PHYSICAL CHARACTERISTICS OF SEASONAL SNOW COVER IN NORTHERN ALASKA 582-74

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Seasonal and Perennial Snow

The fact that research on seasonal and perennial snow has much in common is seldom appreciated because the research efforts are usually done separately, applied to different goals and carried out by different groups of people.

Most research on seasonal snow cover has been directed toward solving engineering problems, such *as* determining the amount of water stored in the snow and the rate at which this water is discharged. This hydrological information is immediately applied to producing hydroelectric power and aiding agricultural and flood control projects. The need for such information gave birth to the field of snow surveying in the western U.S. (Church, 1942). Other major research efforts on seasonal snow cover hope to predict and control avalanches and develop effective means of snow removal and drift control. Basic research on the properties of snow has been included in some studies, but historically the emphasis has been on applied research primarily from a hydrological point of view.

Research on perennial snow has increased along with human activity in Polar Regions. The research on polar snow and ice is generally referred to as glaciological, although the term applies equally well to seasonal snow cover research (Seligman, 1947). Studies on perennial snow also have hydrological and engineering goals, such as the determination of annual accumulation and ablation rates, the solving of over-snow transportation problems, and in the design and construction of large facilities, such as radar or research stations, on the Greenland and Antarctic ice sheets.

Snow and ice so dominate the polar environment that they demand a more basic approach to the research than has characterized research on seasonal snow. Stratigraphic study of perennial snow strata on large glaciers and ice sheets, replaces the snow surveys of seasonal snow cover. It not only provides a means of identifying annual increments of snow and of determining their water equivalent, but also yields information on the physical properties of the snow which has served as a means of defining diagenetic facies on glaciers in general (Benson, 1962, 1967). The needs of science and engineering have stimulated a great deal of interdisciplinary research on the basic properties of snow and ice as a material. The approaches used in powder metallurgy have been useful in studies on the densification of snow. The deformation, flow and fracture of ice have been studied by using theoretical developments in the fields of plasticity and solid state physics; these studies have been applicable to research on metamorphic rocks as well as to glaciology.

Alaskan Snow Cover

Snow forms a thin veneer on the earth's surface over most of Alaska for 1/2 to 3/4 of the year. The physical properties of this snow layer and the physical processes which occur in, above, and below it are important and fascinating. The Alaskan snow differs from the hydrologically important mountainous snow of the western United States in that its temperatures are lower, steeper temperature gradients occur in it, and there is less of it per unit area; however, it lasts longer and enters more directly into human activity as snow itself rather than serving primarily as a cold storage water reservoir. This is of course especially true of snow which falls in glacier basins and enters into the complex glacier-hydrology system. Some of it may appear as runoff during the same year it was deposited, but much of it becomes locked in the glacier system for many years before it appears as runoff.

Although Alaska is famous for its glaciers and has a large amount of perennial snow cover, it is especially well suited for the study of seasonal snow cover. Indeed, Alaska is virtually a made-to-order snow laboratory because it contains maritime, extreme continental, and Arctic climatic zones in proximity. The differences in the snow cover from one zone to the next are striking. This fortuitous situation is the result of two sharply defined climatic boundaries which cross the state:

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Reprinted Western Snow Conference 1974

(1) The Alaskan coastal ranges separate the north Pacific maritime climate from a severe continental climate.

(2) The Brooks Range separates the interior continental climate from the Arctic polar basin climate.

The two boundaries give three major climatic types which contain all varieties of snow cover:

(1) The coastal mountains and lowlands of southeastern and south-central Alaska receive heavy maritime snowfall, which may be wet at low altitudes. This area receives precipitation from Pacific cyclonic disturbances which move through the Gulf of Alaska.

(2) The interior, between the Brooks and Alaska Ranges suffers an extreme continental climate and the most notable feature of its snow cover is the low density, loosely consolidated depth hoar which makes up most of the snowpack in the lowland brush forest areas. The interior receives most of its precipitation from cyclonic disturbances which move eastward from the Bering Sea.

(3) The Arctic Slope is characterized by a wind-packed, dry, sastrugisculptured snow cover. Its precipitation comes from cyclonic disturbances moving eastward from the Bering Sea or from along the Siberian Arctic coast.

The Snow. Cover of the Arctic Slope

Aside from the perennial snow of the mountainous areas, the snow cover lasts longest on the north slope of the Brooks Range. For three quarters of each year, the entire Arctic Slope, from the foothills across the tundra to the Arctic Ocean, is covered with dry, wind-packed snow. This snow has several distinct features and research on it emphasizes the common ground which exists between studies of seasonal and perennial snow cover. It forms a wind-swept sastrugi surface which strongly resembles the year-round surfaces of the Greenland and Antarctic ice sheets, or the winter snow surface of the adjacent Arctic Ocean.

The similarity to polar ice sheets does not stop at the surface. Indeed, the structure of the entire snowpack (thin as it may be) resembles the top annual stratigraphic unit of the perennial dry-snow facies of the Greenland or Antarctic Ice Sheets; it consists of a hard, high-density, wind-packed layer, overlying a coarse, low-density, depth hoar layer. Although there is considerable variability in the stratigraphy of this snow, one can generally describe it by referring to only four major varieties of snow. In approximate order from top to bottom in the snowpack these are:

Snow type	Grain size (mm)	Range or density ($g\ cm^{-3}$)*
1. Fresh new snow, variable crystal forms	0.5 to 1.0 sometimes < 0.5	0.15 to 0.20
2. Wind slab, hard, fine grained	0.5 to 1.0	.35 to .45
3. Medium grained snow	1 to 2	.23 to .35
4. Depth hoar, coarse loosely-bonded crystals	5 to 10	0.20 to 0.30

* The density ranges are only approximate. However, they indicate the differences one may expect between the various layers.

The Snow Cover of Interior Alaska

The land south of the Brooks Range is forested and the forest cover prevents the snow from exercising the same dominant control on the albedo that it does on the Arctic Slope. The boreal forest has about half the albedo (surface reflectivity) of clear snow-covered areas within it such as lakes and bogs (McFadden and Ragotzkie, 1967). South of the Brooks Range the albedo has generally lower values (47 to 48% compared with 83%) and is more variable than it is on the North Slope.

The winter climate of the interior lowlands of Alaska, where most of the population is located, is typified by cold air and calm winds. The snow-covered surface favors the development of strong surface inversions which restrict the calm, cold air to a surface layer 50 to 100 m thick. However, hills such as those around Fairbanks effectively "poke through" the inversion layer which lies in the flats. Thermograph records from points on Birch Hill (Fairbanks) can be used as an approximation of the free air temperature at those levels (Benson 1970).

The snow cover lying within the altitude range spanned by the inversion layer is subject to negligible winds - often through the entire winter. It is also subjected to very low temperatures at its upper surface for several months. However, the ground beneath the snow does not experience temperatures below -5^{o} or $10^{o}C$, so strong temperature gradients prevail in the snow. This leads to extensive depth hoar development. The snowpack is often referred to by residents as being "soft and fluffy"; the average density is generally less than 0.20 g cm^{-3}.

The dense air in the surface inversion layer is virtually detached from the air above (Benson, 1970), and winds in the upper air mass can be strong (Gotaas and Benson, 1964). Occasionally the boundary between the dense, calm air in the valleys and windy air aloft may be seen in the form of a frost line on the forest. Delicate frost crystals cover the branches of trees below the boundary, while the trees above are free of frost. This might be explained partly by the fact that the lower temperatures below the boundary cause more condensation and crystal growth. However, the boundary has been observed to be very sharp following wind action at higher levels while negligible winds occurred below. The boundary layer in the Fairbanks area lies slightly more than 100 m above the valley floor, just above the steepest inversion layer.

Hard-packed wind slabs develop on top of Ester Dome, about 600 m above the flats just west of Fairbanks. These slabs consist of fine grains (1 mm) which are firmly bonded; the density values generally range from 0.35 to 0.45 g cm^{-3}. At 200 m above the Tanana Valley, for example on top of Birch Hill, northwest of Fairbanks, the snow shows little wind packing, as in the valleys below. About 300 m above the valley floor wind action on the snow becomes noticeable, and significant wind packing occurs every winter at altitudes in excess of 400 m. The snow density in these windy places is twice as great as it is in the valley bottoms.

Although it is not possible at present to express wind packing simply as a function altitude, it is possible to give an altitude of demarcation in selected areas which may be useful. In the Fairbanks area this altitude is about 300 m above the valley floor. Above this altitude the snowpack consists of wind-packed layers overlying depth hoar layers. The depth hoar layers vary in thickness from 20 cm down to about 1 cm at the base. In wooded areas the wind packing may be absent. But wind slabs are common above timberline and where the forest cover is thin. Below this altitude the snowpack may be predominantly depth hoar. In the Delta Junction area, wind packing occurs in valley bottoms wherever forests are absent because of the strong winds from Isabelle Pass in the Alaska Range (Benson, 1972).

Toward the Bering Sea, especially west of Koyukuk (about $158^{o}W$) on the Yukon-Kuskokwim delta, temperatures and winds are higher than farther east and the climate becomes more maritime; many of the snowstorms are mixed with rain and the snow cover is characterized by significant amounts of icing with depth hoar at the bottom.

Physical Processes in the Snow

Several physical processes which have especially important effects on the snow of Northern Alaska will be briefly discussed.

Snow Drifting

The snow cover on the Arctic Slope is thin but continuous across the tundra and lake surfaces, with large drifts forming at the edges of river and lake banks. The drifts can be separated into two groups; one is formed by storm winds (which bring new snow) from the west, the other is from the prevailing winds which blow from the northeast.

The general shapes of the drifts are reproduced each year. This is especially true of the prevailing-wind drifts; their sizes and shapes are virtually independent of the amount of snowfall. However, the size of storm-wind drifts varies significantly according to the amount of snowfall. Drifts along favorably (N-S) oriented river banks may be several kilometers long, up to 20 m wide, and 6 to 8 m deep; they contain 2 to 4 x 10^4 Kg of water equivalent per meter of length along the bank. Cross sections of drifts on the Meade River measured between 1962 and 1967 are shown in Figure 1. The drifts from the storm winds were at a minimum in 1964 and a maximum in 1967, yet the size of the prevailing wind drifts were nearly constant during all years of the study (Benson, 1969).

At Prudhoe Bay in 1972 the storm wind drifts along N-S oriented roads were twice as great as those produced by prevailing winds from the East. However, the dust which blows on the snow from exposed roads and other bare ground areas was moved most effectively by the prevailing winds. This is partly because the dust sources are exposed in spring when the general frequency of wind shifts predominantly to the East (Benson et al, 1974).

Formation of Depth Hoar

Depth hoar is the coarsest grained snow structure that can form in the absence of the liquid phase. It consists of large well-developed skeletal crystals which are weakly bonded together so that depth hoar layers are fragile. It forms in seasonal and perennial snow strata as a result of upward vapor transport along vapor pressure gradients produced by temperature gradients in the snow.

The development of depth hoar in interior Alaska is extreme. It has the lowest density (less than or equal to 0.20 g cm^{-3}) of depth hoar formed anywhere. This is the result of the very steep temperature gradients which exist in the snow for long periods of time, up to five months. Not only are the gradients strong, but they also include relatively high temperatures at the base about -5^{o}C. A comparison between the top 50 cm of snow on the Greenland ice sheet and that of the Fairbanks area is revealing. Assume that both have a surface temperature of -45^{o}C. If we go 50 cm below the snow surface in the Greenland case, we find a temperature of about -40^{o}C, while in the Alaskan case the soil-snow interface, at the same depth would have a temperature of -5^{o}C.

In this example the vapor pressure difference in the Alaskan case is 70 time greater than the Greenland case (3.943 mb compared with 0.056 mb).

An experimental arrangement was set up in the Fairbanks area to observe the formation of depth hoar. The apparatus consisted simply of a set of tables, painted white, upon which snow could be deposited. The lack of wind in this region made it possible to carry out this experiment. Thus one can observe two adjacent snowpacks with identical depositional history but with a drastically different thermal environment. The snow on the table is subjected to negligible temperature gradients because air is in contact with the bottom of the table as well as with the top of the snowpack. On the other hand the snow resting on the soil has air temperature at its top but the much higher soil-snow interface temperature at its bottom.

Temperature, density and stratigraphy profiles of the adjacent snowpacks have been made approximately once a week for nine years. By comparing densification rates in the two cases an upward flux of water vapor has been determined to be 0.025 g H_2O cm^{-2} day^{-1}. This is an order of magnitude greater than flux rates calculated by a pure diffusion model.

The large flux is due to air convection in the snow. The formation of depth hoar is accompanied by a measurable removal of impurities from the snow and by a fractionation of the stable isotopes, H^2/H^1 and O^{18}/O^{16}, within the snow (Benson and Friedman, 1974). The upward flux of water vapor in the snow also exerts a significant and measurable drying action on the soil and vegetation below. The flux of water vapor from the top 5 cm of soil is about 10 times less than the flux measured in the overlying snow. These studies are discussed in greater detail by Trabant and Benson (1972) and Benson and Trabant (1973).

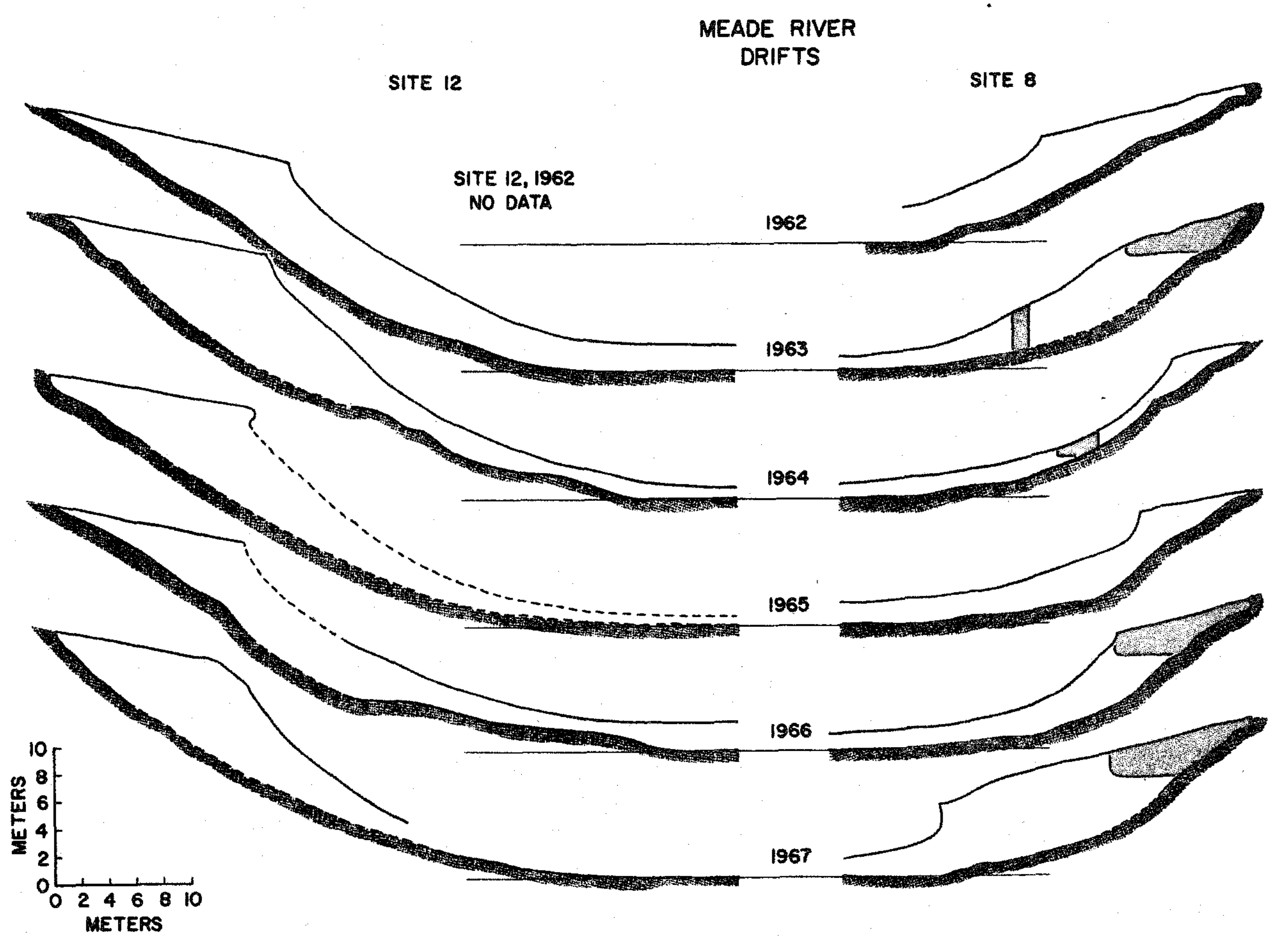

Figure 1. Drift profiles on banks of the Meade River at Atkasuk (70°29'N.;157°25'W.) drawn as seen from the north. The drifts at Site 8 are formed by storm winds from the west and vary in size with the amount of snowfall. The drifts at Site 12 are formed by prevailing winds from the east and are virtually independent of the amount of snowfall. The gray stippled areas in the drift sections at Site 8 indicate the locations of pits excavated across the drifts for detailed measurements (Benson, 1969).

Melting

During spring melt the snow cover on the Arctic Slope develops ice lenses in it and at its base. The process is analogous to the formation of superimposed ice on glaciers. Smaller ice lenses, usually only near the surface form in the snow of interior Alaska. The more extensive icing in Arctic snow results from the lower temperatures in the snow and the potential for a longer period with slight surface melting followed by colder weather (Benson, et al, 1974). The effects of the icing processes on small animals, such as lemmings, which live in the snow are being investigated (Melchior and Benson, 1974).

ACKNOWLEDGEMENTS

The investigations described in this paper have received support from the National Science Foundation (NSF Grant 22224), the Office of Naval Research (ONR Task NR 307-272) through the Arctic Research Laboratory (NARL) at Pt. Barrow, Alaska, from the Arctic Institute of North America on Subcontract No. ONR-403, and from the Tundra Biome International Biological Program, National Science Foundation.

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