Nocturnal Maximum Winds in the Planetary Boundary Layer at White Sands Missile Range, New Mexico

LAURENCE J. RIDER AND MANUEL ARMENDARIZ

Atmospheric Sciences Lab., U. S. Army Electronics Command, White Sands Missile Range, N. M.

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ABSTRACT

Ninety-one cases of nocturnal low-level maximum winds are examined in detail and are classified into three basic types, based on the synoptic weather pattern existing at the time, and the average height above ground at which the maximum wind developed. Typical synoptic surface and 850-mb patterns associated with each of the three types are presented. The time of most frequent occurrence is discussed, certain factors which appear to be conducive to the development of significant low-level maximum winds are given, and some additional characteristics of the wind maxima are presented.

1. Introduction

Nocturnal meteorological soundings at White Sands Missile Range (WSMR) often reveal a wind speed maximum in the upper portion (100–1000 m) of the planetary boundary layer. This phenomenon is commonly termed the “low-level jet,” and has been observed in several geographical areas; namely, Quebec, Canada, by Rooke (1965), western Peru by Lettau (1967), eastern Africa and the western part of the Indian Ocean by Findlater (1969), and the Great Plains of the United States by Wexler (1961), Lettau and Davidson (1957), and Hoecker (1963). Neyland (1956) has emphasized the importance of the low-level jets in aircraft operations, and there is an apparent relationship to nocturnal thunderstorms and squall lines in the central United States (Means, 1952; Pitchford and London, 1962). Barad (1961) summarized other practical implications of strong low-level maximum winds, including effects on maneuvering aircraft, parachute deployment of men and materials, etc.; furthermore, Blackadar (1957) quotes Byram as suggesting that these jets may be responsible for “blow-up” of forest fires. The vertical wind shear existing in low-level maximum winds presents a difficult problem to missile and sounding rocket launchings, the extent of which is beyond the scope of this paper. Most studies published on the occurrence of low-level jet winds have used data from a single observation site; however, to be more correct, to be called a low-level jet, a low-level maximum wind should exhibit horizontal speed gradients as well as vertical. This type of data is exemplified by the work of Hoecker (1963) in which vertical and horizontal gradients across the southern plains of the United States are presented.

In the past several years, hundreds of daytime and nighttime low-level wind profiles have been collected

at WSMR in the operational support of sounding rocket and missile firings. Many cases of marked low-level maximum wind are observed in these data, and nearly all cases occurred during nighttime. However, a few were noted when apparently the low-level maximum developed during the night and persisted 1–3 hr after sunrise in spite of the fact that the surface temperature inversion had broken down. This supports the findings of Kaimal and Izumi (1966) in which they state that an early breakdown of the surface inversion does not necessarily mean the destruction of the low-level jet wind itself. It was also apparent that the occurrence of low-level maximum winds was more frequent during certain months and almost nonexistent in others. Consequently, during 1969–70, several periods of nighttime data collection were initiated, consisting of three simultaneous soundings at sites on a line approximately normal to the mean wind flow to show the jet-like characteristics of the low-level maximum wind. These wind data were obtained using a radar-tracked balloon, whereby a continuous analog trace of both horizontal components of the wind speed were recorded. The purpose of this paper is to present the results of these soundings and some of the operational data, to classify low-level maximum winds occurring in the WSMR area according to synoptic patterns and height above ground, and to point out some additional characteristics and factors which appear to be conducive to the development of a “ribbon-like” layer of winds stronger than would be indicated by the usual geostrophic scale.

2. Discussion of data

Seventy-nine of the 91 cases of nighttime low-level maximum winds (analyzed in this paper and presented in Table 1) were observed during 3–5 hr periods with wind profile measurements being made at 10–30 min

TABLE 1. Characteristics of nocturnal low-level maximum winds observed at White Sands Missile Range.*

Date	Time (MST)	Horizontal wind speed (m sec ⁻¹)	Direction	Height (m)	Type	Date	Time (MST)	Horizontal Wind speed (m sec ⁻¹)	Direction	Height (m)	Type
13 Jan 65	0725	10.4	NNW	185	I	13 Nov 69	0000	14.3	NNW	920	III
30 Jan 64	0530	8.4	NNW	240		16 Nov 64	0800	12.5	W	760	
18 Feb 58	0721	9.1	N	215		17 Nov 65	0310	9.9	NNW	610	
2 Apr 65	0530	9.4	N	210		25 Nov 64	0445	6.7	W	225	
7 Apr 64	0640	8.5	NNEI	245		27 Nov 63	0705	10.9	NNW	370	
12 Apr 63	0703	7.7	NNE	125		16 Dec 64	0420	14.7	W	370	
12 Apr 65	0727	7.3	NNE	185		6 Jan 64	0001	11.5	SSE	620	
17 Apr 62	0645	10.1	NNE	150		28 Jan 64	0700	14.9	SE	430	
17 Apr 69	0330	14.0	N	190		4 Mar 69	0425	18.3	SE	430	
20 Apr 65	0530	9.4	N	185		17 Mar 65	0310	9.8	NNE	610	
21 Apr 64	0530	8.5	NNE	245		18 Mar 65	2001	12.5	SE	430	
26 Apr 65	2300	7.5	NNE	215		18 Mar 67	0200	12.5	SE	430	
4 May 70	0600	7.8	N	300		19 Mar 68	0200	12.5	SSE	430	
5 Jun 60	0501	6.1	NNE	110		19 Mar 70	0030	18.4	N	275	
27 Jun 60	0600	9.7	N	275		29 Mar 65	2252	13.0	SSE	550	
20 Jul 68	0500	8.1	NNE	125		7 Apr 70	0200	13.4	SSE	610	
21 Jul 59	0350	7.6	NE	125		30 Apr 69	0100	20.2	S	490	
17 Oct 57	0330	11.2	ENE	155		8 May 65	0355	12.6	SSW	250	
17 Nov 60	0645	8.9	NNE	110		10 May 67	0500	8.9	SW	370	
19 Nov 69	0030	10.2	NW	180		14 May 63	0325	8.6	S	215	
2 Dec 65	0800	11.8	NNE	185		15 May 58	0430	12.5	SSW	430	
5 Dec 63	0745	7.6	NNE	95		19 May 70	0200	16.5	S	460	
13 Dec 61	0330	9.6	NNE	120		20 May 67	0200	9.3	S	460	
20 Jan 65	0100	23.8	NNW	370		21 May 67	0600	13.4	S	660	
28 Jan 70	0230	29.1	WSW	610		6 Jan 63	0310	9.2	SSE	275	
30 Jan 65	0015	8.2	NNW	245		10 Jan 69	0300	7.2	SSW	125	
5 Feb 64	0700	15.4	NNE	600		17 Jun 63	2040	9.7	ESE	125	
11 Feb 69	0400	7.3	N	460		20 Jun 63	0520	7.8	SE	150	
11 Feb 70	0300	12.3	NNW	370		25 Jun 63	0350	9.0	SSE	150	
12 Feb 64	0230	15.1	NW	910		28 Jun 63	0330	7.7	SSE	150	
12 Feb 65	2320	9.8	N	610		14 Jul 69	0100	9.4	SSE	610	
17 Feb 64	0130	14.0	NNW	305		15 Jul 66	2235	14.4	SE	305	
24 Feb 64	2130	12.2	N	910		15 Jul 69	0000	11.2	S	660	
5 Mar 70	0500	10.7	WSW	610		12 Aug 65	0800	9.4	SSE	610	
12 Mar 65	2030	17.4	WSW	305		20 Aug 69	0100	11.2	S	650	
12 Mar 66	2300	17.4	WNW	610		22 Aug 64	0130	12.7	N	340	
28 Mar 63	2345	11.2	WNW	245		20 Sep 63	0545	9.7	SE	305	
15 Apr 65	0100	14.3	NNE	155		22 Sep 63	0130	12.7	SE	340	
25 Apr 69	0030	16.3	WNW	370		10 Oct 63	0018	7.2	SSW	250	
4 May 65	0230	15.2	WNW	490		13 Oct 69	2128	14.6	SE	310	
4 May 66	0231	13.7	W	370		16 Oct 69	0330	14.6	SE	310	
25 May 63	0315	11.0	WSW	225		30 Oct 64	0610	13.6	S	245	
10 Jun 64	0525	9.0	W	370	II	14 Nov 64	0325	5.9	SW	490	
15 Jun 60	0700	8.1	WNW	270		30 Nov 61	0715	7.6	SSW	370	
17 Jun 63	2040	9.7	WSW	225		16 Dec 64	2345	5.8	SSW	275	

* Maximum speed ≤ 3 m sec than the minimum speed at the next highest level.

intervals. The remaining cases were observed during 8 hr of data collection (0000–0800 MST) with measurements made at 30-min intervals. These 91 cases had developed to what is considered in this paper to be a significant degree. The criterion for significance is that the wind speed at the height of its maximum was 3 m sec⁻¹ or greater than the minimum at the next highest level. This is analogous to the criterion used by Blackadar (1957) for significant maxima in which the wind speed at the level of the maximum exceeds the wind speed at the level of the next higher minimum by 5 kt or more. In addition, there were indications that the wind was supergeostrophic to some degree.

The low-level wind maximum does not occur at the same time of day at all latitudes. The occurrence of the wind maximum at midnight or soon after in the mid-latitudes of the Great Plains has been observed many

times. Calculations by Lettau (1967) agree with this time for 45N, and he states that the time of development occurs later in the day as one moves southward, e.g., the time of greatest development at 23.5N should be about noon. In addition, computations by Krishna (1968) generally agree with the above findings. Of the 91 cases of LWM (low-level wind maxima), 10% were observed during the period 2000–0000, 56% during the period 0000–0400, and 34% during the period 0400–0800 (all times MST). This greatest frequency of occurrence (56%) between 0000 and 0400 generally agrees with the theoretical findings of Lettau (1967) and Krishna (1968) since the latitude at WSMR is 32N.

After detailed analysis of 91 LWM cases at WSMR, it appears that there are basically three types, depending simply on the general synoptic weather pattern in the lower levels and the height of the maxima above

ground, corresponding to the "nose" of the wind speed profile. These three types are as follows:

a. Type I

This is a northerly maximum wind, generally found at heights of 100–400 m and occurring on nights when there is a high pressure system over the central and southern Rockies with mostly clear skies and decreasing geostrophic winds with height over New Mexico. An example of this is shown in Fig. 1 together with a temperature profile at 0400 MST. Note that the maximum development of wind speed occurs between 0300 and 0430. These data were collected on 17 April 1969, and the surface synoptic weather pattern is presented in Fig. 1b. This type (together with those of Type II discussed below) have an interesting feature in common with the northwesterly wind maxima of New England as described by Kuettner (1959). He points out that they typically occur with strong geostrophic winds near the ground and a pressure gradient decreasing sharply aloft due to the presence of a cold high to the west.

b. Type II

This is a west-northwest or northwest LWM occurring as a cold trough aloft (weakening with height) moves eastward through the area during the night after

a surface temperature inversion has developed. Timing of these conditions appears to be important. If the trough moves through the area before the temperature inversion develops, the surface winds and the winds in the adjacent layers are strongly katabatic in nature and the typical LWM profile is nonexistent. An example of of this type of LWM occurring on 28 January 1970 shown in Fig. 2a. Note the temperature inversion at 0200, the maximum wind of 28 m sec^{-1} at 600 m at 0230, and its weakening as the inversion broke up when the cold trough moved eastward. Abnormally strong winds can occur at a height of a few hundred meters when there is a large source of colder air upstream as suggested by Reiter (1963) while at the same time surface winds remain relatively light. Landing jet aircraft under such conditions can be hazardous because of the large wind shear and rapid drop in airspeed. The height of the LWM at WSMR is generally 600–1000 m. The 850-mb chart is presented in Fig. 2b and is typical for this type of LWM.

c. Type III

This LWM is generally found with southerly winds (varying from southeast to south-southwest) and occurs at heights of 400–600 m. These heights compare favorably to those found in previous studies of southerly low-level jet winds over the Great Plains area by Holton

FIG. 1. Wind speed (m sec^{-1}) vs time and height (17 April 1969) and the corresponding surface pressure analysis (0500 MST 17 April 1969).

FIG. 2. Wind speed (m sec^{-1}) vs time and height (28 January 1970) and the corresponding 850-mb analysis (0500 MST 28 January 1970).

(1967) and Gerhardt (1962). An example is shown in Fig. 3a where it can be seen that the LWM reached its greatest development from 0400–0600 with a wind speed of 18 m sec^{-1} at a height of 500–600 m. These data were collected on 4 March 1969. The top of the inversion was slightly below 400 m at 0200. A copy of the 850-mb chart is shown in Fig. 3b and is typical for this type of LWM.

The Type III LWM is frequently referred to as a low-level jet over the plains area just east of WSMR by a number of authors. It has received extensive study by Blackadar (1957) and Lettau and Davidson (1957) and was designated as an inversion wind maximum (IWM) by Reiter (1963). A cross section of this LWM, as observed at 0530 from three sites separated by a distance of approximately 25 km, and a temperature profile measured at 0700 at a nearby site, are presented in Fig. 4. Skies were clear over WSMR and the surface wind southerly from $1\text{--}4 \text{ m sec}^{-1}$ during the period from midnight until sunrise on 4 March 1969. A similar cross section of an LWM (or its apparent equivalent, a low-level jet) was measured at 2330 on 29 April 1969. A schematic of this situation with a wind maximum of 16 m sec^{-1} at a height of $\sim 600 \text{ m}$ is shown in Fig. 5. A temperature profile obtained nearby at 0200 shows an inversion up to 480 m.

d. Additional examples and characteristics

Fig. 6 presents an interesting case of a deepening of the temperature inversion and a rise in the height of the level of maximum wind during a period from 0130–0430 on 30 November 1966. An explanation of the process involved is that as the vertical shear increases, a certain residual amount of turbulence will be maintained; in this manner, heat and momentum will still be transported toward the ground where they will be

FIG. 3. Wind speed (m sec^{-1}) vs time and height (4 March 1969) and the corresponding 850-mb analysis (0500 MST 4 March 1969).

transformed by radiation and friction at a slower rate than during the day when the eddy diffusivity is greater. By this relatively slow process, the inversion layer is able to deepen in the course of the night.

Another interesting LWM situation is presented in Fig. 7. The wind measurement period began at 2330 MST 30

FIG. 4. Simultaneous wind speed (m sec^{-1}) at three locations (0425 MST 4 March 1969).

FIG. 5. Simultaneous wind speed (m sec^{-1}) at three locations (2330 MST 29 April 1969).

April 1969 with a maximum wind of 15 m sec^{-1} from the south at a height of 370 m. A temperature profile at 2300 shows a surface inversion at 185 m which changed to isothermal by 0330. The low-level wind maximum continued until 0230, after which, as shown by the profiles from 0230–0630, there was a marked change from southerly flow to westerly and thence to northwesterly at the level of maximum wind. An examination of the 850-mb chart (not presented here) shows that a trough moved eastward across WSMR at about 0230, followed by a weak ridge which explains the wind shift to the northwest accompanied by a decrease in speed.

Some additional examples of typical Type I, II and

III nocturnal low-level wind maxima are presented in Figs. 8–10, respectively. A list of the 91 cases, giving wind maximum, height, and time of occurrence, is presented in Table 1.

The frequency of a significant low-level wind maxima is of some interest. Thus, at WSMR, each of the 91 cases observed occurred during one of the 154 periods of nighttime data collection, each of which covered 3–8 hr; LWM were thus found during 59% of the observation periods. By months, the greatest frequency occurred in March, April, May and June, with about equal numbers in each of the four months. A secondary maximum occurred in November. The months of July,

FIG. 6. Wind speed and temperature profiles (30 November 1966).

FIG. 7. Wind speed and temperature profiles (30 April 1969).

August and September had the least number of cases. It is suggested that this can be attributed to the fact that this is the rainy season of the year, with showers

and thunderstorms occurring at night as well as day-time, with associated steep lapse rates, large values of eddy viscosity, and little if any nocturnal temperature

FIG. 8. Wind speed (solid lines) and temperature (dashed lines) profiles characteristic of a Type I nocturnal low-level maximum wind.

FIG. 9. Wind speed (solid lines) and temperature (dashed lines) profiles characteristic of a Type II nocturnal low-level maximum wind.

FIG. 10. Wind speed (solid lines) and temperature (dashed lines) profiles characteristic of a Type III nocturnal low-level maximum wind.

inversions resulting in minimum decoupling between the lower and upper parts of the planetary boundary layer. In addition, there must certainly be some alteration of the southerly wind maxima due to the mountain ranges which are oriented north-south on the west and east side of WSMR, possibly creating localized jets as shown in Figs. 4 and 5. It is also interesting that Jehn and Durie (1963) found a maximum frequency of wind maxima in July in the 1961–62 data from the Cedar Hill Tower. Bonner (1968) also found in the analysis of two years of radiosonde and rawinsonde data a summertime predominance of wind maxima over the Great Plains, particularly when only southerly jets were considered.

3. Summary and conclusions

Nocturnal low-level wind maxima are very complex phenomena which occur frequently at WSMR and develop as the result of various forcing functions and are altered by the topography of the area. In the interest of simplification, the many cases listed in this paper are classified into three types based upon the synoptic weather pattern, height of the maxima above ground, and the direction of the wind. Type I is a northerly wind at a height of 100–400 m occurring on nights when there is a high-pressure system over the central and southern

Rockies, with clear skies and decreasing geostrophic winds aloft over New Mexico. Type II is a west-northwest or northwest wind at a height of 600–1000 m occurring when there is a cold trough moving eastward through the area during the night with mostly clear skies and a well-developed surface temperature inversion. Type III is a southerly wind, varying from south-east to south-southwest, occurring at a height of 400–600 m predominately at night, with a surface temperature inversion and a low-pressure system moving eastward in the vicinity of the Arizona-New Mexico border.

Some additional characteristics of the nocturnal low-level wind maxima observed at WSMR are as follows.

- 1) The height above ground of the maxima and the magnitude of the wind speed are erratic or fluctuate somewhat with time (10–30 min), particularly when the height of the nose of the speed profile is well above the temperature inversion and when there is a premature breakdown of the inversion.
- 2) A low-level maximum of significant magnitude may exist for a time with temperatures decreasing with height. A breakdown of the inversion does not necessarily result in the dissipation of the low-level maximum at the same time.
- 3) The sharper the temperature inversion profile at the inversion, the sharper will be the nose of the wind speed profile.

Various hypotheses have been offered to explain the low-level wind maxima by emphasizing different physical processes, among them being the blocking of the large-scale flow by the Rocky Mountains. Any more comprehensive explanation would require detailed examinations of low-level maxima situations along an east-west cross section which extended from WSMR to the eastern plains of New Mexico, West Texas and western Oklahoma.

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