Effects of radiative forcing on stable boundary layer development and diurnal temperature range over the central Heihe River Basin, China

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Abstract
Using observations from the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) datasets, the effect of radiative forcing on the development of the stable boundary layer (SBL) and diurnal temperature range (DTR) during summer over the central Heihe River Basin is investigated in this paper. Using a radiative temperature scale based on net longwave radiation (LWnet24), the DTR and the strength of SBL (δTS) are scaled, and the cycle and the year-to-year variability before and after scaling are analyzed. The results show that both DTR from air and surface temperatures have a significant correlation with LWnet24, and their correlation coefficients are different over different underlying surfaces. The cycle of DTR from 5-m air temperature is similar with that of LWnet24. There is only a diurnal cycle in terms of 5-m air temperature after scaling. Both the trends of the scaled DTR (DTRsc) and the scaled strength of SBL (δTSsc) increase with the growth time of the stable boundary layer (SBL) (τS). The period of τS is similar with that of DTRsc. τS is longer at the oasis site than at the Gobi site, which is related to the oasis effect. In addition, the greater the friction velocity, the smaller the DTRsc and δTSsc. The wind shear enables heat to disperse during SBL.

Keywords
diurnal temperature range, Heihe River Basin, radiative forcing, stable boundary layer

1 | INTRODUCTION

The diurnal temperature range (DTR) has been decreasing worldwide in recent decades (Liu et al., 2004; Makowski et al., 2009; Wild et al., 2007; Wang and Dickinson, 2013). The 24-hour mean surface net longwave radiation flux (LWnet24) decreases with an increase in cloud amount (Henderson-Sellers, 1992; Dessens and Bucher, Dessens and Buecher, 1995; Jones, 1995). There is a close coupling between LWnet24 and DTR (Dai et al., 1999; Qian et al., 2006; 2007; Wild, 2009; Wang and Dickinson, 2013).

The daily cycle over land areas is driven mainly by radiative heating and nocturnal surface longwave radiative cooling (Betts et al., 2003). The development of the mixing layer model is mainly dependent on our
understanding of the daily cycle in the unstable dry convective boundary layer (Betts, 1973; Carson, 1973; Tennekes, 1973) and of cumulus clouds in the mixing layer. The effect of radiative forcing over the surface and top of the boundary layer leads to turbulence that causes fairly well-mixed layers.

In addition, net radiation also plays a very important role in the stable surface energy balance model (Holtslag and De Bruin, 1988; Monteith, 2007). Stable boundary layer (SBL) similarity theory has been widely developed in recent decades (Stull, 1988). However, this type of model does not consider the effect of cooling by radiation at the earlier times. Later on, the European Centre for Medium-Range Weather Forecasts’ SBL model has been rewritten to reduce the cold and warm biases in winter at the continental scale (Viterbo et al., 1999). This version modifies the stability function and introduces the Richardson number in the strong stable condition, thus increasing the coupling impact between the surface and atmosphere, and reducing the decrease in temperature caused by radiative cooling. Furthermore, in order to investigate the effect of radiative forcing on the strength and depth of the nocturnal boundary layer, Betts (2006) proposed a radiation-scale method based on LW_{net24}.

However, in the arid and semi-arid areas of China, there are many complex heterogeneous surfaces (Cao et al., 2018; 2020; Liu et al., 2011; Li et al., 2013; Zhang et al., 2016), including Gobi, desert, rural, and oasis areas, among others. The DTR should differ significantly over these surfaces, which may have different relationship with LW_{net24}. Besides, radiative forcing may have different effects on the development of the SBL.

In this paper, the data gathered during the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) campaign are used to analyze the relationship between the SBL and radiation temperature scale. The method of scaling (Betts, 2006) directly relates the DTR and the strength of the SBL (δT_s) at sunrise is defined as a temperature difference to a radiative temperature scale, associated with the slope of the Stefan–Boltzmann equation. First, we investigate how both air and surface temperatures show the correlative relationship with net longwave radiation; second, we investigate the dependencies of the scaled DTR and δT_s, including growth time of the SBL (τ_s) and wind stress, defined by friction velocity. Finally, the influence of scaling on the cycles and year-to-year variability of air temperature at 5 m and DTR are investigated. These results suggest that the DTR may give a useful estimate of surface net longwave radiation flux from an observational perspective. In addition, this study provides a reference for relating model physical parameterizations in terms of the DTR and the strength of the SBL.

2 | DATA AND CLIMATE BACKGROUND OF THE HEIHE BASIN

The Heihe Basin is located in the central region of the Eurasian continent, and is home to the second largest inland river in China (i.e., the Heihe River). The source of the Heihe River is in the Qilian Mountains, and it covers an area of more than 143,000 km² within (97°–101°E, 38°–43°N), with a length of approximately 821 km (Figure 1).

The highest elevation of the Heihe Basin is in the south, and the lowest is in the north. The surface is heterogeneous, including many different kinds of surface. The basin is characterized by its distinct cold and arid landscapes: glaciers, frozen soil, alpine meadows, forest, irrigated crops, riparian ecosystems, and desert, which are distributed upstream to downstream.

The Heihe Basin climate background is different from west to east and from north to south, and is mainly affected by cold air and the westerly circulation from middle and high latitudes. The central plain is the most appropriate area for agricultural development, being exposed to long-duration solar radiation, minimal evaporation, and sufficient precipitation. The annual average lowest temperature is about 3°C, and the maximum is 8°C.

FIGURE 1 Elevation map and land cover map of the Central Heihe River Basin using time series HJ-1/CCD data (Zhong et al., 2014). The land cover types are defined in the international geosphere–biosphere Programme (IGBP) (Loveland et al., 2000; Zhong et al., 2014)
The climate downstream is continental, the quantities of solar radiation and evaporation are very large, and the precipitation amount is small, at around only 42 mm. The difference in temperature between daytime and nighttime is large, and winds are very strong. The annual average maximum air temperature is about 42°C, while the annual average minimum air temperature is about −35°C.

Data from the Multi-Scale Observation Experiment on Evapotranspiration over heterogeneous land surfaces (MUSOEXE), gathered during the summer months (June, July, and August) from 2012 to 2016 as part of HiWATER, are used in this paper (Li et al., 2013). The dataset comprises two instrument arrays, including a large instrument array (30 km × 30 km) in the oasis–desert area and a small instrument array (5.5 km × 5.5 km) in the oasis interior. These instrument arrays are located in the central Heihe Basin. These instrument arrays contain four groups of large-aperture scintillometer systems, 22 eddy covariance systems, and one automatic meteorological system. The large instrument array has four observation sites distributed over the heterogeneous land surfaces. They are: Gobi site, Huazhaizi desert site, rural site, and Daman oasis site (Table 1, Figure 1). Each site includes one eddy covariance (EC) and one automatic meteorological system (Tables 2 and 3).

The original sampling frequency of the EC system is 10 Hz. The released EC data is processed by EdiRe software to 30-min intervals. The main processing steps include spike detection, lag-time correction of H₂O/CO₂ relative to the vertical wind rotation, coordinate rotation using the planar fit method, density (WPL) corrections, ultrasonic virtual temperature correction, and frequency response correction. In addition, each flux value has undergone quality evaluation, including tests for atmospheric stability and turbulence development characteristics (ITC).

### Table 1: Field information for all sites

| Site        | Altitude (m) | Longitude (°) | Latitude (°) |
|-------------|--------------|---------------|--------------|
| Gobi site   | 1,562.00     | 100.30        | 38.91        |
| Desert site | 1,594.00     | 100.49        | 38.78        |
| Oasis site  | 1,556.01     | 100.37        | 38.85        |
| Rural site  | 1,561.86     | 100.35        | 38.87        |

### Table 2: Instrument characteristics of the automatic weather systems

| Observation variables                      | Sensor type | Manufacturer          | Accuracy                          | Sampling height/depth |
|-------------------------------------------|-------------|-----------------------|-----------------------------------|-----------------------|
| 5-m air temperature, humidity             | HMP45C      | Vaisala (Finland)     | Temperature: ±0.2°C Humidity: ±2% | 5 m                   |
| 5-m horizontal wind speed                 | 010C-1      | MetOne (USA)          | ±0.11 m/s                         | 5 m                   |
| 10-m air temperature, humidity           | HMP45C      | Vaisala (Finland)     | Temperature: ±0.2°C Humidity: ±2% | 10 m                  |
| 10-m horizontal wind speed and direction  | 010C-1/020C-1| MetOne (USA)          | Wind speed: ±0.11 m/s Wind direction: ±4° | 10 m                  |
| Pressure                                  | CS100       | Campbell (USA)        | ±0.5 mb                           | 2 m                   |
| Precipitation                             | 52,202      | R. M. young (USA)     | ±1%                               | 4 m                   |
| Downward and upward shortwave flux        | CM3         | Campbell (USA)        | ±10%                              | 6 m                   |
| Downward and upward longwave flux         | CG3         | Campbell (USA)        | ±10%                              | 6 m                   |
| Soil heat flux                            | HFP01       | Campbell (USA)        | ±2%                               | −0.06 m               |
| Soil temperature                          | 109         | Campbell (USA)        | ±0.2°C                            | −0.02 to −0.04 m −0.10 to −0.20 m −0.40 to −0.60 m −0.10 m |
| Soil moisture                             | CS616       | Campbell (USA)        | ±2%                               | −0.02 to −0.04 m −0.10 to −0.20 m −0.40 to −0.60 m −0.10 m |
The 30-min flux data were screened according to the following criteria: (a) data were rejected when the sensor was malfunctioning; (b) data were rejected when precipitation occurred within 1 h before and after collection; (c) incomplete 30-min data were rejected when the missing ratio was larger than 3% in the 30-min raw record; and (d) data were rejected when the nighttime friction velocity was below 0.1 m/s. Suspect data caused by instrument drift and other reasons were marked in red (Foken et al., 2004; Liu et al., 2011; 2013; Xu et al., 2013; Wang et al., 2015).

Processing and quality control of observational data from the automatic weather station included the following steps: (a) missing data were marked “–”; (b) repeated records were eliminated; (c) data obviously beyond the physical meaning or the range of the instrument were deleted.

### 3 | INTRODUCTION OF METHODS

#### 3.1 | Scaling of the diurnal cycle

We use the data at the Gobi, desert, rural, and oasis sites and the method of scaling (Betts, 2006) to carry out the calculation. The DTR is defined as

\[ \text{DTR} = T_{\text{max}} - T_{\text{min}}, \]

where \( T_{\text{max}} \) and \( T_{\text{min}} \) are the maximum and minimum values of air temperature at 5 m or the surface temperature based on the 30-min means.

To investigate the correlation between DTR and \( \text{LW}_{\text{net}}^{24} \), the relative radiation temperature scale \( \Delta T_R \) is employed, which is defined as

\[ \Delta T_R = -\lambda_0 \text{LW}_{\text{net}}^{24}, \]

where \( \lambda_0 = 1/(4\sigma T^3) \) is the radiation sensitivity parameter from Stefan–Boltzmann theory, in which \( \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \) is the Stefan–Boltzmann constant. When \( T = 293 \text{ K}, 4\sigma T^3 = 5.7 \text{ W m}^{-2} \text{ K}^{-4}, \lambda_0 = 0.175 \text{ K (W m}^{-2})^{-1} \) is obtained.

The disturbance of 24-hour average temperature scaled temperature at 5 m \( (T_{\text{sc}}) \) is used as follows:

\[ T_{\text{sc}} = (T_5 - T_{\text{24}})(\Delta T_R)^{-1} \tag{3} \]

The SBL is defined as when the surface sensible heat flux \( (H) \) is <0. Corn is planted in the oasis during summer. The height of corn is about 2 m, so the observation height is 5 m. \( T_5 \) is the unscaled temperature when \( H \) turns to negative, corresponding to the scaled temperature \( T_{\text{Scaled}} \). After that, the SBL begins to grow. To better estimate \( T_{\text{Scaled}} \), the adjacent hour is obtained by the \( T_{\text{Scaled}} \) when \( H = 0 \). When \( T_{\text{Scaled}} = T_{\text{min scaled}} \) and \( T_5 = T_{\text{min}} \), the SBL is considered as reaching the maximum. \( T_{\text{min scaled}} \) is the scaled daily minimum temperature. \( T_{\text{max scaled}} \) is the scaled daily maximum temperature. The scaled DTR \( (\Delta \text{DTR}_{\text{Scaled}}) \) is obtained after \( T_{\text{Scaled}}, T_{\text{max scaled}}, \) and \( T_{\text{min scaled}} \) are obtained.

The strength of the SBL \( (\delta T_5) \) can be defined as the difference between the surface temperature at sunrise and the temperature during the SBL:

\[ \delta T_5 = T_S - T_{\text{min}} \tag{4} \]

The scaled strength of the SBL \( (\delta T_{\text{Scaled}}) \) is defined as follows:

\[ \delta T_{\text{Scaled}} = T_{\text{Scaled}} - T_{\text{min scaled}} \tag{5} \]

#### 3.2 | Wavelet analysis

Wavelet analysis is a method that decomposes a time series into time-frequency space (Torrence and Compo, 1998). It can be used to analyze localized variations of power within a time series. The main oscillation and its corresponding period can be obtained by the maximum spectrum value in the power spectrum curve. To investigate the influence of scaling based on Equation (3) on the cycle of \( T_5 \) and DTR, the Morlet wavelet basis

| Sampling height | Manufacturer | Uncertainty | Random error | System error |
|-----------------|--------------|-------------|--------------|--------------|
| Gobi site: 4.6 m desert site: 4.6 m | CSAT3 + LI-7500/7500A (LI-COR, USA) | Sensible heat flux: 18%; Latent heat flux: 16%; CO2 fluxes: 21% (Wang et al., 2015). | 5% (Wang et al., 2015). |
functions are selected to determine the wavelet power spectrum of $T_s$, $T_c$, DTR, and DTR$_{sc}$ at Gobi, desert, rural, and oasis site during the summer from 2012 to 2016.

4 | RESULTS

4.1 | Relationships between DTR from air temperature or surface temperature and net longwave radiation

The results show that 5-m air temperature has a significant correlation with net longwave radiation at the Gobi, desert, rural, and oasis sites (Figure 2). The correlation coefficients at the Gobi and desert sites are greater than those at the rural and oasis sites. This is because the surface at the two former sites is bare, while the surface at the two latter sites is covered by corn. In addition, the DTR at the Gobi and desert sites are larger than those at the rural and oasis sites.

Surface temperature shows significant correlation with net longwave radiation at the Gobi, desert, rural, and oasis sites (Figure 3). The correlation coefficients at the Gobi and desert sites are greater than those at the rural and oasis sites, which is similar to the results of air temperature. However, the DTR at the Gobi and desert sites are smaller than at the rural and oasis sites, which is different from the air temperature results. In previous studies, 2-m air temperature was used to estimate the DTR over many different river basins (Betts, 2006). However, according to our results, the estimation of DTR should use air temperature at one height for rural and oasis sites, but surface temperature over the Gobi and desert sites.

4.2 | Dependencies of DTR$_{sc}$ and ($\delta T_{Sc}$) on growth time of the SBL ($\tau_S$) and wind stress ($u*$)

First, $\tau_S$ at the oasis site is longer than that at the Gobi site (Figure 4, Table 4). This is because the SBL at the
The evaporation of water will consume large amounts of solar radiation over the oasis site, while only a small fraction of energy will be used in the same way at the Gobi site. There is a large latent heat flux, but a small sensible heat flux at the oasis site. The sensible heat flux shows negative values in the afternoon, and even remains negative for the whole day at the oasis site (Figure 4). Therefore, the SBL occurs earlier over the oasis site than the desert site.

Second, the trend of \( \delta T_{\text{ssc}} \) is similar to that of \( T_{\text{5}} \) at the oasis and rural sites. Both increase with \( \tau_S \) and then remain stable at a constant value at these two sites (Figure 5c,d). However, the trends of \( \text{DTR}_{\text{sc}} \) and \( \delta T_{\text{ssc}} \) increase with \( \tau_S \) at the Gobi and desert sites with passing through the M-K trend test (Mudelsee, 2010), although they are either steady or decrease between 10 and 11 hours of \( \tau_S \) (Figure 5a,b). Over the Gobi site, the time of occurrence of the SBL is later than that of the maximum temperature, which always occurs in the afternoon (Figure 4). The longer the \( \tau_S \), the larger the \( \text{DTR}_{\text{sc}} \) and \( \delta T_{\text{ssc}} \) would be. However, the situation is different at the oasis site, where the occurrence times of the SBL and maximum temperature are similar. Sometimes the occurrence time of the SBL is earlier than that of maximum temperature, and when this happens, the \( \text{DTR}_{\text{sc}} \) and \( \delta T_{\text{ssc}} \) no longer increase with the increase in \( \tau_S \). These results indicate that radiative forcing has a substantial effect on short-duration SBLs in desert and Gobi areas, but the effect remains constant when the duration of the SBL is excessively long in oasis and rural areas.

In addition, the difference between \( \text{DTR}_{\text{sc}} \) and \( \delta T_{\text{ssc}} \) at the desert and Gobi sites is larger than that at the oasis and rural sites; and the \( \text{DTR}_{\text{sc}} \) at the desert and Gobi sites is smaller than that at the oasis and rural sites. In previous studies, the value of \( \text{DTR}_{\text{sc}} \) has been very close to the value of \( \delta T_{\text{ssc}} \), and they both increase with the growth of the SBL (Betts, 2006). However, according to our results, the trends of \( \text{DTR} \) and \( \delta T_{\text{ssc}} \) are not similar, indicating that the relationship between the growth of SBL and the strength of SBL is related to the underlying surface.

The \( \text{DTR}_{\text{sc}} \) and \( \delta T_{\text{ssc}} \) decrease slightly with the increase in friction velocity (\( u^* \)) (Figure 6), indicating that the greater the \( u^* \), the smaller the \( \text{DTR}_{\text{sc}} \) and \( \delta T_{\text{ssc}} \). The wind shear enables heat to disperse during SBL. The results at the Gobi site are similar to those at the oasis site (Figure 6), indicating that the wind shear has a similar effect over these land-surface types.

### 4.3 Effects of scaling on the cycles and year-to-year variability of air temperature at 5 m and DTR

First, the year-to-year variability in terms of \( T_5 \) and \( T_{\text{sc}} \) are compared (Figure S1, Table S1). The trends of \( T_5 \) and \( T_{\text{sc}} \) are tested by the Mann–Kendall trend test (Mudelsee, 2010). \( T_5 \) at Gobi, desert, rural and oasis decrease by 1.4, 1.4 and 1.6°C from 2012 to 2016 during the summer, respectively. \( T_5 \) at rural site increases by 1.1°C from 2012 to 2016 during the summer. However,
both the daily and summer average of \( T_{sc} \) are 0. There is no intraseason and year-to-year variability in terms of \( T_{sc} \). Second, the year-to-year variability in terms of DTR and DTRsc are compared. DTR at Gobi, desert, rural and oasis site fluctuate by no more than 1 \(^\circ\)C. DTRsc also fluctuates by no more than 0.1.

To investigate the cycle of \( T_5 \), \( T_{sc} \), DTR and DTRsc, the Morlet wavelet analysis is used to calculate their power spectrum. First, the power spectrum of \( T_5 \) and \( T_{sc} \) at Gobi, desert, rural and oasis site fluctuate by no more than 1 \(^\circ\)C. DTRsc also fluctuates by no more than 0.1.

In terms of air temperature, it filters out the low frequency signal such as QBWO and ISO, but retains the high frequency signal such as diurnal cycle.

Second, the power spectrum of DTR and DTRsc at Gobi, desert, rural, and oasis sites from 5-m air temperatures are shown in Figure 8a–h. In terms of DTR, there are periods of 13 and 35 days at oasis and rural site (Figure 8c,d), while there are cycles of 5, 12 and 35 days at Gobi and desert sites (Figure 8a,b), which is similar with cycles of LWnet24 (Figure S1). The significant correlation shown in Figures 2 and 3 and the similar cycle between the DTR and LWnet24 could demonstrate the causal relationship between the DTR and LWnet24. DTR is determined by the LWnet24 (Betts, 2004).

In terms of DTRsc, there is period of 90 days (about 1 yr) at oasis and rural sites, while there is period of
32 days at Gobi and desert site. The period of DTRsc at different sites is different from DTR. This scaling method changes the cycle of DTR. Figure 8i–l shows cycles of $\tau_S$ at different sites. The period of $\tau_S$ is 90 days (about 1 yr) at oasis and rural sites, while the period is 30 days at Gobi and desert, which is similar with the period of
DTRsc. Figures 5 and 8 demonstrate that the correlation between DTRsc and $T_S$ is better than that between DTR and $T_S$. DTRsc is dependent on $T_S$. The causes of the period of $T_S$ may be related to the effect of different underlying surface with different vegetation parameters and soil parameters (Vereecken et al., 2016). There is corn planted over oasis with the cycle of 1 yr, which may have effect on occurrence time of SBL, which needs to be further studied.

5 | SUMMARY

Using observations from the HiWATER datasets, the effect of radiative forcing on the development of the SBL and diurnal temperature range (DTR) during summer is investigated in this paper. Using a radiative temperature scale based on net longwave radiation (LWnet24), the DTR and the strength of SBL ($\delta T_S$) are scaled, and the cycle and the year-to-year variability before and after scaling are analyzed.

The results show that both DTR from air and surface temperatures have a significant correlation with net longwave radiation (LWnet24). The correlation coefficients between 5-m air temperature ($T_S$) and LWnet24 at the Gobi and desert sites are greater than those at the rural and oasis sites. The DTR from air temperature at the Gobi and desert sites are greater than those at the rural and oasis sites, while the DTR from surface temperature at the Gobi and desert sites are smaller than those at the rural and oasis sites. This is because the surface at the Gobi and desert sites is bare, while it is the covered by corn at the rural and oasis sites.

The growth time of the SBL ($T_S$) is longer at the oasis site than at the Gobi site. The DTRsc trend is similar to that of $\delta T_{sc}$ at the oasis and rural sites; both increase with $T_S$, and then remain stable at a constant value. However, both the trend of DTRsc and $\delta T_{sc}$ increase during the SBL at the Gobi and desert sites. These results indicate that radiative forcing has a substantial effect on short-duration SBLs in Gobi and desert areas, whereas the effect remains constant when $T_S$ is excessively long in oasis and rural areas. In addition, the difference between DTRsc and $\delta T_{sc}$ at the desert and Gobi sites is larger than that at the oasis and rural sites. In addition, as friction velocity increases, the DTRsc and $\delta T_{sc}$ decrease. The wind shear enables heat to disperse during SBL.

The year-to-year variability of $T_S$ is different over different underlying surfaces, while there is no intraseason and year-to-year variability in terms of $T_{sc}$. $T_S$ at different sites have cycles of 1 day, 10 days, and 90 days (about 1 yr), which corresponding to the three main periods in the atmosphere over the Tibetan Plateau. However, there is only diurnal cycle at these sites in terms of $T_{sc}$. In terms of DTR, there are periods of 13 and 35 days at different sites, which is similar with cycles of LWnet24. DTR is determined by the LWnet24. The period of $T_S$ is similar with that of DTRsc. DTRsc is dependent on $T_S$.

These research results suggest that the DTR may give a useful estimate of surface net longwave radiation flux from an observational perspective. In addition, this study provides a reference for relating model physical parameterizations in terms of the DTR and the strength of the SBL.

ACKNOWLEDGEMENTS

The observation data in this study was provided by the Multi-scale Observation Experiment on Evapotranspiration over heterogeneous land surfaces (MUSOEXE) from 2012 to 2016 as part of the Heihe Basin Allied Telemetry Experimental Research (HiWATER) campaign (see http://westdc.westgis.ac.cn/archives/news/sciencenews/archive-144.html for details). This work was funded by the National Key Research and Development Program of China (2018YFC1505702), the Desert Meteorological Science Research Fund of China (Sqj2018006), and the Applied Basic Research Foundation of Sichuan Province of China (2019YJ0408).

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SUPPORTING INFORMATION

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

How to cite this article: Cao B, Zhu L, Zheng Y, et al. Effects of radiative forcing on stable boundary layer development and diurnal temperature range over the central Heihe River Basin, China. Atmos Sci Lett. 2021;22:e1011. https://doi.org/10.1002/asl.1011