change in soil moisture from *t1* to *t2*.

Using $P_{1,2}$ as precipitation and $E_{1,2}$ as evaporation from *t1* to *t2*,

$$\Delta WS_{1,2} = P_{1,2} - E_{1,2} \tag{3}$$

or the evaporation from soil to atmosphere from *t1* to *t2* is

$$E_{1,2} = P_{1,2} - \Delta WS_{1,2} \tag{4}$$

We chose several precipitation events to test the validity of the above water balance. At site D66, there was no precipitation on 18 and 20 July, but it rained 7.0 mm on 19 July. The soil moisture content in the 0- to 160-cm layer increased 4.8 mm from 18 July to 20 July (from 149.6 to 154.4 mm). Similarly, there was 10.9 mm of precipitation from 12 to 14 July, and none on 15 July; from 12 to 15 July the soil moisture increased by 6.1 mm. The precipitation during 3 and 4 August was 8.9 mm, and the soil moisture content increased 7.8 mm from 3 to 5 August.

At the Tuotuohe site, it rained 15.0 mm on 26 August. The soil moisture content increased 12.7 mm (from 260.0 to 272.7 mm) between 25 and 27 August. At site D110, it precipitated 10.2 mm on August 3, and the soil moisture content increased 8.8 mm between 2 and 4 August. And at the Amdo site, it precipitated 30.9 mm on August 18 and the soil moisture content increased 21.8 mm between 17 and 19 August.

A precipitation event can occur at any time of day. Maximum surface evaporation occurs when the surface is wet after a precipitation event and during the daytime when it is clear. The precipitation events listed above were all relatively strong even though the average daily precipitation is not great. Precipitation during July and August (rainy season) only averages 2.5 mm d^{-1} at D66, 4.3 mm d^{-1} at Tuotuohe, and 5.3 mm d^{-1} at Amdo. Typically, precipitation events occur frequently, but each event brings little moisture. Because the rainfall data collection interval is 1 h, we assume the rainfall rate is uniform over 1 h. The rainy season average hourly precipitation rates during rainfall events are: 1.02 mm h^{-1} at D66, 1.11 mm h^{-1} at D110, and 1.14 mm h^{-1} at Amdo. Field observations provide comparable results.

Strong local convection promotes precipitation mainly on the local scale. Because of the strong ground surface evaporation after rainfall and the lack of significant surface runoff, the equation of $E = P - \Delta WS$ basically holds. Therefore, based on the difference of soil moisture content, ΔWS, and the total precipitation from time *t1* to *t2*, the moisture transport from soil to atmosphere can be estimated quantitatively.

Results and Discussion

As an example, the soil moisture content at D66 in the 0- to 160-cm layer was 143.0 mm on 1 July and 151.9 mm on 31 July. During the same period, the precipitation totaled 49.3 mm. This indicates that 8.9 mm (18.1%) of the precipitation was used to increase the soil moisture content and 40.3 mm (81.9%) of the moisture evaporated (including evaportranspiration). Similarly, the precipitation in August totaled 37.7 mm, of which 10.6 mm (28%) went to increase the soil moisture content and 27.1 mm (72%) evaporated back to atmosphere. Table 1 shows these results and those for other sites.

The data show significant differences between the precipitation and the surface evaporation at the observation sites north versus south of the Tanggula Mountains (Table 1). Therefore, we analyzed the average values on either side of the Tanggula Mountains. Data from sites D66 and Tuotuohe were averaged for the north side, and Amdo and MS3637 were averaged for the south side. The precipitation on the south side was 90% greater than that on the north side, while the surface evaporation was 142% greater (Table 2). However, the soil moisture content supplied by precipitation was only 21% larger on the south side than on the north side.

What caused the much greater surface evaporation on the south side of the Tanggula Mountains compared to the north? Based on the average measured temperatures at the 4, 20, 40, 60, 80, 100, 130, and 160 cm depths, we found that the average soil temperature in the 0- to 160-cm layer differs by less than 0.3°C between the two sides of the mountains in July and August. Considering only the shallow layer, we found that average temperature in the surface layer (0–20 cm depth) in July and August was actually a bit lower on the south side of the mountains (11.1 versus 11.2°C). During the same period, however, the average soil moisture content in the surface layer was 20% on north side and 30% on south side, a 50% difference. Also, the average air temperature for July and August was 6.4°C in north

TABLE 1

July and August 1998 water distribution at study sites.

		D66	Tuotuohe	D110	Amdo	MS3637
July	Precipitation (mm)	49.3	95.8		90.4	120.9
July	Increase in soil moisture content (mm)	8.9	44.0		49.7	22.4
July	Evaporation (mm)	40.3	51.8		40.7	98.5
July	Increase in soil moisture content as a percentage of precipitation	18.1	45.9		55.0	18.5
July	Evaporation as a percentage of precipitation	81.9	54.1		45.0	81.5
July	Daily mean soil moisture content, 0–160 cm (mm)	152.3	209.5		343.3	444.0
August	Precipitation (mm)	37.7	71.4	190.6	152.2	120.7
August	Increase in soil moisture content (mm)	10.6	44.1	142.5	39.0	19.0
August	Evaporation (mm)	27.1	27.3	48.2	113.2	101.7
August	Increase in soil moisture content as a percentage of precipitation	28.0	61.8	74.7	25.6	15.7
August	Evaporation as a percentage of precipitation	72.0	38.2	25.3	74.4	84.3
August	Daily mean soil moisture content, 0–160 cm (mm)	160.0	260.9	411.4	386.1	461.8

TABLE 2

Water and temperature distributions from July to August 1998 in flat areas on opposite sides of the Tanggula Mountains.

	North side of Tanggula Mts.	South side of Tanggula Mts.	Differences between south and north	Percentage differences between the south and north sides of Tanggula Mts.
Precipitation (mm)	127.1	242.1	115.0	90
Increase in soil moisture content (mm)	53.8	65.0	11.2	21
Evaporation (mm)	73.3	177.1	103.8	142
Increase of soil moisture content as a percentage of precipitation	42.3	27.9		
Evaporation as a percentage of precipitation	57.7	72.2	14.5	20.8
Daily mean soil temperature, 0–20 cm depth (°C)	11.2	11.1	−0.09	−0.8
Daily mean soil temperature, 0–160 cm depth (°C)	8.4	8.7	0.27	3.2
Daily mean air temperature (°C)	6.4	8.5		
Daily mean soil moisture content, 0–20 cm depth (*V*/*V*)	0.2	0.3	0.1	50

side and 8.5°C in south side (Table 2). Albedo is low on wet surfaces, but the heat capacity of wet soil is larger than that of dry soil. Therefore, the temperature increase per unit of heat input is small in wet soil compared to dry soil. On the other hand, the energy required for surface evaporation may play a more important role. Surface evaporation conveys the latent heat as well as the soil moisture to the atmosphere. As we showed above, the surface evaporation in July and August on the south side was more than double that on the north side. Therefore, the loss of energy to the atmosphere by evaporation may be responsible for the lack of differences in soil temperature.

The precipitation difference between the two sides of the Tanggula Mountains produces differences in the surface soil moisture content, which cause differences in the surface soil evaporation, and consequently differences of the air humidity. These differences provide feedback to affect the amount of precipitation.

The water vapor reaching the northern Tibetan Plateau derives mainly from the Bay of Bengal via the Brahmaputra/Yaluzangbu (aka Yarlung Zangbo) River valley. But some portion of the water vapor in our study area arrives directly via atmospheric transport and some portion will have been recycled by precipitation and evaporation as it travels to the inner part of the Tibetan Plateau by monsoon circulation. The surface evaporation in July and August in flat areas south of the Tanggula Moutains was 177 mm, which was 73% of the precipitation. In flat areas north of the Tanggula Mountains, the surface evaporation is 73 mm, which was 58% of the precipitation. The evaporation difference between the two sides of the mountains primarily reflects the difference in precipitation.

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