NOTES AND CORRESPONDENCE

Analysis of Nighttime Drainage Wind in the HEIFE Region

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(Manuscript received 31 March 1995, in revised form 14 September 1995)

Abstract

When the influence of a synoptic system is weak, nighttime drainage wind often occurs along the front range of the Qilian Mountains, the southwest fringe of the Hexi Corridor, which blows to the gobi (rock desert). The features of the drainage wind were analyzed using the data from two meteorological stations at the foot of the Qilian Mountains. The maximum wind was found at the 8 m level and the depth of the flow was shallow. The flow dissipated quickly over the oasis. A sudden decrease in air temperature was observed below the 10 m level, associated with the passage of the leading edge of the drainage flow. The upward momentum flux and the downward heat flux due to the turbulence increased just when the leading edge of the flow was passing.

1. Introduction

Nighttime drainage wind is a typical feature of a stable boundary layer over complex terrain. In the transition region from mountain to plain, the cool flow drains away from the mountain to the plain, forming a gravity current after sunset. The drainage wind affects the structure of the planetary boundary layer (PBL) and the interaction between land and atmosphere. Brost (1978) and Mahrt (1981) showed that even if the slope is very small, a significant drainage flow can form along the slope. Hootman and Blumen (1983) and Blumen (1984) analysed the characteristics of drainage winds that occurred along the eastern slope of the Rocky Mountains and the structure of the PBL when the drainage flow approached, based on the data observed by the Boulder Wind Network.

The region of the HEIFE experiment is located in the arid area at mid-latitudes of Asian continent. The experimental area is bounded to the south by the Qilian Mountains, at the northern edge of the Tibetan plateau. The north of the experimental area stretches into the desert. In the middle of the experimental area there is an oasis which stretches from the northwest to the southeast. During the Intensive Observing Period of HEIFE, a large amount of continuous observation data were obtained. When the influence of a synoptic system was weak, much

of these data showed that nighttime drainage winds often occurred along the front range of the Qilian Mountains in the Gobi area. The purpose of this paper is to analyse the characteristics of the nighttime drainage winds in the Heihe region and its influence on the structure of the PBL, although the present study is based on the observations at only two stations.

2. Instrumentation and data

The data used in this paper are taken from the data observed in Huayin station (Gobi) HY, which is located in the foothills of the Qilian Mountains, Xiaotun station (Oasis) XT, located at the central part of the experimental area. Figure 1 shows the location of the two observation sites and the topography of the region. About 10 km southwest and 15 km west of Huayin station are high mountains with an elevation of about 3 or 4 kilometers. The foothills are oriented approximately northwest-southeast. The drainage flow often forms on the slope of the foothills just to the southwest or south of HY. An oasis with numerous different crops and trees is located to the east, north and northwest of HY. Xiaotun station, surrounded by short-stemmed crops, is 10 km north to the Huayin station.

There is a meteorological tower at Huayin station, instrumented at six levels: 0.5, 1, 2, 4, 8 and 16 meters. At each level the mean air temperature is measured by a Pt resistance thermometer

Fig. 1. Topography of the experiment region. The locations of the HY and XT observation sites are also shown. The numbers indicate the height above sea level in meters.

and the mean wind speed by a cup anemometer. The accuracy is 0.1°C for temperature and 0.2 m/s for velocity, respectively. The observed data were taken every hour using these instruments. An ultrasonic anemometer (DAT-300) is installed at a height of 8 m to measure three orthogonal components of wind velocity. A fast-response fine-wire Pt thermometer is also installed at the same height to measure temperature fluctuations. The sampling rate of the measurements is 16 times per second. The data handling procedure for the ultrasonic anemometer and the fast-response thermometer includes checking the three components of velocity and the fluctuating temperature, averaging the data every 10 seconds, determining the average wind direction and the mean horizontal wind, calculating the fluctuating components along the longitudinal and lateral directions, the mean temperature and its fluctuating component, and calculating the turbulent variances and turbulent covariances. This is the useful information for the study of drainage winds, which do exhibit unique turbulent characteristics. Two tether-sonde systems (a kind of tethered balloon made by AIR Inc. USA) are used to measure the structure of the PBL. Under normal conditions, the measuring height can reach 800 m , with measuring accuracy of 0.5 m/s for wind speed, 0.2°C for temperature and 3% for relative humidity. The interval of tether-

sonde system measurement is 1 or 2 hours.

3. The development process and characteristics of drainage wind

Nighttime drainage winds, which are a kind of gravity current, often occur in transition region between mountain and plain after sunset. Due to the strong interaction between the drainage wind and the underlying surface, as the drainage wind blows along the slope, the intensity of the drainage wind decreases gradually. Therefore, the influenced region and existing time of drainage wind are limited.

In the Heihe area, due to the complexity of terrain and very dry surface, the drainage wind along Gobi slope has its own special characteristics such as the stronger wind speed and the longer duration compared with those in other areas such as Boulder case (Hootman, 1983).

In order to demonstrate the principal characteristics of drainage winds in the Heihe region, a case study of the typical nighttime drainage wind is presented in this paper, using the data obtained from October 11 to October 12, 1991.

From 1600 LST October 11 to 900 LST October 12, 1991, the large area of northwest China was covered by a high-pressure anticyclone. The horizontal pressure gradient is relatively weak in Heihe region and there is no cloud in the sky. The PBL structure of the experimental area was relatively unaffected by external influences but mainly influenced by the local terrain condition.

Figure 2 shows the wind profiles (absolute value) of the lower boundary layer at different times after sunset on October 11, 1991. The wind below 16 m was measured by the cup-anemometers installed in the tower and the wind above 20 m was measured by the tether-sonde system. At about 1900 LST, the mean wind velocity throughout the boundary layer was very small and the vertical velocity gradient was relatively small too. After that, the wind speed in the surface layer increased sharply. The wind velocity at 8 m increased to 4.1 m/s at 2000 LST. At 2200 LST, the level of maximum velocity dropped to 4 m with the value of 3.7 m/s . Although there was no tether-sonde observation at 2200 LST, the main feature of the wind profile was clearly demonstrated. The maximum velocity increased to 4.9 m/s at 2300 LST at 8 m . Throughout this process, we notice that the strong wind is only in a relatively thin layer below 40 m , and the height of the maximum velocity is very close to the surface.

Figures 3a, 3b, 3c and 3d show the temporal variations of air temperature, wind speed, wind direction and vertical velocity at the 8 m level, respectively, during the "burst" of the cooled drainage flow. The abrupt change of the wind speed is clearly observed around 1915 LST (Fig. 3b). Before 1915 LST, the wind speed was less than 2 m/s . After that, the

Fig. 2. Wind speed profiles at different times. The numbers close to the profiles indicate the observation time (LST).

Fig. 3. The time series of the temperature ($^{\circ}\text{C}$) (a), the wind speed (m/s) (b), the direction ($^{\circ}$) (c) and the vertical velocity (m/s) (d) at 8 m at HY (Gobi) when the drainage flow arrives on October 11, 1991.

wind speed increased sharply to about 4 m/s in just 5 minutes. These features can be regarded as the arrival of the leading edge of the drainage wind. We can see that such a strong wind lasted for about one hour, as will be shown later (Fig. 5). A sudden drop in temperature took place around 1915 LST when the leading edge of the drainage wind approached (Figs. 3a and 3b). Before the arrival of the drainage flow, the cooling of the lower layer is most likely caused by the long-wave radiational loss. After that time the temperature dropped almost 1°C . This sudden change was followed by relatively weak fluctu-

ations. According to the analysis of wind direction (Fig. 3c), when the “jet” took place, the direction of wind changed suddenly from WNW to SW. It means that the “jet” drained the flow from the southwestern mountain, which is about 10 km away from the station. At the same time, the very weak downward motion, possibly associated with the synoptic-scale high-pressure system overlying the region, changed into a relatively strong upward motion within a few minutes (Fig. 3d). This significant upward motion seems to be related to the passage of the drainage

Fig. 4. Time series of momentum flux $\overline{w'u'}$ (m^2s^{-2}) (a) and sensible heat flux $\overline{w'T'}$ (Kms^{-1}) (b) at 8 m at HY (Gobi) on October 11, 1991.

current.

These characteristics suggest that the jet which appeared at the Gobi station as seen in Fig. 3 is a kind of nighttime drainage flow which is quite similar to that in Boulder and reported by Hootman and Blumen (1983).

Figure 4a and 4b show the temporal variation of the momentum flux $\overline{w'u'}$ and the heat flux $\overline{w'T'}$ at 8 m estimated with the ultrasonic anemometer and the fast-response temperature sensor data, respectively, at HY (Gobi). A significant increase in the magnitude of the fluctuation of the momentum flux appears at almost 1915 LST, associated with the sudden changes of the wind speed, temperature and vertical velocity, when the drainage wind approaches. Before 1915 LST, $\overline{w'T'}$ is very weak in the surface layer (so is the momentum flux). This non-turbulent behavior is related to the strong inversion in the surface layer. After the front of the drainage wind arrives, the fluctuations of $\overline{w'T'}$ also show an increase in magnitude. This burst of turbulence lasts a long time associated with the duration of the drainage flow. The strong turbulence associated with the drainage wind is beneficial to the exchange between the underlying surface and the air aloft. These facts suggest that intense three-dimensional turbulent is activated at the front or head of a drainage flow.

In order to know how the drainage flow influences the vertical structure of the lower PBL, it is better

Fig. 5. The time series of air temperature ($^{\circ}\text{C}$) at different levels (a) and wind speed (m/s) at 8 m level (b) at HY (Gobi). The numbers beside the curves indicate the measuring heights.

to demonstrate the changes at the different levels. Figure 5a shows the variation of the mean air temperature at the five levels (1, 2, 4, 8 and 16 m), together with the time sequences of the wind speed at 8 m from 1700 LST to 2100 LST in Fig. 5b. It is noted that the sudden fall of the mean air temperature was most prominent at the 4 m level, where the maximum wind speed was observed during the burst of the nighttime drainage wind. It is also noted that the temperature below that level still decreases by more than 3°C after the leading edge of the drainage flow passed by. This phenomenon means that not only the leading edge of the flow but also the flow behind the leading edge affects the structure of the lower part of the PBL greatly throughout the drainage wind process. The fluctuation of the temperature at 1 m is relatively small. The rate of the temperature decrease at 1 m is almost constant, which means that the temperature at this level is influenced not by the drainage wind. However, above the 2 m level, the air temperature seems to be strongly influenced by the nighttime drainage wind.

All these features associated with the drainage wind at the Gobi station are not recorded at XT (Oasis). This can be seen from the dashed line Fig. 2, which represents the wind profiles at Xiaotun station at the same time. Figure 2 implies

Fig. 6. The time-height cross sections of the wind speed (m/s) from October 7 to 8 at Huayin station. The thick solid line denotes the height of the inversion top.

Table 1. Drainage wind events identified during IOP-2 and IOP-3

Date	Peak speed at 8 m (m/s)	Wind Direction	Decreased temperature (18–21 LST) (8 m)	Decreased temperature (18–21 LST) (4 m)
8.16	3.6	S	4.1	4.7
8.17	3.2	SW	3.9	4.4
10.6	4.9	SW	3.4	3.7
10.8	4.2	S	3.4	4.1
10.11	4.1	SW	3.9	5.6
10.12	4.2	SW	3.4	4.1

that the drainage flow does not reach the central part of the Oasis. The disappearance of the drainage flow at Xiaotun station suggests that the complex underlying surface, with different crops, trees and other vegetation from Gobi and Oasis, decelerates the drainage flow. This situation is somewhat different from that in Boulder. Between Boulder station and the foothills of the Rocky Mountains, there is a relatively flat grassland. In the Heihe region, although the drainage flow can extend a long distance over the arid and flat Gobi slope, it dissipates quickly when it enters the Oasis because of the heterogeneous terrain and the surface covering. The characteristics of the drainage flow can produce important effects on the PBL structure of the arid area and Oasis in the Heihe region.

Similar to the occasion which happened on October 11, 1991, during IOP-2 and IOP-3 experiments, the cooled drainage winds occurred, on many occasions, after sunset. We use the following conditions as the criteria for identifying drainage winds: (1) the experiment area was covered by a high-pressure system and it was required that the region be nearly

Fig. 7. Same as in Fig. 6, except for the period from October 11 to 12, 1991, when a distinct drainage flow appeared over the Gobi slope.

cloudless during the flow. (2) After sunset, there exists the wind peak with its maximum value at least 2 m/s greater than the wind speed before sunset. The duration of the peak wind was no more than one or two hours, sometimes only dozens of minutes. (3) The layer of the peak speed was relatively shallow with a large vertical wind-speed gradient. Above the layer the wind speed was very low. (4) The wind must blow from the southern or the southwestern mountain areas. (5) The flow must be accompanied by a significant decrease in air temperature. These requirements can be used as the criteria to distinguish the drainage winds from those wind flows caused by synoptic-scale processes and the phenomena associated with convection and precipitation.

Based on these criteria, we analyse all the observed data obtained from the tetheredsonde system and the meteorological tower during IOP-2 (from August 6 to 20, 1991) and IOP-3 (from October 6 to 13, 1991). Table 1 lists the incidence of drainage winds during the experiments. Actually, these criteria are so strict that some drainage flow events were systematically excluded. If we eliminate the condition (3), then the data obtained from the tower, which had been used for more than two years, indicate that the drainage winds often occur in fall and winter. More than ten drainage wind events occurred each month in September and October.

4. The influence of the drainage flow on the structure of PBL

The nocturnal low-level jet (NLLJ) is not an unusual phenomenon of the PBL which has already been thoroughly studied by many field experiments and numerical models. According to Blackadar's (1957) inertial oscillation theory, the height of the

low-level wind maximum is related to the top of the inversion. Mahrt (1979) suggested that the top of the inversion is about 25 % higher than the level of the maximum wind speed. In the Heihe region, the NLLJ often occurs after midnight. Figure 6 shows the development of the NLLJ at HY from October 7 to 8, 1991. In this period the drainage wind did not occur in this region. The height of the maximum wind speed is approximately coincides with the top of the inversion. The elevation of the maximum wind speed tends to increase with time. At the same time, the depth of the inversion layer also increase with time. This situation is quite similar to the jet in the normal nocturnal stable boundary layer.

However, once the cooled drainage wind occurs, the height of the inversion is usually very low. Figure 7 shows the time-height cross section of the mean wind speed at HY from October 11 to 12 1991, when the drainage wind occurred. After sunset, the relatively strong wind layer near the surface (below the 30 m level) is the cooled drainage wind. The NLLJ was formed around midnight at the 150 m level. Another one was formed at the 50 m level thereafter. However, although the wind speed reached 7 m/s at 500 LST, the height of the maximum wind was at the 50 m level and did not increase so much as the case for October 7–8. Thus, the drainage wind seems to affect considerably the evolution of the NLLJ. Many details about the influence of the drainage wind on the PBL are unknown. Therefore, in order to understand the interaction between land and atmosphere in the Heihe region, it is important for us to study the drainage wind further.

5. Summary and conclusions

The present paper analyses the characteristics of the drainage flow along the Gobi slope in the HEIFE region as a case study for 11–12 October 1991.

(1) Over the Gobi slope, the drainage flow from the foothills of the Qilian Mountains to the plain was clearly observed. However, the drainage flow dissipates quickly and could not reach the central part of the Oasis.

(2) The height of the maximum wind associated with the drainage flow is very low (the 8 m level) and the depth of the drainage flow is shallow. The gradient of wind speed below and above the level of maximum wind is relatively large.

(3) The sudden decrease in air temperature below the 10 m level (*e.g.* about 4°C at the 4 m level) was observed accompanied by the passage of the leading edge of the drainage flow. It is noted that the upward momentum flux and the downward heat flux due to turbulence increased just when the leading edge of the drainage flow was passing.

(4) Although the nocturnal low-level jet (NLLJ) was generated several hours after the passage of the drainage flow front, its height did not increase much (up to about 50 m) compared to the case when no drainage flow exists (about several hundred meters). In the present case with the drainage flow, the height of the inversion base did not increase much. This might affect, in some way, the evolution of the NLLJ, although detailed studies are need for understanding the relating processes.

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HEIFE 領域で観測された夜間下降流**Qiang Wang, Ping Zhu, Bangzhong Wang and Ruibin Jiang**

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総観規模擾乱の影響が弱いときには河西回廊の南西縁の祁連山脈から麓のゴビ (磧砂漠) に向かって吹く夜間下降流がしばしば発生する。祁連山脈の麓にある2箇所の観測地点の観測データを用いて、この夜間下降流の特徴を解析した。夜間下降流は最大風速が地上8 m程度にある薄い層に限られる。この流れはオアシス上では急激に弱まる。地上10 m以下の層では、夜間下降流の先端が通過するとともに気温が急激に下がり、このとき乱流による上向きの運動量輸送と下向きの顕熱輸送が増大する。この夜間下降流はHEIFE領域での夜間の低層ジェットの構造にも影響を与えている。