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Influence of Anthropogenic Activities on Elevation-Dependent Weakening of Annual Temperature Cycle Amplitude Over the Tibetan Plateau

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Key Points:

- The amplitude of the annual temperature cycle decreased over the Tibetan Plateau, and this diminished trend was amplified with elevation
- Influence of anthropogenic forcing on the elevation-dependent weakening of annual temperature cycle amplitude is detectable
- The increase in anthropogenic aerosols may be the main contributor

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Abstract

The annual cycle is the dominant component and the most prominent climate oscillation for the temperature variation over the Tibetan Plateau (TP). Identifying the relative contribution of anthropogenic and natural forcing to the changes in the annual cycle, namely, detection and attribution, is an important aspect for mountainous climate change research. The present study documents the elevation dependence of the trend in the annual temperature cycle (ATC) amplitude over the TP and detects the influence of anthropogenic activities on it. An elevation-dependent weakening of the ATC amplitude occurs over the TP during the period 1961–2014. This variation with altitude can mainly be ascribed to the seasonal difference in warming. The influence of anthropogenic activities is detectable, with increased aerosols being the main contributor. Under aerosol-only forcing, the larger decrease in snow-related albedo at higher altitudes in winter can explain the amplified negative tendency of the ATC amplitude with elevation.

Plain Language Summary

The present study documents the variation with altitude of the trend in the seasonal temperature difference over the TP and detects the influence upon it of anthropogenic activities. The seasonal temperature difference weakened in most regions of the TP during 1961–2014. Also, the higher the altitude, the more notable the decrease. The trend in the temperature seasonality over the TP and its variation with altitude can mainly be ascribed to the difference in the rate of warming between winter and summer. The greater warming in winter in higher-altitude regions over the TP causes the negative tendency of the seasonal temperature difference to amplify with elevation. The model-simulated responses are able to capture the observed variation with altitude of the trend in the temperature seasonality only if anthropogenic forcing is involved. Moreover, the influence upon it of anthropogenic activities is statistically detectable, with the increase in anthropogenic aerosols being the main contributor. In the model-simulated response to anthropogenic aerosol–only forcing, the larger decrease in snow-related albedo at higher altitudes in winter can explain the amplified warming there in winter and thereby the weakening with elevation in the seasonal temperature difference.

1. Introduction

The climatic responses to global warming in mountainous regions and their elevation dependence are hot topics internationally among scientists working in mountain climate research (Pepin et al., 2015; Rangwala & Miller, 2012; You et al., 2020). Mountain areas act as amplifiers of global warming, and an increasing number of studies have shown that climate warming is enhanced with altitude (e.g., Giorgi et al., 1997; Minder et al., 2018; Pepin et al., 2015; Rangwala et al., 2010). Among the numerous mountainous regions of the world, the Tibetan Plateau (TP) is well known for its vast area, having some of the highest altitudes in the world, and extremely complex terrain. The response of the TP to climate change is more sensitive than that of other regions at the same latitude (Qiu, 2008; Yao, Thompson, Mosbrugger, et al., 2012, Yao, Thompson, Yang, et al., 2012) and it is closely related to altitude (e.g., Palazzi et al., 2017; Pepin et al., 2015; Rangwala et al., 2009, 2013; Thakuri et al., 2019), especially in winter. Compared with other seasons, both the highest rate of warming and the most significant elevation-dependent warming over the TP occur in winter (Dimri et al., 2018; Liu & Chen, 2000;

Liu et al., 2009). Accordingly, an interesting question arises. Has the amplitude of the annual temperature cycle (ATC) over the TP decreased owing to the difference in the rate of warming between winter and summer? If the amplitude has decreased, does this weakening trend in temperature seasonality vary with altitude as a result of the seasonal difference in elevation-dependent warming?

The annual cycle refers to the dominant variability of numerous climate variables in the extratropics at the daily and monthly time scales (Qian, Fu, et al., 2011; Qian, Wu, et al., 2011; Qian & Zhang, 2015; Stine et al., 2009; Stine & Huybers, 2012; Thomson, 1995). A growing number of studies have shown that climate change is reflected not only in the change of the annual mean for a climate variable but also in the long-term change in the amplitude and phase of its annual cycle (e.g., Stine et al., 2009; Thomson, 1995, 2009; Wang & Dillon, 2014). Changes in the amplitude of the ATC influence the estimation of climate variability and trends (Qian, Fu, et al., 2011; Thompson, 1995), such as the classification of El Niño/La Niña years (Qian, Wu, et al., 2011). Taking into account changes in the amplitude of the ATC in temperature reconstructions have also been suggested (Jones et al., 2003). Moreover, changes in the ATC could strongly affect biological and ecological systems, such as bird and mammal distributions (Porter et al., 2000), plant developmental genetics (Li et al., 2010), and insect population dynamics (Vasseur et al., 2014).

The TP is species-rich, and the distribution of animals and plants has obvious features of transition with altitude. Climate change in the different altitudinal zones within a mountain range has important implications for ecosystems, farming and species along an elevation gradient (e.g., Freeman et al., 2018; González-Orozco & Porcel, 2021; Liancourt et al., 2020; Wen et al., 2018), as well as the high-elevation cryosphere and associated runoff and even the source of water for large populations in lower-elevation regions (e.g., Immerzeel et al., 2010, 2012; Yao, Thompson, Mosbrugger, et al., 2012; Yao, Thompson, Yang, et al., 2012; Yao, et al., 2019). The social, economic and eco-environmental impacts arising from altitude-related climate change over the TP could therefore be large, hence justifying further research. Elevation-dependent warming in mean temperature and its mechanisms (e.g., Minder et al., 2018; Pepin et al., 2015; You et al., 2020) have been well documented. However, knowledge of mean temperature alone has important limitations when applied to understanding the effects of environmental variance on ecological and evolutionary processes (Ruel & Ayres, 1999). Changes in temperature variation can have profound effects that match or even exceed the impacts of mean temperature (e.g., Bauerfeind & Fischer, 2014; Paaijmans et al., 2010, 2013; Seddon et al., 2016; Vasseur et al., 2014). For instance, temperature seasonality and topography are more important indicators of species diversity than mean annual temperature (Shrestha et al., 2018). Variables related to temperature seasonality seem to be more important than variables related to mean temperature for distinguishing biomes (Silva de Miranda et al., 2018). Compared to the mean annual temperature, frost, which is correlated with temperature seasonality (Hänninen, 2016), is identified as a more important driver of tree growth (Marquis et al., 2020), and seems to better explain the altitudinal and latitudinal range limits of tree species (Du et al., 2019; Kollas et al., 2014; Körner et al., 2016; Vitra et al., 2017). Therefore, knowledge of not only changes in mean temperatures but also changes in temperature variation is required to reasonably understand and predict the biological consequences of climate change (Karl et al., 1995).

In recent decades, as the dominant component and the most prominent climate oscillation, the amplitude of the ATC has displayed a decreasing trend in much of the Northern Hemisphere middle-to high-latitude land areas (e.g., Qian & Zhang, 2015; Stine et al., 2009; Thomson, 1995; Wang & Dillon, 2014). Furthermore, anthropogenic forcing has been indicated to impose a detectable influence on the changes in the ATC in certain regions (Mann & Park, 1996; Qian & Zhang, 2015; Santer et al., 2018; Wallace & Osborn, 2002). With regard specifically to the ATC of the TP, many uncertainties and unanswered questions remain. For instance, although a reduced ATC amplitude has been observed over the TP above 4,000 m (Duan et al., 2017), it remains ambiguous how the ATC amplitude at other altitudes of the TP has changed, whether this variation is related to elevation, and whether human activity has a detectable influence. These questions will be addressed in this paper by analyzing and comparing observed and model-simulated changes with altitude in the amplitude trend of the ATC over the TP.

2. Data and Methods

The regular surface meteorological observations for surface air temperature (SAT) applied here are provided by the China Meteorological Administration. The present analysis is based on these data over the TP above 1,000 m with 101 stations for the period of 1961–2014. It comprises the same data records as the model output discussed

Table 1
List of CMIP6 Models, Experiments, and Ensemble Numbers for This Study

No.	Models	Historical	Hist-nat	Hist-GHG	Hist-aer (SAT/RSDS/RSUS)	Hist-aer SNC	piControl
1	ACCESS-ESM1-5	7	3	1	1	0	18
2	CESM2	9	3	3	2	2	22
3	CNRM-CM6-1	4	4	4	4	4	9
4	FGOALS-g3	1	1	1	1	0	13
5	GFDL-ESM4	1	1	1	1	1	9
6	GISS-E2-1-G	5	5	4	4	4	30
7	HadGEM3-GC31-LL	4	4	4	4	4	9
8	IPSL-CM6A-LR	6	6	2	2	2	41
9	MIROC6	10	10	1	4	4	15
10	MRI-ESM2-0	7	5	5	5	5	17
11	NorESM2-LM	3	3	3	3	3	8
	Sum (models)	57 (11)	45 (11)	29 (11)	31 (11)	29 (9)	191 (11)

Note. Figures in parentheses in the last row indicate the total number of models for each forcing.

in the following study. Missing values account for less than 0.5% of the total records during the research period; hence, the quality of the data is reasonable. Moreover, missing values in this study were addressed using the method applied in Duan and Wu (2008).

Monthly mean SAT from models participating in the World Climate Research Program's Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016; https://esgf-node.llnl.gov/projects/cmip6/) are applied in this study. Among them, historical simulations from 1961 to 2014 are employed to estimate the responses of model-simulated temperature to different external forcings. Preindustrial control simulations (piControl), which are divided into multiples of nonoverlapping 54-year intervals, are adopted to assess natural internal climate variability. The climate model-simulated responses to external forcings considered here are obtained from five different experiments as follows: all-forcing simulation (ALL), historical natural-only run (NAT), anthropogenic forcings simulation (ANT), historical well-mixed greenhouse gases forcing only (GHG), and historical anthropogenic aerosol-only run (AER). The model-simulated responses to anthropogenic forcings are obtained by subtracting the natural forcing from the all-forcing simulation (e.g., Hu & Sun, 2021; Paik & Min, 2020; Seong et al., 2021). Eleven models are selected as they provide both historical simulations under all abovementioned and preindustrial control simulations, as well as surface altitude (Table 1). Moreover, due to the lack of surface albedo data in simulation output, monthly mean surface downwelling shortwave radiation (RSDS) and surface upwelling shortwave radiation (RSUS) under anthropogenic aerosol-only forcing are also employed in our study to calculate surface albedo, which is expressed as the ratio between the RSUS and the RSDS. To ensure equal weights for different models, the multimodel ensemble mean is obtained by calculating the individual model ensemble mean and then averaging across multiple models.

To quantify the possible influence of external forcings on the elevation dependence of the amplitude trend, we use a correlation-based method of detection analyses here, which is applied in many studies (e.g., Qian & Zhang, 2015; Santer et al., 1995; Wan et al., 2015). The series for mean amplitude trend values on non-overlapping altitudinal ranges in observations and model-simulated responses to the abovementioned external forcings are compared by computing correlation coefficients between observations and simulations. To determine the statistical significance of the correlations, we also calculate the correlation coefficients between observations and each of the 191 intervals of piControl simulations. If the correlation coefficient between the observations and the model-simulated response to a forcing is above the 90th percentile of the correlation coefficients between the observations and the piControl intervals, that correlation is considered to be statistically significant at the 90% confidence level over internal variability, and the forced response is detectable in the observations. We need to address a large number of model simulations in this study. The seasonal maximum for SAT over the TP occurs

10.1029/2021GL095494

in JJA, and the minimum occurs in DJF. Hence, the amplitude of the ATC is calculated via a simplified scheme mentioned in the literature (Qian & Zhang, 2015):

$$A = \frac{(T_{\text{JJA}} - T_{\text{DJF}})}{2} \tag{1}$$

where A is the amplitude, and T_{JJA} and T_{DJF} are the temperature in the current JJA (June–July–August) and the temperature in the following DJF (December–January–February), respectively.

3. Results

3.1. Elevation-Dependent Weakening of the ATC Amplitude

The amplitude of the ATC for most stations over the TP shows a decreasing trend during the 1961/1962–2013/2014 period (Figure 1a). More importantly, larger weakening trends tend to occur in higher-altitude regions, especially above 2,500 m, where the trends averaged within every altitudinal range are all significant at the 95% confidence level (Figure 1b). That is, an elevation-dependent weakening of the ATC amplitude is apparent over the TP. This significant elevation dependence for the amplitude trend is clearly demonstrated in Figure 1c, where the correlation coefficient between the trend of the ATC amplitude and the elevation for the 101 stations is −0.24 ($p < 0.05$).

To investigate the cause of the changes with altitude in the ATC amplitude, the relationships between the trend of the ATC amplitude and the annual or seasonal temperature trends over the TP are analyzed in Figures 2a–2c. The trend of the ATC amplitude over the TP shows a significant correlation with the annual mean temperature trend (Figure 2a) and the winter temperature trend (Figure 2c), with the correlation coefficients of −0.444 ($p < 0.01$) and −0.739 ($p < 0.01$), respectively. However, the correlation between the summer temperature trend and the amplitude trend is not significant (Figure 2b). In general, the SAT for annual mean, summer and winter presents an increasing trend over the TP (Figures 2d–2f), and the warming in winter is more striking than that in summer, which contributes to the diminishing seasonal temperature difference in Figure 1. More notably, the SAT over the TP represents elevation-dependent warming in winter (Figure 2f), and the correlation coefficient between the winter temperature trend and the altitude is 0.311 ($p < 0.1$). For summer, the result is completely different (Figure 2e). The correlation between elevation and the summer temperature trend is not significant. Thus, the greater warming in winter in higher-altitude regions over the TP causes the negative tendency of the ATC amplitude to amplify with elevation (Figure 1).

3.2. Detection and Attribution

Detection and attribution analyses are performed for the central-eastern TP (CE-TP, 25°N–40°N, 85°E–106°E) as most of the meteorological stations are located there. Amplitude trend anomalies in Figure 3 are calculated by removing the regional mean values over the CE-TP above 1,000 m. The altitudinal range is further refined to obtain more samples. The multimodel ensemble mean under ALL forcing can capture the observed change in the trend of the ATC amplitude with altitude, and similar detection results are obtained when the ANT forcing signal is estimated (Figure 3a). The responses to NAT forcing do not show these characteristics. The results suggest that the elevation-dependent variation in the amplitude trend is consistent with the observations only if anthropogenic forcing is involved.

Moreover, the model-simulated response to ALL or ANT forcing is detectable in Figure 3b, whereas that to NAT forcing is not detectable. The correlation between the observations and the model-simulated responses, including to ALL forcing and to ANT forcing, is significant, as tested by a one-sided Monte Carlo test conducted with piControl simulations (Figure 3b), with correlation coefficients of 0.771 and 0.756, respectively. This finding indicates that the responses to ALL and ANT forcing can be detected at the 95% confidence level, whereas the NAT signal cannot be detected. Furthermore, the trend of the ATC amplitude in the AER response displays a discernible elevation-dependent weakening which is similar to that observed (Figure 3c), with a correlation coefficient of 0.732 ($p < 0.05$), while the correlation between the observations and the response to GHG forcing is not significant (Figure 3c), with a correlation coefficient of 0.627 ($p > 0.1$). It appears that the detectable variation in the ANT response is primarily derived from AER forcing.

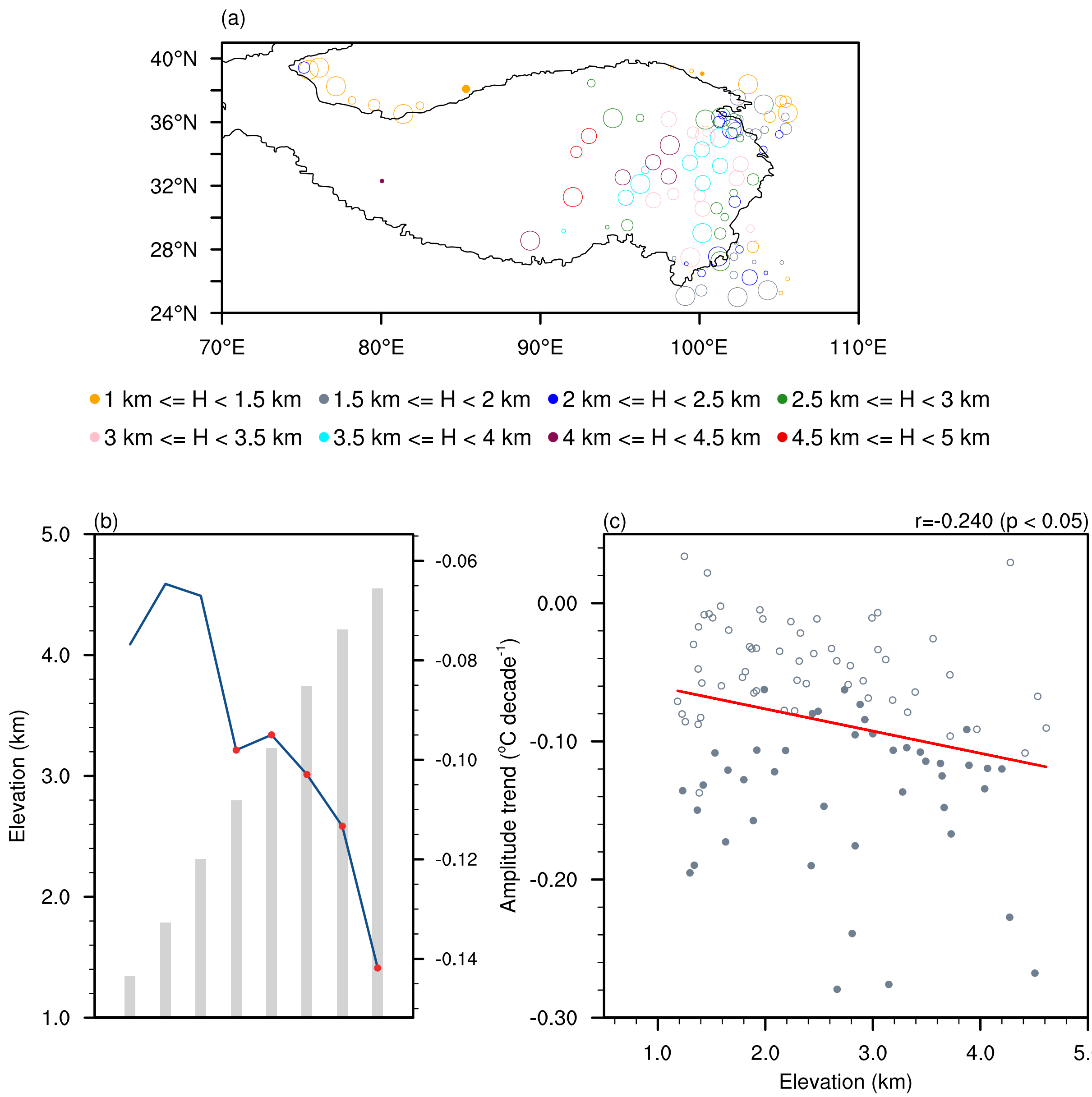

Figure 1. (a) Spatial distribution of the linear trend of the annual temperature cycle (ATC) amplitude over the Tibetan Plateau (TP) at altitudes above 1,000 m. The open circles represent negative values, and the solid circles represent positive values. The larger is the circle, the larger the absolute value. The black curve outlines the TP area above 2,000 m. (b) Average trend of the ATC amplitude for every altitudinal range (line). Values exceeding the 95% confidence level are presented in dots. Bars represent mean altitudes. (c) Relationships between the trend of the ATC amplitude and the altitude over the TP. The solid circles represent the stations where ATC amplitude trends exceed the 90% significance level.

In general, the similarity in the changes between the observations and the model-simulated responses indicates that the influence of anthropogenic activities on the elevation-dependent weakening of the ATC amplitude is detectable and that the increase in AER is the main contributor.

The TP is located in the immediate vicinity of densely populated and industrialized regions. Growing evidence has demonstrated that exogenous air pollutants can enter the TP's environments and impact the cryosphere (e.g., Di Mauro, 2020; Kang et al., 2019; Li et al., 2016; Sarangi et al., 2020; Xu et al., 2009). Carbonaceous particles and dust can be transported from the west and southwest to the hinterlands of the TP by prevailing wind (Ji et al., 2015; Kang et al., 2019; Xia et al., 2011). Reduced Arctic sea ice intensifies aerosol transport to the TP (Li et al., 2020). The deposition of these light-absorbing particles can substantially accelerate snowmelt (Gautam

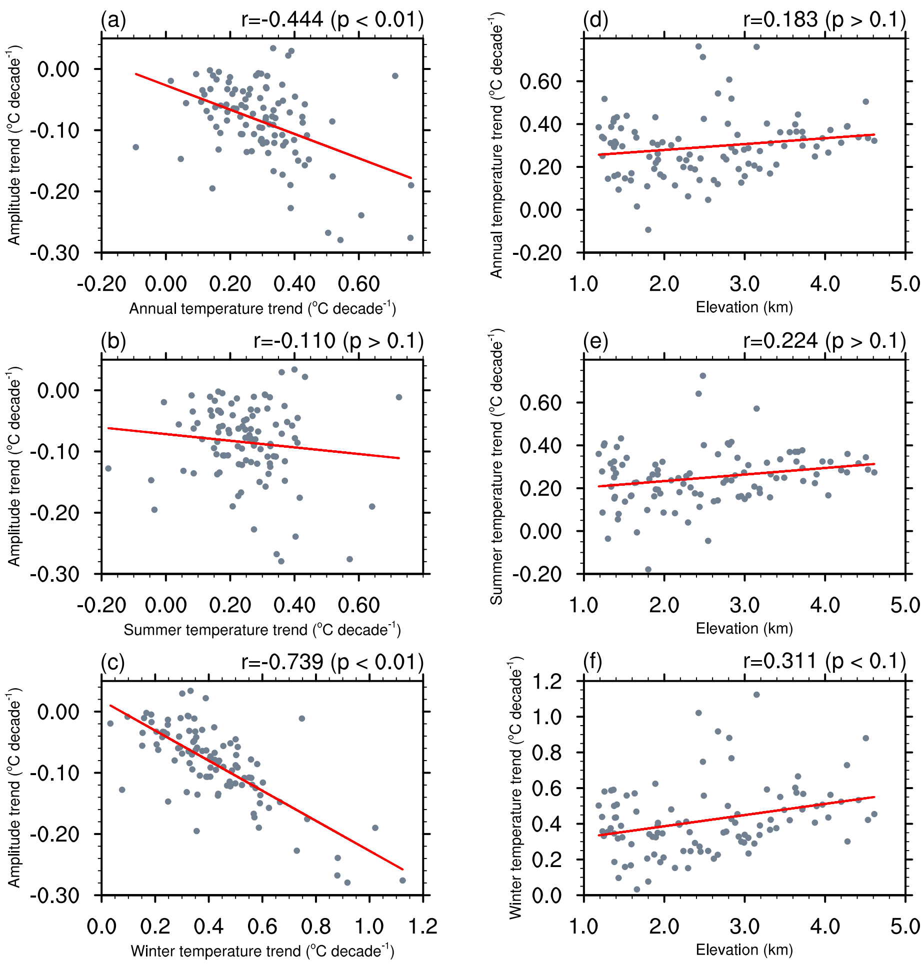

Figure 2. Relationships between the trend of the annual temperature cycle (ATC) amplitude and the (a) annual temperature trend, (b) summer temperature trend, and (c) winter temperature trend, as well as relationships between the (d) annual temperature trend, (e) summer temperature trend, and (f) winter temperature trend and the altitude over the Tibetan Plateau (TP).

et al., 2013; Lau et al., 2010; McKenzie Skiles & Painter, 2018; Painter et al., 2013; Qian et al., 2015; Xu et al., 2009). Moreover, dust aerosols in the atmosphere warm clouds and increase the evaporation of cloud droplets, eventually leading to less precipitation (Huang et al., 2014). Enhanced snow loss at higher elevations over the TP cause development of elevation-dependent warming, especially in winter (Guo et al., 2021). Accordingly, trends in snow area percentage (SNC), albedo and SAT over the TP for model-simulated responses to AER forcing and their relationships were analyzed to demonstrate the impact of aerosols on ATC amplitude. The SNC over the TP in the model-simulated responses to AER forcing decreased strikingly as the altitude increased in winter, particularly above 2,500 m (Figure 4a). This finding may be relevant to the signature of the increasing dust-induced snow darkening with surface elevation over High-Mountain Asia (Sarangi et al., 2020), which enhances snowmelt trends over high-altitude regions. The slight trend of SNC in summer may be related to the seasonal variation in aerosol deposition (Chen et al., 2015; Cong et al., 2015; Kang et al., 2019; Wan et al., 2017). Seasonal variation in altitude-dependent SNC trends could cause the albedo of the high elevation decrease in winter to be more obvious than that in summer (Figure 4b), followed by a signature of amplified warming with elevation in winter (Figure 4c). The correlation between the albedo trend and the SAT trend is significant in both summer and winter (Figures 4d and 4e), with correlation coefficients of −0.45 ($p < 0.1$) and −0.686 ($p < 0.01$), respectively. This finding confirms the conclusion that aerosols may have made an important contribution to elevation-dependent warming over the TP (Kang et al., 2019; Xu et al., 2009; You et al., 2020). The greater warming in winter in higher-altitude regions acts as the main contributor to the elevation-dependent negative tendency of the ATC

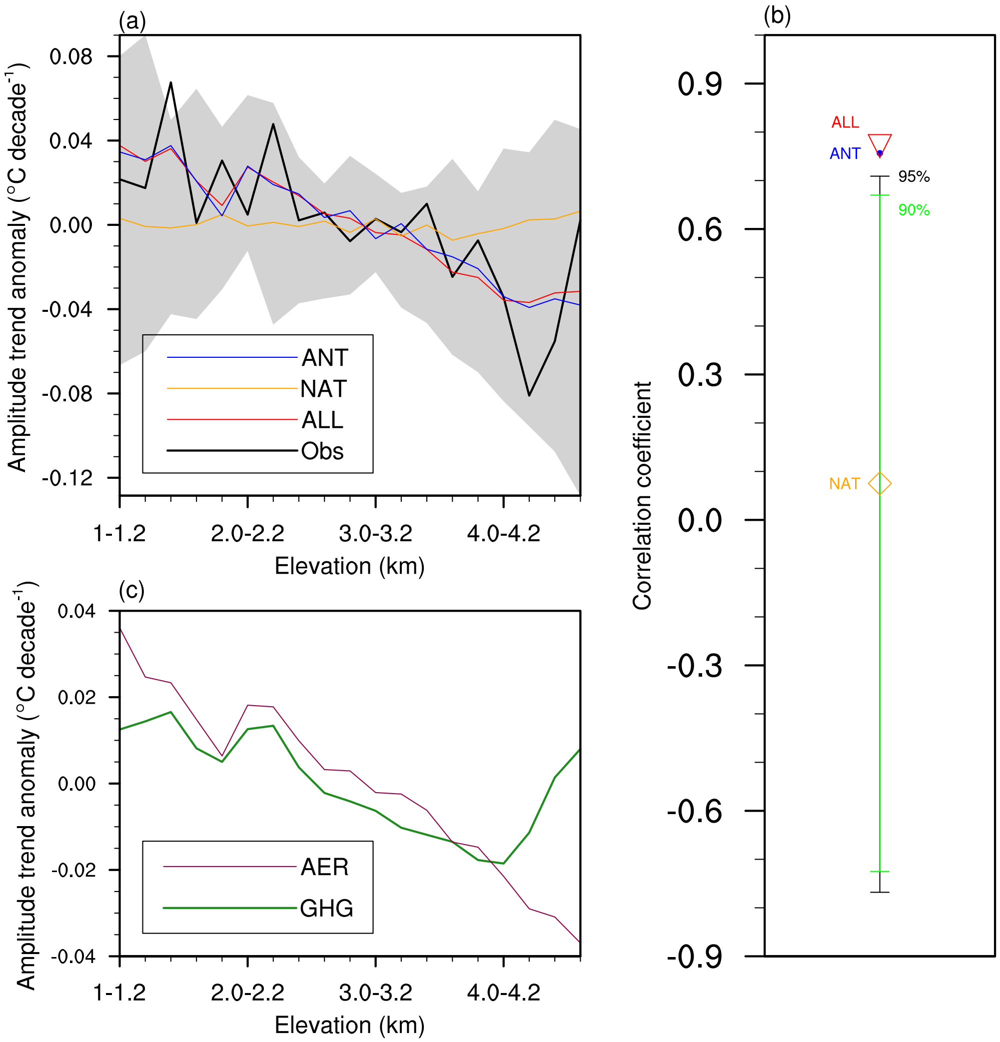

Figure 3. (a) The 200-m altitudinal-range mean trend anomalies of the annual temperature cycle (ATC) amplitude in the observations and model-simulated responses to all-forcing simulation (ALL), historical natural-only run (NAT), and anthropogenic forcings simulation (ANT) forcing are shown. The range of the 5th–95th percentile amplitudes simulated from 57 individual model runs under ALL forcing are shown in gray. (b) Correlation coefficients between the observed average trend and model-simulated average trend of the ATC amplitude for the 19 altitudinal ranges. The red triangle, blue spot, and orange diamond mark the correlation coefficients between the observations and model-simulated responses to ALL forcing, ANT forcing and NAT forcing, respectively. The 5th–95th and 10th–90th percentile ranges of the correlation coefficients between the observations and 191 intervals of piControl simulations are expressed by black error bars and green error bars, respectively. (c) The 200-m altitudinal-range mean trend anomalies of the ATC amplitude in the model-simulated responses to anthropogenic aerosol-only run (AER) and greenhouse gases forcing only (GHG) forcing are shown. Amplitude trend anomalies are calculated by removing the regional mean values over the CE-TP above 1,000 m.

amplitude (Figures 2c and 2f). Quantitatively, compared with summer (Figure 4f), the decreasing albedo over high regions in winter, as a consequence of elevation-dependent shrinkage in SNC, is the main contributor to the amplified negative tendency with elevation for the ATC amplitude in the model-simulated response to AER forcing (Figure 4g). The correlation between the ATC amplitude trend and the winter albedo trend is significant at the 99% confidence level, with a correlation coefficient of 0.763 (Figure 4g). However, the correlation between the amplitude trend and the summer albedo trend was not statistically significant (Figure 4f).

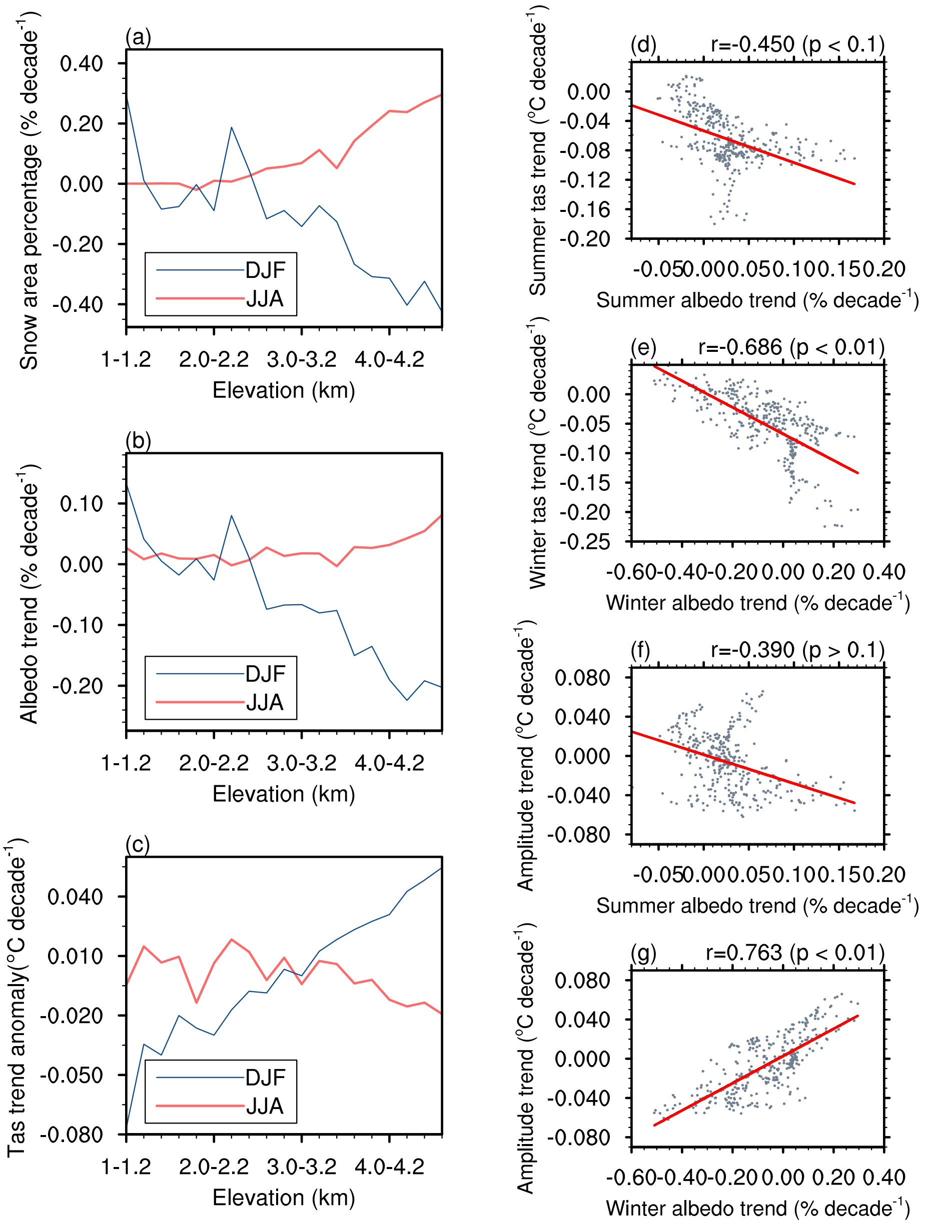

Figure 4. The 200-m altitudinal-range mean (a) snow area percentage (SNC) trend, (b) albedo trend and (c) SAT trend anomaly in the model-simulated responses to anthropogenic aerosol-only run (AER) forcing (d and e) Relationship between the SAT trend and albedo trend in (d) summer and (e) winter over the CE-TP at altitudes above 1,000 m for the 1961/1962–2013/2014 period (f and g) As shown in (d and e) but for the relationship between the trend of the annual temperature cycle (ATC) amplitude and the albedo trend in (f) summer and (g) winter.

4. Conclusions

The amplitude of the ATC decreased in most areas of the TP during the period 1961–2014; this diminished trend was amplified with elevation. Compared with the trend in the annual mean temperature and summer temperature, the warming in winter and its elevation dependence may to a large extent account for the negative tendency in the ATC amplitude and its amplification with altitude. The influence of anthropogenic forcing on the elevation-dependent weakening in the ATC amplitude over the TP can be separated from that of natural forcing, and the increase in anthropogenic aerosols may be the main contributor. In the model-simulated response to anthropogenic aerosol–only forcing, aerosols force a greater reduction in SNC and even surface albedo at higher altitudes in winter and thus enhance elevation-dependent warming in that season, thereby resulting in the negative tendency of the ATC amplitude to enlarge with altitude over the TP. Additionally, further studies on the impact of aerosols on snowmelt and snowfall, as well as their relative contribution to shrinking SNC at high elevations, would be conducted by combining application of satellite-based datasets and modeling experiments to understand the complex physical mechanism of cryospheric changes associated with aerosols.

Conflict of Interest

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

Data Availability Statement

The CMIP6 models used in this study are listed in Table 1, and the model outputs are available at https://esgf-node.llnl.gov/search/cmip6/. The calculated trends of ATC amplitude based on original meteorological station data are available at https://doi.org/10.7910/DVN/87X4VY.

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