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Reflecting on the status of precipitation data collection in Alaska: a case study

Douglas L. Kane and Svetlana L. Stuefer

ABSTRACT

Measuring precipitation, especially solid, at high latitudes is a challenge. In Alaska (USA), the extreme topography, large regional extent, and varying climate result in annual precipitation values ranging from 120 in. (3,050 mm) to 10 in. (254 mm). The state's precipitation network recently has expanded significantly, but there is still room for improvement. A recent intensity-duration-frequency (idf) exercise for the state showed that: (1) although density and spatial coverage of stations have increased, large areas in northern and western Alaska are still without gauge coverage; (2) the number of gauges at higher elevations is insufficient, although growing (e.g., the number of stations above 1,000 ft (305 m) increased from 26 gauges in 1963 to 134 gauges in 2012); (3) solid precipitation is difficult to quantify, and at unmanned sites, the phase of precipitation (liquid or solid) is hard to determine, as air temperature is often the only other measured variable; (4) corrections for gauge undercatch need to be made but too often information on the shielded status of gauges and wind speed is lacking; and (5) in the recent idf analysis only about one-third of the existing and historical stations were used because of data-quality issues. Obviously, overall improvements in precipitation data collection can and should be made.

Key words | Alaska, annual precipitation maxima, frequency analysis, high latitudes, precipitation, precipitation phase

Douglas L. Kane (corresponding author)
Svetlana L. Stuefer
Institute of Northern Engineering,
University of Alaska Fairbanks,
Alaska 99775,
USA
E-mail: *dlkane@alaska.edu*

INTRODUCTION

Next to air temperature, precipitation is the most widely observed and used environmental variable. Real-time precipitation data are used in a variety of water resource management applications such as flood forecasting, urban runoff design, and rural highway drainage structures. Another use of historical measurements of precipitation is the generation of either intensity-duration-frequency (idf) or depth-duration-frequency (ddf) curves (also referred to as precipitation frequency estimation (PFE)). These curves are used in a number of engineering design applications.

Traditionally, precipitation stations in Alaska have been sparse. A closer look at the distribution of stations reveals that most of the stations are still located at low elevations along the coast or on major tributaries, corresponding generally to where communities are located. Alaska (Figure 1(a)) is a very large state (1,480,000 km^2; 570,000 mi^2), spanning approximately 20° latitude (~51° N to 70° N) and 57° longitude (~130° W to 173° E), an area almost equivalent in range to the contiguous United States. This geographic size results in five to seven regional climate categories, depending on the criteria used (Shulski & Wendler 2007). Six regional climate categories ranging from Arctic to maritime are described in this paper (Figure 1(b)) – Arctic, Interior, West Coast, Aleutians, Cook Inlet, and Alaska Southeast Coast.

Significant precipitation data collection in Alaska was initiated around 1900. The first precipitation frequency atlases for Alaska were published in the early 1960s (Miller 1963, 1965). Frequency analysis was based on precipitation measurements, which varied in duration from 24 hours (234 stations), to 6 hours (18 stations), to 1 hour (nine stations). Also, data from 33 Canadian stations along

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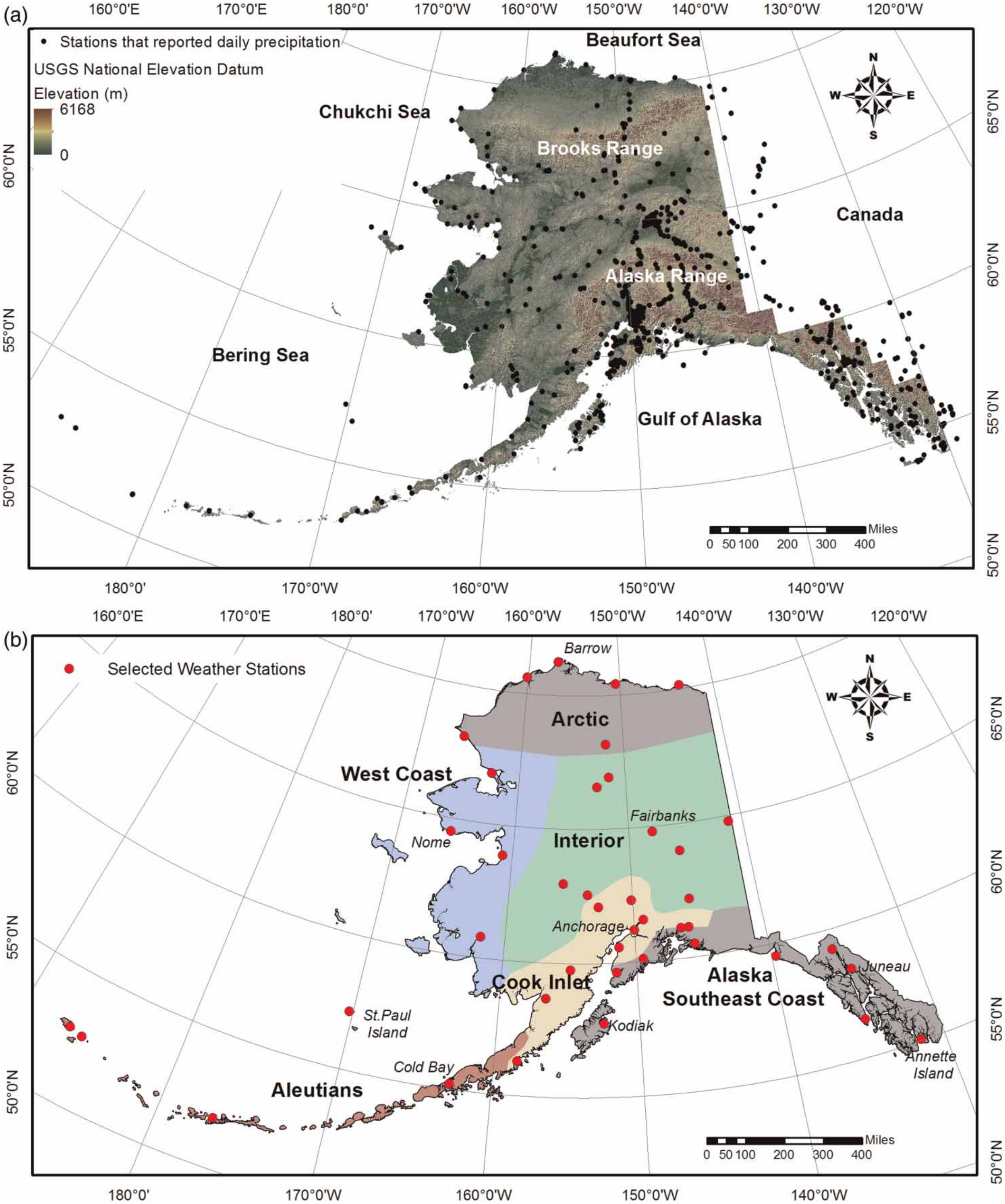

Figure 1 | (a) Location map of state of Alaska showing elevation range. Green circles show the location of 24-hour (daily) precipitation gauges. (b) Six major climatic zones in Alaska with the location of meteorological stations (red dots) used in the analysis of solid/liquid precipitation.

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the Alaska–Canada border were used. The two major challenges encountered in this early study were the lack of data in remote and mountainous areas of Alaska's broad reach and the absence of computers for use in the analysis and spatial distribution of results.

For the latest PFE (Perica *et al.* 2012), there was the potential of using data from 1,653 stations in Alaska (913 daily stations, 667 hourly stations, and 73 15-minute stations), and data were additionally available from Canadian stations (60 daily and 10 hourly stations). In the final precipitation frequency analysis, Perica *et al.* (2012) used annual maximum series (AMS) data from only 396 daily and 121 hourly Alaska stations, and the data available from the Canadian stations.

Other precipitation data products for Alaska are the two maps of mean monthly precipitation produced by the Alaska Geospatial Data Clearinghouse and Spatial Climate Analysis Service (at Oregon State University). A comparison of these two maps was made by Simpson *et al.* (2005). While their goal was to determine which of the two groups produced the best spatial coverage of monthly mean precipitation in Alaska, the authors raised many of the same issues that are presented here.

The biggest advantage of the 2012 frequency analysis over the 1963 results was the additional 50 years of collected precipitation data. Although some of the earlier stations had been discontinued prior to the 1963 report or during the intervening 50 years since that report, several new stations had been installed.

The contiguous United States has enough National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS) stations (high density with duration of at least 30 years) for adequate idf frequency analyses. Because of the sparseness of stations in Alaska, data from any source were considered for use in the state's recent precipitation frequency analysis (Perica *et al.* 2012). The following sources provided data: Alaska Department of Transportation and Public Facilities; Environment Canada; USDC Midwestern Region Climate Center; USDC National Climatic Data Center; National Interagency Fire Center; USDC Western Region Climate Center; USDA Natural Resources Conservation Service; USDI Geological Survey; Federal Aviation Administration; and University of Alaska Fairbanks. Data from Environment Canada were collected along the Alaska–Canada border (eastern Alaska). Alaska's south, west, and north boundaries are open ocean/seas (with scattered islands).

This paper presents a review of the strengths and weaknesses of the precipitation data set that has been building in Alaska for over 100 years. Most of the distinctive features of the Alaska precipitation data set discussed here are described in Perica *et al.* (2012), where all sources of precipitation data were compiled and examined. Clearly some of these characteristics were already known when the first Alaskan PFE was carried out in the early 1960s.

CHARACTERISTICS OF THE HISTORICAL PRECIPITATION NETWORK IN ALASKA

Measuring the 'true' amount of precipitation is a challenge, as all gauges undercatch with the biases being greater for solid precipitation. In Canada (the only country to do so), two gauges are used to measure precipitation: one (Nipher) for solid and one (Type B) for liquid precipitation (Metcalfe *et al.* 1997). Young *et al.* (2006) showed that the percentage of solid precipitation to liquid precipitation increases at higher latitudes and, therefore, quantifying total annual precipitation is more difficult because of the poorer performance of gauges when measuring solid precipitation.

Often, data sets are not compatible because precipitation gauges with different performance characteristics have been used. Today, the precipitation gauge most used in the United States is the standard NOAA/NWS 8 in. (~20 cm) orifice gauge (Figure 2) in various configurations. The Wyoming gauge system is used in the western United States by the USDA, Natural Resources Conservation Service. The details of gauges used around the world are described in Sevruk & Klemm (1989).

For all types of gauges, the quality of precipitation data from unmanned sites are compromised by the environment, wildlife interference, lack of reliable power source, poor communication, and in most cases the inability to measure solid precipitation during the cold season. In earlier data collection, a large number of non-standard gauges was used. Because of the sparseness of precipitation data for Alaska, Perica *et al.* (2012) collected data from as many sources as could be found for use in the frequency analysis, as long as

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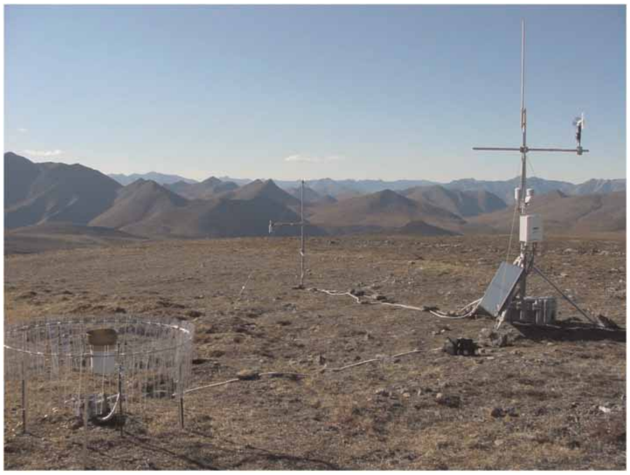

Figure 2 | Standard NOAA/National Weather Service 8 in. (~20 cm) orifice precipitation gauge with an Alter (wind) shield at a remote site north of the Arctic Circle in the Brooks Range, Alaska. The station is visited twice per year (early spring and late summer) and powered with a solar panel and 12-volt batteries. It does not collect precipitation data during the cold season and communicates by radios and the Internet with the University of Alaska Fairbanks.

the data passed certain quality tests. Data sources included research projects by various groups. The main advantage of such precipitation measurements is that they often are made in remote areas and at high elevations, where previous measurements have been lacking. The primary disadvantage of precipitation measurements from research projects is that the record length of these data sets is often too short to use in the frequency analysis. In many cases, researchers who collected these data likely did not anticipate that their data record would later be used for precipitation frequency analysis. For example, the Water and Environmental Research Center at the University of Alaska Fairbanks had a 3-year funded research project in Imnavait Creek on the North Slope of Alaska that started in 1985. As it turns out this site is an exception, precipitation data collection has continued for the past 29 years.

Density of stations

The density of precipitation stations in Alaska is at least an order of magnitude less than in the contiguous states, mainly due to rugged terrain, climate extremes, sparseness of population centers, and the vast size of the state (1,480,000 km^2; 570,000 mi^2). As an example, in California (424,000 km^2; 163,700 mi^2), where a precipitation frequency analysis was recently completed, there is approximately one precipitation gauge for every 50 km^2, while in Alaska, there is one precipitation gauge about every 900 km^2. Gauge density in California is approximately 18 times greater than it is in Alaska. Although data from 1,653 precipitation stations were potentially available for use in Alaska's recent PFE (Perica *et al.* 2012), data from only 396 daily and 121 hourly stations were used (one station every 2,863 km^2) (Table 1). Stations were also deleted in the California precipitation frequency study. After those deletions, the actual density of stations used in the California analysis was only 13 times greater than the density of stations used in the Alaska analysis.

In Perica *et al.* (2012), the distributions of these daily and hourly (including sub-hourly) stations in Alaska and western

Table 1 | The number and density of total and utilized stations in the 2012 PFE for Alaska, plus the density of daily stations above 1,000 ft (305 m) and 3,000 ft (914 m) in TP 47 (Miller 1963) and Atlas 14 (Perica *et al.* 2012)

	Land area			Density (1 station per area listed below)	
Region	**km^2**	**mi^2**	**Number of stations**	**km^2**	**mi^2**
Daily and hourly stations combined					
State of Alaska (AK)	~1,480,000	~570,000	Total: 1,653	895	345
			Used for PFE: 517	2,863	1,102
Daily stations					
AK land above 1,000 ft (~305 m)	740,000	285,000	TP 47: 26	28,462	10,962
			Atlas 14: 134	5,522	2,127
AK land above 3,000 ft (~915 m)	251,600	96,900	TP 47: None	None	None
			Atlas 14: 10	25,160	9,690

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Canada are shown (Figures 4.4.2 and 4.4.3). In this paper, Figure 1(a) shows all daily precipitation stations in Alaska and that portion of Canada bordering Alaska – not just those used in the final analysis. The sparseness of stations, particularly in western and northern Alaska, is visible in this figure. In several cases, a delineation of many of the road corridors in Alaska (which again correspond to population centers) is evident. In a few cases, river drainages are indicated by the precipitation gauge pattern of remote rural villages without roads. Finally, note that the Canadian gauges used differ from those used in Alaska and therefore have different catch efficiencies.

It is clear that the density of the precipitation data network in Alaska is far less than what is preferred for capturing local climatological variation; however, even this marginally sparse data set provided a markedly improved analysis of Alaska precipitation frequencies in comparison with the 1960s study. The initial criteria for precipitation frequency analysis used by NOAA/NWS for Alaska were relaxed on station duration (30 years to 15 years or even less for a few stations in remote areas) and percent of annual missing data (from 20 to 90%) to increase the number of stations that could be used in the analysis. In later checks, these data may still eventually be excluded. Also, use was made of data collected externally by any agency or institution as long as it met certain quality criteria (see Perica *et al.* 2012; http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_ak.html).

Precipitation stations with elevation

The population centers of Alaska are generally located along the coast or at low elevations on major drainages. Not surprisingly, these locations are where a majority of existing and historical meteorological stations that are/were collecting precipitation data have been established. Over 50% of Alaska's land area is above 1,000 ft (~305 m) elevation, 30% is above 2,000 ft (~610 m) elevation, and 10% is above 4,000 ft (1,220 m) elevation (Figure 3). In the 1963 analysis, there was approximately one station for every 10,000 mi^2 (28,500 km^2) above 1,000 ft (~305 m). In the 2012 analysis (Perica *et al.* 2012), this statistic had improved by about a factor of 5 (one station every 2,100 mi^2 (5,500 km^2)). While the number of stations at higher elevation has increased with time, it is still dramatically low. Note that most runoff originates in the unpopulated headwaters of catchments at high elevations, so it is important to have good estimates of precipitation at high elevation. In the 2012 analysis, 134 stations were above 1,000 ft (305 m), and 10 were above 3,000 ft (915 m). In 1963, 26 stations were above 1,000 ft (305 m), and none were above 3,000 ft (915 m). Areas of significant relief, such as along much of the southern coast, are where local climatological variation is presently not captured.

Close proximity

In a state with very few precipitation stations, it is surprising to find some that are located near each other (5 mi (8 km) with consideration to elevation). On examination, however, very few stations in Alaska are located proximally and collecting data at the same time. The exceptions are in population centers like Anchorage and Fairbanks, where stations with overlapping data are in operation, although separated by 5 to 10 mi (8 to 16 km) or less. In 1929, the main weather station in the city of Fairbanks was located downtown. Since then, it has moved five times, from a distance of a city block to 3 miles (5 km), with the maximum distance between its various locations equaling 6 mi (10 km). What generally happened was that the station was moved within proximity of the most recent location. In some cases, overlapping data were collected at both sites for a year or two and then terminated at the previous site. In order to get a longer record for cases such as Fairbanks, co-located data sets were combined, thus effectively reducing the number of useable stations, but extending the record length of the original station.

Gauge undercatch

It has been known for some time (Alter 1937; Larkin 1947; Larson & Peck 1974; Sevruk 1989) that an accurate gauge for measuring precipitation in windy environments has not been developed (Goodison *et al.* 1998; Yang *et al.* 1998, 1999, 2000). Sevruk & Klemm (1989) illustrate most of the national gauges presently in use around the world. With the lone exception of a gauge in blowing-snow conditions, when it captures snow just traveling horizontally

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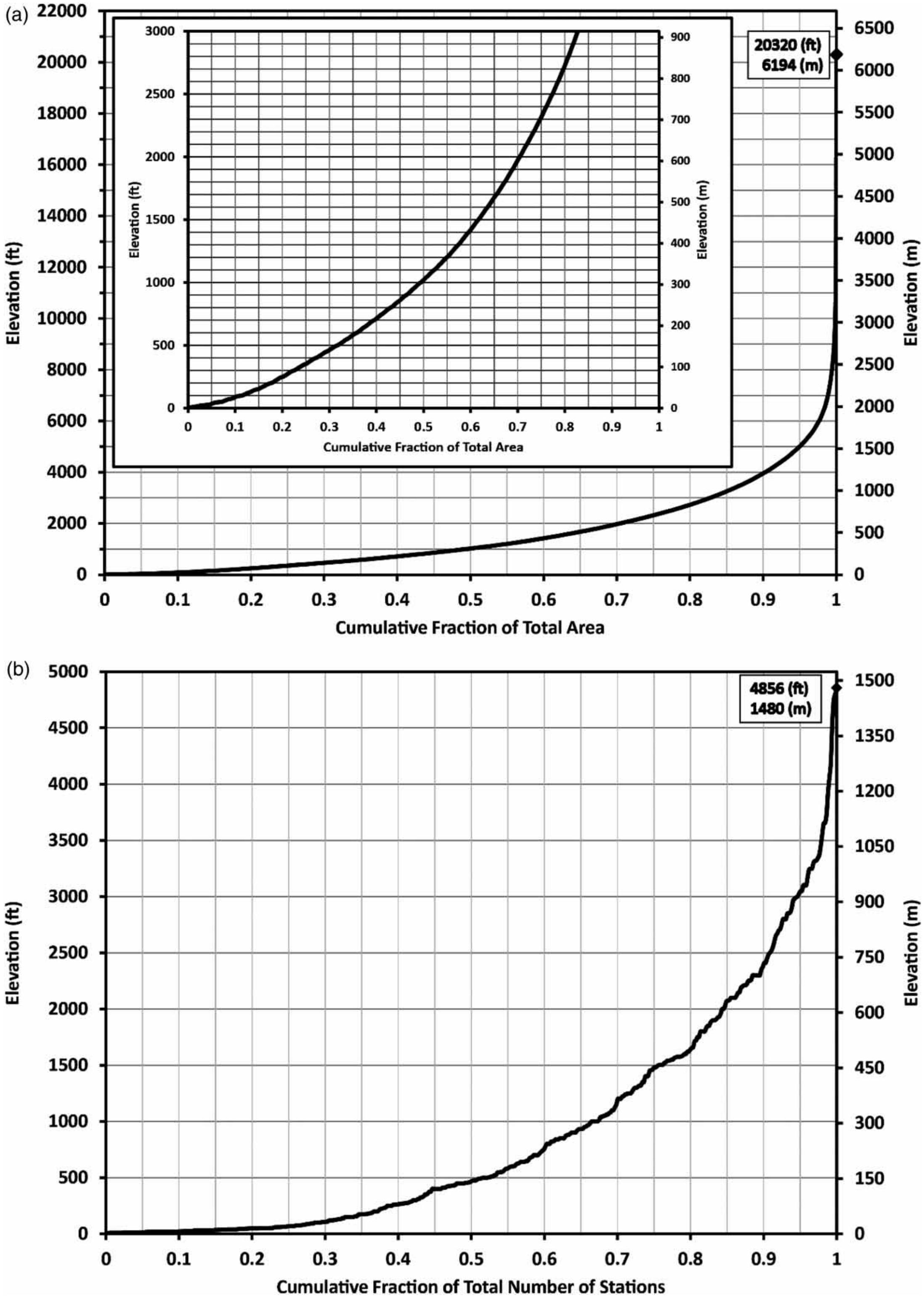

Figure 3 | (a) Hypsometric curve for Alaska showing the full range of the elevations from sea level to 20,320 ft (6,194 m). The inset shows more detail for the lower 80% of Alaska's area. (b) Cumulative fraction of precipitation stations as a function of elevation. Gulkana weather station maintained by the USGS has the highest elevation on this graph at 4,856 ft (1,480 m).

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along the ground, all precipitation gauges undercatch the actual amount of precipitation. Data corrections for the NOAA/NWS 8 in. orifice gauge (shielded and unshielded) have been suggested for both solid and liquid precipitation (Goodison *et al.* 1998; Yang *et al.* 1998). The procedure recommended is to make corrections to unshielded gauge data until the shield is added, and then make additional, but different, corrections for the measurements of the shielded gauge. The data corrections for unshielded gauges are greater than the corrections for shielded gauges, and the corrections for solid precipitation are greater than for liquid precipitation.

A comparison study between gauges (Goodison *et al.* 1998) showed that catch efficiencies varied for each gauge type. Eventually the double fence intercomparison reference (DFIR) with a Tretyakov gauge was determined to have the highest catch efficiency. Prior to the mid-1940s (Larkin 1947), it was also determined that wind shields on the US 8 in. (~20 cm) orifice gauge could significantly increase gauge catch. In the late 1940s, the use of Alter 'wind' shields was initiated on some US gauges used by the National Weather Service. The earliest we can document a wind shield in Alaska is 1954 at Annette Island. Although the Alter shield was added in 1954, it was not documented until the 1990s. Generally, it was not possible to determine from station notes when or if Alter shields were added to other gauges in Alaska.

Annette Island, a rather windy coastal site in southeastern Alaska, provides an example of annual maximum precipitation undercatch. The average magnitude of the undercatch (when adjusted to the DFIR) at Annette Island (Station ID 50-0352) for the 24-hour AMS (period 1984–2008) for a gauge with a documented Alter shield was estimated to be 15% (Table 2(a)). For the AMS during this 25-year record, the estimated increase in precipitation ranged from 8.4% for the least windiest event to 24.7% for the windiest event.

By contrast, Fairbanks station (without a wind shield), a region with less wind (average wind speed one-third of that at Annette Island during AMS events) had calculated precipitation increases that ranged from 4.4% (least windy) to 14.7% (windiest), with the average increase for 25 years of data equaling 9.8% (Table 2(b)). The 25-year record for Fairbanks is not continuous, because for a couple of years,

Table 2 | Estimated magnitude of the wind undercatch correction for annual maximum 24-hour storms ($n = 25$ years) at two stations: (a) Annette Island, Alaska (Alter shield) and (b) Fairbanks International Airport (unshielded gauge)

	Wind speed		Adjusted P		Measured P		Increase in P
AMS date	m/s	f/s	cm	In	cm	In	%
(a)							
10/03/84	3.31	10.86	9.1	3.58	8.3	3.26	9.7
01/15/85	9.12	29.92	6.3	2.47	5.2	2.05	20.6
09/22/86	7.82	25.66	8.5	3.36	7.2	2.84	18.4
09/22/87	2.73	8.96	8.9	3.52	8.3	3.25	8.4
01/19/88	2.77	9.09	9.6	3.52	8.8	3.47	8.6
09/24/89	2.82	9.25	8.4	3.31	7.8	3.05	8.6
10/23/90	2.86	9.38	7.5	2.94	6.9	2.70	8.8
12/20/91	2.91	9.55	9.5	3.73	8.7	3.43	8.8
09/27/92	2.95	9.68	8.4	3.32	7.8	3.05	8.9
02/26/93	11.53	37.83	12.0	4.74	9.7	3.80	24.7
10/16/94	7.38	24.21	6.1	2.41	5.2	2.05	17.6
10/01/95	7.47	24.51	6.7	2.64	5.7	2.24	17.7
02/12/96	7.51	24.64	6.4	2.52	5.4	2.14	17.8
12/12/97	10.64	34.91	12.6	4.94	10.2	4.01	23.2
08/28/98	7.51	24.64	8.3	3.26	7.0	2.77	17.8
10/21/99	6.04	19.82	8.8	3.48	7.7	3.02	15.1
08/21/00	7.38	24.21	9.8	3.86	8.3	3.28	17.6
09/21/01	7.69	25.23	7.7	3.04	6.5	2.57	18.1
11/20/02	5.77	18.93	6.9	2.72	6.0	2.37	14.6
10/25/03	5.99	19.65	16.0	6.30	13.9	5.48	15.0
12/02/04	4.83	15.85	6.3	2.47	5.6	2.19	12.8
11/08/05	8.81	28.90	8.3	3.28	6.9	2.73	20.1
04/07/06	5.68	18.64	8.9	3.50	7.8	3.06	14.5
10/23/07	6.80	22.31	10.1	3.96	8.6	3.40	16.6
08/23/08	5.50	18.04	9.5	3.73	8.3	3.27	14.2
Average	6.20	20.34	8.8	3.47	7.7	3.02	15.1
(b)							
8/12/1967	3.4	11.0	9.8	3.88	8.7	3.42	13.3
7/17/1982	3.1	10.2	1.6	0.62	1.4	0.55	12.8
8/20/1983	1.6	5.4	2.5	1.00	2.3	0.92	8.6
7/21/1984	3.3	10.8	2.6	1.04	2.3	0.92	13.2
6/25/1985	2.0	6.5	1.6	0.65	1.5	0.59	9.7
7/19/1986	2.1	7.0	2.9	1.12	2.6	1.02	10.1
7/23/1987	2.6	8.4	1.4	0.56	1.3	0.50	11.3
6/16/1988	1.9	6.3	1.9	0.74	1.7	0.68	9.5
6/24/1989	1.7	5.4	2.9	1.14	2.7	1.05	8.7

(*continued*)

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Table 2 | continued

	Wind speed		Adjusted P		Measured P		Increase in P
AMS date	m/s	f/s	cm	In	cm	In	%
8/26/1990	1.6	5.2	3.8	1.50	3.5	1.38	8.4
7/6/1992	1.7	5.4	2.6	1.03	2.4	0.95	8.7
8/25/1994	1.6	5.3	2.1	0.82	1.9	0.76	8.5
6/26/1995	3.9	12.9	2.7	1.08	2.4	0.94	14.7
8/9/1996	3.5	11.5	1.8	0.73	1.6	0.64	13.7
6/8/1997	2.2	7.2	2.1	0.83	1.9	0.75	10.3
7/7/1998	2.2	7.3	2.3	0.90	2.1	0.82	10.4
9/26/1999	1.7	5.5	2.2	0.85	2.0	0.78	8.8
7/28/2001	1.1	3.7	1.4	0.55	1.3	0.51	6.9
4/26/2002	2.4	8.0	2.6	1.02	2.3	0.92	11.0
7/27/2003	2.6	8.5	6.4	2.53	5.8	2.27	11.4
5/6/2004	1.7	5.5	1.7	0.65	1.5	0.60	8.8
7/18/2005	1.2	3.9	2.8	1.09	2.6	1.02	7.1
7/5/2006	1.1	3.5	2.1	0.84	2.0	0.79	6.7
7/22/2007	0.5	1.7	2.3	0.89	2.2	0.85	4.4
7/28/2008	1.5	5.0	3.1	1.23	2.9	1.14	8.2
Average	2.1	6.8	2.8	1.09	2.5	0.99	9.8

the annual maximum occurred during the cold period as solid precipitation. The year 1967 was included in this table as it represents the highest 24-hour precipitation in the AMS for this site. The corrections for Fairbanks would have been lower had a wind shield been installed on this gauge.

During the Alaska precipitation frequency project, two problems were faced relative to gauge catch: (1) some of the sites (especially older ones) had no wind shields initially, and it was not known when the transition to shields occurred; and (2) data used for Alaska's eastern boundary were from Canadian gauges, which are distinctly different in gauge catch characteristics when compared with the standard NOAA/NWS 8 in. orifice gauge. At first it was thought that undercatch corrections to the US gauges for the two conditions of 'with' and 'without' wind shields could be made. As indicated above, unfortunately, only in rare cases was documentation available on when Alter shields were added to these Alaska gauges. It was concluded that if the timing of wind shield installations for all gauges was not known, then justification for making corrections for undercatch could not be made. Corrections could have been made only to the Canadian gauges, but that would have produced a larger discrepancy between the Canadian and American gauge results along the eastern border of Alaska.

Since documentation as to wind shield installation was not available, an alternate approach was attempted. If Alter shields were added, it was expected that an increase in precipitation catch would occur and, if cumulative annual precipitation versus time was plotted, a significant positive change in slope could be detected. Seven first-order stations (Figure 1(b)) having the best-quality data (Anchorage – Station ID 50-0280; Barrow – Station ID 50-0546; Cold Bay – Station ID 50-2102; Fairbanks – Station ID 50-2968; Juneau – Station ID 50-4100; Ketchikan – Station ID 50-4590; and Nome – Station ID 50-6496) and widely distributed over the state with a relatively long period of record were selected, and the results were plotted. The outcomes were not conclusive (Figure 4). Anchorage, Barrow, Fairbanks, and Ketchikan deviated little from a constant slope. During the period of record, Cold Bay and Juneau, where data collection started around 1950, initially had a decrease in slope followed by an increase around the mid-1980s. Although the Nome station was started in 1908, it was missing over 20 years of data (1930–1952); after 1952, the slope decreased briefly and then increased, returning to its original value. Although some stations (Anchorage, Cold Bay, and Juneau) showed a slightly increasing slope around 1976, this was at the same time that Ebbesmeyer *et al.* (1991) documented a step-like change in 40 wide-ranging environmental variables associated with climate change for the Pacific Ocean and the Americas. Overall, this approach did not provide any insight into when Alter shields were added. Therefore, the precipitation data used in the frequency analysis were not corrected for gauge undercatch caused by wind.

An increase in AMS due to bias correction would have been most pronounced at the stations in open, windy locations. The example above (Annette Island station; Figure 1(b)) is representative of significant gauge undercatch due to its coastal location. Other locations (e.g., the Fairbanks station) are rarely exposed to strong winds during precipitation events, so the magnitude of gauge

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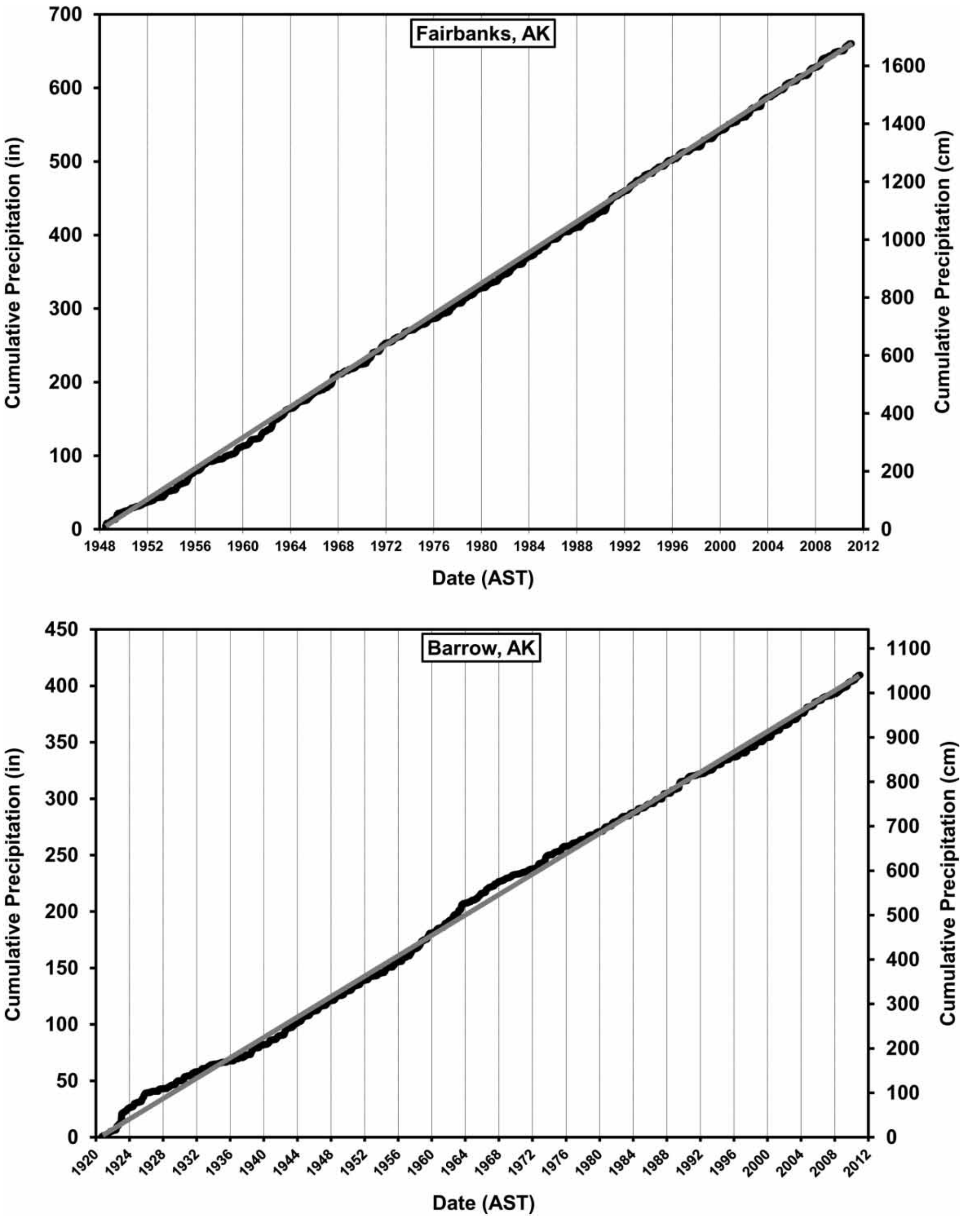

Figure 4 | Cumulative annual precipitation at Fairbanks International Airport (Station ID 50-2968) and at Barrow Post-Rogers Airport (Station ID 50-0546) for the period of record. The gray line represents a constant slope, while the dark line represents cumulative annual precipitation. Fairbanks has a very consistent slope over the period 1948 through 2012; Barrow shows some short-term increases in precipitation, but they are not sustained. These plots show no indication of constant increased gauge catch due to the addition of wind shields.

undercatch due to wind would be significantly less. Another possible concern is heterogeneity in the precipitation time series due to adding wind shield corrections to different precipitation gauge results. One should expect that positive trends in the precipitation data could be triggered by a cause other than climate change, such as the addition of Alter shields, which would increase gauge catch.

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Length of data collection

As a rule of thumb, the NWS requires a station record length of 30 years or longer for precipitation frequency analysis. The biggest advantage of the 2012 Alaska analysis versus the 1963 results is the 50 additional years of collected data. In 1963, the maximum record length was about 50 years; in 2012, the maximum record length increased to about 100 years. The average record length for stations used in the 2012 study (Perica *et al.* 2012) was 32 years for daily stations ($n = 396$) and 18 years for durations less than 24 hours. Stations with as few as 5 years of data were included in the 1963 study; in the recent study, all stations with 15 years were retained (including some, 9 hourly and 10 daily, with as few as 9 to 10 years in remote areas with limited data).

Missing observations

Precipitation frequency analysis is based either on maximum events recorded each year (AMS) or on maxima above a selected threshold (partial duration series, or PDS). Under the best conditions, selection of AMS or PDS occurs from data reported consistently over an entire year (no missing data). In reality, the historical precipitation records in many northern regions have a high percentage of missing data, mostly during the winter. Under missing-data conditions, it is important that criteria are selected that allow a decision about whether available data actually did capture precipitation maxima for that year. For example, if a station reports 'missing data' during 100 days in 1 year, is it advisable to trust that the maximum precipitation event was captured during the remaining 265 days? Allowing missing data may result in including an underestimated annual maximum. Inclusion of these events can bias the outcomes of the frequency analysis as well as introduce trends in AMS.

The problem of missing data was ubiquitous throughout the recorded observations used in the PFE. Missing data are generally more common during the cold season than during the warm season. Also, most annual precipitation maxima (hourly and daily) occur during the rainy season; therefore it is easier to tolerate missing data in the cold season (see the section on 'Segregation of liquid and solid precipitation' for more information). At many research sites (generally remote and unattended), daily and hourly precipitation data are collected only during the warm season (end-of-winter snow surveys are typically performed just prior to ablation to quantify the cumulative snow water equivalent on the ground). One significant impediment at remote sites is the lack of instrumentation robust enough for measuring solid precipitation. Other impediments at weather stations are related to power, communications, environment, and wildlife encounters. For the idf analysis (Perica *et al.* 2012), annual maxima were initially acceptable if less than 33% of the wet season (liquid precipitation likely) was missing. The wet season for each of the six climate regions is listed in Table 3. Before being used in the idf analysis, the data had to pass further checks.

Climate change

At the time that precipitation networks were being developed around the world, no thought was given to climate

Table 3 | Climate regions of Alaska and average daily air temperature threshold, determined as temperature at which both rainfall and snowfall have an equal probability of occurrence; lower than this temperature, solid precipitation is more likely to occur, and above this temperature, the likelihood favors liquid precipitation

Region	Number of stations	Wet season	Range of elevations ft	Range of elevations m	Air temperature threshold °F	Air temperature threshold °C
Arctic	6	June–September	5–2,100	1.5–640	31.0	– 0.5
West Coast	4	June–October	333–1,570	101–478	33.0	0.6
Interior	8	June–October	10–102	3.0–31	33.0	0.6
Cook Inlet	9	July–December	30–2,502	9.1–763	33.8	1.0
Aleutians	5	July–February	17–78	5.2–24	35.5	1.9
Southeast Coast	10	August–January	12–109	3.6–33	35.6	2.0

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change; so an antiquated system is being used in the study of climate change, an application for which it was never intended. It is generally assumed when performing hydrologic frequency analysis that data from the events are random, independent, homogeneous, and not affected by climate cycles and trends. Intensity-duration-frequency analysis is based on the assumption of stationarity (same mean and variance over the period of data collection). The user assumes that these conditions will prevail over the design time frame that follows, which could be several more decades. Numerous environmental changes have been documented for Alaska and the surrounding area: warmer permafrost (Lachenbruch & Marshall 1986), reduced sea ice extent (Maslanik *et al.* 1999; Vinnikov *et al.* 1999), vegetation changes (Sturm *et al.* 2001), mass wasting of glaciers (Arendt *et al.* 2002), increased active layer thickness (Overduin & Kane 2006), shorter seasonal snow cover (Robinson *et al.* 1993), later freeze-up and earlier break-up of river and lake ice (Magnuson *et al.* 2000), and changes in the arctic freshwater system (Hinzman *et al.* 2005; White *et al.* 2007). In addition, evidence of freshwater cycle intensification in the Arctic has been reported (Rawlins *et al.* 2010). For 12 hourly stations and 154 daily stations with a minimum record length of 40 years, Perica *et al.* (2012) found that 8% of the stations showed positive trends, 7% showed negative trends, and 85% showed no trend (using the parametric *t*-test and nonparametric Mann–Kendall test at 5% significance level).

At present, these data analyses do not appear to yield statistically significant change in the magnitude of annual precipitation maxima. This result does not preclude that the amount of annual precipitation in Alaska is changing; only that no regional pattern of consistent change in the AMS is apparent.

Data quality

Evaluating the quality of data collected by others is always a challenge, especially in a region as vast and varying as Alaska when those collecting the data might not anticipate future uses. While Perica *et al.* (2012) did not attempt to address quality issues for all the precipitation data collected, all values (annual maxima of hourly and daily precipitation) used in the precipitation frequency analysis were scrutinized.

A majority of the NWS precipitation stations (especially daily) are run by cooperative observers who volunteer their time. Many problems with data collection seemed to appear when an observer left the site (medical emergency, vacation, etc.) and another person collected the data until the observer's return. In some cases, it appeared that daily readings of precipitation were not taken for one or more days (an opinion based on the lack of precipitation measured at a gauge while neighboring gauges recorded precipitation). When the precipitation measurement was resumed, the cumulative amount of precipitation from the previous unmeasured days was reported with the current data. In some cases, an attempt was made to correct this measurement on the original data work sheets, but often the problem was not identified at the time of data collection or later, before the data were released. On these monthly work sheets, changes in handwriting were evidence of a change in observer. The problem for the precipitation frequency analysis is that these errors often appear as annual maxima for daily durations. So, prior to using the data, outliers (in this case, annual maxima that depart significantly from the trend of other corresponding maxima in the data set) had to be identified. Both low and high outliers were identified, as they can significantly affect the statistical parameters, especially for small data sets, which are common in the Alaska setting. High AMS were verified by looking at historic events. For instance, in the interior region, the daily rainfall rate that caused the historic 1967 flood in the Tanana River valley and the city of Fairbanks was set as an upper limit for the realistic AMS in that area. Maximum 24-hour rainfall of 3.42 in. (87 mm) was recorded in Fairbanks on August 12, 1967. As part of the AMS quality control procedures, Perica *et al.* (2012) also identified a new state record for 24-hour precipitation. The original state record (15.2 in.; 386 mm) was reported for Angoon station (Station ID 50-0310) on October 12, 1982; however, data for the surrounding area did not support this claim. The updated state record for 24-hour precipitation was found to be 15.05 in. (382 mm) measured in Seward on October 10, 1986 (Perica *et al.* 2012).

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Segregation of liquid and solid precipitation

In non-mountainous tropical areas, all precipitation events are rainfall with an immediate rainfall–runoff response; at both high latitudes and high elevations, annual maximum runoff can result from snowmelt. Precipitation frequency estimates are usually used to represent immediate rainfall–runoff response, and they are not suited for snowmelt runoff predictions. One of the questions raised early in the PFE study was, 'Could we separate and compare the annual maxima of liquid and solid precipitation?'

As mentioned before, data for PFE were collected from a variety of agencies. Some stations reported rainfall-only data, other stations reported precipitation without indicating the form of the precipitation, and some stations did report the form of the precipitation. Many precipitation stations in remote areas are unmanned, and therefore the phase of the precipitation is unknown. Regardless, almost all of these stations had an accompanying record of air temperature, and some of the National Data Climate Center daily stations had data that included snowfall record.

In many situations – say for hydrologic modeling, flood runoff predictions, gauge corrections for undercatch, and in our case, precipitation frequency estimates – the precipitation data user needs to know whether the data reflect liquid or solid precipitation. While rainfall can rapidly convert to runoff, solid precipitation goes into surface storage and runoff is initially delayed. Several efforts (see list of references in Marks *et al.* (2013)) have been directed at developing tools for determining storm precipitation phase (liquid or solid). Early attempts to resolve the phase of precipitation were quite simple and only involved using air temperature (Auer 1974). Recent attempts are more sophisticated (Marks *et al.* 2013; Harder & Pomeroy 2013) and require more detailed data often not collected at stations.

A combination of precipitation, snowfall, and air temperature data (for those stations where available) were used in the precipitation frequency analysis to segregate solid from liquid precipitation. If snowfall was reported, precipitation on those days was classified as solid (and as liquid on days without snowfall). If only air temperature was available, threshold air temperature was used to segregate solid and liquid precipitation. The resultant rainfall data set was used to perform rainfall idf analysis, and resultant rainfall frequency graphs were compared against the precipitation frequency graphs. Results of this comparison are summarized in Perica *et al.* (2012).

As our goal was to segregate solid and liquid precipitation for data recorded as far back as the early 1900s, the only option was to rely on air temperature records, realizing that this approach was not optimal. For each of the six climate regions of Alaska, a threshold air temperature that can be used to separate solid and liquid precipitation was identified. Forty-two stations with air temperature and both form and amount of precipitation were used for this analysis. Form of precipitation was retrieved from the snowfall records. Precipitation records on days with snowfall were classified as solid precipitation (including mixed); precipitation records on all other days were classified as rain. Figure 1(b) shows the location of selected stations within each climate zone. Table 3 specifies elevation range and number of stations in each climate region. Generally, stations represent an elevation range of from 5 to 2,502 ft (1.5–763 m). The probability of occurrence for daily solid and liquid precipitation at different air temperatures was calculated based on combined data from all stations within each climate region (Figure 5). The threshold air temperature was identified as the air temperature at which both solid precipitation and liquid precipitation have equal probabilities of occurrence. This approach is similar to that of Auer (1974).

Calculated threshold temperatures increase from higher to lower latitudes over Alaska; they vary from 31 °F (−0.5 °C) in the Arctic to 35.6 °F (2.0 °C) in southeast Alaska. Although the transition from liquid to solid is designated as a specific temperature, Figure 5 shows that the two forms of precipitation can be found over a range of temperatures. In addition, the recording of either solid or liquid precipitation depends upon the observer; mixed precipitation (rain/snow) can occur in a 24-hour event. Mixed precipitation events have a high probability of occurrence, especially at longer durations. In the Alaska Arctic, where it can snow any day of the year, a major storm in August 2002 (from the 11th through the 17th) alternated between rain and snow (Kane *et al.* 2008), with the air temperature dropping below freezing on four occasions with appreciable

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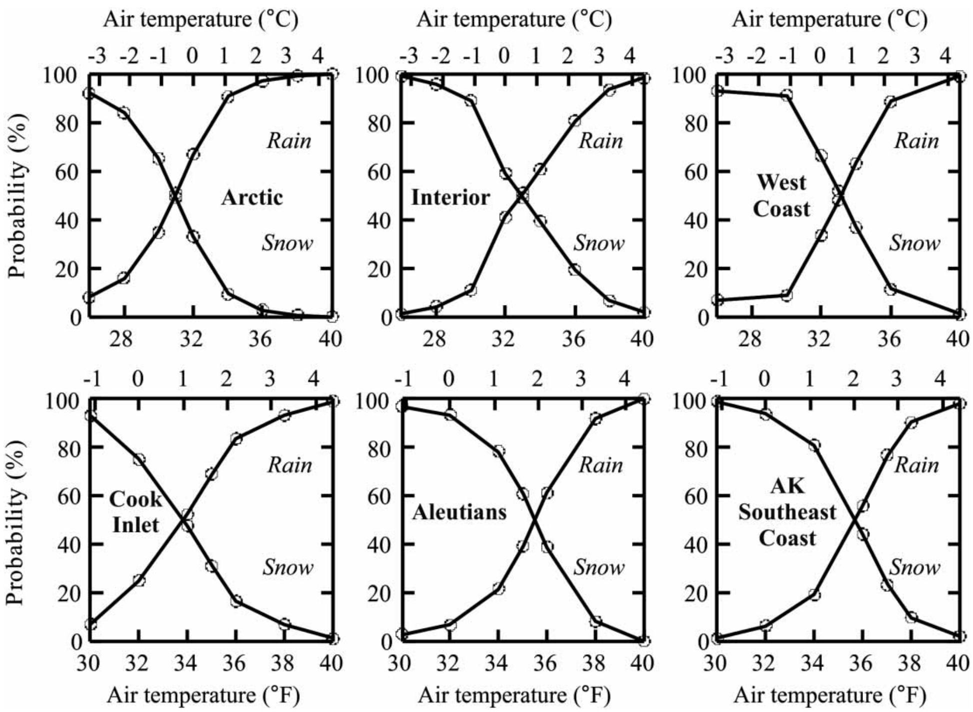

Figure 5 | Probability of occurrence for snow and rain at different air temperatures. Intersection of two lines defines the threshold air temperature. For example, the threshold temperature is 31 °F (−0.5 °C) for the Arctic Region. At or above that temperature, it is more likely to be rainfall, and below that temperature, it is more likely to be solid precipitation.

solid precipitation. Clearly, in such cases it is challenging to categorize both hourly and daily precipitation as either rain or snow.

DISCUSSION

Several government agencies collect precipitation data in Alaska; they use different gauges and different settings (some with and some without wind shields). While these data are used mostly to address Alaskan problems, recent interest in climate change has given the precipitation records global significance. Although climate and climate change know no political boundaries, each circumpolar country has its own precipitation gauge type, each gauge with its own catch efficiency and, therefore, not compatible with each other. Goodison *et al.* (1998) and others have carried out studies to make the results of these national gauges more comparable through corrections for undercatch, comparing national gauges against the DFIR with a shielded Tretyakov gauge. From these studies, it was determined that, of all gauges, the DFIR gauge had the highest catch efficiency, although it still undermeasures 'true' precipitation.

Yet though it was known that precipitation data need to be corrected for wind undercatch, it was not possible to make corrections to stations used in the recent idf analysis for Alaska due to lack of information about whether gauges had wind shields or not. To illustrate the magnitude of this correction, results on wind-induced undercatch were presented for two stations: one in a windy environment (Annette Island, Southeast Alaska) with a wind shield and one in a not-so-windy location (Fairbanks, Interior Alaska) without a wind shield. The corrections for wind-induced undercatch of annual 24-hour maximums ($n = 25$ years) averaged 15.1 and 9.8% for Annette Island and Fairbanks, respectively. The precipitation gauge at the Fairbanks International Airport was equipped with an Alter shield in 2009. The number of stations in Alaska presently equipped with a wind shield is not well documented. Yang *et al.* (1998) analyzed the magnitude-of-bias correction for daily precipitation measured at ten NWS stations in Alaska; only two of the stations had an Alter shield.

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Ideally, precipitation gauge networks should have the following characteristics: gauges with the same construction, that capture 100% of precipitation (or undercatch of gauges documented), are well distributed horizontally and vertically, are efficient for both solid and liquid precipitation, are capable of performing well in remote/unmanned locations, and which provide measurements representative of large areas; and easy access to data and metadata (pictures, history), instrumentation (gauge type and gauge height above ground), quality assurance/quality control (QA/QC), etc.

In the Cryosphere Theme Report 'For the Monitoring of Our Environment from Space and from Earth' by the Integrated Global Observing Strategy (IGOS 2007) working group, numerous recommendations relative to solid precipitation observations that are relevant here were made, including the following: continue the present conventional point precipitation measurements; sustain and enhance the gauge network in cold regions; develop guidelines on minimum station density required for climate research; examine the impact of automation on precipitation measurements and related QA/QC challenges (including compatibility of national data, and manual versus automatic gauge observations); develop digitized metadata; provide support for new instruments including intercomparison testing; and expand the use of wind shields. Liquid precipitation was of primary interest in the Alaska idf estimation; however, it is recognized that better solid precipitation measurements (for climate change studies) are needed. If steps are taken to improve solid precipitation observations, it follows that improvements in liquid precipitation observations will occur also.

In several reports citied earlier, a threshold temperature for the transition from a liquid to a solid phase of precipitation was discussed. Both Marks *et al.* (2013) and Harder & Pomeroy (2013) present approaches more complex than the simple method used that was based solely on air temperature. At a significant majority of the stations, the only two variables historically reported are precipitation and air temperature. To develop regional threshold values for each climate region, four to ten stations with the known form of precipitation were used, although it was realized that this value is only an average for each region and can vary with elevation and time.

Improvements are being made in the density of stations, the number of stations at higher elevations, and the added length of data collection for Alaska. Data quality and missing data are two areas where improvements are needed. As mentioned earlier, most of the missing data occur in the cold season in the solid phase. The quality of data is good for the 21 first-order stations in Alaska's more populated towns; generally, in the remote manned and unmanned stations is where data are missing and quality is sometimes poor.

CONCLUSIONS

In Alaska, precipitation data collection (number of stations, stations at high elevations, duration of record, etc.) has improved over time; but collecting good-quality precipitation data, with adequate spatial representation is still a challenge for us. While for spatial coverage, it is an advantage to have numerous parties (government agencies, private sector, universities) collecting precipitation data, the quality of data between parties is not always compatible. It is well-known that all of the precipitation gauges being used undercatch the actual amount of precipitation; that each gauge type has different performance characteristics; and that unmanned gauges are fraught with problems related to the environment, wildlife, power, and communication. Many diverse groups are collecting precipitation data in Alaska because the data are needed and because the particular information needed is not being collected through the efforts of others. The precipitation gauge network in Alaska is operated and maintained by several state and federal agencies, plus the University of Alaska Fairbanks, with the final precipitation product oriented to the specific institutions' tasks and needs. Coordinated standards/guidelines on precipitation measurements between these agencies would greatly benefit the quality and compatibility of precipitation data for all.

It is recommended that all contributors to the present precipitation efforts participate in a meeting to address the issues raised in this publication so that the quality of the product produced by all parties for use by all parties can be improved. Some agencies are specifically directed to collect precipitation data over the long term. Others collect data mainly for their specific needs. It is rare, however, for universities to collect long-term precipitation data, but in

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Alaska there are some exceptions. A major obstacle in Alaska is the establishment of sites at uninhabited locations.

If a major overhaul of the precipitation data-collection network in Alaska (or USA) were to occur, it would require substantial resources. Lack of viable funding reduces the likelihood of any major issues being addressed, such as replacing the type of precipitation gauges used so that more accurate precipitation measurements are possible. If a meeting of data-collection agencies could be convened, the first thing that participants should do is identify what the constraints are. Next, the participants should determine if solutions are physically and financially possible. Most likely, changes in the present precipitation network are going to happen in small steps, not generous ones. Many precipitation data-collection issues in Alaska also exist at high elevations in the western United States and in other circumpolar Arctic countries.

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