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The warming of Tibetan Plateau enhanced by 3D variation of low-level clouds during daytime

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ABSTRACT

The Tibetan Plateau (TP) has experienced evident warming in recent decades, but the exact reasons for this warming remain unclear. In this study, we investigated the possible effect of the three-dimensional (3D) variations of cloud during daytime on climate warming over the TP from 2007 to 2015 based on CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. We found that the 3D changes occur mostly to low clouds, whose fraction and geometrical depth decrease by approximately 4.2% and 130 m, respectively. These changes result in the increase of the surface shortwave radiation (SSR) by approximately 29.7 W/m^2, which is one magnitude larger than that of anthropogenic CO_2. The increase in SSR leads to the increase in direct solar radiation absorption in the surface, which significantly enhances the warming of the TP.

1. Rapid warming of Tibetan Plateau

The Tibetan Plateau (TP) is the highest and most extensive highland in the world, with an average elevation of over 4000 m above sea level (a.s.l.) and a spatial extent of approximately 2.5×10^9 km^2 (You et al. 2013). The TP has significant influence not only on local climate and environment, but also on global atmospheric circulation through its thermal and mechanical forces (Immerzeel et al. 2010; Ke et al. 2015; Wang et al. 2013). A growing evidence shows that a significant climate warming event began over the TP during the last half century, which may continue into the future, with warming conditions that are more serious than those of the rest of the world (Pepin et al. 2015).

The global mean surface temperatures have risen by 0.12 °C/decade, while the rate over the TP is 0.36 °C/decade, as estimated through the linear trend over the last half century (IPCC 2013; Wang et al. 2008). Although we have been experiencing a warming hiatus, which is mainly attributed to the dynamically induced variability, since the late 1990s, it is temporary (Guan 2015; Huang et al. 2016). Previous studies have suggested that the increased warming in the 20th century might be due to the increases in atmospheric gas and particle concentrations, such as CO_2, ozone, and aerosols (Ramanathan et al. 2007; Yang et al. 2014). However, these climatic factors are only partially responsible for the rapid warming observed over the TP, given that their impacts imply a warming of one order of magnitude lower than what has been observed. The exact reasons for the discrepancy remain unclear (Kang et al. 2010; Yang et al. 2012).

Clouds are crucial to the atmospheric energy cycle, the water circulation, and Earth's climate system (Van Tricht et al. 2016). Duan and Wu (2006) proposed that the surface warming over the TP is enhanced by the contrasting trends of total and solely low-level cloud amounts during daytime and nighttime. Yang et al. (2012) suggested that the rapid warming is related to increases in water vapor and deep cloud cover. Moreover, the changes of cloud cover may be attributed to the decreasing trend of the diurnal temperature range, which exhibits a strong negative correlation with cloud cover (Englehart and Douglas 2005). However, these previous studies have insufficiently discussed the possible effect of cloud vertical variation on surface warming or cooling. The meteorological stations, the reanalysis and passive remote sensing techniques used by previous studies are difficulty in quantifying the contributions of the three-dimensional (3D) cloud variations to climate change (Mace et al. 2009; Pan et al. 2015).

In this study, we investigate the effect of 3D cloud variations during daytime on recent climate change over the TP from 2007 to 2015 based on CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). The primary motivation of this study is to quantify the radiative effect of 3D cloud variations on the surface and further assess the connection between the cloud variations and the recent climate warming over the TP.

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2. Data and methods

2.1. Data and uncertainty

CloudSat and CALIPSO were launched in April 2006 and became a part of the A-Train constellation with a tight orbital coordination (Winker et al. 2009). Cloud Profile Radar (CPR), which is the only instrument on CloudSat, has a 1.3-km cross-track and a 1.7-km along-track footprint resolution, and its effective vertical resolution at nadir is 240 m (Sassen et al., 2008). Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) is the primary instrument in CALIPSO, and their maximum vertical and horizontal resolutions are 30 m and 333 m, respectively (Yu et al. 2012).

CALIPSO is highly sensitive to thin cirrus clouds and does not penetrate cloud layers which optical depths exceed three to five (Winker et al. 2010). Consequently, CALIPSO cannot measure the true base height of an opaque layer and overestimates the true layer base height (Winker et al. 2009). Although CloudSat can probe an optically thick cloud layer, it is likely to miss small-scale clouds; it also has a lower sensitivity to optically thin clouds than CALIPSO (Sassen et al., 2008). Most previous studies have verified that the combination of CALIPSO and CloudSat can provide the vertical structure of cloud layers, which can range from optically thin cirrus and boundary layer clouds to deep and optically thick precipitating systems (Mace et al. 2009). Therefore, the information on the middle and low clouds detected by CloudSat and the high clouds sensed by CALIPSO are considered credible for studies on vertical cloud variations (Liu et al. 2012; Mao et al. 2015).

L'Ecuyer et al. (2008) detected biases between the radiative data of 2B-FLXHR from CloudSat and Clouds and the Earth's Radiant Energy System with the monthly and 5° mean in the global scale. The biases of outgoing shortwave radiation, outgoing longwave radiation, surface shortwave radiation (SSR), and surface longwave radiation were $<0.1\ W/m^2$, $5.5\ W/m^2$, $13\ W/m^2$, and $16\ W/m^2$, respectively. Fortunately, the uncertainties in 2B-FLXHR fluxes decrease significantly for longer time-scale averages (L'Ecuyer et al. 2008). Although the cloud radiative effect (CRE) derived from CloudSat largely ignores the contribution of high thin clouds, this contribution is much smaller than that of low clouds (Henderson et al. 2013). In this study, the shortwave (SW) solar radiation ($<4\ \mu m$) was assumed as the total incoming solar radiation at the top of atmosphere (TOA) because the longwave (LW) solar radiation ($>4\ \mu m$) contributes $<1\%$ of the total incoming solar radiation. Therefore, CRE derived from CloudSat can credibly describe the radiative effect of clouds, especially that of the middle and low clouds, in large space- and time-scales.

2.2. Principle and methods

In this study, we employed CloudSat 2B-CLDCLASS and 2B-FLXHR R04 products, as well as CALIPSO Level 2 cloud layer products from March 1, 2007 to February 28, 2016 to analyze the effects of 3D cloud variations during daytime on the recent climate warming of the TP. Note that CloudSat and CALIPSO data from March 1, 2011 to February 29, 2012 were excluded due to the lack of CloudSat data during this period. Strict selection procedures were implemented to control the quality of data products and to ensure credible conclusions, which include the CPR cloud mask and the radar reflectivity from the 2B-GEOPROF being >20 and −28 dbZ, respectively, and the quality flag from the 2B-CLDCLASS being confident to CloudSat (Mace and Zhang 2014). For CALIPSO, data quality is maintained by screening the cloud layer with cloud and aerosol discrimination (i.e., >20) (Hu et al. 2009).

Based on the study by You et al. (2013), we selected the region within the red line as the study region, which contains most of the TP above 4000 m a.s.l., as shown in Fig. 1. Considering the terrain of the TP, we define low and high clouds with cloud base heights (CBH) lower than 6.5 km a.s.l. and higher than 10 km a.s.l., respectively, according to the classification scheme of clouds from traditional surface observations (Sassen et al., 2008). Clouds mainly have a cooling effect on the Earth with annual globally mean SW CRE and LW CRE of $-47.3\ W/m^2$ and $26.2\ W/m^2$, respectively (IPCC 2013). Similarly, the SW cooling effect is stronger compared with LW warming of cloud over the TP, especially in surface (Henderson et al. 2013; Loeb et al. 2009). Accordingly, this paper mainly discusses the 3D cloud variations and their effect on SW radiation. We do not restate the daytime specificity of the study in the rest of the paper.

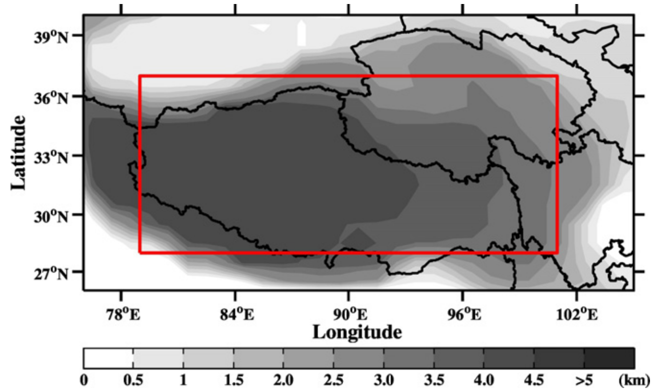

Fig. 1. Distribution of terrain in the TP and its surrounding areas, and the study area (within the red line) in this study.

3. Results and discussion

3.1. Changes of 3D cloud distribution

Fig. 2a shows the total cloud fraction detected by CloudSat declines rapidly by approximately 4.0% from 2007 to 2015. The total cloud fraction detected by CALIPSO was approximately 75% with a slight decrease due to the sensitivity of CALIPSO to high thin clouds. The probability of a cloud layer to be detected by CALIPSO as transparent is essentially

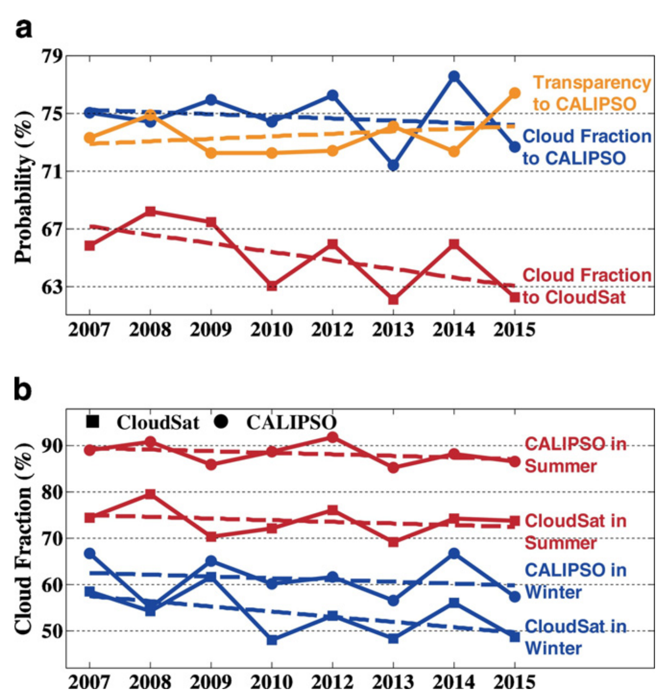

Fig. 2. Variations in (a) annual and (b) seasonal total cloud fraction detected by CloudSat and CALIPSO, and probability of transparent cloud layer to CALIPSO during daytime over the TP from 2007 to 2015.