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Authors

Alley, R. B
Saltzman, E. S
Cuffey, K. M
et al.

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SUMMERTIME FORMATION OF DEPTH HOAR IN CENTRAL GREENLAND

R.B. Alley¹, E.S. Saltzman², K.M. Cuffey¹, J.J. Fitzpatrick³

Abstract. Summertime solar heating of near-surface snow in central Greenland causes mass loss and grain growth. These depth hoar layers become seasonal markers which are observed in ice cores and snow pits. Mass redistribution associated with depth-hoar formation can change concentrations of immobile chemicals by as much as a factor of two in the depth hoar, altering atmospheric signals prior to archival in ice. For methanesulfonic acid (MSA) this effect is not significant because the summer maximum does not coincide with the density minimum, and the amplitude of the annual (MSA) signal is more than a factor of ten.

Introduction

Ice cores contain a paleoenvironmental record of many atmospheric chemicals with seasonal time resolution. Seasonal variations in the physical properties of snow and ice provide layering which can be used to time changes in chemical inputs. Here we use data collected during June and July, 1990 at the GISP2 site [38.5°W long., 72.6°N lat., 3210 m elev; Hodge et al., 1990], near the Summit of the Greenland ice cap, to show that low-density, coarse-grained layers called depth hoar are caused in this region by summer insolation.

The large crystals of depth hoar form when steep temperature gradients cause rapid vapor flux past relatively few nucleation sites (crystals or grains). Because low-density snow has fewer grains and lower thermal conductivity than high-density snow, depth hoar forms when low-density snow is subjected to temperature gradients [Colbeck, 1983; 1989b; Sommerfeld, 1983; Perla and Ommanney, 1985; Alley, 1988].

Background

Low-density snow can be produced depositionally (e.g. by snowfall without wind packing, or by burial of low-density surface hoar) or diagenetically (via mass loss

from snow originally of higher density). Depositional depth hoars can form at any time of the year, but exhibit certain characteristics (general thinness, tendency to fill low spots in the underlying snow surface) that allow them to be distinguished from diagenetic depth hoars [Alley, 1988].

Benson [1962] observed that in Greenland a stratigraphic discontinuity forms in late summer or autumn, with a coarse-grained, low-density layer often containing depth hoar overlain by a finer, denser layer. Traditionally, formation of the depth hoar in such a sequence on ice sheets has been linked to diagenesis during the autumn in the seasonal temperature cycle, when summer-warmed snow loses vapor to colder overlying air, by diffusion, convection, and wind pumping [e.g. Bader, 1939; Benson, 1962; Gow, 1968; although summertime formation of depth hoar has been recognized, e.g. Benson, 1962].

Colbeck [1989b] modeled the effects of annual and diurnal temperature cycles and solar radiation on grain growth in polar, alpine, and seasonal snows. He calculated that diurnal radiative and temperature forcing should cause rapid grain growth near the surface of seasonal and alpine snows; however, he assumed a low value for radiative heating in polar snow, and estimated that depth-hoar formation on ice sheets must be linked to the annual temperature wave.

A potential problem with forcing polar depth-hoar formation by seasonal temperature changes is that we typically observe depth hoars to be a few centimeters thick, with sharp basal contacts, but the 1/e depth for penetration of the warmth of a summer is several meters; there does not seem to be a good mechanism for concentrating the mass loss from such a broad temperature gradient into a thin layer with a sharp base, as observed. Below we show that the radiative forcing on summer days in central Greenland is sufficient to cause strong near-surface warming and surface-temperature gradients, localizing depth-hoar formation near the surface.

Methanesulfonic acid (MSA; CH_3SO_3^-) is an sulfur-bearing anion formed from the atmospheric reaction of dimethylsulfide (DMS) with OH radicals. In high-latitude regions, aerosol MSA exhibits a strongly seasonal signal with high concentrations during the summer months [Saltzman et al., 1986; Watts et al., 1987; Ayers et al., 1986]. This seasonality stems from two factors: 1) spring/summer increases in oceanic productivity cause increased DMS emissions; and 2) lack of wintertime photochemistry causes atmospheric OH concentrations to be low and thus DMS conversion to MSA to be slow. The seasonality of MSA in recent snow and ice reflects its

¹ Earth System Science Center and Department of Geosciences, The Pennsylvania State University.

² Rosenstiel School of Marine and Atmospheric Science, University of Miami.

³ Branch of Sedimentary Processes, United States Geological Survey.

distribution in the aerosol, as demonstrated by the relationship between MSA and oxygen isotopes in ice from southern and central Greenland [Whung et al., 1989]. In Greenland, MSA may originate from either regional emissions from the surrounding Greenland and Norwegian Seas, or from long-distance transport from lower-latitude regions in the North Atlantic. MSA is an excellent seasonal tracer because it is chemically stable, and is not subject to contamination by sampling or polar-camp operations [Saltzman, unpublished data].

Methods

We undertook a series of observations of snow in the top few meters at the GISP2 site. Detailed observations were undertaken in one two-meter pit which was back-lit to highlight stratification, and in a series of shallower pits dug every few hours to few days. Less-detailed observations were conducted in other pits as deep as six meters. Measurements included qualitative observations, volume-mass density sampling using box samplers or standard SIPRE snow-density tubes, and thin sections prepared using dimethyl phthalate as a pore filler. Samples were collected for MSA analysis using stainless-steel box samplers and were stored frozen in sealed plastic bags prior to analysis.

We also conducted high-resolution temperature measurements in our pits to monitor diurnal forcing. We used a digital thermometer with a single thermocouple probe (K-type) having a time constant of a few seconds. To avoid radiative heating of the probe, air temperatures were measured in the shadow of the observer. For shallow snow, we inserted the probe into a layer, shaded it, and observed the temperature evolution. Rapid cooling of the probe was followed by a break in slope and slower cooling of the snow; we extrapolated the snow-cooling curve back to time zero to obtain the snow temperature.

Measurements of MSA were made on-site with a modular anion chromatograph with chemical suppression, using AG4/AS4 and AMMS columns (Dionex). The eluant used for the analysis was 5.5 mM NaOH, with 11.25 mM H₂SO₄ as the regenerant. Samples were injected using an anion preconcentration column; volumes ranged from 5 to 8 ml. The detection limit of the analysis under these conditions is 0.2 ppb.

Results

Near-Surface Observations

A series of wind- and snowstorms at the GISP2 site ended during the evening of 19 June 1990, leaving a surface with scattered new fine-grained, dense dunes (sastrugi) and with a widespread but discontinuous wind crust (1 to 5 mm-thick wind-packed layer) overlying flat-lying regions and older dunes (1-2 days old; typically 100

mm high and 1-2 m wide) of relatively homogeneous, fine-grained snow. A surface hoar about 5 to 10 mm thick was deposited that night.

Over the next week, clear skies, high temperatures (afternoons greater than -10 C), and light winds prevailed. After only 24 hours of this weather pattern, a 5 to 10 mm thick depth hoar developed in the slopes of older dunes facing the afternoon sun. On the dune we studied in greatest detail, the depth hoar developed larger grains (mean intercept more than doubled in three days) and lower density than the snow just beneath it (less than 220 kg/m³, compared to 388 kg/m³ after four days); the depth hoar thickened during the days following our initial observations, but did not appear to change density greatly. The snow at the same depth as the depth hoar but on the shady side of the dune appeared similar to the snow beneath it and to the snow beneath the depth hoar when first observed, and maintained this appearance until a shady-side depth hoar began forming two to three days later.

MSA concentrations were measured on material from within, above, and below the depth hoar, and from the equivalent depth 10 to 20 cm away on the shady side of the dune. These data, shown in Figure 1, are consistent with vapor loss causing increased MSA concentrations in the depth hoar. Based on MSA concentrations and densities in the material below the depth hoar, it appears that the vapor loss occurred primarily upward, causing surface-hoar growth or loss to the free atmosphere.

Over the few days following 6/21, depth hoar first developed beneath flat areas and beneath the sides of dunes that were shaded during afternoons, and then on the new, fine-grained dunes lacking wind crusts. This order may suggest some role for wind crusts in depth-hoar formation, or that the very fine grains and high density of the new dunes reduced solar heating by conducting heat away efficiently, or that densification by sintering of the fine-grained dunes kept pace with the mass loss.

Temperature Measurements

Based on Colbeck [1986b], we hypothesized that the observed near-surface mass loss was caused by solar heating. We then collected detailed temperature profiles beneath a flat region at one- to two-hourly intervals (Figure 2), which show steep temperature gradients that would cause net vapor motion out of the depth hoar forming near 10 mm depth. Vapor motion would be by diffusion, and possibly by wind pumping and thermal convection, and could involve direct transfer or repeated condensation and sublimation from grain to grain [Colbeck, 1983; Sommerfield, 1983]. The diffusive mass flux alone (estimated by a numerical integration of eq. 7 in Whillans and Grootes [1985]) would remove 100 kg/m³ from the developing depth hoar in three to five

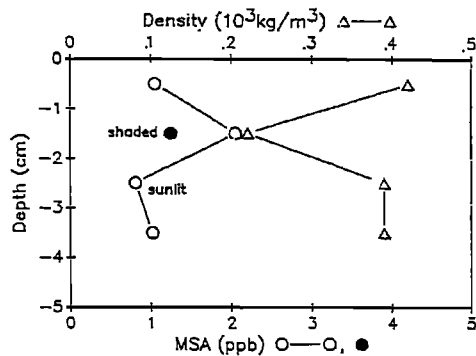


Fig. 1. MSA concentrations and densities measured in a shallow snowpit on a dune on June 21. Mass loss and resulting increase in MSA concentration are evident near 1 cm depth on the sunny side of the dune where a depth hoar has formed, but not in deeper snow or on the shady side of the dune where no hoar formation has occurred.

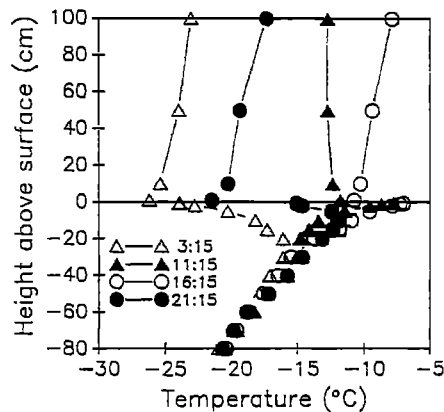


Fig. 2. Selected temperature profiles, above and below surface, for one day during depth-hoar formation.

days (Figure 3). Given the possibility of wind pumping [Clarke et al., 1987; Colbeck, 1989a] and thermal convection [Johnson et al., 1987], the energy available is sufficient to explain the observed density loss in the near-surface layer warmed by solar radiation.

Pit Observations

Our detailed observations in deeper pits (2 to 6 m) confirm the near-surface data. Some of the depth hoars in the pits show scours on their upper surfaces, indicating that they formed at very shallow depth. In density, thickness, and other characteristics, the depth hoar we observed forming is completely comparable to those in the pits.

MSA data also show that at least over the last several years, depth hoars have formed during the summer. As illustrated in Figure 4 from our detailed 2 m pit, the peak concentration in MSA typically occurs above the main depth hoar for that year. Because depth hoar forms essentially at the surface, this indicates that the depth

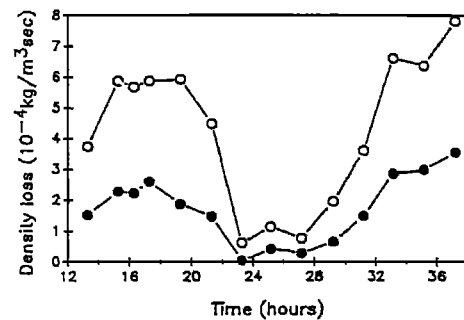


Fig. 3. Rate of density loss by diffusion from depth hoar calculated from measured temperature profiles. The upper curve applies if the air temperature measured 1 cm above the surface also applies at the surface. The lower curve applies if the temperature varies linearly from 1 cm above the surface to the depth hoar.

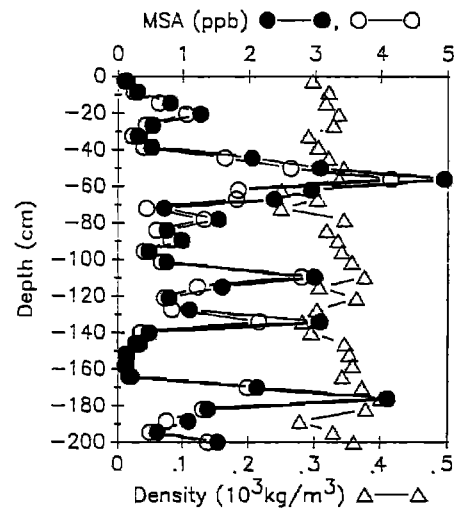


Fig. 4. MSA concentrations, densities, and depth-hoar locations in the detailed 2 m snow pit. MSA peaks typically occur above depth hoars and are larger than can be explained by mass transfer associated with depth-hoar formation.

hoar forms before the late-summer MSA peak. It is worth noting that the mass loss associated with depth hoars is only about a factor of two, but that the height of the MSA summer peaks is roughly an order of magnitude or more. Thus, the vapor flow associated with depth-hoar formation cannot be responsible for the observed concentration peaks.

Conclusions

Direct observations show that a depth hoar formed during late June and early July at the GISP2 Summit site. Formation occurred at a depth of about 5 to 10 mm, where solar radiation caused a temperature rise of several degrees compared to overlying air or underlying snow. The measured increase in MSA concentration is consistent with measured loss of mass during formation

of the depth hoar. These observations are fully in accord with the calculations of Colbeck [1989b] showing that intense solar heating and high temperatures are necessary and sufficient for growth of the coarse crystals of depth hoar.

Comparison of depth-hoar occurrences with the late-summer peaks of MSA in snow pits shows that the depth hoars have formed during the summer over at least the last few years. We suggest that summertime processes at Summit, and possibly at other polar sites, are responsible for the annual hoar layer, and that this annual hoar layer can be used as a seasonal marker wherever it is recognized in ice cores. The data also show that, at least at this site, mass loss due to hoar formation is not a significant factor determining the annual cycle of MSA concentrations in the snow. It may, however, change the concentration of other immobile impurities in hoar layers by as much as 50-100% during the first year, depending on the seasonality of deposition.

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R.B. Alley and K.M. Cuffey, Earth System Science Center and Department of Geosciences, The Pennsylvania State University, University Park, PA 16802.

E.S. Saltzman, Department of Marine and Atmospheric Chemistry, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149-1098.

J.J. Fitzpatrick, Branch of Sedimentary Processes, United States Geological Survey, Denver, CO 80225

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