EVALUATION OF A NATIONAL SEASONAL SNOWFALL RECORD AT THE MOUNT BAKER, WASHINGTON, SKI AREA

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Abstract

During the 1998-99 July-June snowfall season, the Mount Baker Ski Area in northwest Washington state reported 1,140 inches of snowfall. As the season progressed and heavy snow continued to fall, the ski area became increasingly aware of the potential to exceed the existing and accepted record of 1,122 inches, set in 1971-72 at the National Weather Service (NWS) cooperative observing station at Paradise Ranger Station on the southern slopes of Mount Rainier 150 miles to the south. The 1971-72 snowfall was first published as a new U.S. record by the editor of Weatherwise Magazine (Ludlum 1972). Later that year, the value was also recognized by the NWS (Ruscha 1972). The Rainier - Paradise record has been cited as a North American record snowfall by Krause (1998) and others.

Because the Mount Baker snowfall is a significant record and would likely be referred to for many years unless exceeded, and because a measure of economic self interest accompanies these measurements, the National Climate Extremes Committee (NCEC) was asked to judge whether the measurement program had adequately followed snowfall observing conventions for acceptance as an official record. The NCEC was formed in 1997 to evaluate the validity of climate extremes that challenge existing national records and make a recommendation to the National Oceanic and Atmospheric Administration (NOAA) regarding acceptance of the observations in question. The NCEC is comprised of several permanent members: National Climatic Data Center, National Weather Service (Andrew Horvitz, Robert Leffler), and the President of the American Association of State Climatologists. Additional experts can also serve as appropriate to the particular record in question. For this event, the chairman was Robert J. Leffler. The Committee also included Kelly Redmond (Western Regional Climate Center) and Raymond Downs (NWS Office of Climate, Water, and Weather Services). The comprehensive evaluation leading to the recommendation that a new record was set is discussed herein. The problems in measuring snow depth are also reiterated.

1. Introduction

Some of the heaviest seasonal snowfall totals in the United States and the world have been recorded in the western mountains of the conterminous United States. Especially noteworthy are amounts, which have fallen in the Cascade Mountains of the state of Washington, where annual averages exceed 600 inches on windward slopes at elevations ranging between 4,000 and 7,000 feet.

These heavy snowfall totals are the result of several factors. Winter is naturally the wettest season as the west-to-east planetary circulation expands southward and strengthens in speed, with storms striking the Pacific Northwest every few days. Air laden with moisture, after its traverse across the Pacific Ocean, is forced to ascend the Cascade Range, dropping abundant precipitation. The freezing level over the area averages about 4,000 feet for the winter months. Near this altitude, snowfall amounts increase very rapidly with just small increases in elevation.

During the 1998-99 season, a moderately strong La Niña accentuated the normally stormy pattern, with a much higher frequency of wet and cold weather systems especially affecting the area from the Cascade Range westward. Freezing levels remained abnormally and consis-

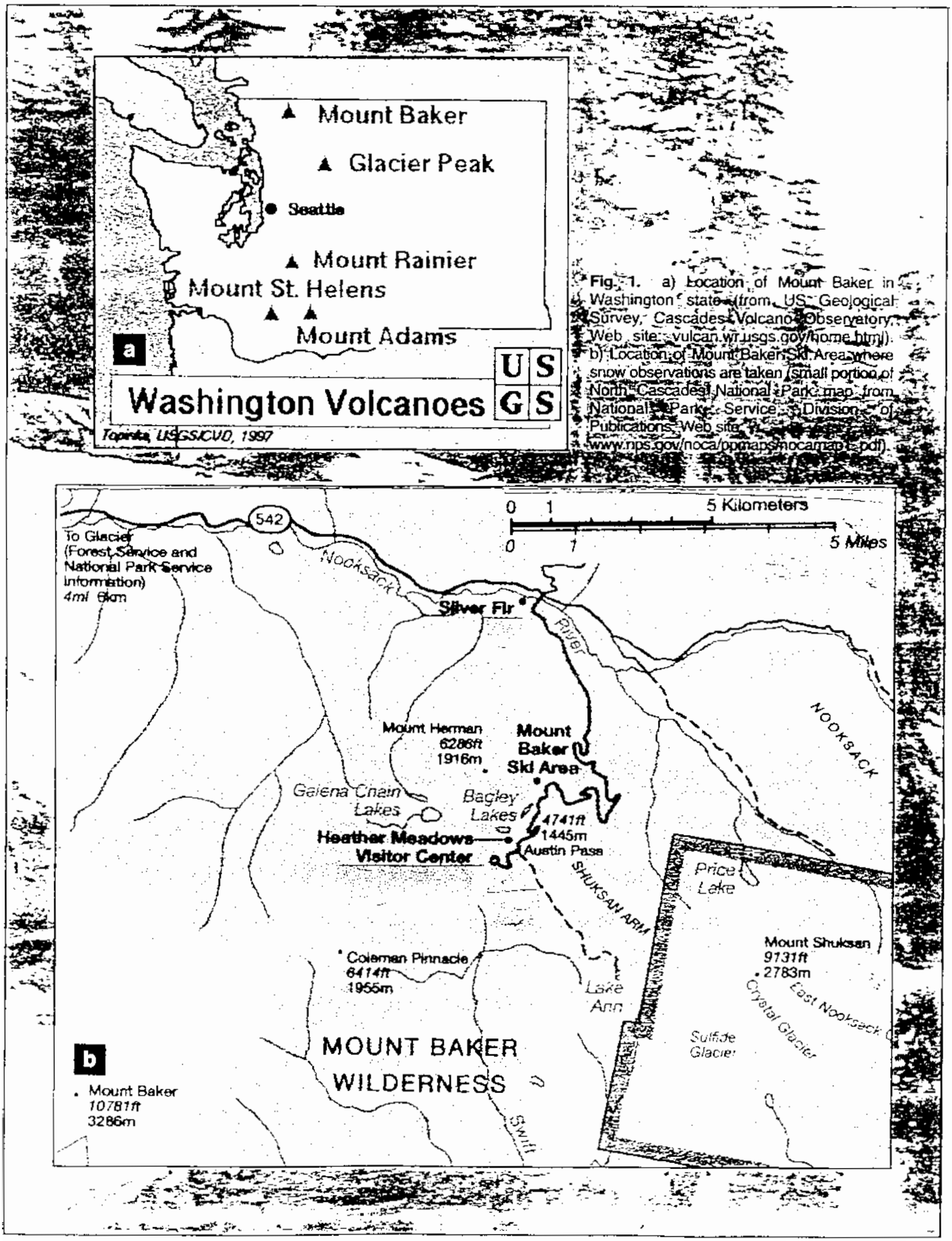

Fig. 1. a) Location of Mount Baker in Washington state (from US Geological Survey, Cascades Volcano Observatory, Web site: vulcan.wr.usgs.gov/home.html). b) Location of Mount Baker Ski Area where snow observations are taken (small portion of North Cascades National Park map from National Parks Service, Division of Publications, Web site: www.nps.gov/noca/ppmaps/nocamap1.pdf).

tently low throughout the winter. Therefore, record snow measurements were probable, but had to be evaluated before official acceptance.

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2. Measurement Site

The 1998-99 Mount Baker snowfall measurements were made at the Mount Baker Ski Area, at an elevation of about 4,200 feet. (This report uses the original American system of units.) The location is about 9 miles northeast of the summit of the Mount Baker volcano (10,781 feet) and 10 miles south of the Canadian border (Fig. 1). The ski area occupies a north facing bowl below the 4800-5000 feet crest of an east-west oriented spur (Shuksan Arm) on the western flank of Mount Shuksan (9,131 feet) whose summit is about 3 miles east. The ski area base has been historically known as Heather Meadows. The ski area drains north into White Salmon Creek, and then into the upper reaches of the westward-flowing North Fork of the Nooksack River. Just over Shuksan Arm to the south, Swift Creek drains south into southward-flowing Baker Creek, and then into the westward-flowing Skagit River.

Snowfall measurements are taken in the parking lot adjacent to the employee housing building. The measurements are taken in support of operations for the privately owned and operated Mount Baker Ski Area. The site is open to the wind from all quadrants. After snowpack accumulates to several feet or more, the plowed parking lot increasingly begins to act as a depression or pit, which this year eventually reached a depth of 20-25 feet. The plowed area is approximately 100 by 200 feet.

3. Measurement Methodology

Snowfall is one of the most difficult climatological elements to measure accurately and consistently (Doesken and Judson 1996). It settles, melts, and drifts from place to place when wind is present. The amount measured can vary greatly depending on the frequency of measurement and the surface upon which it is measured (e.g., grass, wood, and asphalt). In the interest of accurate national record keeping and climate variability research, the Committee's most fundamental mission was to evaluate the snow measurement methodology and determine the accuracy of the snowfall totals.

The Mount Baker Ski Area measurements were taken by four different ski area personnel (observers), with 10 to 33 years experience in snow measurement at this location (average was 22 years). None of the observers had formal NWS snow measurement training but one had participated in USFS Avalanche Center snow course measurements in the surrounding mountains in years past. According to one ski area manager, "good common sense was applied" in taking the snowfall measurements.

Fig. 2. NCEC members analyzing the snow depth site at Mount Baker Ski Area.

Daily snowfall measurements were made at least once each day at about 0500 local time. Rulers, yardsticks or tape measures were used in determining the new snowfall amounts. Measurements were typically taken on the resort's asphalt parking lot, with occasional utilization of the hoods of vehicles. When temperatures were near or above freezing and snow was melting as it fell, a snowboard was used.

Snow depth (total depth of snow on the ground) measurements were made each day, also at about 0500 local time, in a semi-open meadow surrounded by mature conifer trees, several hundred feet east of the daily snowfall measurement location (Fig. 2). The snow depth site appeared to be an excellent location: open, unaffected by structures, plowing, or ski area activities, yet with enough nearby trees to reduce drifting. A snow stake located on this site was the source for snow depth measurements. The stake was reportedly the same equipment, in the same location, used in the 1920's when the station was originally established by the NWS as a published cooperative station. At that time, the area was staffed year-round.

4. Snowfall Data

The daily snowfall (new snow) values were made available to the Committee upon request, first as a spreadsheet output, later as original daily log sheets. Most measurements were to the nearest inch, with just a few to the nearest half-inch. Two daily totals were decreased a half-inch each by the Committee because the values had been rounded up to the nearest inch to obtain the Ski Area's publicly announced 1,141 inch total (standard practice is to retain tenths).

5. Comparison to Other 1998-99 Observations

The Washington Department of Transportation (WDOT) is responsible for plowing the state highway to the Mount Baker Ski Area. On many days, separate snowfall measurements were taken and recorded by snowplow drivers at a site not far from the end of the plowed road.

WDOT snowfall observation times varied daily and thus did not always represent 24-hour totals. This made meaningful comparison to the Ski Area daily totals difficult. Instead, daily snowfall amounts for both the ski area and WDOT were totaled by calendar month for days when both recorded amounts. The results showed WDOT totals to be 10 to 29 percent lower than the Ski Area totals in all six months for which comparisons were made.

Some Committee members expressed concern about the consistently greater amounts at the Ski Area. However, WDOT de-emphasized their measurements and deferred to Ski Area numbers as "an accurate reflection of what actually occurs on the mountain."

Upon consideration and debate, the Committee concluded that the uncertainties in the potentially corroborative WDOT snowfall values were sufficiently large to reduce their influence in the evaluation.

Comparisons were sought with climatologically similar locations. A logical choice was the NWS cooperative station on Mount Rainier at Paradise Ranger Station, at elevation 5,430 feet on the south slope. The Rainier - Paradise station is normally the snowiest in the U.S., with a 30-year (1961-90) average of 682 inches (56.8 feet) of snowfall during a typical July - June season. A comparison of these two 1998-99 monthly and seasonal snowfall totals is presented in Table 1.

During the 1998-99 season, Mount Rainier - Paradise recorded 1,035.0 inches, the second most snowfall recorded there since the station was established in 1920 (on-site values; some days were omitted from forms submitted to NCDC). The maximum snow depth at Paradise was 290 inches on March 30 (record is 327), which was 28 inches less than the Mount Baker Ski Area maximum depth of 318 inches, also reached on March 30, and a record depth for that site. Snow creep had pushed the steel snow stake at Paradise about 20 degrees from vertical by late winter.

An established USDA Snow Survey snow course and Snotel site at Beaver Pass, 25 miles east at 3680 feet, showed the highest May 1 snow water content in its 47 year record, exceeding the 1953-54 record of 57.6 inches by 9 percent (63 inches). A Pearson III frequency analysis puts this at a 100 to 200-year return period. On 1 May 1972, for comparison with Rainier - Paradise, snow water content stood at 50.6 inches at this site, the 4th largest for May 1st.

It should be emphasized that in the Washington Cascades snowfall and snowpack can vary dramatically (many feet) with small changes (200-300 feet) in the vertical and with minor changes (a few degrees) in topographic orientation and in flow patterns. Examples were observed first-hand during the site visit.

Table 1. Comparison of 1998-99 Monthly and Seasonal Snowfall Totals for Mount Baker Ski Area and Mount Rainier - Paradise NWS cooperative station as reported by the observers. Units = inches.

Month	Mt. Baker	Mr. Rainier
July	Unknown	0.0
August	Unknown	0.0
September	Unknown	0.0
October	Unknown	23.5
November	178.0	144.3
December	225.0	205.2
January	182.5	175.8
February	303.0	237.2
March	194.0	138.0
April	24.5	47.5
May	30.0	57.5
June	3.0	6.0
Seasonal Totals	1,740.0	1035.0

6. Physical Evidence

To assist with the evaluation, the Committee visited and photographed the observing site (8 June 1999) and interviewed observers. On that day, the depth of snow on the level ground was observed to be 19.5 feet (234 inches). Ten days later (18 June), WDOT reported that the road at Galena (close to the Ski Area) was still closed due to high avalanche danger. This was the latest date in memory that this road had stayed closed.

Severe damage was noted to trees in the forest adjacent to the highway as it ascended above 3,000 feet. Interviews with several ski area personnel with up to 30 years experience in the area clearly indicated that the number and age of trees snapped by either avalanches or snow creep (slow downhill movement of the heavy snow pack) was unprecedented. According to WDOT, 120 year-old trees were observed snapped off in the woods near the road about 3 miles from the ski area. Investigation of nearby avalanche chutes also revealed that 75 year-old trees had been destroyed by unusual snow slides (Fig. 3).

7. Comparison of Snowfall Totals to Historical Data

The Cascades have long been noted for heavy snow (Phillips 1972). Intermittent snowfall data exists for Mount Baker (Heather Meadows) from about 1927 to 1950, but there are a number of years of complete seasonal snowfall reports. The present Mount Rainier - Paradise NWS coop station began operation in 1920.

Eleven years of overlapping seasonal snowfall records between Mount Baker (Heather Meadows) and Rainier-Paradise were compared (1927-28 through 1934-35 and 1936-37 through 1938-39; Table 2). This interval is well known in the region for extended drought conditions, evident in the very low snowfall at both sites, and formed the basis for sizing many reservoirs.

Evaluation of the 11 overlapping years indicates the Mount Rainier - Paradise station is normally the snowier of the two, averaging 40 inches (8 percent) more that Mount Baker. However, in three of the eleven snow seasons, Mount Baker totals exceeded Mount Rainier - Paradise totals, and in one of those seasons (1928-29),

Fig. 3. Photograph of tree damage at Mount Baker.

Mount Baker exceeded Mount Rainier by 96 inches (24 percent).

The historical data show that the 4,200 foot Mount Baker station can readily receive heavier seasonal snowfall than the normally snowier and higher (by 1,200 feet) Rainier - Paradise to the south. The 1,140 inch total reported for 1998-99 at Mount Baker Ski Area was 105 inches (10 percent) greater than Rainier - Paradise, well within the historical relationship.

8. Committee Findings and Recommendation

The evaluation of the Mount Baker Ski Area snowfall measurements revealed strengths and weaknesses of the observation methodology and related evidence. The supportive evidence follows:

Table 2. Snowfall comparisons, overlapping snowfall seasons, Heather Meadows (Mount Baker) and Paradise (Mount Rainier) coop stations. Units: Inches.

Season	Heather Meadows (Baker)	Paradise (Mt. Rainier)	(Baker minus Rainier)	Ratio (Baker/ Rainier)
1927-28	501.5	405.9	95.6	1.24
1928-29	490.0	554.2	-64.2	0.88
1929-30	354.5	390.0	-35.5	0.91
1930-31	484.5	443.9	40.6	1.09
1931-32	512.4	751.0	-238.6	0.68
1932-33	591.6	624.0	-32.4	0.95
1933-34	295.3	316.5	-21.2	0.93
1934-35	535.5	543.0	-7.5	0.99
1935-36	Missing	Missing	Missing	Missing
1936-37	557.7	693.5	-135.8	0.80
1937-38	580.8	541.3	39.5	1.07
1938-39	489.5	573.5	-84.0	0.85
Average (11 yrs)	490.3	530.6	-40.3	0.92

The snowfall measurement methodology was found to meet measurement guidelines.

- Observations were taken daily at the same time (within 15 minutes of 0500 local time) - consistent with Federal standards and NWS observing handbooks, (i.e., FMH-1, U.S. Dept. of Commerce 1995; WSOH No. 2, U.S. Dept. of Commerce 1989; and WSOH No. 7, U.S. Dept. of Commerce 1996).
- Only one snowfall observation was taken daily (conservative - four allowed, no more frequent than one per six hours; 1,140 inch total could have easily been exceeded). Surface brushed clean of past snowfall each observation.
- When drifted, accepted practice followed of averaging a variety of sample depths.
- Observation locations considered acceptable and representative (snowfall and snow depth).
- No obstructions present at observation site to bias measurements.
- Snowboard used when appropriate.
- Record keeping (documentation) of daily snowfall data was found to be satisfactory.
- Observational data provided in a timely fashion by Ski Area staff.
- Observers were knowledgeable in their observations of snow (primary snowfall observers had 10 to 33 years experience with average of 22 years).
- October snowfall did occur, but not considered by Ski Area staff or Committee in the 1,140-inch seasonal total. Estimates by Mount Baker personnel (when present) suggest that another 10 inches may have fallen in October. WRCC statistical analysis strongly suggests an October total closer to 20-30 inches.
- Damage to ski area infrastructure and nearby forests (by avalanches and snowcreep) was unprecedented in the Ski Area.
- WDOT and others confirmed the 318-inch maximum snow depth (30 March 1999), same day as maximum depth at Mount Rainier (290 inches).
- USDA Snow Course and Snotel sites nearby recorded snow water equivalents with 100-200 year return values.
- For first time in 33-year history, the Mount Baker Ski Area was closed (23-24 February) for too much snow. Chair lifts and plow parking areas had to be dug out from record-setting snow accumulations.

Areas of concern:

- Many ski areas have low credibility for accurate measurements since economic self-interest is served by reporting favorable snow conditions.
- Significant differences (10-30 percent) in snowfall amounts reported between Mount Baker Ski Area and WDOT personnel. Explanation from plow operator reduces emphasis on these observations.

Although committee members harbored some reservations regarding the measurement process, in the end the preponderance of the physical evidence and record-keeping supported their conclusion that the measurements met NWS snowfall observation standards and practices, and were thus considered to be an accurate depiction of the snowfall amounts that fell. The Committee voted unanimously to recommend that the Director of NCDC accept the measurements as official.

9. NOAA Decision

On 2 August 1999, citing a unanimous recommendation from the six-person National Climate Extremes Committee, the Director of NCDC accepted the Mount Baker (1998-1999) seasonal snowfall total of 1,140 inches, making it the new official national record for the most snowfall ever measured in the U.S. in a single 1 July through 30 June snowfall season. As it happens, this figure also stands as a world record.

A press release on the decision was disseminated by the NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) on 2 August 1999.

Authors

Robert J. Leffler chaired the National Climate Extremes Committee for this project. He is a physical scientist in the Climate Services Division of the NWS Office of Climate, Water and Weather Services. Mr. Leffler also chaired the committee that evaluated "The Reported 11-12 January 1997 Montague, New York, 77-inch, 24-hour Lake-Effect Snowfall." He authored the *NWS Snow Measurement Guidelines* for cooperative observers.

Michael J. Changery, recently retired from NOAA, was the NCDC representative and Chair of the National Climate Extremes Committee. He received B.S. and M.S. degrees in Meteorology from Pennsylvania State University. During his career at NCDC, he was primarily involved in climate applications for NASA, Nuclear Regulatory Commission, National Institute for Science and Technology, Department of Energy and the DOD. During his final two years of government service, he managed the Climate Monitoring Branch at NCDC which provided assessments of global and U.S. climate and extreme events.

Kelly Redmond grew up in southwest Montana, received a Physics degree from the Massachusetts Institute of Technology, and graduate degrees in Meteorology from the University of Wisconsin in Madison. He has served as Oregon State Climatologist and for the past 12 years has been Regional Climatologist and Deputy Director of the Western Regional Climate Center at the Desert Research Institute in Reno, Nevada.

Raymond Downs works in the NWS Office of Climate, Water, and Weather Services, Observing Services Division and is responsible for updating Weather Service Handbooks Numbers 7 and 8, and Federal Meteorological Handbook Number 1. Since 1987, Mr. Downs has been the focal point for Micro Computer Aided Paperless Surface Observation (MAPSO).

George Taylor is the State Climatologist for Oregon, and a faculty member at Oregon State University's College of Oceanic and Atmospheric Sciences. He manages the Oregon Climate Service, the state repository of weather and climate information, and supervises a staff of seven. Recently, he published two books: *The Oregon Weather Book* and *The Climate of Oregon*. He served as President of the American Association of State Climatologists during this evaluation. He has been certified by the American Meteorological Society as a Certified Consulting Meteorologist. George received a B.A. in Mathematics from the University of California at Santa Barbara and an M.S. in Meteorology from the University of Utah. He has been active in private and public sector meteorology since 1971.

Andrew Horvitz is the National Cooperative Observer Program Manager for the NWS in the Office of Climate, Water, and Weather Services, Observing Services Division. Mr. Horvitz is a NWS representative of the National Climate Extremes Committee. Mr. Horvitz is also chair of the NWA Awards Committee.

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