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Suppression of precipitation by dust particles originated in the Tibetan Plateau

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ABSTRACT

Dust aerosols play an important role in modulating the hydrologic cycle. The Tibetan Plateau (TP) is little polluted by human activities as an ideal site to study the effect of dust aerosol on precipitation. In this study, observational data of dust storms and precipitation in the TP and its vicinities as well as CALIPSO satellite data were used to analyze the distributions and vertical structure of dust storms on the plateau. The results showed that dust storms occur with high frequency and raise dust particles into the troposphere from ground level to a height of 5–9 km to modulate the hydrologic cycle in the TP. There are significant negative correlations between dust aerosol and precipitation in the dust source regions during the period of both 40 and 200 years. It is found that the role of precipitation in suppressing dust storms could be unimportant, while dust aerosol may play an important role in suppressing precipitation in the hinterland of the TP. Our study provides a potential approach to better understand the climate changes in the TP.

1. Introduction

The Tibetan Plateau (TP) is lofty in the midlatitude westerly zone in the Northern Hemisphere and plays an important role in modulating the regional and global climate (Li and Fang, 1999; Nie et al., 2008). It is a "water tower" for Asia. The Mekong, the Yellow River, the Yangtze, the Yarlung Tsampo (Brahmaputra), the Indus, and the Karnali all originate from the TP and support hundreds of millions of people downstream. Even tiny changes in the TP's hydrologic cycle will have important implications for the climate, ecosystem, and economy for the TP itself and the surrounding regions. For example, the variations of snow cover over the TP affect not only the hydrologic cycle in the TP itself but also the precipitation pattern, such as flooding in South China and drought in north China (Liu and Yanai, 2002; Zhu and Ding, 2007). Recent studies (Jacobson, 2002; Nober et al., 2003) suggested that aerosols can substantially alter the energy balance of the atmosphere and the earth's surface, thereby modulating the hydrologic cycle. Dust aerosol is the most important constituent of aerosols, accounting for nearly half of the total aerosols in the troposphere (Lohmann and Feichter, 2005). Because of the limitation in observation data for the interaction of cloud and aerosols, the research on the condensation nuclear effect now depends mainly on hypothesis and numeral simulation (Teller and Levin, 2006). Many recent studies showed aerosols tend to invigorate convection and to intensify ice processes (Khain et al., 2005, 2008; Lynn et al., 2005a,b), and aerosols can both increase or decrease precipitation depending on environmental conditions. However, under comparatively dry atmospheric conditions, the experiment performed by Rosenfeld et al. (2001) in the Sahara area indicated that desert dust can suppress precipitation. Central Asia is one of the most important source regions of dust storms, inferior only to the Sahara Desert, supplying dust particles to modulate the regional hydrologic cycle (Zhao et al., 2006). Using a two-dimensional spectral resolving cloud model, the effects of mineral dust particles on development of cloud microphysical and precipitation were simulated in North China (Chen et al., 2007; Yin and Chen, 2007). The results showed that when dust particles are involved in cloud development as CCN (cloud condensation nuclei) and IN (ice nuclei) at the same time, the increased dust aerosol will suppress the precipitation because the enhancing effect of GCCN is almost suppressed by the stronger suppressing effect of IN (Chen et al., 2007; Yin and Chen, 2007). Furthermore, Han et al. (2008a) found that the role of precipitation in suppressing dust storm occurrence is unimportant and that dust aerosol may play a more important role in suppressing the precipitation in the arid and extra-arid regions. However, the constituents of aerosols are complex because of dense population, industry, and severe pollution caused by human activities in northern China.

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Considering the influence of natural dust aerosol, we chose the TP for our research area due to its harsh climate, the existence of vast dust sources (Li et al., 2001) as well as very little human activity. Many sand dunes exist in the TP, ranging from the distant geologic past to modern time (Fang et al., 2004). Because of global warming and other factors, the desertification of the land is rapidly increasing, with a total desertification area in the TP of 506,074.79 km^2 in 2003 (Wang, 2005b). The total desertification area of the TP is greater than that in the four great deserts of China (Taklimakan, 337,000 km^2; Gurbantunggut, 48,800 km^2; Badain Jaran, 44,300 km^2; Tengger, 42,700 km^2, for locations, see Fig. 1). The TP was also considered as an important dust source region (Fang et al., 2004; Han et al., 2008b), where dust storms occurred mainly in winter and spring with high frequency, as determined by the visibility observations from surface meteorological stations. The centers of dust storms move gradually from the south to north, which is closely coupled with the northward shift of the westerly jet from winter to spring over the TP (Han et al., 2008b). Compared with the other 12 dust source areas in China, the TP is one of the key dust source areas for long-distance dust transport because of its high frequency of dust storm occurrence and its elevation, which causes fine particles to be more easily lifted into the zone of the westerly jet stream (Fang et al., 2004). Furthermore, the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) revealed that dust storms occur even more frequently in the summertime than previously observed by the TP surface observations (Huang et al., 2007). Very few surface observed data were available over the remote Northwestern TP due to the sparse meteorological stations. Moreover, the dust aerosol over the TP may enhance the Indian monsoon by the "elevated heat pump" (Lau et al., 2006), which is a major source of precipitation on the TP. Likewise, the dust storms or dust devils may be induced by vast dust resources, gales, and strong dry heat convection in the TP (Han et al., 2008c), and these conditions can lift many fine dust particles into the atmosphere to modulate the hydrologic cycle of the TP and the surrounding regions.

There is little disturbance from human pollution in the TP, and it provides an ideal site to study the effect of dust aerosol on precipitation. In this work, the spatio-temporal distributions and vertical structure of dust storms are investigated on the TP, and relationship between the precipitation and dust index is analyzed. Furthermore, possible physical mechanism of negative correlation between precipitation and the dust index is examined. The research provides a potential approach to better understand the climate changes such as the snow cover, dust storms and precipitation in the TP and the surrounding regions.

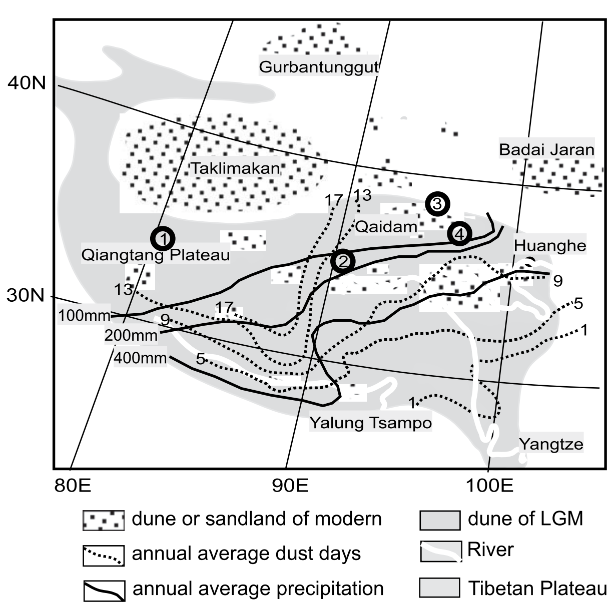

Fig. 1. Distribution of the modern and last glacial sand dunes, desertified sandy land, and the mean annual dust storm days and precipitation from 1961 to 2000 on the TP (black solid line: precipitation; black dashed: dust storm days; black circle including the number representing the following locations: 1, Guliya ice core; 2, Malan ice core; 3, Dunde ice core; 4, Delingha tree ring).

2. Study region and data

2.1. Study region

The studied region includes nearly the whole TP, where the topography inclines from the northwest at an average altitude of 5000 m a.s.l. to the southeast at about 3500 m a.s.l. being much higher than the surrounding desert areas (e.g., the Taklimakan Desert to the north, about 840–1200 m a.s.l.; the Badain Jaran Desert, about 1300–1800 m a.s.l.; and the Tengger Desert to the northeast, 400–1600 m a.s.l.). This region accounts for about one-fourth of the total area of China. The total area of desertified land in the TP is 506,074.79 km^2 in 2003, the net increasing area is 38,743.07 km^2 compared with the area in the 1970s with a rate of increase of 8.3% per year over 30 years (Wang, 2005b). Of this total, the maximal increasing rate for severely, moderately, and slightly desertified lands occupy 311.5%, 68.9%, and 86.9%, respectively (Wang, 2005b). According to previous researches (Fang, 1995; Fang et al., 1998; Jin et al., 1998; Li et al., 2001), the desertification lands are distributed mostly in (1) the Qiangtang Plateau in the northern TP; (2) the valleys of Yarlung Tsampo (River) and its tributaries in the southern region of the TP; (3) the headwater regions of the Yangtze and Yellow rivers in the center of the TP; (4) the Qaidam basin and surrounding mountainous regions; and (5) the Gonghe basin and peripheral regions of the Qinghai Lake (for location, see Fig. 3). The sand dunes are discontinuously distributed in spots, strips, and patches (Fang et al., 2004; Li et al., 2001). Moreover, desertified meadow and grass soils occupy the much wider area than sand dunes including almost all source areas of the Yangtze and Huanghe rivers except sand dunes and mountain bedrocks. The parent materials of these soils are relatively homogeneous and consist mostly of silts and fine sands (Fang et al., 1998). These sand dunes were formed mostly at around 14–24 ka BP in the last glacial maximum, indicating that much stronger desertification occurred in the last glacial maximum (LGM) (Fang et al., 1998). These widely distributed sand dunes and desertified land environments provide plenty of raw materials to generate dust storms.

2.2. Data

This work investigates interannual variations of dust storm source regions by analyzing the records of dust storms or blowing sand of 91 stations in the TP from 1961 to 2000. The dust and precipitation data come from the National Climate Center of the China Meteorological Administration, and its dust index is calculated by averaging the annual number of days of dust storm occurrence at the Wudaoliang (35.2°N, 93.1°E) and Shenza (30.57°N, 88.38°E) stations in the interior of the TP. We ascertained the vertical structure of dust aerosol distribution over the TP from the CALIPSO satellite data. The CALIPSO launched on April 28, 2006, and combines an active lidar instrument with passive infrared and visible imagers to probe the vertical structure and properties of thin clouds and aerosols over the globe. The dust storm over the TP was probed by CALIPSO on April 1, 2007, from the NASA Langley Research Center Atmospheric Sciences Data Center.