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Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL105932

Coastal Mountains Amplified the Impacts of Orbital Forcing on East Asian Climate in the Late Cretaceous

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Key Points:

- East Asian climate was sensitive to orbital forcing in the Late Cretaceous
- East Asian coastal mountains amplified orbital forcing on East Asian climate variability
- East Asian coastal mountains were likely higher than 2 km in the Late Cretaceous

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Zhang, J., Flögel, S., Hu, Y., Zhao, A., Chu, R., Zhu, C., & Wang, C. (2023). Coastal mountains amplified the impacts of orbital forcing on East Asian climate in the Late Cretaceous. *Geophysical Research Letters*, *50*, e2023GL105932. https://doi.org/10.1029/2023GL105932

Received 13 AUG 2023
Accepted 17 NOV 2023

Abstract During the Cretaceous, there were two factors that had important influences on the East Asian climate, the East Asian coastal mountains and Earth's orbital cycling. An important question is how the coastal mountains modulated the variability of East Asian climate over orbital timescales. Here, we perform simulations with the coastal mountains of 0, 2, and 4 km high and three orbital configurations to answer the question. Our results show that a mountain range at the East Asian coast can amplify the impacts of orbital forcing on East Asian climate. Specifically, precipitation over the Songliao Basin in Northeastern China has significant changes as the coastal mountain range is about 4 km high. Combining our simulation results with orbitally-controlled sedimentary deposits from the Songliao Basin, we conclude that the altitude of the coastal mountain range was very likely higher than 2 km in the Late Cretaceous.

Plain Language Summary Tectonic events and solar insolation are the two important factors impacting variations of the climate system in the geological past. Regional climate responses to variations in the radiation from the sun over 10^4–10^5 years were often magnified or dampened by tectonic events. Cretaceous sedimentary records in East Asia suggest that East Asian climate was influenced by the solar insolation. Geological evidence showed that a mountain range existed along the East Asian coast then. Would this mountain range modulate impacts of solar insolation on East Asian climate? Our modeling results show that the influence of solar insolation on East Asian climate can be amplified by the coastal mountain range, depending on the mountain elevation. When the coastal mountain range is ~2 km high, the amplification effects become significant. When its altitude reaches ~4 km, the response of East Asian climate to solar insolation is considerably strengthened, and such a condition is supported by the rhythm induced by the climate variation due to solar insolation archived in the Cretaceous strata in the Songliao Basin. Thus, we speculate that the East Asian coastal mountains might have reached an altitude more than 2 km in the Late Cretaceous.

1. Introduction

The Cretaceous (145–66 Ma) is one of the greenhouse worlds (Poulsen et al., 2001; Voigt et al., 2004; Wang et al., 2013), with global mean surface temperatures much higher than that of the present (Huber et al., 2002; Wilson & Norris, 2001). The Cretaceous climate was equable, but its variation was still extensively recorded in deposits (Jiang et al., 2004; Miller et al., 2005; Wang et al., 2013), especially over orbital timescales (Beckmann et al., 2005; Floegel et al., 2005; Wu et al., 2009, 2013, 2022). While most geological records of orbital-scale climatic variabilities were archived in marine sedimentary strata (Beckmann et al., 2005; Floegel et al., 2005; Flögel et al., 2008; Meyers et al., 2012), there are also sedimentary records in terrestrial intra-continental basins, such as the Songliao Basin in Northeastern China (Wu et al., 2009, 2022).

The East Asian Monsoon system influences the livelihoods of billions of people (e.g., Chang et al., 2012; Huang et al., 2007), and is associated with the tropical intertropical convergence zones and El Niño-Southern Oscillation (Geen et al., 2020; Yancheva et al., 2007; Zheng et al., 2014), mid-latitude westerlies (Chen et al., 2021; Chiang et al., 2017), and high-latitude climatic conditions (Beck et al., 2018; He et al., 2017), thus its evolution has been linked with northern hemisphere glaciations (Beck et al., 2018; Zan et al., 2023) and widely studied (An et al., 2001; Farnsworth et al., 2019; Guo et al., 2002; Hu et al., 2023). Previous studies have demonstrated that it was strongly affected by orbital forcing during the Cretaceous. For example, multiple desert cycles on

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time scales of 10^3–10^5 years were identified in the Ordos Basin (Jiang et al., 2004). These desert cycles reflect variations in wind direction and hydrology. Transitioning between warm/dry and cool/wet states is also reflected by orbital-scale variations of lithologies in the Zhangye Basin, Northwestern China (Liu et al., 2017). As the largest Cretaceous continental rift basin in East Asia, the Songliao Basin has continuous records of Cretaceous strata (Wang et al., 2013). Using magnetic susceptibility, natural gamma-ray (GR) and thorium (Th) logging data of the Songliao Basin, Wu et al. (2009, 2022) identified significant orbital signals. All these records used in Wu et al. (2009, 2022) are sensitive to changes in precipitation-evaporation ratios and/or water-level changes, indicating that the climate around the Songliao Basin was strongly regulated by orbital forcing. Recently, Li et al. (2022) and Yang et al. (2020) also detected nearly all significant Milankovitch frequencies from geochemical records of sediments preserved in the Songliao Basin, corroborating the influence of orbital forcing on East Asian climate.

East Asian climatic variations induced by orbital forcing during the Cretaceous have also been reproduced by modeling studies (Park & Oglesby, 1991; Zhang et al., 2019). However, the simulated precipitation changes in mid-latitude East Asia were very weak, or even not significant (Zhang et al., 2019), in contrasting with the strong orbital signals recorded in sediments (Wu et al., 2022; Yang et al., 2020). In addition, amplitudes of climatic variations in East Asia induced by orbital forcing are also discrepant during different time periods (Yang et al., 2020). These results imply that there must be some factors, which have not been resolved in previous studies, amplifying the responses of East Asian climate to orbital forcing. This raises an important question of what amplifies the response of East Asian climate to orbital forcing during the Cretaceous.

A few factors were proposed to explain the amplification of the influence of orbital forcing on regional and/or global climates. Among these, high topography is a critical one. Liu et al. (2003) found that the existence of the Tibetan Plateau (TP) amplifies orbital-scale variabilities of the East Asian monsoon, which led to stronger southerly winds prevailing over Eastern China and strengthened precipitation in Northeast China. Moreover, the TP uplift can also intensify the response of the South Asian summer monsoon to orbital forcing (Wu et al., 2018).

Reconstructions suggested that a meridionally oriented mountain range had existed along the East Asian coast during the Late Cretaceous (Chen, 2000), and that it had attained an altitude of much more than 2 km in the early Late Cretaceous and became lower afterward (Chen et al., 2022; Zhang et al., 2016). Therefore, it is likely that the strong signal of orbital forcing in the Songliao Basin was due to the East Asian coastal mountains. The purpose of the present study is to test the hypothesis whether and how a coastal mountain range might have magnified responses of East Asian climate to orbital forcing in the Late Cretaceous by using a coupled general circulation model.

2. Model and Methods

2.1. Model

The model used in this study is the fully coupled Community Earth System Model 1.2.2 (CESM1.2.2) (Vertenstein et al., 2013). Its atmospheric module, the Community Atmosphere Model 4 (CAM4) (Neale et al., 2013), is run at a horizontal resolution of T31 ($3.75° \times 3.75°$) with active ocean and at a resolution of f09 ($0.9° \times 1.25°$) with prescribed sea surface temperatures (SSTs) and sea ice fractions. The CAM4 has 26 vertical levels. The land module, the Community Land Model 4.0 (CLM4.0) (Lawrence et al., 2012), uses the same horizontal resolution as CAM4. Its ocean module, the Parallel Ocean Model 2 (POP2) (Danabasoglu et al., 2012), employs a gx3v7 grid which has 116 and 100 grid points in the meridional and zonal directions, respectively, and has 60 vertical levels. The sea ice module, the Community Sea Ice Model (CICE) (Hunke & Lipscomb, 2008), is run on the same horizontal grid as POP2. The river transport model routes all runoff to the oceans and is run at the default resolution ($0.5° \times 0.5°$).

2.2. Experimental Design

The paleogeography (Figure S1a in Supporting Information S1) and paleovegetation (Figure S1b in Supporting Information S1) at ~90 Ma (Text S1 in Supporting Information S1) from Sewall et al. (2007) are modified and used in this study. The solar constant is reduced to 1,348.75 W m^{-2}, about 0.9% lower than the modern value of 1361 W m^{-2} (Gough, 1981). Atmospheric CO_2 concentration is set to 1,120 ppmv, and other conditions are described in Text S2 in Supporting Information S1.

To study orbital effects on East Asian climate, three sets of experiments (Table S1 in Supporting Information S1) are conducted with different orbital configurations. In the first set (Set A), the eccentricity of Earth's orbit is fixed at 0 and the obliquity at 23.5° (Figure S2a in Supporting Information S1), during which the modeled climate is nearly the averaged condition over orbital timescales. In the second set (Set B), the eccentricity of Earth's orbit is fixed at 0.066 (close to the max. eccentricity) and the obliquity at 24.5° with a perihelion precession (Figure S2b in Supporting Information S1), which resembles the orbital configuration of the maximum solar insolation during boreal summer. In the third set (Set C), the eccentricity of Earth's orbit is fixed at 0.066 and the obliquity at 22.5° with an aphelion precession (Figure S2c in Supporting Information S1), which represents the orbital configuration of the minimum solar insolation during boreal summer.

The role of orbital forcing in influencing the climate system is facilitated by changing the spatio-temporal distribution of solar insolation at the top of the atmosphere (STOA). The STOA averaged between 20°N and 40°N is higher (≥360 W m^{-2}) in the summer-half year, but lower (<360 W m^{-2}) in the winter-half year (Figure S3a in Supporting Information S1). During the summer half-year, it is greater in Set B than in Set A, with the greatest change of ~70 W m^{-2} (Figure S3b in Supporting Information S1); while it is decreased in Set C compared to Set A, with the greatest change of ~60 W m^{-2} (Figure S3b in Supporting Information S1).

For each set of experiments, four model runs were carried out. The first one is a coupled experiment, which was run with the CAM4 and CLM4.0 at a resolution of T31 and POP2 and CICE at a resolution of gx3v7. In order to simulate the effects of the East Asian coastal mountains on the East Asian climate, another three uncoupled experiments in each set were run at a resolution of f09, in which the CAM4 and CLM4.0 were run with prescribed SSTs and sea ice fractions from the first coupled experiment. In the three uncoupled experiments, the topography (Figure S4a in Supporting Information S1) in the first one (OrbA_0km, OrbB_0km, or OrbC_0km) is the same as in the coupled experiment (Figures S1a and S4a in Supporting Information S1); In the second (OrbA_2km, OrbB_2km, or OrbC_2km) and third (OrbA_4km, OrbB_4km, or OrbC_4km) experiments, the topography is the same as the first one, but a mountain range of 2 km (Figure S4b in Supporting Information S1) and 4 km (Figure S4c in Supporting Information S1) high, respectively, has been added between 20°N and 40°N along the East Asian coastal margin.

3. Results and Mechanisms

3.1. Effects of Orbital Forcing on the East Asian Climate

Summer precipitation dominates the annual rainfall in the East Asian monsoonal region. Thus, the largest change in precipitation in East Asia, due to orbital variations, must occur in summer (Farnsworth et al., 2019; Zhang et al., 2019). Therefore, we only focus on the summer (May to September) climate here. For Set B, moisture transport from the low-latitude ocean is strengthened, and summer precipitation increased significantly compared to the control set (Set A) (Figures 1a–1c). For Set C, moisture transport from the low-latitude ocean is weakened and summer precipitation decreased significantly compared to Set A (Figures 1d–1f). These are consistent with continental sedimentary records influenced by orbital forcing in China (Wu et al., 2022; Yang et al., 2020) and previous modeling studies (Park & Oglesby, 1991; Zhang et al., 2019).

It is found that orbital effects on the East Asian climate largely depend on the altitude of the East Asian coastal mountains. When there are no coastal mountains, precipitation changes little (mostly ≤1 mm d^{-1}) in the East Asian coastal areas for Set B compared to Set A (Figure 1a). As the coastal mountains reach 2 km high, moisture transport to East Asia is strengthened and precipitation is significantly increased, with the peak value higher than 2 mm d^{-1} (Figure 1b). When the coastal mountains reach 4 km high, moisture transport is further strengthened, and precipitation is increased more, with the peak value >6 mm d^{-1} (Figure 1c). Moreover, precipitation increases become significant at mid-latitudes (Figure 1c). In contrast, Comparison of Set C with Set A shows the magnitudes of the precipitation decrease in East Asian also increase from ~2 to >6 mm d^{-1} when the coastal mountains are uplifted from <1 to 4 km (Figures 1d–1f), as well as the decrease of the moisture transport. These results indicate that the East Asian coastal mountains indeed magnify the responses of the East Asian climate to orbital forcing.

Songliao Basin is the only one basin with nearly whole Cretaceous continuous sedimentary records in East Asia (Wang et al., 2013), and all orbital periods are obtained by analyzing the climate-sensitive proxies (Wu et al., 2022), suggesting the climate around and in the Songliao Basin was very sensitive to orbital forcing during that period. In our simulations with a coastal mountain range of ≤2 km high, Songliao Basin precipitation changes little between Set B and Set A (Figures 1a and 1b and 2a). In contrast, precipitation increases significantly when

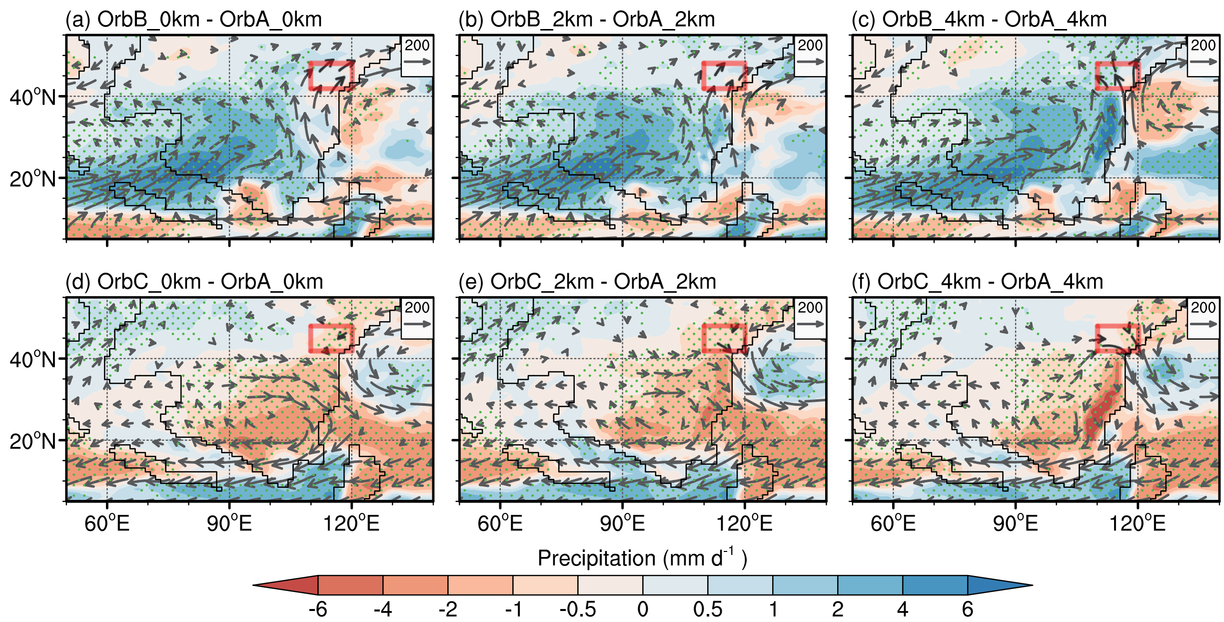

Figure 1. Summer precipitation (shaded; units: mm d^{-1}) and moisture transport (vector; units: kg m^{-1} s^{-1}). Top panels represent differences between Set B and Set A. Bottom panels represent differences between Set C and Set A. From left to right the coastal mountain altitudes are 0, 2, and 4 km, respectively. In each panel, only the areas with confidence levels >95% (the Student's *t*-test) are labeled for the water vapor transport changes and dotted for the precipitation changes. The red rectangle denotes the location of the Songliao Basin.

the coastal mountain reaches 4 km high (Figures 1c and 2a). The Songliao Basin precipitation changes in Set C compared to Set A are not monotonous with the coastal mountain altitude (Figure 2b), but their changes are still significant (Figures 1d–1f).

In addition, precipitation changes over the East Asia between Set C and Set A are different from that between Set B and Set A (Figures 1 and 2), although the changes in solar insolation are comparable (Figure S3 in Supporting Information S1). This suggests that the responses of the East Asian precipitation to the insolation change due to orbital cycling are nonlinear (Ganopolski & Calov, 2011). It is characteristic of monsoon for the East Asian climate (Hu et al., 2023), and its sensitivity response to solar insolation is dependent on the monsoon strength (Yi et al., 2018). However, such the nonlinear response of the East Asian climate to orbital forcing is not the subject of this study, so are not discussed in detail here.

3.2. Mechanisms

The modern Tibetan Plateau in summer is a heat source for the atmosphere and works like a "pump" to have a strong influence on the Asian climate (Wu et al., 2012). The East Asian coastal mountains had the similar impact

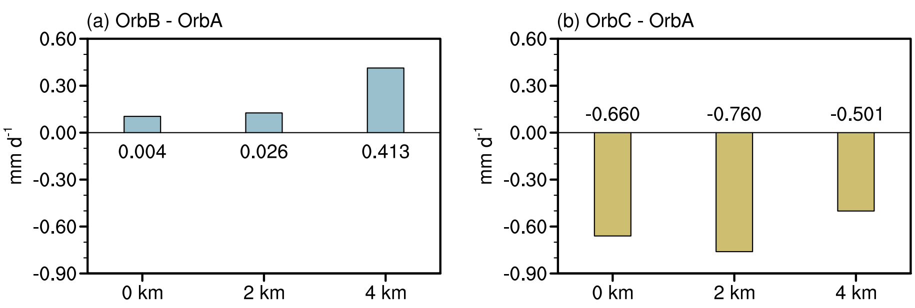

Figure 2. Summer precipitation change (mm d^{-1}) between experiments in Set B and Set A (a) and between experiments in Set C and Set A (b). In Panel a, precipitation changes for coastal mountain altitudes of 0 and 2 km are little. To clearly show bar plot in a, the left two bar heights are amplified, so the exact values of summer precipitation change for each condition are presented below or over their corresponding bars, respectively.

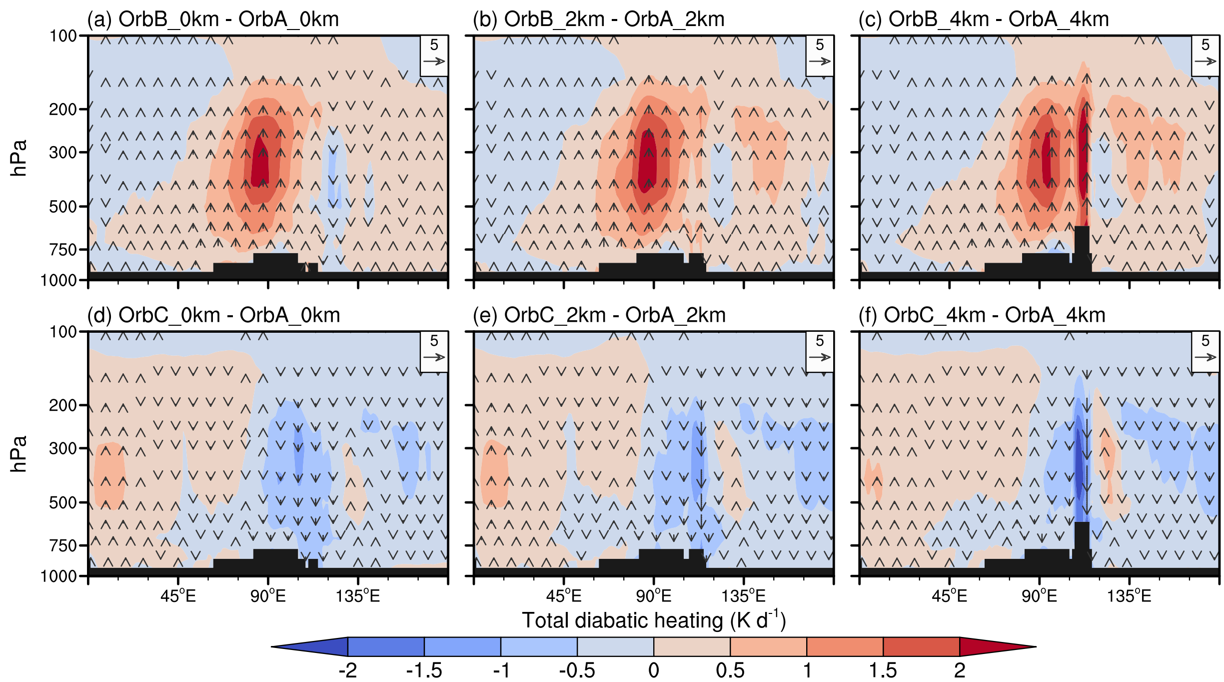

Figure 3. Zonal-vertical cross sections of total diabatic heating during summer (shaded; units: K d^{-1}) and vertical velocity (vectors; units: ×0.01 Pa s^{-1}) averaged within 20–40°N. Top panels: differences between experiments in Set B and Set A. Bottom panels: differences between experiments in Set C and Set A. From left to right: coastal mountain altitudes are 0, 2 and 4 km, respectively.

on the East Asian climate during the Cretaceous (Zhang et al., 2021). They warm the lower troposphere and enhance the lower tropospheric upward motions in summer (Figure S5 in Supporting Information S1). When air masses are raised, they condense and release latent heat. It consequently further increases the upward motions. When the STOA increases, the coastal mountains act as a stronger "pump" in summer. Total diabatic heating is increased by >2 K d^{-1} aloft the coastal mountain range as its altitude reaches 4 km, and the anomalous heating center moves eastward (Figures 3b and 3c).

Associated with the diabatic heating changes, the difference of the geopotential heights between the Asia and the Northwestern Pacific Ocean also increases with coastal mountain altitude, as well as the southerly winds over East Asia (Figures 4a–4c). Thus, the summer precipitation change increases as the coastal mountain altitude (Figures 1a–1c). When the STOA deceases, the circulation changes over East Asia are opposite (Figures 3d–3f and 4d–4f). The results here demonstrate that the coastal mountains can intensify orbital forcing on East Asian climate, through the uplifted heating by high topography and more latent heat release initiated by the uplifted heating (Liu et al., 2003; Wu et al., 2012).

4. Conclusions and Discussion

In this study, we have demonstrated that a sufficiently high mountain range along the East Asia coast was able to amplify the influences of orbital forcing on the East Asian climate in the early Late Cretaceous. In the run without a coastal mountain range, there is little precipitation change over East Asia in response to orbital forcing. In contrast, the runs with a coastal mountain range of 2 and 4 km high show significant precipitation changes in the mid- to low-latitude East Asia. Especially, when the coastal mountain range reaches ∼4 km high, the precipitation change in the Songliao Basin becomes considerably and significantly strengthened. The role of the coastal mountain range in amplifying orbital forcing on the East Asian climate is similar to that of the TP on the Asian summer monsoon (Liu et al., 2003; Wu et al., 2018). Our simulation results with a mountain range of 4 km high are qualitatively consistent with the orbital-scale signals derived from the geological deposits in the Songliao Basin. Therefore, we speculate that the East Asian coastal mountain range could have been higher than 2 km during the Late Cretaceous. This estimate is in line with previous geological studies (Chen, 2000; Zhang et al., 2016) and recent deduction by comparing the modeled Asian aridity with sandy deposits (Zhang

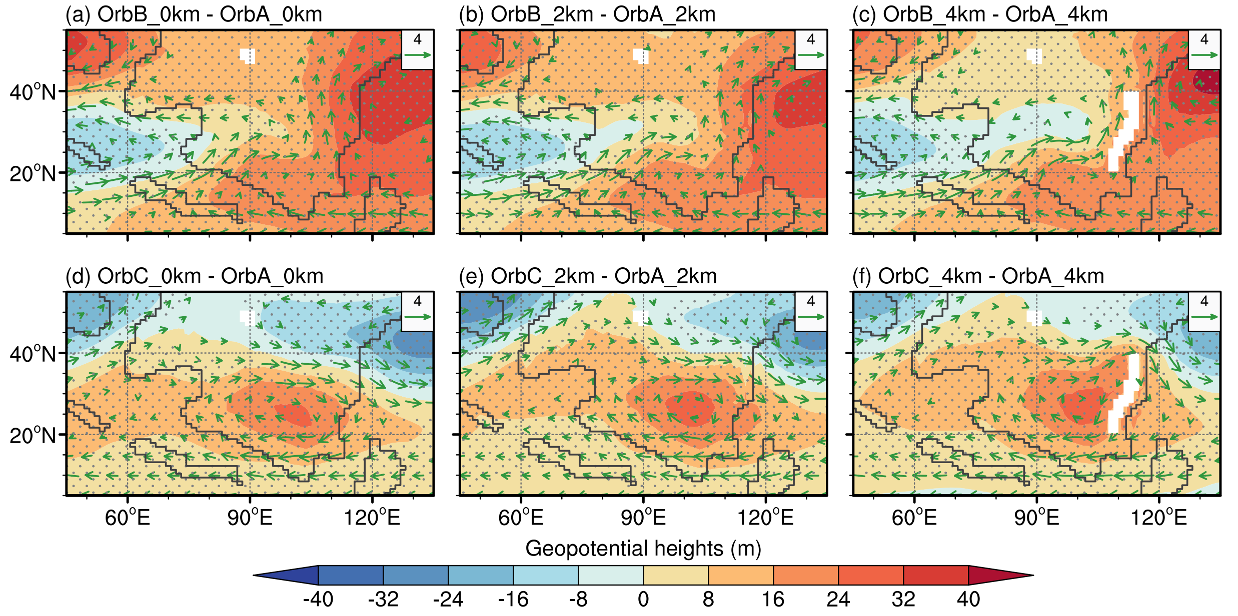

Figure 4. Geopotential heights (shaded; units: m) and winds (vector; units: m s^{-1}) at 775 hPa. Top panels: differences between experiments in Set B and Set A. Bottom panels: differences between experiments in Set C and Set A. From left to right: coastal mountain altitudes are 0, 2, and 4 km, respectively. In each panel, only the areas with confidence levels >95% (the Student's *t*-test) are labeled for wind difference and dotted for the geopotential heights changes.

et al., 2021). The simulation results provide an independent constraint on the altitude of coastal mountain range. Such a meridionally oriented mountain range is different from the zonally oriented Himalayas, and it together with orbital forcing induces stronger summer monsoon precipitation, which might broaden the monsoon dynamic theories (Biasutti et al., 2018; Hu et al., 2023).

How the coastal mountain range was formed and how high it was are still questionable. It was argued that in the Jurassic the paleo-Pacific Plate subducted westwards beneath the Asian continent with the transition from the passive continental margin of East Asia into an active one (Suo et al., 2019). Since then, an Andean-type active continental margin had developed along the East Asian continental margin (Li et al., 2012, 2019; Suo et al., 2019), and a coastal mountain range or plateau was uplifted there (Chen, 2000; Xu et al., 2019). The situation might be similar to that of present-day western North America (Li, 2000; Suo et al., 2019). During the late Early Cretaceous-early Late Cretaceous (~115–90 Ma), the collision of the Okhotomorsk Block within the Izanagi Plate with East Asia in a northwestward direction occurred, thus altitude of the coastal mountains attained 3.5–4 km (Chen, 2000). Afterward the Okhotomorsk Block drifted northward and collided with the Siberian Craton at ~80 Ma (Suo et al., 2020; Yang, 2013), the subduction zone of the paleo-Pacific Plate also retreated eastward during the Late Cretaceous (Li et al., 2019), and Southeast China underwent regional extension (Suo et al., 2019). This tectonic setting is not favorable for the maintenance of such a high range, but the coastal mountains were still >2 km high during the Late Cretaceous (Chen et al., 2022; Zhang et al., 2016).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The model data for all the figures can be found in Zhang (2023).

Acknowledgments

We sincerely thank Dr. Jacob Ogilvie Sewall for providing the paleogeography and paleovegetation data, and Dr. Laiming Zhang for providing information about the East Asian coastal mountain range. This study was co-supported by the National Natural Science Foundation of China (Grants 41888101 and 42372120) and the National Key Scientific and Technological Infrastructure project "Earth System Numerical Simulation Facility" (EarthLab). SF thanks HGF-project ARCHES for financial support. Simulations are conducted at the High-performance Computing Platform of Peking University.

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