# WHERE HAS ALL THE SNOW GONE? SNOWPACK SUBLIMATION IN NORTHERN ARIZONA[1]

Charles C. Avery, Leland R. Dexter, Robert R. Wier,
William G. Delinger, Aregai Tecle[2] and Robert J. Becker[3]

## Abstract

Climatic data for twenty-one winters was used to construct an index to assess the significance of evapo-sublimation at Flagstaff, Arizona. Large intra- and inter-annual variability was noted in the record using this "sublimation opportunity index" as well as a similar one based on ("corrected for") the presence of a snowcover.

An instrument to record evapo-sublimation has been developed and preliminary data is presented which compares values from this "sublimimeter" to the index values for periods in 1990-91 and 1991-92. While the index is not a predictive model, relatively good ($r^2 = 0.62$, cross-correlation coefficient = 0.89, cross association value = 79%) agreement is found between the index values and the observed values.

It appears that at least 22% and as much as 70% of the snowpack at this high elevation site may be lost to sublimation and, therefore, that the date of snowpack accumulation is critical to the runoff efficiency of high elevation snowpacks.

## Introduction and Background

The disappearance of a snow cover from the landscape is due to either melting alone or to the combination of evapo-sublimation and the melting of the snowpack. Thus snow ablation processes should be included in snow enhancement schemes as well as in snow management considerations. Figure 1 illustrates some of the pathways by which snow can evapo-sublimate. It also underscores the reality that not all the snowpack water always enters the soil as meltwater.

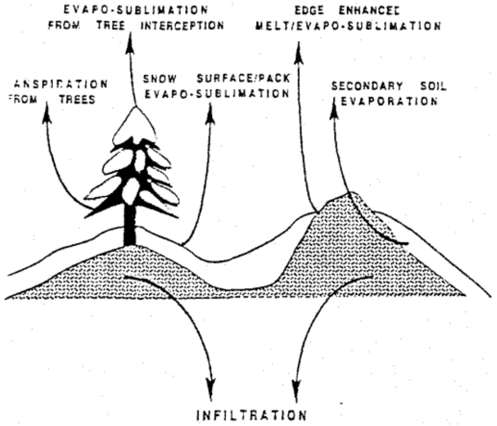

Figure 1. Pathways for Snow Ablation

However, evapo-sublimation is given only a slight treatment outside of definitional considerations in the primary literature. For instance, Dunne & Leopold (1982) refer to evaporation from snow as being energy-limited and state "only under conditions of bright sunshine, warm air temperatures, and strong winds does evaporation from snow become significant." The classic U.S. Army Corps of Engineers report (1956) on snow hydrology suggests the equation

$$E_s=0.0231\ z_o^{-0.33}u_a(e_s-e_a)$$

where $E_s$=cm day$^{-1}$, $z_o$=m above snow for wind ($u_a$) and vapor pressure ($e_a$=mb) measurements, $u_a$=km day-1. Radiant energy considerations as well as direct input of advected heat energy are missing from this formula. Not the least of the difficulties in resolving the issue of its

---

[1] Presented at the 60th Western Snow Conference, Jackson Hole, Wyoming.

[2] Northern Arizona University, Flagstaff, Arizona.

[3] The Navajo Nation, Window Rock, Arizona,

"Reprinted from Proceedings of the Western Snow Conference, 1992"

importance is the difficulty related to separating sublimation losses from other abstractions and uncertainties. Between 1960-1980 several significant papers called for definitive measurements of evapo-sublimation in order to assess its significance to (total) ablation. In addition, since the reliability of most snowmelt forecasts would be increased if evapo-sublimation losses could be tracked, many years ago the direct measurement of factors assumed responsible for evapo-sublimation was proposed [Peak, 1969]. To date no methodology for determining total seasonal sublimation loss has been forthcoming.

Sublimation is defined as the conversion of a solid substance into its gaseous state. For many substances the vapor pressure of the solid material is extremely small; for others, like water and carbon dioxide, there is an appreciable vapor pressure under ambient conditions so, under those conditions, the solid phase can be converted to the gaseous phase of the material in a relatively short time. The often-cited "triple-pint" expresses that place on the temperature-vapor pressure curve where all three phases can co-exist: for water that point is found at 4.6 millimeters (Hg) pressure and at 0.01 degrees (°C) temperature. The process of evapo-sublimation (i.e., the conversion of a solid to its vapor phase either directly or through the liquid phase) also requires that the latent energy needed both for vaporization and for melting be supplied to the surface. As there is considerable uncertainty regarding the partitioning of the energy balance into the fractions for latent energy and for sensible energy, it remains unclear whether a sufficiently steep vapor pressure gradient and/or sufficient net radiation is the driving force for evapo-sublimation. Assuming the surface of the snow to be at 0°C, no vapor pressure deficit would occur were the actual vapor pressure greater than 6.11 mb.

### Comparative Studies

A review of published sublimation literature underscores the reason that rather limited importance that has been given to this process, mainly its wide reported variability. Data from eight sites which could be reduced to a sublimation rate was arranged by latitude, continentality and elevation, as shown in Table 1.

Table 1
Comparison of Geographic Studies, by Author

| LATITUDE | CONTINENTALITY | ELEVATION | mm/DAY | mm/MO | AUTHOR |
|---|---|---|---|---|---|
| 65 | 0 | 100 | 0.45 | 13.95 | Bengtsson |
| 40 | 1425 | 2750 | 1 | 31 | Bergen & Swanson |
| 52 | 780 | 2000 | 1.6 | 49.6 | Golding |
| 40 | 1425 | 2750 | 0.8 | 24.8 | Hutchison |
| 47 | 650 | 3030 | 1.13 | 35.03 | Kaser |
| 41 | 1500 | 2750 | 2.7 | 83.7 | Meiman & Grant |
| 41 | 1500 | 2750 | 2.4 | 74.4 | Meiman & Grant |
| 39.5 | 275 | 2134 | 0.15 | 4.65 | West |

and the multiple regression that best fits this series has the form

$$\text{MM/DAY} = -3.80292966 + 0.06673232 * \text{Lat} + 0.00129282 * \text{Cont} + 0.00035565 * \text{Elev}$$

and it does so with an unadjusted $r^2$ of .58. It should be noted that reported sublimation rates were found to increase as the investigation took place at increasingly inland sites, increasingly higher sites and, somewhat, at increasingly more northerly sites.

### Literature Review

Only a few studies have focused on the effect of sublimation on snow runoff. George Peak (1969) was one of the first workers to try to identify factors empirically which influenced sublimation and he identified temperature, wind speed, radiation, and humidity. He later compiled and distributed a report entitled "Ice Ablation Formulae."

Since Peak's work, other scientists have attempted to determine the range of factors affecting sublimation. Schmidt (1991), who focused his attention on sublimation from snow intercepted by tree canopies, lists humidity, temperature, wind speed, radiation, height of the canopy and leaf area as pertinent.

**Implications**

Snowpack enhancement predictions often cite a range of possibilities as justification for the investment needed. However, it must be noted, these values do not translate directly into spring runoff. And while it is true that continuously-updated snowpack runoff predictions are used in forecasting reservoir inflows, these equations reflect past and not current sublimation effects. But by far the major ramification of sublimation—and its wide variability—is found when a physical basis for the effects of land management practices on snowpack accumulation is sought. Sublimation, in the vernacular of an old-time snow surveyor, is a "thief," and one not easily recognized at that!

## An Index of Sublimation Opportunity

### Methods

The objective of this work was to assess the variability and significance of evapo-sublimation to snowpack ablation in northern Arizona. The approach we took for this assessment was to develop a "Sublimation Opportunity Index" based on available archived climatic data for Flagstaff, Arizona, and primarily built on bulk aerodynamic considerations. Although indices are imprecise aggregations of assumed factors, their utility is not without recognizable value and wide acceptance (i.e., The Palmer Drought Severity Index) because the rational construction of an index may lead to clarifying some otherwise obscure relationships. We determined to construct an evapo-sublimation algorithm based on the four factors which we could reasonably derive from National Weather Service three-hourly observations for the period 1965-1986. These factors are 1) vapor pressure gradient, 2) wind run, 3) incoming radiation and 4) air temperature.

We were required—due to an absence of certain parameters to approximate several of the components needed to formulate or approximate the above-noted factors [namely, snow depth, snow surface temperature and net radiant energy values].

Four of the factors identified by Schmidt (1991) were used by this research effort. We transformed relative humidity into a vapor pressure gradient term, (making several assumptions about snowpack conditions), and we included other climatic factors that influence sublimation and which are conventionally available. Our index accounts for advected energy (as wind and temperature) and incoming short wave radiation (as attenuated potential radiation) (Avery and Dexter 1991). The archived 3-hour parameters used are: (1) air temperature, (2) relative humidity, (3) wind speed, and (4) opaque cloud cover. "Snow-on-the-ground at 5 am" was also obtained from the published record. With this data and with calculated potential radiation values for specific dates at Flagstaff's latitude, we built a Sublimation Opportunity index, using a simplified Goff-Gratch equation (see Linsley, Kohler & Paulhus, 1982 and List, 1958) to calculate vapor pressure assuming a 200 centimeter difference between the snow surface and the measurement height. (The snow surface temperature was also assumed to be -5°C if the air temperature was below freezing; otherwise it was assumed to be at 0°C). The Index is based on the presence of at least 2 inches of snow at 5 a.m. (if that amount of snow was present at 5 a.m., evapo-sublimation was assumed to be possible throughout the entire 24 hour period).

From the data available to us, we constructed a data index value for the 21-year record. The index values were summed over each day in each of the eight winter months (October-May) for the year of interest. Figure 2 illustrates this procedure and the scaling factors used to weight the values.

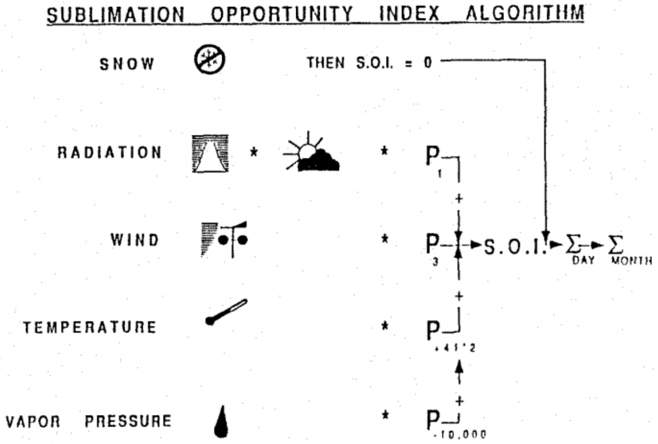

Figure 2. Schematic for SOI Formulation

The original intent was to scale each of the factors in the index to relatively the same value.

## Results and Discussion

From the 21-year data set we developed two indices: the first is the basic SOI while the second is an index value adjusted ("corrected") for the sublimation which occurred when snow was present. The results of the basic SOI are indicated by Figure 3. See Appendix A for SOI Formulation.

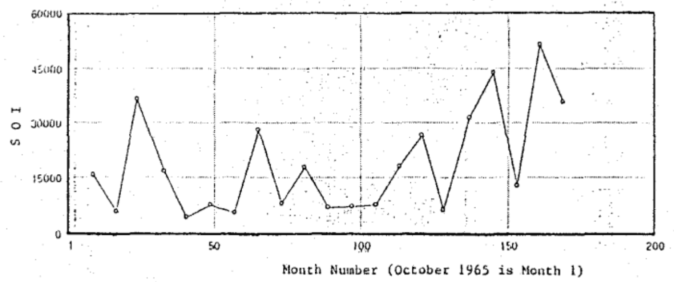

Figure 3. Basic SOI, October 1965 to May 1986

The between-year variability illustrated by Figure 3 is further expanded by Figure 4 and Figure 5 which demonstrate the intra-year variability by months as a function of the percentage of each month with snow. The years chosen for these figures were years with exceptional snowfall and little runoff (1967-68) and low snowfall but average runoff (1984-85). Note that Figure 4 uses the basic SOI values, while Figure 5 uses "corrected" SOI values.

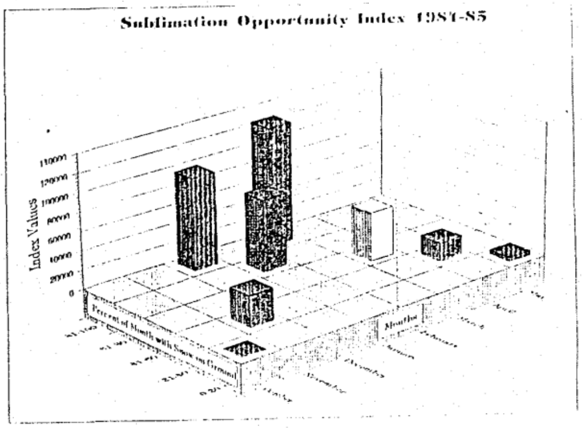

Figure 4. Basic SOI for 1967-68, by months and by percentage of days with snow in each month.

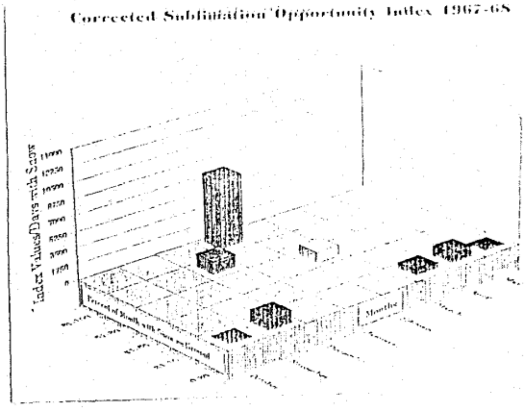

Figure 5. "Corrected" SOI for 1985-86, by months.

## Verification of SOI

### Methods

A mass balance approach which accounts for snow (and ice) ablation was implemented by the construction of a simple "sublimimeter" that appears to function reasonably well. It was used throughout the snow season of 1990-91 and 1991-92 at two sites to track the components of snowpack ablation and to verify the reasonableness of the index developed solely on theoretical considerations.

A dual-chamber sublimimeter was constructed with its top chamber made from Thermax brand closed cell foam insulation 2.5 cm thick. A regular box shape was used. (Inside dimensions equal 35 cm x 35 cm x 10 cm which allows full range (6000 g.) use of the selected electronic balance given maximum snow densities of 400 kg $m^{-3}$). The aluminum foil backing of the Thermax was left on the outside surface to reflect radiation; however, the backing was removed from the inside surface as experiments had shown it conducted heat and altered the snow-foam contact more severely than the uncoated foam.

The floor of the foam box was perforated with a grid of drain holes to remove melt water by gravity into a lower chamber. The holes were 0.25 inches in diameter and each was fitted with a 5 cm. long section of rigid plastic tube to increase the liquid tension and improve melt water scavenging. The melt water was delivered to a teflon coated metal pan which was bolted to the overlying foam chamber and sealed with a soft foam weatherstrip product to minimize evaporative loss from the melt water. Figure 6 illustrates this plan.

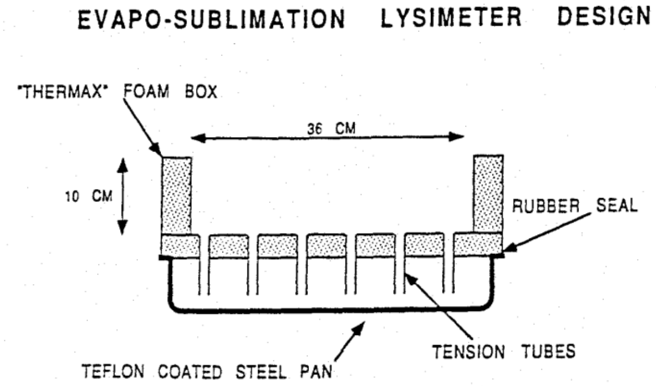

Figure 6. Sublimimeter Construction Details

Each measurement site was equipped with two sublimimeters (evapo-sublimation/snowmelt lysimeters) and both lysimeters were situated a fixed distance above the dry ground surface. One of the two lysimeters was shielded from open sky conditions (thereby blocking incoming shortwave radiation, retarding outgoing longwave radiation and minimizing new snow disturbance). The second lysimeter was left exposed to ambient sky conditions. The shielding was accomplished by building an open sided, flat roofed shelter above the lysimeter. The supports for the sublimimeters were 210 liter (55 gallon) drums painted white and capped with 5 cm thick styrofoam for thermal isolation. The shelters consist of a 1.3 meter square flat plywood roof of double thickness (each panel separated by a 2.5 cm free-air gap to minimize heat transfer). This roof is supported by wooden legs and is 1.5 m above the ground surface. The design is schematically illustrated in Figure 7.

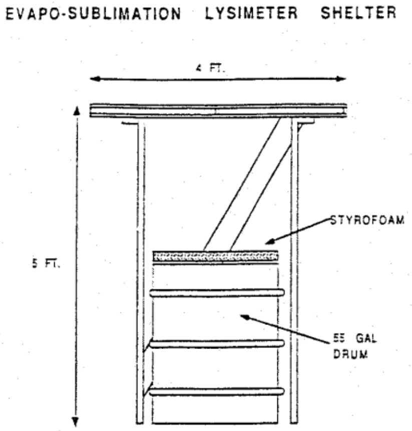

Figure 7. Sublimimeter Shelter Details

The "field life" of the sample was noted to be longer under shielded conditions so if site maintenance could not be performed in a timely manner or if accumulating precipitation were to affect the site, the covered lysimeter would provide more reliable results.

An Ohaus CT-6000 balance was used with its serial interface to permit continuous data logging. However, as what was termed "digital" input capability on either a Campbell C-21 or an Omnidata "Easy-Logger 800" turned out to be only on-off recording capability, neither brand of data logger could be used to accept the RS-232 serial output and thus log the digital balance data. (We finally modified a single board computer and used it with an associated battery pack for this task).

We began manually recording sublimimeter weights from the onset of the first snow in November of 1990 and all data reported here had been collected using manual data measurement techniques.

## Results & Discussion

Results from the two (shaded and unshaded) sublimimeters are compared and contrasted, suggesting differences between open and shaded locations. In 1991-92 a ground level location was also utilized.

Figure 8 illustrates the time domain pattern of evapo-sublimation losses for the two winter seasons while Figure 9 illustrates the relationship of evapo-sublimation loss to lysimeter exposure in units of millimeters day$^{-1}$ SWE. That comparison is based on 1991-92 means. Figure 10 expresses similarly-exposed site melt loss for the same time period. Table 3 presents the summary statistics for both years.

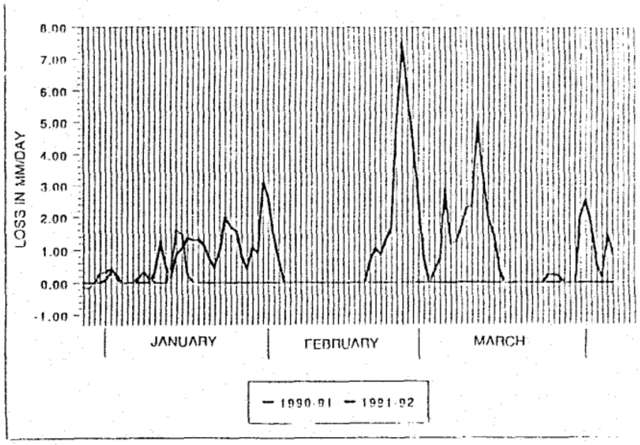

Figure 8. Evapo-Sublimation Losses in mm/day, 1990-91 and 1991-92.

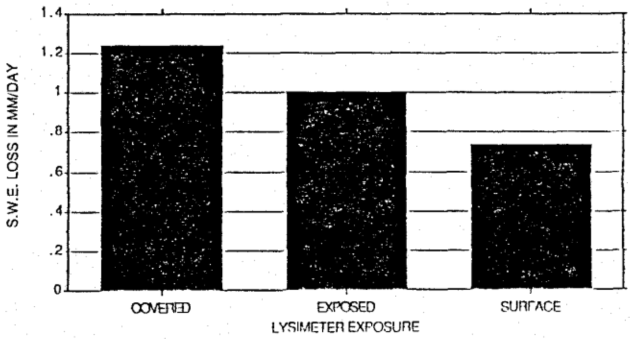

Figure 9. Sublimimeter Exposure Versus Evapo-Sublimation Loss (mm/day)

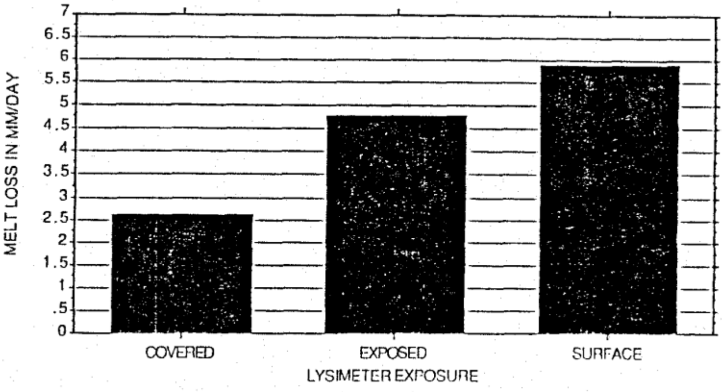

Figure 10. Sublimimeter Exposure Versus Melt (mm/day)

Table 2
Summary Statistics for 1990-91 and 1991-92 Study Season

| 1990-91 SEASON | Mean | Standard Deviation | Standard Error | Maximum | Minimum |
|---|---|---|---|---|---|
| COVERED #1 EV/SUB | 1.33 | 1.10 | 0.23 | 4.31 | 0.11 |
| COVERED #1 MELT | 4.13 | 6.45 | 1.35 | 26.40 | 0.00 |
| EXPOSED #1 EV/SUB | 0.69 | 0.71 | 0.15 | 1.91 | -0.56* |
| EXPOSED #1 MELT | 5.82 | 6.05 | 1.26 | 17.15[1] | 0.00 |
| COVERED #2 EV/SUB | 2.11 | 2.78 | 0.58 | 12.48 | 0.14 |
| COVERED #2 MELT | 3.21 | 4.24 | 0.88 | 14.49 | 0.00 |
| EXPOSED #2 EV/SUB | 1.09 | 1.17 | 0.24 | 3.77 | -0.75* |
| EXPOSED #2 MELT | 6.06 | 5.89 | 1.23 | 5.90 | 0.00 |

37 ACTIVE CASES
1 questionable data
* represent deposition (frost events)
units are in mm day-1

| 1991-92 SEASON | Mean | Standard Deviation | Standard Error | Maximum | Minimum |
|---|---|---|---|---|---|
| COVERED EV/SUB | 1.96 | 1.66 | 0.27 | 7.33 | 0.09 |
| COVERED MELT | 4.23 | 5.62 | 0.92 | 21.29 | 0.00 |
| EXPOSED EV/SUB | 1.63 | 1.82 | 0.30 | 8.52[2] | -0.04* |
| EXPOSED MELT | 7.74 | 9.11 | 1.50 | 30.36 | 0.00 |
| SURFACE EV/SUB | 1.19 | 1.49 | 0.25 | 6.62 | -0.05* |
| SURFACE MELT | 9.55 | 10.35 | 1.70 | 30.85 | 0.00 |

23 ACTIVE CASES
2 24 February 1992, clear, windy and bright period
* represent deposition (frost events)
units are in mm day-1

The comparison of observed values of evapo-sublimation to the constructed SOI values is made in figure 11, a time series plot for January 1992. The observed data represent evapo-sublimation as millimeters per day of SWE loss, and the SOI values represent the cumulative index values from five one-hourly values (0500, 0800, 1100, 1400 and 1700 hours) throughout the day: the summation is scaled by a factor of 0.001 for plotting purposes. Because the index appears to anticipate the observed evapo-sublimation loss by 24 hours (for an as-of-yet unknown reason), it is lagged by 1 day.

The data yields a corrected $r^2$ of 0.62, a time series cross-correlation value of 0.89 and a non-parametric cross association value of 79%.

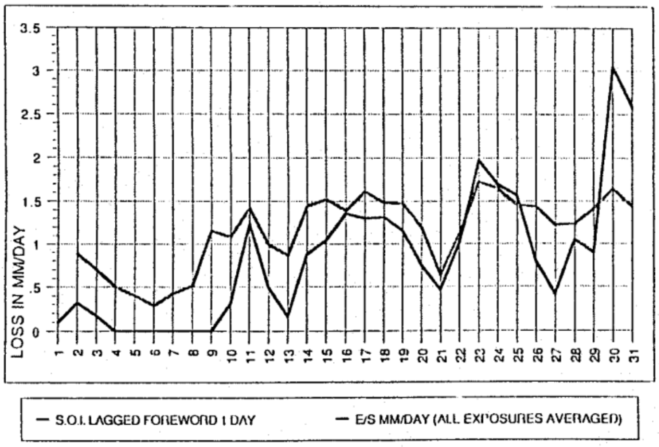

Figure 11. Basic SOI Values Versus Measured Evapo-Sublimation Loses, January 1992.

## Conclusions

For two snow seasons (1990-91 and 1991-92) a mean loss of 1.56 millimeters per day of snow water equivalent (SWE) as evapo-sublimation was recorded at Flagstaff, Arizona (Lat=35°N, elev=7000 ft), while a maximum evapo-sublimation loss of 8.52 mm $day^{-1}$ was recorded under clear, dry and windy conditions.

Sites that were sheltered from clear sky exposure appear to lose more snow water (equivalent) to evapo-sublimation and exposed sites transform more snow water (equivalent) to meltwater. Using mean value ratios for evapo-sublimation to melt (based on lysimetry alone), approximately 20 percent of the snow water (equivalent) was lost to evapo-sublimation (and 80% was transformed to meltwater) for this period. By using a "worst-case" approach (see Table 4), where the snow pack accumulates early in the season, we estimate up to 70 percent of a season's snow water (equivalent) could be lost to evapo-sublimation.

Table 3
Possible Water Balance for Winter Months, Flagstaff, Arizona

| Month | Cumulative Days | Cumulative History Ppt. @ SWE (mm) | Cumulative Evapo-Sublimation Loss @ 1.3 mm/day | Residual |
|---|---|---|---|---|
| November | 30 | 31.00 | 39.00 | -8.00 |
| December | 61 | 75.20 | 79.30 | -4.10 |
| January | 92 | 124.70 | 119.60 | 5.0 |
| February | 121 | 175.00 | 157.30 | 17.70 |
| March | 152 | 223.50 | 197.60 | 25.90 |
| April | 182 | 256.50 | 236.60 | 19.90 |

The Sublimation Opportunity Index presented here (with its cross-correlation value of 0.89) may be useful for simple estimations of evapo-sublimation losses.

**DISCLAIMER:**

The sublimation index presented here was not and is not meant to be a predictive mechanism or model; rather it is a methodology to demonstrate the variability over time of sublimation.

No statistical validity of the index model is implied.

## Acknowledgements

This work has been made possible in part by the support of the Salt River Project, the USDA Rocky Mountain Forest & Range Experiment Station and the authors' institutions.

**Literature Cited**

Avery, C. C. and L. R. Dexter. 1991. Assessing the significance of evapo-sublimation in Northern Arizona. Proceedings of the 1991 meetings of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona-Nevada Academy of Science. Flagstaff, Arizona, April 1991. pp. 65-75.

Bengtsson, L. 1980. Evaporation from a snow cover: review and discussion of measurements. Nordic Hydrology 11:221-234.

Bergen, J. D. and R. H. Swanson. 1964. Evaporation from a winter snow cover in the Rocky Mountain Forest zone. Proceedings of the 32nd Annual Western Snow Conference, Nelson, B.C.

Dunne, T. and L. B. Leopold. 1978. Water in Environmental Planning. San Francisco: W. H. Freeman.

Golding, D. L. 1978. Calculated snowpack evaporation during Chinooks along the eastern slopes of the Rocky Mountains in Alberta. Journal of Applied Meteorology. 17: 1647-1651.

Hutchinson, B. A. 1966. A comparison of evaporation from snow and soil surfaces. Bulletin of the I.A.S.H., 11: 34-42.

Kaser, G. 1982. Measurement of evaporation from snow. Archives for Meteorology, Geophysics, and Bioclimatology, 30: 333-340.

List, R. J. 1958. Smithsonian Meteorological Tables. 6th ed. (rev.) Publ. 4014. Washington, DC: Smithsonian Institution.

Linsley, R. K., M. A. Kohler and J. L. H. Paulhus. 1982. Hydrology for Engineers. Third Edition. New York: McGraw-Hill.

Meiman, J. R. and L. O. Grant. 1974. Snow-air interactions and management of mountain watershed snowpack. Completion Report, OWRR Project No. B-037-COLO, Washington, D.C.

Peak, G. W. 1969. A snowpack evapo-sublimation formula. Proceedings of the 37th Annual Western Snow Conference, Salt Lake City, Utah.

Peak, G. W. n.d. post 1972. Ice Ablation Formulae. Unpublished.

Schmidt, R. A. 1991. Sublimation of snow intercepted by an artificial conifer. Agricultural and Forest Meteorology, 54: 1-27.

U. S. Army Corps of Engineers. 1958. Snow Hydrology. Portland, Oregon.

West, A. J. and K. R. Knoerr. 1959. Water losses in the Sierra Nevada. Journal of the American Water Works Association, 51(4): 481-488.

## Appendix A SOI Formulation

- input parameters
  - -for each 3 hour reporting period
    - Air Temperature (F)
    - Relative Humidity (%)
    - Wind Speed (knots) (ten-minute average)
    - Opaque cloud cover (tenths of sky)
  - -for each day
    - Snow-on-ground at opening of station
- calculated values
  - potential (incoming) radiation at 35°N (for each 3 hour period of each calendar day)
- transformations
  - ·(°F) to (°C) <u>to</u>
  - ·saturated vapor pressure over water, or saturated vapor pressure over ice <u>to</u> actual vapor pressure <u>to</u> vapor pressure gradient
  - ·potential radiation to attenuated radiation
- scalar modifications for SOI construction
  - vapor pressure gradient x 10000
  - wind speed x 3
  - attenuated incoming radiation x 1
  - temperature ((°C) +41) / 2
- listing of formulae from spreadsheet
  - AR = (Pot Rad*((10-OSC)/10)
  - °C = ((°F)-32)*5/9

VP(°C<0) = (35558000000)*Exp(-6141.9/((°C)+273)) = $e_{s\ ice}$

VP(°C>0) = Exp(21.382-5347.5/((°C)+273)) = $e_{s\ water}$

VP = If((°C)<0,VP(°C<0)*(RH/100),(VP(°C>0)*(RH/100))
VPG = If(J2< = 0,(M2-3.96257)/200,(M2-6.1073)/200)
C VPG = VPG(-10000)
C RAD = I2
C TEMP = ((°C+41)*2)
C WSPD = WSPD*3
RSOI = Sum(C VPG + C RAD + C TEMP + C WSPD))
SOGI = If (SOG > 1,1,0)
SOI = RSOI*SOGI

where:
AR = attenuated incoming radiation
Pot Rad = calculated potential radiation
OPC = opaque sky cover
(°F) = temp in °Fahrenheit
(°C) = temp in °celsius
VP(C<0) = saturated vapor pressure over ice (mb)
VP(C>0) = saturated vapor pressure over water (mb)
VP = actual vapor pressure (mb)
RH = relative humidity (%)
VPG = vapor pressure gradient (mb $cm^{-1}$)
C VPG = scaled vapor pressure gradient
C RAD = scaled attenuated radiation (lys $hr^{-1}$)
C TEMP = scaled air temperature (°C)
TEMP = air temperature(°C)
C WSPD = scaled wind speed (knots)
WSPD = wind speed (knots)
RSOI = raw sublimation opportunity index
SOGI = snow-on-ground index
SOI = sublimation opportunity index