Forecasting ChuWally Winds

(Chinook/Foëhn type winds) at Anchorage, Alaska

by Waldo J. Younker,

National Earth Satellite Service
SFSS, Anchorage, Alaska

Affiliation March 1987
NOAA, National Weather Service
WSFO, Anchorage, Alaska

**This 1987 paper retyped and edited
For Internet web site April 2002**

Note: Several Other papers have been published by others testing the conclusions presented herein. The author wishes to reference any such works in this publication. Please send information concerning such works to E-MAIL AUTHOR....Thank you.

ABSTRACT

The complex terrain near Anchorage, Alaska, gives rise to a variety of local wind phenomena. The most troublesome of these are the occasional damaging Chinook-type winds that blow down the slopes of the Chugach Mountains east of Anchorage. More than twenty strong Chinook wind events were studied. The most highly correlated atmospheric, oceanic sea surface temperatures, and topographic variables were identified and their effective limits determined. From these variables, a real-time ongoing Chinook wind forecast model was developed. The model uses the latest observed upper air Anchorage 1000-500 MB. thickness value in addition to observed surface parameters on an hourly basis from three stations. This information is then used to update the same parameters ingested earlier from the National Meteorological Center MOSS forecasts. Although it is somewhat early to determine how well the model works over the long run, it shows remarkable accuracy in the three-year period since implementation. With hindsight from the intervening years through 2001, the original choice of parameters has proved to be accurate in all incidences of Chinook wind events.

1. Introduction

The city of Anchorage is normally protected by the surrounding mountains from strong atmospheric pressure gradient winds; however, the city is occasionally subjected to strong, sudden, and warm winds from the east. These Chinook winds descend the mountain slopes to the east of the city, in an increasingly populated area. Property losses because of the winds in 1980 exceeded 60 million dollars. An intensive search for a forecast procedure was begun in 1980 following a Chinook storm January 18, in 1980 that caused an estimated 2 million dollars in property damage. In addition to the winds, a record breaking high temperature of 7°C was recorded 9 km west of the wind-damaged area. The sudden warming from this storm caused ice-glazed roads that resulted in one death from an automobile accident as the accompanying wind blew the car off the highway. There were also numerous power outages and avalanches in the Palmer/Anchorage/Kenai Peninsula areas.

This paper examines several Chinook wind variables for the Anchorage area and describes the development of a forecast methodology that is easily available, and usable in a real-time mode by operational forecasters. Before the results of this study were utilized, Chinook windstorms at Anchorage were unpredictable. More than 20 cases were studied with the results used to make an operational Chinook wind-forecasting model. Regardless of the validity of some of the meteorological assumptions made in the model development, the results of the model are important since they have been found to be unusually reliable.

2. Setting

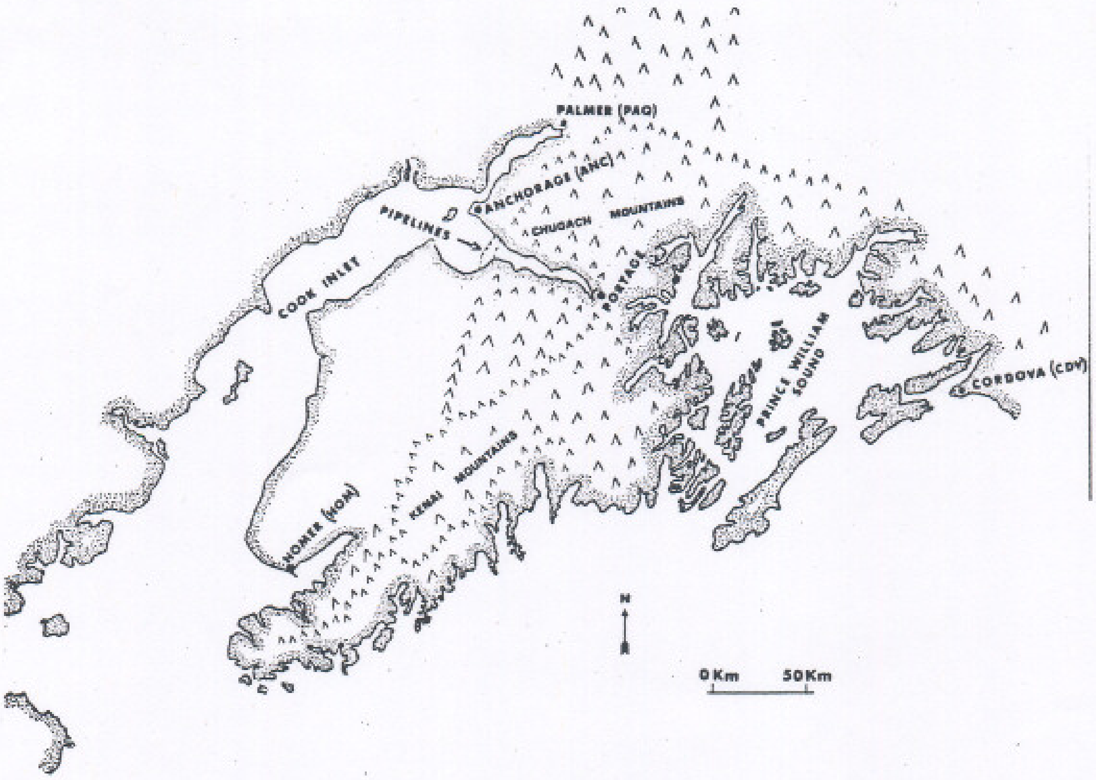


FIG. 1
Map of south-central Alaska showing the Chugach Mountain Range, other geographic features, and the city location of Anchorage, Palmer, Cordova, and Homer.

The Anchorage/Palmer area of south-central Alaska lies on the west side of the Chugach Mountains that extends north-northeast from the Kenai Peninsula as shown in Fig. 1. This range, over 50 km in width, has mountain peaks 1000 to 1500m in elevation from sea level. The east side of the range terminates abruptly at the shores of Prince William Sound. The waters of Prince William Sound adjacent to the Gulf of Alaska remain unfrozen the entire year (LaBelle, 1983), but considerable ice forms in the Cook Inlet waters during the winter. Knik Arm, a tongue of water off the north end of Cook Inlet, extends northeast from Anchorage to Palmer.

The basin north of Cook Inlet and Knik Arm to the Alaska Range is the Susitna Valley, while the area south of this coastline to the Gulf of Alaska is the Cook Inlet Basin. Another tongue of water off the north end of Cook Inlet, extending east along the south side of Anchorage into the Chugach Mountains is called Turnagain Arm. This arm nearly cuts off the Kenai Peninsula from the Alaska mainland. The elevation of Portage pass between Turnagain Arm and Prince William Sound, a distance of only 16 km, is only 155 m. Strong easterly Turnagain Arm winds are common and occur in all seasons through this narrow channel. The strongest of these occur along with most other severe wind events at Anchorage only during the cooler months of the year when strong surface temperature and pressure gradients are most prevalent.

Chinook winds for east Anchorage occur only when strong east winds are calculated and known to be present in Turnagain Arm, with the most typical of these synoptic patterns shown in Fig. 12. Comparative observational data used to develop the wind equation now used to calculate these winds is no longer available. The strongest Chinook gusts reported since that equation was developed, however, averaged 87% in eight of the first nine Chinook wind cases studied. An understanding of the Turnagain Arm wind regime is thus necessary to fully develop the Chinook wind forecast procedure.

3.Evolution of understanding Chinook winds at Anchorage
a. Turnagain Arm (Jet) Wind

In the early 1960's, a natural gas pipeline was buried in the glacial silt of Turnagain Arm (Fig. 1). Wind data was collected during the installation of that pipeline from helicopter pilots servicing the operation. A wind equation was empirically derived to depict the strength of the winds the helicopter pilots repeatedly found, reached a maximum while crossing the arm near the center and at and elevation of 155 m. Some of the winds that blew either up or down the arm at this level were reported as high

30 m/s that summer, but higher calculated velocities from 30 to as high as 70 m/s calculated later by that equation for other seasons, had not been verified in a similar manner. Steady winds calculated to be as strong as 70 m/s though are probably close to reality, because surface gusts that strong have been measured at Portage Glacier lodge east of Turnagain Arm (at sea-level). Winds this strong incidentally would be equivalent to 81 m/s at Boulder, Colorado due to air density considerations.

Wind gusts to 53 m/s have been reported at ABK, an automatic station mid-way down the Chugach Mountain bluff along the north side of Turnagain Arm. However, it had frozen up for about 3 months in each of the past 3 winters it was in operation. Therefore, reports of the stronger wind events there went unrecorded. In the only direct comparison of the component gusts velocity at ABK along the orientation of the arm against the calculated ones, a peak velocity of 41 m/s occurred 1 hour before a calculated peak of 39 m/s. Since winds calculated for the 155 m level often exceed those taken 20 km northwest by radiosonde data (at the same and higher elevations), these winds are assumed to be in the form of a low-level jet core exiting Turnagain Arm. Consequently, they will be referred to as TAJ winds for the remainder of this paper.

These TAJ winds that fan out after exiting the arm at and angle of about 100° from true north, have considerable effect on the local surface winds in the Anchorage area, depending on whether they then turn north, south or continue westward. The north or south deflection can be related to the reported pressures at Anchorage International Airport (ANC) and the Homer airport (HOM) about 160 km south-southwest. Using the effective pressure difference (pressure difference plus the isallobaric wind equation term), gives a better indication of the angle of deflection than just using only the measured pressure difference. When the pressure at HOM is significantly lower than ANC, the TAJ winds turn south. In this case, the surface winds at ANC are relatively light from the NNE (Fig. 2a). When the pressure is only 1-4 mb lower at HOM than ANC, the TAJ continues west out of the arm, but in the shear areas on either side of the core, on the right exit, an anticyclonic eddy is apparent in the surface data centered just southwest of ANC (Fig. 2b).

It is presumed that a corresponding cyclonic eddy prevails in the surface data on the left exit of the TAJ at this same time. The third surface flow pattern (Fig. 2c) is locally referred to as "Turnagain winds", which are moderate southeast winds with gusts normally less than 20 m/s over most of the city. This flow pattern occurs when PA - PH <= 1 MB. Although this is a windy condition, it is much less so than can occur under condition 2b if standing mountain wave winds hit the surface as a Chinook wind.

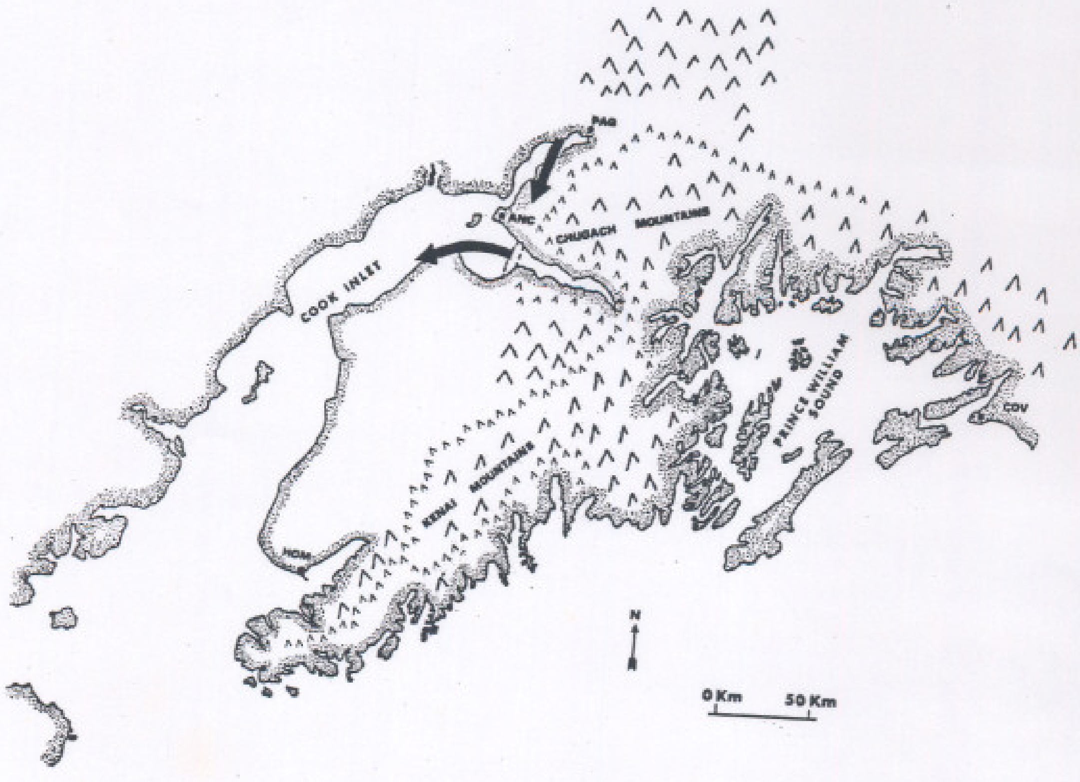


FIG. 2A.

Map showing north-northeast flow at Anchorage when Turnagain Arm Jet (TAJ) winds turn south after exiting the Arm which occurs when the surface pressure at Anchorage International Airport (ANC) is 4 mb or more than Homer (HOM) so (Pa - Ph => 4). No Chinook winds have been observed in this regime.

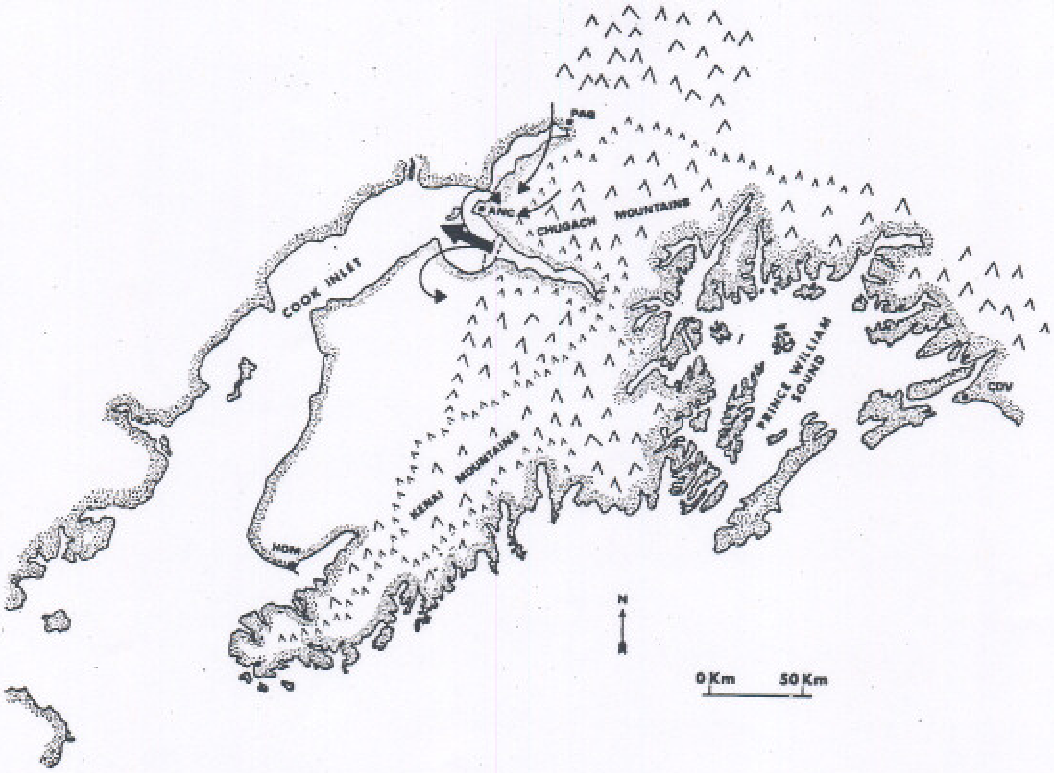


FIG. 2B.

Map showing "eddy" circulation when the pressure at ANC is 1 to 4 MB greater than HOM so that (1 < Pa - Ph < 4). Chinook winds are only possible in this regime.

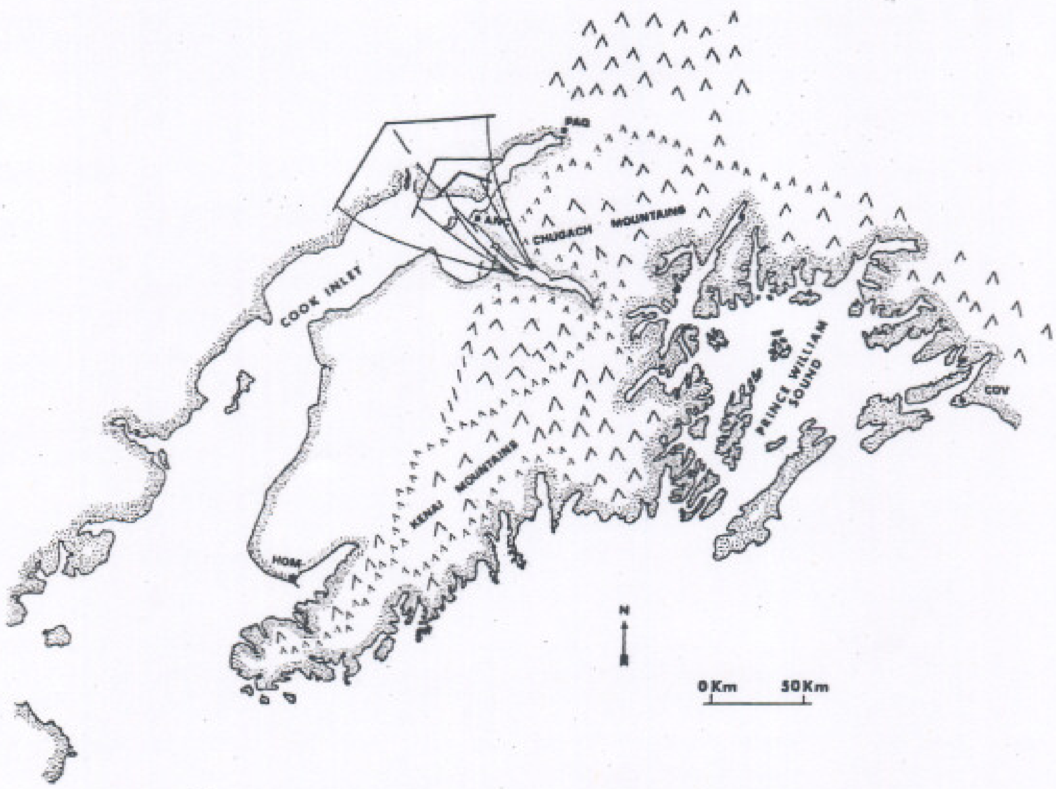


FIG. 2C.
Map showing "Turnagain winds" as the TAJ deflects to the north when the surface pressure at HOM is higher than ANC or within 1 mb lower, so (Pa - Ph =< 1 mb). Chinook winds will end if these Turnagain winds develop.

b. Chinook wind characteristics

Local average Chinook wind velocities vary considerably, apparently because the stronger Chinook winds frequently remain aloft and only occasionally sink or skip to the surface. Consequently, only the surface gust velocities (which most often are several times the mean wind spread) have strong correlations with the TAJ speed. Unless otherwise noted, Chinook winds refer to the first wave of winds that surface below the 300 m elevation contour of the Chugach Mountains in east Anchorage. These warm dry winds from the east or southeast never extend more than about 8 km west of the 300 m contour. With one exception in about the previous 65 cases, there was never any rain in this area, and most often, a band of clear sky (lee break) was visible parallel to the mountains. The east edge of this zone or band of clear skies extends vertically above the western most peaks in the Chugach Mountains from ANC north to Palmer (PAQ). This clear area extends further east above the cloud base so that the cloud edge is in the shape of an airfoil or roller. The rest of Cook Inlet and the Susitna Valley are generally overcast. Occasionally there is rainfall in western portions of the Anchorage/Palmer area, but precipitation is prevalent over the western portion of the basin. The clouds that begin over central or west Anchorage beyond the lee of the mountain break, are normally chaotic with cloud bases averaging near 1400 m. Frequently additional lower cloud streaks are near 1000 m, and sometimes there is even lower stratus clouds associated with blowing spray which can be seen along the shoreline just south of Anchorage. These stratus clouds are generally normal to the other clouds, and extend west into the Turnagain Arm exit. The overcast layers that begin west of the lee break, are of the specie lenticularis with each higher layer beginning a little more east of the layer below.

Much of what appears to be a rounded wall of clouds down into the tops of the mountains in east Anchorage is actually an obscuration due to blowing snow. The Chinook winds that extend down the slopes from that area, are known to only reach the surface in this first mountain wave, before ending in a line of updraft vortices that delineate the west edge of the Chinook wind zone (Fig. 3 and 4). When there is sufficient daylight and minimal snow cover, these vortices can become visible in the form of large dust devils. West of the line of updraft vortices, the stronger Chinook winds remain aloft while reaching their next lowest point in the second standing wave trough (Fig. 4 and 5). This point is normally about 20 km downstream (Anderson, 1973). Local radiosonde observations and pilot reports have confirmed the position of the second trough reasonably well. Flights into ANC are on final approach as they pass through this trough,

and their reports of severe updrafts or downdrafts in this area have been quite informative.

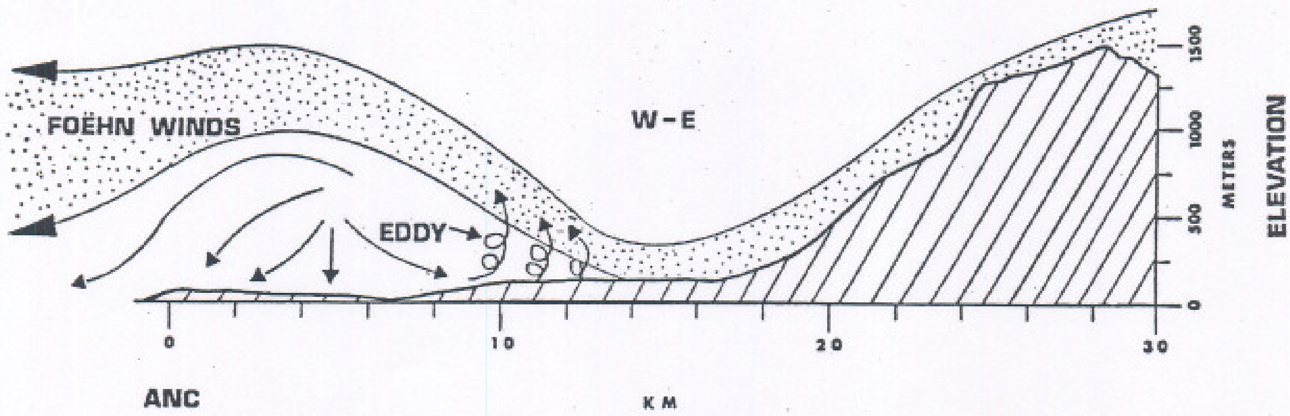


FIG. 3.
Vertical cross-section of streamlines and topography... looking north from the exit area of Turnagain Arm during a Chinook windstorm.

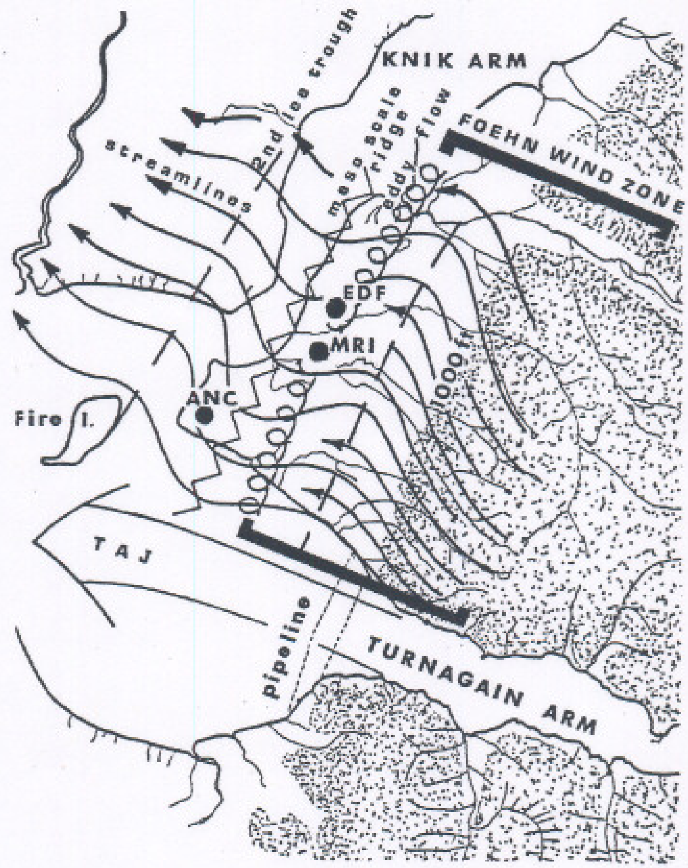


FIG. 4.
Map of Anchorage showing typical streamline flow during Chinook wind events.

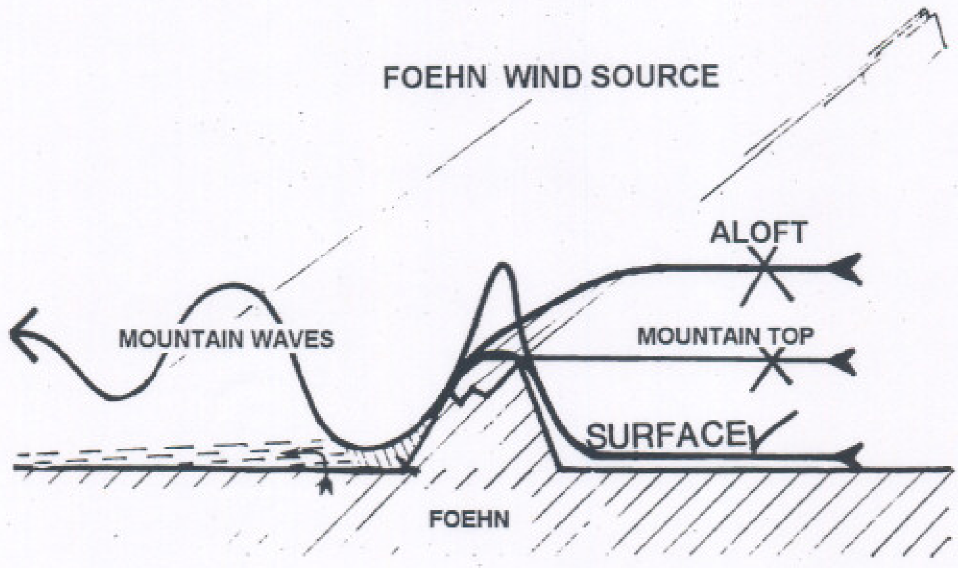


FIG. 5.
Diagram indicating that the major source of air for Chinook (Foëhn) wind events at Anchorage is from the surface of Prince William Sound waters and any entrainment from of air over or upstream from the mountains from near the mountain top level (or higher) is negligible.

Although gusty surface winds over the western portion of Anchorage often accompany Chinook wind events, these velocities are normally only 25 to 50% of those reported along the mountains east of the line of updraft vortices. The wind directions west of the Chinook wind zone can be from many directions, but those winds appear to have a prevailing direction dependent on the location that part of the city has in reference to the standing waves aloft. There is no prevailing direction however in the immediate vicinity of the updraft vortices. These prevailing directions reported at four airports in Anchorage and from other observers, was the basis of the conceptualized streamline flow indicated in Fig. 4.

c. Wind speed formula

Turnagain Arm is oriented along a line for ANC to Cordova airport CDV (x axis in a rectangular coordinate system). Since the low level winds in this Arm are dependent on the pressure gradient along the x axis, it can be seen that any attempt to use the geostrophic wind equation as a starting point in developing an equation must split the wind into components and first change the usual u component from a partial derivative with respect to the y axis to the x axis. u = -1 Δ p/(fr(Δ y))then becomes -1 Δ p/(fr(Δ x)) where the Coriolis parameter at 60.5°N at ANC f = 1.269 10-4 radians sec-1 air density r = 12.42 at a pressure of 1000mb & temperature 280°K with the distance CDV-ANC = 258 km = x the u component in meters per sec now becomes u(m/s) = -633 Δ p/258 = -2.46 (PCDV - PANC) equation (1)Reports from pilots crossing the west exit of the Arm prior to the pipe laying operation had already indicated that this constant calculated at -2.46 ...(Eqn. 1) should be more on the order of -3.1, which was presumably due to some venturi effect.

The daily helicopter reports later confirmed this new choice of a constant during steady state condition, but they indicated that an acceleration factor was needed when the pressure difference from CDV-ANC was changing. The u component of the isallobaric wind equation, dependent on the time differential of the pressure difference along the x-axis, was used for this purpose. U(isallobaric wind component) = -1 Δ Δ p/(f2r Δ x Δ t)...(Eqn. 2) Since the smallest increment of time that pressure differences from regularly scheduled weather reports is available is 1 hour, the appropriate conversion factor for the additional 1/f term when using 3600 seconds for 1 hour, becomes 2.2 at this latitude. By changing the sign of the u component so that a wind exiting the Arm to the west is now positive, and rotating the x-axis 16° to line up with the compass heading CDV to ANC of 106°, the full equation becomes: TAJ = 3.1 (Pc - Pa + 2.2 (Pc - Pa) - 2.2(Pc-1 - Pa-1)), ...(Eqn. 3)
Therefore, the equation in units of meters/second is 3.1 times the pressure difference (in millibars) added to 2.2 times the change in that pressure difference during the previous hour. The computer program smoothed this data to eliminate

spikes that should not be considered trends, by averaging two of the current reported values to that of the hour before and the hour later (4 values). The last hourly pressure however was an average of three values 2 of the current and 1 of the hour before.

d. geostrophic wind direction limits and ANC-CDV pressure difference limits

A study of the data reveals additional Chinook wind characteristics. Local Chinook wind events never occur unless four (4) weather parameters fall within certain delineating criteria simultaneously, and when they do in the Anchorage area, the maximum gust speeds reported will be opposite of the Chugach Mountain passes and proportional to 87% +/- 8% of the TAJ velocities calculated. This was true using only three of the parameters in the eight of the first nine cases studied. The reason the TAJ suggested much stronger winds than were observed in the ninth case, determined the fourth parameter which will be discussed last.

The first criterion deals with the calculated orientation (angle) of the surface geostrophic wind. Since the dividing line between "eddy" surface circulation and Turnagain winds" is dependent on the Anchorage pressure being more or less than 1.0 mb higher than Homer, it is easy to set up CDV-ANC and HOM - ANC "effective pressure differences" (actual pressure differences with the added isallobaric term) to calculate "effective surface geostrophic wind directions. These would be the wind if the wind blew parallel to isobars (lines of equal pressure) with no deflection or velocity change due to friction. In this case, it is the geostrophic wind equation with the exception that the isallobaric wind component is now directed along the isobars instead of orthogonal as a few textbooks indicate. I don't intend to defend the reality of whether the concept of isallobaric winds are real or imaginary, but I do believe that if the concept is used wisely, it can provide a valuable acceleration factor. The concept may also be of value just because of the problem of working with data with finite differences in time and distance. In other words, it may just be a mathematical trick to better estimate wave motion in pressure gradients as opposed to linear interpolation.

When using isallobaric components in wind equations involving stations about 95 km apart, the data most often appears to be very noisy because small errors are magnified such as those caused by observations not taken exactly at 1 hour intervals. When trying to interpolate on scales using stations 375 km or more apart, small scale pressure systems can move into or through the pressure field of the larger pressure fields trying to be analyzed. Distances of 258 km and ANC to HOM 193 km appear to be ideal ½ b wavelengths in the pressure field when using the isallobaric wind component concept. These surface geostrophic winds with the acceleration factor applied in this manner will be referred to as "geostrophic+A" winds hereafter. The only allowable wind directions calculated this way were from approximately 148 to 196 degrees. This is roughly from a direction of parallel to 45° to the right of the mountain range orientation on the east side of Anchorage.

The second criteria needed for Chinook winds to generate is an effective minimum pressure difference of 8 MB from CDV-ANC. This equates to a surface wind of 25 m/s along the axis of Turnagain Arm of 106°, or a geostrophic+A wind of 20 m/s perpendicular to his axis. The third criteria involve vertical air mass stability, which was found related to one definition of an "arctic front" found prevalent in Alaska. . This Chinook study began in earnest following the January 18, 1980 storm, by summarizing all facts known up to then about these local events that occur up to 15 times a year. In the previous 20 years, the WSFO at Anchorage had a zero percent verification on local Chinook wind forecasts. This means that all that were forecast never verified, and none that occurred had ever been forecast. Although it was possible to forecast the magnitude if they would occur, what or when they would switch on or off was unknown. Then it was finally recalled that during these winter events, not one occurred with the surface temperature remaining below freezing. This seemingly trivial fact was responsible for unraveling the nature of these events.

This fact suggested that Chinook wind storms at Anchorage might be related to one type of "Arctic front" as indicated by Mathews (1984), sometimes called the 0°C wet-bulb front. At temperatures near freezing, the surface location of this front can be found by analyzing the mean between the dry-bulb and dew point temperatures to obtain an estimated wet-bulb temperature for each station. This type of front, common to ice-free coastal areas of Alaska during the colder seasons, divides the cold dry arctic continental air mass from the warmer maritime air over the Gulf of Alaska. These fronts which separate freezing or frozen precipitation falling on the cold side from precipitation (if any) as rain on the warm side. The 1000-500 MB thickness values associated with this change in precipitation phases, are typically in the range of 528 to 534 decameters.

During the severe storm study of January 18, 1980, it was observed that the Chinook air reached the ground along the

base of the mountains in east Anchorage at the time the estimated dew-point temperature rose above 0°C. More importantly, during the entire period following a 13-hour period while Chinook gusts averaged more than 40 m/s, the difference in approximate wet-bulb temperatures between Cordova and Anchorage never varied more than 0.5°C. This seemed rather startling in view of the fact that during this same period, the temperature at ANC varied from 1°C to 4°C higher than CDV, and the calculated hourly Chinook wind gust velocities from Equation 3 varied from 33 to 56 m/s. The estimated 1000-500 MB thickness value (between radiosonde observations) at the time this storm began was 531 decameters, midway between the 528-534 values normally associated with the zero degree wet-bulb type "Arctic fronts".

In order for the wet-bulb temperature at ANC to hold nearly constant during this period, the hourly dew-point temperature curve must inversely mirror the hourly temperature curve. Since only equivalent potential temperatures and wet-bulb potential temperatures are conserved during both moist and dry adiabatic processes (Hess, 1959), the conservation of the wet-bulb temperature from Prince William Sound to Anchorage during, and not before or after the period of Chinook winds, suggests the following hypotheses:

(1) Chinook winds are a pseudo-adiabatic process where the surface air in the Cordova area of Prince William Sound is both lifted over the Chugach Mountains and then forced downward on the Anchorage side.

(2) If the above statement is true, entrainment from air aloft into the air mass arriving at Anchorage from Prince William Sound at low levels must be relatively insignificant. If not, conservation of the wet-bulb temperature would not be expected.

(3) If both the above statements are true, simple computation based on conservation of momentum for sea-level wind velocities in Prince William Sound may yield sea-level Chinook wind velocities at Anchorage, irrespective of the intervening pressure gradients and velocities aloft. The TAJ equation based only on one pressure differential between these two areas, thus might be more proportional to the Chinook velocities at Anchorage without the need to determine what accelerations or decelerations take place in the actual Chinook air as it ascends and descends the mountains.

Several things tend to show the above hypotheses 1 & 2 are true. The most significant indication is that the surface temperature at Anchorage is always above freezing and the presumed source temperature, which is the SST (sea surface temperature) of Prince William Sound during the Chinook wind events. The temperature at Anchorage, in fact, often breaks the daily record high during these events. It is interesting to note that a graph of record daily high temperatures at Anchorage for the cooler period from September 15 through April 15, mirror the climatological SST curve for Prince William Sound. This is the portion of the year when the climatological 1000-500 MB thickness values at ANC fall below those based on a moist adiabatic lapse rate from the SST temperature of Prince William Sound. These record high temperatures can be accounted for simply by the release of latent heat in the pseudo-adiabatic process as the air crosses the mountains. The graph in Fig. 6 showing an omega shaped curve for the Anchorage daily record highs versus a sine curve for the record minimums suggest the majority, if not all record high temperatures for the colder months of the year were set during Chinook wind events.

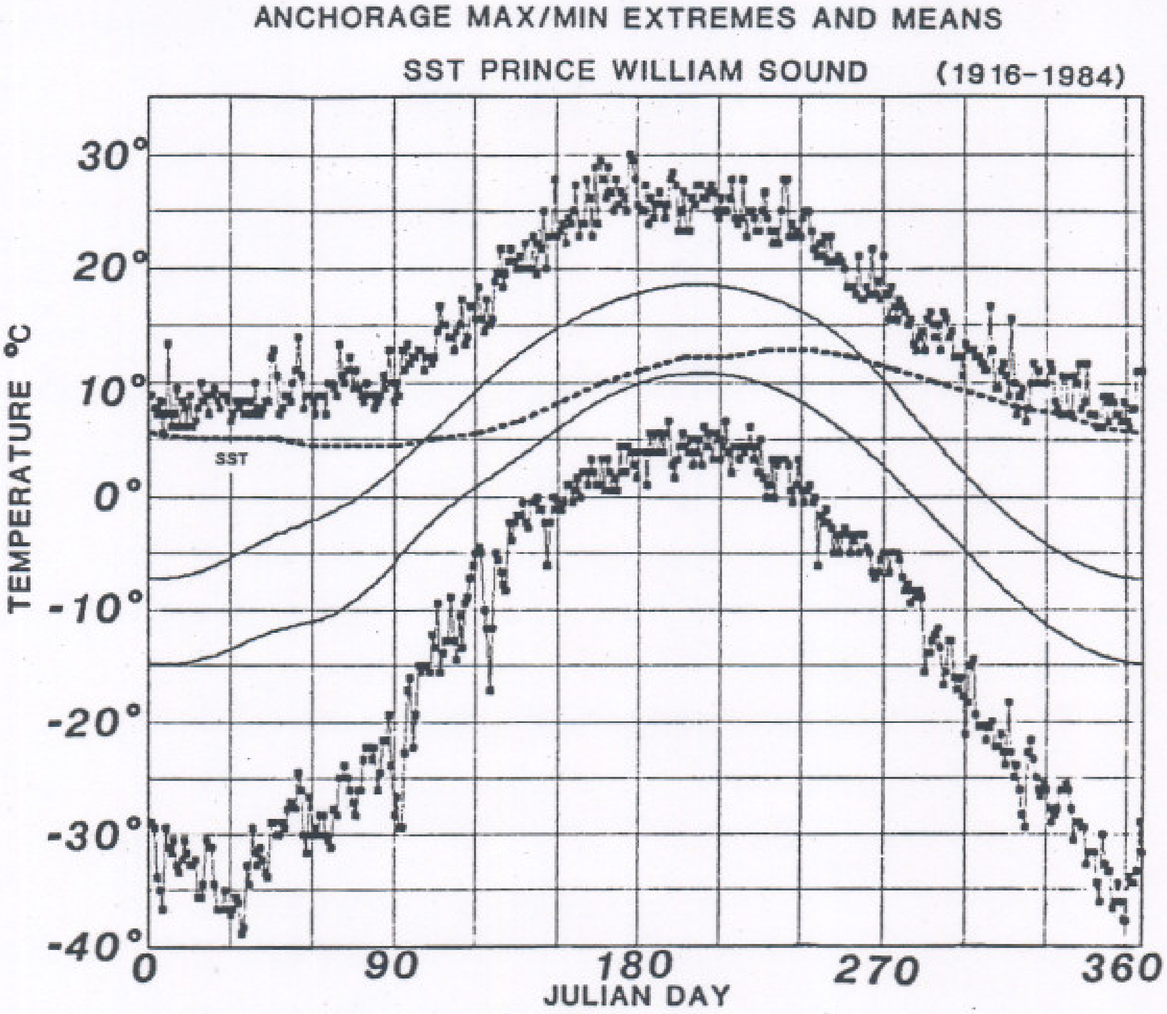


FIG. 6.
Graph of the Anchorage average and extreme daily high and low temperatures for the record period 1906-1984. Note that all but two of these high temperature extremes at ANC during the colder months exceed the average sea surface temperatures (SST) for Prince William Sound on the opposite side of the Chugach Mountains.

These extremes cannot be due to insolation at this latitude during the cooler months of the year, nor from advection over the waters of Cook Inlet, which averages about 5°C colder than Prince William Sound. Precipitation always occurs during these events at Whittier (a sea port at the east end of Portage pass) as evidenced by the average annual precipitation of 442 cm (which includes 669 cm of snowfall). These high precipitation amounts in comparison with an annual precipitation average of only 39 cm at Anchorage indicates the strong orographic effect of the Chugach Mountains in which even weak onshore flow from the southeast normally results in precipitation at Whittier. It was therefore concluded that Anchorage Chinook wind events are a pseudo-adiabatic process from sea level to sea-level (Fig. 5), as opposed to just katabatic or non-pseudo-adiabatic process from a mountain top source region tried in a previous local study, with minimal success.

In order to distinguish this type of Chinook from other winds that result in warm dry down slope flow from many different causes (Glenn, 1961), the usage here will be for down slope winds with gusts in excess of 20 m/s as a result of standing mountain waves. Only the wind in this area out to the line of updraft vortices (Fig. 4) will be considered a Chinook. This is the area of maximum warming due to compression after latent heat has been added from the rising air on the windward slopes. The area downstream from the updraft vortices called the "Chinook belt" is the area of dampening out standing mountain waves. Since the previous environmental air there is only partially replaced with mixing processes involved, there is less wind, warming, and a delay in the occurrence of one or both involved. The airport ANC about 24 km west of the mountains and never in the zone of Chinook winds scouring the mountains, only receives 25-50% of those velocities. ANC experiences about the same maximum surface temperatures, but there is often a delay of up to 2 hours before experiencing those reported in the actual Chinook wind area.

Hypothesis 3 may not be true in part, but direct comparisons of observed winds on either side of Portage Pass at 155m were not available through 1987. What can be stated is that the strongest calculated value of the TAJ (which uses an acceleration factor) seems to occur at the same time that the maximum Chinook winds are observed. Both of these involve venturi effects since the strongest Chinooks are reported just downstream from major mountain passes in the Chugach Mountains between Anchorage and Palmer. In addition, the derived TAJ equation 3 correctly accounted for the development and demise of low level turbulence reported by pilots in the Anchorage vicinity. When the TAJ calculated at less than 10 m/s, pilots said the winds were calm while crossing the arm exit, but turbulence developed as the calculations increased to 15 m/s. These turbulence reports began well before a linear pressure difference (without an isallobaric wind component being added), would calculate at 15 m/s, and end well before the linear wind decreased below 15 m/s. This is because the isallobaric component often contributed to as much as 50% of the TAJ value in speeds below 25 m/s.

Further examination of vertical temperature profiles (stability) can be shown graphically. If one assumes that Prince William Sound (PWS) is the source area for Chinook winds at Anchorage, the reason for the lack of these winds during the warmer months can be shown by looking there at conceptualized vertical temperature profiles (VTP). Fig. 7 shows two common profiles (summer & winter). Profile (Ls) shows the inversion caused by the cold water of PWS or the Gulf of Alaska. The inversion precludes the lifting of low-level air from the surface, up over the mountains without some very strong forcing effects (which are rarely present in the summer). Profile (Lw) represents unstable conditions when the waters of PWS are much warmer then the over-riding air mass. The relatively warm water creates an unstable condition where much less forcing (kinetic energy) is required to lift the surface air high enough to cross the mountains.

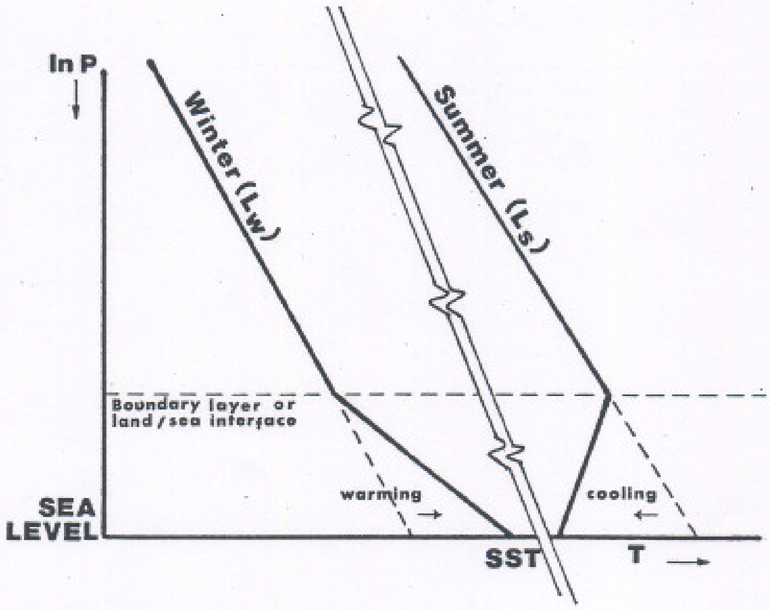


FIG. 7.

FIG. 7. Emagram with generalized winter and summer vertical temperatures profiles. Profiles (Lw and Ls) showing the warming and cooling with the resultant destabilizing or stabilizing effects of the SST of Prince William Sound and/or the adjacent Gulf of Alaska waters.

All types of VTPs were next examined for both PWS and Anchorage to see how a parcel undergoing a pseudo-adiabatic lifting process between these points, could return to sea level at Anchorage. Although there are many possible combinations of ambient air (environmental) curves with parcel curves, there were no reasonable solutions found that would allow this process from internal (potential) energy alone. Since the higher pressure against the east slope of the Chugach Mountains would most likely be the external kinetic energy mechanism needed for Chinook winds, environmental and parcel temperature profiles were examined from this viewpoint. If the surface air should become unstable as shown with the profile (Lw) in Fig. 7, the air parcel lifted pseudo-adiabatically from CDV by internal buoyancy forces would accelerate until crossing the environmental temperature curve. The parcel would then decelerate until reaching a maximum height (Z1 in Fig. 8a).

The vertical line passing through the intersection of the temperature curve of the lifted parcel, and the environmental temperature profile (not shown), is a line of mean virtual temperature. This separates the equal areas of positive and negative buoyancy energy. Assuming the parcel was crossing the Chugach Mountains during this time, the parcel would now fall at a dry adiabatic rate. If the mean virtual temperature for the layer Z1 to the surface was the same during the descent at ANC as on the ascent from CDV, Fig. 8b shows the following would happen. Equal energy considerations indicate the parcel would sink to the lowest height (Z2), well above the initial height at the surface. The additional energy needed to force the parcel to the surface is shown by the hatched area below Z2.

FIG 8a

Stüve Diagram

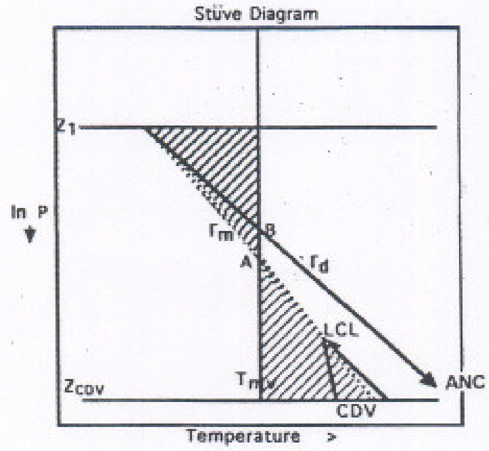


FIG 8b

Stüve Diagram

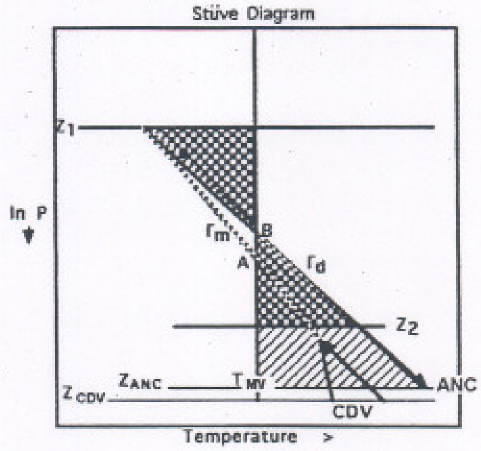


Fig. 8c show that if the missing energy were added to the internal energy buoyancy energy lifting the parcel in Fig. 8b to Z1, the parcel would reach Z3, and then could sink back to the surface without any change in the mean virtual temperatures. The external energy in this case could be kinetic energy of the wind field at the surface, which could drive the parcel up the inclined mountain slope.

Fig. 8d shows that the parcel could also descend to the surface at Anchorage without any need for external forcing, if the parcel was transported to an environment with a higher mean virtual temperature before descending. Ideally, after the parcel reached the lowest point in Fig. 8b, 8c, & 8d, the vertical oscillations would dampen out until the parcel reached equilibrium at a height (B) where the mean virtual temperature of the environment intersects the dry adiabat of the descending parcel.

FIG 8c

Stüve Diagram

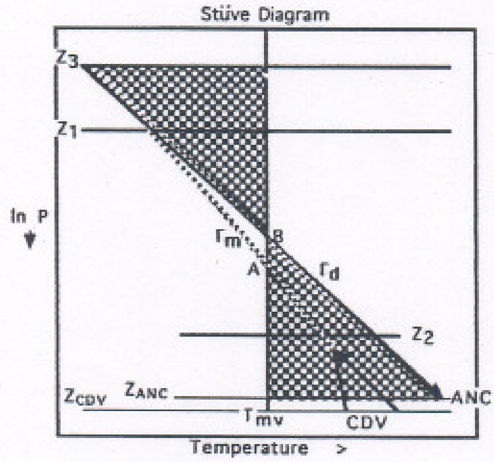
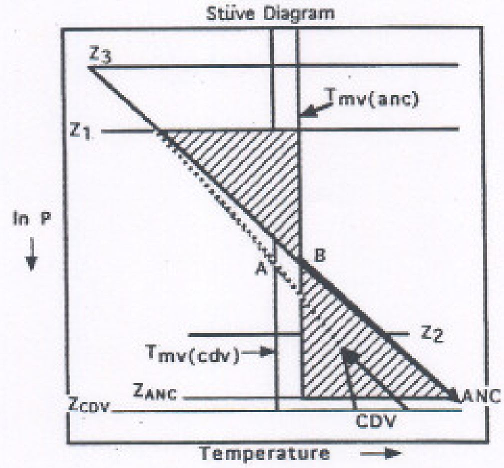


FIG 8d

Stüve Diagram



Now mean virtual temperatures (thickness) are not readily available for a layer of a variable pressure interval, which is dependent on the maximum height, obtained by the parcels. The 1000-500MB thickness layer consequently was examined to see if the thickness relationships that probably must be present in the layer involving the parcel, would be reflected through this deeper standard layer that is normally analyzed and forecast on weather charts. The lifted parcel will invariably be mostly a moist adiabatic process due to both (1) the prefrontal conditions necessary for Chinook winds, and (2) the source of Chinook air being from the moist Pacific Ocean. This means the least amount of external forcing is needed when the mean temperature over Anchorage is nearly equal, or slightly warmer, than that from the source area.

The new Chinook wind parameter #3 was thus assigned numerical values, by converting source area climatic mean sea

surface temperatures (SST) of PWS near CDV, into thickness values (List, 1949) as determined by a completely moist adiabatic environmental lapse rate from the seasonal SST values. The stability criteria #3 for Chinook winds to develop, is that the observed or forecast thickness value at ANC must equal or exceed that of a moist adiabatic lapse rate from the SST of PWS.

This initial estimated limiting lower thickness value was found to be slightly too high to allow for cases in which the surface moisture or pressure was lower than normal, so probability curves for lower thickness values to account for these considerations, was empirically derived as shown in Fig. 9. This figure is quite useful in making Chinook wind predictions as much as 36 hours in advance, but probably has the most value in determining which strong southeasterly surface pressure gradient situations have no significant chance of resulting in Chinook wind storms.

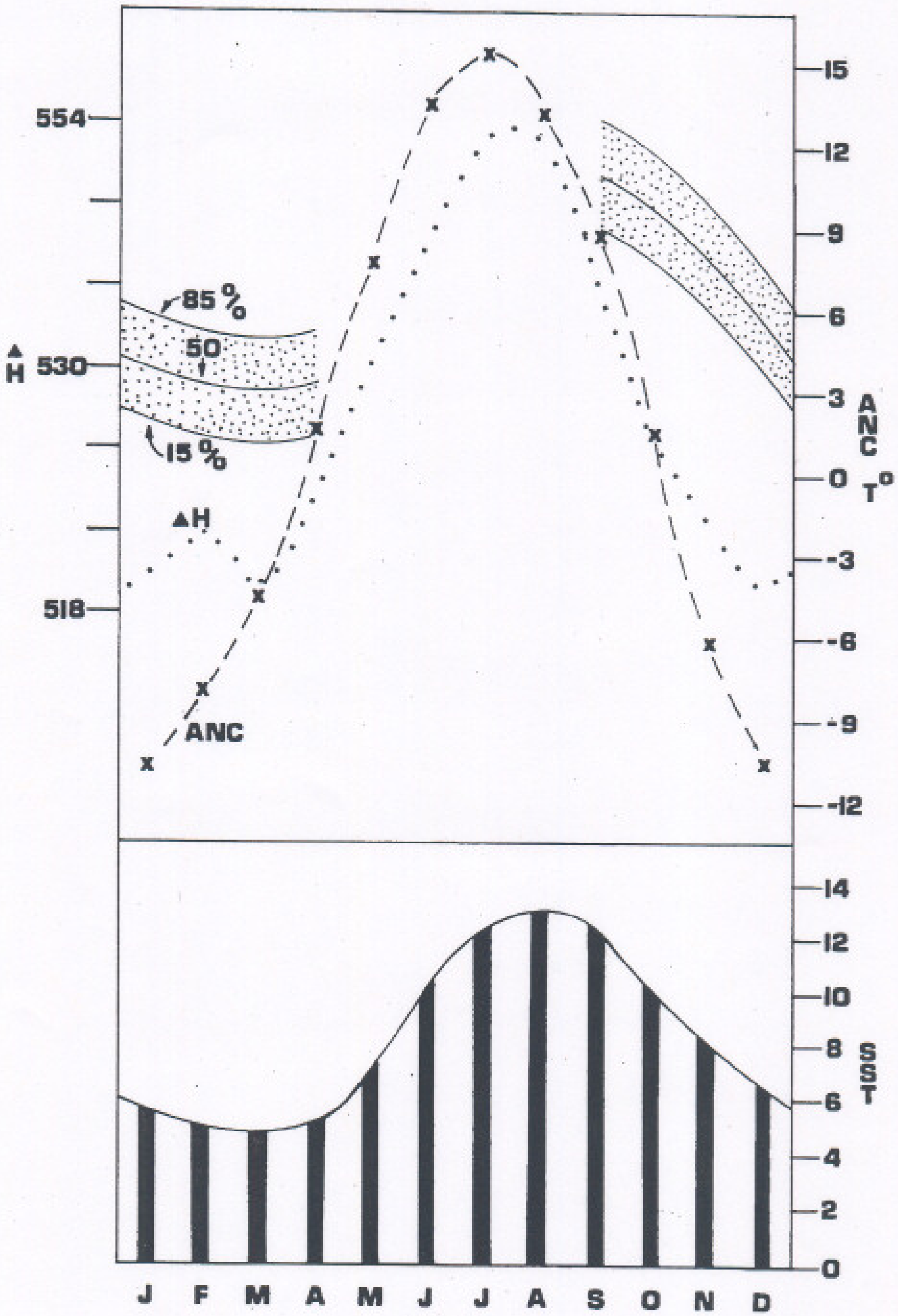


FIG. 9.

FIG. 9. The Anchorage average thickness curve (dotted line based on climatology) crosses the Chinook wind lower limiting 1000-500mb. Thickness set of probability curves in two places. Chinook wind events occur more often at these times at the end and beginning of the cooler seasons as should be expected. The probability curves 15%, 50% and 85%indicated the probability of Chinook winds when all the other three requirements have been met.

The three parallel curves of thickness values chosen were assigned percentage values as indicated from observed thickness values from an initial small sample of 9 Chinook wind events from 1978 to 1980. The curve marked TANC is the Anchorage climatological mean surface temperature. The area where this curve rises above the SST climatological curve for the southeast portion of PWS approximately coincides with the non-Chinook wind seas at Anchorage. Note that a thickness value is being used here to determine whether the air mass at CDV is absolutely stable, a criteria necessary for Chinooks to occur. The thickness value can be an exact means of determining the mean stability if it is used in conjunction with other CDV surface weather parameters. If the temperature, moisture, or pressure would be higher than normal for the season, a particular thickness forecast for CDV might not be high enough to insure a condition of absolute stability in such a case. Consequently, only probability values can be assigned to particular thickness values when using this SST curve as a first guess as to whether the CDV surface air is stable.

A nomogram (Fig. 10) was later constructed to improve on climatological considerations indicated in Fig. 9, to fully integrate four actual or forecast surface parameters. These surface parameters of temperature, moisture and pressure at CDV along with the expected maximum effective pressure difference CDV-ANC can yield three important parameters as shown in Fig. 10. This nomogram not only indicates the lowest allowable thickness value at ANC conducive for Chinook winds, but also an upper thickness limit, thus providing a narrow allowable thickness window. The maximum temperature to expect at ANC due to the compressional heating during the Chinook winds is also determined (often a record breaking temperature for that date).

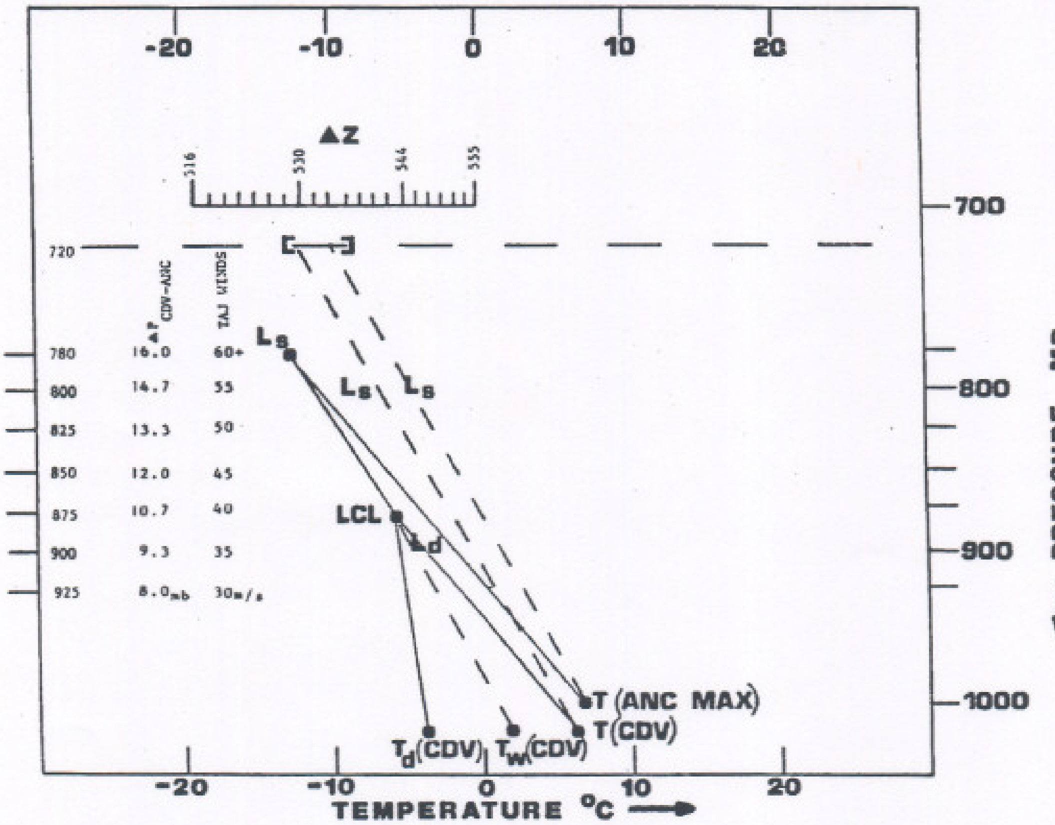


FIG 10

Nomogram used to forecast the highest temperature at ANC associated with a Chinook wind event. See text 4.a. and 4.b. for explanation.

Fig. 10 is used by entering the current or short range forecast of temperature T(CDV) and dew point Td(CDV) at CDV at the proper surface pressure level. The parcel then is lifted adiabatically to the pressure level shown on the left side of the nomogram that corresponds to the highest expected TAJ velocity. This is because it was found that the horizontal kinetic forcing perpendicular to the mountains was proportional to the apparent height obtained by the parcel (Fig. 8c)

as indicated by the resultant temperature after sinking and warming adiabatically. Since a TAJ of 61 m/s is equivalent to an effective pressure difference CDV-ANC of 20 MB, a 20% allowance for the isallobaric portion of this difference would equate to an expected actual pressure differential of 16 MB. The parcel is then lowered dry-adiabatically to the current or forecast surface pressure at ANC. This surface temperature can be expected if Chinook winds sink below the 300-meter level of the Chugach Mountains. The 1000-500mb thickness window shown as DZ is from 529-534 decameters. This window of values that will allow Chinook winds is obtained from the moist adiabatic temperature curves from the CDV data, and the moist adiabatic thickness from the just derived ANC maximum expected temperature. The temperatures at 720 MB are used as the mean virtual temperature of the 1000-500 MB layer and are directly converted to 1000-500MB thickness values for those temperatures (List, 1949).

Since no verification has been done on the presumed upper thickness limit other than noting in the first nine Chinook cases studied that those derived values were never exceeded, only the lower limit is of primary concern. This derived lower thickness limit corresponds to the thickness expressed by the percentage curves from climatological considerations shown in Fig. 9. It is only presumed that such an upper thickness limit exists because too warm an air mass over the waters of PWS would prevent the surface air from lifting out of the Sound due to the implied high static stability at low levels.

Although Fig. 10 was based on eight of the first nine Chinook storms studied, the actual illustration shown is of the April 1, 1980 storm and Anchorage. The thickness value at the time of this storm of 533 decameters fell within the window indicated, and exceeded the climatological 85% lower thickness limiting value of 532 decameters indicated in Fig. 9.

The temperature accuracy obtained with these eight storms was +/- 0.6°C from the official high temperature recorded in the Chinook belt at ANC. These maximums were up to 1°C cooler and their occurrence being delayed up to several hours from those reported in the stronger wind Chinook zone at the time the maximum TAJ was calculated. The computer program being used in 1987 lifted the parcel 173 meters/effective $\triangle$P (CDV-ANC), starting at 673 meters once the minimum differential of 8MB is met, up to a maximum of 2141 meters. Four inputs indicated in the first paragraph on page 17 were used. The program prints the latest CDV, ANC, and other PWS surface observation to help in choosing values for these four items. No significant loss of accuracy was noted in the temperatures calculated by the computer this way in more than 35 cases tested after the program was implemented.

e. Environmental vs. Chinook parcel temperature profiles

When Chinook winds suddenly sink to the surface in east Anchorage, there is no sudden change in the surface pressure noted at ANC. In fact, the pressure trace is generally quite flat or falling slightly. Consequently, mass has been conserved in the total air column as the environmental air is displaced by the pseudo-adiabatic parcel air, and no significant change in the mean temperature in the 100-500MB column takes place either. However, the temperature profiles observed before and during a Chinook wind event at Anchorage show considerable change from the surface through the 500MB level (fig. 11). The greatest change in parcel temperatures during these events takes place in the lowest layer. The descending parcel assumes a dry adiabatic lapse rate from the top of the mountains (1200-1500 meters) to the surface. The layer above is moist and follows a moist adiabatic lapse rate up to about the 2450-meter level, to be capped by a 300-600 meter subsidence inversion.

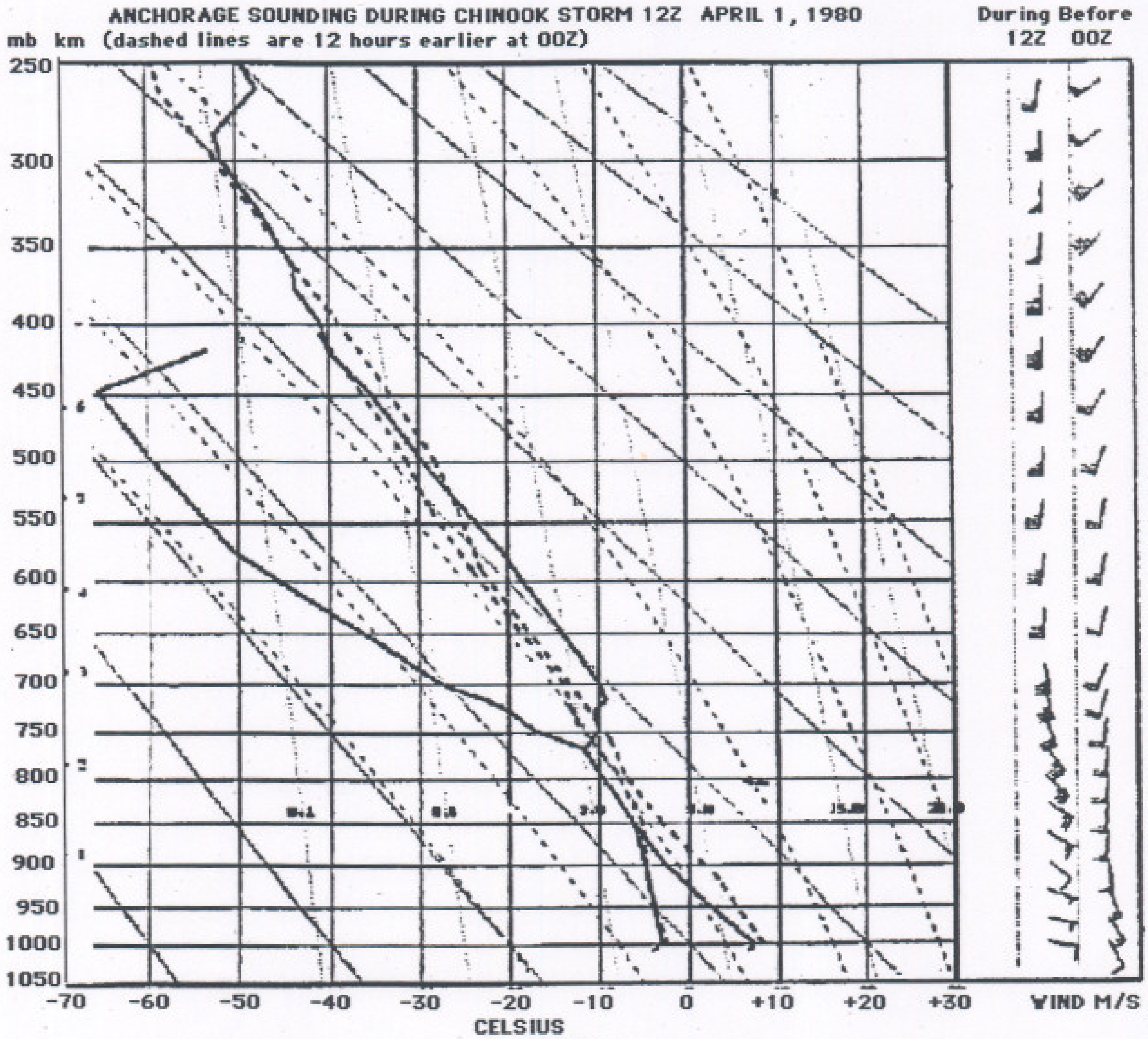


FIG. 11.

Anchorage radiosonde Stüve diagrams before and during the worst Chinook storm April 1, 1980. The 1000-500mb thickness value remained unchanged from the environmental area sampled at 00Z (GMT) and the pseudo-adiabatic Chinook wind air sampled at 12Z. The calculated surface geostrophic+A wind at the release time of the 12Z radiosonde was 45 m/s from 176°, nearly equal in magnitude and direction to the observed winds of 33 m/s from 170° at 700 MB and 36 m/s from 180° at 500 MB.

Since the mass was conserved, only a rearrangement of air mass densities has taken place. The resultant rearrangement in the air densities below 500 MB were so extreme in this case, that the reported temperatures in this meso-scale event at 12GMT could not be used for normal synoptic scale upper air analyses. Since the actual temperature profile only indicates whether environmental or Chinook (parcel) air was sampled because of time or location considerations, a typical Chinook temperature profile must be considered an effect and not the cause of Chinook winds. Consequently, only the thickness or mean virtual temperature of observed or forecast temperature profiles seem to offer precursory information about the probability of Chinook wind events, since upstream soundings from ANC are not available.

f. Quasi-barotropic atmosphere

The final property of the larger scale flow found necessary for Chinook winds to develop at Anchorage was a quasi-barotropic atmosphere below the 500 MB level. This was determined by comparing only those synoptic situations that met the three previously discussed criteria involving surface pressure gradient orientation, intensity and stability (thickness values). Remember that the thickness of the environmental air mass at Anchorage must be equal or slightly higher than that at CDV, and that this value probably must exceed those indicated by a nearly moist adiabatic lapse rate from the seasonal SST of PWS. In addition, the thickness value at Anchorage must fall within a narrow window determined by the moist adiabatic lapse rate from the derived high temperature at Anchorage, and another thickness

value for the lifted parcel from CDV under the influence of onshore flow from the Pacific. It is not known or implied that this narrow thickness requirement is common to Chinook type wind situation elsewhere, however it would be surprising if this were not so.

A quasi-barotropic air mass implies that the flow aloft at the 700 and 500 MB levels be nearly equal in direction and magnitude of the calculated surface geostrophic flow. The necessity of a barotropic atmosphere also has a long list of other implications and clues, which can be employed in making these forecasts. Some of these implications are:

(1) Cold or warm advection cannot occur under barotropic conditions and therefore sustained surface pressure rises or falls should not be expected during Chinook wind events at Anchorage. The previously noted pressure falls during some Chinook wind occurrences may be due to either weak warm advection, or movement of a barotropic system.

(2) One of the few places to find quasi-barotropic air embedded in the baroclinic area usually associated with the requisite strong surface pressure gradient and high thickness values, is in the warm sector of a frontal system.

(3) Since the warm sector of a frontal system is on the anti-cyclonic shear side of the jet stream aloft, a southerly jet stream must be just west of Anchorage.

(4) The 1000-500 MB thickness ridge, where the thickness gradient is flat, must be over the ANC & CDV area in order for the thickness values to be nearly equal and unchanging. Otherwise, the thickness values at either ANC or CDV would change too fast to stay within the allowable thickness window needed for the production of Chinook winds.

Although the above rules are normally viewed from a static position, it should be remembered that these necessary barotropic areas are seldom stationary. Cold advection first reaching CDV from the southeast during a Chinook wind event (Fig. 12c), will normally indicate a temporary, but false increase in calculated Chinook velocities from the TAJ equation, due to the probable presence of an intervening cold frontal pressure gradient discontinuity. The 9th case mentioned in section 3d in which the strongest reported Chinook velocities did not fall within +/- 8% of 87% of the TAJ, fell into this category. Chinook winds in this case will likely continue at the previously calculated velocities until the colder air has time to travel the intervening 258 km distance CDV to ANC. The first indication of strong pressure rises at CDV (indicating cold advection), signal the end of the Chinook event within the next few hours at Anchorage. This is probably because of the sinking flow in the colder air down isentropic surfaces will not allow this air to be lifted or forced out of the Sound any longer due to stability considerations, besides, the calculated geostrophic+A wind direction would likely not remain in the allowable window from 148° to 196°. However, this air can still go around mountains resulting in increasing TAJ velocities even though the Chinook storm has ended.

FIG 12

(a) (b) (c)

FIG. 12. Typical synoptic frontal and thickness patters conducive for Chinook wind events along the west slopes of the Chugach Mountains. Anchorage is: (1) in the quasi-barotropic warm sector where thickness values are nearly equal or exceed those at Cordova; (2) the surface gradient here is mostly likely to meet the limiting directional (196° - 148°) and magnitude (>20 m/s) requirements: and (3) thickness values (>531) decameters) are most likely to be nearly equal or exceed those of a most adiabat from the SST of Prince William Sound.

Pattern a) Associated with widest Chinook wind zone (Fig. 4) when the thickness value at Anchorage (A) is higher than at Cordova (C), causing Chinook winds to sink to the lowest elevations.

Pattern b) Associated with longest Chinook wind duration when minor waves on a cold front temporarily stall the strong gradient ahead of the front, over Anchorage.

Pattern c) Associated with short duration Chinooks which are normally restricted to higher elevations and often can only be forecast from satellite meteorology if they were below the resolution afforded by NMC guidance.

If strong pressure rises (indicating cold advection) reach Anchorage before Cordova (Figs. 12a and 12b), Chinook winds will immediately stop since the Chinook air arriving from the east will be forced aloft over the colder air arriving from the west. In addition, a strong deceleration factor will rapidly diminish the calculated TAJ moving west out of Turnagain Arm. Some occurrences of a negative isallobaric term being so great that a strong easterly TAJ shifts to a weak westerly one, has been supported by observation.

g. Forecasting by numerical forecasts and prognostic charts

Four criteria found necessary for the production of Chinook winds at Anchorage are: (1) limiting window of surface geostrophic+A wind directions (196° - 148°); (2) limiting minimum component across the Chugach Mountains (TAJ > 25 m/s) which is equivalent to approximately a geostrophic+A component along 196° of 20 m/s; (3) a condition of barotropy; and (4) a limiting 1000-500 MB thickness window. Routine National Meteorological Center (NMC) prognostic charts or numerical forecasts, provide all the necessary information to forecast Chinook winds since they provide:

1. Forecast of the 1000-500 MB thickness values
2. Thickness gradients or other evidence of a condition of barotropy
3. The surface pressure gradients
4. The orientation of the surface gradient

Chinook wind forecasts at Anchorage are thus largely dependent on the accuracy of these chart or numerical forecasts for nearby stations.

h. Forecasting by satellite imagery

Prognostic charts and numerical forecasts cannot be expected to handle the meso-scale vorticity centers frequently apparent in satellite imagery, especially those that move rapidly and have a short life span. NMC charts or numerical forecasts often will not reflect short-lived strong pressure gradients and associated large acceleration factors which can result in effective pressure differences conducive for Chinook storms. Satellite imagery, besides being extremely valuable in locating the anticyclonic shear side of the jet stream necessary for Chinook winds, can even be the primary forecast tool as long the thickness considerations for the season as indicated by Figs. 9 & 10 are met. Modeling meteorological parameters in the vicinity of a rapidly moving upper cloud circulation center (Carr, 1985) as shown in Fig. 13, can often provide the other three parameter values necessary for the production of Chinook winds. The center, which is the focal point of the cloud hook or spiral, is frequently referred to as a vorticity center. The term "vorticity center" will not be used here to avoid confusion with the point of maximum vorticity frequently modeled by NMC upstream of the upper cloud circulation center seen in satellite imagery. In order for closed flow to be evident in motion pictures of the cloud circulation center, there has to be return flow seen moving in the opposite direction the center is moving (translating), with respect to the Earths surface. This means that for an upper cloud circulation center to move (translate) at a speed of 30 m/s to the east in the northern Hemisphere, the velocity maximum just to the right of the circulation center is translating, has to exceed 60 m/s. Otherwise closed flow with some westerly flow in the opposite direction on the left side would not be apparent. Although there is no rules governing the horizontal shear possible on the left of this wind maximum, inertial instability considerations allow modeling on the other side of concern. Since the modeling of isotachs aloft over the warm sector of a frontal system should also be reflected in the geostrophic surface flow velocities due to a condition of barotropy, surface Chinook gusts can be estimated at 75 to 90% of the respective isotachs at the jet stream level which one would project to pass over Anchorage. These upper cloud circulation centers must approach the vicinity of Homer, Alaska from the SE or SSE to meet the directional requirements of geostrophic+A flow previously indicated as a requirement for the production of Chinook winds at Anchorage. The rapid movement of some cloud circulation centers allows timing of these particularly short 1-3 hour Chinook events to within an hour or two. These upper cloud circulation centers typically are elongating along the direction of movement as they move onshore, and continue to shear out and dissipate as they move inland. Summarizing these three satellite derived parameter considerations:

(1) The cloud circulation center (comma cloud) must approach from an angle of 148-196° since this should be the approximate angle the surface of the warm sector isobars, which normally align with the surface geostrophic wind angle.

(2) The limiting minimum of 25 m/s must be exceeded by the isotachs projected to pass over Anchorage by using standard modeling techniques while packing the highest velocities into the smallest possible area. On this anticyclonic shear side, this would be decreasing the velocities at a rate of 10 m/s per degree latitude. (3) The limiting minimum velocity must be exceeded in the modeled warm sector area of a frontal system (where a condition of barotropy is met).

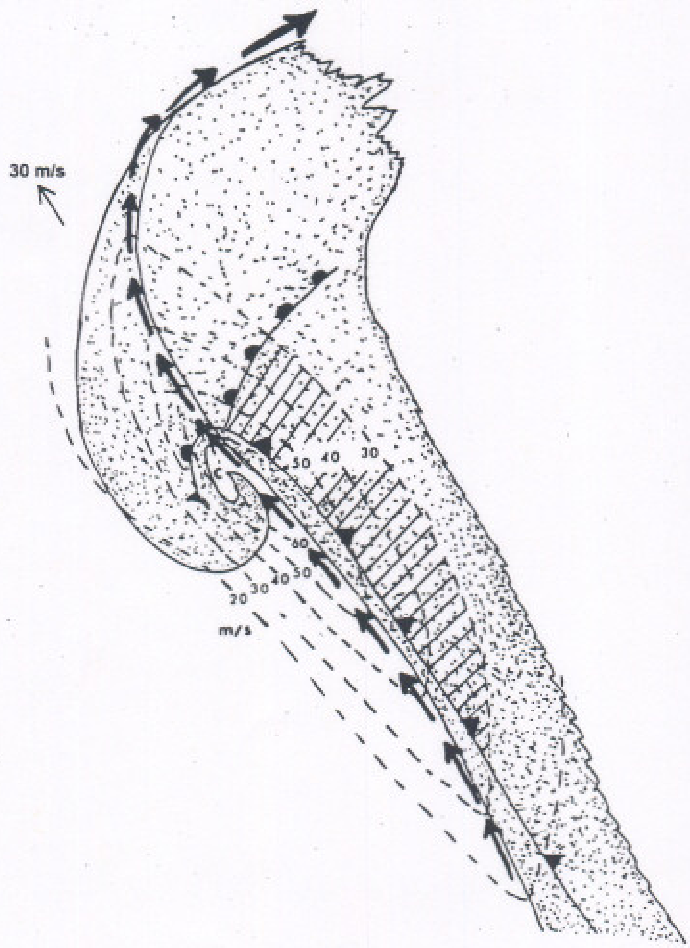


FIG 13

Upper circulation comma cloud pattern as seen in satellite imagery, showing modeled isotachs for a system translating at 30 m/s in the direction of the jet stream arrows. The isotachs spaced as close as 1 degree latitude per 10 m/s of horizontal shear in the warm sector area of the modeled frontal system, results in the smallest possible area of Chinook wind potential. The highest isotachs used as a reference is modeled by using 2 times the speed of translation.

If these three satellite picture derived criteria are expected to be met or exceeded at a time when 1000-500MB thickness values are forecast to exceed the seasonal values indicated in Fig. 9, then a Chinook wind forecast based on the respective probabilities indicated in Fig. 9 can… and should be issued.

i. Indirect hourly monitoring by computer and automated forecasting

While short-term forecasts of three of the four criteria can sometimes be made from satellite meteorology, all four criteria can be monitored on an hourly bases. The first two criteria involving direction and speed can be derived from normal hourly aviation weather reports, and subsequently monitored. Although the third and fourth criteria cannot be monitored directly, certain proxy variables for them however can be monitored directly. The computer routine uses the smoothed surface pressure trace at ANC as a proxy variable for a condition of barotropy. The empirical limits placed on

the pressure trace at ANC are a pressure fall less than 1.2 MB/hour and a pressure rise of less than 0.5 MB/hour.

The surface wet-bulb temperature difference between CDV and ANC is used at a proxy variable for monitoring thickness considerations. The thickness value as it is used in the study in itself is already a proxy variable for determining the mean stability of the 1000-500MB air column at ANC. The surface wet-bulb temperature difference from CDV to ANC must be +/- 2.5°C at all times during a Chinook event wherein the winds scouring the mountainside sink below the 300-meter contour at ANC. The reason is that in order to have enough surface pressure gradient for Chinook conditions, the zone of strong gradient upstream from ANC will normally be wide enough to extend even east of CDV, and therefore the wet-bulb temperature at CDV will be representative for the PWS source region. This wet-bulb temperature roughly estimated by taking the mean between the dry bulb and dew-point temperatures, then acts as a reference to compare with ANC to see if both are in the same air mass. The explanation of Fig. 8 on pages 14 & 15indicates there are two possible ways (or a combination of both), which will allow the lifted parcel at CDV to sink as a Chinook at Anchorage. Although the first method involving the use of horizontal forcing was used in Fig. 10, evidently the second method (Fig. 8d) is also involved to some extent. This is indicated by the following guidelines relating to set-bulb temperature differences observed (ANC-CDV).

1) -2.5°C Infrequent Chinook wind gusts down to the 300-meter elevation contour on the west slopes of the Chugach Mtns.

2) -1.7°C Frequent gusts below the 300-meter contour, and extending west up to 3.2 km beyond this contour

3) 0.0°C Frequent gusts at the surface up to 4.1 km west of the 300-meter contour

4) +2.5°C Frequent gusts up to 5.5 km west of the 300-meter contour

For estimated wet-bulb temperature differences greater or less than 2.5°C, the trough of the standing wave (if any) does not reach the surface below the 300 m contour. It is assumed that guideline 4 above only occurs when the thickness at ANC is slightly higher than that at CDV as indicated by method (b) in the discussion of Fig. 8. This window of allowable wet-bulb temperature differences of only 5°C has never been breached since it was first used… on more than 65 Chinook events. Since such a window exists in the surface wet-bulb temperature data, it is unlikely that an upper thickness limit does not exist as indicated in Fig. 10. The fact that the normal thickness window of 6 decameters as indicated by Fig. 10 (a mean virtual temperature range of 6°C) is almost the same as the surface wet-bulb temperature difference of 5°C, is probably not a coincidence.

j. Automated Chinook computer monitoring and written forecast generation

Half backlighting the video CRT display of the above parameters that fall within the criteria limits, with full backlighting on hourly observations and calculations in which all four criteria are met simultaneously, alerts the forecaster and provides a method to indirectly monitor the intensity and aerial coverage of existing Chinook winds. Trends in the parameters in the monitoring display can be used as forecast tools. Other Chinook program options include notes, pertinent observations, and high temperature calculation from latest observed or forecast parameters used in Fig. 10, and other items of interest. The most important program feature is the automatic generation of Chinook wind situation as to time of the beginning and ending and velocities to be expected on the hillside. This forecast is generated only when all four Chinook parameters are forecast as determined from NMC numerical forecasts, with the exception that the initial NMC parameters have been adjusted to match current observations.

k. Reliability

The restrictions placed on the four criteria shown necessary for the development of Chinook winds in this paper, have proven to be extremely reliable in the last 40 cases. In the last 40 local Chinook wind events, all met the previously indicated criteria, and were verified by the cooperative observer network formed after the damaging windstorms in 1980 that did an estimated $60,000,000 in property damage. All issued forecasts by the NWSFO of "strong winds along the hillside" (Chinooks) resulted in winds in excess of 18 m/s to be observed. Normally, only 50% with gusts to 75% of the highest gust expected when using 87% of the TAJ projections are issued in the public forecasts. This is done to provide the most representative forecast for the hillside area, rather than mention the extremes that are more restricted to the higher and less populated areas.

There was one case after 1982 in which Chinook winds which I coined ChuWally winds (Chugach Mtns. + Wally, since natives of this area didn't refer to this weather event by a specific name), were forecast. However they did not develop, because forecasters only used three of the four necessary criteria. To help prevent a reoccurrence of such an error by making the forecast technique less subjective, a completely objective computer written Chinook wind forecast was developed.

There was also one case after 1982 in which Chinook winds occurred during a very short 2-hour period when none were forecast, because the falling pressure tendency of 1.3 mb/hour exceeded that in the computer of 1.2 mb/hour. This limit was never adjusted in order to discriminate as much as possible, and the same problem had not repeated in the following four years. This however points out that the accuracy in determining these winds is dependent on the skill in forecasting whether the meteorological parameters will fall within the defined limits. Since this study began, Chinook wind forecast verification by the Anchorage NWSFO improved from the 0% during all the years from 1960 to 1980, to about 95% on the 21 events immediately prior to April 1985. Verification was based on whether winds in excess of 18 m/s were reported when strong hillside winds were forecast, and not on the actual velocities forecast. Forecasters issued 22 Chinook wind forecast and 21 were observed, but on one that was forecast, the warning issued was cancelled prematurely before the strongest winds actually occurred.

The computer-monitoring program indicated only 20 of the 21 occurrences because of the excessive pressure tendency noted above. The objective LFM program missed one of the 21 by under-forecasting a gradient that was much stronger. When considering that a verification rate of 30% might be good for rare weather events, it is gratifying to go from a zero verification rate in 20 years up to 1980, to nearly 100% within a few years as this Chinook wind study was being developed. Not only were the wind forecasts improved, associated temperature forecasts improved nearly as much. High temperature forecast errors of as much as 20°C were common from these unexpected Chinook wind events prior to 1980. High temperature forecasts now are much better, but still are usually under forecast, even though the tools to do better are now available.

L. Conclusions

A common criteria examined in many discussions on Chinook winds by others, is the wind magnitude and angle of attack at the height of the mountain ridge. For instance, one author (Alaka, 1967) states, "Forchtgott's observation that the wind should be nearly normal to the mountain ridge for waves to be possible, is also confirmed by other observers. It is generally agreed that unless the wind direction is within about 30 degrees from a direction normal to the mountain ridge, no well-defined standing waves can be maintained." Although this may also hold true at Anchorage, examination of the surface geostrophic+A angle seems to offer a more definitive criteria and is available on an hourly basis. They avoid problems inherent in dealing with measurements taken in either environmental or Chinook (parcel) air at levels affected by varying amounts of drag and frictional ageostrophic components.

When using the geostrophic+A directions, different limiting angles of parallel to about 45° to the right of parallel to the mountain ridgeline, were found. In addition, it was found that optimum conditions for Chinook events at Anchorage should have winds aloft above the frictional zone (about twice the height of the mountains) to the 500 MB level equal in magnitude and direction to the calculated surface geostrophic+A winds (thus no shear), with velocities at these levels in excess of 20 m/s (Fig. 11).

The source of Chinook air at Anchorage is surface air from the windward side of the mountains with little or no significant entrainment from above, and Chinook events are a pseudo-adiabatic process. Once the wet-bulb temperature at the surface on the windward side is representative of that air mass, a precise wet-bulb temperature difference exists between the windward and lee sides of the mountain that will allow mountain waves to surface as Chinook winds. In addition, this difference is related to the vertical and/or horizontal extent of the Chinook wind zone.

This study and forecast technique departs from others by finding that the lower and middle tropospheric thickness patterns and values between the lee and windward slopes are equally as important as pressure orientation and magnitude considerations in Chinook wind events. Upstream wind and temperature profiles, in fact, were not even available for this study. Since thickness values are dependent only on the vertical mean temperature and not the vertical temperature profile and associated stabilities for thinner layers, only the relationship between these thickness values from the different sides of the mountains were found of primary importance. The typical downstream Chinook wind temperature profile (12 GMT in Fig. 11) is therefore considered an effect of the Chinook winds, and not a cause. Upper level temperatures sampled in the massive adiabatic meso-scale Chinook areas vary significantly from that of the environmental air. Therefore, these readings should not be used in synoptic scale upper air analyses. Any discussion of stabilities during these events seems inappropriate without additional data, and unless a distinction is first made between, the scales (synoptic versus meso) and the air involved (environmental versus parcel).

Acknowledgements. The author acknowledges those on the staff of the National Weather Service, Anchorage, Alaska. Special thanks to Stuart Bigler and wife Jeanne for their encouragement; to Frances Parmenter Holt and Albert Comiskey for the encouragement and editing; and to David Henry for the challenge he gave.

REFERENCES

Alaka, M. A., 1967: Aviation aspects of mountain waves. Tech. Note No. 18, WMO, pp. 11-27.

Anderson, R. K., Jerome P. Ashman, Golden R. Farr, Edward W. Ferguson, Galinna N. Isayeva, Vincent J. Oliver, Frances C. Parmenter, Tariana P, Popova, Rance W. Skidmore, Arthur H. Smith and Nikolai F. Veltishchev, 1973: The use of satellite pictures in weather analysis and forecasting. Tech. Note No. 124, WMO, p. 219.

Carr, Frederick H., James P. Millard, 1985: A composite study of comma clouds and their association with severe weather over the great plains. Mon. Wea. Rev., 113, pp. 370-387.

Glenn, C. L., 1961: The Chinook. Weatherwise, Vol. 14, pp. 175-182.

Hess, S. L., 1959: Introduction to Theoretical Meteorology, Holt-Dryden, pp. 63-103.

LaBelle, Joseph C., James L. Wise, Richard P. Voelker, Robert H. Schulze, Gary M. Wohl, 1983: Alaska Marine Ice Atlas, Univ. of Alaska, pp. 100-115.

List, R. J., 1949: Smithsonian Meteorological Tables. Smithsonian Institute Press, pp. 141-244.

Mathews, T., Lester, P. F., Hicks, R. B., 1984: Sodar Observations of Chinooks and Arctic Front. Atmosphere-Ocean, 22, 331.