

## Columbia Gorge Gap Winds: Their Climatological Influence and Synoptic Evolution

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### ABSTRACT

This paper quantifies the impact of the Columbia Gorge on the weather and climate within and downstream of this mesoscale gap and examines the influence of synoptic-scale flow on gorge weather. Easterly winds occur more frequently and are stronger at stations such as Portland International Airport (KPDX) that are close to the western terminus of the gorge than at other lowland stations west of the Cascades. In the cool season, there is a strong correlation between east winds at KPDX and cooler temperatures in the Columbia Basin, within the gorge, and over the northern Willamette River valley. At least 56% of the annual snowfall, 70% of days with snowfall, and 90% of days with freezing rain at KPDX coincide with easterly gorge flow.

Synoptic composites were created to identify the large-scale patterns leading to strong winds, snowfall, and freezing rain in the gorge. These composites showed that all gorge gap flow events are associated with a high-amplitude 500-mb ridge upstream of the Pacific Northwest, colder than normal 850-mb temperatures over the study region, and a substantial offshore sea level pressure gradient force between the interior and the northwest coast. However, the synoptic evolution varies for different kinds of gorge weather events. For example, the composite of the 500-mb field for freezing rain events features a split developing in the upstream ridge with zonal flow at midlatitudes, while for easterly gap winds accompanied by snowfall, there is an amplification of the ridge.

### 1. Introduction

The states of Washington and Oregon are divided into two climate regimes by the Cascade mountains, which are located about 250 km inland of the Pacific Ocean and extend north–south through both states. The average elevation along the crest of this range is 1.5 km with several peaks rising over 3.0 km. The Columbia River gorge, the only near sea level gap through the Cascades (Fig. 1), has an average width of about 5 km (3 mi) at river level and a length of about 190 km (120 mi). Its western entrance is less than 20 km east of Portland International Airport (KPDX). The Cascade crest lies about 72 km (45 mi) east of Portland between the towns of Cascade Locks and Hood River where the surrounding terrain reaches a height of 1200 m above the valley floor and there are peaks over 3000 m within 50 km to the north and south. To the east of the crest, there is a rapid transition from a wet maritime to a dry continental climate (Figs. 1b and 1c).

Contrasts in lower-tropospheric air temperature and density across the Cascade Range can create substantial east–west pressure gradients across the barrier, especially when combined with favorably oriented synoptic-scale pressure differences. Downgradient air movement

through gaps and passes due to such pressure differences is known as gap flow. Columbia Gorge gap flow, which produces surface winds over  $18 \text{ m s}^{-1}$  (35 kt) several times per year, plays a profound role in defining the weather and climate within the gorge and downstream of its western exit, including the densely populated Portland metropolitan area. Every few years, gorge winds exceeding  $30 \text{ m s}^{-1}$  (60 kt) are observed. Apart from damaging winds, gorge gap flow often brings frigid temperatures, snowfall, or freezing rain.

Although gorge gap flow has important social and economic impacts, the role of the gorge in shaping regional climatology has not been quantitatively assessed and its structural and dynamical characteristics have not been investigated in detail. This is surprising because the Columbia Gorge is an excellent natural laboratory for studying gap flow. Dynamical analysis is simplified because there is little change in elevation along the length of the gorge, and with one notable exception near Cascade Locks (see Fig. 1), the gap is relatively straight. In addition, because of its closeness to major population centers, the gorge is well instrumented.

The gorge is one of the windiest places in the Northwest; several regional wind studies (e.g., Baker et al. 1978; Wantz and Sinclair 1981; Hewson 1975, 1977) have shown it to be a promising site for wind power generation. Indeed, several wind farms have been constructed within the eastern end of the gorge during recent

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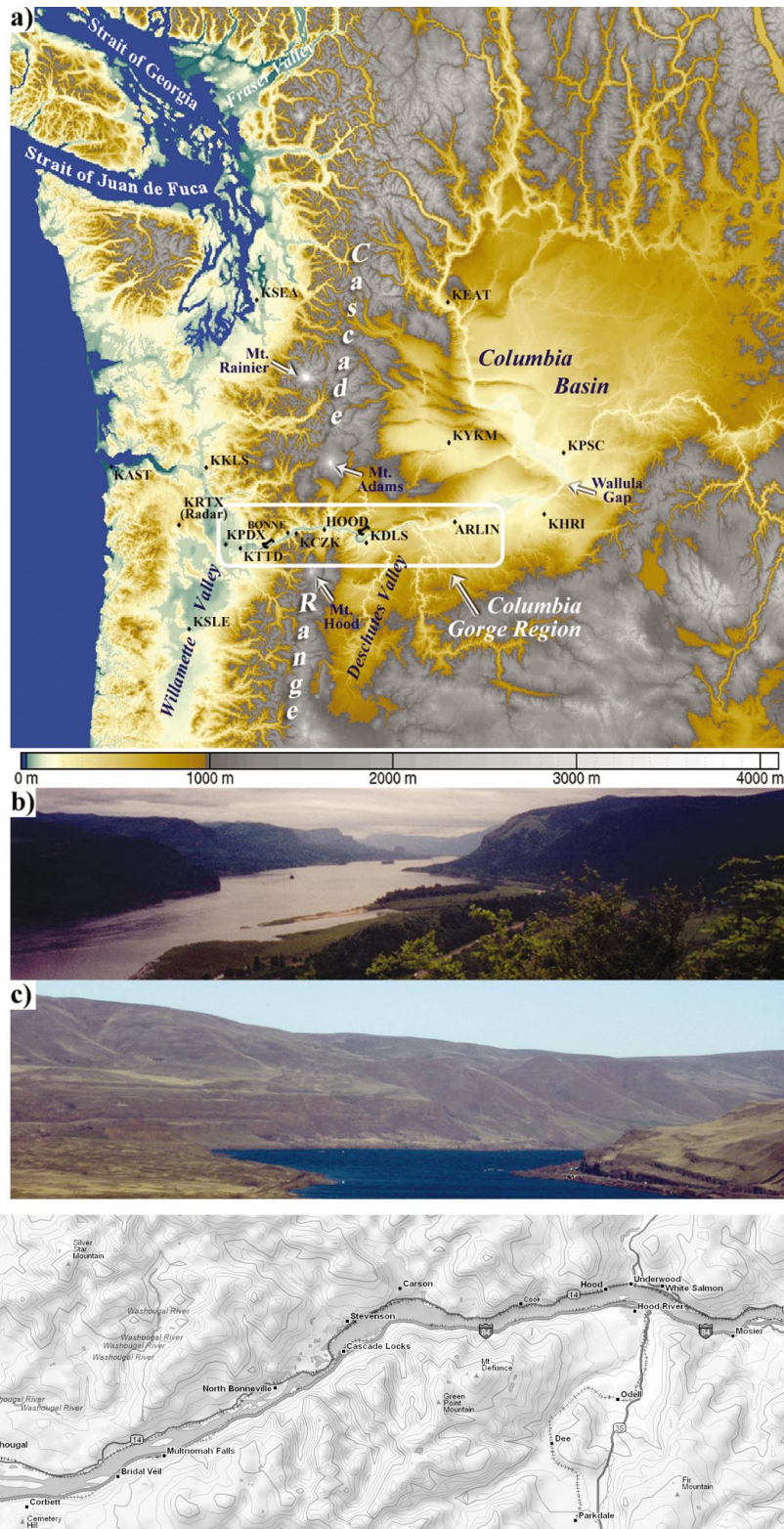


FIG. 1. Geography and topography of the Columbia Gorge and surrounding region. (a) Topographic map showing key geographic locations. Pushpins mark photograph locations. (b) Photograph showing the western portion of the gorge. (c) Photograph of the gorge east of the Cascade crest. (d) Close-up topographic map of the gorge showing elevation and key features. Major contours are every 500 m; minor contours are every 100 m.

years. The consistently strong winds have also made the gorge one of the world's premier windsurfing locations. Windsurfing conditions are best during the summer when large temperature gradients between the east and the west ends of the gorge drive westerly winds. The combination of westerly winds and easterly river currents provide excellent windsurfing conditions. However, the strong winds of the gorge have had detrimental, sometimes disastrous, effects. Within the gorge, and close to the western exit, severe easterly gales are frequent in the cold season. Average winter wind speeds are much higher within the gorge and near its western exit than at nearby stations away from its influence. Strong westerly winds are also common within the eastern gorge following the passage of strong cold fronts, as air surges eastward through the gorge driven by rapidly rising pressure west of the crest.

The city of Portland is located in the western exit region of the gorge and is greatly influenced by the gap, especially during the winter months. The city is windier than locations immediately to the north and south and the wind direction differs from the regional prevailing wind. For example, the average December–February wind for Portland's airport is  $4.29 \text{ m s}^{-1}$  from the ESE, while 74 km to the south at Salem the corresponding wind is  $3.53 \text{ m s}^{-1}$  from the SSW (Meteorology Committee 1968). During periods of local east flow through the gorge, Portland may be significantly colder than other locations at similar elevations on the west side of the Cascades. In such cases, precipitation in the Portland area may fall as snow or freezing rain while farther north it falls as rain. Warm moist air from approaching storms can overrun the cold air exiting the gorge causing ice storms over Portland, such as the severe icing event of January 1979 (Decker 1979) and the ice storm of January 2004 that closed Portland International Airport for almost 4 days. Wolyn (1995) notes that 70% of Portland snowstorms occur during periods of east winds through the gorge. The overrunning effect is even more pronounced within the gorge, where freezing rain is a common hazard (Cameron 1931; Graham 1953).

Gorge gap flow is also responsible for a number of other climatological effects within and downstream of the gorge. For example, strong easterly gap flow during the winter cannot only lower daytime maximum temperatures in the western part of the gorge, but can also inhibit the formation of nighttime surface inversions, reducing winter diurnal temperature variation (Cameron 1931). This fact combined with the relative dryness of easterly flow exiting the gorge greatly reduces the number of hours of ground fog in the Portland area compared to other lowland locations west of the Cascades (Cameron 1931; Graham 1953). Other impacts of the gorge winds include increased fire risk in the gorge and to its west during periods of easterly flow (Graham 1953, Cramer 1957) and severe turbulence in the strong shear zone between the low-level easterlies in the gorge and

prevailing westerlies above (Cameron and Carpenter 1936).

## 2. Previous gap flow/Columbia Gorge research

It was quickly identified in early work that gap winds are highly ageostrophic and driven by the along-channel pressure gradient, with the air accelerating downgradient from high to low pressure. Cameron (1931) noted large pressure gradients between the east and west ends of the Columbia Gorge during strong easterly gales through the gorge. He observed that strong gap flow sometimes continued even when the synoptic pressure gradient was weakening if there was a large thermal contrast across the Cascades. Such a thermal gradient can create a low-level mesoscale pressure gradient across the gorge. Reed (1981) found that the pressure gradient across the Cascades was sufficient to account for the gap winds downwind of both the gorge and Stampede Gap (a higher-elevation gap through the central Washington Cascades) during a windstorm in November 1979. Overland and Walter (1981) used aircraft observations to determine that the pressure gradient could explain the gap flows through the Strait of Juan de Fuca. Several factors other than pressure gradient also contribute to the characteristics of gap flow in a channel, in particular surface friction and the entrainment of air from above the channel, so the acceleration due to the along-gap pressure gradient provides an upper limit to the strength of the gap winds at the exit of the channel.

The Venturi effect is a popular explanation for the strong winds observed in gaps (e.g., Reed 1931). This effect is based on simple mass conservation principles that dictate that the strongest wind should be at the narrowest part of a gap. However, observations of gap flow indicate that the strongest winds are generally located in the exit areas of gaps (Overland and Walter 1981; Bendall 1982; Dorman et al. 1995; Colle and Mass 2000; Sharp and Mass 2002). This fact implies that the primary cause of the strong winds seen in gap flows is *not* the Venturi effect. Rather, it is acceleration down the pressure gradient, which is often largest at the exit, that plays the most important role. Additional wind maxima may also be present within a gap due to Venturi and other hydraulic effects (Jackson and Steyn 1994; Sharp and Mass 2002).

Stephens (1952) showed that in a winter east flow regime, a cold stable layer deepens upstream (east) of the Cascades. Air within this layer will cross the mountains preferentially through gaps and passes. The lowest of the Cascade passes has an elevation of over 900 m, in contrast to the near-sea-level elevation of the Columbia Gorge. Therefore, the gorge is the only conduit through which the low potential temperature air close to the surface in the Columbia Basin can be transported

to the west of the Cascade Range.<sup>1</sup> Because this low-level air is potentially colder than the air above it, simple hydrostatic arguments indicate that the effective pressure gradient between two points on opposite sides of the Cascades will be higher if both points are at sea level than if one point is at pass level (Reed 1981). Thus, one would expect the strongest gap flow to be associated with the lowest gap—in this case the Columbia Gorge. However, this is not always the case. Within a downward sloping gap, gap and downslope winds may occur simultaneously producing stronger winds than observed in lower gaps. Mass and Albright (1985) described a hybrid gap wind–downslope windstorm in December 1983 that caused substantial damage west of Stampede Pass in the Washington Cascades with peak gusts up to  $50 \text{ m s}^{-1}$ . The peak gust at KPDX during the windstorm was  $22 \text{ m s}^{-1}$ .

It is convenient to categorize Columbia Gorge effects into those resulting from easterly flow (which is dry; hot in summer, cold in winter) and those associated with westerly flow (which is moist; cool in summer and relatively mild in winter). Westerly flow in the gorge is typically associated with high pressure building or moving toward the coast (Graham 1953) and tends to be stronger, more frequent, and more persistent in the warm season when a subtropical ridge over the eastern Pacific intensifies and moves north resulting in generally higher surface pressure offshore (Baker et al. 1978). In addition, the warm season pressure gradient is enhanced by the thermal low that often develops over the hot interior. The increased thermal gradient due to daytime heating gives summer westerlies a significant diurnal variability, with strongest flow during the daytime, typically in early afternoon. During westerly flow events, the pressure gradient across the Cascades (the 135-km distance between Portland and The Dalles) is rarely greater than 6 mb and produces moderately strong westerly winds within the gorge. Occasionally, severe westerly winds are observed at the eastern end of the gorge. These gales are usually associated with surges through the gorge accompanying the passage of synoptic-scale systems (generally strong cold fronts) and rarely last longer than a few hours. On 15 December 2000, such a westerly surge resulted in winds greater than  $25 \text{ m s}^{-1}$  over the eastern gorge and blew a tractor-trailer truck off a bridge across the Columbia River at Biggs (27 km east of The Dalles).

Easterly gorge flow is most common during the winter season. Cramer (1957) describes four synoptic features that yield winds with an easterly component across the

Cascade Range: a continental high building inland, a cyclone approaching the coast, an offshore thermal trough, and a cyclonic storm centered in southern Oregon or northern California. The first two features, which are most prevalent during the cold season, are the most important precursors of enhanced easterly gap flow through the gorge and other Cascade gaps. Periods of strongest east flow occur when several of these synoptic-scale features occur simultaneously (Graham 1953; Reed 1981; Mass and Albright 1985). Cameron and Carpenter (1936), Graham (1953), and Baker et al. (1978) describe similar synoptic conditions leading to strong wintertime easterly flow through the Columbia River gorge. Advection of cold, continental air from interior British Columbia and rapid radiational cooling associated with often clear skies east of the mountains result in the formation of a cold pool<sup>2</sup> in the Columbia Basin that is surmounted by subsiding air aloft. An inversion at the interface between these two air masses decouples the flow aloft from the low-level flow entering the gorge. Mesoscale high pressure associated with the cold pool increases pressure east of the Cascade Mountains and intensifies the pressure gradient across the Cascades. The gradient may be further enhanced if some of the cold air becomes dammed up along the eastern slopes of the barrier or if pressure falls to the west of the Cascades due to an approaching storm. During such scenarios, the pressure gradient between Portland and The Dalles is frequently greater than 6 mb and occasionally exceeds 12 mb. As the only low-level gap, the Columbia Gorge serves as the main drain for this “pool” of cold air east of the Cascades. As the air flows down the pressure gradient through the gorge, it may accelerate to very high velocities if the gradient is large, producing severe easterly gales within the western Columbia Gorge and near its western exit (Cameron 1931; Cameron and Carpenter 1936; Graham 1953; Cramer 1957) that may continue for several days. For example, the wind at Crown Point, in the western part of the gorge, can be expected to reach  $27 \text{ m s}^{-1}$  (55 kt) from the east or northeast once every 2 yr (Wantz and Sinclair 1981).

### 3. Motivation and objectives

The research described in this paper is part of a larger effort to describe gap flow through the Columbia Gorge, its synoptic and mesoscale controls, and its influence on regional weather. When studying or forecasting any mesoscale weather phenomenon, it is critical to first have a solid grasp of the local climatology, to understand the importance of the phenomenon in shaping that climatology, and to be aware of the different synoptic-scale pattern evolutions that lead to occurrence of the

<sup>1</sup> The only other low-level gap in the Cascades is the Fraser River Gap, in the northern part of the range. Though the western portion of the Fraser Gap is near sea level, the gap leads to a basin with an elevation of over 350 m. Thus, the air moving down the Fraser Gap experiences a considerable change of elevation before it reaches the lowlands. In contrast, air moving through the Columbia Gorge experiences an elevation loss of less than 100 m.

<sup>2</sup> Whiteman et al. (2001) and Zhong et al. (2001) discuss Columbia Basin cold pool climatology, evolution, and dynamical characteristics in more detail.

phenomena. This analysis quantifies the climatological effects of the gorge and an accompanying synoptic compositing study identifies typical synoptic evolutions leading to gorge gap flow. A subsequent paper will describe a case study that utilizes high-resolution observational and model data to document both the structure and evolution of a gorge event and the important dynamical mechanisms. These studies will elucidate the detailed structures and dynamics associated with a level gap and will provide guidance to forecasters interesting in predicting weather in the gorge and similar gaps.

#### 4. Columbia Gorge climatology

The climatology study presented here illustrates and quantifies the large climatological gradients that exist within and near the gorge. The contribution of gorge gap flow to these gradients is explored, with particular attention given to the Portland metropolitan area.

The effect of gorge gap flow on regional climatology was analyzed using the daily peak gust (the maximum peak gust speed and direction for a day) and the daily resultant wind (the daily vector average of all hourly observations) records from KPDX to determine climatological averages of several parameters as a function of wind speed and direction. Wind data from Troutdale (KTTD) would be preferable for such an analysis since its location at the western exit of the gorge makes wind direction there an almost perfect indicator of gap flow within the gorge. However, no long-term wind record was available for KTTD. KPDX was therefore chosen because it is the closest station to the gorge for which a long record of daily wind data is available and because the wind direction at KPDX is strongly correlated with gap flow in the Columbia Gorge. The validity of this approach was tested by comparing hourly observations from KTTD and KPDX for 1 January 2002 to 1 April 2004. During this 822-day period, there were 195 days where the wind was at least  $5 \text{ m s}^{-1}$  from the east at KTTD for 6 h or more. The daily peak gust at KPDX was from the east and greater than  $5 \text{ m s}^{-1}$  on 147 (75.4%) of these days. Of the remaining 627 days, 43 (6.9%) had a peak gust from the east at KPDX. Thus, there were 190 days considered easterly by the KPDX daily peak gust method, of which 43 (22.6%) were *possibly* false alarms. By comparing daily peak gusts at KTTD to those at KPDX, it was shown that at least 17 of the possible false alarms were actually days with a short period of easterly flow at KTTD. This reduced the false alarm rate to at most 13.7%. Most details of the data analysis methodology, including differences between resultant wind and peak gust, are given in the appendix.

##### a. The wind climatology of Portland International Airport

The wind speed and direction at Portland International Airport (KPDX) are greatly influenced by gap

flow within the gorge. Wind roses in Fig. 2 describe the wind distributions at KPDX and Salem (KSLE) for the summer, transition (spring and autumn), and winter seasons. The wind roses were produced using the daily resultant wind records for each station, collated into 16 cardinal directions with each bin subdivided into four speed categories. Similar results (not shown) were obtained using the peak gust. Salem, located 75 km to the south of KPDX, is relatively uninfluenced by the gorge and thus has a wind climatology that is more typical of western Oregon and Washington.

Northwesterly winds prevail at KPDX during summer, occurring on about 70% of days. A similar summer pattern is seen at Salem except that the wind is biased toward a more northerly direction. The northerly component of the flow at both locations is associated with offshore high pressure, which dominates the weather of the Pacific Northwest during the warm season, with little evidence of any gorge influence. Local-scale topographic channeling effects account for the differences between the two locations (see Fig. 1).

In winter, east-southeasterly and southeasterly winds dominate at KPDX, in contrast to KSLE where southerly winds are strongest and by far the most common. The prevalence of southerly wind at Salem is caused by channeling of the synoptic-scale wind through the Willamette River valley. Despite its location at the northern end of the Willamette Valley, the wind distribution at KPDX is different because as storms approach the Pacific Northwest and the pressure gradient increases across the Cascades, the synoptic-scale south to southwesterly wind (seen in the Salem wind roses) is initially overwhelmed at low levels within and near the gorge by a steady, moderate to strong easterly gap flow. This gap flow is eroded from aloft by warm southerly flow as the storm approaches, reducing the strength and extent of the outflow jet. Thus, strong south or south-southwest winds are often briefly observed at KPDX prior to the passage of cold or occluded fronts. This can be seen in an analysis of the peak gust speed (not shown).

The spring and autumn wind distributions at KPDX are very similar. During these transition periods the wind at KPDX is influenced by both the winter and summer regimes. The same is true at KSLE.

##### b. Portland area wind speed–pressure gradient correlations

The pressure gradient between The Dalles (KDLS) and Portland International Airport is commonly used by forecasters to predict the strength of gorge gap flow. While it is true that wind speeds in the western part of the gorge and at locations immediately downstream of the gorge exit are well correlated with the pressure gradient along the gorge, it is important for forecasters to be aware that the pressure field does not vary smoothly along the gap or in the exit area and that other factors

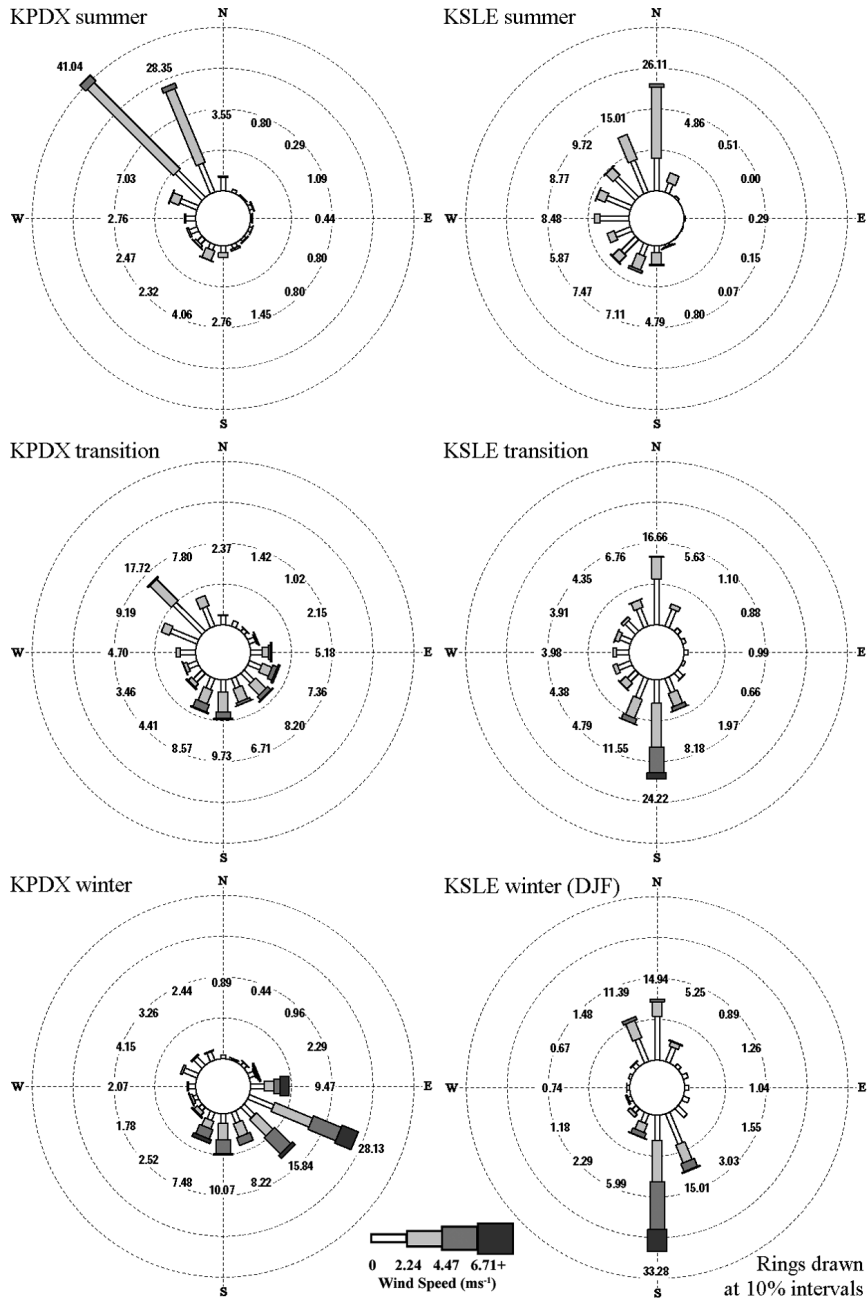


FIG. 2. KPDX and KSLE wind roses, based on the daily resultant wind data, for summer, transition, and winter seasons.

are important. Gorge gap flow is associated with very large and complex local-scale pressure perturbations that are intimately tied to topography.

Hourly data from January 2002 to March 2004 were used to examine the relationships between east–west pressure differences and wind speed at stations downstream of the gorge exit. Figure 3a illustrates a moderately strong relationship (correlation coefficient,  $r = 0.69$ ) between the KDLS to KPDX pressure difference

and the wind speed at KPDX for observations with easterly flow at KPDX. Figure 3b shows that the pressure gradient in the gorge exit region (KTTD to KPDX) is also a good predictor of the wind speed at KPDX during periods of easterly flow ( $r = 0.69$ ). For winds at KTTD (Fig. 3c), the closest station to the gorge exit, the correlation is much stronger ( $r = 0.89$ ), with almost 80% of the observed variance explained by the pressure difference between KDLS and KTTD. The final scatterplot

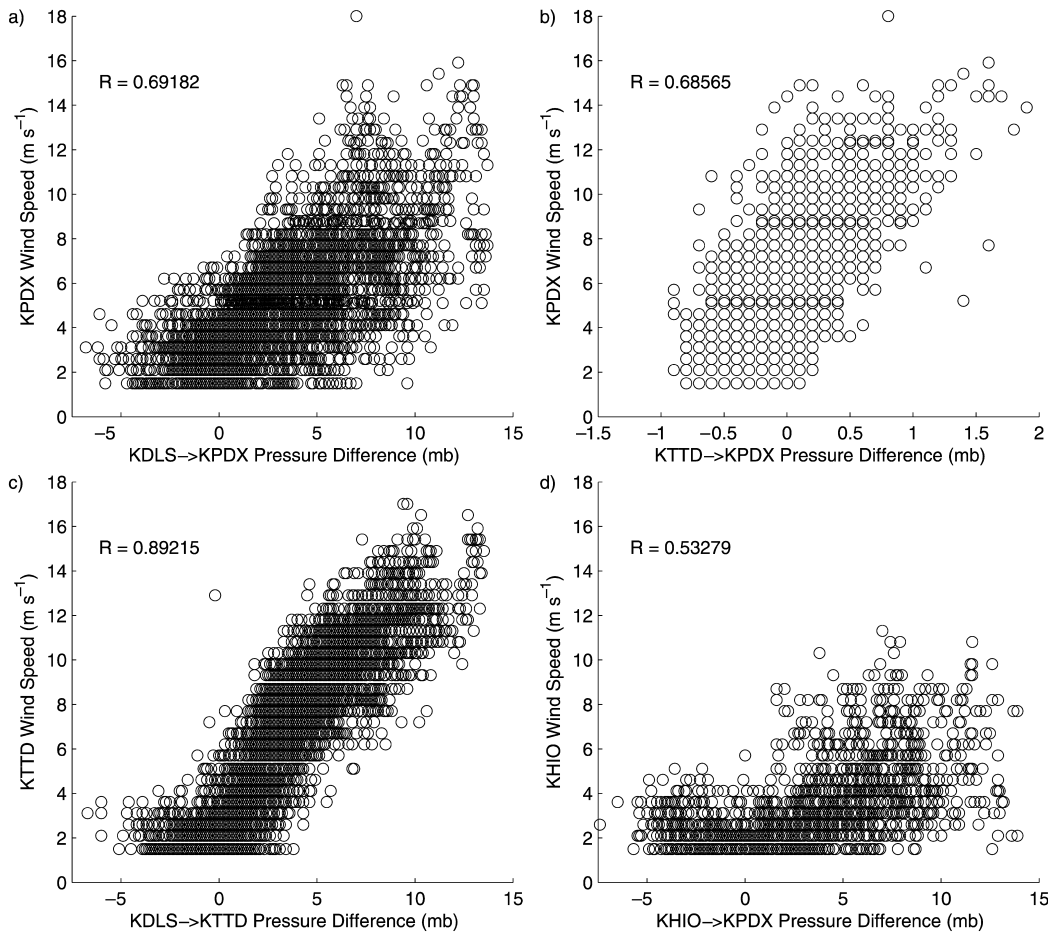


FIG. 3. Scatterplots showing the relationship between pressure gradients and wind speed for observations where the wind was easterly at each respective station. (a) Pressure difference between KDLs and KDPX vs wind speed at KDPX. (b) Pressure difference between KTTD and KDPX vs wind speed at KDPX. (c) Pressure difference between KDLs and KTTD vs wind speed at KTTD. (d) Pressure difference between KDLs and KHIO vs wind speed at KHIO.

(Fig. 3d) shows that farther from the gorge, at Hillsboro, the correlation between the pressure gradient and wind speed declines substantially ( $r = 0.53$ ).

Table 1 summarizes the pressure gradient–wind speed correlations seen in the figures, as well as providing additional statistics. Interestingly, the results are insensitive to whether the cross-Cascade gradient applied extends to the gorge exit (KTTD), Portland International Airport (16 km west of KTTD), or Hillsboro (42 km

west of KTTD). It is also noteworthy that the pressure gradient–easterly wind correlations for both KDPX and KHIO are virtually unchanged if the pressure gradient between the Portland to Hillsboro pressure gradient is considered. On days where the wind is easterly at all three sites, this negative correlation becomes quite significant ( $r = -0.34$  at KTTD and  $r = -0.41$  at KDPX). As will be discussed in a subsequent paper, this negative correlation is related to lee troughing and hydraulic collapse associated with easterly flow, resulting in lowered pressure downstream of the gap (thus reducing the pressure gradient between Portland and Hillsboro).

TABLE 1. Correlation coefficients between various pressure gradients and easterly wind speed conditions.

Pressure difference	Wind speed of observations with easterly wind		
	KTTD	KDPX	KHIO
KDLs to KTTD	0.89215	0.65701	0.52071
KDLs to KDPX	0.88564	0.69182	0.53484
KDLs to KHIO	0.88407	0.69493	0.53279
KTTD to KDPX	0.13578	0.68565	0.47969
KDPX to KHIO	-0.21401	-0.16125	-0.14819

*c. Regional and local temperature climatology*

Figure 4 presents winter average maximum temperatures for the Washington–Oregon region. A detailed topographical map is also provided (Fig. 4a). East of the Cascades average winter temperature maxima are

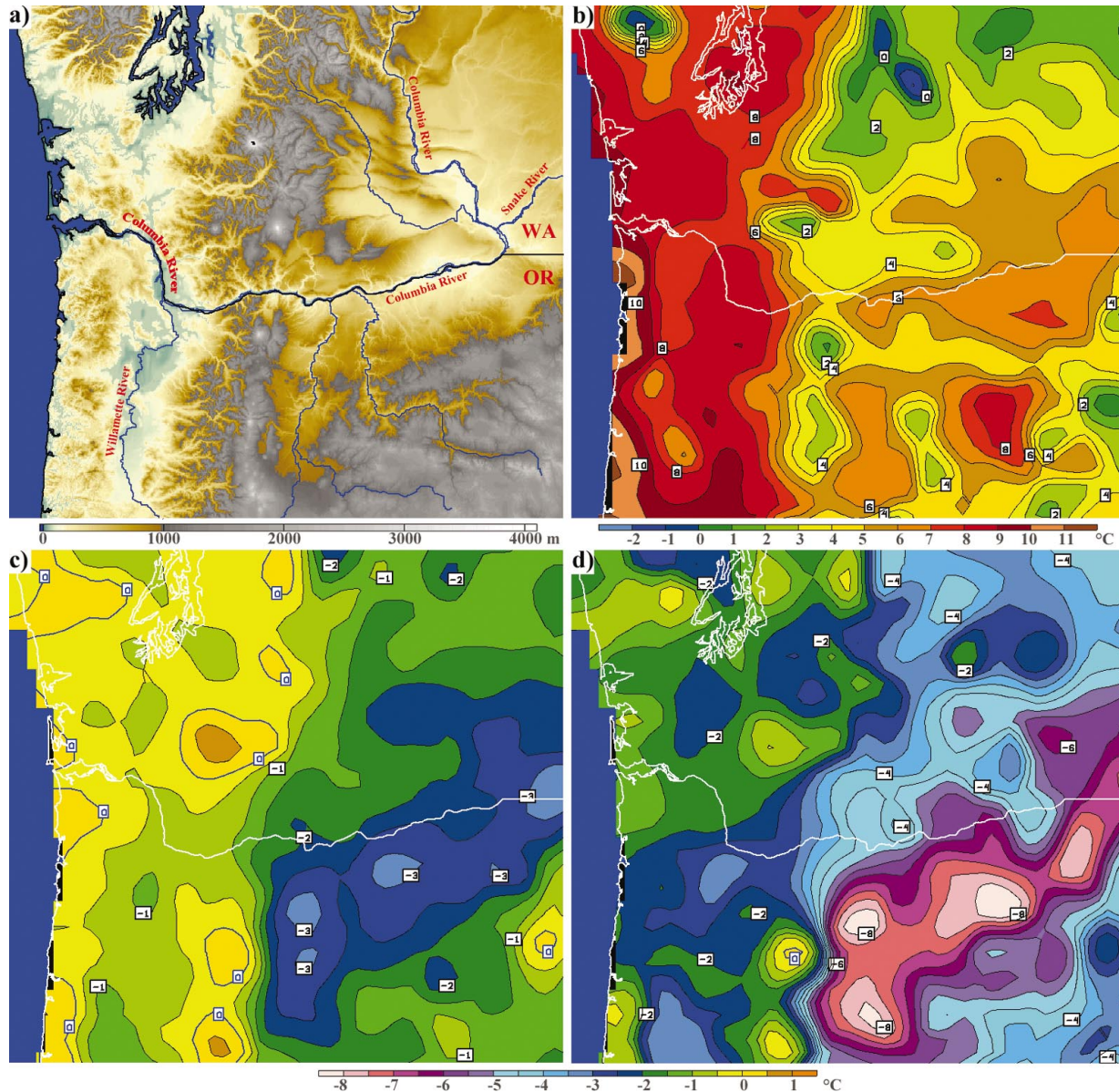


FIG. 4. Winter (DJF) regional maximum temperature derived from NOAA COOP data: (a) terrain for reference, (b) average maximum temperature distribution, (c) average deviation of maximum temperature from DJF climatology for days where peak gust direction at KPDX was either east or east-southeast and gust speed  $\geq 4.5 \text{ m s}^{-1}$ , and (d) same as (c) except peak gust  $\geq 15.6 \text{ m s}^{-1}$ .

$2^{\circ}$ – $4^{\circ}\text{C}$  lower than to the west of the mountains (Fig. 4b). The average winter temperature minima (not shown) are  $4^{\circ}$ – $9^{\circ}\text{C}$  lower. The strongest temperature gradients are located across the Cascade crest, including the Columbia Gorge. Though elevation obviously contributes to cooler temperatures in the higher terrain, much of the area east of the crest, particularly the Columbia Basin, lies at elevations less than 300 m above sea level. Cold low-level air in the Columbia Basin can form in place due to radiational cooling and drainage or may have a continental polar origin. In both cases, this air is isolated from the marine influence of the Pacific by the Cascades and is retained by the basin, re-

sulting in the contrast in low-level temperature between locations east and west of the Cascades.

In order to explore the relationships between easterly gorge flow and regional temperature anomalies, the data for each station were segregated using the KPDX peak gust direction as a proxy to the presence of easterly gap flow through the gorge. Days with easterly gap flow were further categorized by the strength of the gap flow. To remove the strong dependence of temperature on elevation, average deviations from climatology were calculated at each station for each strength category. The deviation from climatology of maximum temperature for days where the peak gust at KPDX was at least



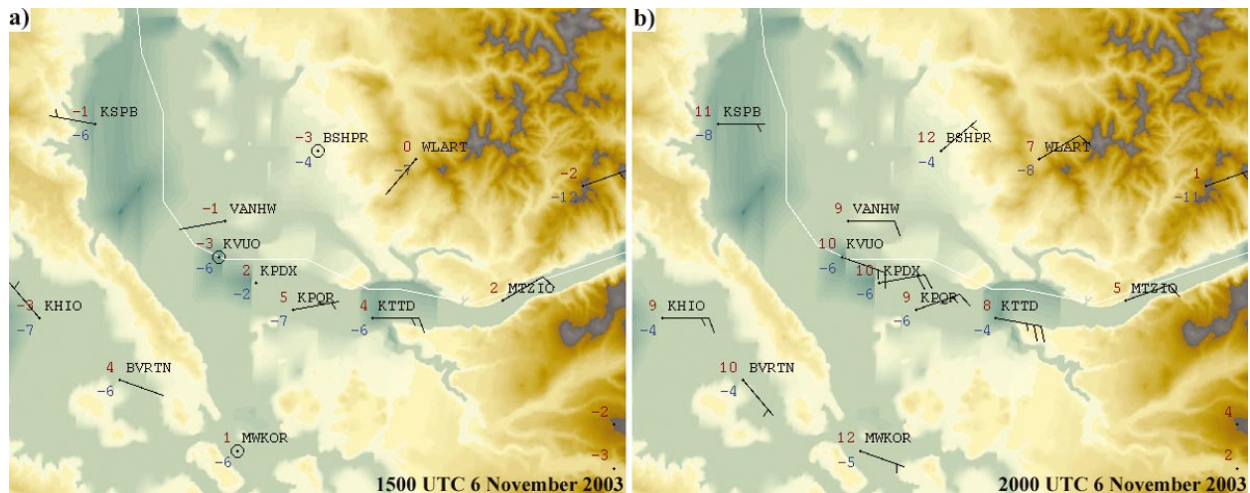


FIG. 5. Surface observations of wind ( $\text{m s}^{-1}$ ), temperature ( $^{\circ}\text{C}$ ), and dewpoint ( $^{\circ}\text{C}$ ) near the gorge exit on (a) 1500 UTC 6 Nov 2003 [0700 Pacific standard time (PST)] and (b) 2000 UTC 6 Nov 2003 (1200 PST). These observations illustrate how easterly gap outflow reduces the diurnal variation near the gorge.

$4.5 \text{ m s}^{-1}$  ( $10 \text{ mi h}^{-1}$ ) is shown in Fig. 4c. In Fig. 4d, the speed threshold is increased to  $15.6 \text{ m s}^{-1}$  ( $35 \text{ mi h}^{-1}$ ).

Figure 4c confirms that easterly flow through the gorge is correlated with colder than normal temperatures in the Columbia Basin, with much of eastern Washington and northeastern Oregon  $1.5^{\circ}$ – $3^{\circ}\text{C}$  below normal. The largest deviations are found in low-lying areas, especially in the southern part of the Columbia Basin in southeastern Washington and northeastern Oregon. The low-elevation Deschutes Valley, which is essentially an extension of the Columbia Basin, is also the site of large deviations. The strongest gradient in temperature deviation is located along the eastern slopes of the Cascades. To the west of the Cascade crest, temperatures are almost normal in most locations except through the Columbia Gorge and into the Willamette Valley where temperatures are  $0.5^{\circ}$ – $1^{\circ}\text{C}$  below normal.

Stronger easterlies are associated with a qualitatively similar pattern, but with larger deviations (Fig. 4d). In this case, most of the area to the west of the mountains is at least  $1.5^{\circ}\text{C}$  below normal because cold air from the interior is moving west through the gaps and passes of the Cascades. Despite this general cooling, the gorge exit region and Willamette Valley still represent the most consolidated area of below normal temperatures west of the Cascades, with deviations of  $3^{\circ}\text{C}$  below normal immediately downstream of the gorge. The largest deviations (up to  $8^{\circ}\text{C}$  below normal) are found in the southern portion of the Columbia Basin and in the Deschutes Valley. However, large deviations to the east of the crest are no longer limited to low elevations. These results are consistent with the idea that stronger gorge winds usually occur when a deep layer of cold air becomes entrenched east of the crest and is often associated with the southward movement of Arctic air out of British Columbia and Alberta.

A similar analysis was performed for minimum temperature (not shown). The deviation of temperature minima from climatology on days with easterly flow at KPDX is negative almost everywhere and the deviation is proportional to the wind speed. The size of the deviation is greater than for the deviation of temperature maxima, except in low-lying parts of the Columbia Basin. However, there is less cooling directly attributable to cold air flowing through the gorge. In fact, some of the areas influenced by gorge flow exhibit *less* deviation than sheltered valleys to the north.

The clear and dry synoptic weather pattern that is most common during sustained easterly flow through the gorge explains the differences between the minimum and maximum temperature deviations. In such a regime, associated with synoptic ridging over and to the east of the area, the region west of the Cascades experiences more radiational cooling at night and more insolation during the day than is typical. Where the wind is light, nighttime inversions readily form, increasing the deviation in minimum temperature, while increased mixing in areas influenced by gorge outflow inhibits the inversion formation. An excellent example of this occurred on 6 November 2003 when the minimum temperature near the gorge exit at Troutdale (KTTD) was  $4^{\circ}\text{C}$  and the maximum was  $9^{\circ}\text{C}$ , while stations less than 25 km away but outside of the easterly exit jet reported minima as low as  $-3^{\circ}\text{C}$  and maxima as high as  $12^{\circ}\text{C}$  (Fig. 5). Figure 5 also shows that in this case the number of stations influenced by the outflow is greater during the daytime. This is because the easterly outflow often lifts off the surface downstream of Troutdale at night. The synoptic pattern described above is also conducive to the formation of fog in the low-lying parts of the Columbia Basin, reducing daytime insolation and nighttime radiational cooling. This explains why there is a large cold deviation in maximum temperatures but a

TABLE 2. Stations used for the gorge analysis, listed from west to east. Troutdale is located at the western end of the gorge.

Station	ID	Lat (°)	Lon (°)	Elevation (m)	Period of record
Astoria Regional Airport	KAST	46.15	-123.88	3.0	1953-98
Portland International Airport	KPDX	45.60	-122.60	6.1	1948-98
Troutdale Airport/Substation	KTTD	45.57	-122.40	9.1	1948-98
Bonneville Dam	Bonne	45.63	-121.95	21.3	1948-98
Hood River Experimental Station	Hood	45.68	-121.15	152.0	1948-98
The Dalles	KDLS	45.62	-121.15	73.2	1948-98
Arlington	Arlin	45.72	-120.18	85.3	1948-98

much smaller negative deviation in minimum temperatures in the Columbia Basin.

To obtain a clearer picture of the climatic gradients within the gorge, temperatures from reliable stations located at or near river level (Table 2) were examined as a function of wind speed and direction at KPDX. Days were categorized into four bins centered on north, east, south, and west.<sup>3</sup> The climatological average min-

imum and maximum temperatures along the gorge for the summer, transition (spring and autumn combined), and winter seasons are shown in Fig. 6 using thick dashed lines with diamond markers. Solid lines show average minimum and maximum temperatures calculated for days when the peak gust at KPDX was over 8.9 m s<sup>-1</sup> (20 mi h<sup>-1</sup>) and was in either the easterly (open squares) and westerly (open circles) quadrants. The gradient in average maximum temperature along the gorge is largest during the summer, when Arlington, to the east, is on average about 6°C higher than Portland. The pressure gradient that results from this thermal gra-

<sup>3</sup> The influence of days with NE, SE, SW, and NW directions that lie on the intersection of two bins were weighted to equally divide them between the adjacent categories.

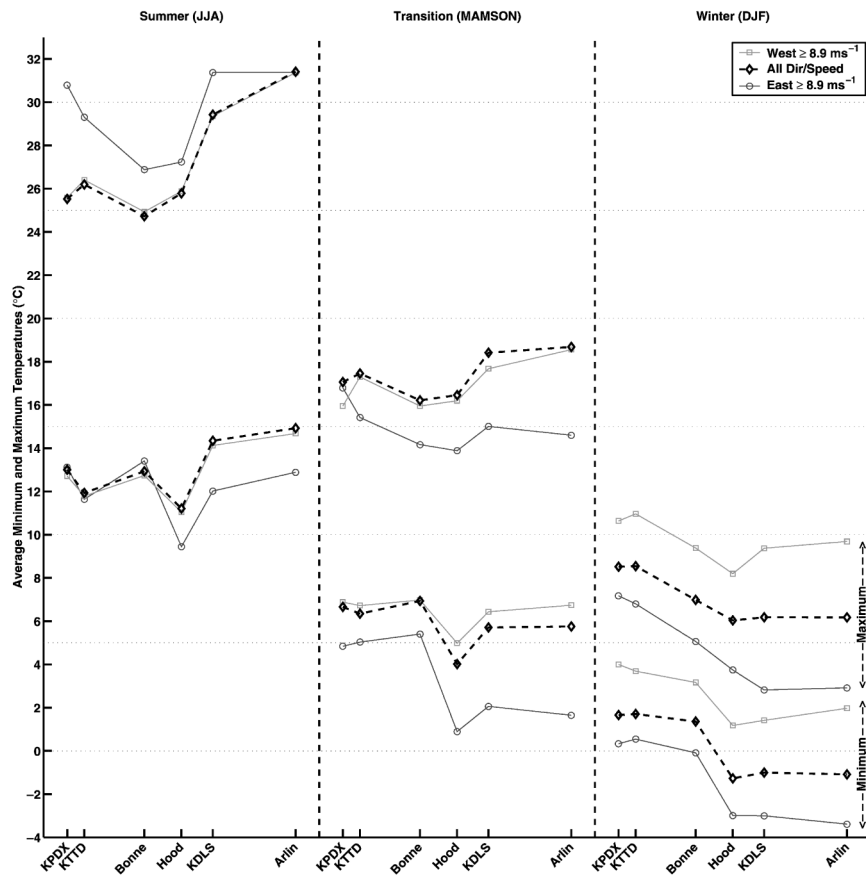


FIG. 6. Seasonal average maximum and minimum temperatures at stations along the Columbia Gorge. Heavy dashed lines with diamond markers show the overall means. Thin solid lines show averages calculated using data only from days with westerly (open squares) or easterly (open circles) peak gusts of 8.9 m s<sup>-1</sup> (20 mi h<sup>-1</sup>) or greater.

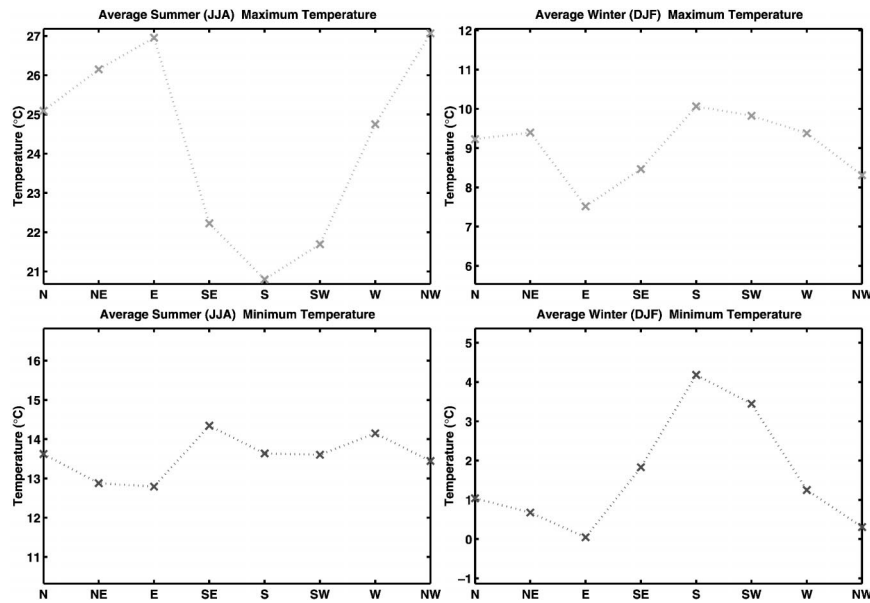


FIG. 7. Average summer and winter maximum and minimum temperatures at KPDX as a function of resultant wind direction. A large,  $45^\circ$  bin size was used to provide enough days for statistical significance in less common wind direction categories.

gradient is responsible for the moderately strong westerly winds that blow through the gorge during summer days and make the area so attractive for windsurfing. This westerly wind has a large diurnal variability because the gradient of minimum temperature across the gorge is far smaller than that of maximum temperature. Warmer summer maximum temperatures are correlated with increasing east wind strength, especially west of the Cascades. This is because summer easterly flow at KPDX is generally associated with the California heat trough moving northward and lowering the surface pressure west of the Cascades.

The winter average temperature gradient across the gorge is the reverse of the summer gradient. Maximum temperature at Arlington is on average  $2.5^\circ\text{C}$  lower than at Portland and the average minimum temperature is about  $5^\circ\text{C}$  lower. Days with easterly (westerly) winds at KPDX are significantly cooler (warmer) than normal at all the stations examined. Cooling increases as easterly wind speed at Portland increases (not shown).

Spring and autumn temperature distributions along the gorge are very similar and have therefore been plotted together. Such transition periods combine the characteristics of both summer and winter. Generally, maximum spring and autumn temperatures at stations to the east of the Cascades are warmer than stations to the west, which is a summer characteristic. However, as seen in winter, a cooler regime appears with easterly winds.

The relationship between wind direction and temperature immediately downstream of the gorge was more closely examined using resultant wind and temperature data from KPDX (Fig. 7). Summer maximum

temperatures are highest when the wind is between northwest and east, with peaks for directions (east and northwest) that are most favorable for subsidence off the higher terrain of the Cascades or the Coast Ranges. Summer minimum temperatures show little dependence on wind direction or speed. In winter, the cooling effect of easterly gap flow is apparent in both maximum and minimum temperatures. The effect of warm advection in southerlies ahead of storms is also clear. Nighttime minimum temperatures during winter are not dramatically different between easterly and more northerly directions. This is because winter northerly winds at KPDX are normally light (see Fig. 2) and accompanied by clear skies. This results in a strong nocturnal inversion at night. Though easterly flow through the gorge generally advects cooler air into the Portland area, increased mixing due to the stronger winds opposes the formation of a nocturnal inversion and, thus, tends to offset the cold advection.

#### d. Regional and local precipitation climatology (rain, snow, and freezing rain)

The annual precipitation climatology for the gorge region is shown in Fig. 8a. This figure uses the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset, which combines National Oceanic and Atmospheric Administration (NOAA) Cooperative (COOP) station precipitation with elevation and slope-based regressions to provide extra detail where data are sparse. Although not perfect, this dataset provides a reasonable regional-scale representation of annual precipitation. (See the PRISM Web site for more details:

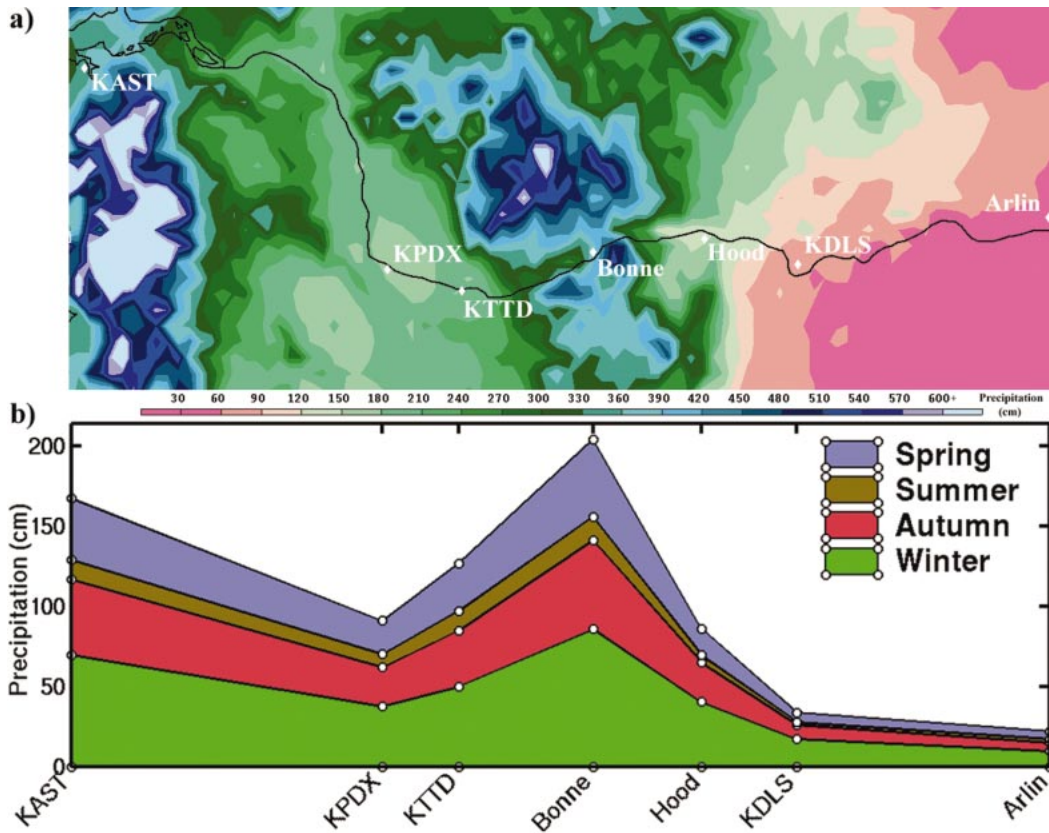


FIG. 8. (a) Annual precipitation (cm) for the region surrounding the Columbia Gorge created using the PRISM dataset. (b) Seasonal contribution to the total annual precipitation (cm) at COOP stations along the Columbia River. The uppermost curve is the cumulative sum of the seasonal contributions and thus represents the annual total.

[http://www.ocs.orst.edu/prism/prism\\_new.html](http://www.ocs.orst.edu/prism/prism_new.html)). The effects of windward enhancement and lee shadowing are clear. It is also possible to see relative maxima in precipitation on higher peaks and minima through the lower passes, including the Columbia Gorge. Figure 8b traces the cumulative contribution of each season to average annual precipitation for COOP stations along the Columbia River (see Table 2 for station locations). Although the elevation along the gorge does not vary much, the precipitation distribution in this cross section is largely forced by the surrounding orography (cf. Fig. 1). There is a peak at the coast (Astoria Regional Airport, KAST) due to the coastal range, with a trough in the rain-shadowed Willamette Valley (KPDX and KTTD), followed by another peak at Bonneville, just west of where the Cascade Range crests to the north and south. There is then a rapid decrease to Hood River just east of the crest. Precipitation continues to fall off quickly to semiarid levels at The Dalles, then more slowly to Arlington. Precipitation trends by season are similar along the length of the gorge; summer is dry, winter is wet, and spring and autumn are transition seasons.

Regional and along-gorge variations in snowfall were studied. Despite its low elevation, the gorge receives

abundant snowfall, especially adjacent to the Cascade crest, with some locations receiving over 100 cm yr<sup>-1</sup>. In order to remove the strong dependence of snowfall on elevation and determine the influence of the gorge upon regional snowfall climatology, average snowfall at each station was calculated as a function of wind speed and direction at KPDX and the deviation of this value from the station climatology was determined. The results of this analysis (not shown) indicate that the outflow from the gorge plays an important role in the occurrence of snowfall in the northern Willamette Valley. For example, around the western end of the gorge and into the northern Willamette Valley a positive deviation in snowfall is seen that equates to a seasonal deviation of about 5.1–15.2 cm (2–6 in.) for days with an easterly peak gust  $\geq 4.5 \text{ m s}^{-1}$ . Taken in the context of the actual annual snowfall, which is around 15 cm (6 in.) through most of the Willamette Valley, this is a very significant deviation. The correlation between an easterly wind at KPDX and snowfall in the Willamette Valley becomes even more pronounced as the wind speed threshold is increased.

An along-gorge plot of the annual snowfall distribution by peak gust direction (Fig. 9) illustrates the correlation between gorge gap flow and snowfall. Days

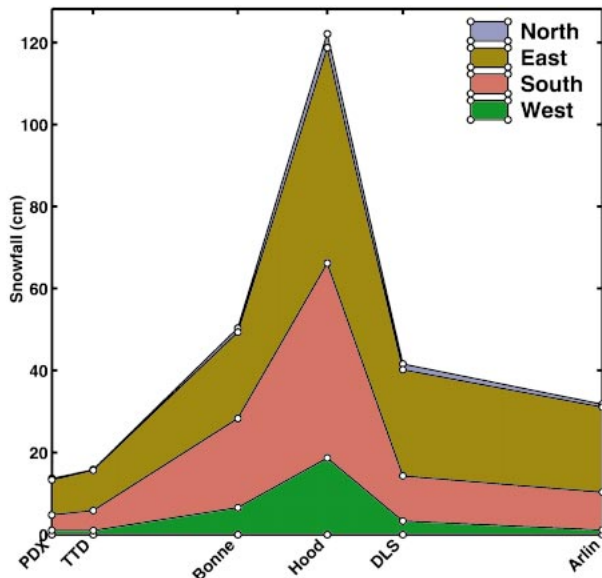


FIG. 9. Annual snowfall (cm) (actual amount, not water equivalent) at stations along the gorge subdivided by peak gust wind direction at KPDX.

with easterly gap flow are most favorable for snowfall at all stations, both within and downstream of the gorge. These results are contrary to those found at stations in the higher parts of the Cascades where easterly flow at KPDX is correlated with reduced snowfall. Within the gorge at low levels, the availability of cold air, not the amount of precipitation, is the limiting factor for snowfall. Meanwhile, in the mountains, though most winter precipitation falls as snow, days with easterly flow at KPDX are on average drier. In the gorge exit region (KPDX and KTTD), snowfall totals for easterly flow are about double the totals of all other directions combined. For all directions, the peak snowfall in this cross section is at Hood River. Note the eastward shift of the snow maximum compared to the precipitation maximum (cf. Fig. 8b). Hood River is most favorable for snow because it is far enough east to remain in cold low-level air longer (Fig. 6), but still far enough west to receive plentiful precipitation (Fig. 8).

Rainfall and snowfall data from KPDX were used to quantify the influence of the gorge on precipitation at Portland (Fig. 10). The four panels in Fig. 10a show the distribution of average precipitation by resultant wind speed and direction for each season. The majority of the precipitation at KPDX occurs when the wind direction there is between southeast and southwest. Lit-

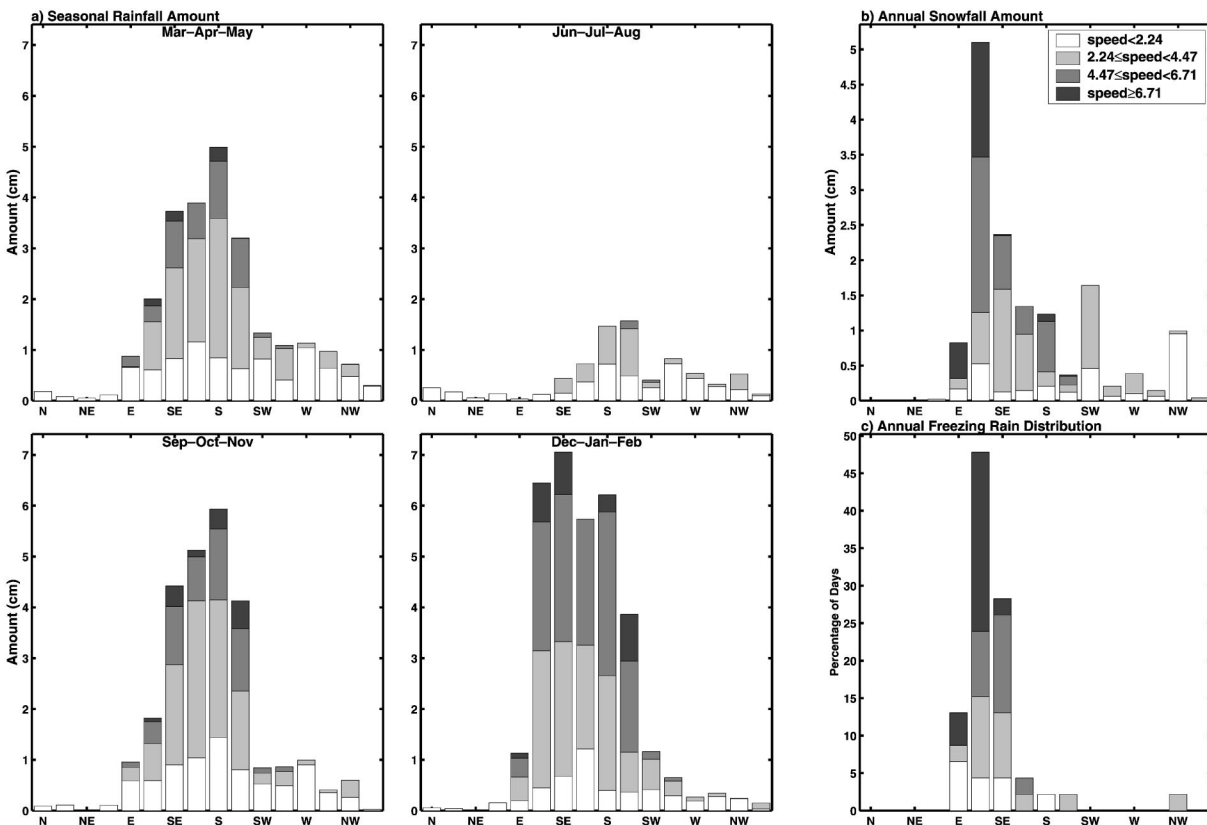


FIG. 10. Precipitation (all types), snowfall, and freezing rain statistics for KPDX as a function of resultant wind: (a) seasonal precipitation distributions, (b) annual distribution of snowfall amount, and (c) annual freezing rain frequency distribution.

the precipitation falls when the wind is northwest to northeast. Winter is by far the wettest season (December, November, January, and February are the wettest months in that order), and summer is very dry. These results are typical for the Pacific Northwest, indicating that the majority of precipitation occurs with the approach and passage of fronts associated with synoptic-scale storms. The only discernable signal of the Columbia Gorge is that the peak precipitation lies in the east-southeast and southeast directions in the winter. This is atypical for the Pacific Northwest where most stations receive the majority of their rainfall on days when the wind lies between south-southeast and southwest. The difference can be attributed to low pressure systems approaching from the west producing a westward pressure gradient force across the gorge. Thus, easterly gap flow and precipitation often occur on the same day.

In contrast to precipitation (mostly rainfall), the KPDX snowfall climatology exhibits a strong correlation between east to southeast surface winds at KPDX and increased snowfall amount (Fig. 10b) and snowfall frequency (not shown). Almost 70% of days with snowfall occur when the daily resultant wind direction is between  $79^\circ$  and  $147^\circ$ . This direction was coincident with 57% of the annual snowfall at KPDX during the 15-yr resultant wind record and 69% of the snow falling during the 36-yr peak gust record (not shown). The ESE direction is particularly prominent with over a third of the annual snowfall and nearly a third of the recorded snow days. In addition to the correlation between easterly wind direction and snowfall, a strong correspondence exists between the strength of the easterly wind and snowfall amount.

Statistics for freezing rain frequency (Fig. 10c) are even more striking. There were 46 occurrences of freezing rain over the 15 yr of resultant wind records, of which 38 were in winter, 7 were in autumn, and 1 was in spring.<sup>4</sup> The figure shows that freezing rain at KPDX is almost exclusively restricted to days with an easterly wind component. As for snowfall, freezing rain occurs more frequently as the easterly wind strength increases.

In summary, the strong correlations between easterly flow at KPDX and the occurrence of snow and freezing rain indicate that cold outflow of air from the Columbia Gorge plays a crucial role in creating conditions that support frozen precipitation in the western gorge and the northern Willamette Valley, including the Portland area. This effect is especially important during spring and autumn when significantly cooler than normal air is required to support snowfall and freezing rain west of the Cascades. An increase in snowfall and freezing rain with stronger easterly wind is expected since stronger flow is often due to a greater temperature gradient

along the gorge and thus a cooler and possibly deeper flow through the gorge.

## 5. Composite analysis

Composite analysis is a useful technique for identifying synoptic patterns that are associated with particular weather events and for examining how these patterns develop over time. For example, Ferber et al. (1993) used composites to identify the synoptic patterns that typically lead to snowfall over the Puget Sound lowlands. Composite fields can be created by averaging data from a gridpoint dataset for all days that a meteorological event occurs. The data source used in this study was the National Meteorological Center [NMC, now known as the National Centers for Environmental Prediction (NCEP)] Grid Point Data Set available on compact discs from the University of Washington (Mass et al. 1987). The dataset has a horizontal resolution of 380 km and is based on the National Meteorological Center's operational analyses for 0000 and 1200 UTC between 1948 and 1994.

In addition to the composite field, climatology, deviation from climatology, standard deviation, and statistical significance are calculated. The climatology field is a weighted average of monthly climatological averages of the months used in creating the composite. The deviation of the composite field from climatology is the difference between the composite and this weighted climatology. The standard deviations of the composited days are calculated to provide an indication of spread. Finally, the statistical significance of the deviations from climatology is calculated using the Student's *t* test (Panofsky and Brier 1968). Statistical significance was consistently high near regions of large deviation from climatology. Therefore, statistical significance and standard deviation fields are not shown here.

Composites are presented for occurrence of east and southeast winds satisfying different speed thresholds at Portland International Airport, days when 5.1 cm (2 in.) or more snow fell, and days on which freezing rain occurred. The COOP data from KPDX, described in the last section, were used to determine which days met these criteria. Since gorge gap flow events often last several days, care must be taken to ensure that data for a particular day are used only once in the production of composites.<sup>5</sup> Thus, only dates corresponding to the onset of an event were considered and an interval of at least 48 h not meeting the composite criteria was required for the next event to be considered independent from the previous one.

<sup>5</sup> For example, consider a case where winds above  $15 \text{ m s}^{-1}$  are being composited. If three consecutive days have winds within this criterion, and no precautions are taken, then the second day would be included in the composite for the time of the event, 24 h prior to the event and 24 h after the event. This will smooth the composite and mask interesting features in the temporal development leading up to the event and is therefore undesirable.

<sup>4</sup> This analysis was also performed using the longer (36 yr) peak gust time series during which there were 97 freezing rain events (2 in spring, 10 in autumn, and 85 in winter).

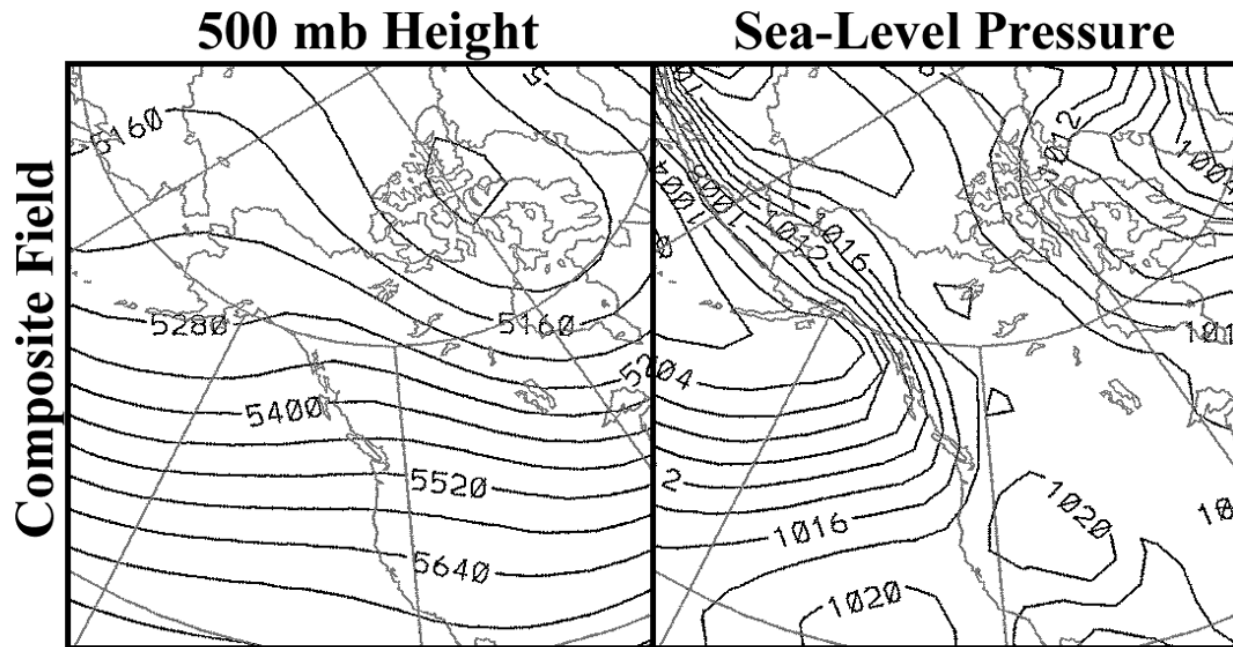


FIG. 11. DJF climatology composite for 1948–94 for 500-mb heights and sea level pressure. The contour intervals are 60 m and 2 mb, respectively.

The composites presented here only consider events occurring in December, January, and February (DJF). To provide a context for comparison of the results that follow, cold season climatological fields were determined by compositing the entire dataset for this period. This climatology for 500-mb heights and sea level pressure is given in Fig. 11.

*a. Easterly winds of  $13.4 \text{ m s}^{-1}$  ( $30 \text{ mi h}^{-1}$ ) or more at Portland*

Composites were created for times relative to the first day of easterly flow events for which the peak gust was  $13.4 \text{ m s}^{-1}$  ( $30 \text{ mi h}^{-1}$ ) or greater at KPDX. For these composites, easterly was considered as either an east or east-southeast wind. Dates between 1959 (when daily peak gust records began at KPDX) and 1994 (the last year in the NMC analysis dataset) were considered. During this period, a total of 289 days in DJF had east or east-southeast gusts of  $13.4 \text{ m s}^{-1}$  or more. Of these, 144 were at the start of a strong easterly flow event and therefore used to produce the composites.

Figure 12 shows the evolution of the composite 500-mb height field and its corresponding deviation from climatology, from 48 h prior to the beginning of the event to the time of the event. A similar figure for sea level pressure is presented in Fig. 13. Forty-eight hours prior to the onset of easterly flow at KPDX, the Pacific Northwest is downstream of a weak upper-level ridge at 500 mb. The features in this pattern are similar to those of climatology (Fig. 11) except that the amplitude of the eastern Pacific ridge within the midlatitudes is

30–60 m above average. Between  $-48 \text{ h}$  and the beginning of the event, this ridge amplifies rapidly, which is conducive to the southward advection of cold continental air from Alaska, the Yukon, and northern British Columbia; such cold advection is reflected in the 850-mb composite evolution (not shown). Forty-eight hours prior to the event, there is little deviation from climatology in the 850-mb temperature field anywhere in western North America; however, by the onset of easterly flow at KPDX, deviations from climatology of up to  $6^\circ\text{C}$  are present over southwestern Canada and the northwest United States.

The winter sea level pressure climatology (Fig. 11) shows a large pressure gradient between the east Pacific coast and Alaska–Yukon interior. This gradient is also evident in the composite plot for sea level pressure 2 days prior to the event (Fig. 13). At this time, pressure along the northwest U.S. coast is higher than normal in response to the developing upper ridge. As the ridge builds, surface pressure increases downstream and moves southward through British Columbia, translating the strong surface gradient with it. At  $-24 \text{ h}$ , the high pressure is centered over British Columbia, with positive deviations of up to 8 mb centered on the Queen Charlotte Islands. The pressure gradient across Washington State becomes weakly offshore but the area of strong pressure gradient is still well to the north. Toward the time of the event, the surface anticyclone strengthens and moves southward, with the strongest pressure gradient located over Washington State.

Considering the mesoscale terrain features of the Pacific Northwest, this synoptic evolution provides the

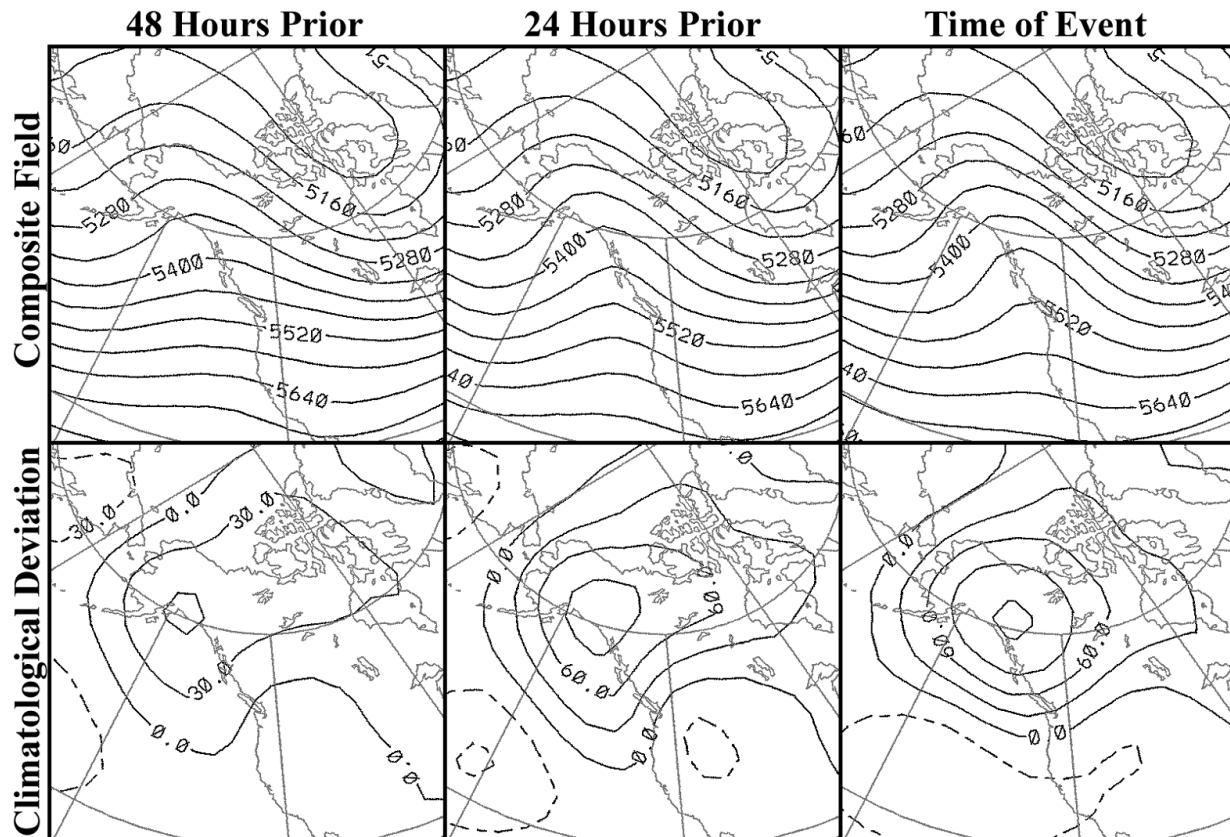


FIG. 12. The 500-mb height composite evolution leading to easterly wind events where the peak gust was greater than  $13.4 \text{ m s}^{-1}$ . (top) Composite field plotted at 60-m intervals. (bottom) Deviation of composite from climatology contoured every 30 m.

conditions required for strong gap flow through the Columbia Gorge. The development and positioning of the 500-mb ridge along the coast results in the development of a strong anticyclone east of the British Columbia Coastal Range that subsequently moves south to the east of the Cascade Range. This air mass is cut off from the moderating effect of the Pacific Ocean. Strong cooling at the surface strengthens the anticyclone by developing an extremely stable pool of cold air that is unable to move downgradient except through gaps or mountain passes that are lower than the depth of the cold pool. As a result, a strong pressure gradient is concentrated across the mountains. The Columbia Gorge, located at the southwest end of the Columbia Basin, is the lowest-elevation channel through which the cold air is able to move down the pressure gradient.

Substantial variation in gap flow duration limits the usefulness of compositing beyond event initiation. That said, composites for 24 h after initiation (not presented) show weakened climatological deviations but little qualitative change, suggesting that once established, synoptic conditions conducive to gap flow often remain for more than 24 h. Observational data corroborate this, indicating that the Columbia Basin cold pool is maintained by diabatic surface cooling. However, reduced cold advection into the Columbia Basin and the eastward

movement of the 500-mb ridge axis results in a gradual weakening of the inland anticyclone and hence the gap flow. The ultimate end of a strong easterly wind event is often marked by low pressure passing through the region. This may briefly revive the gap flow before removing the cold pool. Such events are discussed further below.

#### *b. Comparison of composites by wind speed and direction*

Using the KPDX peak gust data, composites were created for easterly wind speeds of  $8.9\text{--}13.0 \text{ m s}^{-1}$  ( $20\text{--}29 \text{ mi h}^{-1}$ ),  $13.4\text{--}17.4 \text{ m s}^{-1}$  ( $30\text{--}39 \text{ mi h}^{-1}$ ), and  $17.9 \text{ m s}^{-1}$  ( $40 \text{ mi h}^{-1}$ ) or more, as well as for events with a southeasterly peak gust of  $13.4\text{--}17.4 \text{ m s}^{-1}$ . The number of independent events composited for each category was 137, 118, 49, and 72, respectively. Note that for the southeasterly cases at KPDX the wind is easterly within the gorge but turns to southeasterly between the gap exit and KPDX. Figures 14 and 15 show the composites and deviations from climatology for the 500-mb height and sea level pressure fields for each of these categories for the day that the event began.

When evaluating the 500-mb height pattern (Fig. 14) as a function of easterly flow strength, two things stand



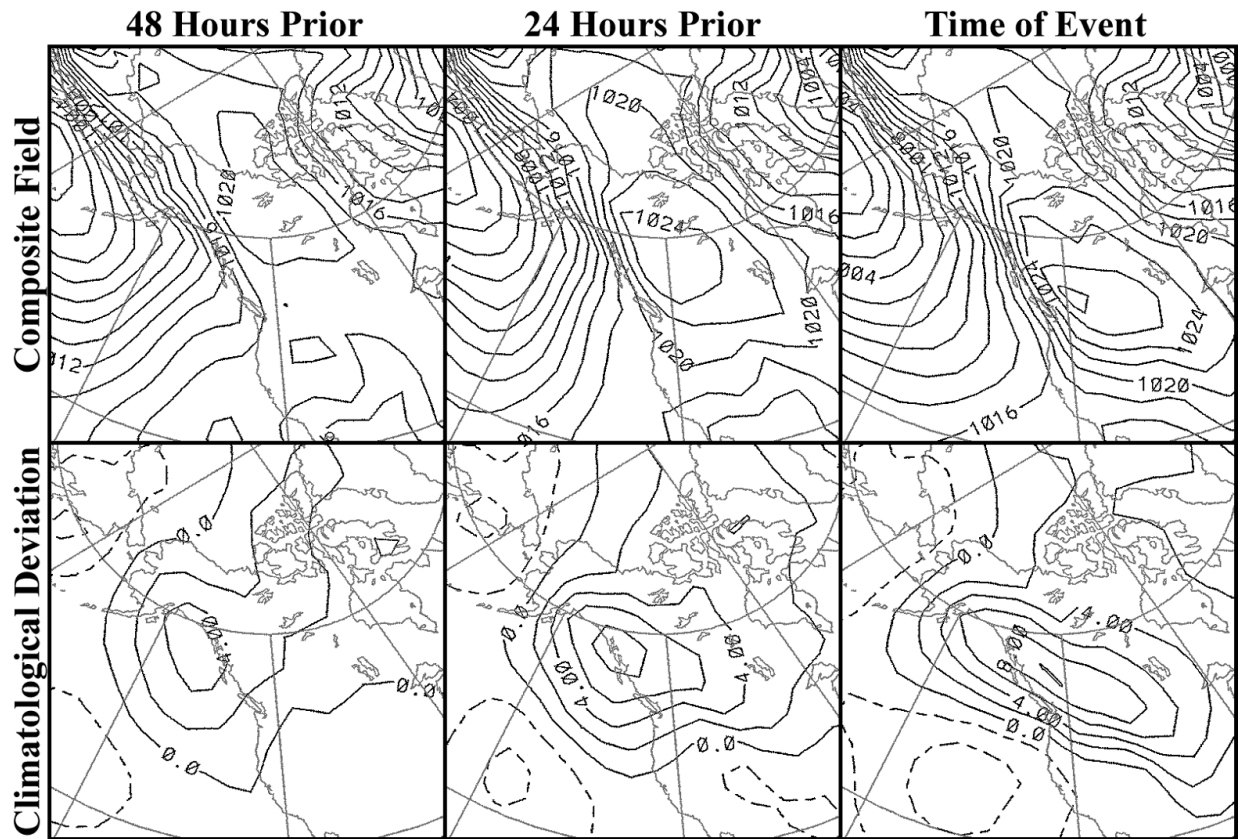


FIG. 13. Sea level pressure composite evolution leading to easterly wind events. All contours plotted at 2-mb intervals.

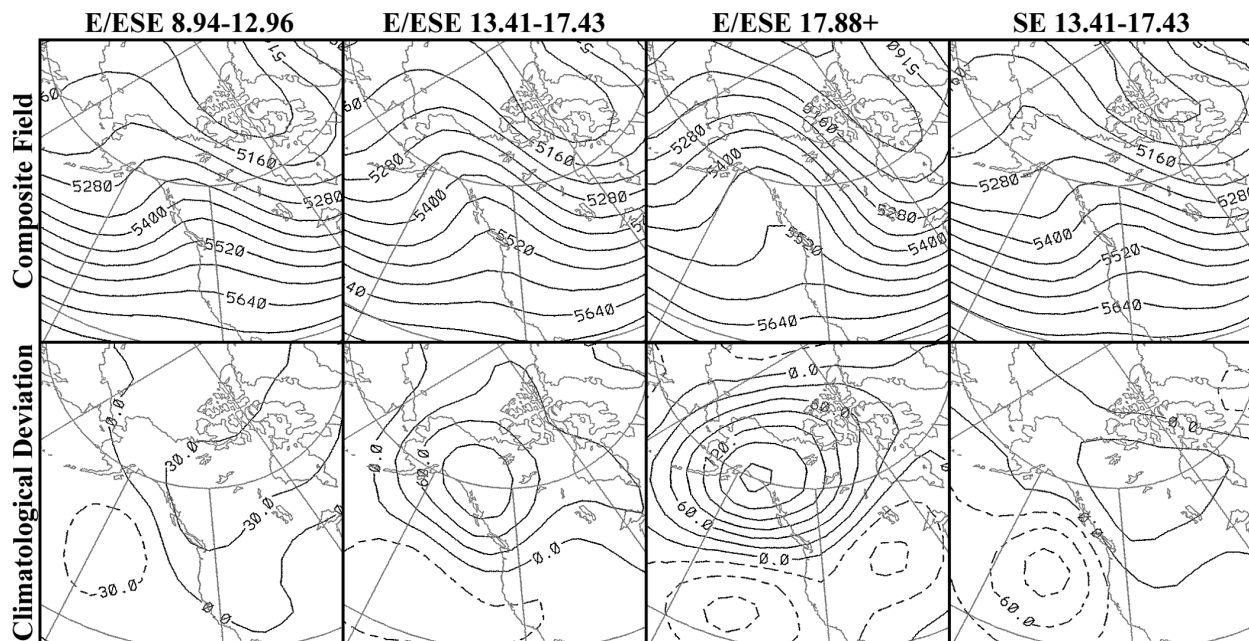


FIG. 14. The 500-mb height composites for easterly wind events of different strengths ( $\text{m s}^{-1}$ ) and directions based on data from the first day of the event. (top) The composite field has a 60-m contour interval and (bottom) the deviation field is plotted at a 30-m interval.

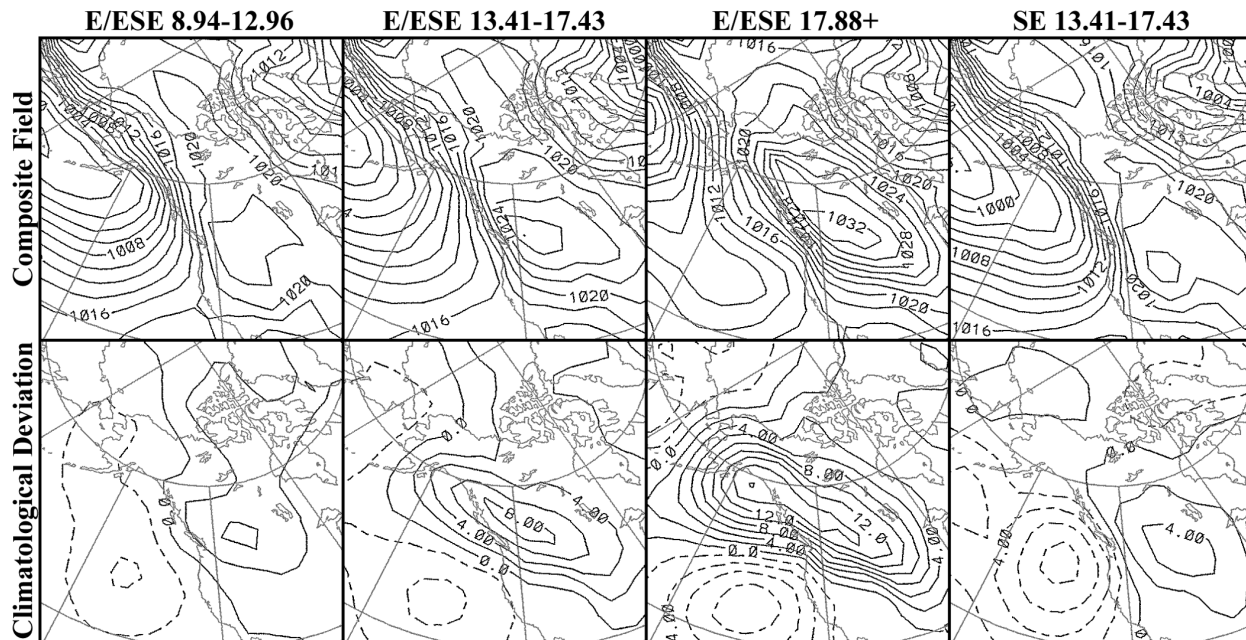


FIG. 15. The same as in Fig. 13 except for sea level pressure. The contour interval is 2 mb for both the composite and deviation fields.

out. First, there is a strong correlation between the magnitude of the height deviations from climatology in the region of the upper ridge and the strength of the easterly flow. Second, the location of the upper ridge axis is progressively farther west and more amplified as the strength of the wind increases. These differences, reflected in the 850-mb composite temperature (not shown) as an area of progressively stronger cold advection into the Pacific Northwest, result in higher surface pressure and a larger pressure gradient developing across the region (Fig. 15).

When the sea level pressure composites of east–east-southeast winds with speeds from 13.4 to 17.4  $\text{m s}^{-1}$  (Fig. 15, second left) are compared to those for the same wind speed range but from the southeast direction (Fig. 15, far-right), the pattern at first seems very similar. However, the plots of deviation from climatology are very different. In the case of the easterly wind at KPDX, the gradient is forced by anomalously high pressure east of the Cascades. Pressure over the whole northeastern Pacific is higher than usual, but the large inland anomaly still generates a very large offshore gradient. In the case of the southeasterly winds, pressure east of the Cascades is still a little higher than normal, but the large gradient is mainly generated by anomalously low pressure offshore due to an approaching storm.

Similar differences are apparent in the deviations from climatology of the 500-mb height field (Fig. 14, second left and far-right). While heights over the northeastern Pacific are higher than normal in the case of easterly wind, they are lower than normal in the case of the southeasterly direction. This is a consequence of the fact that the upstream upper-level trough is much

deeper and the trough axis farther west. The strongest flow is directed into the Pacific Northwest. To the north, the flow is weaker and by 24 h after the start of the event (not shown), the northern part of the ridge splits away while at midlatitudes the ridge weakens and moves eastward.

Events in which the flow exiting the gorge becomes southeasterly are much more likely to be accompanied by precipitation. Precipitation fell on 35% of the days with an east–east-southeast peak gust of 8.9  $\text{m s}^{-1}$  (20  $\text{mi h}^{-1}$ ) or more at KPDX compared to 64% for days with southeasterly flow of that magnitude. Thus, strong easterly gap flow within the gorge may be categorized into two families with distinct characteristics. Type A, driven mainly by high pressure anomalies to the east, tends to be dry, with gap outflow that remains easterly beyond the gorge exit. Type B is driven by low pressure anomalies to the west, tends to be wet, and the exit jet turns increasingly southeasterly outside the gorge exit. The differences in behavior at the gap exit probably relate to the depth of the outflow and the direction and strength of the wind above it. The 850-mb temperature composites and deviation plots (not shown) indicate that type A events coincide with colder than normal temperatures at that level. In addition, 850-mb height composites (not shown) indicate a synoptic-scale component to the easterly flow (i.e., the geostrophic flow aloft has some easterly component). Thus, the cold pool depth and shear profile in these cases are favorable for promoting relatively deep gap flow. Type B events are accompanied by approximately normal temperatures at 850 mb, which indicates that the gap flow will likely be shallower. In addition, the southerly synoptic-scale

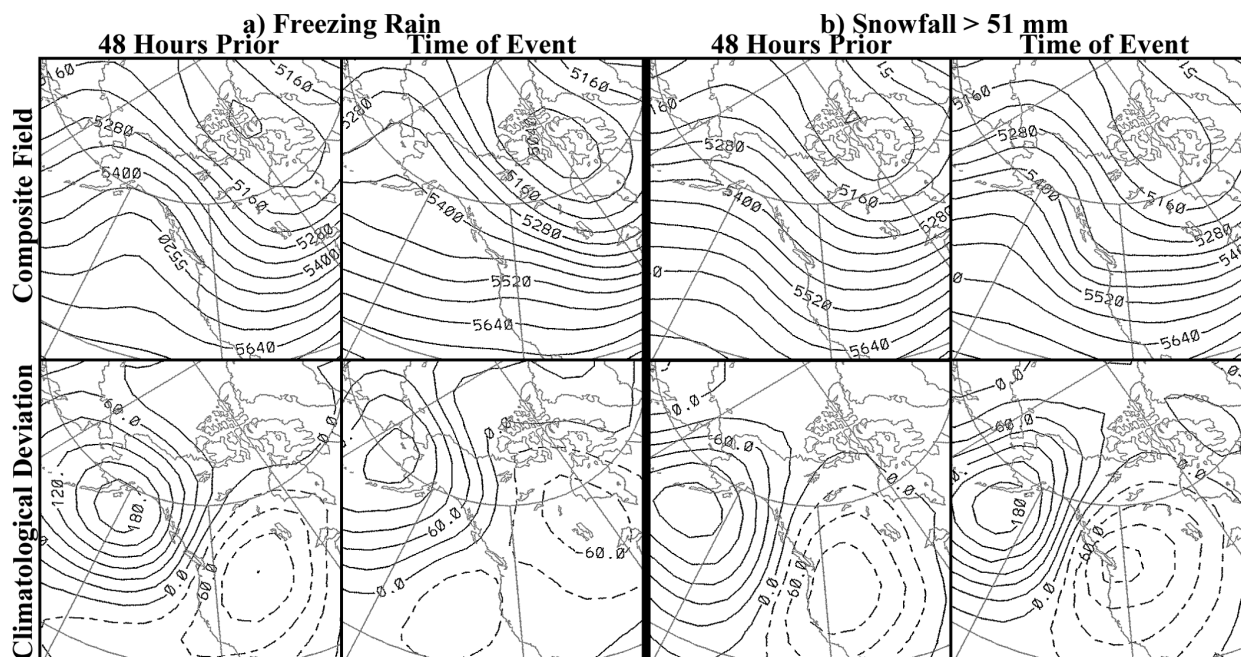


FIG. 16. The 500-mb height composites for freezing rain and snowfall events. Contour interval is 60 m for composite plots and 30 m for the deviations.

wind causes large shear across the interface. Thus, in the gap exit, southerly momentum is entrained into the exit jet causing the outflow to become more southeasterly.

### c. Freezing rain and snowfall at KPDX

Composite fields showing the evolution of synoptic patterns leading to freezing rain and snowfall were analyzed. Between 1948 and 1994, there were 145 days (129 in DJF) during which freezing rain fell and 222 days (189 in DJF) with over 5.1 cm (2 in.) of snow. Using only days in DJF, 62 freezing-rain days and 100 snow days were at the onset of events and used to produce composites. Figures 16 and 17 compare composites of 500-mb height and sea level pressure for the 48 h leading up to the onset of freezing rain and snowfall. Freezing rain and snowfall are associated with high-amplitude 500-mb ridging over the eastern Pacific, with the ridge axis and downstream trough farther west than in the composites for all east wind events (Figs. 12 and 13). A large pressure gradient is present across the Cascade Range at the onset of freezing rain and snow, so easterly gap flow is likely present, as expected given the correlation between frozen precipitation events at KPDX and easterly flow (see section 4d).

Two days prior to the onset of freezing rain, there is already a high-amplitude, full-latitude ridge over the eastern Pacific (Fig. 16a), with height anomalies of up to 180 m. The 850-mb thermal field (not shown) indicates that cold air was already present over the region at this time. The cold anomaly and strong ridging aloft

are reflected in the sea level pressure field with anomalously high pressure over the eastern Pacific and western British Columbia. A moderate pressure gradient exists across the gorge and easterly gap flow through the gorge is probably occurring at this point.

In the 48 h preceding the onset of freezing rain, the 500-mb ridge splits, resulting in zonal flow and falling surface pressure over the eastern Pacific south of 50°N. The northern branch of the ridge maintains its location and strength, providing continued cold advection into the northwest interior. The high pressure center east of the Canadian Coastal Range moves slowly south, strengthening the synoptic pressure gradient across the Columbia Gorge. South of the split, the composites indicate a weak upper-level trough approaching the coast. Pressure over the eastern Pacific falls as a surface low develops in response to the trough and the pressure anomaly offshore of Washington and Oregon reverses from over 4 mb above normal to 4 mb below normal. Warm air surges northward in the strong southerly flow ahead of the surface low, but east of the Cascades the warm advection above crest height is unable to erode the very stable cold pool in the Columbia Basin. The large cross-Cascade thermal gradient helps to intensify the mesoscale pressure gradient along the gorge, sustaining the movement of very cold air from the base of the cold pool westward through the gorge. Sleet and/or freezing rain occur in the gorge and its exit area where overrunning precipitation (rain) falls into this freezing layer. Analysis of the synoptic evolution of several individual events reveals that the 500-mb pattern will of-

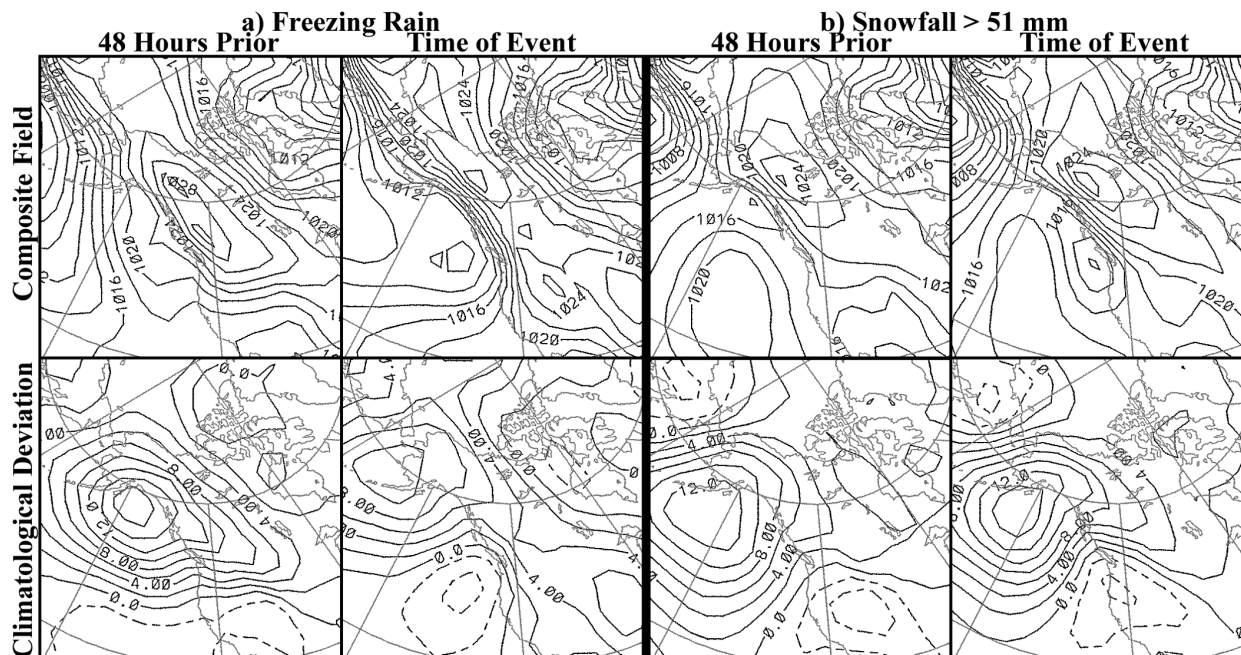


FIG. 17. Sea level pressure composites comparing freezing rain and snowfall synoptic evolution. Contour interval is 2 mb for all plots.

ten reamplify after the storm passes inland so that the evolution described above is repeated.

During freezing rain events, the pressure gradient is driven by pressure anomalies on both sides of the Cascades. Retrogression and subsequent splitting in the 500-mb ridge results in the storm track returning to the eastern Pacific, lowering pressure offshore of Washington and Oregon, but still providing for high pressure and cold advection inland. The result is a cold and wet event that is a hybrid of the type A and type B wind events that were mentioned above. Observational analyses confirm that freezing rain usually occurs when a storm approaches the coast after a period of sustained strong easterly flow accompanied by anomalously cold temperatures.

For snowfall (Figs. 16b and 17b), the evolution again begins with a strong upper-level ridge bringing a northerly upper-level flow to the West Coast. In this case, 48 h prior to snowfall initiation, the ridge axis is farther offshore than for the other composites and the downstream trough is much farther west. High surface pressure dominates the eastern Pacific, so the pressure gradient across the West Coast terrain is not great. By the time snow begins, the ridge does not evince the split seen in the freezing rain composite. This continues the cool northerly flow over the eastern Pacific. In the 850-mb temperature composite (not shown), cold air extends much farther offshore than it does in composites of other phenomena. Embedded between the ridge and trough axes is a sharp short wave extending across Vancouver Island and over the Washington and Oregon coasts, with an area of low surface pressure forming in response. Cold outflow through the gorge provides reinforcement

of the cold air that has reached northwestern Oregon from the north, helping to sustain a layer of cold air deep enough to support snow. This synoptic development is consistent with the pattern for snowstorms over the Puget Sound lowlands shown in the composites presented in Ferber et al. (1993). Note that the freezing rain composite evolution may also produce snowfall prior to the onset of freezing rain. Most often, the amount is less than the 5.1 cm required for inclusion in the survey above, but occasionally (and hence not discernable in the snowfall composites), when very cold air is in place, significant snow may fall at KPDX. The snow- and ice storm of January 2004 is an example of such a case.

6. Summary

This research has examined the significance of gap flow through the Columbia River gorge, the sole near-sea-level gap through the Cascade Mountains of Washington and Oregon. Gorge gap flow has large societal impacts, since the Columbia Gorge is a major transportation corridor (road and rail) and the densely populated Portland metropolitan area is close to the eastern terminus and greatly affected by gorge flow. Gorge gap flow events can bring damaging winds and conditions that support snowfall and/or freezing rain both in the gorge and downstream. The gorge is an excellent study area for gap flow research since it is relatively straight, level, accessible, and well instrumented.

Easterly gap flow in the gorge is common in the winter, when temperatures are 2°–9°C lower east of the Cascades. Thus, such events are often associated with

colder than normal low-level temperatures within and downstream of the gorge. The impact of the gap outflow on surface temperature extends south through the Willamette valley at least as far as Salem (74 km south of Portland). To the north of the gorge, the impact is more limited and, except in rare cases, does not extend far past Scappoose (29 km northwest of Portland). Strong winds due to the outflow extend no more than 25 km from the gorge exit, though moderate easterly flow may reach as far east as Hillsboro, almost 45 km west of the gap's eastern terminus. Temperature minima in and around the gorge are less correlated to gap flow strength than temperature maxima because the gorge flow causes vertical mixing, which opposes radiational cooling of the surface layer. Frozen precipitation is much more likely in the northern Willamette valley during gorge gap flow events. Specifically, at Portland International Airport, 70% of days with snowfall and 90% of days with freezing rain coincide with easterly gap flow.

In the summer, the cross-Cascade temperature gradient reverses, with the maximum temperature in the Columbia Basin being 6°C or more higher than at comparable elevations west of the Cascades. The hydrostatic pressure gradient associated with this thermal contrast results in a diurnally varying westerly wind in the gorge. Summer easterly winds bring warmer than normal temperatures to stations within and downstream of the gorge. The fact that the highest temperatures and largest temperature deviations during easterly conditions are downstream of the gorge suggests that subsidence off the surrounding terrain is a more important cause of warming than advection of warm air down the gorge.

Using 27 months of hourly reports from The Dalles (KDLS), Troutdale (KTTD), Portland (KPDX), and Hillsboro (KHIO), Oregon, it was shown that the pressure gradient across the Cascades is a good predictor of wind speed at the gap exit (KTTD), accounting for over 80% of the variance in easterly gap wind speed. This relationship diminishes with distance from the gap terminus, but the correlation is significant at KPDX ( $r = 0.69$ ) and still present at KHIO ( $r = 0.53$ ) over 42 km from the gap exit (see Table 1). The correlations between the pressure gradient across the gap exit region (KTTD–KPDX) and the easterly wind strengths at KPDX and KHIO are similar to the cross-Cascade pressure gradient–wind speed correlation. Forecasters should be aware that there are influences other than cross-Cascade pressure gradient that contribute to surface wind speed at these stations. For example, winds at KPDX sometimes diminish overnight or become light northwesterly even when the cross-Cascade pressure gradient is increasing.

The compositing study found that the synoptic evolutions leading to strong easterly winds, freezing rain, snowfall, and anomalously cold days within and near the gorge have several features in common: a high-amplitude 500-mb ridge upstream of the Pacific Northwest, a cold anomaly in 850-mb temperatures over British Columbia and the northwest United States, and a

strong sea level pressure gradient that is concentrated across the Cascades. However, comparison of composites classified by wind speed, occurrence of snow, or incidence of freezing rain revealed a distinct synoptic evolution and character for each type of event. Comparisons of medium-range synoptic forecast model output to the various synoptic patterns and evolution seen in the composite results may be useful to forecasters not only in identifying when gap flow is likely to develop, but also to identify the probable nature of the event.

Composites, including all easterly wind events at Portland (KPDX), exhibit a full-latitude, negatively tilted ridge, the axis of which lies along the North American west coast. A negative anomaly in 850-mb temperatures is centered over Montana extending westward into Washington, and high sea level pressure is centered over southwest British Columbia. The anomalies in all the fields become larger if only days with easterly winds stronger than  $13.4 \text{ m s}^{-1}$  ( $30 \text{ mi h}^{-1}$ ) are considered. In contrast, for days with a southeasterly wind at KPDX, the 500-mb ridge axis is shifted inland and the 850-mb temperature anomaly is farther east. There is still a large pressure gradient across the Cascades but this is forced by anomalously low pressure offshore. Split flow distinguishes the 500-mb pattern for freezing rain. Large 850-mb cold anomalies, in place over the Pacific Northwest well before freezing rain events begin, erode during the course of the events due to strong warm advection but persist longest in the Columbia Basin. The large pressure gradient during freezing rain events is driven by anomalously low pressure offshore and anomalously high pressure inland. Composites of snowfall at KPDX do not exhibit the split-flow pattern seen for freezing rain. The high-amplitude 500-mb ridge and trough are both farther west than in other composites, with the trough axis extending offshore from the west coast of North America. The cold anomaly at 850 mb extends farther offshore and southward than in any of the other composites. The largest positive sea level pressure anomalies and gradients are located farther north than in the other cases and there is a coastal low off the Washington–Oregon coastline.

In addition to the climatology study and the composite analyses reported in this paper, a detailed case study of a sustained gap flow event that occurred in December 2000 has also been completed. The case study utilized high-resolution mesoscale model simulations, contemporary observing platforms, such as radar and Aircraft Communications, Addressing and Reporting System (ACARS) data, and traditional surface reports. As well as defining the evolution and dynamical structure of the gap flow present during this event, the case study also verified that the gorge gap flow can be accurately modeled using a high-resolution numerical weather prediction model and determined the resolution and physical parameterizations required. A detailed summary of this work will be presented in a forthcoming

paper. Research is also on going to determine the structure and dynamical characteristics of gorge gap flow resulting from a broad range of different initial conditions using idealized high-resolution model simulations. This research will produce further insight and understanding of the dynamical mechanisms responsible for gorge gap flow.

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## APPENDIX

### Data Analysis Methodology

The dataset used in the climatological analysis was obtained from the National Climate Data Center (NCDC). It contained a record of all daily observations made at 826 NOAA COOP stations in Washington and Oregon. Data prior to 1948 were not considered, as coverage was sparse. An exhaustive quality control procedure was applied to the data to ensure that only reliable data were used in the analysis.<sup>A1</sup>

For most stations in the dataset, only maximum and minimum temperature, precipitation, snowfall, and snow depth were available. At some Surface Airway Observation (SAO) sites within the cooperative network, daily data existed for other meteorological fields including wind speed and direction for part or all of the period of record. Portland International Airport (KPDX) was the closest station to the gorge that had a long, largely unbroken record of daily wind parameters. Several other useful parameters were available for KPDX including a continuous record of daily significant weather reports (e.g., occurrence of freezing rain, snow, or fog) that were used to identify events for the composite analysis.

The resultant wind record for KPDX, which was reported to the nearest degree, spans a 15-yr period. The peak gust speed and direction were reported at KPDX for a 36-yr period. The direction was supposedly reported on a 16-point cardinal scale (i.e., at intervals of 22.5° from 0° to 360°), but it was clear that most of the data for KPDX lay on the eight major points (i.e., N, NE, E, etc.) so the directional resolution had to be reduced to 45°. Whenever the peak gust was used to categorize winds, the same analysis was repeated using the resultant wind parameter. There was good agreement in all cases. There were, however, consistent differences that can be explained by the different ways that the parameters are defined. Systematic shifts in wind speed and direction are reflected in the resultant wind. For

example, a period of easterly winds at KPDX usually ends with an abrupt shift to southerly or southwesterly winds. Thus, the resultant wind on days with such a transition will have more of a southerly component than the peak gust (assuming the peak was from the east). The choice of parameter for presenting results here was based upon which one best suited each particular analysis. Because the peak gust record is significantly longer, it was used when the largest possible overlap with other data was required, for example, to select dates for compositing or when categorizing the data at other stations. Resultant wind was used in presentation of single-station data because of its better directional resolution.

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<sup>A1</sup>This included discarding data that passed NCDC quality control but were found to be suspect. Monthly and annual values calculated from the daily data were also compared to monthly and annual averages obtained from the Western Region Climate Center for the same stations. A good match was obtained. Details of the quality control can be found in Sharp (2002).

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