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Reexamining the barrier effect of Tibetan Plateau on the South Asian summer monsoon

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The Tibetan Plateau's barrier effect

G.-S. Chen et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

|◀ | ▶|
◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

The Tibetan Plateau has been conventionally treated as an elevated heat source driving the Asian monsoon system, especially for the South Asian monsoon. Numerous model simulations with general circulation models (GCMs) support this hypothesis with the finding that the Asian monsoon system is weak or absent with all elevated topographies removed. A recent model simulation shows that the South Asian summer monsoon circulation is little affected with only the Himalayas (no Tibetan Plateau) kept as a barrier, leading to a hypothesis of the barrier "blocking" mechanism of the Tibetan Plateau. In this paper, a new series of experiments are designed to reexamine this barrier effect. We find that with the barrier, the large-scale summer monsoon circulation over South Asia is simulated in general agreement with the full Tibetan Plateau, which is consistent with the previous finding. However there remains significant differences in both wind field and precipitation field elsewhere, suggesting a role of the full Tibetan Plateau as well. Moreover, the proposed barrier "blocking" mechanism is not found in our experiments. The energy of the low-level air and the convection is lower/weaker over the Indian subcontinent in the full Tibetan Plateau experiment than that in the no-Tibetan Plateau experiment or the barrier only experiment, which is opposite to the barrier "blocking" hypothesis. Instead, there is a similar candle-like latent heating in the middle troposphere along the south edge of the Tibetan Plateau in both the full Tibetan Plateau and the barrier experiments, whereas this "candle heating" disappears in the no-Tibetan Plateau experiment. We propose that this candle heating is the key to understand the mechanisms of the Tibetan Plateau on the South Asian monsoon. Future studies are needed to check the source of the "candle heating" and its effect on the Asian monsoon.

1 Introduction

Numerous efforts have been made to understand the mechanisms of how the Tibetan Plateau can affect the regional as well as global climate, either mechanically or thermodynamically. In 1957, Yeh et al. (1957) and Flohn (1957) first found, using observations, that the Tibetan Plateau acts as an elevated heat source for the atmosphere in summer to drive the Asian monsoon. Later, with advances in computer technologies and developments of numerical climate models, general circulation models (GCMs) were employed to study Tibetan Plateau effects on the Asian monsoon with and without the topography (Manabe and Terpstra, 1974; Hahn and Manabe, 1975; Kutzbach et al., 1989, 1993; Broccoli and Manabe, 1992; Kitoh, 1997, 2002) or with a gradual uplift of the Tibetan Plateau (An et al., 2001; Liu and Yin, 2002; Abe et al., 2003). These modeling results confirmed the impact of the Tibetan Plateau on the establishment and development of the Asian summer monsoon as well as on the evolution of the Asian monsoon and the aridity in Central Asia. Yanai and Wu (2006) gave a thorough review of the importance of the thermal influences of the Tibetan Plateau on the Asian monsoon based on different datasets and numerical experiments. The hypothesis that the Tibetan Plateau drives the Asian monsoon by thermal forcing is hereafter referred to as the thermal mechanism. It is understood that the phrase thermal forcing includes sensible heating, latent heating (especially on the south and east borders of the Tibetan Plateau) and net radiation heating as demonstrated starting with Manabe and Terpstra (1974).

However, this thermal mechanism was challenged recently by Boos and Kuang (2010) (hereafter BK10) because of the fact that the peaks of the upper-tropospheric temperature and the center of the Tibetan High are located south of the Tibetan Plateau. Alternatively, they hypothesized that the topography of the Tibetan Plateau may drive the South Asian monsoon by insulating high entropy (warm) tropical air (measured in terms of the equivalent potential temperature) over India from low entropy (cold) extra-tropical air at the low-levels (within 25 hPa of the surface). Thus the

warm tropical air over the Indian subcontinent is not diluted and kept favorable for moisture-driven convection (Cane, 2010). This will hereafter be referred to as the barrier "blocking" mechanism. With an Atmospheric GCM (AGCM), BK10 showed that the model reproduced the large-scale South Asian monsoon circulation by only providing the narrow orography of the Himalayas and adjacent mountain ranges.

Nonetheless, Wu et al. (2012) reported, using a different AGCM, that the Asian summer monsoon system is mainly controlled by the thermal forcing induced by the south slope of the Tibetan Plateau, whereas the orographic mechanical "blocking" forcing is not essential. Thus at present there is no consensus on what mechanisms are dominant or whether the results are model dependent.

In this paper, we reexamine the barrier effect of the Tibetan Plateau with the same GCM model and resolution as the model used in BK10. However, there are some important differences in our experimental design. First, in the no Tibetan Plateau experiment, we only remove the orography higher than 1200 m over the Tibetan Plateau region and leave orography elsewhere unchanged. In contrast, mountains were removed globally (not just over the Tibetan Plateau) with surface elevations set to zero in the no mountain experiment of BK10. However, the orography in other regions may contribute to the changes in Asia, such as the high land over the Africa and the Middle East. Second, we use the fully coupled atmosphere-ocean-land model. BK10 only used the atmospheric and land components of the model with prescribed Sea Surface Temperature (SST). Therefore their study did not account for the ocean circulation changes due to the orography change. Early studies show that experiments with a slab ocean (Kutzbach et al., 1993; Kitoh, 1997) or a coupled ocean (Kitoh, 2002; Abe et al., 2003) could have significantly different Sea surface Temperatures (SSTs).

The structure of the paper is the following. Section 2 describes the model and experimental design. The responses of the Asian monsoon to different topographic settings are shown in Sect. 3 and the mechanisms of the responses are studied in Sect. 4. The conclusion and discussion are provided in Sect. 5.

The Tibetan Plateau's barrier effect

G.-S. Chen et al.

The Tibetan Plateau's barrier effect

G.-S. Chen et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◀ | ▶|

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2   Model and experiment design

2.1   Model

The model used in this study is the Community Earth System Model, Version 1.0 (CESM1.0) of the National Center for Atmospheric Research (NCAR), which is a state-of-the-art fully coupled global climate model. The fully coupled model includes the Community Atmosphere Model (CAM4/CAM5), Community Land Model (CLM4), Parallel Ocean Program (POP2), Community Ice Sheet Model (CISM), and Community Ice code (CICE4). To have the same configurations of the model as those used in BK10, CAM4 is chosen for the Community Atmosphere Model. The finite volume dynamical core is chosen for CAM4. The horizontal resolution used is 1.9° (latitude) $\times 2.5^\circ$ (longitude) for CAM4 with 26 vertical levels and CLM4 has identical horizontal resolution.

The CESM1.0 chosen here is identical to the Community Climate System Model version 4 (CCSM4). CESM1.0 has numerous improvements compared with it predecessors (Gent et al., 2011). Both shallow convection and deep convection are included. The changes to the deep convection scheme improve the El Nino-Southern Oscillation and Madden–Julian Oscillation. The new parameterizations in POP2 lead to an improved simulation of the Gulf Stream path and the North Atlantic Ocean meridional overturning circulation. Changes to the CLM4 improve the annual cycle of water storage in the tropics. The simulations of the Asian and Australian monsoons are also improved (Meehl et al., 2012). The maximum values of precipitation in the eastern Arabian Sea and Bay of Bengal are closer to observations. Also the location and magnitude of orographic precipitation over the southern edge of the Tibetan Plateau and over the Western Ghats are generally improved, although precipitation is still higher than observed in these regions. With the present-day topography, the model produces similar positions for the centers of the upper-troposphere temperature and low-level entropy as observed, though the peak values of the temperature and the entropy are lower than the observed (Boos and Kuang, 2010).

2.2 Experiments

Three experiments were performed (Fig. 1). The first experiment was designed with the present-day topography of the Tibetan Plateau, termed as FULL_TP (Fig. 1). In the no Tibetan Plateau experiment, we only removed the portion of the plateau higher than 1200 m by setting the topography to 1200 m at each model grid in the Tibetan Plateau region (60–115° E, 22–54° N) (Fig. 1). The reason for retaining a plateau elevation of 1200 m is to avoid creating a "valley" in the region of the high plateau because areas around the plateau are as high as 1200 m; retaining this minimum elevation also avoids altering the river directions in the CLM component. We refer to this experiment as NO_TP (Fig. 1). In the third experiment, a barrier was retained along the south edge of the Tibetan Plateau with the maximum height of two-thirds of the maximum height of the Tibetan Plateau at a particular longitude between 60° E and 115° E to mimic the Himalayas (Fig. 1). We exactly followed the approach of BK10 to create a barrier, but north of the barrier elevations were not set to zero. Instead, they were identical to NO_TP. This third experiment is termed as BARRIER.

Therefore, the difference between the climate of the FULL_TP and NO_TP (BARRIER and NO_TP) should give the effect of the full Tibetan Plateau (barrier) on the Asian monsoon. Each experiment was run for 60 yr. The last 50 yr of each experiment are analyzed in this study. Except for the topography, all other boundary conditions in all experiments were kept at the present-day conditions. Student's t tests are used to identify the statistical significance of the differences between the simulations. All differences described in the text are statistically significant at the 95 % significance level.

3   Results

3.1   Full Tibetan Plateau effect

With the full Tibetan Plateau (FULL_TP minus NO_TP) present, the model produces a stronger Asian summer monsoon circulation with significant increase in the wind speed (up to $3\,\mathrm{m\,s^{-1}}$) over the region of the Somali Jet, the Indian continent, and the East Asia region (Fig. 2a). Precipitation strongly increases over the East Asian monsoon region by $1\,\mathrm{mm\,day^{-1}}$ and the south/east edge of the Tibetan Plateau by $3\,\mathrm{mm\,day^{-1}}$ (blue color). These changes are similar to those found in other model simulations (Hahn and Manabe, 1975; Kutzbach et al., 1989, 1993; Kitoh, 1997, 2002; Liu and Yin, 2002; Abe et al., 2003; Boos and Kuang, 2010).

However, precipitation over the region of the Somali Jet, the north of India, and Southeastern Asia decrease significantly (red color). This result is significantly different from the findings in the previous model studies with fixed or slab ocean where all global mountains were removed (Hahn and Manabe, 1975; Kutzbach et al., 1989, 1993; Kitoh, 1997, 2002; Liu and Yin, 2002). A similar finding can be found in Abe et al. (2003) in which a fully coupled model was used, but the decreases in precipitation are limited to the north of the Arabian Sea and Southeastern Asia. We note that our modeling result of precipitation decrease over the north India due to the Tibetan Plateau is supported by paleoclimate data. A wealth of geologic observations indicates that the eastern part of Tibetan Plateau expanded and uplifted over the past 15–10 Ma, along with increased precipitation over the eastern Tibetan Plateau, while northwestern Indian became drier – and model diagnostics help explain this phenomenon (Molnar and Rajagopalan, 2012).

3.2   Barrier effect

With a barrier along the south edge of the Tibetan Plateau (BARRIER minus NO_TP), the large-scale South Asian monsoon circulation is also strengthened (Fig. 2b, bold

vectors). Surface wind increases over the southern Arabian Sea, the south of India, the Bay of Bengal, Southeastern Asia, and East Asia – especially that part of East Asia north of the "barrier". The South Asian monsoon circulation is therefore simulated in general agreement with the full Tibetan Plateau effect, although with some differences (Fig. 2a). However, the overall precipitation field and the wind field in other regions have significant differences relative to the full Tibetan Plateau experiment. For example, with the full Tibetan Plateau, there is much more precipitation in East Asia and the eastern region of the plateau (more blue color in East Asia and the eastern region of the plateau in Fig. 2a) and much less precipitation in northern India (more red color in the Northern India in Fig. 2a). Also the southerly monsoon flow over East Asia and the southwesterly monsoon flow over northern India are stronger in the full Tibetan Plateau experiment. These significant differences in precipitation and wind field indicate that although the large-scale South Asian monsoon circulation are simulated in both the BARRIER experiment and the FULL_TP experiment, the presence of the northern portion of the Tibetan Plateau has very important effects on the East Asian monsoon and the northern Indian monsoon.

4 Mechanism of the full Tibetan Plateau

In this section, we examine the barrier "blocking" mechanism. If the full Tibetan Plateau produces a strong South Asian summer monsoon (circulation) mainly by the barrier "blocking" mechanism proposed by BK10, then the low-level entropy should be higher over the Indian subcontinent in the FULL_TP experiment than in the NO_TP experiment. Also convection should be stronger in the FULL_TP experiment. Figure 3 shows the difference in low-level entropy between the FULL_TP and NO_TP experiments (FULL_TP minus NO_TP). We find, however, that the low-level entropy in the FULL_TP experiment is significantly lower than that in the NO_TP experiment over the Indian subcontinent (Fig. 3, blue color), although the low-level entropy is higher over the western and middle Tibetan Plateau in FULL_TP experiment. The Convective Available

Potential Energy (CAPE) in the full TP experiment is lower at the selected three points in the Indian subcontinent, respectively (Table 1), which indicates the convection is weaker in the FULL_TP experiment over the Indian subcontinent. This is opposite to what we would expect based on the barrier "blocking" mechanism, suggesting that the proposed hypothesis of the barrier "blocking" mechanism cannot explain or at least cannot fully explain the changes in the Asian summer monsoon shown in Fig. 2a. Note that in Fig. 2a the "barrier" of the higher regions of the plateau is further north than the Himalayas "barrier", but the basic conclusion is that the "barrier" in Fig. 2a does not produce the hypothesized effects as proposed in BK10.

What mechanism causes the changes in the Asian summer monsoon in Fig. 2a? Why does the BARRIER also produce a strong South Asian monsoon circulation in Fig. 2b? While our study raises questions about the proposed barrier "blocking" mechanism, it remains possible that the diabatic heating forcing of the full Tibetan Plateau is similar to that of the barrier and might help explain the somewhat similar results of the two kinds of orographic forcing. Figure 4 shows the vertical profile of total diabatic heating along $90°$ E in the three experiments. One can see that both the full Tibetan Plateau and the barrier produce a similar candle-like diabatic heating along the southern edge of the Tibetan Plateau between 26–30$°$ N (Fig. 4a and b). But this "candle heating" vanishes in the NO_TP experiment (Fig. 4c). Our analyses show that this "candle heating" is mainly contributed by the latent heating due to the convection along the southern edge of the Tibetan Plateau or the barrier (figures not shown). The convection may be caused by the sensible-heat-driven air-pump (SHAP) (Wu et al., 2007, 2012). We speculate that the "candle heating" is the key to understanding the mechanism of the effect of the Tibetan Plateau on the Asian monsoon. However, currently, we are not sure whether the convection is caused by SHAP or not. Also, we note that in the FULL_TP experiment there is significant heating north of the "candle heating" that may help explain some of the strengthened East Asian monsoon described previously (Fig. 2a). More experiments are needed to explore the mechanisms of the

Title Page

Abstract   Introduction

Conclusions   References

Tables   Figures

◄   ►|

◄   ►

Back   Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Full Screen / Esc

"candle heating" and the entire heating field, in greater detail. We will report our future work in another paper.

5   Conclusion and discussion

In this paper, we reexamine the effect of the Tibetan Plateau on the Asian monsoon with a fully coupled GCM and also the effect of the barrier "blocking" mechanism proposed by BK10. Our results show that the barrier produces a strong South Asian monsoon circulation over the southern India, which generally agrees with the previous finding of BK10. However, there are significant differences in both the wind field and precipitation field between the barrier simulation and the full Tibetan Plateau simulation. With the full Tibetan Plateau, there is much more precipitation over the East Asian monsoon region and less precipitation over northern India. Also the southerly monsoon flow over East Asia and the southwesterly monsoon flow over northern India are stronger in the FULL_TP experiment than in the BARRIER experiment. These significant differences in precipitation and wind field indicate the northern portion of the Tibetan Plateau has important effects on the East Asian monsoon and the northern Indian monsoon. The result of less precipitation over the northern India in the full Tibetan experiment differs significantly from the findings in the previous model studies with fixed or slab ocean where all global mountains were removed, and is supported by a wealth of geologic observations (Molnar and Rajagopalan, 2012). The cause of the decreases in precipitation over northern Indian was studied in detail in Molnar and Rajagopalan (2012). Due to the heating of the eastern Tibet Plateau, subsidence was generated to the west via the monsoon-desert mechanism proposed by Rodwell and Hoskins (1996). Thus the subsidence suppresses precipitation. We also find, using coupled dynamic ocean rather than slab ocean, that precipitation is reduced over the region of the Somali Jet due to the decrease in SSTs caused by strong wind-driven upwelling (Figure not shown).

Whereas BK10 proposed that the full Tibetan Plateau can be treated as a "wide" barrier that drives the South Asian monsoon by blocking the extra-tropical cold air that would dilute the convective potential of the tropical warm air, our experiments do not strongly support this mechanism. By checking the low-level entropy changes in our experiments, we find the proposed barrier "blocking" mechanism cannot explain the climatic response to the full Tibetan Plateau because the low-level entropy (convection) is lower in the full Tibetan Plateau experiment over the Indian subcontinent than that in the no-Tibetan Plateau experiment or the barrier only experiment. This change is opposite to the hypothesis. As mentioned, the location of the barrier, by treating the full Tibetan Plateau as a "wide" barrier, is farther north than the location of the barrier in the BARRIER experiment. However, our experiments with changing the location of a barrier show that the change in the location of a barrier does not significantly affect the low-level entropy over the Indian subcontinent.

Instead, our analyses indicate that the very strong and deep diabatic heating ("candle heating") in the middle troposphere along the south edge of the Tibetan Plateau in both the full Tibetan Plateau and the barrier experiments may be a key to increased understanding of the driving mechanisms of the Tibetan Plateau on the Asian monsoon. We also note that the heating north of the "candle" over the Tibetan Plateau in the full Tibetan Plateau experiment (Fig. 4a) could help explain the increases in precipitation over East Asia and decreases in northern India.

This "candle heating" is mainly latent heating released by the deep convection along the south slope of the Tibetan Plateau. The convection may be generated (or enhanced) by the SHAP mechanism (Wu et al., 2007, 2012). Our results may therefore support and complement the hypothesis of Wu et al. (2012) that the sensible heating on the slope is the driver of the Asian monsoon. However, more experiments are needed to fully explore these mechanisms of exactly how the Tibetan Plateau forces the full Asian monsoon. Our future work will be reported in another paper.

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The Tibetan Plateau's barrier effect

G.-S. Chen et al.

Printer-friendly Version

Interactive Discussion

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 1. Convective Available Potential Energy (CAPE) for Point A (80° E, 20° N), Point B (80° E, 25° N), and Point C (90° E, 25° N) over the northern Indian continent in FULL_TP and NO_TP experiments. The locations of the three points are shown in Fig. 3.

	Point A	Point B	Point C
full_TP	1818 J kg^{-1}	1869 J kg^{-1}	2792 J kg^{-1}
no_TP	1960 J kg^{-1}	2402 J kg^{-1}	3048 J kg^{-1}
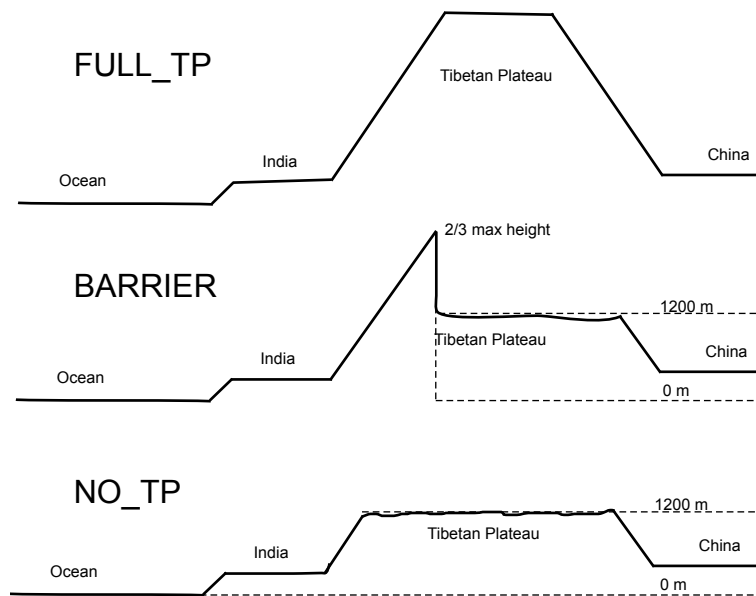
Fig. 1. Schematic topographies used for the FULL_TP, BARRIER, and NO_TP experiments, respectively. The dashed lines of the elevation of 0 m denote the topographies used in BK10's experiments.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion
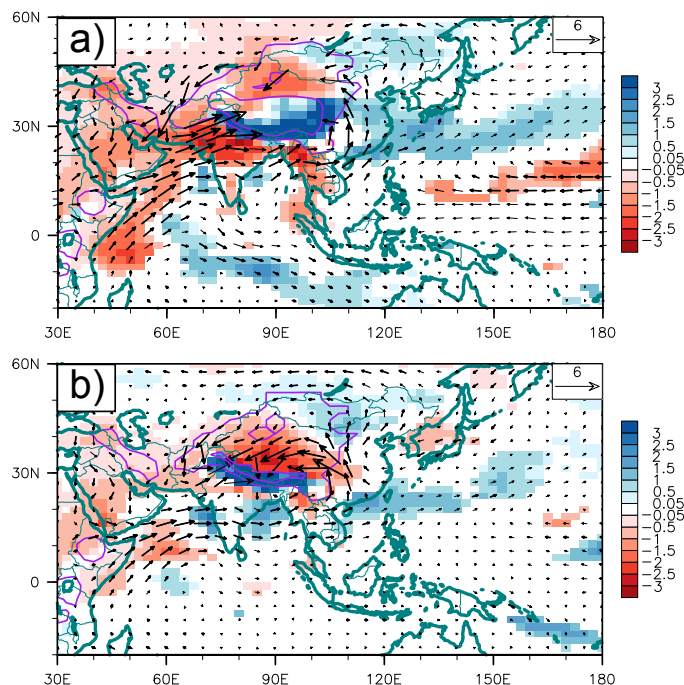
Fig. 2. JJA differences in Surface wind (m s^{-1}) and precipitation (mm day^{-1}) for FULL_TP minus NO_TP **(a)** and BARRIER minus NO_TP **(b)**. Blue indicates positive values, red indicates negative values of precipitation change. Only significant values are shown for precipitation (color shading). Bold vectors indicates the significant changes in wind. Purple contour lines denote the elevations of 1200 m and 3000 m.
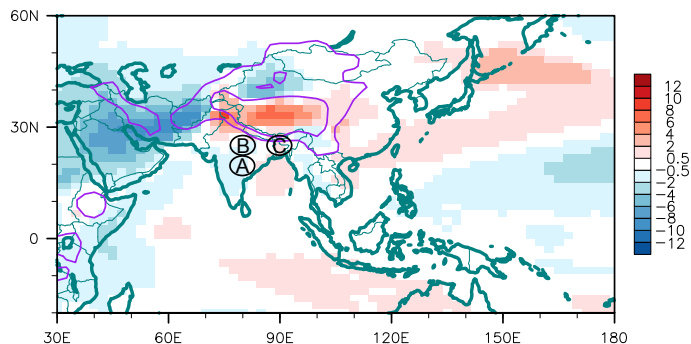
Fig. 3. JJA differences in low-level entropy (Equivalent potential temperature on a terrain-following model level about 20 hPa above the surface) (K) for FULL_TP minus NO_TP. Red indicates positive anomaly. Blue indicates negative anomaly. Only significant values are shown. Letters of A, B, and C indicate the locations of the three points used in Table 1, respectively. Purple contour lines denote the elevations of 1200 m and 3000 m.

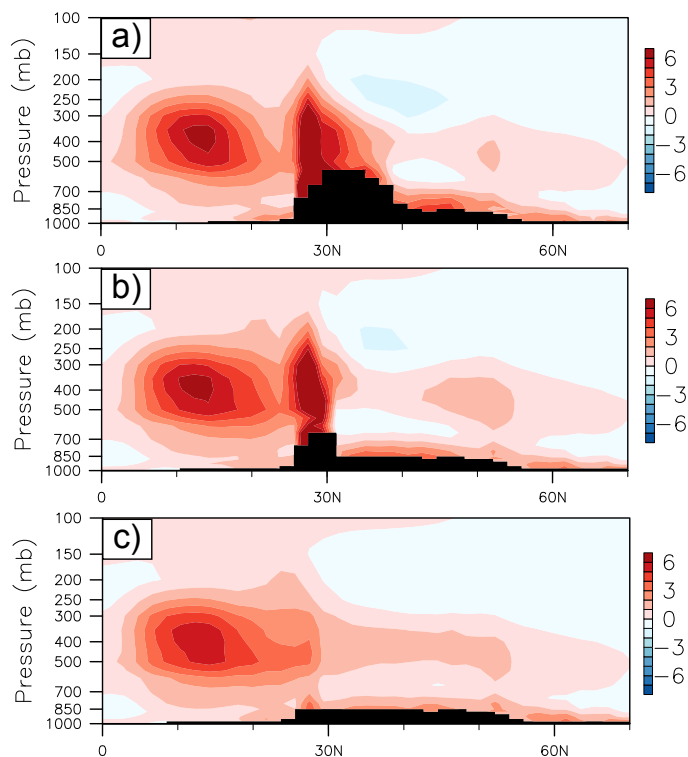**Fig. 4.** Meridional cross section of Total Diabatic Heating (K day^{-1}) averaged between 85–95° E for FULL_TP **(a)**, BARRIER **(b)**, and NO_TP **(c)** experiments, respectively. For all the panels, black shaded region denotes the topography in the experiment.