Distinct response of near surface air temperature to clouds in North China

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Abstract
Using the daily 2 m maximum temperature (Tmax), 2 m minimum temperature (Tmin) and cloud cover data measured at ground sites of the China Meteorological Administration in North China from 2000 to 2017, this study investigates the influence of clouds on the daily temperature range (DTR) defined as the difference between Tmax and Tmin. As expected, the cloud cover shows the similar averaged spatial distribution and monthly variation with Tmin. Surprisingly, it also shows the similar average spatial distribution and monthly variation with Tmax, suggesting the more important roles of regions (latitude) and seasons associated with the variations of land surface temperature, which is further related to solar radiation absorbed and surface heat capacity. By comparing monthly variations of temperature between cloudy and clear skies, we find that clouds can weaken Tmax and increase Tmin, and thus decrease DTR. As a result, the spatial distribution of DTR is opposite to the cloud cover. The clouds have relatively stronger impact on Tmin and DTR over mountain region, which is most likely caused by the stronger longwave cloud radiative forcing associated with higher cloud tops over the mountain region.

KEYWORDS
cloud cover, cloud top, daily temperature range, spatial distribution, temporal variation

1 | INTRODUCTION

Associated with the global warming, the daily temperature range (DTR), which is defined as the difference of daily maximum temperature (Tmax) and daily minimum temperature (Tmin), shows the impact of human activity on climate change (Braganza et al., 2004). Higher DTR has adverse impacts on human health (He et al., 2021; Phosri et al., 2020; Ponjoan et al., 2020). There are many factors that can affect DTR, such as radiation, greenhouse gases, cloud cover, aerosol, water vapor, soil moisture, surface condition, precipitation, and so on (Chen & Dirmeyer, 2019; Dai et al., 1999; Feddema, 2005; Liu et al., 2016; Martin et al., 2007).

Clouds are one of the important factors regulating the climate system (Edenhofer & Seyboth, 2013), with the total cloud cover in the world about 70% (Stubenrauch et al., 2013). The reduction of DTR primarily attributes to the increase of cloud cover (Dai et al., 1999). As a factor affecting DTR, cloud is also of great significance to
climatic. Thus, studying the impact of cloud on DTR can help human beings to grasp climate change information from more aspects.

Lauritsen and Rogers (2012) used a stepwise multiple linear regression method to analyze the effects of cloud cover, soil moisture, precipitation, and leaf area index on Tmax, Tmin, and DTR. Jackson et al. (2010) used non-linear regression to study the influence of different factors on DTR. Correlation analyses were used to show the relationship between cloud cover and DTR in different seasons. It was found that cloud cover and DTR in four seasons showed opposite variations (Leathers et al., 1998; Dietmüller et al., 2008; Zhou et al., 2009; Jackson et al., 2010; You et al., 2016). Clouds reflect the solar radiation during the day to weaken Tmax, and at night, by trapping the long-wave radiation from the surface to enhance Tmin, and finally affecting the near-surface air temperature and DTR (Forsythe et al., 2015). In order to further explore the impact of clouds on DTR, previous studies have found that clouds can reduce DTR by comparing the differences in DTR between clear and cloudy skies (Xue et al., 2019). Previous studies have found that low clouds have a more pronounced effect on DTR reduction in warm and dry seasons (Dai et al., 1999; Dietmüller et al., 2008; Zhou et al., 2007; Zhou et al., 2009).

Although there have been studies on the effects of different underlying surfaces on DTR (Feddema, 2005; Gallo & Easterling, 1996), there is a lack of studies on the effects of clouds on DTR under different topographies. North China has mountains and plains, as well as coastal and inland areas. By analyzing the relationship between cloud cover and temperature in North China, the influence of cloud cover on temperature is found, and then the influence of cloud on Tmax, Tmin, and DTR is further analyzed under different surface types.

2 | DATA AND METHOD

2.1 | Data

Figure 1 shows the study region along with the distribution of 136 ground weather stations in North China, which is with latitudes 33–43°N and longitudes 110–122°E. Within the study region, 2 m Tmax, 2 m Tmin data, 24 h precipitation and cloud cover data are provided by the China Meteorological Administration (CMA) (http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html) during the time period from January 2000 to December 2017.

The hourly cloud cover data are obtained from the Clouds and the Earth’s Radiant Energy System (CERES) product CERES_SYN1deg_Ed4.1 (https://ceres.larc.nasa.gov/data/#syn1deg-level-3) with a spatial resolution of 1° × 1° from March 2000 to December 2017. Note that both day and night cloud cover data are available in the CERES_SYN1deg_Ed4.1 product, which provides us an opportunity to compare the day and night difference in cloud cover (Doelling et al., 2013). While the surface upwelling and downwelling longwave and shortwave radiation are also available in the CERES_SYN1deg_Ed4.1 product, they are not adopted in this study since they are retrieval results instead of direct observations with relatively large uncertainties (Jia et al., 2018).

ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?TAB=form) is used to get the daily variation of 2 m temperature and then get the occurrence time of Tmax and Tmin. The study period is from January 2000 to December 2017. The temporal resolution is 1 h and the horizontal resolution is 0.25° × 0.25°. Temperature data in ERA5 were selected in this paper because of their high-data quality (Hersbach et al., 2020; Ramon et al., 2019). Note that with the consideration of data accuracy, the ERA5 data is only used for the determination of data period that Tmin and Tmax lie, and all other analyses are based on the ground site observations.

2.2 | Method

This study only uses the good quality meteorology data of temperature from the ground station observations and limits the temperature with a reasonable range of −50 to 50°C by removing the abnormal values. To confirm the reliability of our analysis, we also only account
for the temperature data at stations with missing data no more than 10% in each year (Xue et al., 2019). To analyze the potential effect of clouds on temperature and to ensure sufficient sample, we define the clear and cloudy skies, which are for the cases with daily cloud cover of station less than 10%, and for the cases with daily cloud cover of station greater than 90%, respectively. In addition, when we select cloudy and clear skies, the precipitation is excluded, that is, there is no precipitation (the value is 0) or there is trace of precipitation with 24-hour precipitation amount less than 0.1 mm.

In this study, the effect of cloud on DTR is determined by comparing DTR between cloudy and clear skies, which is defined as $\Delta \text{DTR}$. Thus, the $\Delta \text{DTR}$ is calculated as:

$$\Delta \text{DTR} = \text{DTR}_{\text{clear}} - \text{DTR}_{\text{cloudy}},$$

where $\text{DTR}_{\text{clear}}$ presents DTR under clear sky, and $\text{DTR}_{\text{cloudy}}$ represents DTR under cloudy sky. In the same way, the $\Delta \text{Tmax}$ and $\Delta \text{Tmin}$ are obtained. The correlation coefficient analysis has been adopted in this study to examine the relationship between two physical quantities, and the correlation coefficient are further investigated with student's $t$ significance test.

The hourly ERA5 reanalysis data from 2000 to 2017 are used for statistical analysis to obtain the diurnal variation characteristics of 2 m air temperature, and takes the time period corresponding to the occurrence of Tmax and Tmin in a day as the study period. The diurnal variation of the 2 m average temperature from 2000 to 2017 shows that Tmax appeared in the time period from 6:00 UTC to 8:00 UTC, and Tmin appeared in the time period from 20:00 UTC to 22:00 UTC. Therefore, in the analysis of day and night cloud cover and radiation, the time period of daytime is selected from 6:00 UTC to 8:00 UTC, and the time period of night is selected from 20:00 UTC to 22:00 UTC. Note that all time in this study is in UTC.

3 | ANALYSIS AND RESULTS

3.1 | Spatial distribution of cloud cover and temperature

Figure 2 shows the spatial distribution of both annual (a,f), spring (b,g), summer (c,h), fall (d,i) and winter (e,j) averaged daytime and nighttime cloud cover in North China from 2000 to 2017, respectively. Two regions within the study domain are adopted with the same latitudes, which are plain area squared with black lines and mountain area squared with blue lines. Based on the definition from section 2.2, the day and night time in this study are just typical day and night time which are roughly around the occurrence time of Tmax and Tmin. Figure 2 shows more clouds in the south and less clouds in the north, which is likely related to the spatial distribution of downwelling solar radiation during day time and moisture distribution at night time. The seasonal average cloud cover from 2000 to 2017 showed the largest value in summer (day: 71.8%, night: 61.6%) and the least value in winter (day: 53.5%, night: 53.0%). In summer, affected by the East Asian summer monsoon, more water vapor is brought to land by the southeast winds, causing more cloud cover (Jin et al., 2009); and in winter, affected by the East Asian winter monsoon, dry and cold

![Figure 2](image)
atmosphere along with intense pollution makes the northwestern part of North China with less cloud cover (Jin et al., 2009; Kiemle et al., 2015). For annual and seasonal average day and night time, it is found that the total cloud cover was less in mountainous areas and more in plain areas, which is related to the transported water vapor from the sea.

Figure 3 shows the spatial distributions of seasonal average T_max (a–d), T_min (e–h) and DTR (i–l) from 2000 to 2017. In spring, summer, fall and winter, the average T_max in all stations are 19.0, 29.4, 17.9, and 3.3°C, respectively; the averaged T_min in all stations are 6.8, 19.5, 7.4, and −7.0°C, respectively; and the averaged DTR in all stations are 12.2, 9.9, 10.6, and 10.3°C, respectively. The spatial distributions of Tmax and Tmin both demonstrate high values in the south and low values in the north, which is consistent with the cloud spatial distribution as shown in Figure 2. These similar spatial distributions of Tmax and Tmin are most likely due to the combined effect of solar radiation absorbed and the heat capacity of surface, which causes the land surface temperature and then near surface air temperature high in the south and low in the north. Differently, for a fixed location within a short period, the temporal variation of cloud cover is generally opposite to that of downwelling solar radiation and then Tmax, since clouds can block downwelling solar radiation (Dai et al., 1999; Pyrgou et al., 2019). In addition, clouds can trap LW to increase Tmin (Garrett & Zhao, 2006; Zhao & Garrett, 2015).

The spatial distribution of DTR in Figure 3 shows high values in the north and low values in the south, which is opposite to the spatial distribution of cloud cover, implying the weakening contribution of clouds to DTR. In addition to contributions from clouds, the surface type and other meteorology could also play important roles to DTR. Over mountainous areas, the air is thin with relatively poor thermal insulation for long-wave radiation, resulting in lower T_min values than over the plain area. Thus, while there are also lower Tmax over mountainous areas due to high altitudes, the DTR is generally larger over mountainous areas than over plain area (Geerts, 2003).

3.2 Temporal variation of cloud cover and near surface air temperature

Figure 4 shows the monthly variations of Tmax, Tmin, DTR, cloud cover, and LW radiation in all study region, mountains, and plains of North China from 2000 to 2017. There are similar monthly variations in cloud cover, Tmax, and Tmin, and their values are higher over mountains than over plains. Different from our expectation that the DTR would be the largest in summer since solar radiation is the strongest, the DTR is the smallest in summer, which is most likely affected by the high-summer cloud coverage, heavy rainfall, and high-soil moisture (Dai et al., 1999; Zhou et al., 2009; Houspanossian et al., 2016). While the values of DTR are higher in mountains than in plains, cloud cover is lower over mountains than over plains. The impact of cloud
on DTR will be discussed in next section. The DTR standard deviation shows large values in March, June, August, and November, which is highly related to the monthly variation of Tmin standard deviation.

### 3.3 Impacts of clouds on temperature

Figure 5 shows the multi-year averaged monthly variation of Tmax, Tmin, and DTR over mountain (a,b) and plain (c,d) regions under clear and cloudy skies from 2000 to 2017. Two regions within the study domain are adopted with the same latitudes, which are plain area squared with black lines and mountain area squared with blue lines. The difference of Tmax, Tmin, and DTR between cloudy and clear skies varies among the 12 months. The average monthly difference of Tmax, Tmin, and DTR between cloudy and clear skies is −2.0, 4.6, −6.6°C over high-mountain region, respectively; and is −2.1, 3.0, and −5.1°C over plain region, respectively. At night, clouds have a much greater impact on Tmin over mountain area (4.6°C) than over plain area (3.0°C), and have a similar (just slightly greater) impact on Tmax during the day (−2.1°C vs. −2.0°C), resulting in a larger DTR over mountain area than over plain area. While further causality analysis might be needed in future, the differences in Tmin and Tmax between mountain and plain regions are most likely associated with the difference in cloud heights and depths. As shown in Figure 6 and Figure S1, the cloud tops are much higher while the cloud optical depths are similar (just slightly less) over mountains than over plains, resulting in much stronger longwave cloud radiative forcing (warming) at night over mountain region than over plain area.

### 4 Conclusion

Using the daily cloud cover, 24 h precipitation, 2 m Tmax and 2 m Tmin data at 136 ground stations provided by the China Meteorological Administration, along with the hourly cloud cover data from CERES_SYN1deg_Ed4.1, we investigate the spatial and temporal variations of cloud cover, Tmax, Tmin, and DTR over North China from 2000 to 2017. Several major findings have been obtained.

The cloud cover shows the similar multi-year average spatial distribution and monthly variation with Tmin, also surprisingly with Tmax suggesting the more important roles...
of regions (latitude) and seasons associated with the variations of solar radiation absorbed and surface conditions.

Tmax and DTR are higher in clear sky than in cloudy sky, while Tmin in clear sky is lower than in cloudy sky in both mountain and plain regions. This is associated with the clouds’ trapping effect on long-wave radiation and blocking effect on solar radiation.

The difference of Tmax, Tmin, and DTR between cloudy and clear skies varies with time and location. Clouds have a much greater impact on Tmin over mountain area (4.6°C) than over plain area (3.0°C), and have a similar impact on Tmax during the day (−2.1°C vs. −2.0°C), resulting in a larger DTR over mountain area than over plain area, which is found associated with the higher cloud tops and then stronger longwave cloud radiative forcing.

We would like to acknowledge that the Tmin, Tmax, and DTR are generally affected by the downwelling solar radiation, topography, land surface types, and so on. In addition to clouds, aerosols, water vapor, soil moisture and other factors could also play very important roles to the changes of Tmin, Tmax, and DTR, which need be isolated and further investigated in future. For example, the near surface relative humidity is generally higher at night than during day time. If the near surface relative humidity is large enough, phase transition likely occurs from water vapor to liquid droplets at night time. Then, the Tmin could increase with resulting decreased DTR, particularly over mountain regions or in clear conditions.

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**CONFLICT OF INTEREST**

The authors declare no competing interest.

**DATA AVAILABILITY STATEMENT**

The daily station data of cloud cover, precipitation, 2 m Tmax and 2 m Tmin in January 2000 to December 2017, are provided by the China Meteorological Administration (http://data.cma.cn/data/cddetail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html). The hourly cloud cover data are from CERES_SYN1deg_Ed4.1 (https://ceres.larc.nasa.gov/data/#syn1deg-level-3) with a spatial resolution of 1° × 1° from March 2000 to December 2017.

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**SUPPORTING INFORMATION**

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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