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Extreme Winds and Windthrow in the Western Columbia River Gorge

Abstract

Severe windthrow in the Bull Run watershed of the Oregon Cascade Range has occurred infrequently over the last 50 yr, yet individual storm events have generated extensive windthrow. In this case study, we consider two storm events known to have caused windthrow in the Bull Run. Using long-term meteorological records, we characterize the events and use the Gumbel extreme value distribution to analyze the wind speeds, estimating return intervals for the two storms. When all annual maximum wind speeds are considered for the 47-yr period of data, the 1973 and 1983 storm wind speeds may occur as frequently as every 5 yr or less, but this increases to a 10-15 yr interval when we analyze only east wind events. Extremely low air temperatures, characteristic of the storms, may have increased the likelihood of windthrow, though on at least one occasion a seemingly similar storm event failed to generate any windthrow. This exercise illustrates the complexity of natural disturbances such as windthrow and the inadequacy of simplistic, meteorologically-based models to predict a stochastic event accurately, particularly when natural patterns of windthrow are regularly altered by forest cutting.

Introduction

The Columbia River Gorge, cutting through the Cascade Range at the border of Oregon and Washington, is known for strong winds. Regionally, winter storms that develop over the Pacific Ocean are characterized by southwesterly winds. Less frequently, an easterly-wind storm pattern develops in response to a gradient between continental high pressure systems north and east of the Gorge and oceanic low pressure systems west of the Gorge (Cramer 1957). This phenomenon may be associated with a strong temperature gradient, especially when a continental high moves southward towards the Gorge from Canada and the Arctic. Strong easterly winds and low temperatures develop in the vicinity of the Gorge, which is the only near-sea level passage through the Cascade Range (Cameron 1931, Cameron and Carpenter 1936).

Windthrow, or the uprooting and snapping of trees by wind, is often associated with these high winds. Windthrow has occurred sporadically over the past century in the Bull Run watershed, a 265 km^2 basin located in the Mt. Hood National Forest, ~20 km south of the Columbia Gorge and west of Mt. Hood in north-central Oregon (Figure 1). Storms in 1973 and 1983, and several storms between 1890 and 1931, blew down a total of more than 10% of old-growth conifer stands in the Bull Run watershed (Sinton 1996).

Assessing windthrow risk is an important issue for forest management, ecology, and public safety in western forests. Windthrow has been associated with insect outbreaks, forest fires, and sedimentation of streams (Ruth and Yoder 1953, Gratkowski 1956, Franklin and Forman 1987, Agee 1993, Powers et al. 1999). Because the Bull Run watershed is the primary municipal water source for Portland, Oregon, extensive windthrow is a concern to the watershed's two managers, the city of Portland Water Bureau and the Mt. Hood National Forest.

The observed patterns of windthrow in the Bull Run have been linked to temporal changes in forest susceptibility, as happens when fresh edges are created by forest cutting (Franklin and Forman 1987, Sinton 1996, Sinton et al. 2000). An active timber harvesting program in the Bull Run was initiated by the U. S. Forest Service in 1958, and by the end of 1972, 10% of the forested part of the basin had been logged in scattered clearcut patches (Sinton 1996). Windthrow is commonly found at the edges of openings, such as clearcuts, and the windthrow in 1973 and 1983 displayed a strong spatial correlation with clearcut openings in the forest canopy (Franklin and Forman 1987,

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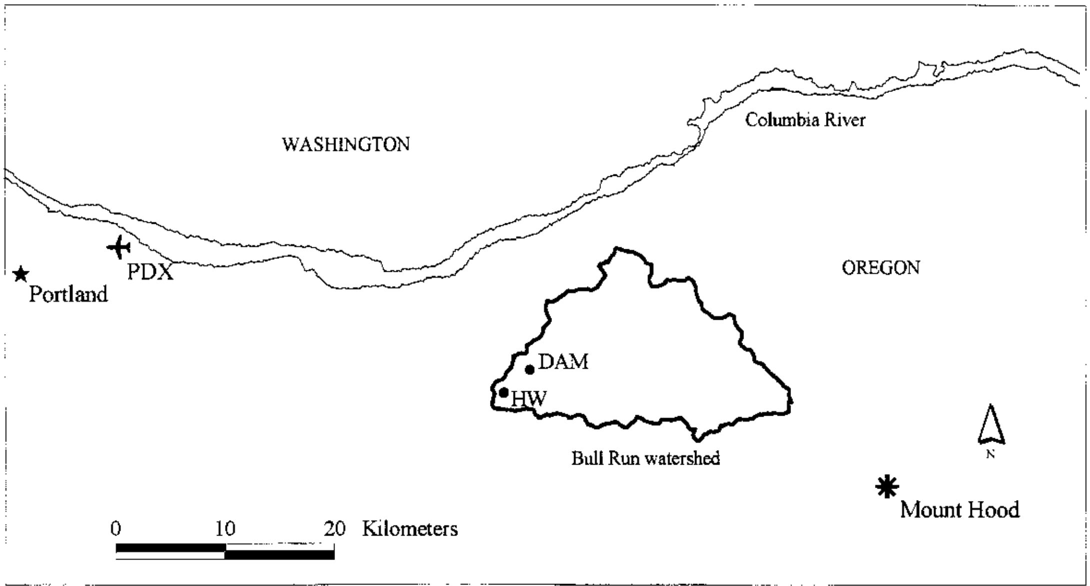

Figure 1. Bull Run watershed (Oregon), its vicinity, and climatic data collection sites. PDX = Portland Airport; HW = Headworks at Reservoir Two; DAM = Dam at Reservoir Two.

Sinton 1996, Sinton et al. 2000). In fact, much of the 1983 windthrow was contiguous to the salvage-related clearcuts that followed the 1973 storm event (Sinton 1996, Sinton et al. 2000).

The precise meteorological conditions contributing to windthrow at a site are rarely observed, making the prediction of windthrow from meteorological data a difficult task. Several windthrow studies suggest that the primary contributing climatic factors are high wind speeds and precipitation, leading to saturated soils that cannot firmly hold tree root systems (Day 1950, Fosberg 1986, Quine and White 1993, Stokes et al. 1995). However, it is not clear whether extreme gusts of wind are responsible for the damage, or sustained high winds over hours or days.

Furthermore, numerous non-meteorological factors contribute to windthrow, including individual tree or species characteristics, root decay, topography, and logging activities (Hubert 1918, Ruth and Yoder 1953, Gratkowski 1956, Fraser 1962, Stathers et al. 1994, Sinton et al. 2000). For example, during the Columbus Day Storm (12 October 1962), windthrow was extensive in the Pacific Northwest, particularly in the coastal regions (Lynott and Cramer 1966). On that day, Portland Airport recorded its highest wind speeds of the century (28.1 m/s), yet virtually no windthrow occurred in the Bull Run, the result of both its distance inland and a possible physiological resistance of the trees from chronic exposure to southwesterly winds (Sinton 1996).

Risk assessment may be performed by calculating a return interval for an event of a certain magnitude, estimating that the event has a certain probability of re-occurrence during that period (Gumbel 1958, Olsen et al. 1998). Using long-term records of wind speeds or stream flow, for example, we can then calculate a 100- or 500-yr event. In reality, an event of similar magnitude could occur multiple times or not at all during that time, as the event only occurs on average once during that period.

This case study identifies the meteorological conditions in the vicinity of the Columbia River Gorge that have been associated with windthrow in the Bull Run watershed. We describe two windthrow-generating storms (1973 and 1983) and consider the rarity of the storms' characteristics. We use a 47-yr record of annual maximum wind speeds to calculate a Gumbel reduced variate, a technique used to classify extreme events (Gumbel 1958), and compute return intervals for the two storm events.

Methods

Study Site

The temperature and precipitation regimes in the Bull Run watershed are typical of the Pacific Northwest: summers are warm and dry, and winters are cool and wet. Average annual precipitation in the Bull Run basin ranges from 2280 to 4300 mm, depending on elevation (Sinton 1996). Steep canyons and broad glacial valleys characterize the basin; 16% of the basin is ≤5° slope and 24% of the area is >20° slope. Elevation ranges from 225 m to over 1400 m, and 32% of the watershed is oriented towards the south and southwest. The primary vegetation is coniferous forest, composed principally of Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), Pacific silver fir (*Abies amabilis*), and western redcedar (*Thuja plicata*). Since 1958, about 17% of the basin has been clearcut; most of the remaining old-growth forest dates from a fire approximately 500 yr ago (Agee and Krusemark 2001).

Climatic Data Collection

We obtained meteorological data from a station located at the dam below Reservoir #2 in the Bull Run (DAM), the Headworks (HW) below this dam, and the Portland Airport (PDX), ~40 km to the west (Figure 1). We selected daily maximum and mean wind speeds, barometric pressure, wind directions, air temperature and precipitation amounts, because of their demonstrated association with windthrow events (Table 1) (Ruth and Yoder 1953, Gratkowski 1956, Quine and White 1993, Stathers et al. 1994). Long-term wind data were available only from PDX; wind speed correlations between PDX and DAM were strongest during east wind events in the winter months (r = 0.47) (Sinton 1996). Daily precipitation values measured at HW were also summed over a preceding 7-day period to create a variable indicative of antecedent soil moisture.

The Bull Run watershed has a moderate marine climate (Table 2). Measurable precipitation occurs on more than 60% of days throughout the year, but daily precipitation is moderate, with fewer than 5% of days receiving more than 2.5 cm of precipitation. Most mean and maximum daily wind speeds at the Portland Airport were low (Table 2). The highest daily mean wind speeds occur in winter, when winds from the east or southeast are more common, whereas low wind speeds characterize the summer months when winds are from the north and northwest. Winds came from the north, northeast, and east only 17% of the time, yet these wind directions are most associated with windthrow in the Bull Run (Sinton 1996).

Windthrow Data Collection

Documented windthrow was limited to events extensive enough to alter stand compositions, in patches greater than 0.56 ha, and be interpreted on aerial photographs (1:7920 or 1:12000, true color) (Sinton 1996). A mylar sheet marked with 0.6 cm^2 grid cells was placed over each photograph, and the presence of windthrown trees visible in any cell was noted. These data were entered into an ArcInfo (Version 6.0 and 7.01) geographic information system (GIS). Only two

TABLE 1. Climatic data collected in and around the Bull Run watershed, Oregon.

	Station Portland Airport (PDX)	Bull Run, Dam at Reservoir #2 (DAM)	Bull Run Headworks (HW)
Period of record	1948-1995	1993-1994	1931-1995
Data source	Oregon Climate Services (OCS)	OCS	OCS
Wind speed and direction			
hourly	X[a]	X[b]	
3-hourly	X[a]		
Daily barometric pressure	X		
Daily air temperature			X
Daily precipitation			X

[a] Wind speed observation frequency changed from hourly to 3-hourly at Portland Airport in 1985. The daily maximum wind represents an observed maximum gust within a one- or three-hour period, not a continuously measured variable or a fastest mile.

[b] Earlier records for the period 1978-1985 were not used because the data collected (rotations of device/day) were inconsistent with the other types of data.

TABLE 2. Characteristics of the climate around the Bull Run watershed, Oregon, 1948-1994. Precipitation and temperature data were recorded at HW; wind speeds and barometric pressure were recorded at PDX (see Figure 1). Variables are daily values, unless otherwise noted.

Descriptor	Precipitation (mm)	Precipitation (antecedent 7-days, mm)	Air temp. (maximum, °C)	Wind speed (mean, m/s)	Wind speed (maximum, m/s)	Barometric pressure (change from previous day, cm/Hg)
Minimum	0.0	0.0	-11.1	0.0	0.4	0.0
Maximum	172.7	365.5	41.1	15.2	22.8	0.78
Mean	5.6	39.2	16.1	3.7	6.3	0.11
Standard Error	0.08	0.31	0.06	0.01	0.02	0.001
Median	0.0	28.2	15.6	3.6	6.3	0.09
Mode	0.0	0.0	10.0	3.1	4.5	0.2
1st Percentile	0.0	0.0	0.6	0.0	2.2	0.001
5th Percentile	0.0	0.0	3.9	1.8	3.1	-0.23
95th Percentile	26.2	120.1	30.0	6.7	10.8	0.25
99th Percentile	46.7	176.5	33.9	8.5	13.4	0.4

such storm events (January 1973 and December 1983) overlapped with our period of wind data availability (1948-1994), and each of these triggered extensive salvage logging efforts (Sinton 1996).

Analytical Approach

We generated histograms and cumulative frequency distributions of the climatic data to characterize the climate of the Bull Run and describe the 1973 and 1983 storm events. We then used the maximum wind speeds per annum to generate Gumbel reduced variates to estimate the extremity of the wind speeds during the 1973 and 1983 storms. The Gumbel equation, also known as the Fisher-Tippett Type I, is commonly used for describing a generalized extreme value distribution with annual maxima data (Graham 1983), including events such as extreme stream and surge flows (Bardsley 1989, D'Onofrio et al. 1999), temperatures (Graham 1983), earthquakes (Dargahi-Noubary 1988) and wind speeds (Cook 1982, Revfeim and Hessell 1984, Linacre 1992, Galambos and Macri 1999, Brabson and Palutikof 2000). In our analysis, we further refined our characterization of the storm winds by recalculating the variate using only easterly maximum winds. With these techniques, we estimate return intervals for storms of similar magnitudes.

Results

Extremity of wind speeds

Gumbel variates and return intervals were calculated by using the annual maximum wind speeds during the 47-year-period of data from the Portland Airport (Table 3). Over two-thirds of these years had maximum winds from the south or southwest. With that data set, a wind speed of approximately 27 m/s would be a 100-year wind event, calculated with a Gumbel variate of 4.6 ($-\ln[-\ln 0.99]$) (Figure 2). Using annual maxima from all directions, the wind speeds from both the 1973 and 1983 storms have return intervals of <5 yr each.

Using only the highest annual easterly wind speeds to calculate Gumbel variates creates different return periods (Table 4). For winds from the east only, the 100-yr wind event would equal about 20 m/s (Figure 3). Based on these variates, the wind speeds recorded during the 1973 storm event would occur on average about every ten years, and the 1983 storm event was about a 15-yr wind event.

Storms in 1973 and 1983

Both the 8-9 January 1973 and 23-25 December 1983 storms were characterized by high maximum and mean daily wind speeds and maximum daily temperatures that failed to reach above freezing (Table 5). During both storms, the mean and maximum wind speeds were from the east and above the 99th percentile in their respective frequency distributions. This is consistent with the day-to-day barometric pressure changes of up to 0.3 cm/Hg, an amount that ranks in the 97th percentile (Table 5). Precipitation amounts were negligible in the 1973 storm, and during the 3-day

TABLE 3. Ranked wind speeds, return periods, and Gumbel reduced variates for all annual maximum winds from the Portland International Airport (PDX), 1948–1994. After Table 6.8 in Linacre (1992).

Annual maximum wind U: (m/s)	ln U	Number of values ≤ U[a]: m	100 C(U) percentile[b]	Exceedance 100 E(U)[c]	Return period[d]: T years	Gumbel reduced variate[e]
12.5	2.53	6	12.5	88	1.14	-0.73
13.0	2.56	7	14.6	85	1.17	-0.66
13.4	2.60	8	16.7	83	1.20	-0.58
14.3	2.66	13	27.1	73	1.37	-0.27
14.8	2.69	18	37.5	63	1.60	0.02
15.7	2.75	22	45.8	54	1.85	0.25
17.0	2.83	24	50.0	50	2.00	0.37
17.5	2.86	28	58.3	42	2.40	0.62
17.9	2.89	36	75.0	25	4.00	1.25
18.4	2.91	40	83.3	17	6.00	1.70
18.8	2.93	41	85.4	15	6.86	1.85
19.3	2.96	43	89.6	10	9.60	2.21
19.7	2.98	44	91.7	8	12.00	2.44
22.4	3.11	45	93.8	6	16.00	2.74
22.8	3.13	46	95.8	4	24.00	3.16
28.2	3.34	47	97.9	2	48.00	3.86

[a] m is the rank order of the value U
[b] i.e. 100 m / (N + 1), the number of values (N) being 47
[c] i.e. 100 – 100 C(U) per cent
[d] i.e. 1 / E(U), or (N + 1) / (N + 1 - m)
[e] –ln [-ln C(U)].

TABLE 4. Ranked wind speeds, return periods, and Gumbel reduced variates for the annual maximum easterly winds, Portland International Airport (PDX), Oregon, 1948–1994. After Table 6.8 in Linacre (1992).

Annual maximum wind U: (m/s)	ln U	Number of values ≤ U[a]: m	100 C(U) percentile[b]	Exceedance 100 E(U)[c]	Return period[d]: T years	Gumbel reduced variate[e]
9.9	2.29	1	2	98	1.02	-1.35
11.2	2.42	4	8	92	1.09	-0.91
11.6	2.46	5	10	90	1.12	-0.82
12.1	2.49	8	17	83	1.20	-0.58
12.5	2.53	18	38	63	1.60	0.02
13.0	2.56	19	40	60	1.66	0.08
13.4	2.60	26	54	46	2.18	0.49
13.9	2.63	29	60	40	2.53	0.69
14.3	2.66	36	75	25	4.00	1.25
14.8	2.69	39	81	19	5.33	1.57
15.7	2.75	42	88	13	8.00	2.01
17.0	2.83	43	90	10	9.60	2.21
17.5	2.86	44	92	8	12.00	2.44
17.9	2.89	46	96	4	24.00	3.16
18.4	2.91	47	98	2	48.00	3.86

[a] m is the rank order of the value U
[b] i.e. 100 m / (N + 1), the number of values (N) being 47
[c] i.e. 100 – 100 C(U) per cent
[d] i.e. 1 / E(U), or (N + 1) / (N + 1 - m);
[e] -ln [-ln C(U)].

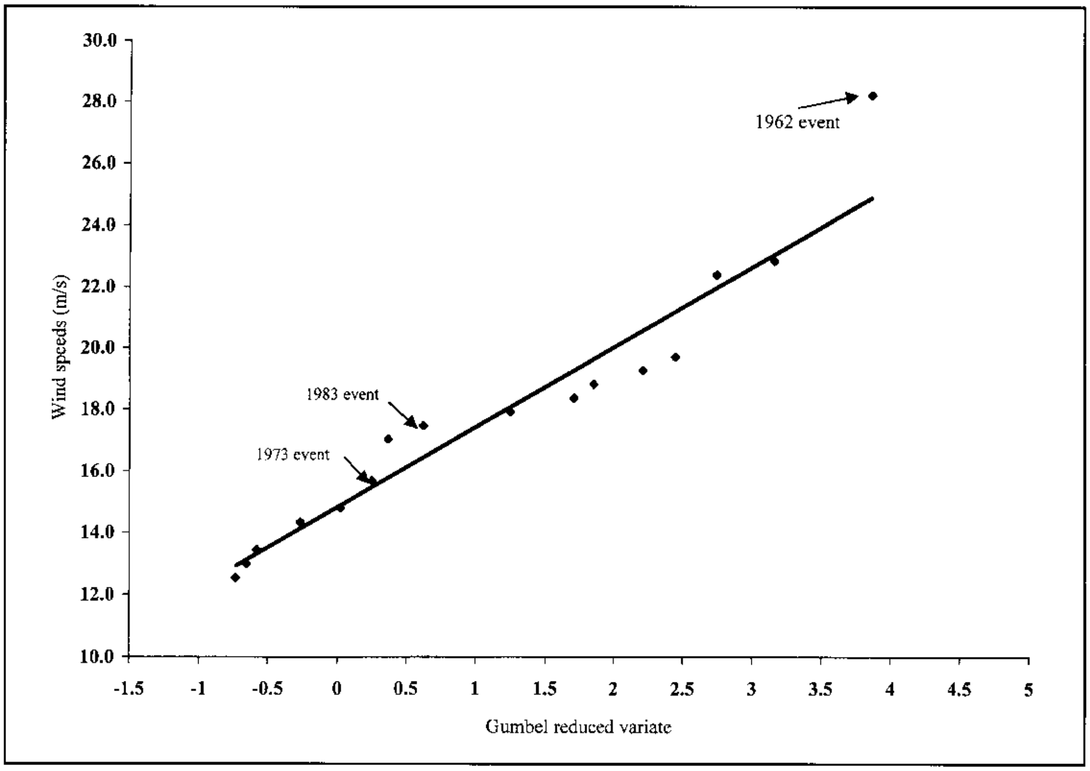

Figure 2. Plot of the Gumbel reduced variate against annual maximum wind speed at PDX (see Table 4).

TABLE 5. Meteorological characteristics of the January 1973 and December 1983 wind storms. Wind speed and barometric pressure data are from Portland International Airport (PDX), Oregon. Temperature and precipitation data are from the Headworks (HW) Station within the Bull Run watershed, Oregon.

Variable	8-Jan-73	9-Jan-73	23-Dec-83	24-Dec-83	25-Dec-83
Mean wind speed (m/s)	12.5	13.9	10.8	15.2	10.8
Maximum wind speed (m/s)	13.9	15.7	15.7	17.5	14.8
Direction of maximum wind	east	east	east	east	east
Change in barometric pressure from previous day (cm/Hg)	-0.21	-0.54	0.02	-0.81	-0.78
Maximum temperature (°C)	-3.3	-0.6	-7.2	-7.8	-0.6
Mean maximum temperature or preceeding two days (°C)	-1.9	-3.3	-6.9	-7.5	-7.5
Precipitation (mm)	0.0	0.0	0.0	2.3	5.3
Precipitation total from previous seven days (mm)	26.2	7.6	7.9	10.2	11.9

1983 event, the precipitation amounts ranked in the 70th percentile or below.

The combination of high easterly wind and low air temperatures occurs infrequently in the Bull Run. There were only 18 days during the years 1948-1994 when both the mean and maximum wind speeds were in the top 1% of their frequency distribution, and maximum air temperatures were in the lowest 1% of their distribution (Table 6). When we group consecutive days into storm events,

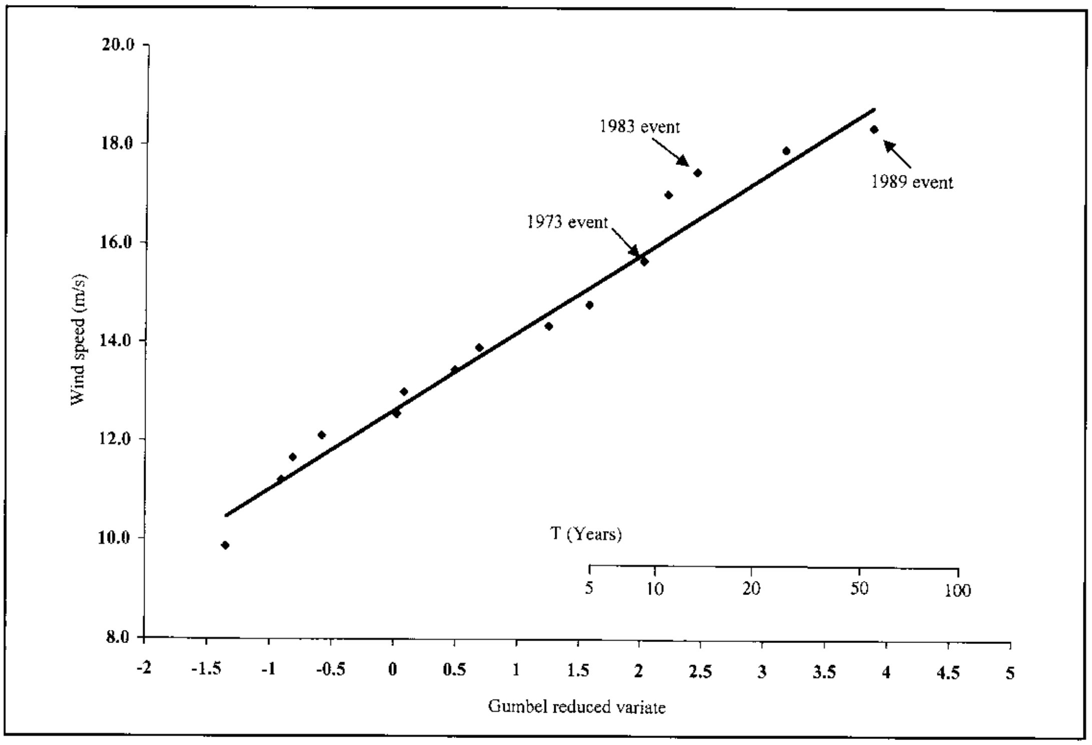

Figure 3. Plot of the Gumbel reduced variate against annual maximum easterly wind speed at PDX (see Table 5). Return intervals for selected years and associated wind speeds are shown on the graph.

TABLE 6. Individual and consecutive days when easterly wind and temperature conditions are within the top 1% of their frequency distribution, 1948-1994. Wind speeds are from PDX and temperature data are from HW. Dates when windthrow is known to have occurred in the Bull Run are highlighted in bold.

Dates	Mean wind speeds (m/s)	Maximum wind speed (m/s)	Direction of max winds	Maximum air temp. (°C)	Maximum air temp. on preceding 2 days (°C)
20-Jan-60	12.1	14.3	east	1	1
03-Mar-60	9.4	14.3	east	0	6
12-Jan-62	10.8	14.3	east	-3	4
19-Dec-64	9.0	13.4	east	1	-2
05-Dec-72	10.3	17.9	east	-3	5
06-Dec-72	9.9	14.3	east	1	-2
08-Jan-73	**12.5**	**13.9**	**east**	**-4**	**-1**
09-Jan-73	**13.9**	**15.7**	**east**	**-1**	**-4**
02-Jan-74	9.0	14.3	east	0	4
04-Jan-79	13.0	14.3	east	1	-1
05-Jan-79	12.1	14.3	east	-1	1
23-Dec-83	**10.8**	**15.7**	**east**	**-7**	**-6**
24-Dec-83	**15.2**	**17.5**	**east**	**-8**	**-7**
25-Dec-83	**10.8**	**14.8**	**east**	**-1**	**-7**
02-Feb-89	13.4	14.4	east	-2	10
03-Feb-89	15.2	18.6	east	-11	2
04-Feb-89	9.0	10.8	east	-4	-2
07-Jan-93	10.4	14.9	east	1	3
08-Jan-93	8.7	11.2	east	0	1

we find that windthrow occurred in the Bull Run on two out of six, 2- or 3-day storms.

Discussion

The easterly winds that generated extensive Bull Run windthrow were not particularly rare or infrequent ones. Meteorological controls on windthrow may be obscured by low spatial and temporal resolution of available data, and because reliable long-term wind records were available only at a site about 40 km from the basin. Accurate prediction of windthrow in the Bull Run would benefit from reliable local wind speed monitoring, rather than extrapolation from a distant site. During the 1983 event, the wind-monitoring device at HW ceased to function on the second day of the storm, so estimating the extremity of local winds was impossible. Furthermore, windthrow may be produced by the highest wind speed sustained for one or two minutes, rather than an arbitrarily selected five- to ten-minute sampling period once an hour, but only recently have wind data at Portland Airport begun to be collected as such fine temporal resolution.

Understanding the infrequent combination of high, easterly winds and sub-freezing temperatures may be critical for windthrow prediction in the Bull Run. Ice-loading in tree canopies has been suggested as a factor contributing to the 1983 Bull Run windthrow (Nancy Diaz and Ivars Steinblums, Mt. Hood National Forest, personal communication), and the conditions existed to create rime ice, formed when fog or other moisture-laden air is blown against a cold surface. While little precipitation was measured during either the 1973 or 1983 storm event itself, fog is a common characteristic of the Bull Run watershed (Harr 1982).

A Gumbel distribution of extreme values can be affected by the nature of the data set. The Gumbel method is designed for use with monthly or annual maxima, with at least a 20-yr-period of data availability (Tabony 1983, Linacre 1992). Brabson and Palutikof (2000) found that their wind speed data fit the Generalized Extreme Value (GEV) (i.e. Gumbel) distribution poorly, while Galambos and Macri (1999) found the Gumbel distribution a good match with their wind data. Mitsiopoulos et al. (1991) evaluated several distributions and found that Gumbel had rates of estimated error similar to or better than the normal, Weibul, and lognormal distributions. The particularly strong linear relationship found with the easterly wind data (Figure 3) suggests that the Gumbel distribution approximates the PDX data set well.

Restricting the Gumbel distribution to only easterly winds was an appropriate step for the Bull Run, but would not be suitable for other sites in the region. Given the prevailing southwesterly winter storm pattern in the Pacific Northwest, windthrow in the region is typically generated from southwesterly storms, particularly along the Coast (Gratkowski 1956, Fredriksen 1965). However, all of the windthrow observed in the Bull Run watershed during the 20th century has been generated by northeast- and east-wind events, with downed trees lying towards the southwest (Sinton 1996), and throughout the western half of the Columbia River Gorge, tree morphology indicated that trees were more frequently affected by easterly winds (Lawrence 1939).

Monitored meteorological conditions alone do not adequately explain the observed patterns of windthrow in the Bull Run. Observed windthrow in 1973 and 1983 was spatially associated with both ephemeral and perennial openings in the forest canopy (Sinton 1996, Sinton et al. 2000). On the other hand, a severe storm of two days duration occurred in February 1989 (Figure 3), with easterly winds of 18.4 m/s, approximating a 50-yr storm event. Although new fresh forest edges had been created by recent salvage of 1983 windthrow, and air temperatures during this event were also low (Table 6), no measurable windthrow was detected in the Bull Run (Sinton 1996). Vulnerable trees along openings may have 1) already been removed by earlier storms; 2) been pruned by other winds and thus had low risk of windthrow; or 3) produced adaptive growth to accommodate an additional wind load (Telewski 1995).

Nevertheless, the lack of windthrow associated with the 1989 storm supports our understanding that meteorological information alone is insufficient to predict windthrow. Topographic, edaphic, and vegetative factors must be considered in each individual case. Windthrow over the past few decades in the Bull Run represents an interaction between two dynamic patterns, the spatial pattern of forest fragmentation and the temporal pattern of infrequent, severe east wind events. While the combination of low air temperatures and high, easterly wind speeds is relatively uncommon, a similar event in the future could still put Bull Run trees at risk for windthrow.

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Literature Cited

Agee, J. K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D. C.

Agee, J.K., and F. Krusemark. 2001. Forest fire regime of the Bull Run watershed, Oregon. Northwest Science 75:292-306.

Bardsley, W. E. 1989. Graphical estimation of extreme value prediction functions. Journal of Hydrology 110:315-321.

Brabson, B. B., and J. P. Palutikof. 2000. Tests of the generalized pareto distribution for predicting extreme wind speeds. Journal of Applied Meteorology 39:1627-1640.

Cameron, D. C. 1931. Easterly gales in the Columbia River Gorge during the winter of 1930-1931: some of their causes and effects. Monthly Weather Review 59:411-413.

Cameron, D. C., and A. B. Carpenter. 1936. Destructive easterly gales in the Columbia River Gorge, December 1935. Monthly Weather Review 64:264-268.

Cook, N. J. 1982. Towards better estimation of extreme winds. Journal of Wind Engineering and Industrial Aerodynamics 9:295-323.

Cramer, O. P. 1957. Frequency of dry east winds over northwest Oregon and southwest Washington. USDA Forest Service Research Paper 24. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Dargahi-Noubary, G. R. 1988. Some newly developed statistical procedures for extreme events. Physics of the Earth and Planetary Interiors 52:102-107.

Day, W. R. 1950. The soil conditions which determine windthrow in forests. Forestry 23: 90-95.

D'Onofrio, E. E., M. M. E. Fiore, and S. I. Romero. 1999. Return periods of extreme water levels estimated for some vulnerable areas of Buenos Aires. Continental Shelf Research 19:1681-1693.

Fosberg, M. A. 1986. Windthrown trees on the Kings River Ranger District, Sierra National Forest: meteorological aspects. USDA Forest Service Research Note PSW-381. Pacific Southwest Forest and Range Experiment Station, Berkeley, California.

Franklin, J. F., and R. T. T. Forman. 1987. Creating landscape patterns by forest cutting: ecological consequences and principles. Landscape Ecology 1:5-18.

Fraser, A. I. 1962. The soil and roots as factors in tree stability. Forestry 35:117-127.

Fredriksen, R. L. 1965. Christmas storm damage on the H. J. Andrews Experimental Forest. USDA Forest Service Research Note PNW-29. Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon.

Galambos, J., and N. Macri. 1999. Classical extreme value models and prediction of extreme winds. Journal of Structural Engineering 125:792-794.

Graham, A. E. 1983. A study of the Gumbel and Weibull methods of extreme-value analysis using air temperature data from six Ocean Weather Stations. Meteorological Magazine 112:303-317.

Gratkowski, H. J. 1956. Windthrow around staggered settings in old-growth Douglas-fir. Forest Science 2:60-74.

Gumbel, E. J. 1958. Statistics of Extremes. Columbia University Press, New York.

Harr, R. D. 1982. Fog drip in the Bull Run municipal watershed, Oregon. Water Resources Bulletin 18:785-789.

Hubert, E. E. 1918. Fungi as contributory cause of windfall in the Northwest. Journal of Forestry. 16:696-714.

Lawrence, D. B. 1939. Some features of the vegetation of the Columbia River Gorge with special reference to asymmetry in forest trees. Ecological Monographs 9:217-257.

Linacre, E. 1992. Climate and Data Resources: a Reference and Guide. Routledge Press, New York.

Lynott, R. E., and O. P. Cramer. 1966. Detailed analysis of the 1962 Columbus Day windstorm in Oregon and Washington. Monthly Weather Review 94:105-117.

Mitsiopoulos, J., Y. Y. Haimes, and D. Li. 1991. Approximating catastrophic risk through statistics of extremes. Water Resources Research 27:123-1230.

Olsen, J. R., J. H. Lambert, and Y.Y. Haimes. 1998. Risk of extreme events under nonstationary conditons. Risk Analysis 18:497-510.

Powers, J. S., P. Sollins, M. E. Harmon, and J. A. Jones. 1999. Plant-pest interactions in time and space: A Douglas-fir bark beetle outbreak as a case study. Landscape Ecology 14:105-120.

Quine, C. P., and I. M. S. White. 1993. Revised windiness scores for the windthrow hazard classification: the revised scoring method. Research Information Note 230. Research Division, Forestry Authority, Forestry Commission, Edinburgh, Scotland.

Revfeim, K. J. A., and J. W. D. Hessell. 1984. More realistic distributions for extreme wind gusts. Quarterly Journal—Royal Meteorological Society 110:505-514.

Ruth, R. H., and R. A. Yoder. 1953. Reducing wind damage in the forests of the Oregon Coast Range. USDA Forest Service Research Paper 7. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Sinton, D. S. 1996. Spatial and temporal patterns of windthrow in the Bull Run watershed, Oregon. Ph.D. Dissertation, Oregon State University, Corvallis, Oregon.

Sinton, D. S., J. A. Jones, J. L. Ohmann, and F. J. Swanson. 2000. Windthrow disturbance, forest composition, and structure in the Bull Run Basin, Oregon. Ecology. 81:2539-2556.

Stathers, R. J., T. P. Rollerson, and S. J. Mitchell. 1994. Windthrow Handbook for British Columbia Forests. Research Program Working Paper 9401. Ministry of Forests Research Program, Victoria, British Columbia, Canada.

Stokes, A., A. H. Fitter, and M. P. Coutts. 1995. Responses of young trees to wind: effects on root growth. Pages 265-275 *In* Coutts, M. P. and J. Grace (editors), Wind and Trees. Cambridge University Press, New York.

Tabony, R. C. 1983. Extreme value analysis in meteorology. Meteorology Magazine 122:77-98.

Telewski, F. W. 1995. Wind-induced physiological and developmental responses in trees. Pages 237-263 *In* Coutts, M. P. and J. Grace (editors), Wind and Trees. Cambridge University Press, New York.

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