DOE/ER/60245--T2

FINAL REPORT
SEASONAL SNOW OF ARCTIC ALASKA
R4D INVESTIGATIONS

DEPARTMENT OF ENERGY
(DE-FG06-84ER60245)

RECEIVED
SEP 03 1993
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FEBRUARY 1993

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ABSTRACT

Seasonal snow is present on the Arctic Slope of Alaska for nine months each year. Its presence or absence determines whether 80% of the solar radiation is reflected or absorbed, respectively. Although life on the Arctic Slope is adapted to, and in some cases dependent upon seasonal snow, little is known about it from a scientific point of view. Its quantity has been grossly underestimated, and our knowledge of its distribution and the extent of wind transport and redistribution is very limited.

This research project dealt with the amount, regional distribution and physical properties of wind blown snow and its biological role in the R4D area of the Arctic Slope. Physical processes which operate within the snow that were studied included the flux of heat and vapor and the fractionation of stable isotopes through it during fall and winter, and the complex heat and mass transfer within the snow and between snow, its substrate and the overlying atmosphere during the melt period.

The distribution of wind-blown snow was mapped in the R4D research area at its maximum extent at the end of winter in 1985, '86, '87, '88, '89, and 1990. The technique of making snow maps over an extended area evolved during the six years that were covered. It included detailed studies in snow pits at selected sites, probing of snow depth along traverses and photographs of the snow cover during the melt season; the photos were taken from control points on the ground and from the air. In 1989 and 1990 we experimented with vertical photos and with video cameras to get mosaics of the snow distribution as the melt season progressed. Continued improvement in mapping snow cover especially over larger areas is being worked on in succeeding projects.

During 1987 and 1988 the snow chemistry was studied, both at the R4D site and along a traverse from the Yukon River along the Haul Road, through the R4D site, to Prudhoe Bay. The purpose was to describe the areal distribution of major ions and trace metals and to discern sources of impurities in the snow. A distinct break in snow chemistry occurred near the Toolik Lake-R4D area. North of it, most impurity concentrations increased by an order of magnitude, pH increased from about 5.5 to 8, and the snow chemistry was considerably more variable. Snow chemistry near Prudhoe Bay is probably influenced by the extensive activities associated with the oil industry. An elution study, done at Fairbanks, and in the R4D area, showed that the first-formed melt water contained 3-9 times higher anion concentrations than nearby bulk snow.

Snowmelt on the North Slope of Alaska is a rapid process, with the winter's snowpack often disappearing within a week to 10 days of initiation of rapid melt. The dates of the initiation and completion of snowmelt, however, may vary by almost a month from year to year. Since the fraction of available solar radiation which is actually absorbed roughly quadruples during snowmelt, the timing of snowmelt is critical to the energy balance of the tundra. The primary external seasonal control on spring warming is the progressive change in the pattern of solar elevation through the day, and this does not change significantly from year to year. Inter-annual differences in snowmelt must therefore depend on secondary factors, primarily the depth of the snowpack (which influences both the effective albedo of the pack and the energy surplus needed for complete melt) and the characteristics of advected air.

The influence of advected air on the start of snowmelt was examined using six years of detailed snowmelt measurements from the Imnavait Creek watershed. We used atmospheric thickness, which is the vertical distance from the 1,000 mb surface to the 500 mb surface in the atmosphere, as a measure of atmospheric warmth. (Atmospheric thickness is directly proportional to Kelvin temperature.) For the six years studied, there was good agreement between the start of snowmelt on the tundra and an interpolated atmospheric thickness of 5400 m, with no obvious effect of either date (early to late May for snowmelt) or depth of the snowpack. The association held strongly enough that we were able to predict correctly the formation of a melt layer when the thickness increased briefly to above 5400 m early in April 1990.

The interpretation of relationships between snow and vegetation was expanded in cooperation with Dr. D.A. Walker.

INTRODUCTION

Alaska is famous for its glaciers which cover an area of nearly 10^5 km². However, glaciers cover only 5% of Alaska's total area (1.5×10^6 km²) all of which 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, above, 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 differs from the hydrologically important 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, but it lasts longer and enters more directly into the ecology (including most human activity) as snow itself 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 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 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).

This project deals with the seasonal snow on Alaska's Arctic Slope. It was done in cooperation with three other R4D projects (directed by D. Kane, K. Everett, and D. Walker). Although the most intensive research was in the R4D area, it is important to relate its snow cover with that of the entire Arctic Slope. The goals included determination of the amount of precipitation which comes as snow, the wind transport of this snow and its depositional pattern as influenced by drifting, the physical properties of the snow, the physical processes which operate in it, the proportions of it which go into evaporation, infiltration and runoff, and the biological role of the snow cover. The most important feature of the snow pack is its control of the radiation balance. The virtually unbroken tundra snow surface has an albedo (surface reflectivity) of about 80% or more. When the snow melts, in late May or early June, it

disappears rapidly (in less than two weeks) and the albedo drops to about 15% (Holmgren et al., 1975). Thus, a four or five-fold decrease in albedo occurs at the same time when the amount of incident radiation is rapidly increasing; the net result is a dramatic change in the amount of radiation absorbed at the surface (McFadden and Ragotzkie, 1967; Weller et al., 1972; Benson et al., 1975).

Topographic and Orthophoto Maps and the UTM Grid Markers

In addition to research on snow, this project included detailed mapping of the entire R4D area.

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.

GRID MARKERS

A grid system was established around the USGS Bench Mark "GAL" on the original maps. The point "GAL" was defined as N 10,000 and E 10,000 to avoid negative grid points in the research area. The "GAL" grid appears on the borders of the maps and is keyed to cross-marks throughout the maps. The grid points were not used by all investigators and there was an apparent need for more detailed grids for individual projects. After discussion at several of our meetings of the Principal Investigators, it was decided that a detailed grid should be established based on the Universal Transverse Mercator (UTM) grid. UTM grid markers are on all USGS and Military maps, so this seemed to be a better choice than creating an arbitrary grid.

Between 12 and 14 July 1988 C. Benson and D.A. (Skip) Walker walked around in the R4D Site to select the best place to set up a UTM grid for the project.

Between 16 and 27 August 1988, C. Benson and two student assistants (David Luchini and Clark Pelz) surveyed and installed a UTM grid in the R4D research area. It consists of a grid laid out in a 1 km² area with 100 m between grid points. Each grid point is marked with a fiberglass stake with UTM coordinates written on it. The field notes are in Benson's Book 53 P. 99-155.

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 that report is attached as Appendix A. The mapping and establishment of the UTM grid in the field were summarized by Benson (1989). The resulting photogrammetric maps and the UTM grid markers in the field have been used by all R4D investigators. Figure 1 shows the orthographic and topographic contour map in the research area with both the "GAL" and the UTM grids on it.

.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).

BROADENING OF THE SCOPE

Our initial attempt, in 1988, to understand the influence of large-scale advection of air masses on snow melt yielded good results. We used the thickness of the 1000 to 500 mb layer as an index of temperature throughout the first 5 km of the atmosphere, and therefore the magnitude of incoming longwave (thermal Infrared) radiation. The original objectives of this research included a regional study of snow on the entire Arctic Slope. During the first year the scope was restricted to the R4D area. In the second and third years the primary focus was also on the R4D area, but measurements were made at Prudhoe Bay, Atkasuk and Wainwright to determine the flux of wind-blown snow on a wider scale. Additional broadening of scope was discussed at the San Diego R4D meetings in April 1986 and 1987, at the extrapolation workshop held at Penn State University in Spring 1987 and again at the review in Annapolis during Spring 1988. The broadening of scope included detailed studies of (a) snow chemistry and (b) controls on snowmelt exerted by large-scale advection of air masses on the longwave, thermal IR, radiation.

Research on Seasonal Snow During 1984 to 1990

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.

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 easier access to food than 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 $20 \pm 3\%$ 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 $^{18}\text{O}/^{16}\text{O}$ and D/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.

Distribution of Snow by Wind on Variable Topography

Distribution of snow across the R4D area was measured by combining several techniques. A major result of this work was to map the water equivalent of the snowpack in the research area. The figure in Appendix A locates the R4D area and Figure 1 shows the grids on the base map. Figure 2 locates key points used in preparing the snow distribution maps which are shown in Figures 3, 4, 5, 6, 7, and 8.

Snow depths, measured along selected traverses, were 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 on the ground at selected time intervals during each melt season. An example of these sequential photographs is presented in Figures 9 through 15 which show the East side of the hill that the survey point GAL is on.

Three or 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. An example of these aerial photos is shown in Figure 16.

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). We were able to make one video mosaic in 1989 (Figure 17), and two of them in 1990 (Figures 18, and 19).

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. 1985 showed maximum wind slab formation and the highest density snow, with maximum values of 0.54 g cm^{-3} . 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 Atkasuk. 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.

We recognize two major types of snow on the Arctic Slope. They differ in depth, density, overall structure, and thermal characteristics. They are: (1) the *veneer facies*, lying on and interacting with the tundra, and (2) the *drift facies* which forms in certain topographic settings usually called drift traps. The structural and wind-transport aspects of the snow are discussed in a paper by Benson and Sturm which is still in press but is attached here as Appendix B.

In general, the variability of snow properties in short spacial distances and from year-to-year is pronounced. In addition to the discussion in Appendix B, it is instructive to note the variation along the main basin transect (Figure 20) which goes through TK8 and passes near the runoff plots (see Figure 2 for locations); and the year-to-year variation measured along this transect (Figure 21).

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.

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 was carried out cooperatively with D. Walker and B. Evans (Evans, et al., 1987).

Snow Chemistry

A study of chemical components in the snow and the sequence and rate of their release during melt began in Spring 1987 and was expanded during the 1988 melt period. It included chemical analyses of snow in the R4D area and along a North-South transect from Fairbanks to Prudhoe Bay (Zukowski, 1989).

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 NO_x 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].

Meteorology and Snowmelt

Micro-meteorological data were 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 (Barnes PRT-5) 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 $+10^\circ\text{C}$. The absorption of radiation by these surfaces warms the air and, with wind action, the melting of adjacent snow patches is accelerated. The PRT-5 measurements were made in 1986, '87, and '88, and each year they showed wide variations over short distances.

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 21). 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°C (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 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 (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.

The influence of advected air on the start of snowmelt was examined using six years of detailed snowmelt measurements from the Imnavait Creek watershed. We used atmospheric thickness, which is the vertical distance from the 1,000 mb surface to the 500 mb surface in the atmosphere, as a measure of atmospheric warmth. (Atmospheric thickness is directly proportional to Kelvin temperature.) For the six years studied, there was good agreement between the start of snowmelt on the tundra and an interpolated atmospheric thickness of 5400 m, with no obvious effect of either date (early to late May for snowmelt) or depth of the snowpack. The association held strongly enough that we were able to predict correctly the formation of a melt layer when the thickness increased briefly to above 5400 m early in April 1990.

The results are summarized in Appendix C. 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. This was true even though the data used for the 1000-500 mb thickness were scaled from interpolated weather maps, the short and longwave radiation balances would be expected to vary strongly with moisture and cloudiness, and sensible heat transfer would depend primarily on the temperature within the lowest few meters of the surface. In view of the potential usefulness of this result both in the 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 on the problems of evaporative loss from the snow-tundra surface during the melt period and in the relationship between water chemistry and runoff and the effect of snow cover on the time lag of runoff. Their participation represented a major asset to this project and the parallel ones under direction of D. Kane and K. Everett.

The products from 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*, 12, p. 270-278.
7. Zukowski, M. D., (1989). A study of Northern Alaskan snow chemistry. M. S. Thesis, University of Alaska Fairbanks.
8. 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 *J. Water Res.*, 1990.
9. 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 *Geochimica Cosmochimica Acta*, 1990.
10. 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.
11. 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.

12. 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.

13. 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.

14. 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 Hierarchical 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.

15. 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.

16. Bowling, S. A. and C. S. Benson, (1992). A Useful Predictor of Interannual Variations in the Timing of Snow Melt on the North Slope of Alaska. Proceedings of the AAAS, 43rd Arctic Science Conference. Valdez, Alaska. Published by University of Alaska Fairbanks, p 39.

17. Jaffe, D.A. and M. D. Zukowski, (1993) Nitrate Deposition to the Alaskan Snowpack. *J. Atmos. Env.* (in press).

18. Benson, C.S., (1993) An Overview of Research on Snow in Alaska. In: Snow Watch '92, Detection Strategies for Snow and Ice; International Workshop on Snow and Lake Ice Cover and the Climate System, held at The Pillar and Post Inn, Niagara-on-the-Lake, Ontario, Canada. Published jointly by Earth-Observations Laboratory of the Institute for Space and Terrestrial Science and the World Data Center A for Glaciology. ed. by R. Barry, B. Goodison, and E. Ledrew. p. 135-143.

19. Benson, C. and M. Sturm, (1993). Structure and Wind Transport of Seasonal Snow on the Arctic Slope of Alaska, *Annals of Glaciol.*, (in press).

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

REFERENCES

- Barrie, L.A., D. Fisher, and R.M. Koerner, 1985. Twentieth century trends in Arctic air pollution revealed by conductivity and acidity observations in snow and ice in the Canadian High Arctic. Atm. Env., 19, 2055-2063.
- Benson, C.S., 1969. The seasonal snow cover of Arctic Alaska, Arctic Institute of North America, Research paper no. 51.
- Benson, C.S., B. Holmgren, R. Timmet, G. Weller, and S. Parfish, 1975. Observations on the seasonal snow cover and radiation climate at Prudhoe Bay, Alaska during 1972. In: Ecological Investigations of the Tundra Biome in the Prudhoe Bay Region, Alaska, Jerry Brown, Ed., Biological Papers of the University of Alaska, Special Report No. 2 (1975), pp. 12-50.
- Benson, C.S., 1982. Reassessment of winter precipitation on Alaska's Arctic Slope and measurements on the flux of wind-blown snow. USG R-288 Geophysical Institute, University of Alaska Fairbanks, Alaska.
- Borys, R.D., 1983. Snow crystal riming and Arctic snowpack chemical composition. In: Precipitation Scavenging, Dry Deposition and Resuspension. H.R. Pruppacher, R.G. Semonin, and W.G.N. Slinn, Eds. Elsevier Pub. Co., Inc. NY, 1983. pp. 1281-1287.
- Charlson, R.J., J.E. Lovelock, M.O. Andreae, and S.G. Warren, 1987. Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate, Nature, 326, 655-661.
- Clagett, G., and C.S. Benson, 1983. What is the true annual precipitation on the Arctic Slope? Paper presented at the Alaskan Branch Meeting of American Water Resources Association, Chena Hot Springs, Alaska, 10-11 November, 1983.
- Davidson, C.I., R.E. Honrath, J.B. Kadane, R.S. Tsay, P.A. Mayewski, W.B. Lyons, and N.Z. Heidam, 1987. The scavenging of atmospheric sulfate by Arctic snow. Atm. Env., 21, 871-882.
- Evans, B.M., D.A. Walker, C.S. Benson, E.A. Nordstrand, and G.W. Peterson, 1987. Spatial interrelationships between terrain, snow distribution and vegetation patterns at an Arctic foothills site in Alaska. Paper submitted to Holarctic Ecology.
- Galloway, J.N., G.E. Likens, W.C. Keene, and J.M. Miller, 1982. The composition of precipitation in remote areas of the world. J. Geophys. Res., 87, 8771-8786.
- Johnson, J.B., M. Sturm, D.K. Perovich, and C.S. Benson, Field observations of thermal convection in a subarctic snow cover. Proceedings of the International Symposium on Avalanche Formation, Movement and Effects, 14-19 September 1986, Davos, Switzerland IASH-AISH publication series, pub. No. 162, pp. 105-118, 1987.

- 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, Alaska 99775-0800.
- 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.
- Trabant, D., and C. Benson, Field experiments on the development of depth hoar. In: Studies in Mineralogy and Precambrian Geology, Geol. Soc. Am. Memoir 135, B.R. Doe and D.K. Smith, Eds., pp. 309-322, 1972.
- U.S. Fish and Wildlife Service, 1987. Effect of Purdhoie Bay reserve pitfluids of the water quality and macro-invertebrates of arctic tundra ponds in Alaska. U.S.F.W.S. report, Fairbanks, Alaska.
- Weiss, H.V., M.M. Herron, and C.C. Langway, Jr., 1978. Natural enrichment of elements in snow. Nature, 274, pp. 352-353.
- Weller, G., S. Cubley, S. Parker, D. Trabant, and C. Benson, 1972. The tundra climate during snowmelt at Barrow, Alaska, Arctic, 25(4): 291-300.

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1986 END OF WINTER SNOW WATER EQUIVALENT MAP **ECOLOGICAL RESEARCH SITE TOOLIK LAKE AREA, ALASKA**

Figure 4

Figure 5

Figure 6

Countour interval 5 cm. Water equivalent

1989 END OF WINTER SNOW WATER EQUIVALENT MAP

ECOLOGICAL RESEARCH SITE TOOLIK LAKE AREA, ALASKA

100 0 100 200 300 400 500
METERS

Figure 7

Figure 8

Figure 9: Photo of survey site GAL, 21 April 1985

Figure 10: Photo of survey site GAL, 11 May 1985

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BASIN TRANSECT

Figure 20: Snowpack water equivalent (cm) variation along the main basin transect

1985-1992.

SNOWPACK ABLATION 1985-1992

Figure 21: Snowpack ablation 1985-1992

APPENDIX A

Topographic and Orthophoto
Maps of the R4D Research Area
by

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Maps of the R4D Research Area
A report to R4D investigators

by Carl S. Benson

This report summarizes construction of the R4D topographic and orthophoto maps; it identifies the grid used on the map, lists coordinates of all ground-control points, and presents a sketch map which locates the research area and the map coverage of it.

Topographic maps at a scale of 1:6000 with 5-meter contour intervals were made of the R4D research area; the R4D intensive study area, within the research area, was mapped at a scale of 1:1000 with 1 meter contour intervals. Orthophoto maps were also prepared. The topographic and orthophoto maps were both prepared from two sets of aerial photographs taken especially for this purpose.

Ground control for aerial photogrammetry was established by precision surveying done by Glen Liston and helpers during July and August of 1984. The primary instrument used was a Zeiss "Elta 2" Total Station (theodolite - Electronic Distance measuring system). A total of 50 points were surveyed, 13 of which were pre-marked for aerial photogrammetry. The 50 points are listed here in seven subsets, including the azimuth point "Lake" which is off the map.

1. The USGS Bench Mark: ΔGal. This point has accurately determined latitude, longitude and altitude and served to locate the map and to define an azimuth. The azimuth was determined by sighting from ΔGal to the USGS bench mark: ΔLake.

- ΔGal: 68°37'13.045"N; 149°16'53.509"W, Altitude, 968.04m.
- ΔLake: 68°29'22.396"N; 149°19'39.209"W, Altitude, 1502.05m.

The azimuth between ΔGal and ΔLake is a bearing of 187°21'45.91" (from True North).

In our survey we have used ΔGal as an origin point and assigned it coordinates:

$x = 10,000.000$ $y = 10,000.000$ $z = 968.045$ (all values in meters).

These values were chosen to avoid negative x and y values. The grid of coordinates shows on the map.

2. Six pre-marked photo-control points for the large maps of the entire area, scale 1:6000 with 5m contour interval.
3. Six pre-marked photo-control points for the small maps of the intensive area; scale 1:1000 with 1m contour interval.

The pre-marked points were marked by white panels of fabric in the form of a cross with arms 6 m long. The arms show on the photos and can be used to identify 12 m lines for scale. The white panels are each 4 m long and there is 4 m gap between them with the point in the center. The arms are oriented True N-S and E-W so they provide azimuth on the photos as well as scale.

4. Eleven surveyed points in the drainage valley lying between the Toolik and Kuparuk rivers. These were not pre-marked for aerial photography but are marked in the field by wooden stakes bearing the designation "T-K". They are spaced at intervals of 500 m in the drainage valley. Each of them is fastened to a steel rebar which goes more than 1 m into the ground; the rebar pieces have marked survey caps on them.
5. Twelve surveyed points in the Toolik drainage valley. These were not pre-marked for aerial photography but are marked in the field by wooden stakes bearing the designation "T". Each is fastened to marked steel rebar as with the T-K series.

6. Three NGS-Alyeska Bench marks along the haul road.
7. Twelve extra points required to complete the survey.

The coordinates of these survey positions are listed in Table 1, and Figure 1 gives an overview of the maps.

Vertical aerial photographs were taken after all the pre-marked survey points were established. Both black and white and color Infra Red photography was done. Because of persistent bad weather in August and September 1984 it was difficult to complete the surveying and the aerial photography. The black and white photos were flown twice before a usable set, free of snow cover, was obtained. The 1984 color I.R. photos were not as good as they could be because the time of maximum chlorophyll had passed. Therefore, color I.R. photos were taken again in the summer of 1985 with excellent results.

We worked closely with the photogrammetrists at North Pacific Aerial Surveys (NPAS) in Anchorage to construct stereomodels for the photogrammetry. All survey points were verified and internally-consistent stereo models permitted us to make several products.

1. Orthophoto negatives were prepared and orthophoto maps were made at the scales of 1:6000 and 1:1000.
2. Topographic contour maps were made of the overall area at scale of 1:6000 with 5 m contour interval. These contour maps were printed on top of the orthophoto maps. Two map sheets at this scale cover the overall area (Fig. 1).
3. Topographic contour maps were made of the intensive study area at scale of 1:1000 with 1 m contour interval. These contour maps were printed on the 1:1000 scale orthophoto maps. Four map sheets at this scale cover the intensive area (Fig. 1).

TABLE 1. Coordinates of survey points established in the field for the R₄D photogrammetric maps.

	X	Y	Z
1) <u>USGS Bench Mark Control</u>			
GAL	10,000.000	10,000.000	968.045
2) <u>Large Map Control Points</u>			
1	6620.440	14,303.380	832.261
2	10,342.548	15,236.551	828.282
3	10,764.286	11,344.228	864.040
4	10,601.854	7067.927	972.881
5	7055.405	6913.080	794.571
6	6615.277	10,948.864	787.614
3) <u>Intensive Map Control Points</u>			
S-1	8232.099	9932.757	899.385
S-2	9167.113	9968.324	936.082
S-3	9415.168	9157.225	938.842
S-4	9453.845	8500.804	946.183
S-5	8651.619	8208.378	903.245
S-6	8280.463	9298.622	893.319
4) <u>Toolik - Kuparuk Drainage Stakes</u>			
T-K Culvert	7591.206	12,510.083	830.202
T-K 1	7783.596	12,048.756	835.711
T-K 2	7976.125	11,587.096	840.799
T-K 3	8168.567	11,125.657	847.503
T-K 4	8360.932	10,664.432	856.453
T-K 5	8553.322	10,203.096	865.909
T-K 6	8614.109	9706.934	871.755
T-K 7	8674.912	9210.688	882.689
T-K 8	8735.707	8714.490	891.926
T-K 9	8893.039	8240.000	899.226
T-K 10	9050.412	7765.385	904.921

5) Toolik River Drainage Stakes

T-Culvert	8554.495	13,063.064	839.996
T-1	8690.366	12,581.879	846.518
T-2	8826.201	12,100.825	854.002
T-3	8962.054	11,619.704	861.590
T-4	9097.980	11,138.302	870.229
T-5	9233.719	10,657.577	881.087
T-6	9369.520	10,176.635	895.396
T-7	9505.393	9695.568	910.817
T-8	9641.251	9217.574	925.170
T-9	9777.005	8733.785	939.989
T-10	9912.840	8252.708	947.123
T-11	10,048.686	7771.590	955.215

6) NGS - Alyeska Bench Marks

H153	7876.283	12,598.361	843.822
J153	9236.657	13,485.151	852.722
K153	10,606.090	14,374.994	834.478

7) Extra Points Required to Complete Survey

TM	9081.070	9965.045	936.170
MS117 Sub Pt	7674.713	11,302.565	865.131
MS117 Gate	7220.838	12,413.415	860.868
Pt 1 Sub Pt	6869.021	13,658.660	840.630
E.T. Hill	8979.280	13,321.220	853.012
J. Hill	9323.033	13,544.071	853.012
K. Flats	10,459.595	14,272.488	838.621
S-4 A	9596.121	8375.936	953.982
S-4 B	10,268.485	7996.386	968.852
T-K5 A	8599.166	10,093.194	868.852
T-K5 C	8590.403	9900.429	871.987
T-8A	9727.422	8909.389	935.013

LOCATION OF THE R4D AREA

R4D RESEARCH AREA
MAPPED AT 1:6000
5 M CONTOURS

INTENSIVE RESEARCH AREA
MAPPED AT 1:1000
1 M CONTOURS

ISOLATED WATERSHED

SNOW RESEARCH AREA

preprints &
abstract
removed
ds