Evidence of decreasing diurnal temperature range in eastern Northern Hemisphere

Xiaodan Guan1,2,*, Chenyu Cao2, Xinrui Zeng2 and Wen Sun2

1 Collaborative Innovation Center for Western Ecological Safety, Lanzhou 730000, People’s Republic of China
2 Key Laboratory for Semi–Arid Climate Change of the Ministry of Education, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: guanxd@lzu.edu.cn

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Abstract
As a key variable in the climate system, the diurnal temperature range (DTR) has received a lot of attention in the atmospheric science community. The majority of published papers interpret DTR change in terms of variables like water vapor, cloud cover, and enhanced vegetation index. In this study, we found that the DTR has an obvious decreasing trend in the semi-arid Northeastern Hemisphere, and the decreasing trend is mainly caused by the continuous release of CO2 closely associated with a drying process in the Northeastern Hemispheric. As a result of the continued high emission of CO2, such accelerated decline changes in DTR in drylands may become much more pronounced in the future, posing a series of environmental problems.

1. Introduction
Global average surface air temperature has increased in the past century, with a faster warming rate since 1950 (IPCC AR6, 2021). In the past decades, both daily minimum and maximum air temperatures significantly increased; but their asymmetrical changes (Tmin rose faster than Tmax) led to an obvious decrease in the diurnal temperature range (DTR) on a global scale (Hansen et al. 2006). DTR is not only a related temperature variable, its variability can affect the growth of plants, ecological system and even the carbon economy illustrating its change worth more investigation. Huang et al. (2012) found the semi-arid region of the Northern Hemisphere (NH) is the most sensitive to the warming change; it has the highest increasing trend of Tmin and Tmax (figure 1(a)). However, the trend of DTR defined by Tmin and Tmax does not show an obvious regional discrepancy (figure 1(c), black line); the most region has a negative trend of DTR except for arid areas. Different from temperature variables, DTR change is easier influenced by local factors (Zhou et al. 2010). Therefore, in this study, we first compare the DTR change between the opposite regional processes of drying eastern NH and wetting western NH, and further identify the effects of CO2, black carbon (BC), SO4, and three forcing factors combined on regional DTR trend. We will also compare the response of DTR change in semi-arid region to the CO2 emission scenarios from low to high.

2. Methods and data

2.1. Dynamic adjustment method
The dynamic adjustment method was introduced in Wallace et al. (2012), and described in detail in Smoliak et al. (2015). The core of the method is the partial least squares (PLS) regression of surface air temperature to the sea-level pressure (SLP) in a pointwise manner. As the method is only effective in the mid-to-high latitudes of the Northern Hemisphere (NH), the SLP poleward of 20 °N is used to predict the time series of temperature. The raw temperature data is divided into two parts, the dynamic and radiative parts. The dynamic part is considered...
majorly decided by the atmospheric circulation patterns, and the radiative part is closely associated with local processes, such as snow, land type, GHGs, and other anthropogenic forcings. Previously, the method was applied to the ‘warming hiatus,’ and we detected the cooling of dynamic temperature and continuous warming of radiative temperature (Guan et al., 2019). The method has also been used to explore the thermodynamic warming in the enhanced warming of semi-arid regions (Guan et al., 2017).

2.2. Dataset

The AI (aridity index) is equal to annual precipitation divided by annual potential evapotranspiration in Feng and Fu (2013), with the precipitation and potential evapotranspiration data from the Climate Prediction Center (CPC). The AI is classified as hyper-arid (AI < 0.05), arid (0.05 < AI < 0.2), semi-arid (0.2 < AI < 0.5), and dry sub-humid (0.5 < AI < 0.65), according to Middleton and Thomas (1997). The AI dataset for this study covers the period from 1948 to 2008 at a resolution of 0.5° by 0.5°. In this study, climatological mean AI from 1961–1990 is used to divide climatic regions.

The monthly T_{min} and T_{max} are obtained from the Climatic Research Unit (CRU) TS dataset, with a resolution of 0.5° by 0.5°. The time period of all temperature datasets used in this study is from 1901 to 2012. The DTR (diurnal temperature range) is equal to daily T_{max} minus daily T_{min}. To explore the future change of DTR, we use the outputs from the Coupled Model Intercomparison Project phase 6 (CMIP6) models. We analyze the future climate simulations and projections under different Shared Socioeconomic Pathways (O’Neill et al. 2017) of nineteen models, which cover the period 2015–2100 (table 1). To isolate the effects of individual radiative factors on T_{max}, T_{min}, and DTR in semi-arid regions, experiments of two scenarios with forcing level of present-day and preindustrial BC, SO₂, and CO₂ were conducted (Xu et al. 2016) by using the Community Earth System Model 1 (CESM1).

3. Results

Figure 1 (a) shows that both daily T_{min} and T_{max} have their highest peaks in semi-arid regions. The amplitude of daily T_{min} is higher than that of daily T_{max}, and there is a non-uniform DTR over different regions. To explore the mechanisms of DTR variability over different regions, we first separate the raw T_{max} and T_{min} into dynamic and radiative parts by applying the dynamic adjustment method which are shown in figure 1 (b), respectively. Figure 1 (b) shows that the radiative-forced daily T_{max} has an obvious peak in semi-arid regions (red line) and has
similar variability as the raw $T_{\text{max}}$ especially in semi-arid regions. The significant peak of the raw daily $T_{\text{max}}$ in semi-arid regions almost reaches 0.014 °C/year, with a radiative daily $T_{\text{max}}$ of 0.012 °C/year. However, the dynamic $T_{\text{max}}$ has a relatively flat change over all regions, with a value of 0.002 °C/year.

In figure 1(b), the curves of the raw, dynamic and radiative $T_{\text{min}}$ are similar to those of $T_{\text{max}}$, but with a larger amplitude. In semi-arid regions, the peak of daily $T_{\text{min}}$ reaches 0.016 °C/year, with a radiative $T_{\text{min}}$ of 0.014 °C/year and a dynamic $T_{\text{min}}$ of 0.002 °C/year. Comparing the differences between dynamic and radiative $T_{\text{max}}$ or $T_{\text{min}}$, we can see that the radiative effect takes a dominant role in the obvious increasing daily $T_{\text{max}}$ and $T_{\text{min}}$ in semi-arid regions. But the distribution of the DTR trend is different from those of $T_{\text{max}}$ and $T_{\text{min}}$ (figure 1(c)), showing that the trend of DTR is similar over different regions.

Huang et al (2016) pointed out that the mid-to-high latitudes of the NH have the opposite regional process of drying and wetting in the eastern and western NH. We compare the trend distributions of DTR over different regions between the eastern and western NH (figure 2). In the eastern NH, DTR shows variability as a function of the AI, with the lowest peak appears in the semi-arid region at decreasing rate of $-0.04$ °C/decade. However, the lowest value of DTR trend in the western NH is in the humid region of AI $> 0.6$; the DTR in semi-arid regions has a weak negative trend or even a positive trend in regions with the AI of 0.3–0.5. Different distributions of DTR trends in the eastern and western NH suggest that DTR change is closely associated with local processes.
Previous results point out the local process is always associated with CO$_2$ (Huang et al 2016; Qian et al 2015), BC (Lin et al 2016; Seinfeld, Pandis 1979), and other radiative factors (Zhang et al 2017). We calculate the average temperature, $T_{\text{min}}$, $T_{\text{max}}$, and DTR in the sensitivity and control experiments as a function of the AI using the model outputs over the last 60 years in the mid-to-high latitudes of eastern NH. Figure 3(a) shows that CO$_2$ (red) led to obvious warming of the daily mean temperature relative to the control experiment, followed by combined forcings (green) and BC (black) in drylands. We also find the combined forcings experiment with respect to the control shows warming with a smaller amplitude compared to the CO$_2$ warming experiment, because warming is offset by SO$_4$. Similar distributions of $T_{\text{min}}$ and $T_{\text{max}}$ are illustrated in figures 3(b) and (c). The warming induced by CO$_2$ in the sensitivity experiment gives larger values of $T_{\text{max}}$ and $T_{\text{min}}$ than those in the control experiment, especially in semi-arid areas. In a warmer climate, the same amount of heating contributes to

Figure 3. Differences between the sensitivity and control experiments concerning black carbon (black), CO$_2$ (red), SO$_4$ (blue), and combined forcings (green) as a function of the aridity index over 20°–50°N in the eastern Northern Hemisphere in the mean daily temperature (a), daily maximum temperature (b), daily minimum temperature (c), and diurnal temperature range (d) in winter for 60 years.

Figure 4. Regionally averaged diurnal temperature range trends in the cold season (Nov.-Mar.) as a function of the annual aridity index in the future simulations of SSP126 (green) and SSP585 (orange) from 2015 to 2100. Shaded areas represent 99% confidence intervals.
stronger warming in drylands than to humid regions (Dai 2016). In drylands, more high upward net longwave radiation contributes to a faster increasing rate of $T_{\text{min}}$ than $T_{\text{max}}$ (Huang et al. 2017).

Figure 3(d) shows differences in DTR between the sensitivity and control experiments. The most obvious difference in DTR appears in the semi-arid regions; the largest differences are seen in the combined forcings experiment, followed by those in the CO$_2$ and BC experiments. In these radiative factors, CO$_2$ has the major effect on DTR decrease in semi-arid regions, and it (red curve) makes the largest contribution in the single experiment relative to BC and SO$_4$. For the dominant factor of CO$_2$ in the DTR trend, the future simulation scenario of high emission has a more obvious decreasing trend in the semi-arid regions of the eastern NH than that of the low emission of scenario. In SSP 126, all the regions show a weak positive trend of DTR. For the highest emission scenario of SSP 585, the DTR shows the strongest decreasing trend around 0.094 °C/decade in semi-arid regions, which is much faster than that in SSP 126 (figure 4). The obvious discrepancy of DTR change between SSP 126 and SSP 585 confirms the key role of the CO$_2$ effect on enhanced DTR trend in the semi-arid region of the eastern NH.

4. Conclusion

Therefore, based on the dynamic adjusted method, the indirect effect of altered concentrations of radiatively active gases has an obvious regional effect compared with their dynamic effect on DTR. In the semi-arid region of the eastern NH, the local process of enhanced release CO$_2$ by drying leads to the most obvious decreasing rate of the DTR. Such effect from CO$_2$ on DTR will be amplified in the high emission of SSP 585. As the most sensitive region in the climate system (Guan et al. 2015), the local radiative process is mainly affected by snow/ice and frozen ground cover changes (Luo et al. 2003), regional human activity (Guan et al. 2016), and atmosphere–land surface interaction (Jin et al. 2016), which further lead to the release of a larger amount of CO$_2$ into the atmosphere, accompanied by occurrences of desertification and enhanced warming Therefore, the metric DTR-trend could identify parts of the world, which are becoming more arid.

Besides the result from Huang et al. (2017), Davy et al. (2017) found that the build-up of carbon dioxide in the atmosphere from emissions associated with human activities reduces the amount of radiation released into space, which increases both night-time and day-time temperatures. However, because at night there is a much smaller volume of air that gets warmed, the extra energy added to the climate system from carbon dioxide leads to a greater warming at night than during the day. Other explanations show that the regional faster warming of $T_{\text{min}}$ is closely associated with clouds. From the result of Cox et al. (2020), the regionally increased cloud cover cools the regional surface during the day and retains the warmth during the night, leading to greater night-time warming.

Besides, the DTR is significantly associated with mortality and morbidity, particularly for cardiovascular and respiratory illnesses. The relationship is also affected by susceptible groups, lag time, ages, and threshold of DTR (Cheng et al. 2014). There is a significant relationship between ambient temperature and mortality. When temperatures exceed a certain limit, being cold winter spells or heat waves, there is an increase in the number of deaths. In particular, it has been shown that at temperatures above 27 °C, the daily mortality rate increases more rapidly per degree rise compared to that when it drops below 27 °C (Calleja-Agius et al. 2021). Under the global warming, the faster increasing night-time temperature results in less time for human bodies to cool off and contributes to more occurrence of morbidity and mortality (Luo et al. 2013). And such expose to DTR changes occurred more easily in the developing countries (Zhai et al. 2021).

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
ORCID iDs

Xiaodan Guan  © https://orcid.org/0000-0003-3716-4503

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