The Nature of Heavy Rain and Flood Events in Alaska

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Introduction

Heavy rain and subsequent flooding events in Alaska have not been studied systematically, although Doswell *et al* (1996) made a brief mention of the September 1995 Kenai Peninsula event in their paper on flash flooding. With the advent of reanalysis datasets, satellite imagery and in-house mesoscale modeling, these events can now be studied in more detail than in previous years. The goal of this paper is to reveal the nature of heavy rain and flood events: common characteristics from one event to the next as well as any outlying features. Table 1 lists the events which are under consideration but is by no means comprehensive. It is obvious that the majority of the events occur in the late summer and autumn timeframe. It should also be noted that heavy rain in a given area does not necessarily produce flooding. The probability of flooding of is also a function of antecedent water levels and soil moisture. Furthermore, some heavy rain and flood events occur in unpopulated areas and hence go unobserved. Flooding on rivers and streams that have short reaches before emptying into the ocean and/or short response times may also go undetected.

Extreme rainfall events have been studied along the West Coast of North America in recent years (Neiman *et al* 2004, Ralph *et al* 2004, Bao *et al* 2006, Neiman *et al* 2008, Smith *et al* 2010). The primary results of these studies are as follows: 1. moisture is advected from the tropics or from a subtropical reservoir of moisture that persists across most of the Pacific. These moisture fluxes are often two or three standard deviations above normal amounts and are frequently referred to as 'atmospheric rivers' (AR). 2. Very moist plumes are typically located in the warm sector of an extratropical low pressure center- in association with the warm conveyor belt (WCB) of strong lower tropospheric winds. 3. Land falling fronts are modified by coastal mountains; the speed of the front decreases as it moves onshore and the front often steepens. 4. Orographic lift in conjunction with various frontal forcings produce enhanced rainfall rates over coastal terrain. 5. Barrier jets significantly modify the near upstream moisture field and rain rates.

From the outset we would expect similar processes to be active in many but certainly not all Alaska cases of heavy rain. One difference between Alaska cases and those of the West Coast is the greater distance that tropical or subtropical moisture is required to travel before encountering terrain. Another difference is that the mountains along the Gulf of Alaska tend to be significantly higher and in some places steeper than the terrain along the West Coast. In addition, we would suspect that at times temperature inversions are considerably stronger and more persistent at 60^{o}N than they are at 40^{o}N in large part due to the cool waters of the Gulf of Alaska.

From the events listed in Table 1 we have identified three broad types of storms based on the geographical distribution of heavy rain: coastal, interior and a hybrid coastal-interior. Coastal and coastal-interior events are associated with extended plumes of moisture originating in lower latitudes. Whether these plumes meet the commonly accepted definition of atmospheric rivers may be debatable (>2000 km in length, <1000 km wide with Integrated Water Vapor [IWV] >50 mm). Coastal-interior events distribute heavy to moderate rain along the coast and some distance inland (>150 km) as well. The August 16-18, 1994 event which was followed a week later (August 24-26) by a second event, are examples where copious amounts of moisture were transported inland via very strong low-level winds from the Bering Sea and produced heavy rainfall over the central Brooks Range some 400 miles (640 km) from the coastline at Norton Sound. The third type of event is the pure interior case which tends to dominated by convective processes. Moisture for the interior events probably originates from two sources: advection from the eastern GOA via the Yukon Territory and from locally 'recycled' sources (Eltahir & Bras 1996). The term 'recycled' is used in the sense that the moisture originates from evapotranspiration over land (and lakes) relatively close to where it falls as rain, in contrast to a maritime moisture source that may travel thousands of miles before falling as rain. Convectively dominated cases tend to be correlated with easterly flow and thermal lows that develop over the warmer/drier portions of the state mainly in July and August. Generally these convective events occur east of 147W and some display characteristics common to Mesoscale Convective Complexes. Also a survey of these cases indicate that winds aloft tend to be very light during periods of heavy rain.

Table 1: Heavy Rain and Flood Events in Alaska

Date	Location	Type	AR
Aug 18-20, 2006	Talkeetna Mtns.	coastal-Interior	yes
Oct 8-11, 2006	Cordova-Valdez	coastal	yes
Nov 22-23, 2002	SW Kenai Pen.	coastal	yes
Oct 22-24, 2002	SW Kenai Pen.	coastal	yes
Oct 1-2, 2003	Eastern Cook Inlet	coastal	yes
Sep 20-21, 1995	Seward, w. Susitna	coastal-Interior	yes
Oct 9-11, 1986	Seward, w. Susitna	coastal-interior	yes
July 10-11, 2010	Interior	?convective	?
July 28-31, 2008	Fairbanks area	interior	No
Aug 16-18, 1994	W coast, c Brooks	coastal-interior	yes
Aug 24-26, 1994	W coast, c Brooks	coastal-interior	yes
Aug 21-24, 1986	Interior	? coastal-interior	yes
Aug 12-15, 1967	Interior	? coastal-interior	yes
Aug 26-28, 1992	North Slope	coastal-interior	?
Aug 15-18,2002	North Slope	coastal-interior	?
Nov 17-24,2005	No. Panhandle	coastal	yes
Oct 19-21, 1998	No. Panhandle	coastal	yes

This survey paper will first discuss coastal, then coastal-Interior and then Interior cases; a number of examples will be given for each type. Case selection is subjective, we have included heavy rainfall events which either produced significant regional flooding or very large rises on streams and rivers. This discussion is then followed by a brief summary of a number of additional cases that warrant attention due to one or two interesting characteristics. After a brief discussion we conclude with suggestions for future work in this area. We make extensive use of the North American Regional Reanalysis (NARR) dataset which gives the best estimate of the state of the atmosphere at three hourly intervals. The terrain used in this model to recast historical meteorological data is roughly equivalent to one grid point every 32 km; hence some caution has to be applied when using this data in complex terrain. In general mountainous regions are not resolved with sufficient detail to allow us to extract local-scale information; despite these limitations the NARR dataset does allow us to study synoptic and mesoscale features as well as general trends.

Case Studies of Heavy Rain Events

I. Coastal Case: October 8-10, 2006

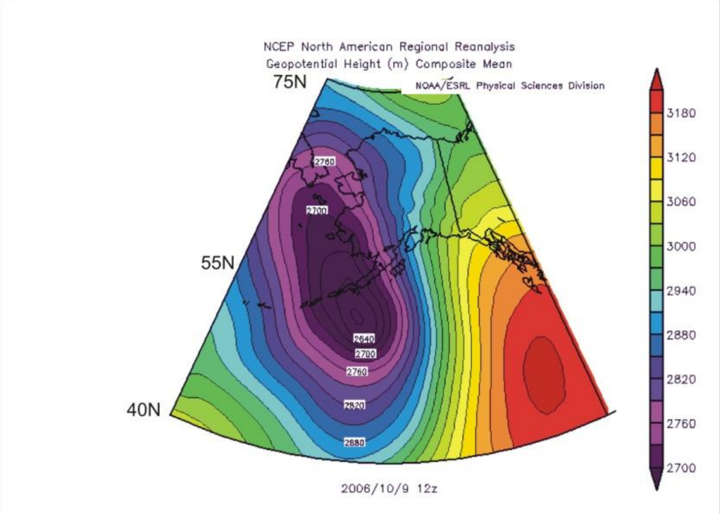

Figure 1:700 mb heights (ci=30 m) valid at 00Z October 9, 2006

North American Regional Reanalysis 700 mb heights for the October 8-10, 2006 rain event which produced major flooding in the Cordova-Valdez region are show in Figure 1. A ridge of high pressure was located over the eastern Pacific near the Pacific Northwest with an elongated low extending from south of the Eastern Aleutians northward through the eastern Bering Sea. This pattern and slight variants are common for coastal type heavy rain events; the net result is strong southerly winds with the fetch often extending down to the subtropics (20^o–30^{o}N). Air temperature, vertical velocity and wind speeds at various levels are shown in Figure 2. At the time of this analysis, corresponding to the onset of heavy rain in the Cordova-Valdez area, a warm front was located in the northern Gulf of Alaska (GOA). As the front approached land the speed of movement was reduced and the temperature gradient increased, the result was a compressed front. Retardation of the front is a result of low-level blocking by the coastal mountains which on average range from 4000-7000 ft (1200-2000 m) in height; blocking is also a function of the strength of low-level stability. Figure 2B shows the omega field (negative indicates upward motion) and it is clear that there is a broad area of ascent associated with the warm front and stronger ascent to the lee of Montague Island (where the low-level winds are SE). Twelve hours later (not shown) the area of ascent is coupled with orographic lift as the front slowly pushes onshore. 925 mb winds are displayed in Figure 2C where it is clear that a barrier jet has developed. Over the next 36 hours the barrier jet becomes narrower and is confined to the area within roughly 100 km of the coastal mountains.

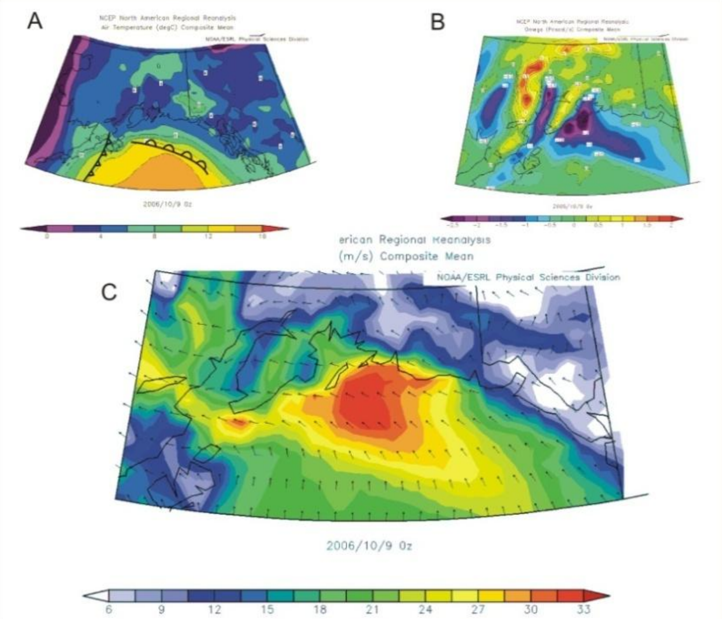

Figure 2: Valid at 0Z October 9, 2006 for A) 925 mb air temperatures (ci=2°C); B) 800 mb omega (ci=0.25 Pa s^{-1}); C) 925 mb wind speed (ci=1.5 m s^{-1}) and directional vectors.

Rainfall for the Oct 8-10, 2006 event was heaviest over the coastal mountains from the Kenai Peninsula eastward to Icy Bay. Observed rainfall was variable in space and time as shown by the data in Table 2. Note that there were moderate to strong east winds across the region at the time of heaviest rain so it is likely that most of these gauges caught less than the actual rainfall amounts. There are several points that should be mentioned: in the town of Cordova rainfall is historically larger (150-200%) than at the airport site (PACV); probably due to location in relation to the terrain and the dominant flow direction. Cordova is situated at the base of the mountains while the airport site is roughly 10 miles upstream (east); for E -SE flow there is considerably stronger orographic lift in town than at the airport. In addition, the amount of rain that moved northward across the Chugach Mountains and into the Copper River Basin was substantial as revealed by the observed amounts at Chitina and Klawasi (10-15% of annual means). This would indicate that the moisture plume extended well into the middle troposphere and was able to move across the mountains without being totally depleted even in a downslope situation. Although no sounding is available for this region, the NARR precipitable water (PW) over the Gulf of Alaska at 12z Oct 9th (not shown) ranged from 1.4-1.6 inches (35-40 mm) which is on the order of 175% of normal for that time of year.

Table 2: Rainfall for Oct 9-10, 2006

Station	Date and Time	Period (hrs)	Rain (in)
Bering Glacier	9th 7Z thru 11th 8Z	50	12.9
Cordova ASOS- PACV	9th 11Z thru 10th 21Z	36	8.8
Cordova - Mt. Eyak	9th 8Z thru 10th 23Z	42	14.1
Cordova - Orca Prwplt.	9th thru 10th	48	18.5
Valdez - PAVD	9th 7Z thru 10th 20Z	38	4.3
Valdez - WSO	9th 9Z thru 11th 9Z	48	7.0
Worthington Glacier-RWIS	9th 9Z thru 10th 22Z	37	7.9
Chitina - RAWS	9th 12Z thru 11th 3Z	39	4.1
Klawasi - RAWS	9th 20Z thru 11th 1Z	28	2.5
Middleton Island - PAMD	8th 20Z thru 10th 13Z	41	3.6
Portage - PATO	8th 6Z thru 10th 13Z	55	7.4
Seward - PAWD	8th 20Z thru 10th 13Z	41	7.4
Seward – 4th July Creek	8th 22Z thru 10th 15Z	41	8.5

In addition, at 0Z October 10 the NARR wind field (not shown) indicated a 130 kt (70 ms^{-1}) polar jet was positioned over the western GOA and extended to Cook Inlet; this period corresponds with the heaviest observed rain in the Cordova-Valdez region. The right exit region of the jet was over the area of heavy rain; hence we suspect that upper level dynamics also enhanced ascent in the coastal region and over the mountains. Heavy rain generated flooding in a number of locations: in Cordova homes situated along the banks of the Eyak River were inundated and the runway at the airport was under water as well. The Richardson Highway in Keystone Canyon washed out at several points as well as the Mineral Creek Bridge near Valdez. The aforementioned transport of moisture over the coastal mountains generated flooding at Squirrel Creek as well as a debris jam near the Tonsina Lodge in the southern Copper River Basin. There was minor flooding in the greater Seward area and in the western Susitna Basin. Snowmelt at the higher elevations in the Chugach Mountains may have contributed to the runoff as freezing levels were on the order 10,000 ft (3000 m); however rainfall amounts were sufficient to generate flooding even without the addition of snowmelt runoff. The USGS estimates of peak river discharge indicate that this was a 100 year event in the Cordova area; but a 200-500 year event for Valdez and the southern Copper River Basin.

Although the details of these coastal type events will vary from one case to the next, there are some common factors. In a general sense the amount of rain that falls is a function of terrain height and steepness, wind speed and direction, moisture supply, stability, and other factors. The bulk of the moisture originates in lower latitudes, including at times the subtropics, as seen in satellite imagery (water vapor channels) as well as in various reanalysis fields. PW valid at 0Z September 20, 1995 is shown as Figure 3A. This PW is associated with heavy rain (~13 inches) and subsequent flooding which occurred primarily in the Seward area. This example shows a plume of high PW extending down to the Hawaiian Islands, earlier plots indicate that moisture had been advected in the southern GOA for over a week. These plumes of moisture generically referred to as 'pineapple expresses' because of their subtropical connection have as noted in the introduction, more recently been labeled 'atmospheric rivers' (AR) because of their river-like properties when viewed in satellite imagery (Fig 3B). This does not mean that all of the moisture transported onshore in the GOA had tropical or sub-tropical origins, as will be discussed below. Some of these coastal type events appear to obtain the bulk of their moisture from the mid-latitude storm track which lies across the central North Pacific in the vicinity of the International Dateline.

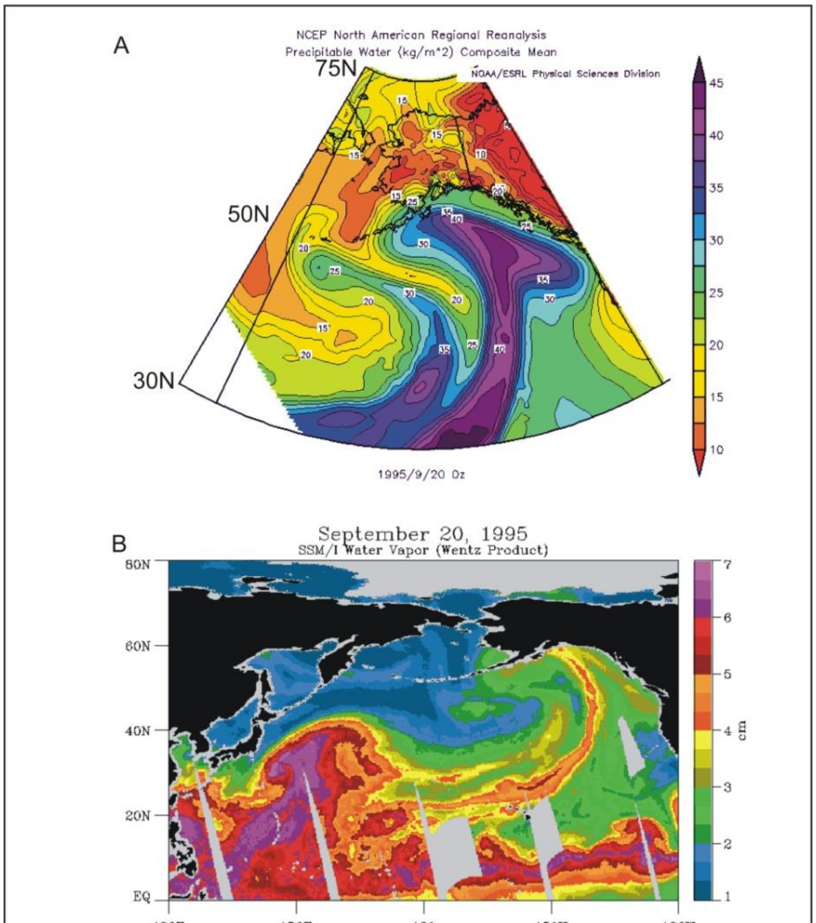

Figure 3: A) Precipitable water (ci=2.5 mm) valid at 0Z September 20, 1995. B) SSMI water vapor composite for North Pacific valid September 20, 1995.

A number of studies have shown that AR's which reach the West Coast tend to form in the warm sectors of extratropical cyclones and tap into a large reservoir of moisture that persists in the subtropics (Neiman *et al* 2002, Bao *et al* 2006). As a given storm center moves northward or eastward it advects copious amounts of moisture with it. One of the main characteristics of these storms is that they contain strong low-level jets (LLJ), also closely related to a 'moist conveyor belt' which transports moisture from low-levels to the middle and upper troposphere. As these strong winds move over the ocean large amounts of moisture is evaporated. The combination of strong winds and high moisture values is what produces a large moisture flux (speed x moisture). When these storms move into the northern GOA and approach the coast the following maybe expected: 1. If there is a front (warm or occluded) it will slow down and steepen; observations indicate that this is when the heaviest rainfall can be expected. Note that most of the heavy rain cases have durations of at least 18 hours which would indicate a stalled front or at least one that moves very slowly. It is also important to note that not all coastal events will have a distinct front- the role of frontal lifting is not clear, and in fact it maybe secondary to orographic lifting. 2. A terrain parallel barrier jet will often form in the lower troposphere. 3. Rainfall is heaviest in the coastal mountains but on a local-scale varies as a function of barrier jet properties, strength of orographic ascent and low-level stability. Strong stability favors extreme blocking and a strong barrier jet with a reduction in terrain perpendicular flow; depending on the height of the terrain this may reduce the amount of rain that is produced over the lee slopes of the coastal barrier. In regions where the terrain is higher than 7000 ft (2100 m), rain (or snow) over the highest summits is probably not impacted by strength of the barrier jet. 4. If the moisture plume is deep (3-4 km) then a significant amount of rain will be produced to the lee of the coastal mountains despite downsloping. 5. Depending on wind direction and strength in the 850-700 mb layer, a large amount of moisture can be transported well inland of the coastline through terrain gaps such as Cook Inlet, Resurrection Bay, Icy Bay, and various channels in southeast, Alaska. For Bering Sea events moisture can be advected well inland through southwest, Alaska where there is little coastal terrain. 6. All of the events that we have analyzed contained strong low-level jets which for coastal types lie outside of the barrier jet zone, and are nearly perpendicular to the long axis of the terrain. In other words orographic lifting is significant and possibly the most important lifting mechanism. In reality the role of various lifting processes will vary from event-to-event and vary in time for a particular event as forcings change. 7. The duration of moderate to heavy rainfall (0.15-0.30” per hour) typically ranges from 18 to 24 hours, on occasions longer.

In order to demonstrate the dominance of certain fields during periods of heavy rain, a composite based on ten heavy rain events in the northeastern GOA is shown in Figure 4. In this example the criteria is six inches or greater of rain within 24 hours at Yakutat (PAYA). In panel A) low pressure is positioned over the western GOA and high pressure is centered over British Colombia the pressure gradient and associated southerly winds are strongest in the central GOA. In B) the plume of high PW extends to the subtropics and is coincident with the area of strong winds. This does not mean that all of the moisture in this plume will reach the coast, the pattern may slowly change and the winds weaken so that a considerable amount of PW remains over the ocean. In addition, these instantaneous shots in time do not prove that the moisture moving on shore at 60^{o}N originated in the tropics or sub-tropics. Analysis of the IWV flux indicates that the atmosphere in the central Pacific storm track remains consistently moist, it is only when developing baroclinic systems, to use Ralph *et al* (2011) terminology, ‘tap into’ this reservoir of moisture, that an atmospheric river begins to extend towards the GOA.

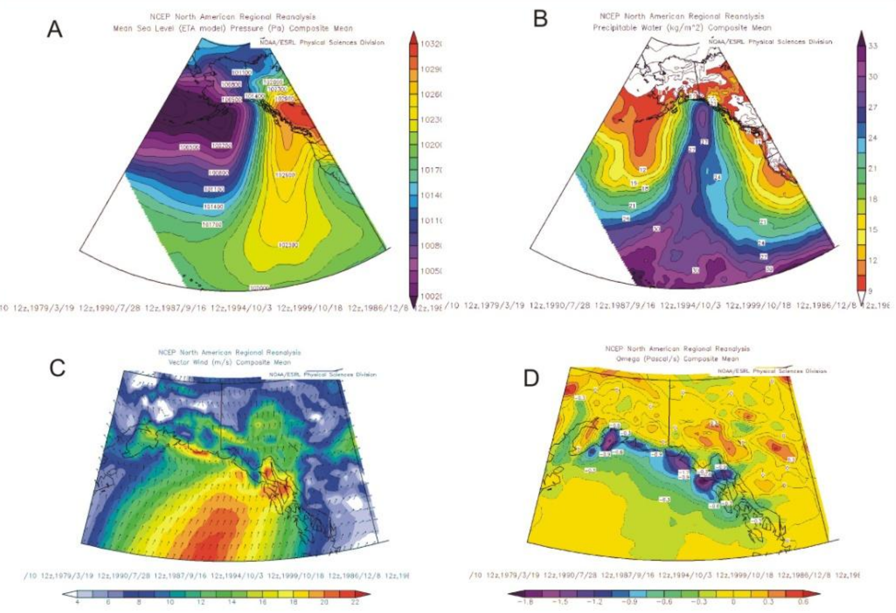

Figure 4: Composite fields for heavy (>6 inches) 24 hour rainfall at Yakutat (PAYA). A) MSLP (ci=150 Pa); B) Precipitable water (ci=1.5 mm); C) 850 mb wind speed (ci=1 m s^{-1}) and directional vectors; D) Omega at 850 mb (ci=0.15 Pa s^{-1}).

Vector winds at 850 mb are shown in Figure 4C; the main LLJ is distinct over the GOA. Near the coast even the lower resolution terrain dataset used by NARR shows gap winds in the northern Panhandle and a barrier jet to the west, extending from Icy Bay to Prince William Sound. The omega field at 850 mb is shown in 4D where the strongest areas of ascent are along the coastal mountains; however, ascending motion possibly associated with frontal lifting, extends well offshore as well. The composite temperature field (not shown) also indicates a fairly strong thermal front located in the northeastern GOA, suggestive that frontal lifting is indeed playing some role, at least upstream. The combination of a LLJ and strong ascent over the coastal mountains suggests that orographic lift is the dominant forcing in the coastal zone, as noted by Neiman *et al* (2002) in their study of rainfall in the coastal mountains of California.

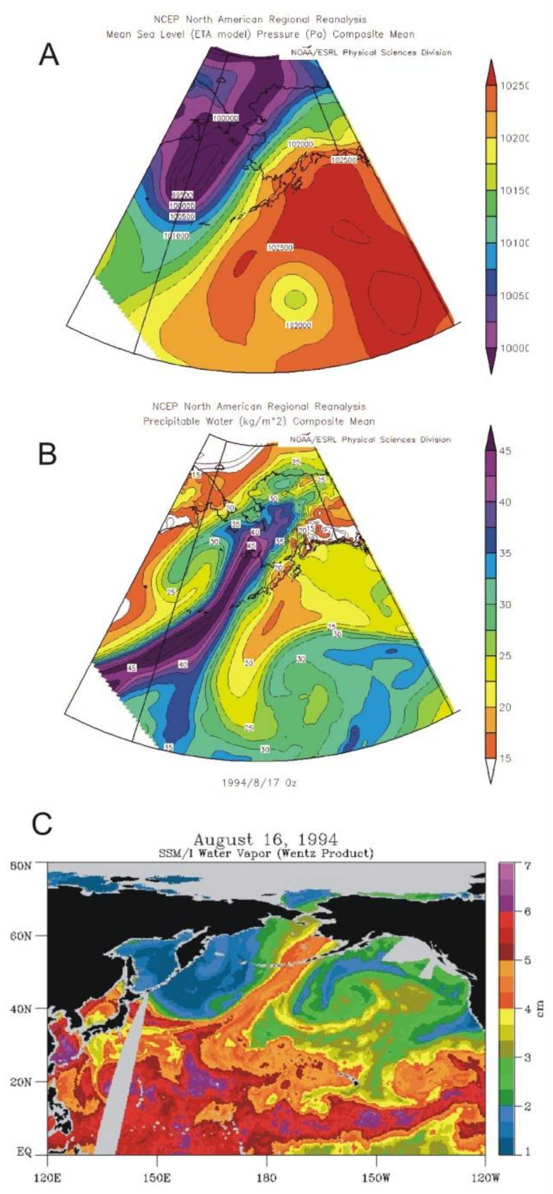

Figure 5: A) MSLP (ci=250 Pa) and B) Precipitable water (ci=2.5 mm) valid at 0Z August 17, 1994. C) SSMI water vapor image valid August 16, 1994.

II. Coastal-Interior Case: August 16-18, 1994 and August 24-26, 1994

The second half of August 1994 was a period of very high rainfall in the central and western Brooks Range and the uplands to the south. Two separate weather systems the first on the 16-17th and the second on 24-26th, were responsible for the rain and flooding. At Bettles (PABT) rain for the first event (two days) was 27% of the mean annual precipitation while the second event (three day duration) was near 20%. Figure 5 shows the MSLP pattern across the greater Bering Sea and the PW at the time of heavy rain at Bettles. A low over the western Bering Sea and eastern Chukoski Province of Russia in conjunction with high pressure over the GOA and North Pacific was a pattern that had been established earlier in the month. This particular pattern with a low to the west and high to the east is the same fundamental pattern that is common for GOA heavy rain events. By the 15th a developing system near the southern tip of the Kamchatka Peninsula moved over the Western Aleutian Islands and then by the 17th had elongated toward the Bering Strait. The net result was strong southwest flow from the surface through tropopause which extended geographically from the North Pacific across the Bering Sea and into northwest Alaska.

Figure 5B shows the PW associated with this event. A closer analysis of the moisture plume (not shown) indicates that in the days prior to the first heavy rain event, large amounts of moisture, in some cases close to 2.0 inches (50 mm) of PW, were transported into the Bering Sea from the North Pacific. This represents a 200% increase in the mean PW over the Bering Sea for that time of year. A composite integrated water vapor image is shown in Figure 5C which clearly indicates a long plume of moisture extending from the North Pacific through the Bering Sea and into western Alaska. The lower tropospheric temperature field on Aug 15 indicated a warm (occluded?) front located over the northern Bering Sea, however it became very diffuse as it moved onshore into southwest Alaska on the 16th. There was a quasi-stationary SW-NE oriented cold front in the western Bering Sea during the event as well. It is difficult to assess the role of frontal forcing versus other process in the context of rainfall along the coast. At Nome for example, during a 24 hour period spanning Aug 15-16 some 1.78 inches was recorded. Reanalysis indicates that there was significant vertical motion in the lower half of the troposphere as the moist plume moved northward on the 15th. We associate this with frontal forcing as the warm front, strong ascent and heavy rain are coincident. Along the Norton Sound coast we suspect that frontal and orographic lift, in some combination, were important. It is certainly possible that frictional convergence as the low-level flow transitions from the ocean to land played some role as well. Once inland however, at least for this first event, heavy rain tended to be a function of orographic lift. It is interesting to note that at 0Z Aug 17 the sounding at Bethel showed 1.71 inches (43.6 mm) of PW, a very large value, but the daily rainfall was only 0.46" (11.7 mm). In other words a vast amount of moisture was transported over southwest Alaska, however lifting via frontal or convective processes was weak or nonexistent and hence rainfall amounts were minimal until this moisture reached higher terrain.

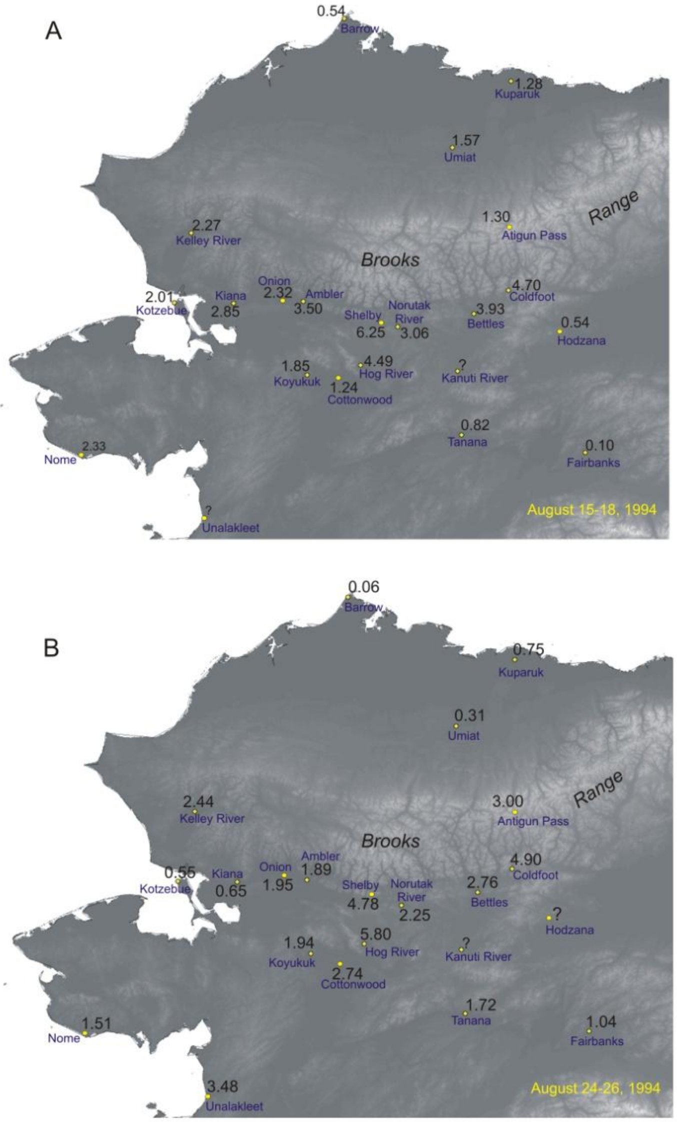

Figure 6: Rainfall totals (inches) for: A) 15-18 August 1994 and B) 24-26 August 1994.

Despite limited raob coverage in this area it is clear from NARR that a 100 kt (+60 m s^{-1}) polar jet moved onshore from the Bering Sea into northwest Alaska early on the 17th and then continued to the NW reaching the southern Beaufort Sea on the 18th. As in the GOA case of October 2006, a strong polar jet transported large amounts of moisture into the region and created an environment conducive to strong orographic lift. Storm total (Aug 15-17) rainfall amounts along the west coast and inland stations situated some distance from the mountains ranged from 1.9 to 2.3 inches (Figure 6), in comparison to stations at the base of the southern slopes of Brooks Range where rainfall ranged from 2.6 to 4.7 inches (the latter at Coldfoot DOT). In addition, moisture transport over the Brooks Range was substantial: Umiat recorded 0.97 inches on the 16th with 0.60 inches on the 18th. Further north along the arctic coast Barrow received 0.54 inches on the 17th and Kuparuk reported 1.28 inches on the 18th. These amounts are substantial in the context that the area north of the Brooks Range typically receives 6-10 inches of annual precipitation. Freezing levels started out early on the 16th below 10,000 ft (3000 m) but by the 17th were on the order of 11,800 ft (3600 m) over the central Brooks Range.

The second event which occurred from August 24-26 had a similar synoptic pattern as the first event with the following exception: the low-level storm center moved further to the east as the event progressed. In fact the pattern over the Bering Sea and eastern Siberia remained persistent through the period between the two events. The three day rainfall totals were not quite as high in the central Brooks Range but moderate to heavy rainfall was more widespread across the central Interior. In this event Bethel received 3.01 inches of rain with a maximum PW of 1.35 inches (34.3 mm) at 0Z August 26; compare this to the first event which transported considerably more moisture aloft but which produced little rainfall at Bethel. A warm front moved over southwest Alaska on the 24th (not shown), but stalled over the McGrath-Denali N.P. area on the 25th. The omega field indicates widespread ascent over western Alaska in association with the warm front. It would appear that this second rain event maintained a significant amount of frontal lifting that generated widespread rain over southwest Alaska which was absent from the first event. Nevertheless the LLJ moved onshore late on the 24th, and where it interacted with the terrain rainfall was significant. Rainfall totals in the central Brooks Range (Upper Koyukuk Basin) were comparable to the first event with a storm total at Bettles of 2.92 inches and 5.2 inches at Coldfoot. There was a strong 300 mb jet over NW Alaska for most of the period from the 24-26th, with the LLJ positioned to the southeast of the upper jet. The PW plume was coupled with the LLJ. The upper level winds and associated lifting may have contributed to the cross barrier transport of moisture as it did in the first event. Rainfall totals at Umiat were 0.31 inches and 0.38 inches on the 26th and 27th respectively while Kuparuk recorded 0.62 inches and 0.36 inches on those same dates. Freezing levels over the central Brooks Range started at 5200 ft (1600 m) early on the 25th a rose to a maximum of 9800 ft (3000 m) late on the 27th.

There was minor flooding in the Noatak Basin and moderate flooding in the Kobuk Basin in response to the first rain event. Water levels in these basins were the highest on record for non-ice impacted events up to that time. The resulting flooding in the Koyukuk Basin was a combination of the two rain events. An initial crest on the Koyukuk River occurred on the 20th which resulted in minor flooding at Allakaket. There was some reported erosional and mudslide damage to the Dalton Highway at various points. The primary flooding at Alakaket and Alatna occurred on the 28-29th where water levels were on the order of 9 ft higher than on the 20th. The USGS estimated that this was a 100 year event with flooding on the order of 10 ft in the village of Allakaket and a peak discharge 10 miles downstream of 330,000 cfs (Meyers 1995). There was also a report that Loon Lake, located in the John River Basin north of Bettles, had released an unknown amount of water into the Koyukuk River; but subsequent investigation showed that the amount of water released was minimal compared to the direct runoff from rainfall.

Even though this synoptic pattern is not common, especially the persistence of very moist southwest flow into the western and central Brooks Range, there are some aspects of the two events that should be noted. Abnormally high (~200% of normal) amounts of PW can be advected from the Bering Sea into the interior part of the state. Strong low-level winds can move onshore and produce large amounts of orographic precipitation in the Interior mountain ranges as long as there is a moisture source. Flooding is not only a function of rainfall but antecedent soil moisture and water levels. Note that during the 16-17th rain event in the central Brooks Range, the primary damage was erosional and mass wasting as water levels in the major rivers were starting from a low base flow. It was the second rain event in rapid succession to the first that generated the serious flooding in the central Koyukuk, a set of circumstances which is not likely to occur with any regular frequency. Widespread rain from these types of patterns is a function of frontal forcing and general synoptic lift, while the more intense localize rain is a result of embed convection and orographic lift, which may vary in space and time throughout the life of a particular event.

III. Interior Case: August 12-15, 1967

This event generated the most severe urban flooding in the history of Alaska which prompted the development of a water storage facility outside Fairbanks known as the Chena Project in order to alleviate future flood problems in the city. The synoptic pattern for the event had similar characteristics to the two August 1994 events; an elongated low pressure complex over the western Bering Sea with a SW-NE oriented high over the western GOA (Figure 7). A plume of moisture which had moved into the western Bering Sea on August 8 (possibly from ex-tropical storm Hope), was transported in W-SW flow into the interior of the state on the 12th from the eastern Bering. Over the next 36 hours the moisture plume slowly migrated eastward into the western GOA with strong moisture advection up Cook Inlet.

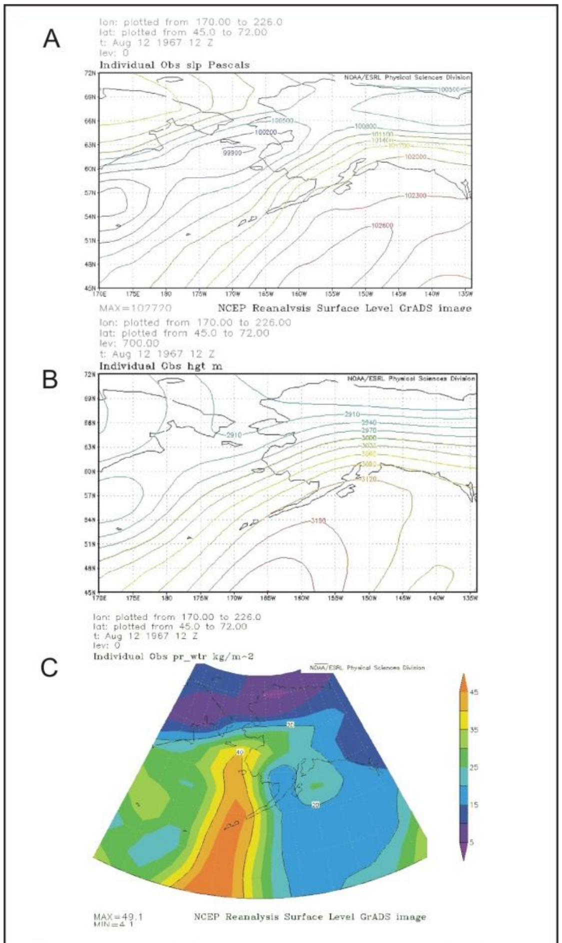

Figure 7: Valid at 12Z August 12, 1967 for: A) MSLP (ci=250 Pa); B) 700 mb heights (ci=30 m); C) Precipitable water (ci=2.5 mm).

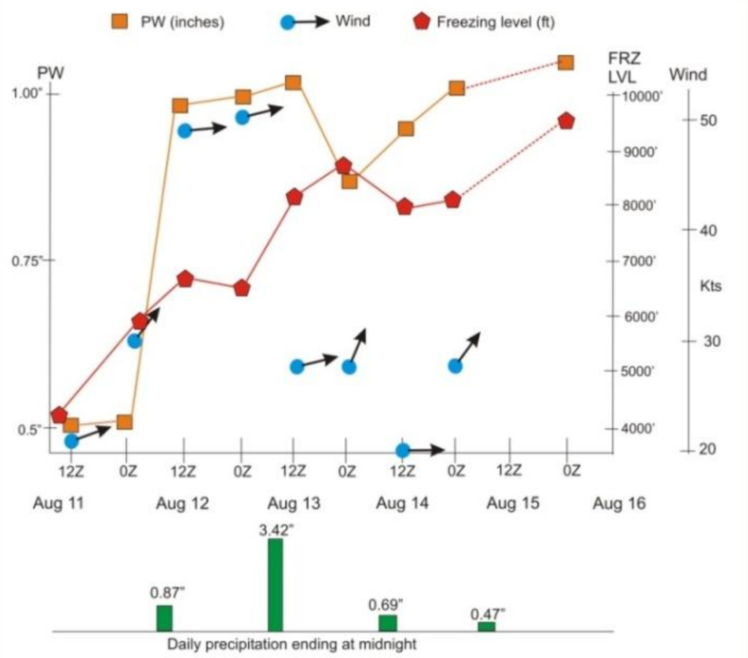

Figure 8: Top) Precipitable water (inches), wind speed (kts) and direction, freezing level (ft) for August 11-16,1967. Bottom) Daily precipitation (inches) measured at Fairbanks Airport (PAFA).

Analysis of Fairbanks soundings taken during the event indicates that the freezing level was 8600 ft (2600 m) on the 13th with a PW of 1.08 inches (27.4mm). The atmosphere remained moist (~1 inch) through August 15 as seen in Figure 8. Interestingly rainfall in the Fairbanks area peaked on the 12th and 13th and then greatly diminished on the 14th. The 3.61 inches observed at the Fairbanks airport (PAFA) on the 13th is still the greatest single daily total since the inception of the observation site in 1929. Figure 9 shows rainfall analysis for a three day period; there was a large area of greater than four inches centered over the Fairbanks area. What is of interest is the fact that with persistent SW flow, there were not significantly larger rainfall values in the Alaska Range around Denali National Park.

Peak rainfall occurred when the 850-600 mb layer wind speeds ranged from 50-70 kt with a +100 kt (+60 ms^{-1}) jet at 300 mb. Although moisture levels remained high on the 14th and 15th the lower and mid-tropospheric wind speeds had diminished to 20-40 kts while the upper level jet had dissipated. We believe that the peak rainfall was a direct result of extremely moist winds forced to rise over the hilly terrain of the Chena and Salcha Basins where the elevation ranges from 3000-4000 ft (900-1200 m). The post event write-up published by the USGS notes the presence of an arctic front over the central interior of the state at the time of the event as well. Reanalysis does show a large area of weak low pressure over the Interior and a well-defined thermal front at 925 mb, it is certainly possible that additional lifting originated from the LLJ forced over the cooler air (front) to the north. However the arctic front remains in place even when the rain has tapered off, which leads us to believe that the primary forcing was the LLJ interacting with the terrain.

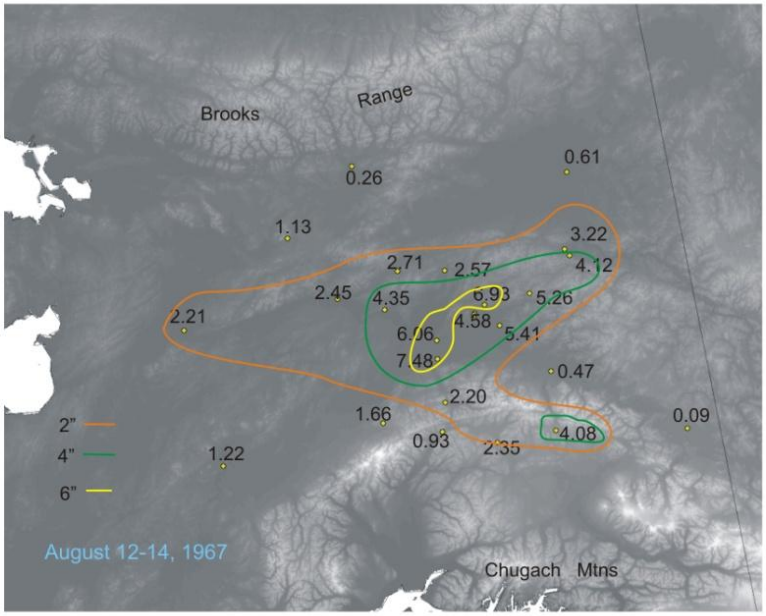

Figure 9: Storm total rainfall (inches) for August 12-14, 1967.

A testament to the widespread nature of heavy rain is the fact that water levels in many of the major rivers to the north and east of Fairbanks rose sharply in the subsequent days. The Porcupine River did not flood but the flow rose 80,000 cfs from August 13th to the 17th. Flow on the Yukon River at Rampart rose 138,000 cfs from August 13th to the 20th and the peak flow of the Chena River at Fairbanks was three times larger than the previous peak flow. There was also considerable erosion on creeks and streams that did not flood and a sizable number of mudslides throughout the region. Due to the eastward migration of the moisture plume a heavy band of rain was also observed from the upper Susitna River Basin northeastward to the upper Delta River Basin north of Paxson. The USGS estimated the mean basin rainfall for the 1910 sq. mile Nenana River Basin in the central Alaska Range for the month of August 1967 was an impressive 7.90 inches.

Additional Events:

Interior: The Interior of Alaska displays the broadest spectrum of heavy rainfall events of any region in Alaska due to the interplay between stratiform processes, strong convection and terrain. The following summarizes several additional cases that are worthy of note. The Fairbanks Airport received some 3.43 inches over a 20 hour period spanning the 26-27 of July 2003. The 850 mb flow was predominately SW 30-50 kts (15-25 m s^{-1}) with the PW on the order of one inch (25 mm). A closed low was positioned over the southern Beaufort Sea from the surface to the tropopause with high pressure over the GOA and into the southern Bering Sea. A strong thermal front moved from eastern Siberia over western Alaska on the 26th where it remained quasi stationary. It appears that moisture was transported from the northern Bering Sea between Norton Sound and Nunivak Island. Closer inspection of thermal and PW fields shows that lower tropospheric temperatures over eastern Siberia at this time were extremely warm, leading to very high values of PW (1.2-1.35 inches or 30-35 mm) as well. It is certainly possible that the bulk of the moisture advected into Alaska originated from eastern Siberia rather than from the Bering Sea. In any case the McGrath sounding for the 26th and 27th indicated PW on the order of 1.2 inches (29 mm) with a saturated atmosphere up through 12,000 ft (+3600 m). This disproves the notion that deep moisture is exclusively of sub-tropical origin.

Heavy rainfall also occurred in the central Interior from August 21-24, 1986 when a closed low was positioned over the southern Beaufort Sea, similar to the August 2003 pattern. A layer of deep moisture was transported into the Interior from the Norton Sound region via strong westerly flow. We also notice significant values of CAPE over the area during this event and suspect that embedded convection played a major role as well. This last example might be classified as a mixed stratiform-convective case.

Some of the historical heavy rainfall cases in the Interior have been primarily forced by convective processes rather than orographic or frontal lifting. The July 10-11, 2010 rain and flood event in the Porcupine and Fortymile Basins along the Canadian border does appear to be a product of widespread convection. The NARR dataset does not reveal very many clues to the origin of this rain except that there was considerable CAPE over the region at 0Z on July 12 and a closed low positioned directly over Alaska-Canada border. A thermal low stretched from the Seward Peninsula across to the central Mackenzie River Basin in the Yukon. The moisture source for this event is obscure; the PW field and Whitehorse sounding indicate considerable moist southerly flow from the northeastern GOA across the northern Panhandle and into the Yukon Territory on July 10. It is possible that this moisture, PW on the order of one inch (25 mm,) was transported into the closed low and circulated with NE flow into the Porcupine Basin late on the 11th. We also cannot discount that some of the moisture was continentally recycled (Eltahir and Bras 1996)). In other words a high percentage of the moisture in this event may have been derived from evapotranspiration over the Yukon Territory and eastern Alaska. In cases like this moisture is only transported several hundred miles instead of thousands of miles as in the case of atmospheric rivers. Dirmeyer *et al* (2009) looked at the climatology of recycled precipitation across the globe and found that that a large percentage of the June-July-August precipitation over eastern Alaska and the Yukon Territory (their figure 2) is from recycled sources.

Coastal-Interior: There have been a number of additional events in which heavy rain occurred along the coast as well as several hundred miles inland. The October 9-11, 1986, September 20-21, 1995 and August 18-20, 2006 events are similar in nature in that significant rain fell along the North Gulf coast and considerable moisture was advected northward through Cook Inlet to the Susitna Basin. A brief analysis of the Aug 18-20, 2006 event which generated considerable flooding in the western and central Talkeetna Mountains, follows. At the start of the heavy rain a low was positioned over the central west coast of Alaska, near Unalakleet, and then tracked to the NE over the next 48 hours. Strong SW flow dominated the lower troposphere from Kuskokwim Bay eastward. The Anchorage sounding reveals the classic signature of heavy rainfall: 20-40 kts of SW flow up Cook Inlet, and PW around one inch (25 mm)- which is not extreme but when combined with the strong low-level winds generated a large moisture flux. Additionally, freezing levels were on the order of 8000-10,000 ft (2400-3000 m) through the event. The net result was 2.75 inches storm total rain at PANC. In Talkeetna (PATK) 3.71 inches (94.2 mm) was recorded on August 18 with 0.81 (20.5 mm) inches and 0.95 inches (24.1 mm) on the following two days for a total of 5.47 inches (138.9 mm). Several inches of rain were also recorded at the cooperative observing site on the Maclaren River. The three day total of 8.34 inches (211.8 mm) at Hatcher Pass (~2500 ft) is more than three times the 2.5 inches that was observed 15 miles to the west at Willow Creek. In other words the orographic component of this storm would appear to have been very substantial. Flooding was extensive along the western slopes of the Talkeetna Mountains.

Although heavy rain events along the Arctic Slope of Alaska are not well documented in large part due to very sparse observations, from time-to-time they do occur as on August 26-28, 1992 and again on August 15-18, 2002. In the August 26-28, 1992 case moderate NW flow over the Arctic Slope advected considerable moisture from the southern Beaufort Sea inland to the Brooks Range from a low positioned just off the Arctic Coast near Barter Island. On Aug 26th observed rainfall was: 0.80 inches at Kuparuk, 0.55 inches (14 mm) at Umiat and 0.69 inches (17.5 mm) at Bettles. The NARR indicates a PW plume extending from near Banks Island to the central Brooks Range with values of 0.8-1.0 inches (20-25 mm) over the Arctic Slope. It would appear from a sequence of PW plots (not shown) that a considerable amount of the PW originated over the Yukon Territory in addition to that from the southern Beaufort Sea. The Kuparuk River which is gaged by the USGS near the village of Kuparuk peaked on Aug 28th at 30,800 cfs which is substantial for a non-snowmelt and non-ice impacted case. The second event occurred from August 15-18, 2002. Strong west-northwest low-level winds from the southern Chukchi Sea associated with a low positioned over the northern Beaufort Sea produced an unknown amount of rain over the north slopes of the Brooks Range. The only reported rain along the arctic coast was at Colville which had 0.59 inches (15 mm) and a maximum temperature of 59° F on Aug 15. Daily rain totals of 0.57 inches (14.5 mm) and 0.47 inches (11.9 mm) of rain were reported at Kuparuk on the 15th and 16th respectively. The Kuparuk River peaked on the 18th at 33,600 cfs. It is clear that strong flow into the Brooks Range, from the

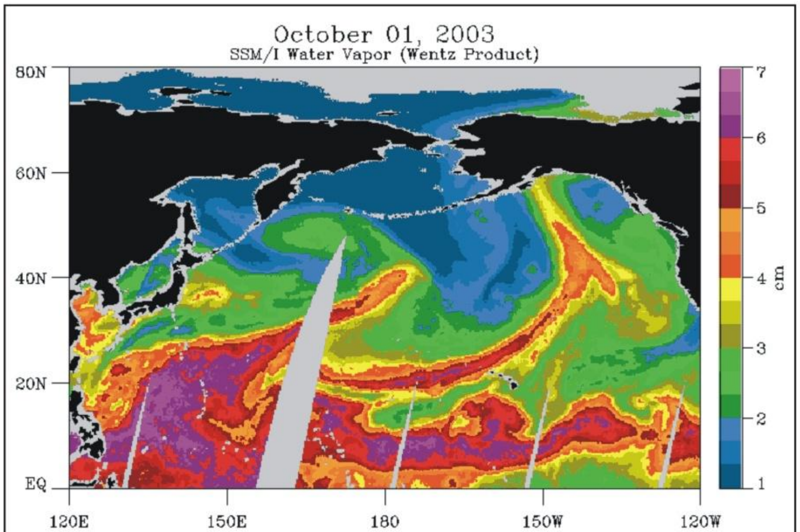

Figure 10: Composite Water Vapor Imagery (cm) valid at 01 October 2003.

surface through 300 mb (25-35 kts at 850 mb), advected large amounts of moisture from the Arctic Ocean which subsequently fell as orographic rain.

Coastal: September 30-October 3, 2003 is a good example of strong E-SE winds which generated significant downsloping in various regions in Southcentral Alaska but large amounts of rainfall in other areas. This storm developed in the baroclinic zone of the mid-latitudes (40^{o}N) whereupon the center moved over the southern tip of the Alaska Peninsula. High pressure had persisted over the Panhandle for a number of days. The IWV is shown as Figure 10. Storm total rainfall (Sept 30-Oct 3) was 7.50 inches (190.5 mm) at Kodiak City, 1.33 inches (33.8 mm) at King Salmon, and 0.83 inches (21.1 mm) at Homer. The largest amount of observed rain fell on the west side of Cook Inlet between Williamsport located on Iliamna Bay and Lake Iliamna. A USGS operated storage precipitation gage located near the village of Pile Bay recorded 14.98 inches (380.5 mm) from October 1-3. The terrain in this area, the northern extension of the Aleutian Range, consists of 2000-4000 ft (600-1200 m) mountains. The rain gage at Iliamna (PAIL), located 38 miles to the NW from Pile Bay across the lake, recorded 3.90 inches (99.1 mm) during the same period while Port Alsworth received 2.13 inches (54.1 mm). The very large rainfall gradient extending from the coast to inland stations suggests that orographic lift played a major role as strong low-level winds were forced upward over the terrain. NARR indicates that low-level winds through Kennedy Entrance and southern Cook Inlet on the order of 50-60 kts (25-30 ms^{-1}). The C-Man station on Augustine Island (AUGA2) had SE sustained winds of 40-45 kt (20-23 ms^{-1}) with five second averaged gusts of 50-60 kts (25-30 ms^{-1}). These strong winds would have generated a large amount of ascent when they encountered the terrain along the coastline. The Kodiak sounding indicates 1.5 inches (38 mm) of PW at 0Z October 1 which is on the order of 200% of the climatological normal for that time of year. Like other events previously described, there was a shallow (925 mb) warm front present in the northeastern GOA during the heavy rain, however ascent associated with the front appears to have been weak compared to orographic lifting.

Another interesting event is that of November 22-23, 2002 along the southern Kenai Peninsula, this was very similar to the event of Oct 22-24, 2002. Heavy rain generated flooding which washed out numerous points on the Sterling Highway between Kenai and Homer. From a meteorological perspective what is of interest is that heavy rain fell in the Homer environs including the Ninilchik Hills despite strong downsloping. Sustained east winds of 20-25 kts (10-13 m s^{-1}) with gusts to +30 kts (15 m s^{-1}) were recorded at Homer airport (PAHO). Despite these winds 0.72 inches (18.2 mm) of rain fell on the Nov 22nd and 2.09 inches (53.1 mm) on Nov 23rd, the latter being an extreme amount for downslope conditions. A storm total of 4.82 inches (122.4 mm) was recorded across Kachemak Bay at Seldovia. NARR data indicates that a LLJ was positioned directly over the southern tip of the Kenai Peninsula with speeds on the order of 70 kts (35 m s^{-1}). Storm total rainfall at the Nuka Glacier site in the Kenai Mountains near the Bradley Lake Hydro Project in contrast to the sites on Kachemak Bay, was 12.36 inches (313.9 mm). The NARR PW field indicates values around 0.85 inches (20 mm) over the southern tip of Kenai Peninsula during the period of heaviest rain. These amounts are about 200% of normal for this time of year but not extreme compared to late summer values that range from 1.0-1.3 inches (30-35 mm). We believe that downsloping was indeed very strong over Kachemak Bay, as indicated by the rainfall gradient from the Nuka Glacier to Homer; however, the LLJ was so strong that copious amounts of moisture were advected to the lee of the mountains over the bay. Had the LLJ been weaker given an identical moisture supply, rainfall around Kachemak Bay and north would have been greatly reduced.

Discussion-Conclusions:

The list of events given in Table 1 indicates that there is some seasonality to heavy rain events segregated by geographic area. In the Interior mid-July through early-September is the peak season. In the Bering Sea and GOA heavy rain (or snow) can occur any time of year although there is a distinct peak from late August through October. This peak would appear to be in response to the re-intensification of the polar jet over the North Pacific (Mesquita *et al* 2009). Heavy rainfall events have occurred at Yakutat and other Panhandle locations in mid-winter as warm advection is strong enough to raise the freezing level several thousand feet above sea-level. One aspect of these events we have not attempted to analyze is the contribution of snowmelt to runoff. A late season rain event with abnormally high freezing levels after a significant snowpack has started to accumulate in the mountains is no doubt a factor in the runoff equation, but difficult to quantify. Another point of interest is something we refer to as 'pattern locking' which is when a specific synoptic pattern is repeated or remains quasi-stationary over a period of a several weeks. The best example of this is the August 1994 event(s) in the Brooks Range during which the pattern over the greater Bering Sea underwent little change for most of the month. Other examples of coastal type events have occurred where a series of moisture plumes have developed in the GOA and made landfall in similar locations over a short span of time. It has been noted above that heavy rain (precipitation) can occur anytime of the year along the GOA coast; in this context it should be further noted that during the winter months the moisture content of the extra-tropical atmosphere in general is reduced compared to summer months (Neiman *et al* 2008), but stronger wind speeds in the winter due to enhanced baroclinicity, make up for the moisture deficit; the net result is that the IWV flux is as large or larger during the winter when compared to summer. During the winter at these higher latitudes there is a trade-off between the height of the freezing level, which is a function of the strength of warm advection, wind

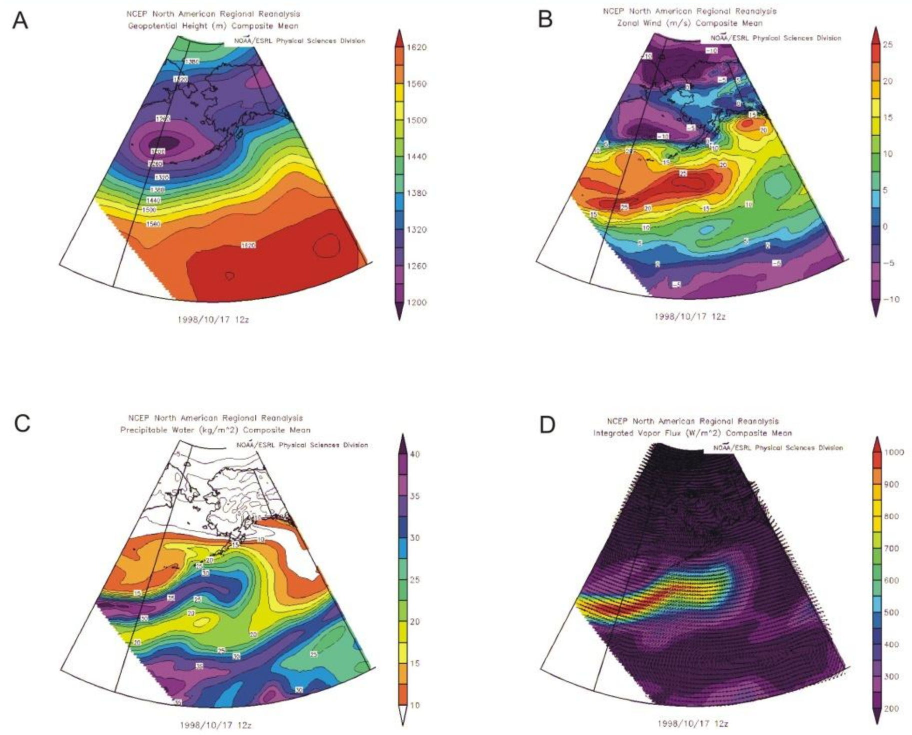

Figure 11: Valid at 12Z October 17, 1998 two days prior to onset of heavy rain in the northern Panhandle. Lower border in plots corresponds to 30°N latitude. A) 850 mb geopotential heights (ci=30 m); B) 850 mb zonal wind speeds (ci=2.5 m s^{-1}); C) Precipitable water (ci=2.5 mm); D) Integrated water vapor flux (ci= 50 kg m s^{-1}).

speeds and moisture content for any given storm. In fact five of the ten composite heavy Yakutat rain fall cases presented as Figure 4 occurred in the December-January time period.

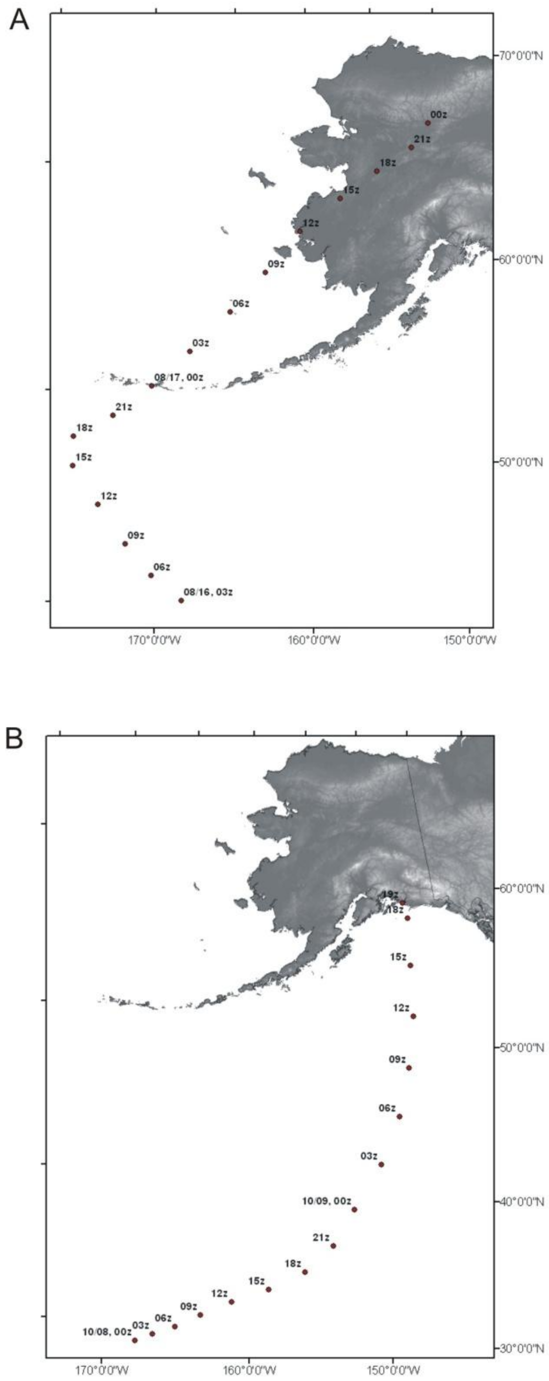

Figure 12: 850 mb back trajectories from NARR for: A) August 16-18, 1994 and B) October 8-9, 2006 at three hour intervals.

In the literature there has been considerable interest in the tropical or sub-tropical origin of moisture in storms that have generated heavy rain along the West Coast (Neiman *et al* 2002, 2008, Bao *et al* 2006, Smith *et al* 2010). For the events investigated in this paper there is the <u>apparent</u> coupling between rainfall and moisture advection from the sub-tropics as seen in reanalysis fields of PW, IWV flux, or on satellite imagery. However we offer without any definitive support that the bulk of the moisture that is advected into the state during these events originates from the Central Pacific baroclinic zone which tends to lie centered on 35^{o}-40^{o}N. As storms intensify over this region the LLJ increases as well as evaporation. With a typical LLJ speed of 40-50 kts (20-25 ms^{-1}) it would take a parcel of moisture on the order of 40 to 50 hours to reach the northern GOA from this baroclinic zone. Ralph *et al* (2004) looked at IWV and cloud liquid water content in 5^{o} latitude bins stretching from the tropics through 40^{o}N in the eastern Pacific. They found little difference in IWV with latitude but a considerable increase in cloud liquid water with increasing latitude. In addition, the width of the IWV plume (AR) tended to narrow with increasing latitude possibly due to low-level convergence as storms mature. In a study of warm conveyor belts Eckhardt *et al* (2004) found that the majority originate at latitudes between 25^{o}N and 45^{o}N, since AR represent the strongest warm conveyor belts it at least suggests that <u>some</u> of the AR's that reach into the GOA originate in the mid-latitude storm track. These same authors also found that during the summer months, warm conveyor belts originate a little further north when compared to winter.

As evidence of an event with moisture 'originating' in the mid-latitudes we offer the analysis of the October 19-21, 1998 heavy rain event which occurred in the northern Panhandle (7.28 inches in Juneau). It is clear that this storm which eventually produced the rain developed in the 35-40^{o}N baroclinic zone in association with a strong LLJ as seen Figure 11a,b. Notice in Figure 11C there are two moisture plumes, a broad area near the southern border of the plot and the other in the baroclinic zone to the north. In Figure 11D which displays the IWV flux, only the northern baroclinic zone plume is significant because it is associated with strong zonal winds while the winds over the southern plume (reservoir) are very light (Fig 11b). The origins of the moisture in the baroclinic zone may have originated days earlier in the sub-tropics or tropics, but it is the LLJ that transports it northward. This does not preclude certain storms which we have already noted in which a south-to-north quasi-stationary LLJ extends from the vicinity of Hawaii into the Gulf of Alaska. The resulting pattern of low pressure centered over the Alaska Peninsula with high pressure over western Canada is quite common. There have also been events linked to ex-typhoons or tropical storms. For example, the flooding across Southcentral Alaska that resulted from the September 1995 rain event was for associated with ex-typhoon Oscar, which had moved up from the east coast of Japan and morphed into a strong extra-tropical storm. The basic result is that moisture may have a direct connection with the sub-tropics or it may be a product of the mid-latitude storm track over the central North Pacific. Figure 12 shows back-trajectories for two events noted above. These are only estimates but give some indication of the track of a hypothetical parcel at the 850 mb level for a 40 to 48 hour period. In addition, what is unknown is the amount of moisture that a developing LLJ or warm conveyor belt in the baroclinic zone can gain via local evaporation versus the amount which already exists in situ and is advected northward.

Table 3: Integrated Water Vapor Flux (gm m^{-1} s^{-1})

DATE	LOCATION	Maritime	Coast or Interior
Aug 18-20, 2006	Talkeetna Mtns.	500	300-400
Oct 8-11, 2006	Cordova-Valdez	1000-1200	600-800
Nov 22-23, 2002	SW Kenai Pen.	600-700	500
Oct 22-24, 2002	SW Kenai Pen.	600	400
Oct 1-2, 2003	Eastern Cook Inlet	1100-1200	700-900
Sep 20-21, 1995	Seward, w. Susitna	1100-1200	700-900
Oct 9-11, 1986	Seward, w. Susitna	900	600-750
July 10-11, 2010	Interior	***	200-300
July 28-31, 2008	Fairbanks area	***	200-350
Aug 16-18, 1994	W coast, c Brooks	900-1200	900-1200
Aug 24-26, 1994	W coast, c Brooks	700-900	500-700
Aug 21-24, 1986	Interior	350-450	250-350
Aug 12-15, 1967	Interior	na	na
Aug 26-28, 1992	North Slope	***	200-300
Aug 15-18,2002	North Slope	500-700	400-600
Nov 17-24,2005	No. Panhandle	600-700	400-600
Oct 19-21, 1998	No. Panhandle	900-1000	600-800

Some of the general findings of this study are as follows: 1. many of the heavy rain events discussed in this paper represent 10-15% of the mean annual precipitation. 2. Although beyond the scope of this survey paper, some of the large convectively forced events that have occurred in the Interior probably contained a significant percent of recycled moisture that originates in the Yukon Territory or Interior Alaska. 3. As shown by several examples, large amounts of moisture can be advected from the northern Bering Sea or southern Chukchi Sea hundreds of miles inland. 4. Although not specifically addressed in this paper, our collective experience suggests that due to terrain blocking there are preferred 850-700 mb wind directions for heavy rain/precip to occur at coastal stations: Kodiak: E-S, Cook Inlet (east side): S-SW, Seward: SE-S, Valdez: S-SW, Cordova: SE-SW, Yakutat: SE-SW. 5. And finally flooding is not only a function of direct runoff but antecedent conditions are fundamental as well. A series of storms in a given geographic location over a short time span, even if they are not in and of themselves extreme rain events, can pre-condition the hydrosphere for the next larger rainfall. In addition, some of the regions within Alaska, typically Kodiak Island and the Panhandle have a larger problem with mudslides and mass wasting than with river flooding. Once again soil moisture is one of the key indices.

The key to forecasting these heavy rain events is the presence of both moisture and strong lower-tropospheric winds. The IWV Flux parameter incorporates both of these fundamental properties; hence the presence of a large IWV flux near Alaska would indicate the potential for heavy rain. Critical IWV flux values have not been established with any confidence since a climatological study has not been conduction to date; however actual values will change according to geographic location and season. Table 3 lists the major events and IWV fluxes as derived from NARR. Fluxes greater than 600 kg m s^{-1} in the Bering Sea or GOA during the warmer months should alert the forecaster to potential problems, while values greater than 300 kg m s^{-1} for the Interior can be used. Some of the events discussed in this paper had IWV fluxes on the order of 1100 kg m s^{-1} when in the GOA, which is on par with values for major events along the West Coast as reported in Neiman *et al* (2008). In general, West Coast cases tended to have slightly larger PW values when they made landfall compared to Alaska cases, but the wind speeds were often a little higher for the latter. The primary parameters to monitor are: 1. abundant moisture supply. 2. Strong low-level winds and possible strong upper level jet as well. 3. Presence of a warm or occluded front for additional lifting. 4. Quasi-stationary or slow moving pattern that allows for >18 hours of rain. 5. Preferred wind direction for any given location.

In the future we hope to: 1) develop a climatology of atmospheric rivers that form north of 50°N. We would further segregate these by those that made landfall from those that remained at sea. It would also be beneficial to explore the potential link between various teleconnection indices and the presence of AR in or near Alaska. Ralph *et al* (2011) noted the casual connection between the phases of the MJO, central Pacific convection and the formation of AR in the eastern Pacific. 2) We would like to use the WRF model to simulate a number of cases that we have presented in this paper in the hopes of gaining an understanding of the interactions between AR's, terrain, fronts and barrier jets. 3) The importance of fronts in the generation of heavy rain is not clear, especially in relation to orographic lift. Further analysis is needed and hopefully modeling results would help shed some light on this topic. 4) A climatology of the northeast Pacific moisture reservoir located off the east coast of Japan. 5) We have concentrated in this paper on rain events; however some analysis of heavy snow or snow-on-rain events in the context of AR's is also warranted. 6) In our analysis we have come across several AR's which moved onshore but generated what we considered remarkably light rainfall (<0.50 inches or <13 mm) at many stations. These 'non-events' should be analyzed so we can understand why some AR's generate heavy rain and why others produce light amounts.

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