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Long-term trends of precipitable water and precipitation over the Tibetan Plateau derived from satellite and surface measurements

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A B S T R A C T

This study investigated the long-term trends of precipitable water and precipitation over the Tibetan Plateau using satellite and surface measurements. The results show that precipitable water in the 680–310 hPa layer of the atmosphere has increased significantly since the 1990s, with an upward trend of 6.45 cm per decade and particularly high increases in summer. However, precipitation has not shown a significantly increasing trend, and the land surface has become drier in parts of the Himalayas. The increased moisture in the atmosphere may be the result of two processes: (1) the rapid melting of glaciers and snow over the Tibetan Plateau due to enhanced regional warming and (2) a small increase in water vapor transported from low-latitude ocean sources and the Arabian Sea. Analyses of precipitation, evaporation, and the Palmer drought severity index (PDSI) indicated that the water resources on the Tibetan Plateau are decreasing and that the water storage capacity in the Himalayas may be permanently lost.

1. Introduction

The Tibetan Plateau is the highest and largest plateau on Earth and includes some of the most complex terrain on the globe. After the Antarctic and Arctic, the Tibetan Plateau is also one of world's largest stores of ice, although this feature of the Tibetan Plateau receives comparatively little attention. The high altitude, geographic location, and topography of the Tibetan Plateau make it an important "Asian water tower," holding glaciers, snowpacks, lakes, and rivers. The runoff from the Tibetan Plateau feeds seven major rivers in Asia, including the Yangtze, Yellow River, Ganges, Indus, Brahmaputra, Salween, and Mekong [1–3]. These waters sustain life and agricultural and industrial water usage for nearly 40% of the world's population.

Water vapor in the atmosphere plays an important role in supplying the Asian water tower. A water vapor maximum occurs above 500 hPa in the atmospheric columns over the Tibetan Plateau [4]. In the lower troposphere, water vapor is the main resource for precipitation in all weather systems, generating latent heating and dominating the structure of diabatic heating in the troposphere [5]. Water vapor in the atmosphere directly affects the water storage of the Tibetan Plateau. Thus, understanding changes in water vapor over the plateau is important because any changes might affect the water supplies for billions of people. In this study, we investigated the long-term trends in precipitable water over the Tibetan Plateau and presented possible explanations for the trends observed. We also studied the potential impacts of these changes.

2. Data and methodology

We used three types of data for this study: (1) satellite remote sensing data, (2) meteorological station data, and (3) reanalysis data. The satellite remote sensing dataset consisted of the following. Monthly mean cloud cover and monthly mean precipitable water for 680–310 hPa were obtained at a

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spatial resolution of 2.5° by 2.5° from the D2 dataset of the International Satellite Cloud Climatology Project (ISCCP), which began in July 1983 [6]. The snow depth dataset was based on passive microwave satellite observations from the US National Snow and Ice Data Center (NSIDC) including observations made by the Scanning Multichannel Microwave Radiometer (SMMR) (1978–1987), Special Sensor Microwave Imager (SSM/I) (1987–2008), and the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) (2002–2010). Because the three sensors were boarded on different platforms, the data acquired by the sensors displayed a systemic inconsistency. Dai and Che improved the temporal consistency of the brightness temperature via a cross-calibration of different sensors and they retrieved the snow depth using an improved algorithm, which was specialized for the China region based on the Chang algorithm [7–9]. These data also had a spatial resolution of 2.5° by 2.5°. In addition, snow cover data for the last 12 years (2000–2011) observed by the Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra were obtained from the NSIDC. Considering that the snow cover over an area is typically described by the fraction of snow-covered land, monthly composites of the snow cover fraction (SCF) in a 0.05° by 0.05° climate modeling grid (MOD10CM) were used in this study [10]. The quality of MODIS snow data over the Tibetan Plateau has been previously evaluated [11–13].

Meteorological station data for the Tibetan Plateau has been reported directly from benchmark surface weather stations and automatic weather stations since 1951. The analyzed variables include annual mean surface air temperature, annual mean surface precipitation, and daily small pan evaporation.

The reanalysis data included mean monthly surface air temperature and precipitation data from the Climate Research Unit (CRU version TS3.1) with a resolution of 0.5° by 0.5° for the period of 1901 to 2009 provided by the University of East Anglia [14]. A monthly dataset of the Palmer drought severity index (PDSI) from 1850 to 2010, derived using historical precipitation and temperature data for global land areas, was also used [15]. In addition we used the South Asia monsoon index (SAMI) from 1948 to 2010 [16]. To compare results, all the datasets consulted included the period of 1984–2009.

To study trends over the Tibetan Plateau, we first calculated regional average values for several variables over the Tibetan Plateau domain (25–40°N, 70–105°E) as the simple arithmetic mean of all stations or grids higher than 2500 m a.s.l. In the following analyses, anomaly values from the CRU and station data were computed relative to 1961–1990; this period was chosen because it had the best coverage of CRU data, which facilitated comparisons between stations [17]. Annual temperature anomalies were also computed relative to the 1961–1990 mean. For the other datasets, anomaly values were calculated over the time series provided by the data. Finally, to detect trends, we used the following linear regression:

$$y = a + bx$$

where y denotes the variable anomaly at time x (in years), a is the intercept, and the trend b is the slope of the straight line, which represents the rate of increase or decrease of the variable anomaly. The regression coefficients a and b were determined by a least-square fitting.

3. Analysis of results

A pool of concentrated water vapor over the Tibetan Plateau has previously been reported [4], especially at high levels. For the period 1984–2009, the trend in the spatial distribution of precipitable water at 680–310 hPa over the Tibetan Plateau was significantly different from that over surrounding areas. An increasing trend was found over nearly the entire plateau, and for most of the area this was significant at the 0.01 level. The highest positive trend occurred over the central region of the Tibetan Plateau, where the maximum increase was as much as 10 cm per decade (Fig. 1a). The farther from the center of the plateau an area was, the lower the positive trend was. Comparing different seasons, Fig. 2b shows intense increasing trends for summer (June–August) and autumn (September–November) but weak trends for spring (March–May) and winter (December–February). Although the summer trend was most pronounced, with a maximum value of 1.89 cm/decade ($p < 0.01$), the summer precipitable water in the $680-310$ hPa anomaly had the largest variability, especially after 1998. Unfortunately, the exact reason for the "jump" feature during 1997–1998 is still unknown. There is not a specific event that occurred during 1997–1998 which would explain this. In a study of large-scale atmospheric moisture processes, Peixoto et al. [18] found that water vapor levels contrasted between summer and winter. This pattern was not observed in spring and autumn, when instead the pattern resembled that of the antecedent seasons. The results for the Tibetan Plateau are consistent with their finding. In addition, the standard deviation of the spatial distribution of precipitable water in the $680-310$ hPa level shows that the area with the highest positive trend also had the maximum difference between precipitable water datas.

Water vapor in the atmosphere is the main source of moisture for precipitation and runoff on land areas by lateral transport, and precipitation is the primary channel for bringing water to the surface. Zhai and Eskridge [19] noted that although it is difficult to explain the cause and effect between precipitable water and precipitation, the correlation between them is significant. Fig. 2a using the CRU data shows the trends of precipitation over the Earth, Northern Hemisphere, and Tibetan Plateau. We found that during 1984–2009, global and Northern Hemisphere precipitation displayed a clear increasing trend of 15.35 mm per decade ($p < 0.01$) and 12.55 mm per decade ($p < 0.01$), respectively. However, over the Tibetan Plateau, annual precipitation displayed only a small increase of about 0.27 mm per decade ($p < 0.3$). Our analysis of station data confirmed this result. A small increasing trend was found for 97 in situ measurements of precipitation, but the value was less than 1 mm per decade.

A drought index usually measures the departure from the local normal conditions and is a moisture variable based on its historical distributions [20]. Fig. 2c shows the spatial distribution of the PDSI trend over the Tibetan