Major Extratropical Cyclones of the Northwest United States: Historical Review, Climatology, and Synoptic Environment

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ABSTRACT

The northwest United States is visited frequently by strong midlatitude cyclones that can produce hurricane-force winds and extensive damage. This article reviews these storms, beginning with a survey of the major events of the past century. A climatology of strong windstorms is presented for the area from southern Oregon to northern Washington State and is used to create synoptic composites that show the large-scale evolution associated with such storms. A recent event, the Hanukkah Eve Storm of December 2006, is described in detail, with particular attention given to the impact of the bent-back front/trough and temporal changes in vertical stability and structure. The discussion section examines the general role of the bent-back trough, the interactions of such storms with terrain, and the applicability of the “sting jet” conceptual model. A conceptual model of the evolution of Northwest windstorm events is presented.

1. Introduction

Although the cool waters of the eastern Pacific prevent tropical cyclones from reaching the shores of the northwest United States, this region often experiences powerful midlatitude cyclones, with the strongest possessing winds comparable to category 2 or 3 hurricanes. Such cyclones are generally far larger than tropical storms and the resulting damage is greatly enhanced by the region’s tall trees. Even though Northwest extratropical cyclones have produced widespread damage and injury, national media attention has been less than for their tropical cousins. Only a handful has been described in the literature (Lynott and Cramer 1966; Reed 1980; Reed and Albright 1986; Kuo and Reed 1988; Steenburgh and Mass 1996), and questions remain regarding their mesoscale and dynamic evolutions, including interactions with terrain. A review of the National Oceanic and Atmospheric Administration (NOAA) publication Storm Data and newspaper accounts suggests a conservative estimate of damage and loss since 1950 due to cyclone-based windstorms over Oregon and Washington of 10 to 20 billion (2009) U.S. dollars (USD). Perhaps the richest resource describing the powerful cyclones that strike the region is the extensive series of Web pages produced by Wolf Read (more information available at http://www.climate.washington.edu/stormking/), which reviews over 50 storms.

The Pacific Northwest is particularly vulnerable to strong cyclone-based windstorms because of its unique vegetation, climate, and terrain. The region’s tall trees, many reaching 30 to 60 m in height, act as “force multipliers,” with much of the damage to buildings and power lines associated not with direct wind damage but from the impact of falling trees. Strong winds, predominantly during major cyclones, account for 80% of regional tree mortality, rather than old age or disease (Kirk and Franklin 1992). Heavy precipitation in the autumn, which saturates Northwest soils by mid-November, enhances the damage potential, since saturated soils lose adhesion and the ability to hold tree roots. The substantial terrain of the Northwest produces large spatial gradients in wind speed, with enhanced ageostrophic flow near and in major topographic barriers that produces localized areas of increased damage. The most destructive winds from major Northwest storms are overwhelmingly from the south and generally occur when a low center passes to the northwest or north of a location.

The closest analogs to major Northwest cyclones are probably the intense, and often rapidly developing, extratropical cyclones of the North Atlantic that move...
northeastward across the United Kingdom and northern Europe. Cyclones striking both regions develop over the eastern portion of a major ocean and thus exhibit the structural characteristics of oceanic cyclones, as documented by Shapiro and Keyser (1990). Several of the European events have been described in the literature, including the 15–16 October 1987 storm (Lorenc et al. 1988; Burt and Mansfield 1988), the Burns’ Day Storm of 25 January 1990 (McCallum 1990), the Christmas Eve Storm of 24 December 1997 (Young and Graham 1999), and the series of three storms that struck northern Europe in December 1999 (Ulbrich et al. 2001). Browning 2004, Browning and Field (2004), and Clark et al. (2005) present evidence that a limited area of strong winds associated with evaporative cooling and descent (termed a sting jet) occurred during the October 1987 storm. As discussed later, a major difference in the environment for the landfalling major cyclones of Europe and the northwestern United States is the substantial coastal terrain of the latter, which contrasts with the lesser coastal topography of the United Kingdom and the European mainland. The importance of the Northwest terrain on windstorm winds is examined in the discussion section.

This paper documents the climatology of strong Pacific Northwest cyclones, examines the synoptic environments in which they develop, describes some intense events with large societal impacts, considers a well-simulated recent event (the 2006 Hanukkah Eve storm), and identifies some outstanding scientific questions regarding their development and dynamics.

2. Historical review

This section describes the general characteristics and societal impacts of a collection of strong midlatitude cyclones that have produced substantial damage and economic loss over the northwest United States. The selection of these events is based on both objective evidence (such as surface wind speeds) and subjective information from newspaper articles, research papers, and weather-related publications such as NOAA’s Storm Data.

a. 9 January 1880

The first documented cyclone-associated windstorm of the Northwest occurred on 9 January 1880. Regarded by the Portland Oregonian as “the most violent storm . . . since its occupation by white men,” the cyclone swept through northern Oregon and southern Washington, toppling thousands of trees, some 2–3 m in diameter. Two ships off the central Oregon coast reported minimum pressures of 955 hPa as the cyclone passed nearby, and wind gusts along the coast were estimated at 120 kt (62 m s\(^{-1}\)). Sustained winds exceeding 50 kt (26 m s\(^{-1}\)) began in Portland during the early afternoon, demolishing or unroofing many buildings, uprooting trees, falling telegraph wires, and killing one person. Scores of structures throughout Oregon’s Willamette Valley were destroyed and hundreds more, including large public buildings, were damaged.

b. The Olympic Blowdown Storm of 29 January 1921

The “Great Olympic Blowdown” of 29 January 1921 produced hurricane-force winds along the northern Oregon and Washington coastlines and an extraordinary loss of timber on the Olympic Peninsula. Over the southwest flanks of the Olympic Mountains more than 40% of the trees were blown down (Fig. 1), with at least a 20% loss along the entire Olympic coastline (Day 1921). As noted in Ferber and Mass (1990) and discussed later in this paper, the localization of damaging winds probably resulted from mesoscale pressure perturbations produced by the Olympics. A Weather Bureau observation at the North Head lighthouse, on the north side of the mouth of the Columbia River, indicated a sustained wind of 98 kt (50 m s\(^{-1}\)), with an estimated maximum gust of 130 kt (68 m s\(^{-1}\)) before the anemometer was blown away.\(^1\) Although the coastal bluff seaward of North Head may have accelerated the winds above those occurring over the nearby Pacific, the extensive loss of timber around the lighthouse and the adjacent Washington coast was consistent with a singular event. At Astoria, on the south side of the Columbia, there was an unofficial report

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\(^1\) Before 1928, winds were measured by the Weather Bureau with a four-cup brass anemometer, compared to current three-cup anemometers. Thus, pre-1928 wind speeds are not strictly comparable to those reported for latter storms.
of 113 kt (58 m s\(^{-1}\)) gusts, while at Tatoosh Island, located at the northwest tip of Washington, the winds reached 96 kt (49 m s\(^{-1}\)).

c. 12 October 1962: The Columbus Day Storm

By all accounts, the Columbus Day Storm was the most damaging windstorm to strike the Pacific Northwest in 150 years. It may, in fact, be the most powerful nontropical storm to affect the continental United States during the past century. For example, Graham and Grumm (2007) found that the Columbus Day Storm had greater synoptic wind and geopotential anomalies than any other midlatitude cyclone for the period 1948–2006. An extensive area stretching from northern California to southern British Columbia experienced hurricane-force winds, massive tree falls, and widespread power outages. In Oregon and Washington, 46 died and 317 required hospitalization. Fifteen billion board feet of timber were downed, 53,000 homes were damaged, thousands of utility poles were toppled, and the twin 158-m steel towers that carried the main power lines of Portland were crumpled. At the height of the storm approximately one million homes lost power in the two states, with damage estimated at a quarter of a billion (1962) USD.

The Columbus Day Storm began east of the Philippines as a tropical storm, Typhoon Freda, and followed the passage of a moderate storm the previous day. As it moved northeastward into the mid-Pacific on 8–10 October, the storm underwent extratropical transition. Approximately 1900 km northwest of Los Angeles, the storm abruptly turned northward and deepened rapidly, reaching its lowest pressure (roughly 955 hPa) approximately 480 km southwest of Brookings, Oregon, at around 1400 UTC 12 October 1962 (see Fig. 2 for the storm track). Maintaining its intensity, the cyclone paralleled the coast for the next 12 h, reached the Columbia River outlet at approximately 0000 UTC 13 October with a central pressure of 956 hPa, and crossed the northwest tip of the Olympic Peninsula 6 h later (Fig. 3a). At most locations, the strongest winds followed the passage of an occluded front that extended eastward from the storm’s low center.

At the Cape Blanco Loran Station on the southern Oregon coast, sustained winds reached 130 kt (67 m s\(^{-1}\)) with gusts to 179 kt (92 m s\(^{-1}\)), at the Naselle radar site in the coastal mountains of southwest Washington gusts hit 139 kt (72 m s\(^{-1}\)), and 130-kt gusts (67 m s\(^{-1}\), the instrument maximum) were observed repeatedly at Oregon’s Mount Hebo Air Force Station on the central Oregon coast. The winds at these three locations were undoubtedly enhanced by local terrain features, but clearly were extraordinary. Away from the coast, winds gustied to 80–110 kt (41–57 m s\(^{-1}\)) over the Willamette Valley and the Puget Sound Basin. Strong winds were also observed over California, with sustained winds of 50–60 kt (26–31 m s\(^{-1}\)) in the Central Valley and gusts of 104 kt (54 m s\(^{-1}\)) at Mt. Tamalpais, just north of San Francisco.

![Fig. 2. Tracks of some major midlatitude cyclones striking the Pacific Northwest.](http://journals.ametsoc.org/mwr/article-pdf/138/7/2499/4259957/2010mwr3213_1.pdf)
FIG. 3. Sea level pressure analyses for (a) the 1962 Columbus Day and (b) 1993 Inauguration Day cyclones. Short-term (3 h) sea level pressure forecasts for (c) the 2006 Hanukkah Eve storm and (d) the December 2007 coastal storm from the 12-km domain of the University of Washington regional prediction system. Contour interval is 1 hPa; (a) is from Lynott and Cramer (1966) and (b) is from Steenburgh and Mass (1996).
Lynott and Cramer (1966) performed a detailed analysis of the storm, noting that during the period of strongest winds at the surface nearly geostrophic southerly flow aloft was oriented in the same direction as the low-level ageostrophic southerlies that were accelerating down the north–south-oriented low-level pressure gradient. The strongest surface winds occurred when stability was reduced after passage of the occluded front, thus facilitating the vertical mixing of stronger winds aloft down to the surface. They also noted that the particular track of the storm, paralleling the coast from northern California to Washington State, was particularly conducive to widespread damage (Fig. 2). The storm was poorly forecast, with no warning the previous day.

d. 13–15 November 1981

A number of major Northwest windstorms have come in pairs or even triplets during periods of favorable long-wave structure over the eastern Pacific (specifically, a long-wave trough), and this period possessed such back-to-back windstorms, with the first producing the most serious losses. The initial low center followed a course similar to the Columbus Day Storm except that it tracked about 140 km farther offshore, with landfall on central Vancouver Island (Fig. 2). Over the eastern Pacific this storm intensified at an extraordinary rate, with the pressure dropping by approximately 50 hPa during the 24-h period ending 0000 UTC 14 November 1981. At its peak over the eastern Pacific, the storm attained a central pressure of just under 950 hPa, making it one of the deepest Northwest cyclones of the century; coastal winds exceeded hurricane strength, with the Coast Guard air station at North Bend, Oregon, reporting a gust of 104 kt (52 m s\(^{-1}\)). Winds over the western Oregon and Washington interiors reached 60–70 kt (30–35 m s\(^{-1}\)).

Thirteen fatalities were directly related to the November 1981 storms: five in western Washington and eight in Oregon. Most were from falling trees, but four died in Coos Bay, Oregon, during the first storm when a Coast Guard helicopter crashed while searching for a fishing vessel that had encountered 9-m waves and 70-kt (35 m s\(^{-1}\)) winds. Extensive power outages hit the region with nearly a million homes in the dark.

Reed and Albright (1986) found that this cyclone was associated with a shallow frontal wave that amplified as it moved from the relatively stable environment of a long-wave ridge to the less stable environment of a long-wave trough. Both sensible and latent heat fluxes within and in front of the storm prior to intensification contributed to the reduced stability. As with all major storms before 1990, the guidance by National Weather Service numerical models was unskillful, with the Limited-Area Fine Mesh (LFM) model 24-h forecasts providing little hint of intensification. Kuo and Reed (1988) successfully simulated the 1981 storm using the fourth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM4), and found that roughly half the intensification in the control experiment could be ascribed to dry baroclinicity and the remainder to latent heat release and its interactions with the developing system. Their numerical experiments suggested that poor initialization was the predominant cause of the problematic operational forecast.

e. 20 January 1993: The Inauguration Day Windstorm

Probably the third most damaging Northwest storm during the past 50 years (with the 1962 Columbus Day Storm being number one and the 2006 Hanukkah Eve event in second place) struck the region on the inauguration day of President Bill Clinton. Winds of over 85 kt (43 m s\(^{-1}\)) were observed at exposed sites in the coastal mountains and the Cascades, with speeds exceeding 70 kt (35 m s\(^{-1}\)) along the coast and in the interior of western Washington. In Washington State six people died, approximately 870 000 customers lost power, 79 homes and 4 apartment buildings were destroyed, 581 dwellings sustained major damage, and insured damage was estimated at 159 million (1993) USD.

The Inauguration Day Storm intensified rapidly in the day preceding landfall on the northern Washington coast. At 0000 UTC 20 January, the low-pressure center was approximately 1000 km east of the northern California coast with a central sea level pressure of 990 hPa. The storm then entered a period of rapid intensification, with the central pressure reaching its lowest value (976 hPa) at 1500 UTC 20 January, when it was located offshore of the outlet of the Columbia River (Fig. 3b). A secondary trough of low pressure associated with the storm’s bent-back occlusion/warm front extended south of the low center, and within this trough the horizontal pressure differences and associated winds were very large. During the next six hours, as the low-pressure center passed west and north of the Puget Sound area, the secondary trough moved northeastward across northwest Oregon and western Washington, bringing hurricane-force winds and considerable destruction.

Official National Weather Service forecasts were excellent for this storm, with the skillful predictions reflecting the substantial improvement in numerical weather prediction during the previous 10 years. Steenburgh and Mass (1996) investigated the effects of terrain on the storm winds using the fifth-generation PSU–NCAR Mesoscale Model (MM5). They found that pressure perturbations created by the interaction of the bent-back front with the Olympic Mountains extended the time period of
high winds in the Puget Sound area but did not enhance peak winds.

f. 12 December 1995

Of all the major windstorms to strike the Pacific Northwest, few were better forecast or studied more intensively than the event of 12 December 1995. Hurricane-force gusts and substantial damage covered a large area from San Francisco Bay to southern British Columbia, leaving five fatalities and over 200 million (1995) USD of damage in its wake. A number of locations in western Oregon and Washington experienced their lowest pressure on record as the storm’s low center bottomed out near 953 hPa off the Washington coast. The storm struck northern California early in the day, with gusts of 90 kt (45 m s\(^{-1}\)) at San Francisco; later along the Oregon coast, from Cape Blanco to Astoria, winds gusted 85–105 kt (43–53 m s\(^{-1}\)), while over the Willamette Valley and Puget Sound basins gusts approached 80 kt (40 m s\(^{-1}\)). Approximately 400,000 homes in Washington, 205,000 customers in Oregon, and 714,000 homes in northern California lost power during this storm.

A field program called Coastal Observation and Simulation with Topography Experiment (COAST) was underway during the December windstorm, and the NOAA WP-3D aircraft examined storm structure both offshore and as the system approached the coastal mountains of Oregon and Washington. Flying offshore of the Oregon coast at around 1300 m, the plane experienced winds of 85–105 kt (43–53 m s\(^{-1}\)) in a highly turbulent environment, with salt spray reaching the plane’s wind shield as high as 600 m above the wind-whipped seas (N. Bond 2009, personal communication).

g. 14–15 December 2006: The Hanukkah Eve Storm

The most damaging winds since the Columbus Day Storm of 1962 struck the region on 14–15 December 2006, with winds gusting to 80–90 kt (40–45 m s\(^{-1}\)) along the Northwest coast, 60–70 kt (30–35 m s\(^{-1}\)) over the western lowlands, and 85–105 kt (43–53 m s\(^{-1}\)) over the Cascades. Over 1.5 million customers lost power in western Oregon and Washington, at least 13 individuals lost their lives, and estimates of damage ranged from 500 million to a billion (2006) USD.

The December 2006 storm approached the region as a 970-hPa low and followed a more westerly trajectory than typical of major Northwest windstorms, which generally enter from the south to southwest (Fig. 2). Intensifying as it approached the coast, the storm’s central pressure fell rapidly to approximately 973 hPa just prior to making landfall along the central coast of Vancouver Island. As the low-pressure center moved inland over southern British Columbia, the region of largest pressure gradient and winds, associated with the bent-back trough on its southern flank, moved across western Washington, bringing widespread wind damage (Fig. 3c).

Over western Washington, the damage associated with the 2006 storm substantially exceeded that of the 1993 Inauguration Day Storm. Nearly twice as many customers lost power than in 1993 and restoration took several weeks in some neighborhoods. Although the winds in 2006 were comparable to those of 1993, extraordinary wet antecedent conditions produced saturated soils and poor root adhesion, which resulted in substantially more tree loss and subsequent damage.

h. 3–4 December 2007

One of the region’s most unusual, long-lasting, and intense windstorms struck the northern Oregon and southern Washington coastal zones for an extended period on 3–4 December 2007. Two-minute sustained winds of 45–65 kt (23–33 m s\(^{-1}\)), with gusts as high as 130 kt (67 m s\(^{-1}\)), produced extensive tree falls, building damage, and power outages from Lincoln City, on the central Oregon coast, to Grays Harbor County of coastal Washington. The extraordinary winds toppled or snapped off trees throughout coastal Oregon and Washington, including extensive swaths of forests (Fig. 4). The December 2007 storm was highly localized: while winds were blowing at hurricane force over the coastal zone, surface winds were light to moderate over Puget Sound and the Willamette Valley.

The December 2007 event was singular in several ways. First, most major Northwest windstorms are associated with intense and fast-moving low-pressure centers that move rapidly northward along the coast, producing strong winds for only three to six hours. In contrast, the long period of hurricane-force gusts from this windstorm was associated with a persistent area of large pressure gradient, between a deep, slow-moving low offshore and much higher pressure over the continent, which remained over the northern Oregon/southern Washington coastlines for nearly 24 h (Fig. 3d). Second, this storm was associated with extraordinary rainfall over the coastal mountains, with some locations in the Chehalis Hills of southwest Washington receiving 700 mm of rain in little over a day. In general, few cyclone-based windstorms are associated with sustained heavy rains and flooding, as found with this event.

3. Climatology of windstorm events

In this section, a climatology of major cyclone-related windstorm events is presented using an objective approach based on surface wind observations. Because most of the population in the region lives along the
interior corridor west of the Cascade Mountains and east of the coastal terrain, this analysis will focus on identifying and characterizing strong southerly wind events within that region. The wind climatologies at interior stations (not shown) indicated that although most had their strongest winds from a southerly direction, some sites experienced high winds from other directions because of regional terrain features such as gaps. For example, Portland, Oregon (PDX), reported a high frequency of strong winds from the east, the result of gap flow through the Columbia River Gorge (Sharp and Mass 2004). For most stations, the primary or secondary wind maxima were from a southeasterly to southwesterly direction, and these maxima are associated with the major cyclones that cross the region. Thus, to isolate cyclone-related high-wind events, the direction between $135^\circ$ and $225^\circ$ was used as a directional criterion. To aid in the identification of regional windstorm characteristics, the region of interest was split into four subregions (Fig. 5).

An event was identified as a major windstorm if two or more adjacent stations in a north–south line of 10 stations (Fig. 5) experienced 35 kt (18 m s$^{-1}$) or greater sustained southerly winds (the National Weather Service high-wind warning threshold) in a 24-h period. Using this criterion, 32 separate events were identified since 1948 (Table 1), all associated with Pacific cyclones. The largest number of events (18) occurred in the northernmost division (region 1) and the least (7) over the southern Oregon section (region 4). We found it interesting that most of the events in the southern three regions occurred before 1965, in contrast to region 1, where only 22% of the events occurred before that date. Some events influenced more than one region, particularly the 1962 Columbus Day Storm, which affected all four.

The number of cyclone-related windstorms is greatest in December (Fig. 6). Other major windstorm months include November, January, and February, with reduced, but significant, numbers in October and March.

4. Synoptic composites of Northwest windstorms

An important question deals with the synoptic environment associated with major storms and how that environment differs from climatology. To that end, composites of sea level pressure (SLP), 850-hPa temperature, and 500-hPa height for the dates of major windstorms noted above were created using the NCEP–NCAR reanalysis (Kalnay et al. 1996). These data are at 2.5° spatial resolution and 6-h temporal resolution and are available from 1948 to the present. A daily climatological mean is calculated by interpolating monthly means, assuming they are valid for the midpoint of each month. The composites for each region were calculated for the time of strongest winds (0 h) and for 24 and 48 hours before ($-24$, $-48$ h). In addition, anomalies from climatology and the areas in which the anomalies differ from the mean.
at the 95% and 99% confidence levels were calculated using a Student’s *t* test. In what follows, only the composites for region 2 are shown, the composites for the other regions are qualitatively similar, but with key features displaced to the north or south.

Turning to the region 2 sea level pressure composites, a large area of low pressure dominates the northeastern Pacific two days before the high winds, with deviations from climatology approaching −14 hPa (Fig. 7). During the subsequent 48 h, a trough over the southwestern portion of the domain rapidly moves northeastward and amplifies into a closed low, which is found just north of region 2 at the time of strongest winds (0 h). The result is an intense north–south gradient over Washington and Oregon. There is relatively little SLP variance over the Northwest at the time of strongest winds, and the significance of the key trough/low center exceeds the 99% level.

At 500 hPa, a broad, large-scale trough dominates the eastern Pacific two days before the strong winds (Fig. 8). A short-wave trough moves through this long-wave feature and approaches the Pacific Northwest at the time of strongest winds. Associated with this trough is enhanced southwesterly 500-hPa flow over the eastern Pacific. The deviations from climatology of this trough exceed 250 m and are significant at the 99% level.

Significant deviations of 850-hPa temperatures from climatology accompany these windstorms (Fig. 9). Two days before the strongest winds, an east–west zone of enhanced baroclinicity is found over the subtropical Pacific between a large cold anomaly over the north Pacific and a warm anomaly west of southern California. This cold anomaly, with a magnitude exceeding 6°C, moves toward the Pacific Northwest in association with a short-wave trough, while a warm anomaly pushes northward to the east. The significance of the cold anomaly exceeds the 99% level.

5. A recent example: The Hanukkah Eve Storm of 14–15 December 2006

Since the Hanukkah Eve Storm was extremely well forecast two days prior to the strongest winds, the MM5
was used to illustrate its synoptic and mesoscale evolutions. The strongest winds struck western Washington between 0600 and 1200 UTC 15 December 2006 and simulations initialized at 0000 UTC 14 December and 0000 UTC 15 December are considered.

The 500-hPa geopotential heights from this storm are reminiscent of the composites, with a broad long-wave trough over the eastern Pacific and an intense short-wave trough moving northeastward toward the northwest along an enhanced jet stream/height gradient (Fig. 10). The 12-h sea level pressure forecast for 1200 UTC 14 December shows a 978-hPa low making landfall on central Vancouver Island, and an intense sea level pressure gradient associated with the bent-back trough and front to the south of the low. During the next 6 h, the low center moved northeastward into southern British Columbia, while the intense pressure gradient associated with the bent-back trough rotated into western Washington (Figs. 11d,e).

The simulated 10-m wind speeds and sea level isobars during the hours leading up to landfall are shown in Fig. 12. At 2100 UTC 14 December, when the low was still offshore, the strongest sustained winds, reaching 45 kt (23 m s\(^{-1}\)), were associated with the bent-back front to the west and northwest of the low center (Fig. 12a). At this and previous hours there was some suggestion of

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Fig. 6. The number of windstorm events influencing at least one of the regions shown in Fig. 5 for the period 1948–2006.
coastal acceleration along the Oregon coast and to a lesser degree southeast of the Olympics. Six hours later the low deepened to 972 hPa and sustained winds in the bent-back front and trough had increased to over 55 kt (28 m s\(^{-1}\); Fig. 12b). The coastal acceleration has disappeared, and as suggested later, this may be due to the destabilization of the atmosphere as cooler air moved in aloft. By 0600 UTC, the strongest winds with the bent-back front were poised to make landfall as the low center began crossing central Vancouver Island (Fig. 12c). Finally, at 0900 UTC, the extraordinary pressure gradient and winds with the bent-back trough had moved over western Washington (Fig. 12d). At the same time, the low center was moving to the north over the British Columbia mainland.

As noted by Von Ahn et al. (2005, 2006), scatterometer winds are useful for determining the wind distributions in intense oceanic cyclones. The QuikSCAT scatterometer winds at approximately 1400 UTC 14 December 2006 indicate that the strongest sustained winds, reaching 50 kt (26 m s\(^{-1}\)) or more, were associated with the warm front to the north of the cyclone and in the bent-back trough/front to the south of the low center (Fig. 13a). A later view of the storm just before landfall (0400 UTC 15 December) shows the strongest winds [exceeding 50 kt (26 m s\(^{-1}\))] to the south and southwest of the low center in the bent-back trough (Fig. 13b). Both of these scatterometer wind fields are consistent with the model simulations shown above, and reflect common structures in strong oceanic midlatitude cyclones.

A frequently observed feature of oceanic cyclones is an intense, bent-back front whose baroclinicity increases rapidly with height in the lowest few thousand feet above the ocean surface, and which weakens in the middle troposphere. Figure 14 shows the simulated 850-hPa thermal structures, heights, and winds for the storm before and during landfall. At 0000 UTC 15 December, an intense warm front is found west and north of the low center; it weakens south of the low (Fig. 14a). As in cases documented by Shapiro and Keyser (1990), Neiman
and Shapiro (1993), and Neiman et al. (1993), the strongest winds are closely aligned with this intense bent-back baroclinic zone. During the period before the bent-back trough makes landfall, the intense bent-back temperature gradient and associated winds rotate around the low in counterclockwise fashion (Figs. 14b,c). There is also evidence of a warm-seclusion structure as the cold air circles the low, a feature noted by Shapiro and Keyser (1990), Neiman and Shapiro (1993), and Neiman et al. (1993).

To explore the differences in conditions on the coast and within the western Washington interior associated with this storm, Figs. 15 and 16 present the temporal evolution of surface parameters at two sites: one 15 km off the Pacific coast (Destruction Island) and another over central Puget Sound (West Point lighthouse). At Destruction Island, the winds increased rapidly and switched from easterly to southeasterly around 1800 UTC 14 December as the warm front pushed north of that location (Fig. 15). The approach of the bent-back front and trough produced continuing pressure falls, and the arrival of the bent-back front resulted in temperatures falling after 0300 UTC 15 December. As the trough passed, pressure rose rapidly, winds shifted to northwesterly and the winds peaked at 62 kt (31 m s\(^{-1}\)) around 0900 UTC 15 December. At West Point, inland between two main regional barriers (the Olympics and the Cascades), winds increased considerably later in the day with warm frontal passage between 2000 UTC 14 December and 0100 UTC 15 December. The winds during this period, constrained between the two barriers, maintained a southerly (roughly 200°) direction. The bent-back trough moved through between 0900 and 1000 UTC and was associated with the strongest gusts, reaching 55 kt (27 m s\(^{-1}\)) but little change in direction. As at Destruction Island, the strongest winds occurred during the period of rapid pressure rises and cold advection, a characteristic of most Northwest cyclonic windstorms.

A critical element of strong Northwest cyclone events is the evolution of the shear and stability profiles aloft prior to and during the strongest winds. As first noted by Lynott and Cramer (1966), winds accompanying such
windstorms often increase rapidly during the transition to lower stability after passage of occluded or warm fronts. Figure 17 presents the wind and temperature aloft over central Puget Sound based on Aircraft Communications Addressing and Reporting System (ACARS) data during ascents and descents into Seattle Tacoma and Boeing Field airports as well as surface observations at Seattle Tacoma Airport during the December 2006 event. Prior to warm/occluded front passage (1800–2300 UTC 14 December), modest low-level winds were generally easterly and the lower atmosphere was stably stratified (nearly isothermal). A large shear in horizontal wind existed between the surface [southeasterly at ~5–15 kt (~2–7 m s\(^{-1}\))] and above approximately 1000 m [over 50 kt (25 m s\(^{-1}\))]. The front crossed Puget Sound at the surface at approximately 0030 UTC 15 December, with a shift in the surface winds from southeasterly to southwesterly, a strengthening of the winds aloft, and a reduction of vertical stability. The back-bent front/through started moving in after 0300 UTC, resulting in cooling and further destabilization aloft. Strong winds lowered toward the surface up to the time of maximum wind gusts, near 0800 UTC.

Reflectivity and Doppler wind velocities from the National Weather Service Camano Island radar (Fig. 18; the radar is located 50 km north of Seattle) illustrates the changes in wind and precipitation structures in time. Although the coastal zone is blocked by the Olympic Mountains, this radar gives a good view down the Strait of Juan de Fuca and over the interior lowlands. At 1934 UTC 14 December, a few hours prior to the passage of the surface warm front, moderate to heavy rain had spread over the region, and an S-shaped configuration of the zero-Doppler velocity line, characteristic of warm advection, was evident. Low-level winds near the radar were from the southeast at 10–30 kt (5–15 m s\(^{-1}\)). At 0054 UTC 15 December, the warm front was moving through and precipitation became more showery. A band of high reflectivity, marking the surface front, was associated with intense rainfall, approaching 2.5 cm over an hour at some locations. Extraordinary urban flooding occurred, causing the drowning death of a Seattle woman.
in her basement. Low-level winds had shifted to southerly and increased to 50–60 kt (26–31 m s\(^{-1}\)); they slowly increased during the next four hours in the postfrontal showers (0405 UTC). By 0806 UTC, the bent-back trough had reached the region and the winds had strengthened further. As the trough moved through the Puget Sound region, strong westerlies began to push eastward into the Strait of Juan de Fuca (also evident in the radar by the tongue of blue color). Convergence at the leading edge of the westerlies produced an area of greatly enhanced reflectivity. Finally, by 0959 UTC, the bent-back trough had moved sufficiently eastward for strong westerly flow to push through the Strait into the northern Sound, with the leading edge of enhanced precipitation approaching the western Cascade slopes. Westerly winds aloft produced a north–south rainshadow east of the Olympics and the mountains of Vancouver Island.

6. Discussion

The above historical and climatological reviews of major cyclone-based windstorms affecting the Pacific Northwest interior reveal some of the essential synoptic characteristics of these events, while the case study of the Hanukkah Eve Storm illustrates important mesoscale features. In this section, mesoscale aspects will be examined in more detail and some of the major outstanding questions are discussed.

a. The role of the bent-back trough and front

Simulations and mesoscale analyses of strong, recent Northwest cyclone/windstorms (e.g., Steenburgh and Mass 1996) reveal common structural elements, with the bent-back trough and front being the focus of strongest winds in most events. In these Northwest cyclones, the largest temperature gradients above the boundary layer are in a bent-back front that passes through and south of the low center. The strongest winds are at low levels (lowest kilometer) on the cold side of this front, which extends southward into the bent-back trough south of the low center. The strongest winds are at low levels (lowest kilometer) on the cold side of this front, which extends southward into the bent-back trough south of the low center. Structurally, this configuration is similar to those found in oceanic cyclones during major field programs such as the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) and the Genesis of Atlantic Lows Experiment (GALE) (e.g., Neiman and Shapiro 1993; Neiman et al. 1993) and is frequently evident in scatterometer winds over the oceans (Von Ahn et al. 2005, 2006; Fig. 13). As in the strong maritime cyclones studied by Neiman and Shapiro (1993) and Neiman et al. (1993), intense Northwest cyclones often possess a warm core structure produced by cold air rotating around the low center, and this geometry produces a reverse vertical shear and weakening of the winds above the lower
troposphere. As noted earlier, strong oceanic cyclones strike northern Europe and the United Kingdom, and the association of strong winds with the bent-back front and trough is evident both in observations and in realistic modeling studies (e.g., Burt and Mansfield 1988; Clark et al. 2005).

b. Interactions of storms with terrain

Unlike the situation in much of continental Europe and the United Kingdom, major Northwest windstorms interact with substantial coastal and near-coastal topographic barriers, with some terrain exceeding 2 km in vertical extent. Such interactions have the potential to greatly alter mesoscale pressure and wind distributions, and thus the impact of these storms. An important issue is the degree to which low-level storm winds are accelerated over the coastal waters by terrain, which ranges from the relatively low, but extensive, coastal mountains of Oregon to the isolated, but higher, Olympic mountains.

FIG. 11. SLP (hPa) and 925 hPa temperatures (°C, color) at (a) 1200 UTC 14 Dec, (b) 0000 UTC 15 Dec, (c) 0300 UTC 15 Dec, (d) 0600 UTC 15 Dec, and (e) 0900 UTC 15 Dec 2006. Isobar contour interval is 1 hPa; (a) and (b) are from the 36-km domain and (c)–(e) from the 12-km domain.
Ferber and Mass (1990) showed that strong southerly or southeasterly winds interacting with the Olympic Mountains produces an intense pressure gradient on the southwest side of the mountains between the mesoscale pressure ridging to the south of the barrier and pressure troughing to the north (Fig. 19). This enhanced pressure gradient often greatly accelerates winds along the central coast of the Olympic Peninsula during the initial periods of major windstorm events when southerly flow in the lower atmosphere approaches the barrier. Such topographically enhanced winds may well have contributed to the extensive forest blowdown along the central Olympic coastline during the severe 1921 storm. Enhanced winds are also observed over northern Puget Sound and the eastern Strait of Juan de Fuca during such periods caused by the hypergradient created by troughing to the lee (north) of the Olympics (also see Fig. 19). Under extreme situations with very high Froude numbers of the incoming flow, the lee trough can intensify into a well-defined mesoscale low with large pressure gradients.

Fig. 12. MM5 10-m wind-speed forecasts (kt) valid at (a) 2100 UTC 14 Dec, (b) 0300 UTC 15 Dec, (c) 0600 UTC 15 Dec, and (d) 0900 UTC 15 Dec 2006. SLP isobars (hPa) are shown in solid lines, 1-hPa contour interval.
FIG. 13. QuikSCAT scatterometer surface winds for approximately (a) 1400 UTC 14 Dec and (b) 0400 UTC 15 Dec 2006. Wind speeds (kt) are color-coded.
Such a situation occurred during the Hood Canal windstorm event of 13 February 1979, when the strong flow of a synoptic cyclone approaching the coast intersected the Olympic Mountains, resulting in an intense low to the northeast of the barrier that accelerated winds to over 100 kt ($51 \text{ m s}^{-1}$; Reed 1980). Steenburgh and Mass (1996) examined the influence of coastal terrain on the winds associated with the Inauguration Day Storm of January 1993. Starting with a realistic high-resolution MM5 simulation, the coastal terrain was removed to determine its impact. The results suggested only minimal terrain enhancement of winds along the coast during the period of strongest winds, and that troughing in the lee of the Olympics prolonged the period of high winds over the northern Puget Sound area.

Another obvious influence of regional terrain is the strong ageostrophic winds within and downstream of gaps and channels in the mountains prior to and during major cyclone-based windstorm events. As the low centers move northward or northeastward along the coast, large east–west pressure gradients can develop across gaps in the Cascade and coastal mountains, resulting in strong downgradient flow, either associated with sea level gaps (such as the Columbia River Gorge or the Strait of Juan de Fuca) or higher-level gaps or passes, such as Stampede Gap of the central Washington Cascades, with the latter associated with hybrid gap/downslope winds.
Such downslope flow descending Stampede Gap has produced strong easterly or southeasterly winds reaching 70–120 km/h (31–62 m s\(^{-1}\)) prior to the development of strong southerly winds that occur as the low center makes landfall to the north. As a result, some lowland sites downstream of gaps can experience two wind maxima associated with cyclone-based windstorms: an easterly maximum when the low center is immediately offshore and a southerly peak when the low passes north of the region.

Strong downgradient ageostrophic flow up the major north–south “channels” west of the Cascade crest (such as the Willamette Valley, the Puget Sound basin, and the Strait of Georgia) is a hallmark of the cyclone-based windstorms of the region. As described by Overland (1984), when isobars are parallel to terrain barriers, the winds can be nearly geostrophic, but when the isobars are oriented normal to the mountain barrier crests so that there is a substantial along-barrier pressure gradient, air tends to accelerate downgradient ageostrophically within a Rossby radius of deformation of the terrain under stable conditions. In such situations, the Coriolis force is not an effective restraint on flow acceleration and the major balance is between pressure gradient, drag, and acceleration. It is partially for this reason that the greatest wind speeds in the interior lowlands occur when the low center moves north of the point in question, since that configuration produces a large along-barrier pressure gradient and ageostrophic acceleration at low levels. In addition, when

![Fig. 15. Destruction Island, WA, surface observations from 1200 UTC 14 Dec to 0000 UTC 16 Dec 2006.](http://journals.ametsoc.org/mwr/article-pdf/138/7/2499/4259957/2010mwr3213_1.pdf)
a low center is northwest of a location, the winds aloft generally have a southerly component; thus, low-level ageostrophic acceleration to the north is supported by the downward mixing of southerly momentum from aloft. Furthermore, when a low center has moved northward, there is generally lower-tropospheric cold advection and destabilization, thus enhancing the downward mixing of higher momentum air from above.

Bond et al. (1997) and Bond and Walter (2002) noted that winds measured at 600–1400 m MSL off central Oregon by the NOAA WP-3 aircraft during the 12 December 1995 windstorm did not evince any acceleration over the coastal waters as the low made landfall to the north. During that period, the lower troposphere was well mixed with a high Froude (Fr) number (roughly 3), where

$$\text{FR} = \frac{U}{(hN)}$$

$U$ is the incoming flow speed, $h$ is the height of the terrain, and $N$ is the Brunt–Väisälä frequency. In contrast, substantial coastal acceleration has been found when strong flow approaches the much higher terrain of southeast Alaska and Vancouver Island (Overland and Bond 1993, 1995; Loescher et al. 2006; Colle et al. 2006; Olson et al. 2007).

Examining simulations from the 2006 Hanukkah Eve storm and dozens of landfalling storms during 2008 and 2009, the authors have often noted coastal wind enhancement immediately upwind of the Oregon coastal terrain with landfalling cyclones during periods of greater lower-tropospheric stability that precedes occluded/warm front passage. To illustrate this enhancement, Fig. 20 shows the near-surface winds every six hours from a
realistic MM5 simulation of the 2006 Hanukkah Eve storm using 4-km grid spacing. During the initial time, winds north of the warm front (positioned along the southern Oregon coast) were southeasterly with no evidence of coastal acceleration (1200 UTC; Fig. 20a). There is a suggestion of coastal enhancement south of the warm front, where the winds had increased and shifted to southwesterly. Six hours later (1800 UTC; Fig. 20b), the warm front had reached the Oregon/Washington border and coastal acceleration is evident, particularly north of Cape Blanco, on the southern Oregon coast. At 0000 UTC coastal enhancement was still apparent along the Oregon coast, but not along the Washington coast where the mountains are less continuous (Fig. 20c). During the next 12 h, as the bent-back trough approached, cooler air moved in aloft, the vertical stability lessened, the wind veered to a more westerly direction, and the coastal enhancement weakened and subsequently disappeared (Figs. 20d,e).

To better understand the simulated coastal wind enhancement, the model soundings during the event at Salem, Oregon, in the Willamette Valley, are shown in Fig. 21. The initial sounding at 1200 UTC 14 December, immediately before surface warm frontal passage at that location, indicated an unsaturated and stable boundary layer, with considerable shear between weak southeast-erlies at low levels and moderate southwesterlies aloft (Fig. 21a). Six hours later, after warm frontal passage, the winds were southwesterly through depth, but considerable stability and shear remained in the lowest 100 hPa (Fig. 21b). It is during this time that low-level coastal speed enhancement became apparent (Fig. 20). Over the next 12 h, low-level stability slowly decreased as cooler air spread in aloft (Figs. 21c,d). Simultaneously, coastal wind enhancements declined, either because of increased momentum mixing from aloft or lesser coastal blocking. Vertical shear was considerably reduced in Salem’s winds during this period. By 1200 UTC 15 December, there was a deep adiabatic layer extending from just above the surface and little evidence of coastal wind acceleration (Figs. 21e, 20). In short, when the lower atmosphere was characterized by onshore flow and considerable stability, coastal wind enhancement was evident. In contrast, during the period of strongest winds, a period with considerable destabilization aloft due to cold air advection, there is little suggestion of coastal wind enhancement along the Northwest coast. These findings are consistent with the aircraft observations taken during the 1995 windstorm (Bond et al. 1997) in which no coastal enhancement was noted during the latter portion of the storm as the low made landfall to the north.

Finally, almost all landfalling storms weaken rapidly as they approach and cross the largest terrain barriers of the region (the Cascades of Oregon and Washington, and its extension, the Coast Mountains, of British Columbia).

c. Application of the sting jet conceptual model to the northwest United States

As noted previously, a number of European researchers (e.g., Browning 2004; Browning and Field 2004; Clark
FIG. 18. (top) Doppler velocities (kt) and (bottom) reflectivity (dBZ) from the NWS Camano Island radar during the Hanukkah Eve Storm of 14–15 Dec 2006. Images from 1934 UTC 14 Dec and 0054, 0405, 0806, and 0959 UTC 15 Dec.
et al. 2005) have suggested the importance of a sting jet mechanism in major cyclones in which mesoscale areas of particularly strong winds are associated with evaporative cooling and descent. Specifically, they propose that the most damaging winds emanate from the evaporating tip of a hooked cloud head on the southern flank of the cyclone, with evaporative descent bringing high-momentum air down to the surface. Furthermore, they noted a banded structure in the hooked cloud field that they suggested was caused by slantwise convection.

There are reasons to question whether this mechanism is significant in Northwest windstorms. First, away from terrain there is little evidence for mesoscale localization of high winds for most large windstorms, a fact supported by the radar imagery shown for the recent Hanukkah Eve storm (Fig. 18) and for other events (not shown). Second, satellite imagery for a collection of major Northwest windstorm events do not suggest the cloud geometry noted by Browning (2004) and others during the period of strongest winds; namely, strong winds downstream of an evaporating cloud edge (Fig. 22). Finally, high-resolution simulations of Northwest windstorms (e.g., Steenburgh and Mass 1996; the Hanukkah Eve event shown above) can produce realistic strong winds without any evidence of sting jet structures and dynamics. It is, of course, possible that this mechanism could occur over the Northwest, but at this point, there is little evidence of its importance.

d. Cyclone central pressure versus wind speed

Central pressure is a useful, but imperfect, measure of wind speed and damage associated with Northwest mid-latitude cyclones; the major cyclone-based Northwest windstorms that produced extensive damage had central pressures as low as the mid-950s hPa to as high as approximately 980 hPa. To illustrate, Table 2 presents the central pressures at landfall of the strongest windstorms striking region 2 (see Fig. 5) since 1958. The greatest windstorm in terms of the extent and magnitude of strong winds (the 1962 Columbus Day Storm) possessed a very low central pressure (956 hPa), but so did strong, but lesser events (November 1981, December 1995). In contrast, extremely damaging contemporary storms (January 1993 and December 2006) had considerably higher central pressures (970s hPa). Clearly, factors other than central pressure are important: storms vary in size; the surrounding pressure fields differ among storms leading to different pressure gradients even if the central pressures are the same; the speed of motion and vertical stability properties of storms vary, as do storm trajectories with respect to major terrain barriers. Regarding the environment, if unusually high pressure is in place, then a nearby, but modest low, or a strong one well offshore can produce large pressure gradients associated with extreme winds. This latter situation occurred on 3–4 December 2007 when the contrast between unusually high pressure over land and a low-pressure system (ranging from 955 to 970 hPa) far offshore produced winds exceeding 100 kt (51 m s$^{-1}$) along the northern Oregon and Washington coasts for nearly 24 h, in contrast to most cyclone-based wind events that last 3–9 h as a deep low quickly passes through the region. Figure 3d shows the sea level pressure forecast from the MM5 near the height of the event (27 h, valid at 1500 UTC 3 December 2007).

e. Predictability

Great strides have been made in the prediction of intense cyclonic windstorms striking the northwest United States. Virtually every major storm prior to 1990 was not correctly forecast by the National Weather Service (NWS) because of the inability of operational numerical weather prediction systems to correctly initialize and forecast major cyclones. For example, showers and light winds were predicted over western Washington for the day of the great Columbus Day Storm of 1962. For the 14 November 1981 windstorm, the NWS operational high-resolution model at that time—the Limited-Area...
FIG. 20. The 10-m winds (kt) from an MM5 simulation (4-km grid spacing) initialized at 0000 UTC 14 Dec 2006 for forecasts verifying at (a) 1200 UTC 14 Dec, (b) 1800 UTC 14 Dec, (c) 0000 UTC 15 Dec, (d) 0600 UTC 15 Dec, and (e) 1200 UTC 15 Dec 2006. Simulated SLPs (hPa) are also shown.
Fine Mesh (LFM) model—only predicted a weak trough, but the availability of satellite imagery (from a local television station) gave the NWS a tool for providing some warning. Kuo and Reed (1988) using the MM4 for that storm found that improving the initialization with supplementary data produced a moderate cyclone, albeit still weaker than observed. In contrast, the 20 January 1993 Inauguration Day Storm and the 12 December 1995 event were well forecast by the Eta Model. Similar skill was noted for the December 2006 Hanukkah Eve event using the Global Forecast System (GFS) and North American Mesoscale (NAM) models.

A clear contributor to more skillful windstorm forecasts has been improved initialization over the Pacific.
because of enhanced observations (mainly from satellites) and better data assimilation. However, significant forecast failures for major storms still occur. For example, for the 3 March 1999 windstorm, listed in Table 1 above, the 48-h forecast of the Eta Model valid 0000 UTC 3 March 1999 predicted a low center that was 24 hPa too weak and positioned 500 km southeast of the observed location (McMurdie and Mass 2004). The initialization of the Eta Model over the Pacific was poor and the quality control scheme rejected good buoy data. The 48-h forecast from the NCEP Aviation Model (AVN) was better but still possessed large errors, with the central pressure of the low center being 13 hPa too weak and displaced 200 km to the south of the observed position.

Another recent failure was the 8 February 2002 “Valley Surprise” event, which brought winds gusting to 80 kt (41 m s$^{-1}$) in the southern Willamette Valley without any warning from the U.S. forecast models (McMurdie

<table>
<thead>
<tr>
<th>Landfall date</th>
<th>Pressure</th>
</tr>
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<tbody>
<tr>
<td>24 Feb 1958</td>
<td>978 hPa</td>
</tr>
<tr>
<td>12 Oct 1962</td>
<td>956 hPa</td>
</tr>
<tr>
<td>14 Nov 1981</td>
<td>956 hPa</td>
</tr>
<tr>
<td>20 Jan 1993</td>
<td>976 hPa</td>
</tr>
<tr>
<td>12 Dec 1995</td>
<td>954 hPa</td>
</tr>
<tr>
<td>15 Dec 2006</td>
<td>970 hPa</td>
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FIG. 22. Satellite imagery of three major Northwest windstorms at the time of maximum winds over western Washington. The 0900 UTC 15 Dec 2006 (a) infrared and (b) water vapor Geostationary Operational Environmental Satellite (GOES) imagery. Infrared imagery at (c) 1330 UTC 3 Mar 1999 and (d) 1800 UTC 20 Jan 1993.
and Mass 2004). For the 2002 event, there was a substantial variability in skill among major forecast centers, with the Met Office model producing the most skillful prediction.

f. A conceptual model of Northwest wind events

Most major Northwest windstorm events caused by strong midlatitude cyclones can be divided into four stages (Fig. 23). In this schematic evolution, we consider a wind event over western Washington, but the ideas are appropriate for most areas west of the Cascade crest by shifting the features north or south. As noted above, the vast majority of such storms move to the northeast as they approach and make landfall.

In the prefrontal stage, the low center is well offshore and a warm front or warm occlusion extends westward south of the area of interest (Fig. 23a). Isobars are oriented roughly north–south, cool air is in place over the region at low levels, and winds are light (generally southeasterly). Strong winds are often observed at the exits of gaps in the regional mountains and extensive precipitation has spread over the region at this time. With frontal passage (Fig. 23b), low-level winds accelerate substantially and temperatures rise, with the orientation of the isobars shifting to be less parallel to the north–south terrain. Thus, there is an increased pressure variation along the regional terrain barriers (which are generally oriented north–south) and an increase in the southerly ageostrophic wind component. After frontal passage, precipitation becomes lighter and more showery in character, with vertical stability considerably lessened, allowing more effective mixing of southerly momentum down to the surface. This downward southerly momentum mixing is enhanced by the increasing southerly and southwesterly winds aloft as the low center approaches. Winds at this stage often gust to 20–40 kt (10–21 m s\(^{-1}\)) and some initial damage may be reported. The most damaging period of windstorm events occurs as the bent-back trough south of the low center rotates into the region (Fig. 23c). Winds can increase to 40–100 kt (20–51 m s\(^{-1}\)), with the strongest gusts limited to a period of 3 to 6 h. As the bent-back trough and associated low center move to the northeast, the winds shift to westerly or northwesterly aloft and winds weaken substantially (Fig. 23d). One exception is in the Strait of Juan de Fuca, where the passage of the low produces a large along-gap pressure gradient that often results in a westerly surge with winds reaching 30–60 kt (15–30 m s\(^{-1}\)).

Many of the strongest storms are associated with large-magnitude isallobaric pressure couplets, characterized by large pressure falls prior to the cyclone and even larger post-low pressure rises. The strongest surface winds are generally during the periods of large pressure rises. Are isallobaric wind accelerations (Gill 2003) important, considering the already highly ageostrophic nature of the low-level winds in this mountainous region? Another issue is the relative importance at lower elevations of downward mixing of geostrophic momentum aloft compared to ageostrophic, downgradient acceleration. Clearly, the strongest windstorms had both factors contributing, but to what degree can either alone produce powerful damaging winds at the surface? A frequently observed deficiency of model simulations of major events, even at very high resolution, is excessively geostrophic winds near the surface; the origin of this problem, possibly because of deficiencies in planetary boundary layer parameterizations such as excessive vertical mixing in the lower troposphere during stable conditions, needs to be identified and fixed. Further examination is needed regarding the relationship of major storms and the phase of the El Niño–Southern Oscillation (ENSO); initial results from a study of the eight largest cyclonic windstorms since 1880 suggests that the most significant events generally occur in neutral ENSO years (Mass 2008).

7. Summary and conclusions

Landfalling oceanic extratropical cyclones can bring strong, damaging winds to the Pacific Northwest that are comparable to those associated with hurricanes. Northwest windstorms are most frequent from November through February; since 1948 there have been 32 events that have brought sustained and spatially extensive winds greater than 35 kt (18 m s\(^{-1}\)) to the western Oregon and Washington interiors, with many more events along the coast. Roughly once a decade, a storm brings hurricane-force winds to the Puget Sound lowlands or the Willamette Valley, while on the coast this is usually a yearly event. It is interesting that during the past 60 years the frequency of major cyclonic windstorm events appears to have decreased over northern California and Oregon but increased over Washington State.

The strongest winds generally occur when a deep northeastward-moving low center passes north of a location. Major windstorms of the region are generally associated with central pressures ranging from 955 to 980 hPa, although major wind events over limited areas have accompanied storms with higher pressures (980–995 hPa). Strong Northwest cyclones have resulted in tens of billions in USD of damage and the loss of several
hundred lives during the past 60 years; the Columbus Day Storm of 12 October 1962 was the most powerful Pacific cyclone to strike the region over the past 150 years, and perhaps the most powerful midlatitude cyclone to affect the United States in a century. The predictability of these events has improved dramatically; prior to 1990 few were accurately forecast a day ahead, whereas since that time, most storms have been well predicted by operational numerical models.

The synoptic evolution associated with the major storms is generally characterized by an extensive long-wave trough over the eastern Pacific in which an embedded short-wave trough initiates a major development as it moves into the downstream (eastern) side of the long-wave...
trench. For western Washington, the most intense events are associated with intense lows moving across the northwest Olympic peninsula or the lower portion of Vancouver Island, while for Oregon events the low crosses Washington State.

The structure of most major landfalling storms resembles the midlatitude ocean cyclones described by Shapiro and Keyser (1990) and others. A bent-back occlusion or warm front is generally evident and the largest pressure gradients and winds are associated with the bent-back trough south of the low center. As the low approaches the coast, the winds are generally light and southeasterly and in the cool, stable air north of the associated warm or warm-occluded front. After frontal passage, the winds accelerate rapidly as the isobars change orientation, creating an along-barrier pressure gradient and ageostrophic acceleration to the north. Furthermore, the lessening of stability after frontal passage facilitates the downward mixing of momentum. Winds then increase further as the intense pressure gradient of the bent-back trough moves in and the influx of cooler air aloft further lessens vertical stability.

Coastal acceleration with such major cyclones appears limited to the early period of relatively high stability and onshore flow; as cooler air moves in aloft with the bent-back trough and vertical stability declines, near-shore wind enhancement declines. Northwest windsstorms appear to have structural and synoptic similarities to the intense storms that make landfall on England and France; however, there is little evidence to date of the sting jet phenomenon, whereby mesoscale areas of enhanced wind and damage are associated with evaporatively cooled downdrafts. Central pressure is a useful but imperfect measure of wind speed and damage; the major cyclone-based Northwest windsstorms that produced extensive damage had central pressures as low as the mid-950s hPa to as high as approximately 980 hPa. Significant questions about Northwest windsstorms remain, including the significance of isallobaric effects, the importance of vertical stability variations, and the excessively geostrophic nature of storm winds in current mesoscale models.

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