SNOW IN MOUNTAIN WATERSHEDS:
CONNECTIONS TO CLIMATE AND ECOSYSTEM HEALTH

R. A. Sommerfeld
D. G. Fox
R. C. Musselman

Rocky Mountain Forest and Range Experiment Station
240 W. Prospect Street
Fort Collins Colorado 80526

Abstract

Snow is important in Earth processes at all scales. On the global scale, the unique radiation properties of snow help control energy balance processes that control climate. On the continental scale, snow plays an important role in mass and energy processes coupling atmospheric interactions with the landscape. On a local scale, snow affects soil, lake, and biosphere chemistry, as well as plant community dynamics. We are pursuing comprehensive studies of these interactions at the Glacier Lakes Ecosystem Experiments Site (GLEES) in southeastern Wyoming.

1 Introduction

Snow is an important actor in determining global climate. Snow, and the ice that forms from it hold the largest fraction of fresh water in the Earth system (Meier, 1986). Because the optical properties of snow and ice are very different from those of soil and vegetation (Warren, 1982; Warren and Wiscombe, 1985), a snow cover's interaction with the atmosphere must be treated distinctively. Snow and ice are involved in both positive and negative feedback processes within the global climate system, that is, processes that both accelerate and decrease effects of anthropogenic influences on the climate. For example, snowy regions of the earth cause the system to lose energy. Snow has a very high albedo (reflectivity) in the visible band causing it to absorb relatively little incoming solar energy. However, it radiates very efficiently. According to Planck's law, at a temperature of 0°C snow emits longwave energy with a spectral peak at 10 μm. At this wavelength, the albedo of snow is low, and it is a good radiator of energy at wavelengths where the atmosphere is relatively transparent. However, synthetic greenhouse gasses absorb radiation strongly at wavelengths near 10 μm and strongly affect the cooling of snow covered surfaces (Ramanathan, 1988).

The low albedo of snow in the longwave has two effects. The snow is efficient in acquiring advected heat from clouds and warm air masses and it is efficient in radiating such heat when the sky is clear. Thus snow covered regions lose energy, cause more surface cooling and tend to increase the size of the snow cover; one type of positive feedback (Meier, 1986). Vegetation in snowy areas tends to limit this feedback (Lashof, 1989).

Thus it is easy to understand that snow affects global climate. Global climate modeling indicates that the intensity of the monsoon in Southeast Asia is inversely related to the size of the snow cover in Eurasia (Barnett *et al.*, 1989). The snow cover acts to help reduce the large scale temperature contrast that is instrumental in producing a strong monsoon.

The character of runoff is different depending on the precipitation type (Barron, *et al.*, 1989). When the precipitation is snow, the ratio of precipitation to evaporation at the time of runoff is much larger, enhancing the runoff.

While snow cools the overlying atmosphere, it provides an insulating cover over the ground, slowing the loss of heat that accumulates in the ground during the summer and fall. Thus, thickness of the snow cover affects the ability of plants to survive the winter, and controls the extent of permafrost development. The thickness and density of the snow cover also determines the length of the growing season in snowy areas. The sensitivity of plants to snow depth is easily seen in alpine environments. Distinct patterns of vegetation form where the water from snowmelt is no longer effective in promoting plant growth; or where the snow does not melt soon enough to allow time for the development of some plant species. Thus the effects of snow are complicated;it has both positive and negative effects on most important systems.

While snow cover is a large scale parameter for the general circulation, the physics that controls its distribution and energy exchange processes occur over a wide range of spatial scales from the snow microstructure on up. For example, the near infrared albedo is affected by grain size and type and the shortwave albedo is affected by low concentrations of soot (Warren, 1982; Warren and Wiscombe, 1985). The details of the processes controlling these effects are critical to the performance of the global climate models that are used for evaluating climate change caused by anthropomorphic influences.

Snow and sea ice also fit into a unique space-time scale as far as climate is concerned. They cover a spatial scale of about 1000 km and a time scale of about 1 year, responding rapidly to temperature. Glacier ice covers a similar area but a time scale of millennia (Meier, 1986). Obviously, this spatial scale is important in global climate, and the different time scales are important in determining how energy is exchanged in the Earth system. Hansen *et al.*, (1981) suggest that the albedo feedback for snow and sea ice is on a 10 to 100 year time scale.

We are developing a process-level understanding of certain of the interactions between the atmosphere and ecosystems. We have selected the alpine/subalpine ecosystem because it is very sensitive to changes in the atmosphere, *e.g.* especially climate but also of chemical input. Considerable research is addressing large scale atmospheric interactions using satellite remote measurement technology to provide observations that can be organized with theory developed out of general circulation models of the coupled atmosphere-Earth system. The large scale dynamics of these models are limited only by computational power.

At small scales, however, there are problems. One problem relates to the need to model or parameterize small scale nonlinear physical processes with simple algorithms that can be incorporated into the model. For example, differences in the responses of various global climate models to increased CO_2 levels have been partly attributed to differences in how they parameterize snow and sea ice albedo (Barron *et al.*, 1989).

A related, but more fundamental difficulty is our understanding of the processes themselves. Our basic understanding of the physics of the exchange processes between atmospheric chemicals at the growing ice surface of a snow crystal, for example, needs improvement. We approach our research recognizing that such fundamental understanding is often lacking in many aspects of the interactions between the atmosphere, snow, and ecosystems. However, to focus our attention toward processes of greatest significance, we feel it is necessary to put these studies within the context of an actual ecosystem, namely the Glacier Lakes Ecosystem Experiments Site (GLEES). The GLEES affords us the opportunity to scale up from microscale processes, often where theory and laboratory experimentation are powerful tools, to ecosystem and even landscape (multiple interacting ecosystems) scales where applicable tools are only just being developed.

The GLEES is located in southeastern Wyoming in the Snowy Range of the Medicine Bow Mountains. It was selected in 1987 for the study of relationships between the atmosphere and the biosphere by a project of the Rocky Mountain Forest and Range Experiment Station. The site covers approximately 300 ha at an elevation of 3000 m. It has three small lakes which each drain a small watershed. As the name implies, snow is an important feature of this alpine-subalpine site. The mean annual precipitation is 100 cm H_2O. The mean annual snow accumulation is 2 m with a density of 400 kg m^{-1} at maximum accumulation. A perennial snow field exists on the site. A wide variety of studies are being conducted at the GLEES and snow studies are an important part of the program.

2 Snow Quantity

Estimating the quantity of snow to the GLEES is an important part of the total program. The major part of the water input to GLEES comes from snowmelt. While the snow quantity is measurable, in principal, doing so is time consuming and difficult. It is estimated that to produce about ± 5% accuracy using snow core survey techniques, about 1500 to 2000 points would have to be sampled (Elder *et al.*, 1988; in prep.) Therefore, we are seeking less direct methods that have acceptable accuracy.

2.1 Martinec-Rango estimate

A method of estimating snow quantity was developed by Martinec and Rango (1987) as part of a snowmelt runoff model. It is one of a class of models that use air temperature to index the amount of snow melted. In the Martinec-Rango (M-R) model the depth of snow melted each day is indexed by the degree days above 0°C for that day. The areal coverage of the snow for each day is estimated from a plot of areal coverage versus degree days determined from some remote sensing method. In our case, we use monthly aerial photographs. By summing the product of the depth and areal coverage lost each day, the total yearly accumulation can be estimated.

The method is attractive because of the limited amount of data required to make the estimate. Temperature measurements are easily obtained using modern data loggers. Aerial photos are easy to analyze for areal snow coverage and are inexpensive relative to more direct measurement techniques. However, in estimating the depth of snowmelt each day, the method ignores all of the processes that are involved in melting snow. Radiation, latent heat exchanges, and advected heat are all indexed by the simple degree-day constant. Because the M-R model is not based on physical processes, its accuracy must be assessed for particular applications.

On the positive side, the areal snow coverage can be measured to a high degree of accuracy. If the vertical melt and the horizontal depletion are approximately equal, then the change in areal coverage constitutes about 2/3 of the estimated daily melt. Thus the largest component of the estimate is the most accurately determined. It would be possible to obtain aerial photos every day and determine the depletion curve with virtually no error. However, the character of the depletion curve is such that a high density of data is not necessary to determine the curve to an accuracy that is acceptable. Martinec and Rango have determined that the curve is relatively smooth for a wide variety of cases. Also, in the absence of snowfall during the melt season, it must decrease monotonically. Thus a few points are sufficient to constrain the curve to a narrow band of possible values.

TABLE 1

Estimates of Snow Water Input to the GLEES

Method	Water Equivalent		Bias
	1988	1989	
Martinec and Rango (1987)	85	69 cm H_2O	Unknown
Wooldridge *et al.* (in prep.)	80	55 *	Low average
SRO Precipitation Gage	65	55	Very low
NADP Precipitation Gage	82		Low
Subcatchment core survey:			
Non-random	73		Low
Random		77	Minimal

*Corrected each year according to SCS snow course data.

TABLE 2

Ratios of Water Volumes: West Glacier/East Glacier

Year	Snow (M-T)	Flume
1988	4.73	4.49
1989	4.82	not available

We now have two years of data using the M-R method for estimating the yearly snow accumulation. A preliminary comparison with other methods of estimating the accumulation indicates that the M-R method has an accuracy better than ± 20% (Table
Sommerfeld *et al.*, in press). It also appears to give correct ratio of accumulatio
two GLEES watersheds, the catchments that feed East and West Glacier Lakes (Table
Our data indicate that the M-R method is consistent between years. Thus, it appear

that at least we can calibrate the method for use as a monitoring method for our watershed.

2.2 Direct Measurements

The next step in this part of our research program is to measure the amount of snow in the GLEES. We will accomplish this using a combination of cores, for depth and density, and probes for additional depth measurements (Bartos, 1972). We will obtain 1500 to 2000 measurements on a grid pattern with points more concentrated in areas of high variability. The variability will be estimated from aerial photos and from snow depths isopleths derived from a grid survey of snow damage to trees (Sommerfeld, *et al.*, in press; Wooldridge, 1989; Wooldridge, *et al.*, in prep.)

2.3 Improvements on Martinec-Rango

The most important process that the M-R method ignores is the radiation energy balance. To provide subsidiary data for possible improvements to the M-R method, we are measuring visible and near infrared total and net radiation.

3 Snow Quality

The GLEES is a relatively pristine area. We have the opportunity to determine conditions and processes which are close to background. For snow, we are pursuing a comprehensive program to quantify the processes involved in wet and dry deposition and to monitor the chemical composition of the snow at the GLEES.

3.1 Snow pits

Snow pits have been dug for the snow lysimeter study described below. We now have data from six pits, three each for the 1988 and 1989 melt seasons. Densities are measured in each layer using a 1 l wedge shaped cutter developed by R. Perla. Snow is classified according to the classification of Sommerfeld and LaChapelle (1970). The entire depth of each layer is sampled for chemical analysis using a length of 3 in. ID PVC pipe fashioned into a corer. As part of our project, we maintain a laboratory capable of a wide range of chemical analyses using ion chromatography, atomic absorption spectrophotometry, flow injection analysis, carbon analyses, pH, conductivity, and inductively coupled plasma spectroscopy.

We now monitor the chemistry of the snowpack at the GLEES at eight snow pit sites. The pits are located on the four cardinal aspects. Each set of pits consists of a high and low deposition area as determined by the snow depth. The reason for choosing high and low deposition areas for each pair of pits is that we expect that dry deposition will obey physical laws similar to those that determine snow deposition patterns. Sampling of a pair of pits is done each week in rotation so that each set is sampled once every four weeks.

3.2 Laboratory studies

The processes by which snow acquires, stores, and transports impurities are not well known. Volatile impurities can adsorb on the ice surface. Ice exhibits surface premelting where a surface layer acquires liquid like properties at temperatures below the melting point. For this reason, the surface adsorption of volatile impurities is expected to exhibit anomalies at temperatures that are common in the seasonal snowpack. To determine the chemistry that controls these processes we are doing careful laboratory measurements of primary volatile impurities adsorbed on a fine grained artificial snow (Sommerfeld and Freeman, 1988).

Results to date are as follows: Nitric oxide does not adsorb on ice in environmentally significant amounts. Its adsorption is approximately 10^{-13} gm cm^{-2}. This translates to only about 20 gm in our entire watershed. Preliminary work on nitrogen dioxide indicates similar small adsorption on a time scale of hours but there is some indication that larger amount may be adsorbed on longer time scales. Sulfur dioxide exhibits higher adsorption on the short time scale (Sommerfeld and Lamb, 1986) but still not very significant amounts. On a longer time scale it may adsorb significantly (Clapsaddle and Lamb, 1989). In natural snow SO_2

oxidizes to sulfuric acid (Bales *et al.*, 1987). The vapor pressure of sulfuric acid is very low so that the oxidation changes the sulfur impurity from volatile to nonvolatile and fixes it in the snow until melt. We have identified the oxidant as hydrogen peroxide (Conklin, 1988; Conklin *et al.*, 1989) which occurs naturally in snow (Neftel *et al.*, 1987). We can make artificial snow that has controlled amounts of hydrogen peroxide and we are currently determining the reaction mechanisms of the oxidation on the surface of ice. In this case, the surface of ice appears to behave similarly to water.

4 Snow Metamorphism

Snow metamorphism in the dry snowpack moves any impurities to the surfaces of the ice crystals. In the dry snowpacks in our region, recrystallization continues up to a melt season that usually has a well defined onset. The major cause of snow metamorphism is thermal gradients in the snowpack. We have modeled temperature gradient metamorphism in three dimensions and are now able to quantify some of its effects (Christon, 1990). Under thermal gradients that are common in nature, temperature gradient metamorphism will cause the complete recrystallization of a snow layer in a few days. This means that any impurities included within the snow crystals are efficiently moved to the exterior surfaces of the snow crystals, which will affect the chemistry of the snow melt as described below. Because grain size and impurity concentration affect albedo, metamorphism affects albedo. The results we have obtained should aid in parameterizing these effects.

5 Snowmelt

The GLEES normally has a distinct onset of the melt season with little prior melting. The soluble impurities are available to the first meltwater, so that the conditions for an unambiguous impurity pulse are very good. This contrasts with climates where melting occurs throughout the winter. We have observed the effects of impurity pulses in the GLEES lakes at the start of the snowmelt season.

5.1 Snow lysimeters

We have been studying the impurity pulse from the base of the snowpack using long narrow lysimeters of unconventional design. The design is intended to minimize the effect of the lysimeter on blocking vapor flow from the ground, which could effect metamorphism. The design also eliminates the possibility of dry deposition contamination prior to the establishment of the snowpack (Bales *et al.*, 1990). We have verified that the impurity pulse commonly occurs and is similar to those observed in other areas and with more conventional lysimeters. Thus the pulse we detected is real; it is not influenced by vapor blocking common in large lysimeters, nor is it the result of dry deposition prior to the establishment of the snowpack. Work is continuing with these lysimeters to gather enough data to test snowmelt models as they apply to chemical transport.

5.2 Laboratory studies

Snow is heterogeneous on the scale that is important in meltwater transport of chemicals. Channeling, and piping are commonly observed at the time of first melt flow from the base of snowpacks (Wakahama, 1968). This calls into question the ability of one dimensional, film flow based models (Colbeck, 1975) to accurately model the flow of chemicals from the base of snowpacks. Film flow models can be modified using statistical distributions of properties but this seems an ad hoc solution to the problem. A second possibility would be to develop more physically based models on observed processes of water flow. McGurk and Kattlemann (1988) indicates that much of the flow during the initial phases of melting may be due to droplet penetration. We are initiating a program of studying the initial melting of natural snow under controlled conditions to attempt to determine the physical processes involved.

6 Relationship to other spheres

The GLEES is intended to be a site for long term ecological studies. As such, the relationship of snow to other aspects is of primary importance. Snow comes from and interacts with the atmosphere. During melt, it releases material into the biosphere, the most important being water. The chemical component of the melt is also important, particularly in aquatic systems.

6.1 Atmosphere

The GLEES is in a windy environment with a mean annual wind speed of 34 km h^{-1}. Snow is redistributed by the wind. Unprotected areas are commonly denuded of snow, which is deposited in deep drifts in the more protected areas. A map of snow depths was developed using data from a tree deformation survey (Sommerfeld *et al.*, in press; Wooldridge, 1989; Wooldridge *et al.*, in prep.). It was corrected using aerial photos taken in mid-June when the deepest drifts are easily identified. This map will continue to be corrected from aerial photos and from the intensive survey described above.

We have initiated a study to determine whether or not the chemical deposition patterns are related to the snow deposition patterns. We are also developing eddy correlation techniques that will allow us to measure dry deposition.

6.2 Biosphere

More than 80% of the water supplied by the atmosphere to the GLEES comes in the form of snow. The water sustains a variety of plant life. Vegetation habitats at GLEES are controlled to a large degree by the timing and quantity of the snowmelt water. However, the plant communities cannot begin their seasonal growth until the snowpack is melted or nearly melted. The area of the deepest drifts can be determined after the snow has melted by the differences in the resulting vegetative communities. Where the snow lies longest, the growing season may be too short to allow some plant species to become established. Some vegetative habitats with little soil water holding capacity become extremely droughted after the snowmelt water is gone. These habitats support communities that exist only in the short window between last snowmelt and soil water reservoir depletion. A snowpack uphill from some areas can sustain those habitats longer, as evidenced by different plant communities. We have established over 90 permanent plots in different plant communities to examine snow-vegetation interactions at the GLEES.

To study these relationships, it is necessary to estimate the time when the snow leaves the plots where these plant communities are located. To determine the snow free season would require the daily observation of the plots over the course of the melt season. We are attempting to estimate the time the snow leaves the plots by using a technique derived from the M-R method described above. We are developing snow depletion versus degree-day curves for the individual snow patches that cover each plot by using aerial photos. A few points should serve to fix each curve to an accuracy of a few days in time. Then the areal coverage that just exposes each plot and its average time of occurrence can be estimated. This will be a dynamic estimate so that we can predict the phenology each year.

The snowmelt period is also important in the life of the lakes in the GLEES. We are monitoring lake chemistry on a daily basis during snowmelt to correlate with the snow measurements. Phytoplankton and zooplankton populations change throughout the year and may be related to the changes in chemical input from the snowpack; the largest chemical pulse into the lakes occurs at first melt.

There is some evidence from soil lysimeter samples that the carbon dioxide level in the soil is enhanced at snowmelt, indicating biological activity at temperatures near freezing. Observations at the GLEES have shown that soil is frozen only at the top 1-2 cm after snowpack buildup. Lake outlet stream flow occurs and macroinvertebrate activity is present under 3 or more meters of snow. Studies in Alaska (Coyne and Kelley, 1974) have reported that the snow cover traps gases resulting from biological activity that starts with the melt season. We are sampling gases from the soil, at the base of the snowpack and within the snowpack to quantify this process. The results will be important in quantifying the effect of snow cover on plant communities and on soil processes at the start of snowmelt.

7 Conclusions

Snow is important in studying global climate change from two different aspects: atmospheric and biospheric. The properties of snow and its wide and variable distribution have important effects on the energy balance of the Earth. This makes snow an important component of any climate model that hopes to give realistic results. Also, the radical differences in the biosphere environment in the presence or absence of snow makes it an important component of the biosphere. Many of the questions raised in studying the effects of snow on energy balance and on the biosphere are at the forefront of current snow research.

The spatial scales that are important range from sub-millimeter microstructure to thousands of kilometers. Our program attempts to understand snow on the smaller scales where processes can be determined and understood. We hope to be in a position to use this understanding to expand our modeling to landscape scales and to provide background information for expansion to global scales. By integrating our snow studies with studies of the atmosphere and biosphere, we hope to broaden our understanding of the role snow plays in the total alpine-subalpine ecosystem.

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