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REGIONAL WIND PATTERNS OF THE INLAND WATERS OF WESTERN WASHINGTON AND SOUTHERN BRITISH COLUMBIA

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REGIONAL WIND PATTERNS OF THE INLAND WATERS
OF WESTERN WASHINGTON AND SOUTHERN BRITISH COLUMBIA[1]

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ABSTRACT. This study generalizes a time series of regional wind fields in an area of strong topographic influence. Wind speed and direction measured by 6 meteorological buoys and 1 tower anemometer were used in addition to routinely available surface observations. The data were measured during the last three weeks of February and the first week of March in 1980 when the region's upper-level flow was dominated by a quasi-stationary ridge, which broke down midway and again in the last 5 days of the period to allow passage of small-amplitude troughs.

The 850-mb wind direction measured at Quillayute, Washington, was chosen as an indicator of synoptic-scale flow uninfluenced by the topography. The directions measured at 12-hour intervals were divided into 11 classes of 30° each. The corresponding surface wind fields were then grouped, and the resultant vector and persistence fields were mapped for each class. The 11 wind field composites showed that while the wind field varied in a regular fashion as the synoptic-scale flow varied, Bernoulli-type down-pressure-gradient flow in restricted channels and geostrophy both operated as balancing mechanisms to the imposed synoptic-pressure gradient in different areas simultaneously. As the 850-mb wind became parallel to the Strait of Georgia and Puget Sound, 140°-190°, and then shifted to the west, the surface wind fields abruptly shifted from primarily an east-west orientation to a north-south orientation. In the absence of a pressure gradient between Port Hardy, B.C., and Portland, Oregon, of greater than 3 mb, a diurnal wind circulation was observed in the eastern Strait of Juan de Fuca, the southern Strait of Georgia, and Puget Sound.

1. Introduction

In common with other parts of the northwest coast of North America, the Pacific Northwest, which includes western Washington State, coastal British Columbia, and southern Vancouver Island, is notable for its mountains intersected by several low-level gaps and sea-level channels with the coastal mountain ranges (fig. 1a). Puget Sound in western Washington State is a complicated inland body of water with many bays, passages, and islands and is oriented principally in a north-south direction with the Cascade Mountains to the east and the Olympics to the west. Roughly perpendicular to Puget Sound, the Strait of Juan de Fuca is a sea-level channel of about

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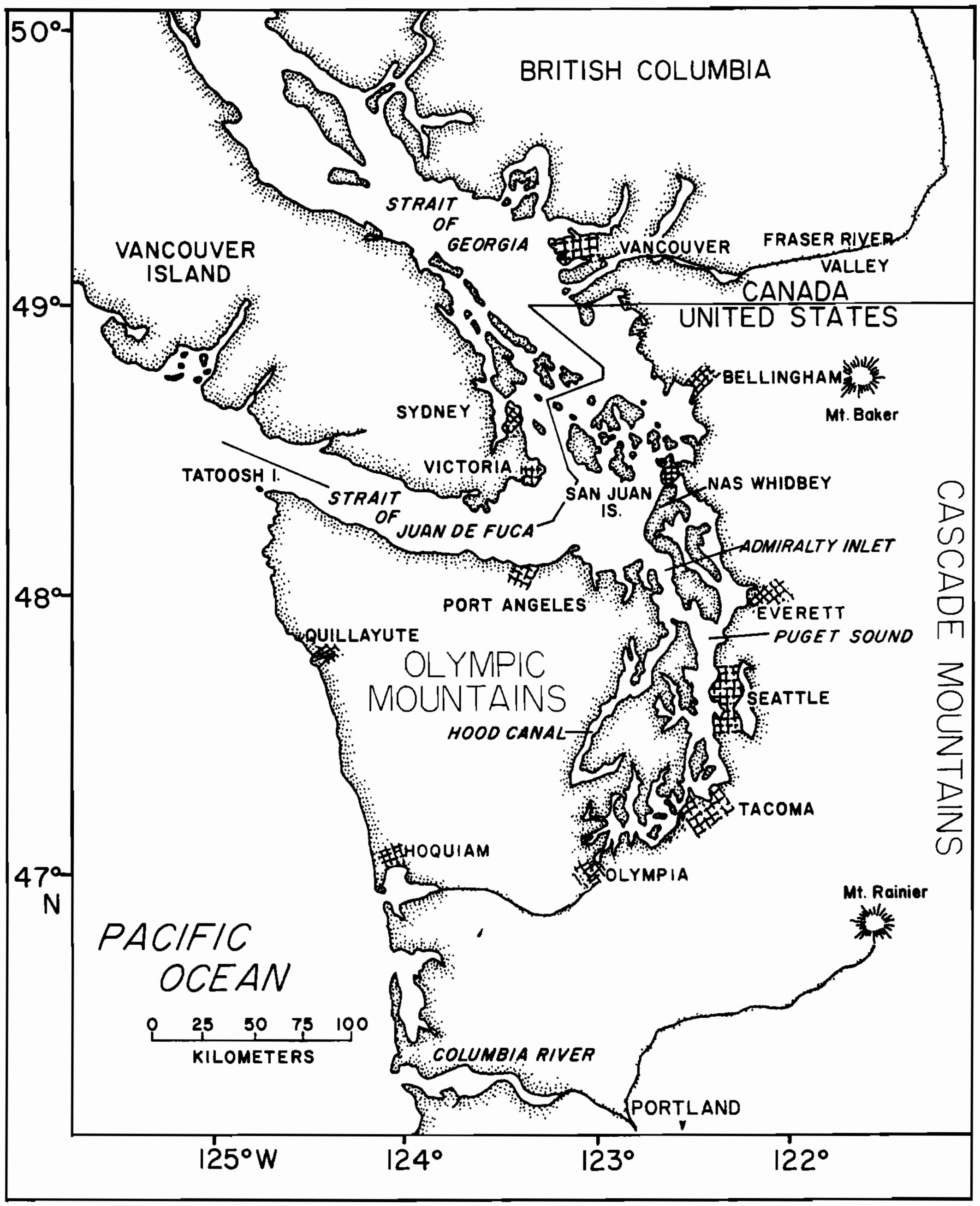


Figure 1a. Location map for western Washington and coastal British Columbia.

20 km in width lying between mountainous Vancouver Island to the north and the Olympic Mountains to the south, and joins Puget Sound with the Pacific Ocean. The Chehalis Gap south of the Olympics is a low-level opening in the topography extending from southern Puget Sound to the Pacific Ocean. In British Columbia, the northwest-southeast oriented Strait of Georgia is about 25 km in width and separates Vancouver Island from the Coast Range to the east. South of the Strait of Georgia, the low-lying San Juan and Gulf Islands are intersected by Haro and Rosario Straits, which are channels 5 to 10 km wide through which the Strait of Juan de Fuca can be reached from the Strait of Georgia.

Figure 1b presents the heights of the mountain ranges. The Cascades and the coast mountains commonly rise above 1500 m, while many isolated peaks have altitudes above 2500 m. Only in the northeast corner of the Olympics are heights above 1500 m with few peaks higher than 2300 m. The mountains of Vancouver Island rise to between 300 and 1500 m.

This complex arrangement of high mountains close to intersecting waterways and low-level gaps near the Pacific Ocean gives rise to a regional meteorology strongly influenced by topography. An understanding of this influence has been the purpose of a number of studies describing the topographical influence on the local wind, cloud, precipitation, and temperature patterns during various synoptic-scale events.

The first such paper studied the meteorological conditions of gap winds, that is, locally accelerated easterlies in the Strait of Juan de Fuca. Reed (1931) compiled wind and pressure fields for 75 days with easterly winds greater than 50 mph at Tatoosh Island at the western end of the Strait of Juan de Fuca from a 5-year period and made two observations. First, he noted that winds measured at gale force in the east-west oriented Strait of Juan de Fuca were rarely also of gale force in the nearby north-south oriented Puget Sound on the same days. Observing secondly that the gales occurred when unusually high pressure existed northeast of the Strait of Juan de Fuca for a variety of offshore locations of low-pressure centers, he concluded that the easterly gales were winds accelerated by the component of the pressure gradient oriented parallel to the Strait of Juan de Fuca.

Staley (1957) calculated resultant winds, mean pressures, and average sky cover for each hour of the day for July and August 1950. Each of 20 hodographs described mostly clockwise diurnal wind direction variations but counterclockwise variations at Port Angeles and Port Townsend on the southeast shore of the Strait of Juan de Fuca, and at Tacoma on Puget Sound shore. The mean pressures reached a maxima/minima 2-3 hours earlier inland than on the coast. Differences in mean pressures were greatest between Tatoosh and Port Angeles and changed diurnally only in magnitude, but were always directed eastward from Tatoosh, while in Puget Sound the differences changed direction diurnally but were always less than 1 mb. Observing the diurnal variation of average cloudiness, Staley suggested that diurnal upslope/downslope winds perpendicular to the inland waterways were responsible for diurnal changes in divergence/ convergence along the inland waterways.

Lynott and Cramer (1966) documented the destructive Columbus Day windstorm which passed through the Pacific Northwest in October 1962 and showed the rapid deepening of the weather system as it propagated northward.

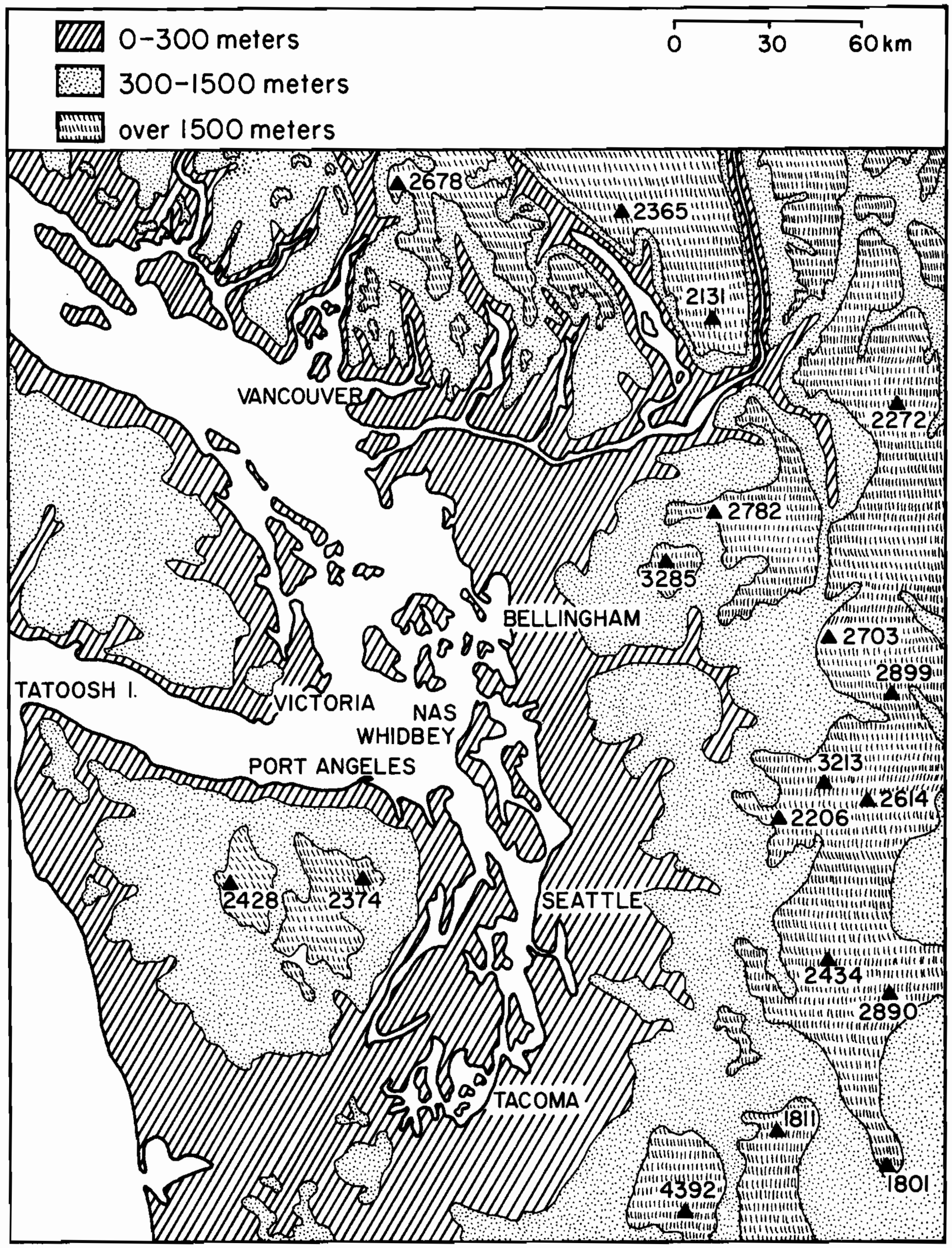


Figure 1b. Topographic map for western Washington and coastal British Columbia.

More recently, interest was centered on the extreme winds which develop in the lee of the Olympic Mountains during certain southwesterly wind conditions along the Washington coast. The first of these studies, Morris (1968), is an analysis of the extreme wind event of 12 January 1968. On that day, a surface low-pressure center and associated front were located near Queen Charlotte Island, northwest of Washington State. A substantial mesoscale trough of low pressure oriented along the axis of the Strait of Juan de Fuca formed, and 22 m s^{-1} wind speeds with gusts to 30 m s^{-1} were measured at Victoria, B.C., while elsewhere the measured winds were 2-10 m s^{-1}.

The second such event to be studied is presented by Reed (1980), who examined the meteorological conditions in the vicinity of the Hood Canal Bridge when it sank on 13 February 1979. As on 12 January 1968, a deep low was centered northwest of Washington State, but with an associated front passing through central Washington. In this case, a mesoscale low pressure formed in the lee of the Olympics, north of the Hood Canal Bridge. The observed sustained winds at the bridge were 35 m s^{-1} gusting in excess of 45 m s^{-1}, more than double the speeds measured at nearby Puget Sound stations. As the synoptic pressure gradient was not sufficient to explain the extreme winds near the Hood Canal Bridge, Reed concludes that the presence of the mesoscale low was a critical factor leading to those winds.

In order to more closely study this type of event, three missions were flown by a NOAA research aircraft in the lee of the Olympics during coastal south to southwesterly wind conditions. The aircraft was flown on 18 and 29 February 1980, when surface low pressure was located northwest of Washington State, and on 9 March 1980, when a surface high-pressure ridge was centered over Washington State. In all three cases, light and variable winds were measured in the eastern Strait of Juan de Fuca.

Drawing upon theoretical studies of stratified flow around isolated obstacles, Walter and Overland (1982) contrast these three cases with the 13 February 1979 case and show that the internal Froude number, given by $F = V/hN^2$

for V = upstream velocity
h = mountain height
N^2 = Brunt Väisälä frequency
$= \frac{g}{\theta}\frac{d\theta}{dz}$
g = gravity
θ = potential temperature,
z = height

can be useful in understanding the interaction of the large-scale flow and the Olympic Mountains. As the atmospheric lapse rate in all 4 cases was noted to be weakly stable, the critical factor appeared to be the upstream velocity. In the 1980 observation flights, the upstream velocity was 15 m s^{-1}, F was calculated to be 1.0-1.4, and in agreement with theoretical studies, no mesoscale low pressure formed; light winds were measured in the lee of the Olympics. For the 1979 event, where the upstream velocity was greater, F was calculated by Walter and Overland (1982) to be 4.6, and mesoscale low pressure was observed to form in the lee of the Olympics. Strong pressure gradients then made localized high wind speeds possible on that day.

The next topic of recent study was the occurrence of severe easterly winds in the east-west oriented channels and gaps in the topography. Reed (1981) described meteorological conditions giving rise to the windstorm of 28 November 1979, which damaged buildings and trees in the east central Puget Sound lowlands and at openings of valleys in the Cascades connecting the lowlands of Puget Sound with the large interior basin of eastern Washington. Portland, Oregon, which is downwind of the Columbia River Gorge also sustained damage during this storm. On the synoptic scale, low pressure centered west of Washington State deepened and high pressure moving inland over British Columbia intensified as the windstorm developed. At the surface, an extremely large pressure difference between the cold air of eastern Washington and the milder air of western Washington was sustained along the Cascade Mountain range, except in the vicinity of gaps. The surface winds were light and northerly in eastern Washington, and light and variable west of the Cascades. In the areas of wind damage already mentioned and in the Fraser River Valley, the Strait of Juan de Fuca, and at Hoquiam, all downwind of large gaps in the topography, observed winds were all easterly, 8 to 15 m s^{-1} with a peak gust to 25 m s^{-1} at Renton, Washington. Reed accounted for the windstorm's localized, extreme velocities in the areas of damage by equating acceleration with the observed pressure gradient parallel to the channel using the Bernoulli equation for flow in a channel of variable height.

Overland and Walter (1981) present two cases of accelerating easterly wind conditions in the Strait of Juan de Fuca and one case of accelerating southerly wind conditions in the Strait of Georgia from February and March 1980 when research aircraft missions were flown. In all three cases, the synoptic-scale pressure gradients were oriented parallel to the channel where the winds were measured, and the resulting mesoscale wind patterns showed a strongly cross-isobaric, accelerating flow through the channels. Overland and Walter (1981) calculated channel wind speeds using the Bernoulli equation for a sea-level channel, $\Delta \frac{u^2}{2} = \frac{\Delta p}{\rho}$. They note that these calculated values were similar to observed channel wind speeds and conclude that the local winds within channels were in approximate ageostrophic balance between inertia and the sea-level pressure gradient.

These studies of the development of mesoscale low pressure in the lee of the Olympics and of accelerating, high-speed easterlies in gaps and channels in western Washington are interpretations of wintertime events. Mass (1980; 1982) extended the regional meteorology to predominantly spring and summertime events by examining the localized effects of topography on wind, cloud, precipitation, and temperature fields.

In the earlier paper by Mass, the low-level, topographically induced Puget Sound convergence zone is studied by compositing 25 cases. The composite shows that for certain synoptic conditions, when the winds within Puget Sound are southerly and the winds in the Strait of Juan de Fuca become westerly, a convergence zone forms in the northern Puget Sound and propagates southward. Associated with this zone is a band of enhanced cloudiness and precipitation, while to the north can be found northerly winds, low clouds, rain, and cooler temperatures, and to the south are warmer temperatures, clear skies, and southerly winds. The greater frequency of these events during the spring and early summer months is apparent in the long-term mean precipitation data for the northern Puget Sound areas.

The effects of diurnal heating were studied in the second of these two papers, by calculating resultant winds for each hour of the day for the months of July and January with three years of data. The July winds are shown to interact on several different scales: onshore plus upslope flow during the day, and offshore plus downslope flow during the night. In addition, the winds are shown to turn clockwise during the diurnal cycle on the coast; within the channels of western Washington, the turning is clockwise on the eastern (north) sides and counterclockwise on the western (south) sides of the channels. The resulting diurnal low-level convergence and divergence within Puget Sound modulates cloudiness and precipitation patterns such that in early morning hours convergence dominates the central Sound. The convergence weakens with time until it is displaced in early afternoon by centers of divergence. In January, the resultant wind vectors are shown to have diurnal components, but they are significantly weaker.

That topography is a significant influence on the wind fields of the Pacific Northwest is clear from the evidence presented in these studies. This memorandum extends the examination of the influence of topography on the region's windfields during particular synoptic-scale events by seeking an understanding of the effect of topographical forcing from a continuous time series of the region's surface wind measurements. This is accomplished by using the wind direction measured at 850 mb at Quillayute as the indicator of the synoptic-scale forcing and classifying the region's wind fields based upon these directions. An overview of the synoptic-scale weather during the study period and the use of 850-mb winds at Quillayute to typify the synoptic scale are discussed in section 2. Section 3 presents the data and the method of compositing that data. Section 4 is a discussion of the composite wind fields and the representativeness of individual stations of those wind fields, section 5 discusses composite pressures and their implications, and section 6 summarizes.

2. Synoptic Overview

The upper-level, synoptic-scale motions from 6 February to 6 March 1980 were dominated by the presence of a large-amplitude blocking ridge along the west coast of North America. However, twice during the month, the ridge broke down and small-amplitude waves propagated eastward through the region. Thus, the month can be roughly divided into the following four sections listed in Table 1 with wind directions and speeds measured at 850 mb at Quillayute, Washington:

a. 6 February 1980 to 19 February 1980

At 1200 GMT on 6 February 1980 at 850 mb, the ridge extended from off the California coast northeastward, and a closed low was centered over SW Alaska (fig. 2). At the surface, high pressure was centered west of California, low pressure over Alaska, and a front extended southward along 140°W longitude. The surface pressure pattern in the Pacific Northwest region was weak and diffuse. On 11 February 1980 a trough dug southeastward from the closed low located over Alaska. Within 24 hours an upper-level closed low formed west of California, and the ridge, then east of its position on 7 February, extended along the length of the West Coast (fig. 3). At the surface, the pressure pattern was well defined, with high pressure centered northeast of Washington State and low pressure located west of California. Within two days, on 14 February 1980 (fig. 4), the upper-level low and its associated surface low pressure drifted north towards the Washington coast, filling during the following 24 hours. On 16 February 1980, another upper-level low located west of California drifted north and filled west of Washington State on 17 February 1980, while a third upper-level low formed west of California.

b. 19 February 1980 to 21 February 1980

On 19 February 1980, a closed upper-level low was located northwest of Washington State, having begun drifting northward two days earlier. A small-amplitude trough is visible on the 850-mb map in the generally westerly flow upstream of Washington State (fig. 5). At the surface, low pressure was centered northwest of Vancouver Island and extended south along 130°W longitude. In the following 48 hours, the upper-level trough passed eastward, and another small-amplitude wave formed in the upper-level flow (fig. 6). This second wave formed farther to the south of the first trough and its associated low-pressure system traveled eastward over California.

c. 22 February 1980 to 02 March 1980

After the second small-amplitude upper-level wave moved into the Rockies, the ridge reformed along the west coast and a closed upper-level low was located in the North Pacific south of Alaska.

At the surface, low pressure was located in the North Pacific and a weak and diffuse high-pressure pattern existed over western

Table 1. Description by day of synoptic-scale motions and the 850-mb wind measured at Quillayute, Washington. Directions are in degrees and wind speeds, in parentheses, in m s^{-1}.

February 1980

	6	7	8	9	10
0000 GMT		310(5.7)	350(6.7)	120(5.1)	100(5.1)
1200 GMT	185(15.4)	310(6.2)	060(3.1)	160(5.1)	060(5.1)

synoptic overview: At 850 mb, a ridge was located off the west coast, and a closed low was centered in the Gulf of Alaska.

	11	12	13	14	15	16	17	18
0000 GMT	095(3.0)	100(2.6)	290(4.6)	090(5.7)	090(2.6)	175(7.7)	150(8.7)	190(15.0)
1200 GMT	030(1.0)	310(1.0)	070(11.3)	090(4.1)	150(2.6)	179(9.8)	135(8.2)	160(25.0)

synoptic overview: The 850-mb ridge moved eastward to lie along the west coast, steering surface lows northeastward from west of California towards Washington State.

	19	20	21
0000 GMT	220(9.0)	085(1.5)	245(7.7)
1200 GMT	215(8.7)	260(4.6)	060(2.1)

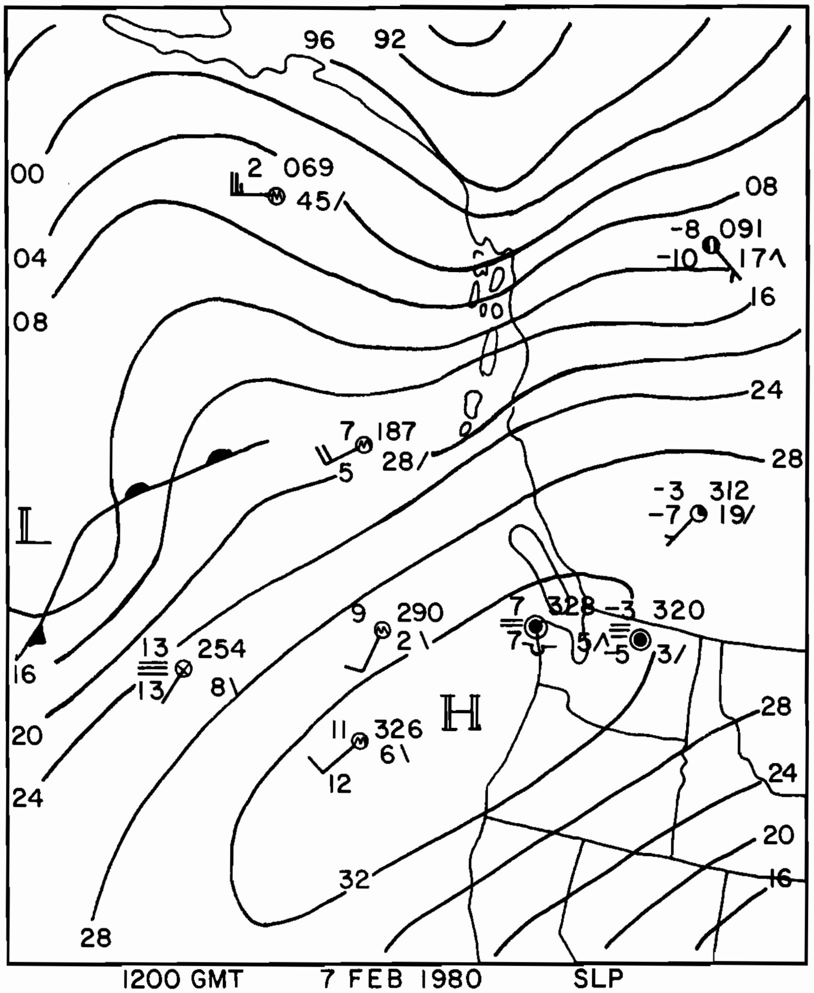
synoptic overview: The 850-mb ridge moved still more eastward to lie over the Rocky Mountains and an 850-mb closed low became stationary northwest Washington State. In the westerly flow upstream of Washington State, two small-amplitude troughs propagated through the region.

Table 1, cont.

	February 1980				
	22	23	24	25	26
0000 GMT	125(0.5)	145(4.6)	150(12.9)	180(13.9)	190(19.0)
1200 GMT	145(8.7)	125(7.7)	155(21.6)	165(20.1)	200(29.8)

				March 1980	
	27	28	29	01	02
0000 GMT	185(9.8)	180(29.3)	210(15.9)	170(13.4)	165(9.3)
1200 GMT	190(17.0)	180(18.0)	175(11.3)	165(9.3)	200(10.8)
synoptic overview	The 850-mb ridge reformed west of its previous position and now lay along the west coast. A closed 850-mb low was located south of Alaska.				

	March 1980			
	03	04	05	06
0000 GMT	000(0.0)	345(1.0)	145(7.2)	140(2.1)
1200 GMT	220(3.6)	285(7.2)	340(2.6)	040(2.6)
synoptic overview	The 850-mb ridge weakened and two closed 850-mb lows with associated surface lows passed to the south of the Pacific Northwest.			



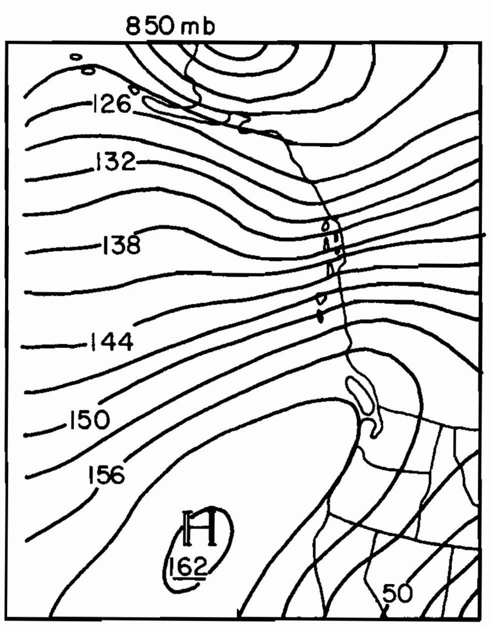


Figure 2. Sea-level pressure analysis and 850-mb geopotential height contour analysis for 1200 GMT 7 February 1980.

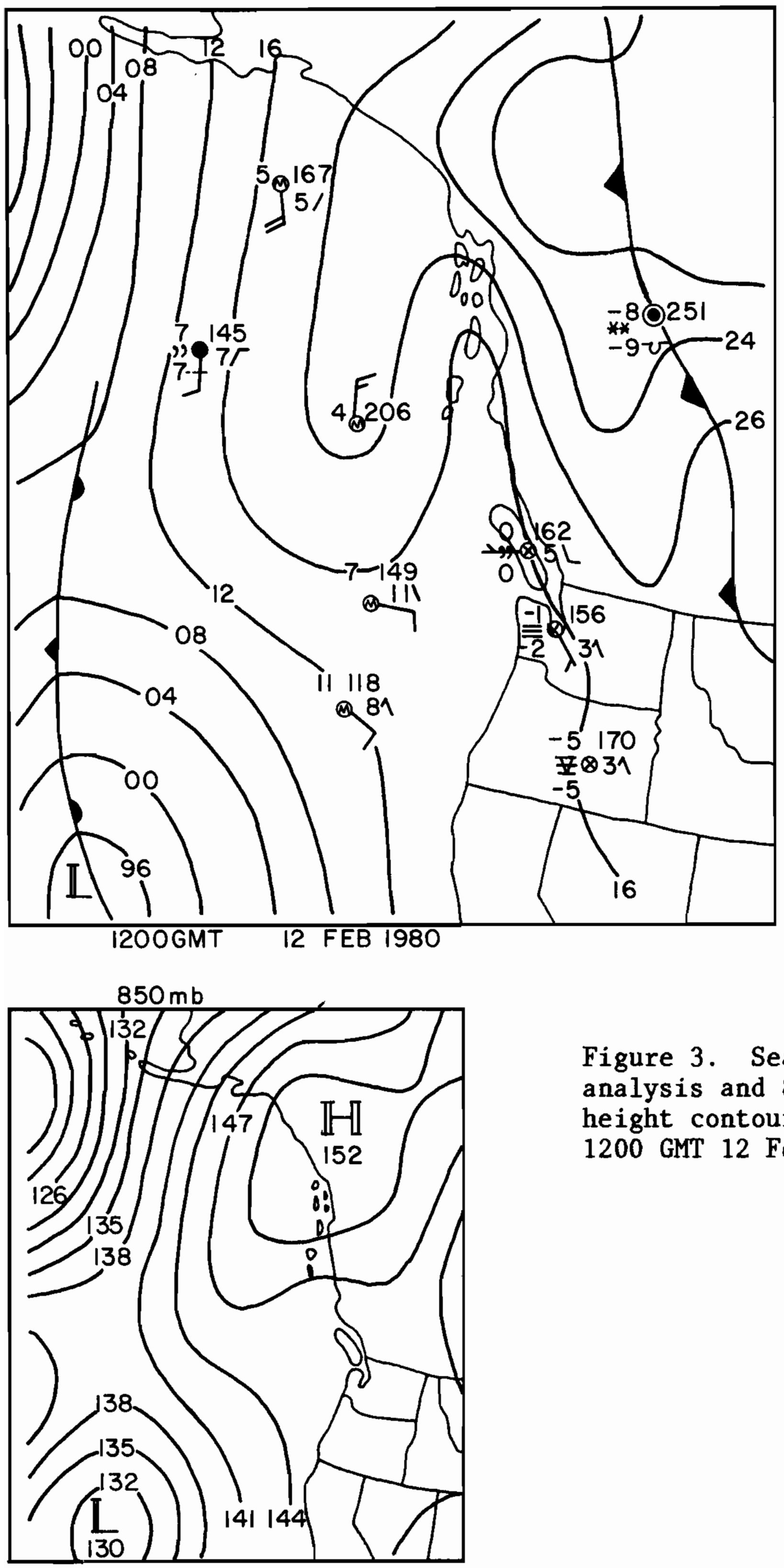
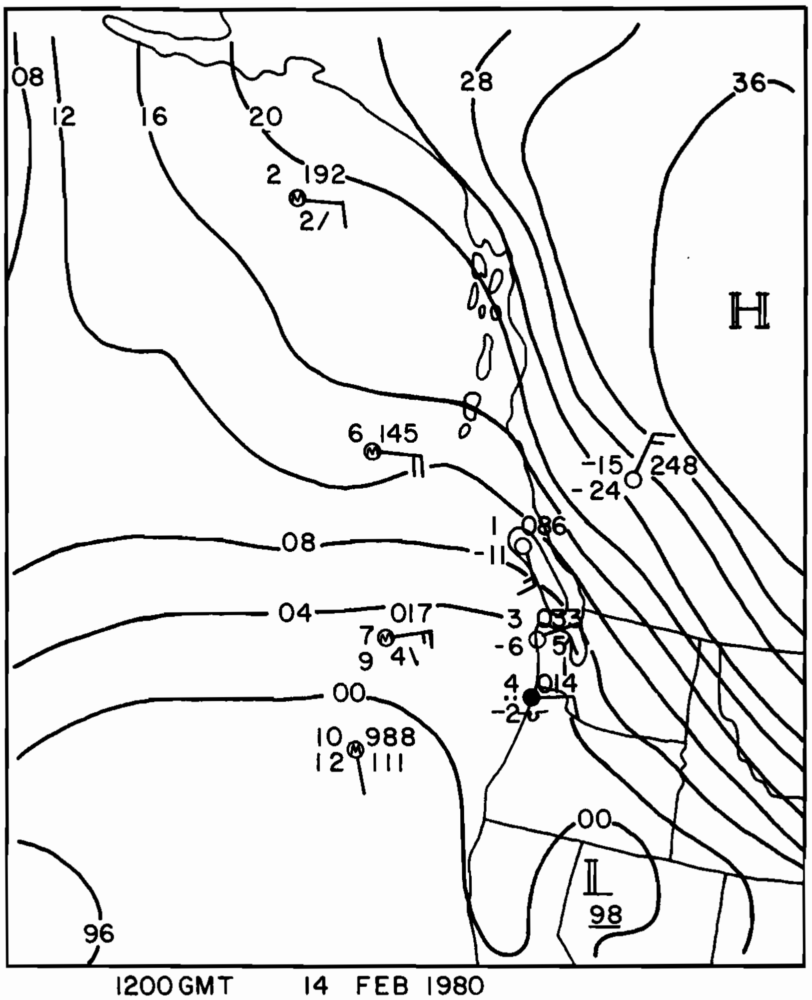


Figure 3. Sea-level pressure analysis and 850-mb geopotential height contour analysis for 1200 GMT 12 February 1980.



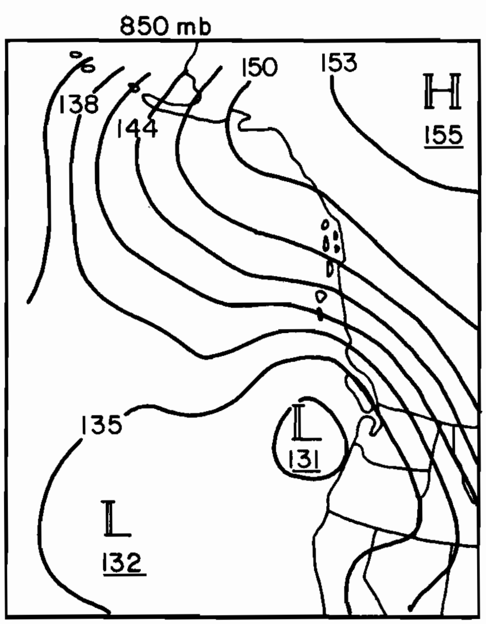


Figure 4. Sea-level pressure analysis and 850-mb geopotential height contour analysis for 1200 GMT 14 February 1980.

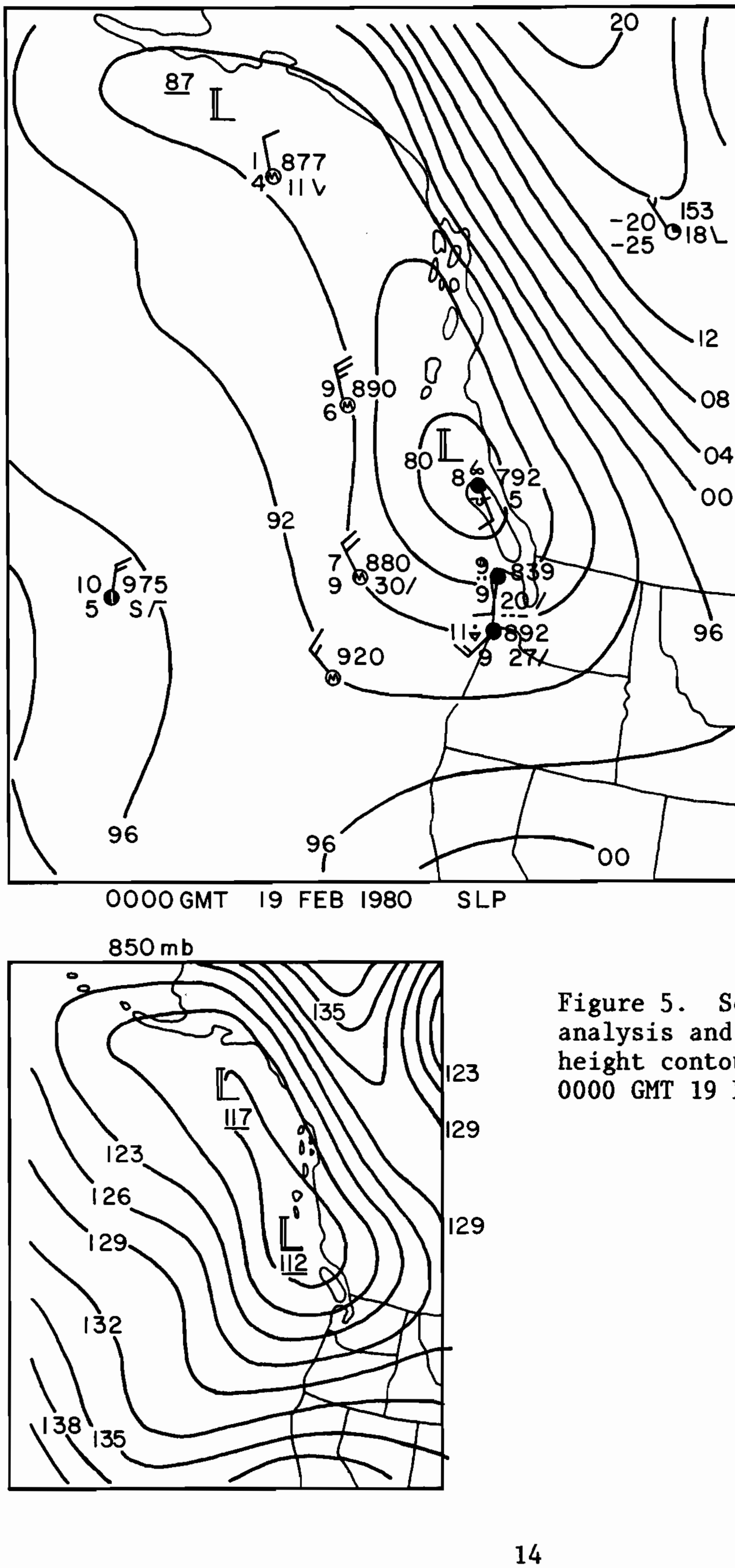
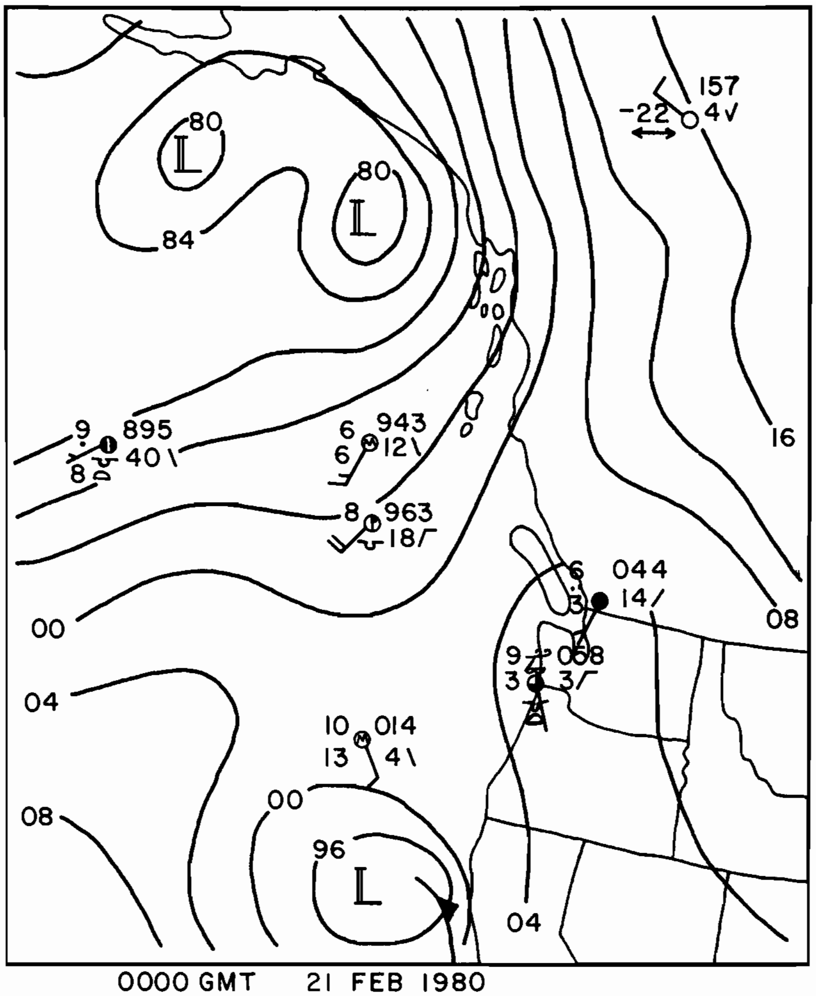


Figure 5. Sea-level pressure analysis and 850-mb geopotential height contour analysis for 0000 GMT 19 February 1980.



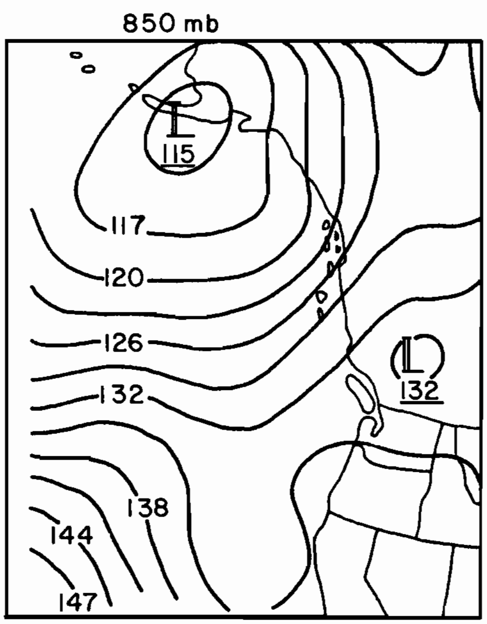


Figure 6. Sea-level pressure analysis and 850-mb geopotential height contour analysis for 0000 GMT 21 February 1980.

North America (fig. 7). From 22 February to 2 March a succession of surface low-pressure systems followed the upper-level flow, approaching the Washington coast in a northeasterly direction, and slowly filling as they continued up the British Columbia coastline. On 1 March 1980, the upper-level ridge at 850 mb weakened in the Pacific Northwest region, and there were two closed lows present, one centered over the Aleutians and the other located west of Oregon (fig. 8).

d. 03 March 1980 to 06 March 1980

At 0000 GMT on 3 March 1980, a closed upper-level low and associated surface low-pressure system moved eastward across California (fig. 9). Again, on 5 March 1980, a closed upper-level low and associated surface low-pressure system approached the west coast. During the next 48 hours, they moved eastward across Oregon (fig. 10).

These four divisions in the synoptic weather of 6 February-6 March 1980 are apparent also in the time series of 850-mb winds measured at Salem, Oregon, and Quillayute (fig. 11). On 6 February 1980, a small-amplitude trough was located immediately west of Washington State, and the winds at both stations were southwesterly. Within 12 hours, the winds became light and variable, and remained so for the next 10 days.

At 1200 GMT 18 February 1980, the wind speed increased to a peak of 25 m s^{-1} at Quillayute when the first of the small-amplitude waves of the second period approached the Washington coast. The winds at Quillayute changed from southwesterly to easterly on 20 February 1980, to southwesterly and again to easterly on 21 February 1980 as the two waves propagated through the region. While the same peak in wind speed is evident at Salem, changes in wind direction did not occur.

When the upper-level ridge returned on 22 February 1980, the axis was located farther to the east over the Rocky Mountains. The wind speeds began increasing, and Quillayute and Salem had similarly strong and southerly winds for the next 8 days. The wind directions at Salem remained between 170° and 230° while at Quillayute they slowly clocked from 130° and 200° with a maximum speed of 30 m s^{-1} on 26 February 1980. On 1 March 1980, the winds decreased to less than 13 m s^{-1}, and the wind directions showed large variations at both stations as the ridge broke down again and upper-level closed lows passed through Oregon.

However, since the peaks of the Cascades, the coast mountains, and the northeast section of the Olympics commonly rise above the 850-mb heights measured at Quillayute (fig. 12), a comparison of the 850-mb Quillayute winds with those measured at 700 mb can also be helpful in showing the reasonableness of using the 850-mb flow to

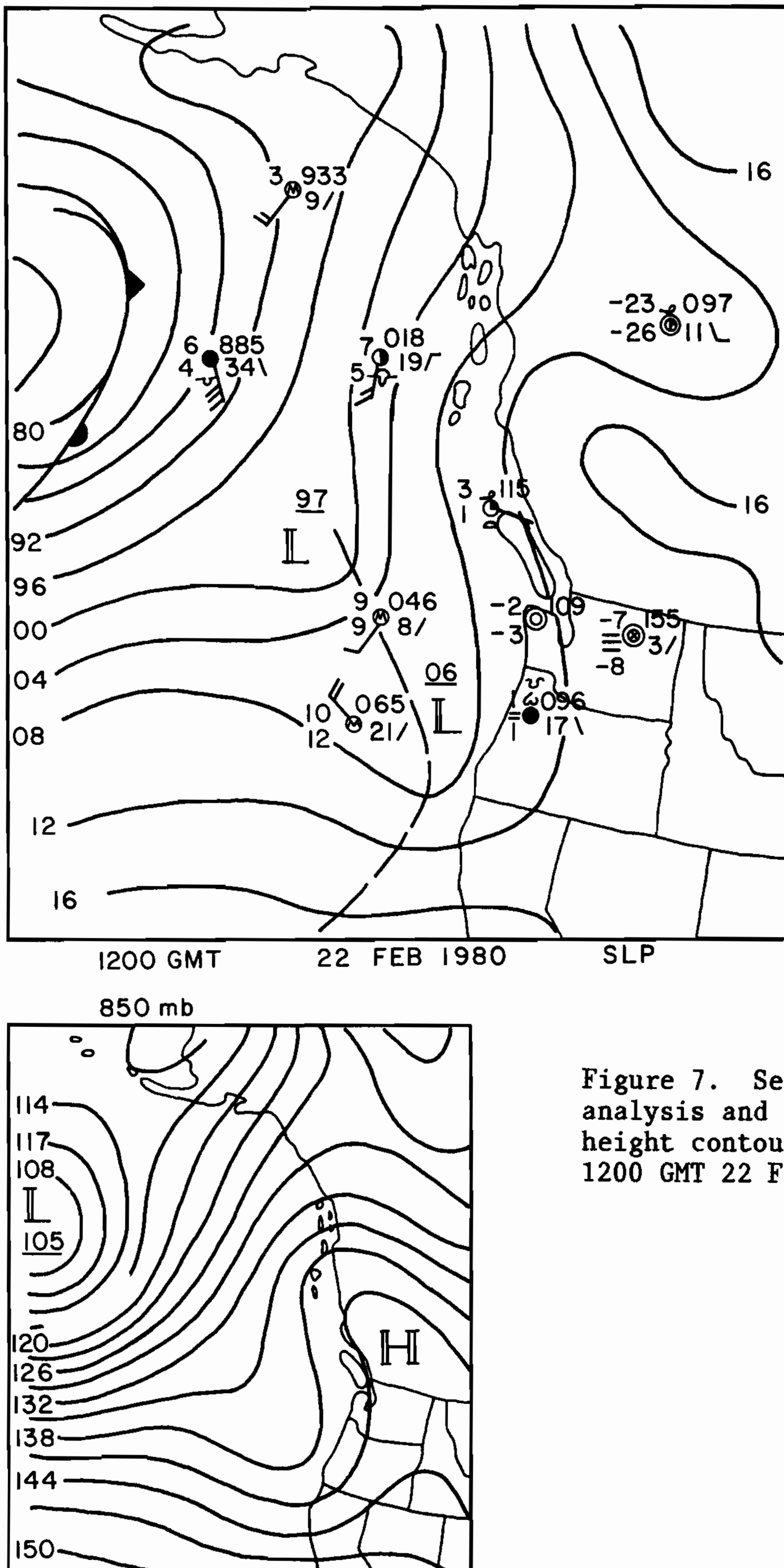
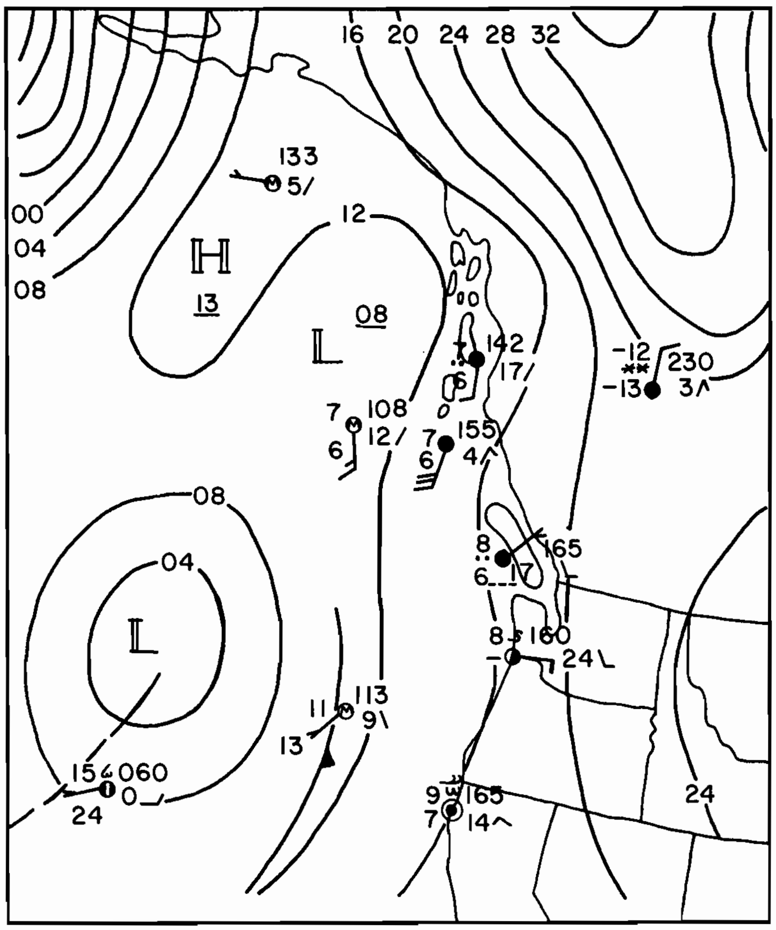


Figure 7. Sea-level pressure analysis and 850-mb geopotential height contour analysis for 1200 GMT 22 February 1980.



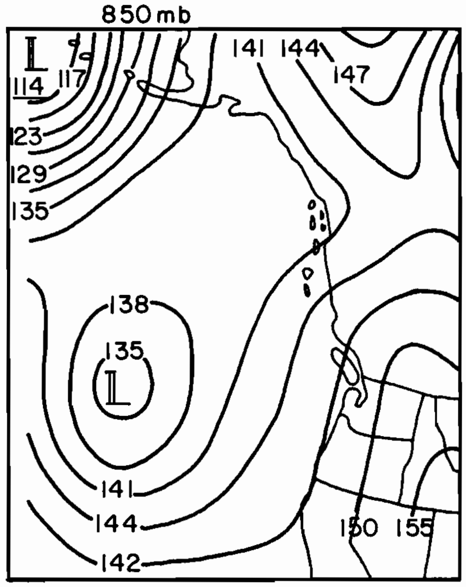
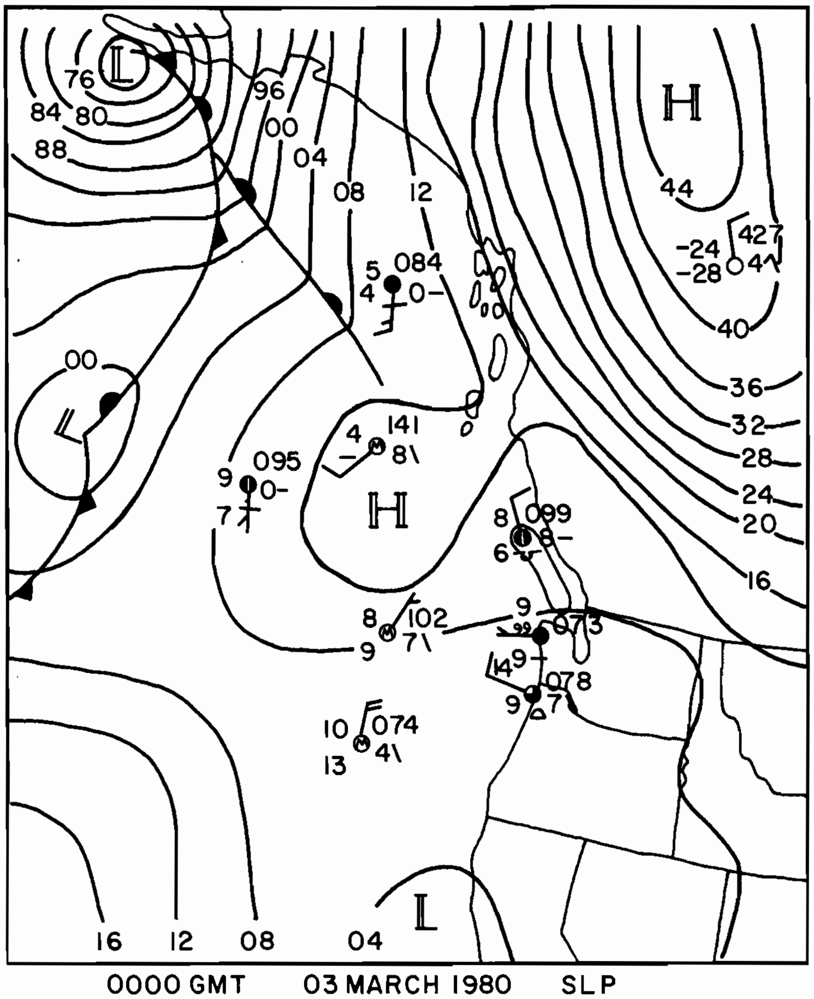


Figure 8. Sea-level pressure analysis and 850-mb geopotential height contour analysis for 1200 GMT 1 March 1980.



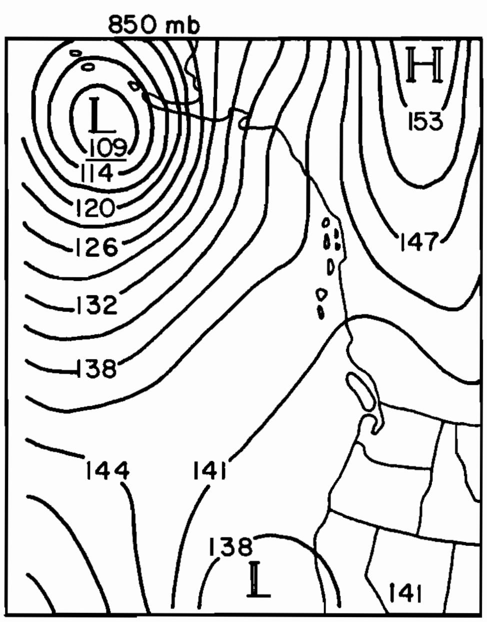
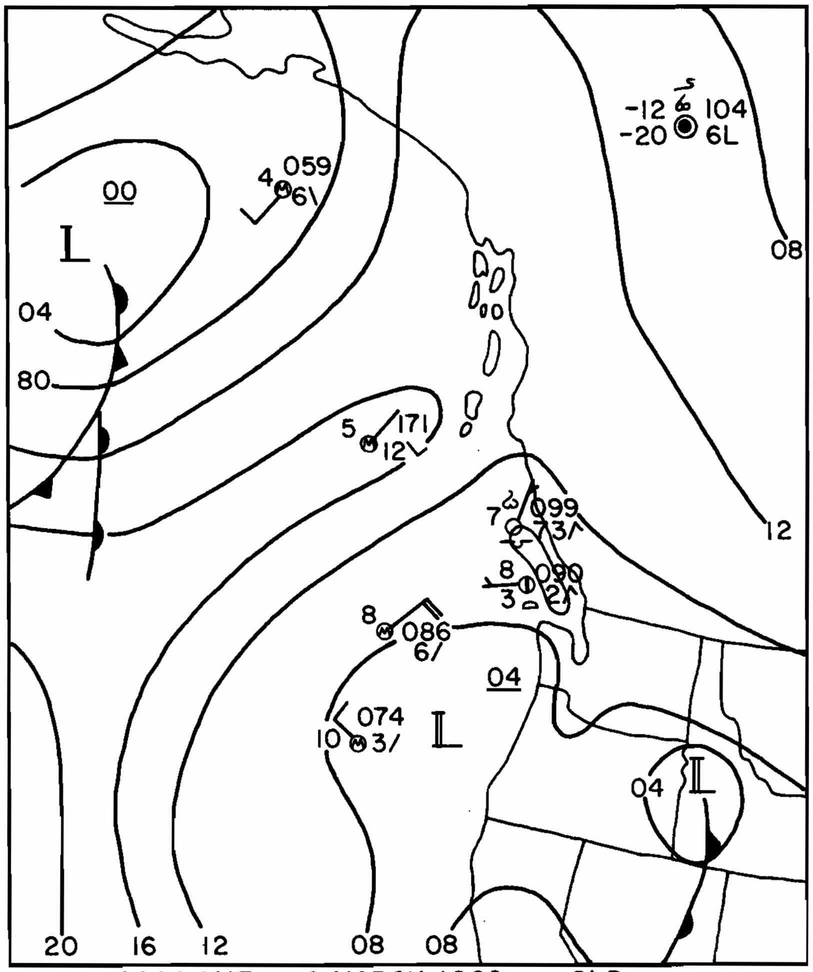


Figure 9. Sea-level pressure analysis and 850-mb geopotential height contour analysis for 0000 GMT 3 March 1980.



850 mb

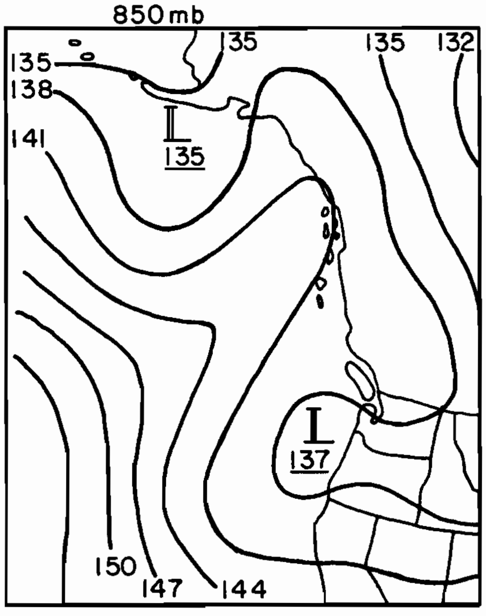


Figure 10. Sea-level pressure analysis and 850-mb geopotential height contour analysis for 0000 GMT 6 March 1980.

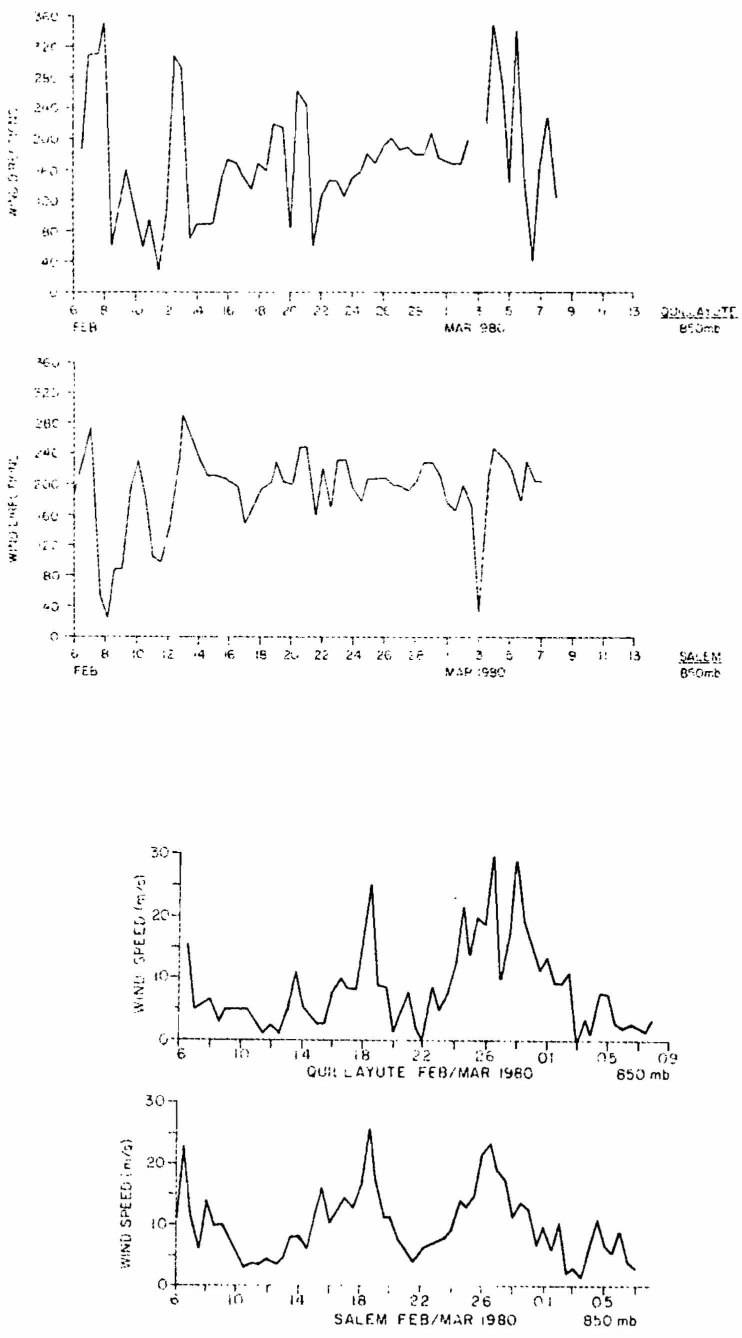


Figure 11. Time series of wind directions and speeds reported for Quillayute, Washington, and Salem, Oregon.

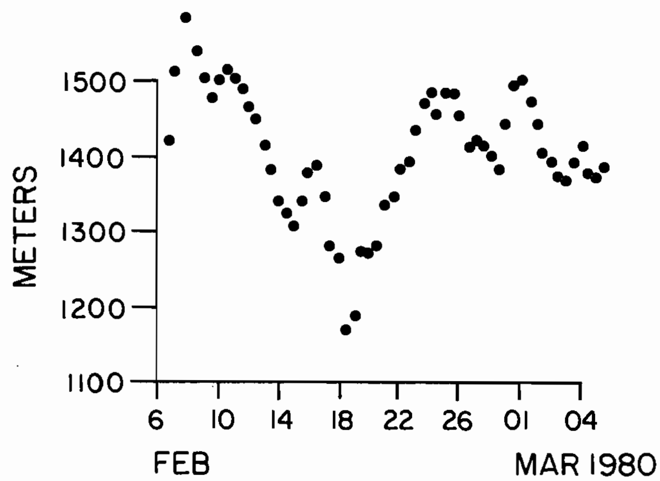


Figure 12. Geopotential heights of the 850-mb surface at Quillayute, Washington.

typify the synoptic scale in the Pacific Northwest. That Quillayute's 700-mb heights are exceeded only occasionally by isolated peaks, points to the unlikelihood that the winds at this level are significantly influenced by the topography.

Histograms of the 700-mb and 850-mb wind directions are shown in figure 13. The wind directions are sorted into 12 groups of 30° each, and the numbers of observations with directions falling within each group determine the length of the columns. The appearance of the two histograms is quite similar with the 700-mb winds shifted 30° relative to these at 850 mb. One large peak occurs within the southerly wind directions at both levels and two small peaks occur within the easterly directions and the northwesterly directions. At both levels, the largest peak is due to the southerly wind reported from 22 February to 2 March when the axis of the blocking ridge was located over the Rocky Mountains. The peaks in easterly and northeasterly winds are due at both levels to reports made between 7 and 14 February when the ridge axis passed along the Pacific coastline and the upper-level winds at Quillayute wavered between east and northwest. The southwest-to-west wind directions at both levels are dominated by reports from 19-21 February and 2-5 March when small-amplitude troughs were passing through the area. I thus conclude that the 850-mb winds are a reasonable representation of the synoptic-scale pressure gradient over the Pacific Northwest.

3. Data

With the 850-mb winds at Quillayute grouped into 12 bins of 30° each, surface wind fields were similarly grouped into the 12 bins. Composed of all routinely available surface observations taken by U.S. and Canadian sources at varying times, the surface wind fields were block averaged and resampled at times corresponding to those of the 850-mb wind measurements. The data sources are listed in table 2 and their locations are shown in figure 14. The majority of the Canadian data were measured at uneven intervals with the most common reporting times of 0200, 0400, 1200, 1300, 1430, 1700, 1930 and 2300. Two Canadian stations, the Vancouver and Victoria airports, record hourly weather observations, including pressure, 24 hours per day. About half the U.S. stations used for this study are Coast Guard stations reporting generally at 3-hour intervals beginning with 0000 GMT. The remaining routinely available U.S. stations are operated by NWS, FAA, USN, and the USAF and report hourly weather observations which include pressure.

In addition to the routinely available surface observations, six buoys and one tower-mounted anemometer provided additional data. Two buoys were placed well offshore in the eastern Strait of Juan de Fuca at Ediz Hook and Dungeness Spit. Two other buoys were placed in the Rosario Strait and a fifth buoy was placed offshore at Point Partridge on Whidbey Island. The sixth buoy was moored off Alki Point in Puget Sound. The surface buoys all measured wind direction, speed, and air temperature at ten-minute intervals. The

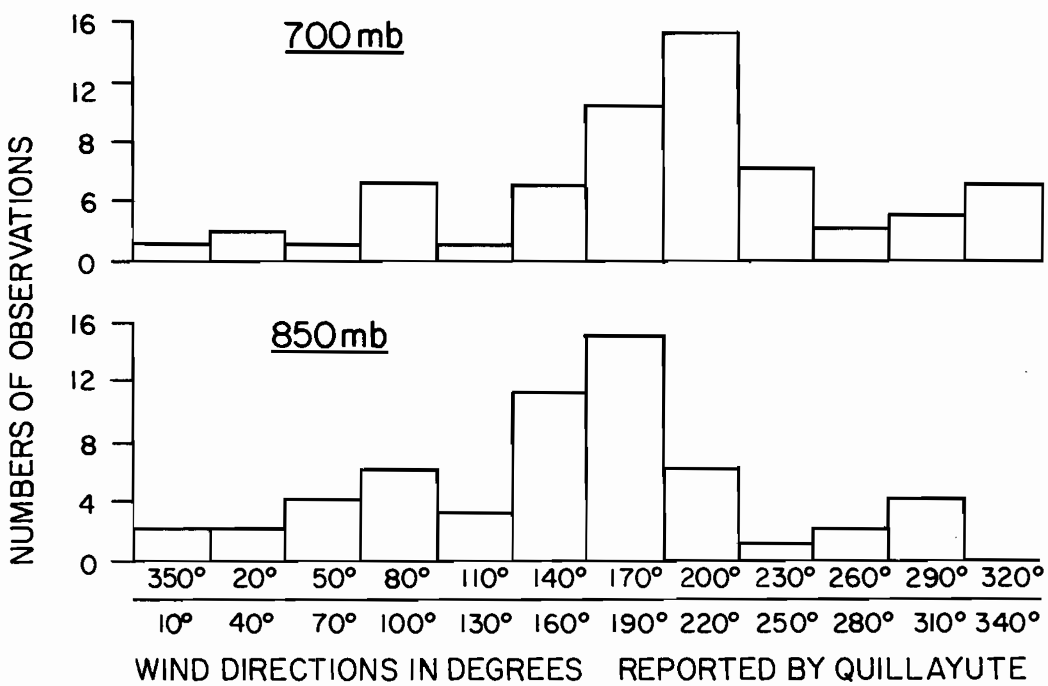


Figure 13. Histogram of 700-mb and 850-mb wind directions reported for Quillayute, Washington.

Table 2. Data sources.

ID	Station Name	Report Times
1.	Alki Point	H
2.	Alki Point "T"	G
3.	Amphritite Point	A
4.	Ballenas Island	B
5.	Bellingham	F
6.	Boeing Field	F
7.	Burrows Island	H
8.	Bush Point	F
9.	Cape Beale	A
10.	Carmanah	A
11.	Discovery Island	D
12.	Dungeness Spit "R"	G
13.	East Point	C
14.	Ediz Hook	G
15.	Entrance Island	B
16.	Friday Harbor	I
17.	Grays Harbor	H
18.	Hoquiam	F
19.	Merry Island	C
20.	Neah Bay	H
21.	New Dungeness	H
22.	Olympia	F
23.	Pachena	A
24.	Paine Field (not shown)	E
25	Point Atkinson (not shown)	C
26.	Point No Point	I
27.	Point Partridge "SA"	G
28.	Point Robinson	I
29.	Point Wilson	H
30.	Port Angeles	H
31.	Portland	F
32.	Quillayute	F
33.	Quillayute River	H
34.	Race Rocks	D
35.	Renton	E

Table 2, cont.

ID	Station Name	Report Times
36.	Rosario (north) "CA"	G
37.	Rosario (south) "RB"	G
38.	Sandhead	C
39.	SeaTac	F
40.	Sherringham	D
41.	Smith Island	H
42.	Tacoma	E
43.	Tofino	A
44.	Trial Island	D
45.	Tsawwassen	
46.	Vancouver	F
47.	Victoria Airport	F
48.	Victoria Gonzales	E
49.	West Point	H
50.	Whidbey Island	F

Report times:
A. 0200, 0400, 1200, 1300, 1430, 1700, 1930, 2300 GMT
B. 0200, 0400, 1200, 1300, 1400, 1700, 2000, 2300 GMT
C. 0200, 0400, 1200, 1300, 1500, 1700, 2000, 1200 GMT
D. 0200, 0400, 1200, 1500, 1700, 2000, 2300 GMT
E. Hourly, 1600 - 0000 GMT or 1600 GMT to 0400 GMT
F. Hourly
G. 6 observations per hour
H. every 3 hours
I. 1800, 2100, 0000 GMT

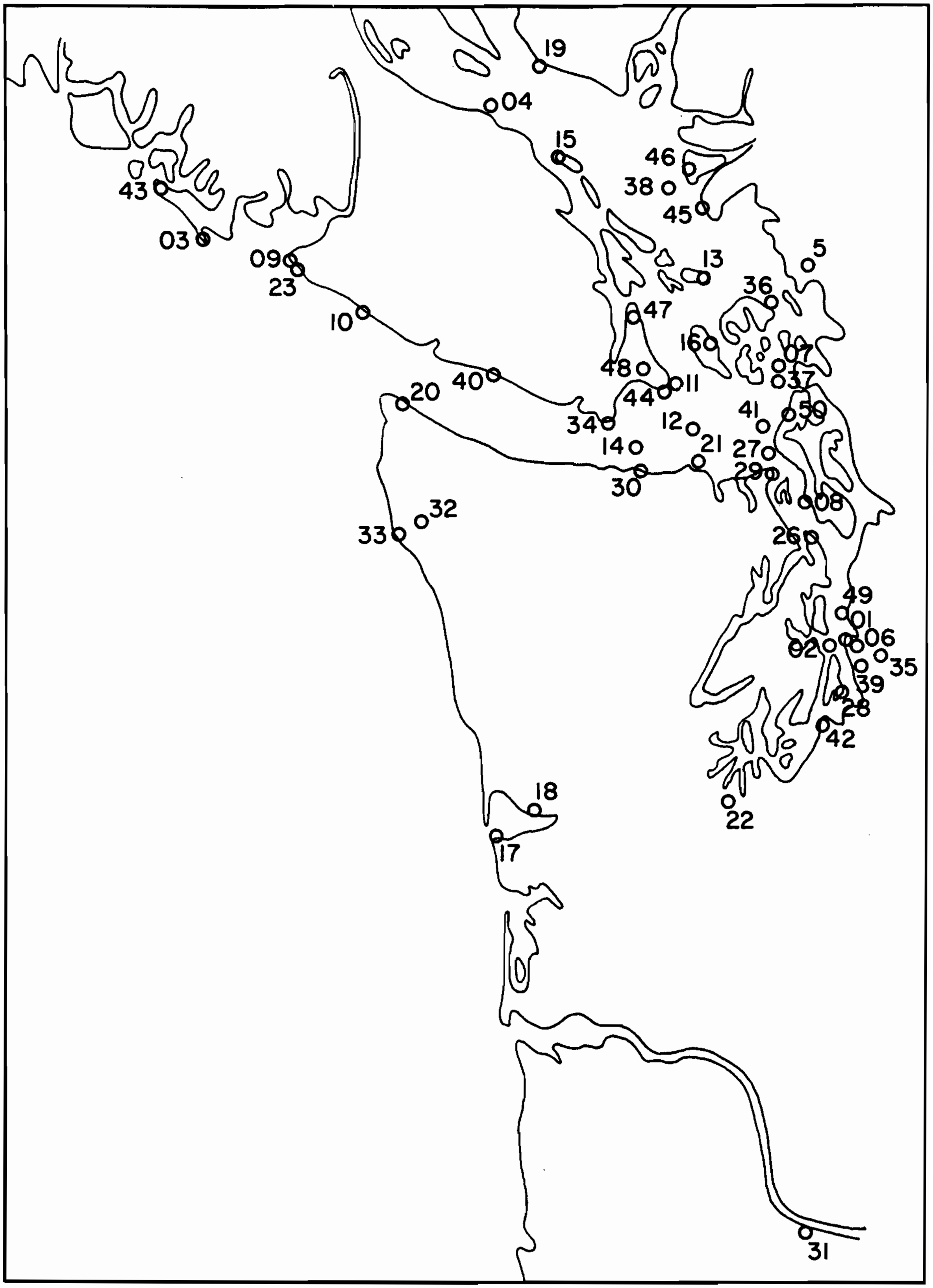


Figure 14. Locations of data sources.

surface buoy records are incomplete, ranging from 13 days at Ediz Hook to 22 days at North Rosario Strait. But in all cases, the records cover the first part of the study period. An exception is the Alki Point buoy which recorded data from 1800 GMT 7 February 1980 to 1500 GMT 6 March 1980 covering nearly the entire study period. The remaining non-routine station was an anemometer placed on the U.S. Coast Guard tower at Bush Point on Whidbey Island, measuring wind speed, direction, and temperature hourly from 10 February through 6 March 1980.

For the purposes of this study, isolated missing data points for stations reporting at intervals greater than one hour are filled with zeroes. For stations reporting at intervals of one hour or less, missing data points are replaced by linearly interpolated values. In order to minimize variations in the data due to the different reporting times and reporting agencies, all data records are block-averaged from three hours before to three hours after each data point and then resampled at 0000 GMT and 1200 GMT or 2300 GMT and 1100 GMT, as appropriate. The Canadian stations which had gaps in the data between 0400 GMT and 1200 GMT were block averaged between 1200 GMT and 1500 GMT and resampled at 1200.

The wind directions measured at 850 mb at Quillayute, Washington, and reported at 12-hour intervals for the period 6 February to 6 March 1980 are divided into 12 classes of 30° each in figure 13. Table 3 lists Quillayute's 850-mb wind directions, average speed, and numbers of occurrences for each class. While the most commonly reported wind directions were between 135° and 194°, all directions with the exception of 315°-344° are represented in the upper-air data.

The following three observation times were left out of the data set: 0000 3 March 1980 GMT, 0000 20 February 1980 GMT, 1200 5 March 1980 GMT. On the first of the three times, Quillayute measured calm winds at 850 mb. On the last two times Quillayute reported winds at 850 mb that do not appear to characterize the 850-mb flow as analyzed by the National Meteorological Center.

The region's 0000 GMT and 1200 GMT surface wind fields were grouped into 11 of the 12 classes represented by 30-degree bins of the 850-mb wind directions. Within each of the 11 classes a resultant wind vector was calculated for each station by vector-averaging the velocity. The persistence of each station's wind within a class was calculated by dividing the speed of the class resultant vector with the class average speed. The resultant vector and persistence fields are mapped in figures 15 through 25. The large arrows indicate direction of flow through a channel and the heavy dashed lines enclose areas with persistence less than 0.5.

Table 3. Composite of winds measured at 850 mb at Quillayute, Washington.

Class	1	2	3	4	5	6	7	8	9	10	11
Directions (°true)	350°-10°	20°-40°	50°-70°	80°-90°	110°-130°	140°-160°	170°-190°	200°-220°	230°-250°	260°-280°	290°-310°
Average speeds (m s^{-1})	3.9	1.8	5.4	3.9	4.4	9.7	14.6	14.0	7.7	5.9	4.4
Number of occurrences	2	2	4	6	3	11	15	6	1	2	4

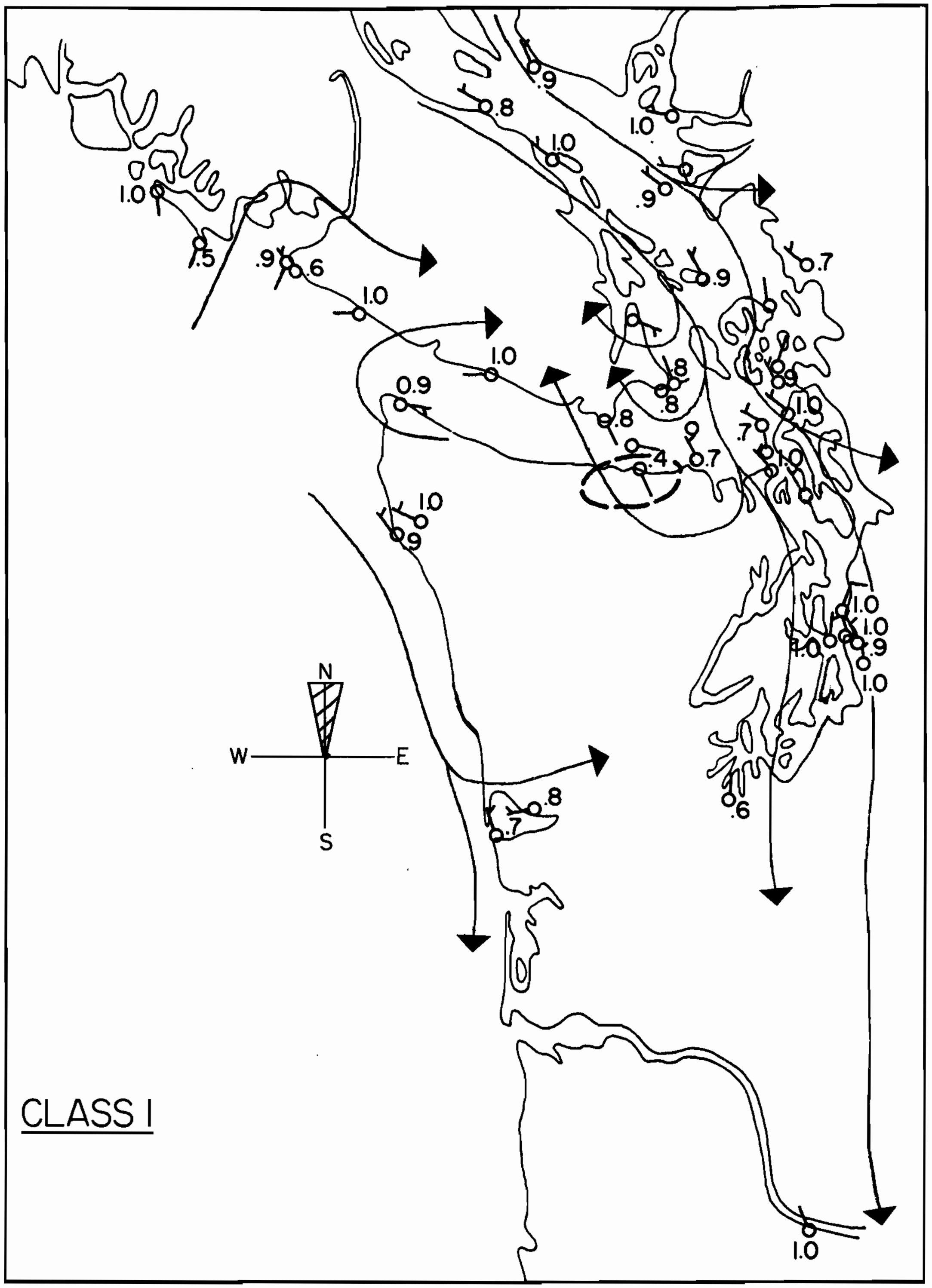


Figure 15. Resultant surface wind vector and persistence fields for class 1. Heavy arrows indicate direction of flow and dashed lines enclose areas of persistence less than 0.5. The direction from which the wind was blowing at 850 mb at Quillayute is shown by the shaded region of the compass.

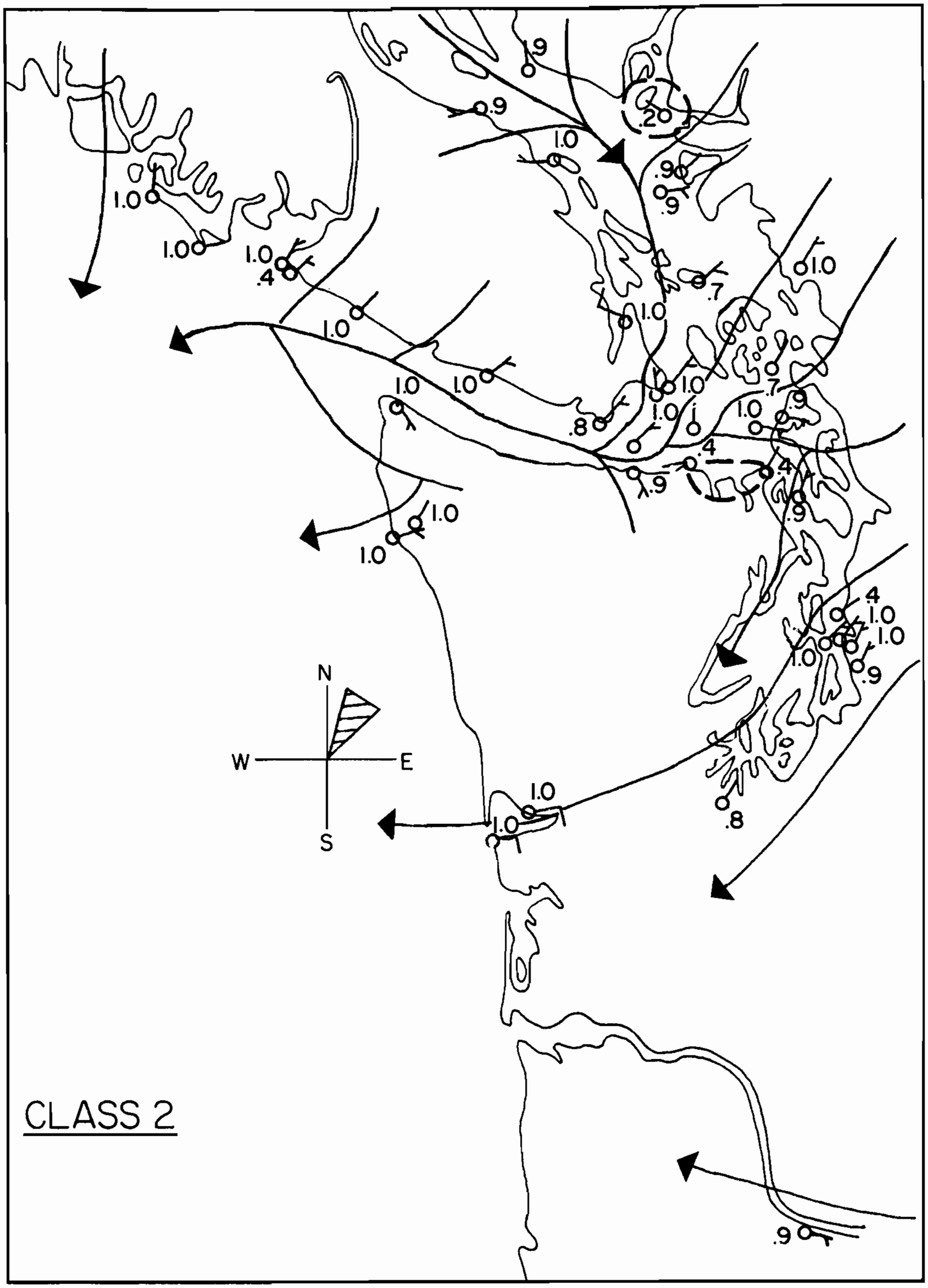


Figure 16. Resultant surface wind vector and persistence fields for class 2. Symbols as in Figure 15.

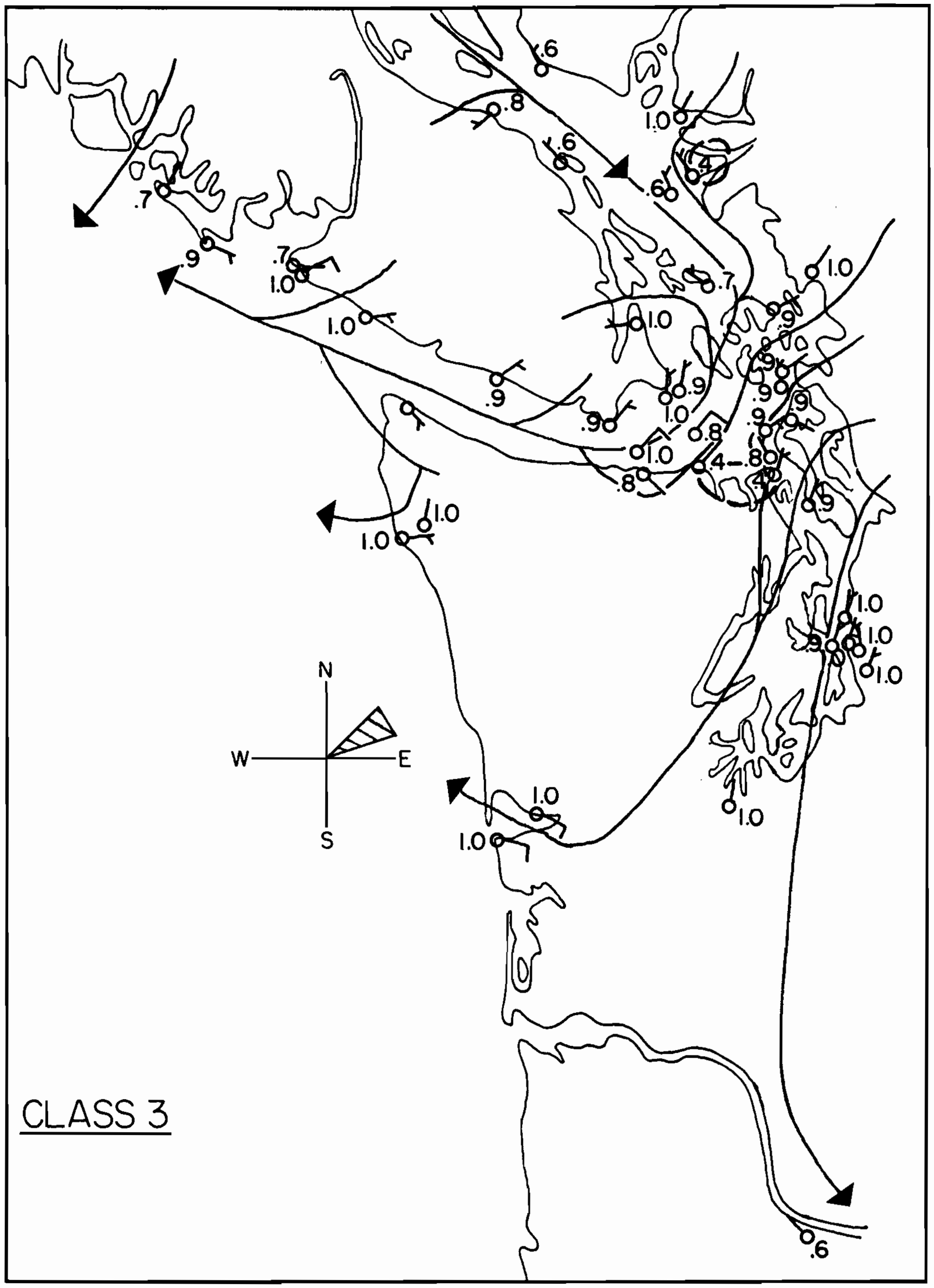


Figure 17. Resultant surface wind vector and persistence fields for class 3. Symbols as in Figure 15.

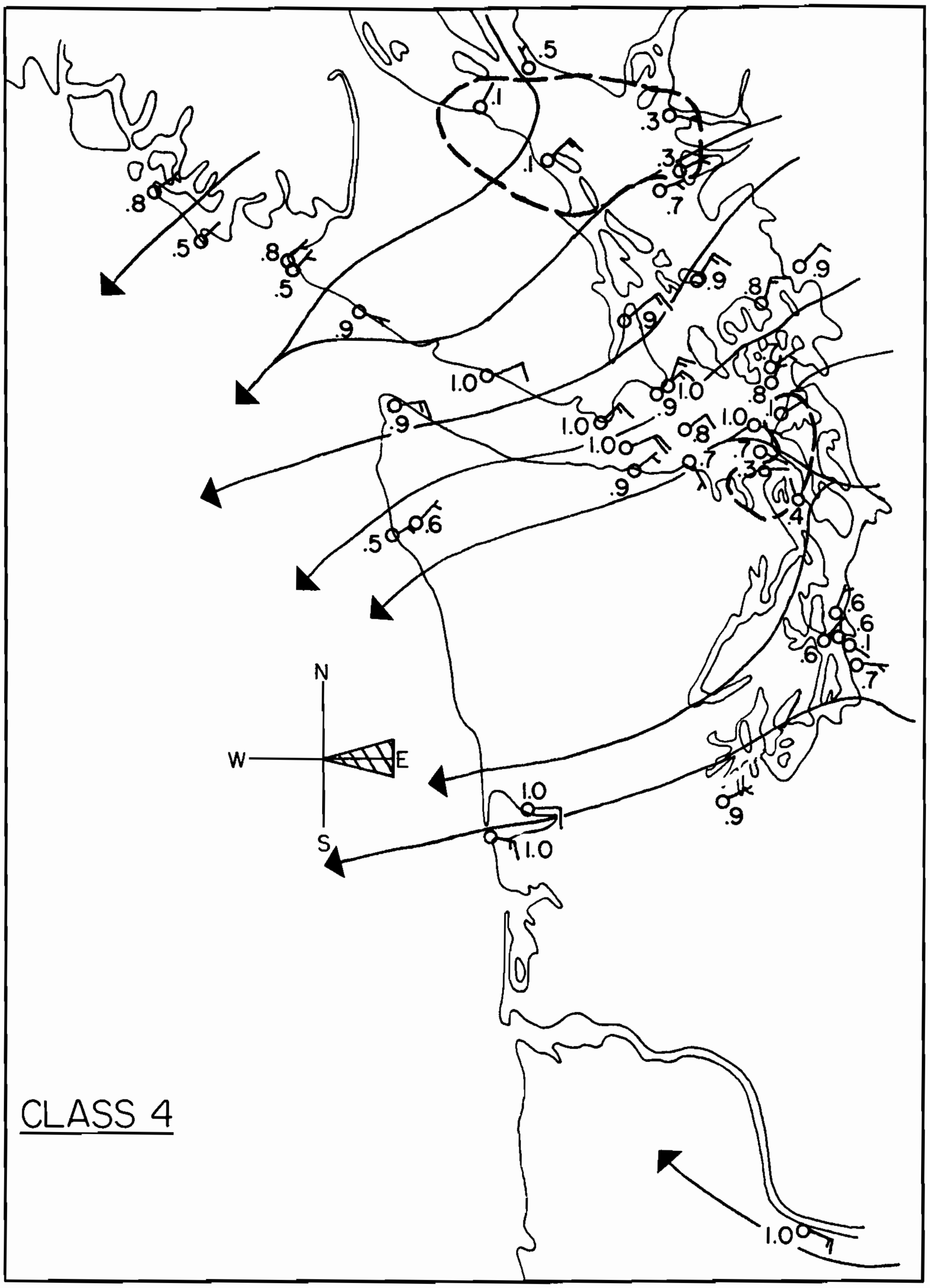


Figure 18. Resultant surface wind vector and persistence fields for class 4. Symbols as in Figure 15.

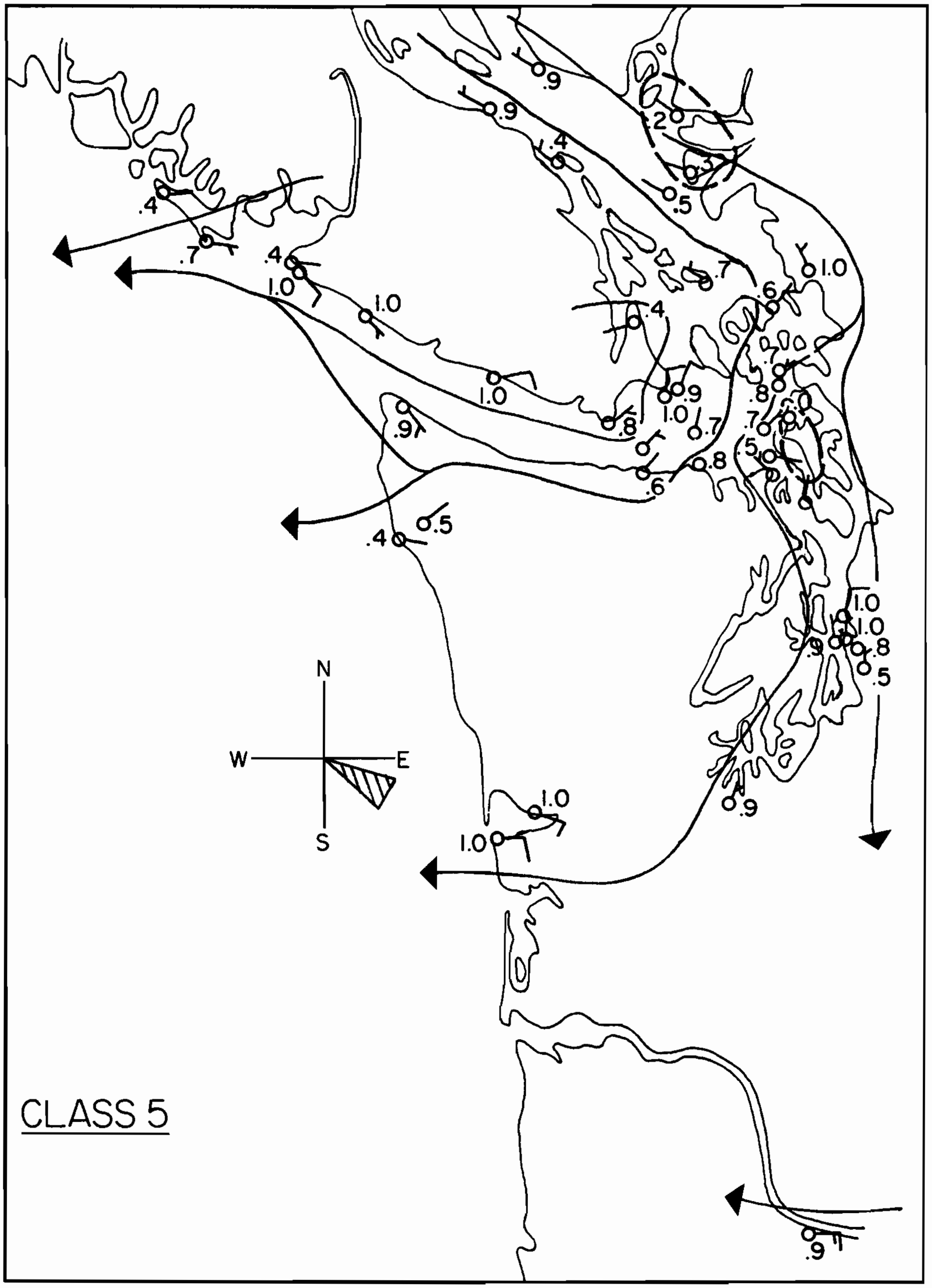


Figure 19. Resultant surface wind vector and persistence fields for class 5. Symbols as in Figure 15.

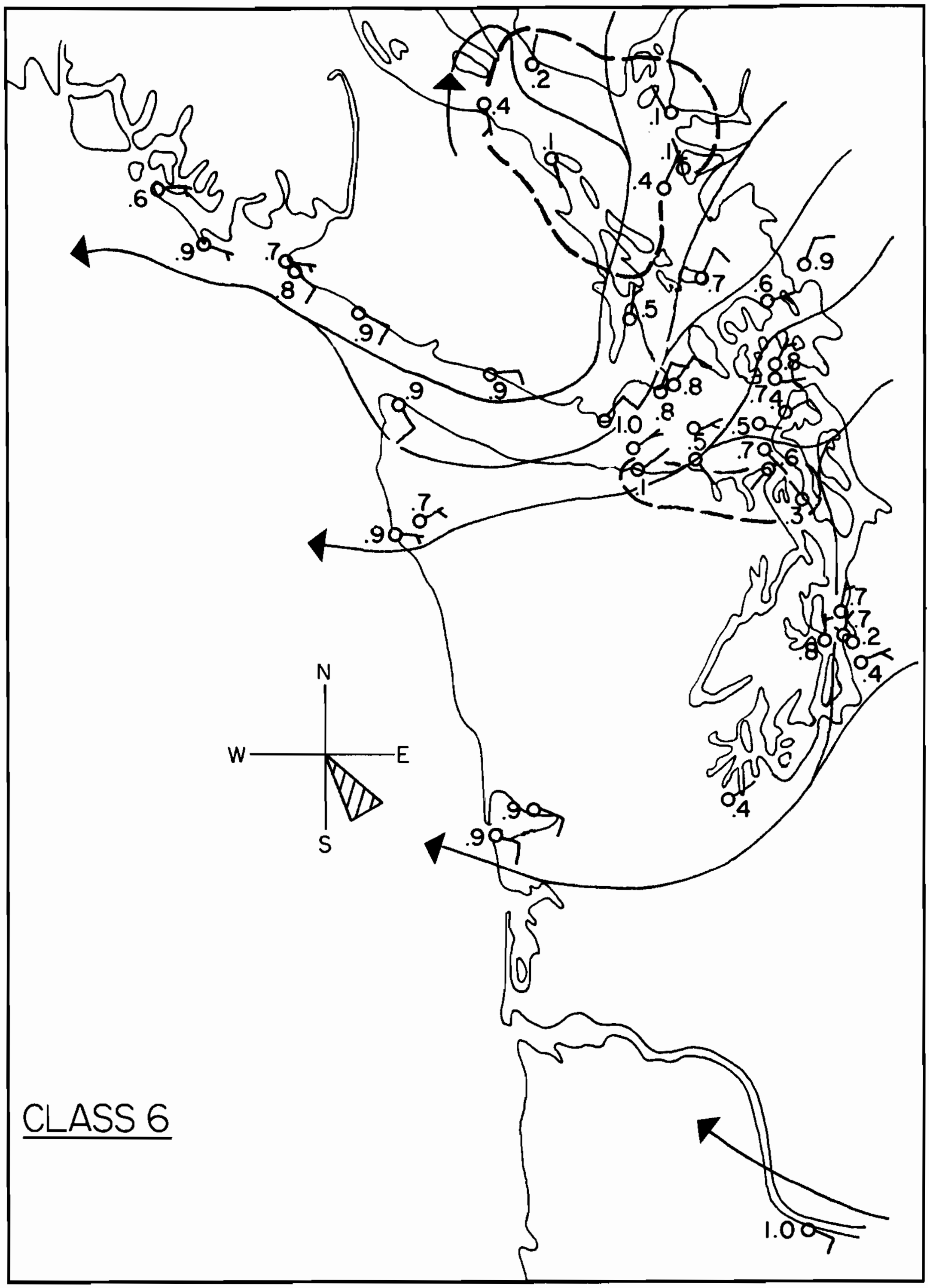


Figure 20. Resultant surface wind vector and persistence fields for class 6. Symbols as in Figure 15.

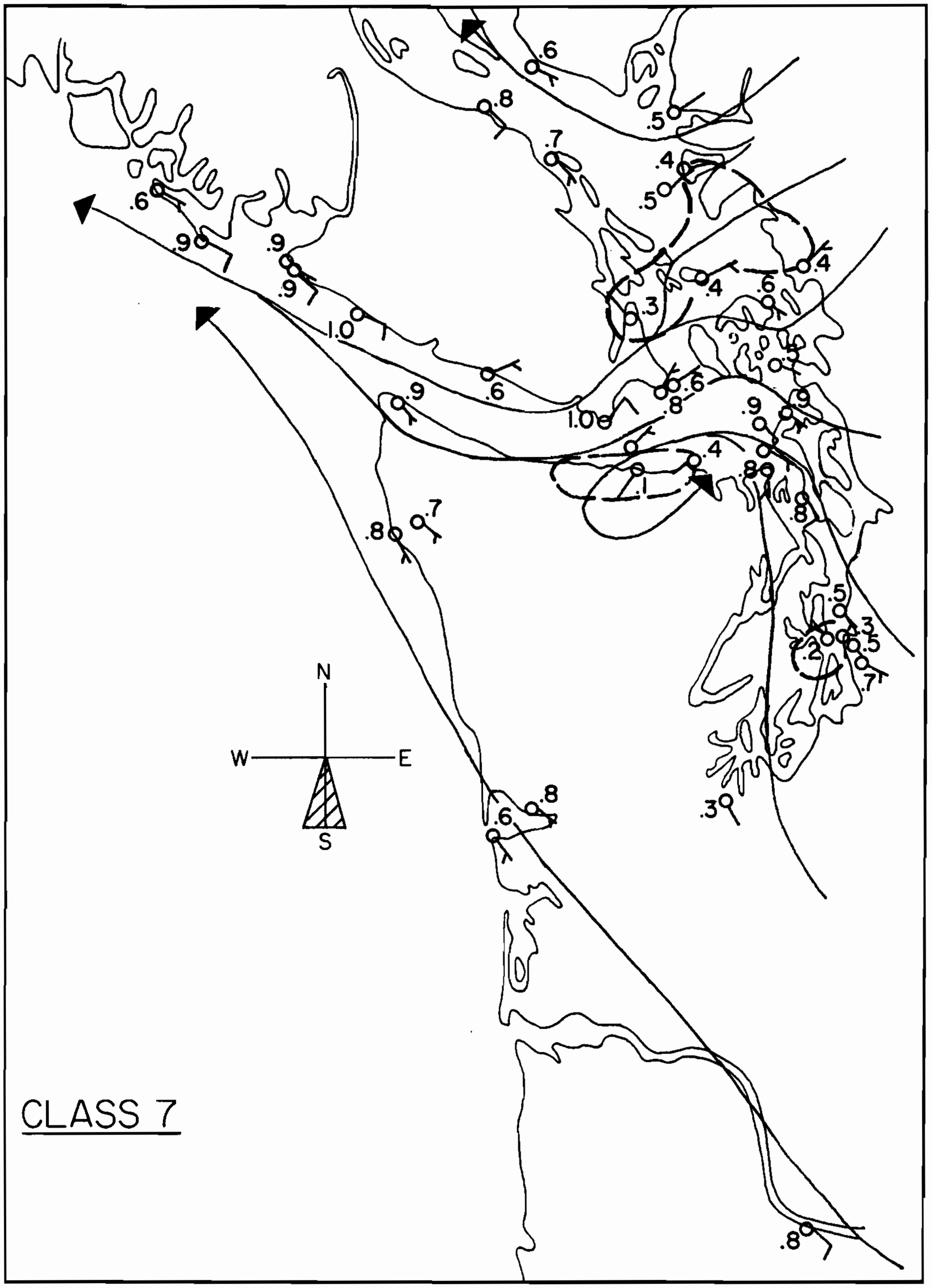


Figure 21. Resultant surface wind vector and persistence fields for class 7. Symbols as in Figure 15.

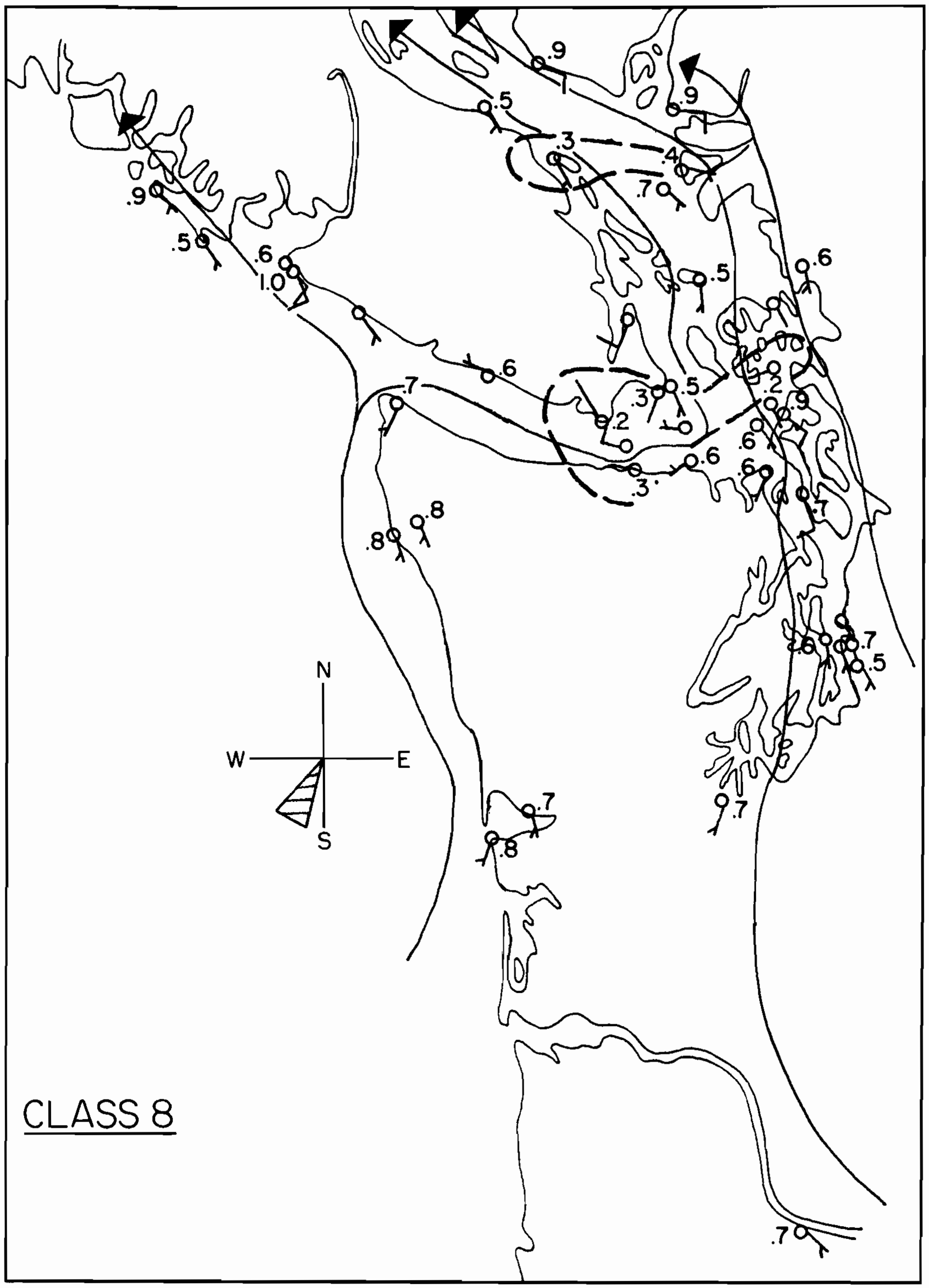


Figure 22. Resultant surface wind vector and persistence fields for class 8. Symbols as in Figure 15.

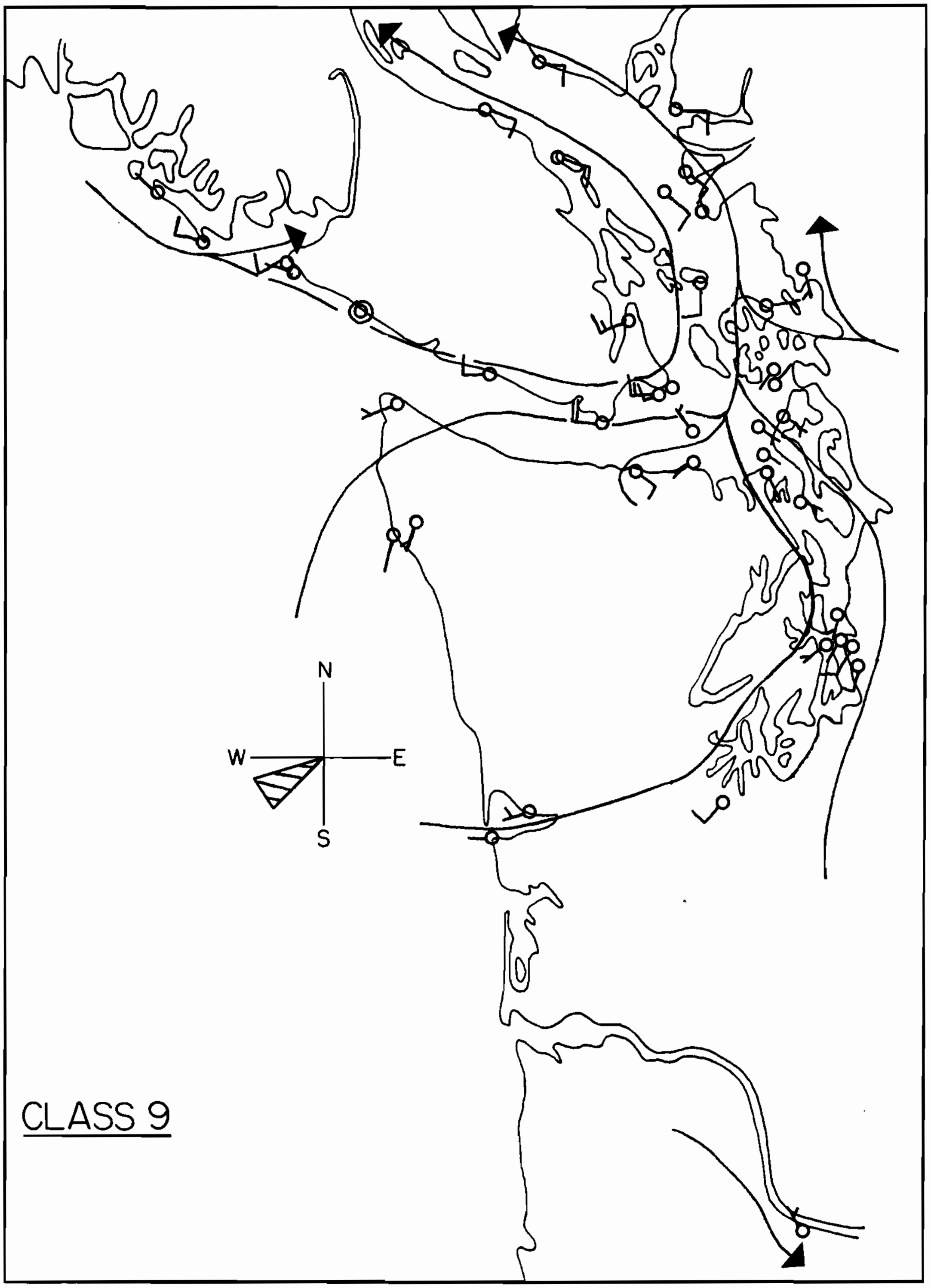


Figure 23. Resultant surface wind vector and persistence fields for class 9. Symbols as in Figure 15.

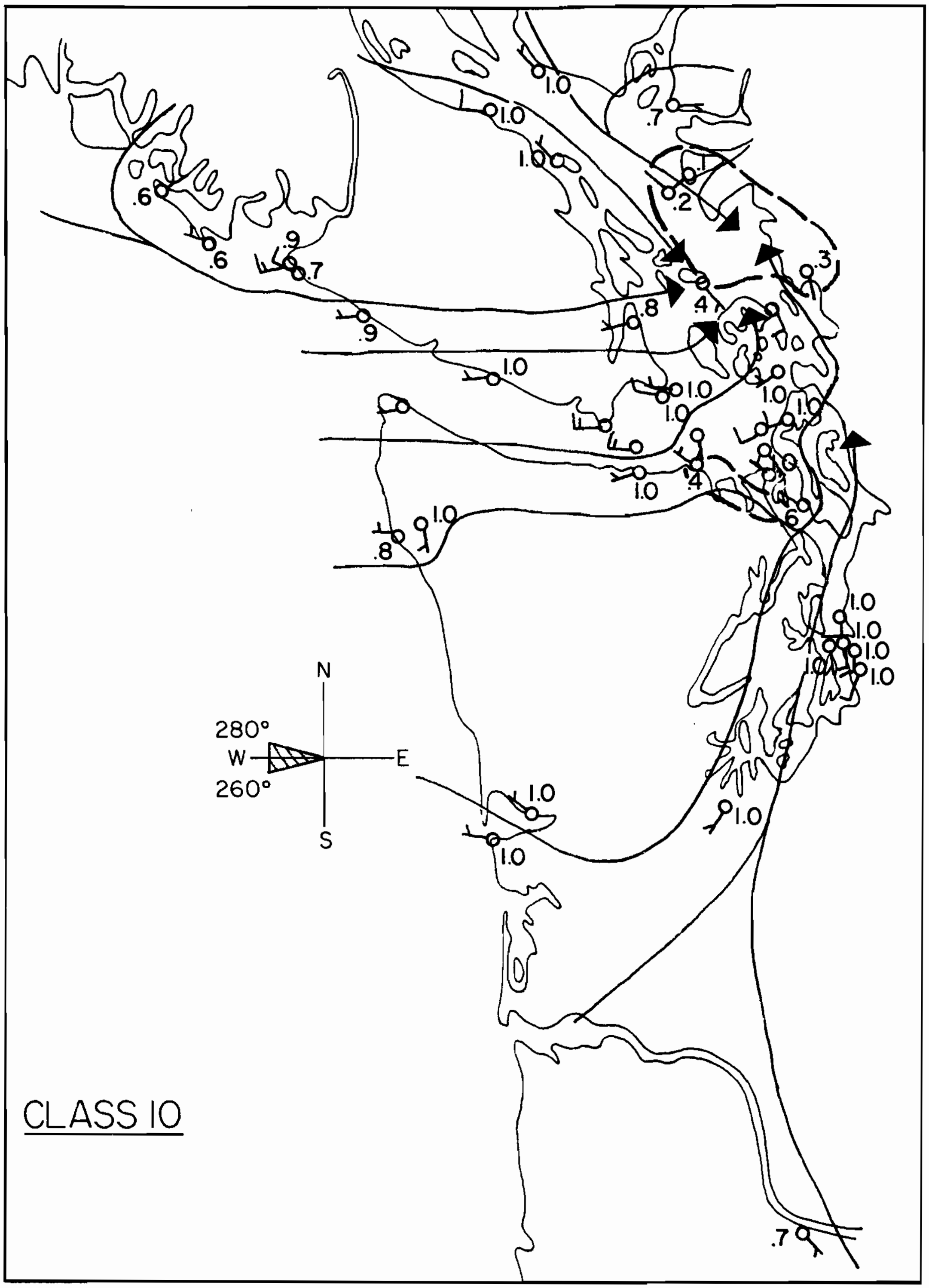


Figure 24. Resultant surface wind vector and persistence fields for class 10. Symbols as in Figure 15.

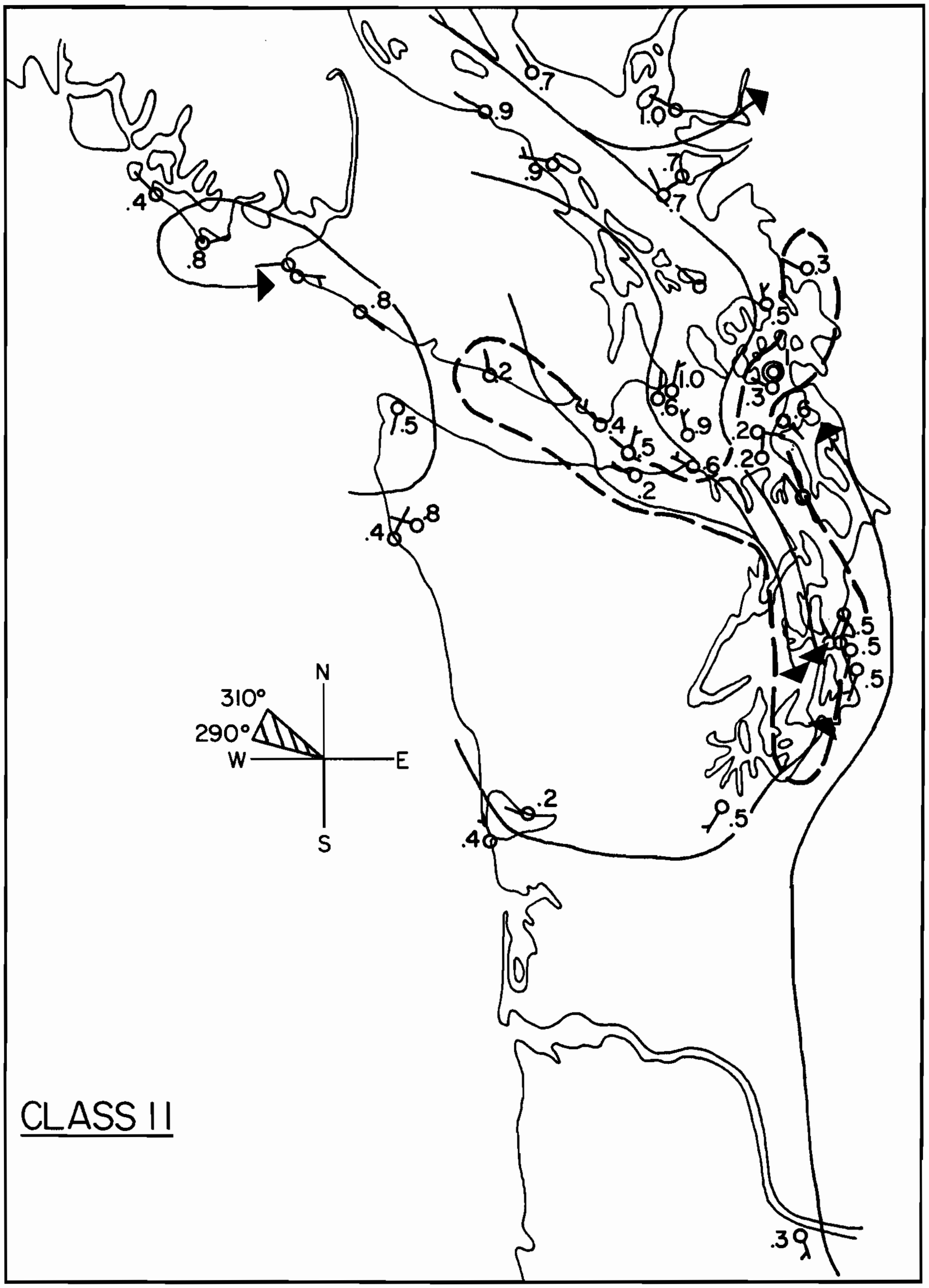


Figure 25. Resultant surface wind vector and persistence fields for class 11. Symbols as in Figure 15.

4. Regional Wind Patterns

In spite of the low numbers of occurrences of many 850-mb wind directions at Quillayute, the sequence of maps does show consistency. Beginning with class 1 (fig. 15) for which Quillayute twice reported 850-mb winds of 350°-10°, the flow pattern was continuously northwesterly to north through the Strait of Georgia, Haro and Rosario Straits, the Strait of Juan de Fuca as far west as New Dungeness, and through Puget Sound. On Washington's Pacific coast, the winds were also northwesterly while Vancouver Island's Pacific coast winds were discontinuous with occasional low persistence. Along the right side of the flow when facing downstream in the eastern Strait of Juan de Fuca, distinct eddies formed apparently as the wind was turned aside by the Olympic Mountains to the south.

As the 850-mb Quillayute winds became 20° to 40° in class 2 (fig. 16), a change occurred at many of the stations. In the composite made from two occurrences, the winds became northeasterly from Vancouver south to Puget Sound, northeasterly through much of the Strait of Juan de Fuca, and along the Pacific coast of Vancouver Island and at Quillayute, but southeasterly from Port Angeles to Neah Bay. At Portland and Hoquiam the winds were easterly. In the northern Strait of Georgia, the winds remained north to northwesterly. The flow everywhere was very strong offshore, so that in the Strait of Georgia, for example, the Ballenas Islands had westerly winds, while across the Strait, Merry Island showed northerly winds. Areas of low persistence existed at New Dungeness and Point Wilson in the Strait of Juan de Fuca, and at Pt. Atkinson in the Strait of Georgia.

For class 3 (fig. 17), the 850-mb winds were measured three times at Quillayute between 50°-70°, but little change occurred in the surface wind field. The area of confluence in the Strait of Georgia moved closer to the eastern shore. The 850-mb winds at Quillayute for class 4 (fig. 18) were 80° to 100° occurring six times in the data, and some change was evident at the surface. In the Strait of Juan de Fuca and in Haro Strait the winds were northeasterly and in the northern Strait of Georgia all the stations showed low persistence. The area of low persistence in the Strait of Juan de Fuca moved east to encompass Pt. Wilson and Bush Point.

Quillayute's 850-mb winds were 110°-130° for class 5 (fig. 19). On three occasions, Quillayute's 850-mb winds fell within this range. The composite winds were northwesterly in the Strait of Georgia and as far south as Sydney, Bellingham, and Point Wilson. Some stations on Vancouver Island's Pacific coast and along Washington's Pacific coast showed southeasterly winds. The offshore component of the flow in the Strait of Georgia and Puget Sound disappeared. The area of low persistence in the Strait of Georgia decreased in area and became confined to Point Atkinson and Vancouver while the area of low persistence near NAS Whidbey Island was unchanged.

In class 6 (fig. 20), Quillayute's 850-mb wind directions were 140° to 160° on 11 occasions. The areas of persistence less than 0.5 were more extensive in the Strait of Georgia and along the southeastern shore of the Strait of Juan de Fuca. The land stations in Puget Sound also exhibited a low persistence. Except the southeasterly winds along the Pacific coasts, the class 6 wind field looks similar to the class 4 wind field.

By class 7 (fig. 21), the wind field began to respond to changes in the synoptic scale. Quillayute measured wind directions 170°-190° 15 times for this class. In Puget Sound north to Whidbey Island, in the northern Strait of Georgia and along the Pacific coasts the predominant composite winds were southeasterly. This southeasterly flow was interrupted by a northeasterly flow from the Fraser River delta to Sherringham. The flow was diffluent in the southern Strait of Georgia and confluent along the San Juan Islands. An eddy formed in the Port Angeles-Dungeness Spit area. There were three areas of low persistence. In the Strait of Georgia low persistence became more extensive and included Sydney and Bellingham, and in the Strait of Juan de Fuca the New Dungeness and Port Angeles winds had low persistence. Puget Sound was also an area of low persistence.

Figure 22 represents the composite wind field for 850-mb wind directions at Quillayute of 200°-220°, class 8, which is a composite of 6 occurrences. The most notable change took place in the Strait of Juan de Fuca where the predominant wind was westerly. The southerly winds expanded to include the southern Strait of Georgia which was an area of low persistence on the previous map. The flow was southerly on the Washington coast but still southeasterly along Vancouver Island's outer coastline.

Quillayute measured a wind direction between 230°-250° at 850 mb for class 9 only once during the period of study. The corresponding surface winds are shown in figure 23. The winds in Puget Sound and on the Pacific coasts of Washington and Vancouver Island became southwesterly to westerly. The Strait of Juan de Fuca winds remained westerly along the northern shore, and in the Strait of Georgia they remained southeasterly as for class 8. Eddies with light wind formed near Port Angeles and Dungeness Spit and in the southern Rosario Strait.

The class 10 composite (fig. 24) represents the surface wind field for the two occasions when the 850-mb winds at Quillayute were between 260°-280°. The winds on the Pacific coasts became westerly to northwesterly and fell within the range of that needed to produce a Puget Sound convergence zone (Mass, 1981). The winds in the Strait of Georgia became northwesterly. An intricate, convoluted flow developed in the southern Strait of Georgia, an area of low persistence, and in the eastern Strait of Juan de Fuca at the confluence of Puget Sound's southerly flow, the Strait of Juan de Fuca's westerly flow, and the Strait of Georgia's northwesterly flow. This suggests that another criterion for predicting a Puget Sound convergence zone may be northwest winds in the Strait of Georgia.

Quillayute's 850-mb wind directions were measured between 290°-310°, class 11, four times during the period of study. The corresponding composite surface wind field in figure 25 shows winds were light and variable everywhere but in the Strait of Georgia, where they were light and northwesterly. Puget Sound, the Strait of Juan de Fuca, Rosario Strait, and along the Pacific coast of Washington were areas of low persistence. The 850-mb wind speeds were low for this case, however, so class 11 surface winds may not be representative of strong northwesterly flow that occurs in other seasons of the year.

5. Discussion

a. Relation to regional pressure gradient

Table 4 lists by class resultant wind speeds and directions within the three inland waterways and along the Pacific coast. Table 5 lists by class composite sea-level pressure differences between two pairs of stations, Buoy 46005 with Portland, Oregon, and Port Hardy, British Columbia, with Portland, Oregon. Figure 26 illustrates the class composite wind vectors of one station in each of the four main channels as a function of these pressure differences. Buoy 46005 is located about 550 km due west of Portland, Oregon. Port Hardy, British Columbia, is located on the extreme end of Vancouver Island 720 km northwest of Portland, Oregon. Pressures for stations within the region of study were available but were excluded from Table 5 in favor of the differences between Port Hardy and Portland, and Buoy 46005 and Portland for two reasons. The pressure differences between stations within the region were smaller, and their trends in the class sequence were similar to those of the differences between Port Hardy and Portland, and Buoy 46005 and Portland. On the other hand, without pressures from stations along the northwest and south shores of the Strait of Juan de Fuca, and the north and northeastern sections of the Olympic Peninsula, the network of stations measuring pressure was too coarse to detect mesoscale pressure features where they have been known to occur, and no new information could be obtained from pressure differences between stations within the region.

The most general statement that can be made about the two sets of composite differences is that no significant pressure gradient directed from west to east developed in any class, while the gradients between Port Hardy and Portland did reverse in the sequence of classes. That is, generally, high pressure throughout the sequence was located inland, and low-pressure centers located offshore moved in the sequence of classes from south to north of the region. When the pressure differences directed from Portland to B46005 decreased from 11.6 mbs for class 7 to 4.7 mb for class 8, the differences

Table 4. Composite surface wind directions, speeds in m s^{-1}, and the persistence in parentheses.

Class	1	2	3	4	5	6	7	8	9	10	11
Strait of Georgia											
Merry	332°	345°	345°	335°	308°	358°	112°	103°	97°	318°	334°
Island	2.2	1.2	1.6	1.4	2.6	0.9	2.5	5.7	6.2	3.4	1.1
	(0.9)	(0.9)	(0.6)	(0.5)	(0.9)	(0.2)	(0.6)	(0.9)	(1.0)	(1.0)	(0.7)
Sand	297°	80°	330°	66°	299°	19°	60°	125°	120°	312°	341°
Head	3.4	1.4	2.3	2.7	1.0	2.1	1.7	3.6	3.8	0.7	0.6
	(0.9)	(0.9)	(0.6)	(0.7)	(0.5)	(0.4)	(0.5)	(0.7)	(1.0)	(0.2)	(0.7)
Strait of Juan de Fuca											
Race	171°	42°	36°	51°	59°	46°	39°	329°	270°	270°	313°
Rocks	1.0	2.1	2.3	6.9	3.3	6.0	4.3	.6	9.8	6.7	1.4
	(0.8)	(0.8)	(0.9)	(1.0)	(0.8)	(1.0)	(1.0)	(0.2)	(1.0)	(1.0)	(0.4)
Neah	100°	150°	133°	93°	137°	136°	136°	198°	251°	248°	192°
Bay	1.5	3.5	2.3	7.9	2.9	4.2	3.4	3.0	2.2	3.1	1.1
	(0.9)	(1.0)	(1.0)	(0.9)	(0.9)	(0.9)	(0.9)	(0.7)	(1.0)	(0.9)	(0.5)

Table 4, cont.

Class	1	2	3	4	5	6	7	8	9	10	11
<u>Puget Sound</u>											
Bush	325°	22°	11°	340°	5°	337°	139°	167°	84°	294°	329°
Point	2.4	1.6	1.4	0.9	0.8	1.2	4.5	5.2	1.6	1.2	0.1
	(1.0)	(0.9)	(0.9)	(0.4)	(0.5)	(0.3)	(0.8)	(0.7)	(1.0)	(0.6)	(0.3)
Alki	311°	55°	15°	50°	359°	354°	314°	184°	227°	193°	352°
Point	1.3	1.4	1.7	1.1	1.9	1.3	0.2	1.3	0.9	3.5	0.4
	(1.0)	(1.0)	(0.9)	(0.6)	(0.9)	(0.8)	(0.2)	(0.6)	(1.0)	(1.0)	(1.0)
<u>Pacific Coast</u>											
Cape	203°	45°	94°	55°	106°	89°	118°	142°	246°	253°	270°
Beale	0.9	1.7	0.9	2.1	0.2	1.5	3.5	3.8	4.3	7.1	0.6
	(0.8)	(1.0)	(0.7)	(0.8)	(0.4)	(0.7)	(0.9)	(0.6)	(1.0)	(0.9)	(0.7)
Grays	336°	95°	102°	101°	90°	112°	148°	203°	267°	278°	352°
Harbor	2.0	4.9	4.0	6.8	4.9	3.9	3.1	3.2	0.8	3.4	1.2
	(0.7)	(1.0)	(1.0)	(1.0)	(1.0)	(0.9)	(0.6)	(0.8)	(1.0)	(1.0)	(0.4)

Table 5. Composite sea-level pressure differences in mb.

Class	1	2	3	4	5	6	7	8	9	10	11
1. Between Port Hardy, B.C., and Portland, OR											
	+0.1	+0.1	+6.4	+3.0	-0.6	-1.5	-5.4	-6.1	-3.1	-3.0	-1.4
2. Between B46005 and Portland, OR											
	-0.1	-0.8	-2.7	-0.9	-7.4	-7.7	-11.6	-4.7	-4.6	-2.5	-2.1

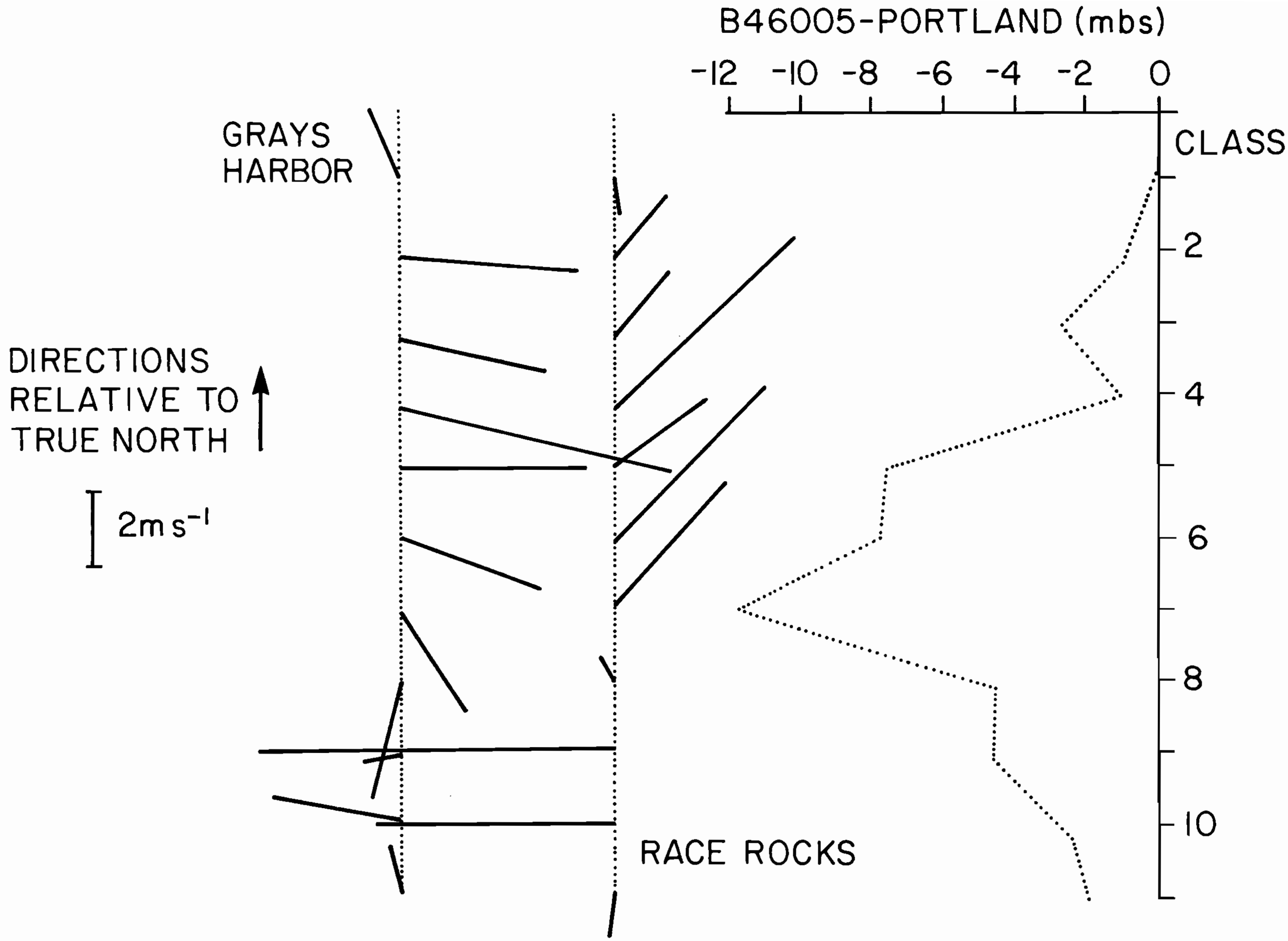


Figure 26. Wind directions in Puget Sound, the Strait of Juan de Fuca, and the Strait of Georgia as a function of pressure differences between Port Hardy and Portland and Buoy 46005 and Portland.

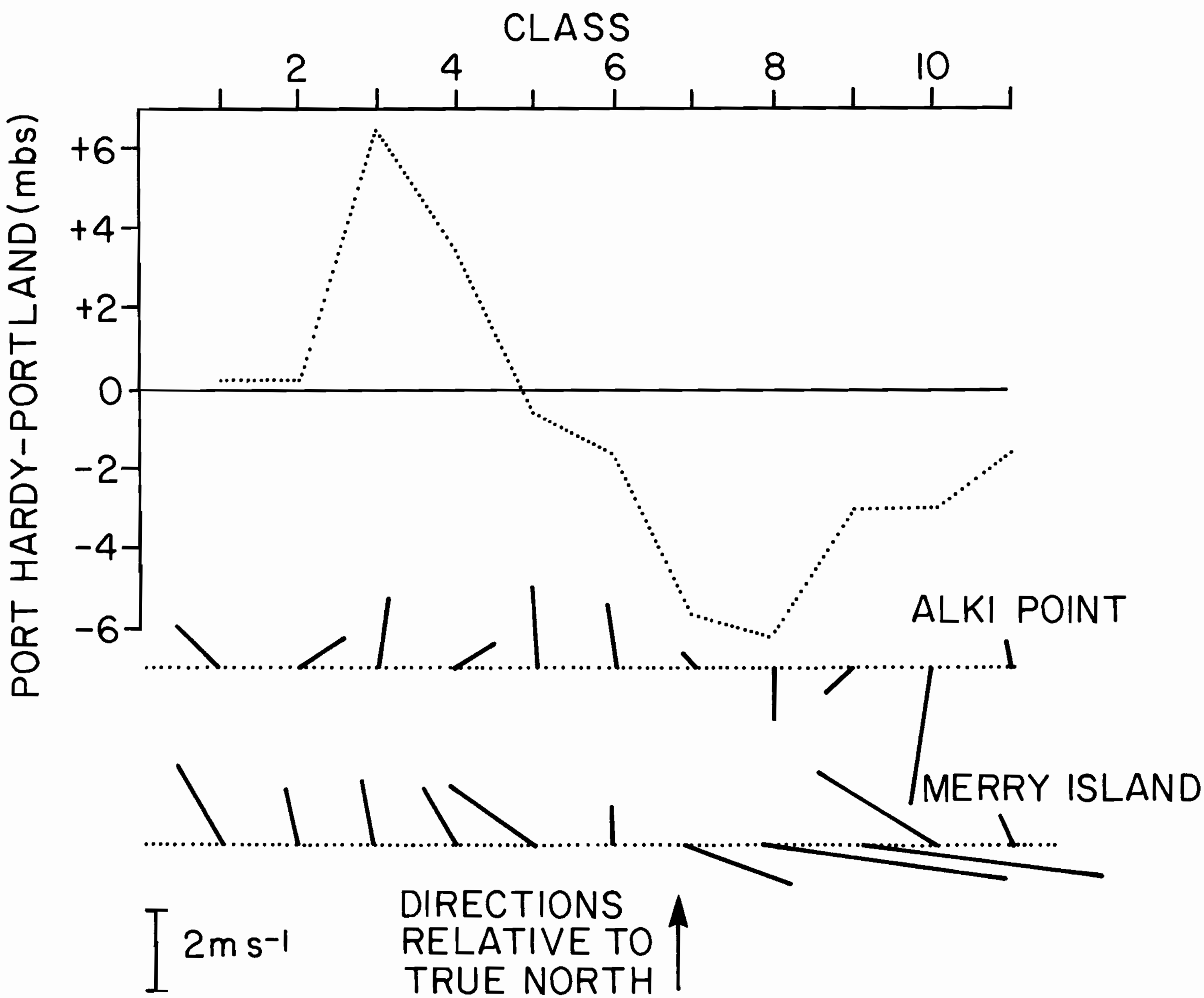


Figure 26, cont.

directed toward Port Hardy from Portland increased from 5.4 mb for class 7 to 6.1 mb for class 8 as the center of composite low pressure moved northward. The pressure differences directed from Portland to Port Hardy for classes 9 and 10 decreased to 3 mb, while the pressure difference directed from Portland to B46005 decreased to 4.6 mb for class 9 and 2.5 mb for class 10. For the individual members of these classes, low-pressure centers were located north of Vancouver Island but were filling.

The composite winds of Grays Harbor and Cape Beale along the Pacific coastline reflected these changes in the position of low centers in classes 7 through 11. They changed gradually from 148° to 352° at Grays Harbor and 118° to 270° at Cape Beale, just as Quillayute's 850-mb winds shifted from 170° to 310° for classes 7 to 11, and just as wind in geostrophic balance would change in response to a change in the direction of the pressure gradient.

For classes 2-6, with higher pressure north and east of the region, the composite winds were steady at Grays Harbor at 90°-112° and were their strongest, 4 to 7 m s^{-1}. For these classes, Cape Beale's composite winds were more variable, ranging from 45° to 106°, and lighter at speeds never greater than 2 m s^{-1}. Cape Beale's winds also displayed lower persistence.

In a similar manner, the Strait of Juan de Fuca had easterly winds for a series of pressure gradient directions for classes 2-7. The composite winds at Race Rocks for those classes were northeast, 36° to 59° at 2 m s^{-1} to 7 m s^{-1}. At Neah Bay, the composite winds for those classes ranged from 93° to 150° at 2 m s^{-1} to 8 m s^{-1}. This is consistent with the observations of Reed (1931) who noted that easterly gales at Tatoosh Island occurred for a variety of low-pressure locations when high pressure was located east and north of the region. The steadiness of these winds for differing locations of pressure centers suggests that the winds responded only to the pressure gradient force and were not in geostrophic balance. The class 4, 9.0-mb pressure difference between B46005 and Portland was deceptively small. Three of the six members of this class belong to the gap wind event of 14-15 February 1980 when a large pressure gradient existed north and east of the region (Overland and Walter, 1981).

When the winds at Grays Harbor became southwest for class 8 and west for classes 9 and 10, the winds in the Strait of Juan de Fuca also became westerly. In spite of pressure directed from Portland to B46005 and from Portland to Port Hardy, Race Rocks had composite winds of 329° at less than 1 m s^{-1} with an unusually low persistence of 0.2 for class 8 and 270° at 10 m s^{-1} and 7 m s^{-1} for classes 9 and 10. The resultant winds at Neah Bay were 198° at 3 m s^{-1} for classes 8, 9, and 10. This suggests that under the conditions of low pressure to the north of the Strait of Juan de Fuca, the winds there could have been geostrophic. In Lynott and Cramer's (1966) analysis of the 1962 Columbus Day windstorm, the winds at Neah Bay were easterly and at Port Angeles they were northeasterly and steady, until the low-pressure center passed north of the Strait of Juan de Fuca. At that time, the winds at Neah Bay became northwesterly. Reed (1980) presented a series of regional sea-level pressure maps of the windstorm of 13 February 1979. In that case, the winds in the Strait of Juan de Fuca became westerly only when the pressure gradient changed from an east-west direction to a south-north direction. Yet, the unusual strength of the westerly winds at Race Rocks points to the possibility of mesoscale pressure features producing a locally strong pressure gradient. The lack of pressure data in that region makes impractical any more definite conclusions.

With the exception of class 10, the Strait of Georgia and Puget Sound wind fields responded similarly to the reversal in the class sequence of the pressure gradients between Port Hardy and Portland. For classes 7, 8, and 9, the winds in the Strait of Georgia were southeasterly, 97° to 112°, and 2.5 to 6 m s^{-1} at Merry Island, while the pressure differences were directed from Portland to Port Hardy with values of 3.1 to 6.1 mb. In Puget Sound, the composite winds for these classes were 84° to 167° and 1 to 5 m s^{-1} at Bush Point. At Alki Point winds occurred at 314° and less than 1 m s^{-1} with the low persistence of 0.2 for class 7. The class 8 and 9 winds at Alki Point were light and southerly to southwesterly.

The exception, class 10, had composite winds in the Strait of Georgia that were 318° at 3.4 m s^{-1} at Merry Island and winds that were 193° and 3.5 m s^{-1} at Alki Point in Puget Sound. The composite winds at Bush Point were westerly, 294° at 1.2 m s^{-1} while the pressure was directed from Portland to Port Hardy at 3 mb and from Portland to B46005 at 2.5 mb. It may be that the winds within the Strait of Georgia continued in geostrophic balance while the winds in Puget Sound flowed toward low pressure.

The pressure differences of classes 3 and 4 were of similar magnitude to those of classes 7, 8, 9, and 10, but were directed from Port Hardy to Portland. For these classes, the wind fields in the Strait of Georgia and Puget Sound were light and northerly. They were 335° and 308° at 1.4 and 2.6 m s^{-1}, and at Bush Point they were 15° and 50° at 1.7 to 1.1 m s^{-1}.

Classes 11, 1, 2, 5, and 6 were alike in having small composite pressure differences between Port Hardy and Portland. In spite of the different directions of the pressure gradients for these classes, the wind fields were northerly and light in Puget Sound and light and northwesterly in the Strait of Georgia.

At this point, two types of wind field forcing are indicated by the composite pressure differences and the 850-mb winds. In Puget

Sound channeling predominated with down-pressure-gradient flow reversing with the pressure reversal and strengthening of the pressure gradient. In the Strait of Juan de Fuca the flow with exceptions was down-pressure-gradient. The exception occurred when low pressure was indicated by the 850-mb flow to be north of the region. For those conditions the Strait of Juan de Fuca winds were westerly as would be expected for geostrophically balanced winds. The unusual strength of the westerlies, however, points to the possible presence of mesoscale pressure features. On the Pacific Coast down-pressure-gradient flow predominated as long as higher pressure existed inland with lower pressure to the south, while geostrophically balanced westerly winds were observed when lower pressure was located to the west and north of the region. Similarly, in the Strait of Georgia, channeling by the pressure gradient predominated while a more geostrophic northwesterly flow was observed when low pressure was located to the north. However, the areas of low persistence in the southern Strait of Georgia and along the southeastern Strait of Juan de Fuca were evident throughout the composite map series. In section 5b, the subdivisions of classes 6 and 7 are discussed in terms of the pressure gradients, and an explanation of the dynamics of the areas of low persistence are offered.

b. Subdivision of classes 6 and 7

As Quillayute's 850-mb winds changed from 140°-160° to 170°-190° in classes 6 and 7, a change occurred in the composite wind fields while the pressure difference directed from Portland to Port Hardy strengthened from 1.5 mb to 5.4 mb. Areas of low persistence in the southern Strait of Georgia and southeastern shore of the Strait of Juan de Fuca were evident on both maps and on class 7's composite map the central Puget Sound also became an area of low persistence. In order to understand the forcing of the two wind fields and the existence of the areas of low persistence, the sea-level pressures for classes 6 and 7 are listed individually by members in tables 6 and 7.

On the whole, the class-6 pressure gradients were weak. Of the 11 reports, 8 had pressure differences less than 3.0 mb. and 3 had pressure differences greater than 3.0 mb, all directed toward lower pressure at Port Hardy. Of the 8 members with small pressure differences, those measured at 0000 GMT reported northerly winds in the areas of low persistence while those measured at 1200 GMT reported southerly winds in those same areas. Of the three members with large pressure differences between Port Hardy and Portland, two were reported at 1200 GMT, and the remaining report was measured at 0000 GMT; yet all reported southerly winds in the areas of low persistence, and there is no diurnal pattern apparent in the wind directions. The resultant wind vector and persistence field of those class-6 members measured at 1200 GMT together with that measured at 0000 GMT on 24 February 1980 when a large pressure gradient existed in the north-south direction, can be seen in figure 27. Figure 28 shows the resultant wind vector and persistence field for the remaining 0000 GMT observations.

Table 6. Sea-level pressures measured at Port Hardy, B.C., and Portland, Oregon, and their differences for class 6.

Class 6	Port Hardy, B.C.	Portland, OR	Differences
9 Feb. 1200 GMT	1021.2	1021.5	-0.3
15 Feb. 1200 GMT	1009.1	1008.3	+0.8
17 Feb. 0000 GMT	1002.5	1001.8	+0.7
17 Feb. 1200 GMT	994.9	996.1	-1.2
18 Feb. 1200 GMT	980.2	984.8	-4.6
22 Feb. 1200 GMT	1011.5	1010.8	+0.7
23 Feb. 0000 GMT	1013.9	1014.6	-0.7
24 Feb. 0000 GMT	1017.6	1020.8	-3.2
24 Feb. 1200 GMT	1010.2	1017.0	-6.8
5 Mar. 0000 GMT	1011.7	1012.4	-0.7
6 Mar. 0000 GMT	1009.9	1008.8	+1.1

Sea-level pressures are in mb.

Table 7. Sea-level pressures measured at Port Hardy, B.C., and Portland, Oregon, and their differences for class 7.

Class 7	Port Hardy, B.C.	Portland, OR	Differences
6 Feb. 1200 GMT	1009.9	1019.9	-10.0
16 Feb. 0000 GMT	1012.8	1011.2	+ 1.6
16 Feb. 1200 GMT	1009.0	1011.7	- 2.7
18 Feb. 0000 GMT	988.1	992.2	- 4.1
25 Feb. 0000 GMT	1016.4	1020.7	- 4.3
25 Feb. 1200 GMT	1013.9	1020.7	- 6.8
26 Feb. 0000 GMT	1007.2	1017.9	-10.7
27 Feb. 0000 GMT	1001.3	1012.3	-11.0
27 Feb. 1200 GMT	1006.9	1010.2	- 3.3
28 Feb. 0000 GMT	1004.2	1009.2	- 5.0
28 Feb. 1200 GMT	1001.2	1011.2	-10.0
29 Feb. 1200 GMT	1014.0	1024.3	-10.3
1 Mar. 0000 GMT	1015.4	1021.2	- 5.8
1 Mar. 1200 GMT	1017.4	1016.4	+ 1.0
2 Mar. 0000 GMT	1013.3	1012.8	+ 0.5

Sea-level pressures are in mb.

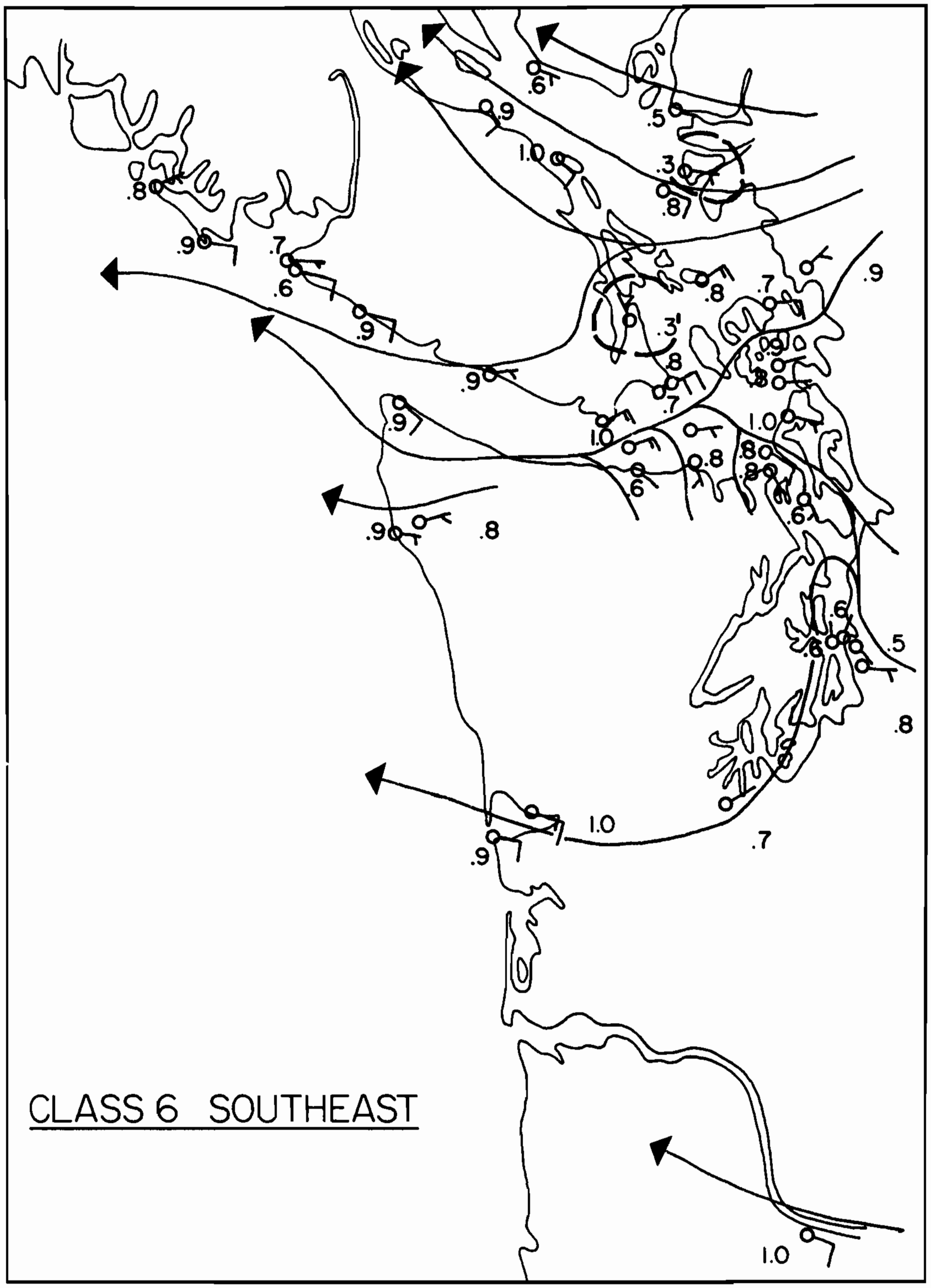


Figure 27. Resultant surface wind vector and persistence fields of class-6 members reported at 1200 GMT plus the observation of 0000 GMT 24 February 1980.

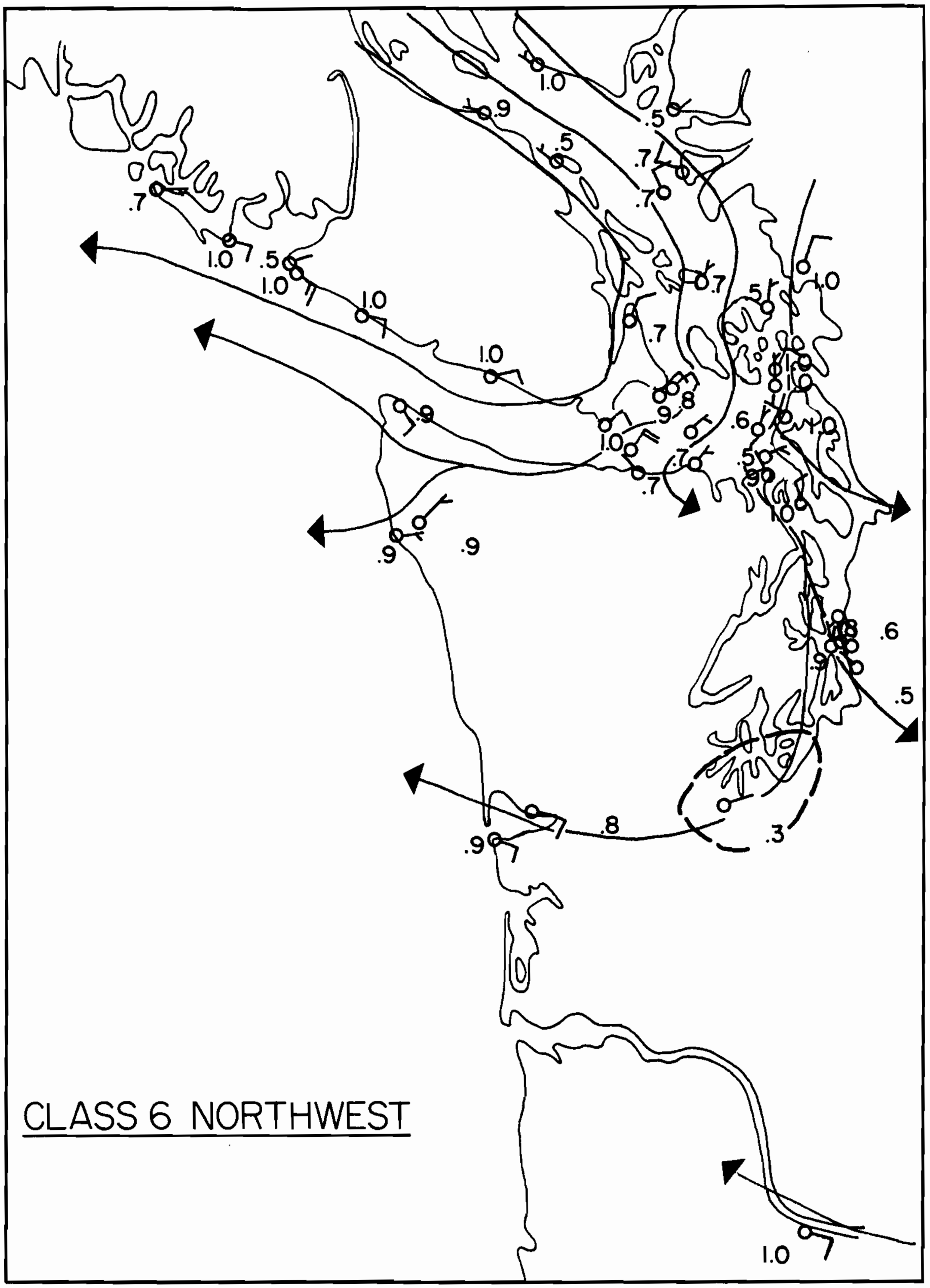


Figure 28. Resultant surface wind vector and persistence fields of remaining class-6 members reported at 0000 GMT.

A comparison of figure 27 with figure 28 shows that the winds changed from southeast to northwest in the Strait of Georgia, and at NAS Whidbey Island south to Bush Point and west to Port Angeles, both areas of low persistence (fig. 20), while in Puget Sound the winds changed from southeast to northerly. This diurnal wind pattern is similar to the diurnal pattern of the deviation winds calculated by Mass (1982), suggesting that when the north-south pressure gradient was weak, a topographically forced diurnal circulation determined the wind directions only along the inland waterways. However, with southeast upper-level flow, the existence of three instances of large pressure gradients directed toward lower pressure at Port Hardy suggests that a pressure gradient as small as 3 mb overcame the effects of diurnal heating, but that the surface pressure gradients that developed from these synoptic conditions produced a surface wind field very similar to that produced by diurnal cooling. The winds at Bellingham, Trial and Discovery Islands, Race Rocks, in the Strait of Juan de Fuca west of Port Angeles, and along the Pacific coasts did not show any diurnal pattern at all and responded in class 6 only to the strong pressure gradient directed towards lower pressure in the west.

For class 7 when 850-mb wind directions at Quillayute were from 170° to 190°, pressure differences (table 7) between Portland and Port Hardy greater than 3 mb was the more common report. Five of the members reported differences less than 3 mb, and the remaining 10 members reported differences greater than 3 mb directed toward lower pressure at Port Hardy. Using the absence or presence of a surface pressure gradient greater than 3 mb as a criterion for subdividing class 7, we constructed two composites. Figure 29 represents the composite wind field with a strong north-south pressure gradient. The winds were southerly along Washington's Pacific coast, within Puget Sound, and north to Rosario Strait, and were southeasterly in the Strait of Georgia. Race Rocks and Trial Island were northeasterly while Discovery Island and Bellingham were more easterly. The winds were easterly also at Vancouver and Point Atkinson. Figure 30 is the composite resultant wind vector and persistence field of those times when the pressure field was relatively flat in the north-south direction. In the Strait of Georgia a large area of low persistence developed while Vancouver and Sand Head showed northwesterly winds. Bellingham, Haro and Rosario Straits, and the north shore of the Strait of Juan de Fuca had northeasterly winds. Dungeness Spit southeast to Bush Point was a region of low persistence. Winds were northerly in Puget Sound while on the Pacific coast the wind directions were easterly.

A comparison of the two subclasses suggests that class 7 is a transition point: when a surface pressure gradient did not develop between Port Hardy and Portland, the wind field was more similar to classes 2 through 6. When a surface pressure gradient greater than 3 mb formed between Portland and northern Vancouver Island, a profound change in the wind direction occurred at all stations with the exception of the north shore of the Strait of Juan de Fuca.

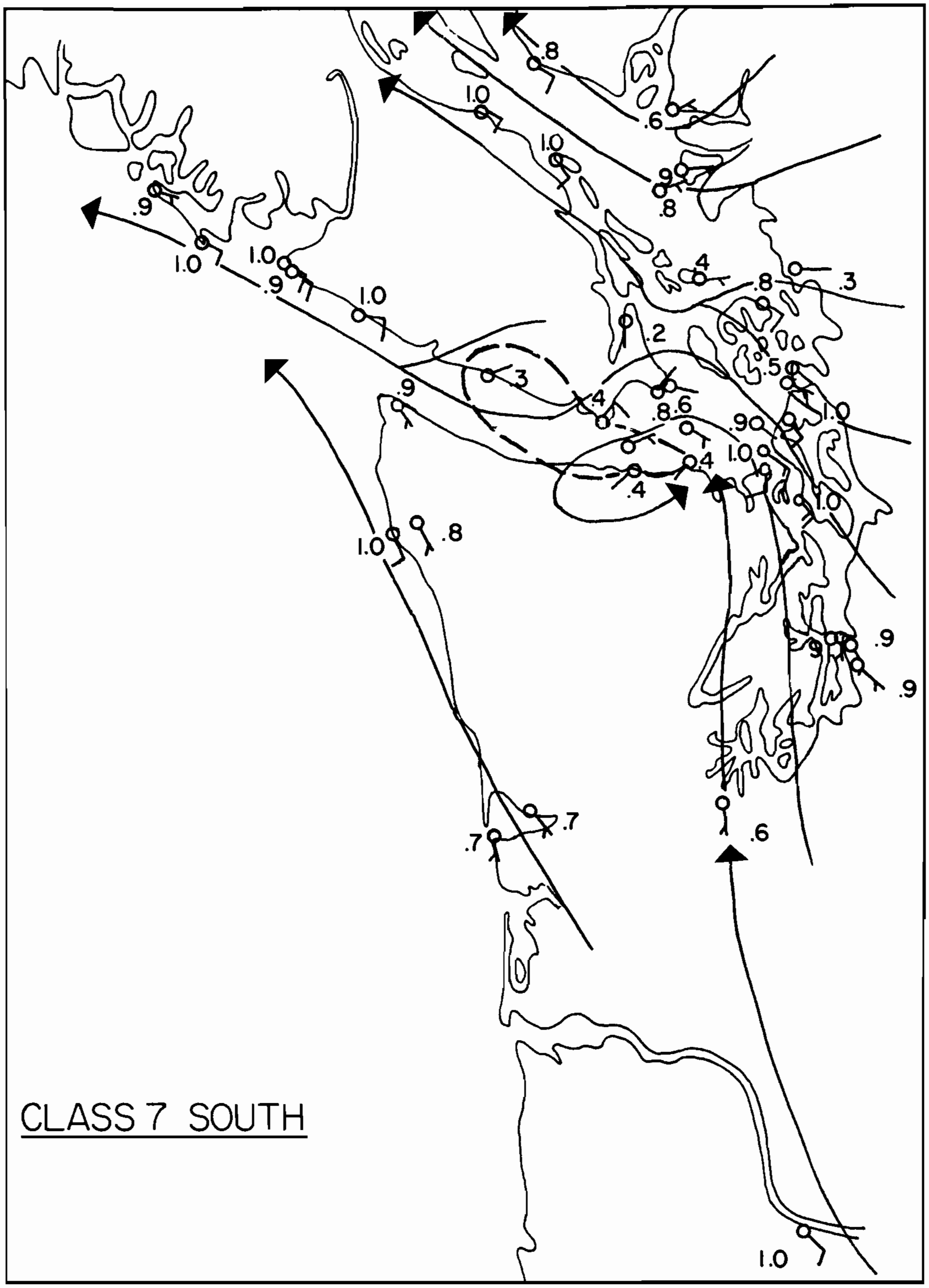


Figure 29. Resultant surface wind vector and persistence fields of class-7 members for which a Portland to Port Hardy pressure gradient existed.

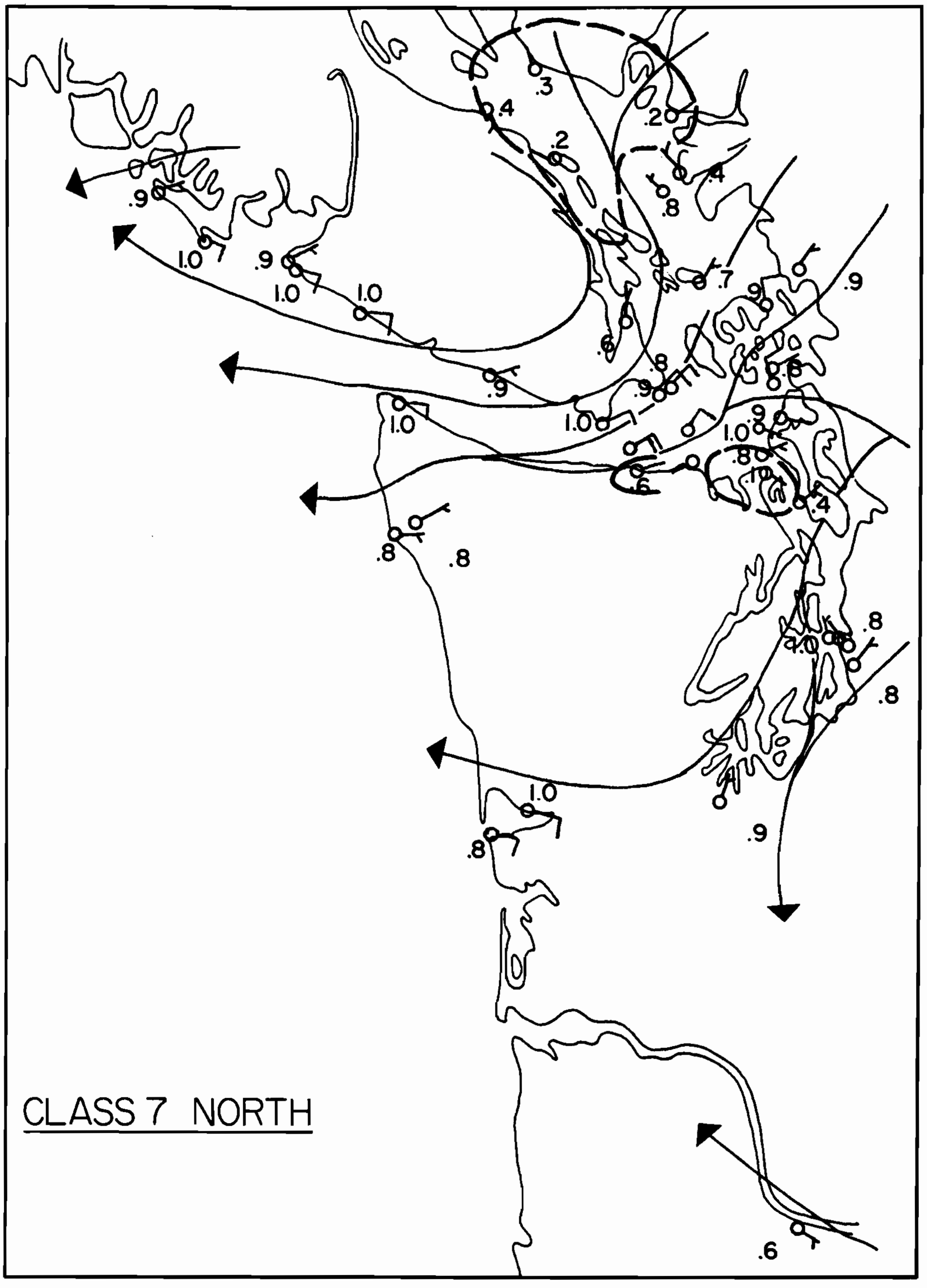


Figure 30. Resultant surface wind vector and persistence fields of class-7 members for which no Port Hardy to Portland pressure gradient existed.

6. Summary

Using the 850-mb wind directions at Quillayute as the synoptic-scale criterion, composites of the surface wind and persistence fields of the Pacific Northwest were constructed for the month 6 February to 6 March 1980. While the upper-level flow for the study period was dominated by a large-amplitude blocking ridge and the most commonly reported 850-mb wind directions were 150°-190°, nearly all other wind directions were represented. The 850-mb wind directions were sorted into 11 or 12 possible bins of 30° each. The surface wind fields were block averaged, resampled at times corresponding to the times of Quallayute's upper-air measurements, and then placed into bins identical to those created by the 850-mb wind directions.

Taken in sequence, the composite wind fields and surface pressure gradients showed that the wind directions in the sea-level channels of the region varied in a regular fashion as the synoptic-scale flow varied. While the winds of the Straits of Georgia and Juan de Fuca and of the Pacific coast were often parallel to the channels and directed down the pressure gradient, they appeared to be in geostrophic balance when the synoptic-scale surface pressure gradient changed from a predominantly east-west direction to a more south-north direction. The winds observed in the Strait of Juan de Fuca were also generally parallel to the channel and down-pressure-gradient except in the case of surface westerly winds when geostrophically balanced winds would be expected to be westerly. However, the strength of the westerly winds in the Strait of Juan de Fuca suggested the possible presence of mesoscale pressure features.

While many 850-mb wind directions at Quillayute were represented by few members and persistence was not very meaningful in those cases, the areas of low persistence were noticeable in the southern Strait of Georgia and along the southeastern shore of the Strait of Juan de Fuca throughout the sequence. Station pressures were examined for classes 6 and 7, which contained the largest number of members. As the north-south pressure gradient was weak for most of the members of class 6, this class was subdivided into groups of 0000 GMT and 1200 GMT observations, and the resultant wind vector and persistence fields suggested that the areas of low persistence in the southern Strait of Georgia, along the southeastern Strait of Juan de Fuca, and in Puget Sound, were the result of a wind reversal due to the diurnal heating cycle.

Examining class 7, which could be subdivided by the existence or lack of existence of a north-south surface pressure gradient, showed that this class is a transition point between the primarily east-west surface pressure surface gradient that exists when the 850-mb flow has an easterly component, and the more north-south surface pressure gradient that forms when the 850-mb flow no longer has an easterly component.

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