Dynamical role of the Rocky Mountain controlled by East Asian topographies in modulating the tropospheric westerly jet in northern winter

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ABSTRACT

Large-scale mountains like Asian topographies and the Rocky Mountains have important influences on subtropical jet streams (STJs) over downstream regions in winter. The dynamical role of the Rocky Mountains in modulating STJs with and without the existence of East Asian (EA) topographies in northern winter is investigated via numerical experiments. In agreement with previous studies, the Rocky Mountains (topographic forcing), with the existence of EA topographies, can only strengthen the STJ from the east coast of North America to the western Atlantic region. The independent role of the Rocky Mountains, however, strengthens the STJ over not only the east coast of North America but also over Pacific regions. It is found that the existence of EA topographies can dramatically strengthen the EA trough, as well as a downstream ridge which, in the upstream of the Rocky Mountains, acts to partly cancel out the strengthening of the anticyclone to the north of the Rocky Mountains and the northward warm air transport in the high latitudes of Pacific regions due to the Rocky Mountains’ forcing alone. Such circulation changes effectively weaken the Rocky Mountains–forced strengthening of the meridional temperature gradient in the midlatitude North Pacific, and thus the STJ there. Therefore, EA topographies are of great importance in modulating the role of the Rocky Mountains as a dynamical forcing of STJ variability.

KEYWORDS

Rocky Mountains; East Asian topographies; topographic forcing; subtropical jet stream

1. Introduction

The wintertime subtropical jet stream (STJ) varies on a wide range of time scales, and its position and strength are closely related to stratosphere–troposphere exchange (Langford 1999), storm tracks (Brayshaw, Hoskins, and Blackburn 2008; Nakamura et al. 2008), and tropospheric weather and climate (Yoshikane, Kimura, and Emori 2001). Studies have found that the locations of tropospheric teleconnection patterns tend to coincide with the locations of the major jet streams (Ambrizzi, Hoskins, and Hsu 1995). For instance, the North Atlantic Oscillation pattern in the northern winter hemisphere is connected to the fluctuation in strength of the climatological Atlantic jet streams (Wallace and Gutzler 1981).

According to thermal wind balance theory, STJs result from the meridional temperature gradient and geostrophic balance. Their variability can be attributed to various factors, e.g. Earth’s rotation (Hunt 1979), radiative forcing (Held and Hou 1980), and topographic forcing by large-scale mountains (Wu et al. 2007; Brayshaw, Hoskins, and Blackburn 2009). Among these factors, large-scale mountains have gained the most attention because of their considerable role in modifying and generating atmospheric motion on multiple scales. In northern winter, the dynamical forcing role of large-scale mountains is more important than their thermal forcing role in maintaining the atmospheric circulation (Lin 1982; Sato 2009). The STJ, as one of the key components of the midlatitude circulation.
system, is greatly influenced by the dynamical forcing of large-scale mountains. Studies have found that East Asian (EA) topographies have marked influences on the STJ, especially the Tibetan Plateau (Wu et al. 2007; Shi et al. 2015; White, Battisti, and Roe 2017). EA topographies act as a barrier to the STJ and deflect it into two branches, with an anticyclonic deflected flow in the north and a cyclonic deflected flow in the south. These two branches meet over the EA coastal region and dramatically strengthen the STJ over the western Pacific (Ren et al. 2011). Besides, the Rocky Mountains have been reported to strengthen the STJ in the downstream Atlantic region, and lead to a southwest–northeast tilt of the STJ there, as the southeast–northwest tilt of the Rocky Mountains can block more air and intensify the southward deflection of westerly flow (Brayshaw, Hoskins, and Blackburn 2009).

Most previous studies considered the role of these two topographies in forcing the STJ variability separately, with little attention having been paid to the interaction between them. Held (1983) reported that EA topographies might play a more significant role than North American topographies in generating and maintaining downstream circulation, based on numerical experiments. Yanai, Wu, and Wang (2006) and Sato (2009) documented that EA topographies not only have a regional influence, but also a global influence, on tropospheric weather and climate. Accordingly, we hypothesize that EA topographies might exert a significant impact on the role played by the Rocky Mountains as a topographic forcing of the STJ. In this study, we use numerical modeling to investigate the role of EA topographies in controlling the Rocky Mountains’ dynamical forcing of the wintertime STJ. The findings will help achieve a better understanding of the role of large-scale topographic forcings, as well as their interactions, in giving rise to tropospheric weather and circulation.

2. Model and experimental design

The Whole Atmosphere Community Climate Model, version 4 (WACCM4), based on the Community Atmosphere Model, version 4, is used in this study. WACCM4 is a ‘high top’ model, with the model top reaching ~150 km (66 levels), and the horizontal resolution is 1.9° × 2.5° (latitude × longitude) (Marsh et al. 2013).

To capture the dynamical role of topographies in winter, we conduct a January perpetual run with fixed SSTs and sea ice. All experiments are integrated for 6935 days, with a spinup period of 1460 days discarded. We design four experiments to yield the dynamical role of the Rocky Mountains with and without the indirect influence of EA topographies, as shown in Figure 1. Figure 1(a) is the control (CTL) run, while Figure 1(b) shows the second experiment with the Rocky Mountains having been flattened (NA) (20°–70°N, 90°–150°W), denoted as EA & noNA. Figure 1(a) minus Figure 1(b) represents the topographic forcing of the Rocky Mountains under the control of EA topographies. Figure 1(c) shows the third experiment, in which EA topographies (including the Tibetan Plateau and Mongolian Plateau (20°–60°N, 50°–120°E)) have been flattened, denoted as noEA & NA. The fourth experiment removes both EA topographies and the Rocky Mountains (denoted as noEA & noNA), as illustrated in Figure 1(d). By comparing Figure 1(c,d) we can reveal the independent dynamical role of the Rocky Mountains. Note that topographies in all four experiments are flattened to 500 m to keep the smoothness of the basic platform.

3. Results

3.1. Role of Rocky Mountains in modulating the STJ when EA topographies exist

Displayed in Figure 2 is the climatological mean zonal wind velocity at 200 hPa in the experiments including EA topographies (i.e. CTL and EA & noNA). It can be seen from Figure 2(a) that, in the northern winter hemisphere, the climatological STJs are located mainly in the latitudinal band between 20°N and 35°N, with a maximum speed exceeding 70 m s⁻¹. There are two major jet stream cores: one is located from Japan to the western Pacific regions; and the other is located from the east coast of North America to western Atlantic regions. The former jet stream core is almost twice the intensity of the latter. Such features can still be seen in the experiment without the Rocky Mountains (Figure 2(b)). Comparing Figure 2(a,b) we can see that the role of the Rocky Mountains is indeed to strengthen the STJ over the region from the east coast of North America to the western Atlantic, by about 2 m s⁻¹ (Figure 2(c)). These model results are closely consistent with previous work (Held 1983; Brayshaw, Hoskins, and Blackburn 2009) reporting that the STJ can be strengthened over the downstream region of the mountains due to the topographic forcing.

Note, however, that the topographic forcing of the Rocky Mountains here is with the existence of EA topographies. How does the dynamical forcing of the Rocky Mountains change when EA topographies do not exist?

3.2. Independent role of the Rocky Mountains

To investigate the independent role of the Rocky Mountains, we perform another two experiments (i.e, noEA & NA and noEA & noNA), and the associated
circulation anomalies are shown in Figure 3(a,b). As we can see from these results, there is almost no change to the spatial distribution of the STJ under the independent forcing of the Rocky Mountains. The two major jet stream cores still exist, but their strength in Figure 3(b) looks to be weaker than in Figure 3(a). The results of experiment noEA & NA minus those of noEA & noNA, shown in Figure 3(c), indicate that the STJ cores over both the Pacific and the east coast of North America regions are intensified, by almost 3–4 ms\(^{-1}\), with the independent forcing of the Rocky Mountains.

Comparison between Figures 2(c) and 3(c) reveals the indirect impact of EA topographies on the dynamical role of the Rocky Mountains. It can be seen that the STJ over the east coast of North America is almost 2 m \(s^{-1}\) weaker in Figure 2(c). This implies that EA topographies dampen the

*Figure 1.* Orographic maps of the four numerical experiments (shading; units: m): (a) control run; (b) with Rocky Mountains flattened; (c) with EA topographies flattened; (d) both EA topographies and Rocky Mountains flattened.
Rocky Mountains–forced strengthening of the STJ over the east coast of North America. In addition, the remarkable intensification of the STJ over Pacific regions is no longer seen in Figure 2(c), but is clear in Figure 3(c), which indicates that the existence of EA topographies entirely offsets the Rocky Mountains–forced strengthening of the STJ over the Pacific. Therefore, the existence of EA topographies significantly modulates the Rocky Mountains’ forcing of the STJ, especially the Pacific STJ.

3.3. Understanding the controlling role of EA topographies

Since the strength and location of the STJ are dominated by the meridional temperature gradient (Hunt 1979), we next attempt to understand the controlling role of EA topographies in weakening the role of the Rocky Mountains in formulating the STJ, from the perspective of how the meridional temperature gradient is modulated. Displayed in Figure 4 is the air temperature and horizontal wind averaged from 500 hPa to 200 hPa in the four experiments (i.e., CTL, EA & noNA, noEA & NA and noEA & noNA). From Figure 4, we can see clearly the dynamical role played by the Rocky Mountains in the tropospheric circulation and temperature in the middle troposphere with and without the existence of EA topographies. The Rocky Mountains (with the indirect impact of EA topographies included) force an anticyclonic anomaly in the northern part of the mountains, with a cold anomaly on the east side of the anticyclone; while a cyclonic anomaly is found in the southern part, with a warm air anomaly on its east side (Figure 4(c)). Thus, the role of the Rocky Mountains is to enhance the meridional temperature gradient over downstream regions (120°–60°W), as shown in Figure 4(d). Such features in the temperature and horizontal wind fields are easy to explain, as follows. The Rocky Mountains can deflect the westerly jet into northward and southward branches (Bolin 1950; Brayshaw, Hoskins, and Blackburn 2009). The northward branch that goes over the mountains can generate an anticyclonic anomaly over the northern part of the mountains, which is favorable for the southward transport of cold air over downstream regions. Simultaneously, the southward branch that goes around the mountains will generate a cyclonic anomaly over the southern part of the mountains and
transport warm air along the eastern coast of North America. Therefore, the meridional temperature gradient over downstream regions will be strongly reinforced, as will the Atlantic STJ.

Recall that the independent role of the Rocky Mountains not only strengthens the Atlantic STJ, but also the Pacific STJ. But why would the existence of EA topographies entirely cancel out the Rocky Mountains’ strengthening of the Pacific STJ and weaken the strengthening of the Atlantic STJ? Next, we attempt to understand the weakened Rocky Mountains’ impact on the Pacific STJ with the existence of EA topography modulation by comparing Figure 4(f,b). It can be seen that the existence of EA topographies deepens the EA trough, which will result in the development of a downstream ridge over the northeastern Pacific region on the west side of the Rocky Mountains. Therefore, the Rocky Mountains–forced strengthening of the northward branch, and the anticyclone generated in the northern part of the mountains, will be partly cancelled out by the indirect impact of EA topographies. Comparing Figure 4(g,c) the anomalous high generated by the independent forcing of the Rocky Mountains is much stronger, and can extend to higher latitudes. To the west side of the anomalous high, i.e. on the northwestern side of the mountains, the southerly winds transport more warm air into the polar region (about 1 K warmer; Figure 4(g) vs Figure 4(c), and decreases the meridional temperature gradient from 60°N to the pole over the Pacific regions (Figure 4(h)). The weakening of the meridional temperature gradient leads to an easterly wind anomaly over the North Pacific (Figure 4(g)), which together with the westerly jet streams around 30°N enhance the cyclonic anomaly over the Pacific regions at midlatitudes. In Figure 4(g), there is a cyclonic circulation anomaly over the Pacific regions under the independent forcing of the Rocky Mountains. The cyclonic anomaly indicates a reinforced EA trough, leading to more cold air mass being transported into the midlatitude Pacific (Figure 4(g)), and thus strengthening the meridional temperature gradient within 20°–45°N over the Pacific (Figure 4(h)), and then intensifying the Pacific STJ (Figure 4(h)).

With the existence of EA topographies (Figure 4(a,b)), the key features of the circulation and temperature system over the Pacific, including the warm air anomaly at high latitudes, the cold air anomaly and the cyclonic anomaly at midlatitudes, cannot be seen, indicating that the Rocky Mountains’ strengthening of the Pacific meridional temperature gradient and STJ is entirely offset by the indirect impact of EA topographies. As for the Atlantic STJ, the independent role of the Rocky Mountains shows an intensified anticyclone in the north of the mountains would result in enhanced
southward cold air downstream (60°–90°W) and lead to an enhanced Atlantic STJ (Figure 4(h)). However, with the existence of EA topographies (Figure 4(a,b)), the southward cold air over the downstream regions (60°–90°W) is much weaker (about 1 K; Figure 4(c)), since EA topographies offset the anticyclonic anomaly in the north of the Rocky Mountains, which effectively weakens the meridional temperature gradient (Figure 4(d)). Therefore, the Rocky Mountains’ strengthening of the Atlantic STJ is partly cancelled out by the indirect impact of EA topographies.

4. Conclusions and discussion

This study investigates the dynamical role of the Rocky Mountains with and without the control of EA topographies in modulating the STJ in winter via performing a series of numerical experiments using WACCM4. Results show that the Rocky Mountains (topographic forcing), with the indirect impact of EA topographies, can only strengthen the STJ over downstream regions of the mountains, which is consistent with previous studies. However, the independent role of the Rocky Mountains can intensify the STJ over both the Pacific and Atlantic regions, which indicates that non-negligible interactions between these two large-scale topographies play an important role in modulating the dynamical forcing of the Rocky Mountains.

By assessing the meridional temperature gradient averaged from 500 hPa to 200 hPa, we have found that an anomalous anticyclone in the north of the Rocky Mountains, generated by the Rocky Mountains’ independent forcing, can bring more warm air into higher latitudes of the Pacific region, and decrease the meridional temperature gradient there. The decreased temperature gradient at higher latitudes of the Pacific region, together with the easterly wind anomaly there, strengthens the EA trough and the meridional temperature gradient over the Pacific region at midlatitudes, and thus the STJ over Pacific regions is intensified. Besides, the anomalous anticyclone in the north of the Rocky Mountains can transport cold air in downstream regions, which strengthens the meridional temperature gradient over the western Atlantic region, leading to a strengthening of the Atlantic STJ.

When including EA topographies, the EA trough and downstream ridge are strengthened, which acts to partly cancel out the strengthening of the anticyclone generated in the north of the Rocky Mountains due to the Rocky Mountains’ independent forcing. The weaker anticyclone in the north of the Rocky Mountains then leads to a weaker meridional temperature gradient in the subtropics, which effectively weakens the STJ over Pacific regions. The Atlantic STJ downstream of the Rocky Mountains would also be weakened due to the weaker cold-air transport generated by the weaker anticyclone in the north of the Rocky Mountains, though the weakening is not as severe as for the Pacific STJ. These model results illustrate why it seems that the Rocky Mountains (with the indirect impact of EA topographies) can only strengthen the STJ over downstream regions of the mountains, whereas the independent role of the Rocky Mountains can intensify the STJ over both the Pacific and Atlantic regions.

The significant control of EA topographies over the Rocky Mountains’ role in modulating the STJ naturally leads us to question the indirect impacts of the Rocky Mountains on the role played by EA topographies. Based on preliminary results, they do exist, but are relatively much weaker in relation to the much lower altitude and smaller size of the Rocky Mountains. Also, because of the limited scope of this study, we do not include this aspect, leaving it instead for a separate paper in the future.

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Disclosure statement

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