Gap Winds in the Strait of Juan de Fuca[1]

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ABSTRACT

Gap winds can be defined as a flow of air in a sea level channel which accelerates under the influence of a pressure gradient parallel to the axis of the channel. In February 1980 two distinct cases of gap winds were observed in the Strait of Juan de Fuca between western Washington State and British Columbia during a study that measured spatial variation of low-level marine winds and other parameters from the NOAA P-3 research aircraft and a dense network of surface stations which included eight meteorological buoys. These two cases were a high-pressure region over central British Columbia and a low-pressure system propagating northward, seaward of the Washington coast. Both cases produced strong easterly winds of 13–15 m s^{-1} at the western end of the Strait of Juan de Fuca. The high-pressure region provided a drainage air mass from the interior of British Columbia which flowed through the Straits of Georgia and Juan de Fuca and eventually into the Pacific Ocean. This air mass remained nearly homogeneous and was capped by a well-defined inversion. For the offshore low-pressure center, the lower atmosphere was stably stratified throughout the region, and weak winds were observed at the eastern end of the Strait of Juan de Fuca with strong winds at the western end. Although the features of the flow fields were complex, major characteristics of the wind fields can be accounted for by the combined effect of topography and the synoptic pressure field. Local winds were in approximate ageostrophic equilibrium between the inertia term and the imposed sea level pressure gradient.

1. Introduction

The combination of large-scale synoptic forcing and the configuration of surrounding topography leads to the formation of unique local winds in many areas of the world. Studies and catalogs of local winds have been made for various geographic regions by Schamp (1964) and Vialar (1948), and in particular for Japan by Sekiguti (1940) and near the Mediterranean Sea by Levi (1965). Yoshino (1975) discussed a number of examples of mountain, land, sea and valley breezes, their locations, local names and causes. Our focus will be on the wind phenomenon of the Strait of Juan de Fuca between western Washington State and British Columbia termed "gap winds" by Reed (1931).

Topography of the Puget Sound/Strait of Juan de Fuca region is the primary controlling factor in the formation of local winds (Figs. 1 and 2). The region has a north-south length of 165 km, and most of the shoreline is faced by bluffs that range from 30–150 m in elevation. The region does not have a simple, well-defined body of water; many channels, bays, smaller sounds and inlets, as well as numerous islands give the topography a broken character. Puget Sound's main connection with the sea is the Strait of Juan de Fuca, a channel 20–30 km wide and 150 km long, bounded on the north by mountains on Vancouver Island and on the south by the Olympic Peninsula with rugged mountains of nearly 2400 m elevation. The Fraser River Valley just south of the city of Vancouver is an important break in the Cascade Mountains and can have a strong influence on the flow in the Strait of Juan de Fuca and the Strait of Georgia.

According to Reed (1931), the "easterly gales at the west end of the Strait of Juan de Fuca constitute one of the most notable climatic eccentricities of the North American Continent." He applied the term "gap winds" to these easterly gales and characterized these winds as "not being, properly speaking, gradient winds in that geostrophically balanced pressure gradients are totally inadequate alone to account for the velocities observed." Reed (1931) defined gap winds as the flow of relatively homogeneous air in a sea level channel with a source region or reservoir at one end. This flow is driven by a component of pressure gradient parallel to the channel causing the flow to accelerate along the channel. He also concluded that the high velocities resulted from a venturi effect caused by the converging sides of the channel. As will be shown later, gap winds can result from quite different synoptic conditions, and acceleration along the pressure gradient alone rather than converging sides is suf-

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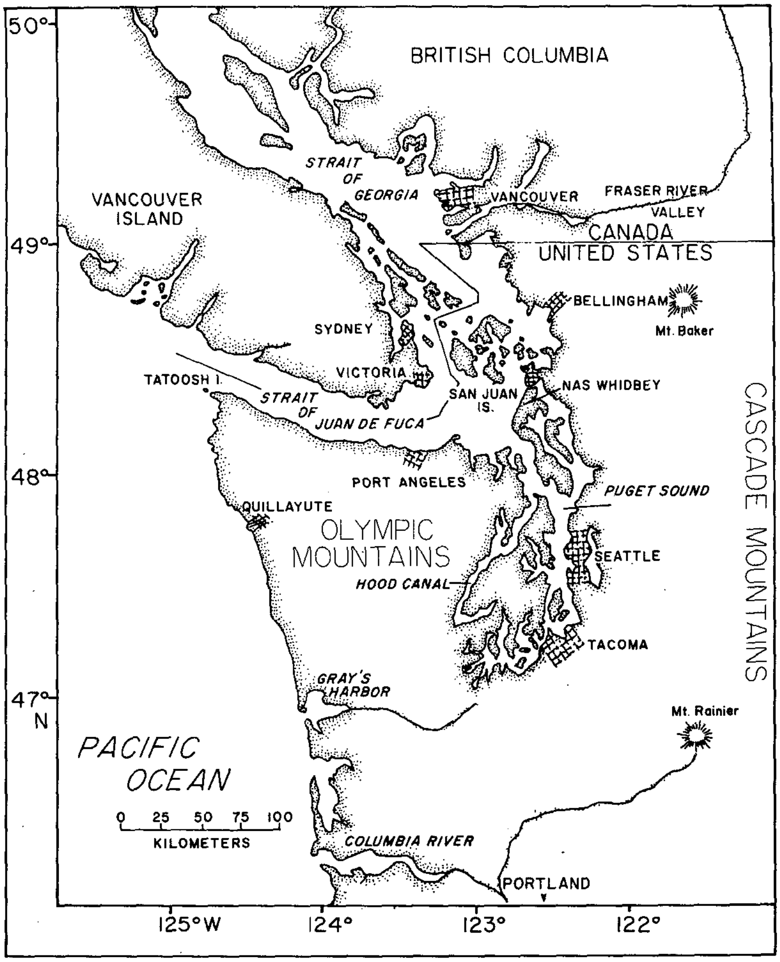

FIG. 1. Location map of western Washington State and southwest British Columbia.

ficient to explain the observed wind magnitudes. The variety of synoptic conditions encountered in our study capable of producing gap winds confirms a result of Reed (1931), who, after constructing a composite isobaric chart of all the situations, concluded that the chart "demonstrated by the very weakness of the composite gradient the fact that such blows may occur under the most diverse individual conditions of pressure distribution."

Reed (1931) based his study on winds measured at Tatoosh Island at the entrance to the Strait of Juan de Fuca for the years 1924–27. The wind data showed that of 450 gales (wind speeds > 18 m s^{-1}), 219 were from an easterly quarter and the vast majority of these easterly winds occurred during the winter. In studying a subset of 75 easterly wind cases Reed noted that predominant easterly components in the winds at Tatoosh did not simultaneously occur over the region at the east end of the Strait of Juan de Fuca or within Puget Sound. The best conditions for easterly winds at Tatoosh Island were high pressure to the northeast or low to the southwest. Reed also found that when Tatoosh winds were compared with winds measured at a lightship in mid-channel at the entrance to the Strait of Juan de Fuca 25 km NW of Tatoosh there was agreement during easterly gale conditions. Thus gap winds were not just peculiar to the south side of the channel but also were present in mid-channel. During a mesoscale wind study in the Puget Sound region during February–March 1980, using an instrumented aircraft and surface buoys, several easterly wind situations were noted. The characteristics, behavior, and origin of these winds will be discussed within the framework of Reed's earlier work.

2. Puget Sound wind study

During the period 10 February–10 March 1980, a study of mesoscale marine winds was carried out in Puget Sound, the Strait of Juan de Fuca, and the Strait of Georgia using a Seattle-based

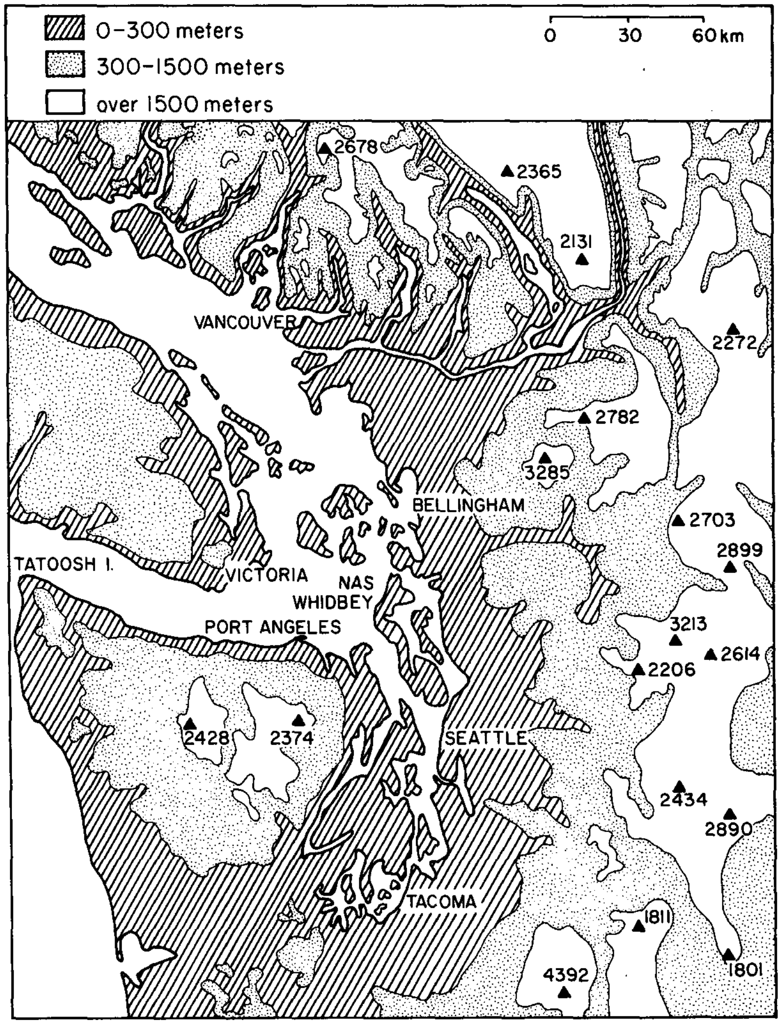

FIG. 2. Topographic map of the region.

NOAA WP-3D aircraft, which flew six missions at a height of 50 m above the water surface. Aircraft data include wind, temperature, dew-point temperature and vertical wind speed at flight level, sea level pressure, sea surface temperature and vertical profiles of temperature, moisture and wind from omega dropwindsondes. A typical flight pattern is shown in Fig. 3; deviations from this pattern occurred on any specific flight because of visibility limitations or to avoid restricted areas. The total time required to fly these tracks was on the order of 3 h. Flight-level winds were computed by combining inertial navigation system (INS) outputs with measurements of air-speed, angle of attack, and angle of side slip (Merceret and Davis, 1981). After data are corrected for orientation of the aircraft with respect to the wind direction and drift of the INS, the absolute accuracy of each wind component is better than ± 1.0 m s^{-1}. Aircraft sea level pressure observations are accurate to ± 1 mb.

Eight meteorological buoys were deployed as part of the study to provide direct measurements of over-water winds and air temperature (Fig. 4). Ground-based data were collected from U.S. and Canadian Coast Guard and Weather Service stations and FAA facilities; measurements include wind, temperature, dew point and pressure. All U.S. surface pressure stations were compared with a standard pressure sensor and found to be within ± 0.3 mb of the standard. Four upper air sounding stations were occupied to supplement data routinely available from two observation sites. Soundings were taken daily at 0000 GMT, and at 1800, 2100 and 0000 GMT on days with aircraft flights.

3. Case study: 13 February 1980

a. Description

During the experiment, aircraft measurements were taken during two different events that led to

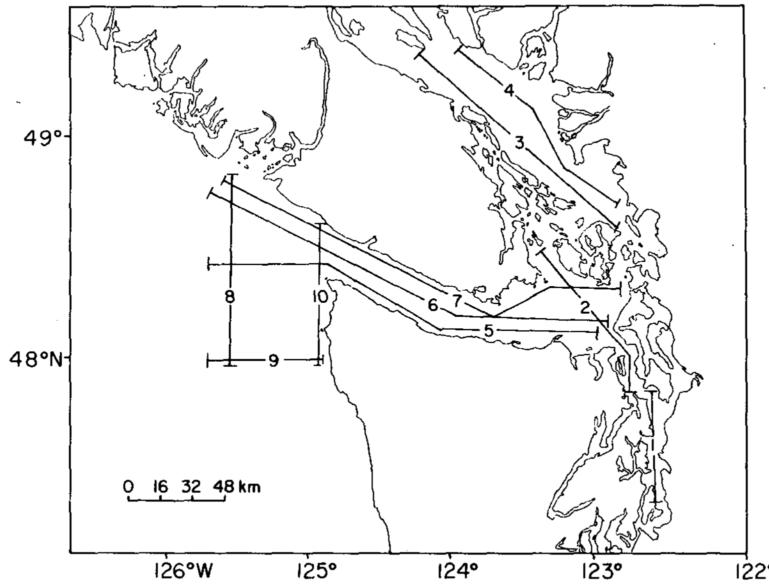

FIG. 3. Typical flight tracks for the NOAA P-3. Total flight distance was on the order of 1000 km.

strong easterly wind conditions in the Strait of Juan de Fuca. In the first case, a 1042 mb high-pressure region (Fig. 5) situated over the interior of British Columbia created a strong pressure gradient oriented NNE-SSW to the northeast of Washington State. The 500 mb chart (Fig. 6) shows a trough over southern British Columbia and Alberta with NNW winds over the Puget Sound area.

Fig. 7 shows the mesoscale sea level pressure field at 2100 GMT 13 February 1980 based on sea level pressures measured by land-based stations and on 1 min average values derived from meas-

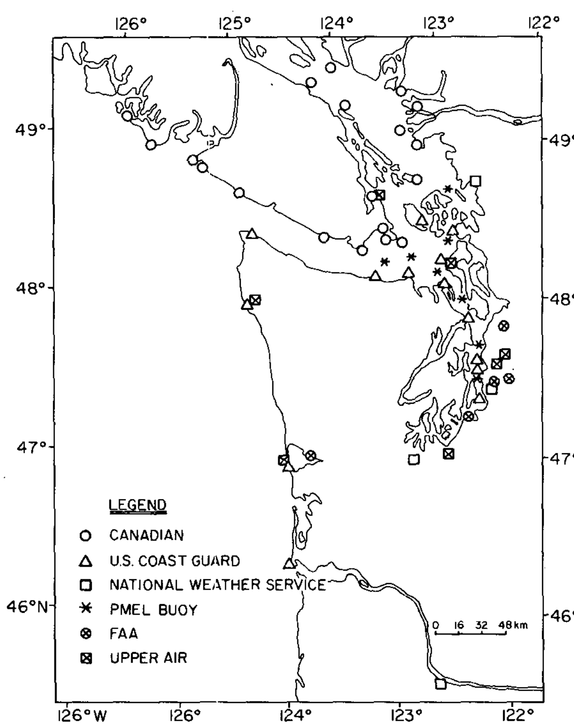

FIG. 4. Surface and upper air data sources and locations.

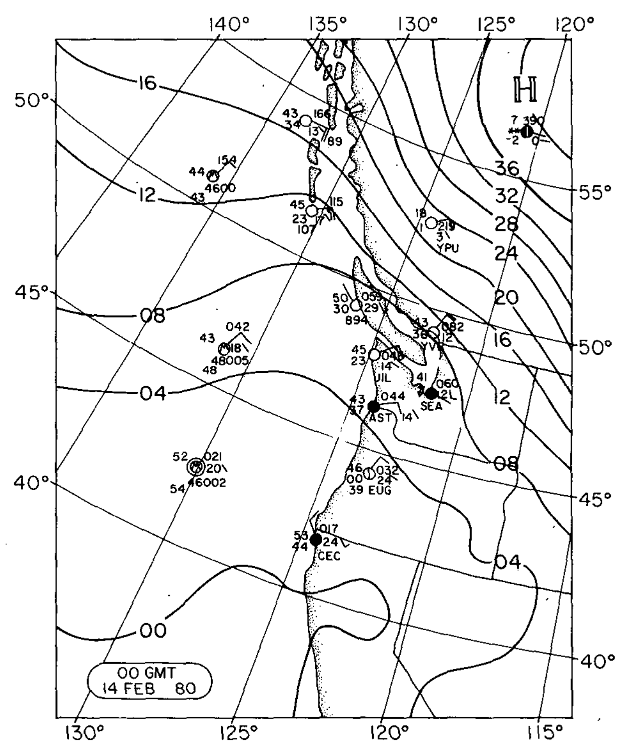

FIG. 5. Sea level pressure analysis 0000 GMT 14 February 1980.

urements from the P-3 adjusted to 21 GMT. The wind pattern (Figs. 7 and 8) was dominated by the high-speed (15–17 m s^{-1}) flow of air which originated from the Fraser River Valley and moved across the southern part of the Strait of Georgia and Vancouver Island and out the Strait of Juan de Fuca. The boundaries of this air mass were sharp and were defined by both large horizontal wind shears and the difference in dew-point temperature T_d between the air in the jet ($T_d < -5$°C) and that outside ($T_d \approx 0$°C) (Fig. 8). Conditions at Hope, B.C., approximately 130 km east of Vancouver in the Fraser River Valley, showed the wind from the east at 5 m s^{-1} and $T_d \approx -9$°C.

Outside the entrance to the Strait of Juan de Fuca (125°15′W) a sharp transition took place from conditions in the high-speed flow with winds of 8–10 m s^{-1} from the ENE and $T_d \approx -9$°C to a situation where the winds were 2–5 m s^{-1} from the SE and $T_d \approx -2$°C. Winds along the eastern part of the Washington side of the Strait of Juan de Fuca were very low, e.g., <2 m s^{-1} at Port Angeles, and dew points were −1 to −3°C. The air was more moist than it was further north and west in the Strait of Juan de Fuca. The regions of light wind near Port Angeles and at the entrance to the Strait of Juan de Fuca were seen from the aircraft as an abrupt change in roughness of the water surface.

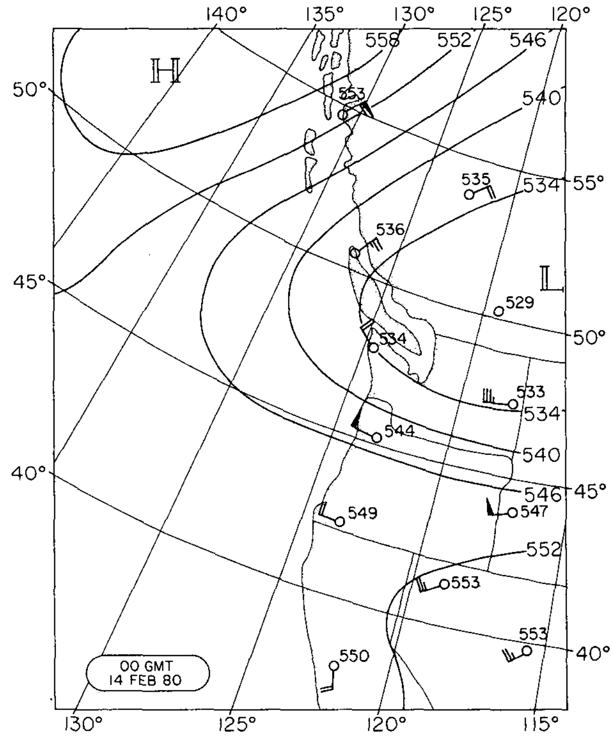

FIG. 6. 500 mb height analysis 0000 GMT 14 February 1980.

Fig. 9 shows plots of the vertical profiles of temperature, dewpoint temperature, and velocity at Quillayute, Whidbey Island, Syndey, B.C., and from two dropwindsondes released from the P-3 aircraft. Sydney showed a relatively well-mixed boundary layer to ~900 mb (≈1 km) with a capping

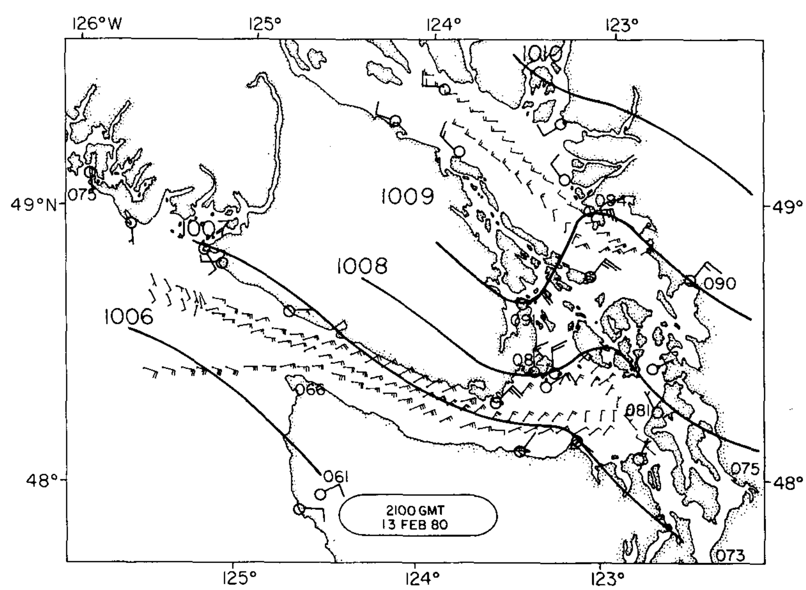

FIG. 7. Local sea level pressure field computed from shore and aircraft data. Non-simultaneous aircraft measurements were interpolated to 2100 GMT 13 February 1980 by correcting for the time rate of change of the shore pressure stations which were decreasing at an average rate of 0.4 mb h^{-1}. Flight-level wind measurements are shown as small wind arrows. Bold arrows with circles indicate surface station or buoy reports. Wind convention is in kt.

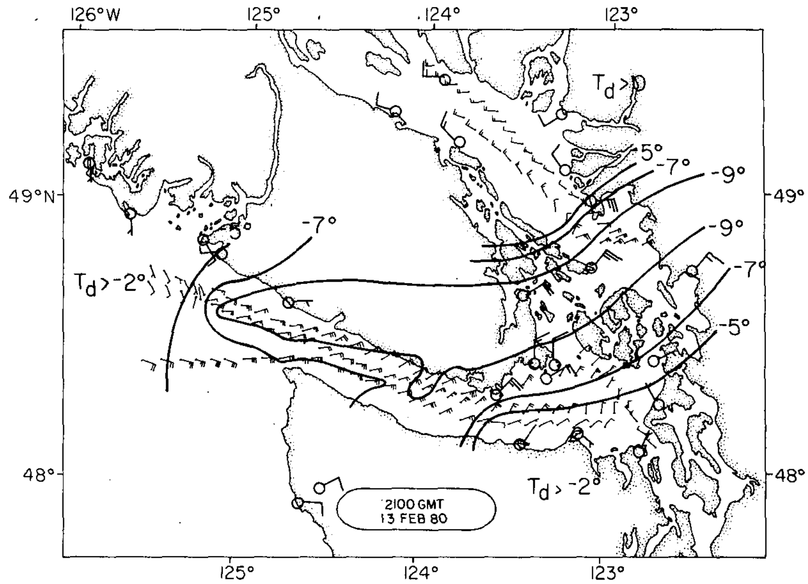

FIG. 8. Wind and dew-point fields from surface and aircraft reports 2100–2400 GMT 13 February 1980.

inversion above. At sonde 2 in the inner Strait (48°15′N, 123°20′W) the inversion had risen to 850 mb (1.5 km), and at sonde 1 in the outer Strait (48°29′N, 124°43′W) the inversion had grown to 800 mb (2 km). The boundary layer below the inversion at sondes 1 and 2 was relatively well mixed. The soundings taken at Whidbey Island at 1800, 2100 and 0000 GMT showed the progressive drying out of the lowest 1 km as the effects of the dry air from the Fraser River Valley became dominant. However, even at 0000 GMT the air had not become well mixed and was stable to above 700 mb. Above 800 mb the profiles at sonde 1, 2, Quillayute, and Whidbey Island were out of the topographic influence and showed quite similar behavior. The vertical profile of wind measured at Sydney in the

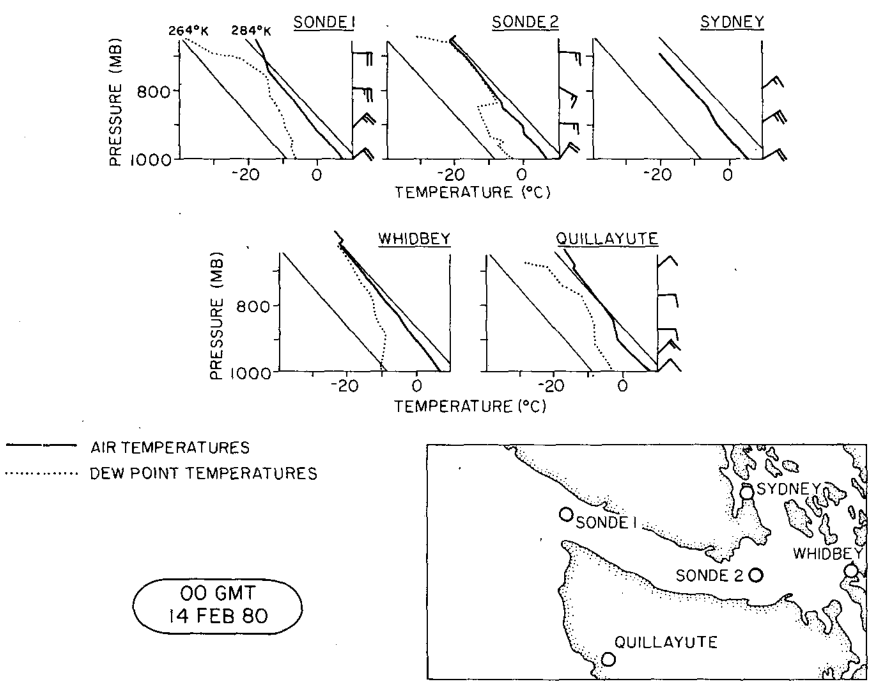

FIG. 9. Atmospheric soundings 0000 GMT 14 February 1980.

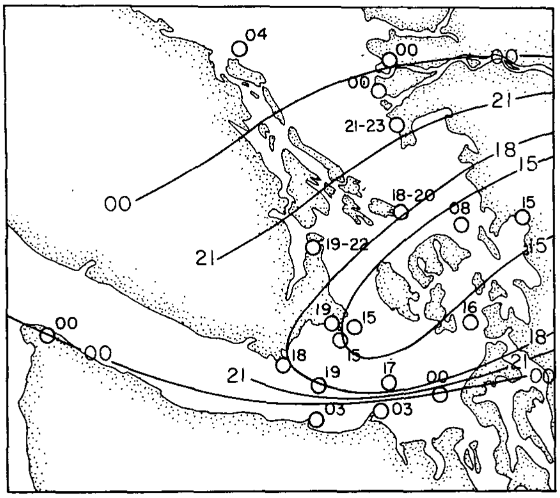

FIG. 10. Time of arrival at selected stations of the Fraser River air mass based upon dewpoint temperature and wind velocity. Arrival times begin at 0800 GMT 13 February 1980 and progress through 0000 GMT 14 February and eventually 0300 and 0400 GMT in southeast Juan de Fuca and northern Georgia Strait.

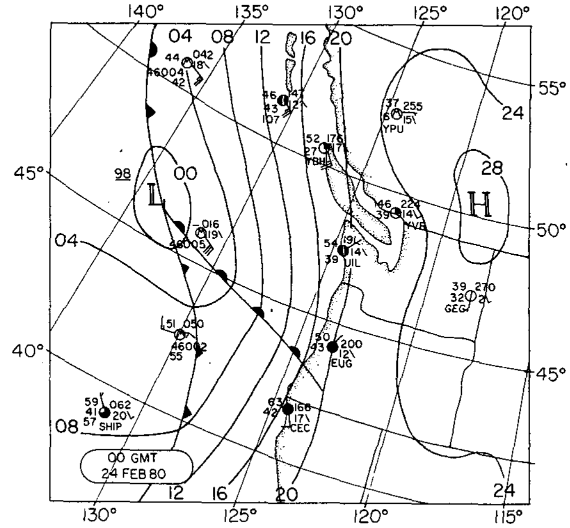

FIG. 11. Sea level pressure analysis 0000 GMT 24 February 1980.

Fraser air mass was relatively uniform in direction from the northeast throughout the lower 2 km with a maximum in speed at 700 m.

The time evolution of the jet from the Fraser River Valley can be followed by considering both dewpoint temperature and wind measurements from the marine stations and the meteorological buoys. Fig. 10 shows the stations and the times when the dry, high-speed airflow from the Fraser was first detected. The first stations to measure the outflow were in the vicinity of Bellingham. The air mass then extended across the eastern end of the Strait of Juan de Fuca and eventually into the Pacific Ocean and central Strait of Georgia.

b. Discussion

Comparison of the wind and pressure fields shows that the winds in Georgia Strait had a strong cross-isobaric component in the Fraser River outflow region. Winds in the eastern and central part of the Strait of Juan de Fuca also were strongly cross isobaric except along the south shore near Port Angeles where the winds were modified by the sharp rise of the Olympic Mountains.

The situation on 13 February has many characteristics of the behavior of a two-dimensional jet. The dry continental air flowing out of the Fraser River Valley displaced the more moist marine air as it flowed across Georgia Strait and was ultimately channeled out of the Strait of Juan de Fuca. These winds formed a jetlike band similar to the Big Delta, Alaska, winds (Ehrlich, 1953; Mitchell, 1956) with very strong horizontal velocity shear near its boundaries. Using the dew-point temperature to mark the boundary, the velocity of the air in the jet remained essentially constant while spreading laterally and growing in depth as shown by the downstream increase in inversion height in Fig. 9. The total momentum contained in the jet increased with distance because of the presence of a pressure gradient along the flow direction. It is a problem, however, to explain the maintenance of sharp boundaries between the dry air and marine air over such large length scales.

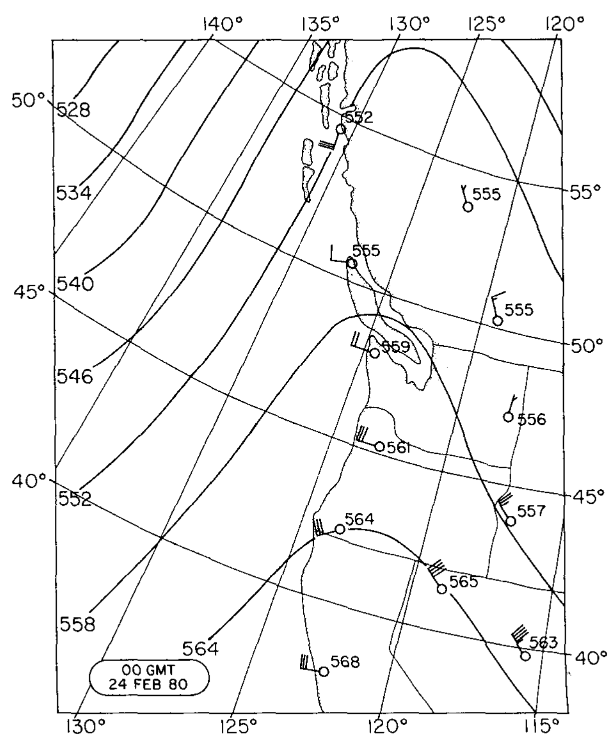

FIG. 12. 500 mb height analysis 0000 GMT 24 February 1980.

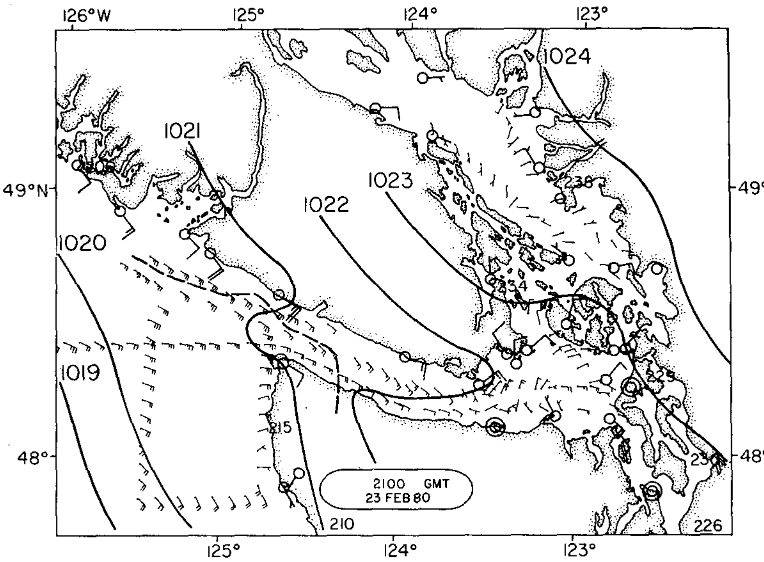

FIG. 13. Local wind field on 23 February and sea level pressure analysis for 2100 GMT 23 February 1980. The synoptic pressure field was decreasing uniformly over the region at 0.4 mb h^{-1}. Surface wind observations are in bold print. The heavy dashed line at the entrance to the Strait of Juan de Fuca represents the transition from subsidence on the north and east side to positive vertical motion seaward of the line.

Abramovich (1963) considered the behavior of a two-dimensional jet with a longitudinal pressure gradient superimposed on the system, which is qualitatively similar to the case of the air flowing from the Fraser River Valley. The presence of a pressure gradient reduces the rate of spread of the jet and helps maintain the integrity of its properties. In addition, the moist air north of the jet had a component of motion toward the jet leading to a convergence along its edge which also could produce a reduction in the spreading and a sharpening of the boundary.

The southern edge of the air mass turned toward the west 5–10 km north of the southern shore of

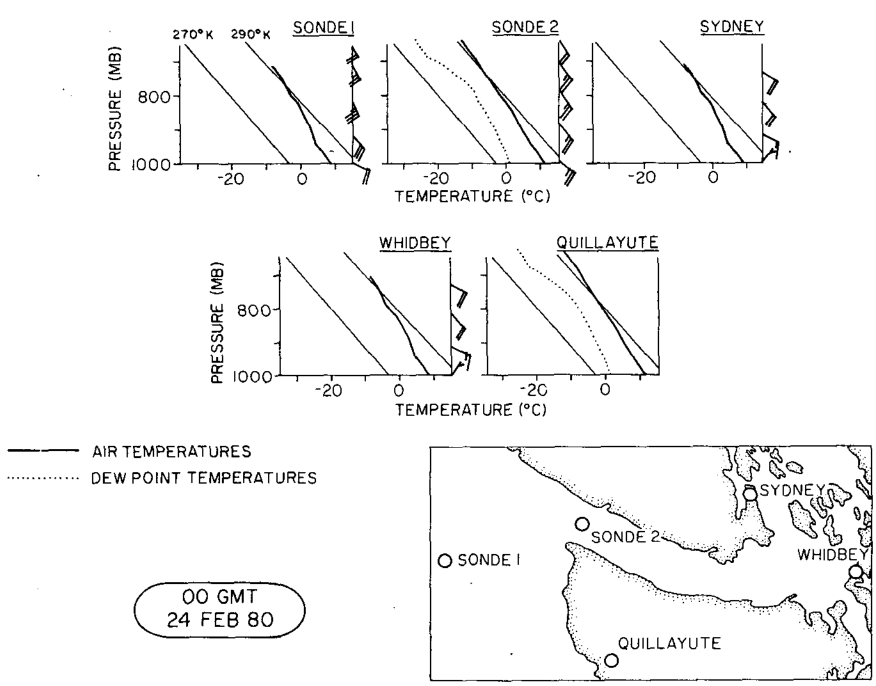

FIG. 14. Atmospheric soundings for 0000 GMT 24 February 1980.

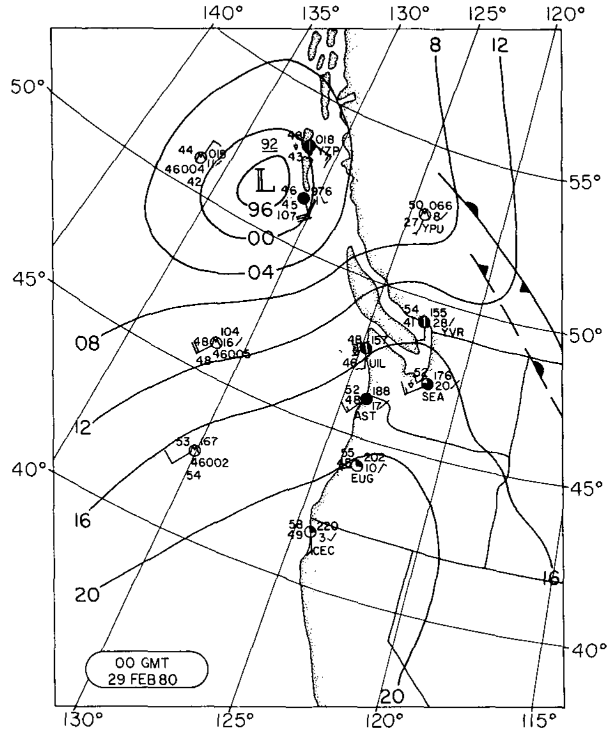

FIG. 15. Sea level pressure analysis 0000 GMT 29 February 1980.

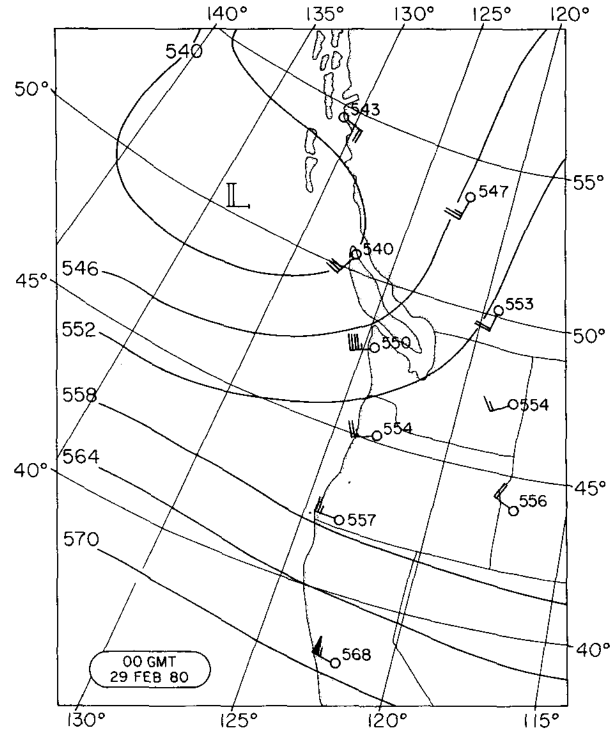

FIG. 16. 500 mb height analysis 0000 GMT 29 February 1980.

the Strait of Juan de Fuca (Fig. 8). At the edge of the jet there was a northerly component to the winds which must have led to surface convergence and significant vertical velocities. This may have induced a secondary circulation cell adjacent to the mountains but there is no direct supporting data.

The eddylike feature beyond the entrance to the Strait of Juan de Fuca had light southeast winds to the west of its boundary and strong (10–12 m s^{-1}) winds from the east to the east of the boundary and may have been a result of a hydraulic jump. Vertical wind speeds as recorded by the aircraft were downward at 1 m s^{-1} on the east side and upward at 0.4 m s^{-1} on the west side of the boundary. Freeman (1948) indicated that the most rapid vertical accelerations and velocities in the fluid below an inversion occur at jumps. The phase speed of the jump calculated from sonde 1 (Arakawa, 1969) is 16 m s^{-1} using an inversion height of 1800 m and the observed potential temperature profile. The wind speed recorded by sonde 1 was 12 m s^{-1} and constant throughout the lower layer; aircraft winds measured between the position of sonde 1 and the boundary of the light winds were all between 10 and 12 m s^{-1}.

4. Case studies: 23 February and 28 February 1980

a. Description

At 0000 GMT 24 February 1980, a 998 mb low-pressure center was located 725 km off the Washington coast (Fig. 11). The isobars were oriented parallel to the coast with the strongest gradient at the coastline. At the 500 mb level (Fig. 12) a well-developed ridge was located over the west coast with winds from the west over the Puget Sound area.

Fig. 13 shows the mesoscale sea-level pressure field present over the region at 2100 GMT 23 February 1980. As before, the data used for the figure include sea level pressures as measured by both land-based stations and the P-3 aircraft adjusted to the common time of 2100 GMT. Fig. 13 shows that the winds were generally consistent with a down-gradient flow relative to the mesoscale pressure field. Winds in the Strait of Georgia were light and variable where the pressure gradient was flat. In the eastern part of the Strait of Juan de Fuca the flow was generally disorganized but tended to have an easterly component. Flow south from the San Juan Islands was decreased and turned by increasing sea level pressure approaching the south shore of the Strait near Port Angeles. Westward along the Strait of Juan de Fuca the component of the pressure gradient along the axis of the channel remained nearly uniform while the winds increased to 14 m s^{-1} at the entrance of the Strait.

The effects of the Olympic Mountains on the flow can be seen in the north-south flight tracks offshore. On the nearshore track the easterly flow from the Strait dominated north of 47°55′N. On the outermost north-south track a wind shift is evident

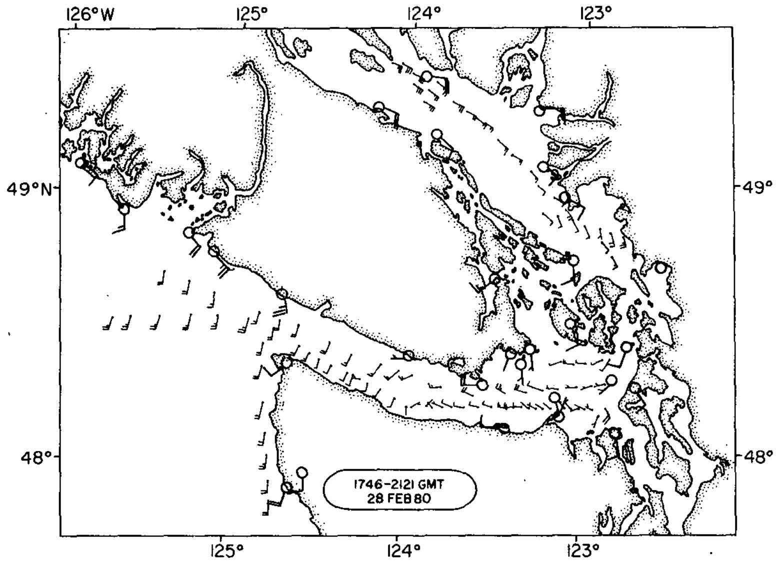

FIG. 17. Local wind field for 28 February 1980.

near 48°05′N, where the winds from the Strait merge with the coastal winds.

Vertical wind speed measurements indicate that subsidence was occurring over the inner part of the Straits of Juan de Fuca and Georgia. There was a transition to positive vertical motion (dashed line, Fig. 13) seaward of 124°20′W, and, except for a band of negative motion along the shore of Vancouver Island, positive vertical motion continued to more than 100 km offshore. Temperature and moisture profiles (Fig. 14) show stable stratification from the surface to above 700 mb. The vertical profiles of wind at sondes 1 and 2 were uniform in direction (SE-SSE) and strong (~15 m s^{-1}) from the surface to 700 mb (3 km) where they decrease to 8–10 m s^{-1} and veer to the southwest. Winds at Sydney were light (2 m s^{-1}) from the northeast in the lowest 50 mb (400 m) possibly showing the

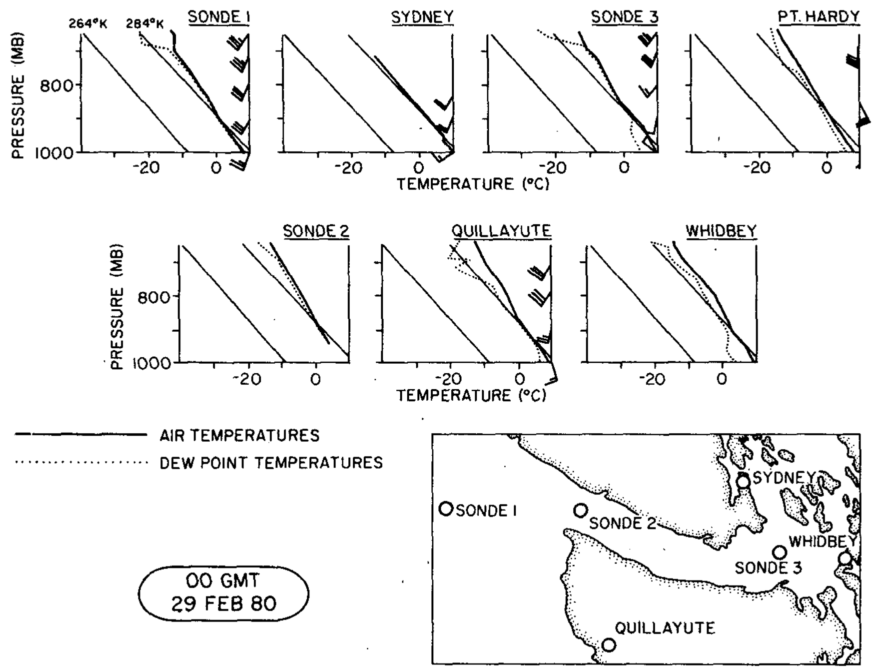

FIG. 18. Atmospheric soundings for 0000 GMT 29 February 1980. Port Hardy (50°45′N, 127°30′W) is located at the north end of Vancouver Island off the map.

shielding effect of the surrounding topography. Above this level the winds were from the east at 5 m s^{-1} and increase in speed to 10–12 m s^{-1} while veering to the southeast with increasing height.

A situation similar to the 23 February case occurred in the Strait of Georgia on 28 February when a 992 mb surface low was situated at 52°N, 132°W, west of the Queen Charlotte Islands, with a pressure gradient oriented NW-SE along the Strait of Georgia (Fig. 15). At 500 mb (Fig. 16) a low was situated over the surface low with a trough oriented NW-SE lying just off the British Columbia coast. Winds at this level over the Puget Sound area were west-southwest. Wind measurements (Fig. 17) show light winds from the southeast in the southern part of the Strait of Georgia that increased in magnitude northward becoming 16 m s^{-1}.

The soundings taken at 0000 GMT 29 February 1980 at Sydney, B.C., Whidbey Island, Quillayute, Port Hardy, and three dropwindsondes from the P-3 (Fig. 18) show, as in the 23 February case, a stable stratification from the surface to above 700 mb with the exceptions of Sydney and sonde 3. The vertical profile of winds offshore at sonde 1 were uniform in direction (SW) and speed (15–17 m s^{-1}) from the surface to 500 mb. Winds for the soundings over land were light near the surface (3–7 m s^{-1}) and merged with the S-SW flow of 20 m s^{-1} at 500 mb.

b. Discussion

The atmospheric structure existing on 23 and 28 February contrasts with that of 13 February. In the 13 February case the boundary layer was mixed and capped by an inversion, while on 23 and 28 February the boundary layer was stably stratified. On 13 February the greatest pressure gradient was over the inner part of the channel, whereas in the other cases it was situated over the outer portions of the channels. The wind fields reflected these differences.

TABLE 1. Scale analysis for Juan de Fuca winds.

Term	$\frac{\partial u}{\partial t}$	$u\frac{\partial u}{\partial x}$	fv	$\frac{1}{\rho}\frac{\partial p}{\partial x}$	$K\frac{\partial^2 u}{\partial z^2}$
Scale	$\frac{u}{t}$	$\frac{u^2}{L}$	fu	$\frac{\Delta p}{\rho L}$	$\frac{Ku}{H^2}$
Magnitude (m s^{-2})	10^{-3}	10^{-2}	10^{-3}	10^{-2}	10^{-4}

The gross behavior of the wind fields for the 23 and 28 February cases can be adequately described by considering the acceleration of a surface layer oriented along a channel under the influence of a pressure gradient. The equation of motion appropriate for a scale analysis is given by

$$\frac{du}{dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + K\frac{\partial^2 u}{\partial z^2}. \tag{1}$$

Variables in (1) have their standard meteorological meaning: u is horizontal velocity, ρ is density, f is the Coriolis parameter, p is pressure and K is an eddy viscosity. For the mesoscale motions of interest, typical values of scaling parameters are: $u \sim 10^1$ m s^{-1}, $L \sim 10^4$ m, $t \sim 10^4$ s, $H \sim 10^3$ m, $\Delta p \sim 10^2$ Pa, $f \sim 10^{-4}$ s^{-1}, $\rho \sim 1$ kg m^{-3} and $K \sim 10^1$ m^2 s^{-1}. Substitution into (1) is summarized

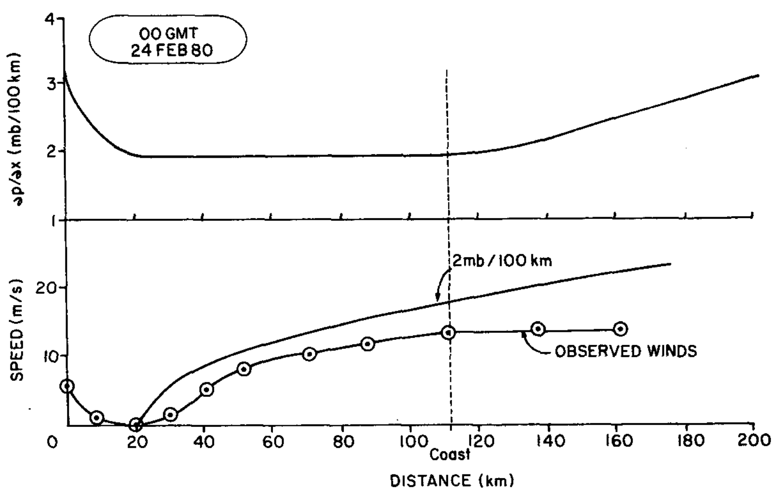

FIG. 19. Observed pressure gradient for the central axis of the Strait of Juan de Fuca beginning at the east end. Also shown are the observed wind speeds and the computed wind speeds from (2) for a constant pressure gradient of 2 mb (100 km^{-1}).

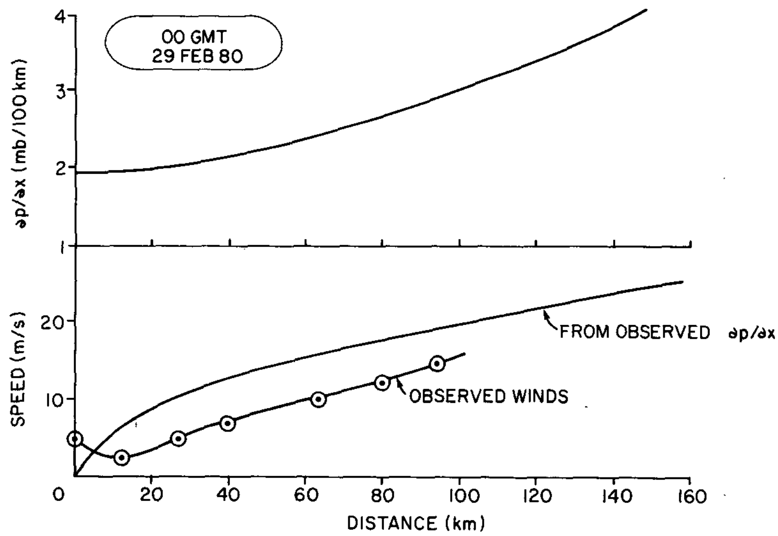

FIG. 20. Observed pressure gradient and winds for the Strait of Georgia. Also shown are computed winds from (2) using the observed pressure gradient.

in Table 1. For mesoscale features on the order of the width of the Strait of Juan de Fuca the inertia term provides the primary balance to the pressure forces

$$\frac{du}{dt} = \frac{d}{dx}\left(\frac{u^2}{2}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x} . \qquad (2)$$

In integrated form, this gives the Bernoulli equation

$$\frac{u^2}{2} = \frac{u_0{}^2}{2} - \frac{\Delta p}{\rho} , \qquad (3)$$

where u_0 is the initial velocity and Δp is the pressure difference. The wind field can be considered to be in approximately ageostrophic equilibrium with the surface-pressure field imposed both by the synoptic situation and generated locally by orography.

Integration of (2) for a constant pressure gradient of 2 mb $(100\ \text{km})^{-1}$ with $u = 0$ at $x = 20$ km is shown in Fig. 19 along with the observed winds and east-west pressure gradient at 0000 GMT 24 February in the Strait of Juan de Fuca. Observed winds have a similar form to that computed for a constant pressure gradient up to just seaward of the coastline. At that point, the observed pressure continues to increase but the wind speed remains constant, which can be interpreted as a transition toward geostrophic balance. Fig. 20 shows the observed pressure gradient, wind speed, and the solution to (2) for the observed pressure gradient for 0000 GMT 29 February in the Strait of Georgia. Simple pressure-inertia balance is quite capable of creating the observed magnitudes and distribution of velocity in both channels.

5. Conclusion

Two quite different synoptic situations have been studied which led to gap-wind conditions as originally defined by Reed (1931). In one case, a high-pressure system present over interior British Columbia caused a high-speed flow of air from the Fraser River Valley to be funneled out the Strait of Juan de Fuca. In the other, a low-pressure system off the coast of Washington led to an increase in wind speed with distance westward along the Strait of Juan de Fuca. For comparison, a situation similar to the latter case was shown for the Strait of Georgia. These cases can be included within the definition of gap winds. Although the features of the flow fields were complex, many of the characteristics of the wind fields can be adequately accounted for by consideration of the combined effect of topography and the synoptic pressure field. Local winds were in approximate ageostrophic equilibrium between the inertia term and the imposed sea-level pressure gradient.

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