SOUTHCENTRAL ALASKA COLD ADVECTION WIND EVENT: MARCH 11-15, 2003

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[figures are at the end of paper]

Introduction

Cold advection north wind events of moderate strength, events with frequent gusts <50 kts, typically occur three to five times per winter across northern Cook Inlet and the Matanuska Valley. Figures 1 and 2 show the topography of the region. Strong events, with frequent gusts >50 kts, generating various amounts of damage, have over the past decades occurred once every few years. One of the more recent damaging wind events occurred 11-15 March 2003 across a large area of Southcentral Alaska, including the Matanuska Valley and northern Cook Inlet. Sustained winds speeds taken on a 2-minute average were on the order of 28-40 kts (15-22 ms^{-1}) with 5 second averaged gusts ranging from 50-60 kts (25-32 ms^{-1}) at Palmer and Anchorage. An unofficial instantaneous gust of 95 kts (53 ms^{-1}) was recorded at the top of the 35 m high FAA control tower located at Ted Stevens Anchorage International Airport. Damage in the Anchorage and Palmer areas was on the order of $16 million. The strong winds blew out a number of large windows in several high-rise buildings in the downtown area and numerous private aircraft at Lake Hood Seaplane Base were flipped upside down or ‘pushed’ into adjacent aircraft. On the west side of Anchorage, damage to roofs with asphalt shingles and fences was commonplace.

One aspect of this event that separates it from more generic events was its duration: sustained winds greater than 20 kts (11ms^{-1}) with gusts greater than 30 kts (16 ms^{-1}) lasted 44 hours in Anchorage (12Z/12 through 8Z/14) while in Palmer winds of this intensity had a 54 hour duration (4Z/12-10Z/14).

Although discussed in greater detail later in this paper, the common synoptic-scale signature for these types of damaging cold advection wind events is a ridge of high pressure or anticyclone located over the Bering Sea or extreme eastern Siberia, with a trough or cut-off low positioned over the Yukon Territory or northern British Colombia. Associated with this pattern is a strong north-south Arctic jet which typically advects cold air from either the Arctic Ocean or northern Yukon Territory into Alaska. An arctic jet as well as deep cold air are vital to development of damaging bora winds across Southcentral Alaska.

This paper documents and analyzes the 11-15 March 2003 Southcentral Alaska cold advection wind event via surface observations, radiosonde data, both the NCAR/NCEP Global Reanalysis and North American Regional Reanalysis (both referred to as ‘Reanalysis’ hereafter). In addition, using the Weather Research and Forecasting (WRF) model we have been able to simulate this event and analyze the meso-γ scale structure of bora and gap winds.

Terrain

Southcentral Alaska, from southern slopes of the Alaska Range to the Gulf of Alaska, in many respects typifies the classic complex terrain scenario so frequently alluded to in literature.

High glaciated mountains interspersed with deep valleys or fjords are the norm. As shown in Figure 1, the most dominant terrain feature is the Alaska Range which forms a 600+ km arc which separates the Interior from Southcentral Alaska. The height of this range varies considerably, with the highest terrain being situated in the west and gradually lowering to the east. A reasonable estimate of an 'effective' barrier height is 2,000-3,000 m. There are some significant north-south gaps through the range which allow for the intrusion of cold air from the Interior into Southcentral. From west-to-east these are: Broad (700 m), Isabell (1068 m), Mentasta (885 m), and Nabesna (920 m) Passes. To the south of the central portion of the Alaska Range lies the Talkeetna Mountains with barrier heights of 1,500-2,000 m. Further south, the Chugach Mountains, with barrier heights of 3,000-4,000 m, sit astride the north coast of the Gulf of Alaska. To the west of the Chugach and Talkeetna Mountains are the Susitna Valley and Cook Inlet. To the east is the Copper River Basin, which is bordered on the east by the imposing Wrangell-St Elias Mountains, with a barrier height of 4,000 m.

Besides the aforementioned gaps through the Alaska Range, there are there several additional mountain gaps that have a substantial impact on regional weather, especially during the winter months. The Copper River Delta located in the southeastern Chugach Mountains acts as an outlet for deep cold air that is frequently advected into the Copper River Basin from the Interior. Satellite imagery has shown that strong winds (60-100 kts) blowing out of the delta can extend a hundred kilometers into the Gulf of Alaska. Another important terrain gap is Thompson Pass (823 m), which connects the town of Valdez with the Copper River Basin. Tahneta Pass (1,012 m) separates the Copper River Basin to the east from the Susitna Valley and Cook Inlet to the west. The Matanuska River which flows through the valley of its namesake has formed a deep valley through the Chugach Mountains to the south and the Talkeetna Mountains to the north, as shown in Figure 2. On the western terminus of the Matanuska Valley lie the communities of Palmer and Wasilla, both of which are subject to a number of significant wind events each winter.

It should be readily apparent from the short description given above that Southcentral Alaska's complex terrain is a major factor in regional weather patterns. Specifically, bora-like and gap winds of various intensities are common during the winter months and represent a sub-class of wind events that are a challenge to meteorologists attempting to forecast their duration and intensity. A fundamental understanding of the underlying physics of cold advection events will aid the forecast process. The primary challenges of forecasting these events are: differentiating localized gap winds from mesoscale bora events; understanding the mechanism that causes the Palmer winds to have a much longer duration than those in Anchorage; understanding the role stable layers and inversions play during strong gap wind events; and identifying relevant atmospheric variables.

Previous Wind Studies

Wintertime cold advection wind events differ from the more common warm advection (i.e.- downslope) events which occur across northern Cook Inlet , especially in Anchorage and Palmer. Warm advection cases are a product of a strong west-to-east surface pressure gradient along the northern coast of the Gulf of Alaska. With higher pressure in the east, this particular scenario generates a coastal or barrier jet offshore of the coastline. The added high pressure mass over the

Gulf of Alaska flows through the Turnagain Arm terrain gaps or over the western Chugach Mountains into northern Cook Inlet as described by Hopkins (1994). Cold advection cases in contrast are 'forced' by deep cold air that is advected from the Interior into the Copper River and Susitna River Basins. Although northern Cook Inlet cold advection wind cases have not been studied previously, they share common traits with events that have been documented near Juneau, Alaska (Coleman & Derking, 1992), Barren Islands and Shelikof Strait (Lackmann & Overland 1989, Macklin et al 1990), as well as in the greater Puget Sound region (Reed 1981, Mass & Albright 1985, Jackson & Styen 1994, Mass *et al* 1995, Colle & Mass 1998).

These bora/gap wind studies have several primary findings. Bora winds are frequently associated with gap winds, however, gap winds may occur without an accompanying bora event. Essentially a bora is a type of downslope wind event that produces cold advection at lower elevations despite compressional warming as the air descends from elevated terrain. Observations indicate that some type of 'critical' layer is frequently located directly above and within 1 km of the barrier crest. A critical layer can be composed of wind shear zones, an elevated inversion or deep stable layer. Smith (1987) notes from his aircraft observations of five bora events in the Dinaric Alps that the vertical distribution of stability varies considerably from one event to the next. On the meso-γ scale the acceleration of the air within a gap or valley is due to the hydrostatic difference that exists between the two ends of the terrain feature. Within the gap however, air is locally accelerated as it is 'squeezed' through channeled areas referred to as control points. An ascending or descending low-level inversion over or within a valley can also act as a control point.

Synoptic Overview: March 11-15, 2003

Troposphere

A developing ridge over the North Pacific on March 4-5 moved northward forming a warm-core anticyclone centered over the Chukchi Peninsula (65^{o}N, 180^o) by March 7. To the east a cut-off low was positioned over Hudson Bay while a weak trough was located over the Gulf of Alaska. The anticyclone, although remaining quasi-stationary throughout the March 11-15 wind event, weakened substantially. Reanalysis data indicates that 500 mb heights within the anticyclone decreased from 5700 m on March 10 to 5300 m on March 14, as shown in Figure 3. Concurrent with the weakening of the anticyclone was the intensification of the cut-off low centered over the Yukon Territory. Additionally, the weakening of the anticyclone allowed a lobe of the Yukon low to develop over the northern Gulf of Alaska. By 0Z March 14 at 500 mb, this 'secondary feature', centered at Kodiak Island (57^{o}N 153^{o}W), had deepened to 4750 m and become the dominate synoptic system in the eastern North Pacific.

With an anticyclone to the west and a developing low to the east, the greater part of Alaska was under northeast-to-northwest flow from March 10 through 14. As indicated in Table 1, these north winds, which essentially produced an arctic jet of 35-74 kts at 500 mb, advected deep cold air from the Arctic Ocean into the interior of Alaska and subsequently south of the Alaska Range. Between 0Z/11 and 0Z/13, air temperatures over Fairbanks decreased 15^{o}C at 850 mb and 20.6^{o}C at 700 mb. Evidence of this cold layer was seen in the 1000-500 mb thickness at Fairbanks, which reached a minimum of 4822 m at 12Z/13.

Substantial cold air advection occurred south of the Alaska Range on March 12 as evident in the Anchorage soundings. 850 mb temperatures decreased by 13.4^{o} C over a 24 hour period as a result of strong north-to-northeast winds as displayed in Figure 4. Cold air advection into Southcentral, Alaska diminished significantly after 12Z/13 as the middle/upper tropospheric trough began to deepen over the northern Gulf of Alaska and the arctic jet moved further to the west. It should also be noted that the troposphere was extremely dry over the region during this event. Also, dew point temperatures were from 10^{o} to 15^{o} C below ambient air temperatures throughout the troposphere, and the most prevalent sky condition noted in the surface observations was ‘clear.’ Reanalysis omega fields indicate a general subsidence under the jet throughout most of the region south of Alaska Range, the exceptions being areas with strong localized ascent due to mountain wave activity.

	0Z/11	12Z/11	0Z/12	12Z/12	0Z/13	12Z/13	0Z/14	12Z/14	0Z/15
Anchorage									
850 mb Temp	-12.9	-10.7	-7.9	-13.1	-21.3	-26.5	-24.3	-19.1	-9.3
700 mb Temp	-20.5	-12.7	-12.1	-17.9	-24.7	-35.3	-28.5	-22.9	-19.9
1000-500 mb thickness (m)	5159	5252	5274	5163	5027	4909	4962	5022	5116
Fairbanks									
850 mb Temp	-12.5	na	-23.3	-24.9	-27.5	-29.9	-29.7	-30.9	-27.7
700 mb Temp	-14.9	na	-24.9	-32.7	-35.5	-36.5	-33.3	-33.5	-22.3
1000-500 mb Thickness (m)	5202	na	5054	4916	4862	4822	4881	4920	5001

Table 1: Air temperatures (^{o}C) and 1000-500 mb thickness (m) derived from radiosonde data.

<u>Surface</u>

While the middle and upper tropospheric anticyclone was forming over the Chukchi Peninsula during the first week of March, high pressure was forming at the surface over the Chukchi and Beaufort Seas. By the onset of the wind event late on the 11th, surface high pressure extended across Alaska in an arc from the Yukon to the Chukchi Sea, 1030 to 1047 mb respectively. Equally important, a broad swath of low pressure between 990-980 mb, extended across most of the North Pacific between 40^{o}N and 55^{o} N, as shown in Figure 5. By 12Z/12 this surface trough had evolved into a single 967 mb low centered in the southeastern quadrant of the Gulf of Alaska. Over the subsequent 36 hours this system slowly moved to the north and then to the west, obtaining minimum pressure of 958 mb at 0Z/13 while located in the northeastern Gulf of Alaska.

This surface system eventually coalesced with the aforementioned middle/upper tropospheric trough that was developing over the northern Gulf of Alaska on March 12. 500 mb Reanalysis indicated that these two systems developed independently but merged late on March 13.

The development of a surface low on March 13 was important for the continuity of the Southcentral wind event, as the arctic jet had by this time moved into western Alaska. Cold air moving off the mainland over the relative warmer water of the Gulf of Alaska may have played an important role in the intensification of this system. A very intense lower-tropospheric pressure gradient had formed between the interior of Alaska and the northern Gulf of Alaska, prolonging that strong low-level northerly advection.

Observed Surface Winds

Although moderate to strong surface winds were widespread across Southcentral Alaska from March 11-15, the strongest observed winds during this event were recorded at Palmer Municipal Airport (PAAQ) and at Ted Stevens Anchorage International Airport (PANC), elevations 70 and 39 m respectively. The onset of the winds was rapid at both locations, however the decline was more gradual. At Talkeetna PATK, elevation 107 m, 125 km north of Anchorage, the onset occurred at 23Z/11. The onset occurred at 03Z/12 in Palmer, and just after 04Z/12 in Anchorage, as shown in Figure 6. Further to the east, in the Copper River Basin, the onset of strong winds at Gulkana, PAGK, occurred at 00Z/12. The town of Valdez also experience strong gusts of 40+ kts (22+ms^{-1}) starting around 01Z/12.

During a generic Southcentral gap wind event, deep cold air originating from northern Alaska or the Yukon Territory is advected into the Copper River Basin. Once this cold air has reached a sufficient depth, it forms a north-south hydrostatic pressure gradient, with the area of highest pressure being located in the northern part of the basin. Consequently, air flows out through mountain gaps, specifically, the Copper River Delta east of the coastal community of Cordova. It flows over Thompson Pass at 823 m into Valdez, and over Tahneta Pass at 1,012 m where it moves down the Matanuska River Valley, through the communities of Palmer and Wasilla. Cold air moving down the Matanuska River Valley is accelerated during its decent, producing moderate to strong northeast gap winds in Palmer and Wasilla. Moderate events occur roughly three to five times per year in these communities and strong events occur roughly once per year.

For the March 2003 event, the strongest winds at Palmer commenced at 07Z on March 12. To illustrate the acceleration of the winds down the Matanuska Valley, we compared the observed winds at a cooperative weather station at Sheep Mountain, 24 km west of Tahneta Pass at 902 m, with those at Palmer Airport some 90 km down valley. The observed, sustained 2-minute averaged wind speeds at Sheep Mountain during the event were on the order of 5 to11 kts (2.6 to 6 ms^{-1}). No gust instrumentation was used. Meanwhile, at Palmer Airport, sustained northeast winds ranged from 25 to 47 kts (13 to 25 ms^{-1}) with 5-second averaged gusts up to 64 kts (35 ms^{-1}).

In Anchorage, 68 km southwest of Palmer, the onset of strong north-to-northeast winds occurred a little over an hour after the onset at Palmer. The winds at PANC increased from variable at 5 kts (3 ms^{-1}) at 04Z/12 to northeast 16 kts (9 ms^{-1}), gusts of 27 kts (15 ms^{-1}) approximately 25 minutes later. During the period of strongest winds, sustained speeds ranged from 25-42 kts (14-23 ms^{-1}) with peak gusts on the order of 62 kts (34 ms^{-1}). Around 09Z/13 the anemometer located on the control tower at Ted Stevens Anchorage International Airport recorded a peak gust of 95 kts (52 ms^{-1}), causing air traffic controllers to abandon the 35m high tower. In turn, airport operations were terminated for several hours.

Further down Cook Inlet, wind speeds in the 25-40 kts (14-22 ms^{-1}) range were common at Kenai, Homer and Drift River. Northerly gap winds of a similar magnitude were also observed at Seward and Whittier. The advection of cold air into the Gulf of Alaska is evident from the ASOS located on Middleton Island, 140 km south of the coastline, where ambient temperatures reached a minimum of -11^{o}C at 06Z on March 13. Winds throughout this period were northeast 20-30 kts (11-17 ms^{-1}) with gusts to 38 kts (21 ms^{-1}).

Another indicator of the bora nature of this event across the region is that surface air temperatures either remained unchanged or decreased as the winds increased. A weak diurnal pattern existed in some locations. This is in direct variance with the typical warming that occurs during wintertime strong wind events, as mixing within the boundary layer transports warmer air from the top of the inversion down to the surface. In the case of a bora however, cold air is at least several kilometers deep with a near dry adiabatic lapse rate. Hence, once mixing commences, ambient temperatures within the boundary layer may continue to decrease or remain constant.

Pressure Gradient Analysis

A mean sea-level pressure (MSLP) analysis across Southcentral indicates that the occurrence of peak winds at stations like Palmer, Anchorage and Kenai roughly coincided with the maximum (7Z-14Z, 13 March) regional pressure difference. An isallobaric analysis across Southcentral Alaska suggests that there is also substantial correlation between the highest wind speeds at a given location and the rate of change in the MSLP. In this case, a MSLP decrease of 3.0 to 4.5 mb occurred over a three hour interval. We are not however convinced that every case is going to follow this particular structure. Mass and Albright (1985) noted that the strongest winds to the lee of the Cascades during the December 23-25 event occurred while the MSLP tendency was increasing rapidly. In contrast, during the February 12 Cascade bora event, Colle and Mass (1998) noted that the greatest lee-side winds occurred while the cross-barrier MSLP was near its maximum value.

Monitoring mean sea-level pressure gradients and trends is of mainstays used by forecasters. However, the correlation between the mesoscale pressure gradient and wind speed at a given location varies considerably (Table 2). It appears that correlations are highest at the beginning of an event through the time of peak winds. As the speeds ramp down however, the correlations tend to decrease as well. We have noticed that once a surface low has formed in the northern Gulf of Alaska, the orientation of the isobars becomes roughly east-to-west, resulting in a weaker MSLP gradient between the Copper River Basin and northern Cook Inlet. During this same period however there was little change in the wind speeds at PAAQ or the Wasilla Airport (PAWS) when compared to periods when the MSLP gradient was twice as strong. If we use the entire event, the Gulkana-Palmer pressure gradient has a moderate correlation with the sustained winds at Palmer and Wasilla. Closer inspection of the data indicates that correlation is quite high up through 12Z/13, but decreases thereafter.

Table 2: MSLP difference correlated with sustained and wind gusts at various locations.

MSLP difference	Winds at:	Sustained	Gusts
PATK -- PAHO	PANC	0.38	0.11
PATK -- PALH	PANC	0.79	0.78
PAGK -- PAAQ	PAAQ	0.03	0.58
PAGK -- PALH	PAAQ	0.30	0.67
PAGK -- PALH	PAWS	0.33	0.47
PAGK -- PAWS	PAWS	0.43	0.54
PAGK -- PAMD	PAVD	0.26	0.38

The lack of sensitivity to cross-barrier pressure gradient at certain times may be a result of two factors. First, wind speeds at any given location can be a function of cold air drainage in the case of gap wind events, or lee-side downsloping in the case of bora events. Secondly, station pressure <u>may</u> be modified by localized processes. These processes include nocturnal cooling of the boundary layer, warm/cold temperature advection, and the formation of vortices and low-level rotors. It is apparent that mesoscale analysis of surface pressure does not in and of itself provide an adequate explanation of this wind event, so additional factors should be considered. We conclude that momentum mixing from stronger winds aloft (850 mb-700 mb) was pivotal through about 0Z/14. Once deep cold air had been advected south of the Alaska Range, especially into the Copper River Basin, cold air drainage became the driving mechanism after 0Z/14. This latter period also corresponds with the formation of a low pressure system in the northern Gulf of Alaska which facilitated cold air drainage from the mainland into the low center. Although discussed below in the section on Forecasting Tips, we believe that once cold advection has terminated in the Copper River Basin, nocturnal cooling of the boundary layer produces higher pressure at PAGK, not truly representative of the cross-barrier forcing.

Table 2 indicates that gusts have a higher correlation with the mesoscale pressure gradient than the sustained winds, with the exception of the first two entries. We are not sure why this occurs because the correlation between sustained winds and gusts, measured during a 10 minute observation window, ranges from 0.80 in Valdez to 0.95 in Anchorage. Additionally, we note that the Palmer-Wasilla MSLP difference during the period of strongest winds is negative most of the time. The two cities are 15 km apart, and the lower pressure was at Palmer. Assuming well-calibrated sensors, it is possible that a small meso-γ scale area of low pressure vortices forms around the Palmer airport as the flow exits the Matanuska Valley and over an extension of the protruding ridgeline to the east. It should be noted that it is possible that the cold air exiting the Matanuska Valley at Palmer may be producing fluctuations in the station pressure in a similar fashion as noted by Finnigan *et al* (1994) in their study of Howe Sound gap winds. In the case of Howe Sound, microbarograph observations during a gap wind event clearly showed a variation in station pressure as the depth of cold air changed throughout the event.

In order to fit the March 11-15, 2003 MSLP trends into a broader context, we analyzed MSLP trends using Reanalysis and station data for a number of additional bora-type wind events that have occurred over the past 25 years in the region. MSLP trends for five of the strongest bora-type events in the northern Cook Inlet area typically follow one of two scenarios. As in March 2003, the March 16-17, 1997 case had a continuously falling pressure. In three cases, the pressure initially rose during the first half of the event, and then decreased during the second half as a low pressure center developed or moved into the Gulf of Alaska. The dates of those cases were: Feb. 6-8, 1979; March 2-4, 1989 and Feb. 18-20, 1994. We analyzed 11 additional moderate cold advection cases and found that two cases indicated distinct pressure decreases over Cook Inlet, four had sharp pressure rises, and the remaining five cases displayed mixed pressure trends.

Discussion- Twin Forcing Mechanisms

Previous studies have indicated that strong gap wind events are frequently embedded within bora events (observed: Reed 1981, Smith 1987, Colman & Dierking 1992; modeled: Colle & Mass 1998a,b, Jackson & Steyn 1994). We note that this also holds true for the strong cold advection cases in Southcentral, Alaska. Essentially we believe that the strong winds emanating from the Matanuska Valley during this event had two causes. From 6Z/12 through approximately 12Z/14, the winds were a product of both mid-tropospheric forcing and cold air drainage, bora and gap winds respectively. From 12Z/14 to the event's conclusion, the winds were a consequence of cold air drainage down valley, purely gap winds. These findings are based on Anchorage soundings, reanalysis temperatures and geopotential height fields as will be shown later by mesoscale model results.

Evidence of a bora is revealed as there was extreme cold air advection throughout the region even as air moved downslope from the surrounding mountain ranges. Station air temperatures decreased from 12^{o}-18^{o}C between 0Z/12 and 12Z/13 despite strong winds. The transition from a mixed mode of bora and gap winds to a cold air drainage (gap) flow regime, occurred during the 12Z/13 to 12Z/14 period. By 15Z/13 the winds at Gulkana diminished substantially, to 10 kts, a time at when cold air advection over Southcentral had reached its maximum. The mid-tropospheric temperature gradient (north-south) diminished at this time as well. This transition period also corresponded with a decrease in 700 mb north-south height gradient over the Copper River Basin from 150 m at 12Z/13 to 50m at 12Z/14.

Inspection of the Reanalysis omega fields indicates that up through 12Z/14 there was considerable downward (positive) motion throughout the troposphere. As shown in Figure 7, values taken from the 700 mb level near Palmer range from 0.2 to 0.4 Pa s^{-1} during the period of strongest winds on March 13. Values at 850 mb were only slightly weaker than at 700 mb. However, the 500 mb values for omega were about 70% of those at 700 mb. This indicates that there was substantial momentum transfer from the middle of the troposphere to the lower levels in conjunction with widespread subsidence. We conclude that momentum mixing from stronger winds aloft was pivotal during the first half of the event. It should also be noted that during this period compressional warming and subsidence had minimal impact on lower tropospheric temperatures because the air mass was extremely cold from the surface well above 500 mb. Figure 8 shows the PANC sounding at 12Z/13 indicating an inversion around 3000 m, which in the following 24 hours subsided to 1200 m. Between the surface and the inversion, the lapse rate was nearly dry adiabatic. Over the subsequent 24 hours, this inversion intensified but remained centered around 1000 m. In addition, from 12Z/13 onward the strongest winds were confined below this persistent inversion. Other studies of bora/gap winds have noted the presence of lower and or middle-tropospheric inversions (Reed 1981, Mass *et al* 1995), although they are not apparently an essential element in every case (Smith 1987). We suspect that from 0Z/14 onward the inversion acted as an upper lid, limiting the declining momentum transfer into the lower troposphere, causing the Matanuska and Cook Inlet winds to became pure gap winds. Once the deep cold air had been depleted, the wind event was essentially terminated.

Modeling Results

Overview

By using a mesoscale model we hoped to identify the role of gap winds versus downslope (bora) winds in the March 2003 case. The coarse density of surface and raob observations in Alaska makes it difficult to verify the presence of the downslope component, so a mesoscale model can enhance our understanding of these events. Specially, we wanted to determine whether a high resolution model could successfully replicate the details of gap winds that were observed at Palmer, in addition to any downslope component that may have been generated to the south of the Alaska Range or west of the Talkeetna and Chugach Mountains. We also hoped to clarify the exact role that the 500 mb arctic jet planned in this event, and the transition to a lower tropospheric down gradient flow regime that occurred between 12Z/13 and 12Z/14. Additionally, we are interested in seeing if the model indicates a lowering of the tropospheric inversion during the second half of the event, and whether this inversion acts as control point for air moving down the Matanuska Valley. A lowering of an inversion, or stable layer, along the length of a valley effectively ‘squeezes’ air between the inversion and the surface producing significant along-valley accelerations. This effect was noted by Jackson and Steyn in their examination of gap flow through Howe Sound, British Columbia (1994). Finally, we hoped the model would indicate whether strong winds exiting the Matanuska Valley weaken or stay coherent as they flow down Knik Arm toward Anchorage.

Model Parameterization

We used the Weather Research and Forecasting (WRF) Environmental Modeling System in a three nested-grid configuration, as depicted in Figure 9, using non-hydrostatic dynamics. The outer grid, G1, was configured with a 32-km grid spacing on a polar stereographic projection. GI encompassed the Alaska Range to the north, extended southward to the northern Gulf of Alaska, and spanned Alaska from the west to the Wrangell Mountains in the east. G2 was configured with a 8-km grid spacing and was centered over the mountains of Southcentral Alaska. G3 was configured with a 2-km grid spacing and encompassed the Matanuska Valley and northern Cook Inlet. The simulation was run with one-way grid interaction and the microphysics package was de-activated since this event occurred under a cold deep arctic high that contained little moisture. There were 42 vertical levels in the sigma coordinate system reaching up to the 50 hPa level. The model was initialized at 12Z on March 11 and ran through 12Z on March 15. Initial and boundary files were from the NARR 32-km data set, with boundary forcing set for 6 hours intervals. Model output for each grid was written at 3 hour intervals.

General Results

In order to evaluate the overall performance of the model we looked at geopotential heights, air temperature, and surface pressure on grids G1 and G2. The model clearly shows the north-south oriented 500 mb arctic jet over Southcentral during the first half of the event, eventually moving westward out of the model domain late on March 13. Air temperatures were initially coldest over the northern reaches of the Copper River Basin but in time this cold air move west and south. 700 mb temperatures on G2 above Anchorage are on order with the values measured by the PANC raobs during the event. For example, model 700 mb temperatures cool from -14^{o}C 0Z/12 to -33^{o}C on 12Z/13, warm to -22^{o}C on 12Z/14, consistent with the values displayed in Table 1. In addition, there was significant cold air advection into the northern Gulf of Alaska on March 13 throughout the lower troposphere, with a marked warming occurring on March 14 and 15. Coldest air temperatures were on the order of -11^{o}C. The model however greatly under estimates nocturnal cooling which occurred over the Copper River Basin on the night of March 13-14. This deficiency in turn produced model station pressures over the lower valley which were 7-9 mb too low when compared to observations at PAGK.

A comparison of observations between Sheep Mountain at 902 m and Palmer Airport at 70m indicates a mean lapse rate between the two stations on the order of 8^{o}C per 1000 m. The model lapse rate between these two areas ranges from 8^{o}-12^{o}C per 1000 m. A lapse rate between Cantwell at 668 m and Talkeetna at 108 m for a limited number of observations averaged 15.5^{o}C per 1000 m. With limited observations from mountain locations, we are not confident in the actual observed lapse rates besides those from the raob flights. There can be considerable local effects with respect to observed surface temperatures at a point at high latitudes during the winter. This is likely before and after periods of higher wind speeds when boundary layer mixing is absent and nocturnal and/or radiative cooling is prevalent.

Model MSLP fields throughout the simulation as portrayed on G1 are in accord with those depicted in Reanalysis. MSLP decreases across the entire G1 domain after 0Z/12. However, values in the Gulf of Alaska decrease more rapidly when compared to the Interior, resulting in a net increase in the north-south pressure gradient during the simulation. The maximum MSLP gradient across the G1 domain is on the order of 40 mb which occurred during the period spanning 12Z/13 to 0Z/14. On G2 we have noted that the model performs well depicting MSLP over the Susitna Valley and Cook Inlet. Over the Copper River Basin recall that the model does not resolve shallow nocturnal cooling, resulting in model MSLP that are too low after 18Z/13.

Model output also indicates considerable wave activity in the middle troposphere over and to the western slopes of the Talkeetna Mtns and south of the Alaska Range during the period of strongest northeast to east gradient winds. This is a common occurrence during bora events as noted by Smith (1987) as well as Klemp and Durran (1987) during field observations in the Dinaric Alps, and in the modeling study of Colle and Mass (1998). Mountain wave activity, often located below a stable layer or inversion, acts as a critical layer in that air upstream at the same level is ‘squeezed’ between the mountain and this layer. As this air flows down the lee slope it accelerates, referred to as ‘shooting flow’ in hydrodynamics. It should be re-emphasized that during a bora, descending parcels of air are subject to compressional warming. In our case, since the atmosphere was essential dry, temperatures increased approximately at the dry adiabatic lapse rate. The air was however initially so cold, that despite the increase in temperature within the parcel, the region to the lee of the mountain experienced cold advection.

Matanuska Valley and Knik Arm Jets

Y-Z cross-sections of model winds in Figure 10 at the outlet of the Matanuska Valley near PAAQ clearly indicate a distinct jet core, ‘Mat Jet’, developing between 18Z and 21Z on March 11, a few hours early with respect to the observations. Once fully developed, the average height of the jet core ranges from 500m to 1000m above ground level (AGL). This particular Y-Z cross-section is located at Palmer at the confluence of the Matanuska and Knik Valleys. The lower wind speeds south of the valley are the exit region of the Knik Valley where there are minimal along-valley winds. Speeds within the core of the Mat Jet are typically 40-80% higher than those in the lowest model layer. The strongest winds occur in the lower valley as seen in Figure 11. A speed increase of 100% between Sheep Mountain and Palmer is the norm throughout most of the simulation. There is a broad area of weak subsidence between 5 and 10 Pa s^{-1} over the Matanuska Valley from 0Z/12 through 06Z/14, after which there is minimal vertical motion.

The model also clearly indicates that the north-to-northeast winds over the greater Anchorage area are derived from the Matanuska Valley's ‘Mat Jet’ via the Knik Arm's ‘Knik Jet’ as seen in the streamline plot of Figure 12. Winds over northern Cook Inlet tend to be out of the north as the Susitna Valley-Cook Inlet pressure gradient deflects the northeast Knik Jet toward the south. Essentially, the Knik Jet is a extension of the Mat Jet. Initially at 12Z/12, the Knik Jet was a low-level feature with a core some 300-500 m AGL, but by 6Z/13 as the Susitna Valley-Cook Inlet pressure gradient weakened, the jet weakened as the core migrated northward. As the Knik Jet weakened and migrated northward, the low-level winds over west Anchorage and the adjacent portions of northern Cook Inlet slowly diminished. The strongest winds within the simulated Knik Jet occur from 18Z/12 to 06Z/13 with speeds on the order of 47-54 kts (26-30 ms^{-1}). As noted by Belusic and Klaic (2004), the highest winds found anywhere within the boundary layer are a good estimate of gusts that can reach the surface.

During the period of strongest outflow from the Matanuska Valley, 0Z/13-06Z/14, the core is located almost due west of Wasilla and some 500-800 m AGL. The PATK-PAEN pressure gradient of 9 mb on 18Z/13 diminishes to 4 mb by 06Z/14. As this north-south pressure gradient weakens, not only does the Mat Jet migrate northward, but it also extends further west into the Susitna Valley. Near the community of Houston, 36 km west of the Palmer airport, there is an area of low-level wind convergence between the weak northerlies flowing down the Susitna Valley and the strong easterlies emanating from the Mat Jet. Rising motion in this convergence zone on average varies from 5 to 25 Pa s^{-1} in a layer 500-1500 m AGL. The location of convergence zone at its associated area of weak surface winds at any given time is therefore a function of the strength of the Mat Jet as well as the Susitna Valley-Cook Inlet pressure gradient.

We also looked at the evolution of the vertical temperature profile on G3 over the Matanuska Valley, as depicted by the solid lines in each panel of Figure 11. The nature of any given profile is a function of location. For example, in the lower valley and exit region a low-level isothermal layer is present through March 12, but develops into a pronounced inversion from 06Z/13 to 18Z/13. A mid-valley low-level inversion develops at the same time but remains intact through 12Z/14. Further to the east over the elevated plateau from which the upper Matanuska Valley originates, the inversion forms around 0Z/14 but weakens after 21Z/14. The development of inversion is in response to warm air advection starting after 18Z/13 between the surface and 500 mb. Lower tropospheric flow over the Copper River Basin is initially from the east but veers to the southeast as the low east of Kodiak Island deepens. The abrupt warming which occurred on March 14 in the lower troposphere is due to warm air being transported inland from the northeastern Gulf of Alaska. Figure 13 shows the evolution of lower tropospheric temperatures at 12 hour intervals at a single point within the lower Matanuska Valley. Significant cold followed by warm advection is evident as is the deep isothermal layers. The base of the isothermal layer is indicated by a dotted line. Recall the weak appearance of the near surface modeled temperature lapse rate, the temperature contrast between higher and lower elevation sites. What affect this has on the height and strength of isothermal layers or inversions is unknown.

Despite the complexity of the temperature structure over the Matanuska Valley, there is a common theme. The base of the inversion lowers 1200-1500m from inception to the time when it either transforms into an isothermal layer or the lapse rate becomes nearly adiabatic. Additionally, in order to test our hypothesis that an inversion or stable layer acts as a vertical control point, we have analyzed core speeds within the Mat Jet in relation to the strength and elevation of the inversion. Our findings suggest that in the exit region and lower valley there is qualitatively a modest correlation between the inversion and speeds in the core. However the relationship is weaker up-valley. This leads us to believe that during the period when the Mat Jet reaches is peak value at 12Z/13, it is forced partly by the east-to-west mid-tropospheric gradient wind as well as the down valley acceleration of cold air. There is a transition period from 18Z/13 to 03Z/14 during which the gradient wind over the crest of the mountains decreases as seen in Figure 14. During this period the height of the Mat Jet core lowers from 1750 m to 750 m, and slowly weakens from 65 to 32 kts (36 to 18 ms^{-1}). By 09Z/14 the flow within the valley is essentially a katabatic regime, pure gap wind. In time as the source of cold air over the Copper River Basin diminishes, the Mat Jet weakens as well. Recall that there is considerable warm advection throughout the lower troposphere from the Gulf of Alaska which eventually replaces the cold air.

Cook Inlet Winds

During the majority of cold advection outbreaks in Southcentral, Alaska, moderate to strong north-to-northeast winds are observed in Cook Inlet. The width of the inlet ranges from 120 km to 75 km, the narrowest section being in the lower inlet from the hills north of Homer across to the eastern slopes of Mt. Illiamna. Wind sensors located at Kenai Airport, Drift River and Augustine Island measured sustained winds on the order of 29-49 kts (15-25 ms^{-1}) with gusts to 58 kts (30 ms^{-1}). Model winds from G2 are in agreement with the observations and indicate that there is significant acceleration in the lowest model layer winds, within 1000 m of the surface, between southern Susitna Valley and lower Cook Inlet. The zone of maximum acceleration occurs between the mouth of the Susitna River and Kalgin Island. This region appears to act as a convergence zone as air from the Susitna and Matanuska Valley is squeezed in the 70 km distance between Mount Susitna on the west and the Chugach Mountains on the east, as shown in Figure 12. The model also indicates that at times there is a distinct jet core typically located over the western shoreline some 1000-1500 m AGL. Finally, it should be noted that there can be ‘residual’ moderate winds 29-39 kts (15-20 ms^{-1}) in lower Cook Inlet even after the winds in the Susitna Valley and Mat Jet have diminished to less than 19 kts (10 ms^{-1}). The observations at Augustine Island, and to a lesser extent further north at Drift River, indicate a notable decrease in wind speeds from 01Z/14 through 03Z/15. This seems to correlate with a decrease in the MSLP gradient between Talkeetna and Anchorage, an indication of the decrease in mass in the source region.

Valdez and Thompson Pass Winds

From the inception of strong winds at 02Z/12 through about 0Z/14 the majority of strong winds through Thompson Pass, Lowell Canyon and Port Valdez as depicted on G3 are due to the winds moving down from higher terrain. This means that flow east to west through Port Valdez for example is a function of inflow from side drainages. Mineral Creek drainage is the dominate side channel inflow during northeast wind events. The model indicates an area several miles long between Mineral Creek and the exit of Lowell Canyon which forms a eddy with relatively light winds. Additionally there is considerable cross channel variation in wind speeds across Port Valdez. At times, the greatest along valley acceleration in the winds occurs just upstream of Valdez Narrows, and at other times it appears to be more uniform over the length of Port Valdez. After 0Z/14, the mid-tropospheric forcing diminished and the flow through the valleys and canyons became more of a gap wind regime, with the majority of the acceleration occurring in the vicinity of Valdez Narrows. Overall, the nature of the complex terrain in this region generates considerable localized variations in wind speed and at times direction as well.

Forecasting Tips - Mat Jet strong events:

1) Very deep cold air advection over the Copper River Basin or all of Southcentral. Air temperatures at 700 mb over the region should be on the order of <-28^{o}C . In addition, expect cross-barrier 700 mb temperature gradient on the order of 8^{o}-12^{o}C during period of peak wind speeds. Exit region will be Matanuska Valley to elevated plateau around Lake Louise.

2) MSLP gradients from PAGK to PAAQ on the order of 7-10 mb at start of event, which is indicative of cold air advection from the north.

3) For the strongest Mat Jet wind events, a low typically forms somewhere in the northern Gulf of Alaska. This produces strong east-to-west flow in the lower troposphere of 850-700 mb over the Chugach and southern Talkeetna Mountains which reinforces the Mat Jet. In time as the low in the Gulf strengthens, there will be significant warm air advection over the Copper River Basin as the flow originates from the northeastern Gulf of Alaska. As a result expect considerable warm advection over the Copper River Basin.

4) Keep in mind that once the Mat Jet has formed, the MSLP gradient between the Copper River Basin and the Palmer area may diminish significantly, with little change in wind speeds at Palmer. Cold air advection has become warm air advection. Once the lower tropospheric height gradient has diminished, the Mat Jet becomes a true drainage wind, with speeds steadily decreasing over the next 12-18 hours. Beware of nocturnal cooling, especially in the Copper River Basin that may produce a local increase in MSLP which is not reflective of the true cross-barrier forcing. In these circumstances it would be better to monitor 850 mb height gradients and tendencies for some indication of cross barrier forcing rather than MSLP alone. Mass and Albright (1985) noted a similar situation in conjunction with the termination of the December 23-25, 1983 bora wind event in the Washington Cascades in which the MSLP gradient across the Cascades was still strong but the 850 mb gradient had weakened dramatically.

Strong Mat Jet events can be distinguished from more moderate events in that the latter have limited cold air advection as regards to depth and minimum temperature. Additionally, the formation of a low in the Gulf of Alaska is absent or weak at best, hence there is minimal forcing from the 850 mb gradient wind.

Conclusions

We have documented one of a number of bora wind events that occur from time to time during the winter months in Southcentral, Alaska. A WRF model simulation of the March 11-15, 2003 wind event has increased our understanding of these events. Although the simulation did not capture every detail, it did reproduce qualitative agreement with the observations. Essentially the longevity and intensity of the March 2003 11-15, Southcentral Alaska wind event is a result of the convergence of three synergistic atmospheric events, described below.

1) The presence of an anticyclone to the west and a trough/low to the east of Alaska favored the transport of cold air from the Arctic into Southcentral Alaska. The intensification of the middle and upper tropospheric winds on March 11 greatly enhanced cold air advection south of the Alaska Range. We envision that momentum mixing, as indicated by the strong positive omega values, from aloft was an important factor in the onset of this wind event.
2) Once a deep 'cold dome' had formed over Southcentral Alaska, katabatic cold air drainage via Tahneta, Thompson Passes and through the Copper River Delta was the primary forcing. Acceleration of the winds through channeled terrain and down mountain valleys maintained strong winds in northern Cook Inlet once upper level support had moved into western Alaska.
3) The development of an upper level trough over the Yukon Territory and its subsequent movement over the northern Gulf of Alaska late on March 13 played a role as well. We believe the relocation of the upper level disturbance and the advection of cold air over the relatively warm waters of the northern gulf, partly caused the movement of a developing surface low pressure system from the southern into the northern Gulf of Alaska on March 14. A similar synoptic situation was documented by Colle & Mass (1998a) during the onset of bora winds in western Washington, associated with the February 12, 1995 storm. Essentially, the strongest winds were forced by the mid-tropospheric height gradient and cold air drainage. Katabatic flow formed gap winds.

Acknowledgements

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References

Belusic, D., Z.B. Klaic. 2004: Estimation of bora wind gusts using a limited area model. *Tellus*. **56A**, 296-307.

Colle, B.A., C.F.Mass. 1998: Windstorms along the western side of the Washington Cascade Mountains. Part I: A high-resolution observational and modeling study of the 12 February 1995 event. *Mon. Wea. Rev*. **126**, 53-71.

Colle, B.A., C.F.Mass. 1998: Windstorms along the western side of the Washington Cascade Mountains. Part II: Characteristics of past events and three-dimensional idealized simulations. *Mon. Wea. Rev*. **126**, 53-71.

Colman, B.R., C.F. Dierking. 1992: The Taku wind of Southeast Alaska: its identification and prediction. *Wea. Forecasing*, **7**, 49-64.

Finnigan, T.D., J.A. Vine, P.L. Jackson, S.E. Allen, G.A. Lawrence, D.G. Steyn. 1994: Hydraulic physical modeling and observations of a severe gap wind. *Mon. Wea. Rev***.** **122**, 2677-2687.

Hopkins, 1994 was cited in the "Previous Wind Studies" section.

Jackson, P.L., D.G. Steyn 1994: Gap winds in a Fjord. Part I: Observations and numerical simulation. *Mon. Wea. Rev*. **122**, 2645-2665.

Jackson, P.L., D.G. Steyn. 1994: Gap winds in a Fjord. Part II: Hydraulic analog. *Mon. Wea. Rev*. **122**, 2666-2676.

Klemp, J.B., D.R. Durran. 1987: Numerical modeling of Bora Winds. *Met. & Atmos. Physcis*. **36** 215-227.

Lackmann, G.M., and J.E. Overland. 1989: Atmospheric structure and momentum balance during a gap wind event in Shelikof Strait, Alaska. *Mon. Wea. Rev*. **117**, 1817-1833.

Macklin, S.A., N.A. Bond, and J.P. Walker. 1990: Structure of a low-level jet over lower Cook Inlet, Alaska. *Mon. Wea. Rev*. **118**, 2568-2578.

Mass, C.F., M.D. Albright. 1985: A severe windstorm in the lee of the Cascade Mountains of Washington State. *Mon. Wea. Rev*. **113**, 1261-1281.

Mass, C.F., S. Businger, M.D. Albright, Z.A. Tucker. 1995: A windstorm in the lee of a gap in a coastal mountain barrier. *Mon. Wea. Rev*. **123**, 315-331.

Reed, R.J. 1981: A case study of a bora-like windstorm in western Washington. *Mon. Wea. Rev*. **109** 2383-2393.

Smith, R.B. 1987: Aerial observations of the Yugoslavian Bora. *Jr. Atmos. Sci*. **44** 269-297.

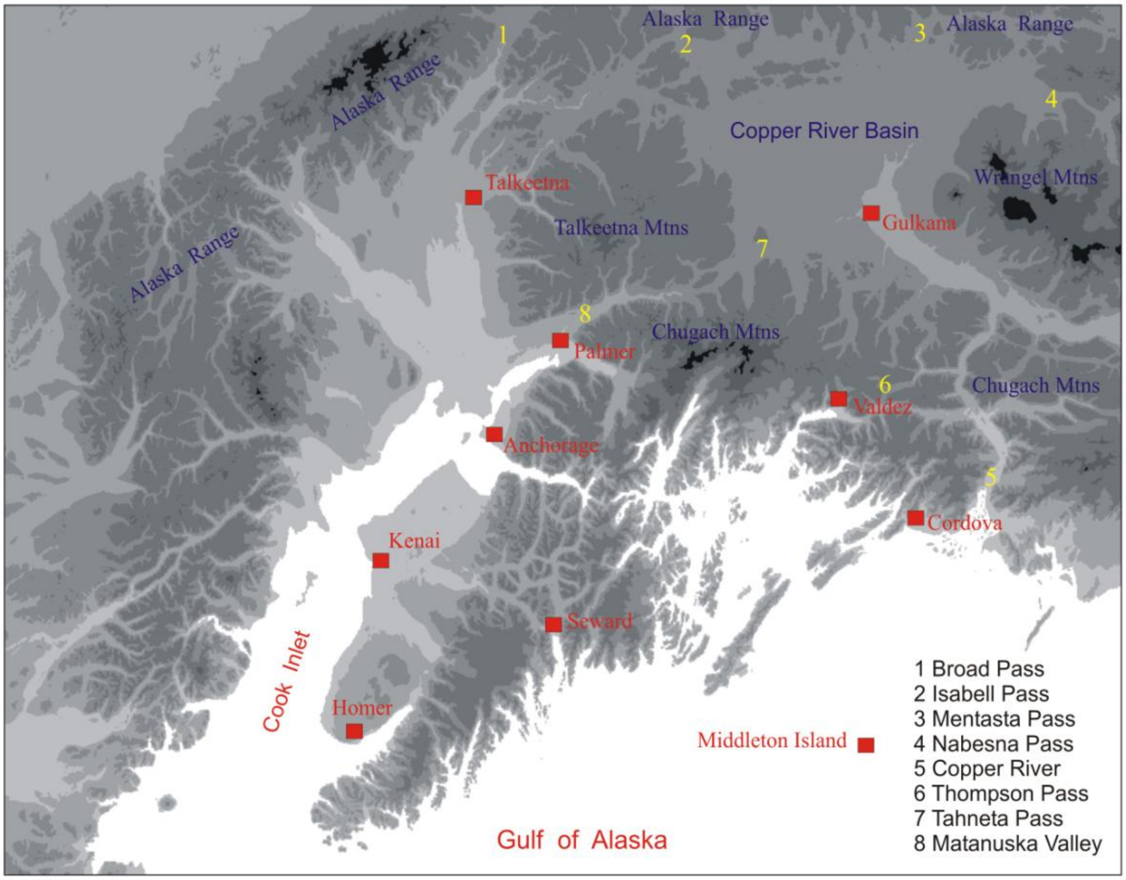

Figure 1: Topography of Southcentral Alaska.

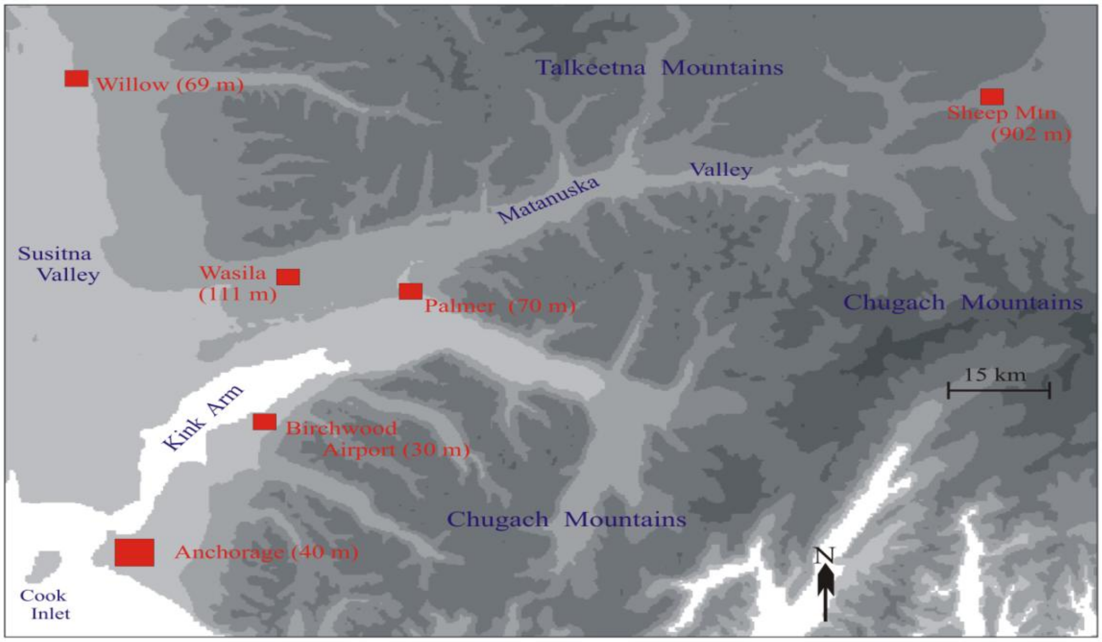

Figure 2: Topography of the Matanuska Valley and northern Cook Inlet.

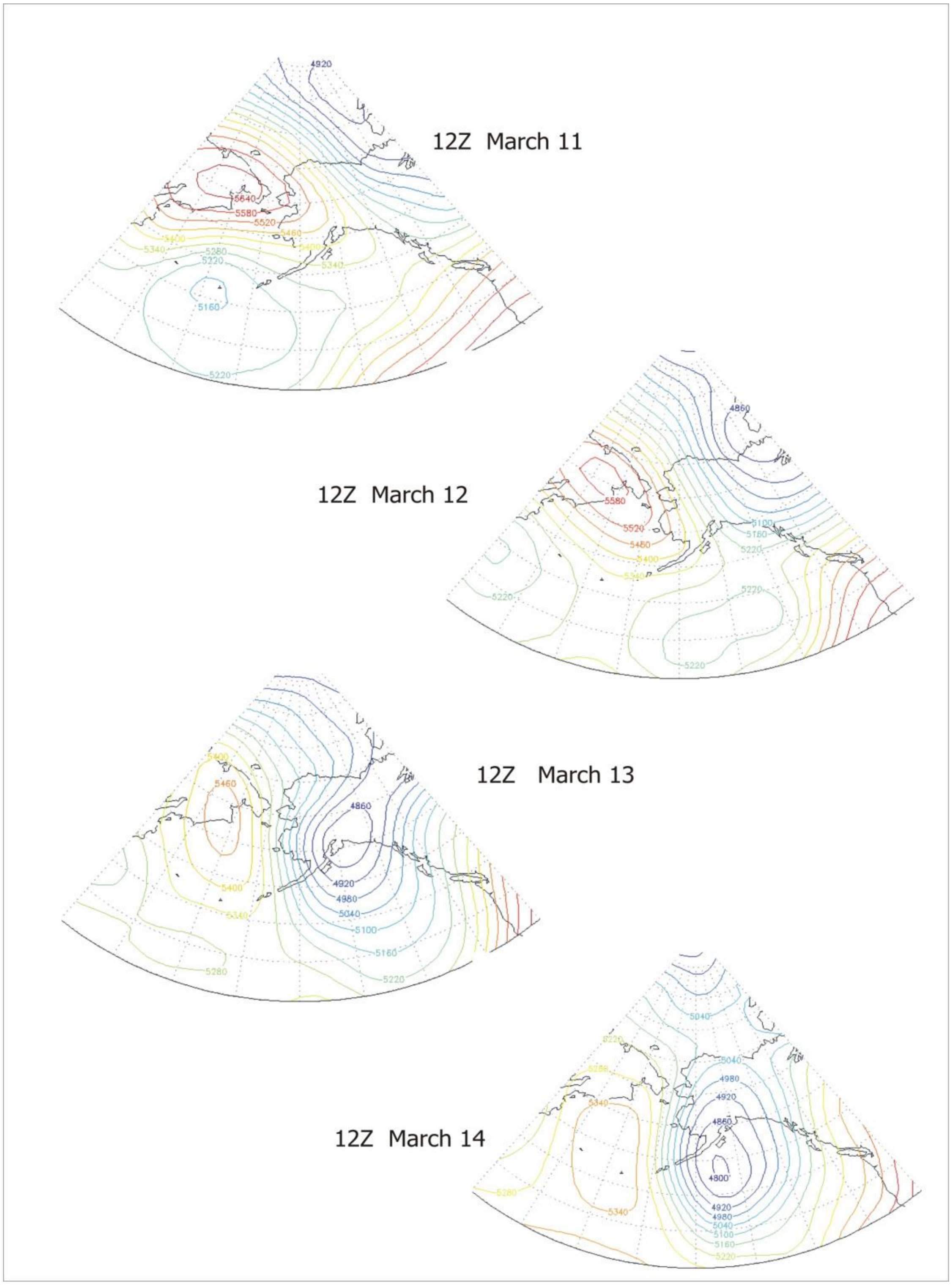

Figure 3: 500 mb heights (m) for 11-14 March, 2003. Contour Interval = 60 . Plots from NCAR/NCEP Reanalysis.

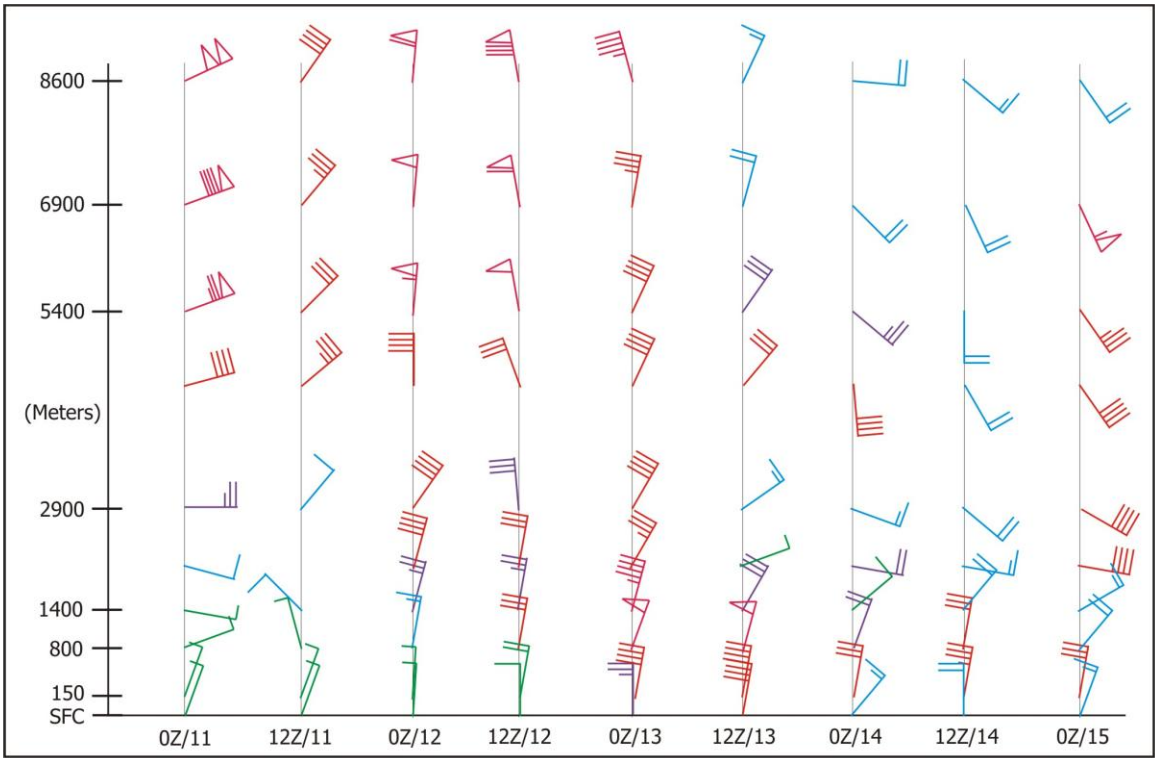

Figure 4: Anchorage radiosonde winds (kts) from 0Z 11 March through 0Z 15 March. Full barb is 10 kts while half-barb is 5 kts.

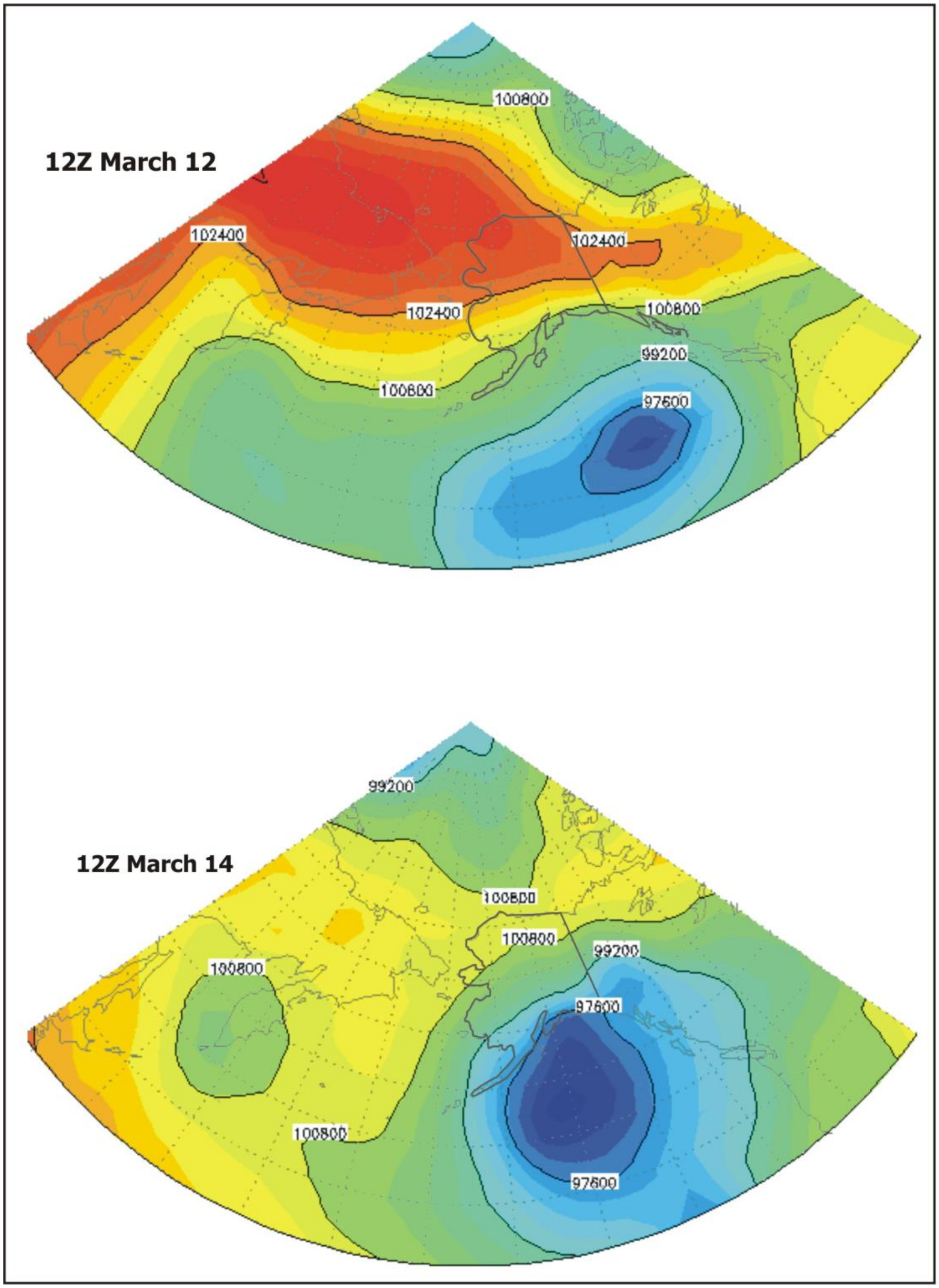

Figure 5: Mean sea-level pressure (pascals) for 12Z 12 March and 12Z 14 March. Color contour interval is 400 pa, solid line contour interval is 1,600 pa. Plots from NARR Reanalysis.

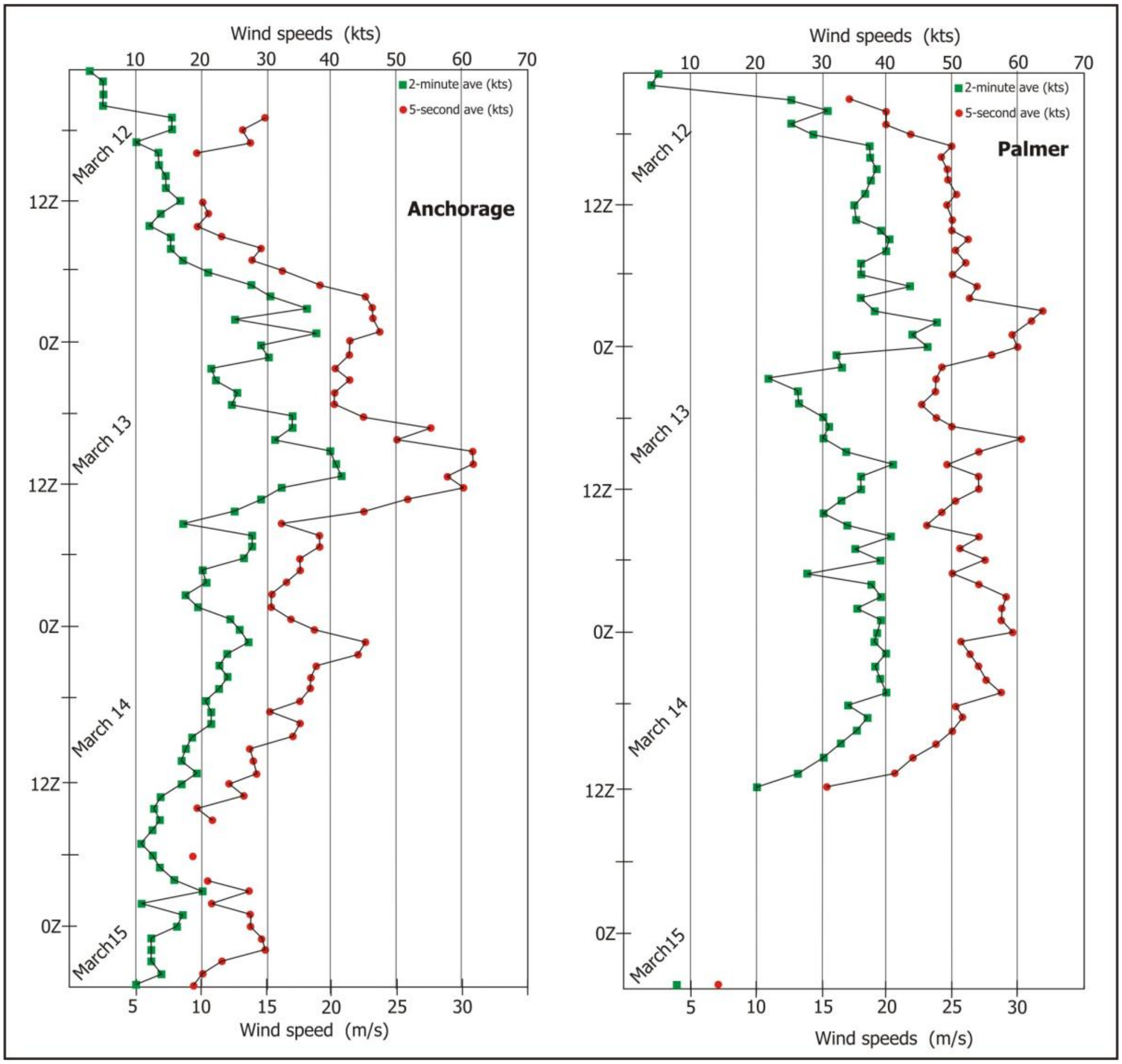

Figure 6: Sustained (2-minute) and peak wind gusts (5-second) at Anchorage and Palmer. The missing data at Palmer after 12Z/14 is due to temporary sensor failure.

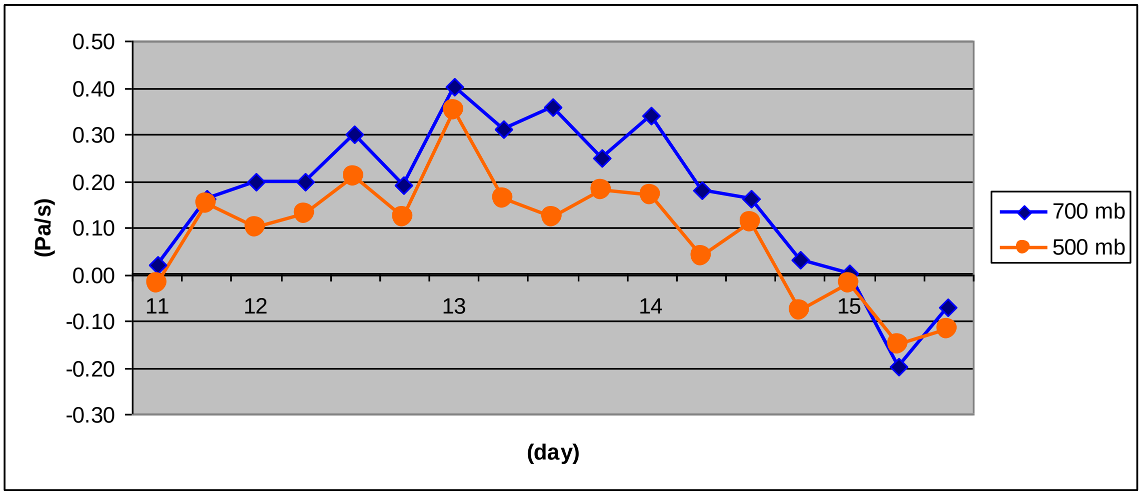

Figure 7: Omega (Pascals per second) at 700 mb (diamonds) and 500mb (circles) obtained from NCAR Reanalysis at a grid point (62^{o}N, 150^{o}W) near Palmer, Alaska. (positive values indicate downward motion)

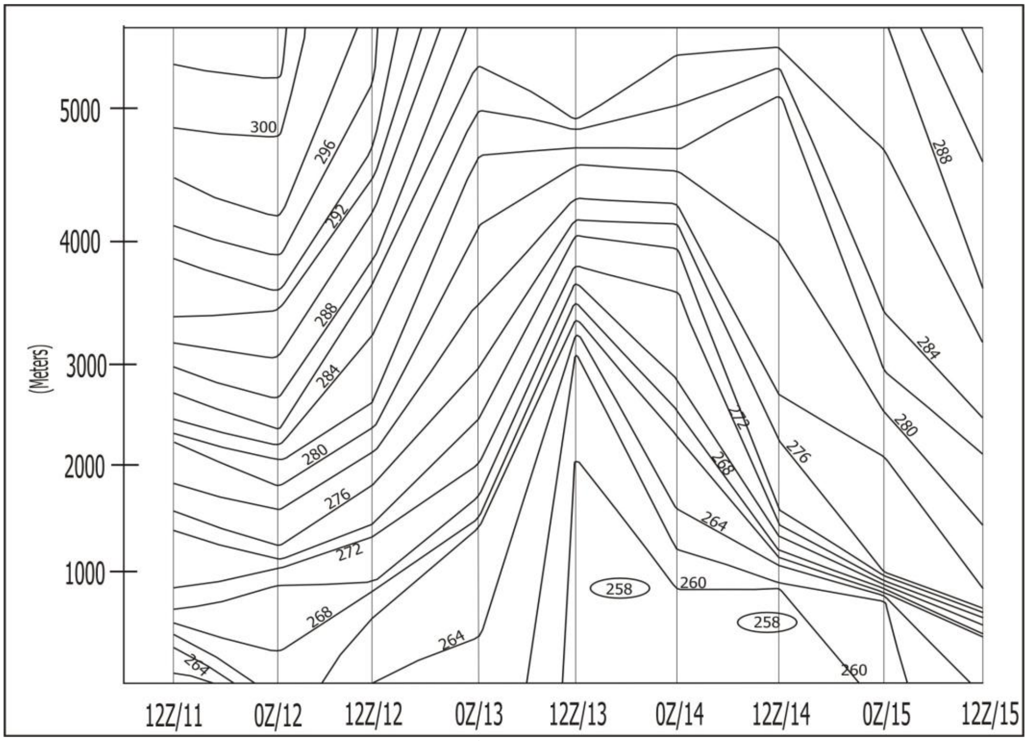

Figure 8: Potential temperature (^{o}K) evolution at Anchorage based on radiosonde flights.

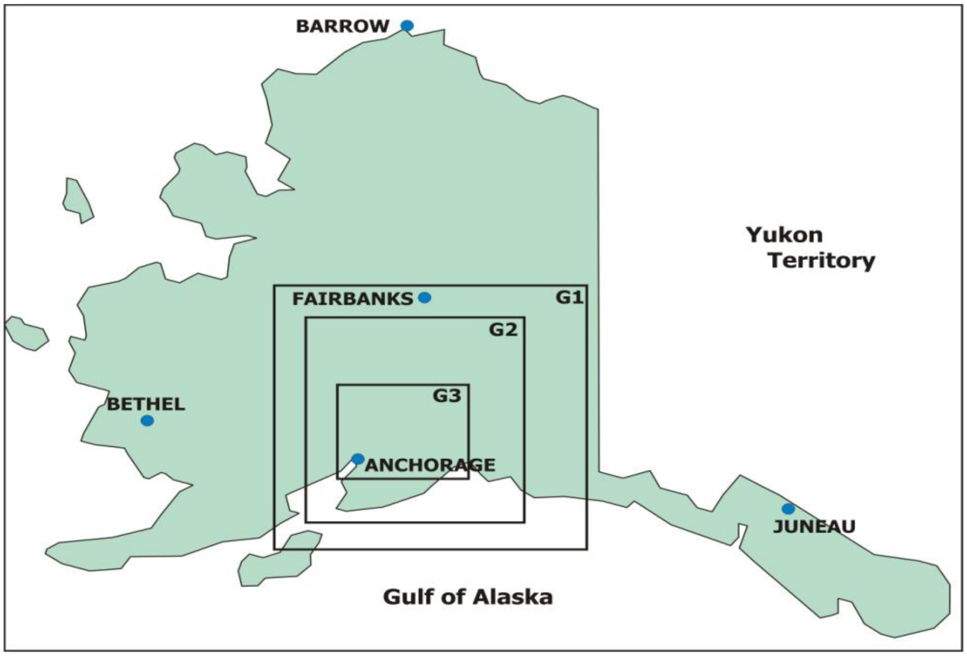

Figure 9: Three grid configuration for WRF model simulation. G1=32 km, G2=8 km, G3=2 km. Actual grids are on a polar stereographic projection.

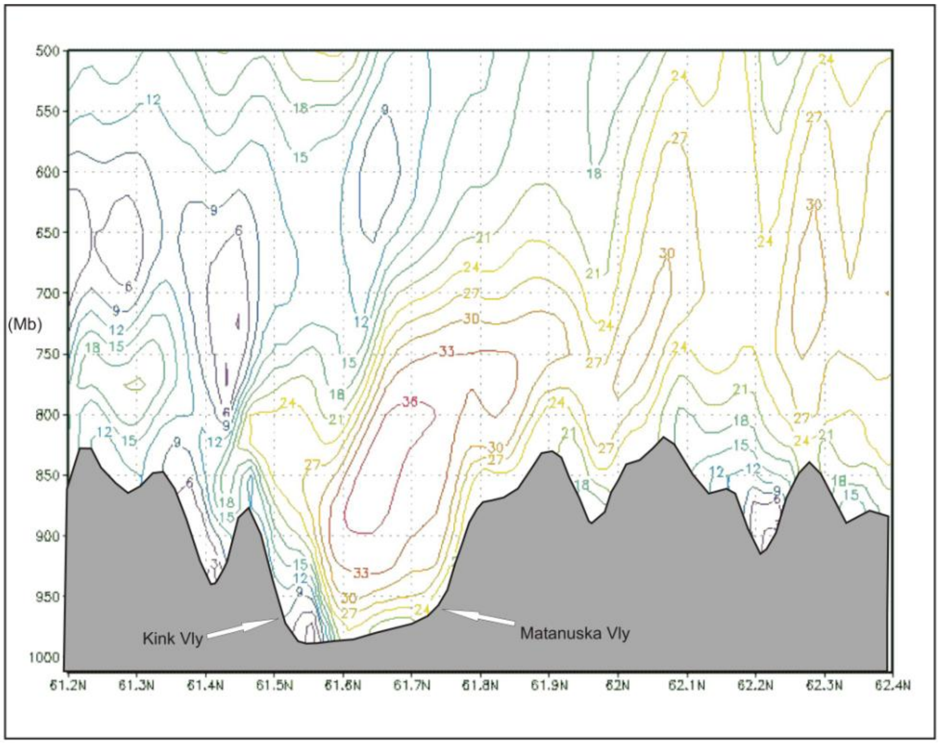

Figure 10: Y-Z modeled Matanuska Valley winds near Palmer valid at 06Z/13. Winds speeds are in ms^{-1}. North is on the right hand side.

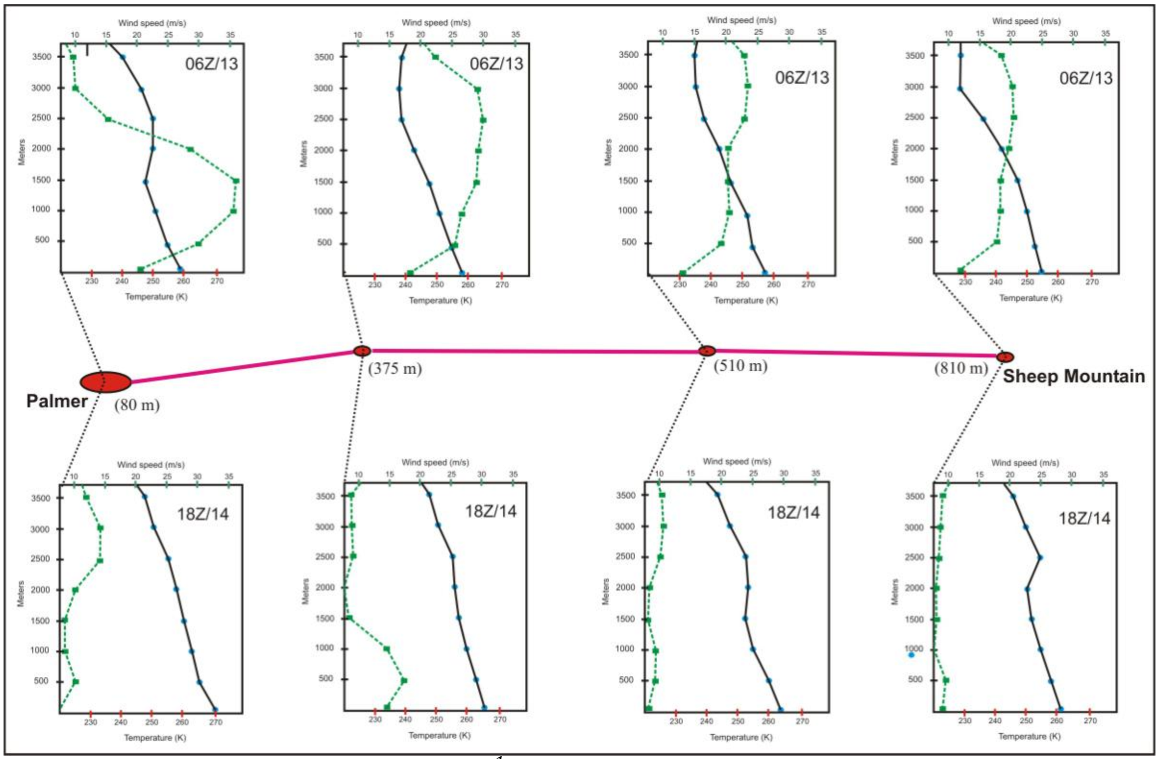

Figure 11: Modeled wind speeds (ms^{-1}) and temperatures (K) at four locations in the Matanuska Valley valid at 06Z/13 and 18Z/14.

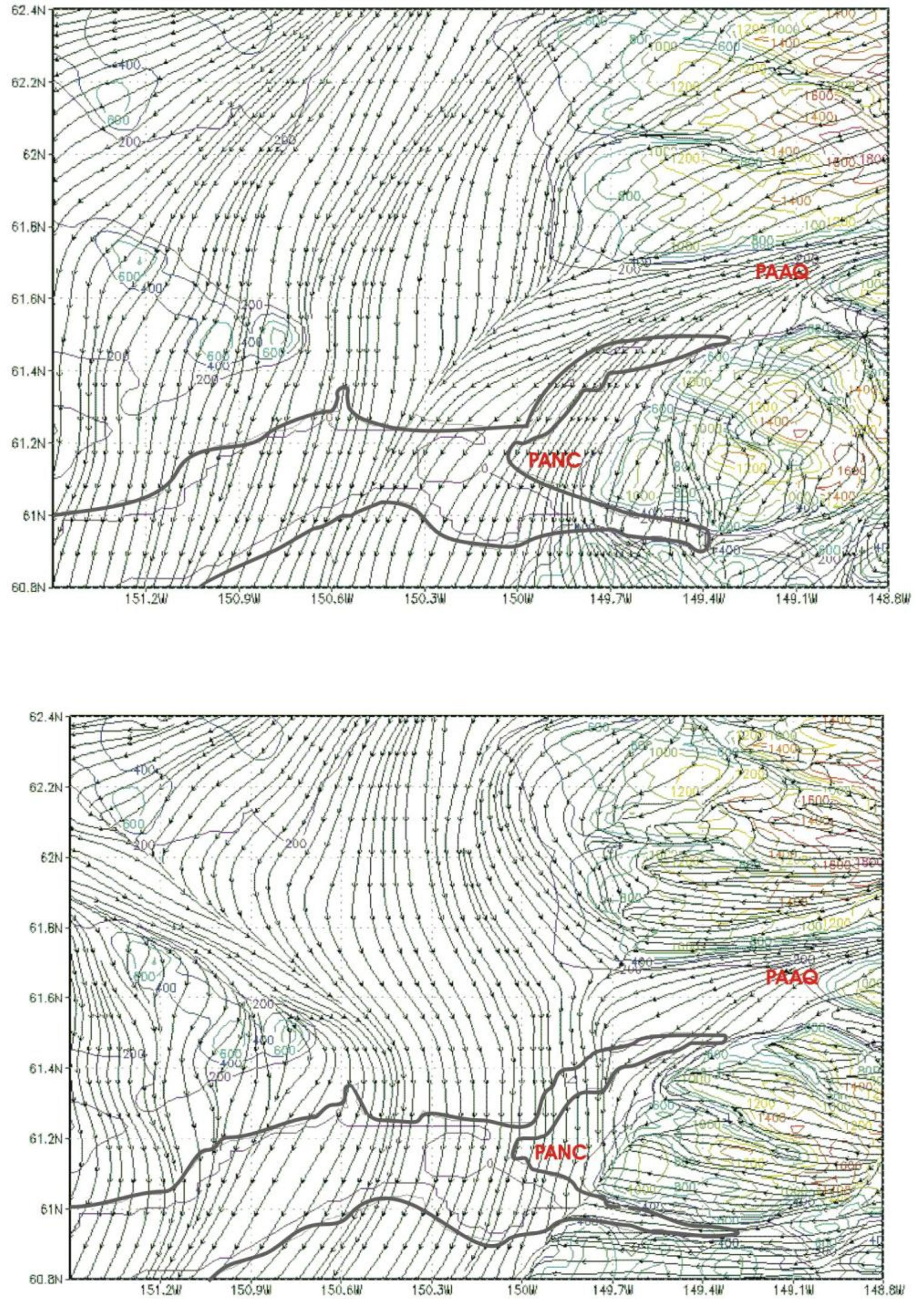

Figure 12: Streamline plots of model output valid at 0Z/13 and 18Z/14 at the lowest model layer. In the bottom panel notice the flow around Mt. Susitna.

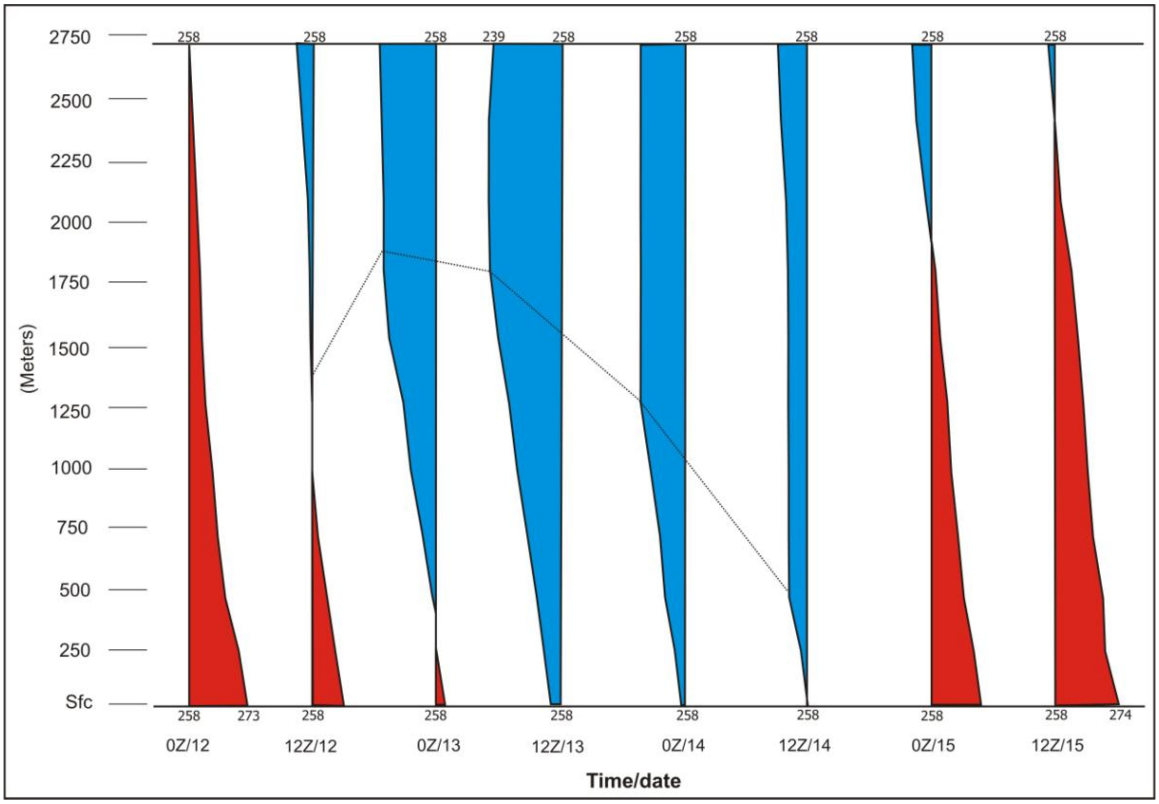

Figure 13: Modeled temperature evolution within the lower Matanuska Valley. Reference temperature is 258^{o}K which is the mean value from the surface to 2700 m. Red shading presents values above 258^{o}K while blue those below. Thin solid line represents the approximate height of an isothermal layer or inversion.

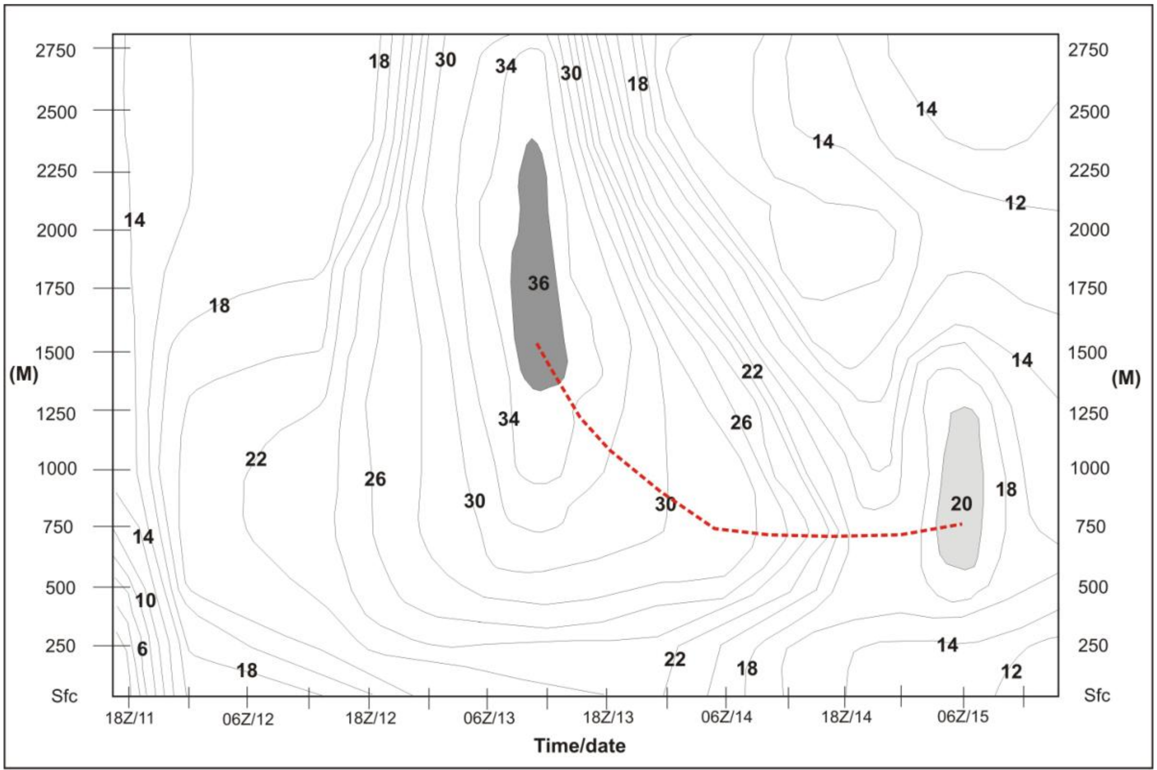

Figure 14: Modeled wind speed (ms^{-1}) at a point in the lower Matanuska Valley. Dashed line indicates the lower of the jet core in time.