The Dry Side of Atmospheric Rivers in Alaska

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Abstract

Very moist plumes of water vapor and cloud water known as 'atmosphere rivers' (ARs) are a fairly common occurrence across Alaska during the warmer months of the year. However, despite very large amounts of available moisture that could be converted into rain, not all ARs generate large amounts of rain. This paper shows a number of cases in which large fluxes (~3 st dev) of moisture moved onshore from the Bering Sea into western Alaska and the Interior, but the resulting rainfall was light to moderate. Summer rainfall, in areas lacking steep terrain, is a function of frontal lifting and convection even during the intrusion of an AR.

Motivation:

In the last decade there has been considerable interest in the impacts of atmospheric rivers (ARs), extended plumes of high precipitable water (PW) or cloud water originating over oceans (Neiman et al 2004, Neiman et al 2008, Ralph et al 2005). In a study of ARs in the Alaska region and their connection with heavy rain and flood events, Papineau & Holloway (2011) found that most of the historical rain generated flood events were associated with ARs. However, they did note that not all ARs produced copious amounts of rain as they moved onshore and transported moisture across the state. A case in point occurred on August 9, 1994, when the PW from the Bethel upper air sounding was 1.45 inches, a very high value (~3 St dev.); however, the 24 hour rainfall at the station was only 0.09 inches. This plume of moisture continued to move north and eventually produced 3-5 inches of widespread rain over the southern slopes of the Brooks Range. This motivated the authors to investigate the frequency with which these types of non-events occur. From a hydrometeorological perspective, it is essential for forecasters to understand the transport of deep moisture, which originates in the surrounding oceans, onto the mainland, as well as what forcing mechanisms transform water vapor and cloud water into rain.

Methodology:

As a starting point, we found the top 50 PW values at each upper air site in Alaska (Figure 1) which had a corresponding 24 hour rain observation (Table 1, for Bethel, contact authors for complete list). In other words, our list is not necessarily the top 50 PW ever observed at a given station, as we required a rain observation as well. The 24 hour rain was estimated by using the values listed in each station's Local Climatological Data (LCD) produced monthly by the National Climatic Data Center (NCDC). This restricted our data to the 1957-2010 period, with the emphasis on the 1965-2010 period - as rainfall observations were more readily available from the LCD's during this timeframe. In order to estimate the 24 hour rainfall, we took values from 12 hours on either side of the hour that the sounding was generated. In case of older data, we used the daily (midnight-to-midnight) value. This was also the method used when we collected rainfall observations from non-first order stations. The actual methodology has only minor impact on the final results. It is obvious that the majority of these events occur during mid-summer, with a peak in August. There is some geographic variability; in western Alaska virtually all of the events occur from mid-July through the first week of September. In the Gulf of Alaska region events can occur from late-June through late-September, with a substantial increase in September east of 155^{o}W. We suggest that this occurs because of the eastward shift in the storm track from its mid-summer position just east of the dateline into the Gulf of Alaska in the fall. In addition, maximum PW tend to decrease from south-to-north and from coastal-to-interior locations.

Once the highest 50 PW cases were determined, and the corresponding 24 hour rainfall recorded, we needed to determine some criteria that discriminated between a typical rain event and a heavier case. We took 30 years of August rainfall data (the majority of ARs occur in August) from each station and, using fundamental statistics, established light, moderate, and heavy rainfall criteria. Since rainfall data is heavily positively skewed (long right-hand tail; median value significantly smaller than the mean value), we took the arithmetic average of the median and mean and made it the criteria between light and moderate rain. For example, at Bethel there are 544 August values from 2011-1982 with a mean of 0.18 inch and a median of 0.10 inch. Thus, for Bethel, we then set the light-moderate criteria at 0.14 inch. In order to determine what constitutes a heavy rain event we took the 85% percentile of the 30 year data. At Bethel this turned out to be 0.38 inch. Granted, these criteria are subjective, however we were consistent from each upper air station to the next in determining these criteria. Once the criteria had been established, we segregated the PW cases into light, moderate, and heavy rainfall bins. At Bethel, for example (Table 1), we found that 42% of the 50 highest PW cases corresponded with light rain (<=0.14 inches) while 32% were considered heavy events (>=0.38 inches). For Interior stations the criteria separating light from moderate rain ranged from 0.10 inches to 015 inches per 24 hours. The results which will be described shortly justify our first assumption that ARs do not always produce heavy rain. In reality, they frequently only produce light rain, especially in southwest Alaska and the Interior.

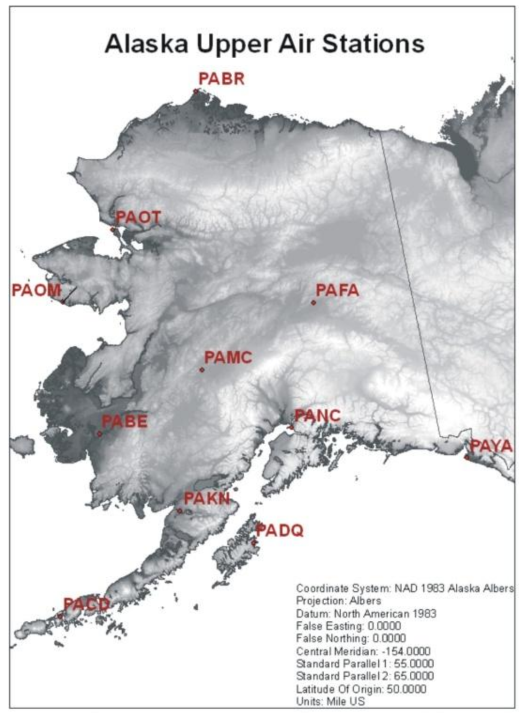

Figure 1: Alaska upper air sites. Light (dark) shading represents higher (lower) terrain.

In various studies of ARs that have made landfall along the West Coast of North America (Neiman *et al* 2004, Ralph *et al* 2004, Smith *et al* 2010) importance of the integrated water vapor flux (IWV flux) is stressed. IWV flux is simply the vertical integration of water vapor within a layer, multiplied by the average windspeed within that layer. In practice the total PW multiplied by the average windspeed is a reasonable estimate. We wanted to see if there was any correlation between the IWV flux and rainfall for

Table 1: Bethel, Alaska							
Year	Month	Day	Hour	PW (in)	Rain (in)	IWV flux [1]	Omega [2]
1975	7	10	12	1.77	0.07		
1997	8	3	12	1.76	0.10	800	-0.20
1994	8	17	0	1.67	0.41	1050	-0.15
1961	7	30	12	1.66	0.39		
1990	8	26	0	1.65	1.64	1100	-0.70
2007	8	12	0	1.61	0.12	775	-0.40
2003	8	11	0	1.60	0.37	550	-0.25
1971	7	11	12	1.60	0.02		
2011	8	12	12	1.59	0.67		
2003	8	7	12	1.57	0.46	325	-0.30
2004	8	13	12	1.56	0.20	775	-0.60
1967	7	16	0	1.56	0.22		
1963	8	17	0	1.56	1.00		
1985	6	29	12	1.55	0.27	675	-0.50
1959	8	26	0	1.54	0.44		
1998	8	2	0	1.54	0.01	575	-0.60
2004	8	19	12	1.53	0.00	275	-0.10
1963	8	16	12	1.52	0.94		
1959	8	26	12	1.51	1.03		
1975	7	10	0	1.50	0.01		
2001	8	15	12	1.50	1.11	550	-0.35
1984	8	2	0	1.50	0.08	850	-0.80
1956	7	27	3	1.50	0.03		
1967	7	23	12	1.50	0.29		
1990	8	25	12	1.49	0.88	1150	-0.70
2001	8	14	0	1.49	0.51	875	-0.45
1967	7	22	12	1.49	0.36		
1984	8	3	0	1.49	0.15	825	-0.60
2007	8	12	12	1.48	0.12	825	-0.45
1981	8	24	12	1.48	0.36	575	-0.50
1974	7	29	0	1.48	0.24		
2003	8	10	12	1.48	0.21	625	
1994	8	17	12	1.48	0.37	1050	
2005	8	11	12	1.47	0.00	575	-0.10
2003	8	10	12	1.47	0.21	600	
1997	8	4	0	1.46	0.00	800	-0.20
1966	7	26	0	1.45	1.22		
1997	8	6	0	1.45	0.00	350	
1994	8	9	12	1.45	0.09	925	-0.40
1982	8	13	12	1.44	0.72	800	
2004	8	14	0	1.44	0.13	825	
1994	8	10	0	1.42	0.05	900	
1975	7	9	12	1.42	0.01		
2001	7	15	12	1.41	0.20	400	
2004	8	3	12	1.41	0.09	325	
1967	7	24	12	1.40	0.11		
1975	7	22	0	1.40	0.00		
2001	7	30	0	1.40	0.18	275	
2002	9	4	12	1.39	0.00	700	
1966	7	25	12	1.38	0.34		
1: IWV flux in gm m^{-1} s^{-1}; 2. Omega at 850 mb in Pa s^{-1}							

these cases. We took the IWV flux from the North American Regional Reanalysis (NARR) when available (1979-2010), and it is shown in column seven of Table 1. The number in the table is the maximum value that occurred during the 24 hour period spanning the balloon flight. Further examination of the Bethel data indicated that there is no meaningful correlation (0.28) between the amount of rain and the IWV flux (14 light cases with an average IWV flux of 680 gm m^{-1} s^{-1}; seven heavy cases at 835 gm m^{-1} s^{-1}). This should not be too surprising for areas that lack topography, since it is well documented that ARs occur in the warm sector of extratropical storms in association with low-level jets (Ralph *et al* 2005; 2011). When the jet or AR reaches the topography, strong ascent typically occurs, with the subsequent development of precipitation. We also used the NARR omega field at 800 mb to see if there is any strong correlation between rainfall and moderate to strong ascent. As seen in the last column of Table 1, despite limited data, no significant correlation is established as a number of light rain cases corresponded to strong ascent while some heavy rain events display weak ascent. Why only light rain occurs with moderate to strong ascent and an extremely moist atmosphere remains a mystery. We also wanted to investigate whether or not the transport of moisture onshore from the Bering Sea was uniform with height, or if there was some preferred vertical pattern. In order to accomplish this we obtained the Bethel soundings and used linear interpolation to estimate the mixing ratio at fixed heights at 500 m intervals, from the surface through 5000 m. We only used the difference between the sounding peak PW and the sounding 24 hours earlier; we discarded soundings that were already very moist (PW> 25 mm) as we are only interested in the transport of moisture. The 25 event average for each height level is shown as Figure 2. This plot indicates that the largest increase in moisture is in the 1000-4000 m layer, although the increase from 4000 to 5000 m is substantial as well. The implication is that it takes a considerable forcing, whatever form it may take, in order for this water vapor to undergo the transformation into cloud water or eventually rain. In the absence of significant terrain, a front or convective processes are required.

Table 2 shows the percentage of light, moderate, and heavy rain cases for each of the stations that we analyzed. First, it is clear that light rain is more common than we thought *a priori* to the analysis, given the very large amounts of water vapor in the local atmosphere. Secondly, despite only ten stations spread out over a large area, it appears that coastal stations tend to have a higher probability of moderated to heavy rain than Interior stations. There is considerable variability from one station to the next, but in general the stations that lack any significant topography within a given radius tend to have a larger number of light rain events than those stations that are adjacent to mountainous terrain. This implies that topographic forcing is a dominant forcing in the microphysical process- but there are other considerations such as frontal lifting and local convection that have to been taken into consideration. There are a number of notable results from this analysis: for example, at Kodiak 80% of the highest PW events generated light rain; given the complex terrain on Kodiak Island we would have thought *a priori* thought that this number would be half this value. Inspection of the 700 mb winds shows that the dominant wind direction for high PW events is southwest. We suspect that in most cases there is considerable downsloping in Kodiak City, which limits rainfall to lighter amounts. However, the few heavy cases that did occur in our list of top 50 PW cases did occur under a south to southwest flow regime. In addition, Table 2 shows that at Nome 26% of the events were in the light category while 42% were considered heavy; results that we would have thought to be flip-flopped. Further consideration is needed to understand why our analysis generated these results, but we suspect that the higher terrain (Kigluaik Mountains) 30 miles to the north, which is upstream for most flow regimes, plays a significant role; although low-level convergence as air transitions from the ocean to the land may be important as well.

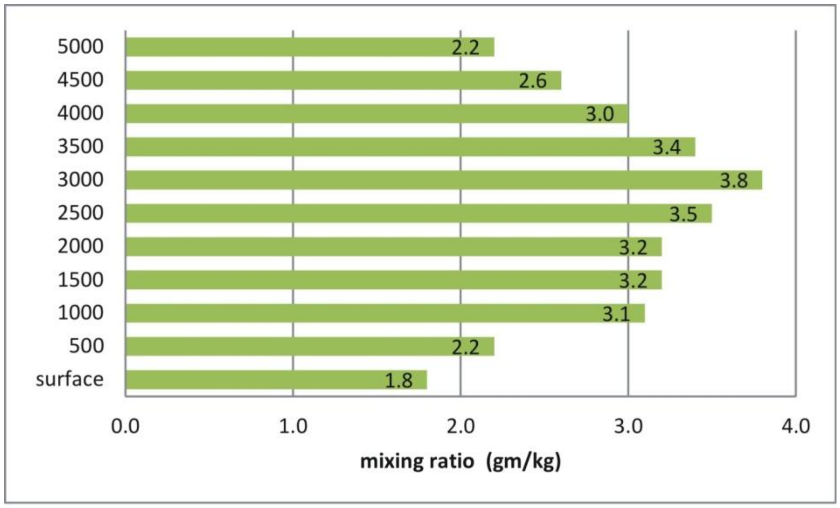

Figure 2: Bethel 24 hour difference in precipitiable water.

Table 2: Percentage of rain by category

Station	Light	Moderate	Heavy
Bethel	42%	30%	28%
McGrath	48%	24%	28%
Nome	26%	32%	42%
Kotzebue	54%	22%	24%
Barrow	60%	18%	22%
Fairbanks	74%	12%	14%
Anchorage	46%	32%	22%
King Salmon	58%	18%	24%
Kodiak	80%	18%	2%
Yakutat	32%	26%	42%

In general, ARs are highly correlated with high IWV fluxes and heavy rainfall, as noted by various authors cited above. In order to gain some understanding of the relationship between the transport of moisture into and across Alaska and the generation of precipitation, a number of cases that we are coining 'dry atmospheric river' cases are presented.

<u>August 3-6, 1997</u>:

This multiday event represents one of the most significant intrusions of moisture into western AK and the Interior since routine weather observations are available. Figure 3 shows the PW on August 4th where a moist plume extends from the eastern Bering Sea through western Alaska. On August 6th the plume extends from the north central Bering Sea across western Alaska well into the northeast Interior.

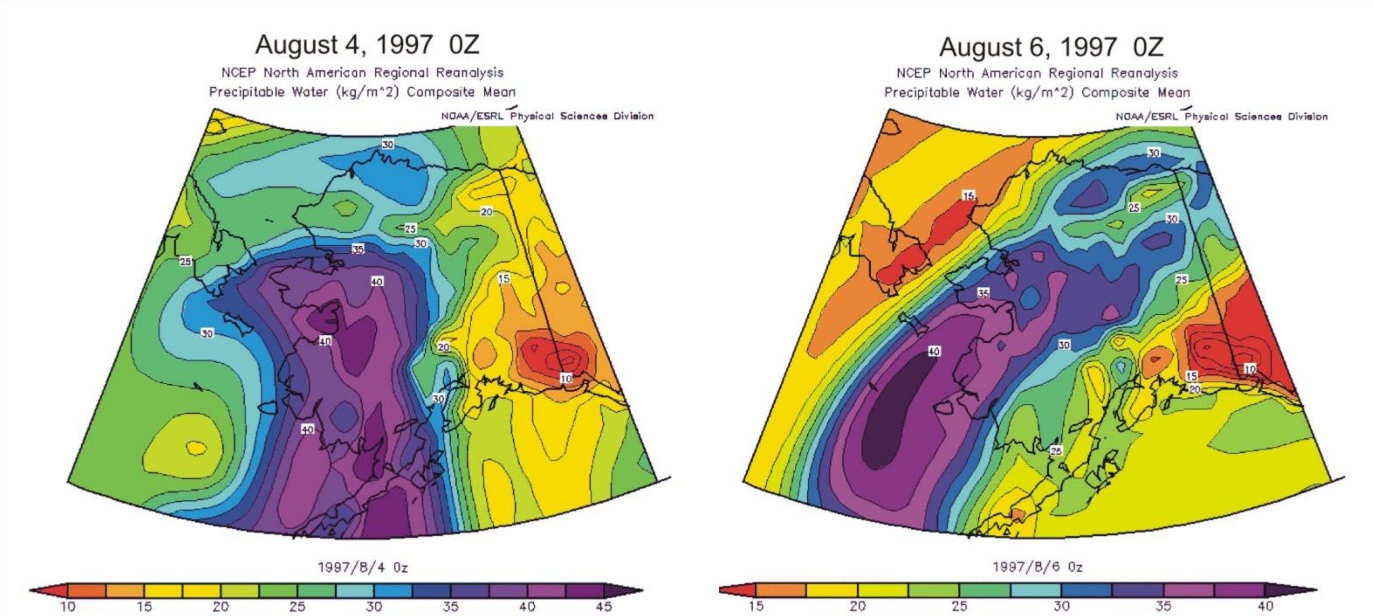

Figure 3: Precipitable water (mm) over Alaska.

The synoptic pattern was dominated by high pressure over the central Interior with a low pressure center over Far East Siberia; strong south to southwest winds transported moisture into western AK. The NARR integrated water vapor flux ranged from 900-1000 gm m^{-1} s^{-1} in the northern Bering to 600-700 gm m^{-1} s^{-1} as moisture moved on shore through Norton Sound.

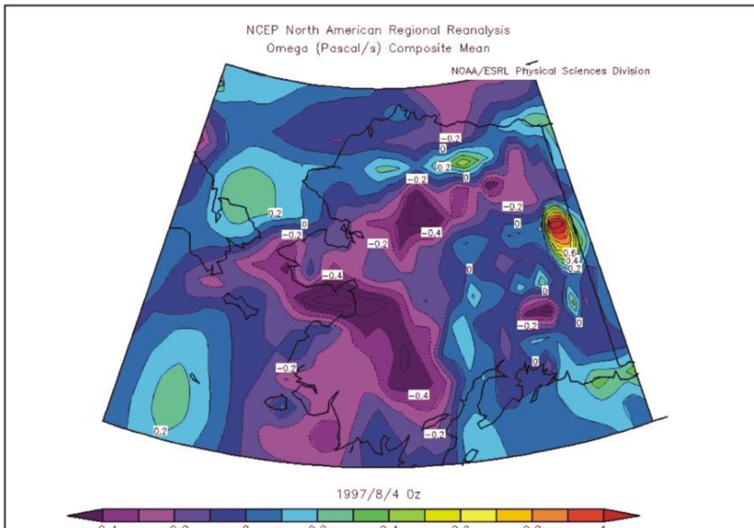

Figure 4: Omega (ci=0.1 Pa s^{-1}) valid August 4, 1997 at 0Z. Negative values indicate ascent.

Analysis of the NARR omega (Figure 4) and thermal fields, as well as the vector wind in the 850-700 mb layer, indicates that areas of moderate rain on the 3rd are highly correlated with the leading edge of the warm sector (i.e. front) which also corresponds with moderate to large ascent. Bethel received 0.10 inches on the morning of the 3rd, while 0.22 inches was observed at McGrath on the morning of the 3rd. Once the 'front' moved through a region, PW remained high, but in the absence of a forcing mechanism little rain was produced. For example, PW values remain in the 35-40 mm range (1.38-1.57 inch) on the 5th and 6th over most of the west and Interior but, as noted above, the only significant rain was in the central Interior on the 6th.

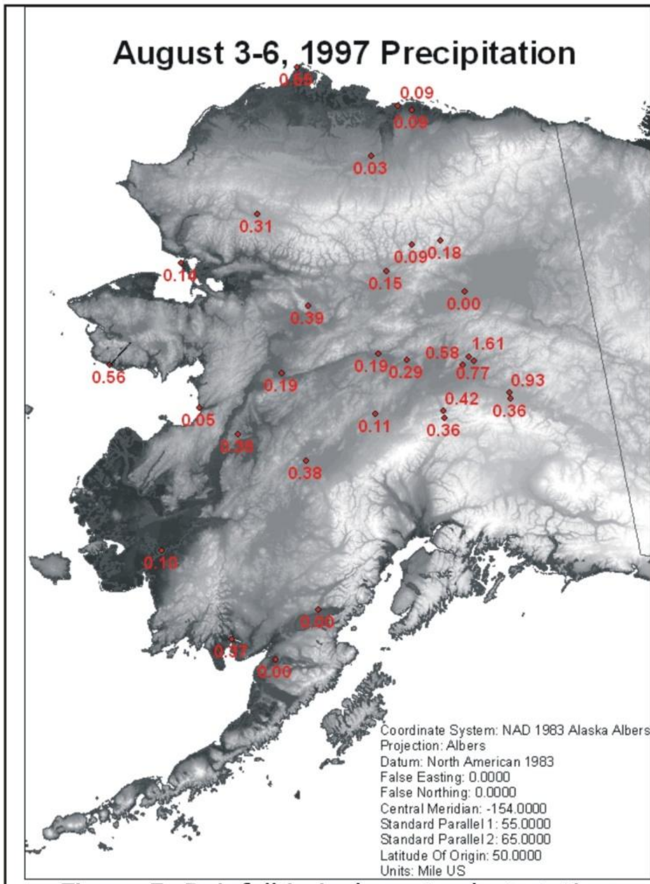

Figure 5: Rainfall in inches at select stations

This rain was probably due to convection, as the observed rain (Figure 5) shows considerable geographic variability over short distances and there is no evidence of any front in the NARR fields. In additions, the flow of the Kuskokwim River at Crooked Creek increased by some 2000 cfs from August 3rd to the 5th, which equates to less than 0.01 inch over the entire basin per day. In other words the observed rain (McGrath 0.38 inch over four days) was probably quite localized.

Moderate rain (0.32 inch) at Nome on the morning of the 6th is difficult to assess- there is little evidence that indicates ascent over the region- some type of convective process may have been responsible. Overall rainfall during this period was relatively light or absent, especially considering the fact that this was ranked at or near the top of our list of top 50 PW events at multiple stations and the period spans four days.

August 13-14, 2004

This is an interesting event because there was moderate rain in the northwest and a few other stations, but many other sites had little rain despite the very high PW values. A plume of moisture moved up into western Alaska in the warm sector of a low-level jet. There was moderate rain at both Bethel and Nome at the beginning of the event. On the other hand McGrath, which had 1.55 inches of PW on the 13th (3rd on our list of events), only received a trace of rain during the entire multiday event. NARR height fields indicate a ridge of high pressure over Southcentral AK on the 12th, which moves into the Yukon Territory late on the 13th. An elongated low persisted over the southern Bering Sea during the event. A strong warm front and associated Low Level Jet (LLJ) moved from the Bering Sea onshore over the Kuskokwim Delta starting around 21Z on the 12th (marked “F” in Figure 6). At Bethel 0.43 inches fell on the 12th (midnight-to-midnight) on the leading edge of the warm front (note that 24 hr rain in Table 1 usually differs from daily values because of the time shift). At Nome, where most of the observed rain also fell on the 12th, 850 mb air temperatures indicate that a nose of cooler air moved eastward into western AK from the northern Bering Sea on the 12th, giving the appearance of a weak cold front. We speculate that this cooler air generated frontal lifting and/or embedded convection across a large region of western AK.

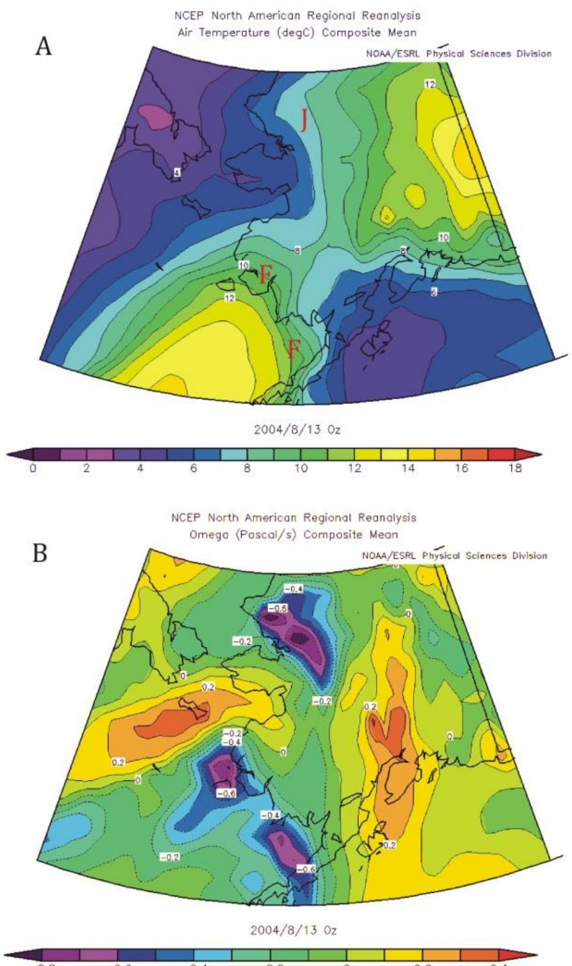

Figure 6: Valid August 13, 2004 at 0Z; A) 850 mb temperatures (ci= 1°C) where "F" marks the location of the warm front and leading edge of the LLJ. B) 700 mb omega field (ascent are negative values).

Moderate rain fell at a number of stations in the northwest, and it is noteworthy that an upper level jet (300 mb) was positioned over the Chukchi Sea at 12Z on the 13th. It would seem that the jet would have provided very strong ascent throughout the troposphere in the area of the right entrance region which was over the Koyukuk and upper Kobuk Basins (marked "J" in Figure 6). Galena, which was under this area received 0.71 inches of rain, and Bettles received 0.61 inches on the 13th. We suspect that as deep moisture was transported into this region in the leading edge of the LLJ, the upper level dynamics took it and generated considerable cloud water and subsequent rain.

Note that on August 16 a large amount of PW remained over the Seward Peninsula and northwest Alaska, however very little rain was observed: Nome had a trace, Kotzebue 0.00 inches and Noatak 0.02 inches. Wind speeds in the lower troposphere were less than 25 kts and there were no fronts to produce ascent; the upper level jet had moved off and a high dominated the upper troposphere. Therefore, despite the continued presence of large amounts of PW, a lack of forcing meant that there was little observed rain.

<u>Barrow:</u>

The upper air station located at Barrow is in a unique position in that it is one of the few sites located in the Western Arctic with a long-term record. In order to gain some understanding of how moisture is transported over Alaska's Arctic Slope we extend our analysis to include Barrow. As one would suspect *a priori,* the top 50 PW values are in absolute terms 5-10% smaller than stations to the south but are still substantial. Our 700 mb wind analysis shows that 71% of the time winds are from the NW to SW, indicating that in the short-term moisture is generally being transported from the Chukchi Sea. Using NARR to trace the various plumes of moisture further back in time shows that many originate in the NW Pacific and move through the greater Bering Strait region into the Chukchi Sea. There are a number of cases (16%), however, where considerable moisture is transported over the Brooks Range - for example on August 10, 1994 as seen in Figure 7. This is a case with heavy rain on the south slopes of the Brooks Range, and, as Figure 7 indicates, large amounts of PW are transported over the mountains to the Arctic Slope. However, the observed 24 hour rainfall at Barrow spanning this period was 0.02 inches. Based on our 50 cases of moderate-to-heavy PW, rainfall at Barrow is not highly or even moderately correlated with any particular wind direction/speed, flow pattern or omega value.

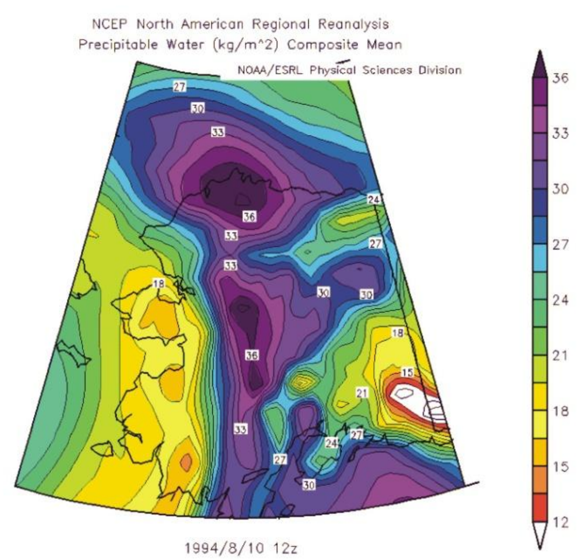

Figure 7: PW (ci=1.5 mm) valid at 12Z August 10, 1994.

<u>Forecasting Considerations</u>: Western Alaska and the Interior

1. The typical synoptic pattern for ARs is a ridge of high pressure over eastern Alaska and/or western Canada with a low or series of lows to the west over the Bering Sea and Far East Siberia. A strong LLJ with 850 mb wind speeds on the order of 40-50 kts located in the warm sector of the extratropical low transports moisture from the North Pacific into the state (see Papineau & Holloway 2011 for more details). ARs typically remain over the state from two to four days, depending on the progression of the synoptic pattern.

2. A significant number of ARs only produce light to moderate rain over a broad area of western and Interior AK. <u>Widespread</u> moderate to heavy rain does occur at times, but forecasters have to note that unless they see some type of strong forcing, rain in southwestern AK is usually going to be less than several tenths of an inch. Rain does not necessarily correspond with a peak in PW at a given station, rain is not only a function of PW, but forced ascent as well.

3. Most of the rain that falls is associated with the leading edge of the warm sector (warm or occluded front). There is plenty of evidence in the NARR omega, air temperature and precipitation fields that strong vertical ascent does occur over the Bering Sea - where of course there is no terrain. Hence frontal forcing is important and may be dominant on the synoptic scale, with terrain acting in a secondary role more on the local scale. Deep warm air associated with a LLJ would tend to limit convection to some degree. Forecasters should look for a strong front in the 850-700 mb layer and moderate to strong winds (> 30 kts) in this layer as well. The preferred wind direction for moderate to heavy rain is S to SW over most of the west and Interior.

4. In the Gulf of Alaska (GOA) region, with onshore 850-700 mb flow, a higher percentage of the vertical forcing is due to orographic lift than frontal lifting when compared to western Alaska and the Interior. This does not mean that fronts are unimportant in the GOA, but rather the frontal lifting is supplemented by orographic lift. Due to the high terrain surround the Gulf, the bulk of the moisture is confined to the Gulf and coastal zone.

5. Terrain influence in the west and Interior: orography may play some role in rainfall at Nome and in the foothills of the southern Brooks Range. However, for most of the first order and RAWS sites in the west and Interior terrain has little impact. The Kuskokwim Mountains, for example, being low and rounded, probably have little impact on McGrath rainfall in the type of cases we have noted in this paper. In other words, these mountains generate minimal orographic lift. The Woods-Tikchik Mountains however, are a substantial barrier to onshore flow - but with virtually no observations around this range it is difficult to know what impact they have on regional precipitation.

6. Peak PW values occur from late June through mid-August throughout the west and Interior, with PW decreasing from south-to-north roughly 1 mm per 100 km of distance. In the Gulf of Alaska, region maximum in PW occur from mid-June through late September, with a distinct peak in August. There is a trade-off between high values of PW and strong onshore flow, hence many of largest rain events along the gulf occur in the September-October timeframe, past peak PW values - but this is made up for by a stronger LLJ.

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