Temperature oscillations observed in the stable boundary layer over four different underlying surfaces

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ABSTRACT

Nocturnal temperature is crucial in stability determination, as well as parameterization in numerical models. In the present research, data from four tall towers are used to investigate the temperature oscillations observed in the stable boundary layer, including the 307-m Boseong Tower on the southern coast of Korea, a 100-m tower in a grassland area of northern China, a 70-m tower in a desert area in northwestern China, and the 325-m Beijing Tower. Large temperature oscillations, with amplitudes of about 2 °C and periods of several minutes to tens of minutes, are detected. Using the empirical mode decomposition method working as a high-pass filter, the oscillations of temperature are extracted from the original non-stationary and nonlinear temperature data. The daily variations and vertical distribution of the temperature oscillations are discussed. Generally strong temperature oscillations are found at tens of meters high during nighttime in the coastal area, in the steppe, and in the desert, when stable conditions have formed. Much weaker nocturnal temperature oscillations are observed in Beijing, where the large heat capacity of buildings and streets and artificial heat sources prevent the boundary layer conditions from becoming stable. Static stability expressed by the Brunt–Väisälä frequency is found to be an important factor for such temperature oscillation events, which is worthy of model parameterization.

1. Introduction

Compared to the heat-oriented turbulence in the convective boundary layer, forcing in the stable boundary layer is relatively weaker and makes it difficult to measure or model (Fernando and Weil 2010). Mixtures of multi-scale processes, including internal gravity waves, low-level jets, Kelvin–Helmholtz billows, meanderings, density flows, and other mesoscale motions, interact with the intermittent turbulence, significantly affecting the energy and material exchange between the air and the ground (Finnigan, Einaudi, and Fua 1984; Mahrt 1999; Blumen et al. 2001; Sun et al. 2002, 2004; Banta, Pichugina, and Brewer 2006; Mahrt 2007).

The stable boundary layer can be generated when warm air flows over a cold surface, but the most common reason for the stable boundary layer is radiative cooling at night (Stull 1988). With clear sky, dry air, and no artificial heat source, substantial cooling at the surface layer generates the so-called very stable boundary layer, in which the strong stratification suppresses the turbulence and thus the slight vertical flux strengthens the stratification. In the very stable boundary layer, turbulence is highly intermittent, and the classical Monin–Obukhov similarity theory fails (Grachev et al. 2013; Mahrt 2014). A series of studies on the distinction between stable boundary layer regimes have been conducted (Sun et al. 2012; Van de Wiel et al. 2012; Van Hooijdonk et al. 2015), but the fundamental
characteristics of the very stable boundary layer remain unclear (Mahrt 2014).

Temperature is not only a decisive factor of stability in the stable boundary layer, but also crucial in calculating the heat transfer between the underlying surface and the air, which is important for the parameterization of boundary layer processes in numerical models (Derbyshire 1999). Meanwhile, as a scalar, temperature turbulence shows different characteristics to the velocity turbulence. A theoretical framework as well as observational results on how internal gravity waves affect temperature oscillations, and vice versa, have been investigated (Sun et al. 2015). Furthermore, a simulation has been conducted in which intermittent turbulence and temperature oscillations were found (Zhou and Chow 2014), and the impacts of a largescale cold front on nocturnal warming have also been considered (Hu et al. 2013). However, few studies have focused on the characteristics and structure of temperature oscillations in the stable boundary layer.

With their apparent diurnal cycle and seasonal cycle, atmospheric temperature time series appear to be non-stationary at multiple time scales (Andreas et al. 2008). For research on boundary layer temperature oscillations, traditional global filters, such as the Fourier transform filter, do not work. Huang et al. (1998) adopted an adaptive decomposition method called empirical mode decomposition (EMD) in the Hilbert–Huang transform, which has been broadly used in geophysical studies and other non-stationary data analyses (Huang and Wu 2008; Xu and Hu 2014). In this paper, EMD is used to decompose the temperature time series into a set of intrinsic mode functions (IMFs — see definition in Section 3) and extract the oscillations with certain frequencies.

In the present research, large temperature oscillations under stable conditions are observed at four tall towers. Oscillations are extracted using EMD, and their characteristics are discussed. A relationship between the temperature oscillations and static stability is proposed. The sites and data used are described in Section 2; the EMD method is introduced in Section 3; results are presented in Section 4; and conclusions are provided in Section 5.

2. Sites and datasets

Four datasets obtained from towers with different underlying surfaces, in Boseong (Korea), Xilinhaote (Inner Mongolia, China), Minqin (Gansu, China), and Beijing (China), are used in this study.

Data-set 1: Boseong. These data are recorded from the 307.19-m high Boseong Meteorological Observation Tower (Figure 1) on the south coast of Korea (34.764°N, 127.213°E). The Boseong Tower is located approximately 1.5 km northwest of the southern coast of Korea. Instruments are deployed at 11 levels of the tower, at 10, 20, 40, 60, 80, 100, 140, 180, 220, 260, and 300 m. Booms are installed in three different directions, i.e. south, northwest, and northeast, in 120° intervals at each level. Temperature is measured on the south boom at the 11 levels using thermometers (5628PRT, Fluke, US) at a temporal resolution of 1 min. Data from 3 April to 26 November 2014 are used. A quality-control system based on WMO guidelines (WMO 2004) is applied to the data from the tower, and few suspect or erroneous data are found.

Data-set 2: Xilinhaote. These data are collected at a 100-m tower (44.124°N, 116.297°E) situated northeast of Xilinhaote city in Inner Mongolia, China, located in a horizontally uniform and flat steppe (Liu, Hu, and Cheng 2011). The mean horizontal wind speed and wind direction are measured by vanes (China-made) with a frequency of 1 Hz, and the temperature is recorded by thermometers (HMP45C, Campbell, US), with a frequency of 0.1 Hz, at six levels, including 4, 10, 30, 50, 70, and 100 m. A block average of 1 min is applied to the temperature data, and hereafter analyses of the temperature from Xilinhaote are based on the averaged data. A consistency check is applied to the data to eliminate spikes (WMO 2004). The observations are conducted from May 2009 to April 2010.

Data-set 3: Minqin. The data are collected at a dust-monitoring tower established in the national desert grassland ecosystem field station in the Badan Jilin Desert in Minqin County, Gansu, China (38.618°N, 102.920°E) (Cheng, Hu, and Zeng 2014). The experiments are conducted during 2–30 April 2013. This tower is 70 m tall and is equipped with thermometers and vanes mounted at 2, 8, 16, 32, and 63 m above the ground. The temporal resolution of the thermometers (010C, MetOne, US) is 1 min. We apply a
spike check (WMO 2004) to the data, and few spikes are found.

Data-set 4: Beijing. The data are obtained from a 325-m meteorological tower located in north-central Beijing (39.967°N, 116.367°E). The tower was set up in 1978 by the Institute of Atmospheric Physics, Chinese Academy of Sciences. The underlying surface is a typical complex urban area consisting of buildings of various height, roads, parklands, trees, and rivers (Al-Jiboori and Hu 2005). Instruments are deployed at 15 levels of the tower, at 8, 16, 32, 47, 65, 80, 100, 120, 140, 160, 180, 200, 240, 280, and 320 m. Temperature, at a temporal resolution of 1 min, is measured by thermometer (HC2-S3, Rotronic, Swissland). The data used in the present research are from 1 January 2014 to 31 December 2014, measured by the instruments installed on the boom facing northwest. The quality-control system based on WMO guidelines (WMO 2004) is also applied to these data.

3. Method

EMD is a method adopted by Huang et al. (1998) to decompose non-stationary and nonlinear data into a series of IMFs. IMFs are defined as functions that satisfy

![Figure 2](image-url)
the following requirements: (1) the number of extrema and the number of zero crossings must be either equal or differ by one at most in the whole data-set; (2) the mean of the envelopes defined by local maxima and minima, respectively, is always zero. In contrast to the wavelet method or Fourier transform, where the basic function is fixed, EMD is based on direct extraction from the data. The EMD method decomposes the time series through a sifting process starting from the fastest oscillations. Local maxima and minima are detected, and two cubic splines are defined through the maxima and minima as upper and lower envelopes, respectively. The mean of the upper and lower envelopes is subtracted from the original time series, \( T(t) \). This process is repeated with the remaining signal until it satisfies the definition of the IMF, which is defined as the first IMF, \( x_1(t) \). The second IMF is then extracted from the subtraction between the original signal and the first IMF, and so on. Ultimately, the time series is decomposed into IMFs and can be written as

\[
T(t) = \sum_{i=1}^{N} x_i(t) + \varepsilon(t),
\]

where \( N \) is the number of IMFs and \( \varepsilon(t) \) is the remaining trend of the time series.

*Figure 3.* Temperature series high-pass filtered by empirical mode decomposition at (a) Boseong, from 1800 LST (local standard time) 17 May to 1800 LST 19 May 2014; (b) Xilinhaote, from 1800 LST 30 May to 1800 LST 1 June 2009; (c) Minqin, from 1800 LST 8 April to 1800 LST 10 April 2012; and (d) Beijing, from 1800 LST 20 April to 1800 LST 22 April.
Each IMF extracted from the original time series has various instantaneous frequencies. By combining the IMFs with certain frequencies while removing the others, we create a frequency filter of the signals. In the present paper, the IMFs with average periods larger than 1 h are removed and a high-pass filter is created.

4. Results

Figure 2 shows the temperatures at the four sites. At each location, we select a 48-h period from 1800 to 1800 local standard time (LST) as examples of temperature oscillations occurring at night. Different temperature oscillations are

Figure 4. Vertical-time distribution of the OSD (standard deviation of the temperature oscillation series) at (a) Boseong, (b) Xilinhaote, (c) Minqin, and (d) Beijing.
apparent during the day from those at night. Temperature oscillations have frequencies of several minutes to tens of minutes, and common amplitudes larger than 2 °C during nighttime, whereas temperature oscillations occurring in the daytime have smaller amplitude. These features are common throughout the observation period at Boseong, Xilinhaote, and Minqin. As for Beijing, large temperature oscillations at night are observed only at 140 and 240 m at the Beijing Tower, which are less common than at the other three sites. Similarly large temperature oscillations have been mentioned previously (Sun et al. 2004, 2015).

To extract the temperature oscillations and eliminate the long-term trend, EMD is applied to the non-stationary temperature time series as a high-pass filter, as described in Section 3. The IMFs with averaged periods less than 1 h are combined as the temperature oscillation time series. Figure 3 shows the temperature oscillation time series of the same time as Figure 2. After eliminating the trends, the oscillation series retain the oscillation patterns well. Larger amplitudes of temperature oscillations are obtained during nighttime. The hourly averaged standard deviation of the temperature oscillation series (OSD) is calculated to denote the strength of the temperature oscillations. Figure 4 shows the vertical-time distribution of the OSD. In Boseong, Xilinhaote, and Minqin, similar patterns are found. The OSDs at the three sites increase over time, from sunset to around midnight, and maxima can be observed from midnight to sunrise at tens of meters high. The average wind speed at 4 m at Xilinhaote is 5.73 m s⁻¹, while the wind speeds are 2.82 m s⁻¹, 3.40 m s⁻¹, and 1.38 m s⁻¹ at 10 m at Boseong, 8 m at Minqin, and 8 m at Beijing, respectively. An extra maximum is observed close to the ground at Xilinhaote, probably because of the higher wind shear generated by higher low-level wind speed (Stull 1988). On the other hand, temperature oscillations at Beijing show different features. Instead of having a maximum, the temperature oscillations remain at low values during nighttime compared to those in the daytime. During nighttime, the OSD increases with height.

The fact that nocturnal temperature oscillations are weak in the city indicates that the temperature oscillations might be related to the stable boundary layer, because the large heat capacity of buildings and streets and the heat released from human activities lead to the disappearance of the inversion at night in the surface layer in urban areas (Oke 1995). Figure 5 shows the averaged vertical profile of potential temperature during nighttime at the four sites. The shapes of the profiles reflect the stabilities of the nocturnal boundary layers. The stability in the surface layer is strongest at Minqin, which is in a very dry dessert area with a commonly clear sky. At Boseong and Xilinhaote, moderate inversions are observed, while at Beijing the stability is near neutral. This result is consistent with previous research (Oke 1995).

The relationship between the nocturnal temperature oscillation and stability is further investigated. Rather than the commonly used Richardson number, the square of the Brunt–Väisälä frequency \( N_{bv}^2 \) is used to denote the static stability (Costa Frola et al. 2013), because the Richardson number can be difficult to calculate under nearly calm wind conditions and the vertical gradient of the wind speed can be close to zero or even negative. \( N_{bv}^2 \) is calculated as follows:

\[
N_{bv}^2 = \frac{g}{\theta} \frac{\partial \theta}{\partial z}^2
\]

where \( \theta \) is the potential temperature and \( g \) is the acceleration of gravity. The vertical gradient of \( \theta \) is calculated by the difference between two adjacent levels. Figure 6 shows the relationship between \( N_{bv}^2 \) and the OSD. \( N_{bv}^2 \) is separated into several bins, with edges from \( 10^{-4} \) to \( 10^{-2.7} \), arranged in log linear scale, and the mean and standard deviation of the OSD with the corresponding \( N_{bv}^2 \) in each bin are presented in the figure by lines and vertical bars, respectively. The OSDs at all four sites appear larger with larger \( N_{bv}^2 \). At Boseong, the OSD increases as stability increases, at every level, and the tendency is stronger at higher levels. Similar features are found at Xilinhaote and Minqin, except at the lowest level of each site. As for Beijing, the OSD appears to be positively correlated with \( N_{bv}^2 \) from 32 to 120 m only. Large standard deviations of OSDs, denoted by the wide vertical bars, imply that stability is not the only factor affecting the strength of the temperature oscillation. Other factors, such as wind speed, wind shear, or intermittent turbulence, can contribute to temperature oscillation.

Figure 5. Mean nocturnal vertical potential temperature profiles at the four sites from 0000 LST (local standard time) to 0300 LST during the whole observation period.
5. Summary and discussion

Large-amplitude oscillations in temperature are detected in the stable nocturnal boundary layer at Boseong Tower (Korea), Xilinhaote (China), and Minqin (China), while at Beijing Tower smaller oscillations are found. The EMD method is applied to the temperature data to extract the oscillations. The basic features of the oscillations are described, and the relationship between the temperature

Although in the very stable atmospheric boundary layer the averaging heat flux becomes very small, vertical motions never completely vanish as long as flows exist. Internal gravity waves and intermittent turbulence caused by various mesoscale motions can trigger large temperature oscillations under a very stratified condition. On the contrary, a large vertical gradient of temperature leads to large temperature oscillation, even for smaller amounts of vertical motion.

Figure 6. Mean OSD (standard deviation of the temperature oscillation series; curves) and range of one standard deviation (vertical bars) of OSD, for each bin of $N_{BV}$ (Brunt–Väisälä frequency), at (a) Boseong, (b) Xilinhaote, (c) Minqin, and (d) Beijing.
oscillations and the static stability ($N^2_0$) are analyzed. Our conclusions are as follows:

1. Large-amplitude temperature oscillation is a common phenomenon in the stable boundary layer. Temperature oscillations of about 2 °C are found in the coastal area of Boseong, in the steppe near Xilinhaote, and in the desert area at Minqin. Data from the three towers show that temperature fluctuates more strongly during nighttime than daytime, and the maximum nocturnal temperature oscillation takes place at about 70 m.

2. On the other hand, much weaker nocturnal temperature oscillations are found at Beijing, which is on an urban underlying surface. While inversions are detected at the other three sites, the average potential temperature profile at Beijing is near neutral, because of the enlarged heat capacity and heat released from human activities in the city.

3. The nocturnal temperature oscillation is closely related to the stability of the boundary layer. The strength of oscillation shows a positive correlation with the degree of static stability at all four sites, although the correlation is weak at Xilinhaote.

Although large temperature oscillations are easily observed in the stable boundary layer, their common characteristics and reasons are unclear. Internal gravity waves, low-level jets, meanderings, and other mesoscale phenomena, might be linked to temperature oscillations. In all probability, a single theory will not be able to account for all the temperature oscillations detected in this study. Greater efforts with higher spatial and temporal resolution observations of the nocturnal boundary layer and studies of intermittent turbulence are needed to obtain a better understanding of nocturnal temperature behaviors.

Acknowledgements
The authors thank the National Institute of Meteorological Sciences of Korea for providing the Boseong Tower data, and thank Ms. PARK Sora, Dr. KIM Yeonhee, and Mr. KIM Kihoon for helpful advice regarding this paper.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This work was supported by the National Natural Science Foundation of China (grant number 11472272); and the National Key R&D Plan [grant number 2016YFC0208802].

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