The Columbia Gorge is the only near–sea-level passage through the Cascade Mountains of Washington and Oregon (Fig. 1). Otherwise, with the exception of a few mountain passes, the Cascade Range is a continuous barrier that separates moist maritime air to the west from dry continental air to the east. Gap flow through the gorge plays a profound role in determining the weather and climate both within and adjacent to the gorge, including populated areas such as Portland, Oregon.

Gap flow occurs in the Columbia Gorge when a pressure gradient develops across the Cascades. When pressure is higher to the east, flow within the gorge is normally easterly and, conversely, when there is higher pressure west of the gap, the flow is usually westerly. In both cases, the flow is parallel to the gap and is highly nongeostrophic. Westerly flow in the gorge is most frequent during the warm season when the subtropical ridge over the eastern Pacific moves north, resulting in higher surface pressure offshore. This synoptic pressure gradient is often enhanced in summer by a thermal low that develops over the hot interior. Since the thermal low intensifies during the day, the pressure gradient and westerly flow are typically strongest during the afternoon. Dependable westerly winds have made the gorge a premier wind surfing location.

In contrast, easterly gap flow is more common in the cool season when synoptic-scale high pressure often develops east of the Cascades and low pressure systems frequently approach from the west. Sustained, strong easterly flow is particularly likely when synoptic-scale high pressure east of the Cascades promotes radiational cooling, forming a mesoscale pool of cold, dense air in the Columbia Basin that increases pressure east of the barrier. Strong static stability prevents the air from moving west across the mountains, leaving the Columbia Gorge as the main drain for this pool of cold air. The resulting easterly gales can bring sustained periods of damaging winds to the western end of the gorge and downstream of the exit and may push cold, continental air west of the Cascades. If the outflow is subfreezing, precipitation overrunning the...
cold gorge flow will reach the ground as snow or freezing rain (Portland’s “Silver Thaw”).

Figure 2 illustrates the impact of the gorge gap flow on the wintertime climate at Portland International Airport (KPDX). Frequent easterly gap flow through the gorge produces a prevailing east-southeasterly wind at Portland and the majority of strong winds blow from directions between east and southeast (Fig. 2a). Snowfall occurs almost exclusively during easterly gap flow, with amounts increasing with wind speed (Fig. 2b). Over 90% of freezing rain in Portland occurs when the wind direction is between east and southeast at KPDX (Fig. 2c) and freezing rain occurs more frequently near the gorge than at locations to the north and south.

Between 11 and 15 December 2000, a gorge event brought sustained strong winds, freezing temperatures, and wintry precipitation to the Portland area. On 10 December, a high-amplitude upper-level ridge was moving toward the west coast of North America (Fig. 3). To the east of the ridge axis, northerly flow helped push arctic air southward through British Columbia. Along and behind the arctic air boundary, surface pressure increased in response to the upper-level pattern and low-level cold advection. The arctic front entered Washington at 1500 UTC on 10 December and pushed quickly through eastern Washington, accompanied by rapidly falling temperatures and dewpoints as well as rising pressure. West of the Cascades, the front was much weaker and its progress was slowed by the blocking effects of the mountains. By 1200 UTC 11 December, the eastern portion of the front had moved into northeastern Oregon, while west of the Cascades it had stalled in southwestern Washington (Fig. 4). As a result, the pressure difference across the Cascades began to increase rapidly, initiating the gorge gap flow event that continued until 0000 UTC 15 December.

Figure 5a shows how the pressure gradient changed as three successively stronger disturbances moved through the Pacific Northwest. The first two disturbances were weak and did not affect the low-level cold pool over the Columbia Basin. Passage of a cold front associated with the third, stronger system abruptly ended the easterly gap flow. Winds suddenly switched to strong westerlies, and temperature, dewpoint, and surface pressure rose rapidly on the
A strong correlation between the pressure gradient across the gorge and wind direction at Troutdale (TTD; located close to the western exit) is apparent in Fig. 5a. The correlation between pressure gradient and wind speed at Troutdale is strong but not perfect (Fig. 5b), indicating that other factors such as stability and mixing are also important in modulating gorge winds. Wind at The Dalles (KDLS; located within the gorge, to the east of the Cascade Crest) is weak throughout the event, except for a brief peak coinciding with falling temperatures and dewpoints (Fig. 5c) that marked the initial surge into the gorge of cold dry continental air behind the arctic front. The dewpoint drops a few hours later at Troutdale (Fig. 5d), but temperatures there do not drop significantly because the outflow begins at night and dissipates a preexisting nocturnal inversion. In addition, strong vertical mixing at the gap exit also mixes warmer air above into the low-level gap flow.

A regional hand analysis at 1800 UTC 13 December (Fig. 6a) shows a strong pressure gradient across the Cascades and a nose of high pressure extending from the Columbia Basin into the gorge that reflects the westward movement of dense cold air into the gap. Observations in an expanded view (Fig. 6b) show the acceleration of air in the exit region of the gorge.

Part of the motivation for studying the December 2000 event was the availability of data from contemporary observing platforms such as the Aircraft Communications Addressing and Reporting System (ACARS) and WSR-88D. Figure 7a shows ACARS soundings from commercial aircraft ascending from or descending into Portland International Airport. Because the runway is oriented west–east, aircraft ascend or descend directly along the gorge outflow axis. The panels show the gap flow at three times: during initiation as the winds became easterly (0708 UTC 11 December), when the gap flow was fully developed and deepest (0534 UTC 12 December), and during the final stages of the event when strong southwesterly flow aloft was eroding the outflow leaving only a shallow surface layer of cold easterly flow (1646 UTC 14 December). Figure 7b shows radial velocity data from the Portland WSR-88D, located to the west of Portland. Unfortunately, the high elevation of the radar (514 m) allows only the upper portions of gap outflow to be seen. The images in the figure are from an early part of the event, when precipitation was present and the flow was still deep enough to be cap-
tured by the radar beam. The gap outflow is clearly visible on both the 0.5° and 1.5° scan angles as a narrow swath of inbound velocities between 25 and 35 kt to the southeast of the radar. Outbound flow is also apparent to the northwest.

A major question is whether narrow gaps, such as the gorge, can be successfully modeled by high-resolution numerical simulations. To that end, the December 2000 gorge event was simulated at high resolution using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5). A comparison of model output at 36, 12, 4, 1.333, and 0.444 km found that a horizontal grid spacing of 1.333 km or less is required to accurately represent the meteorological structures within the gap and exit regions. Figure 8 shows a vertical section through the lowest part of the gorge for the 36-, 4-, 1.33-, and 0.444-km domains. The gorge is indicated as a 700-m high pass through the Cascades when 36-km grid spacing is used. Consequently, cold air remains dammed to the east and only weak easterly flow develops. There is only modest improvement at 12- (not shown) or 4-km grid spacing because the gorge is still being represented as an elevated gap. At 1.33 km, a dramatic improvement is realized, as the terrain becomes sufficiently resolved to allow air to flow through rather than over the Cascades.

Although accurate verification at very high resolution is difficult, a subjective evaluation of the simulation using a grid spacing of 444 m indicated some improvement over the 1.33-km run. Plots of horizontal sections (such as the one in Fig. 9) also show substantial improvement in the representation of outflow structure as resolution is increased. Simulations with a vertical resolution of 44 levels (with 17 levels in the lowest 1 km) captured the gap interface better than simulations with 32 and 38 levels.

**Fig. 7.** Observations of gorge outflow from nontraditional platforms. (a) Temperature and wind soundings derived from ACARS data. [EAST] indicates aircraft taking off and ascending eastward toward the gorge, [WEST] indicates aircraft approaching from the west to land at —PDX. (b) Base radial velocity plots from the RTX WSR-88D radar with 0.5° (left) and 1.5° (right) beam elevation.
Fig. 8. Cross sections at 2100 UTC 13 Dec (forecast hour 2100) of potential temperature (color filled and labeled every 5 K) and wind field (full flag represents 5 m s$^{-1}$, with isotachs also plotted in white every 5 m s$^{-1}$). The cross sections follow the river through the lowest part of the gorge and compare output from successively higher-resolution domains.
The high-resolution model output provided a level of detail not available in the observational network, enabling analysis of the three-dimensional atmospheric structures within and near the gap. For example, the model wind field from the 444-m domain (Fig. 9) shows that the air does not accelerate significantly in the eastern (upstream) portion of the gap. Instead, the zone of greatest acceleration and velocity is located near the exit of the gorge where the gap flow spreads and collapses as it becomes less constrained by surrounding terrain (see also Fig. 8d). By looking at other model output (not shown), it can be seen that the region of strongest winds slopes upward back into the gorge and that the low-level pressure drops rapidly from east to west as the cold air shallow. The Venturi Effect is a popular conceptual model used to explain gap flow.

The evidence from this study suggests, however, that the Venturi Effect is relatively unimportant and that, instead, hydraulic effects cause most of the acceleration of the flow. In other words, the acceleration of the air stream in the gorge is produced by the pressure gradient associated with the decreasing depth of the cold air in the gap exit, not the convergence of air streams on the upstream side. The high-resolution output also provides considerable detail about the behavior of the flow once it leaves the gorge. The exit jet continues to become shallower and widen and maintains a coherent structure for some distance downstream. The coldest outflow is near the surface and is diverted south into the northern Willamette Valley.

High-resolution modeling and new observational assets have illuminated the structures and dynamics associated with narrow gaps such as the Columbia River Gorge and suggest the potential for improved prediction of gap winds and associated weather features. Routine high-resolution forecasts of gorge flow that produce more realistic structures like those shown here will soon become operationally feasible as increasing computer power becomes available.

**FOR FURTHER READING**


