NOTES AND CORRESPONDENCE

A Numerical Study on the Nocturnal Frontogenesis of the Sea-breeze Front

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Abstract

A numerical simulation of a sea-breeze front (SBF) is carried out to investigate the nocturnal frontogenesis (FG) phenomenon that occurs as the SBF propagates inland during the nighttime. At first, we reproduce the FG event of the nighttime SBF based on high-resolution numerical modeling. Then, to reveal its formation mechanism, the FG equation is used, and contributions of each term in the FG equation are estimated for explaining this nocturnal FG event. The results show that the nocturnal FG event of the nighttime SBF: (1) is mostly attributed to the confluence effect due to the horizontal velocity convergence and intensification of the horizontal potential temperature gradient at the front; (2) is partly attributed to the no significant tendency of the turbulence effect associated with the surface cooling.

1. Introduction

In our previous paper (Ogawa et al. 2003), we investigated the interaction between sea-breeze front (SBF) and convective cells within the well-mixed boundary layer in an early afternoon stage by using a two-dimensional numerical model with very high spatial resolution ($\Delta x = 50$ m). In that study, the frontogenesis (FG) and frontolysis (FL), which are defined as the intensification/attenuation of the horizontal

temperature gradient, are seen alternately at the foremost part of the sea-breeze head, and the mechanism of the FG/FL is also clarified by using the FG equation. Although we could provide a novel viewpoint associated with the daytime SBF, no attention was paid for the SBF in the nighttime when convective motions over the land surface were diminished due to the surface cooling. In this subsequent paper, we examine in detail the features of the nighttime SBF, especially concentrating on the nocturnal FG phenomenon often observed during the evening time.

During the nighttime when the convective activity in the atmospheric boundary layer ceases, intensification of the horizontal temperature gradient across the SBF, i.e., the nocturnal FG phenomenon has been reported in some

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literature. For example, Reible et al. (1993) analyzed the SBF strength for different days, and found the intensification of the front occurred during late afternoon and evening. This phenomenon was further confirmed in recent studies of the nocturnal SBF (Koo and Reible 1995; Atkins and Wakimoto 1997; Tijm et al. 1999; Lapworth 2000). Although the nocturnal FG event in SBF was noted by previous researchers, there has been no comprehensive study that deals with the mechanism of the nocturnal FG event in SBF. For more complete understanding of this phenomenon a detailed analysis based on a high-resolution numerical simulation is needed.

The main objectives of this study are therefore; (1) To reproduce the nighttime SBF with emphasis on the nocturnal FG event by using a numerical model with very high spatial resolution; (2) To explain how and why the nocturnal FG process occurs. In section 2, a brief summary of the numerical model is documented. The nighttime SBF, especially concerning to the nocturnal FG, is described in section 3. In section 4, the reason for the nocturnal FG event is analyzed based on the FG equation. Finally, in section 5, a summary and outlook for future work are presented.

2. Model and numerical setting

The numerical model used in this study is developed by Sha et al. (1991) and modified in our previous paper (Ogawa et al. 2003). Here, we just describe a brief summary of the numerical setting.

The numerical arrangements employed in this experiment are the same as in our previous paper (Ogawa et al. 2003). The numerical domain is rectangular with 250 km width and 5.1 km height. The bottom of the domain is covered with 100 km sea surface and 150 km land surface. The number of grids is 2476×60 , and the smallest grid interval is $\Delta x = 50$ m and $\Delta z = 20$ m which are fine enough to reproduce the fine structures related to the SBF. The region having minimum horizontal spatial resolution $\Delta x = 50$ m extends landward to 85 km from the coast, which is sufficiently wide to investigate the evolution of the nighttime SBF. No ambient wind and a temperature lapse rate of 0.006 K/m are imposed all over the domain as the initial conditions. The temperature on

the sea surface is preserved at a constant value (25.5°C), while the land surface temperature is given as a 24-hour-period sinusoidal oscillation ($25.5 \pm 6.0^{\circ}\text{C}$) with maximum at 14:00 LST and minimum at 2:00 LST. The time-step is 30 seconds. Total calculation period is 2 days, and results are analyzed for the latter day.

3. Nighttime SBF and its nocturnal FG event

After sunset, the land surface begins to cool and the adjacent air layer becomes stably stratified. However, as the temperature of the sea-breeze layer is still cooler than that of the surrounding air, the SBF continues to propagate inland during the nighttime.

Cross sections of the wind vector and temperature field for two different stages are shown in Fig. 1 and Fig. 2. Here, the potential temperature deviation is obtained by subtracting the initial potential temperature at the surface, i.e., the value 25.5°C at AM 8:00 LST. At the late-afternoon stage (18:00 LST; Fig. 1), the land surface temperature drops to nearly the same as that over the sea surface. The temperature field shows an almost neutral layer ahead of the SBF because of the cooling of the land surface, although the velocity field still exhibits rather intense convective motions ahead of the SBF. The velocity field also exhibits intense frontal updraft, but the magnitude is less than that of the early-afternoon stage. The horizontal velocity in the sea-breeze layer is about 3 m/s. The form of the sea-breeze head shown in the temperature field exhibits a classical density current head, and the raised-head shape of daytime SBF in the FG event (seen in Fig. 3a, Fig. 5a, Ogawa et al. 2003) is no longer seen at this late-afternoon stage due to the attenuation of the frontal updraft.

At the evening stage (21:00 LST; Fig. 2), the land surface temperature becomes cooler than that of the sea surface. Ahead of the SBF, the almost neutral residual layer of the temperature field associated with calm region of the velocity extends up to about 800 m height. Near the surface, a weakly stable layer develops due to the surface cooling. The sea-breeze head exhibits a flattened wedge-like shape formed by the nighttime SBF penetrating into the ground-based stable layer. The horizontal velocity in the sea-breeze layer is around 3 m/s at this

Fig. 1. Vertical cross section of the nighttime SBF for the late-afternoon stage at 18:00 LST. Arrow below each figure indicates the SBF position. The numbers on the horizontal axis denote distance from the coastline $x = 100$ km. (a) The velocity vectors. (b) The potential temperature deviation depicted by every 0.2 K contours.

stage. In addition, the horizontal potential temperature gradient of the SBF at the evening stage becomes more intense than that of previous stages.

In Fig. 3, the horizontal distribution of the potential temperature deviation at 50 m height is presented for late-afternoon to evening stages. This figure shows that the hori-

zontal potential temperature gradient at the front intensifies as it goes from the late afternoon (17:00 LST) to the evening stage (21:00 LST). In addition, Fig. 4, which shows the time series of the maximum value of the horizontal potential temperature gradient at the front, apparently exhibits the evidence of the horizontal potential temperature gradient intensi-

Fig. 2. Same as in Fig. 1 but for the evening stage at 21:00 LST.

fication after 18:00 LST, i.e., the nocturnal FG event of the nighttime SBF occurred. However, as the surface temperature is described by the idealized sinusoidal function, and the physical process of the atmospheric radiation is not included in this model, the nocturnal temperature cooling, which is usually observed ahead of the nighttime SBF in the atmospheric boundary layer, couldn't be appropriately represented. So, in comparison with the actuality

the possibility of emphasizing the strengthening of the horizontal potential temperature deviation gradient in Fig. 3 and Fig. 4 is sufficiently considered.

4. Mechanism for the nocturnal FG event in the nighttime SBF

In this section, we present an analysis on the nocturnal FG event based on the following FG equation;

Fig. 3. Sequence of the potential temperature deviation at $z = 50$ m from late-afternoon stage to evening stage. Horizontal axis represents the horizontal distance relative to the SBF.

Fig. 4. Time series of the maximum of the horizontal potential temperature gradient near the SBF at the height of 50 m.

$$\frac{d}{dt} \left(\frac{\partial \theta}{\partial x} \right) = - \frac{\partial u}{\partial x} \frac{\partial \theta}{\partial x} - \frac{\partial w}{\partial x} \frac{\partial \theta}{\partial z} + \frac{\partial}{\partial x} \left[\frac{\partial}{\partial x} \left(K \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial z} \left(K \frac{\partial \theta}{\partial z} \right) \right],$$

where θ, u, w, K and t have usual meanings, and the same expression as above has been

used and proven to be effective for the analysis of the FG events (Kraus et al. 1990; Kraus 1992; Arritt 1993; Finkeler et al. 1995; Ogawa et al. 2003). In our previous paper (Ogawa et al. 2003), the mechanism for FG-FL events observed at the daytime SBF was explained by estimating these terms. Similarly we calculate these terms for the typical SBF at the evening stage to understand the mechanism of nocturnal FG event. In the following, all terms in the FG equation at 21:00 LST are calculated, and the characteristics of the spatial distribution of these terms are examined.

In Fig. 5a, the confluence term, i.e., the first term in the right of the equation, exhibits positive value at the front with a maximum value of about 9.0×10^{-6} K/m/s. So, it is seen that the confluence term be of the frontogenetical tendency on the nighttime SBF. This maximum value is about three times larger than that of the daytime FG event (seen in Fig. 7a, Ogawa et al. 2003). As described in previous Sec. 3, we couldn't represent the nocturnal temperature cooling well in the model. As a result, this value may be excessively evaluated. The confluence effect is mostly attributed to the horizontal velocity convergence at the front and intensification of the horizontal potential temperature gradient itself during the nocturnal FG event of the nighttime SBF. In Fig. 5b, the tilting term, i.e., the second term in the right of the equation, exhibits negative value at the front with a minimum value of about -3.5×10^{-6} K/m/s. So, it is seen that the tilting term is of the frontolytical tendency on the nighttime SBF. This is formed by the combination of the frontal updraft and ground-based stable layer. Compared with that of the daytime FG event (seen in Fig. 7c, Ogawa et al. 2003), it is found in Fig. 5c that the turbulence term, i.e., the third term in the right of the equation, exhibits no significant tendency due to the cessation of the turbulent activity associated with the surface cooling. In Fig. 5d, the total tendency, i.e., the left-hand side of the equation shows an intense positive value, which is about twice that of the daytime stage (seen in Fig. 7d, Ogawa et al. 2003). The stronger frontogenetical tendency at night is explained mostly by the enhancement of the confluence effect and partly by the attenuation of the turbulence effect.

Fig. 5. Vertical cross section of the spatial distribution of the terms in FG equation at time 21:00 LST of the nocturnal FG event. (a) Confluence term. (b) Tilting term. (c) Turbulence term. (d) Total tendency. Contours are depicted every 0.5×10^{-6} K/m/s. Arrow below each figure indicates the SBF position. The numbers on the horizontal axis denote distance from the coastline $x = 100$ km.

5. Summary and outlook

In this work, we first reproduce the nocturnal FG event of the nighttime SBF with a high-resolution model. The mechanism for the nocturnal FG event is then analyzed by using the FG equation. The results show that the intensification of the horizontal potential temperature gradient at the evening stage, i.e., the nocturnal FG event of the nighttime SBF, is mainly due to the confluence effect at the front. The attenuation of the turbulent activity also partly attributes to the nocturnal FG event as the daytime frontolytical tendency of the turbulence effect is almost diminished during the night.

It is known that the nighttime SBF sometimes continues to propagate inland until midnight, and dissipates frequently in the form of a bore (Clarke et al. 1981; Clarke 1983b), surge (Clarke 1983a, 1984), or sea-breeze cutoff vortex (Simpson et al. 1977; Sha et al. 1993). Recently, there is a paper which first reports this kind of a bore-like disturbance observed

in Japan (Ogura and Hoshino 2001). Although many researchers have investigated this interesting phenomenon (Simpson et al. 1977; Physick 1980; Clarke 1983a, 1984; Physick and Smith 1985; Sha et al. 1993), there still exist problems remaining to be solved. For instance, why and how does the sea-breeze cutoff vortex form? And what is the condition for the generation of the sea-breeze cutoff vortex? We expect to answer these questions in future.

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