



**Observed  
high-altitude  
warming and snow  
cover retreat over  
Tibet**

Y. Xu et al.

# Observed high-altitude warming and snow cover retreat over Tibet and the Himalayas enhanced by black carbon aerosols

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Received: 12 May 2015 – Accepted: 11 June 2015 – Published: 10 July 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

Himalayan mountain glaciers and the snowpack over the Tibetan Plateau provide the headwater of several major rivers in Asia. In-situ observations of snow cover fraction since the 1960s suggest that the snow pack in the region have retreated significantly, accompanied by a surface warming of 2–2.5 °C observed over the peak altitudes (5000 m). Using a high-resolution ocean–atmosphere global climate model and an observationally constrained black carbon (BC) aerosol forcing, we attribute the observed altitude dependence of the warming trends as well as the spatial pattern of reductions in snow depths and snow cover fraction to various anthropogenic factors. At the Tibetan Plateau altitudes, the increase of atmospheric CO<sub>2</sub> concentration exerted a warming of 1.7 °C, BC 1.3 °C where as cooling aerosols cause about 0.7 °C cooling, bringing the net simulated warming consistent with the anomalously large observed warming. We therefore conclude that BC together with CO<sub>2</sub> has contributed to the snow retreat trends. Especially, BC increase is the major factor in the strong elevation dependence of the observed surface warming. The atmospheric warming by BC as well as its surface darkening of snow are coupled with the positive snow albedo feedbacks to account for the disproportionately large role of BC in high-elevation regions. These findings reveal that BC impact needs to be properly accounted for in future regional climate projections, in particular on high-altitude cryosphere.

## 1 Introduction

Himalayan mountain glaciers and snow packs have a major impact on the water systems of major rivers throughout Asia and the people living in the river basins. Recent observations suggested a continuing decline in Himalayan mountain glaciers and snow cover. Bajracharya et al. (2008) observed that the Himalayan glaciers are retreating at rates ranging from 10 to 60 myr<sup>-1</sup>, and many small glaciers have disappeared. Gardner et al. (2013) also showed with satellite observations the steady reduction of Western

### Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Observed  
high-altitude  
warming and snow  
cover retreat over  
Tibet**

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

China glaciers with the most rapid decline observed in the Himalayan mountain regions. Changes in the cryosphere are accompanied by documented surface warming trends over Tibet, which reveals a strong altitude dependence of surface warming with peak warming trends of 2–2.5 °C at 5000 m from 1961 to 2006 (Liu et al., 2009).

The last few decades also witnessed rapid growth in human population and economic activities, causing intense air pollution over the Asian region. Among the many air pollutants, black carbon (BC) aerosols have been shown to have a significant impact on global and regional climate change (Ramanathan and Carmichael, 2008). Many previous studies have linked Asian aerosols (including sulfates and BC) with monsoon systems and have demonstrated the aerosol impact on summer rainfall (Ramanathan et al., 2005; Meehl et al., 2008). The impact of BC aerosols have also been shown to have impact on warming trends over the Himalayan/Tibetan region (Ramanathan et al., 2007), on the retreat of Himalayan glaciers (Menon et al., 2010; Qian et al., 2011), and on Eurasian snow cover (Flanner et al., 2009). Observationally, using ice-core samples to reconstruct historical BC content over Tibet, Xu et al. (2009) suggested BC is a significant contributing factor in causing the glacier change.

To date global climate models forced by various radiative forcing scenarios have difficulty in simulating either the record surface warming or its anomalously strong altitude dependence. Few of these earlier studies of the Himalayan and Tibetan climate change have considered the combined effects of all the following factors: BC direct heating of the atmosphere, the heating of snow packs and glaciers by BC darkening the snow and ice, the greenhouse effect of CO<sub>2</sub> and the surface cooling effects by aerosols other than BC.

In this study, we used a state-of-the-art global climate model to conduct a suite of model experiments to understand BC's role in the cryosphere change over the Himalaya and Tibetan region. A unique feature of the present study, compared with earlier studies, is that BC radiative forcing is constrained with multiple sources of observations (satellite observed aerosol optical depths and ground network of spectral sun-photometer measurements). We also used a newly developed method to separate the

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

BC contribution to solar absorption from other aerosols (sulphates, organics and brown carbon) and calculate its direct radiative forcing (Bahadur et al., 2012; Xu et al., 2013). Previous studies (Ramanathan et al., 2007; Lau et al., 2010; Menon et al., 2010; Qian et al., 2011) included the effects of BC on the atmosphere and the cryosphere, but the simulated BC radiative forcing by these “standard” models used in CMIP5 (Coupled Model Intercomparison Project Phase 5) is strongly biased to low values (Bond et al., 2013) due to emission inventory biases and missing physical treatments (Jacobson, 2012). As shown in Bond et al. (2013), current models are underestimating BC solar absorption over South Asia by a factor of two to five. In this study, we scaled the simulated BC forcing in the climate model by factors ranging from two to four to bring the simulated values closer to the observationally constrained values (Xu, 2014). Another improvement in this study is that the simulations were conducted using a fully coupled ocean–atmosphere–land model at a high resolution of  $1^\circ$  by  $1^\circ$ , in which a new land snow module is adopted (Lawrence et al., 2011) to account for BC deposition effect on snow and ice.

## 2 Methods

### 2.1 The global climate model

CESM1 (Community Earth System Model 1) is a coupled ocean–atmosphere–land–sea-ice model. CESM1 climate simulations have been documented extensively (Meehl et al., 2013). The CESM1 (CAM5) used in this study is a version with a finite volume nominal 1-degree horizontal resolution ( $0.9^\circ$  by  $1.25^\circ$ ) and 30-level vertical resolution. The highest model level is about 36 km (4 hPa) in the stratosphere, and lower levels close to surface (boundary layers) have vertical resolutions of about 100–200 m.

CESM1 (CAM5) can include forcings from greenhouse gases (GHGs) as well as concentrations of tropospheric ozone and stratospheric ozone (Lamarque et al., 2010). The concentrations of various gases were calculated off-line and prescribed into model

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



simulations, unlike the aerosol loading calculated online from the emissions. The three-mode modal aerosol scheme (MAM3) has been implemented (Liu et al., 2012) and provides internally mixed representations of number concentrations and mass for Aitken, accumulation, and coarse modes of various aerosol species (SO<sub>4</sub>, BC, organic carbons, dust, sea salt). The new cloud microphysics scheme (Morrison and Gettelman, 2008) allows the number concentration of cloud drops and ice crystals to be affected by aerosol concentrations and therefore accounts for the “indirect radiative forcing” of aerosols.

The land model (CLM4) also includes major updates, making it more versatile in simulating snow packs (Lawrence et al., 2011). The sub-grid processes including melting, metamorphism, deposition and redistribution are considered in a snow cover fraction parameterization (Niu and Yang, 2007). Other parameterizations include snow compaction (Lawrence and Slater, 2010) and the albedo calculations for snow on or around vegetations (Wang and Zeng, 2009). Compared to the previous model versions, the albedo contrast between snow-covered and non-snow-covered area is more consistent with observations.

## 2.2 BC treatment in the model

- a. Treatment of BC albedo effects. The deposition of BC particles, due to gravity or rainfall removal, is a mechanism to remove aerosols from the atmosphere, and therefore a sink term for the atmospheric BC mass balance. BC particles deposited onto surface of high-albedo snow or ice would reduce surface albedo. The snow model of CLM4 is significantly modified via the incorporation of SNICAR (Snow and Ice Aerosol Radiation) module, which represents the effect of aerosol deposition (BC, organic carbon and dust) on albedo, introduces a grain-size dependent snow-aging parameterisation, and permits vertically resolved snowpack heating (Flanner et al., 2007). This new module considers the albedo change by counting the surface concentration of BC and it calculates the surface radiative

energy flux at multiple wavelengths. The surface albedo change will consequently alter the energy balance at the surface and in the atmosphere.

- b. BC atmospheric radiative forcing. The present-day emission is adjusted from the standard model emission inventory to account for the potential model underestimation of BC forcing. Our previous analysis (Xu et al., 2013; Xu, 2014) showed that such a correction would improve model-simulated radiative forcing compared with direct observations. Without the observationally constrained values, the modelled forcing (and simulated temperature change) would be lower by about a factor of two to four.

### 2.3 Model experiments

To isolate the climate impact of individual forcing agents, we contrasted the perturbed model simulations with present-day forcing (b) to the long-term pre-industrial control simulations (a). The approach is similar to the classical instantaneous CO<sub>2</sub> doubling experiment (Manabe and Wetherald, 1975). Additionally we conducted fixed-SST experiment for radiative forcing diagnostics (c) and 21st century transient runs to better compare with observations. The details of these sets of simulations are below.

- a. Control simulation for pre-industrial climate. We have a 319-year-long pre-industrial control run, and extended it with an additional 75 year run to test if there was any discernible drift in the mean climate state. The Northern Hemisphere temperature does not show any statistically significant drift. Therefore, we lay the foundation for our analysis by employing the original 319 year run and the extended 75 year run (394 years in total) as a control case. Natural variability of the climate system is examined from the unforced 394 year pre-industrial simulations.
- b. Perturbed simulations with instantaneously imposed present-day BC, SO<sub>4</sub> and CO<sub>2</sub>. We ran the perturbed simulations in fully coupled mode for 75 years, starting from the end of the 319th year of the control simulation. The difference between

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion









### 3 Observed snow cover reduction linked with BC

The National Snow and Ice Data Centre (NSIDC) dataset (Armstrong and Brodzik, 2005) show that the snow cover over the Himalayan mountain range has declined at a rate of more than  $10\% \text{ decade}^{-1}$  since the 1960s (Fig. 1). The snow cover retreat is greater along the Himalayan mountain range than in Eurasia during the same period. In-situ studies about regional glaciers and snow pack also reported strong declining trends. For example, Ma and Qin (2012) used 754 stations in China to document statistically significant declining trends of spring snow for the Qinghai–Tibet Plateau for the 1951–2009 period. Consistently, permafrost degradation has been reported on the Tibet Plateau (Cheng and Wu, 2007; Li et al., 2008).

Several satellite measurements since 2001 provided additional observations in snow cover fraction. The observed trend over this shorter period (2001–2012) in NSIDC dataset is less significant (Fig. S1a) and negative trends are only found along some portion of Himalaya range. Consistently, the 5 km MODIS (The Moderate Resolution Imaging Spectroradiometer) dataset (Fig. S1b) also shows that the snow cover fraction averaged over the entire Tibet region only has a slight decrease. But as other studies have pointed out (Pu et al., 2007; Pu and Xu, 2009), the highest altitudes of 5750–6000 m exhibits larger negative trends ( $-6\% \text{ decade}^{-1}$ ). We note that at shorter time-scale (10 years), the snow cover trend is heavily influenced by natural variability and less significant. For example, during 1980–1991 (Fig. S1c) or during 1990–2001 as examined in Menon et al. (2010), the declining trends are much larger. Nevertheless, the declining trend during the 40–50 year timescale (Fig. 1) is more robust and warrants further investigation on its causes, which is the main objective of this study.

To understand the causes of the observed trends of snow reduction over the multi-decadal timescale, we conducted global climate model simulations, in which BC emissions,  $\text{CO}_2$  concentration or  $\text{SO}_4$  emissions are increased instantaneously from pre-industrial to present-day levels. Figure 2 (left column) shows the simulated change of snow cover fraction due to the increase of BC,  $\text{CO}_2$  and  $\text{SO}_4$  aerosols. The pattern

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of snow cover decline in the BC model simulation captures the broad features of the observed decline (Fig. 1), with the largest snow reduction along the mountain range. The Tibetan Plateau on average showed a reduction in snow fraction of 1.9 % due to BC. The snow fraction shrinks by 2.9 % due to present-day CO<sub>2</sub>. Along the Himalayan mountain range, where the near-permanent snow cover exists, the reduction of snow fraction exceeds 10 % in both BC and CO<sub>2</sub> cases.

Menon et al. (2010) attempted to simulate reduction trends during 1990s but the spatial distribution of the trend was not well simulated mainly due to the coarser resolution of the model. Qian et al. (2011) also acknowledged their model's limitation in capturing the snow cover climatology and therefore may have biases in estimating BC deposition over snow. The modeling work presented here is a major step forward in terms of the spatial resolution (about 1° by 1°) at global scale, as opposed to the earlier studies (2.8° by 2.8° in Flanner et al. (2009) and Qian et al. (2011); and 4° by 5° in Menon et al., 2010). Future studies, especially using regional climate models with even higher resolutions, are needed to improve the fidelity of model simulations of snow pack and glaciers over topography-complicated regions such as the Himalayas and the Tibetan Plateau.

One consequence of the snow cover reduction is the decrease in surface albedo, which provides a positive feedback mechanism to localized warming. Such a surface albedo change in response to sea ice loss has been observationally detected (Kay and L'Ecuyer, 2013; Pistone et al., 2014) and is important in explaining amplified Arctic warming. Flanner et al. (2011) also used observations during recent decades to calculate the surface albedo feedback in Northern Hemisphere large-scale snow-covered regions. Our simulations show that surface albedo over the Tibet region decreased by over 2 % (Fig. 2, right column) in response to BC. The maximum reduction occurs right along the Himalayan mountain range and part of the Tibet–Sichuan mountain regions.

The surface albedo decrease due to CO<sub>2</sub> shares a similar spatial pattern with BC (Fig. 2, right column) but with a smaller magnitude (Table 2b). Moreover, the snow depth reduction in response to CO<sub>2</sub> is only 30 % of that due to BC (Table 2c and Fig. 2),

and this highlights the larger effect of BC in causing the regional cryospheric change over the Himalayas and Tibet. Not surprisingly, in the simulations the snow cover and surface albedo are increasing in response to cooling aerosols like  $\text{SO}_4$  (Fig. 2), but in a smaller magnitude than that of the decreases due to BC and  $\text{CO}_2$ .

#### 4 Warming at high altitudes enhanced by BC

The Tibet region has witnessed increasing surface temperature by  $0.3^\circ\text{C decade}^{-1}$  – more than twice the global average (Wang et al., 2008). One feature of the surface-warming trend over Tibet is that the warming magnitude increases significantly with altitude (Liu et al., 2009). To understand this anomalous feature, we show in Fig. 3 the tropospheric temperature responses (as a function of altitude and latitude) to BC as well as  $\text{CO}_2$  and  $\text{SO}_4$ . BC-induced heating rate (Fig. 3a) is more concentrated over the Northern Hemisphere (NH) due to larger emissions there from industrial activities, consistent with radiative forcing distribution (Table 1). The notable feature of BC response is the elevated warming at altitudes of 4000 to 8000 m and  $30$  to  $60^\circ\text{N}$  (Fig. 3b), in particular over the Tibetan Plateau. Figure S2 shows the normalized temperature profile averaged just over the Tibetan Plateau.

The  $\text{CO}_2$  warming pattern (Fig. 3b) features an amplified warming at the surface of the Arctic and in the upper tropical troposphere.  $\text{CO}_2$  induced warming in the upper atmosphere (500 hPa) over Tibet is  $1^\circ\text{C}$ , larger than BC induced warming of  $0.5^\circ\text{C}$ , but the vertical gradient is much smaller (Fig. S2).  $\text{SO}_4$  cooling features an even stronger north–south asymmetry (north cooling; south slightly warming) but is more confined to the surface (Fig. S2).

Ground based observations have shown that the last three decades were subject to a factor of two greater warming in the high-altitude interior of the Tibetan Plateau than at the edge of the plateau and at lower altitudes. The observations in Liu et al. (2009) were made between 1965 and 2006 from ground meteorological stations on the Tibetan Plateau region, and they revealed clear altitude dependence in the daily-minimum sur-

### Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

face temperature (purple line in Fig. 4). The vertical profile of temperature change based on daily-average measurement from another reanalysis dataset (Fig. 5) also reveals similar altitude dependence. What's driving the larger warming at high-altitude regions?

Figure 4 shows the model-simulated change of the daily-minimum surface temperature as a function of elevation due to three different forcing agents ( $\text{CO}_2$ ,  $\text{SO}_4$  and BC). The surface temperature responses are calculated from all of the model grid cells over the Tibetan Plateau and the surrounding region ( $20\text{--}50^\circ\text{N}$ ,  $70\text{--}110^\circ\text{E}$ ) to capture the altitude variation in this region. As shown in Fig. 4, the altitude dependence of the surface warming is mostly determined by the response to BC forcing (red dots). At altitudes below 1000 m the warming is minimal, but with increasing altitudes the magnitude of the warming increases up to  $2^\circ\text{C}$  at 5000 m. The dependence of the surface warming on altitude is much smaller in the  $\text{CO}_2$  case, which only increased from  $1.2^\circ\text{C}$  warming at low altitudes to  $1.6^\circ\text{C}$  warming at higher altitudes (yellow dots).

The combined temperature response (black triangles in Fig. 4) by adding the individual trends due to BC,  $\text{CO}_2$  and  $\text{SO}_4$  is largely consistent with the observed trend. To test the additivity of the temperature response, we conducted another simulation in which all of the three forcings were imposed simultaneously. The warming profile simulated by the combined anthropogenic forcing experiment largely agree with the sum of the individual responses within 30% (Fig. 5). Some non-linearity is expected as discussed in other modelling studies (Ming and Ramaswamy, 2009). The agreement of the simulated and the observed warming profiles provides a qualitative estimate of the relative contributions of BC,  $\text{CO}_2$  and  $\text{SO}_4$ . Over the entire Tibetan Plateau,  $\text{CO}_2$ -induced surface warming is  $1.3^\circ\text{C}$ , compared to the BC-induced warming of  $0.84^\circ\text{C}$  (Table 1b). Almost half of the surface warming at the highest altitudes (around 5000 m) is due to BC.

A potential complexity arises due to the internal variability of the climate systems, which has been shown to be important in determining decadal trends over individual regions (Deser et al., 2012). To examine the role of natural variability, we calculated

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

the temperature trend from all 350 consecutive 45 year period out of 394 years simulations. The 80 % probability range of temperature change is shown in Fig. 5 (light blue shading). The magnitude of the warming rarely exceeds  $0.5^{\circ}\text{C}$  in any 45 year period in the long-term pre-industrial control simulations without any external forcing. Therefore we infer that the vertical gradient of the temperature trend found in the simulations is very unlikely due to natural variability.

Note that the climate simulations shown in Figs. 4 and 5 are driven by the instantaneous increase of present-day forcing. Since the real forcing trends were time dependent, we further analysed a set of 20th century transient simulation output from the same model (Fig. 6), as part of CMIP5. The relative contributions of  $\text{CO}_2$  and  $\text{SO}_4$  to the simulated warming are consistent between the two sets of simulations (the instantaneous forcing and transient forcing). But the trends estimated from the 20th century transient forcing simulations are smaller than the quasi-equilibrium response to instantaneous forcing (parenthesis in Table 1b). The reason is that only 70 % of  $\text{SO}_4$  forcing and about 60 % of  $\text{CO}_2$  forcing in the transient simulation were applied after 1960. The standard BC forcing (red solid line in Fig. 6) only lead to a weak warming, not exceeding the range of natural variability. As a result, the combined all-forcing responses (black triangles) did not capture the altitude dependence in observations very well.

Only when we adjusted historical BC forcing using the same scaling factors constrained by present-day observations, transient BC forcing induced a robust warming and amplification over high altitudes (red dots in Fig. 6), similar to what's shown in instantaneous forcing experiment. However, note that the historical time dependence of the BC forcing is more uncertain, and also we were only able to produce one ensemble of adjusted BC simulation, more subject to the influence of decadal variability. Therefore, the response to the instantaneous present-day BC forcing seems a more reliable indicator of the BC effects. While the absolute values of warming profile needs more model tests, our inference regarding the relative role of BC and  $\text{CO}_2$  in the observed decrease of snow cover as well as the major role of BC on the altitude dependence of the warming trends is robust.

## 5 Physical mechanisms of elevated warming due to BC

Both CO<sub>2</sub> and BC contribute to the elevated warming at 5 km as shown in Fig. 4. However, BC is mostly responsible for the vertical gradient of the simulated warming trend. Most of the BC aerosols in the region are emitted over India and China and subsequently transported to the Tibetan Plateau and the Himalayan mountain range. The physical mechanisms for the amplified warming at higher altitude due to BC are three-fold:

1. Direct heating in the atmosphere. BC absorbs a significant amount of solar radiation, as much as 25 % in typical pollution events as directly measured by multiple unmanned aircrafts over the Northern Indian Ocean (Ramanathan et al., 2007). The BC layer placed at higher altitude is even more efficient in absorbing solar radiation than at sea level, due to stronger solar radiation and the brighter underlying cloud surface. In our model simulation, the BC atmospheric heating rate is concentrated in the Northern Hemisphere (maximum at 30° N), coincident with the location of the maximum temperature change (Fig. 3). The elevated BC layer, due to the topography of the Tibetan Plateau and the Himalayan mountain range, contributes to the elevated heating which is more than 0.1 °C day<sup>-1</sup> and about 0.03 °C day<sup>-1</sup> at 4 km (Fig. S3a). Such anomalous heating in the atmosphere over the elevated regions will contribute to the loss of ice and snow in two ways: (a) it will increase melting of the glaciers and snowpack; and (b) more of the precipitation will fall as rain instead of snow. CO<sub>2</sub> increase also induces longwave heating of the atmosphere (Fig. 3c), but it is well known that warming enhancement at the upper tropical troposphere is mostly due to moist convection processes (Manabe and Wetherald, 1975) and the warming enhancement at high altitudes is not showing sharp gradient as in BC case (Figs. S2b and 4).
2. Surface darkening by BC deposition. Snow and ice have a high surface albedo and reflect as much as 50 to 90 % of incoming solar radiation. Transported BC

### Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



aerosols over the Himalayas and the Tibetan Plateau are removed from the atmosphere due to precipitation. When BC aerosols are deposited over the snow and ice, they increase the absorption of solar radiation and cause surface warming (Wiscombe and Warren, 1980; Chýlek et al., 1983).

Recent studies have also suggested the influence of BC aerosols over regions like the Alps (Painter et al., 2013) and Eurasian land (Flanner et al., 2009). Model-based studies on the Himalayan Mountains are limited because the current generation of models still has limited capacity in the land component in simulating land ice and glacier change. Menon et al. (2010) found that when the model includes snow albedo change due to BC the snow cover reduction is twice as large as the simulation with BC atmospheric heating effect only. Flanner et al. (2009) also suggested that BC surface albedo darkening effects are important in causing Eurasian springtime snow-cover decline and are comparable to that of CO<sub>2</sub>.

The surface radiative forcing due to BC deposition over Tibet is estimated to be 4.6 W m<sup>-2</sup> based on a 5 year fixed SST (sea-surface temperature) simulation (Fig. S3b). Because of this strong positive surface forcing associated with surface darkening, the shortwave forcing due to BC at the surface increased from -1.5 W m<sup>-2</sup> (initially due to BC dimming effect) to a positive value of 3.1 W m<sup>-2</sup>. This positive forcing imposed directly at the surface is larger than the adjusted atmospheric heating due to BC over Tibet (1.6 W m<sup>-2</sup>). A recent modelling study (Ménégoz et al., 2014) also examined the role of BC deposition over snow in this region (with smaller forcing estimates of 1 to 3 W m<sup>-2</sup>), but their study did not include the atmospheric heating effect of BC. The radiative forcing due to snow deposition is sensitive to model parameterization (Yasunari et al., 2013). More observational constrains from both in-situ (Wang et al., 2013) and laboratory measurements (Hadley and Kirchstetter, 2012) are needed to constrain model parameterizations.

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

3. Snow albedo feedback. The melting snow in response to the two initial heating mechanisms discussed above will further decreased surface albedo and increase solar absorbing at the surface. The results based on the 60 year coupled model simulation suggest the surface albedo will further decrease by 1.4 % and effectively impose an additional  $3.2 \text{ W m}^{-2}$  short wave forcing at the surface. Note that snow albedo feedback mechanism is also operating in the  $\text{CO}_2$  warming (or  $\text{SO}_4$  cooling). In summary, the elevated heating and surface darkening due to BC are simultaneously causing local warming and snow melting. The snow cover reduction further reduces surface albedo and then provides a positive feedback. Figure S6 shows the seasonality of snow depth and suggests the early spring melting is important for this feedback. The net results of such a positive loop is an amplification factor of four for BC-induced Tibet warming from the global average values and significant snow and ice retreat.

## 6 Conclusions

15 The observed surface warming over the Tibetan and Himalayan region of about  $0.5^\circ\text{C}$  at sea level to about  $2\text{--}2.5^\circ\text{C}$  at 5000 m (from 1961 to 2006) has been an outstanding feature of climate trends. The more than  $2^\circ\text{C}$  warming is close to the peak warming trend observed anywhere on the planet. For comparison, the Arctic warming associated with large sea-ice retreat during this period is  $1.2^\circ\text{C}$ .

20 The high-resolution coupled ocean–atmosphere model in this study was able to attribute the observed warming trends and their high altitude enhancement to imposed increases in  $\text{CO}_2$ , BC, and  $\text{SO}_4$  aerosols. The simulated changes with all forcing imposed were consistent with the observations. The key to the success is that we obtained the BC forcing from the reconstruction of ground-based and satellite-based observations.

25 The imposed BC forcing was about two to four times (depending on the regions) larger than that simulated by the models using bottom-up emission inventories. The analysis of model simulations highlights that the high-altitude warming due to BC is as large as



CO<sub>2</sub> warming over the Tibetan Plateau and the elevated warming profile is unique in BC responses.

The observed record warming is accompanied by retreat of glaciers and snow cover as well as thinning of the snow packs. In response to the pre-industrial to the present-day increase in BC emissions, the annual averaged snow cover fraction over the Tibetan Plateau is reduced by more than 6 % (relatively), and the snow depth by approximately 19 %. The surface albedo decreases by more than 5 % along the Himalayan mountain range and 1.4 % over the entire Tibet, providing a positive local feedback to the enhanced local warming. In stark contrast, despite having five times larger effect in global mean temperature than BC, over Tibet CO<sub>2</sub> impact is only 1.5 times stronger in snow cover decrease, and only one-third in snow depth decrease.

We conclude that BC is instrumental in causing snow retreat and its effects are manifested simultaneously through a three-fold process: (i) direct atmospheric heating, (ii) darkening of the snow surface and (iii) the snow albedo feedback. It is important to note that, without the scaling factor we applied to bring the model BC forcing to the observationally constrained values, the impact of BC on the observed temperature trends would have been marginal. This perhaps explains why the models used in IPCC assessments have not simulated the role of BC in the large warming trend over the Himalayas.

**The Supplement related to this article is available online at doi:10.5194/acpd-15-19079-2015-supplement.**

*Acknowledgements.* This study was funded by the National Science Foundation (NSF, ATM07-21142) and by the Regional and Global Climate Modeling Program (RGCM) of the U.S. Department of Energy's Office of Science (BER), Cooperative Agreement DE-FC02-97ER62402. Y. Xu is also supported by the postdoctoral fellowship from the Advanced Study Programme (ASP) of National Center for Atmospheric Research (NCAR). NCAR is funded by the NSF.

**Observed high-altitude warming and snow cover retreat over Tibet**

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## References

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ACPD

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**Observed  
high-altitude  
warming and snow  
cover retreat over  
Tibet**

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Observed  
high-altitude  
warming and snow  
cover retreat over  
Tibet**

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**Observed  
high-altitude  
warming and snow  
cover retreat over  
Tibet**

Y. Xu et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


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**Observed  
high-altitude  
warming and snow  
cover retreat over  
Tibet**

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

**Table 1. (a)** TOA (top-of-atmosphere) radiative forcing ( $\text{W m}^{-2}$ , shortwave + longwave), due to BC (direct radiative forcing; pre-industrial to present-day; not including snow albedo effect),  $\text{CO}_2$  (pre-industrial to 400 ppm), and  $\text{SO}_4$  (direct and indirect effect, so-called “adjusted forcing”; pre-industrial to present-day). The radiative forcing is calculated by running the atmospheric model with fixed sea-surface temperature for 5 years. The domains of the Tibet are 30 to 40° N and 80 to 100° E. **(b)** Surface temperature change ( $^{\circ}\text{C}$ ) in response to different forcings in **(a)**. Surface temperature change is calculated by averaging the last 60 years of a 75 year coupled model simulation. The values in parenthesis are temperature change in the 20th century time-dependent forcing simulations (1960–2005). The linear trend ( $^{\circ}\text{C decade}^{-1}$ ) is first calculated and then multiplied by 4.5 to obtain the change with 45 year time frame. BC responses include the range of using “standard” and adjusted emissions.

(a) TOA net forcing ( $\text{W m}^{-2}$ )	BC	$\text{CO}_2$	$\text{SO}_4$
Global	0.5	1.7	−0.9
NH	0.7	1.7	−1.5
Tibet	1.1	0.6	−0.3
(b) Surface temperature change ( $^{\circ}\text{C}$ )	BC	$\text{CO}_2$	$\text{SO}_4$
Global	0.21 (0.04–0.15)	1.2 (1.0)	−0.5 (−0.4)
NH	0.29 (0.06–0.21)	1.3 (1.2)	−0.7 (−0.5)
Tibet	0.84 (0.22–0.69)	1.5 (1.0)	−0.7 (−0.3)

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)




## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

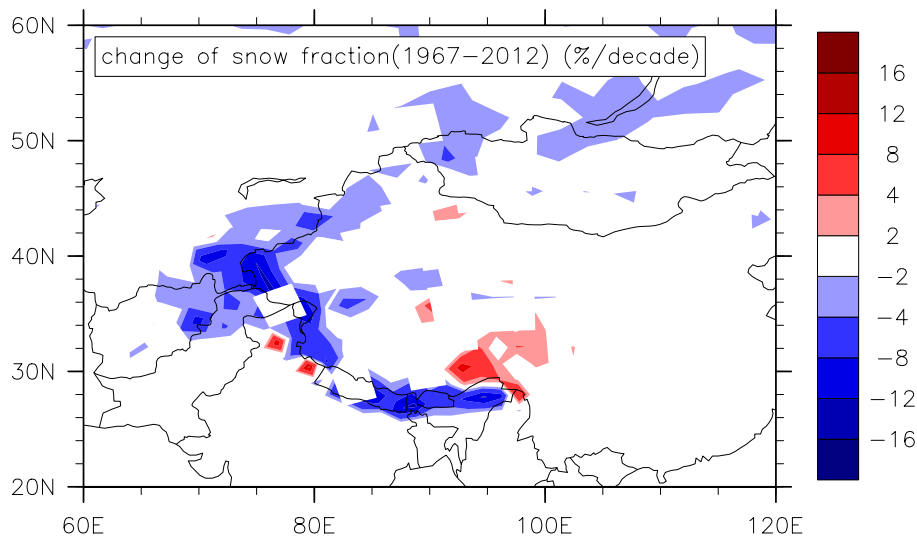
Interactive Discussion

**Table 2.** (a) Snow fraction (%), (b) surface albedo (%) and (c) snow depth over land (water equivalent, cm) change in response to different forcings. The relative change as a percentage is shown in parenthesis next to the absolute change.

(a) Snow fraction (%)	BC	CO <sub>2</sub>	SO <sub>4</sub>
Global	−0.13 (−2%)	−0.35 (−4%)	0.14 (2%)
NH	−0.26 (−3%)	−0.67 (−7%)	0.36 (4%)
Tibet	−1.9 (−6%)	−2.9 (−9%)	1.65 (5%)
(b) Surface albedo change (%)	BC	CO <sub>2</sub>	SO <sub>4</sub>
Global	−0.2 (−1%)	−0.68 (−4%)	0.28 (2%)
NH	−0.3 (−2%)	−0.79 (−5%)	0.44 (3%)
Tibet	−1.4 (−2%)	−1.1 (−2%)	1.1 (2%)
(c) Snow depth (cm)	BC	CO <sub>2</sub>	SO <sub>4</sub>
Global	−0.06 (−2%)	−0.15 (−4%)	0.1 (3%)
NH	−0.11 (−6%)	−0.28 (−14%)	0.2 (10%)
Tibet	−0.2 (−19%)	−0.06 (−6%)	0.16 (15%)

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.

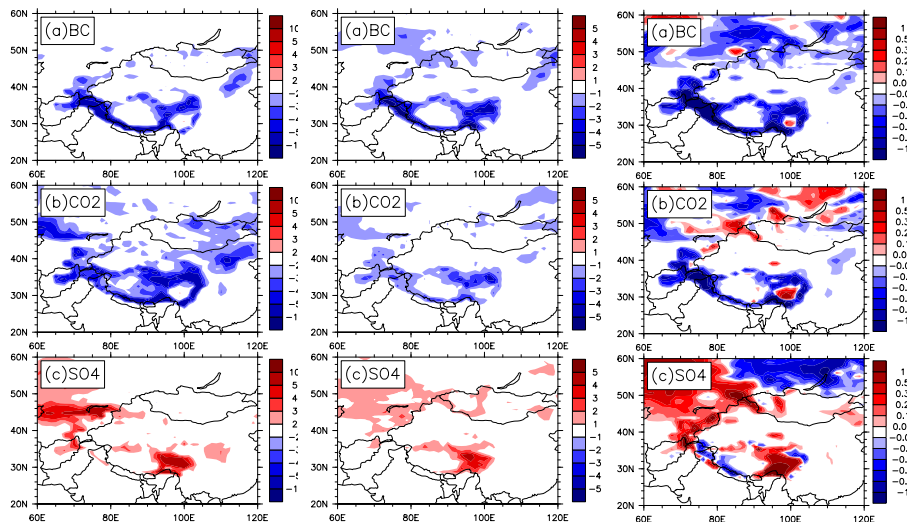


**Figure 1.** Observed snow fraction change ( $\% \text{decade}^{-1}$ ) from 1967 to 2012. Insignificant changes (confidence interval  $< 75\%$  calculated from student's  $T$  test) are not shown.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## Observed high-altitude warming and snow cover retreat over Tibet

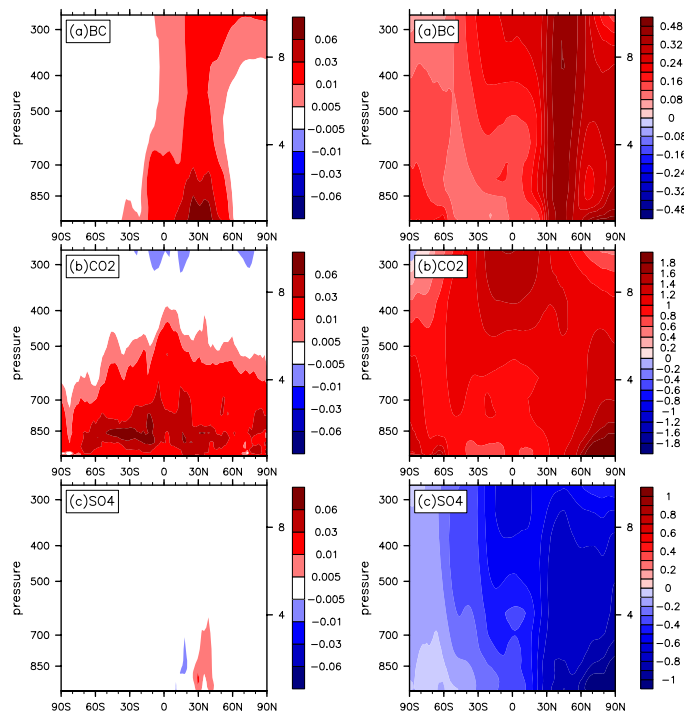
Y. Xu et al.



**Figure 2.** Left: **(a)** simulated change of snow fraction (%) due to present-day BC (vs. its pre-industrial level), **(b)**  $\text{CO}_2$  and **(c)**  $\text{SO}_4$ . Middle: same as left, but for surface albedo (%). Right: same as middle, but for snow depth (water equivalent, cm). The regionally averaged statistics are shown in Table 2.

## Observed high-altitude warming and snow cover retreat over Tibet

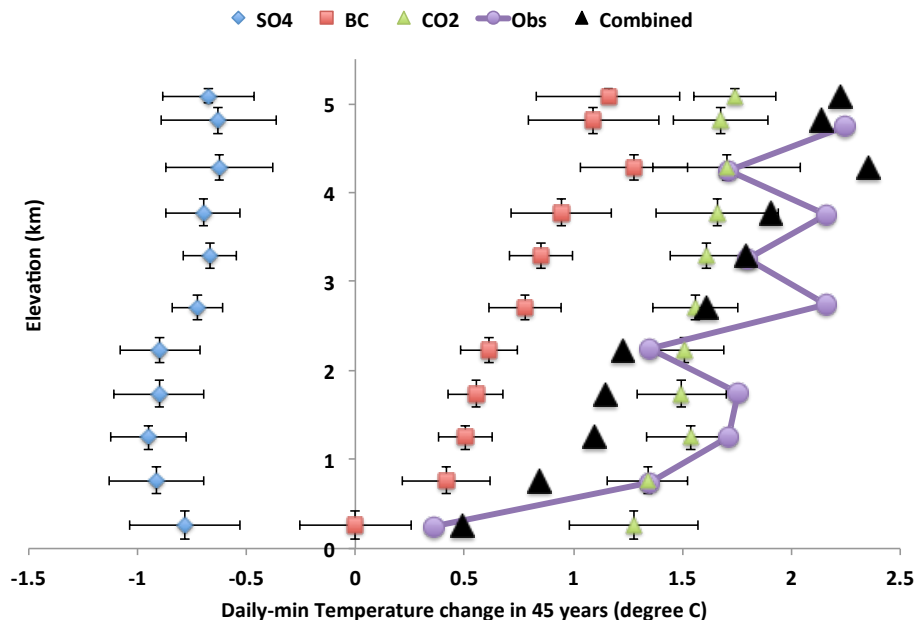
Y. Xu et al.



**Figure 3.** Left: radiative heating rate ( $\text{K day}^{-1}$ ) as a function of altitude and latitude due to **(a)** BC, **(b)** CO<sub>2</sub> and **(c)** SO<sub>4</sub>, calculated from the 5 year fixed SST simulations using the instantaneous radiative diagnostic procedure. Shortwave fluxes for BC and SO<sub>4</sub>, and longwave flux for CO<sub>2</sub>. Right: the temperature response ( $^{\circ}\text{C}$ ) due to **(a)** BC, **(b)** CO<sub>2</sub> and **(c)** SO<sub>4</sub>, calculated as the difference of the last 60 years of 75 year perturbed simulation and the 319 year long-term control.

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.



**Figure 4.** The change of daily-minimum temperature ( $^{\circ}\text{C}$ ) as a function of elevation (km). The observation from 1961 to 2006 are from Liu et al. (2006). The simulated temperature responses due to instantaneous increase of forcings ( $\text{CO}_2$ ,  $\text{SO}_4$  and BC) are calculated from model grid cells over the Tibetan Plateau and its vicinity ( $20\text{--}50^{\circ}\text{N}$ ,  $70\text{--}110^{\circ}\text{E}$ ) including low-lying regions and high-altitude regions. The standard deviation due to spatial variation of temperature response is shown as error bars. The sum of  $\text{CO}_2$ ,  $\text{SO}_4$  and BC responses are shown in black triangles.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

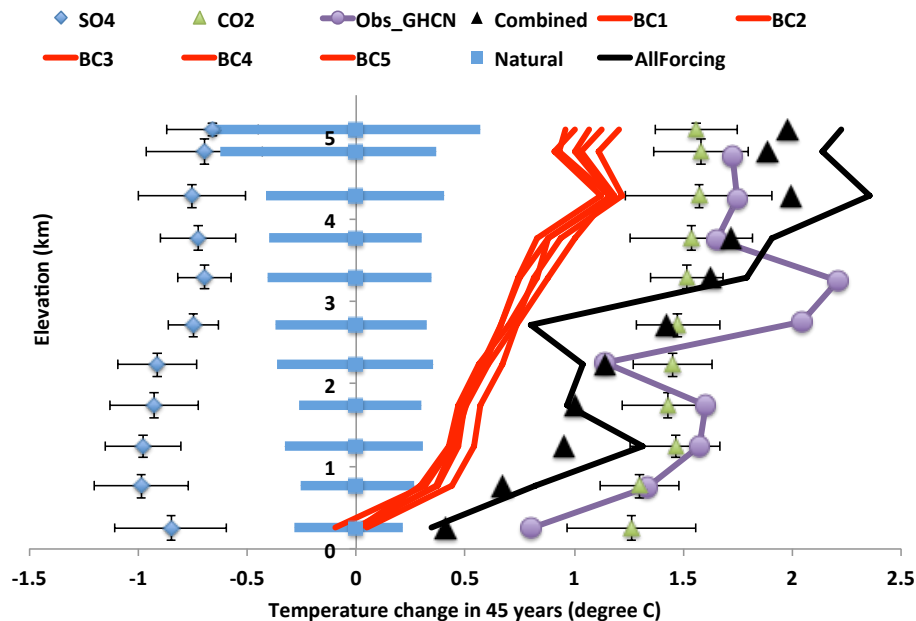
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.



**Figure 5.** Similar to Fig. 4, but with the following differences: (1) daily-mean surface temperature, not daily-minimum temperature, are shown; (2) the spread of five-ensemble member of BC simulations are shown in red lines; (3) the observations are from GHCN dataset (1961 to 2006); (4) the range of temperature change found in unforced pre-industrial control simulations is shown in blue shading and (5) the combined forcing simulation (black line) is shown in comparison with the sum of individual responses (black triangles).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

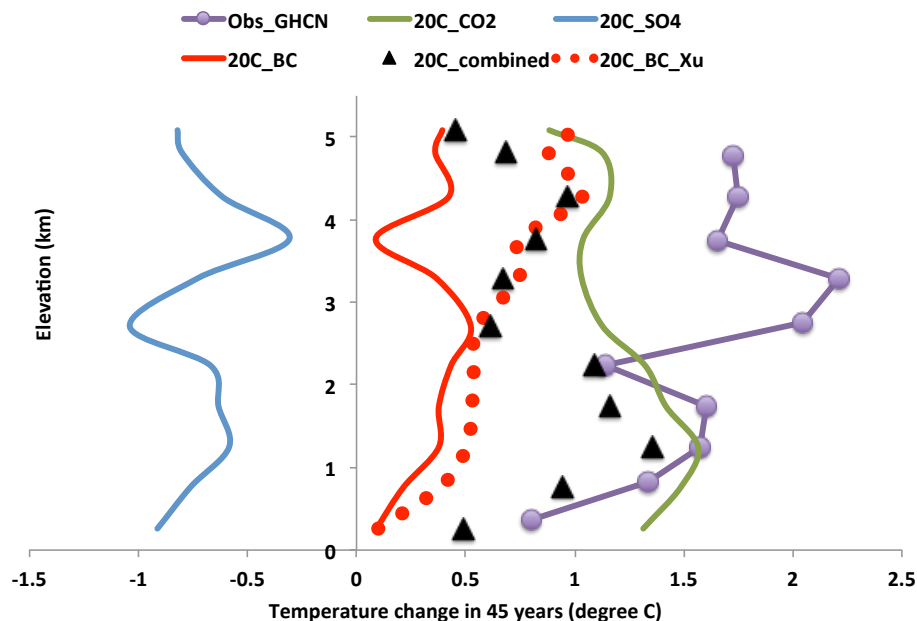
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Observed high-altitude warming and snow cover retreat over Tibet

Y. Xu et al.



**Figure 6.** Similar to Fig. 5 but showing results from the 20th century transient simulations (3 ensembles for each single forcing run). Note that the “standard” BC single forcing simulation used smaller BC emissions as in other CMIP5 models (red solid line). An additional simulation with adjusted larger BC emissions were shown (red dash line, one ensemble only).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion