Warm Air Advection and the Development of Barrier Jets in the Northern Gulf of Alaska

JOHN M. PAPINEAU
National Weather Service, Anchorage, Alaska

February 18, 2000

SUBMITTED TO WEATHER AND FORECASTING

Corresponding Author Address: Dr. John Papineau National Weather Service,
6930 Sand Lake Road, Anchorage, AK 99502 email: john.papineau@noaa.gov.us

ABSTRACT

This paper describes two well developed barrier jets that formed in the northeastern Gulf of Alaska, near the town of Yakutat. During the cooler months of the year barrier jets are a common occurrence in Yakutat as warm moist air from the south and southwest is blocked by the very steep terrain of the St. Elias Range. One of the important results of this study is that the typical Yakutat barrier jet develops when warm mid-level tropospheric air moves over the St. Elias Range. This warm air produces very high values of static stability at mountain crest levels.

In addition, there is little evidence of the formation of a dome of cold air on the windward side of the St. Elias Range during barrier jet episodes. This could be due to 1) the low resolution of the surface observations in the region, or 2) it may indicate that additional processes are operative in cases where the terrain is extremely steep. If the latter is true, than blocking upstream of the St. Elias Range may occur because of dynamic processes. Strong summit-level cross-barrier flow could generate upstream propagating gravity waves, which would in turn decelerate low-level onshore flow. As a consequence, a region of high pressure would be produced over the windward slopes, which may create a barrier-parallel wind jet if the synoptic and meso-scale pressure gradients are large enough.

During the onset and dissipation of barrier jets it is common for the surface winds at Yakutat airport to remain light, while between 300 m and 1500 m the winds are on the order of 15-25 m s^{-1}. In addition, pressure differences between Yakutat and other coastal stations give a rough indication of strong barrier jet winds, but are not in general highly correlated with surface wind speeds at Yakutat. As a result of this study, a simple conceptual model of the life cycle of Gulf of Alaska barrier jets is presented.

1. Introduction:

Strong along-shore winds are a common occurrence from September through April along the coastline of the northern Gulf of Alaska (referred to as the Gulf). These winds occur in association with deep low pressure systems that migrate through, or intensify in the Gulf. It is the juxtaposition of relatively warm Gulf water, high mountains, large glaciers, extensive snowcover, and cold Arctic air that facilitates the development of deep lows in the Gulf during the cooler months of the year. When a high amplitude ridge builds over western Canada, Gulf lows often become quasi-stationary or move north to northeast up the west side of the ridge, advecting warm moist air into Alaska. Strong low-level along-shore winds or barrier jets are frequently observed in the communities of Yakutat and Cordova when a deep low is positioned in the western or central Gulf. These wind events, especially those that are poorly forecasted, are a serious hazard to both the aviation and marine communities. Wind shear, especially speed shears are the primary hazard to pilots, while a rapid increase in near-shore winds and wave heights is a concern to mariners. Of the various types of strong low-level winds that can occur in this region, along-shore winds can be the most difficult to forecast due to their ageostrophic nature. In addition, due to the low resolution of operational Numerical Weather Prediction (NWP) models available to forecasters working this region, model output gives little direct indication of barrier jet formation along the Gulf coast. As a consequence, forecasters must recognize a particular synoptic pattern as being conducive to the formation of strong along-shore winds.

This paper reviews several cases of barrier jet events that occurred in the vicinity of Yakutat (YAK). The goal of this work is to develop a conceptual model of a barrier jet life cycle, in order to provide forecasters with a better understanding of how they form and dissipate. Actually there are several classes of strong along-shore (southeasterly) winds over YAK; those due to the southwest-northeast orientation of the synoptic-scale pressure gradient (coastal jets), and those due to the formation of barrier jets. There is some merging of these two types of wind jets as disturbances migrate through the Gulf. As a result, a strict definition of what constitutes a barrier jet along this particular northern stretch of the Gulf is not easy to formulate.

In the following section a brief summary of previous barrier jet studies and associated upstream blocking is presented. Section 3 consists of a geographic and topographic overview of the northeastern Gulf coast. In section 4 two YAK barrier jet cases are analyzed, while section 5 consists of a discussion of some of the principle elements of these cases. This paper concludes in section 6 where a conceptual model of the life cycle of Gulf of Alaska barrier jets is offered.

2. Barrier jets and blocking- a literature review:

Barrier jets have been observed and described in a variety of mountainous environments, including the Antarctic Peninsula (Schwerdtfeger 1975), the Sierra Nevada (Parish 1982, Marwitz 1983), the Appalachians (Bell and Bosart 1988), the Front Range of Colorado (Wesley 1991; Marwitz and Toth 1993), Vancouver Island and the Olympic Mountains (Overland and Bond 1995), as well as along the central California coast (Doyle 1997).

Bluestein (1993) offers an explanation for the formation of barrier jets. Due to large static stability above the windward slopes of a steep mountain range, and due to the adiabatic cooling of air as it tries to rise up the windward slope, geostrophically balanced low-level cross-barrier flow decelerates and becomes blocked. As air accumulates over the windward slopes it forms a localized area of high pressure (meso-high). Over the course of 4-8 hours, as the blocked layer expands vertically as well as upstream, the pressure in the meso-high continues to increase. As a result of the synoptic and meso-scale pressure gradients, a barrier-parallel wind (barrier jet) develops as air moves down the combined pressure gradient. In the Northern Hemisphere the direction of the barrier jet is to the left of geostrophic flow due to the decrease in the Coriolis deflection, which is a function of the speed of the flow. The width or upstream extent of a barrier jet is confined to the Rossby radius of deformation ($L= NH/f$), where N is the Brunt-Väisällä frequency, H is the height of the barrier, and f is the Coriolis parameter. In a theoretical study of cold air damming, Xu (1990) noted that the speed of barrier-parallel jets is a function of mountain height and the speed of the upstream cross-mountain flow.

Overland and Bond (1995) used scale-analysis in order to determine the flow properties of barrier jets. They suggest that barrier jets are best developed when the mountain Froude number (F_m) ~1. In this instance $F_m= (U/HN)$, where U is the mean layer wind speed. They point out that typically when $F_m << 1$, the upstream mountain-normal flow is too weak for blocking to become well developed, and when $F_m > 1$, N is usually small, allowing mountain-normal flow to move over the barrier. The authors document two cases of barrier jet development; the first on the Pacific Ocean side of Vancouver Island and the second on the westside of the Olympic Peninsula. Aircraft flight tracks through these cases revealed a roughly 50% increase in low-level wind speeds along the coastline, compared to winds further offshore.

Marwitz (1993) studied two barrier jet cases that occurred in the Sierra Nevada. In the first case he observed a +3 mb pressure difference over the windward slopes compared to the pressure at the same height 60 km upstream over the Central Valley of California. He attributed this pressure anomaly to the cooling of the air as a result of the melting of solid phase hydrometeors as they fell through the 700-800 mb layer. The second case occurred when regions of the lower troposphere were convectively unstable. Marwitz found that a line of convection located over the windward slopes helped to block some of the mid-level cross-mountain flow as well as transport low-level air into the middle troposphere.

Using the COAMPS model, Doyle (1997) investigated the partial blocking and formation of a coastal jet as a cold front approached the central California coast. He found that wind speed maxima were nearly coincident with near-shore pressure perturbation gradients. In addition, as the coastal jet formed between the coastal mountains and the approaching front, the speed of the front was reduced and moist Pacific air was forced to rise over the coastal jet. This process enhanced precipitation on the windward sides of the mountains as the coastal jet acts as “effective topography”, displacing ascending motion and subsequent condensation well upstream of the coastal mountains (Marwitz 1983, Marwitz and Toth 1993).

Pierrehumbert and Wyman (1985) used a simple 2D model to simulate barrier jets. Their model was able to confirm that barrier jets are confined within the Rossby radius of deformation from the barrier. They also noted that neither total blocking of the cross barrier flow or the geostrophic balance of the barrier-parallel wind are necessary for the formation of barrier jets. An import implication of their modeling effort is that terrain smoothing in numerical models reduces the strength of the blocked flow, and as a consequence, reduces the strength of the simulated barrier jet (Pierrehumbert 1984). The effects of wave breaking over a mountain barrier and the generation of upstream propagating columnar disturbances is discussed in Baines and Hoinka (1985), Pierrehumbert and Wyman (1985), as well as Smolarkiewicz and Rotunno (1990). Columnar disturbances are horizontally propagating gravity waves which typically move upstream of the barrier, decelerating the upstream flow, and producing a layer of blocked air in the process.

The work of Georgelin and Richard (1996) indicates that the transient nature of the Tramontana barrier jet that develops along the northern Pyrenees in the winter, is linked to transient blocking. The authors suggest that transient blocking is linked with the diurnal heating and cooling of the air directly above the slopes of the Pyrenees. The creation and dissipation of upslope and downslope thermal winds over the windward slopes augmented or weakened blocking.

In a modeling study of flow past mountain ridges of various heights, Olfasson and Bougeault (1996) found that air in the upstream blocked-zone displayed an oscillatory nature in terms of surface pressure fluctuations and vortex development. They attributed this to the quasi-stationary behavior of wave breaking which occurs over the ridge. In addition, for a constant inflow speed, they found that the pressure over the windward slopes increased dramatically as the height of the terrain was increased from 1 km to 3 km (F_m from $1\rightarrow1/3$).

What emerges from both field and theoretical studies is that a spectrum of atmospheric processes is responsible for mountain blocking and if conditions warrant, the subsequent development of a barrier jet. Two broad approaches can be considered: thermodynamic affects as illustrated by the work of Schwertfeger (1975), Parish (1982), Marwitz (1983), Mass and

Albright (1987), and Doyle (1997); or dynamic affects as stated by Baines and Hoinka (1985), Pierrehumbert and Wyman (1985), Smith (1990), Smolarkiewicz and Rotunno (1990), and Olfasson and Bougeault (1996). Despite our incomplete understanding of the blocking process, it is apparent that mountain blocking results from the pooling of higher density air over the windward slopes due to upslope flow or diabatic effects (Marwitz 1983; Marwitz and Toth 1993), or from wave breaking and upstream propagating columnar disturbances, or a combination of these processes. Smolarkiewicz and Rotunno (1990) point out the dependency of barrier aspect ratio β (barrier length/barrier width) on which of these processes occurs for a given flow scenario. When β is O(1) thermodynamic effects dominate, when $\beta \rightarrow 10$, dynamic effects become important. Although not specifically mentioned except by Olfasson and Bougeault (1996), the height or more importanly the relief of the barrier should play an important role as well. Over mountains of modest relief adiabatic cooling probably dominates, in regions with extreme relief, dynamic processes probably control blocking and upstream circulation patterns.

3. The Physical Setting

Figure 1 shows the geographic setting and the topography along the northern perimeter of the Gulf. The dominant features are the mountains which ring the northern and eastern sectors. The Chugach Mountains with a mean barrier height of 3000-3500 m (lower in the east) and a length of 375 km form the northern barrier. These mountains stretch from western Prince William Sound across the Copper River and terminate in the vicinity of the Bering Glacier (143^{o}W). The St. Elias Range (3000-5500 m) which starts in the eastern Copper River Valley (144^{o}W), arcs 480 km toward the southeast eventually terminating in the vicinity of Glacier Bay. The Coast Range (~2000 m) forms the eastern Gulf boundary and separates the maritime climate of southeast Alaska from the more continental climate of central British Colombia.

The small town of YAK sits on glacial deposits on the southern edge of Yakutat Bay. YAK is home to a small fishing fleet and is an important stop on the general aviation route between Southcental and Southeast Alaska. The National Weather Service (NWS) has operated a first-order weather station here since the 1920's. In addition, YAK is one of 13 active Alaskan upper air stations. The annual precipitation measured at the airport in YAK is 3.84 m. Precipitation events are frequent and quite often of high intensity. The frequency of precipitation is due in large part to the high frequency of cyclogenesis in the Gulf during the cooler months of the year. The intensity of precipitation is related to the influence that the St. Elias range has on the region via blocking and upslope flow. Due to the remote location there are, unfortunately, few weather or climate stations to be found anywhere along the coastline outside of YAK. One exception is the automated meteorological station at Cape Spencer (CSP), which is located on a spit of land just to the south of the St. Elias Range, not far from the entrance to Glacier Bay.

The St. Elias Range has a profound impact on the weather in the northeastern Gulf of Alaska. During the winter the St. Elias Range traps cold arctic air to the north, and conversely blocks relatively warm air from advecting into the Yukon Territory. The St. Elias Range consist of a number of identifiable sub-ranges. Lying some 80-120 km north and northeast of Yakutat is the main St. Elias Range with a number of summits lying between 4500-5500 m. This is an area of extensive glaciation, and as a result strong glacier winds frequently reach the coastline, including YAK. The 3800 km^{-2} Malaspina Glacier lies directly north of Yakutat Bay and has a significant impact on temperatures and surface winds across the bay, as well in YAK. The influence of the Malaspina Glacier on the weather and climate of YAK has never been documented, nevertheless glacier winds probably produce localized convergence zones over Yakutat Bay, and at other times produce a shallow cold pool of air over the bay and adjoining areas. The net result of this cold pool of air is to temporarily shield the surface from stronger winds that may be developing aloft.

Two sub-ranges of the St Elias Mountains which play prominent roles in YAK barrier jets are the Brabazon and Fairweather mountains which lie to the southeast of Yakutat Bay. The Fairweather Range which rises from sea-level to a barrier height of 3000-4500 m over a distance of some 30 km, is considered the highest coastal mountain range on earth. The Brabazon Range is considerably lower (~1500 m) but is situated directly to the east and southeast of YAK. Both ranges have a general southeast-to-northwest orientation (140^o-320^o).

Being in a data sparse zone, the northeast sector of the Gulf has received little attention from the meteorological research community in relation to the amount of extreme weather that occurs in the region (Reynolds 1983; Businger and Walter 1988). One of the exceptions is the work of Overland and Bond (1993) and their analysis of the 14 March 1979 Gulf of Alaska storm. This wind event was not properly forecasted by any of the operational NWP models that were available at the time. This subsequently lead to an under forecast of wind speeds and combined sea heights. In this particular case, south to southeast flow was predominate throughout the troposphere (coastal wind jet). The YAK sounding taken during this event indicated evidence of low-level (850 mb) wind amplification. One important aspect of this event was the documented rapid pressure rise that occurred at a number of coastal stations several hours after the passage of a cold front. This rapid pressure rise acted like a pressure surge which moved northwestward up the coastline to YAK. The strongest winds were observed to be at the leading edge of this pressure surge. Overland and Bond suggest that this surge was a type of Kelvin wave which was trapped by the high coastal terrain, although this explanation has been questioned by Steenburgh and Mass (1996).

As eluded too in the introduction, there is a continuum of flow regimes that produce strong southeast winds at YAK. These events range from short-lived coastal wind jets, such as occurred on 14 March 1979, to actual barrier jets which can have durations on the order of several days.

4. Cases Studies

In total, six barrier jet cases were analyzed, two of those cases are presented in this section because they represent typical examples. Data sources consists of surface observations including ship and buoy reports, upper air soundings from YAK, as well as surface maps drawn by forecasters in the Anchorage office of the National Weather Service. In addition, NCAR/NCEP re-analysis was also used extensively.

a) December 14-16, 1988

On 14 December a 967 mb surface low was positioned just off the southern tip of the Alaska Peninsula. This was the first of two surface lows which moved into the western Gulf from the southwest during the period. Aloft, a well developed 500 mb trough was positioned over the southern Bering Sea. Over the next two days this trough slowly moved eastwards into the western Gulf. Along the northern Gulf coast flow was from the south to southwest. At 1200 UTC 14 December (1200/14), there was evidence of a barrier jet developing near the town of Cordova (CDV) and along most of the northern Gulf coast. At the same time further to the east, surface winds at YAK were easterly at 4 m s^{-1}, however the 1200/14 YAK sounding indicated that a barrier jet was developing but had not yet reached the surface. This jet core was located between 300-1500 m (all heights will be given as: above ground level). Within this layer the average wind direction was from140^{o} with a mean speed of 11 m s^{-1}. Above this layer the winds were from the south to southwest as displayed in Figure 2.

The hand-analyzed surface map (not shown) indicates that a warm front was parallel to the north and eastern Gulf coastline at 0000/15. Figure 3 shows the 850 mb geopotential height fields valid at the same time. Notice the extremely long southerly fetch of subtropical air into the Gulf. The 0000/15 YAK sounding indicated easterly surface winds at 5 m s^{-1}, however at 200 m winds were from 125^{o} at 15 m s^{-1}, and at 600 m from 135^{o} at 23 m s^{-1}. During the following 30 hours as the first surface low moved into western Alaska and the second low moved into the western Gulf, the time average surface winds at YAK were 11 m s^{-1} from 120^{o}. The surface analysis valid at 1800/15 is shown in Figure 4.

By 0000/17 the surface and 850 mb low centers were located over western Alaska, while the 500 mb trough was positioned over the western Gulf. This signaled the end of the event as the low-level geopotential height gradients weakened considerably. The barrier jet event over YAK terminated between approximately 2100/16 and 0000/17 as the surface winds became light and variable. In addition, by 0000/17 the YAK sounding indicated light west to southwesterly flow extending from the surface to upper troposphere.

Storm total precipitation measured at YAK airport was 39 cm. During the initial phase of this storm precipitation fell in the form of snow, but by late on 14 December snow turned to rain. On 15 December, 26 cm of rain fell, setting the 24 hour YAK record. At the start of this event surface temperatures at YAK rose from -3^{o} to 6^{o} C over a 24 hour period. Temperatures remained constant at around 6^{o} C during the mature stage of the barrier jet, but cooled back down to 0^{o} as soon as the wind speeds diminished on 17 December. Figure 5 shows temperatures at four levels taken from the YAK soundings over the course of the event. Notice the large temperature rises at 500 mb and 700 mb at the start of the event and the 12-24 hour lag in rising temperatures near the surface.

b) February 25-28, 1992

During this period a series of three surface lows moved into the western Gulf, each one producing barrier jet winds in YAK. In the middle troposphere however, there was considerably less variation as a single 500 mb low slowly moved northward from Bristol Bay into western Alaska during the period. Due to the long southerly fetch of each of these disturbances, warm moist air was advected into the Gulf producing a storm total precipitation of 29 cm at YAK. The first barrier jet event occurred between 0600/25 and 1200/25, and was the weakest of the three events. At 0600/25 the surface winds were 10 m s^{-1} from 140^{o}. Over the next six hours the winds became southerly and dropped to 6 m s^{-1} as the surface low filled and moved into the northern Gulf. However the 1200/25 sounding showed continued southeast flow from 400 m up to about 2500 m, above which the winds veered becoming southwest at 5000 m. This type of feature may be considered an "elevated barrier jet" since the jet core never dissipates despite periods of weak surface winds. Elevated barrier jets seem to occur in association with either the movement or filling of Gulf surface lows. Determining how diminishing surface winds in YAK correlate to changes in the meso-high pressure field is problematic without higher resolution data.

At the start of the second event (0900/26) an elongated 987 mb surface low stretched from the North Pacific (55N 148W) into the Gulf, while a 1028 mb high was positioned over central British Columbia. At the same time the 500 mb low center was located near Cold Bay (CDB). The barrier jet reaches the surface at YAK sometime between 0700/26 and 1200/26 as indicated by the rapid increase in surface wind speeds. The 1200/26 sounding indicates a well developed barrier jet with 950 mb winds from 140^o at 26 m s^{-1}. A hodograph of lower tropospheric winds take from the 1200/26 sounding is displayed in Figure 6. Between 1200/26 and 0000/27 the surface winds at YAK vary from between 9-13 m s^{-1}, with a mean direction of 140^o. During this same period the 850 mb to 500 mb winds over the central Gulf range between 180^o-200^o as seen in Figure 7. As this second barrier jet developed, the Sitka (SIT) minus YAK pressure difference was +6 mb, 12 hours later (0000/27) it was on the order of +13 mb.

By 0000/27 a 982 mb surface low was positioned about 150 km south of Anchorage (ANC), while the 1029 mb surface high located over British Colombia remained relatively unchanged. There was little movement in the 500 mb low over Bristol Bay. In addition, a high amplitude 500 mb ridge located over western Canada helped funnel moisture into the Gulf from the subtropics. Between 0000/27 and 0000/28, the surface winds at YAK decreased from 9 m s^{-1} to 3 m s^{-1}, while the SIT-YAK pressure difference decreased to +3 mb by 1200/27. Both the 1200/27 and 0000/28 YAK soundings indicated that a barrier jet still existed in a layer just above the surface. At 1200/27 for example, the winds at 300 m were from 135^o at 12 m s^{-1}, and at 1400 m from 145^o at 20 m s^{-1}.

The third barrier jet event began around 0300/28 as YAK surface winds increased to 13 m s^{-1} with gusts to 25 m s^{-1}. This was in response to the third surface low which moved rapidly into the Gulf. By 1200/28 the surface low center was located over the interior of Alaska, equally important, high pressure over British Columbia had decreased significantly, weakening the pressure gradient over the eastern Gulf. The net result was that by 1500/28 the surface winds at YAK were from the west. Aloft, the 700 mb geopotential heights for1200/28 indicated that strong southwest flow was still occurring in the northeastern Gulf. The YAK sounding taken at the same time measured a 950 mb wind from 157^o at 25 m s^{-1}. Between 0000/28 and 1200/28 the surface to 700 mb winds veered by 20-30^o in response to the continued northward movement of the low center. The barrier jet diminished sometime between 1500/28 and 1800/28.

Select surface to 500 mb temperatures for this event are displayed in Figure 8. Notice the rapid rise in temperatures in the 700-850 mb layer during the early stages of barrier jet development. Also note the rapid decrease in temperatures at all levels as the event reached its conclusion.

5. Discussion

The salient properties of YAK barrier jets as revealed by the two cases studies presented in the previous section and from the analysis of a number of additional events are:

1) During barrier jet formation, warm air advection occurs in the middle troposphere, followed

some hours later by warm advection in the lower troposphere. This thermal advection pattern occurs in association with the onshore movement of a warm front. This type of strong warm advection should be anticipated since Gulf lows that produce barrier jets advect warm moist air from mid-latitudes and at times from the subtropics

2) The core of maximum winds occurs 300-1500 m above the surface. This is in agreement with the observations of barrier jets in the Sierras by Parish (1982) and Marwitz (1983), where the level of strongest winds were approximately 500 to 1000 m. Along the central California coastline, Doyle (1997) found that the jet core was typically located at about 500 m. Additionally, from time to time a well developed barrier jet is positioned above YAK, but there is little evidence of its existence at the surface. This is especially true of the 25-28 February 1992 event where the *surface winds* displayed three distinct periods of strong southeast winds, while several hundred meters above the surface, the et was consistent throughout the period.

3) Surface winds at YAK are typically one-half to one-quarter as strong as winds in the jet core. In addition, there is considerable fluctuation in surface wind speeds as indicated by the gusty nature of these winds during barrier jet events. Gusty winds are probably a response to shear induced turbulence that works its way to the surface, and in part due to micro-scale pressure surges or waves that propagate along the coastline (Overland and Bond 1993).

4) Pressure differences between SIT and YAK as well as CSP and YAK give a rough indication of the formation and presence of a barrier jet, but cannot be solely relied on to diagnosis near surface winds speeds.

a) Low-level stability

In order to gain some insight into the formation of YAK barrier jets, the Brunt-Väisällä frequency was calculated at 12 hour intervals for the December 1988 and February 1992 cases. Since both events occurred in conjunction with heavy rain in Yakutat, we used the the moist Brunt-Väisällä frequency (N_{moist}) as an indicator of changes in low-level stability. N_{moist} is given as (Durran & Klemp 1982):

$$N_{moist} = [\ g/T * (\Gamma_m - \gamma)]^{1/2}$$

where: g is the acceleration of gravity, T is the mean layer temperature, Γ_m is the moist adabiatic lapse rate, and γ is the observed lapse rate taken from sounding data. Using a set value of 6^o C km^{-1} for Γ_m, N_{moist} is calculated for a layer extending from the surface to 700 mb. The results are displayed in Figure 9. It is evident that the formation of barrier jets occurs after the surface to 700 mb stability has risen dramatically. The largest values of N_{moist} are on the order of 0.01 s^{-1} (corresponding to N_{dry} = 0.015 s^{-1}) which indicates extreme stability. In Figure 9b, the sharp decrease in stability between 1200 UTC February 26 and 0000 UTC February 27 is due to cold air advection which took place above 900 mb. The 800-700 mb layer however, remained very stable despite the temperature change.

The Froude number (F_m) is a commonly used indicator of the degree of low-level blocking upstream of mountainous terrain (Pierrehumbert and Wyman 1985; Chen and Smith 1987). In a saturated or nearly saturated environment N_{dry} is replaced by N_{moist}, leading to (Fritsch *et al* 1995):

$$F_m = U\ /\ (HN_{moist})$$

Using the 0000 UTC 15 December 1988 YAK sounding data to calculate N_{moist}, while re-analysis was used to determine the upstream wind speed (850 mb). This yielded the following values: $U = 20\ \mathrm{m\ s^{-1}}$, $H = 3000$ m, and $N_{moist} = 0.01\ \mathrm{s^{-1}}$, producing a Froude number of 0.7. Since both the inflow velocity and N_{moist} vary in time, a more representative approach would be to suggest that F_m varies between 0.5-1.0 during barrier jet wind events. This range of values is in agreement with the findings of Overland and Bond (1993, 1995) in their studies of coastal wind jets in the Gulf of Alaska and Vancouver Island. It clearly demonstrates that significant blocking is occurring despite low-level wind speeds upstream of the blocked zone that range between 15-20 $\mathrm{m\ s^{-1}}$.

b) Thermal considerations

For the six YAK barrier jet cases analyzed, each one occurs in association with pronounced temperature rises that first occur in the middle troposphere followed some hours later at the surface. Realizing the limitations of this analysis due to sparse data along the coastline and in the Gulf, there is little evidence of cold air damming associated with these wind events. Prior to the start of a barrier jet event, surface winds in YAK are often out of the east with speeds ranging from 3-6 $\mathrm{m\ s^{-1}}$; these typically are glacier winds that flow out of the St. Elias Mountains. Once a low in the western Gulf starts to produce southerly flow, the low-level winds shift to the southeast and there is a 4-6^{o} C increase in surface temperatures at YAK typically over a 6-12 hour period.

One question that ultimately needs to be answered is: can cold air damming occur in the vicinity of the Fairweather Range and not show up in the low-resolution observations? It is unlikely that the answer to this question is positive, for the following reason. Once a barrier jet forms there is little difference between surface air temperatures in the Gulf as reported by ships and buoys, and those at either YAK or CSP. Once the wind event has terrminated, temperatures along the coast and in the Gulf decrease to pre-event values. If cold air damming was occurring on the upstream side of the Fairweather Range, there would be some evidence of it at YAK or CSP. Additionally since Yakutat Bay sits at the base of the main St. Elias Range, cold air damming should occur along the entire length of the range, not only over the windward slopes of the Fairweather Range. As a consequence it is suspected that there should be some discernable temperature difference between YAK and the Gulf, something rarely seen during these events.

The lack of evidence of a deep dome of cold air along the windward slopes of the St. Elias Range and particularly in the vicinity of the Fairweather Range, differs from the classic thermodynamic explanation of barrier jet formation as given by Schwerdtfeger (1975), Parish (1982), Bluestein (1993), and Doyle (1997), where a dome of cold air forms over and at the base of the windward slope due to adiabatic cooling of upslope flow. Due to the lack of evidence of cold air damming in surface data, an alternative explanation for barrier jet formation at the base of the St. Elias Range is suggested. Since barrier jets form in the northern Gulf during the cooler months of the year, when southerly flow advects considerable amounts of warm air into the region, blocking is linked to this intrusion of warm air. Due to the very steep terrain of the St. Elias Range and the Fairweather Range in particular, when mid-level warm advection occurs it produces very high static stability at mountain crest level (Marwitz and Toth 1993). With strong cross-barrier flow and high stability in the 700-500 mb layer, wave breaking commonly occurs over the barrier due to production of oversteepend mountain waves. Upstream propagating gravity waves are generated as a result of wave breaking, these gravity waves in turn produce blocking over the windward slopes as suggested by the work of Baines and Hoinka 1985, Smolarkiewicz and Rotunno 1990. Even though wave breaking is not directly observed except for the occasional upper-level pilot report of moderate to severe turbulence, all of the essential elements are present: strong crest level flow perpendicular to the long-axis of the range, strong mid-tropospheric stability and very steep terrain. The production of a deep blocked layer of air on the windward side of the St. Elias Range produces a meso-high, which in turn generates a barrier jet.

Since many YAK barrier jet events occur concurrent with heavy precipitation (usually rain), the release of latent heat and or the melting of snow during these events (Marwitz 1983, Marwitz and Toth 1993), may have an important affect on the thermal stratification of the air over the windward slopes. One could possibly argue that due to the extremely long southerly fetch associated with most barrier jet producing Gulf lows, warm advection should dominate over any diabatic effects that may occur. On the other hand the release of latent heat in the 850-600 mb layer probably helps retain the high stability during the event. The temperature profile displayed in Figure 8 certainly indicates that on the 12 hour timescale, considerable thermal variation occurred in the middle and lower troposphere. Whether those variations are due to advective or diabatic affects remains to be determined.

c) Forecasting Barrier Jets

Two of the main challenges that forecasters face are the timing of barrier jet formation and dissipation, as well as the production of low-level wind shear. Since the development of barrier jets in the Gulf is intimately linked to warm air advection, one of the keys to forecasting these events is to monitor the progression of warm fronts in the northern Gulf. This is not as easy as it may seem since fronts in the Gulf are analyzed using limited ship/buoy observations as well as satellite imagery. The draw back is that with a low located in the central or western Gulf, the position of a warm front as it extends into the eastern Gulf can be quite tentative.

An additional forecasting tool is to use either the SIT-YAK or CSP-YAK pressure difference. A SIT-YAK pressure difference of >+8 mb is a general indicator of moderate to strong southeast winds at YAK. The caveat is that wind speeds at YAK are not highly correlated with this pressure difference as indicated in Table One. Between 21-24 December, 1999 a number of very well developed barrier jets formed over YAK. What is interesting about these events is that the CSP-YAK (and SIT-YAK) pressure difference was weak. For example, at 1200 UTC 22 December, the CSP-YAK pressure difference was +3.7 mb, while the YAK-CDV pressure difference was +13.4 mb. Figure 10 shows a hodograph of the winds taken from the 1200/22 YAK sounding where a prominent barrier jet is evident. Surface winds at YAK airport three hours on either side of 1200/22 were light, generally less than 6 m s^{-1}.

Pressure differences and pressure tendencies along the coast give an *indication* of strong surface winds and the possible development of a barrier jet, but there is no linear relationship between pressure differences and wind speeds at YAK. The question that needs to be addressed is: Why do barrier jets form when the SIT-YAK or CSP-YAK pressure differences are relatively weak? First, there are times when the surface low center is positioned in the central Gulf, with isobars roughly parallel to the coastline, while the mid-tropospheric flow is aligned perpendicular to the coastline. As a consequence the surface pressure gradient between YAK and CSP or SIT is weak. Above the boundary layer however, onshore flow is blocked by the high terrain producing a meso-high on the windward side of the range. Secondly, due to the development of a meso-high *between* YAK and CSP, the pressure difference between these two stations does not reveal the actual pressure difference between YAK and the meso-high. *As a consequence, monitoring of surface data alone can at times lead to a poor forecast of lower-tropospheric winds at YAK.*

Low-level wind shear poses a serious aviation hazard in the northeastern Gulf during these events. Forecasting low-level wind shear (predominately speed shear) is a challenge for forecasters writing the terminal area forecasts (TAF's) for both CDV and YAK airports. Pilot reports are helpful but have their own limitations. The criteria for low-level speed shear in the vicinity of an airport is: a 10 m s^{-1} speed change within 600 m of the surface (1.6 m s^{-1} $[100 \text{ m}]^{-1}$). This threshold is frequently exceeded at YAK airport during barrier jet events. During the December 1988 and February 1992 events for example, low-level speed shears were on the order of 1.6-3.3 m s^{-1} $(100 \text{ m})^{-1}$. Without a wind profiler or upper air data, the frequency of occurrence of speed shears at airports like CDV is unknown, but is probably pretty high, and subsequently these events are most likely under forecast in the local TAF's. Even at YAK where routine sounding data is available, forecasting wind shear in the period in-between soundings can be difficult because as this study has shown, surface data alone may be a poor indicator of what is occurring several hundred meters aloft. This is especially true at the onset and termination of barrier jets.

6. Conclusions

Since there is limited realtime weather data available in the Gulf and since NWP models do not resolve the terrain properly, a forecaster who has some understanding of barrier jet formation can at least anticipate their formation and dissipation based on the information that is available. Therefore a conceptual model of Gulf coast barrier jets is offered (Figure 11):

I. Developing Stage

1) Geostrophic flow from the south to southwest over the northeastern Gulf of Alaska;

2) Warm air advection occurs in the middle troposphere (700-500 mb layer) a head of low-level warm advection (warm front);

3) As a result of warm air advection, there is a significant increase in the surface to 500 mb stability;

4) When surface to 700 mb southwesterly flow approaches the St. Elias Range, it decelerates and is blocked. The blocking process upstream of very steep terrain is not completely understood, however it is possible that dynamic effects (wave breaking aloft) play a larger role than adabiatic cooling due to upslope flow;

5) As blocking increases over a 4-8 hour period, a meso-high forms over the windward slopes of the St. Elias Range;

6) A barrier-parallel wind jet forms as air flows down the synoptic and meso-scale pressure gradient;

7) In the vicinity of Yakutat Bay, due to cold air drainage from the Malaspina and other adjacent glaciers, a pre-existing shallow dome of cold air may not allow the developing jet to reach the surface until this cold air is eroded.

II. Mature Stage

8) Since onshore flow is variable in time and since wave breaking has some oscillatory characteristics, pressure within the meso-high probably fluctuates on the O(10's minutes), and is a possible source of pressure surges that propagate along the coastline;

9) Shear induced turbulence near the jet core reaches the surface in the form of gusty winds;

10) Due to the formation of a meso-high in a region located in-between observation sites, a synoptic-scale pressure difference index for coastal stations is not as highly correlated with surface wind speeds at YAK as forecasters may wish it to be.

III. Dissipating Stage

11) Barrier jets weaken as the 850-700 mb layer: a) winds become westerly as a result of the low center tracking northward, b) wind speeds decrease as the geopotential height gradient weakens, or; c) stability decreases in response to cold air advection in the middle troposphere;

12) As at the onset, surface wind speeds at YAK frequently drop below 6 m s^{-1}, while the winds at 300-1500 m remain in the 15-25 m s^{-1} range;

13) Four to eight hours after the surface winds at YAK airport have diminished, the barrier jet completely disappears.

As with any conceptual model there are significant deviations from time to time. For example, a shallow layer of cold air may or may not be present over Yakutat Bay prior to the start of a barrier jet event. There are some cases where the geostrophic flow is parallel to the barrier at the start of a wind event, but becomes perpendicular to the barrier as the event progresses. In this last scenario a coastal wind jet eventually becomes a barrier jet. In addition, there are without question a number of meso-α scale processes including pressure surges, density currents, and waves of various types, that add complications to this simplified model and which for the most part go undetected.

In the near future it is hoped that several of these YAK barrier jet events can be simulated using the RAMS modeling system. The steep terrain will be a test of the model's capability to handle a simulation with a horizontal grid interval on the order of 5 km. The fundamental issue that needs to be explored using the model is: what process causes blocking upstream of the St. Elias Range? Is it a result of wave breaking and upstream gravity wave propagation or does upslope cooling dominate? Hopefully model results will be able to clarify this unresolved issue. Additionally, a number of sensitivity runs will be conducted in order to understand how warm air advection, upstream wind speed and direction as well as temporal variations in stability control barrier jet evolution in this part of the Gulf. Likewise, it is hoped that model simulations will indicate whether barrier jets increase precipitation upstream of the St. Elias Range as moist air is forced up and over the jet as well as over the mountains.

Acknowledgments:

I would like to thank Jack Endicott, Meteorologist In Charge of the Yakutat forecast office for some fruitful discussions on this topic. Dr. Scott Lindsey produced the map used as Figure one.

REFERENCES

Bell, G. D., and L. F. Bosart, 1988: Appalachian cold-air damming. *Mon. Wea. Rev.,* **116**, 137-161.

Businger, S., and B. Walter, 1988: Comma cloud development and associated rapid cyclogenesis over the Gulf of Alaska: A case study using aircraft and operational data. *Mon. Wea. Rev.,* **116**, 1103-1123.

Chen, W., and R.B. Smith, 1987: Blocking and deflection of airflow by the Alps. *Mon. Wea. Rev.,* **115**, 2578-2597.

Doyle, J.D., 1997: The influence of mesoscale orography on a coastal jet and rainband. *Mon. Wea. Rev.,* **125,** 1465-1488.

Durran, D.R., and J.B. Klemp, 1982: On the effects of moisture on the Brunt-Väisällä frequency. *J. Atmos. Sci.,* **39**, 2152-2158.

Fritsch, J. M., J. Kapolka, and P. A. Hirschberg, 1992: The effects of subcloud-layer diabatic processes on cold air damming. *J. Atmos. Sci.,* **49**, 49-70.

Georgelin, M., and E. Richard, 1996: Numerical simulation of flow diversion around the Pyrenees: a tramontana case study. *Mon. Wea. Rev.,* **124,** 687-700.

Marwitz, J., and J. Toth, 1993: The Front Range blizzard of 1990. Part I: Synoptic and mesoscale structure. *Mon. Wea. Rev.,* **121**, 402-415.

Mass, C.F., and M.D. Albright, 1987: Coastal southerlies and alongshore surges of the West Coast of North America: Evidence of mesoscale topographically trapped response to synoptic forcing. *Mon. Wea. Rev.,* **115**, 1707-1738.

Olafsson, H., and P. Bougeault, 1996: Nonlinear flow past an elliptic mountain ridge. *J. Atmos. Sci.,* **53**, 2465-2489.

Overland, J.E., 1984: Scale analysis of marine winds in straits and along mountainous coasts. *Mon. Wea. Rev.,* **112**, 2530-2534.

Overland, J. E., and N. A. Bond, 1993: The influence of coastal orography: the Yakutat storm. *Mon. Wea. Rev.,* **121**, 1388-1397.

________, and _________, 1995: Observations and scale analysis of coastal wind jets. *Mon. Wea. Rev.,* **123**, 2934-2941.

Parish, T. R., 1982: Barrier winds along the Sierra Nevada mountains. *J. Appl. Meteor.,* **21**, 925-930.

Reynolds, M., 1983: Occurrence and structure of mesoscale fronts and cyclones near Icy Bay, Alaska. *Mon. Wea. Rev.,* **111**, 1938-1948.

Schwerdtfeger, W., 1975: The effect of the Antarctic Peninsula on the temperature regime of the Weddell Sea. *Mon. Wea. Rev.,* **103,** 45-51.

Smith. R. B., 1979: The influence of mountains on the atmosphere. *Advances in Geophysics,* B. Saltzman, Ed., Vol.21, Academic Press, 87-230.

________, 1982: Synoptic observations and theory of orographically disturbed wind and pressure. *J. Atmos. Sci.,* **39**, 60-70.

________, 1990: Why can't stably stratified air rise over high ground? *Atmospheric Processes Over Complex Terrain,* W. Blumen, Ed., A.M.S. Vol.23, No.45, 105-107.

Smolarkiewicz, P.K., and R. Rutunno, 1990: Low Froude number flow past a threedimensional obstacle. Part II: Upwind flow reversal zone. *J. Atmos. Sci.,* **47**, 1498-1511.

Steenburgh, W.J., and C.F. Mass, 1996: Interaction of an intense extratropical cyclone with coastal orography. *Mon. Wea. Rev.,* **124,** 1329-1352.

Wesley, D. A., 1991: An investigation of the effects of topography on Colorado Front Range winter storms. Ph.D thesis, Colorado State University, 197 pp. [Available from Dept. of Atmospheric Sciences, Colorado State University, Fort Collins, CO]

Xu,Q., 1990: A Theoretical study of cold air damming. *J. Atmos. Sci.,* **47**, 2969-2985.

Figure Captions:

Figure 1: Topography of the northern Gulf of Alaska.

Figure 2: Yakutat winds during the 14-17 December 1988 barrier jet event. Winds barbs= 5 m s^{-1}, half barbs= 2.5 m s^{-1}.

Figure 3: 850 mb geopotential heights at 0000 UTC 15 December 1988.

Figure 4: Surface map for 1800 UTC 15 December 1988. Winds barbs= 5 m s^{-1}, half barbs= 2.5 m s^{-1}.

Figure 5: Temperature profile at select levels taken from Yakutat soundings for 13-17 December 1988.

Figure 6: Hodograph of Yakutat winds for 1200 UTC 26 February 1992.

Figure 7: 850 mb geopotential heights for 1200 UTC 26 February 1992.

Figure 8: Temperature profile at select levels taken from Yakutat soundings for 24-28 February 1992. BJ= barrier jet, EBJ= elevated barrier jet.

Figure 9: Moist Brunt-Väisällä frequency (bold line), surface wind speeds (solid ellipses) and 900 mb winds (open diamonds). Values next to wind speeds are wind direction taken from Yakutat soundings, during period of: a) 13-17 December 1988, b) 24-28 February 1992.

Figure 10: Hodograph of Yakutat winds for 1200 UTC 22 December 1999.

Figure 11: Conceptual model of barrier jet development in the northeastern Gulf of Alaska. a) developing barrier jet, b) mature barrier jet.

Table Captions:

Table 1: Pressure difference and pressure tendencies for select coastal stations as well as Yakutat surface wind speeds for 21-24 December 1999.

Table 1.

	Pressure Difference (mb)			Pressure Tendencies (mb 3 hr^{-1})		
Date/Time	CSP-YAK	YAK-CDV	YAK Winds*	YAK	CSP	CDV
21/21	+3.7	+10.3	5/7	+1.5	+0.7	+3.2
22/00	+3.9	+10.5	8/11	-0.6	-0.4	-0.8

22/03	+3.8	+10.9	8/13	-1.2	-1.3	-1.6
22/06	+5.1	+13.2	7/11	-0.6	+0.7	-2.9
22/09	+2.6	+14.8	9/13	+1.8	-0.7	+0.2
22/12	+3.7	+13.4	4/4	-2.1	-1.0	-0.7
22/15	+3.7	+13.1	6/6	-0.7	-0.7	-0.4
22/18	+3.3	+14.1	6/6	-1.6	-2.0	-2.7
22/21	+4.2	+13.4	7/10	-2.3	-1.4	-1.6
23/00	+4.0	+11.3	8/12	-2.8	-3.0	-0.7
23/03	+4.5	+8.5	10/12	-1.9	-1.4	-0.9
23/06	+5.4	+6.8	9/14	-0.9	0.0	-0.8
23/09	+5.9	+7.3	7/12	+0.9	-1.4	+0.4
23/12	+4.4	+6.0	8/11	+0.1	+1.4	+1.4
23/15	+3.8	+4.1	8/13	-1.4	-2.0	+0.5
23/18	+3.8	+3.9	7/13	-1.4	-1.4	-1.2
23/21	+4.1	+2.6	10/14	-2.3	-2.0	-1.0
24/00	+5.3	+1.2	10/14	-3.9	-2.7	-2.5

* Winds are in m s^{-1}, with first value the highest sustained wind over the previous three hour period, the second value is the highest recorded gusts during the same period.