Topographically Forced Convergence in Western Washington State

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ABSTRACT

Several times a year when the low-level winds from off the Pacific Ocean are within a narrow range of speed and direction, air passes both north and south of the Olympic Mountains of Washington State and is forced to converge in Puget Sound by the north-south oriented Cascade Range. This phenomenon, termed the Puget Sound convergence zone, often results in a band of cloudiness and precipitation in northern and central Puget Sound with clear, subsiding air to the north and south. This paper presents the results of a series of case studies in which the structure of the zone, its meteorological manifestations, and the environmental conditions necessary for its formation are explored. It is shown that the convergence zone is skillfully forecast by surface coastal winds and undergoes a strong annual and diurnal cycle, being most frequent during the late spring and early summer months and during the afternoon and early evening. It is also found that the zone is structurally similar to a shallow cold front and has a significant influence on the precipitation climatology of the region.

1. Introduction

The weather of the Puget Sound region frequently is influenced by a zone of low-level convergence made possible by the topographic configuration found in western Washington State and British Columbia. This low-level convergence, commonly called the Puget Sound convergence zone, often produces a band of enhanced cloudiness and precipitation in the central and northern Sound with clear skies to the north and south (Fig. 1). As a result, convergence zone events create large weather contrasts in Puget Sound with warm temperatures and clear skies in the southern sections but low clouds, rain and substantially cooler temperatures to the north.

The origin of the convergence zone can best be understood from Fig. 2, a map of western Washington State. This figure shows that Puget Sound is surrounded by two mountain ranges. To the east there is the Cascade Range, a nearly continuous north-south barrier, while to the west is the Coastal Range comprised of the Olympic Mountains, the Willapa Hills and the mountains of Vancouver Island. Between these three coastal features are two low-level channels to the Pacific: the Strait of Juan de Fuca to the north and the Chehalis Gap to the south. The convergence zone occurs when, under certain synoptic scale conditions, low-level winds from off the Pacific move eastward through these channels, flow around the Olympics and are forced to converge in Puget Sound by the Cascades.

Although the ability to predict the genesis, motion and structure of the convergence zone is clearly important for satisfactory forecasting in Puget Sound, a comprehensive study of this phenomenon has never been made. Therefore, this paper shall examine most aspects of this mesoscale circulation including horizontal and vertical structure, diurnal and seasonal variability, environmental conditions necessary for formation and effects on the precipitation climatology of the region.

2. Methodology

The main tool used in this study was a set of 25 convergence zone case studies taken from varying synoptic situations and seasons. These case studies made use of a regional network of stations covering the western section of Washington State. Several sources of data were used in the basic network including Federal Aviation Administration (FAA) hourly reports, Coast Guart tri-hourly observations, data from Puget Sound Air Pollution Control Agency stations each quarter hour, and hourly precipitation data from several scattered stations. These reports were supplemented by geostationary satellite imagery, pilot reports, radar summary charts, and the Quillayute and Portage Bay (Seattle) radiosondes. Together these data sources give an excellent regional picture and a very detailed local description of the flow in the Puget Sound basin. For each case study the wind, temperature, pressure and precipitation fields within the network's domain were constructed hourly.

After the case studies were completed, sets of

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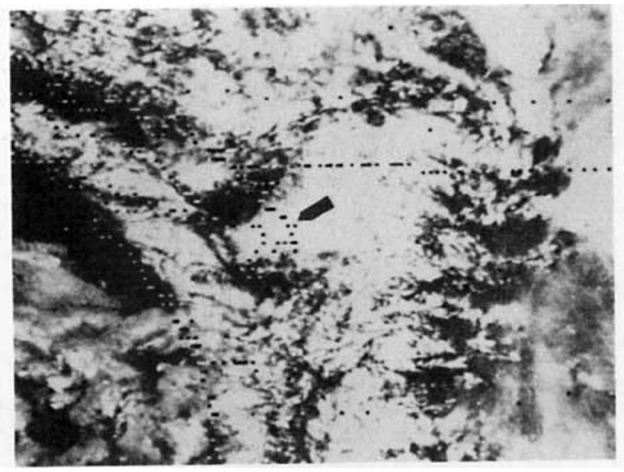

FIG. 1. Visible satellite photograph of the Pacific Northwest at 2246 GMT 15 August 1978. The convergence zone cloud band is indicated by an arrow.

them were selected at random for use in compositing several quantities with respect to the surface wind-shift line. This was done by establishing a north–south oriented movable grid of 8 km wide bands. The central band was centered where the surface wind-shift line crossed the eastern shore of Puget Sound. Each hour the convergence line was south of Everett, in the northern Sound, and north of Tacoma, 75 km to the south, parameters such as temperature and precipitation were sorted into zones and later averaged, thus producing composite descriptions of their variation with respect to the zone.

3. Description of the phenomenon

a. Synoptic-scale control

The convergence zone is a mesoscale phenomenon that is forced by, and thus dependent on, larger scale flow. From the case studies it appears that the wind direction and speed on the Washington coast are the key controlling parameters. These coastal winds are relatively unaffected by local, terrain-induced effects and are indicative of the larger scale flow. It also was found that the synoptic-scale pressure pattern in the coastal region is a useful predictor; this, of course, is hardly surprising considering that surface winds at the coast are roughly geostrophic.

The wind speed and direction at four coastal stations were composited using 10 of the case studies[1] in order to quantify the convergence zone's relationship with the coastal winds. Each hour that the surface convergence line was between Everett, in the northern Sound, and Olympia, at its southern terminus was considered an event. By keeping track of the number of events for each direction and wind speed, a composite picture was created at each coastal station (Fig. 3).

In general, the results indicate that the convergence zone occurs only when the surface, coastal winds are from a narrow range of direction centered on the northwest quadrant and are of moderate speeds. Quillayute River Station (5 m), positioned directly on the Pacific Coast and away from any topographic relief, has probably the best exposure of the group. Its wind composite indicates that only the west-northwest through north-northwest directions produce convergence in Puget Sound; the corresponding wind speeds are almost entirely between 6 and 15 kt. Moving ~8 km inland there is the station at Quillayute (54 m), where the longer parcel trajectory over land and increasing terrain relief modifies but does not essentially change the wind composite results. Here the most frequent wind direction is west-northwest and there is a greater scattering into other directions. Also noticeable are lower wind speeds, including several calms. Although Hoquium (5 m), ~120 km to the south-southwest of Quillayute, is not directly on the Pacific Coast, it is in a well-exposed position on a bay that opens to the ocean. At this location the convergence zone wind-directions are tightly clustered on west-

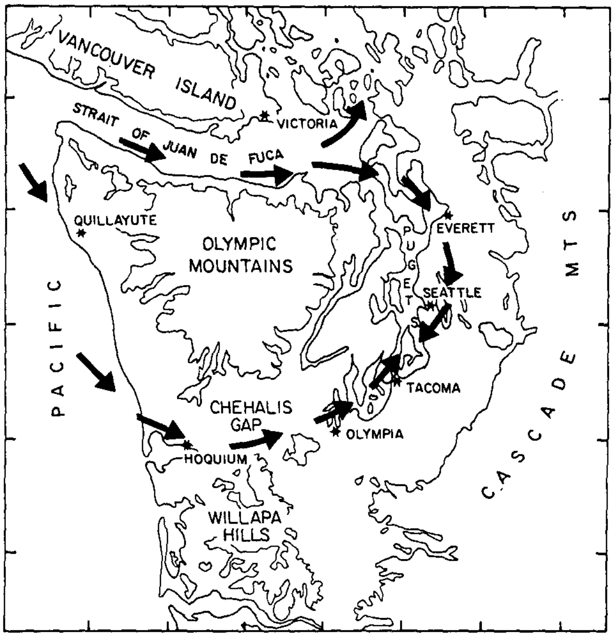

FIG. 2. Major cities and geographical features of western Washington State. The thin solid lines indicate the 300 m elevation contours. The arrows represent typical surface winds during a convergence zone event.

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[1] 20 April and 24 June 1976; 13 April and 3 May 1977; 28 April, 2 and 16 May, 9 July, 15 August, and 20 October 1978.

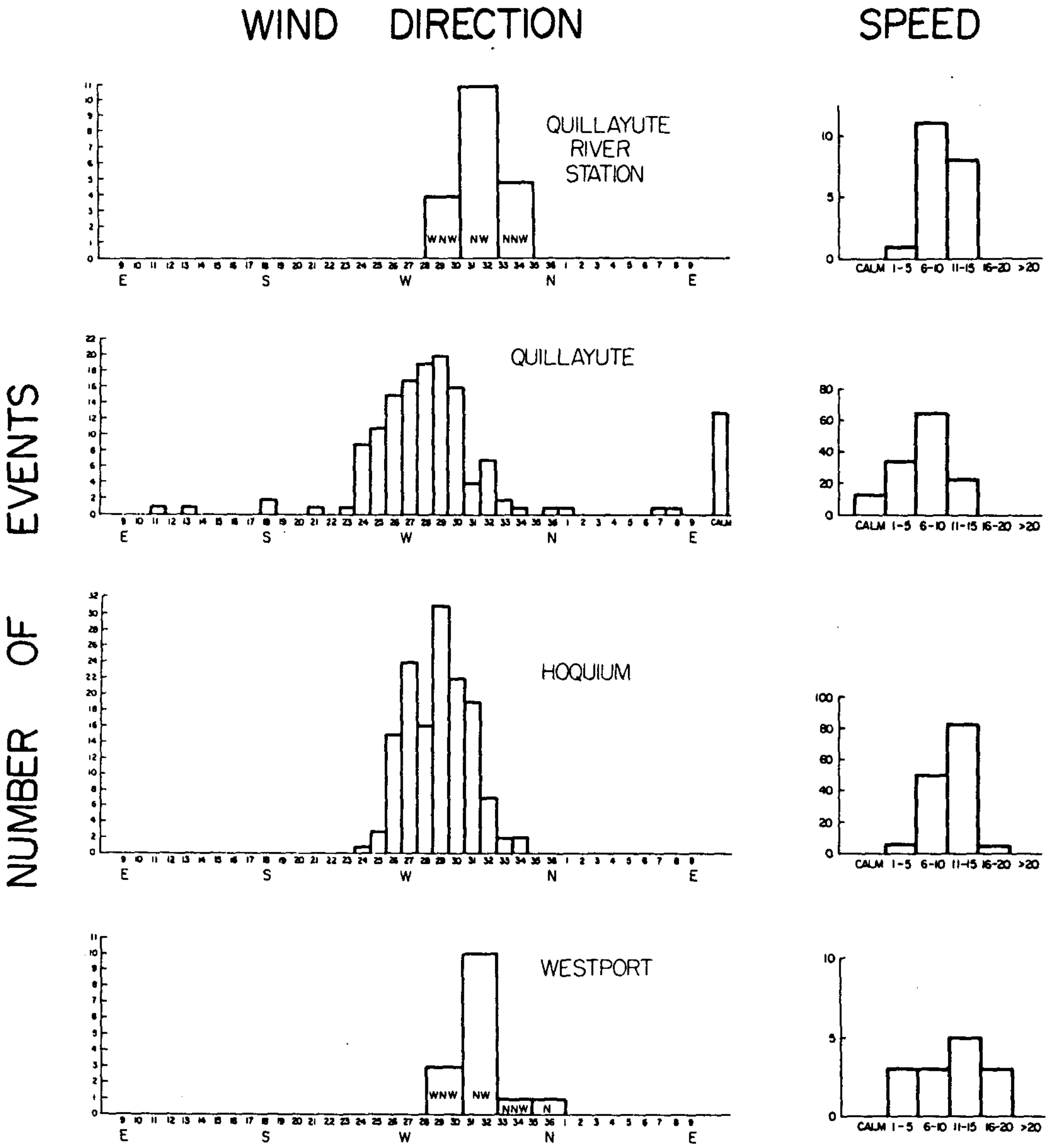


FIG. 3. Wind-speed and direction composites at four coastal stations for 10 convergence zone events.

northwest with nearly all events between 250 and 320°. The final station, Westport (5 m), is just west of Hoquium and nearly on the ocean. Like the other well-exposed coastal location, Quillayute River Station, its most frequent wind direction associated with convergence is northwest.

One can derive further insight into this coastal wind–convergence zone relationship by considering wind direction and speed simultaneously by displaying the composite results on polar diagrams. Fig. 4 shows such a wind diagram for Hoquium; the results are representative of the other coastal stations. This diagram indicates that the highest wind speeds during convergence zone cases are associated with directions between 270 and 300°, and that speeds decrease for more southerly and northerly directions. For the extreme southerly directions, too strong a wind speed would result in southerlies pushing up through Puget Sound while strong winds on the northerly extreme would cause northerly winds to dominate the Sound. Either way the convergence zone does not occur in Puget Sound.

The limited range of coastal wind directions associated with the convergence zone explains why it usually occurs after the passage of a cold or occluded front. The synoptic-scale winds on the Pacific Coast often shift during frontal passage from a southerly direction toward the west or northwest. Thus, as the winds shift through the critical range of angles convergence may occur if there is sufficient

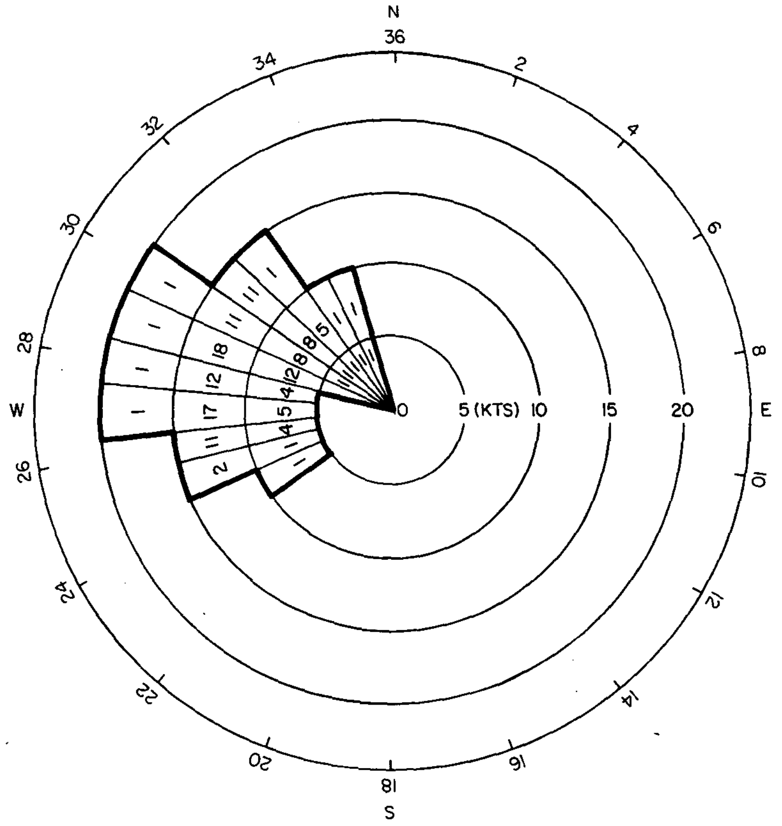


FIG. 4. Polar representation of the wind speed and direction at Hoquium during 10 convergence zone events.

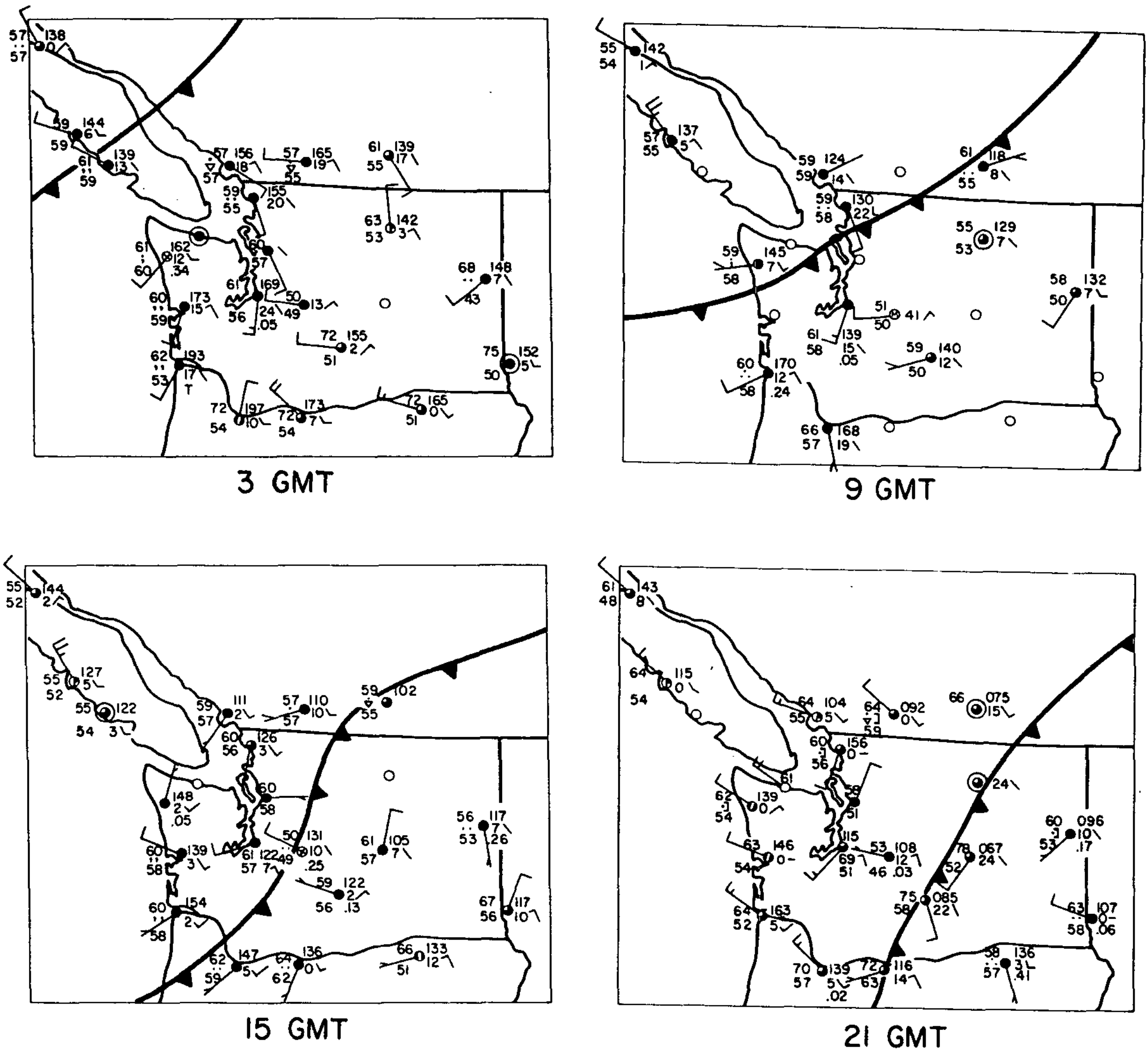
time, proper wind speeds and sufficient stability to produce the necessary channeling.

An illustration of a convergence zone event that was initiated by a cold frontal passage is shown in Fig. 5, a collection of synoptic charts for 15 August, 1978. At the initial time, 0300 GMT, a cold front stretched southwest–northeast along Vancouver Island and southerly winds dominated throughout western Washington State. By 0900 GMT the coastal winds began to veer toward the north as the front crossed the Olympic peninsula. Six hours later (1500 GMT) the front had passed eastward to the Puget Sound lowlands. Surface winds along the northern Washington coast were then from the northwest to north and surface convergence had begun in northern Puget Sound. At 2100 GMT the winds along the entire Northwest coast were from the west-northwest to northwest; the front had proceeded into eastern Washington and the convergence line had propagated southward into Puget Sound. It should be stressed that convergence zone events also can occur without a frontal passage whenever the coastal winds have sufficient force and are within the critical range of direction.

It appears that only minimal stability is sufficient to produce the topographic deflection and channeling required for convergence zone formation. This conclusion was reached by examining vertical soundings at Quillayute, Washington, a well-exposed station upstream of the disturbing effects of the Olympics and Cascades. The twenty individual cases that were examined revealed that most convergence zone events are associated with incoming flows that possess lapse rates below ~750 m that are slightly less than dry adiabatic. Thus, in the lowest layers the incoming flow is normally only marginally stable for an unsaturated displacement. This is illustrated in Fig. 6, which shows the mean vertical sounding of ten cases at 0000 GMT, a time when the convergence zone is normally well-developed. Reed (1980) also noted that only weakly stable conditions were required for the formation of a mesoscale vortex, forced by the deflection of the Olympics during southwesterly flow. Such was also the conclusion of Overland *et al.* (1979) who noted that a deep, well-mixed, near neutral planetary boundary layer could produce strong channeling around the Olympic and Cascade mountains.

b. Horizontal wind field

The evolution of the horizontal wind field during convergence zone cases generally follows a similar


3 GMT

9 GMT

15 GMT

21 GMT

FIG. 5. Surface charts for Washington State and vicinity on 15 August 1978.

sequence of events. The process begins when southerly coastal winds, responding to changes in the larger scale flow, veer into the critical range of directions. As this happens air surges through the Strait of Juan de Fuca and reaches the northern sections of Puget Sound within a few hours. There it meets and slowly displaces the southerlies that had been channeled around the southern flank of the Olympics, creating a rather narrow east-west convergence line. This line, which normally appears in the northern Sound during the morning hours, can reach the central Sound within a few hours and frequently stalls during the middle of the afternoon after which it frequently dissipates. The terminal point is usually between downtown Seattle, in the central Sound, and McChord Air Force Base to the south. Some convergence events do survive the night during which time they frequently move back toward the north. If the large-scale conditions remain favorable, the early morning brings the surviving zone a new lease on life as it again surges southward.

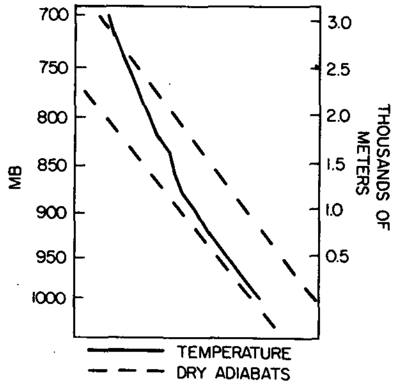


FIG. 6. Average vertical sounding for 10 convergence zone events.

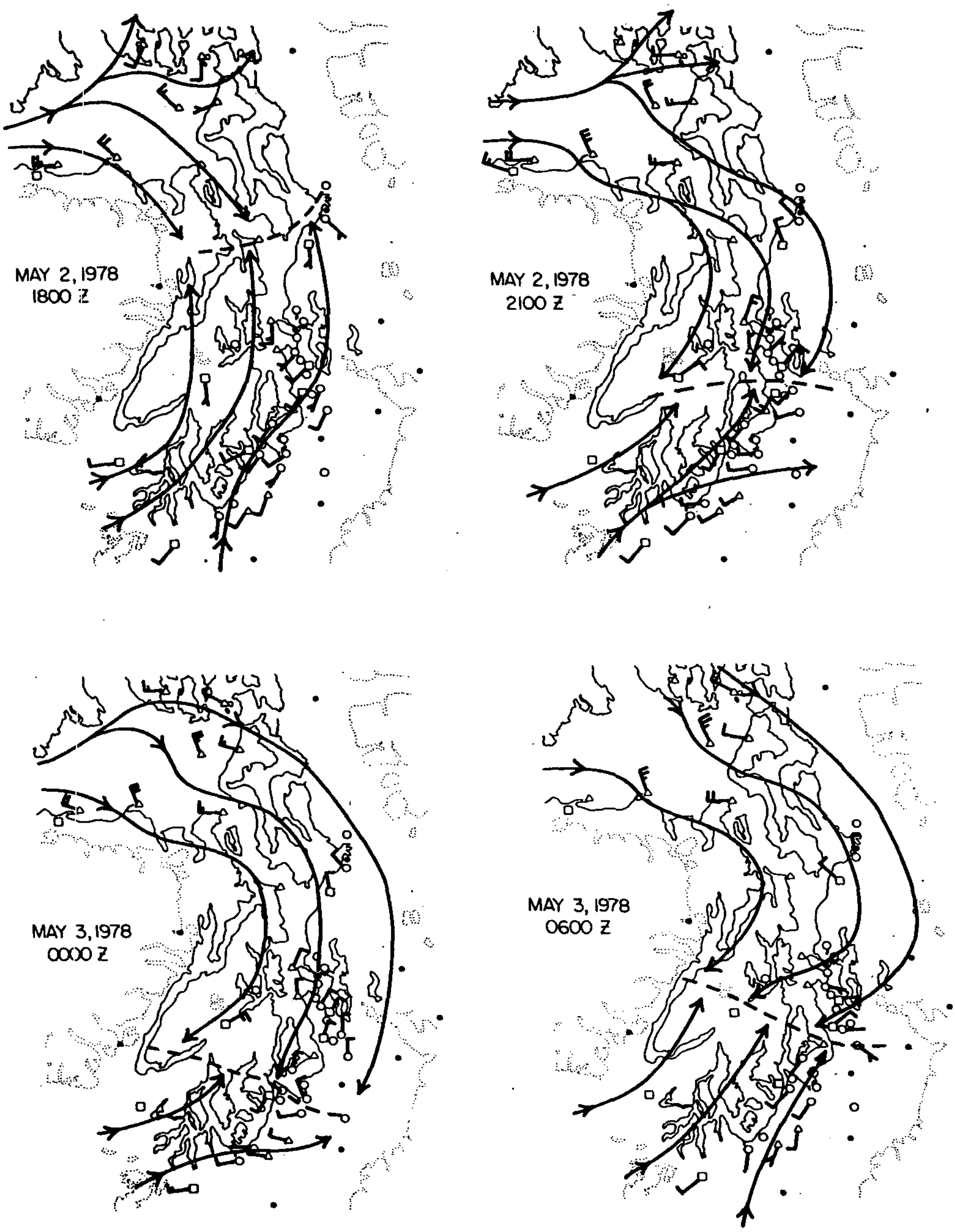


FIG. 7. Surface wind observations and streamlines (solid lines) over the Puget Sound area during the convergence zone event of 2 and 3 May 1978. The position of the surface convergence line is indicated by a dashed line.

An illustration of the wind field within the Sound during a convergence event (2 and 3 May, 1978) is shown in Fig. 7. At 1800 GMT, two hours after the coastal winds had shifted towards the northwest, the surface convergence line was located in the northern Sound. South of the wind-shift line, the flow was from the southeast, nearly 180° from the coastal wind direction. During the next two hours the zone pushed southward at about 10 kt, after which it slowed (5 kt) to its terminal position near the city of Tacoma. As the evening progressed the convergence line slowly retrograded northward to near Seattle-Tacoma airport. At the final time (0600 GMT), the winds north of the wind-shift line were practically due east because of downslope winds from the Cascades. Case studies such as this clearly indicate that the winds in Puget Sound are far from geostrophic; the air parcels are deflected by and flow roughly

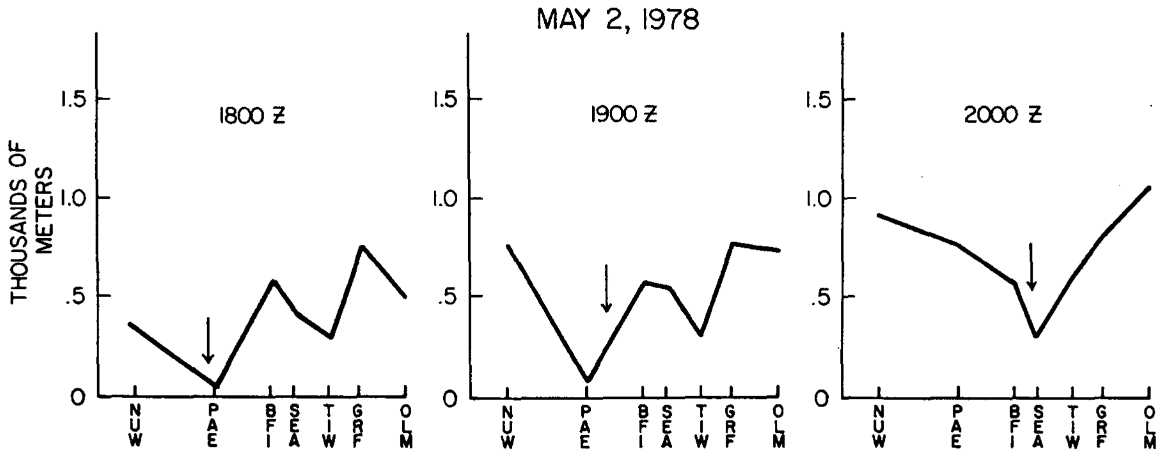


FIG. 8. Longitudinal cross sections along Puget Sound of the lowest cloud decks for the convergence event of 2 May 1978. The arrows indicate the position of the surface convergence line.

parallel to the terrain features while at the same time having a tendency to go from high to low pressure.

The strong diurnal variation of convergence zone activity can be explained by the diurnal wind circulation experienced in the Puget Sound basin during the warm months of the year. During the early morning hours the surface winds are generally weak and variable. As the morning progresses the winds strengthen and increasingly flow toward the surrounding mountains. Accompanying this development is increased northerly flow into northern Puget Sound. This southward flow strengthens during the afternoon to 10–15 kt. Finally, as the evening progresses the northerly winds weaken as the air flows down from the Olympics and Cascades. Thus, the diurnal wind cycle produces increasing northerly winds in the morning and afternoon, approximately the same time that the convergence zone is often propagating southward.

c. Cloudiness and precipitation

Undoubtedly the most obvious manifestation of the convergence zone is its strong modulation of cloudiness and precipitation. During most convergence events there is a band of clouds across the central and northern Sound with the southern cloud boundary close to the surface wind-shift line. This cloud band usually extends across the entire Puget Sound lowlands. To the east there is the Cascades where the band joins and enhances the upslope cloudiness which is always present when a convergence zone band exists. Thus, during these cases the flow is sufficiently moist that some lifting, either from topographically forced convergence or upslope on the mountains, will produce saturation and cloudiness. The locations where both occur simultaneously, i.e., the upslope sections of the convergence band, possess greatly enhanced cloudiness and precipitation. On the western side of the Sound the convergence zone cloudiness is sharply limited by steep eastern slopes of the Olympics.

If no clouds are being advected into western Washington during an event then only the convergence zone cloud band and some upslope cloudiness on the Cascades will be evident. If cloudiness is widespread throughout the region there will be clear zones north and south of the convergence zone band (Fig. 1). Thus, the clear zones are not simply areas in which clouds are absent but, in fact, regions of suppression. It is certain that the rain-shadow effect could not explain these features since the clear zones are upstream of major paths to the Pacific. Section 2e will discuss evidence that the vertical circulation associated with the zone contributes to these features.

Clouds associated with the convergence zone are generally low and barely visible on infrared satellite imagery. Pilot reports (PIREPS) indicate that the cloud tops are normally between 1500 and 2000 m in the central Sound and slope upward toward 3000 m in and near the Cascades. The lowest cloud deck in the Sound is normally at or near the surface convergence line and frequently reaches to the ground. This relation is illustrated by Fig. 8, a cross section of the actual lowest cloud decks during the convergence zone event of 2 May 1978; for comparison, the corresponding surface observations and windfields are shown in Fig. 7. It is evident that as the convergence zone moves southward the lowest deck moves with it.

Associated with the convergence zone's large modulation of cloudiness is its control of precipitation in western Washington. In general, precipitation during a convergence event is limited to the zone's cloud band. There is usually little precipitation in the nearly cloud free areas to the north and south except during the first hours of the convergence zone

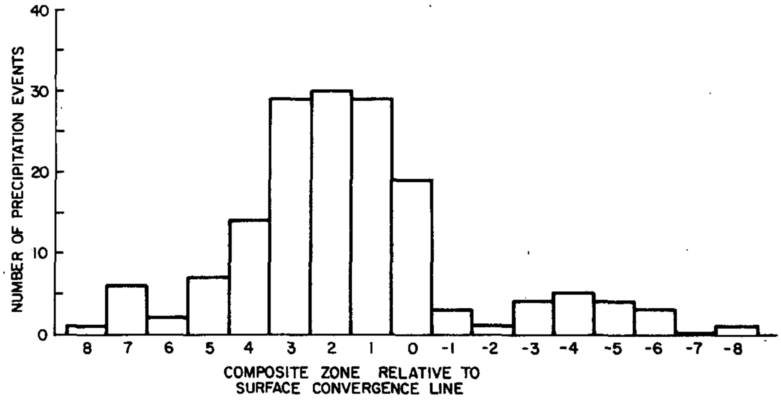


FIG. 9. Summary of the number of precipitation events that occurred in each composite zone during 10 convergence zone events.

when some lingering postfrontal showers might be evident. As the convergence line propagates into the Sound, unrelated precipitation rapidly dissipates. These observations are supported by Fig. 9, a precipitation composite of ten cases.[1] Clearly, most of the precipitation events occurred at and north of the convergence line.

d. Temperature and pressure

The convergence zone can produce large temperature differences (3-6°C) between various sections of the Puget Sound lowlands. As the southward moving convergence line passes over a location and the winds shift from a southerly to northerly direction the temperature drops rapidly, often as much as 3°C in less than a quarter hour. As the convergence line continues moving southward the temperature usually slowly increases but rarely exceeds its prepassage value. This pattern is illustrated in Fig. 10, which shows the variation of temperature, pressure and wind at the University of Washington during the convergence zone event of 15 August 1978.

The explanation for this strong temperature modulation is probably threefold. First, north of the surface convergence line there is normally enhanced cloudiness and precipitation; the first lessens solar insolation while the evaporation associated with the latter produces cooling. Second, the trajectory of the southward moving air north of the convergence line is mainly over the cold waters of the Strait of Juan de Fuca and northern Puget Sound while the southerly flow is over the warmer land to a much greater extent. Finally, there is the possible in-

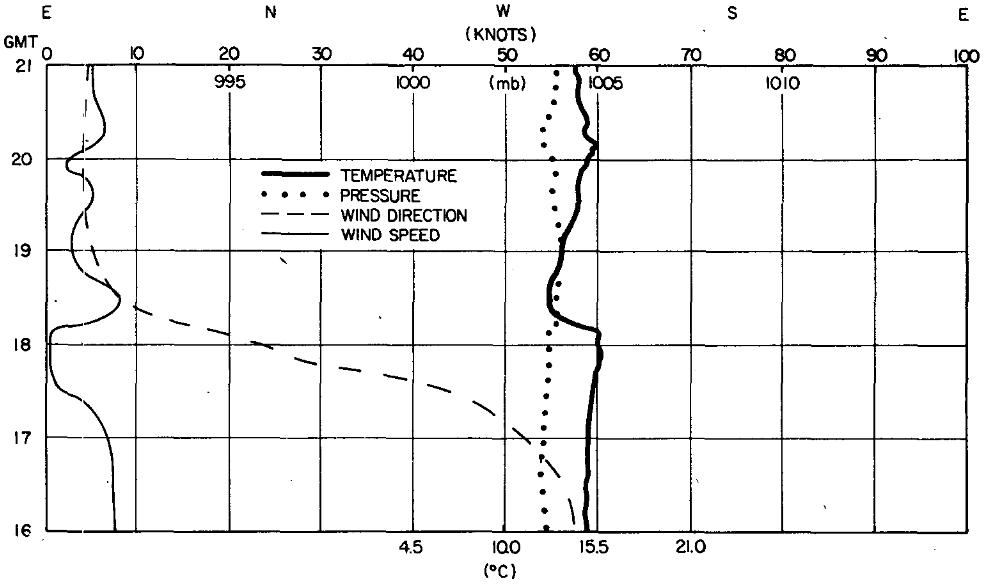


FIG. 10. Variation of temperature, pressure, wind speed and direction at the University of Washington (Seattle) during the convergence zone event of 15 August 1978.

fluence of a secondary circulation associated with the zone. Often it is noted during convergence events that the warmest temperatures are found just south of the surface convergence line in the region of enhanced clearing and probable convergence zone-forced subsidence. Thus, the convergence zone's vertical circulation could support the observed temperature pattern by adiabatic warming south of the convergence line and adiabatic cooling in the cloudy region to the north.

In comparison to temperature, pressure is far less influenced. Microbarograph traces (Fig. 10) generally indicate a slight (0.5–1.5 mb) pressure jump, superposed over the longer term trend, as the surface convergence line passes a station; this is an indication of the shallow nature of the cold northerly flow.

e. Vertical structure

Investigation of the convergence zone's vertical structure is made difficult by the near absence of upper air data within Puget Sound; only for a brief period in the early 60's when ascents were made at Seattle-Tacoma airport four times daily were relevant upper air soundings available. The results of an examination of 28 convergence events during April, May and June of 1961 and 1962 indicate that most have a similar vertical structure, not unlike that of a "classical" front. Northerlies enter the Sound and plow as a wedge into the preexisting southerlies, the windshift line separating the two opposing flows sloping upward to the north. To illustrate this structure a vertical wind cross section through the convergence zone of 18 May 1962 was approximated (Fig. 11) by collecting the Seattle-Tacoma soundings as the zone passed northward during the early morning hours. South of the surface convergence line the winds were directly from the south for approximately the lowest 1200 m with southwesterly and then westerly winds aloft. This wind stratification is hardly surprising since the southerlies are the product of the coastal flow's deflection around the southern Olympics, the general upper level of which is ~1300 m. Just north of the surface convergence line, the northerlies appear to be relatively shallow with southerlies lying immediately aloft. Further northward, the depth of the northerlies progressively increases. An idea of the disturbing effects of the Olympics can be derived from the upper panel of Fig. 11, which shows the vertical soundings at Tatoosh Island during the same convergence event. This island is located at the northwest corner of the Olympic peninsula and thus is upstream of most of the disturbing influences of the mountains. The vertical soundings at Tatoosh do not possess the topographically forced, low-level southerlies and northerlies found in Puget Sound but instead have westerlies through most of the soundings.

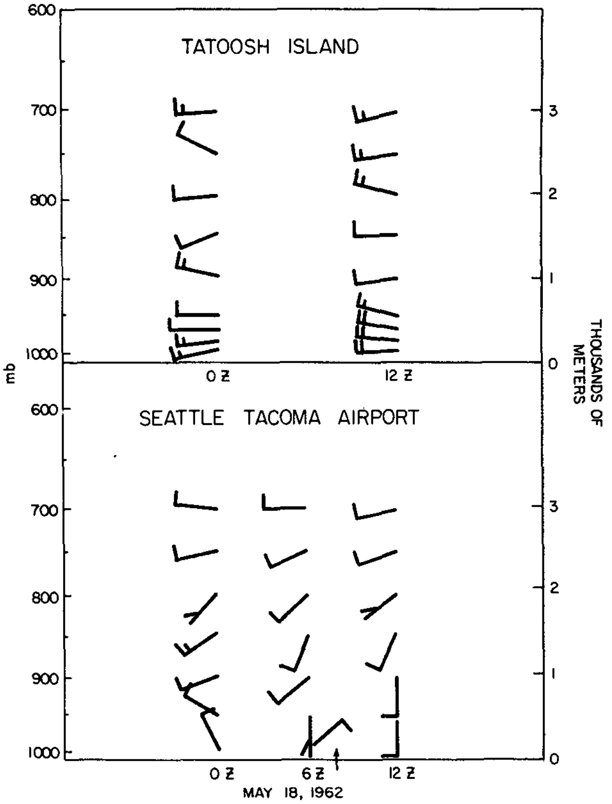


FIG. 11. Vertical soundings at Seattle-Tacoma airport and Tatoosh Island during the convergence event of 18 May 1962. The arrow indicates the time of convergence zone passage.

Amalgamating all available information produced the picture shown in Fig. 12, a meridional cross section of the flow during a convergence zone event. South of the convergence line the surface flow moves northward and is deflected upward by the wedge of cooler northerly air. The initially southerly flow reverses directions as it rises and eventually subsides south of the convergence line. This subsidence could explain the southern cloud free region and its frequently enhanced temperatures (as compared to other cloud-free areas). To the north of this convergence line northerlies follow the zone southward. Further to the north, subsidence in the second clear zone might be associated with the surface diffluence created as air moved both north and south after it passes eastward through the Strait of Juan de Fuca. From an examination of several case studies it appears that this diffluent region can be divergent as well; unfortunately, sparseness of data makes an accurate determination impossible.

f. Seasonal frequency

Although there is some interannual variation, most years have between ten and twenty "major" convergence zone events. Such events are dis-

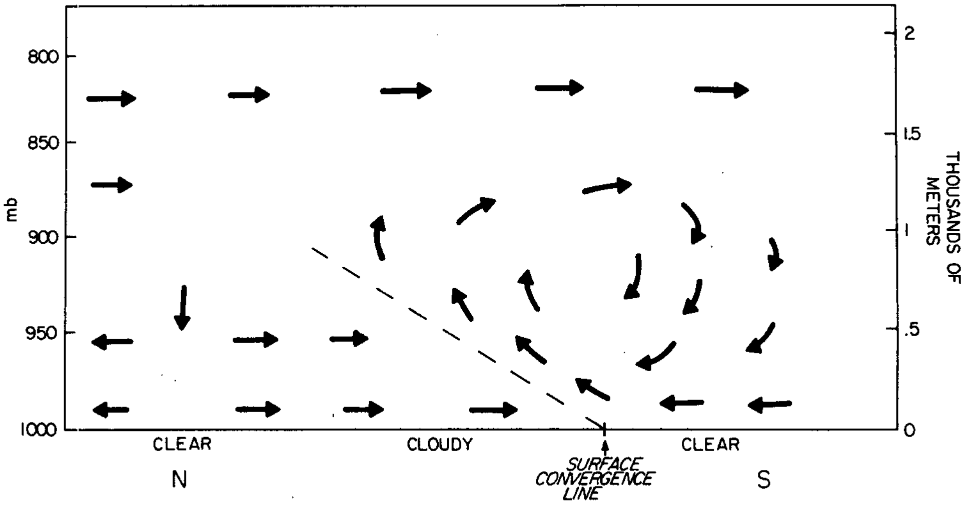


FIG. 12. Schematic meridional cross section of the circulation associated with a well-developed convergence zone.

tinguished by a distinct, topographically forced band of cloudiness and precipitation with adjacent zones of clear or nearly clear skies. In addition, there are usually at least as many "minor" convergence zone events in which the above features are less apparent. These weaker cases can occur when the coastal winds are from the proper direction but with weak wind speeds or when the necessary conditions are fulfilled for only a few hours.

Even though convergence zone events can occur anytime of year, they are most likely during the late spring and early summer months, especially April, May and June. Each of these months can be expected to possess at least two to four major events; one month in particular (June 1976) had eight.

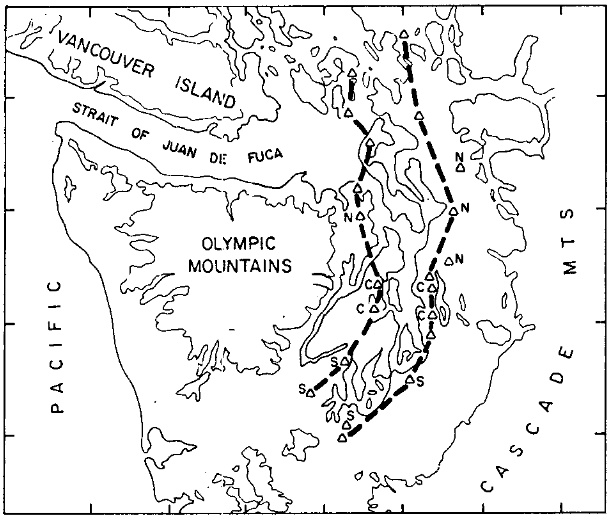


FIG. 13. Location of precipitation cross sections and geographical precipitation groups. Southern, central and northern sound stations are identified by the letters S, C and N, respectively.

The large annual variation in convergence zone events can be understood from the wind climatology of the region and the fact that convergence over Puget Sound can only occur for a very limited range of surface wind directions (west to north-northwest) at the coast. During the winter months (October–March), low pressure dominates the eastern Pacific and as a result the most frequent surface winds on the coast are from the east through southwest. Before most winter frontal passages the winds are from the east to south while after passage they veer slightly toward the south or southwest. Very rarely during this season are the winds from the directions suitable for convergence zone formation. As spring progresses, high pressure builds northward into the eastern Pacific and the coastal winds progressively veer toward the northwest. Starting in late April the most probable directions are from the west to northwest, and thus are within the critical range of angles necessary for convergence zone formation. Most fronts during the spring are preceded on the coast by southerly winds which veer to the northwest after frontal passage. High pressure in the Pacific dominates the region during the summer months (middle June–early September) and usually results in northerly winds, few frontal passages and dry weather. The frequency of major convergence zone events drops during this period not only because the coastal winds are often too weak or too northerly but also because strong vertical stability and lack of moisture results in little apparent weather even when surface convergence exists. Finally, in late September and early October the winds quickly return to the wintertime pattern, thus precluding most convergence zone activity until the following spring.

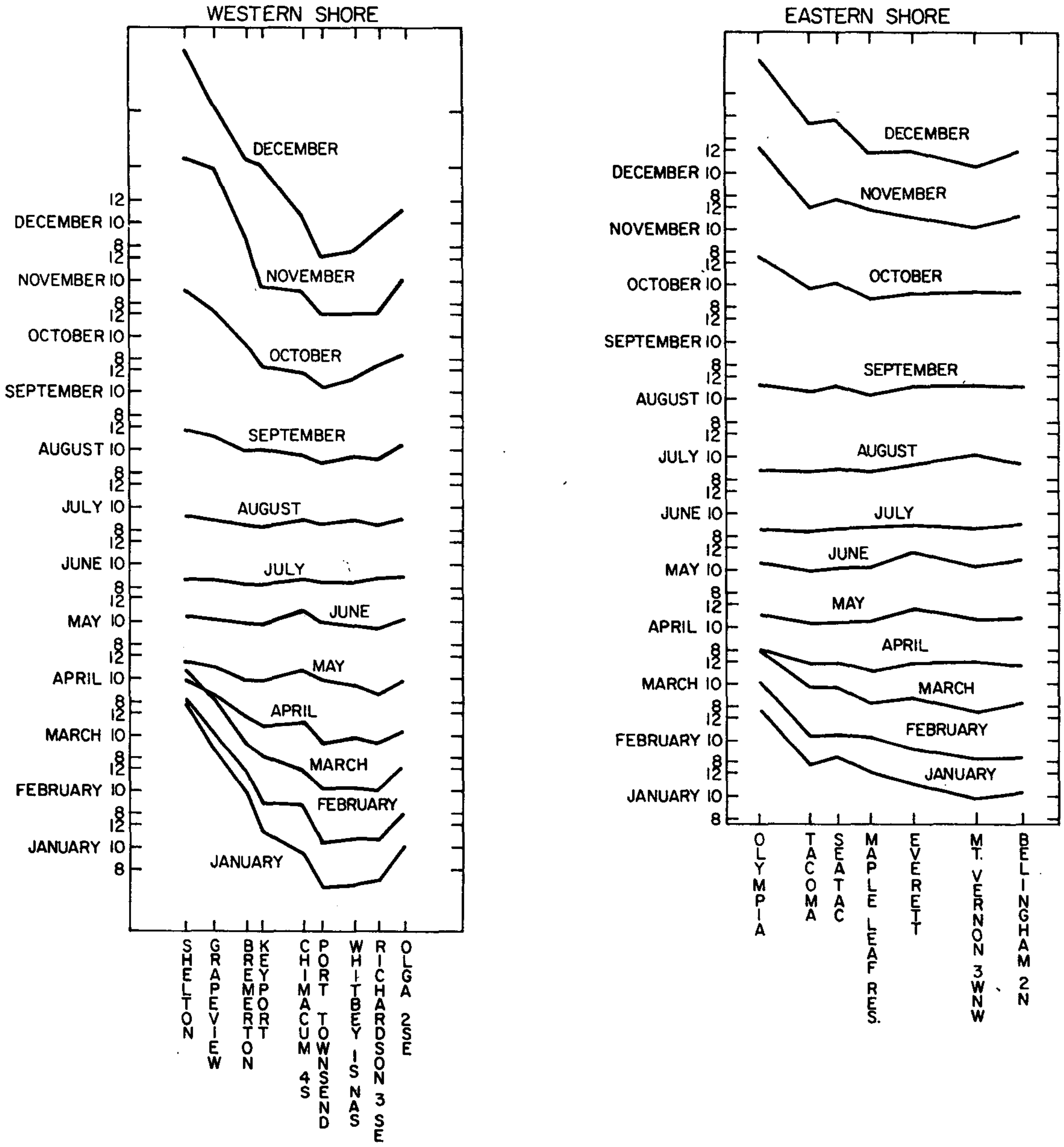


FIG. 14. Mean precipitation cross sections for each month along the eastern and western shores of Puget Sound. Amounts are in centimeters.

g. *The influence of the zone on climatological precipitation*

A major finding of the case studies is that the convergence zone enhances cloudiness and precipitation in northern Puget Sound, especially during the late spring and early summer months. This section will show that this enhancement is also apparent in long-term mean precipitation data.

One useful method for determining the zone's long-term effects is the construction of two, approximately north–south, cross sections of mean precipitation on the eastern and western shores of Puget Sound. Fig. 13 shows their locations. The mean precipitation cross sections were constructed for each month[2] and are shown in Fig. 14.

Examining the eastern section first, one observes that the wintertime pattern, evident in November, December, January and February, shows increasing precipitation from the northern to southern Sound. The spring and summer cross sections, on the other hand, are rather flat except for an enhanced area in

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[2] Data source: *Climatological Handbook Columbia Basin States.* Vol. 2, 262 pp, 1969. Available from Pacific Northwest River Basins Commission, Box 908, Vancouver, WA 98660.

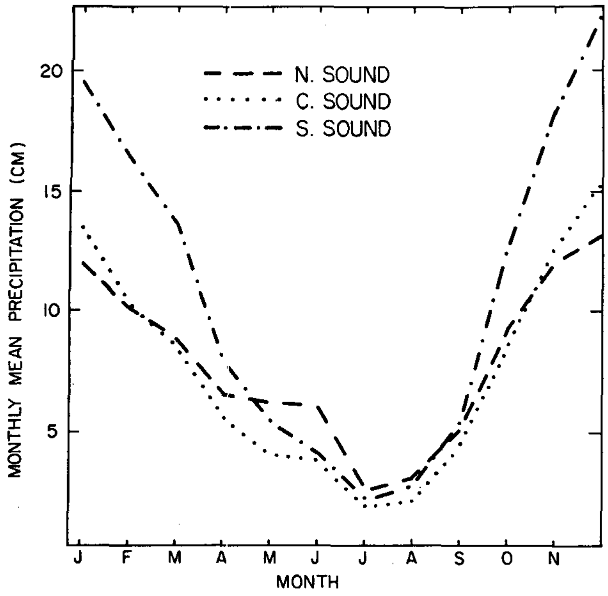

FIG. 15. Annual variation of precipitation for the northern, central and southern Puget Sound regions.

the northern Sound centered near Everett. This enhancement is most evident in May and June and possesses an amplitude of nearly 2 cm of precipitation. The pattern is then relatively flat till October when the wintertime pattern is reestablished. The western section shows a similar temporal progression and also suggests a convergence zone related, late spring-early summer maximum in the northern Sound.

Another method of looking at the mean precipitation effects of the convergence zone is to plot the monthly variation of precipitation at geographically proximate stations with similar precipitation characteristics, i.e., northern, central and southern Puget Sound (Fig. 13). The annual progression of the average precipitation in these groups is shown in Fig. 15. From this figure, one observes that the southern Sound stations, which are not influenced by the convergence zone, possess a steady decrease in precipitation from January through July. Coastal stations, not shown in the figure, behave similarly. The stations of the central Sound follow a similar dropoff from winter to summer except for a minor pause during May and June when the precipitation remains nearly constant. This interruption in the downward trend is dramatically enhanced for the northern Sound stations where the precipitation is nearly constant from April through June. Apparently, this group of stations receives more precipitation in May and June than their southern Sound counterparts even though their annual totals are far less. For instance, Everett in the northern Sound receives nearly 2.5 cm more precipitation in May through July than Olympia in the far southern Sound even though the latter station receives an average of over 43 additional cm of precipitation a year.

In summary, this section has shown that there is some evidence of a substantial late spring-early summer enhancement of precipitation in northern Puget Sound. Since this is the same time and region in which convergence zone events enhance precipitation, there is a strong suggestion the convergence zone is the cause of the climatological enhancement.

4. Forecasting the convergence zone

After an examination of several parameters (e.g., upper and lower level winds, pressure gradients) it appears that the surface wind speed and direction on the Washington coast are the most useful parameters for forecasting convergence zone development. This finding is hardly surprising considering the results of Section 3a which showed that the zone only exists for a narrow range of coastal wind direction and speed. Thus, an accurate prediction of the surface winds on the coast (which are closely related to the larger scale flow due to relatively weak frictional and topographic effects) should make actual prediction of convergence zone events possible. In addition, this criterion can be applied in a "nowcasting" mode in which the observation of coastal winds of the proper speed and direction implies convergence zone formation during the next few hours.

Hoquium (HQM) was chosen for the forecasting experiments since it is a well exposed, near coastal station and is available hourly on the aviation circuits. Based on the previous results (Fig. 4), a convergence zone event was predicted when for four continuous hours at Hoquium wind direction was between 260 and 320° and the wind speed ranged from 5 to 15 kt. This relationship was tested for January, February, April and May 1978 and the results are summarized in Table 1. During this test period there were a total of 23 convergence zone events and only one was not predicted by the criterion. However, there were seven cases in which a convergence event was forecast and none occurred. Especially poor was the performance in January in which three were forecast without a single true oc-

TABLE 1. Forecast experiment results.

Month	Number of CZ events	Number of predicted CZ events	Number of correct predictions
January	0	3	0
February	2	3	2
April	9	11	9
May	12	13	11
Total	23	30	22

currence. Many of these failures were for marginal situations in which the criterion was barely met, e.g., weak winds for only 4 hours. Furthermore, if a second coastal station such as Quillayute was used several of the false alarms could have been eliminated. In short, the criterion based on the Hoquium winds produced very encouraging results; coupled with output of a numerical model of the larger scale flow (e.g., Limited Area Fine Mesh Model, LFM) this diagnostic criterion should improve forecasting of zone formation for periods between 12 and 36 h.

Another area of forecast interest is the direction of convergence line propagation once it has formed. Although this study has not examined this question in detail, it has been noted that when the coastal winds are towards the northerly parts of their allowable directional range and the stronger parts of their speed range the convergence line moves southward; similarly, northward movement occurs on the southerly extremes of the directional range. The pressure gradient between the northern and southern Sound (Whitbey Island–Olympia) does not appear to have any predictive value of convergence line motion.

5. Summary and conclusions

This paper has described the occurrence of topographically forced convergence in Puget Sound and its large effect on the weather of the region. This phenomenon, termed the Puget Sound convergence zone, is established when the surface winds on the Pacific coast are within a narrow range of direction and speed; this allows the flow to simultaneously pass north and south of the Olympics and to subsequently converge in central Puget Sound. It is shown that this convergence enhances cloudiness and precipitation in a band north of the surface convergence line with clear, subsiding air to the north and south of the degraded weather. Furthermore, this modulation even appears in the region's long-term precipitation climatology.

Although it can occur anytime of the year, the convergence zone undergoes a strong annual and diurnal cycle; it is most frequent during the late spring and early summer months and during the afternoon and early evening. Structurally, the convergence zone is somewhat like a cold front when it advances and like a stationary front when it reaches its terminal position. Finally, by understanding the necessary environmental conditions, it is possible to make skillful short-term forecasts of the generation and evolution of the convergence zone.

It is important to note that this study has implications far beyond Puget Sound. First, the convergence-producing topography of the region is not unique; many other locations have terrain that could produce similar results. For example, Edinger and Helvey (1961) described the San Fernando convergence zone which is generated by the coastal mountains of California. Secondly, this study describes the interaction of a flow with a mesoscale, topographic obstacle, a topic of increasing meteorological interest (e.g., GARP mountain subprogram, ALPEX). For example, it is shown that only minimal stability is required to produce the channeling and deflection necessary for convergence. Furthermore, this study indicates that a local diurnal circulation can greatly modify the interaction between the large-scale flow and complex terrain. The final and most important point is that this work is an example of the kind of examination that could be productively applied to other regions, especially those with complex terrain or land-sea boundaries. It is certain that the identification and understanding of the local mesoscale circulations of these areas could substantially improve our ability to forecast and nowcast local weather even without any improvement in large scale numerical guidance.

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REFERENCES

Edinger, J. G., and R. A. Helvey, 1961: The San Fernando convergence zone. *Bull. Amer. Meteor. Soc.*, **42**, 626–635.

Overland, J. E., M. H. Hitchman and Y. J. Han, 1979: A regional surface wind model for mountainous coastal areas. NOAA Tech. Rep. ERL 407-PMEL 32, 34 pp. [Superintendent of Documents, SD stock No. 003-017-00461-9].

Reed, R. J., 1980: Destructive winds caused by an orographically induced mesoscale cyclone. *Bull. Amer. Meteor. Soc.*, **61**, 1346–1355.