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Errors in Rainfall Estimation in the Southern Alaska WSR-88D Network

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Abstract

Very little research has been done regarding the use of weather radars in Alaska, not only to localize them for the unique set of environmental phenomena found in Alaska, but also to evaluate their feasibility as reliable data sources in observation-deficient areas. This study isolated specific areas where the Alaskan radar network has performed well, where its data quality is suspect, and where improvement of the system is desired. Several interviews were conducted with forecasters at all three Alaskan National Weather Service forecast offices, as well as the Alaska River Forecast Center and Alaska Region Headquarters, to learn about perspectives on the radar network. The area chosen for further investigation was the precipitation amount estimates given by various radars. Specific excessive rainfall and flooding cases recommended by local forecasters were evaluated, using two of Alaska's Doppler radars. One-hour, radar-derived precipitation estimates were compared to observed hourly rain gauge data, and WRF model simulations using reanalysis data were also used to “estimate” precipitation from these events. It can be shown that, for river forecasting and flash flooding purposes, radar-derived precipitation estimates very often, though not always, substantially improve upon model forecast estimates. However, even with this improvement, it was found that radar-derived precipitation estimates were rarely accurate within their scale of resolution as compared to rain gauge data, and the error was not consistent from site to site or from event to event. Possible reasons for these errors, particularly with regards to the Alaskan environment, are discussed, as are questions that would require future research.

1. Background

Currently, the NEXRAD (Next Generation Weather Radar) program facilitates the majority of the radar meteorological needs of the United States. Within the Alaska region, there are presently seven Weather Surveillance Radars, model 88-Doppler (WSR-88D) deployed throughout the state, as presented in figure 1. The determination of locations for these radars was accomplished primarily with aviation interests in mind. Complex terrain and scattered population centers make contiguous or overlapping radar coverage virtually non-existent in the Alaska region. For comparison, in the contiguous United States, there is approximately one radar for every 56,900 square kilometers of land area while in Alaska there is approximately one radar for every 245,400 square kilometers. This low-density network leaves much of the state uncovered.

With most rain gauges and other ground-truth measurements often hundreds of kilometers apart located at remote airstrips, the determination of actual rainfall amounts in much of the state is left to remote sensing platforms, including satellite- and radar-derived estimates. In interviews with forecasters working at the Anchorage, Fairbanks and Juneau offices of the National Weather Service, the lack of reliable precipitation data was cited frequently as an issue of great concern to the forecasters.

In a state where most of the population centers, particularly in the interior, have evolved on river banks, river flooding has the potential to be intensely catastrophic. Limited access to these towns further demands that forecasts for potential flooding hazards be issued in a timely and reasonably accurate manner. Good precipitation measurements are essential to ensuring the promptness and accuracy of these forecasts.

Furthermore, in many coastal areas, the sudden transition from ocean to mountainous terrain creates an environment ideal for heavy rain and flooding, and debris flow events. The orographic lifting, enhancing precipitation on the windward, ocean side of the coastal mountains of southern Alaska, contributes to the heaviest rainfall totals in the state being found along the southern coast (figure 2). Furthermore, the steep, rocky terrain on these shores does little to slow runoff from the mountainsides. Small creeks and streams that run from the mountains to the sea can quickly fill and overflow, impacting the cities along their banks and at their mouths. Thus, once again, accurate precipitation estimates are essential for good flash flood forecasts in coastal areas.

Forecasters in the Anchorage and Fairbanks forecast offices of the National Weather Service have brought forward questions about the accuracy of the radar-derived rainfall estimates being displayed to them via the NEXRAD's Radar Product Generator (RPG) and its component Precipitation Processing System (PPS). A general overview of the PPS algorithms may be found in Fulton, et al. (1998). This system relies on conventional Z-R relationships, as well as an option to input other data sources including rain gauge data, to estimate precipitation rate from a given radar volume scan and to integrate this rate across the time between volume scans. From iterations of this procedure, three primary precipitation products are generated at the level III data level—one-hour precipitation, three-hour precipitation, and storm total precipitation.

Limitations of radar-derived precipitation estimates are well-recognized, particularly in areas of complex terrain. Several approaches have been suggested to correct and adapt radars to provide better precipitation estimates. Vivekanandan, et al. (1999) characterized the impact of beam blockage by terrain on radar-derived precipitation estimates, concluding that in complex terrain, standard horizontally-oriented reflectivity data as applied to precipitation estimates tended to underestimate the rainfall accumulation. They also noted that specific phase differential, a dual-polarimetric radar product, performed markedly better in estimating rainfall in areas where there was partial beam blockage. Joss and Lee, 1995, reiterate how important it is to have radar data from as close to the ground and as near to the radar as possible to ensure good precipitation estimates and suggest that appropriate clutter filtering and other physical models may be applied to correct for radar-based errors in precipitation estimates. Pereira, Crawford and Hartzell (1998) found that, in general, the WSR-88D system tended to underestimate precipitation at a site on the Great Plains, but in general provided "good" estimates of the spatial variability of the rainfall rate. They, too, emphasize the sensitivity of range from the radar on the quality of the precipitation estimates.

To an extent, some of these concerns will be addressed with future upgrades to the radar system. The NEXRAD system is currently in the process from upgrading from Build 10 to Build 11 of the RPG software, which includes the Clutter Mitigation Decision algorithm (CMD) designed to automatically detect and mitigate transient clutter from the radars, primarily due to anomalous propagation of the radar beam. A description of this algorithm may be found in Ice, et al. (1999). This helps satisfy the need for good clutter filtering to ensure higher-quality precipitation estimates. Furthermore, within the next few years, the NEXRAD system is expected to be upgraded to a dual-polarimetric radar system, which will allow for the generation of specific phase differential-derived rainfall rates. These rainfall estimates, as observed by Vivekanandan, et al. (1999), tended to be more accurate in areas where there was significant beam blockage due to terrain. Both of these upgrades should enhance the precipitation estimation abilities of the Alaskan radars. The ability to analyze and specifically to modify the multiple adaptable parameters surrounding the Precipitation Processing System (PPS) in the Radar Product Generator (RPG) for research purposes is greatly hampered by the lack of any archive of level II radar data from any radar in the Alaska Region. While efforts are currently underway to negotiate for such archiving, at present the communications bandwidth is not available for transmission of that data stream to a central archiving point from these very remote sites. The Federal Aviation Agency, which is responsible for the maintenance and upkeep of the radar sites, does not currently support the on-site, manual archiving of level II radar data, primarily due to the remoteness of the radar sites. As such, any changes of the adaptable parameters must be handled in the operational environment, which is ill-suited to extensive experimentation. Thus, any analysis performed can only hypothesize on potential solutions as the only data available are level III precipitation products already generated. This study could have benefited from the availability of level II data, as this data could have been re-run through the RPG with different configurations to see the different impacts on precipitation estimates. It is noted that for any further research to be done using the Alaskan radar system, the archiving of level II radar data is a practical necessity.

2. Methodology

Level III, one-hour precipitation data were obtained for ten significant rainfall events across Alaska within the range of the southern Alaska radar network. Events were taken from the years 2002 through 2009 to maintain the most consistency with the current state of the NEXRAD radar system, as well as to agree with the time of archived surface observations that were available. Archived surface rain gauge observations were obtained for sites within the ranges of the radar. Due to the limited number of sites and fragmented data sets within the range of the Bethel (PABC) and King Salmon (PAKC) radars, these sites only received cursory analysis. The primary focus became the Kenai (PAHG) and Middleton Island (PAIH) radars. After additional input from the Fairbanks WFO, the Pedro Dome (PAPD) radar was also considered for case study analysis, but time limitations prevented the inclusion of their data into this report.

Events were chosen based on forecaster recollection of the events as well as an examination of daily rainfall totals for the years 2002 through 2009 at various sites within the range of each radar. To limit the number of cases, only dates when the total accumulated 24 hour precipitation at one or more gauge sites were over 1" were considered. These dates were also limited to the August-November wet season in southern Alaska to ensure seasonal continuity in these precipitation systems.

A clarification issue regarding the interpretation of one-hour precipitation plots from the Radar Product Generator had to be resolved first. As seen in figure 3, the scale given for the color codes of the precipitation plot began at "0.00 in." for the lowest color level, though intuitively the lack of any color shading would imply 0.00 inches, or no data obtained.

Upon discussion with the Radar Operations Center, it was learned that proper interpretation of the image was that the lightest shade of color, labeled "0.00 in." represented areas where more than 0.00 inches of rainfall had been estimated, but less than the next higher value of 0.05 inches. This continues up the scale, with each value being the minimum value for each color level. For the sake of this analysis, a bin on the one-hour precipitation plots was considered “accurate” if the hourly rain gauge measurement for a gauge contained within that bin fell within the range specified by the scheme just described.

Rain gauge data were obtained through the ROMAN Mesowest database, located at http://mesowest.utah.edu/index.html. Gauge sites considered included those in the National Weather Service/Federal Aviation Administration Automated Surface Observation System (ASOS) network at most major airports and the United States Forest Service/Bureau of Land Management Remote Automated Weather Stations. More complete descriptions of the precipitation accumulation measurement methods are detailed for the ASOS system in the ASOS User’s Manual (Federal Aviation Administration, 1998) and for the RAWS system in the RAWS/Fire Weather Station Standards (Heffernan and Arnold, 2008). Data quality mechanisms for both observation systems are also included in those reports. The data sets obtained were mostly consistent and contiguous, though there were some hourly observations that were missing. Several sites were rejected from consideration in this survey due to their data being completely unavailable for one or more of the events considered.

The statistical comparison and analysis of the data was performed in many ways. To minimize false positive readings which would inflate the accuracy of the radar in times where there was no precipitation, only times when either the rain gauge or the radar said there was precipitation in a certain area were considered.

3. Results

a. PAIH—Middleton Island Radar and Associated Sites

The PAIH radar is located on a small island approximately 280 kilometers southeast of Anchorage and 80-100 kilometers south of the barrier islands at the entrance of Prince William Sound. Its placement in this remote, maritime location was primarily to monitor weather conditions along flight routes between the lower 48 states and Anchorage and Fairbanks. This is the primary radar for the entire Prince William Sound area, the mouth of the Copper River, and the eastern Kenai Peninsula. The three largest cities in the coverage area are Valdez (population 4,020), Seward (population 3,016), and Cordova (population 2,327), all of which have nearby ASOS sites. The map in figure 4 shows the locations of these sites.

All three cities are hubs for regional maritime commerce, including strong fishing and tourism economies. In addition, the city of Valdez serves as the terminal city for the Trans-Alaska Pipeline System, and thus its harbor is of vital importance to the transport of crude oil out of Alaska. Due to their relative isolation, these cities are particularly vulnerable to any damage to their infrastructure.

Referring to figure 2, annual precipitation along the Prince William Sound coast is some of the highest in Alaska, with 200-280 inches of rain falling annually in this region. Due to the mountainous terrain, runoff through stream and river valleys can be extreme. Any fluctuations in precipitation can cause disastrous floods.

204 hours of radar data were obtained for comparison between one-hour radar estimates and gauge reported values. Five cases were chosen, all occurring within the "wet" season of late summer into autumn. The specific dates examined were: August 20-21, 2006;

October 9-10, 2006; September 9-10, 2007; October 14, 2007; and November 21-22, 2007.

1) VALDEZ, ALASKA (PAPD)

Of the 204 hours of data considered, precipitation was shown to be present by either the rain gauge or the radar at this site for 148 of those hours. The results of statistical comparison are shown in table 1.

Statistically, the radar precipitation estimate was deemed "inaccurate" nearly 60% of the time, where the precipitation measured by the Valdez rain gauge during a certain hour was not within the range of possible precipitation values estimated by the radar for that same hour. Furthermore, when inaccurate, radar underestimation was more common than overestimation by an approximately 2 to 1 margin. Weighting the mean magnitude of error by the over- and underestimation tendencies yielded a mean weighted error of -0.0211 inches for every hour of radar precipitation data.

2) SEWARD, ALASKA (PAWD)

Of the 204 hours of data considered, precipitation was shown to be present by either the rain gauge or the radar at this site for 101 of those hours. The results of statistical comparison are shown in table 2.

Precipitation estimates at Seward were more inaccurate on average than at Valdez, with gauge observations falling outside of the radar bin precipitation range 68.3% of the time. The radar strongly underestimated precipitation at Seward, with underestimation more common than overestimation by a 9 to 1 margin. The mean magnitude of error was also higher, at nearly .1 in. Weighting this error by the over- and underestimation tendencies gives a mean weighted error of -0.0775 inches for every hour of radar precipitation data.

3) CORDOVA, ALASKA (PACV)

Of the 204 hours of data considered, precipitation was shown to be present by either the rain gauge or the radar at this site for 174 of those hours. The results of statistical comparison are shown in table 2.

There was a more even distribution between over- and underestimates at Cordova, with an almost 50-50 split between the two. However, inaccuracies in the radar estimations were the highest of all three cities, occurring 71.84% of the time. The mean magnitude of the error was at 0.065 inches, and weighting this mean error by the over- and underestimation percentages yielded a mean weighted error of only 0.002 inches, or less than one hundredth of an inch.

b. PAHG—Kenai-Anchorage Radar and Associated Sites

The PAHG Kenai-Anchorage radar (hereafter referred to as the “Kenai radar”) is located on the northwestern corner of the Kenai Peninsula of southern Alaska along the eastern shore of the Cook Inlet, some 90 kilometers southwest of Anchorage. This radar covers several major population centers of southern Alaska, from the Matanuska-Susitna valley to the north, through the Municipality of Anchorage, to the population centers of the western Kenai Peninsula. The effective range of this radar is limited to the west by the Aleutian Range along the western shore of the Kenai Peninsula and to the east and southeast by the Kenai Range along the eastern Kenai Peninsula.

Due to various orographic effects to the north in conjunction with typical prevailing synoptic patterns, several of the northern population centers, including Anchorage, sit in the rain shadow of the western Chugach Mountains. This greatly limits the number of extreme, prolonged rain events in these areas. For this reason, this study focused mainly on several heavy rain events found through the ROMAN Mesowest database and through forecaster input for the cities and rain gauge sites of the western Kenai Peninsula. Of the locations considered, the only gauge sites representing any major towns were the ASOS site at the Homer Airport and the Homer RAWS site to the east of the city of Homer. Other sites considered included the RAWS sites at the small town of Ninilchik on the eastern shore of the Cook Inlet and at Skilak Lake in the central Kenai Peninsula. The map in figure 5 shows the locations of these sites. ASOS and RAWS stations from the major towns of Soldotna and Kenai were discarded from the study as their extreme proximity to the radar limits the effectiveness of the radar precipitation estimates at these locations.

As can been seen in figure 2, the western Kenai Peninsula lies on the typically leeward side of the Kenai Mountains, and thus has significantly lower rainfalls than other areas along the southern Alaskan coast. However, several cases of rain-induced small stream flooding are common along the peninsula, and the area is subject to locally heavy downpours from convective activity in the summer and autumn months.

121 hours of precipitation data were collected from the Kenai Radar, covering five different events. These events included: October 24, 2002; November 23-24 2002; October 10, 2007; November 9, 2007; and November 20-21, 2007. The focus on the autumns of 2002 and 2007 was based on the input of local forecasters at the Anchorage

forecast office, and examination of storm totals from the Mesowest website helped isolate specific dates. Due to all the events being contained in the October-November timeframe (typically the wettest time in the region), seasonal variability in precipitation type and drop size distribution is minimized.

1) Homer RAWS Site, Alaska (HMEA2)

Of the 121 hours of data examined, 101 had precipitation shown to be present at the Homer RAWS site by either the rain gauge or the radar. Some results of the statistical comparison are shown in table 4.

In terms of time, radar precipitation estimates at the Homer RAWS site were inaccurate a comparable amount of time to the Middleton Island sites with the radar bin being inaccurate 66.34% of the time. The mean magnitude of the error was also comparable to previously observed values, with a mean error magnitude of about 0.055 inches. Underestimation was more frequent than overestimation by nearly a 2-1 margin.

2) Homer ASOS Site, Alaska (PAHO)

Of the 121 hours of data examined, 84 had precipitation shown to be present at the Homer ASOS site by either the rain gauge or the radar. This illustrates the spatial and temporal variability of the precipitation events in this region, as the Homer ASOS site is only 15 kilometers from the Homer RAWS site, but had 17 fewer precipitation hours during this survey, a 16.8% difference from the Homer RAWS site. There is a significant elevation difference between the two, though, with the Homer ASOS site at an elevation of 26 meters and the Homer RAWS site at an elevation of 218 m. Some results of the statistical comparison between radar and gauge observations at the Homer ASOS site are shown in table 5.

In comparison with the nearby Homer RAWS site, the Homer ASOS site shows more variability, but a smaller amount of error. The percents of time over and underestimating were slightly more evenly distributed than at the Homer RAWS site and the total percent of time inaccurate was higher, at 75% of time at the Homer ASOS site. However, the mean error of the radar's magnitude of error was much lower, at approximately 0.42 inches, which is within the radar's precipitation bin reporting resolution of 0.05 inches. This implies that, though the radar frequently remains "inaccurate" in its precipitation reports as compared to the rain gauge, when such inaccuracies occur their magnitude is much smaller than at the Homer RAWS site.

3) Ninilchik, Alaska (NCKA2)

Of the 121 hours of data examined, 106 had precipitation shown to be present at the Ninilchik RAWS site by either the rain gauge or the radar. Some results of the statistical comparison are shown in table 6.

Once again we see at Ninilchik that the percent of time when the radar measurement was inaccurate was around 2/3 of the time. The percents of time for over- and underestimation favor underestimation, though this underestimation is not as extreme as some of the other sites examined. The mean magnitude of the error, however, is comparatively high at nearly 0.1 inches per hour.

4) Skilak, Alaska (SGSA2)

Of the 121 hours of data examined, 98 had precipitation shown to be present at the Skilak RAWS site by either the rain gauge or the radar. Some results of the statistical comparison are shown in table 7.

The 2/3 of the time inaccuracy is also seen here at the Skilak site. Underestimation is also favored, and by a similar margin to the other locations previously mentioned under the Kenai radar's range. The mean error magnitude is comparatively high at nearly 0.9 inches.

c. Summary of Gauge Locations and Radar Estimates

It can be seen that, when precipitation is present, the radar's "accuracy" in precipitation estimation is relatively poor, with no site being "accurate" more than 50% of the time. However, the magnitudes of the errors do yield some useful information for interpreting radar estimates for these sites. For example, at Valdez and Cordova, the 99% confidence interval for the mean magnitude of one-hour radar error in precipitation estimation does not extend to include 0.1 inches. This indicates that, for a given 24 hour period, there is at least a 99% chance that the mean magnitude of the error of the hourly precipitation estimates will be less than 0.1 inch. Over 24 hours, this means that it is very likely that the radar will be no more than 2.4 inches away from the actual precipitation amount. With regards to the radar over- or underestimating the precipitation, at sites like Valdez and Seward there is a strong tendency for underestimation, so when evaluating error, forecasters should be aware of this likelihood. Statistically, it is virtually impossible to predict whether radar estimates at Cordova will be higher or lower than gauge observations. With the radar being inaccurate at Cordova almost 72% of the time, forecaster confidence of radar precipitation estimates at this point should be relatively low. However, as mentioned before, it is possible to statistically limit the maximum possible error of the radar and derive some degree of confidence in precipitation tendencies from that limitation.

A remarkable degree of continuity is found in the underestimation of the radar at sites in the Kenai Peninsula. All four sites surveyed had underestimation clearly favored, with a general average approaching a 2-1 margin in favor of underestimation. Furthermore, all four sites on the Kenai Peninsula were inaccurate on average about 2/3 of the time.

Ulbrich and Lee (1999) found that, theoretically, the WSR-88D system using the default, Marshall-Palmer Z-R relationship of $300R^{1.4}$ (which is employed by all radars in the state of Alaska) should underestimate most stratiform rainfall by an average of approximately 25%. However, several stratiform rain cases were found where the radar estimates were 200% or greater below the actual observed gauge precipitation. These more extreme cases were attributed to radar miscalibration by Ulbrich and Lee. For this study, the mean percent errors for these sites were calculated using the average of all errors, making no distinction between over- and underestimation. As seen in table 8, these percentage errors are considerably higher than the 25% underestimation error inherent to the default Z-R relationship. This implies that, while improving the Z-R relationships on the Alaskan radars to more localized schemes to account for different drop size distributions may help reduce radar estimated precipitation errors, both in magnitude and in frequency, there are other factors contributing to the poor precipitation estimates.

At the same time, at all sites the mean percentage errors were below the 200% errors recounted by Ulbrich and Lee as being commonplace in their studies. This would indicate that, while the Alaskan radars are grossly inaccurate as compared to gauge data, this kind of error is not anomalously high as compared to radar precipitation errors observed in other parts of the WSR-88D network. In examining the standard deviations of the error, however, we find that the degree of error in these two radars is not consistent at all, with all of the standard deviations being greater than actual magnitude of the percentages of error themselves. Statistically this would indicate a very low confidence in any sort of consistent bias or otherwise systematic error in the radar's precipitation estimates, at least in terms of *percentage* error. Thus, the errors are probably caused by more random factors that would not be accounted for in a simple system recalibration. The sources of some of these errors will be considered next.

4. Investigation of Potential Rainfall Estimation Errors

a. Terrain Influence

Among many of the forecasters interviewed over the course of this survey, a widely-held belief was that terrain blockage or partial beam blockage due to terrain were leading causes of precipitation estimation errors. Partial beam blockage is a well-documented phenomenon where the radar beam, as it spreads out along its path of travel, only partially encounters a feature of terrain. This can lead to erroneously high reflectivity values being returned to the radar, which in turn may be processed as erroneously high rates of precipitation in this area. Clutter mitigation algorithms, clutter maps, and partial beam blockage correction algorithms in the WSR-88D Precipitation

Preprocessing Algorithm itself all work to mitigate these impacts, as described in Fulton, et al. (1998). However, it is conceivable that the mitigation and algorithms described by Fulton, et al., are not accurately accounting for any beam blockage that is occurring. To help quantify the depth of this problem, terrain cross-sections were derived using 30-second terrain data as analyzed and interpreted by the WRF Preprocessing system, running from the location of the radar to the locations of the various rain gauges investigated. In addition, hypothetical radar beam centerpoints were projected onto the cross sections to simulate the theoretical path of the radar beam. Four radar tilts were simulated, at 0.50, 1.45, 2.40 and 3.35 degrees above horizontal. These represent the lowest four tilts in Volume Coverage Pattern 21, which was the predominant radar scanning strategy for all the cases surveyed. The lowest four tilts are the only ones considered by the Precipitation Preprocessing Algorithm. To model these beam paths, some inspiration was drawn from Gao, Brewster and Xue (2005) who discussed various strategies for modeling beam paths. To simplify matters, atmospheric refraction was not considered in the beam equation, as its variability would have required much more extensive calculations to be done. Height of the radar transmitter above the ground, simple tilt angle and curvature of the earth were used to produce equation 1, a simplified beam path equation.

$$H_{beam} = H_T + r\tan(\alpha) + R_e\left[1 - \sin\left(\cos^{-1}\left[\frac{r}{R_e}\right)\right]\right] \qquad (1)$$

Eq. 1 – A simplified beam path equation. H_T is the height of the radar transmitter above the ground, r is the horizontal distance from the radar transmitter, α is the tilt angle of the radar and R_e is the radius of the earth.

This equation was used to compute idealized beam paths on the diagrams below. Figures 6-8 represent the three gauge sites under the range of the Middleton Island radar.

We can see in all cases that the projected beam heights are well above the simulated terrain, even at the lowest tilt of the radar for all three Middleton Island sites. Similar diagrams for the four sites examined in the range of the Kenai Radar are shown in figures 9-11.

Since all sites surveyed near the Kenai Radar are located generally on the flat plains of the western Kenai Peninsula, there is not nearly as much elevated terrain. Once again, it is evident on all of the beam path diagrams that there should be little to no terrain blockage between the radar and these gauge sites.

b. Freezing Level Influence

Another postulated theory to explain the wide variety of errors in the precipitation estimates was the possibility that during many heavy rain events, the radar beam spends a considerable amount of time traveling through the melting layer aloft, through realms of frozen precipitation even further aloft, or completely overshooting the cloud tops by the time it reaches some of the gauge sites. To evaluate this, archived and model soundings were obtained where possible for all of the cases studied. Since the nearest location where weather balloon launches occur is Anchorage, model soundings generated using a WRF-ARW model configured to the same specifications and parameterizations used by the Anchorage forecast office when running their local WRF-ARW model were used to supplement the observations. Figures 12-15 below illustrate observed and model soundings for two events, two events—October 9-10, 2006 and September 9-10, 2007—

both of which were heavy rain events in the Prince William Sound/Middleton Island Radar area.

As can be seen in these figures, the temperature and wind profiles compare favorably between the model and the observed upper air conditions at Anchorage. In analyzing soundings from all events, it was found that the freezing level, where the temperature profile crosses the 0□C isotherm, during wet season rain events in both the Kenai and Middleton Island radar ranges varied between 1000 m AGL to 3200 m AGL.

Returning to table 7, we can see that at Cordova, the centerpoint of the lowest beam as it arrives over Cordova would be expected to be at approximately 2500 m above sea level. The elevation of the Cordova site is only 13 m, so the site may be considered practically at sea level. It is clear that, for many cases, the radar beam would indeed be passing through and above the freezing level, as 2500 m falls within the 1000-3200 m range of freezing level elevations observed for these events. In figures 6 and 7, we see that at Seward and Valdez, which are even further from the radar, the lowest radar beam is well over 3000 m above sea level by the time it arrives at both sites. This indicates an even greater likelihood that the radar beam is not sampling the liquid precipitation falling near the surface, but rather melting or frozen precipitation aloft. This could account for the considerable variability in the precipitation errors observed.

At the Kenai radar, the four gauge sites analyzed were much closer to the radar than the gauges under the range of the Middleton Island radar. At 107.1 km, the city of Homer is the furthest location surveyed in this study, and by this point the lowest radar beam was projected to be approximately 2250 m above sea level at the Homer gauge sites. The Homer ASOS and RAWS sites are at elevations of 26 and 218 m, respectively, so there is some elevation difference. However, even with that included, it is clear that the radar beam height still falls well within the 1000-3200 m elevation of the freezing level observed on soundings. However, at Ninilchik (only 77.8 km from the radar), the projected lowest beam height is estimated to be at around 1200 m above sea level, and at Skilak (46.4 km from the radar) the beam height is estimated to be at about 600 m above sea level. The Ninilchik station has an elevation of 40 m and the Skilak station is at an elevation of 180 m. In both cases, it is likely that the lowest radar beam had not entered the freezing/melting layer by the time it arrived at both sites. This would normally imply more accurate rainfall estimation at the Skilak and Ninilchik sites, assuming that the freezing/melting layer was playing a significant role in the radar system's error. We see in the data in tables 4-7 that there is a remarkably high degree of consistency between the errors observed at the Homer sites and at the Ninilchik and Skilak sites. It has been well observed that the passage of a radar beam though the freezing/melting layer produces a phenomenon known as the "bright band," a region of elevated reflectivity values from the partially melted hydrometeors in this region. If the radar beam were sampling a region at the lower bounds of the possible freezing/melting layer, it would seem more probable that the precipitation estimates based on reflectivity values in this freezing/melting layer would be favoring overestimation instead of the underestimation actually observed. These findings would seem to indicate that the freezing level location is not as deterministic of a factor in precipitation estimation accuracy at the Kenai radar sites.

This finding also sheds light on a new possibility for the interpretation of the results at the Middleton Island sites. The beam height at Cordova was the only location where the lowest tilt was well-embedded within the possible freezing/melting layer. At both the Valdez and Seward locations, the beam was well above the freezing/melting layer. In examining the percentage of time the radar was over and under estimating precipitation in tables 5-7, we see that both at both Valdez and Seward, underestimation was clearly favored over overestimation. However, at Cordova, the over- and under estimation was rather balanced. Since this represents the only site in surveyed under the Middleton Island radar that did not observe a strong bias towards underestimation (in terms of time), it is possible that the increased likelihood of the radar beam sampling the freezing/melting layer over Cordova helped contribute to more time spent overestimating the precipitation, compensating for what otherwise would be a consistent underestimation bias.

c. Comparison with Model Guidance

It is conceivable that in the absence of any reliable local rain gauge or radar data, the forecaster would consider other options to estimate precipitation, including the use of numerical models. With the apparent inaccuracy of radar-based precipitation, it was deemed prudent to compare the estimates being given by the radar with estimates given by a numerical model simulation for some of these events.

Two of the events at the Middleton Island radar site—October 9-10, 2006 and September 9-10, 2007—were modeled using a configuration of the WRF-ARW version 3.1 modeling system. The models were initialized using GFS analysis data, and were modeled under a 12-km resolution regional grid with a 4-km resolution nest covering Prince William Sound and the Kenai Peninsula. Furthermore, the parameterization schemes were chosen to match those already in use by the Anchorage Weather Forecast

Office in their own regional WRF model for operational use. These accommodations represent the best possible simulation that the forecasters could have hoped to have received for this event and should represent the model's most accurate expected recreation of the events.

Precipitation amounts were written by the WRF model on an hourly basis from the inner, 4-km grid, but the sum, storm-total precipitations were used for this comparison as it is unlikely that a forecaster would be using model data on an hourly basis to determine specific rainfall amounts. A summary of the total precipitation amounts for both the radar and the model for the October 9-10, 2006, event is given in table 9.

In this first event, it is clear that the radar overestimated precipitation at Cordova, strongly overestimated at Valdez, and underestimated precipitation at Seward. This event appears somewhat atypical of the usual pattern at Valdez, as it was already made evident in table 1 that the overall trend was for the radar to underestimate at Valdez approximately twice as often as overestimate. However, it should be noted that the numbers in table 9 are based on the magnitude of the precipitation error and not on the amount of time the radar was in error. In examining the model's findings, the model underestimated precipitation at Cordova, was very accurate at estimating precipitation at Valdez and strongly underestimated the precipitation at Seward. Table 10 gives similar information to table 9, only now regarding the September 9-10, 2007, case.

In examining the data for the second event, the consistency with the first event in the percentage error of the radar at Cordova and Valdez is immediately apparent. At Cordova, the radar overestimated by 19.1% for the first case as compared to 12.8%

overestimation in the second case. At Valdez, the radar overestimated by 62.2% for the first case and 61.6% for the second case. These consistencies may be random coincidences in the data, and more model runs on different events would be necessary to determine the validity of this consistency. At Seward, the radar reversed its trend, strongly overestimating in the second case as opposed to strongly underestimating in the first case.

The model comparisons show far greater variability than the radar comparisons. At Cordova, the model switches from modest underestimation in the first case to strong overestimation in the second case. At Valdez, the model went from being reasonably accurate in the first case to very strongly overestimating the precipitation in the second case, more than doubling the amount of precipitation actually observed. The only relative consistency in the model's predictions was at Seward, where the model consistently and strongly underestimated the precipitation.

It is clear that more model runs of more cases are required before any strong statistical conclusions can be derived about model accuracy versus radar accuracy. Time limitations during the length of this study prohibited the modeling of more events. However, it can be seen that the model varies greatly in its estimates, yet is not subject to the same potential measurement errors already discussed with regards to the radar. Nevertheless, the model is a simulation, reliant on the computer and its algorithms to process these events instead of actually observing what is happening. In general, except for the estimations at Valdez during the first case, the magnitude of the percentage error of the model was always greater than the magnitude of the percentage error of the radar. This would seem to support the hypothesis that the radar, in general, provides more accurate rainfall estimations than model guidance would provide. However, nothing can be said about the radar being more consistent than the model, particularly with such limited data.

5. Conclusions

In examining the overall statistics and not individual case studies for each rain gauge location, some clear patterns emerge in the errors in radar-derived precipitation amounts. It seems readily clear that the radar's "accuracy" at any given point varies widely, and statistically no individual hourly precipitation value given for a certain location can be assumed to be accurate. The magnitudes of error at each individual site except the Homer ASOS site were all beyond the 0.05 in resolution of the radar data, and had confidence intervals often extending through a magnitude of error of greater than 0.10 inches. As could be seen in table 8, in terms of percent error, the average values were all significantly higher than the 25% error inherent to the Z-R relationship used as predicted by Ulbrich and Lee (1999). However, they are all well within the 200% errors known to be commonly observed on radars in the lower 48 states, indicating that the errors observed on the Alaskan network are not extraordinary in any way. The standard deviations of these percentages, however, were often greater than the mean percentages themselves, once again pointing to the apparent random fluctuations in the radar's ability to estimate rainfall from one time period to the next. Ulbrich and Lee also found there to be a general underestimation bias, and this seems to be confirmed at the sites surveyed.

All sites surveyed under the Kenai radar exhibited a tendency towards underestimation, averaging around a 2-1 favoring of underestimation as opposed to overestimation in terms of time. At the Middleton Island radar, both the Valdez and Seward sites both exhibited a similar tendency towards underestimation. The more even distribution of under- and over estimation at Cordova could be due to the radar beam's tendency to be intercepting the freezing/melting layer at that location.

An analysis of 10 cases over the Middleton Island and Kenai radar areas found that during the wet season rain events of August through November, the freezing/melting layer's elevation above ground varied from 1000 to 3200 m. While the observations at Cordova point toward bias of precipitation estimates due to the radar beam intercepting this layer, the beam's similar altitude over the Homer ASOS and RAWS sites produced data inconsistent with any true contamination effects. However, based on a simple beam path equation derived and the 1000-3200 m range in freezing elevation, it can be calculated that forecasters should be aware of potential overestimation tendencies *in the longer term estimates* at all sites greater than 70 km from the radar.

While it is clear that the terrain can locally enhance or inhibit rainfall, no data found seem to support evidence that partial beam blockage or clutter contamination from the terrain were in any way effecting precipitation measurements. At all sites surveyed, it was clear that the lowest hypothetical beam path was well above the height of the terrain surrounding the site and there was no midstream beam blockage due to terrain between the radar and any site surveyed.

Though ideal model data was only obtained for two cases at one radar for this study, analysis of the errors produced by the model provide some enlightenment as to the relative accuracy of the radar. Since it seemed apparent that the magnitude of the errors in the radar estimates of precipitation was almost always less than the magnitude of the errors in the model at all sites surveyed, it is hypothesized that the radar precipitation estimates at least provide slightly more reasonable estimates than model guidance. Should this hypothesis prove to be substantiated, it should give the forecaster greater confidence in the radar's precipitation estimates for usage over model guidance for rainfall totals. In addition, this would suggest that, for the purpose of initializing hydrologic models, radar-derived precipitation estimates would provide a better initialization than using other models for initialization. Once again, many additional case studies would need to be modeled to develop a better substantiation and quantification of this hypothesis.

As noted in the introduction, Vivekanandan et al. (1999) found that dual – polarimetric derived radar precipitation estimates, namely from the specific differential phase product, were markedly more accurate in estimating precipitation amounts than the current system of using a static Z-R relationship. The study found this to be particularly true in areas of mountainous or complex terrain. With an upgrade to dual-polarimetric radars scheduled for the Alaskan WSR-88D system within the next few years, this could increase the accuracy of the radar-derived precipitation estimates available to the forecasters. A later study to search for any such improvements may be warranted one these upgrades are made.

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List of Tables and Figures

TABLE 1. Statistical results for 148 hours of precipitation radar data from Valdez, Alaska. Confidence intervals over a 24 hours period for the mean error indicated are given on the left.

24hr	Precip Only, Valdez RADAR (PAIH)			
	Low (in.)	High (in.)	Mean Error Mag	0.059391892
0.99	0.03655	0.082234	Mean % Error	87.4%
0.95	0.043237	0.075547	% time high	32.19%
0.9	0.046802	0.071982	% time low	67.81%
0.75	0.052773	0.066011	% time inaccurate	59.46%

TABLE 2. Statistical results for 101 hours of precipitation radar data from Seward, Alaska. Confidence intervals over a 24 hours period for the mean error indicated are given on the left.

24hr	Precip Only, Seward RADAR (PAIH)			
	Low (in.)	High (in.)	Mean Error Mag	0.0979208
0.99	0.030322	0.1655194	Mean % Error	164.3%
0.95	0.050114	0.1457281	% time high	9.90%
0.9	0.060663	0.1351785	% time low	89.11%
0.75	0.078333	0.1175087	% time inaccurate	68.32%

TABLE 3. Statistical results for 174 hours of precipitation radar data from Cordova, Alaska. Confidence intervals over a 24 hours period for the mean error indicated are given on the left.

24hr	Precip Only, Cordova RADAR (PAIH)			
	Low	High	Mean Error Mag	0.06500
0.99	0.035304	0.09469581	Mean % Error	103.2%
0.95	0.043998	0.086001551	% time high	51.79%
0.9	0.048633	0.081367166	% time low	48.21%
0.75	0.056395	0.073604891	% time inaccurate	71.84%

TABLE 4. Statistical results for 101 hours of precipitation radar data from Homer RAWS site, Alaska. Confidence intervals over a 24 hours period for the mean error indicated are given on the left.

24hr	Precip Only, Homer RAWS RADAR (PAHG)			
	Low	High	Mean Error Mag	0.054851
0.99	0.034423	0.07528	Mean % Error	115.17%
0.95	0.040404	0.069299	% time high	32.67%
0.9	0.043592	0.066111	% time low	67.33%
0.75	0.048932	0.060771	% time inaccurate	66.34%

TABLE 5. Statistical results for 84 hours of precipitation radar data from Homer ASOS site, Alaska. Confidence intervals over a 24 hours period for the mean error indicated are given on the left.

24hr	Precip Only, Homer ASOS	RADAR (PAHG)		
	Low	High	Mean Error Mag	0.041667
0.99	0.024911	0.058422	Mean % Error	78.50%
0.95	0.029817	0.053516	% time high	39.29%
0.9	0.032432	0.050902	% time low	60.71%
0.75	0.036811	0.046522	% time inaccurate	75.00%

TABLE 6. Statistical results for 106 hours of precipitation radar data from Ninilchik RAWS site, Alaska. Confidence intervals over a 24 hours period for the mean error indicated are given on the left.

24hr	Precip Only, Homer ASOS	RADAR (PAHG)		
	Low	High	Mean Error Mag	0.0928302
0.99	0.042226	0.143434	Mean % Error	115.63%
0.95	0.057042	0.128618	% time high	42.45%
0.9	0.064939	0.120721	% time low	57.55%
0.75	0.078167	0.107494	% time inaccurate	66.98%

TABLE 7. Statistical results for 98 hours of precipitation radar data from Skilak RAWS site, Alaska. Confidence intervals over a 24 hours period for the mean error indicated are given on the left.

24hr	Precip Only, Skilak	RADAR (PAHG)		
	Low	High	Mean Error Mag	0.089694
0.99	0.028996	0.150392	Mean % Error	126.47%
0.95	0.046767	0.132621	% time high	37.76%
0.9	0.05624	0.123148	% time low	62.24%
0.75	0.072106	0.107282	% time inaccurate	66.33%

TABLE 8. The means and standard deviation of the hourly radar error in rainfall estimation at all sites considered in the survey.

Percent Error Mean and Standard Deviation at All Sites Surveyed

	Mean Pct. Error	Percent Error Std. Deviation
Middleton Is		
Valdez	87.39%	94.48%
Seward	164.26%	407.51%
Cordova	103.16%	201.92%
Kenai		
Homer RAWS	115.17%	179.67%
Homer ASOS	78.50%	84.39%
Ninilchik	115.63%	218.01%
Skilak	126.47%	127.24%

TABLE 9. A summary of the total, 48 hour accumulated precipitation from the Middleton Island radar and the WRF model simulation of the October 9-10, 2006, event. Percentage errors are based on the sum of the hourly gauge totals given in the first row.

48 Hour Accumulated Precipitation and Error for October 9-10, 2006

	Cordova	**Valdez**	**Seward**
Gauge Total (in.)	9.03	4.44	6.22
Radar Total (in.)	10.75	7.20	3.60
Radar Error (%)	**19.1%**	**62.2%**	**-42.1%**
Model Total (in.)	6.77	4.50	2.42
Model Error (%)	**-25.0%**	**1.4%**	**-61.1%**

TABLE 10. A summary of the total, 48 hour accumulated precipitation from the Middleton Island radar and the WRF model simulation of the September 9-10, 2007, event. Percentage errors are based on the sum of the hourly gauge totals given in the first row. * The Seward rain gauge data was incomplete for this event and only data from the first 36 hours of the event was considered at this location.

48 Hour Accumulated Precipitation and Error for September 9-10, 2007

	Cordova	**Valdez**	**Seward ***
Gauge Total (in.)	5.85	3.65	0.76
Radar Total (in.)	6.60	5.90	1.15
Radar Error (%)	**12.8%**	**61.6%**	**51.3%**
Model Total (in.)	9.46	7.68	0.41
Model Error (%)	**61.7%**	**110.4%**	**-53.9%**

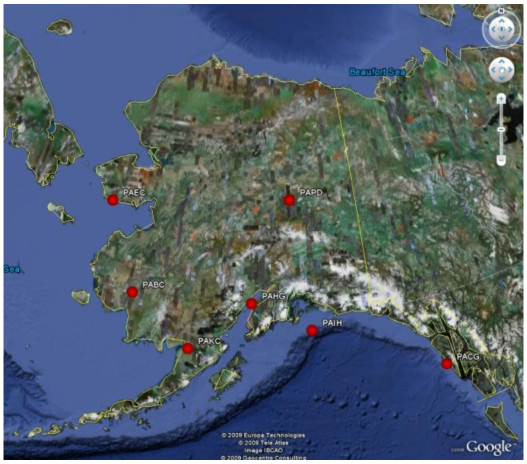

FIG 2. Locations of the 7 Alaskan WSR-88D Radars. Note the relatively sparse coverage and the highly mountainous terrain separating the radars. Image generated with Google Earth.

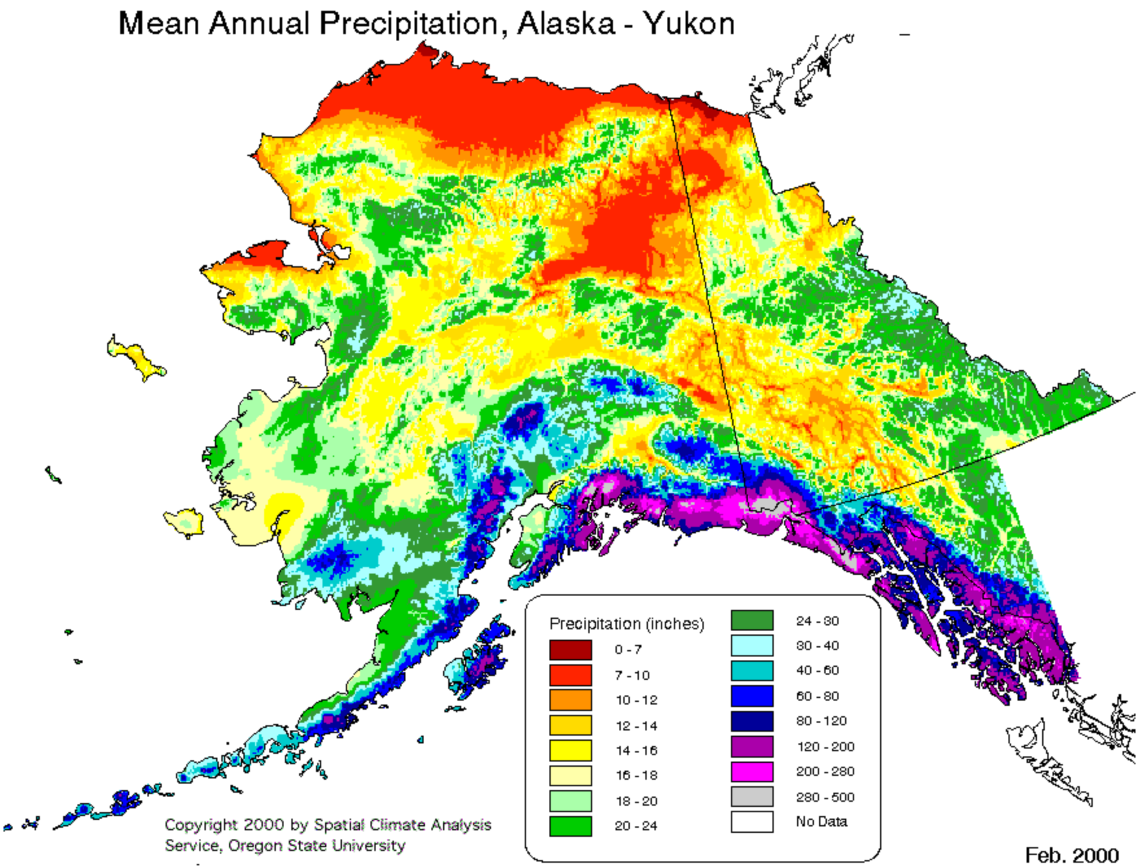

FIG 1. Mean Annual Precipitation for Alaska and the Yukon. Notice the higher precipitation amounts along the southern coast, on the southern slopes of the Chugach and Wrangell mountain ranges. Image courtesy of Oregon State University's PRISM data.

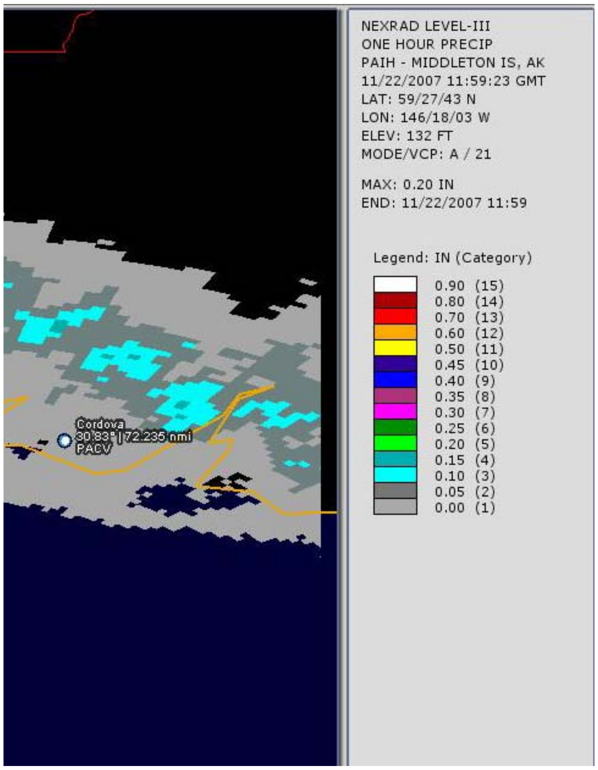

FIG 3. A sample, level III, one-hour precipitation accumulation map from the Middleton Island (PAIH) radar near Cordova with the color scale included. Note the ambiguous "0.00 in." qualification assigned to the lightest color shade.

FIG 4. Map of the locations of the Middleton Island radar and associated gauge sites used in this study. (Image courtesy of Google Earth)

FIG 5. – Map of the locations of the Kenai radar and associated gauge sites used in this study.

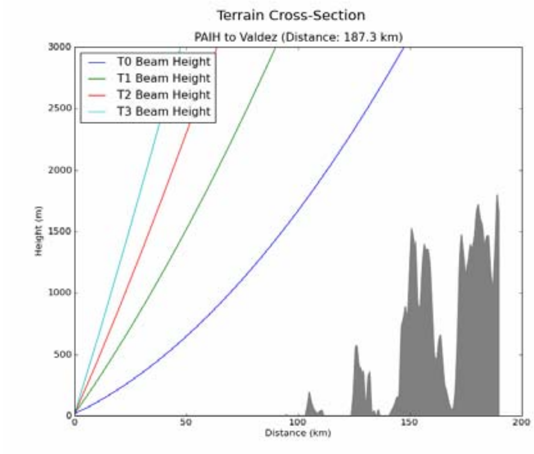

FIG 6. Terrain cross section from PAIH to to Valdez.

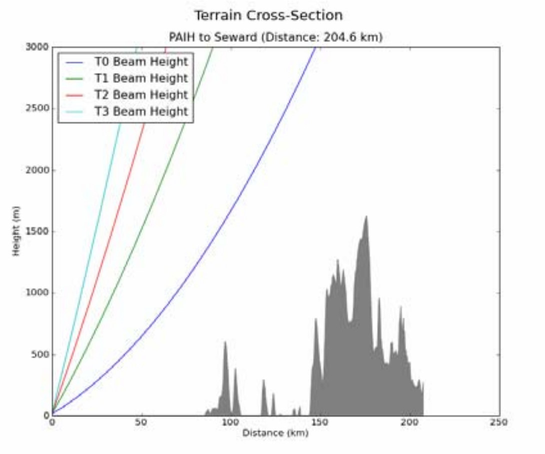

FIG 7. – Terrain cross section from PAIH Seward.

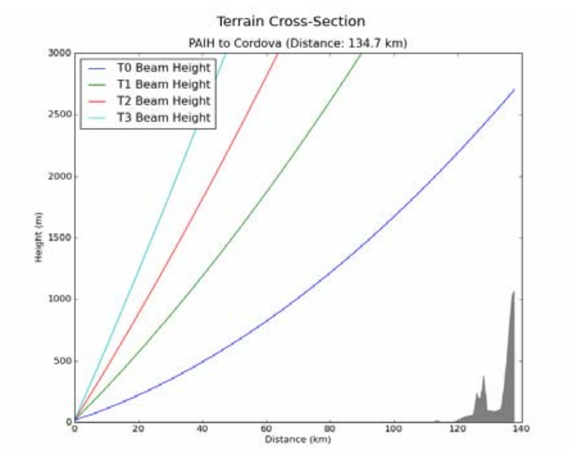

FIG 8. Terrain cross section from PAIH to Cordova.

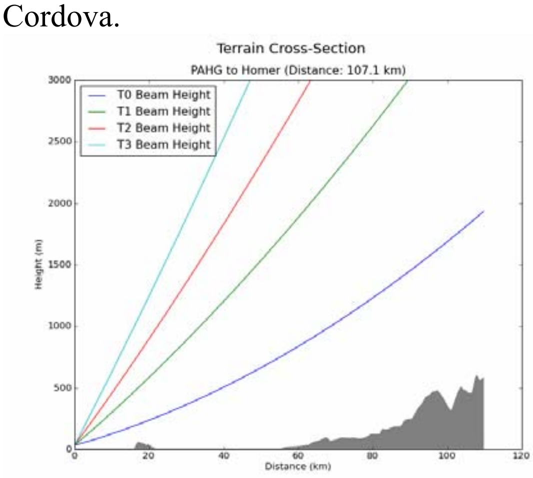

FIG 9. Terrain cross section from PAHG to Homer (RAWS and ASOS

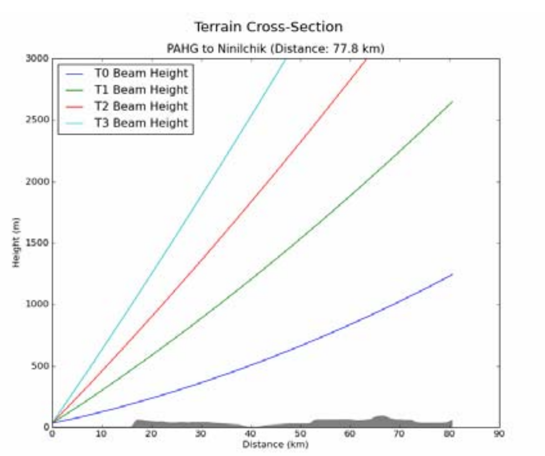

FIG 10. Terrain cross section from PAHG to Ninilchik.

are in proximity to one another).

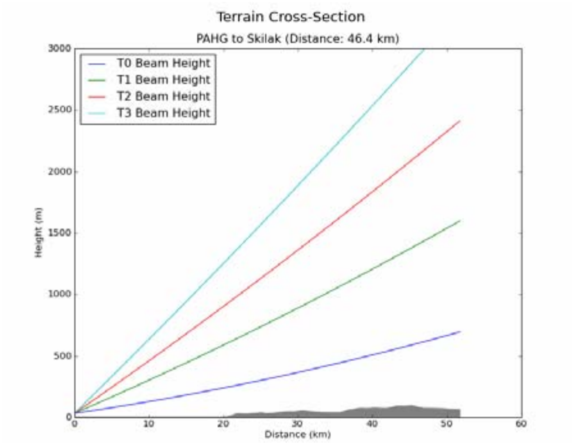

FIG 11. Terrain cross section from PAHG to Skilak.

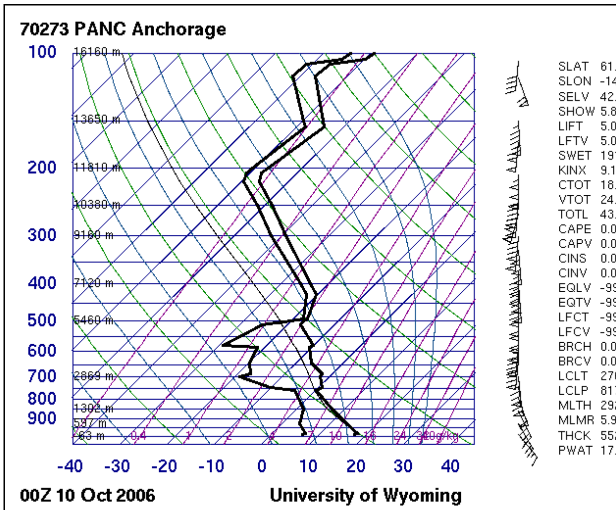

FIG 12. Sounding from Anchorage at 00Z on October 10, 2006

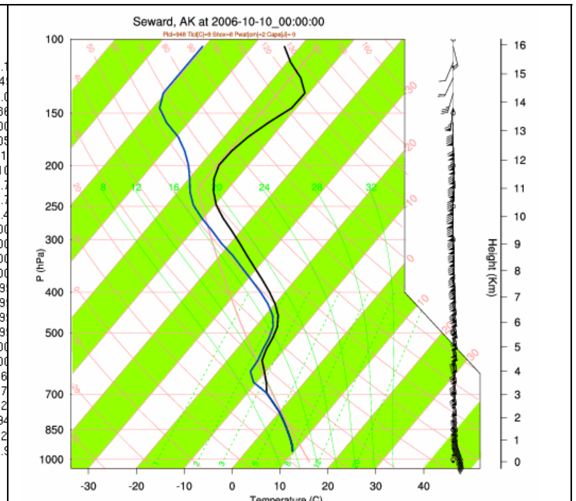

FIG 13. Model sounding from Seward at 00Z on October 10, 2006

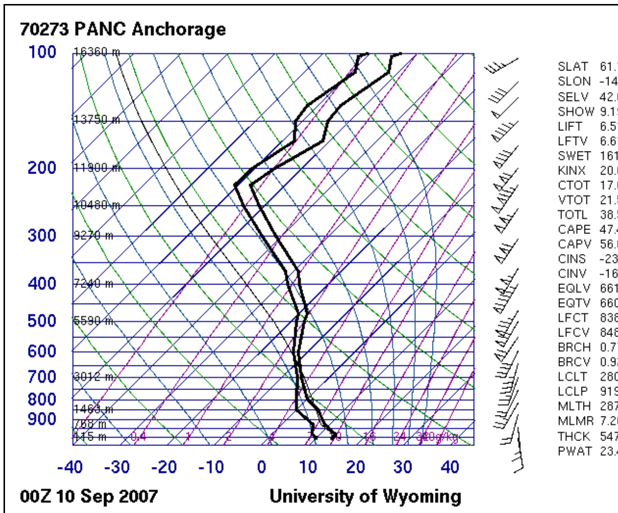

FIG 14. Sounding from Anchorage at 00Z on September 10, 2007

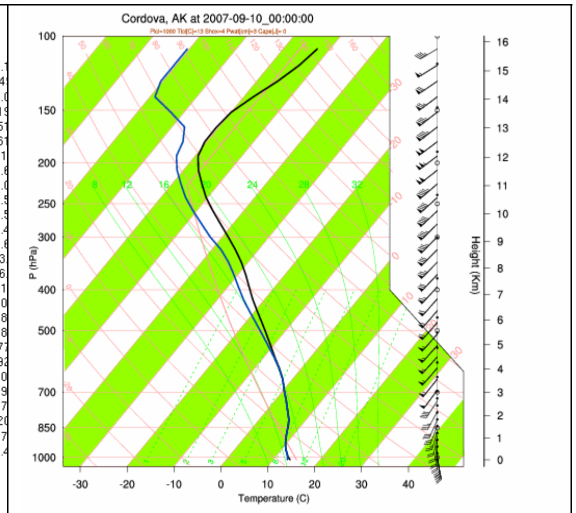

FIG 15. Sounding from Cordova at 00Z on September 10, 2007