Snow Survey Data for the Central North Slope Watersheds: Spring 2009

Fluting snow, photo by Sveta Berezovskaya

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Water and Environmental Research Center

February 2010

Kuparuk Foothills, Bullen Point, and Umiat Corridor Hydrology Projects

Report No. INE/WERC 09.01

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DISCLAIMER

The content of this report reflects the views of the authors, who are responsible for the accuracy of the data presented herein. This research was funded by the Alaska Department of Transportation and Public Facilities (AKDOT&PF), Department of Natural Resources (DNR) and supplemented by data from a National Science Foundation grant. This work does not constitute a standard, specification, or regulation.

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CONVERSION FACTORS, UNITS, WATER QUALITY UNITS, VERTICAL AND HORIZONTAL DATUM, ABBREVIATIONS, AND SYMBOLS

Conversion Factors

Multiply	By	To obtain
	Length	
Inch (in.)	25.4	millimeter (mm)
Inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (mm)
Mile (mi)	1.609	kilometer (km)
	Area	
acre	43559.826	square feet (ft^2)
acre	0.407	hectare (ha)
square foot (ft^2)	2.590	square mile (mi^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
Gallon (gal)	3.785	liter (L)
Gallon (gal)	3785	milliliter (mL)
cubic foot (ft^3)	23.317	liter (L)
acre-ft	1233	cubic meter (m^3)
	Velocity and Discharge	
foot per day (ft/d)	0.3048	meter per day (m/d)
square foot per day (ft^2/d)	0.0929	square meter per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/sec)
	Hydraulic Conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per day (ft/d)	0.00035	centimeter per second (cm/sec)
meter per day (m/d)	0.00115	centimeter per second (cm/sec)
	Hydraulic Gradient	
foot per foot (ft/ft)	5280	foot per mile (ft/mi)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Pressure	
pound per square inch ($lb/in.^2$)	6.895	kilopascal (kPa)
	Density	
slugs per cubic foot ($slug/ft^3$)	515.464	kilograms per cubic meter (kg/m^3)

Units

For the purpose of this report, both English and metric (SI) units were employed. The choice of "primary" units employed depended on common reporting standards for a particular property or variable measured. In most cases, the approximate value in the "secondary" units was also provided in parentheses. Thus, for instance, snow density was reported in kilograms per cubic meter (kg m^{-3}) followed by the approximate value in slugs per cubic feet (slug ft^{-3}) in parentheses.

<u>Vertical Datum:</u>

In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929), a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called *Sea Level Datum of 1929*.

<u>Horizontal Datum:</u>

The horizontal datum for all locations in this report is the North American Datum of 1983.

Abbreviations, Acronyms, and Symbols

AAS	Alaska's Arctic Slope
AKDOT&PF	Alaska Department of Transportation and Public Facilities
F	Fahrenheit (°F).
ft	feet
GWS	Geo-Watersheds Scientific
kg	kilograms
km^2	square kilometers
m	meters
NGVD	National Geodetic Vertical Datum
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
QA	quality assurance
QC	quality control
Slug	slug
SWE	snow water equivalent
UAF	University of Alaska Fairbanks
USGS	U.S. Geological Survey
WERC	Water and Environmental Research Center
www	World Wide Web

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Snow Survey Data for the Central North Slope Watersheds: Spring 2009

1. INTRODUCTION

This report is the fourth in a series of snow survey data reports, published each year since 2006 (Kane et al., 2006; Berezovskaya et al., 2007; Berezovskaya et al., 2008). This year's report differs from earlier ones in that it describes in a single document the snow data collected for three projects—Bullen, Foothills, and Umiat Corridor. Discussed in this report are the snow conditions observed during the 2009 end-of-winter snow surveys in watersheds east of the Colville River, including the Anaktuvuk, Itkilik, Kuparuk, Sagavanirktok, Kadleroshilik, Shaviovik, and Kavik River watersheds. Snowpack field studies focused primarily on the maximum snow water equivalent (SWE) accumulation of the 2008–2009 winter and the snowmelt that followed. Field activities started at the end of April because, by then, the snowpack reflects nearly all precipitation that has fallen from October to April (less sublimation) (Benson et al., 1986). Deficiencies in determining snow precipitation and sublimation imply that measurements of snow accumulated on the ground provide the most reliable observational component of the net winter water budget.

Assessment of maximum snow accumulation is critical information in snow hydrology studies. The seasonal snowpack constitutes winter storage of precipitation, induces considerable differences in surface energy balance, and affects the amount of soil desiccation that occurs within the organic layer overlying the permafrost (Kane et al., 1978). Snowmelt is a major hydrological event each year in the Arctic. For many larger river basins on Alaska's Arctic Slope, particularly in the basins of the Colville, and Kuparuk Rivers, peak discharge is the highest during snowmelt. These rivers drain a large area that extends from the Brooks Range through the northern foothills and across the coastal plain before flowing into the Arctic Ocean. Snow starts contributing to runoff in May in the southern foothills, and melting is usually complete within a month. Due to extremely high snowpack heterogeneity, knowledge of SWE spatial distribution is critical for understanding a river basin's hydrologic response during ablation. This report presents snow depth, snow density and snow water equivalent observational data for the central part of the Alaska's Arctic Slope. It summarizes 2009 data-collection procedures, accuracy of observations, and spatial distribution.

2. STUDY AREA

The study domain covers a 200-by-240-km region of Alaska's Arctic Slope (AAS) that is bound by the Brooks Range on the south and the Arctic Ocean on the north, and includes the Anaktuvuk, Itkilik, Kuparuk, Sagavanirktok, Kadleroshilik, Shaviovik, and Kavik River basins. The Anaktuvuk River, which is 215 km long, flows from a glacier in the Endicott Mountains to the Colville River. The Kuparuk River is 240 km long and has a drainage area of about 8140 km^2. The Sagavanirktok River is about 290 km long and has a drainage area of about 14,900 km^2. More than half (54%) of the basin area is located in the Brooks Range, and an additional 29% lies within the Foothills region. Only 17% of the basin falls within the Coastal Plain region. The Sagavanirktok River is confined between the Kuparuk River basin to the west and the Kadleroshilik and Shaviovik River basin to the east. The Kuparuk, Sagavanirktok, Kadleroshilik, and Shaviovik Rivers flow directly into the Beaufort Sea, while the other streams flow first into Colville River.

Approximately 90% of the Kadleroshilik River basin consists of coastal plain, with the remaining 10% in the foothills. The river is approximately 113 km and encompasses over 1500 km^2 in drainage area. The Shaviovik River, which is located east of the Kadleroshilik River, is the largest river between the Sagavanirktok and Canning Rivers. The river is 137 km and extends into the Brooks Range. The Shaviovik River drainage basin, approximately 4028 km^2 in size, includes the watershed of the Kavik River. The confluence of the Shaviovik and Kavik Rivers is located 18 km from the coast. The Kavik River extends 122 km to the south from this confluence and extends into the Brooks Range.

The southern and northern boundaries of the domain are at 68°10′N and 70°15′N latitude, respectively. The western and eastern boundaries of the domain are at 150°00′W and 146°30′W longitude, respectively. Elevation within the study area ranges from sea level to 2675 m (0 to 8025 ft). The topography is characterized by a flat northern portion (generally referred to as

Coastal Plain) and by gently rolling hills and valleys (*Foothills*) and mountain ridges (*Mountains*) of the Brooks Range to the south (Figure 1).

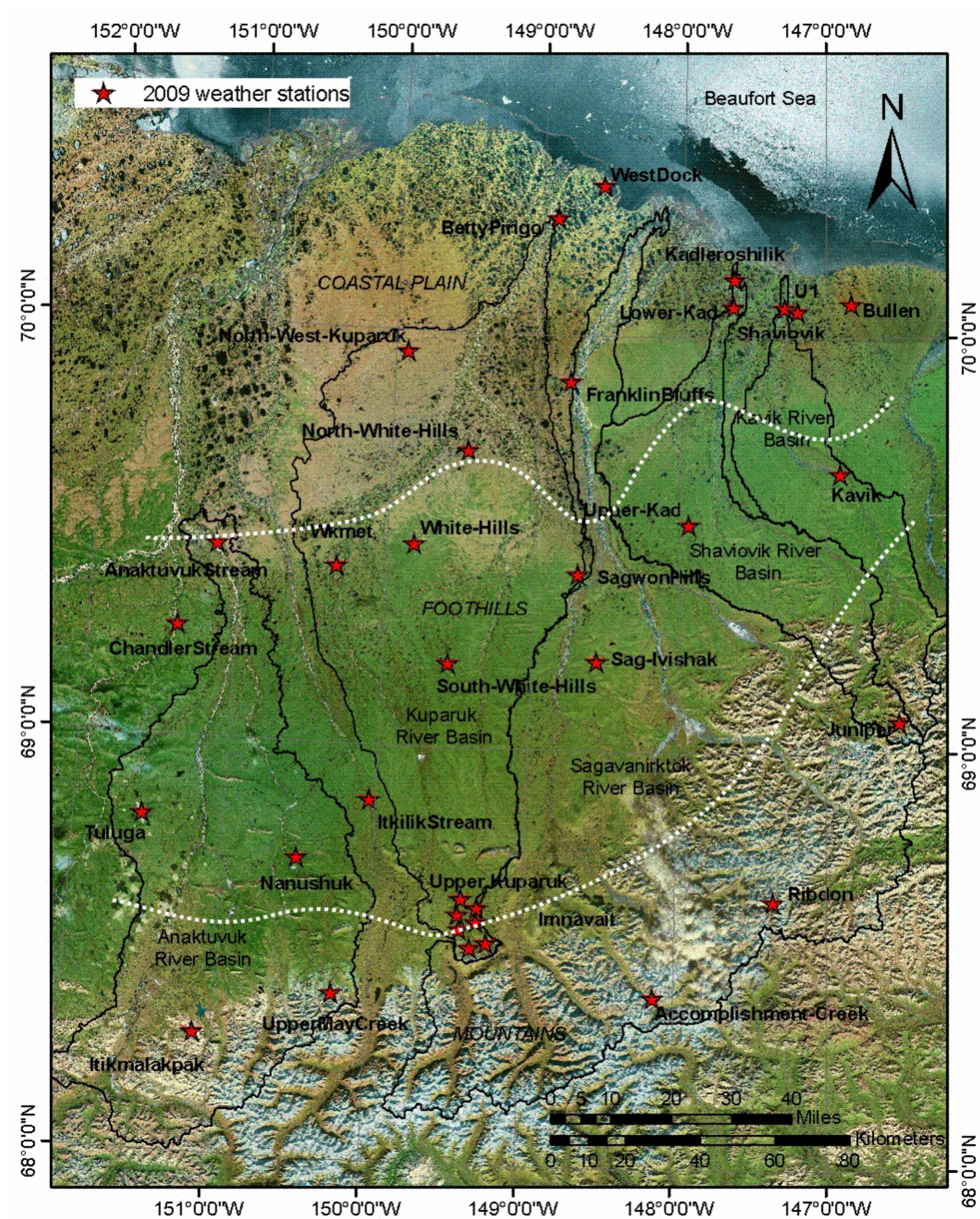

Figure 1. Geographical map of study area. Solid lines show watersheds of major rivers; dashed lines represent approximate boundaries of the Coastal Plain, Foothills, and Mountains regions. Weather stations are shown with star symbol.

Vegetation consists of sedge tussocks and mosses, which cover much of northern Alaska. Occasional groupings of willows, approximately 1 m (3 ft.) high, occur in hillside water tracts and in valley bottoms. The surface organic soils vary from live organic material at the surface to partially decomposed organic matter between 10 and 20 cm (4 in.–8 in.) in depth. The mineral soil in the glaciated areas is silt overlying glacial till (Kane et al., 1989). Overall, the topography and vegetation of the domain are representative of the AAS region.

3. SAMPLING METHODS

Snow surveys are made at designated stations throughout the domain to determine snow depth, as well as vertically integrated density and snow water equivalent. Except when making ablation measurements (see Section 3.2), most of the sites are visited once a year near the peak of snow accumulation, generally the last week of April. Our observations in the Foothills region show that the onset of ablation is typically in May. The end of April is a good time to capture end-of-winter SWE. March, April, and May are often the months of lowest precipitation, and therefore there is usually little accumulation between the end of winter snow surveys and ablation.

In addition to snow surveys, snow depths are collected continuously throughout the winter at meteorological stations, which are equipped with snow depth sensors. Snow depth sensor readings can be collected in near real time or downloaded in the field directly from a data logger.

3.1 Snow Survey

Our snow surveys include gravimetric SWE sampling and snow depth measurements collected over a 25-m-by-25-m area; this technique is often referred to as *double sampling*. The Alaskan snowpack is extremely heterogeneous, with snow depth being more variable than density (Benson and Sturm, 1993). Usually, double sampling yields an areal SWE estimate with a lower variance than is possible using collected snow cores only. Rovansek et al. (1993) showed that double sampling provides improved SWE estimates; they recommended sampling 12 to 15 snow depths for each snow core. This optimal ratio of snow depths to water equivalent, however, appeared to vary greatly (from 1 to 23), depending on weather and snow conditions. Currently, we use an optimal ratio of 10; that is, 50 depths accompany 5 snow cores.

Snow cores are sampled using a fiberglass tube ("Adirondack") with an inside area of 35.7 cm^2, equipped with metal teeth on the lower end to cut through dense layers of snow. The advantage of the Adirondack for shallow snowpack is that its diameter is larger than many other types of snow tubes; thus, it provides a larger sample of the shallow Arctic snowpack. To obtain a complete snow core, the Adirondack tube is pushed vertically through the snow while turning, until soil is encountered. At this point, snow depth is recorded. The tube is then driven further into the organic layer and tipped sideways, retaining a vegetation plug; this ensures that the complete snow column was sampled. The vegetation plug is removed and the snow is collected for weighing later in the laboratory. Five snow cores are usually taken to estimate average snow density.

We use constant 50-m lengths for the snow depth course, with a 1-m sampling interval along an L-shaped transect. Twenty-five depth measurements are made on each leg of the L; this strategy is used to account for the presence of snowdrifts in the area of measurement. The directions of measurement are chosen randomly. Snow depth measurements are collected using a T-shaped graduated rod (T-probe). The probe is simply pushed through the snow to the snow–ground interface.

Snow water equivalent is defined as

$$SWE = (SD * \rho_s) / \rho_w \tag{1}$$

where ρ_s is average snow density from the 5 snow core samples, ρ_w is water density, and *SD* is an average of 50 snow depths.

3.2 Snow Ablation

Starting with the 2007 Kuparuk Foothills snow survey data report, we have summarized long-term snow ablation observations (Table 1) that have been conducted continuously since 1985 from previously funded National Science Foundation, Office of Polar Programs projects.

Table 1. Summary of snow ablation sites from north to south.

Site Name	Period of Record	Comments
Betty Pingo	1993 to 2009	Surveyed near NRCS Wyoming gauge.
West Dock	1999 to 2009	150 m east of West Dock–GC1 Road, approximately one mile south of West Dock Meteorological Site.
Franklin Bluffs	1988 to 2009	Surveyed near Met site 1988 to 1998 (with some missing years), snow site moved west 700 m along access road 1999 to 2009.
Happy Valley	1999 to 2009	Survey site 150 m west of Dalton Highway from Happy Valley Airfield.
Sagwon Hill	1988 to 2009	Adjacent to the Sagwon Meteorological Site.
Upper Kuparuk	1999 to 2009	Adjacent to the Upper Kuparuk Meteorological Site.
Imnavait basin	1985 to 2009	Snow ablation measured at 4 sites on west-facing slope at mid-basin 1985 to 1988, at a 6-site mid-basin transect 1989 to 1997 and at a 6-site transect along UTM 612800 northing from 1999 to 2009.

3.2.1 Observations from 1985 to 2008

Measurement methods have changed over time as techniques have been modified to improve sampling accuracy and as the study area has expanded. From 1985 to 1992, SWE was estimated from 10 randomly collected snow cores. These cores were sampled using Adirondack tubes and weighed using mechanical scales, calibrated in inches of water. To overcome the difficulty of weighing samples in frequent high-wind conditions, cores were placed in ziplock bags in the field and weighed indoors, using the Adirondack mechanical scale and, after 1999, digital scales.

Following Rovansek et al. (1993), the double sampling technique, which was adopted in 1996, is still used (Section 3.1). During the transition period (1993–1995), 5 to 20 snow cores were taken, along with 50 snow depths. Snow depths have been measured using a variety of devices, such as the Adirondack snow tube, avalanche probes, T-handled graduated probes, MagnaProbe, and ski poles and rods with added graduated scales.

A number of observational sites have changed over time (Table 1). In 1985, SWE and ablation were observed only in the Imnavait Creek basin. Sagwon Hill (SH) and Franklin Bluffs (FR) sites were added in 1986 (although measurements were often lacking). Snow surveys at the Sagwon site were usually made just east of the meteorological site. The Franklin Bluffs sampling site was located from 1986 through 1998, adjacent to the meteorological site 1 km east of the Dalton Highway. In 1999, the snow survey and ablation site was moved west approximately 300 m from the highway. The Betty Pingo site on the Prudhoe Bay Oilfield was established in 1992. This snow survey site is located near the NRCS Wyoming snow gauge about 200 m north of the Kuparuk Pipeline Road between P-Pad and Gathering Center 2. Upper Kuparuk, Happy Valley, and West Dock snow survey and ablation sites were added in 1999.

Imnavait Creek basin (IB) differs from others in that it has the longest period of recorded and detailed observations. Several sites were sampled across the basin to capture basin average SWE. From 1985 through 1997, the Imnavait basin SWE was determined from a transect made across the basin, perpendicular to the stream channel. At this time, snow ablation was tracked only at the west-facing slope adjacent to 4 runoff plots (Hinzman, 1990). In 1989, 2 additional sites were added: 1 in the valley bottom and 1 on the east-facing slope of the basin. To provide consistent identification of sites, the transect has been aligned with 7612800 northing (NAD27, UTM6) since 1999.

3.2.2 Observations from 2009

During the 2009 snowmelt season, SWE observations were taken at the Upper Kuparuk station (UKmet), Happy Valley (HV), Sagwon Hill (SH), Franklin Bluffs (FR), Betty Pingo (Betty), and West Dock (WD), and at 6 sites across the Imnavait basin (IB1–IB6). Sites were visited daily or every other day to capture the net volumetric decrease in SWE. We took 5 snow density and 50 snow depth measurements at each site. The snow depth course during snowmelt has an assigned location because of numerous repeated measurements.

3.3 Snow-Depth Sensors

The study domain includes seventeen meteorological stations equipped with a sonic snow depth sensor. Five stations were established in the Anaktuvuk River Basin in June 2009. Twelve stations in the Sagavanirktok and Kuparuk River Basin were established in August 2006 (Table 2). The snow depth sensor type is Campbell Scientific Sonic Ranger 50 (SR50) or SR50(A). The only difference between the SR50 and SR50(A) is the housing encasing the ultrasonic sensor. The sensor emits a 50 kHz sound pulse and measures the time the pulse take to return to the sensor. Ultrasonic sensors can measure the distance to any reflective surface like the ground or water, but sensitivity of the SR50(A) is designed for measuring distance to a snow surface.

Table 2. Meteorological stations with an SR50(A) snow depth sensor included in this report.

	Site Name	General Location
1	Accomplishment Creek (DBM1)	Sagavanirktok River, Brooks Range
2	Ribdon Creek (DBM2)	Sagavanirktok River, Brooks Range
3	Juniper Creek (DBM3)	Kavik River, Brooks Range
4	Sag-Ivishak (DBM4)	Sagavanirktok River, Foothills
5	Upper Kadleroshilik (DBM5)	Kadleroshilik River, Foothills
6	Kavik (DBM6)	Kavik River, Foothills
7	Kadleroshilik (DBM7)	Kadleroshilik River , Coastal Plain
8	Bullen (DBM8)	Near Canning River, Coastal Plain
9	South White Hills (DFM1)	Kuparuk River, Foothills
10	White Hills (DFM2)	Kuparuk River, Foothills
11	North White Hills (DFM3)	Kuparuk River, Foothills
12	Northwest Kuparuk (DFM4)	Kuparuk River, Foothills

The method for measuring snow depth with the SR50(A) is simple subtraction. When there is no snow on the ground, the distance measured is the sensor's height above the ground. When snow has accumulated under the sensor the distance measured is to the snow surface. The difference between distance-to-ground and distance-to-snow surface yields snow depth. For example, if the sensor's height above the ground is 50 inches and 10 inches of snow accumulates, the new distance to surface will be 40 inches. Hence, 40 inches subtracted from 50 inches gives a depth-depth of 10 inches under the sensor.

The ultrasonic pulse has a measurement cone circumference of 22º from the bottom of the sensor. The program for the SR50(A) records measurements at one minute intervals and reports hourly averages.

4. ACCURACY OF OBSERVATIONS

This section reports the problems of measuring and processing observational snow data, so that the reported dataset can be used properly.

4.1 Snow Water Equivalent

Snow density and SWE are estimated using snow core sampling. Woo (1997) showed that a larger tube diameter increases the accuracy of density determination; Woo also showed that the Canadian sampler (similar to the Adirondack in diameter) captures snow density within 5% of snow pit estimates. Our field comparison of Adirondack-to-snow-pit density gives similar results.

The accuracy of a single snow depth measurement depends on properties of underlying organic material. In the area of well-developed organics on top of the mineral soils, snow depth is often overestimated (Berezovskaya and Kane, 2007). While measuring, the probe can easily penetrate low-density organic material, so this additional depth often is incorporated inadvertently into the snow depth measurement. Any type of correction to existing snow depth records is difficult to perform because the error varies strongly from observer to observer and depends on snow and soil conditions at each site.

Whereas snow depths show a systematic overestimation error, snow core densities tend to be close to true value or are underestimated. The difficulty in SWE accuracy interpretations is that actual, accurate SWE is unknown. Comparing different sampling methods, Berezovskaya and Kane (2007) concluded that the SWE of tundra snow, estimated with the double sampling technique, has an error of ±10%.

4.2 Snow-Depth Sensors

High frequency, small amplitude noise is inherent in ultrasonic snow depth sensors and can be an impediment to accurate snow accumulation measurements (Brazenec, 2005). Since the speed of sound in air is affected by the temperature of the air it is traveling in, an air temperature is measured to correct distance readings. Sensor mounting height can influence data quality with higher mounting heights resulting in noisier data. Manufacture's stated accuracy is ±1 cm or 0.4% of distance to snow surface, whichever is greater (Campbell, 2008). Inaccuracies can be caused by difficulty in establishing a zero point due to tussocks/uneven ground, neglecting periodic maintenance requirements (replacement of sensor transducer), high wind, falling snow, low density snow, blowing snow, and change in sensor height due to ground heave and wildlife curiosities.

Sonic snow depth records in this report were adjusted as necessary to account for field observations and erroneous data points. Typically, erroneous data occurred during high wind/blowing snow events as well as beginning and end of season transition periods. Erroneous data was replaced with values interpolated between the first and last good quality data values. Prior to the 2008-2009 snow season, the ground surface under the snow sensors was trimmed of vegetation and leveled with wood bark. This resulted in improved clarity when deciphering the timing and amount of snow accumulation at the beginning and end of the season.

Diligent field practices are essential for accurate measurements and post-processing data correction and QA/QC purposes. Our **field procedures during site visit include:**

- Measuring distance from the sensor to the ground during snow free season. This includes five measurements: one distance is measured directly underneath the sensor and four distances are measured at 22º angles around the sensor.
- Measuring snow depth under the sensor. This includes five measurements: one distance is measured directly underneath the sensor and four distances are measured at 22º angles around the sensor.
- Measuring distance from sensor to snow surface. This includes five measurements: one distance is measured directly underneath the sensor and four distances are measured at 22º angles around the sensor.
- Conduct snow survey near the sensor.
- Inspect sensor and supporting structure for structural soundness.
- Inspect sensor for corrosion, ice and hard-packed snow.

5. SPATIAL DISTRIBUTION OF SNOW SURVEY SITES

Snow survey sites are chosen to represent snow characteristics over a wide range of vegetation and terrain conditions (Figure 3 and Figure 4). Snow water equivalents are measured at elevations from 4 m to 1474 m (13 ft to 4850 ft) (Appendix A1–A3).

To determine regional average SWE, snow sites are classified as Coastal Plain and uplands; the uplands are separated into Foothills and Mountains. Coastal sites are located below an elevation isoline of 500 ft (152 m); uplands sites are located above this elevation isoline. The description of uplands snow sites as either Foothills or Mountains is based on elevation and surrounding topography (Appendix A1–A3). Elevation alone is not always representative for classification, because most of the snow survey sites in the mountains are located in valley bottoms where a helicopter can safely access the site.

We also list lake sites that are visited for chemistry data collection (e.g., Chambers et al., 2006). Snow surveys are usually conducted on the lake surface because lake snow is thinner, denser, and harder, and has less SWE than snow on the surrounding tundra (Sturm and Liston, 2003). If time allows, snow surveys are taken on the surrounding tundra also. Lake snow data collection is not applied to the long-term SWE analysis because different lakes are visited every year. However, lake snow parameters (depth, density, distribution, and thermal properties) are critical input for physical models, to account appropriately for ice thickness and heat loss (Sturm and Liston, 2003). Snow survey measurements were taken on the lake surface of 8 lakes in 2009 (Appendix A3, lines 11-12, 46-51).

Overall, 143 sites were visited in 2009. This number includes 89 sites within the frame of the Foothills project (83 snow survey sites and 6 lake sites), 38 sites within the Bullen Point project (36 snow survey sites and 2 lake sites), and 16 sites within the Umiat Corridor project. Thirty-two sites are located in the Mountains and 60 sites are in the Foothills. Snow sites located on the Coastal Plain include 43 snow survey sites and an additional 8 lake chemistry sites with complementary snow survey data (Table 3).

6. SNOW SURVEY DATA

The average Coastal Plain snow density (0.597 slug ft^{-3}, 298 kg m^{-3}) is higher than the Foothills snow density (0.511 slug ft^{-3}, 263 kg m^{-3}) and Mountains snow density (0.428 slug ft^{-3}, 221 kg m^{-3}) (Appendix A1–A3)

The average Coastal Plain SWE is 5.1 in. (13.0 cm), and snow depth is 18.6 in. (47.2 cm). The average Foothills SWE is 6.2 in. (15.6 cm), and average snow depth is 22.9 in. (58.1 cm). The average Mountains SWE is 3.9 in. (9.8 cm), and average snow depth is 18.0 in. (45.8 cm); both these measurements are generally lower than those of the Coastal Plain and Foothills. Figure 2 and Figure 3 show the snow depth and SWE at each snow survey site. Overall, average end-of-winter SWE tends to be highest in the Foothills (6.2 in., 15.6 cm) and lowest in the Mountains (3.9 in., 9.8 cm) (Figures 2 and 3, Table 2).

The Mountains and Foothills have more end-of-winter SWE in 2009 compared to the previous years (165% to 233% of the 2008 SWE). The Coastal Plain has 98–147 % of the last year's end-of-winter SWE (Table 3).

Table 3. Regional snow water equivalent in 2009.

Region	Number of sites	SWE		Percent of last year	Percent of average 2000–2009
		Cm	in	%	%
Mountains					
Kuparuk River	7	8.1	3.2	233	*
Sagavanirktok, Kadleroshilik, Shaviovik and Kavik Rivers	16	10.7	4.2	197	*
Anaktuvuk River	9	9.7	3.8	*	*
Foothills					
Kuparuk River	43	15.4	6.1	165	135
Sagavanirktok, Kadleroshilik, Shaviovik and Kavik Rivers	10	12.6	5.0	186	*
Anaktuvuk River	7	11.4	4.5	*	*
Coastal Plain					
Kuparuk River	33	13.4	5.3	147	143
Sagavanirktok, Kadleroshilik, Shaviovik and Kavik Rivers	10	9.8	3.9	98	*
Anaktuvuk River	0	-	-	*	*
Total					
Kuparuk River	83	12.3	4.8	168	128
Sagavanirktok, Kadleroshilik, Shaviovik and Kavik Rivers	36	11.0	4.3	149	*
Anaktuvuk River	16	11.4	4.5	*	*

* no data collected for comparison

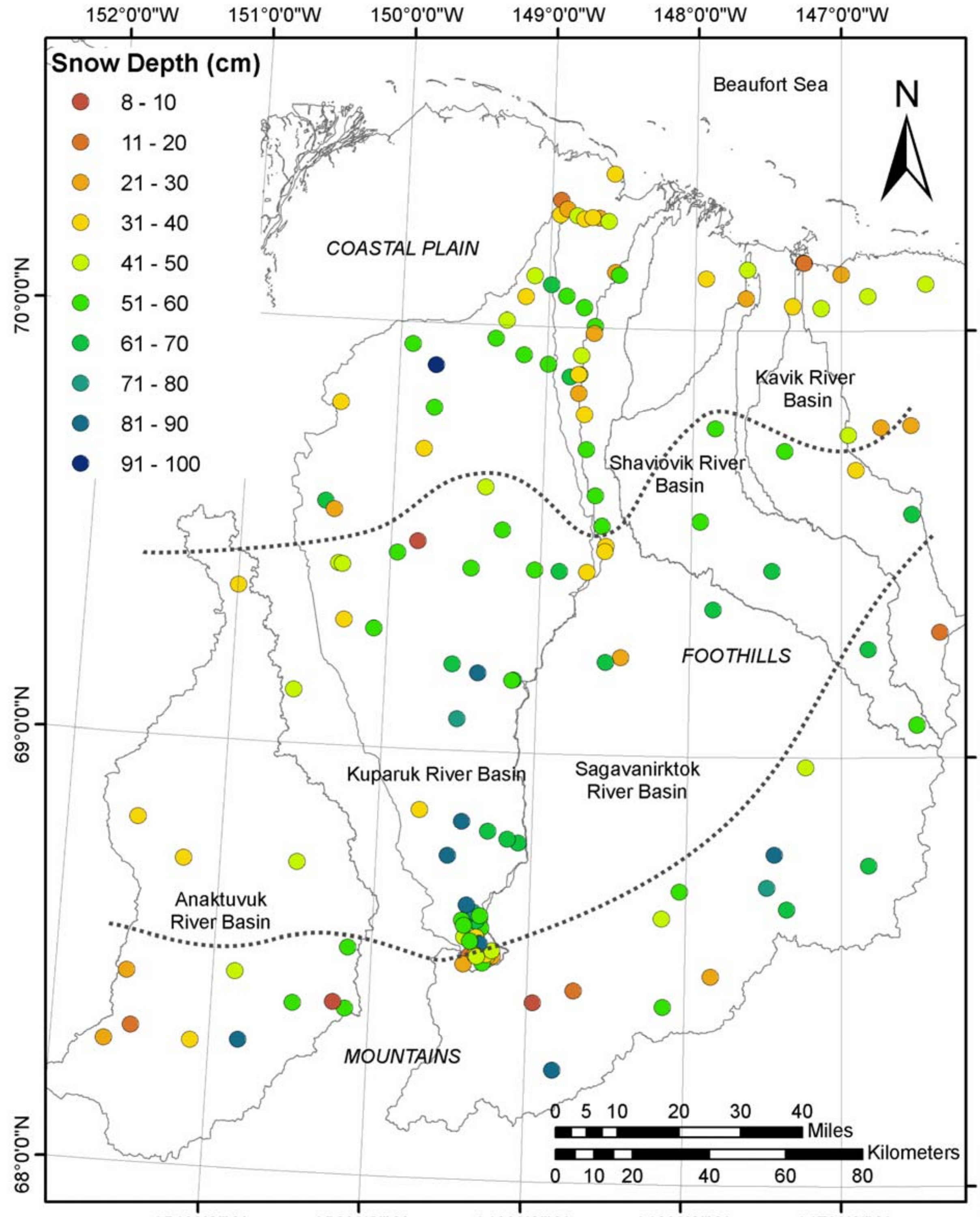

Figure 2. Snow depth (cm) on the North Slope of Alaska in spring 2009. Each point represents average from 50 snow depths.

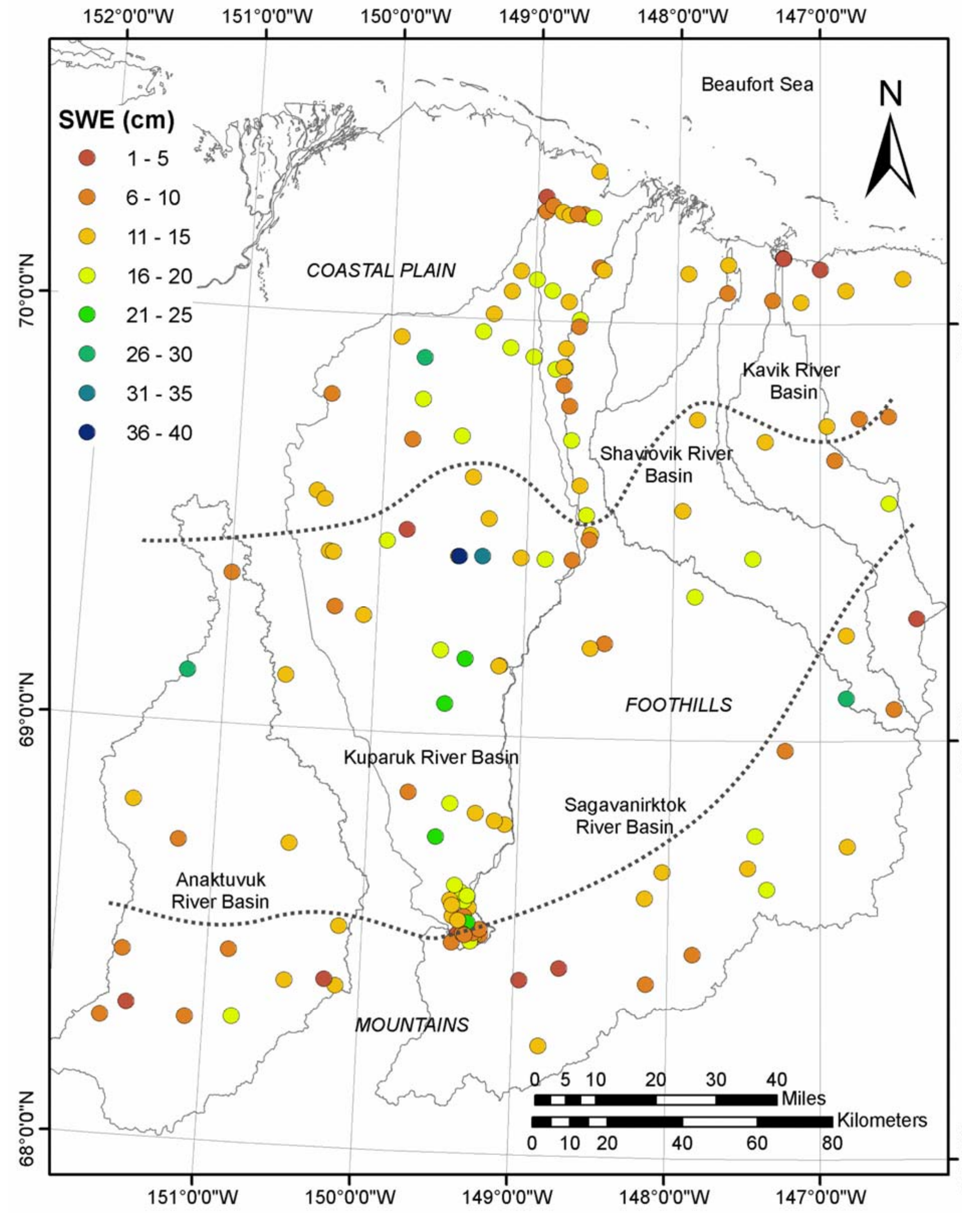

Figure 3. End-of-winter snow water equivalent (cm) on the North Slope of Alaska in spring 2009.

Long-term observations in the Kuparuk River

Long-term snow surveys on the AAS have been maintained by the U.S. Department of Agriculture (USDA) since the 1970s. The USDA Natural Resources Conservation Service (NRCS) reports that the SWE on the AAS in 2009 (average from 2 snow courses) accounts for 96% of the long-term average SWE and the Dalton highway (average from 3 snow courses) has accumulated 95% of the long-term average SWE (McClure et al., 2009).

Our snow survey dataset collected from the Kuparuk River basin covers a relatively short period of time (2000–2009) when compared with the NRCS period of record, yet it has more detailed spatial coverage: 83 snow courses in the Kuparuk River basin. End-of-winter SWE over the Kuparuk River watershed in 2009 accounts for 128% of the 10-year average SWE (Table 3). The 2009 end-of-winter SWEs for the Foothills and Coastal Plain represent 135% and 143%, respectively, of the 10-year average SWE (Table 3). The Foothills and Coastal Plain have the highest 10-year SWE average (15.4 and 13.4 cm, 6.1 and 5.3 in.). The Mountains had 8.1 cm (3.2 in.) end-of-winter SWE in 2009, which is more than last year's SWE (3.5 cm, 1.4 in.) but much less than the maximum SWE (14.7 cm, 5.8 in.) measured in 2003. This database has become long enough that we can start to analyze variability from year to year (Table 4).

Table 4. Maximum, minimum, and average snow water equivalent in the Coastal Plain, Foothills, and Mountains regions of the Kuparuk River basin (2000–2009, *n*=10), including the basin average.

Region	Maximum		Minimum		Average	
	cm (year)	in.	cm (year)	in.	cm	in.
Mountains	14.7 (2003)	5.8	3.5 (2008)	1.4	8.4	3.3
Foothills	15.4 (2009)	6.1	8.9 (2006)	3.5	11.4	4.5
Coastal Plain	13.4 (2009)	5.3	8.4 (2001)	3.3	9.4	3.7
Kuparuk River basin	12.7 (2003)	5.0	7.3 (2008)	2.9	9.6	3.8

7. SONIC SNOW DEPTH DATA

While end-of-winter snow surveys provide areal average snow depth accounting for spatial snowpack heterogeneity, the SR50(A) measures snow depth directly under the sensor during the entire winter. All meteorological stations, except for the South White Hills (DFM1), reported good quality data during the 2008 - 2009 winter (Figures 4-15). The South White Hills (DFM1) station had a malfunctioning snow sensor.

The advantage of snow sensor information is its high temporal resolution which can capture the timing and magnitude of snow events. Records show that the snow accumulation began in late September – early October, 2008. The majority of stations reported high snow accumulation (up to 50 cm / 20 inches) in late October – early November, 2008. Following the early season accumulation, the Coastal Plain stations generally remained at a consistent snow depth throughout the season. Snow depth records at Mountains stations have more erosion and accumulation episodes throughout season. Accomplishment Creek, Juniper, Lower Kad, and White Hills stations reported maximum snow depth by January, 2009. Ribdon, Sag-Ivishak, Upper Kad, Kavik, Bullen, Northwest Kuparuk stations reported maximum snow depth in April and May 2009.

Differences in micro-topography and vegetation cause large variability in snow depth at a station, even though the stations are located with the same orographic zone. For instance, White Hills Station (Figure 13) reported shallow snow depths for the entire past three winters. This station is located on top of a ridge, where snow is eroded by persisting strong winds. Kavik Station (Figure 9) reports a relatively shallow snow depth. The immediate surrounding area of this station is flat with low lying vegetation making it susceptible to scouring. Note that the adjacent 50 snow depth measurements show the depths to be generally greater. North White Hills Station (Figure 14) is located on a very slight knoll consisting of tussock tundra compared to the surrounding shrub/high grass environment; the sensor snow depths have consistently over a three year period been less than the adjacent snow surveys.

Snow sensor data used in conjunction with snow survey data can enhance and expand the information gained with each added sampling method. Since a snow depth sensor records snow depth at a point, the additional fifty snow depth measurements near each station represent local-scale variability relative to the measurement area under SR50(A) sensor (Figures 4-15 and Table 5). Accomplishment Creek, Kavik, and North White Hills sensor readings reflect the lowest depths measured from snow surveys (Figure 4, 9, and 14 respectively). Ribdon, Juniper, Bullen, White Hills, and Northwest Kuparuk sensor values are near the middle range of snow survey depths (Figure 5, 6, 11, 13, and 15 respectively). In general, the SR 50 results are lower than the average of the 50 snow depth measurements. There is also considerable variability from year-to-year at a site. At the Ribdon station (Figure 5), at the end of the 2008 winter, the SR50 results compared favorably with the nearby snow survey: however, in 2009 the average was higher. Just the opposite can be found for the Northwest Kuparuk site (Figure 15).

On-site checks as part of the sensor QA/QAC include measurement of four snow depths at a 22° angle around sensor and one directly underneath. At the time of station visit sensors were reporting typically within 0.5 in (1.2 cm) of actual snow depth. The greatest discrepancy was Bullen station where sensor values were 4.3 in (10.9 cm) less than the average observed snow depth (Table 5). Considering all stations the average difference between sensor and measured snow depth is 1.0 in (2.7cm).

The majority of station data for 2008-2009 winter season reported higher snow accumulation than the previous two years of record (Figures 4-15). Coastal stations, Lower Kadleroshilik (Figure 10) and Bullen (Figure 11), in the northeast of the study area reported similar depths as 2006 and 2007, while coastal plain station, Northwest Kuparuk (Figure 15), located to the west reported greater depths than the previous two years. Generally, Mountain and Foothill stations reported the highest snow depths during 2008 - 2009 winter, based on observational period from 2006 to 2009.

Table 5. Snow depth information from meteorological station and co-located snow survey. Range and average snow depth from snow survey. Observed snow depth under SR50(A) snow sensor, reported SR50(A) snow depth at time of observed measurement, and difference between observed and reported snow depth.

Meteorological Station	Snow Survey Depth Range (in/cm)	Snow Survey Depth Average (in/cm)	Observed Depth Under SR50(A) (in/cm)	SR50(A) Reported Depth at Time of Observed Depth (in/cm)	Difference Between Observed and SR50(A) Reported Depth (in/cm)
Accomplishment Creek (DBM1)	9.8-40.9/25-104	21.3/54.1	7.1/18	7.6/19.2	-0.5/-1.2
Ribdon Creek (DBM2)	6.3-37.4/16-95	25.4/64.6	22.0/56	21.9/55.7	0.1/0.3
Juniper Creek (DBM3)	10.2-33.9/26-86	20.9/53.1	19.4/49.4	19.1/46.0	1.3/3.4
Sag-Ivishak (DBM4)	16.1-35.8/41-91	24.9/63.3	22.0/56	22.5/57.2	-0.5/-1.2
Upper Kadleroshilik (DBM5)	14.2-31.1/36-79	22.8/57.8	25.7/65.4	27.7/70.3	-1.9/-4.9
Kavik (DBM6)	5.9-28.0/15-71	12.7/32.2	6.4/16.2	6.9/17.6	-0.6/-1.4
Kadleroshilik (DBM7)	5.1-20.1/13-51	10.4/26.3	8.1/20.5	9.3/23.6	-1.2/-3.1
Bullen (DBM8)	11.8-24.8/30-63	19.6/49.9	17.5/44.4	13.2/33.5	4.3/10.9
South White Hills (DFM1)	15.4-39.0/39-99	25.3/64.4			
White Hills (DFM2)	0-9.1/0-23	3.4/8.6	3.9/10	5.6/14.2	-1.7/-4.2
North White Hills (DFM3)	5.5-51.2/14-130	25.7/65.3	4.6/11.8	4.4/11.1	0.3/0.7
Northwest Kuparuk (DFM4)	7.9-32.3/20-82	19.7/50.1	22.5/57.1	22.7/57.8	-0.3/-0.7

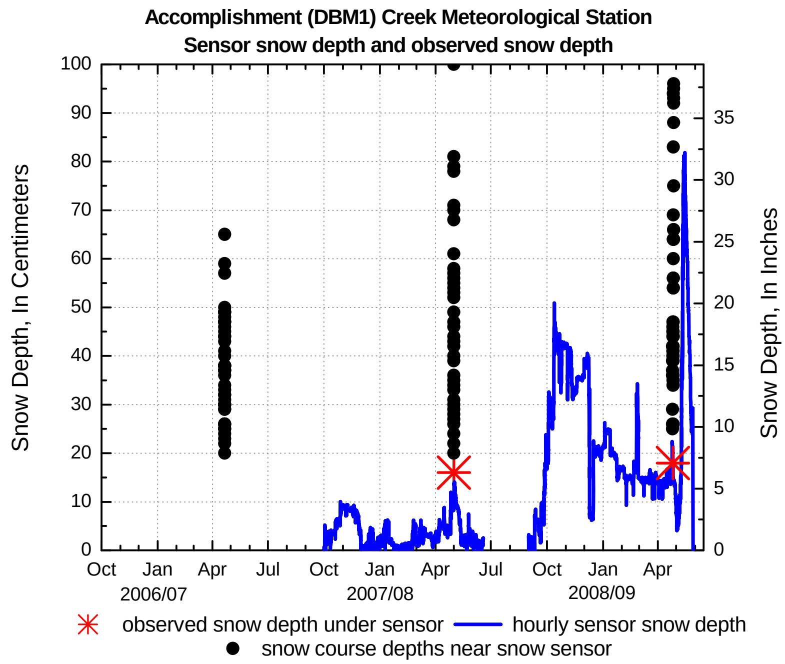

Figure 4. Accomplishment Creek meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

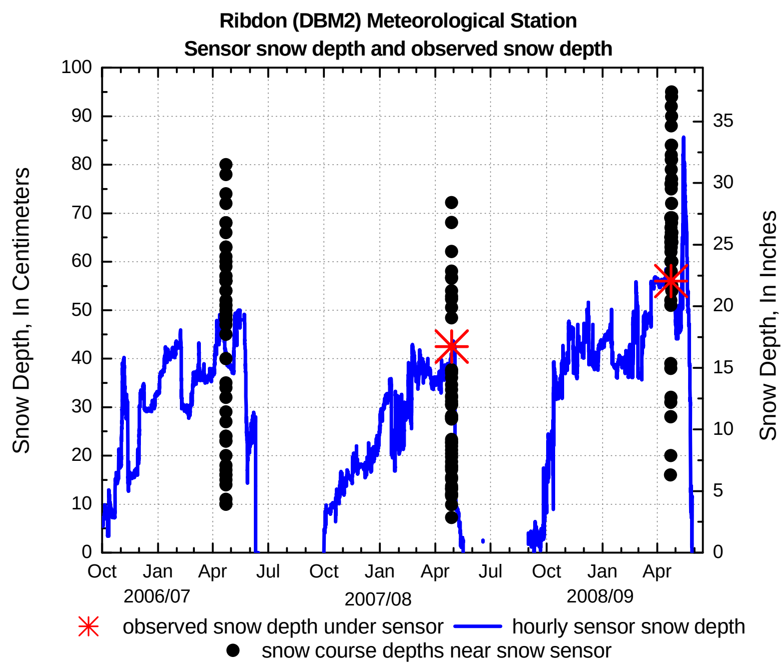

Figure 5. Ribdon meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

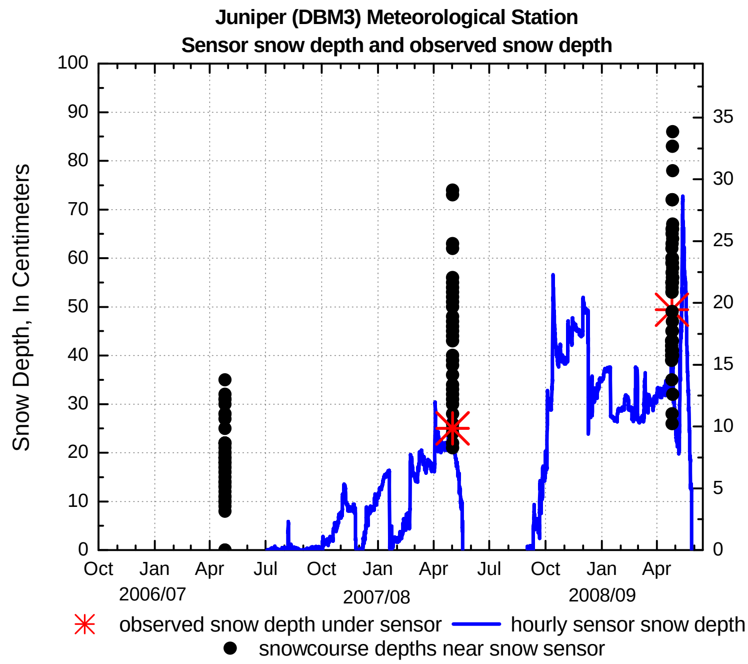

Figure 6. Juniper meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

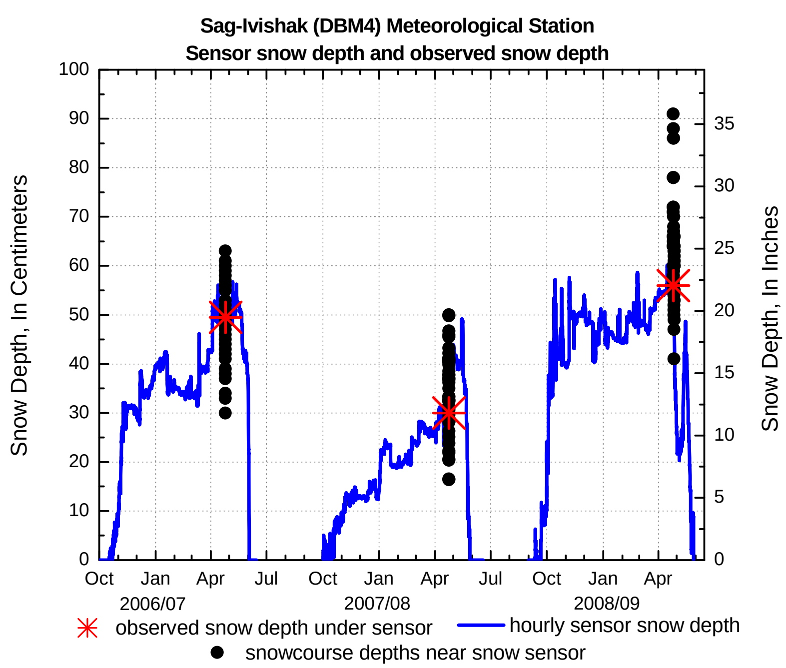

Figure 7. Sag-Ivishak meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

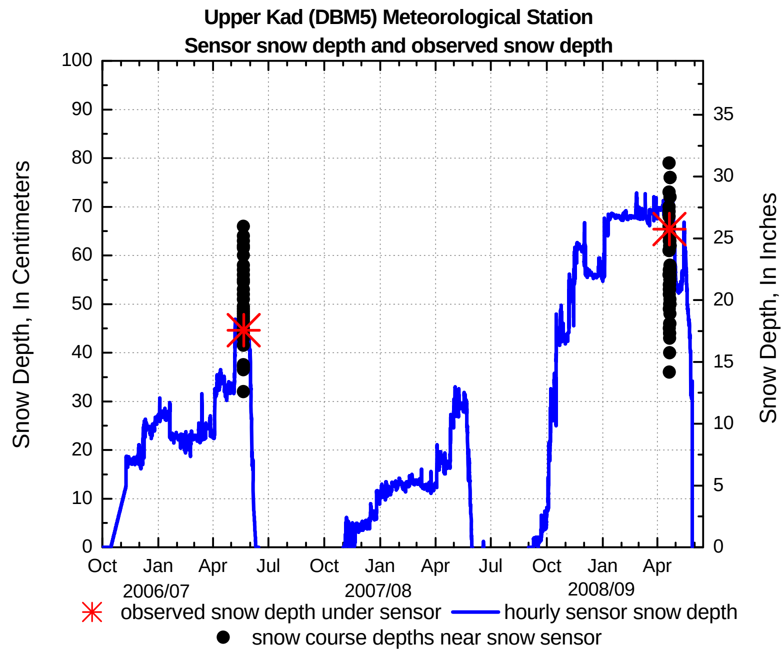

Figure 8. Upper Kadleroshilik meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

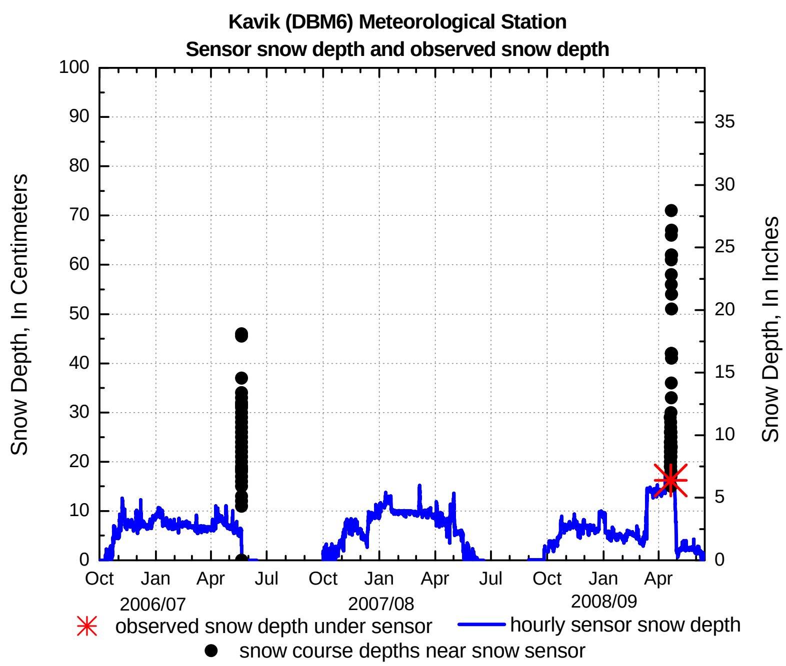

Figure 9. Kavik meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

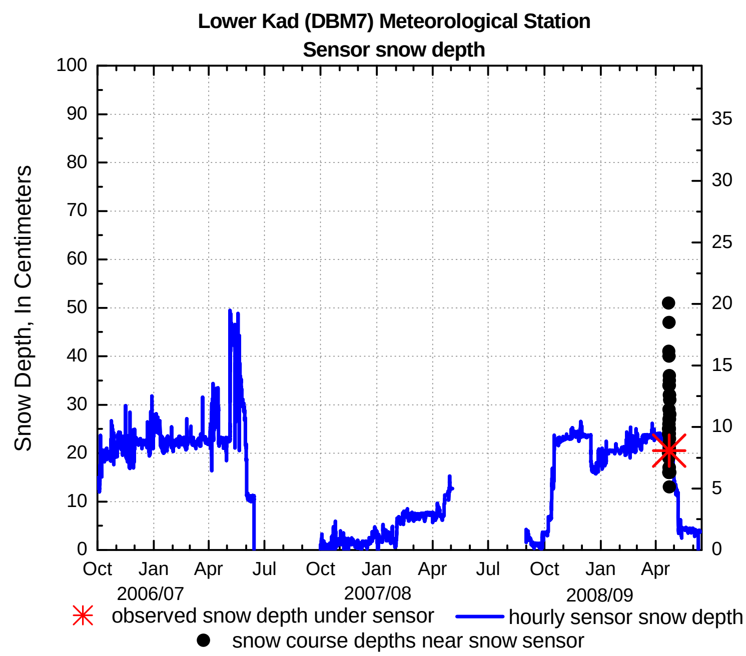

Figure 10. Lower Kadleroshilik meteorological station hourly SR50 sensor snow depths measured over the winter, observed snow depth under the sensor, and snow survey depths measured near sensor.

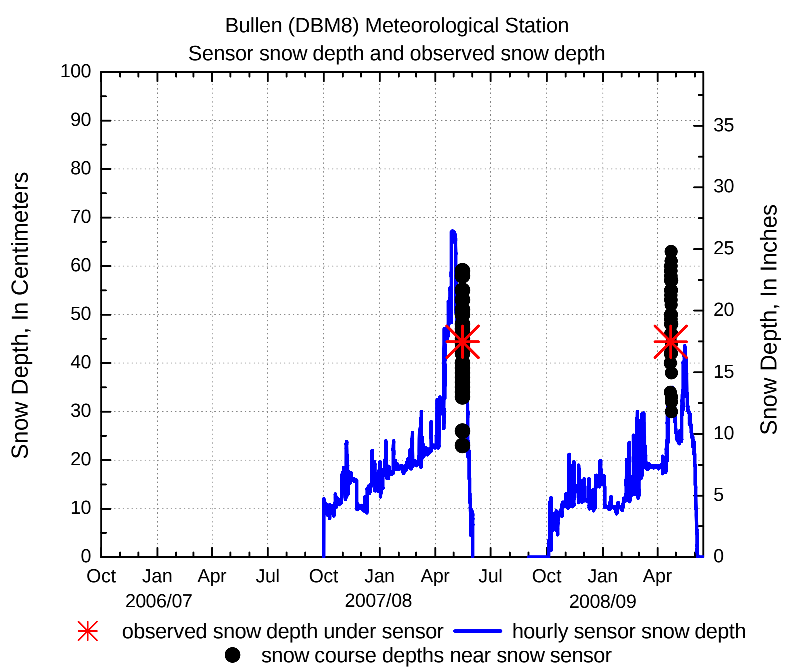

Figure 11. Bullen meteorological station hourly SR50 sensor snow depths measured, observed snow depth under the sensor, and snow survey depths measured near sensor.

South White Hills meteorological station

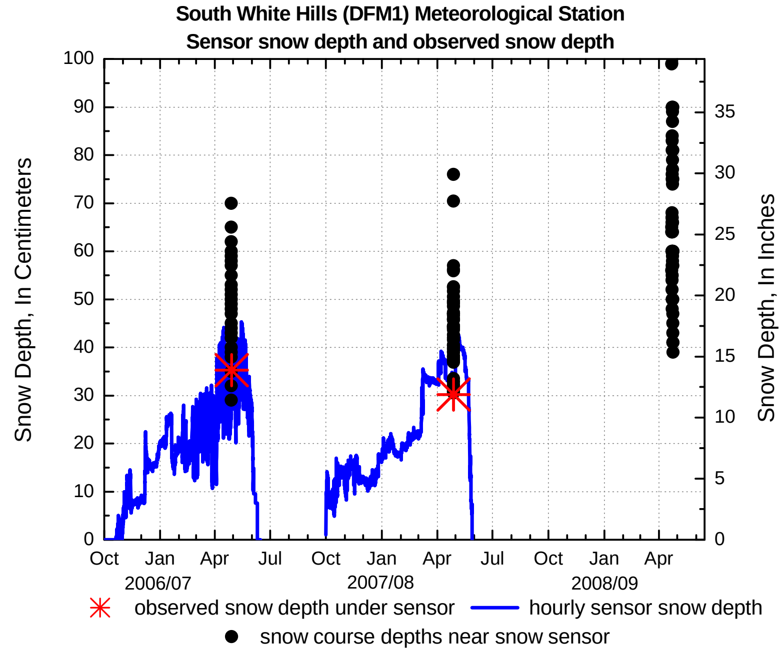

Figure 12. South White Hills meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

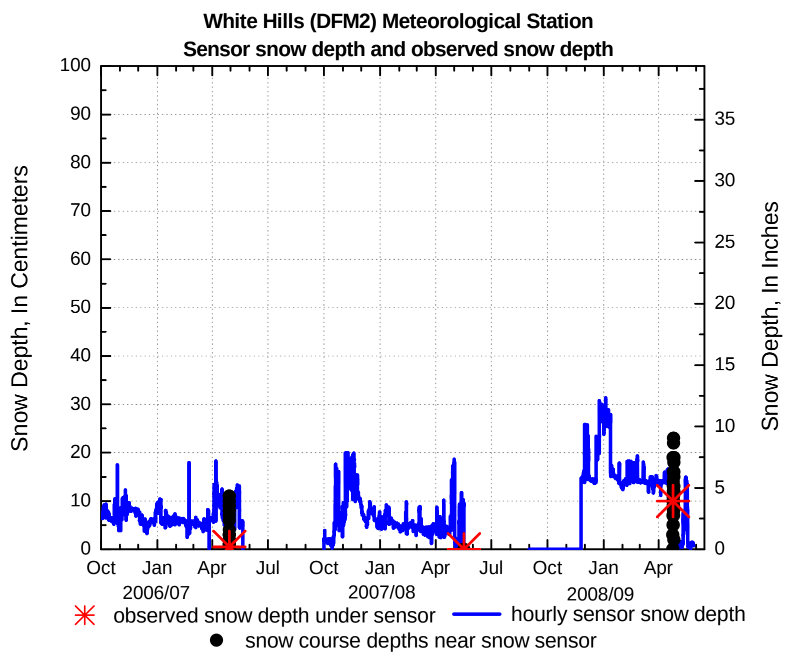

Figure 13. White Hills meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

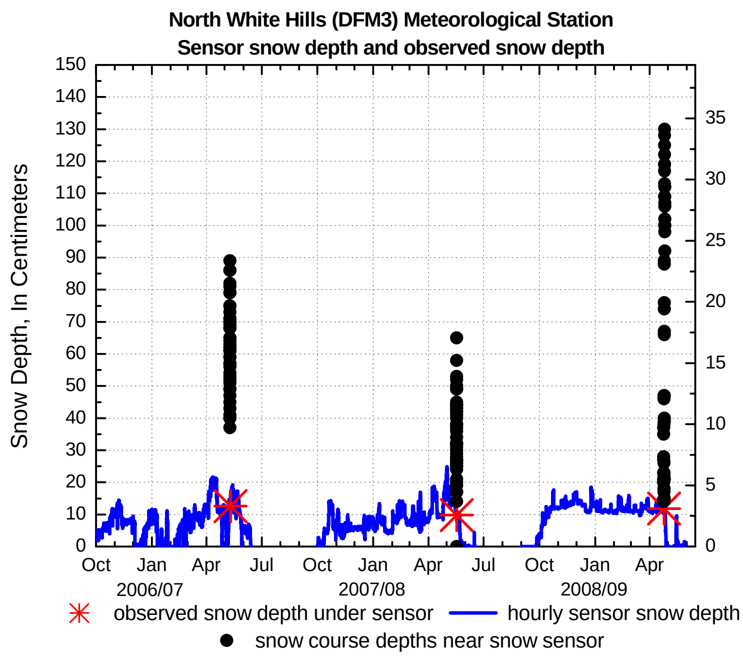

Figure 14. North White Hills meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

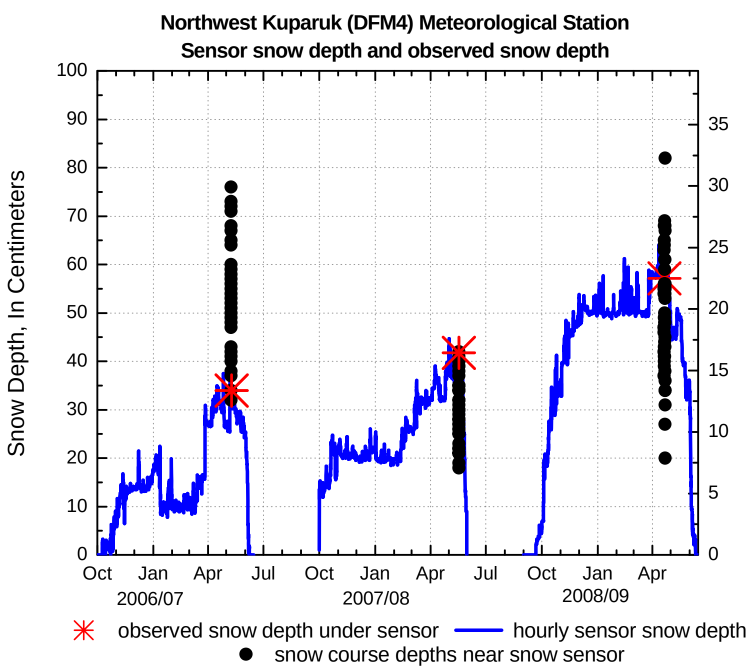

Figure 15. Northwest Kuparuk meteorological station hourly SR50 sensor snow depths, observed snow depth under the sensor, and snow survey depths measured near sensor.

Spring 2009 differed in that air temperature rose above freezing for about a week from late April through early May, initiating snow melt (Figure 4 – Figure 15). Our field observations suggest that the snowpack did not reach isothermal conditions at that time, and no runoff was generated. Analysis of sonic snow depth data showed that most of the weather stations reported additional snow accumulation from May 9 to May 15. This rapid accumulation and ablation was more pronounced at stations located to the south and less to the north. No additional snow accumulation was recorded after May 20, 2009.

8. ABLATION DATA

Historical ablation data collected at six sites (see Section 3.2) are summarized in Appendix B. The ablation window varies greatly, depending on meteorological conditions and snowpack depth. The 2009 snowpack completely melted by May 26 in northern sites, i.e. Betty Pingo and Franklin Bluffs. It took another week for the snowpack to melt in southern foothills, i.e. the Imnavait Creek basin and Upper Kuparuk (Figure 16). Snowpack across the entire Kuparuk River basin melted by June 12, 2009.

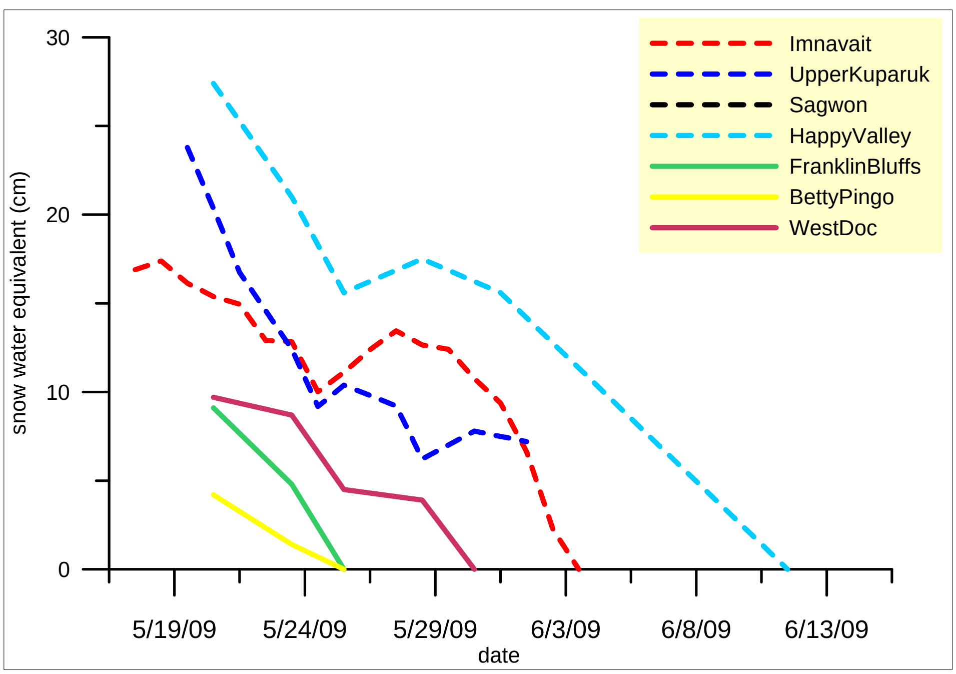

Figure 16. Net volumetric decrease in SWE. Snow ablation curves at the Foothills are shown as dashed lines and, on the Coastal Plain, as solid lines. A shallow snowpack and an early warm event resulted in no measurements being made at the Sagwon site this year

The Imnavait basin ablation curve differs in that it is an average of six sites across the basin. Within a few days of sustained melt, the entire watershed becomes a patchwork of snow-covered and bare tundra. The west-facing slope (~80% of catchment) melts off sooner than the rest of the watershed, because it retains less snow and has more direct solar radiation in the afternoon when air temperatures are highest (Hinzman et al., 1996). In contrast, the east-facing slope has deeper snowpack and receives its maximum irradiance in the morning while convective heat transfer is smaller. Fourteen days were required to complete ablation in the Imnavait watershed in 2009 (Figure 17).

9. SUMMARY

This report describes snow depth, snow water equivalent, and snow density data collected in April–May 2009 in the Alaskan Arctic. Snow surveys were conducted in the watersheds of the Kuparuk, Anaktuvuk, Sagavanirktok, Shaviovik, Kadleroshilik, and Kavik Rivers. As of 2009, the Kuparuk River watershed has 10 years of repeated end-of-winter snow survey data. There are snow survey data in the Kuparuk River basin prior 2000, but they were not available for this report. Sagavanirktok, Shaviovik, Kadleroshilik, and Kavik River basins have 4 years of repeated snow surveys data, from 2006 to 2009. Snow survey observations in the Anaktuvuk River basin were initiated in 2009.

Overall, 143 snow survey sites were visited in 2009. This number includes 89 sites within the frame of the Foothills project (83 snow survey sites and 6 lake sites), 38 sites within the Bullen Point project (36 snow survey sites and 2 lake sites), and 16 sites within the Umiat project.

The Kuparuk River watershed end-of-winter SWE observed in 2009 accounts for 128% of the 10-year average SWE. The Foothills and Coastal Plain end-of-winter SWE observed in 2009 represent 135% and 143%, respectively, of the 10-year average SWE. The Foothills and Coastal Plain have the highest 10-year SWE average (15.4 and 13.4 cm, 6.1 and 5.3 in.). The Mountains have 8.1 cm (3.2 in.) of end-of-winter SWE in 2009, which is more than last year's SWE (3.5 cm, 1.4 in.), but less than the maximum SWE (14.7 cm, 5.8 in.) measured in 2003. Snowpack across the entire Kuparuk River basin melted by June 12, 2009.

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APPENDIX A. 2009 SNOW SURVEY DATA

Appendix A1. Snow water equivalent, snow depth and snow density in the Mountains.

N	ID	ELEV	LAT	LON	SWE		Snow Depth		Snow Density	
		m	dd	dd	cm	in	cm	in	kg m-3	slug ft-3
1	RIB1	609	68.6174	-148.1527	10.5	4.1	49	19.4	213	0.413
2	RIB2	800	68.4848	-147.8357	5.4	2.1	24	9.6	222	0.431
3	RIB3	918	68.6931	-147.4782	12.9	5.1	74	29.2	174	0.338
4	SAG1	678	68.4150	-148.9600	1.4	0.6	8	3.1	178	0.345
5	SAG2	868	68.2597	-148.8256	13.5	5.3	82	32.3	165	0.320
6	SAG3	830	68.4462	-148.7042	3	1.2	12	4.6	262	0.508
7	SAV1	955	68.7705	-147.4323	16	6.3	83	32.7	192	0.372
8	ECH1	868	69.1022	-146.8254	25.6	10.1	107	42.1	239	0.464
9	IVI1	521	68.9767	-147.2339	6.3	2.5	40	15.9	157	0.305
10	IVI2	810	68.7464	-146.8227	11.8	4.6	63	24.8	187	0.363
11	JUN_1	615	69.2526	-146.8229	12.2	4.8	67	26.5	181	0.351
12	KAV1	733	69.2920	-146.3480	3.1	1.2	13	5.1	238	0.462
13	LUP1	747	68.6817	-148.0412	10.4	4.1	53	21.0	195	0.378
14	DBM1	1474	68.4116	-148.1365	8.9	3.5	54	21.3	164	0.318
15	DBM2	1478	68.6425	-147.3518	19.8	7.8	65	25.4	307	0.596
16	DBM3	1319	69.0762	-146.5049	9.9	3.9	53	20.9	187	0.363
17	UK05	1021	68.5200	-149.2267	5.1	2.0	25	9.7	207	0.402
18	UK06	1050	68.5199	-149.2623	10.2	4.0	38	14.8	271	0.526
19	UK14	1027	68.5638	-149.4108	10.1	4.0	46	18.2	218	0.423
20	UK16	1045	68.5207	-149.3725	3.3	1.3	12	4.9	262	0.508
21	UK17	1109	68.5007	-149.4105	5.9	2.3	23	9.0	256	0.497
22	UK19	1115	68.5037	-149.2885	15.2	6.0	55	21.5	279	0.541
23	UK20	1024	68.5247	-149.2685	7.1	2.8	33	13.1	214	0.415
24	MTN1	1096	68.3852	-150.15205	14.6	5.7	59	23.3	247	0.479
25	MTN2	1378	68.3985	-150.22773	2.1	0.8	8	3.2	266	0.516
26	MTN3	1080	68.3917	-150.48432	11.3	4.4	53	20.7	214	0.415
27	MTN4	1179	68.2972	-150.81245	18.1	7.1	85	33.5	213	0.413
28	MTN5	1180	68.2901	-151.11512	6.8	2.7	31	12.3	219	0.425
29	MTN6	986	68.2814	-151.66058	5.7	2.2	20	8.0	282	0.547
30	TLK1	988	68.5279	-150.14880	13	5.1	54	21.4	239	0.464
31	TLK2	824	68.4580	-150.85755	9.8	3.9	49	19.2	196	0.380
32	TLK3	868	68.4441	-151.54603	5.8	2.3	26	10.4	219	0.425

Appendix A2. Snow water equivalent, snow depth and snow density in the Foothills.

N	ID	ELEV	LAT	LON	SWE		Snow Depth		Snow Density	
		m	dd	dd	cm	in	cm	in	kg m-3	slug ft-3
1	MD2	334	69.7688	-147.8492	14.4	5.7	53	20.9	273	0.530
2	MD3	319	69.7170	-147.3804	13.1	5.2	52	20.4	252	0.489
3	MD6	170	69.7772	-146.5296	8.3	3.3	28	10.8	301	0.584
4	UP1	194	69.2276	-148.4540	6.1	2.4	25	9.7	247	0.479
5	UP2	318	69.3439	-147.8502	15.5	6.1	64	25.0	244	0.473
6	UP3	393	69.4356	-147.4600	17.3	6.8	67	26.4	259	0.502
7	UP4	350	69.5689	-146.5295	16	6.3	68	26.6	237	0.460
8	DBM4	431	69.2156	-148.5519	13.6	5.4	63	24.9	215	0.417
9	DBM5	209	69.5495	-147.9418	14.7	5.8	58	22.8	254	0.493
10	DBM6	198	69.6734	-146.9006	7.3	2.9	32	12.7	277	0.537
11	UK01	912	68.5849	-149.3063	11.2	4.4	60	23.5	188	0.365
12	UK02	834	68.6010	-149.3381	16.1	6.3	68	26.8	236	0.458
13	UK03	827	68.5639	-149.3353	7.2	2.8	38	15.0	189	0.367
14	UK04	908	68.5335	-149.2310	8.7	3.4	47	18.4	187	0.363
15	UK07	848	68.5489	-149.3112	21.4	8.4	85	33.5	251	0.487
16	UK08	968	68.5222	-149.3380	6.5	2.6	28	11.1	229	0.444
17	UK09	763	68.6241	-149.3790	12.2	4.8	62	24.4	197	0.382
18	UK10	801	68.6173	-149.3839	19	7.5	77	30.4	247	0.479
19	UK11	796	68.6215	-149.3605	17.3	6.8	71	27.8	244	0.473
20	UK12	904	68.6022	-149.4304	11.9	4.7	53	20.8	225	0.437
21	UK13	937	68.5899	-149.4164	13.3	5.2	59	23.1	227	0.440
22	UK15	951	68.5540	-149.3727	12.4	4.9	60	23.6	207	0.402
23	UK18	981	68.5187	-149.3275	6.7	2.6	42	16.3	161	0.312
24	Ukmet	778	68.6374	-149.4039	19.5	7.7	80	31.6	243	0.471
25	SM01	732	68.7879	-149.0871	14.1	5.6	64	25.3	219	0.425
26	SM02	680	68.7956	-149.1576	12.2	4.8	62	24.3	199	0.386
27	SM03	651	68.8122	-149.2838	14.6	5.7	61	24.0	239	0.464
28	SM04	612	68.8336	-149.4557	17.1	6.7	81	31.8	211	0.409
29	SM05	568	68.8565	-149.7332	9.8	3.9	34	13.4	289	0.561
30	SM06	609	68.7521	-149.5393	21.4	8.4	86	33.9	248	0.481
31	Happy Valley	314	69.1519	-148.8389	41.3	16.3	129	50.7	321	0.623
32	HV1	365	69.1682	-149.1548	14	5.5	67	26.5	208	0.404
33	HV2	353	69.1667	-149.1621	10.7	4.2	52	20.3	207	0.402
34	HV3	386	69.1816	-149.3900	22.5	8.9	83	32.8	270	0.524
35	HV5	179	69.2937	-150.2842	7.4	2.9	35	13.7	212	0.411
36	HV6	218	69.2756	-150.0869	11.4	4.5	54	21.1	212	0.411
37	Wkmet	159	69.4259	-150.3417	13.1	5.2	50	19.6	264	0.512
38	WK1	218	69.4265	-148.8722	19.4	7.6	68	26.6	287	0.557
39	WK2	226	69.4278	-149.0376	14.8	5.8	60	23.6	247	0.479
40	WK3	174	69.4291	-149.2981	34.2	13.5	129	50.9	264	0.512
41	WK4	203	69.4269	-149.4609	13.4	5.3	51	20.0	264	0.512
42	WK5	197	69.4269	-149.4570	36.9	14.5	112	44.2	329	0.638

43	WK6	195	69.5199	-149.2623	15	5.9	50	19.8	297	0.576
44	WK8	173	69.4576	-149.9525	15.8	6.2	58	22.9	272	0.528
45	WK10	214	69.6173	-149.3839	14.6	5.7	46	18.0	318	0.617
46	Sagwon	275	69.4262	-148.6909	8.8	3.5	40	15.7	219	0.425
47	H02	172	69.8020	-150.3838	9.5	3.7	36	14.0	268	0.520
48	IB	897	68.6134	-149.3176	16.1	6.3	60	23.6	260	0.504
49	MI6	159	69.5344	-148.5987	16.1	6.3	57	22.3	284	0.551
50	MI7	175	69.4887	-148.5678	12.5	4.9	40	15.6	314	0.609
51	DFR1	508	69.0726	-149.5145	21.3	8.4	72	28.5	295	0.572
52	DFM1	293	69.2007	-149.5585	17.5	6.9	64	25.4	272	0.528
53	DFM2	337	69.4865	-149.8214	2.4	0.9	9	3.4	284	0.551
54	ANA1	107	69.3604	-150.9942	9.4	3.7	32	12.5	294	0.570
55	ANA2	595	68.3158	-151.4967	2.9	1.1	15	5.8	198	0.384
56	GUN2	547	68.7208	-150.5027	12.2	4.8	49	19.2	251	0.487
57	GUN3	469	68.7146	-151.2331	7.7	3.0	37	14.4	210	0.407
58	GUN4	521	68.8041	-151.5464	10.3	4.1	38	15.0	270	0.524
59	SWB1	243	69.1233	-150.5891	10.6	4.2	43	16.9	247	0.479
60	SWB2	226	69.1218	-151.2492	26.7	10.5	108	42.4	248	0.481

Appendix A3. Snow water equivalent, snow depth and snow density on the Coastal Plain.

N	ID	ELEV	LAT	LON	SWE		Snow Depth		Snow Density	
		m	dd	dd	cm	in	cm	in	kg m-3	slug ft-3
1	MD4	113	69.7544	-146.9543	11.5	4.5	43.3	17.0	265	0.514
2	MD5	130	69.7721	-146.7313	8.8	3.5	29.7	11.7	295	0.572
3	BL1	10	70.1184	-147.9254	11.4	4.5	38.2	15.0	268	0.520
4	BL3	43	70.0516	-147.1370	14.8	5.8	47	18.5	271	0.526
5	BL4	62	70.0566	-147.3330	9.8	3.9	36.7	14.4	279	0.541
6	BL6	29	70.1073	-146.4210	12.2	4.8	45	17.7	347	0.673
7	SHAV	5	70.1586	-147.2591	5.1	2.0	23.5	9.3	218	0.423
8	BDM	4	70.1310	-147.0001	4.8	1.9	20.4	8.0	234	0.454
9	DBM7	24	70.0734	-147.6500	7.6	3.0	26.3	10.4	289	0.561
10	DBM8	26	70.0799	-146.8194	13.9	5.5	49.9	19.6	279	0.541
11	KAD1	15	70.1405	-147.6441	14.4	5.7	43.7	17.2	330	0.640
12	SHAV-lake	5	70.1576	-147.2562	4.9	1.9	14.2	5.6	347	0.673
13	WestDock	5	70.3602	-148.5697	10.2	4.0	33.2	13.1	307	0.596
14	FranklinBluffs	71	69.8886	-148.7747	16	6.3	48	18.9	334	0.648
15	FB1	71	69.8828	-148.8387	18.8	7.4	65.1	25.6	289	0.561
16	FB2	64	69.9108	-148.9923	15.9	6.3	55.4	21.8	287	0.557
17	FB3	58	69.9316	-149.1563	15.6	6.1	56.1	22.1	278	0.539
18	FB4	52	69.9676	-149.3512	17.9	7.0	53.5	21.1	334	0.648
19	FB5	42	70.0113	-149.2829	12.6	5.0	43.2	17.0	292	0.566
20	FB6	38	70.0667	-149.1600	11.1	4.4	39.3	15.5	281	0.545
21	FB7	32	70.1160	-149.1010	13	5.1	46.1	18.1	282	0.547
22	FB8	34	70.0960	-148.9868	18.8	7.4	61.2	24.1	307	0.596
23	FB9	34	70.0710	-148.8780	17.2	6.8	51.2	20.2	335	0.650
24	FB10	40	70.0451	-148.7580	13.6	5.4	54.3	21.4	251	0.487
25	FB11	21	70.1294	-148.5477	7.5	3.0	24.3	9.6	308	0.598
26	FB12	20	70.1227	-148.5213	14.3	5.6	59.2	23.3	270	0.524
27	P01	12	70.2955	-148.9373	3.6	1.4	10.6	4.2	341	0.662
28	P02	15	70.2614	-148.9396	9.9	3.9	35.5	14.0	278	0.539
29	P03/BettyP	11	70.2744	-148.8908	8	3.1	27.4	10.8	293	0.568
30	P04	12	70.2601	-148.8211	12.4	4.9	42.5	16.7	293	0.568
31	P05	15	70.2532	-148.7716	10.1	4.0	30.4	12.0	332	0.644
32	P06	12	70.2562	-148.6701	8.9	3.5	29.4	11.6	304	0.590
33	P07	12	70.2566	-148.7160	8.4	3.3	34.5	13.6	243	0.471
34	P08	12	70.2486	-148.6041	17.1	6.7	48.5	19.1	353	0.685
35	MI1	48	70.0032	-148.6792	17.9	7.0	52.8	20.8	339	0.658
36	MI2	60	69.9336	-148.7677	11.8	4.6	47.4	18.7	250	0.485
37	MI3	90	69.7950	-148.7361	8.1	3.2	31.1	12.2	260	0.504
38	MI4	90	69.7130	-148.7165	17.1	6.7	57.4	22.6	298	0.578
39	MI5	140	69.6050	-148.6487	13.5	5.3	51.3	20.2	263	0.510
40	H01	113	69.5687	-150.4478	12.5	4.9	60.2	23.7	208	0.404
41	H04	77	69.9000	-149.7500	25.9	10.2	96.1	37.8	269	0.522
42	H05	90	69.8000	-149.7500	15.5	6.1	51.1	20.1	304	0.590

43	WK7	137	69.4243	-150.3145	11.5	4.5	49.7	19.6	232	0.450
44	DFM3	84	69.7149	-149.4705	15.2	6.0	165.3	65.1	233	0.452
45	DFM4	124	69.9475	-149.9169	13.8	5.4	50.1	19.7	275	0.534
46	W0702	93	69.7024	-149.8095	9.8	3.9	31	12.2	317	0.615
47	W0802	108	69.5500	-150.3896	10.3	4.1	25.1	9.9	412	0.799
48	S0901	86	69.8449	-148.7782	9.4	3.7	26.1	10.3	360	0.698
49	ANNIE	58	69.9866	-148.6844	9.3	3.7	26.7	10.5	348	0.675
50	MP29	76	69.8894	-148.7821	14.7	5.8	39.9	15.7	368	0.714
51	S0903	180	69.4766	-148.5751	9.5	3.7	30.3	11.9	314	0.609

APPENDIX B. HISTORICAL ABLATION DATA

Appendix B1. Snow water equivalent (cm) in the Imnavait Creek basin (basin average).

Month and Day	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
30-Apr											14														
1-May																									
2-May										8															
3-May				7.5																					
4-May							8.2																		
5-May																									
6-May										4.6	6.8														
7-May																					12				
8-May	10.6									1.7	5.3														
9-May	10.3		10	6.9		9.9	1.1												15.7	12.0					
10-May	9.7		8.8	5.1			0.3			1.3	1.3								14.4						
11-May	7.9		8.6	4.8			0.2												14.9						
12-May			7.6	1.9		7.8	0.14												14.3				11.3	8.3	
13-May	8.1		7.4	0.4		6.9	0.12		10.1				12.5		6.9				14.4		5.7	9.6		8.4	
14-May	7.5		7.5	0.0		6.5	0.06			0.1			10.5		5.7				14.4	9.3	4.5			8.8	
15-May				0.0		4.9	0						11.0	9.5	5.1		13	12.4	15.1	8.2	3.3	6.8	12.4		
16-May			7.7			3.6				0	0		7.3	8.7	3.9			12.2	15.1	7.8	1.4		11.0	7.7	
17-May			7.5		13	1.8			5.8			10.1	5.8	6.5	3.6			12.6	15.4	6.0	2.1	4.0	11.3	5.9	
18-May	8.0		6.9			1.1			0.7				5.3	6.2	3.2		13	12.1	14.8	4.3		3.4	11.1	4.9	16.9
19-May	7.3		5.2		12.3	0.4			0.1				4.5	4.2	2.2	11.2	14	11.2	15.2	2.0	1.8	2.9	10.4	4.3	17.4
20-May	6.9		3.9		12.0	0.02			0.0			10.2	3.7	1.5	1.1	10.7		11.1	15.4	2.1	2.1	1.3		2.9	16.1
21-May	6.2		2.6		12.0	0.0							2.8	1.5	0.6	10.2	14	9.3	18.5	1.8	1.0	0.3	9.5	2.6	15.4
22-May	6.2		1		11.4								2.2	0.1	0.4	9.2		7.0	18.4	1.1	0.9	0.5	9.4	2.8	15.0
23-May	5.7		0.2		10.7							10.2	1.9	0.0		9.5	14	5.4	16.4	0.2	0.8	0.1	6.7	0.2	12.9
24-May	4.4		0.0		10.5			15.3				9.0	1.4			9.3		0.5	15.3	0.0	0.4	0.0	5.0	0.1	12.8
25-May	1.8				9.3							6.6	0.7			8.0	14	0.0	17.1		0.2		3.0	0.0	10.0
26-May	0.9				8.6			14.6				4.8	0.4			7.5	13		17.3		0.1		1.8		11.1
27-May	0.6	11.4			7.6			13.9				2.6	2.5			7.3	12		15.1		0.0		0.9		12.4
28-May	0.3	11.2			4.5			13.9					2.2			6.4	12		15.3				0.2		13.4
29-May	0.1	10.2			2.0			14.1				1.6	2.2			3.9	12		14.5				0.0		12.6
30-May	0.0	10.2			0.0			13.7				0.4	0.8			0.2	9.6		12.8						12.4
31-May		8.9						13.0					0.6			0.01	4.6		11.4						10.8
1-Jun		7.4						10.8				0.0	0.0			0.0	6.0		11.7						9.4
2-Jun		5.1						9.7									5.9		7.2						6.6
3-Jun		4.1						8.8									3.1		3.6						2.3
4-Jun		2.3						7.5									2.2		0.4						0.0
5-Jun		0.3						5.8									0.8		0.0						
6-Jun		0.0						5.1									0.2								
7-Jun								5.2									0.0								
8-Jun								4.0																	
9-Jun								2.7																	
10-Jun								1.0																	
11-Jun								0.0																	
12-Jun																									

Appendix B2. Snow water equivalent (cm) at the Upper Kuparuk (UK) site

Month and Day	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
30-Apr																15		10	14	18	18		12		
1-May																									
2-May																									
3-May																									
4-May																									
5-May																									
6-May																									
7-May																									
8-May																									
9-May																			17.4						
10-May																			17.0						
11-May																			15.3		13.0				
12-May																			12.3		11.5			12.1	
13-May															4.7							12.4		10.6	
14-May															3.6			12.9		16.4	6.0			12.6	
15-May															1.7		17	12.5	18.3	17.0	13.2				
16-May															1.2			15.3	17.4			8.0	14.2	10.1	
17-May															1.0						9.1	7.8		11.8	
18-May															0.0			15.2	18.1	11.5		6.4	13.0	9.6	
19-May																	14		18.7	9.8	7.2	4.5	13	7.2	
20-May																20.5	16			7.7	8.1	1.8		7.5	23.8
21-May																		12.6		9.2	5.5	0.0	11.8	5.6	20.3
22-May																	17				0.3			4.0	16.7
23-May																		5.8		5.9			8.0	0.9	
24-May																	17		17.6				5.4	0.0	12.4
25-May																		0	17.9	1.1					9.2
26-May																	18		17.3	0.5			3.1		10.4
27-May																	15						0.0		
28-May																	13		15.2						9.2
29-May																	15								6.2
30-May																	13.3		13.1						
31-May																17.2	10.1								7.8
1-Jun																	13.7		12.3						
2-Jun																17	9.7		10.6						7.2
3-Jun																			7.9						
4-Jun																17	0								
5-Jun																16									
6-Jun																9.8									
7-Jun																4.8									
8-Jun																1.3									
9-Jun																0									
10-Jun																									
11-Jun																									
12-Jun																									

Appendix B3. Snow water equivalent (cm) at the Happy Valley (HV) site.

Month and Day	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
30-Apr																	14	15	13	23	24		7.3		41
1-May																									
2-May																									
3-May																									
4-May																									
5-May																									
6-May																									
7-May																									
8-May																									
9-May																									
10-May																			16.4						
11-May																									
12-May																									
13-May																						22.0			
14-May																		13.1							
15-May																					28.3				
16-May																		12.5							
17-May																							8.1		
18-May																		9.6						20.0	
19-May																15.3				17.4		22.0			
20-May															7.4		19	6.7			30.0				
21-May																			17.7	14.9					27.4
22-May															10			0.8				14.1	7.8	16.2	
23-May																		0.0	11.1	14.7	28.6				
24-May																						13		12.6	21.0
25-May																			20.2	8.2			6.9		
26-May																	14				26.7	8.2		6.2	15.6
27-May																									
28-May																			11.0		21	7	6.3	3.0	
29-May																				0					17.5
30-May																16.0					19	4.2	5.8	0	
31-May																			24.3						
1-Jun																	11.7				13	0	4.7		15.6
2-Jun																13			4.4						
3-Jun																	9.2				10		1.7		
4-Jun																12									
5-Jun																	4.1				4.3		0		
6-Jun																11									
7-Jun																	0								
8-Jun																2.3									
9-Jun																									
10-Jun																0									
11-Jun																									
12-Jun																									0

Appendix B4. Snow water equivalent (cm) at the Sagwon (SH) site.

Month and Day	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
30-Apr				8.1	9.1	4.4	6.0		5.6			8.3	12			10	6.4	10	8.1	11	5.5		7.5		4.3
1-May																									
2-May																									
3-May																									
4-May																									
5-May																									
6-May																									
7-May							1.7																		
8-May						2.0																			
9-May				5.4																					
10-May																									
11-May																									
12-May																									
13-May				3.9			1.7															6.0			
14-May																		7.9							
15-May			5.2													7.9					3.6				
16-May																		7.7							
17-May				3.9												7.7							7.3		
18-May				4.4														3.3						8.0	
19-May												0.4				3.3				8.2		0.0			
20-May						1.1								1.7	5.8		8.1	0.0			4.3				
21-May				3.9												0.0			8.4	4.8					0
22-May															7.7								7.2	7.0	
23-May																			10.2	4.9	3.4				
24-May				3.8									1.1		4.1									3.7	
25-May					5.9				2.3											2.8			7.1		
26-May				3.7													6.6				2.9			1.5	
27-May																									
28-May				3.7															9.2		2.2		7.1	0.0	
29-May																				2.8				8.0	
30-May				2.6																	0.3		6.3		
31-May																			2.0						
1-Jun				2.4													5.7			2.3	0		4.7		
2-Jun																									
3-Jun				1.8													1.8			1.3			0		
4-Jun																									
5-Jun				1.7													0.5			0.5					
6-Jun																	0.0								
7-Jun																				0					
8-Jun																									
9-Jun																									
10-Jun																									
11-Jun																									
12-Jun																									

Appendix B5. Snow water equivalent (cm) at the Franklin Bluffs (FR) site

Month and Day	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
30-Apr				9.3		4.7	11.3		12.7					6.5		10		8.5	12		12	10	6.6		
1-May																									
2-May																									
3-May																									
4-May										6.1															
5-May																									
6-May											7.0														
7-May																									
8-May						5.6																			
9-May				2.7																					
10-May																			10.2						
11-May																									
12-May																									
13-May																									
14-May							10.7											8.3							
15-May			8.5																		12.0				
16-May								8.0										6.5							
17-May																			15.6				8.7		
18-May																		4.7	17.6						
19-May												6.9							19.5			8.1			
20-May														7.1		14.5	13	3.3	19.1	9.1	11.5				
21-May							10.9	6.7											12.5					9.2	9.1
22-May				5.4										9.1				1.0	12.3		12.8	5.5	8.4		
23-May																		0.0							
24-May							8.6							8.2					10.0			1.8		8.9	4.8
25-May					22.3				14					9.6					9.2	2.9			7.8		
26-May				4.9										9.1							12.3	0		7.0	0.0
27-May							8.6							8					11.4						
28-May				4.0										8.6					9.4		11		6.5	0.5	
29-May													22.9	7.8						2.9					
30-May				3.4										6.9					7.3		8		6.3	0	
31-May							2.8							6.7		14.7			14.6						
1-Jun				1.6										4.7			13.4			2.3	6		5.8		
2-Jun														2.9					2.6						
3-Jun				0.8										1.9			9.6			1.3	2.7		1.9		
4-Jun														1.4		14			0.5						
5-Jun				0.7										0.7			7.7			0.4	0.4		0		
6-Jun					7.7									0			5.5		0	0.4					
7-Jun				0												9.2	4.5			0	0				
8-Jun																8.2	3.5								
9-Jun																3.5	2								
10-Jun																2	0								
11-Jun																1.2									
12-Jun																0.3									

Appendix B6. Snow water equivalent (cm) at the Betty Pingo (BP) site

Month and Day	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
30-Apr																						12			8.0
1-May																									
2-May																									
3-May																									
4-May																									
5-May																									
6-May											6.6														
7-May																									
8-May																									
9-May											7.6														
10-May											7.1														
11-May											6.3														
12-May											6.0														
13-May											6.0							9					9.3		
14-May											5.9														
15-May											5.8				9.9										
16-May																		8.9							
17-May										7.3			12.8					8.3	10.9						
18-May													12.7					6.3	10.0		7.0				
19-May												4.7	12.9					5.4	11.5	8.1					
20-May										7.2		4.4	13.3					4.5	12.7		9.5				
21-May										6.8		4.6	13.2		9.3	12.8	8.3	4.5	12.6					9.1	4.2
22-May												4.3	12.6		8.5			2.7	12.7						
23-May										4.2		2.8	11.8					0.6	11.3						
24-May									10	3		1.9	11.3		9.2			0.0	9.5	2.7		6.3	8.2	6.9	1.4
25-May									10	1.8	5.8	1.4	13.0		7.5									5.0	
26-May									12	0.9	5.1	1.8	12.3		8.1				11.1		10.8	2.6	8.8	3	0
27-May									12	0.6	4.1	0.7	13.3		8.5				11.8					3.2	
28-May									11	0.8	3.7	0.4			7				11.8			0	9.2	1.0	
29-May									5.5	0.4	3				7.2				11.5	2.6				0.5	
30-May									3.8	0.1	2.1				7				9.8		5.5		7	0.3	
31-May										0	1.3				6.8				10.1	2.6	4.4			0	
1-Jun									0		0				5.7	14.9	8.8		8.9		4.2				
2-Jun											0				5.7				7.1	1.9			6.4		
3-Jun															4.5		4.1		6.5	1.3	3				
4-Jun															3.4				1.9	1.1	2.4		3.1		
5-Jun													9.7		2.9		3.4		0.0	0.6	1.1				
6-Jun													6.6		2.6	8.4	2			0	0.2		0		
7-Jun													4.2			6.7	1.2								
8-Jun													3.4			6.2	0.9								
9-Jun													1.4			3.8	0.7								
10-Jun													0.9			1.7	0								
11-Jun																0.3									
12-Jun																0.0									

Appendix B7. Snow water equivalent (cm) at the West Dock (WD) site

Month and Day	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
30-Apr																6.5	5.7	7.3	18	7	6.3		5.8		10.0
1-May																									
2-May																									
3-May																									
4-May																									
5-May																									
6-May																									
7-May																									
8-May																									
9-May																									
10-May																									
11-May																									
12-May																									
13-May																		7.7					6.5		
14-May																									
15-May																					3.7	8.8			
16-May																		7.6							
17-May																		7.7	7.3						
18-May																		6.5	9.4			7.3			
19-May																		4.8							
20-May																		4.3	14.6	8.2	4.9				
21-May															10.6		6.3	4.3	11.2						9.7
22-May															8.9			3.1	9.3					8.2	
23-May																		1.0							
24-May															12			0.0	11.2					11.0	8.7
25-May															9.6					2					
26-May															11				9.2		3.8		6.2	4.5	4.5
27-May															11				7.3			4			
28-May															11				8.9				6.0	0.0	
29-May															9.1				6.6			0			3.9
30-May															11				10.3	2.4	3.3		8.3		
31-May															8.9	6.2					2				0.0
1-Jun															8		6.3		14.1	2.4	1				
2-Jun															6.8				5.7				7.1		
3-Jun															7.6		4.2		4.9	1	0.6				
4-Jun															5.6				4.0	1	0.2		4.3		
5-Jun															4.7	7.2	2.8			0.8					
6-Jun															4.7	6.8	1.7		0.4	0.4			0		
7-Jun															3.4	5.4	0.9								
8-Jun															2.8	3.4	0.4								
9-Jun															3.3	1.6	0.4								
10-Jun															1.6	0.7	0.2								
11-Jun															0.5	0.6	0								
12-Jun															0	0									