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RESEARCH ON THE SEASONAL SNOW OF THE ARCTIC SLOPE

from

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SEASONAL SNOW OF ALASKA

Alaska is famous for its glaciers which cover an area of nearly 10^5 km^2. However, glaciers cover only 5% of Alaska's total area (1.5×10^6 km^2), while all of the state is subjected to seasonal snow. The physical properties of this snow, its thickness, the length of time it remains on the surface, and the physical processes which occur within it, above it, and below it, are of fundamental importance to the physical and biological environment. Alaskan snow varies significantly within its four climatic zones, but can be described according to three extreme types (Benson, 1982).

1. Tundra Snow - primarily above timberline and on the entire arctic slope.
2. Taiga Snow - primarily in the interior, between the Brooks Range and the Alaska Range.
3. Maritime Snow - primarily in the coastal mountains of Southeastern and Southcentral Alaska.

Tundra Snow of the Arctic Slope

Alaska's seasonal snow lasts longest on the Arctic Slope, where it is present for three quarters of the year. Alaska's arctic snow cover differs from the hydrologically important snow of the Western United States in that it is colder, the temperature gradients within it are steeper, and its thickness is less. However, it lasts longer and enters more directly into the ecology (including most human activity) as snow itself (Pruitt, 1970) rather than serving primarily as a cold storage water reservoir. This snow plays an essential role in physical and biological processes on the Arctic Slope.

The importance of snow on the Arctic Slope as a dominant feature of the environment is being increasingly recognized. The U.S. Soil Conservation Service (SCS) has the prime responsibility for snow surveys in Alaska which began with a network of ten snow courses in 1961 and now operates over 150 of them. For the first fourteen years this network did not include the Arctic Slope. The first snow-course measurements on the Arctic Slope began with a Wyoming gage installed by C. Benson, of the Geophysical Institute of the University of Alaska in 1975. A dozen of these gages operate now in the Arctic and the SCS currently receives more requests for information about snow on the Arctic Slope than for any other region in Alaska (Clagett, personal communication).

From a scientific point of view, there is much to learn about snow on the Arctic Slope. Among the primary questions are:

(1) Quantity

Most precipitation on the Arctic coastal plain comes in the form of snow (80% at Barrow and Barter Island). It is has been underestimated in the Weather Bureau records, which show annual mean precipitation values (from 1961 to 1979) of 11.3 cm for Barrow and 14.4 cm for Barter Island; our corrected values are 25 cm for Barrow and 32 cm for Barter Island (Benson, 1982; Clagett and Benson, 1983). We have found that total precipitation at the R4D site is about the same as at Barter Island. However, the snow to rain ratio measured at the R4D site is comparable to that found in interior Alaska rather than the Arctic coast, i.e., about 35% of the total comes as snow. This apparently results from rain storms which cross over the Brooks Range from the interior and affect the R4D area but do not reach the arctic coastal plain.

(2) Wind Action

Snow on the Arctic Slope is moved by the wind to a significant but largely unknown extent. As seen by the distribution of snow drifts, two wind directions, one from east-northeast, and the other nearly in opposition from the west, transport virtually all of the wind-blown snow on the broad coastal plain of the Arctic Slope. In the west, at Atqasuk, measurements indicate that the transport of wind-blown snow from the eastern winds (average of 72 metric tons per meter normal to the wind) is about twice that from the western winds, and that the values vary significantly from year to year (Benson, 1982).

In the southern part of the Arctic Slope, katabatic winds from the Brooks Range transport snow from the south; this is most pronounced in large river valleys such as the Killik River Valley. Wind transport of snow in the R4D research area is also from the south. The location of the boundary between the two wind systems across the Arctic Slope remains to be determined.

(3) Distribution

Significant east-west and north-south precipitation gradients exist. Snowfall at Barrow is about 80% of that at Barter Island. Snowfall at Barter Island is about 60% of the 50 cm measured on the McCall Glacier 100 km South in the Romanzof Mountains. There are regions with minimum snow cover which lie on the slope between the foothills and the Arctic coast (Holmgren, Benson and Weller, 1975). The boundaries of these regions, and the reasons for their existence need to be investigated. They are of special interest because of their use as prime calving ground by caribou (Kuropat and Bryant, 1980).

(4) Physical Properties

The tundra snow in the Arctic Slope during winter is dry and its wind-blown sastrugi surface strongly resembles the year-round surfaces of the Greenland and Antarctic Ice Sheets, or the winter snow surface of the adjacent Arctic Ocean. In many places the structure of the tundra snow resembles the top annual stratigraphic unit of the dry-snow facies of an ice sheet. It consists of a hard, wind-packed layer overlying a low density depth hoar layer. This snow is counted on by seismic exploration crews to protect the tundra from vehicles. Microtine rodents depend on it for protection from predators and weather during most of their lives.

(5) Physical Processes

The snow, the overlying air and the underlying soil and vegetation form a three-layer system in which heat and mass transfer processes are active. These processes lead to hard, wind-packed layers (wind slabs) and soft, low-density depth hoar layers (Benson, 1969, 1982). These extreme formations are of special biological significance because animals which live under the snow (like lemmings) depend on the soft depth hoar when they make tunnels, and are partially protected from predators by the wind slabs. Animals which feed by digging through the snow (like caribou) avoid the wind slabs and depend on the depth hoar, which provides access to food more easily than would the hard-packed snow.

Especially interesting phenomena accompany the presence and movement of trace gases in the snow. The most important of these gases is, of course, water vapor because its movement in the snow is essential for metamorphism of the snowpack. The water vapor moves by diffusion and convection along vapor pressure gradients which accompany temperature gradients in the snow (Trabant and Benson, 1972; Johnson et al., 1987; Sturm, 1989). This process forms the depth hoar layers and contributes to the formation of wind slabs as well. Movement of water vapor in the snowpack results in a 20% ± 3% reduction of the electrical conductance of the meltwater derived from the snow (Trabant and Benson, 1972). This may result from the loss of volatiles while the snow grains sublime. Measurement of the stable isotopes $^{18}O/^{16}O$ and $^{2}H/^{1}H$ comprising the snow grains demonstrated a significant movement of water vapor within the snow and upward from the frozen soil below into the snow (Friedman, Benson and Gleason, 1990). This research, done in the Fairbanks area to gain insight into the processes, applies equally to the Arctic Slope. During the 1989-90 winter, heat flux and vapor flux from the soil into the overlying snow was measured at the R4D site as well as at Prudhoe Bay, Fairbanks and Valdez. These studies were done cooperatively with Dr. Matthew Sturm of CRREL.

Another interesting gas is CO_2 which is more concentrated within the snow pack (with highest values at the bottom) than in the overlying ambient air. Not only are the values higher, but they show short-term increases by a factor of two or three in the springtime (Kelley, Weaver and Smith, 1968; Coyne and Kelley, 1974). The reasons underlying these phenomena are not understood, and this subject, although not part of the proposed research, should be pursued.

A significant, but unknown, part of the snow deposited on the Arctic Slope is lost directly to the atmosphere by sublimation and evaporation. Much of this loss occurs while the blowing snow is airborne (Schmidt, 1972; Tabler, 1976); the rest is lost from the surface, especially during spring after vegetation perforates the snow surface (Benson et al., 1975; Dingman et al., 1980). This difficult problem requires continued development of theoretical models of snow transport and deposition (Schmidt, 1972; Tabler and Schmidt, 1973; Tabler, 1980), and additional field research (Benson, 1982).

Because the Arctic Slope is underlain by permafrost, infiltration is severely limited and runoff in the streams is characterized by a large, single pulse during spring breakup (Dingman et al., 1980; Kane et al., 1987).

The above phenomena are involved in questions relating to the abiotic environment of natural biological systems and to man-made disturbances of the tundra. Roads and buildings interact with winds to cause variations in the pattern of snow drifts; this in turn modifies temperature and moisture conditions at the base of the snow pack. In particular, drifts formed along roads produce ponding or wet areas parallel to the roads, and research is needed on the physical processes associated with this, including the manner in which impurities, such as road dust, affect melting and evaporative rates.

SUMMARY OF RESEARCH IN PHASE I

Topographic and Orthophoto Maps and the UTM Grid Markers

The need for accurate, large-scale maps was apparent at the beginning of the multi-investigator R4D program. Since this need could not be met by simply enlarging existing U.S.G.S. maps, detailed photogrammetric mapping was done. Ground control was established by precision surveying in July and August 1984 with a Zeiss "Elta 2" total station instrument. A total of 50 points were located, 13 of which were pre-marked for the aerial photography. The U.S.G.S. bench marks: GAL (in the research area) and LAKE (14.6 km southwest of the research area) were both used to determine absolute location and azimuth. Aerial photographs at two scales were obtained using both black and white and color infrared film for each scale. Orthophoto negatives were prepared from which orthophoto maps were made at scales of 1:6000 and 1:1000. Topographic contour maps were also made at scales of 1:6000 with 5 m contours, and 1:1000 with 1 m contours. The contour maps were printed on the orthophoto maps; two sheets at 1:6000 scale cover the entire research area, and four sheets at the 1:1000 scale cover the intensive research area. Additional aerial color infra-red photographs were taken in 1985, and 1986 at the time when maximum chlorophyll was present and a special set was taken from which prints at scale 1:500 were produced. A grid system was established around the point GAL on the original map. A UTM grid was prepared for the site in 1988 and in 1989 a 1 km^2 square area was marked at 100 m intervals in the field with UTM coordinates on each marker. The details of establishing ground control, taking the vertical aerial photographs and preparing the photogrammetric products were presented in a report to the R4D investigators in 1986. The mapping and establishment of the UTM grid in the field were summarized by Benson (1989).

Digitized Maps

A Digitized Elevation Model (DEM) was prepared and combined with snow maps from this project and vegetation maps from Dr. Walker's project (Evans, et al., 1989).

Research on Seasonal Snow During 1984 to 1989

The seasonal snow has been measured to determine its total quantity, its physical structure and its distribution as a function of wind and topography. Observations of meteorological parameters and snowpack characteristics during winter and spring have yielded information on the seasonal evolution of the snow in quantitative terms. Methods for determining melt rates over large regions are being refined, in terms of the energy fluxes which control snow melting. A strong control is exerted by air mass advection on a broad scale.

(1) Evaporative Losses

The amount of the snowpack lost by evaporation varies from year to year but exceeds 40% over the entire area and varies from 10% to over 60% in individual test plots. In some ridge crest areas with shallow snow cover it probably exceeds 90%. Our methods of determining melt rates over large areas are being refined and we are beginning to apply remote sensing, digital techniques to the problem. This will enable us to extrapolate to other areas on the Arctic Slope.

(2) Distribution of Snow by Wind on Variable Topography

Distribution of snow across the R4D area was measured by combining several techniques. Snow depths, measured along selected traverses, are combined with pit studies to measure snow density, temperature and hardness profiles. In addition to providing water equivalent of the snow pack, the pit studies allow us to measure extreme snow types such as wind-slab and depth-hoar layers. Photographs were taken from control points at selected time intervals during each melt season. Three of four sets of oblique aerial photos were also taken during each melt season, except

1988 when the melt was too fast for us to get more than one set of vertical photos. In 1989 we experimented with vertical video data over the site and found it to be very valuable as a guide to mapping snow cover (Stow and others, 1989; George and others, 1990). The photography and video data permit us to extrapolate detailed measurements made at points and on traverses to broad areas. By this means, maps of the maximum end-of-winter snow cover were made.

There was significant difference in strength of wind action from year to year at the R4D site, and 1985 showed maximum wind slab formation. However, the direction of wind transport did not vary significantly. The sensitivity of snow distribution to topography is pronounced. Accumulation on lee slopes was about 65% more than on windward slopes, even though the slope angles were only 2 to 3 degrees. Some of the variability would not have been identified as being so clearly related to topography if our detailed topographic maps were not available.

Snow in the R4D area is transported by winds from the south. Southerly winds from the Brooks Range are felt in the northern foothills across the entire east-west extent of the range. The predominant, and much stronger, winds that affect most of the Arctic Slope (all of the coastal plain) are from the east or west as mentioned above. We have devoted attention to the boundary which separates the south flow from the prevailing east-west flows farther north. This is being done by making aircraft observations of drift directions and by measurements on the ground at Prudhoe Bay, Barrow, Wainwright, and Atqasuk. These observations have been combined with our flights to do oblique aerial photography over the R4D site.

The net winter transport of wind-blown snow can be expressed in units of tonnes (t, 10^3 kg) per meter normal to the wind (t m^{-1}). On the coastal plain the average values are 70 t m^{-1} from east winds, and 35 t m^{-1} from west winds with negligible amounts from other wind directions. In the R4D area the dominant flux is from south winds with values of 10 to 20 t m^{-1}. West winds move more snow than east winds but the transport is only about 1 t m^{-1}. Although the amount varies from year to year, the basic distribution pattern remains remarkably constant.

(3) Snow and Vegetation

A few vegetation types have clear correlations with snow depth. An excellent example is moist dwarf-shrub, fruticose-lichen tundra (cassiope tetragona or salix rotundifolia) which has about 53% of its occurrences in areas with >30 cm of snow water equivalent although only about 1% of the total map area is in this snow class. This aspect of the program is being carried out cooperatively with D. Walker and B. Evans (Evans, et al., 1989).

(4) Snow Chemistry

Being present for over half the year, arctic snow acts as a collection filter for many chemical species, yielding information on the time-integrated depositional processes. Chemical species in the arctic snow pack may be concentrated and deposited by numerous processes including: incorporation of aerosol particles into clouds and subsequent precipitation, direct gas or aerosol deposition onto snow surfaces, wind transport of road or soil dust components, and biological processes. Since the arctic snow pack melts rapidly in the late spring, these chemical species will also be added to arctic ecosystems rapidly, and may represent a large fraction of the total annual input to arctic lakes for some species. Due to the sensitive nature of arctic ecosystems, contributions which arise from anthropogenic activities need to be considered carefully.

Arctic snow chemistry has been considered by Barrie et al [1985], Borys [1983], Weiss et al. [1978], Davidson et al. [1987], and others. Some of these studies suggest that current pollution levels contribute significantly to the concentration of numerous chemical species in arctic snow. For instance, Barrie used concentrations of SO_4^{2-} and NO^{3-} levels found in ice cores obtained from the Canadian Arctic to show that the amount of anthropogenic constituents reaching the Arctic has increased significantly in the 20th century.

Barrie reports pH's for snow of 4.5 to 5.0 in the Canadian Arctic, and attributes the acidity of this snow to contribution from acidic sulfate aerosols (i.e. "arctic haze"). Acidity in precipitation can arise from natural and anthropogenic sources (Charlson et al., 1987). The CO_2 equilibrium point yields a pH of around 5.6 depending on temperature; pH values between 5.0 and 5.6 in areas free of local contaminants often arise as a result of natural contributions; and pH's of less than about 5.0 generally are believed to contain anthropogenic contributions. Wind transported soil and road dusts can significantly increase the pH of snow, due to species such as calcium, magnesium and iron carbonates, oxides, and hydroxides. In the vicinity of Prudhoe Bay, barium salts have been found to increase the pH of ground water significantly (U.S. Fish and Wildlife Service, 1987).

At the R4D site a study of elution during snowmelt was done in 1987 and expanded in 1988. In 1988 elution studies were done in the snow at Fairbanks to prepare for the R4D study and to provide a basis for comparison.

In March 1988, a sampling program was undertaken to collect snowpack samples along the Dalton Highway along a south to north traverse from central Alaska to the arctic coast. Thirty-four samples were collected from seven different sites. Except at the R4D site, all samples were collected at distances greater than 1 km from the highway so as to minimize contributions from wind transported road dust. Near the R4D site, 10 samples were collected at sites between 1 m and 4 km from the Dalton Highway.

Results of the research on snow chemistry were summarized in the M. S. Thesis of M. Zukowski (1989). They show that snow collected in interior Alaska is comparable to precipitation measured in other remote unperturbed sites [Galloway, et al., 1982]. Snow on Alaska's North Slope has significantly higher concentrations of all species measured. Analysis of variance (ANOVA) confirms that at the 95% confidence level, concentrations of all species measured are statistically different on the North Slope as compared to interior Alaska. The elevated concentrations observed in North Slope snow may result from several different sources, including; wind transport of road dust, incorporation of "arctic haze" aerosol into cloud and snow particles, and gas or aerosol emissions from the Prudhoe Bay complex. Data collected at the R4D site indicates that transport of road dust does not exceed 200 meters. However, on the arctic coastal plain, the strength and prevalence of east-west winds and the low topographic relief may transport road dust further. Since NO_{3^-} is not present at high concentrations in road dust, arctic haze, or sea salt, the high NOx emissions from the Prudhoe Bay facility are a likely source of the observed NO_{3^-} in snow. Although little light is present during the dark arctic winter, oxidation mechanisms for NO and NO_2 can still produce HNO_3 either in the atmosphere or on the snow surface [Heikes and Thompson, 1983].

(5) Meteorology and Snowmelt

Micro-meteorological data are being obtained at the R4D intensive study site by Kane and Hinzman. These measurements are being used to determine heat and mass balance at the snow surface. With our radiation thermometer we determined that bare tundra surface surrounded by snow covered areas (at 0°C) experience high (+30 to 40°C) surface temperatures when air temperatures are about +10°C. The absorption of radiation by these surfaces warms the air and, with wind action, the melting of adjacent snow patches is accelerated.

In 1987 we initiated a study to assess the longwave radiation balance governed by large-scale advection of air masses. As a first step in this study, Dr. Sue Ann Bowling and the Principal Investigator determined, twice daily, the thickness of the 1000 to 500 mb layer in the atmosphere over the R4D site. This was done by interpolation from the weather maps. The layer thickness is a convenient measure of the mean temperature in the lowest 5 km of the atmosphere. This in turn is one of the factors that govern the amount of incoming longwave (thermal IR) radiation.

Although the melting of snow at any particular site on the North Slope is normally complete within a week or less, the timing of snowmelt may vary by a month or more (Figure 1). Physically, energy can go into the latent heat of melting of snow if the energy flux toward the snow exceeds the black body flux outward from a surface at 0° (approximately 316 watts/ m^2). The energy fluxes include: (1) absorbed shortwave radiation, which is strictly limited by solar elevation angle (a known function of time of day and time of year), albedo (which has a feedback relationship with snowmelt), and the transparency of the atmosphere (which is determined largely by the humidity, temperature, and vertical motion of air advected into the area); (2) incoming longwave radiation (which is determined by the characteristics of the advected air with some possible modification by surface interactions such as heating of the lowermost layers by snow-free patches of ground); (3) sensible heat conducted or convected downward from the atmosphere and (4) a negative contribution from heat conducted from the surface into the snowpack until the entire snowpack is at the melting point. Term (4) is transient.

Term (3) is often thought of as being the route by which advective heat reaches the surface, but this is probably incorrect, because transfer of sensible heat downward through an inversion is very inefficient, especially at the low surface wind speeds typical of the R4D research site. Regardless of whether variation in (3), (2) or (1) dominates, however, the year to year differences must come from differences in the characteristics of advected air.

We made a preliminary investigation of the relationship between 1000-500 mb thickness, and the timing of snowmelt for four years of this study. The results are summarized in Figure 2. The initiation of snowmelt coincided with thickness values over the site between 5360 and 5400 m, with melt periods ranging from the beginning to the end of May. In April 1990 an exceptionally early, short-lived warm spell produced a large ice layer in the snow. It was the largest pre-melt-season ice layer observed in the six field seasons of this project. The data on thickness of the 1000 to 500 mb layer documented this event very well. The thickness exceeded 5400 m on 8 April. This was the earliest time such a thickness had observed between 1985 and 1990. Within three days it decreased to 5220 m and it did not exceed 5340 m until 10 May when melting began. When it reached 5400 m again on 16 May the melt season was well underway.

The preliminary nature of the above investigation must be emphasized. Three qualifications are considered:

- The 1000 to 500 mb thickness values for 1985, 1986, and 1987 were interpolated from maps prepared by the National Meteorological Center (NMC). These maps show surface pressure and the thickness of the layer between 1000 and 500 mb. Interpolation was necessary because the nearest sounding stations are Barrow (400 km), Barter Island (250 km), Inuvik (600 km), and Fairbanks (500 km). In Spring 1988 the NMC stopped producing the maps which were useful for interpolation and substituted a map at half the scale, which was totally automated. Before this change in format, the maps included some adjustment of contours by hand. The hand contouring made the maps more useful in regions like Alaska which have few data sources and complex mountain systems. Even these lower quality maps were unavailable to us for the 1988 melt season.
  As an additional complication, in January 1989, the National Weather Service Station at Barter Island was closed, so no more soundings are available from this (the closest) station. The 1989 diagram in Figure 2 is based on interpolation from a partial set of the lower quality, smaller scale maps. In 1990 we obtained copies of the original sounding data from

Barrow, Fairbanks, and Inuvik. We have written a program to calculate an interpolated thickness value from these data.

- The short and longwave radiation balances depend strongly on moisture content of the atmosphere and cloudiness over the R4D site. Clearly, we will not be able to obtain moisture data because no soundings are available at the R4D site. Cloud cover data are not complete, but can be estimated from radiometer data collected at the R4D site by Kane and Hinzman.
- Sensible heat transfer depends primarily on wind and temperature within the lowest few meters over the surface. These data are available from Kane and Hinzman and can be used to augment the simple comparisons between the 1000 to 500 mb layer thickness and snowmelt shown in Figure 2.

The thickness data appear to have potential both in forecasting snowmelt and in modeling interaction between the atmosphere and snow cover, further studies are needed: (1) to test the sensitivity of incoming longwave radiation to the properties of advected air masses and (2) to increase the sample size to include taiga sites.

Japanese Co-workers

Three researchers from the Institute of Low Temperature Science (Hokkaido University, Sapporo, Japan), joined us in our research during the 1988 and 1989 field seasons: Drs. D. Kobayashi, Y. Kodama, and H. Motoyama. Their primary interest is in the relationship between water chemistry and runoff and the effect of snow cover on the time lag of runoff. Their participation represents a major asset to this project and the parallel ones under direction of D. Kane and K. Everett.

PRODUCTS FROM PHASE I OF THIS RESEARCH

The products from Phase I of this research include the following:

1. Orthophoto and topographic maps of the R4D research area: Two sheets at 1:6000 scale with 5 m contours, covering the entire R4D area. Four sheets at 1:1000 scale with 1 m contours, covering the intensive area.

2. Liston, G. E., G. J. Burger, J. M. Miller, and C. S. Benson, (1986). Snowmelt on Alaska's Arctic Slope as seen by LANDSAT. Cold Regions Hydrology Symposium, Fairbanks, Alaska, July 1986, Am. Water Resources Assoc. - Poster session.

3. Liston, Glen E., (1986). Seasonal snowcover of the Foothills Region of Alaska's Arctic Slope: A survey of properties and processes. M. S. Thesis, University of Alaska Fairbanks, Fairbanks, Alaska 99775.

4. Hinzman, L. D., D. L. Kane, C. S. Benson, and K. R. Everett, (1987). Hydrologic and thermal properties of the active layer. Presented at the 38th Annual Meeting of the American Institute of Biological Sciences at Ohio State University, 9-13 August, 1987.

5. Kane, D. L., L. D. Hinzman, C. S. Benson, and K. R. Everett, (1989). Hydrology of Imnavait Creek, an Arctic watershed. Holarctic Ecology, Vol. 12, p. 262-269, 1989.

6. Evans B. M., D. A. Walker, C. S. Benson, E. A. Nordstrand, and G. A. Peterson, (1989). Spatial interrelationships between terrain, snow distribution and vegetation patterns at an arctic foothills site in Alaska. Holarctic Ecology, Vol. 12, p. 270-278.

7. Zukowski, M. D., (1989). A study of Northern Alaskan snow chemistry. M. S. Thesis, University of Alaska Fairbanks, Fairbanks, Alaska 99775.

8. Benson, C., 1989. Research on the seasonal snow of Arctic Alaska. Paper presented at AAAS 40th Arctic Science Conference 14-16 September, 1989, Fairbanks, Alaska. P. 10 of proceedings.

9. Zukowski, M., D. Jaffe and C. Benson, (1989). Studies of Northern Alaskan Snow Chemistry. Paper presented at AAAS 40th Arctic Science Conference 14-16 September, 1989, Fairbanks, Alaska. P. 10 of proceedings.

10. Benson, C., (1989). Specialized Mapping in the R4D Research Area near Toolik Lake Alaska. Paper presented at AAAS 40th Arctic Science Conference 14-16 September, 1989, Fairbanks, Alaska. P. 52 of proceedings.

11. Stow, D. A., T. H. George, A. S. Hope and C. S. Benson, (1989). Aerial videography and Radiometry for Spatial Biophysical Studies in Alaska. Paper presented at AAAS 40th Arctic Science Conference 14-16 September, 1989, Fairbanks, Alaska. P. 54 of proceedings.

12. Walker, D. A., M. D. Walker, P. J. Webber, C. S. Benson, A. S. Hope, and D. A. Stow, (1989). History and Pattern of Disturbance in Alaskan Arctic Ecosystems: A Hierarchial approach to analyzing anthropogenic and climate-induced change. Paper presented at AAAS 40th Arctic Science Conference 14-16 September, 1989, Fairbanks, Alaska. P. 9 of proceedings.

13. George, T. H., C. S. Benson, and D. A. Stow, (1990). Applications of Vertical Airborne Video Data. Paper presented at the Annual Alaska Surveying and Mapping Conference of the American Society for Photogrammetry and Remote Sensing, February 5-9, 1990, Anchorage, Alaska.

14. Kane, D. L., L. D. Hinzman, C. S. Benson, and G. E. Liston, (1990). Snow hydrology of a headwater arctic watershed. Presented at the 38th Annual Meeting of the American Institute of Biological Sciences at Ohio State University, 9-13 August, 1987, paper submitted to <u>Journal of Water Resources</u>, 1990.

15. Friedman, I., C. Benson, and J. Gleason, (1990). Isotopic changes during snow metamorphism. Paper presented at the Epstein Symposium on Stable Isotope Geochemistry, December 1989, and submitted to <u>Geochemica et Cosmochimica Acta</u>, 1990.

16. Jaffe, D. and M. Zukowski (1990). Chemistry of the snowpack in Northern Alaska, in preparation.

NOTE: Two M. S. Theses have resulted from this research (items 3 and 7 in the above list).

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