Quantitative analysis of surface warming amplification over the Tibetan Plateau after the late 1990s using surface energy balance equation

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Abstract

Land surface warming is amplified over the Tibetan Plateau (TP) compared with the global climate warming hiatus since the end of the 1990s. Based on in situ observations and two reanalysis datasets, the processes involved were investigated by calculating partial temperature changes using the surface energy budget equation. The results indicated that the enhanced downward longwave radiation under clear-sky condition and the positive surface albedo feedback (SAF) related to the reduced snow cover are responsible for the pronounced surface warming, especially in winter. Meanwhile, the changes in cloud radiative forcing, surface sensible and latent heat fluxes (H + LE), and heat storage (Q) have a much weaker cooling effect. These results indicate that the enhancement of downward clear-sky longwave radiative fluxes and SAF have played an important role in the accelerated surface warming over the TP during recent decades.

Keywords: the Tibetan Plateau; warming amplification; surface energy balance; downward longwave radiation; surface albedo feedback

1. Introduction

Large-scale mountains are sensitive to climate warming and their in situ climate and ecosystem responses provide a unique perspective for understanding the impact of ongoing climate change. Previous studies have reported a warming amplification phenomenon in the Arctic (e.g. Holland and Bitz, 2003; Vavrus, 2004; Cai, 2005; Winton, 2006a, 2006b; Lu and Cai, 2009; Barnes, 2013; Perlwitz et al., 2015) and global mountain regions (e.g. Fyfe and Flato, 1999; Liu and Chen, 2000; Vuille et al., 2003; Pepin and Seidel, 2005; Duan et al., 2006; Rangwala et al., 2010, 2013, 2016; Ohmura, 2012). Possible mechanisms include the changes in radiative forcing related to the enhanced greenhouse effect (e.g. Liu and Chen, 2000; Chen et al., 2003; Rangwala et al., 2013), the surface albedo feedback (SAF) (Ghatak et al., 2014; Pepin et al., 2015; You et al., 2016), changes in surface radiation fluxes (Liu et al., 2009; Rangwala et al., 2010, 2013, 2016; Yan et al., 2016), and changes in water vapour and cloud amount (Duan and Wú, 2006; Rangwala et al., 2010, 2013, 2016; Yang et al., 2012; Rangwala, 2013; Pepin et al., 2015).

In particular, in contrast to the climate warming slowdown or hiatus for the global or hemisphere average since the end of the 1990s (Easterling and Wehner, 2009; Knight et al., 2009; Fyfe et al., 2013; Kosaka and Xie, 2013; Roberts et al., 2015), a persistent increasing trend in air temperature has been reported over the Tibetan Plateau (TP) (Duan and Xiao, 2015; You et al., 2016). However, a quantitative comparison of the relative importance among the involved dynamic and thermodynamic processes is absent. The purpose of this study was to quantitatively discuss the contribution of SAF, the cloud radiative feedback (CRF), the clear-sky shortwave (SW) radiation with effect of SAF already being excluded, the downward longwave (LW) radiation feedback under clear-sky condition, the heat storage (Q), as well as sensible and latent heat fluxes (H + LE), to the amplified TP surface temperature ($T_s$) in 1998–2014 compared with those in 1979–1997 via computing partial temperature changes (PTCs) related to the above processes in the energy budget equation over the TP surface.

2. Data and method

2.1. Data

Four datasets were used in this study. (1) The fourth-daily $T_s$ at 73 regular surface meteorological stations over the TP are provided by the China Meteorological Administration. These stations together with their elevations are shown in Figure 1(b). (2) The Modern-Era Retrospective Analysis for Research and Applications (MERRA) dataset (Rienecker et al.,...
2.2. Method

Following Lu and Cai (2009), the energy budget equation at the earth surface utilized to compare the relative importance of different dynamic and thermodynamic terms to the $T_s$ change can be written as:

$$4\sigma T_s^3 \Delta T = - (\Delta \alpha) \left( \bar{S} + \Delta \bar{S} \right) + \Delta \text{CRF}_s + (1 - \bar{\alpha}) \Delta S^{1,\text{clr}} + \Delta \text{LW}^{1,\text{clr}} - \Delta Q - \Delta (H + \text{LE})$$  (1)

where the overbar in this study indicates the climatic mean state for 1979–1997, and $\Delta$ means the change using the mean value in 1998–2014 minus that of 1979–1997. $\sigma$ is the surface emissivity, $\alpha$ is albedo, and $\cdot^{\text{clr}}$ is for clear-sky conditions.

In this equation, changes of SAF, CRF, SW, LW, $Q$, as well as the sum of $H$ and LE constitute the six terms on the right side, respectively. The fourth term represents the change of the downward longwave radiative fluxes under clear-sky condition, which is due to collectively changes in atmospheric water vapour and temperature, as well as $\text{CO}_2$ concentration.

In Equation (1), each term can be obtained from the MERRA and JRA-55 reanalysis datasets or through calculations for those obtained under clear-sky conditions or when cloud exists. Divided by $4\sigma T_s^3$, the terms on the right hand side represent the individual PTCs leading to the change of $T_s$. The variables used from both datasets were monthly mean values for the time range 1979–2014, and the area mainly focused on was the TP, namely $27^\circ – 40^\circ \text{N}, 65^\circ – 105^\circ \text{E}$.

3. Results and discussions

3.1. Substantial surface warming over the TP after 1998

Figure 1(a) shows the $T_s$ trend during 1980–2014 averaged for the 73 meteorological stations and the gird-averaged results above 2000 m in the JRA-55 and MERRA reanalysis datasets, temperature anomalies are calculated as the departures from the climatological mean of 1979–2014. The $T_s$ variation is flat before 1998 while a substantial warming trend occurs after that, hence, we chose the periods 1979–1997 and 1998–2014 for a comparison in the following study. Consistent with the near surface air temperature change in this period (Duan and Xiao, 2015; You et al., 2016), the $T_s$ over the TP is obviously higher in the second stage than that in the first stage, with a 73-station-averaged anomaly of 0.59°C for 1979–1997 and −0.56°C for 1998–2014 relative to the whole period. A similar result can also be seen in the two reanalysis datasets.

3.2. Relative importance of different processes

By utilizing Equation (1), we decomposed the $T_s$ change after and before 1979–1997 and 1998–2014 to detect the relative importance of the contribution of different processes to the amplified surface temperature and its seasonality. Figure 2 shows the seasonal mean $T_s$ change and the individual PTC corresponding to the terms on the right side of Equation (1) derived from the JRA-55 and MERRA reanalysis datasets. The difference between the $T_s$ change and the sum of all the PTCs ranges from 0.03 to 0.15°C in different seasons, which comes mostly from the linearization of the outgoing longwave radiation at the surface.
The $T_s$ amplification is strongest in spring, and weakest in summer. The SAF reaches its maximum in winter (JRA-55) or spring (MERRA), with the PTC being 0.72 and 0.61 °C, respectively, dominating all other terms. In summer and autumn, however, SAF is relatively weak and contributes less to the $T_s$ change. The changes in surface CRF tend to cool the land surface, but the corresponding PTC is rather small, especially in autumn. Thus, only a small portion of the SAF is balanced out by the negative CRF, which is induced mostly by the increased shortwave radiation reflected by clouds. Similarly, the PTC from SW over the TP surface is negligible. The augment of water vapour influences SW to a large extent by way of expending the absorption of incident shortwave radiation in the air and thus reducing the absorption of solar radiation obtained over the land surface.

The seasonality of the PTC due to the LW variation reveals a similarity to the surface warming over the TP surface in terms of amplitude, suggesting that a large portion of the TP surface warming is associated with the increase in LW, which indicates the total impact of the variation of CO$_2$ concentration, water vapour, and temperature in the atmosphere.

The PTC due to the change in $Q$ is negligible in all seasons, and the sum of $H$ and LE tends to cool the

![Figure 2. The $T_s$ change and the PTCs (°C) due to the variation terms of SAF, CRF, SW, LW, $Q$, the sum of $H$ and LE, and the sum of the PTC over the TP in 1998–2014 minus that in 1979–1997. (a)–(d) For the MERRA dataset. (e)–(h) For the JRA-55 dataset.](image-url)
3.3. Atmospheric water vapour and SAF related to the reduced snow cover

The seasonal dependence of the SAF on the surface warming might be related to the snow cover and depth, because it reaches its annual peak in winter and spring over the TP. A recent study (You et al., 2016) has emphasized that the persistent warming since 1998 should be directly related to the reduced snow cover and depth over the TP. To confirm this point, in Figure 3(a), we show the corresponding snow depth change from observations and the two reanalysis datasets. As the time periods, areas of interest and variables are different, the result was different from which of Che et al. (2008), the snow depth decreases in all seasons especially in winter and spring, implying that the decrease in the SAF and the associated increase in absorbed solar radiation owing to the loss of snowpack play a significant role in triggering the $T_s$ warming.
The enhanced LW should be primarily ascribed to the variations of air temperature and water vapour in the atmosphere. Over the TP, the atmospheric temperature, especially in winter, has increased substantially during the recent global warming hiatus period (Duan and Xiao, 2015; You et al., 2016), which should be responsible for the enhanced winter LW. On the other hand, the total atmospheric water vapour in Figure 3(b) shows a remarkable increasing trend in summer, which can explain the enhanced summer LW. These results indicate the importance of the atmospheric dynamical and thermos-dynamical processes for the surface warming amplification over the TP.

3.4. Seasonal cycle at the same latitudes

Are the $T_a$ amplification and the associated surface energy balance unique over the TP compared with other areas at the same latitudes? As shown in Figure 4, although warming amplification also exists in other regions, such as central Asia and the Rocky Mountains, the relative importance of the changes on the right hand side of the Equation (1) varies with both longitude and season. In particular, the strongest winter warming trend occurs in the TP and the corresponding strong positive SAF can be found only in the TP. This implies that the climate change and surface energy balance over the highest plateau in the world are unique.

4. Conclusion

This study has revealed the surface warming amplification over the TP during recent decades, with the largest and smallest magnitudes appearing in winter and summer, respectively. Diagnosis of the surface energy balance indicated that the combined effect of the enhanced LW and the positive SAF played the dominant role in the stronger surface warming during 1998–2014 compared with that in 1979–1997. Further analysis suggested that the enhanced LW was induced mainly by the increased atmospheric water vapour, while the positive SAF was directly related to the reduced snow cover. Meanwhile, changes in CRF, $H$, and LE, and $Q$ had a much weaker cooling effect in most seasons during 1998–2014. These results demonstrate the importance of the enhancement of downward clear-sky longwave radiative fluxes and SAF in contributing to the surface warming over the TP.

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