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Forecasting

WIND ANOMALIES IN THE RED RIVER VALLEY OF THE NORTH

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ABSTRACT
Forecasting wind in the Red River Valley of the North has always been a problem. Surface wind speed is generally underforecast, while surface direction is sometimes greatly different from adjacent areas. Frontal wind shifts often fail to occur, or occur later than expected. The valley is also subject to severe ground blizzards that do not affect surrounding areas. The objective of this study is to describe the meteorological conditions when anomalies occur and to speculate on their causes.

It was found that most winter wind anomalies occurred during an intense inversion. Based on case studies it was postulated that the shallow valley topography causes an internal boundary layer and intense temperature inversion. The resulting layer is so stable that frontal wind shifts are prevented from reaching the surface and skip over the valley. The shape and orientation of the valley and this stable layer also seem to isolate it from the macroscale flow, causing other wind direction anomalies and speeds that are 10-15% greater than surrounding locations.

1. INTRODUCTION

Despite its low relief, the Red River Valley of the North has an effect on the surface mesoscale wind flow of eastern North Dakota and northwest Minnesota. Cooley (3) showed that minor terrain features similar to those found in the Red River Valley can have a significant effect on wind direction.

Marker (4) and Changnon (5) both dealt with minor topographic features and the apparent large scale effects they have on the lowest 1 km of the atmosphere. They showed how minor topographic slopes can have major impacts in surface-based convective development. Hagemeyer (6) showed the effects minor topographic features have on convective development, in an operational setting. Schultz (7) and Paulson (8) also showed how very subtle topographic variation can have large scale effects in precipitation development, implying a much larger effect than normally expected.
Clarke and McElroy (9), and De Marrias (10) studied the mesoscale wind flows in large metropolitan areas, and focused on the development of the internal boundary layer and associated inversions. Clarke and McElroy (9) dealt with the topographic influences lending to the internal boundary layer/inversion development in a suburban environment.

The major objectives of this report are to show that 1) during certain times of the year, frontal systems and wind shifts crossing the Northern Plains fail to cause a surface wind shift within the valley; 2) under certain atmospheric conditions the surface wind flow within the valley is vastly different from surrounding locations; and 3) the average wind speed within the valley is about 20% higher than surrounding locations, suggesting a well defined funnelling effect.

2. THE TOPOGRAPHY OF THE RED RIVER VALLEY

The Red River Valley of the North (hereafter called the valley), averages 100 km in width east-to-west while the flat valley floor is about 40 km wide. The slope to the west increases from near 0.5 m/km at the Red River to 5 m/km at the edge. East of the valley floor the slope is similar, but increases to 7 m/km at its maximum.

The valley is bounded by several moraines, beaches, and ridges (Figure 1) that are about 170 to 190 m above the valley floor. The Luverne moraine and Kindred ridge mark the western boundary while the eastern boundary is defined by the Hermann beach and the Alexandria moraine complex. To the south, the valley is loosely connected by a broad, shallow trough formed by the Altamont moraine and another moraine paralleling the Altamont moraine to the east. This trough runs into northern Iowa.

Fargo, North Dakota, located near the center of the valley, is 275 m above Mean Sea Level (MSL), while Valley City, North Dakota, near the western edge of

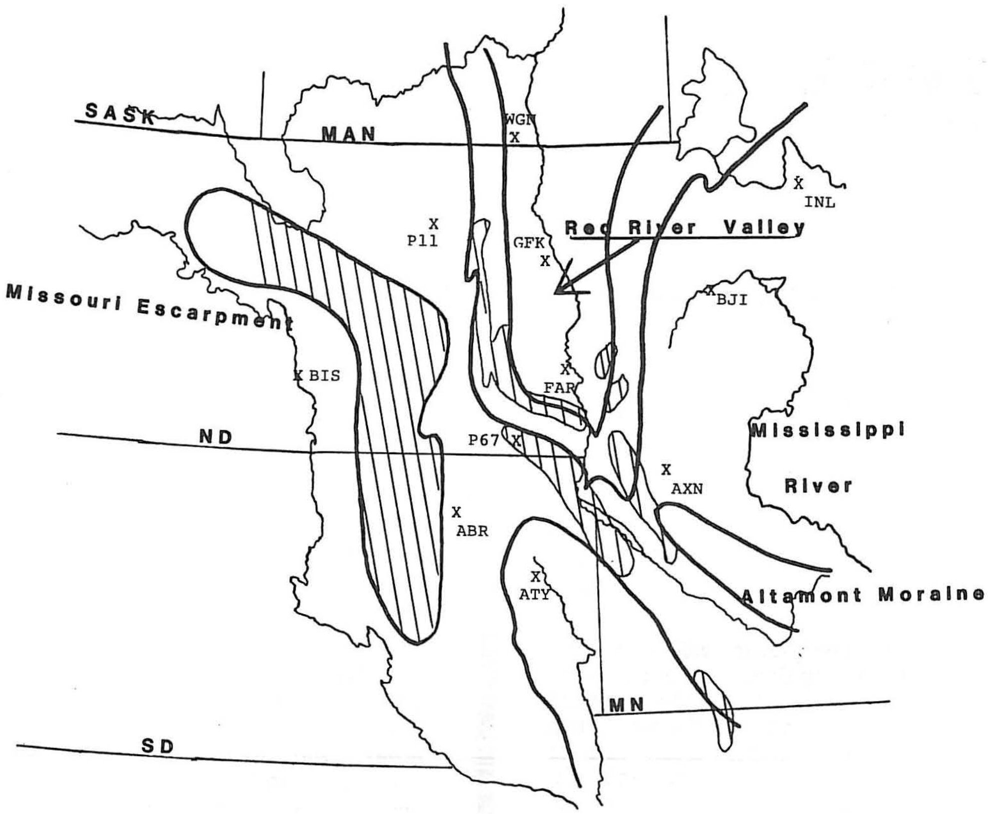

Figure 1. Map of the primary stations used in this study and the major relevant topographic features. Stippled areas are the most prominent radar reflections under super-refractive conditions.

the valley, is 450 m above MSL. Similar topography exists along the western edge of the valley. The valley gradually widens from south to north as the elevation decreases. Grand Forks, North Dakota is only 20 m lower than Fargo, about 100 km distant. Under a southerly wind flow, there is a very gradual down slope and horizontal diffluence in the valley; conversely, weak confluence and upslope exists under a northerly flow.

3. OBSERVATION TECHNIQUES

Descriptions of the surface stations used in this paper are listed in Table 1. The weather radar at the Weather Service Office (WSO) in Fargo is a 10-cm wavelength, 500-KW output device, with a minimum discernable signal of about -111 dBm. The time and area sampled is 15 μ s and 1 km^2 respectively. The antenna is located 30 m above ground level (AGL). During widespread inversions, topographic features as far as 450 km away become visible on the plan position indicator (PPI). Especially prominent are the moraines, ridges and beaches that surround the Red River Valley. The Sisseton Hills in northeast South Dakota, the Turtle Mountains in north central North Dakota, and the Missouri Escarpment in central North Dakota also are visible. This is due to the super refraction of the radar beam along the base of the inversion that forms over the valley (see Federal Meteorological Handbook #7 - Weather Radar Manual, 1981).

Upper-air data are usually collected by rawinsonde, captive or constant-level ballons, or some other real-time collection device. In this study however, only commercial and private aviation pilot reports (PIREPS) were available. The significant difference between PIREPS and rawinsonde observations (RAOBS) is that PIREPS consist of temperatures reported approximately every 0.5 km vertically. The rapid change in altitude, along with potential instrument error, may result in a less accurate vertical temperature structure. Therefore, minor temperature variations are missed. PIREPS reported to WSO Fargo are checked against the latest sounding from one of the four surrounding upper air stations and usually agree well with the RAOB temperatures. The surface temperature reported by the aircraft is compared with the indicated air temperature at WSO Fargo. Only temperatures that are within $\pm 3^{\circ}$C are considered valid. Above 3.0 km AGL, variations of less than 1°C between PIREPS and RAOB observed temperatures are common. However, there are at times surprising differences below 3.0 km (Fig. 2). Comparing the PIREP temperatures with the RAOB temperatures illustrates how and when PIREP temperatures may be used in a Early in the study, inversion data were measured with a sling psychrometer on the roof of the 25-m control tower adjacent to the Fargo WSO. Later, an electronic weather station designed to record wind speed and direction and temperature continuously was placed on the roof of the 25-m tower.

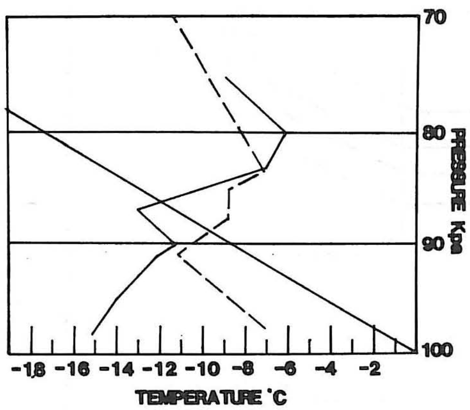

Figure 2. Partial Skew#T-logP diagram showing a Bismarck Rawinsonde sounding (raob/dashed line) and a Fargo pilot report (PIREP/solid line) for 00 GMT March 1, 1983. Right ordinate is pressure in kilopascals; abscissa is temperature in °C, solid angled line is 0°C potential temperature.

In conjunction with PIREPS received at the Fargo WSO, lapse rates over the valley were analyzed, and an average lapse rate of -5° to -15° C/km was discovered. Measurements in the lower 25 m AGL have shown lapse rates of -25°C/km. Enz et al. (11) and De Marrias both have reported inversions of greater intensity. Three km south of the Fargo WSO is a 50-m stack located on the campus of North Dakota State University (NDSU). Five km east-southeast of the Fargo - WSO is the American Crystal Sugar beet processing plant. Both stacks emit plumes that are almost always visible, and illustrate the low-level inversion and boundary layer that exist over the valley during wind anomaly episodes. Studies by Lyons and Cole (12) and Oke (13) describe the dispersion of the smoke plumes under varying atmospheric conditions. In this study, plumes are used to show the differences between surface wind directions and those a few hundred meters AGL.

The heights given for the two plumes used in this study are based on Fargo PIREPS and rotating beam ceilometer readings. Plumes from the two stacks are easily detected when they pass over the ceilometer.

4. INVERSIONS AND INTERNAL BOUNDARY LAYERS OF THE RED RIVER VALLEY

Observed inversions over the valley are most intense and persistent from November through April. Their growth and persistence are aided by short day lengths with low solar angles, frequent occurrences of cloud cover, and high albedo due to snow cover. The study by Enz et al. (11) in western North Dakota supports these statements. Also, the minor diffluence and downslope of the valley under a southerly flow could enhance warming. Since the valley is predominantly agricultural land, small suburban aras probably have no effect on the mesoscale wind flow. Carruthers and Chourlarton (14) modelled the flow of air over low sloping hills under an inversion. The predicted vertical temperature distribution and air flow in some of their models is similar to the observed thermal fields and assumed wind flow of the valley during wind anomaly occurrences.

Hosler (15) studied inversions over the contiguous United States using the Weather Bureau's rawinsonde network. He found that most inversions occur during the fall and winter, but the study was limited by the few observation times and the distance between data points. Enz et al. (11), using instrumented towers designed to study the lower 200 m, monitored inversions over western North Dakota continuously for 4 years. They found inversions to be more common than reported by Hosler, but the distribution throughout the year was similar.

The plumes from NDSU and the sugar beet plant often indicate the internal boundary layer believed to form in conjunction with intense inversions over the valley.

The NDSU plumes may be used only for the lower 300 m AGL because they disperse too rapidly. But because they rise to a greater altitude, the beet plant plumes indicate the wind direction up to 1200 m AGL.

During intense inversions, the emissions from the NDSU stack rise 25 to 50 m and change direction. This indicates an internal boundary layer since the plume doesn't fan out as proposed by Oke (13), but simply shifts in direction while remaining intact (fanning). The beet plant's emissions change direction at a similar level, then rise to an estimated 1200 m AGL before being trapped in the top of the inversion. During this time PIREPS show a steady increase in temperature through 1200 m AGL (Fig. 3).

5. FRONTAL SYSTEM SKIPOVER

When a frontal system or trough of low pressure passes a location without causing a change in wind direction, but a windshift both upstream and downstream of the location occurs, the phenomenon is referred to as "frontal system skipover."

During the night of December 29, 1982, a southerly flow of warm air at the surface produced a warm advection inversion over a large portion of the Northern Plains. PIREPS showed the inversion to be particularly strong over the valley with lapse rates of -10° C/km to -15° C/km. The RAOBs at Bismarck and Huron reflected the inversion also, but the lapse rates were -5° C/km to -10° C/km (Figure 4).

December 30, 1982 was a relatively mild day across the Northern Plains with temperatures in the mid teens. Light snowfall associated with a weak vorticity maximum at 500 mb was forecast to end as a surface trough ushered in a Pacific high-pressure system. At 1500 GMT, PIREPS indicated a strong inversion over the valley. The surface temperature was -15°C, while at 900 m AGL the temperature was -7°C. From 900 to 2500 m AGL, the lapse rate was approximately 3° C/km, well below the dry adiabatic rate of 10° C/km. Surface winds within

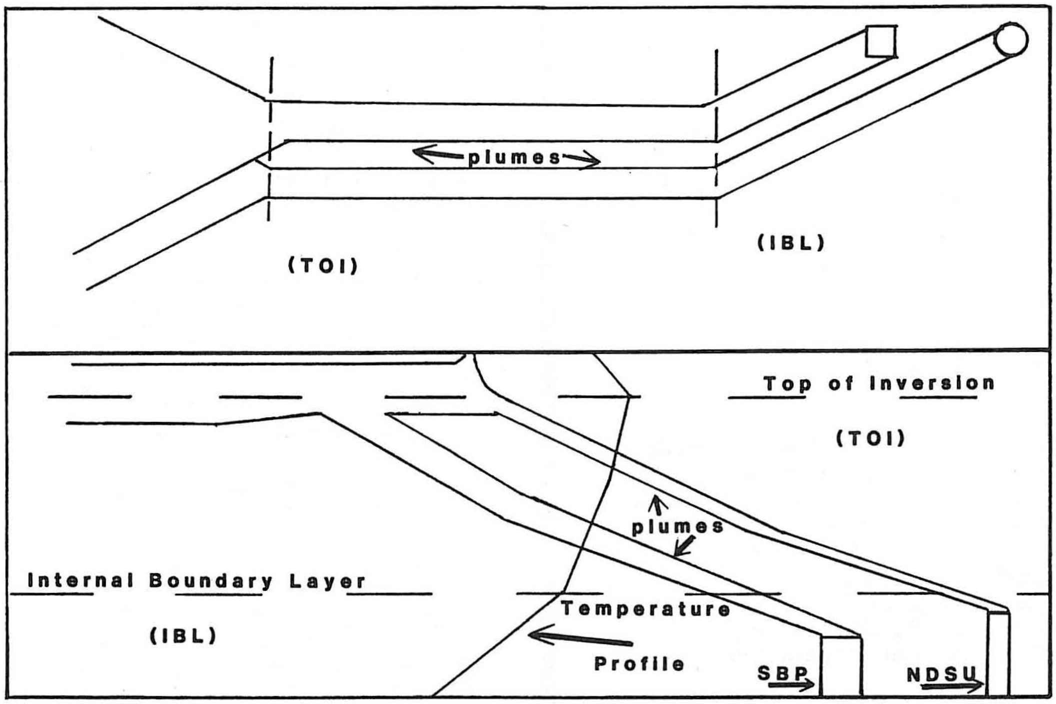

Figure 3. Plume movements through the Internal Boundary Layer (IBL) and the inversion.

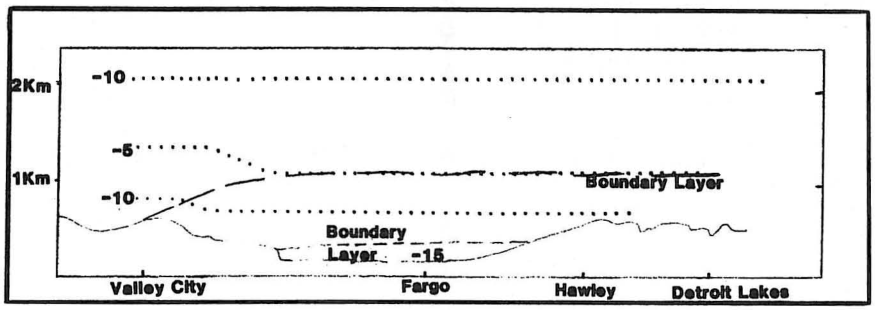

Figure 4. Internal Boundary Layer and vertical temperature distribution over the valley prior to the December 30, 1982, skipover. Dashed lines are the IBLs, and dotted lines are the temperatures every 5°C.

the valley were between 150° and 160° at 1 to 3 m/s. A sharp trough lay across North Dakota along a Bismarck/Minot line and was moving east at 30 km/hr. A modest pressure ridge line was behind the trough moving at a similar speed. The trough was positively tilted; therefore, it passed Devils Lake at 1800 GMT, one hour before passing Jamestown. By use of Local Area Surface Charts (LASCs), the progress of the trough across the State can be shown (Figure 5). At 2100 GMT, the wind shifted to a westerly component at Lidgerwood.

The trough was forecast to cause a shift in the Fargo surface wind between 2300 GMT on December 30 and 0100 GMT on December 31, 1984. However, instead of shifting, the wind at Fargo became calm and the wind at Grand Forks remained light southerly. At 2300 GMT emissions from the NDSU smoke stack and the beet processing plant were observed leaving the stacks at an estimated 230° to 250°, rising a bit, then shifting to 270° to 290°. At 0200 GMT December 31, the surface wind at Alexandria shifted to the west and increased in speed, indicating the front was now east of the valley (Fig. 5).

Since 1982, 12 cases of frontal system skipover have been observed, but only 5 were studied in detail. In all observed cases, strong inversions had formed over the valley during the predawn hours. In the valley, there was a southeast wind flow 2 to 3 m/s greater than surrounding locations.

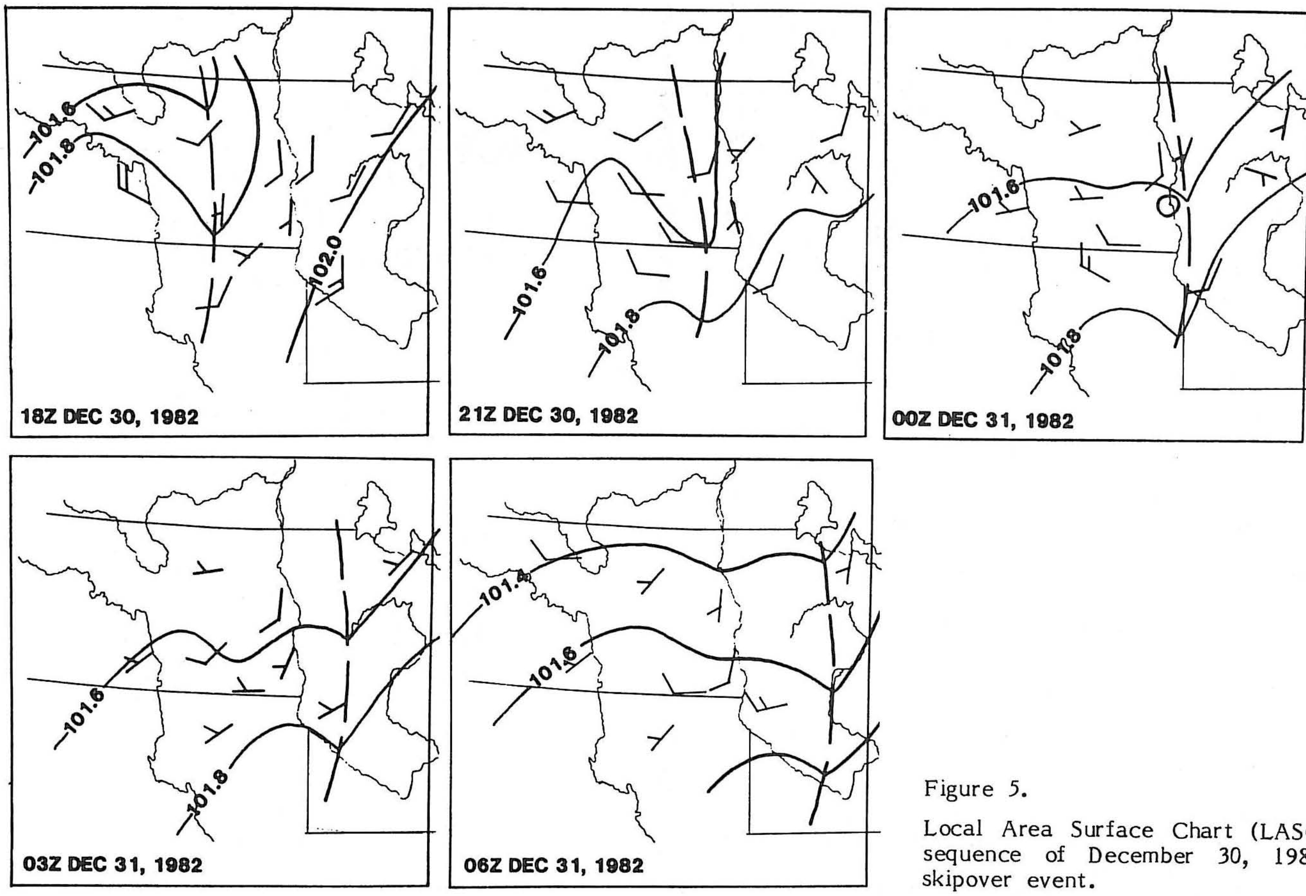

Figure 5.

Local Area Surface Chart (LASC) sequence of December 30, 1982, skipover event.

A cross section of the vertical temperature distribution and assumed boundary layer flow over the valley during frontal skip over episodes is illustrated in Figure 6. Note that the inversion within the valley starts right at or near the valley floor and extends to about 1 km. The wind shift associated with the front cannot affect the surface wind because the lower 100 m are apparently protected by the inversion/internal boundary layer.

The Kindred ridge extends from near Walcott to Valley City, North Dakota. The crest of the Kindred ridge, the top of the NDSU smoke stack, and the crest of the Herman ridge are all at the 300 m above msl level. It is presumed that the internal boundary layer originates at the Kindred and Herman ridge lines (Fig. 6). The westerly flow of air over the Kindred ridge is forced to remain aloft by the stable air below it. A shallow pool of 'cold' air is trapped in the lee of the ridge lines, preventing the wind shift associated with the fronts and troughs from reaching the valley floor. As stated earlier, some temperature measurements in the lower 25 m AGL have shown lapse rates of -25^{o} C/km. This layer of air, though shallow, would have sufficient static stability to preclude turbulent mixing.

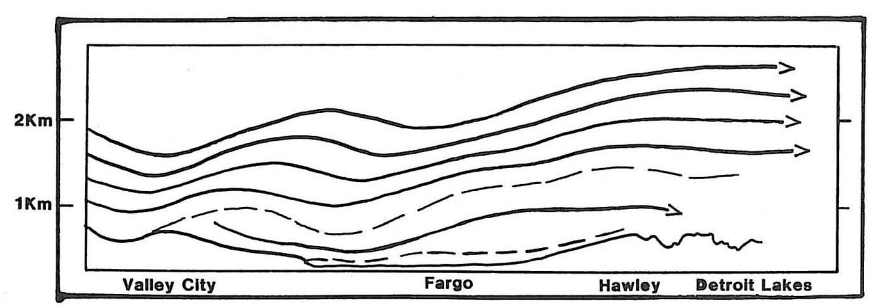

Figure 6. Cross sectional view of the vertical temperature distribution and the Intaernal Boundary Layer (IBL)/Inversion position during the December 30, 1982 skipover. Reconstructed from PIREPS.

As early as 1931, it was shown that turbulent eddies could be completely damped out by an inversion (Durst, (16)). The stable layer of air adjacent to the surface was likened to a 'sticky' compound that resisted mixing due to its higher thermal mass. In the case of the flow within the valley, the inversion is so strong that turbulent eddies are probably damped out before they can initiate sufficient mixing to allow the valley flow to change direction.

Several other theories as to the source of the valley's wind direction anomalies exist; however, they have yet to be tested either mathematically or observationally*

6. RED RIVER VALLEY WIND DIRECTION ANOMALIES

There are times when the surface wind direction within the valley is up to 90° different from that of the reporting stations outside the valley under similar macroscale conditions. This phenomenon is similar to the skipover phenomenon, as it occurs under a strong inversion when the macroscale flow is relatively weak. Unlike skipover, however, wind directions within the valley that are dissimilar to the surrounding region also occur during summer months.

On February 8, 1983, the Dakotas and Minnesota were under the influence of two macroscale systems. One was a high-pressure system centered over Ontario and the other was the lee side trough of the eastern Rockies. At 2100 GMT on February 8, a weak stationary front extended from western North Dakota to northeast Iowa. Much of the upper Plains were under an easterly flow of 5 to 10 m/s (Figure 7), yet the surface flow within the valley was light northerly. The wind direction within the valley continued more northerly than much of the region throughout most of the night time hours. This was also likely due to hydrostatic pumping, or Ekman Spiral distortion, as in the west-to-east flows of valley skipover*. Although several other stations tended towards a northeasterly flow at times, Fargo and Grand Forks favored a more northerly direction.

Figure 8 is the RAOB closeup for 0000 GMT February 9 with a Fargo PIREP for 0100 GMT overlayed. Above 1.5 km AGL, the PIREP and RAOB temperatures are quite similar. While Bismarck's RAOB shows a positive lapse rate followed by an inversion, the Fargo PIREP shows a weak negative lapse rate immediately off surface.

The streamlines, wind speed and relative vorticity for the surface geostrophic level at 0000 GMT February 9, 1983 are shown in Figure 9. Note that the large-scale flow is southeast at 5 to 10 m/s over much of the Northern Plains, and a large portion of the Northern Plains was under negative relative vorticity. As Holton (17) suggested, negative relative vorticity supports divergence at the boundary layer which in turn suggests warming in the boundary layer. At 0000 GMT, near the time of the RAOB, Bismarck was close to the zero relative vorticity line, suggesting slight downward vertical motion. The strong inversion that was present at that time was likely supported by the negative vorticity at the boundary layer top.

In most observed cases of "direction anomaly", the generalized wind flow is east to southeast with wind speed less that 5 m/s. During the winter months, cloud cover is extensive with heights less than 300 m AGL. The time of day is usually not a factor. During the summer months, when weak high pressure covers much of the region, the anomaly frequently occurs at night.

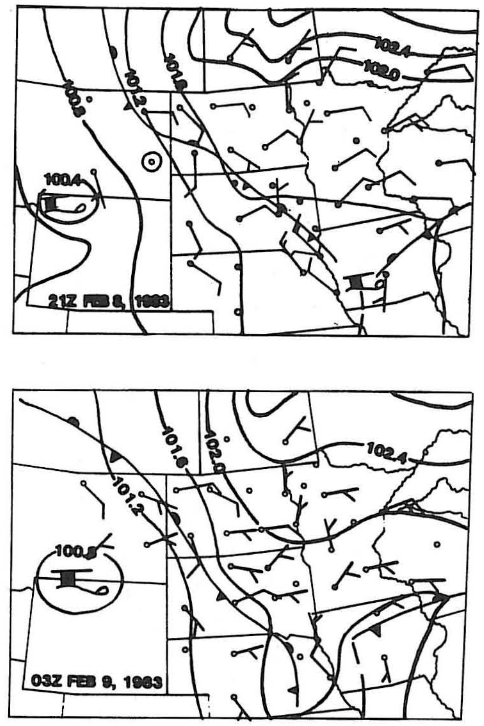

Figure 7. LASC sequence of February 8, 1983, wind deviation event.

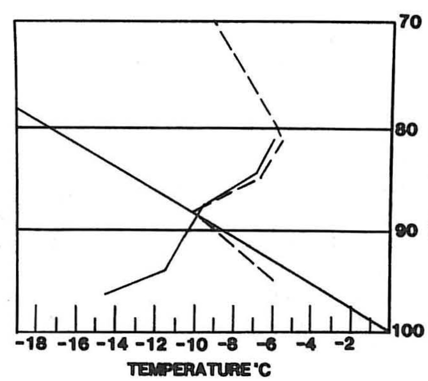

Figure 8. Same as figure 2, except for 00 GMT February 9, 1983.

* Hydrostatic pumping and Ekman spiral distortion are two theories currently under investigation at the University of North Dakota's Center for Aerospace Sciences, Meteorology Department.

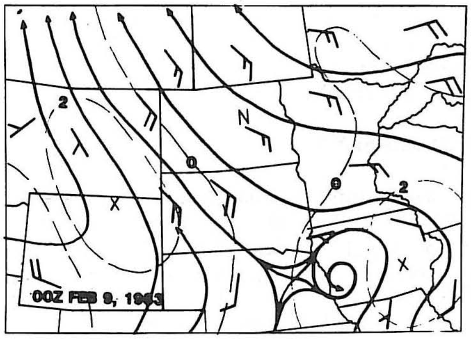

Figure 9. Surface geostrophic wind, relative vorticity, and streamlines for 0000 GMT February 8, 1983. Vorticity centers noted, vorticity in units of 10^{-6} s^{-1}.

7. RED RIVER VALLEY INFLUENCE ON WIND SPEED

On frequent occasions throughout the year, the wind speeds at Fargo and Grand Forks fail to respond to the usual nocturnal decrease common over much of the region. Generally clear skies with less than 2 octals sky cover and low dew points, suggesting excellent longwave radiation loss potential, are found over a large part of the upper plains. Intense temperature inversions are as common as with skipover or direction anomalies.

On September 24, 1983, high pressure was centered over Iowa and low pressure was developing in the lee of the Rockies (Figure 10). Surface wind speeds and directions were fairly uniform over the Northern Plains. As the nighttime-nocturnal inversion formed, surface wind speeds decreased over the region as the surface layer was "uncoupled" from the Planetary Boundary Layer (PBL) flow. However, at Fargo and Grand Forks, the wind speeds increased to 8 m/s (Figure 10). By 1100 GMT September 24, the highest wind speeds in the tri-state region were found in the valley. The strongest surface geostrophic wind speed was east of the valley in a band from southeast South Dakota to central Minnesota.

Blackadar (18) illustrated the connection between the low-level jet maximum and the nocturnal inversion growth. Sangster (19) viewed the relationship between the diurnal variation in the surface geostrophic wind speed and the diurnal temperature variation in the boundary layer. Although minor topographic features were termed negligible, the overall slope he described (1:500) is very similar to the slope of the valley.

As the inversion over the valley intensified, the wind speed in the boundary layer intensified due to the increase in the thermal gradient. Although not likely the main cause for the high winds in the valley, the low-level jet maxima may directly influence the valley's wind speed. Hoecker (20) studied three types of low-level jet systems using the pibal network of the U.S. Weather Bureau. Rider and Armendairez (21) discussed three types of inversion/low-level jet episodes over the White Sands

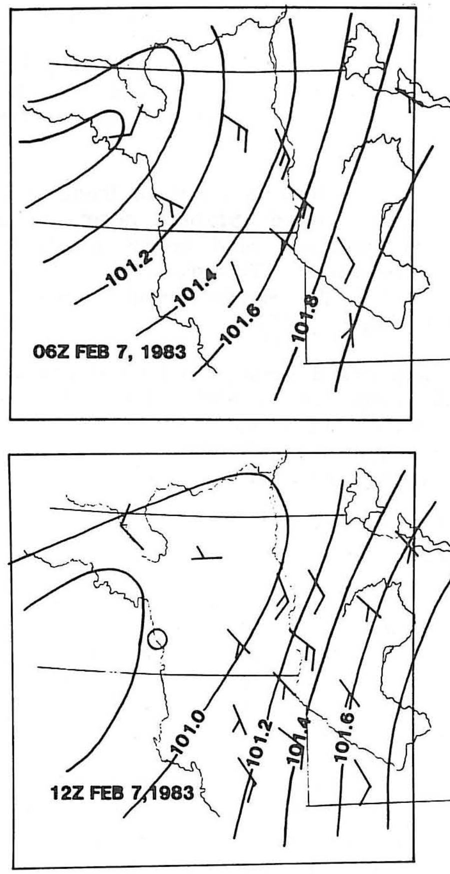

Figure 10. LASC sequence for the September 7, 1983, windspeed deviation event.

Missile Range. In both studies, the low-level wind maximum was at or just above the inversion top. They also supported Blackadars' findings that the low-level jet is supergeostrophic. Very steep negative lapse rates below the wind maximum were discovered, and the low level jet was theorized to assist the growth of the nocturnal inversion through long-wave radiation transfer and friction.

Higher wind speeds in the valley are a common occurrence, especially with a southerly flow. Since the wind speed at Lidgerwood, North Dakota, remained significantly lower than at Fargo, it is suggested that a strong, shallow inversion was present as in skipover/deviation cases. The only evidence on this, however, is that the temperature in the valley remained 2^{o} to 4^{o}C higher than the surrounding areas during this occurrence. Unfortunately, no PIREPS were available at the time.

The surface wind speed may closely reflect the low-level jet maxima speed because of the low surface roughness of the valley. Since most inversions apparently start at the surface, a wind field as described by Blackadar may apply. The low-level jet maxima may be close enough to the surface to exert a significant influence on the wind speed.

Climatology is important to operational meteorology because it can sometimes identify trends in local weather patterns. In the case of the valley, climatology shows that surface wind speeds within the valley are about 20% higher than those of adjacent portions of the Northern Plains. This is a significant long-term difference, and was discussed in the Battelle (22) study on wind power over the Northern Plains.

Hosler (15), while studying inversion frequency within the contiguous United States, notes a distinct nighttime maximum for wind speeds greater than 7 mph within the valley. This maximum was especially prominent during the summer months, with a 70% occurrence rate.

At Fargo and Grand Forks, the frequencies of north and south winds are almost equal, blowing from north to south about 40% of the time. Least favored directions — east and west — occur most commonly during periods of light winds (Table 2).

8. WIND ANOMALIES — GENERAL SYNOPTIC CONDITIONS

As alluded to previously, while nocturnal inversions occur everywhere, the Red River Valley of the North seems to have a high degree of inversion persistence. Out of 24 inversions studied in detail, all were more intense and persistent than those at the surrounding rawinsonde stations.

The overall topography of the valley also suggests that shape and orientation have a great deal to do with observed wind anomalies. The valley, although shallow, is long and narrow. This configuration seems to favor both inversion persistence and the wind anomalies that occur.

During the winter, ground blizzards often strike the Northern Plains. The funnelling effect is quite pronounced; visibility due to blowing snow is drastically reduced within the valley. At locations immediately outside the valley, however, the visibility is usually much higher.

Some doppler radar research done during ground blizzards caused by fast moving cold fronts and very tight gradients strongly support the funnelling effect (Osborne, Hembre (23)).

Frontal system skipover, wind direction deviation and wind speed deviations are all apparently associated with 1) strong persistent temperature inversions; 2) the shape and orientation of the valley; and 3) the overall low surface roughness of the valley floor.

9. CONCLUSIONS

Using case study approaches, it was shown that the Red River Valley of the North has a significant effect on local winds. Wind shifts associated with frontal systems and troughs often do not occur at locations within the valley. This is true most frequently from late fall through early spring.

During periods of light macroscale winds, the surface wind direction within the valley is often vastly different from surrounding locations, favoring northerly or southerly directions. This anomaly has been observed in all seasons, but is most common during the winter months.

Under strong gradient situations, the surface wind direction within the valley strongly favors a direction approximately parallel to the valley walls at that location. The climatological average at Fargo for southerly wind flows of 5 m/s or higher is 160°; for northerly wind flows of equal strength it is reversed at 340° Weak pressure gradient flows are usually east/west in nature.

Long-term measurements show that the wind speed within the valley is 20% higher than surrounding locations. In addition, the wind speed within the valley often does not follow the usual diurnal fluctuation common in the surrounding areas. The wind often remains 2 to 3 m/s higher than adjacent areas.

In cases studied, the wind anomalies occurred only when intense inversions were present over the valley. The local topography apparently favors the occurrence of a boundary layer/inversion combination so stable and so near the surface it causes frontal systems to skip over the valley.

Much more research is needed within the confines of the Red River Valley of the North. The observational data and arguments presented here are sufficient only to spark the interest needed to further study the valley and its environs.

NOTES AND REFERENCES

1. Mark E. Ewens is a Meteorological Technician with the National Weather Service in Fargo, ND. He has 11 years experience in operational meteorology; the last 3 years as a Met Tech, and 8 years in the Air Weather Service specializing in Army Weather Support and Mobil Rawinsonde.

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LOCATION	TYPE
FARGO ND	WEATHER SERVICE OFFICE
INTERNATIONAL FALLS MN	WEATHER SERVICE OFFICE
HURON SD	WEATHER SERVICE OFFICE
SAINT CLOUD MN	WEATHER SERVICE OFFICE
BISMARCK ND	WEATHER SERVICE FORECAST OFFICE
JAMESTOWN ND	FLIGHT SERVICE STATION
ALEXANDRIA MN	FLIGHT SERVICE STATION
WATERTOWN SD	FLIGHT SERVICE STATION
ABERDEEN SD	WEATHER SERVICE OFFICE
THIEF RIVER FALLS MN	SUPPLEMENTARY AERONAUTICAL WEATHER
DEVILS LAKE ND	REPORTING STATIONS (SAWRS)
DEVILS LAKE ND	AUTOMATIC METEOROLOGICAL OB SITE
LIDGERWOOD ND	REMOTE AUTOMATIC METEOROLOGICAL OB SITE

Table 1. List of primary stations and station type used in this study.

FARGO			GRAND FORKS		
DIRECTION	FREQUENCY %	SPEED m/s	DIRECTION	FREQUENCY %	SPEED m/s
N	14	6.1	N	16	6.0
NNE	5	5.0	NNE	4	4.7
NE	4	4.5	NE	2	3.9
ENE	3	4.4	ENE	2	3.1
E	4	4.2	E	4	3.2
ESE	4	4.5	ESE	3	3.7
SE	5	5.0	SE	4	4.1
SSE	10	6.2	SSE	7	5.0
S	15	5.9	S	13	5.0
SSW	4	5.0	SSW	5	4.2
SW	4	4.6	SW	4	3.9
WSW	3	4.5	WSW	4	4.0
W	5	4.7	W	8	4.5
WNW	5	5.2	WNW	7	5.1
NW	7	5.9	NW	7	5.3
NNW	8	6.0	NNW	10	5.9

Table 2. Directional frequency of wind speed category for Fargo and Grand Forks. Fargo period of record 1953-1978; Grand Forks 1949-1968 (Battelle; and all stations 1978-1983, NCDC).