A Case Study of a Bora-Like Windstorm in Western Washington

RICHARD J. REED

Department of Atmospheric Sciences, University of Washington, Seattle 98195

(Manuscript received 16 April 1981, in final form 20 July 1981)

ABSTRACT

This paper examines the meteorological conditions and physical processes associated with the development of strong downslope winds that caused extensive property damage in two areas of western Washington on 28 November 1979. These areas were located downwind of the two largest and lowest passageways through the Cascade Range: the Columbia River Gorge and the Stampede Pass region. Findings are as follows:

1) The destructive winds, marked by gusts of 25–30 m s^{-1}, appeared in conjunction with the formation of a deep cyclone offshore and the simultaneous development of an unusually powerful anticyclone inland.
2) The pressure gradient was greatly enhanced in the vicinity of the mountain range attaining values as large as 12 mb $(100\ km)^{-1}$.
3) Hydrostatically, the large pressure differences can be attributed to the effect of the barrier in separating cold air on the east side from warmer air on the west.
4) Trajectory tracing revealed that the temperature difference formed rapidly as a result of the presence of strong subsidence on the lee side and the absence of low-level subsidence in the confined, inland basin on the windward side.
5) The undisturbed flow normal to the barrier ranged from light easterly at lower levels (5–10 m s^{-1} at most), to zero in the layer between 600 and 700 mb, to light westerly above.

Calculations are carried out to demonstrate that the wind speeds were consistent with the observed pressure differences. The large-scale pressure gradient was well predicted 36 h in advance by the limited-area fine-mesh model (LFM) of the National Meteorological Center.

1. Introduction

Strong, gusty winds hurtling down from the Cascade Range caused extensive property damage and widespread power outages in the lowlands of western Washington during a 36 h period beginning in the late evening of 27 November 1979. The hardest hit area was contained in the polygon shown on the topographical map of the State of Washington appearing in Fig. 1. Within this area damage, caused mainly by falling trees, was estimated to amount to hundreds of thousands of dollars. More than 8000 homes suffered temporary loss of electric power at some time during the storm.

From newspaper reports and a specially conducted survey it appeared that the severest damage occurred in four localities, numbered 1 to 4 in Fig. 1. Three of these localities are situated near the mouths of river valleys. At point one, in southeast King County, about two dozen homes were struck by falling trees. At Enumclaw, position 2, near the mouth of the White River valley, a building under construction was blown down and a wall of a junior high school was cracked. At position 3, at the outlet of the Green River Valley, a barn roof was blown off, a fence toppled and windows blown out. Shingles were ripped from new homes and trees were downed near North Bend, position 4. The openings of Cedar River valley and the valleys of the middle and south forks of the Snoqualmie River are situated in the vicinity.

The only official wind measurements taken in the area were made at Renton Airport (RNT), located at the outer edge of the damage zone. There the peak gust was 23 m s^{-1}. An unofficial measurement, made by a hand-held anemometer at Enumclaw, yielded sustained speeds of 22–24 m s^{-1} and gusts of 30 m s^{-1}.

Although the windstorm of 28 November 1979 was unusually severe, similar storms occur in the area on one or more occasions during most winters. It is worthy of note that under conditions of easterly flow this area lies downwind of the largest and lowest passageway through the Cascades north of the Columbia River gorge (see Fig. 1). The three passes in this outlet region, Snoqualmie, Stampede (SMP) and Green, lie at elevations of 916, 1160 and 1491 m, respectively. Since the second of these passes provides the broadest and least obstructed outlet, we will, for the sake of simplicity, refer to the complex

0027-0644/81/112383-11$06.75

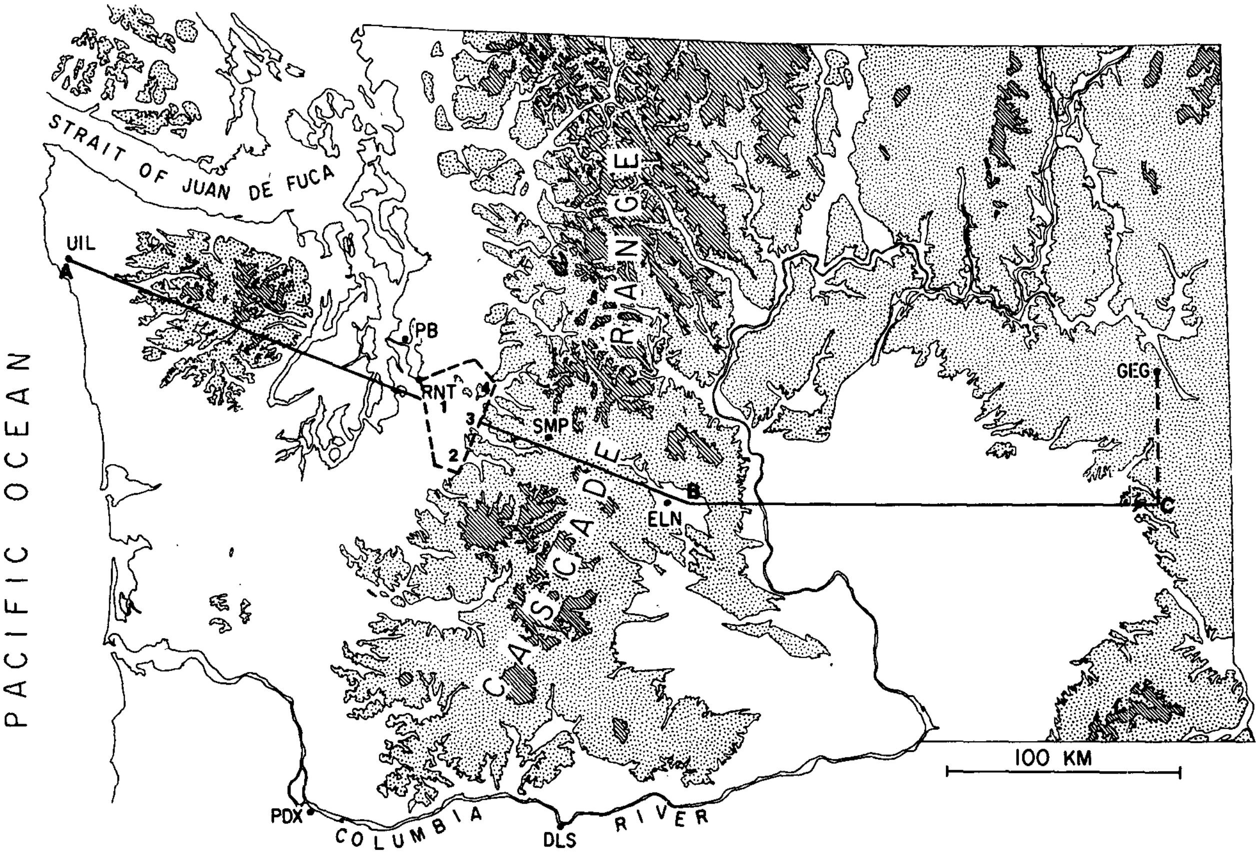

FIG. 1. Topographical map of the State of Washington. Stippled area: above 2000 ft. Hatched area: above 5000 ft.

as Stampede Pass in future discussions. Both Stampede Pass and the Columbia gorge connect the lowlands of western Washington to a large interior basin that lies below 610 m in elevation (Fig. 1).

The area about Portland, Oregon (PDX), near the mouth of the Columbia River Gorge, also sustained wind damage during the period. At nearby Clark County Airport in Orchards, Washington, four airplanes were wrecked when torn loose from their moorings by strong gusts. The peak gust recorded at Portland International Airport was 26 m s^{-1}. Sustained winds reached 17 m s^{-1}. Much stronger winds are known to occur on similar occasions within the gorge itself. Cameron and Carpenter (1936) report an instance when hourly wind speeds attained 26 m s^{-1} and peak gusts reached 35 m s^{-1} at Crown Point, located 38 km to the east of Portland. Cameron (1931) earlier reported a case in which an even stronger gust occurred (53 m s^{-1}).

The purpose of this paper is to document the meteorological conditions that gave rise to the extreme winds and to examine the physical mechanisms involved in their formation. As the title suggests, the winds are believed to belong to the category of cold, downslope wind known as the bora.

2. Synoptic description

a. Large-scale development

The large-scale synoptic situation associated with the formation of the strong downslope winds is illustrated by the sequence of surface, 850 mb and 700 mb charts shown in Fig. 2. The maps, displayed at 24 h intervals, cover the period from 48 h in advance of the wind event to the hour when the winds were at their strongest.

The surface map for 1200 GMT 26 November (Fig. 2a) shows a weak high pressure area with central pressure of 1025 mb approaching the State of Washington from the eastern Pacific. A developing low pressure system is located to the west of the high at 30°N, 151°W. A frontal trough lies to the north of the low and a cold, non-frontal trough is situated behind the front. An explosive deepening of the low occurred during the subsequent 24 h period (Fig. 2b) as it moved northward and interacted with the middle latitude system. The downstream high also intensified markedly and moved inland over British Columbia. By the time of the strong winds, the high had advanced somewhat further eastward and had reached its maximum strength of 1050 mb (Fig. 2c). The offshore low at that hour was north and west of its earlier position and beginning to fill. Ahead of the approaching cold front, pressures were falling slowly and a pressure gradient of moderate strength prevailed along the coast.

The 850 mb maps (Figs. 2d–2f) displayed a corresponding sequence of events. Ahead of the developing ridge, light northerly winds carried cold air into the State of Washington on the 26th and the early part of the 27th. By 1200 GMT on the 28th the ridge had moved eastward to Idaho and western Montana and southeasterly winds prevailed over the State. Wind speeds were light in eastern Washington, where temperatures remained low, and moderate west of the Cascades where temperatures rose sharply.

The extreme amplification of the flow pattern during the course of the 48 h period is well illustrated by the 700 mb charts (Figs. 2g–2i). By 1200 GMT on the 28th an unusually strong ridge was situated directly over the State. Cold northerly winds that prevailed early in the period had been replaced by light winds from the east-northeast in eastern Washington and light south-southeasterlies near the coast. Temperatures had risen everywhere but more pronouncedly to the west of the Cascades. It is apparent from even the crudest estimates of air trajectories that the general warming at 700 mb and the strong warming west of the mountains at 850 mb resulted from subsidence.

On the 500 mb map for 1200 GMT 28 November (not shown), the ridge was still west of the region, and winds were light westerly. The reversal from an easterly to a westerly wind component took place between 700 and 600 mb. Thus the wind flow normal to the mountain barrier varied from light easterly (5–10 m s^{-1}) in the lower troposphere to near zero in the middle troposphere to weak westerly above.

b. Regional maps

A more detailed view of the conditions associated with the windstorm is afforded by the surface, 850 and 700 mb maps for 1200 GMT 28 November appearing in Figs. 3–5.

The outstanding feature of the surface map (Fig. 3) is the extremely large pressure gradient in the vicinity of the Cascade Range. For the most part this gradient is fictitious, merely indicating that the mountain barrier sustained a large pressure difference between the cold air in central and eastern Washington and the air of milder temperature that covered western Washington. In the Columbia River Gorge, where the elevation at The Dalles (DLS) is only 74 m, the gradient is real and reached an extreme value at 1800 GMT of 13.5 mb over the 110 km distance between Portland (PDX) and The Dalles. The damaging winds that struck Portland and nearby areas are easily accounted for by a pressure gradient of such large magnitude, as will be shown subsequently. Clearly, such a gradient could not have formed were it not for the barrier provided by the mountain range.

In eastern Washington light northerly winds generally prevail. At the foot of the Cascades winds are light westerly at Wenatchee (EAT) and Yakima (YKM) suggesting a low-level blockage of the prevailing easterly flow and the formation of a return flow near the surface. Associated with this phenomenon is a thin wedge of high pressure banked against the range. The wind at Stampede Pass is east-southeast 11 m s^{-1} (22 kt) gusting to 17 m s^{-1} (33 kt). West of the Cascades winds are light and variable nearly everywhere. Exceptions occur in the aforementioned area of wind damage, at Hoquiam (HQM) near the coast, in the Strait of Juan de Fuca around Race Rocks (RR) and in the Fraser River Valley near Abbotsford (YXX).

Conditions at 850 mb are shown in Fig. 4. Areas where the 850 mb surface is below the earth's surface are blacked out. To aid in the analysis, estimates of temperature and geopotential height were made in six locations. These are Redmond, Oregon (RDM), The Dalles, Oregon (DLS), 10 km east of Ellensberg, Washington (ELN), Stampede Pass, Washington (SMP), the foothills (FT) of the Cascades between Stampede Pass and Seattle, Washington (PB) and Hope, British Columbia (YHE). The estimates are based on artificial soundings constructed from the following information: 1) surface pressures obtained from reported altimeter settings and the known elevations of the stations (or in the case of Ellensberg and the foothill station on interpolated altimeter settings). 2) Reported surface temperatures [or in the case of Ellensberg an interpolated temperature and in the case of the foothills station the surface temperature given by a later cross section analysis (Fig. 7)]. 3) Interpolated 700 mb temperatures and heights obtained from the analysis shown in Fig. 5. The fields at this level are sufficiently simple that high confidence can be placed in the interpolated values provided the weak easterly flow did not produce a significant temperature perturbation in the vicinity of the mountain range. 4) Shapes of the temperature profiles at the radiosonde stations. The procedure involved plotting the temperature and pressure at the bottom of the sounding and the temperature at the top (700 mb), drawing a profile whose shape agreed with the shapes at nearby stations and adjusting the shape until the

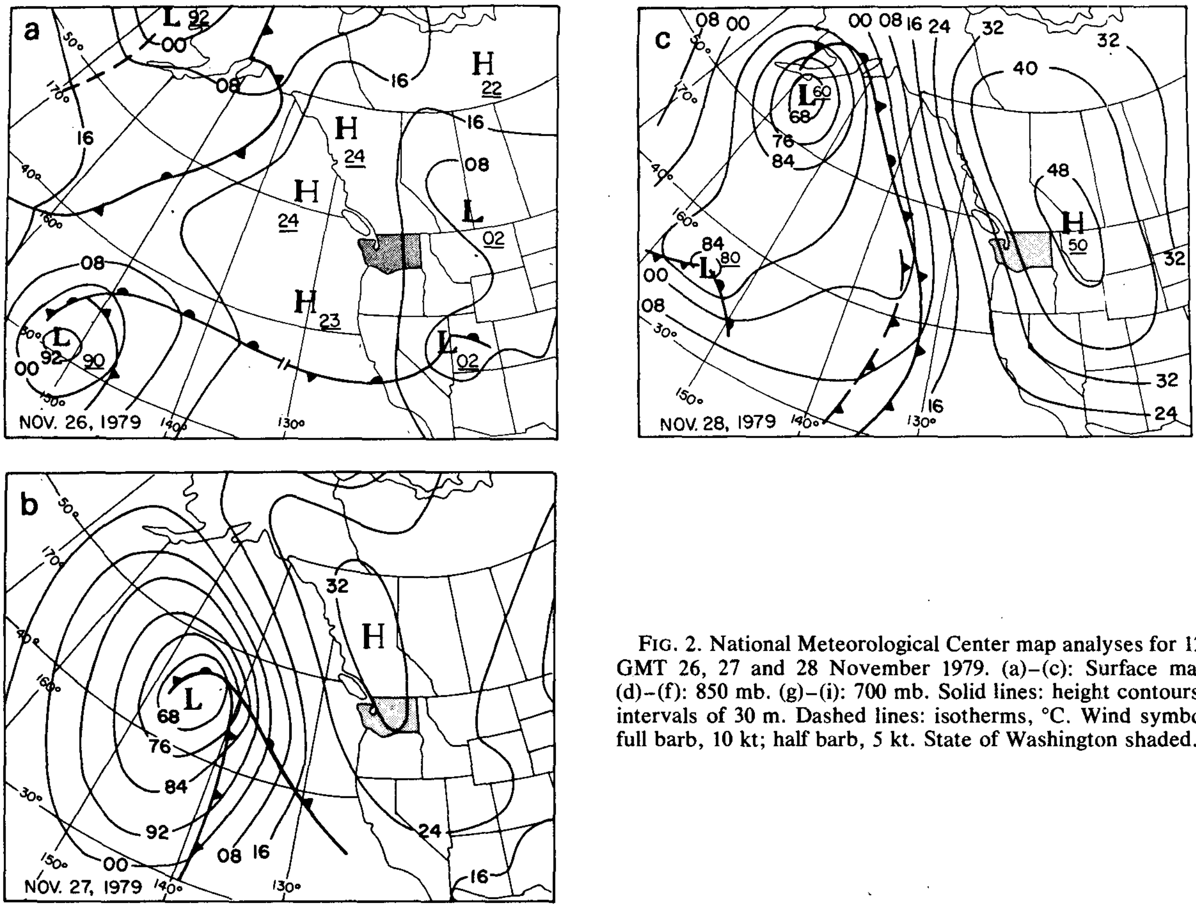

FIG. 2. National Meteorological Center map analyses for 1200 GMT 26, 27 and 28 November 1979. (a)–(c): Surface maps. (d)–(f): 850 mb. (g)–(i): 700 mb. Solid lines: height contours at intervals of 30 m. Dashed lines: isotherms, °C. Wind symbols: full barb, 10 kt; half barb, 5 kt. State of Washington shaded.

mean temperature in the column yielded, with use of the hydrostatic equation, the difference between the assumed 700 mb height and the known surface elevation. Although this procedure does not allow a unique determination of the 850 mb temperatures and heights, it was found that there existed only a narrow range of values at a given station that satisfied the foregoing conditions.

From the contour analysis in Fig. 4 it is seen that a region of enhanced pressure or contour gradient also exists at the 850 mb level in the vicinity of the Cascades. Between The Dalles and Portland the gradient is roughly half that at 1000 mb, attesting to the reduced but not inconsequential barrier effect that occurs at the higher level. Southeasterly winds of 5–10 m s^{-1} velocity prevail at interior locations. An acceleration takes place in the vicinity of Stampede Pass, as shown by the plotted wind speed of 18 m s^{-1}. This speed is an estimate based on the assumption that the peak gusts reported at the surface (1210 m) are representative of the sustained wind speed at 850 mb (1617 m). It appears that the easterly winds caused a lifting of the air along the east slope of the Cascades, despite the large static stability, so that coldest temperatures are found in and to the east of the pass. A rapid warming takes place on the lee slope that obviously must be attributed to subsidence. The persistence of cold temperatures in the Cascade passes during periods of offshore flow in winter is a well-known phenomenon that sometimes produces freezing rain and on other occasions allows precipitation to persist as snow after a change to rain has occurred at higher elevations.

West of the Cascades winds are southeasterly increasing from 5 m s^{-1} in the south to 15 m s^{-1} in the north. The 15 m s^{-1} speed at Portage Bay (PB), Seattle, is probably super-geostrophic in view of the lesser speeds at Salem, Oregon (SLE) and Vancouver, British Columbia (YVR) located at almost equal distances from the Cascades but outside the region of extreme winds.

The 700 mb chart appears in Fig. 5. The flow is generally weak at this level with light easterly winds occurring over the north Cascades of Washington and light westerlies over the south Cascades. As judged by the large-scale flow, the wind is nearly calm above Stampede Pass.

c. *Soundings*

Soundings taken at 1445 GMT 28 November at Portage Bay, Seattle, located 50 km west of the Cas-

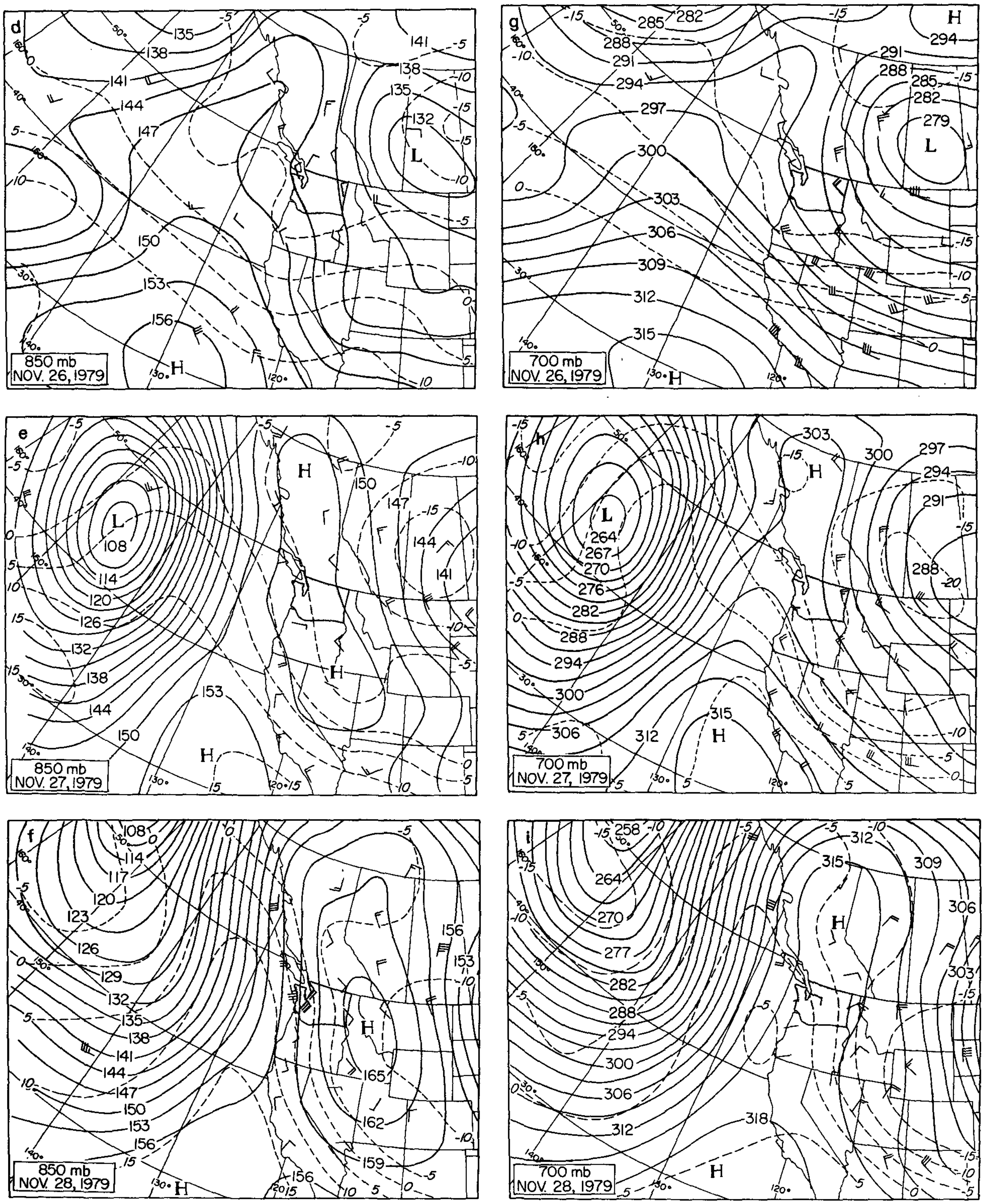

FIG. 2. (*Continued*)

cades, and at 1200 GMT at Spokane, located 200 km to the east (station GEG in Fig. 5), are shown in Fig. 6.

An important feature of the soundings is the inversion layer in the 281–298 K potential temperature range. The layer is located between 800 and 700 mb on the upwind side of the mountain range and between 900 and 800 mb on the downwind side.

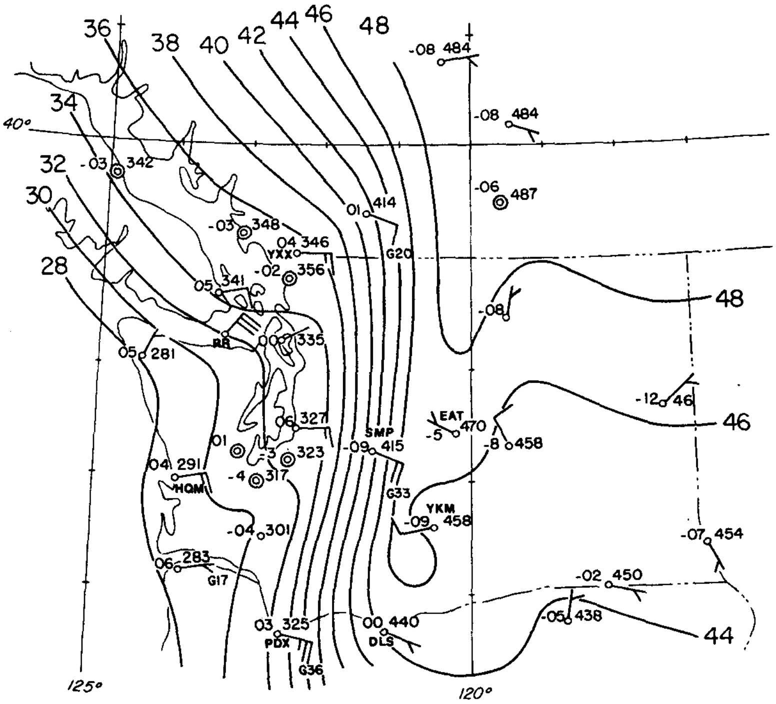

FIG. 3. Surface map, 1200 GMT 28 November 1979. Isobars drawn at intervals of 2 mb. Winds plotted as in Fig. 2. Pressure (mb) plotted to right of station; temperature (°C) to left.

Above and below the inversion layer, lapse rates are close to standard values. Nocturnal inversions exist near the surface and minor inversions of unknown origin near the 300 K potential temperature level. Brunt-Väisälä frequencies in the upstream sounding at Spokane are respectively 1.0×10^{-2} s^{-1}, 2.9×10^{-2} s^{-1} and 1.2×10^{-2} s^{-1} in the layer below the elevated inversion, in the inversion layer and in the layer above the inversion.

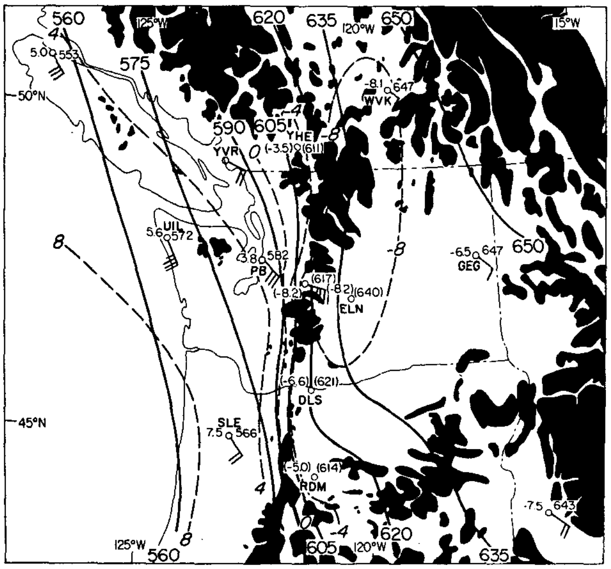

FIG. 4. 850 mb map 1200 GMT 28 November 1979. Area above 1524 m (5000 ft) blacked out. Solid lines, geopotential height contours at 15 m intervals. Dashed lines, isotherms (°C). Geopotential height plotted to right of station. Data from artificial soundings (see text) shown in parentheses. See Fig. 2 for further explanation.

Winds at Spokane were light easterly up to 800 mb, effectively the height of the Cascades. Above this level winds strengthened and backed to northerly. As shown by the 700 mb map (Fig. 5), it is unlikely that the northeasterly current of 10 m s^{-1} at 700 mb maintained this strength as far west as the Cascades.

The wind sounding for Seattle reveals a large increase in speed up to the 4000 ft (1220 m) level and a large veering of direction between 1000 ft (300 m) and 6000 ft (1830 m). As remarked previously, the wind speed at (and just below) 850 mb is believed to be supergeostrophic because of the acceleration of the airflow over the Cascades. The large veering reflects the antitriptic nature of the flow in the near surface layer.

Above 800 mb winds back with height and become light. Since the synoptic maps are characterized by cold advection at higher levels, the backing is believed to indicate the existence of at least approximate thermal wind or geostrophic wind balance above the level of the mountain tops.

To a first approximation the temperature sounding for Seattle appears to be a downward displaced version of that for Spokane. This suggests a common origin for the features, in particular for the

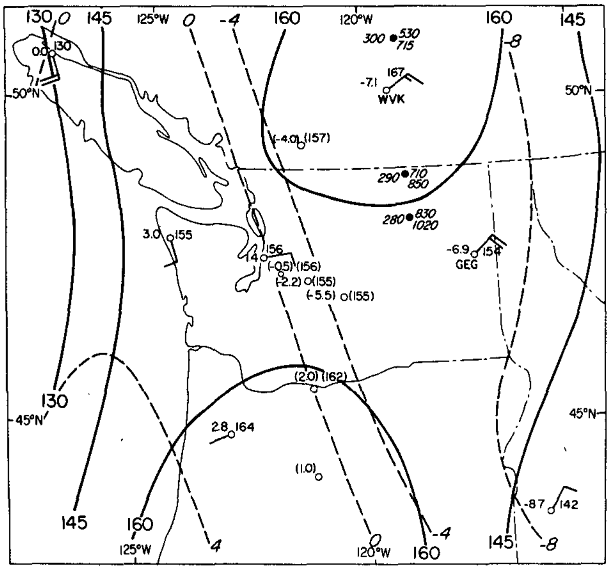

Fig. 5. 700 mb map 1200 GMT 28 November 1979. Starting points, at 0000 GMT 28 November, of trajectories reaching Seattle at 1200 GMT 28 November are indicated by the pertinent potential temperatures (left of solid circles). Beginning (above) and ending (below) pressures.

major inversion layers in the 281–298 K potential temperature range. It is thus of interest to examine soundings in the upstream flow at an earlier time. Trajectories constructed on the 280, 290 and 300 K isentropic surfaces reveal that the air reaching Seattle at 1200 GMT 28 November was located in the region between Spokane and a position somewhat north of Vernon, British Columbia (station WVK in Fig. 5), at 0000 GMT. The temperature soundings for these stations at that hour are shown in Fig. 7, and the starting points of the trajectories are indicated on Fig. 5. The later sounding for Spokane is repeated for convenience. It is apparent that the main inversion layer had already commenced to form at Vernon by 0000 GMT but not at Spokane.

The physical origin of the layer can be understood by reference to the 1200 GMT Spokane sounding repeated in Fig. 7. Subsidence is indicated above the 750 mb level, close to the mean level of the mountain tops in the surrounding area. Little, if any subsidence occurs below this level. It therefore seems likely that the formation of the inversion can be explained by the ability of the air aloft to subside while that below was constrained by the mountain barriers from spreading out. It has been assumed in presenting the above argument that the sounding for Vernon and the earlier sounding for Spokane are representative of conditions upstream from Spokane. Trajectories reveal that the air reaching Spokane had its origin between these stations and Edmonton, Alberta, but sufficiently close to Vernon and Spokane to regard their soundings as applicable.

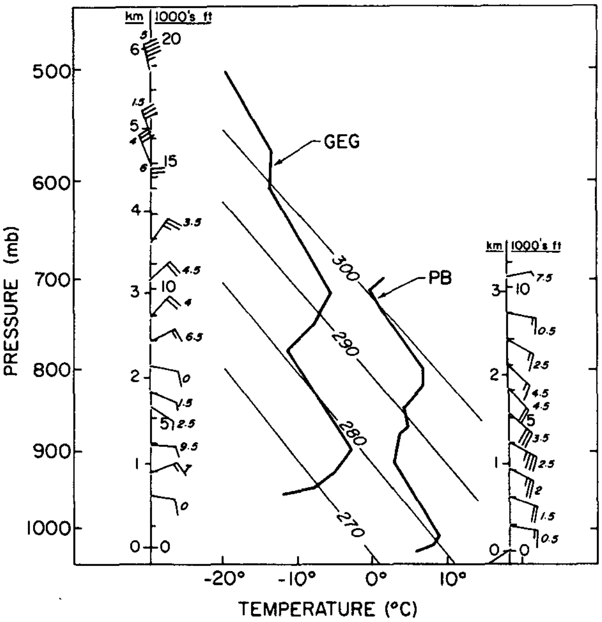

Fig. 6. Temperature and wind soundings for Portage Bay, Seattle, (PB), and Spokane (GEG) at 1445 and 1200 GMT 28 November 1979. Winds in knots: full barb, 10 kt; half barb, 5 kt. Wind direction in tens of degrees with hundreds digit omitted is plotted at end of barb. Slanted lines are dry adiabatics labeled in K.

d. Cross sections

Figs. 8 and 9 depict cross sections for 1200 GMT 28 November of potential temperature and deviation of geopotential height from standard atmosphere values along the lines *AB* and *BC* in Fig. 1. Topographical features are depicted by shading and by

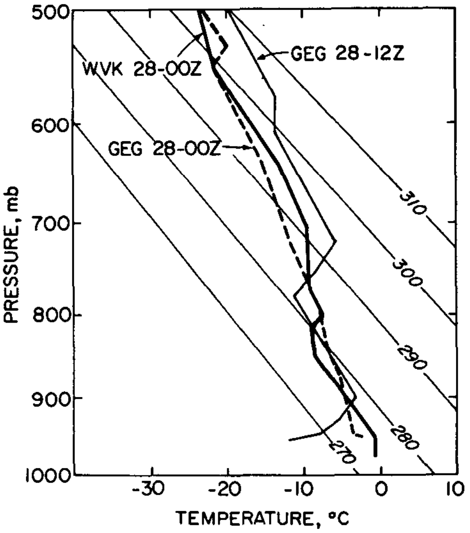

Fig. 7. Temperature soundings for Vernon, British Columbia (WVK), solid line, and Spokane, Washington, (GEG), dashed line, at 0000 GMT 28 November 1979. Also shown is Spokane sounding for 1200 GMT 28 November (thin solid). Slanted lines are dry adiabatics, labeled in K.

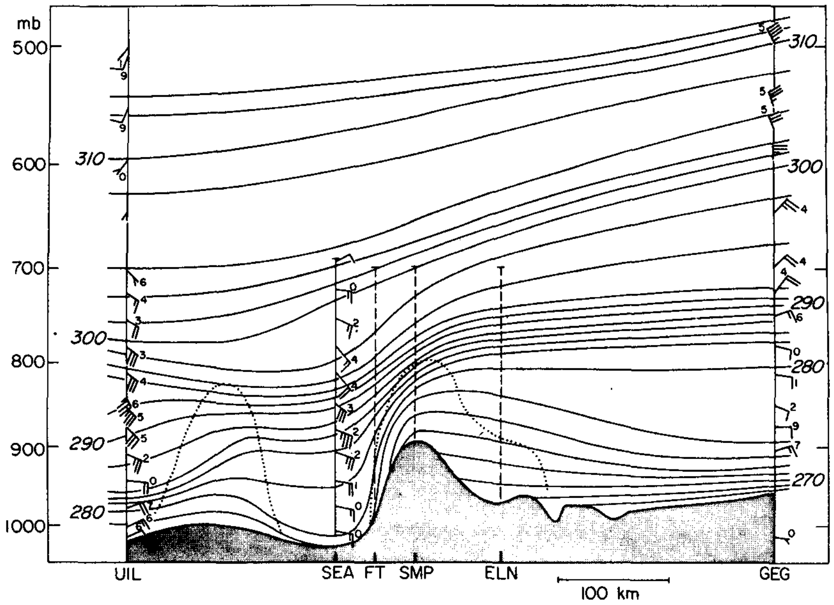

FIG. 8. Cross section of potential temperature (K) along line segments *AB* and *BC* in Fig. 1. Winds are in knots. Full barb: 10 kt; half barb: 5 kt. Dashed vertical lines represent artificial soundings. For further explanation see text.

dots. The upper boundary of the shaded region indicates the level below which no passage of air is permitted in the vicinity of the section (except for the possible passage of a small volume of air at levels between 900 and 925 mb in Snoqualmie Pass). The dots are based on smoothed contours of gross summit topography, defined as the mean altitude of the three highest peaks in 7.5 min quadrangles (areas of 130 km^2) (Porter, 1977, Fig. 1). Above this altitude the air can move relatively unimpeded. Below it the airflow is increasingly blocked until the level of the shading is reached and the obstruction is complete. In analyzing the cross section, soundings for Quillayute (UIL), Portage Bay (PB) and Spokane (GEG) were projected onto the line segments *AB*, *BC* and use was made, as well, of the above-de-

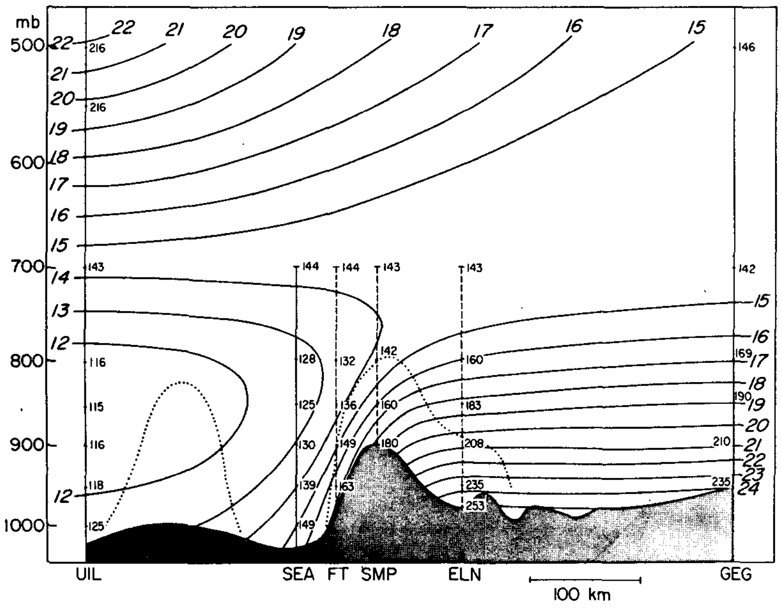

FIG. 9. Cross section of deviation of geopotential height from standard values in units of decameters.

scribed artificial soundings for the foothills, Stampede Pass and Ellensberg. The principle was followed of keeping the structure simple between observation points.

The potential temperature cross section reveals the aforementioned bulging up of the isotherms or cooling along the windward (east) slope of the Cascades. It also reveals the intense horizontal temperature gradient that develops over and to the lee of the mountains as the upper level inversion tilts and lowers in the subsiding air flow. The geopotential deviation likewise displays a strong horizontal gradient in the vicinity of the mountains, in keeping with the essentially hydrostatic nature of the flow.

3. Discussion

From the foregoing analyses it is seen that the destructive winds of 28 November 1979 were connected with a large pressure difference that existed across the Cascade Range at the time of occurrence. The pressure difference developed in conjunction with an unusually strong anticyclogenesis in and to the east of the region and cyclogenesis in the offshore region. Hydrostatically the concentration of the pressure gradient in the vicinity of the range can be explained by the effect of the mountain barrier in separating cold, dense air on its east side from relatively warm air on its west side. The damming effect of the barrier inhibited low-level subsidence in the interior basin thus maintaining cold temperatures on the east side. The warmer air in the coastal lowlands resulted from subsidence heating of cold air from aloft that only a short time earlier had been located over the interior. The basic easterly current upstream of the mountain range did not exceed 10 m s^{-1} at any level and extended to a depth of only 4 km.

It is of interest to inquire whether the observed pressure gradients were sufficiently strong to account for the extreme velocities observed at the mouth of the Columbia River gorge and in the lowlands to the west of Stampede Pass. For frictionless flow constrained in a channel the equation of horizontal motion can be written

$$\frac{du}{dt} = \frac{d}{dx}\left(\frac{u^2}{2}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x}, \qquad (1)$$

where u is the wind speed in the channel direction x, t is time, ρ is density and p is pressure. For flow at a fixed height, (1) can be integrated to yield the Bernoulli equation

$$\frac{u_2^2}{2} = \frac{u_1^2}{2} - \frac{\Delta p}{\rho}, \qquad (2)$$

where u_1 is the entrance velocity, u_2 the exit velocity and $\Delta p = p_2 - p_1$, the pressure difference between exit and entrance points.

Because of the small difference in elevation between Portland and The Dalles, (2) can be applied to the observed pressure difference between these stations to estimate the wind speed at the mouth of the gorge in the absence of friction. For the maximum observed difference of 13.5 mb and the observed density of 1.3 kg m^{-3}, a wind speed of 45 m s^{-1} is obtained at the exit for air starting from rest. This figure is almost twice the size of the observed maximum gust at Portland but no larger than gusts observed within the gorge itself on previous occasions. Clearly, the gradient was more than sufficient to account for the high winds that afflicted the Portland area.

Air flowing over Stampede Pass and down the valleys on the lee side experienced a considerable change of elevation so that (2) is not applicable. Following instead a trajectory of variable height and using pressure coordinates instead of height coordinates, we may write (2) in the alternative form

$$\frac{u_2^2}{2} = \frac{u_1^2}{2} - g\int_{x_1}^{x_2}\frac{\partial D}{\partial x}dx = \frac{u_1^2}{2} - g\frac{\partial \bar{D}}{\partial x}\Delta x, \qquad (3)$$

where g is the acceleration of gravity, D the geopotential height deviation from the standard value for a particular pressure level and $\Delta x = x_2 - x_1$, the difference in horizontal distance between the end and beginning points of the trajectory. $\partial\bar{D}/\partial x$ is the average horizontal geopotential gradient along the trajectory. Under the assumptions that the air followed the 273 K potential isotherm from Ellensburg to Stampede Pass (Fig. 8) and the contour of the ground from there to the base of the mountain range, the geopotential gradients appearing in Fig. 9 yield wind speeds of 20 m s^{-1} at Stampede Pass and 35 m s^{-1} at mountain base for an assumed easterly wind component of 3 m s^{-1} at Ellensberg. These speeds are somewhat greater than observed one-minute wind speeds but not much in excess of observed gusts.

The assumption that the 273 K potential isotherm in Fig. 8 serves as a streamline upwind of the Cascades is based on the relative uniformity in space and time of the temperature in the upwind area at levels below 750 mb (Fig. 7) and on the likelihood that diabatic heating was negligible. Downwind of the range the kinematic boundary condition requires the trajectory to parallel the contour of the ground. From Fig. 8 it is apparent that the potential temperature increases along the trajectory. The increase can be ascribed to the downward heat flux produced by the turbulent winds in the boundary layer.

The lesser wind speed computed in the lee of Stampede Pass than at the outlet of the Columbia River gorge results from the fact that the trajectory starts at a higher elevation where the potential temperature is higher and the cross-mountain geopotential difference is less. Air starting from still higher levels would experience even lesser gradients and accelerations. It is clear that in the type of situation under investigation the potential for strongest surface winds exists in the Columbia River Gorge and for second strongest winds in the lee of Stampede Pass. Air flowing through higher passes and over ridges will attain lesser speeds and, moreover, in the presence of a nocturnal inversion in the leeside valleys may not be potentially cold enough to reach the surface.

A quantitative treatment of the airflow above the ridges would, of course, require consideration of the third (along ridge) dimension and the introduction of the Coriolis force which is not negligible on the time scales involved. The tendency for geostrophic adjustment can already be seen at the 800 mb level on the Seattle sounding (Fig. 6). It should also be remarked that although the horizontal pressure gradient "causes" the horizontal wind acceleration, the source of the kinetic energy in this case is almost certainly the potential energy loss associated with the outflow or downflow of cold air from the interior.

Next, we consider the question of the classification of the strong winds under investigation in terms of standard definitions of local winds. According to the *Glossary of Meteorology* (Huschke, 1959), local winds may be classified into four main groups, of which only two are pertinent to the case at hand. The first of these "includes the effect of local topography in intensifying the general geostrophic flow, generally by being forced through a narrow gap." *Canyon* or *gorge winds* and *mountain-gap winds* are included in this group. Despite the association of the extreme winds in the present case with a river gorge and mountain pass, this category is not fully applicable in that the geostrophic flow was weak in the direction of the channels and the pressure difference was mainly along, not across, the channels.

The second group includes the antitriptic winds, that is down-gradient winds in which the pressure gradient force is balanced by friction. This group contains a number of wind types of which the *fall wind*, defined as a strong, cold, downslope wind, is the most pertinent to this study. The *bora* is a special type of fall wind whose source is so cold that the adiabatic heating is not sufficient to raise the temperature to normal levels. The term was originally applied to the cold northeasterly winds of the Dalmatian coast of Yugoslavia. Defant (1951) defines two types of boras in that area one of which, the *anticyclonic bora*, produces violent winds over land that extend only a short distance to sea. The anticyclonic bora, with its powerful inland anticyclone and narrow coastal strip of strong winds, resembles closely the case under study. The only difference, and probably a minor one, is that the bora is characterized by below-normal temperatures in the lowlands, while in the present case the dynamic warming was sufficient to raise temperatures to near-normal levels despite the cold source.

In terms of the definitions in the *Glossary of Meteorology* it appears that the case under study can be described as a bora in which gap effects, not connected with geostrophic flow, played an important role. Though the Columbia River has no counterpart along the Dalmatian coast, it can be

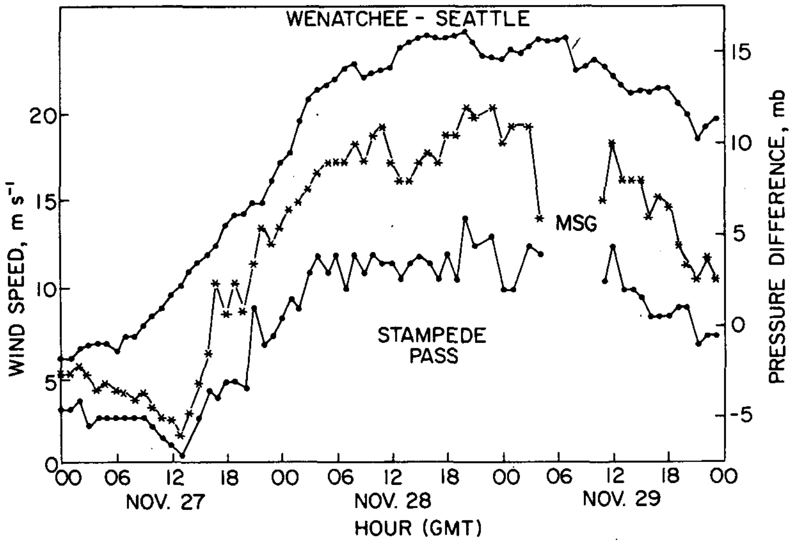

FIG. 10. Comparison of pressure difference between Seattle and Wenatchee (upper curve) and wind speeds at Stampede Pass (lower curves), 0000 GMT 27 November to 0000 GMT 29 November. Lower wind curve gives 1 min speed and upper one gives peak gust. MSG-missing record.

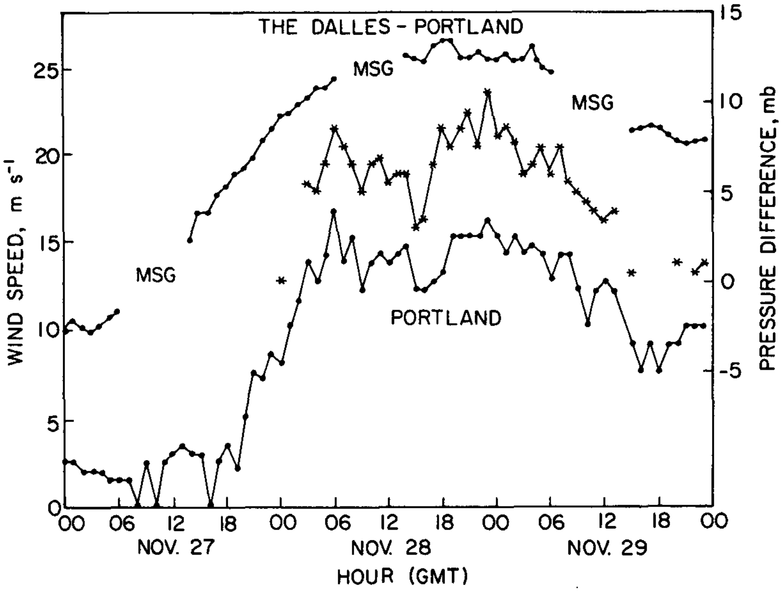

FIG. 11. Comparison of pressure difference between Portland and The Dalles and wind speeds at Portland. See Fig. 10 for further explanation.

speculated that winds similar to the gorge winds of the Columbia would occur there under bora conditions did such a river exist.

Finally, we consider the problem of forecasting the winds in question. From the data presented thus far it would appear that this reduces to the problem of forecasting the pressure difference across the mountain range. That the pressure difference is the controlling factor is attested to by the pressure and wind traces shown in Figs. 10 and 11. The first figure depicts the time variations of the pressure difference between Wenatchee and Seattle, the 1 min wind speed at Stampede Pass and the peak gusts at Stampede Pass. A strong, simultaneous relationship is noted for the main features. Wind speeds at the foot of the mountains were also synchronous with the pressure difference, the damaging winds commencing about 0600 GMT on the 28th and continuing at various localities for a period of 24–36 h.

Equally impressive is the relationship between the wind speed at Portland and the pressure difference between Portland and The Dalles (Fig. 11). The relationship is well known to forecasters at Portland and has been incorporated in a nomogram, a copy of which was provided to the author by J. Wakefield, Meteorologist in Charge. The pressure difference of 13.5 mb is sufficiently large to lie slightly outside the range of the diagram. Extrapolation yields values of 15 m s^{-1} for steady winds and 25 m s^{-1} for gusts in conformity with the observed conditions.

The 36 h Limited Area Fine Mesh (LFM) surface prognosis (not shown) predicted well the anticyclogenesis over the Pacific Northwest, indicating a 15 mb pressure difference across the State of Washington at 1200 GMT on the 28th. The observed difference was 20 mb. It is apparent that the numerical guidance was able to give useful warning of the impending wind storm far in advance of the event. The performance was even better at shorter time ranges. Experience with the LFM prognoses suggests that the success of this forecast was not unusual.

Acknowledgments. This material is based upon work supported jointly by the National Science Foundation and the National Oceanic and Atmospheric Administration under Grant ATM-8103697. This paper is Contribution No. 588, Department of Atmospheric Sciences, University of Washington.

REFERENCES

Cameron, D. C., 1931: Easterly gales in the Columbia River Gorge during the winter of 1930–31—some of their causes and effects. *Mon. Wea. Rev.*, **59**, 411–413.

Cameron, D. C., and A. B. Carpenter, 1936: Destructive easterly gales in the Columbia River Gorge, December 1935. *Mon. Wea. Rev.*, **64**, 264–267.

Defant, F., 1951: Local Winds. *Compendium of Meteorology*, Thomas F. Malone, Ed., Amer. Meteor. Soc., 655–672.

Huschke, R. E., 1959: *Glossary of Meteorology*, 2nd printing, 1970, Amer. Meteor. Soc., 638 pp.

Porter, S. C., 1977: Present and past glaciation threshold in the Cascade Range, Washington, U.S.A.: Topographic and climatic controls, and paleoclimatic implications. *J. Glaciol.*, **18**, 101–116.