EVOLUTION, CHALLENGES AND MANAGEMENT OF MOUNTAIN WEATHER OBSERVATIONS

Mark Moore[1]
Northwest Weather and Avalanche Center, Seattle, WA

ABSTRACT: Mountain weather observation programs in support of avalanche mitigation efforts and forecasting programs have evolved considerably since their humble beginnings over 50 years ago, and they have experienced quantum leaps in equipment as well as data access, reliability and availability during the last 10 years. From periodically recorded manual observations to continuous analog charts to real time digital formats accessible most anywhere at any time, this progression of both quantity and quality of high elevation weather data has been remarkable, spanning a wide spectrum of both observing programs and technology. Although manual observations are still an integral element of most avalanche programs, for the most part this discussion focuses on remote automated high elevation weather stations (RAHEWS). Despite advances in *RAHEWS* infrastructure and sensors, and an even greater evolution in data loggers and communication systems, significant obstacles remain that may limit the usefulness and availability of resulting information. The potential for measurement errors mandates that users exercise caution and common sense in utilizing and applying data. Possible problems also require that any manager of mountain weather data—from those responsible for single weather stations to those overseeing large data networks—expend considerable time and commitment to ensure that data outages are kept to a minimum, output remains at a high caliber, and quality control, sustainability, maintenance, and archiving are ongoing and high priorities. In this paper, recent evolution of mountain weather observations is described, along with the challenges of accurately and continuously measuring the parameters that can render even the most robust station useless at times. As such data has become increasingly important for an expanding set of weather forecasting, climate modeling/research and other concerns, associated data management considerations are also outlined.

Keywords: mountain weather, data, weather observations, avalanche weather, weather sensors, data management

[1] Corresponding author address: Mark Moore, Northwest Weather and Avalanche Center, 7600 Sandpoint Way NE, Seattle, WA 98115-6349; voice: 206-526-6164; fax: 206-526-6094; email: mark.moore@noaa.gov

1. INTRODUCTION

During the past 40-50 years, a gradual but recently accelerating transition has occurred that has seen manual mountain weather observations augmented and in some cases largely replaced by automated measurement solutions. However, installing, operating and managing an automated hourly high elevation weather station to provide consistent, real-time, high quality temperature, wind and precipitation or other data for ski area, highway or other avalanche and weather operations can be a daunting task, especially since substantial commitment and continuing sources of funding are normally required for the stations and resulting data to be continually useful and accurate. Furthermore, the evolution of station infrastructure, sensors, communications and resultant data expectations over the recent past has necessitated that greater and greater amounts of money be available for installing and maintaining such data sites, as well as making their output available in real-time.

Obtaining initial capital equipment funding for such a station is often the easiest part of the Automated High Elevation Weather Station (AHEWS) process to justify; program managers and administrators often like short-term operational solutions, but may dislike long term funding commitments. However, long term expenditures for items such as maintenance, quality control, archiving, access and metadata summaries are critical and must be considered and agreed upon before any significant effort or investment is expended for initial site construction and installation. Significant research, preliminary siting studies, and environmental or other approvals are often required and should be part of the selection process when deciding on optimal site location(s). Power and/or communication requirements may have major impacts on actual site location, and combined with visual, aesthetic or other concerns, optimal station location is often a compromise between meteorological and operational considerations. Significant thought should also be given as to why the site is needed, how representative the station will be, what parameters are best measured at which location, and for what locations is the data going to be representative of? Good station siting for representative wind data is normally not the most suitable for quality precipitation data and vice versa. While collaboration between user groups or agencies desirous of obtaining weather data at similar locations may limit station cost for any one group, differing data goals, conflicting sampling frequencies or rates, incompatible sensors, loggers etc may make such cooperation difficult and perhaps more expensive overall.

Data station managers need to consider the cost of ensuring quality data—for once data leaves the station (and becomes an archived file or used elsewhere), normally only bad things happen to it. This makes it doubly important to make the original data measured as accurate as possible. In most instances, quality AHEWS data is used and useful for far more than the original purpose or motivation behind the installation.

2. EVOLUTION

In addition to the many parameters involved in choosing the proper and most appropriate location for mountain weather stations (see challenges below), major components of high elevation weather stations include:

- infrastructure (towers, power, lightning protection, grounding, mounts)
- sensors
- data loggers
- communication
- data storage and archiving

While significant improvements in all of these AHEWS components have occurred in the recent past (see the timeline table of changes below), in some cases reliable and robust sensor development has not advanced nearly as fast as the associated data telemetry/communication and data storage/display technology that is used to sample, store and disseminate such data. From pencil and paper to analog charts to real-time digital data display, the process of acquiring, transmitting, storing and displaying data has greatly outpaced actual sensor development, or at least surged well ahead of the development and availability of sensors that will reliably operate and sample desired parameters in remote mountain locations (with or without AC power) at a reasonable cost.

From the classic "*leadolithic period*" of the 1950's into the early 1970's (where pencils and paper dominated the AHEWS scene in most avalanche safety operations), through the "*chartolassic era*" of the mid-late 1970's through the 1980's (in which all manner of hand drawn or analog produced storm and parameter charts were found on every available wall space), and finally into the "*microlern epoch*" of the 1990's into the present (where Microsoft, micro-computers and micro dataloggers have come to dominate the landscape of avalanche control operations), this data/sensor discrepancy has become more and more apparent. As Table 1 illustrates, it is now possible to easily output and pipe into most any office or home minute-by-minute averages, maximums, minimums, and any conceivable statistical permutation of current and past mountain weather data, as well as some sophisticated video output that graphically or visually depicts ambient weather conditions. However, all too often a broken or malfunctioning sensor may have already rendered (or will soon render) all of the pretty and automatically generated displays and graphs almost meaningless. Thus it is now entirely possible to output a lot of nothing—endless data arrays that totally misrepresent the real world—and this is a situation that we all want to avoid.

Time Period	Approximate years	Primary data gathering and dissemination methods	Typical sensors
Leadolithic	1950's to early 1970's	Window, Manual observations, Pencil and notebooks, Phone and Radio	Snow stake, cup anemometer and vane, glass thermometer, weighing bucket precipitation gages
Chartolassic	Mid-late 1970's and 1980's	Strip charts & graphs, storm plots, early data loggers, land lines or RF, Phone and phone recordings, Radio & Television	Storm, interval, shoot, 24-hr and total snow stakes, early acoustic depth gages, thermistors, heated wind sensors, early RH sensors, propane and electric heated precipitation gages (various types—cumulative, tipping bucket)
Microlern	1990's through present	Data loggers, RF, satellite, meteorburst, cel phone, Computers, Internet, Email, Television, PDA's, Cel phone displays	Snow stakes & improved automated snow depth sensors, better thermistors, improved heated precipitation gages of various types (cumulative, tipping bucket, differential heating), precipitation identifiers (rain, snow, etc), improved heated and unheated wind sensors (pitot tube, ultrasonic, etc), RH sensors, improved video cameras, addressable sensors (SDI-12)

Table 1. Evolution of mountain weather observations

However, such periodic outages, errors or potential lack of data may be both a blessing and a curse. Such a situation is a curse in that so much depends on the data being readily available at any time of any day, and a blessing in that the very real possibility of not having such data should force field practitioners to continually observe and re-examine the snowpack and weather manually. Subsequent correlation and comparison of AHEWS data with manual observations should help make certain that the automated display remains representative, reliable and meaningful. While many AHWES are intended as replacements for manual observation programs, they are most effective when used to augment rather than replace such human sampling.

3. CHALLENGES

Harsh high elevation mountain weather environments—whether on exposed ridgeline locations or more protected valley sites—offer a host of challenges to be considered during all phases of AHEWS deployment. From planning to installation to maintenance of existing stations, ensuring high quality data output comes only with dedication, constant monitoring, frequent on-site inspection and/or repair, and more often than not entails considerable expense. Station maintenance commonly encompasses all of the problems associated with sites at lower elevations (e.g., difficulties with sensors, towers, animals, people, weather, power (is it available or not?), and communications) plus an expanded set of concerns. Typical higher elevation weather station troubles also include destruction or damage by natural (wind, snow load, creep, riming, lightning, freeze and thaw cycles, dirt and needle accumulations, etc) as well as human, power, animal or insect impacts (vandalism, thievery, construction or other equipment, gunshots, general mischief, power surges, brownouts or outages, bear, moose and other animal damage, rodent chewing, insect and bird nests and/or debris, etc).

While quality equipment is needed to combat the brutal effects of higher elevation weather and this equipment is often expensive, expensive doesn't necessarily equate to good. For reliable weather stations, the appropriate axiom is always "the right equipment in the right place". While you normally get what you pay for, you rarely if ever get more than you pay for. But spending a little more can and usually does help ensure higher quality. If money is a major issue (when isn't it?), and corners are cut at the outset, then ultimately more expenses will be forthcoming for repair, replacement and staff time to keep those initially cheaper components working.

Although this paper is not intended as a review of weather sensing equipment it is helpful to briefly summarize the evolution of key components of AHEWS alluded to in Table 1, and thereby increase awareness of some of the current measurement options. Some of the changes in equipment and data techniques are shown in Table 2 below.

Table 2. Changes in specific mountain weather parameters--then and now

Parameter	Then	Now
Precipitation	Weighing bucket gage	• Heated tipping bucket • Differential plate heater • Automated cumulative gage
Wind direction	Split tail vane	• Heated vane • Ultrasonic sensor • Thrust sensor
Wind speed	Cup anemometer	• Heated rotors • Ultrasonic sensor • Pitot tube • Thrust sensor
Temperature	Mercury in-glass thermometer	• Shielded thermistor • Thermistor arrays
Snow Depth	Manual snow stake	• Acoustic depth gage
Data Storage	Notebooks, charts and chart paper, graphs	• Data loggers • Office or home-based computers & laptops • PDAs
Data Communication	Manual, phone, radio	• Phone line telemetry • VHF/UHF or spread spectrum radio • Meteor burst telemetry • Satellite telemetry • Cel phone telemetry
Data Dissemination	Phone, radio	• Phone recorders • Radio and radio broadcast • WWW / Internet • Television

Planning for associated repair or replacement of damaged or malfunctioning sensors or infrastructure is critical and often makes the difference between reliable and unreliable stations. In any given time period, sensors, communication and data equipment and infrastructure that comprise weather stations are often assigned average life-spans, which form the bases for projecting annual capital equipment budgets necessary to sustain such stations. Although such average MTBF (mean time before failure) or life-of-equipment estimates are exactly that—broad guesses—normal life spans of 8-10 years on the outside or 5-7 years on the inside are reasonable for most components. These life spans in turn yield annual replacement projections of 10-15% (low) to 15-20% (high) of the overall value of all investments in the station. With typical initial capital equipment costs of $10-15,000 per weather station (slightly more for RF, satellite or cel-phone accessed stations), this translates into $1-3,000/year in maintenance costs per station. If you're managing several stations that sample the atmosphere at differing elevations in support of lift operations, avalanche control programs, etc, then that maintenance amount quickly becomes a deep and black hole drain that can significantly impact or eliminate many data sampling efforts.

The initial relatively large dollar outlay necessary for installation of a weather station combined with the estimated costs for maintaining such stations means that not everyone who wishes to will be able to deploy high quality AHEWS. Certainly an AHEWS installation is not THE answer and is not appropriate for everyone. Unfortunately for many in the avalanche community—who are known as a group of "independent thinkers"—building cheap is sometimes a challenge. Overheard conversations might unfold like this: "Wow, that system certainly costs a lot, but if we do this and attach this "*fnoitner*" here and weld that old chassis there, and then bend that old chair clip to hold the sensor, it just might work!" But what is left unsaid is consideration of maintenance of this contraption, and the time and effort to do so safely, and pretty soon, cheap isn't! And for the "do-it-yourself" welders—it's either artwork or it's weather equipment. It's rarely effective as both.

Since greater effort and better components at the outset of station development can increase the lifespan of stations considerably, applying the primary station attributes of Quality, Cost Effectiveness, Reliability and Proper Location will pay big dividends over the long run. Just like when we apply the avalanche or snow stability triangle in avalanche safety education, AHEWS managers must consider the effects of snowpack, weather and terrain on the weather station and its equipment. And all of these impacts and potential problems can be critical since they directly affect data quality. In order to ensure optimal data, managers have to anticipate the effects of weather, terrain, and the snowpack on station infrastructure, sensors, communication and power before installation gets underway.

For infrastructure concerns, safety issues and ease of access for replacement and/or repair must rank high in station maintenance priority lists. AC voltages of 120, 240 or 480 are not to be dealt with lightly and proper grounding and quality cables are a must. On the other hand, poorly constructed or badly guyed towers have resulted in significant injuries and there are many instances in which guy wires are not recommended as snow settlement pressures can easily snap cables or bend guyed towers. Even with well constructed instrument towers, safe climbing practices are mandatory and maintenance and installation efforts should include appropriate training, use of climbing harnesses and multiple belay points and not working alone,. Necessary labor should be planned well in advance and accomplished when weather permits. It should NOT be a titanic struggle against the elements due to poor scheduling or time running out in the fall; ultimately weather will win the majority of such battles. In short, there are a large number of challenges that require coordination of time and effort to achieve a successful installation and it is helpful to summarize some of these considerations. Some typical infrastructure challenges include:

- INFRASTRUCTURE CONCERNS—Towers, mounting brackets, guy wires etc
  - location, siting, environmental concerns
  - logistics of installation and maintenance
  - base installation (size, depth, mass of tower base)
  - type of tower (strong with safe access in all conditions)
  - snow pack settlement pressure (may crush or damage guy wires or struts or towers attached to same)
  - total snow depth (install sensors above max. depth)

- creep and glide of snowcover (can easily buckle or tilt towers, rip improperly buried cables)
- tower and mounting bracket strength & cross section (wind speeds and riming)
- lightning protection, grounding

Once the tower, power and other infrastructure is assured and safe, maintenance and installation challenges turn toward sensor and data concerns:

- SENSOR and DATA CONCERNS—
  - Durability & weather/snow effects
    - sensor thresholds, sensitivity, resolution
    - sampling & averaging method and interval [one size ≠ fit all]
    - riming & icing
    - snow load, snow depth, wind, angle of attack (can be significant!)
  - Location
    - desired data output (multiple needs or multi-use?)—
      - ridge top vs. valley etc—different sets of problems
      - fire vs. avalanche vs. flood vs. pollution vs. ?? weather (aviation, agricultural, etc)
    - protection from human effects
    - environmental, esthetic or other restrictions may result in location compromises
  - Damage
    - vandalism (also malicious mischief—"let's fill up this precipitation gage with lots of water")
    - Adverse effects of hunters, hikers, climbers, skiers, snowmobilers, etc
    - thievery (those coveting batteries, solar panels, etc)
    - animals (unhappy bears or moose, teeth wielding rodents with a hankering for salty cables, woodpeckers or thrushes that prefer metal over trees, etc)
    - insects and insect/bird nests/droppings (seal well all enclosure openings, inspect often)
    - natural weather effects (lightning, rime, snow loading, wind and rime, floods, cold)
    - loose connections at sensor or datalogger, wire kinks, breaks in cable

4. MANAGEMENT

The many considerations and challenges mentioned above are just the tip of the iceberg for effective and useful long term management and longevity of automated high elevation weather stations (AHEWS). Remember that no matter what the original intention is for installing a high elevation weather station (HEWS), it will undoubtedly be utilized for many more purposes than could ever be imagined (Table 3).

Table 3. Potential Uses of AHEWS Data

User	Potential Usage of AHEWS Data
Recreational	Weather conditions for planning and assessing a wide variety of outdoor activities including hiking, climbing, skiing, snowboarding, snowshoeing, etc
Recreational and Safety	Inferring/reconstructing snowpack structure and snow stability conditions
Search and Rescue	High elevation weather conditions to assist in all aspects of SAR operations
Industry (ski)	Weather information for lift and maintenance operations; data for assessing avalanche danger and planning avalanche control operations; data for snow making operations
Industry (highway and railway)	Weather data for highway and rail maintenance and avalanche control operations
Private, Government and Industry (flight/airline))	Weather conditions for flight planning—primarily small private and/or military training operations
Private (highway traveler) & Industry (trucking)	Weather conditions for highway travel
Governmental (state and federal) and private research	Data for weather and climate modeling efforts, climate change and air quality research; provide statistical info on extreme weather conditions
Governmental and private forecasting	Local, regional, national and global weather forecasting;
Governmental, Industry and private	Weather conditions for planning trail maintenance operations (year round, from summer hiking to winter cross country track setting)

These developing and expanding uses and expectations for the data that the station(s) provides may make it difficult to retire the station(s) when the immediate need(s) for the data has past. While continuing to provide quality data is not an obligation for the automated high elevation data site manager, there is often considerable pressure against discontinuing support of weather stations once such sampling is underway. As the table above indicates there are many compelling and documented needs (both practical and research oriented) for continuous and long-lived high elevation data sources. Hence station management becomes a balancing act between satisfying immediate needs for the data and those more esoteric longer term uses. The following outline summarizes some of the most important parameters to consider when installing and managing automated high elevation weather stations (thanks to Dr. Kelly Redmond, Deputy Director of the Western Region Climate and Data Center (WRCC) for sharing many of these thoughts on data considerations).

- WHY
  - Why are the measurements being made? Are the measurements needed for a short time or long term duration? This will impact the quality of infra-structure, sensors, data loggers, communication, etc.
  - Whether you know it or not, your data may be used by and needed for climatological or forecasting purposes, and certainly for many more purposes than originally intended
  - Therefore (as much as possible) it is very important to ensure initial data quality as well as reliable long term storage of the measurements
- SUSTAINABILITY
  - Procurement and installation are often the easy and inexpensive part
  - Justification for initial acquisition often easier than arguments for maintenance, quality control & calibration, archiving, display and access
  - Once measurements are started, they often become part of a climatological or other data base
  - This increased reliance cuts two ways, making it both harder to stop the observation program and more costly since there is an expanded need for both quality and continuity of the data
- MAINTENANCE
  - Bane of all systematic sensing projects
  - Lack of maintenance often responsible for the death of such projects
  - “Automated” systems are often not, and typically require a good deal of human intervention

- Automation may introduce new types of errors (e.g., offsets, averaging problems, sensor drift, damage, data mix-up)

- CLIMATE VARIABILITY
  - AHEWS data is often integrated into climatic sampling programs
  - Hence systems need to record REAL climate variability……NOT FAKE variability
  - Fake climate changes might include
    - Sensor changes (e.g., replacements, upgrades, degradations, animal or insect pollution, etc)
    - Site changes (e.g., vegetation growth, ground cover modifications)
    - Observation method changes (sampling rates, averaging intervals, etc)
  - Weather record variations should be due to real atmospheric changes— NOT to sensor problems or variations
  - Station changes need to be noted in up to date metadata files (see below)
- REPRESENTATIVENESS AND SITING
  - For what locations is the AHEWS site supposed to represent (valley, pass, ridge top etc?)
  - Often practical (power, land use, existing infrastructure, communication requirements) and scientific (best, most representative, etc) considerations may be at odds and lead to compromise locations
- SENSOR QUALITY & ROBUSTNESS
  - Are the proposed or existing sensors and infrastructure adequate for the job? Will precipitation be melted or measured reliably and accurately? Will sensors be de-rimed as necessary?
  - Design for the most extreme conditions—sensors and the system need to effectively and reliably sample the worst weather conditions; often these are the most important ones to sample and record
- DATA ACCESS, STORAGE & DISSEMINATION
  - How and when will the data be accessed? How often?
  - For most operational purposes, two way communication with the station is critical—this allows for remote troubleshooting and much more effective maintenance efforts
  - How will the data be stored? How easily displayed and retrieved?
  - How easily accessed for research, forecasting or other purposes?
  - Display, access and dissemination of data may add more cost to the program
- QUALITY CONTROL (QC)
  - Quality control begins at the station—once data leaves the station essentially only bad things can happen to it
  - Best form of QC is to not let bad data leave the station—good in theory but hard to put into practice
  - Are back up systems and sensors readily available? Normally this shows long term commitment and is an integral part of maintenance programs.
- DOCUMENTATION / METADATA
  - Need a history of all factors that affect the accuracy and/or interpretation of the measurements (metadata). These factors or metadata should include:
    - Sensor history
    - History of physical surroundings of the site
    - Observing practices and reporting conventions
    - Numerical pre-processing, error corrections, averaging or sampling intervals
    - Accurate site location including elevation,

exposure, GPS positions
- Full photographic sets, repeated periodically (every 1-2 years). Photos should show 360 degree view, skylines and foreground, any other pertinent local influences, and any changes through time

5. CONCLUSIONS

Accurate, reliable and representative high elevation weather station data is a highly useful and much sought after commodity by both commercial and recreational interests. Although many advances have occurred in sensor technology during the past 50 years with even more substantial improvements in data logging, display and dissemination techniques, proper installation and maintenance of AHEWS requires dedication and remains a potentially costly and certainly a long term commitment. While such data may initially only be envisioned as locally applicable and desirable, availability and usefulness of the data often quickly expands to a broader audience and into much greater dimensions than originally intended. Managers must be aware of this increased data reliance as well-intentioned but unrealistic expectations on weather station maintenance and quality control efforts may result.