A Methodology for Predicting the Puget Sound Convergence Zone and Its Associated Weather

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ABSTRACT

The Puget Sound Convergence Zone (PSCZ) is a terrain-induced mesoscale phenomenon that occurs in western Washington and has a dramatic impact on local weather. This paper presents the operational forecasting techniques that are used at the National Weather Service Forecast Office in Seattle to forecast the weather associated with the PSCZ. A case study is used to demonstrate both the medium-range and short-range techniques. Future considerations are also discussed in light of the planned modernization of the National Weather Service.

1. Introduction

In western Washington, topographic channeling of low-level onshore flow occasionally produces a regional phenomenon called the Puget Sound Convergence Zone (PSCZ). This phenomenon has significant impact on cloud, precipitation, and wind patterns across the Puget Sound Basin, especially in the spring. A brief description of the PSCZ and its associated weather is given in the next section. With this as a foundation, the current methodology used by the National Weather Service to forecast the PSCZ is presented in section 3. Then, a recent PSCZ event is analyzed in section 4 to illustrate this methodology. Finally, a summary of the work and a discussion of potential advances in forecasting the PSCZ resulting from the modernization of the National Weather Service are presented in the last section.

2. The Puget Sound Convergence Zone (PSCZ)

The Puget Sound lowlands are bound on the east by the Cascade Range and on the west by the Coast Ranges, which include the Willapa Hills, the Olympic Mountains, and the Vancouver Island Ranges. The western barrier is breached north and south of the Olympic Mountains by the Strait of Juan de Fuca and the Chehalis Gap, respectively. (See Fig. 1 for locations of all referenced geographical features and stations.)

Under certain conditions, low-level onshore winds are deflected around the Olympic Mountains to flow through the Chehalis Gap and the Strait of Juan de Fuca. Subsequently, downstream from the Olympic Mountains, components of this flow turn north from the Chehalis Gap and south from the strait. This results in low-level convergence over Puget Sound, the general location of which is determined by the direction of the winds on the outer coast. It is this area of convergence, first discussed by Safford (1967), that has come to be known as the PSCZ (Bundy 1969; Mass 1981). A conceptualization of this flow is shown in Fig. 1.

The typical PSCZ is associated with the passage across Washington State of a 500-mb short-wavelength trough and an associated surface front. The link is the tendency for low-level winds to veer into the west-northwest in this postfrontal environment, which is the necessary direction for PSCZ development. As the west-northwesterly low-level flow impinges on the northwest coast, several interactions occur. First, a sea level pressure trough forms on the lee side of the Coast Ranges that reinforces westerly winds in the Strait of Juan de Fuca and the Chehalis Gap by increasing the onshore pressure gradient. This trough, which is terrain induced, forms within a broad area of postfrontal sea level pressure rises. Second, a mesoscale surface low pressure center forms within the lee trough downstream (northeast) from the highest terrain of the Olympic Mountains. Such an evolution is discussed by Ferber and Mass (1990). The mesoscale low is characterized by 1) a small area of calm winds near its center, 2) weak northerly winds along the northeast side of the Olympic Mountains, and 3) an enhancement of the southwesterly flow across the southern Puget Sound lowlands. The intensification of this mesoscale low seems to initiate the formation of the PSCZ and acts as an anchor point or preferred initial location for the western end of the PSCZ. The mesoscale low may remain quasi-stationary or move from this initial location.

The PSCZ can either follow a synoptic-scale front south over Puget Sound or it may remain behind. Also, the surface front may stall within the PSCZ until the

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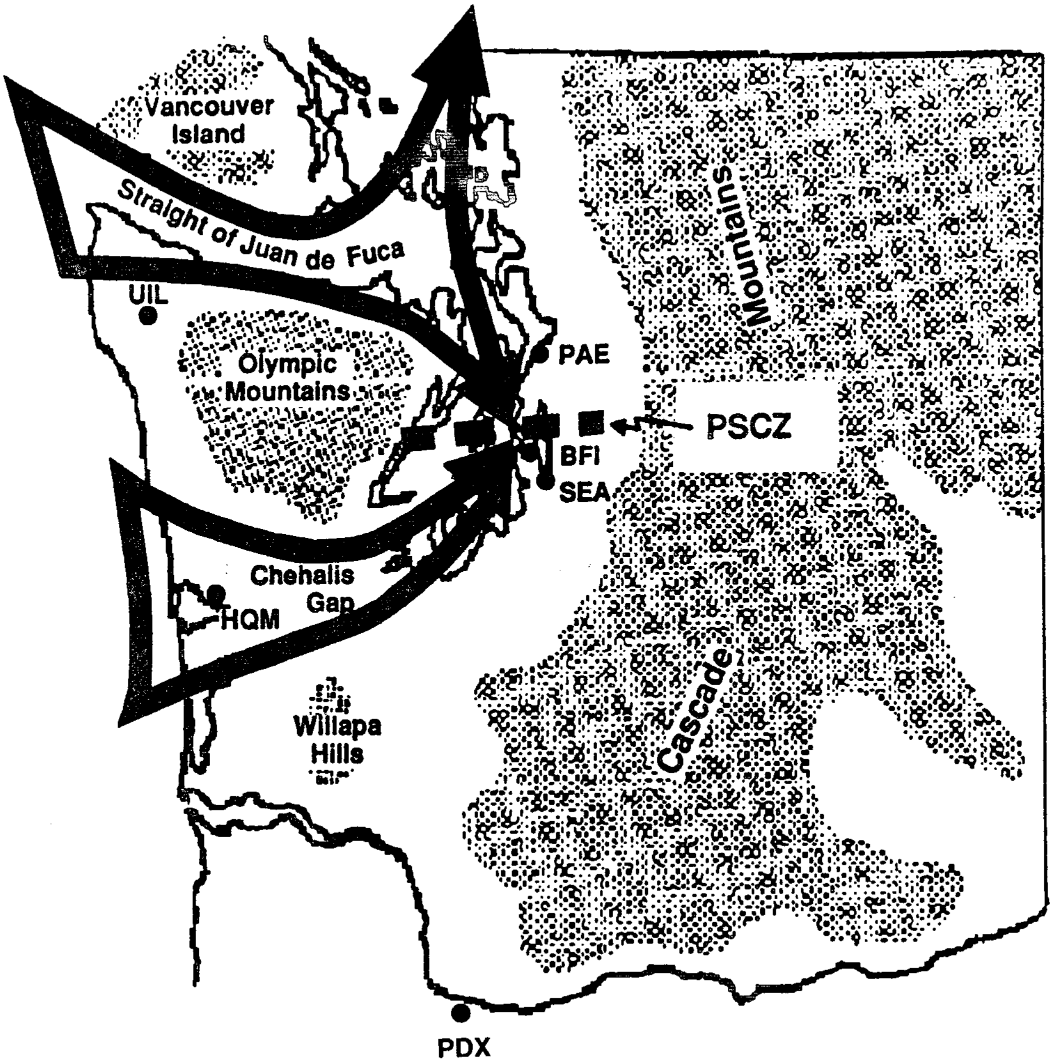

FIG. 1. Topographic map of Washington State and conceptualized flow associated with a PSCZ. Stippled area generally above 600 m (2000 ft).

upper-level short-wavelength trough crosses the Cascades. The specific behavior is governed by the direction and temporal character of the onshore flow. Strongly veering (with time) low-level winds favor the rapid southward advance of the surface front and PSCZ, often in unison. In contrast, a nearly westerly onshore flow favors the stagnation of the surface front within the mesoscale, terrain-induced trough as part of the PSCZ.

The PSCZ has a seasonal cycle with maximum occurrences during the spring and early summer (April–June) when two to four events are likely each month (Mass 1981). Events are less frequent and nearly evenly distributed throughout the remainder of the year. Climatologically, high pressure shifts northward from the subtropical Pacific into the northeast Pacific during late spring. In association, winds along the Washington coast veer progressively from southwest toward northwest into the preferred direction range for PSCZ development. The static stability is also often low in the spring, which is conducive to the initiation of convection by the low-level convergence.

The PSCZ also displays a significant diurnal modulation (Bundy 1969; Mass 1981), especially during the warm season, that is due to a phasing of the synoptic-scale control (i.e., the low-level west-northwesterly winds) with western Washington sea breeze circulations. As the sun heats the western Washington interior, an ocean-to-land wind regime becomes established that increases the westerly flow through both the strait and the Chehalis Gap. There is also a diabatically produced north-to-south acceleration of the winds over the Puget Sound lowlands resulting from heating of the land to the south. These diurnal breezes combine to reinforce the circulation of a PSCZ and favor its southward advance. This reinforcement also combines with an afternoon minimum in static stability to favor increased shower activity. Thus, there is a tendency for PSCZs to form across the northern portions of the sound early in the day and then move southward, reaching the central sound during the afternoon and early evening with a maximum in attendant weather. PSCZs may move back toward the north overnight as the sea breeze circulations dissipate. Additionally, PSCZs are typically much weaker in character at night due to the increasing static stability in the boundary layer.

Under the most favorable conditions, the PSCZ can be strong enough to produce thunderstorms with brief heavy rain, snow, ice pellets, or hail. During the coldest months, heavy snow is possible, especially if the PSCZ should become quasi-stationary; accumulations of over 4 in. (102 mm) can occur, and winter storm warnings are occasionally necessary. In contrast, a weak PSCZ in a dry air mass may produce nothing more than a surface wind-shift boundary.

Clouds and precipitation that form within the PSCZ are advected downstream against the west slopes of the Cascade Range. Near the crest, within the narrow band defined by the PSCZ, very heavy snowfalls can occur that far exceed amounts expected from the background conditions. Furthermore, north and south of this heavy snow band, little or no snow may fall, yielding very significant gradients in snowfall. The Pacific Northwest Avalanche Center (PNAC) has recognized this effect and adjusts its forecasts and discussions accordingly (Ferguson et al. 1990).

During the summer the PSCZ is usually weaker (due to typically lower wind speeds) and often associated with stratocumulus clouds and drizzle (due to increasing static stability). The associated low ceilings and visibilities are particularly significant to the general aviation community. This is true since these conditions often form an east-to-west barrier of poor flying weather across the Puget Sound lowlands in what are otherwise clear skies.

The warm season diurnal wind circulations may also produce "clear-day" PSCZs when the synoptic control is too weak to generate convergence alone. These are common during warm, dry weather, and often are not associated with a particular synoptic feature. There is typically a ridge of higher pressure offshore and light northwesterly low-level flow (Bundy 1969).

3. Forecasting methodology

National Weather Service forecasters in Seattle have developed, and use, a combination of approaches to forecast the PSCZ. Here, these approaches are broken down into those that address the medium-range forecast (beyond 12 h) and those that address the "nowcasting" or short-range forecast (0–12 h); the combination of these form the typical progression of actions taken as a particular event evolves. Thus, the goal here is not to present a new forecast methodology but to describe the current operational approach to this mesoscale forecast problem.

It has been demonstrated (Mass 1981) that certain combinations of wind speed and direction along the Washington coast coincide with PSCZ events. In fact, PSCZs form only for a narrow range of coastal wind direction and speed. Given this sensitivity to characteristics of the base-state synoptic-scale flow, a forecast of the low-level gradient wind is a practical way to assess the future likelihood of PSCZ development and is the one most often taken. Thus, the medium-range forecast problem is to anticipate the combination of physical parameters that will result in a favorable low-level wind field and then qualitatively adjust the forecast using a conceptual model of the PSCZ.

Forecasters use numerical model guidance from the National Meteorological Center (NMC) to recognize potential events at the medium range. Individual forecasters may make some minor adjustments for identified model biases, but are, for the most part, at the mercy of these simulations beyond 12 h. In making a forecast of a PSCZ, forecasters inspect the model simulations for what they consider the salient characteristics and synoptic features. These include 1) the location of an upper-level trough and its forecast path, 2) whether a cold front will move or has moved across the Pacific Northwest, and 3) the location and intensity of sea level pressure systems. Although slightly different in emphasis, these are all indicators of the forecasted low-level base-state wind field—fundamental to PSCZ development and attendant weather. More direct indicators that are used include 1) the strength and direction of the 850-mb winds and 2) the boundary-layer winds from NMC's Nested Grid Model (NGM).

Consideration also needs to be given to the type of weather that will be attendant to a PSCZ. The decision to include clouds and precipitation is based upon the propensity of the base-state environment to produce such elements, and ties back to the aforementioned characteristics. An often used indicator for convection is the lifted index (LI), both from the model and nearby rawinsondes.

Since medium-range adjustments are based solely upon numerical weather predictions (NWP), the only limiting factors on lead time are the decreasing accuracy of the model simulations themselves and the confidence of the forecaster. In practice, modifications with respect to winds, clouds, and precipitation are made to local forecasts 24–36 h prior to an anticipated event. A decision tree outlining this process is shown in Fig. 2.

When the anticipated formation of a PSCZ is only a few hours away, the forecaster's attention shifts from primary reliance upon the numerical models to a variety of observations; these include satellite imagery, buoy reports, surface observations, and rawinsondes. At this time range, near-shore and coastal wind-shift

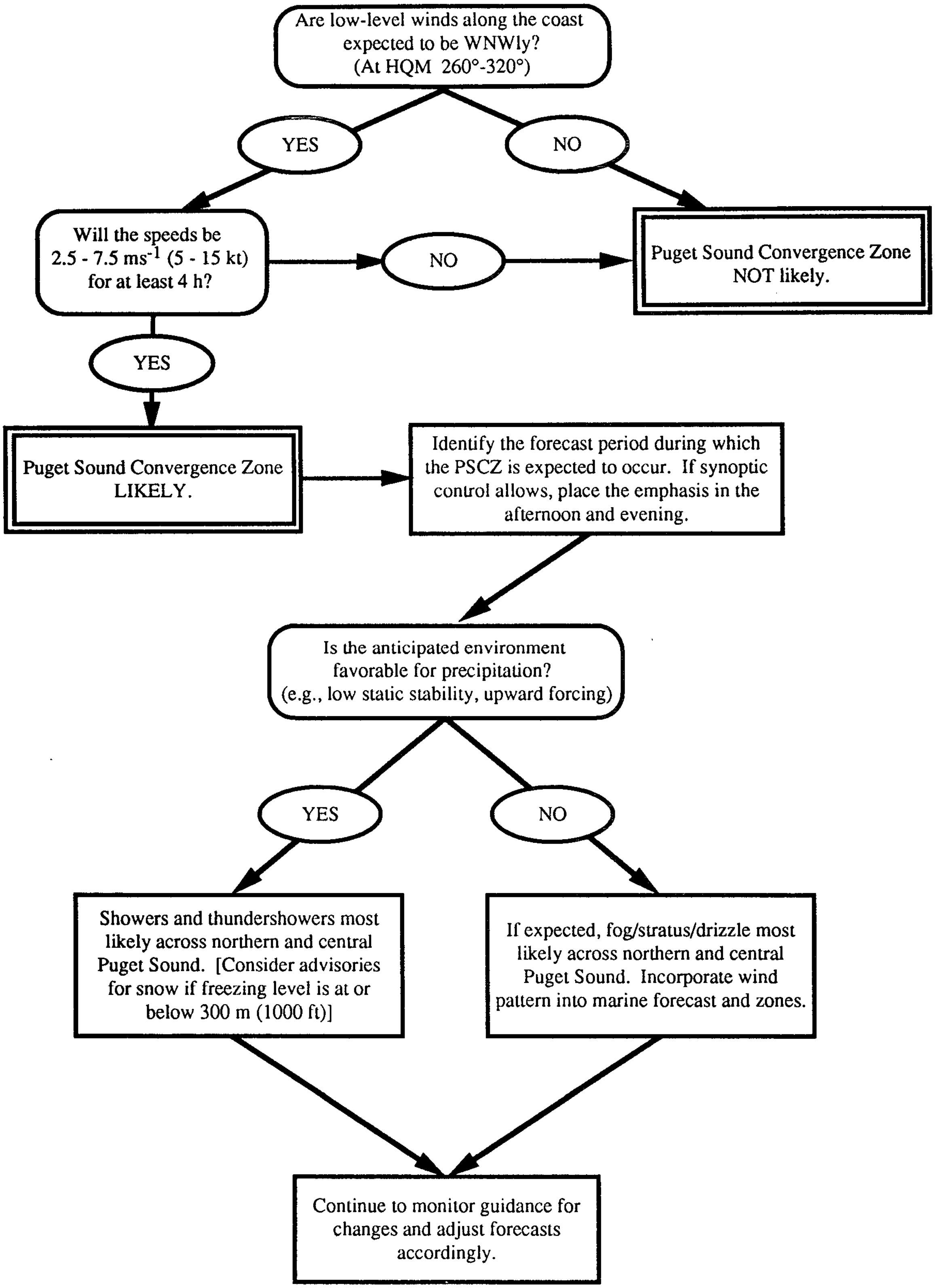

FIG. 2. Decision tree for medium-range forecasting of the PSCZ.

boundaries are important features. Mass (1981) noted that when specified coastal wind-speed and direction criteria are met, the PSCZ forms within a few hours. Thus, a shift in wind direction along the coast from southwest to within the desired range will give the forecaster the necessary lead time to make adjustments in the local forecast prior to PSCZ development. Using Hoquiam (HQM) on the coast (see Fig. 1) as a source for observations, Mass's required criteria are four continuous hours of wind direction between 260° and 320°, and wind speed between 2.5 and 7.5 m s^{-1} (5 and 15 kt). Forecaster confidence usually increases with the use of a second coastal station, and, in operational practice, Quillayute (UIL) is sometimes used.

Once coastal wind criteria are met, the forecaster will watch the winds through the Strait of Juan de Fuca for indications of increasing westerly flow. Many forecasters monitor the along-strait pressure gradient [UIL minus Bellingham (BLI)] to estimate the flow through the strait. This is consistent with work done by Overland and Walter (1981) that showed winds along the strait behave according to gap wind theory. Similarly, forecasters will monitor the pressure gradient from Olympia (OLM), or Portland, Oregon (PDX), to BLI to get a measure of the southerly winds in Puget Sound. The likelihood of a PSCZ increases as the southerly gradient becomes equal to the westerly gradient (Bundy 1969). This is, of course, not an independent parameter but is instead another way of quantifying the imposed gradient wind field.

Surface observations across the northern parts of the Puget Sound are continually monitored for the first signs of convergence in the surface wind field. Satellite imagery is also viewed for characteristic signs of the PSCZ, namely, an area of enhanced cloudiness/showers across the northern Puget Sound. In addition, there is often enhanced clearing to the north and south of the convective band that is apparently due to associated subsidence (Mass 1981).

Once the PSCZ has formed, the forecaster's efforts shift to projecting the movement of the PSCZ and its associated weather through the Puget Sound Basin. Such forecasts are useful to the aviation community, for example, because of the shifting winds, lower ceilings, and reduced visibilities that are often associated with a PSCZ. Forecasts of short-term movement can be derived by simple extrapolation but often rely on trends in the base-state flow and diurnal modulations. For example, Mass (1981) suggested that when coastal winds veer toward 320° with time, an existing PSCZ tends to move south. Conversely, winds backing toward 260° with time favor northward movement of the zone. In addition, especially during the warm season, diurnal modulations caused by differential heating must be considered. More specifically, as noted earlier, an existing PSCZ is more likely to strengthen and move or accelerate southward during the afternoon as the north-to-south sea breeze develops. Overnight, an existing PSCZ will usually weaken and move northward or redevelop across the northern Puget Sound.

The end of a PSCZ event is keyed to the end of the synoptic-scale control (i.e., the west-northwesterly low-level winds); as long as this control is favorable, a PSCZ is likely. Events lasting 2 or 3 days are possible, during which the PSCZ may move north and south and go through periods of growth and decay. Once again, the forecaster resorts to the numerical guidance for clues on changes in the base-state winds and stability (for attendant weather) to adjust the forecasts.

In summary, numerical model output provided by the National Meteorological Center (NMC) is the principal guidance used by the forecasters at the medium range, while the use of satellite imagery and surface observations takes the leading role at the short range. A case study is now presented to demonstrate this forecast procedure.

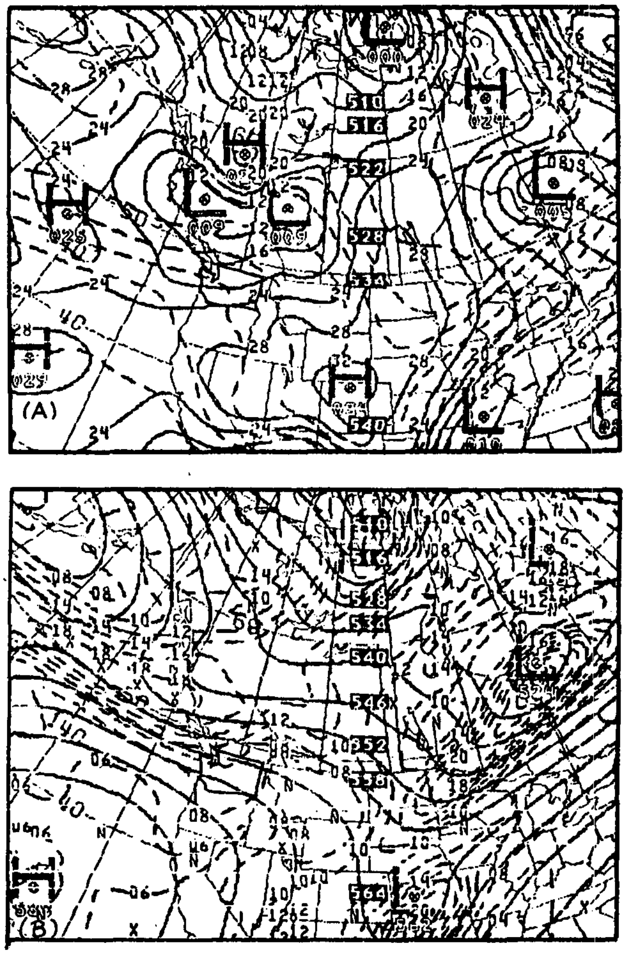

FIG. 3. NGM 48-h forecast valid 1200 UTC 4 November 1990: (a) sea level pressure and 500–1000-mb thickness; (b) 500-mb heights and vorticity. Units are conventional.

4. Case study: 4 November 1990

a. *An example of the medium-range (beyond 12 h) forecast problem*

In Fig. 3a, the NGM 48-h prognostic chart of sea level pressure and 500–1000-mb thickness, valid 1200 UTC 4 November, indicates a cold front will move across western Washington during the morning as a 500-mb trough (Fig. 3b) approaches from the northwest. The surface chart also suggests winds will veer to the west or northwest along the coast behind the front with velocities generally within the prescribed range suitable for PSCZ formation. Given these implied meteorological conditions, the forecaster can anticipate the potential formation of a PSCZ based upon the known interaction between onshore flow and local complex terrain. Furthermore, this is a favorable pattern for postfrontal showers, and any adjustments for a PSCZ should include precipitation. Yet, few details about timing, location, intensity, or movement can be determined. A medium-range forecast for the Puget Sound lowlands would typically express this uncertainty as "a chance of showers, mainly north of Seattle" with a 30% probability of measurable precipitation (PoP), for example.

b. *An example of the short-range (12 h or less) forecast problem*

As the time of PSCZ development nears, a more precise forecast of PSCZ formation, intensity, and movement can be made. (Little is known about forecasting the initial location of a PSCZ.) The forecast procedure changes from an interpretation of numerical guidance to one of analyzing all available real-time data.

At 1200 UTC (0400 PST), the cold 500-mb trough (Fig. 4) extends from the Northwest Territories to north of Vancouver Island. Cold advection over western Washington and a temperature of −25°C at 500 mb over UIL suggest an increasingly unstable air mass behind the front, and are favorable conditions for clouds and showers, especially with a PSCZ. Inspection of the 1200 UTC 300-mb chart (not shown) finds Washington in the left exit region of a wind maximum, and further supports an "active" PSCZ.

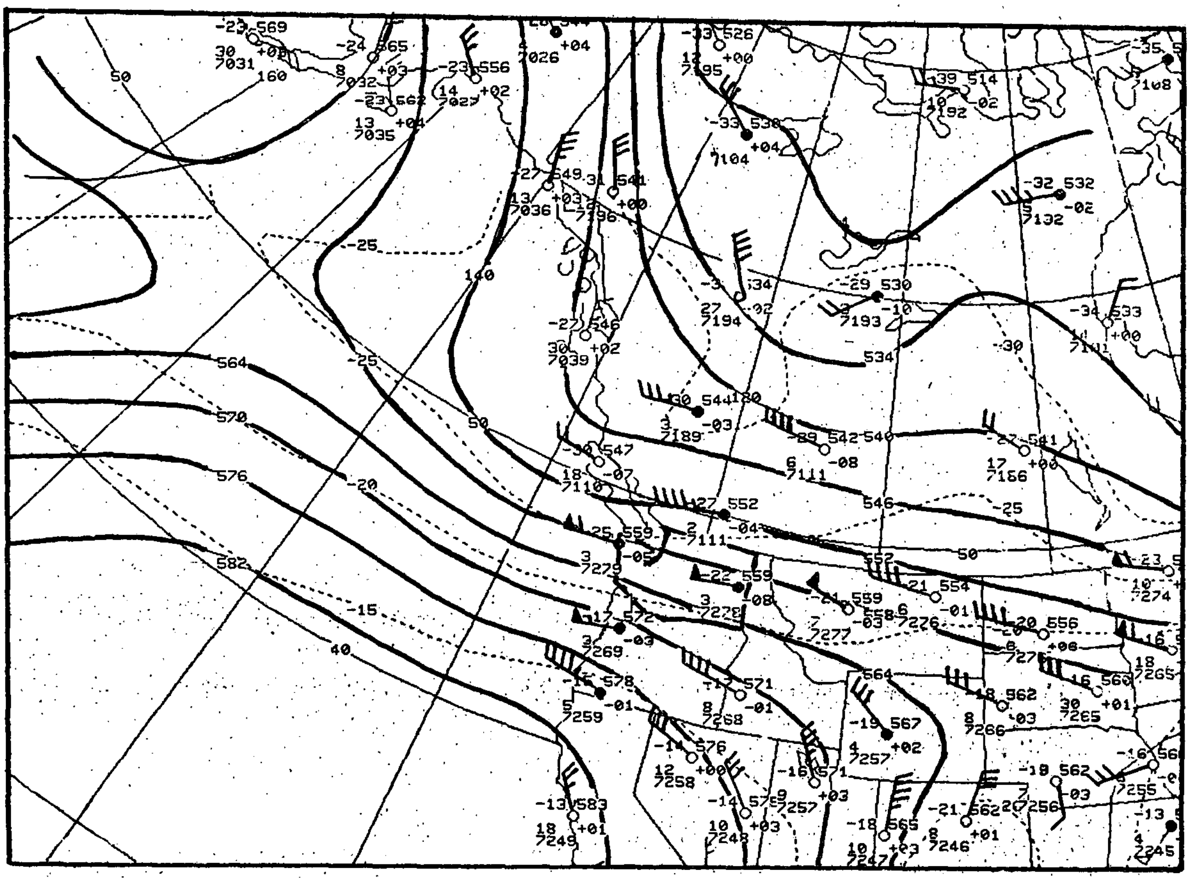

FIG. 4. Here 500-mb heights and temperatures for 1200 UTC 4 November 1990. Conventional station plots with wind speed in knots and height in decameters.

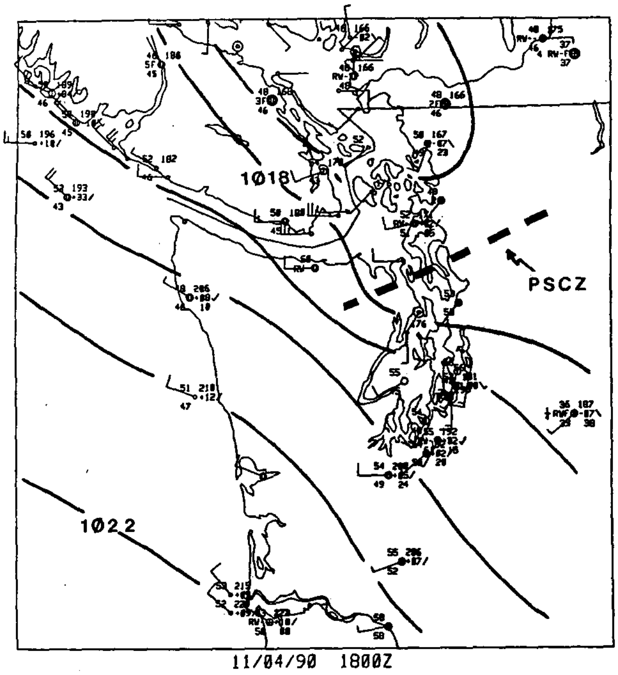

FIG. 5. Surface plot and isobars of sea level pressure for 1800 UTC 4 November 1990. The PSCZ is identified north of PAE. Conventional surface station plots with wind speed in knots, temperatures in degrees Fahrenheit, and sea level pressure in tenths of millibars, with the first two digits dropped.

Although a 1200 UTC surface observation is not available from HQM, the first report at 1405 UTC indicates a wind of 270° at 7 kt (3.5 m s^{-1}), which is within the criteria described by Mass (1981) for PSCZ formation. The winds at HQM remain within direction and speed ranges through 1800 UTC, and a PSCZ has likely formed by this time.

A surface analysis valid 1800 UTC 4 November is shown in Fig. 5. Note the rising sea level pressures and northwest winds (coastal areas)—both indicative of a post-cold front environment. The cross-isobar flow across the southern Puget Sound reflects the highly ageostrophic nature of the local wind field as a result of the rough terrain. Similar downgradient flow is also occurring in the Strait of Juan de Fuca. At this time, as noted in the analysis, there is an area of implied convergence across the northern Puget Sound. This likely marks the incipient PSCZ.

In the 1800 UTC satellite image (Fig. 6) a cloud band produced by the newly formed PSCZ is observed extending toward the northeast from near the northeast tip of the Olympic Peninsula. Also note the enhanced clearing to the north and south of the cloud band. At this time, the short-range public forecast for the Puget Sound Basin might be "scattered showers, especially north of Seattle." The forecaster might explicitly specify a 50% PoP for that area and a 30% PoP elsewhere. This is in contrast to the 30% PoP for the general area issued in the medium-range forecast at a time when forecaster confidence was lower. This forecast is still principally based upon the assumption that the PSCZ will behave in accordance with its known climatology and mainly affect the area between Seattle (SEA) and Everett (PAE).

The aviation forecasts, however, have to be more specific on associated conditions, timing, and probabilities at three airports in the area, namely, Paine Field (PAE) in Everett, Boeing Field (BFI) in Seattle, and Seattle–Tacoma International Airport (SEA) in SeaTac. This specificity is accomplished with the knowledge that the PSCZ is not likely to affect all terminals at the same time and that, of the three terminals, the climatological frequency of occurrence and level of intensity are greatest at PAE in the north and least at SEA in the south. Adjustments in the intensity may also be made based upon the observation that a southward-moving PSCZ is usually a more active weather producer than a northward-moving PSCZ. The speed of propagation is derived partially by extrapolation at its present speed and partially by the nature of the northwest flow impinging on the coast. More specifically, if the winds are veering with time on the coast, a forecaster is more likely to shift the PSCZ southward through the Puget Sound Basin than if the winds are steady or backing.

In this case, the first direct observation of the wind shift associated with the PSCZ occurs at 1845 UTC when winds at Everett's Paine Field (PAE) switch from south to northwest as the PSCZ moves south over the

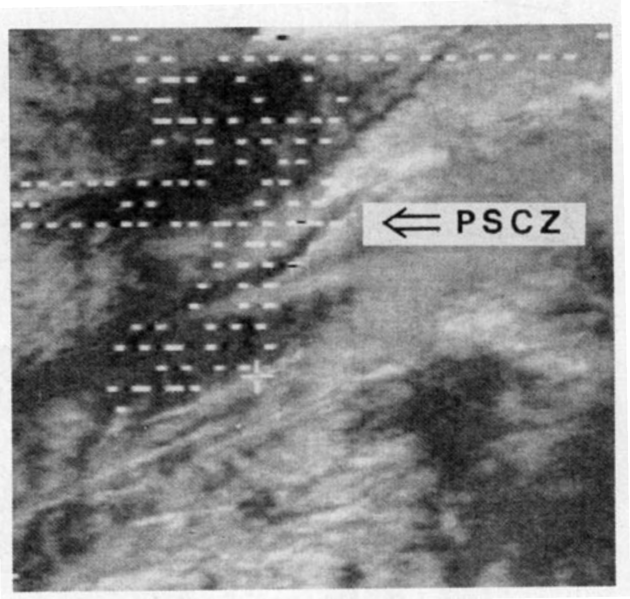

FIG. 6. Visible satellite image for 1800 UTC 4 November 1990.

TABLE 1. Observations taken at PAE starting at 1500 UTC 4 November and ending at 0500 UTC 5 November 1990.

```
04 PAE SA 1445 −X 3 SCT M6 BKN 20 OVC 1LF 51/50/1606/
  007/F3 VSBY E 1/2 W12
04 PAE SA 1545 6 SCT E12 BKN 22 OVC 15 51/50/1908/006/
  VSBY NE 5 BINOVC W
04 PAE SA 1650 5 SCT E10 BKN 90 BKN 20 51/49/1907/006
04 PAE SA 1745 M8 OVC 20 53/50/2207/006
04 PAE SA 1845 3 SCT M8 BKN 15 OVC 20 51/49/3210/007
04 PAE SP 1854 7 SCT M12 OVC 20 3210/00704
04 PAE
04 PAE
04 PAE SA 2145 35 SCT 25 53/43/3010/008
04 PAE SA 2245 35 SCT 25 52/39/3116G23/008
05 PAE SA 2345 35 SCT 25 52/39/3015/008
05 PAE SA 0045 35 SCT 25 50/39/2808/010
05 PAE SA 0145 E35 BKN 25 49/40/3409/011
05 PAE SA 0245 35 SCT E50 BKN 25 48/39/3607/013
05 PAE SA 0345 35 SCT E50 BKN 20 48/40/2908/014
05 PAE SA 0445 25 SCT E65 OVC 15 49/40/0304/015/ LAST
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station (Table 1). The convergence zone continues to shift south, and by 2200 UTC a distinct west-to-east band of cumulonimbi develops from metropolitan Seattle to the Cascade Range, with partial clearing to the north and south of the PSCZ. The southward progression of the PSCZ is supported by the winds at BFI (Table 2), which switch to the northeast at 2250 UTC, 4 h after the passage at PAE.

On this day, the PSCZ moved south beyond BFI, reaching SEA by 0000 UTC 5 November or 1600 PST 4 November (Fig. 7). During this episode, from 1400 UTC to 1800 UTC, winds at HQM veered from 270° to 290°, supporting the southward movement of the PSCZ. The simultaneous backing of the winds at UIL is in opposition to the overall trend and is perhaps a response to the increasing flow through the strait. Typically, and in this example, enough uncertainty exists that forecasting PSCZ movement as far south as SEA remains difficult.

TABLE 2. Observations taken at BFI starting at 1500 UTC 4 November and ending at 0500 UTC 5 November 1990.

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04 BFI SA 1450 M20 BKN 65 OVC 7 54/50/1910/006
04 BFI SA 1545 25 SCT M65 BKN 7 53/50/2010/006
04 BFI SP 1610 M13 BKN 50 BKN 7 1812/006
04 BFI SA 1653 M15 OVC 7 55/50/2014/005/BINOVC
04 BFI SA 1757 15 SCT 200 SCT 7 56/48/2014/005
04 BFI SA 1851 17 SCT 7 57/47/2213/005
04 BFI
04 BFI
04 BFI SA 2150 29 SCT 45 SCT 85 SCT 25 58/45/0000/006
04 BFI SA 2251 E45 BKN 55 OVC 25 54/47/0512/006/BINOV
  MDT CU ALQDS
05 BFI SA 2349 M37 BKN 50 OVC 25RW- 52/45/0606/009/
  BINOVC N
05 BFI SA 0052 35 SCT E44 OVC 25 51/43/1005/010/BINOVC
05 BFI SA 2149 M39 BKN 90 OVC 25 51/43/1005/012/BINOVC
05 BFI SA COR 0149 M39 BKN 90 OVC 25 51/43/1005/012/
  BINOVC
05 BFI SA 0250 M36 BKN 55 BKN 85 OVC 25 49/44/1011/013
  SML BINOVC
05 BFI SA 0350 M21 BKN 35 BKN 85 OVC 25 49/44/0908/014/
  OCNL R- SML BINOVC
05 BFI SA 0450 M22 BKN 35 OVC 10 48/42/1010/015
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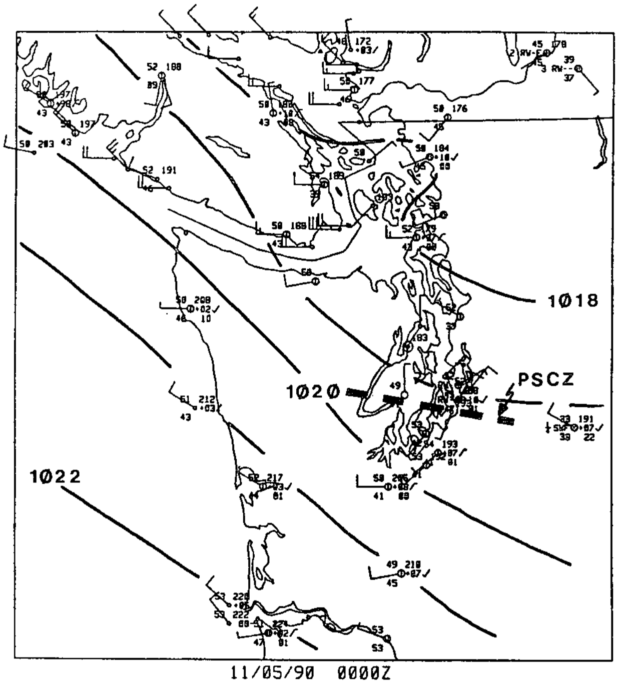

FIG. 7. Same as Fig. 5 except for 0000 UTC 5 November 1990. The PSCZ is identified in southern Puget Sound.

5. Discussion and summary

The PSCZ is a meteorological event having significant impact on clouds, precipitation, and wind patterns of the Puget Sound Basin. It is a terrain-induced mesoscale phenomenon produced when synoptic low-level flow is channeled by mountain barriers and enhanced by leeside low pressure and diurnal effects.

By examining all available data, it is possible to make a reasonably skillful medium-range forecast of the occurrence of a PSCZ. The main emphasis at the medium range is the identification of a period when low-level winds will meet the stated criteria. Additional consideration is then given to determine the kind and amount of attendant weather. The accuracy of this forecast is strongly tied to the accuracy of numerical models since they are used heavily to identify the location and timing of synoptic-scale upper-level troughs and surface fronts.

Short-range detailed forecasts of a PSCZ are also possible, yet are complicated by an incomplete understanding and the lack of a comprehensive real-time dataset. Such forecasts deal with uncertainties concerning movement, cloud bases, visibilities, and precipitation intensity. Short-range forecasting tools include the strength, direction, and tendencies of the surface and 850-mb flow along the Washington coast, satellite imagery, pressure gradients, and surface observations.

Use of the forecasting methodology described here has resulted in some skill in the medium- and short-range forecasting of the PSCZ. One unresolved aspect of the forecast problem is the lack of data necessary to adequately pinpoint the location of an existing PSCZ. Efforts are currently under way to address this problem by gaining access to several local mesoscale networks of automated surface stations. Full-resolution model gridded data (from the NGM) at 6-h frequency are also being investigated as potentially useful indicators of favorable base-state conditions.

As local computing capabilities increase, forecasting possibilities include the use of objective three-dimensional analysis systems like the local analysis and prediction system described by McGinley et al. (1991) and explicit real-time numerical simulations with high-resolution mesoscale models. Using a relatively simple model, Mass and Dempsey (1985) were able to simulate boundary-layer flow convergence downstream from the Olympic Mountains. Current efforts at the University of Washington using the National Center for Atmospheric Research's MM4 community model are also yielding very promising results (Steenburg 1992, personal communication).

Considerable advances should be made in both the understanding and forecasting of the PSCZ when the National Weather Service installs a Doppler radar (WSR-88D) in the northern Puget Sound. These new data will yield information on location, intensity, and movement at a resolution never before possible. The ability to observe similar mesoscale terrain-induced features using research datasets has been demonstrated by Wilczak and Christian (1990) in their observations of the Denver convergence and vorticity zone (DCVZ; Szoke et al. 1984). The National Weather Service in Denver has used Doppler radar data to effectively identify the DCVZ in an operational setting (Dunn 1990). We therefore feel the future of forecasting the PSCZ is a bright one and anticipate continued increases in skill.

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