

The Taku Wind of Southeast Alaska: Its Identification and Prediction

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ABSTRACT

The purpose of this study is to investigate the occurrence of severe winds in southeast Alaska (locally known as Taku winds) based on recent theoretical advances in the understanding of severe downslope windstorms. We found that the Taku wind is a manifestation of an amplified mountain wave. A complicating factor in understanding the Taku is the coincident occurrence of gap flow. Analysis of a number of historical events, in addition to a unique set of wind records from a nearby ridge, shows the separate identity of these concurrent phenomena. A set of criteria is identified that must be fulfilled in order for the downslope winds to occur, which is much more restrictive than the conditions necessary for gap flow. The three necessary criteria are 1) an inversion at or just above ridgetop, somewhere between 1500 and 2000 m MSL, 2) strong cross-barrier flow near ridgetop, typically $15\text{--}20\text{ m s}^{-1}$ in geostrophic wind speed, and 3) cross-barrier flow decreasing with height to a critical level somewhere between 3000 and 5500 m MSL. The similarities to other local downslope windstorms are also discussed.

1. Introduction

Juneau, Alaska, perched at the base of the Coast Mountains on the Gulf of Alaska, has a severe winter climate reflecting the continual battle between moist maritime air and cold continental air (Colman 1986). A fascinating characteristic of the local winter climate is the occurrence of severe northeast winds. The communities of Juneau and Douglas can experience northeast winds in excess of 50 m s^{-1} during outbreaks of bitterly cold Canadian air. Locally known as Taku winds, they are frequently responsible for property damage and occasionally loss of life. The winds also create hazardous conditions for shipping, not so much from high seas (due to a short over-water fetch), but from superstructure icing. In addition, they are very turbulent and present a hazard to aircraft.

We were driven by the apparent capricious nature of the Taku wind to examine current and historical data, hoping to improve the understanding and forecasting of these dramatic local winds. Recent advances in downslope-windstorm theory offered further encouragement in this pursuit.

The terrain of southeast Alaska spectacularly reflects the ongoing battle between orogenic processes and ero-

sion by both water and ice. The rugged, mountainous coast is indented by hundreds of channels and fjords, many of which align with geological faults. These linear features are clearly visible in Fig. 1. Gastineau Channel, one such feature, runs between Juneau and Taku Inlet, approximately 20 km to the southeast (Fig. 2); steep terrain borders the channel on both sides. Salisbury Ridge, on the northeast side, is nearly continuous for 14 km and rises to 1200 m. It is down the steep slopes of Salisbury Ridge that the Taku wind blows.

The Taku River, one of several antecedent rivers that cut through the Coast Mountains, empties into Taku Inlet. The elevation gain following the Taku River valley into British Columbia, through the Coast Mountains, is less than 150 m. As a result, Salisbury Ridge is the most prominent barrier to northeast flow in the vicinity of the Taku River valley. This is well illustrated in Fig. 3, which shows composites of four elevation cross sections. The cross sections used are perpendicular to, and equally spaced along, Salisbury Ridge and extend 90 km northeast through the Coast Mountains. Note the absence of any prominent barrier upstream from Salisbury Ridge.

Another dramatic local feature is the Juneau ice field, which straddles the divide of the Coast Mountains just to the north of Juneau, and is the fifth largest ice field in North America, encompassing nearly 4000 km^2 of ice. The Taku glacier flows from the Juneau ice field into the Taku River valley northeast of Juneau and is the source of the name for the winds that this paper addresses.

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In southeast Alaska, it has been known for some time that local boundary-layer winds are directed along the various channels in a gap-wind fashion (refer to section 2 for a discussion on gap winds). The Juneau National Weather Service Forecast Office (NWSFO) has developed reasonably successful empirical rules that relate surface wind speed to the along-channel pressure gradient for all of the major channels and fjords.

In sharp contrast to the prevalent gap winds are the Taku winds that blow down the slopes of Salisbury Ridge and across Gastineau Channel. Downtown Juneau is on the northern fringe of the highest winds and Douglas is situated on the southwest side of the channel, exposed to their full force. These extreme winds, which frequently exceed 40 m s^{-1} in the populated areas, were first discussed by Kilday (1960). He concluded that these winds were of a katabatic nature, arising from very cold air over the ice field draining towards the south.

The NWSFO has tried to forecast the Taku winds in a manner similar to that used to forecast gap winds. Not experiencing the same success initially, additional criteria were included. When we started this work, the criteria being used to forecast the occurrence of Taku

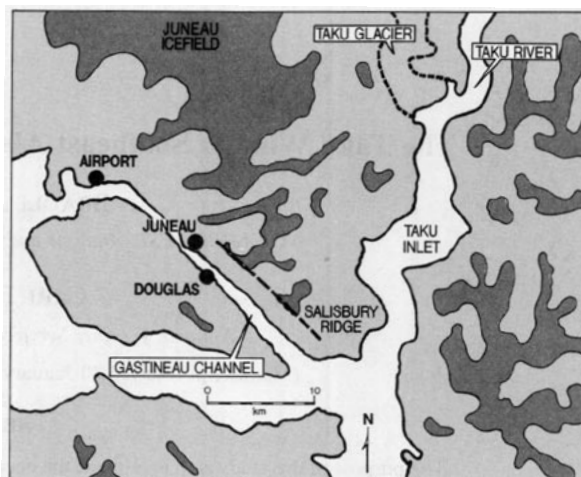


FIG. 2. Expanded view surrounding Juneau and the windstorm area. Dark shading identifies terrain elevations above 1000 m. Geographical features referenced in the text are also identified.

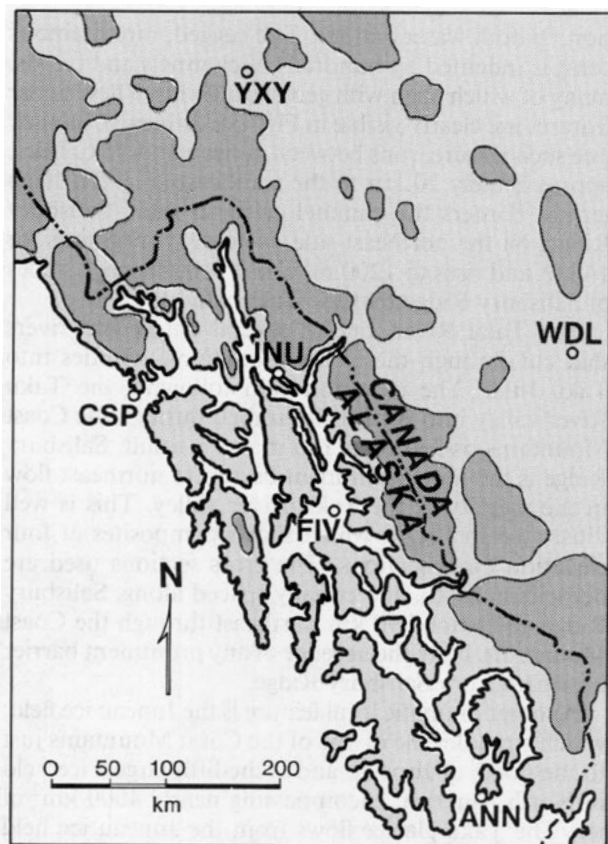


FIG. 1. Topography and station locations for southeast Alaska and parts of northwest Canada. Light shading identifies land areas; dark shading identifies terrain elevations above 1500 m.

winds were 1) the sea level pressure gradients between Juneau and two Canadian stations [namely, Whitehorse, Yukon Territory (YXY), and Dease Lake, British Columbia (WDL)] should exceed 12 mb (see Fig. 1 for locations), and 2) the depth of the Arctic air in northwest Canada should be greater than the height of the Coast Mountains (approximately 2000 m MSL). In identifying these criteria, the working conceptual model was that the cold interior air needed to reach a depth great enough that it could be forced directly over the Coast Mountains (i.e., not be constrained to flow through the various gaps) and then spill over the mountains and down the slopes of Salisbury Ridge. In addition to these criteria, there was some feeling that a northeast wind at 700 mb was favorable and that the storms were often triggered by an approaching low or front.

Our opinion, and the prevalent opinion among other Juneau forecasters, is that these criteria tend to over-forecast the occurrence of severe winds. This poor success suggests that these criteria are necessary, but not sufficient; it even brings the conceptual model into question. Yet, if Taku winds are fundamentally different from gap winds, then why were these criteria at least somewhat successful? Are these the best criteria to use, or are there better ones? Questions such as these provided the impetus for this study.

After reviewing the literature on downslope windstorms, we felt that the environment associated with Taku winds needed to be better defined, particularly concerning those parameters known to be important for wave development. Thus, we decided to composite a set of historical events to identify common characteristics. Individual events were also studied for additional insight and validation of the composite.

In the following section, a theoretical review of gap

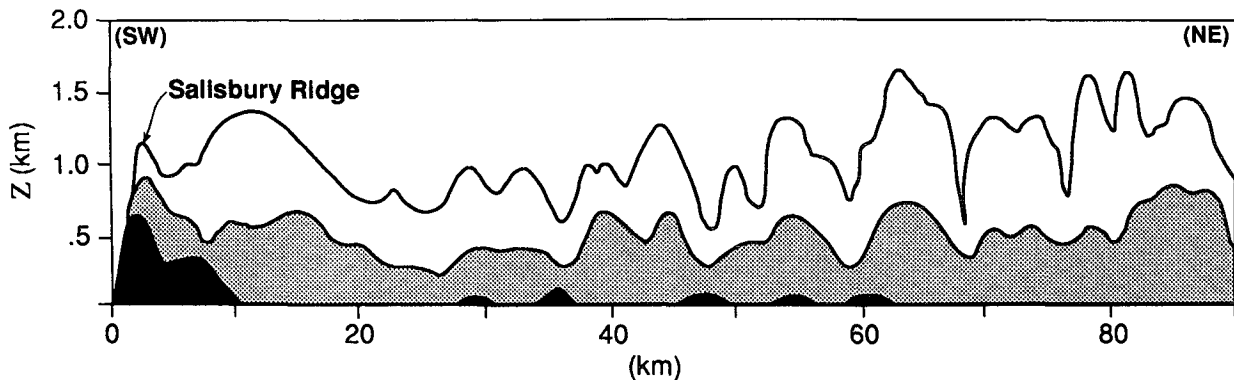


FIG. 3. Elevation cross sections extending northeast from Salisbury Ridge. Shown are the silhouette or maximum, the average (light shading), and the lowest (dark shading) elevations from four equally spaced sections along the ridge.

and downslope winds is given as a foundation for the discussion to follow. Section 3 details the composite techniques used in this study and a description of the composite results. Two supporting case studies are presented in section 4. Section 5 includes discussion related to the operational aspects of downslope windstorms and, finally, section 6 summarizes the work.

2. Theoretical review

In areas of complex terrain there are conspicuous local winds that frequently overshadow the effect of the large-scale pressure pattern; two such winds are gap winds and downslope winds.

Gap winds were first described by Reed (1931) in a study of strong easterly gales occurring in the Strait of Juan de Fuca, located between Washington State and British Columbia. Gap winds are driven by the imposed gap-parallel pressure gradient. The wind is prevented from attaining geostrophic balance by the higher terrain bordering the gap as long as the gap is less than a Rossby radius in width. Overland and Walter (1981) showed that these winds reach an approximate ageostrophic equilibrium between the inertial forces and the gap-parallel pressure gradient. They specified this balance of forces in the along-gap direction as:

$$\frac{d}{dx} \left(\frac{u^2}{2} \right) = \frac{-1}{\rho} \frac{\partial p}{\partial x}, \quad (1)$$

where u is the velocity, ρ is the density, and $\partial p / \partial x$ is the gap-parallel pressure gradient. This equation can be integrated to estimate u at any point in the gap. The magnitude of u is proportional to the gap-parallel pressure gradient and the length of the gap or channel. Qualitatively, wind speeds increase along the gap and are maximized near the gap exit. Equation (1) does not, however, account for the mitigating influences of friction, and likely overestimates speeds. Bell and Bosart (1988) show that friction can strongly offset sustained accelerations during cold-air damming events along the Appalachians. Gap winds have been docu-

mented to occur in many areas—for example, the Columbia River gorge bordering Washington State (Cameron and Carpenter 1936) and the Shelikof Straits in Alaska (Macklin et al. 1984).

The downslope windstorm is a much more complicated phenomenon than the gap wind, and its existence and evolution are highly dependent upon both terrain shape and the vertical structure of the atmosphere; the windstorm occurs when there is strong low-level amplification of a terrain-induced vertically propagating gravity wave. Lilly and Zipser (1972) present observations taken by two research aircraft during a severe windstorm in Colorado that clearly show the associated structure (Fig. 4). In their case, the windstorm was the surface manifestation of a large-amplitude mountain wave that extended upward to 10 km. Note the compression of the isentropes near the surface, downstream (to the right) of the elevated terrain; it is in this area that the surface windstorm occurred.

The exact mechanisms through which wave amplification occurs are not fully understood. The equations for two-dimensional flow over simple terrain were linearized and solved first by Queney (1948). Long (1954) demonstrated that for the highly idealized flow of constant wind and stability, the governing equations are linear without assuming small perturbations; i.e., under these conditions the linearized equations are also valid for finite amplitude disturbances. Long's work served as one basis for future research on mountain waves. For example, Klemp and Lilly (1975) used the linear theory of mountain waves to describe a process whereby a properly tuned atmosphere could generate strong surface winds through constructive reinforcement (superposition) of reflected waves.

Unfortunately, Long's idealized flow is highly restrictive and does not have a broad application. For example, linear theory is not applicable in atmospheres characterized by decreasing wind with height to a level at which there is no cross-barrier flow (known as a critical level). In this case, nonlinear effects become important through wave-mean-flow interaction, and

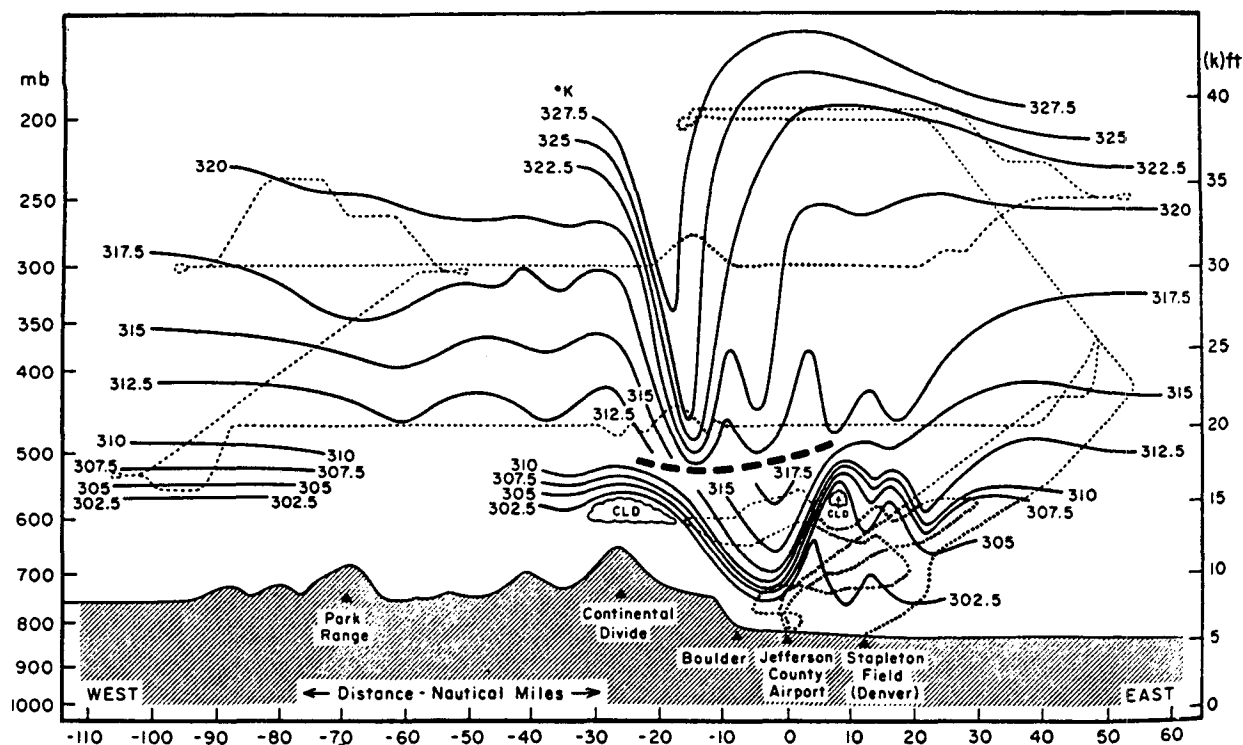


FIG. 4. Analysis of potential temperature (solid lines) from aircraft flight data and sondes taken on 11 January 1972. The dashed lines show aircraft tracks. The heavy dashed line separates data taken by the Queen Air at lower levels before 2100 UTC from those taken by the Sabreliner in the middle and upper troposphere after 0000 UTC (12 January). The aircraft flight tracks were made along an approximate 130–310 azimuth, but the distances shown are along the east–west projection of those tracks.

wave amplification can occur without relying upon constructive reinforcement of reflected, vertically propagating waves. However, analytical work has shown that even with a critical level present, widely contrasting regimes are also possible (Smith 1985). For example, the strong acceleration of low-level flow is sensitive to the height of a critical level. Additionally, Peltier and Clark (1979) showed that for an environment without an upstream critical level, the possibility exists for a growing wave to overturn and generate its own or “self-induced” critical level, ultimately resulting in strong wave amplification. Further investigation by Laprise and Peltier (1989) demonstrated that this amplification occurs due to trapping and overreflection of the waves between the ground and the self-induced critical level.

Wave development has also been shown to be very sensitive to the presence of inversions or strong gradients in static stability. This has been demonstrated recently by using hydraulic theory as an analog for downslope winds (e.g., Durran 1986, 1990; Smith and Sun 1987). In classical hydraulic theory, a neutrally stratified layer of dense fluid (overlain by a less dense fluid) will develop strong downstream flow if a transition occurs from subcritical flow to supercritical flow as the fluid traverses the mountain (Long 1954). For a given situation, the type of flow is determined by the

height of the mountain and the depth of the fluid. Numerical results (Durran 1986) and analytical results (Smith 1987) confirm this sensitivity to the height of an inversion, if one exists, for the atmosphere. This is dramatically illustrated in Fig. 5, which shows two numerical simulations of the windstorm shown in Fig. 4. The only difference in the upstream conditions is that in (b) they have been modified to remove the elevated inversion.

The above theoretical results pertaining to downslope windstorms have been derived from analytical and numerical solutions utilizing simple atmospheric structures and idealized terrain, with the extension into the operational arena still very limited. In addition to limitations arising from these simplifications, seldom are the upstream conditions known in sufficient detail; even the determination of an effective mountain height is a frustrating endeavor, due to upstream blocking and complex terrain.

To date, the most heavily studied downslope windstorms are those that occur in Boulder, Colorado. Brinkmann (1974) looked at 20 Boulder windstorms and found that favorable upstream conditions were 1) a stable layer slightly above mountain top, and 2) a less stable layer above that. No upstream critical level was observed in these cases. The current thought is that wave steepening and breaking (creating a self-in-

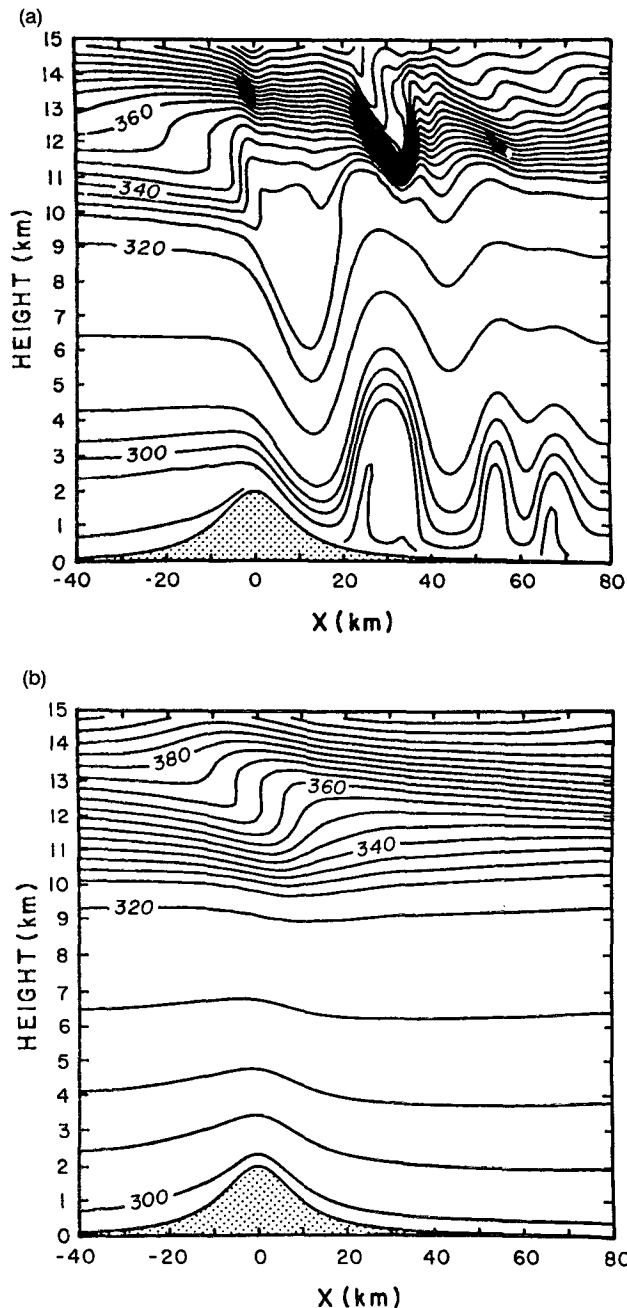


FIG. 5. (a) Isentropes from a simulation of the 11 January 1972 windstorm shown in Fig. 4. (b) As in (a), except that the upstream sounding has been modified to remove the elevated inversion (from Durran 1986.)

duced critical level) is essential for Boulder windstorms where the upstream terrain is relatively high (a relief of 2500 m) and mountain waves can reach the amplitude necessary for overturning. For more shallow terrain, such as Salisbury Ridge (1200 m), observational evidence suggests that an upstream critical level, in addition to other criteria, is necessary for wave amplification.

The most successful application of mountain-wave theory in operations has been accomplished by Brown (1986). He catalogued a number of Boulder windstorms and recorded the values of those parameters known to be important for wave amplification; he was then able to identify the ranges of each for which windstorms occurred. The final result was a decision tree that in a step-by-step fashion leads the forecaster to a probability statement on the potential for high winds. Unfortunately, this approach lacks generality and a separate decision tree must be developed for each location.

Gap winds and downslope winds are also known to occur simultaneously. Mass and Albright (1985) were confronted with this complication in the case study of a severe windstorm that was of a type known to occur on the western slopes of the Cascade Mountains in Washington State (Reed 1981). In their data there were clear indications that both types of flow were present, and they debated their relative contributions. In their final analysis, they felt the wave component was probably not of major importance, and relied upon the horizontal pressure gradient to explain the observed wind.

3. Synoptic composite

a. Data and analysis procedures

Nineteen significant Taku wind events were identified, assembled, and then composited. The selection process was subjective and based upon historical data obtained from various sources. The determination that each identified high-wind event was a Taku was made by reviewing available meteorological analyses and the specific location of the reported damaging winds. The various time periods reviewed were as follows.

First, the period between 1948 and 1954 was selected because it was a brief period when radiosonde data were available from the Juneau airport (Fig. 2), which is northwest of Salisbury Ridge and away from the local windstorm. It was felt that these data would provide details about the vertical structure of the atmosphere not otherwise available. The Juneau newspaper, *The Alaska Daily Empire*, was used to identify Taku wind events during this period through news articles discussing local wind damage, as well as approximate times that the damage occurred. From this information, eight major events were selected.

Second, the period between 1974 and 1976 was selected because the Army Corps of Engineers conducted a wind study on Salisbury Ridge to establish tolerances for power lines and towers. Many difficulties were encountered during the study because of the extreme environment to which the equipment was exposed, and wind traces were incomplete at times because of equipment failures. Despite the problems, five events were selected that had winds well above 50 m s^{-1} , two of which will be discussed in detail in the following section.

Finally, five additional events were selected from references in an earlier study on the Taku (Kilday 1960), and one recent event was selected because of wind gusts to 35 m s^{-1} recorded at the Federal Building in downtown Juneau. Recall that downtown Juneau is located on the fringe of the full force of the wind and therefore does not usually record the more severe values.

For each event, four levels (the surface, 850 mb, 700 mb, and 500 mb) were collected from a microfiche archive and composited. At the outset, a qualitative inspection of the synoptic analyses suggested that there were two basic variations, and some thought was given to breaking the collection into subsets. However, to keep the sample size as large as possible for statistical significance and to prevent predisposing the results, all cases were composited as one set. The synoptic time selected for the composite was the nearest to either the time of damage or a significant rise in measured winds. If the winds continued through more than one synoptic time period, the earliest time was chosen. Geopotential and temperature values were averaged on a grid every 10° of longitude by every 5° of latitude over the composite area (Fig. 6). Contours were subjectively analyzed from the gridded values.

b. Composite results

An examination of the composite results (Fig. 7) provides important insight into the synoptic structure associated with a Taku windstorm. The typical surface configuration has a tightly packed pressure field and strong thermal gradient (suggested by the thickness field) near the coast. This pattern highlights the barrier effect that the Coast Mountains present to the arctic air within the Canadian interior and the warmer maritime air over the northeast Pacific.

The strong contrast between the two air masses, and

their close proximity, significantly impacts the structure of the atmosphere above. The associated thermal gradient imposes a strong thermal wind that is opposite in direction to the low-level geostrophic flow. This successively weakens the gradient in the height fields above the surface, to such a degree that the 500-mb composite is significantly different than the lower levels and shows a much weaker, split trough over southeast Alaska.

In terms of the geostrophic wind field along the coast, the strong offshore flow at the surface decreases dramatically in the vertical as the height-field gradients weaken. A 500-mb streamline analysis would show a col region located over central southeast Alaska between the interior trough and the low offshore.

A composite sounding for Juneau (Fig. 8) was estimated by interpolating the temperature on each pressure surface, and the sea level pressure, to Juneau's location. (Note: This is the correct sounding to investigate assuming the composite represents the background or unperturbed environment.) Surface temperatures were averaged from the individual observations for each case. Strong stability is evident between the surface and 700 mb, yet the lack of information between levels limits details about the character and height of an inversion.

Of the eight Taku events used for the composite that occurred while Juneau was a radiosonde site, only two had nearly complete soundings. One of these is shown in Fig. 9. This sounding agrees well with the implied structure from the composite sounding and shows greater detail. Specifically, the lower-level stability is concentrated in an inversion near 800 mb. Also note the strong northeast flow near this level, and the veering wind above with no cross-barrier flow indicated at 650 mb.

These composites contain, at least qualitatively, conditions that are considered important for the development of a mountain-wave-induced windstorm. As discussed earlier, these conditions are: 1) an extremely stable layer near and just above ridgetop, 2) moderate to strong low-level cross-barrier flow, and 3) cross-barrier flow that decreases with height to a critical level near or below 500 mb.

c. Case-to-case variations

As mentioned earlier, an examination of the individual cases revealed two synoptic variations that produce Taku winds. The two variations differ in the relative strengths of the upper-level ridge to the northwest of Juneau (anticyclonic events) and the cyclonic circulation to the southwest (cyclonic events). Of the 19 events studied, 5 were cyclonic and 14 were anticyclonic.

1) TYPE I: CYCLONIC

For these cases, the low offshore is the dominant feature, with cyclonic flow extending northward to Juneau. Ridgetop winds increase steadily as northeast

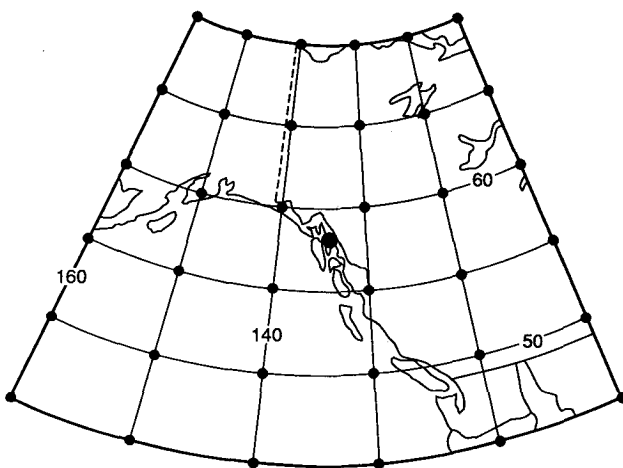


FIG. 6. Domain of the composite grid (6×6) with a resolution of 5° latitude by 10° longitude.

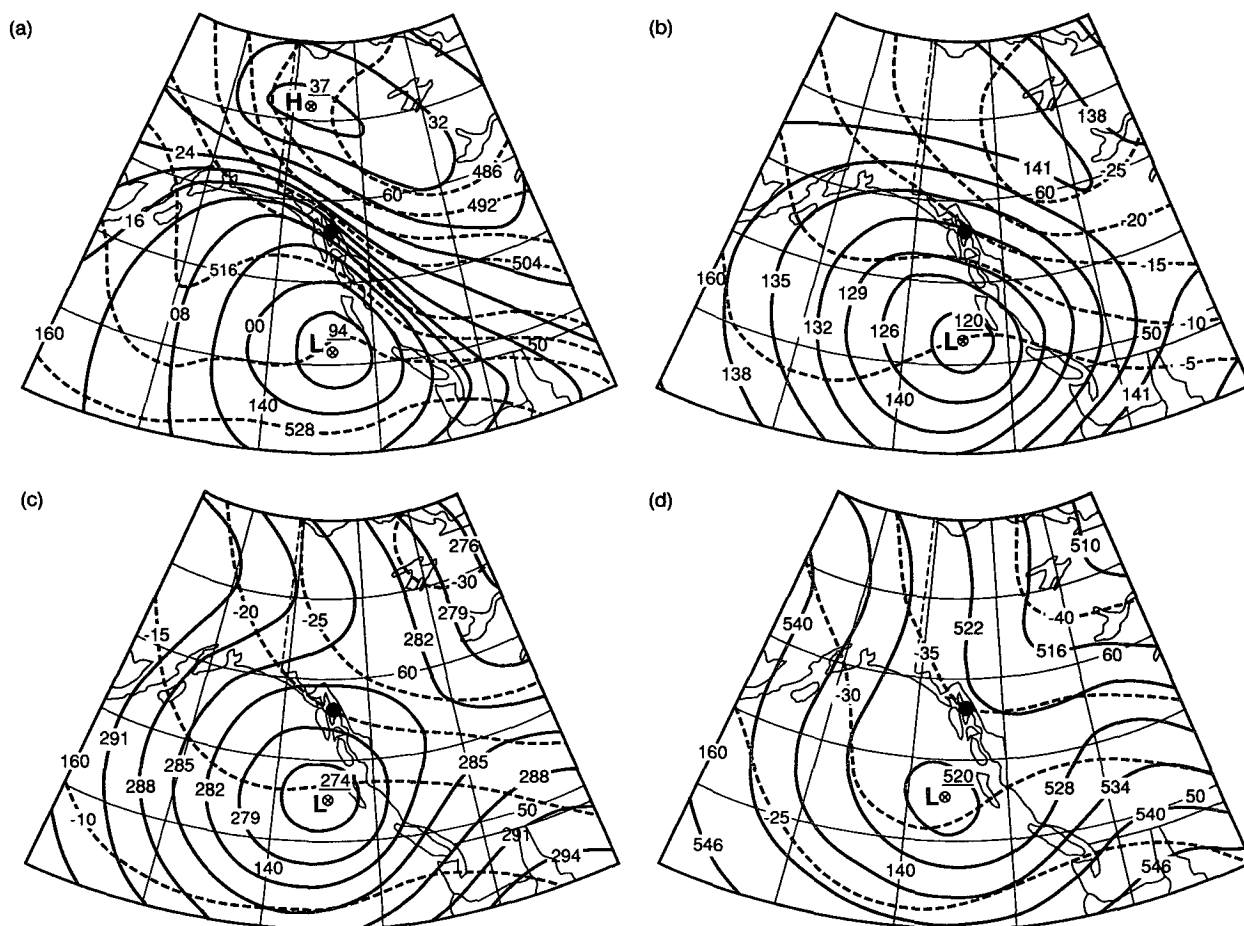


FIG. 7. (a) Composite sea level pressure (solid) and 500-mb/1000-mb thickness (dashed; dekameters) for 19 events. (b) Composite 850-mb heights (solid; dekameters) and temperatures (dashed; °C) for 12 events (850-mb heights were not available for the earlier cases). (c) Composite 700-mb heights (solid) and temperatures (dashed) for 19 events. (d) Same as (c) except for 500 mb.

flow is induced and/or increased by a front or trough approaching from the south. Apparently, ageostrophic effects produce additional turning to increase the cross-barrier flow as the trough approaches. A critical level exists above these low-level northeast winds, as the middle tropospheric winds generally have a westerly component. The Taku winds diminish abruptly after passage of the trough over the area, due to the elimination of the cross-barrier component by the associated wind shift. Taku winds may increase again, however, with the approach of another trough rotating around the nearly stationary offshore low.

2) TYPE II: ANTICYCLONIC

This is generally the stronger and longer lasting of the two types. The ridge aloft is more dominant than the low offshore, which may be nothing more than a trough. Taku winds increase suddenly, instigated by a rotation of the lower-level wind to the northeast. This wind shift is usually caused by the passage of a short-

wavelength trough that has moved over the large-scale upper-level ridge and approached Juneau from the north. The short-wavelength trough slopes upstream with height and, correspondingly, winds back with height above ridgetop level. This results in a decreasing cross-barrier component with height and, usually, reverse flow (southwest winds) in the middle troposphere. Thus, a critical level can be found somewhere in the middle levels. Taku winds of this type are slow to diminish due to the strength and persistence of the ridge aloft. The end of this type of event is marked by either a shifting of the ridgetop wind direction away from northeast, or, more commonly, a switch to northeast winds in the middle levels that eliminates or elevates the critical level.

4. Case studies

a. Cyclonic case: 15 March 1974 (Type I)

Several Type I (cyclonic) Taku wind events occurred during March 1974, as frontal troughs rotated around

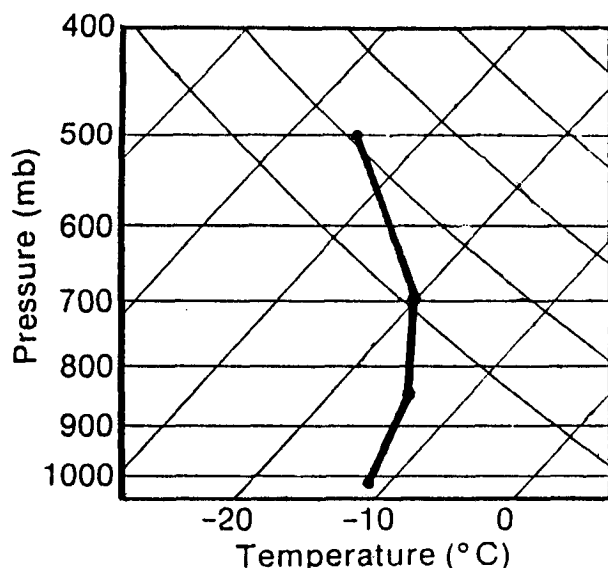


FIG. 8. Sounding for Juneau derived from the composite fields shown in Fig. 7. Temperatures in $^{\circ}\text{C}$.

a nearly stationary low southwest of Juneau and moved northward across the Alaskan panhandle. As each front or trough approached southeast Alaska, offshore-directed pressure gradients strengthened and gap flow increased. Figure 10 shows a graphical summary of surface wind speeds and sea level pressure gradients during the month. Station locations are identified on Fig. 1. Cape Spencer (CSP) and Five Fingers (FIV) were U.S. Coast Guard-manned lighthouses, within 100 km of Juneau, having good exposure to gap flow. It can be seen that the winds at CSP responded to the pressure gradient between JNU (Juneau) and CSP, as did the wind speed at FIV to the gradient between JNU and FIV.

Taku winds occurred on at least four occasions during the month, and sustained winds on the top of Salisbury Ridge were measured near 50 m s^{-1} . The Dease Lake (WDL) to Juneau pressure differences (not shown) were found to have little correlation to these winds, which were measured on a tower exposed to the full force of Taku windstorms. The Federal Building site (JNU), on the other hand, is on the fringe of the main Taku exposure, and is also exposed to gap flow from a nearby mountain pass. These winds have a better response to the WDL-JNU pressure gradient but vary when occasionally experiencing Taku effects.

During the first half of March, the upper limit of 42 m s^{-1} (95 mph) on the Salisbury Ridge anemometer was solidly pegged at least twice. Even after adjustments to the anemometer extended the upper limit to 72 m s^{-1} (160 mph) for the last half of the month, gusts still pegged the top of the scale on two more occasions.

Between 0000 and 1200 UTC on 15 March, winds on Salisbury Ridge increased rapidly, with gusts greater

than 72 m s^{-1} occurring from 1200 UTC on the 15th through 0000 UTC on the 16th (Fig. 10). At the surface, this increase in winds coincided with the approach from the southwest of a 988-mb sea level pressure low and its associated occluded front (Fig. 11a, 1200 UTC 15 March). Combined with the persistence of the high-pressure ridge in Canada, falling pressures offshore produced an overall tightening of the pressure gradients north of the front, and an increase in gap flow. By 0000 UTC 16 March (Fig. 11b), the low had stalled and the weakening front was in the process of moving aloft over the panhandle. The peak in Salisbury Ridge winds occurred shortly before this time and speeds decreased rapidly over the next 12 h.

If not for the extreme intensity and abrupt beginning/ending of the sustained 40 m s^{-1} ridgetop winds, it would be tempting to conclude that all of the winds in southeast Alaska on this day were the direct manifestation of the tightened pressure gradients. Figure 10 shows that FIV and CSP winds, as well as the pressure gradients, peaked at the same time as the ridge winds but much less impressively. FIV and CSP winds were representative of gap flow in their respective channels. However, a closer inspection of the criteria that favor mountain-wave-induced surface windstorms suggests that the winds on Salisbury Ridge were of that type and not gap flow. Again, these criteria are: 1) an inversion at or just above ridgetop, 2) strong cross-barrier flow, and 3) the presence of a critical level. A discussion of these criteria with respect to this case will now be presented.

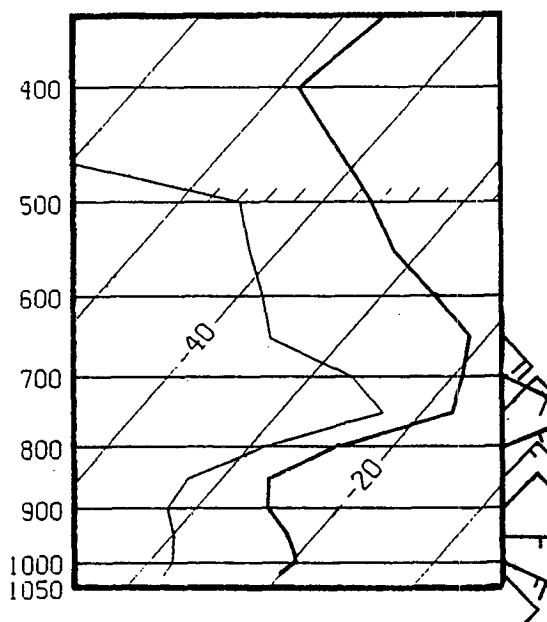


FIG. 9. Juneau rawinsonde for 1500 UTC 21 January 1952; observation taken during a Taku. Temperatures in $^{\circ}\text{C}$; winds in meters per second (full barb, 5 m s^{-1} ; half barb, 2.5 m s^{-1}).

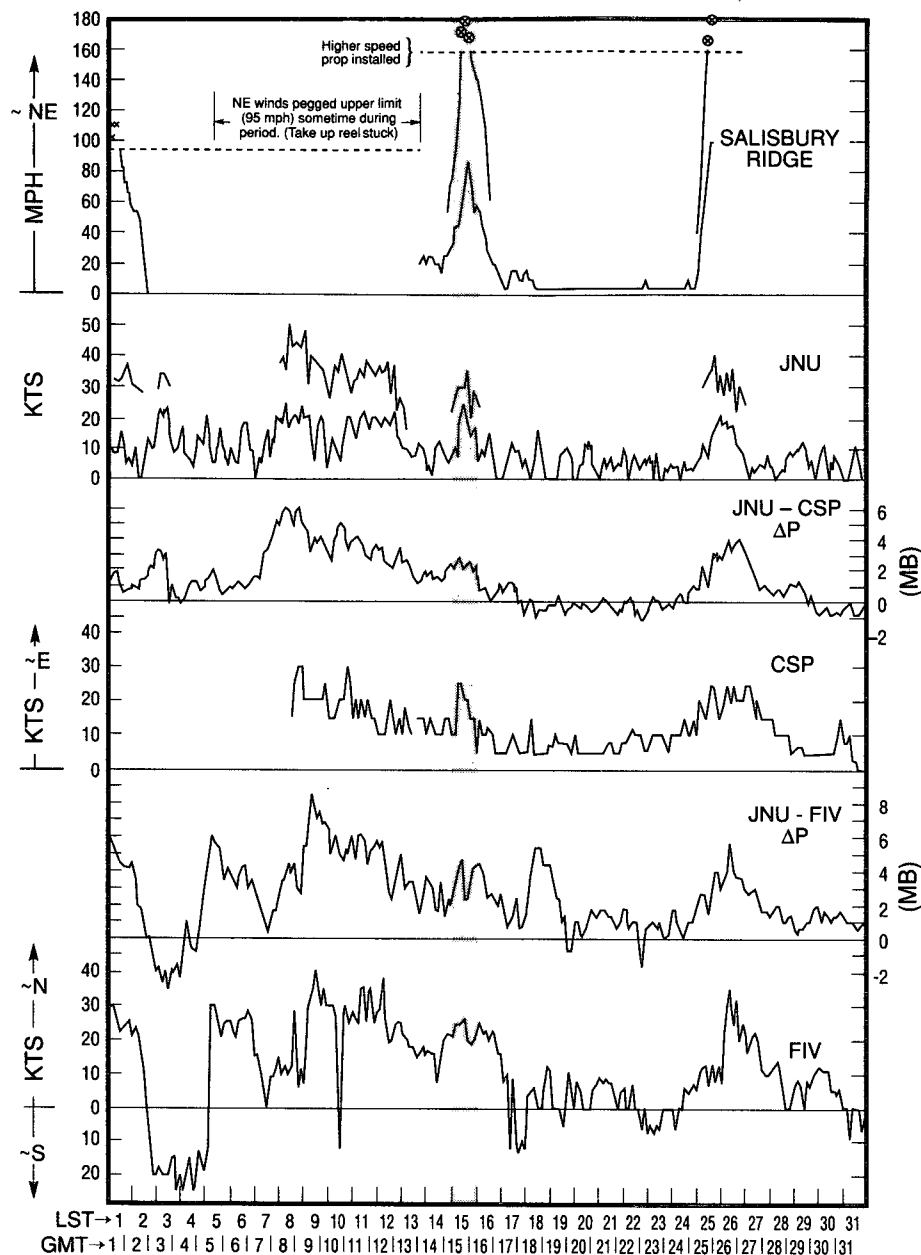


FIG. 10. Time series of various pressure gradients and wind speeds for March 1974. Salisbury Ridge is exposed to the full force of the Taku; JNU is the Federal Building in downtown Juneau; CSP and FIV are Coast Guard stations exposed to gap flows. See Figs. 1 and 2 for locations. Units are as labeled. Significant gusts are also shown for Salisbury Ridge and JNU. Vertical shading identifies the time period of the detailed case study. Estimates of sustained wind are based upon fastest-mile trace and are identified with 'x's; estimates of peak gusts are based upon sustained wind and are identified with circled 'x's.

Evidence of a ridgetop stable layer can be found in a sequence of four soundings (Fig. 12) taken at Whitehorse (YXY, Fig. 1). These soundings are representative of the environment on the continental side of the Coast Mountains. For most of March 1974, the lower atmosphere over northwest Canada was dominated by a deep arctic air mass under the subsiding

part of the upper-level ridge. The lowest 50 mb shows a dramatic diurnal modulation, forced by the strong mid-March sun. However, this modulation occurs well below ridgetop and apparently has little impact on the Taku wind, since no significant diurnal modulation of windstorms has been documented. More important to windstorm development are changes in stability near

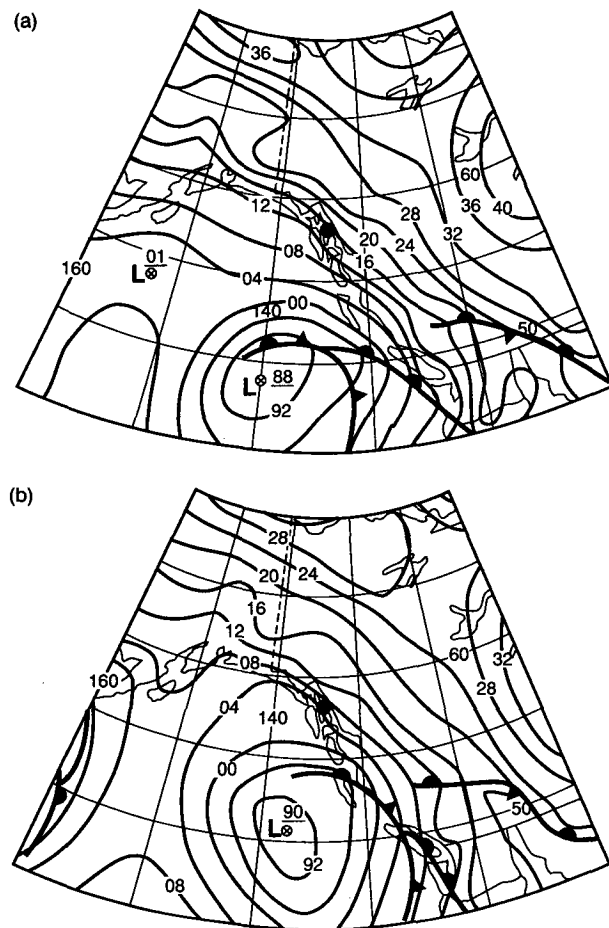


FIG. 11. Sea level pressure (solid) and frontal analysis for (a) 1200 UTC 15 March 1974 and (b) 0000 UTC 16 March 1974.

ridgetop at approximately 850 mb and above. Figure 12a shows the YXY sounding for 0000 UTC 15 March, prior to the onset of strong winds; a shallow inversion was present just below 800 mb. By 1200 UTC 15 March (Fig. 12b), middle-level warming dramatically increased the static stability below 600 mb. This warming continued over the next 12 h, and the top of the stable layer rose to 650 mb (Fig. 12c). It was during this time period that the strong winds were observed.

The 850-mb level is used to examine the strength of the cross-barrier flow and is approximately 200 m above the maximum height of Salisbury Ridge. Ridgetop winds were increasing rapidly at 1200 UTC 15 March (Fig. 10). At this time, the inferred wind direction at 850 mb over Juneau was southeast and backing with time as the low and trough approached (Fig. 13a). This increase and backing of the lower-tropospheric winds can also be seen on the Whitehorse soundings between 0000 UTC 15 March and 0000 UTC 16 March (Figs. 12a–c). By 0000 UTC 16 March (Fig. 13b), the 850-mb geostrophic wind was east-southeast with the low closer and the frontal trough

just south of Juneau. Additional ageostrophic turning of the flow (isallobaric and frictional), would result in northeast ridgetop flow just prior to the passage of the trough aloft. (Recall that northeast is normal to Salisbury Ridge.)

This change in wind direction at the 850-mb level from nearly parallel flow to nearly perpendicular flow coincided with the large increase in ridgetop winds; wind speeds peaked just ahead of the trough. Once the trough passed over Juneau, between 0000 and 1200 UTC 16 March (Figs. 13b,c), the 850-mb wind direction returned to a more southeasterly component (i.e., more ridge parallel). This decrease and veering of the low-level wind, and the dramatic drop in wind speed on the ridge, were concurrent. These changes are also evident in the 1200 UTC 16 March YXY sounding (Fig. 12d).

In considering the presence of a critical level, recall that the composite analyses showed decreasing easterly flow extended through 700 mb and that the critical level was somewhere below 500 mb. The 0000 UTC 16 March YXY sounding winds (Fig. 12c) show a reversal with respect to Salisbury Ridge between 700 and 650 mb and characterize the pretrough environment. This wind profile is likely representative of Juneau's wind profile during the period of peak winds on Salisbury Ridge. Corresponding 700- and 500-mb analyses are shown in Fig. 14; the companion 850-mb analysis is Fig. 13b. At the time of these analyses, the weakening frontal trough is just to the south of Juneau, where 850-mb winds are easterly. At 700 mb the winds are difficult to estimate but are in the process of veering from east to southwest; 500-mb winds are south to southwest. It appears, therefore, that within a narrow band just to the north of the low-level front, there is a critical level within the appropriate height range.

Thus, the characteristics favorable for wave-induced surface windstorms, and identified in the composite fields, all came together at the time of the intense winds. This strongly supports a conclusion that the winds were wave induced.

b. Anticyclonic case: 8 January 1975 (Type II)

During an extraordinary Type II (anticyclonic) Taku wind event on 8 January 1975, it was fortunate that there was an Army Corps of Engineers recording anemometer on a tower near the top of Salisbury Ridge. This Rustrak-type recorder attached to a Skyvane wind sensor measured a dramatic increase in wind speed between 0000 and 1200 UTC on 8 January. Although unofficial, windspeeds reached 100 m s^{-1} before the propeller was blown off at 1530 UTC. Salient features of this event will now be discussed.

The outbreak of arctic air over northern southeast Alaska began on 4 January. That morning, Salisbury Ridge winds shifted from south to north and increased, with gusts exceeding 27 m s^{-1} (60 mph). The sea level

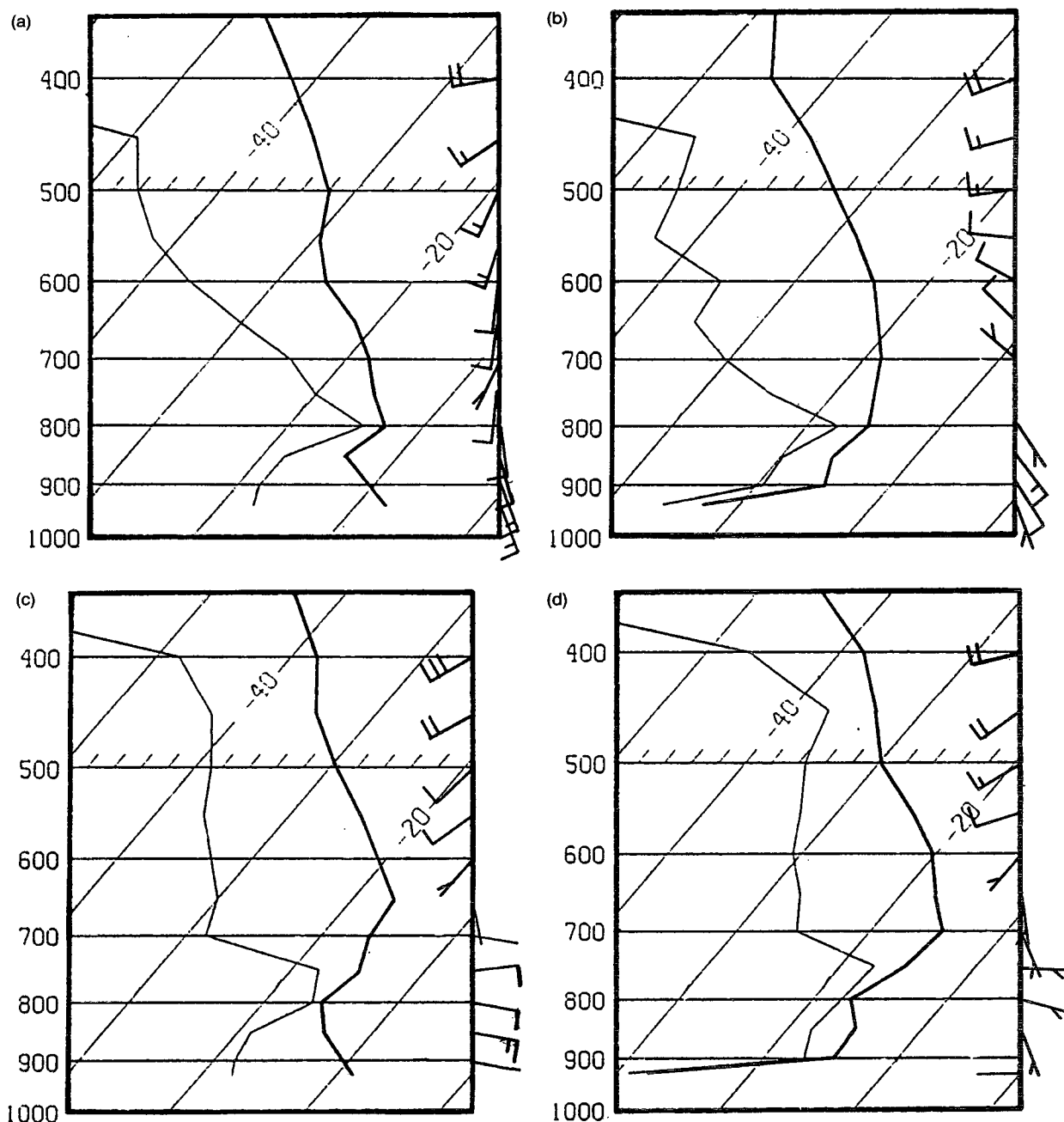


FIG. 12. Whitehorse, Yukon Territory, rawinsondes for (a) 0000 UTC 15 March 1974, (b) 1200 UTC 15 March, (c) 0000 UTC 16 March, and (d) 1200 UTC 16 March. Notation as in Fig. 9.

pressure field (not shown) consisted of the typical, dominating high-pressure center in northwest Canada and a weak trough offshore. Arctic air was entrenched over northwest Canada, with many locations colder than -40°C (-40°F). The associated strong, offshore-directed pressure gradients generated gap winds in the exposed inner channels. These were verified by Alaska State Ferry logs, which reported northerly gales (Beaufort Force 7 and 8; $15\text{--}20\text{ m s}^{-1}$) in southeast Alaska

as early as the 4th and continuing through the 9th. The sea level pressure pattern, temperatures, and gap winds showed only minor variations through this 5-day period. Yet, on 8 January, a significant change must have occurred to account for the observed four-fold increase in wind speed on Salisbury Ridge. Once again, these changes become evident when reevaluating the case in terms of known criteria that favor mountain-wave-induced surface windstorms.

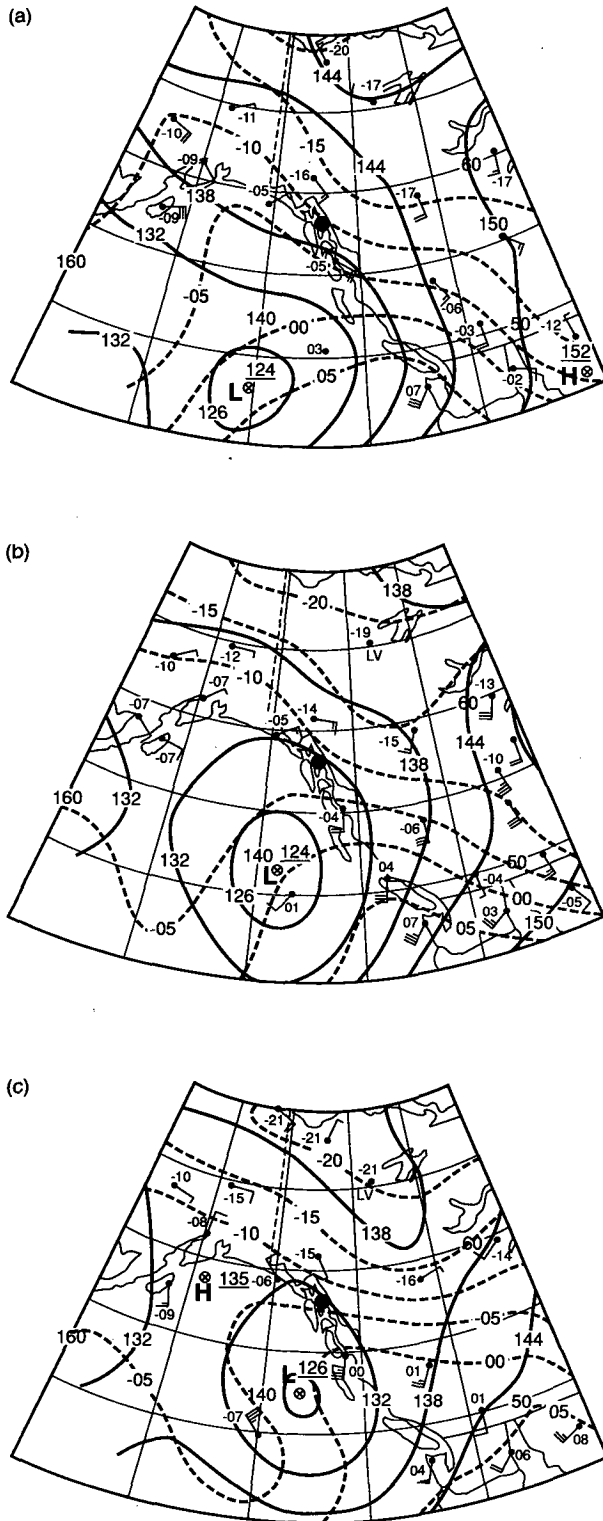


FIG. 13. 850-mb analyses showing geopotential (solid; dekameters) and isotherms (dashed; °C) for (a) 1200 UTC 15 March, (b) 0000 UTC 16 March, and (c) 1200 UTC 16 March. Station plots show wind (flag, 25 m s⁻¹; full barb, 5 m s⁻¹; half barb, 2.5 m s⁻¹) and temperature (°C).

Figures 15a and 15b show the 700- and 850-mb height analyses for 0000 UTC 8 January—just prior to the start of the major wind event. Northeast winds and a tight thermal gradient were already in place at the 850-mb level, providing cross-barrier flow; temperatures at the same level were warmer than surface temperatures (not shown), revealing an extremely stable lower layer (i.e., a near-ridgetop inversion). Thus, two of the three criteria were already satisfied prior to the increase in wind speed.

At 700 mb, a minor trough was located very near Juneau, and the flow over Juneau, although difficult to assess, was most likely light southwesterly, indicating a critical level at or below this level. Over the next 12 h, the upstream-tilted trough moved south of Juneau, increasing the depth of the northeast flow and elevating the height of the critical level (Fig. 16). This occurred coincident with the increase in Salisbury

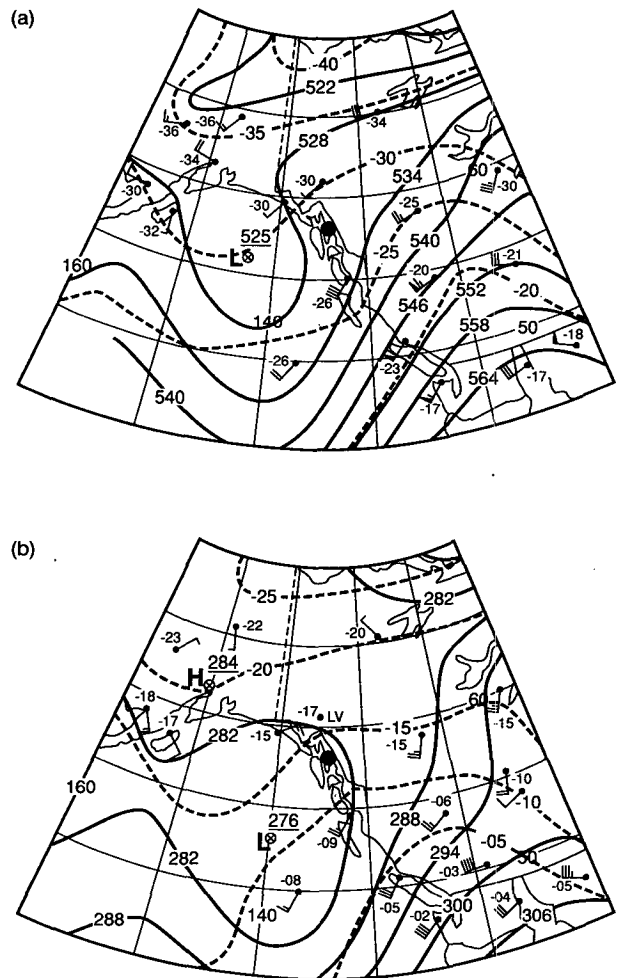


FIG. 14. Analyses of geopotential (solid; dekameters) and temperature (dashed; °C) at 0000 UTC 16 March for (a) 500 mb and (b) 700 mb. Station plots as in Fig. 13.

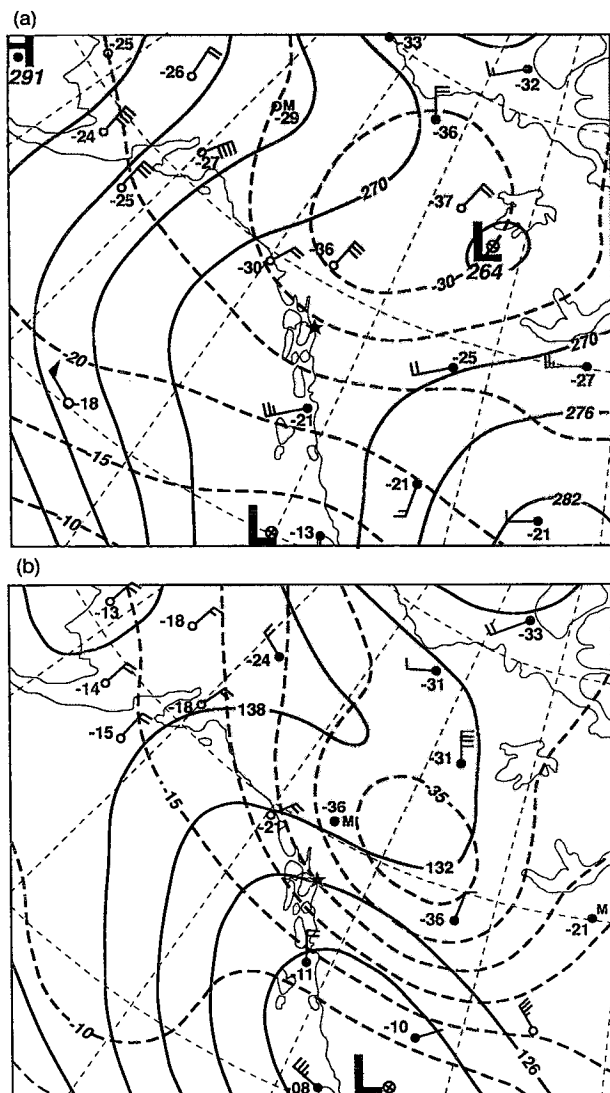


FIG. 15. Analyses of geopotential (solid; dekameters) and temperature (dashed; °C) at 0000 UTC 8 January 1975 for (a) 700 mb and (b) 850 mb. Station plots as in Fig. 13.

Ridge winds. Thus, the development of the severe surface winds appears to be sensitive to the height of the critical level, since development did not occur earlier when lower-level stability and cross-barrier flow were present. In this and the previous case, the critical level was between 700 and 500 mb during peak winds.

Destruction of the anemometer prevented determining the exact timing of the end of the event; however, other observations suggest a significant decrease in Taku winds occurred on 9 January. Observations at the Juneau airport contained remarks "BS OMTNS" (blowing snow over mountains) nearly every hour on 8 January, but not once on 9 January; the Juneau Federal Building anemometer, located on the fringe of the main wind exposure, measured up to 16 m s^{-1} early

on the 8th but dropped to 5 m s^{-1} by the morning of the 9th.

An inspection of the isobaric analyses, valid 0000 UTC 9 January (not shown), revealed low-level cross-barrier flow had weakened due to a gradual veering of the 850-mb wind. Northeast flow continued at 700 mb and deepened to above 500 mb. Both changes act to reduce the favorable mountain-wave environment and are the likely reasons for the observed decrease in wind speeds on 9 January.

c. Discussion

In both case studies, to find that three features identified in the composite and known to favor mountain-wave-induced surface windstorms develop concurrently with the extreme surface winds strongly suggests that the winds are, in fact, produced by a mountain wave. Furthermore, the noted poor correlation between Taku winds and horizontal pressure gradients argues against gap flow as an explanation. Even more fundamentally, only a mesoscale feature of this type could explain the extreme wind speeds observed, particularly given the quadratic relationship between wind speed and pressure gradient for gap flow [Eq. (1)].

5. Implications for operations

These case studies illustrate the difficulty in isolating a mountain-wave event that occurs simultaneously with gap-type winds, the same difficulty Mass and Albright (1985) had in explaining the winds in Washington State. Not surprisingly, there are many similarities between Taku winds and the Washington State winds. Mass and Albright identified the presence of a stable layer near crest level and strong low-level cross-barrier flow. In addition, an inspection of all soundings shown in Reed (1981) and Mass and Albright (1985) show flow reversal in the middle troposphere with respect to the Cascade Mountains. These are all characteristics that favor the surface amplification of mountain waves and raise questions concerning their importance in Washington State storms.

Large pressure gradients and gap flow frequently occur in southeast Alaska without the simultaneous occurrence of Taku winds, but the reverse is apparently not true. This is why large offshore pressure gradients have some predictive value for Taku winds. However, they are likely red herring and not the best predictors. It is clear that any attempt to explain (or forecast) these extraordinary windstorms must involve separating necessary conditions for the occurrence of the two types of flow and treating them independently.

A mountain wave may even enhance gap flow due to the superpositioning of a resultant mesoscale pressure trough downstream from the barrier onto the synoptic-scale pressure field, locally increasing the horizontal pressure gradient. The presence of the wave-

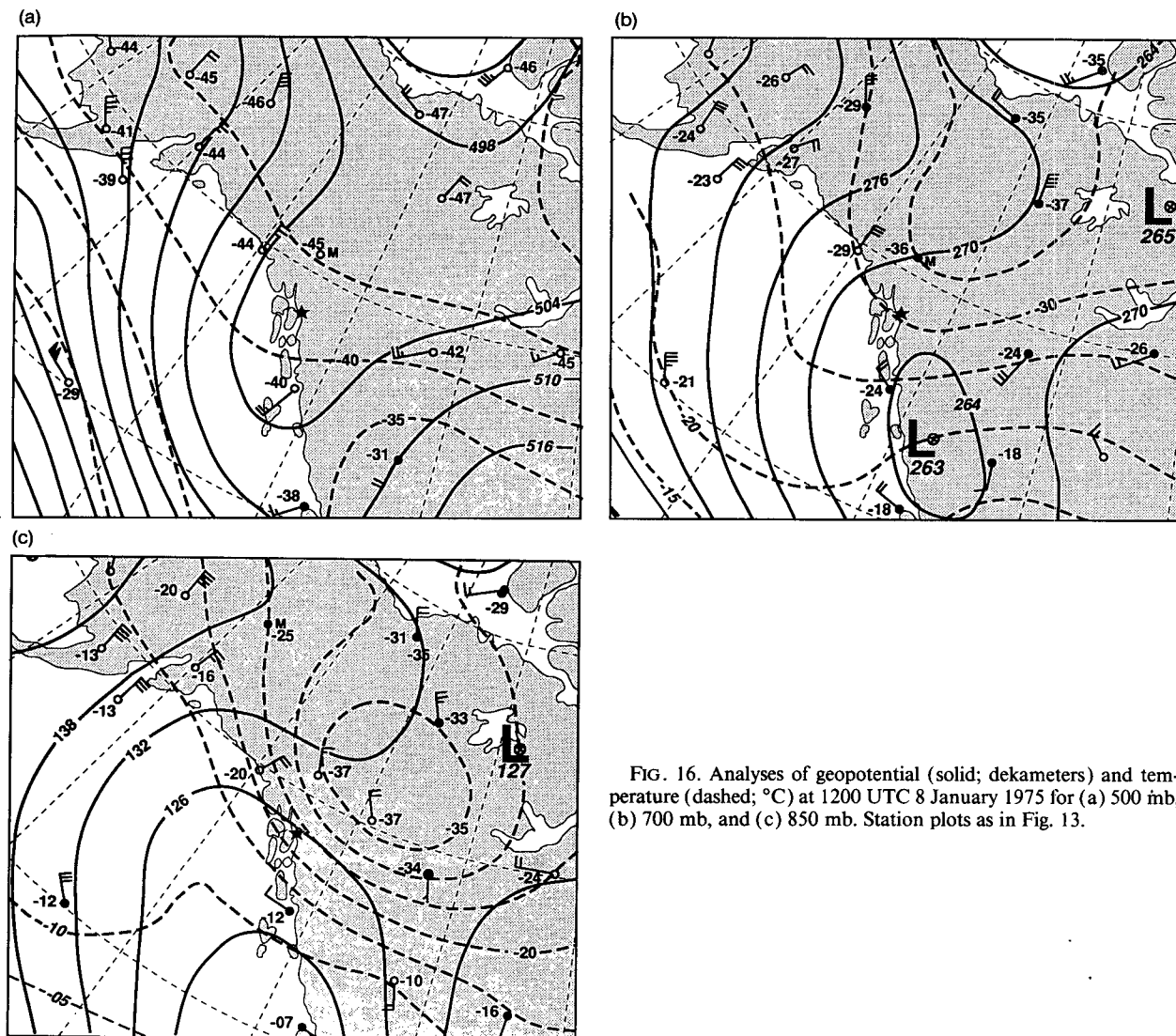


FIG. 16. Analyses of geopotential (solid; dekameters) and temperature (dashed; °C) at 1200 UTC 8 January 1975 for (a) 500 mb, (b) 700 mb, and (c) 850 mb. Station plots as in Fig. 13.

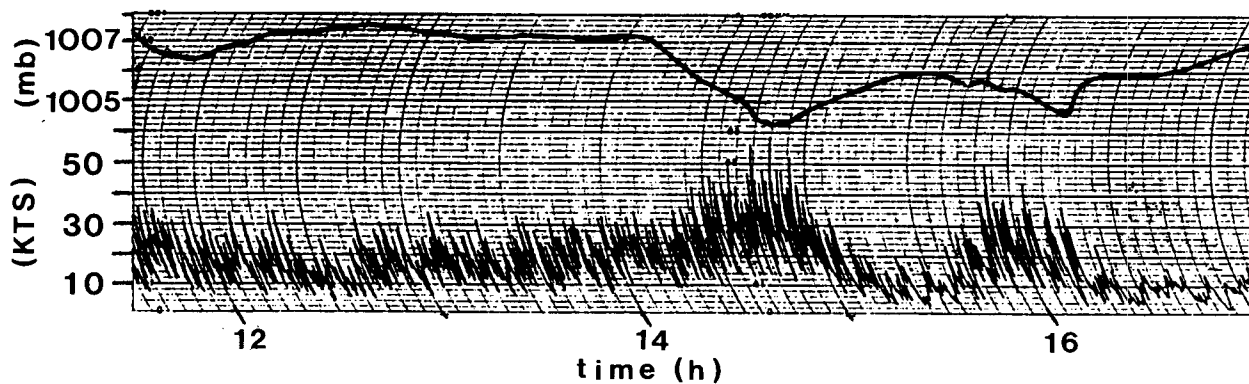


FIG. 17. Gust-recorder trace and superposed microbarograph trace for 6-h period during a recent Taku. Time runs from left to right.



FIG. 18. Photograph taken from near the Juneau airport looking southeast during a Taku windstorm. (Airport is approximately 16 km northwest of the area of strong winds.) Backlit blowing snow dramatically illustrates the airflow down the slope of Salisbury Ridge (from left to right).

induced trough has been demonstrated analytically by Queney (1948) and observationally by Lilly and Zipser (1972). Figure 17 shows an anemometer trace from the downtown Juneau Federal Building for a 6-h period during a recent Taku event; a pressure trace from the same site is also shown. There is a good correlation between peaks in the wind speed and pressure minima. A very sharp pressure jump occurs near the end of the trace, accompanied by a dramatic drop in wind speed, evidently indicating the dissolution of the wave.

Since mountain waves are a mesoscale phenomenon dependent upon local terrain, specific criteria will vary, and forecast parameters need to be determined locally. Initially, for any suspected mountain-wave event, a climatology or composite should be constructed. These data should then be examined with an eye toward specifics on the general criteria listed below (recognizing that they are often restricted by the available data).

1) Inversion at or just above ridgetop. Does one exist? What is the optimum height? What range of heights produce significant winds? How stable is the lower atmosphere? How stable is the atmosphere above the inversion? [Recall Brinkmann (1974) found sensitivity to upper-level stability, as well as a ridgetop inversion.]

2) Cross-barrier flow at ridgetop. How strong were the winds before the event? How strong is the normal component? Do ageostrophic effects produce a more normal component?

3) Decreasing cross-barrier flow (with height) to a critical level. Does a critical level exist? (Recall that some wave-induced windstorms can occur without a critical level.) What is the optimum height or range of heights for the critical level? [Smith (1985) showed a sensitivity to critical-level height for idealized mountain-wave solutions.]

In addition to analyzing the background synoptic fields associated with a particular windstorm, one

should be alert to other possible clues. For example, do the strong winds occur at the base of barriers or the mouths of canyons? Are standing lenticular clouds present at times over the barrier? (Although rare, due to the very dry air typically associated with Taku winds, lenticular clouds have been photographed by the authors over Salisbury Ridge during an event.) In addition, for the Taku, the common presence of blowing snow and blowing spray has helped in visualizing the phenomenon and its character (see Fig. 18).

The end of a wave-induced windstorm can usually be traced to the end of one or more of the favorable conditions just described. At times, however, this may be difficult to anticipate, because a slowly changing mesoscale phenomenon of this type may not be affected initially by the normal or anticipated evolution of the synoptic-scale fields, due to the locally large amplitude of the perturbation. Also, changes in some criteria will produce more dramatic results than others. The degree of change from favorable to unfavorable conditions must be examined for each location in terms of the criteria previously discussed.

6. Summary

A type of severe local windstorm that occurs near Juneau, Alaska, has been examined in light of increased understanding about mountain waves and their effects. The study was based on a historical review of major Taku events. The available data were collected and a composite constructed. Additional data, collected on a nearby ridge, were used to demonstrate the dramatic increase in wind speed that occurs when a Taku windstorm develops.

We found that the occurrence of a Taku is critically sensitive to the vertical structure of stability and wind. The three necessary conditions are: 1) an inversion at or just above ridgetop, somewhere between 1500 and 2000 m MSL, 2) strong cross-barrier flow near ridgetop, typically $15\text{--}20\text{ m s}^{-1}$ in geostrophic wind speed, and 3) cross-barrier flow decreasing with height to a critical level somewhere between 3000 and 5500 m MSL. These three criteria are met in the composite fields and in the individual case studies that have been investigated. It is noteworthy that the two synoptic types identified, namely anticyclonic and cyclonic, are different in synoptic-scale appearance, yet, locally, produce the same required vertical kinematic and thermodynamic structure.

In writing this paper, an effort was made to contrast the prevalent gap flow with the less frequent wave-induced windstorm. It seems the synoptic situation that produces the necessary conditions for wave development also produces strong offshore sea level pressure gradients; this essentially guarantees the occurrence of both types of flow, given the occurrence of the wave-induced storm, and explains why early attempts to forecast the Taku as a gap wind were somewhat suc-

cessful. Similar situations possibly occur in Washington State and many other areas where downslope windstorms occur.

Although their further refinement is ongoing, the identified criteria have already provided valuable guidance in forecasting Taku windstorms this past winter season. Operational forecasters have been able to modify their conceptual models and are now able to separate conditions that favor Taku winds from the more common conditions that favor gap flow.

Two areas not addressed in this paper are the possible interaction of the two flows, and additional three-dimensional effects. An inspection of Fig. 2 reveals that Salisbury Ridge extends southeastward into Taku Inlet, requiring the strong gap flow coming down the Taku River valley to be deflected or spill over the ridge. Clearly, the possibility for interaction exists. The role of the terrain on Douglas Island, which forms the southwest edge of Gastineau Channel, is also unknown. These additional areas present interesting and challenging topics of research.

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