ERDC/CRREL TR-16-6

Cold Regions Research
and Engineering Laboratory

US Army Corps
of Engineers®
Engineer Research and
Development Center

ERDC
INNOVATIVE SOLUTIONS
for a safer, better world

Engineering for Polar Operations, Logistics, and Research (EPOLAR)

Snow Drift Management

Summit Station Greenland

Robert B. Haehnel and Matthew F. Bigl

May 2016

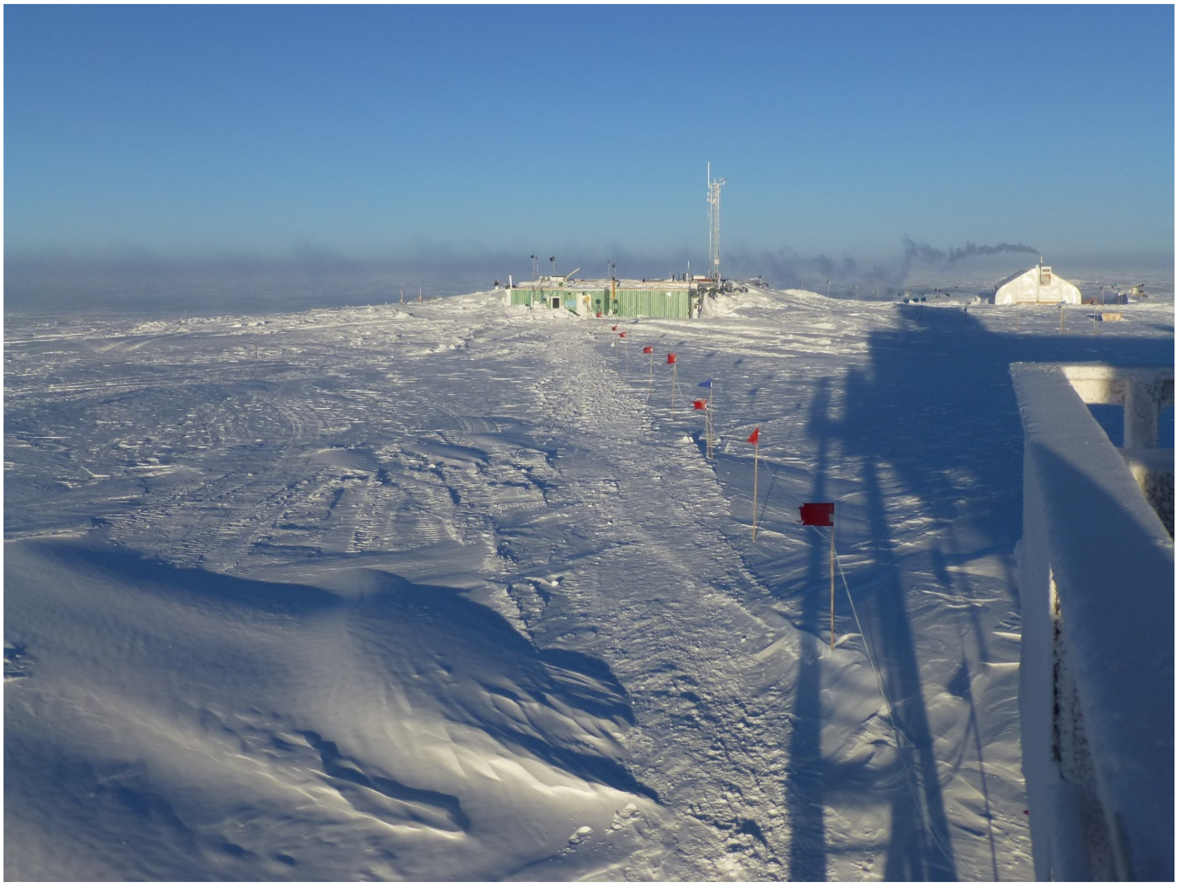


Photo courtesy of Polar Field Services, Littleton, CO

Engineering for Polar Operations, Logistics,
and Research (EPOLAR)

ERDC/CRREL TR-16-6
May 2016

Snow Drift Management

Summit Station Greenland

Robert B. Haehnel and Matthew F. Bigl

U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

Final Report

Prepared for National Science Foundation, Division of Polar Programs,
Research Support and Logistics
Arlington, VA 22230

Under Engineering for Polar Operations, Logistics, and Research (EPOLAR)
EP-ARC-15-33, “Monitoring and Managing Snow Drifting at Summit Station, Greenland”

Abstract

At the request of the National Science Foundation, the U.S. Army Cold Regions Research and Engineering Laboratory reviewed available snow survey data and conducted a drifting snow transport analysis for Summit Station, Greenland, to assess the nature of the drifting problems at this site. The severity of drifting during the winter was significantly greater than during summer months; therefore, snowdrift management strategies should focus on minimizing winter accumulations. The transport analysis showed that the snow is conveyed from two dominant directions, southeast and southwest, which satellite imagery of snowdrifts confirmed.

Computing the elevation difference between fall and spring surveys allowed estimates of the accumulated drift volume during a winter at Summit. Comparing these computed volumes to the snow transport analysis showed that about 25% of the estimated snow that the wind transports to Summit each winter is deposited and forms drifts, mostly in close proximity to the structures. This analysis demonstrates that weather data (wind speed and direction) and a transport analysis can aid in estimating the volume of snowdrifts needing to be managed at Summit.

Further work is required to determine the optimal station layout and building design at Summit to minimize drifting in the bi-modal transport environment present there.

Contents

Illustrations

Figures

Tables

Preface

This study was conducted for the National Science Foundation (NSF), Division of Polar Programs (PLR), Research Support and Logistics (RSL), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ARC-15-33, "Monitoring and Managing Snow Drifting at Summit Station, Greenland." The technical monitor was Patrick Haggerty, PLR-RSL.

The work was performed by Dr. Robert Haehnel (Terrestrial and Cryospheric Sciences Branch, J. D. Horne, Chief) and Matthew Bigl (Engineering Resources Branch, Jared Oren, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Janet Hardy was the program manager for EPOLAR; and Dr. Loren Wehmeyer was Chief of the Research and Engineering Division of ERDC-CRREL. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

We thank John Gagnon, CRREL, for accessing and processing the available weather data at Summit. We thank Art Gelvin, CRREL, for processing the Trimble™ survey data so that it could be imported into GIS for analysis. We also thank Tracy Sheeley and Ben Toth, Polar Field Services, for providing photos, data, and insight on the snow drifting problems at Summit Station. The Polar Geospatial Center provided to CRREL the archived satellite imagery used in this report.

COL Bryan S. Green was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

AFWA	Air Force Weather Agency
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics and Research
ERDC	Engineer Research and Development Center
ESE	East-Southeast
NE	Northeast
NNE	North-Northeast
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NW	Northwest
PLR	Division of Polar Programs
RSL	Research Support and Logistics
S	South
SE	Southeast
SO	Science and Operation
SW	Southwest
SSW	South-Southwest
TAWO	Temporary Automatic Weather Observation
W	West
WNW	West-Northwest

Unit Conversion Factors

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
knots	0.5144444	meters per second
miles (U.S. statute)	1,609.347	meters
pounds (mass)	0.45359237	kilograms

1 Introduction

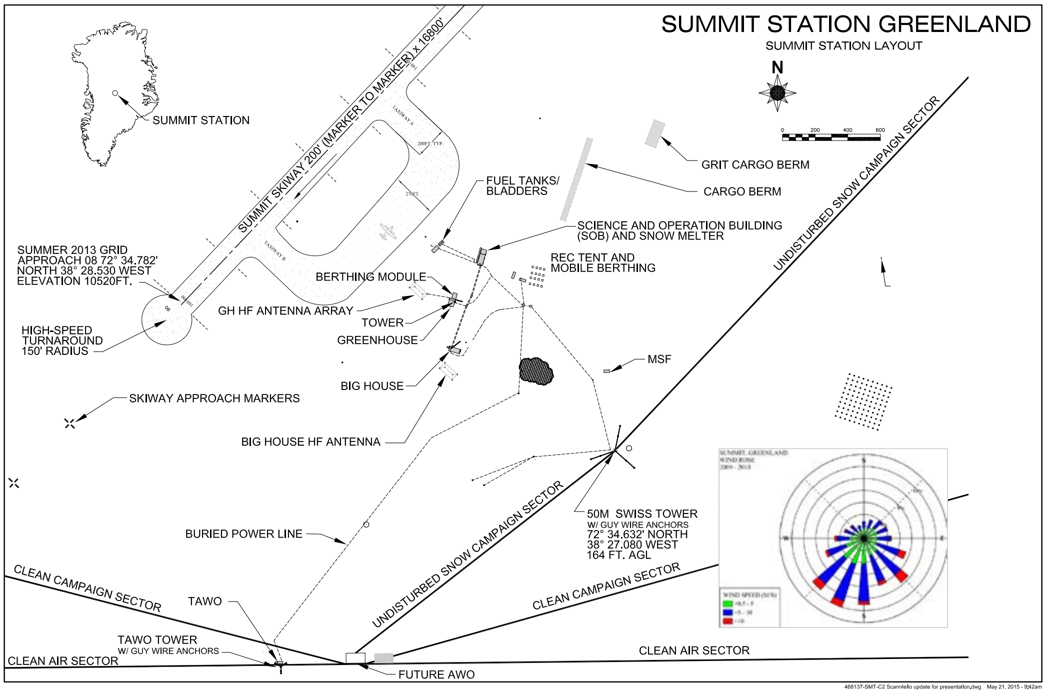
1.1 Background

Summit Station, Greenland, is subjected to heavy winds and drifting snow that forms drifts around the buildings and structures throughout the year (Figure 1). Keeping entrances, vents, and equipment clear of snow requires constant maintenance to continue normal functions and to reduce safety hazards. Seeking to improve survey methods and snow management strategies, the National Science Foundation (NSF) asked the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) to review current practices at Summit and to identify areas where improvements can be made.

Figure 1. Drifting snow around the Green House, February 2015. (Photo courtesy of Polar Field Services, Littleton, CO.)

Figure 2 shows the layout of the station along with a wind rose that gives a summary of the wind distribution from 2009 to 2013. This shows that the prevailing wind is from the south-southwest (SSW), though the wind direction fans across the southerly quadrant. Personnel stationed at Summit take regular surveys of the station to locate where drifts are deposited and to record the volume of the drift accumulations. These surveys can help estimate the amount of snow that needs to be managed annually to clean up after winter and to prepare the station for the following winter.

Figure 2. Plan view of Summit Station, Greenland, with a wind rose (Scannellio 2015).



1.2 Objectives

The objectives of this study were as follows:

1. To review the existing survey data and methods to determine their quality and usefulness and whether improved survey methods may be beneficial for estimating snow management effort required at the station.
2. To perform a snow transport analysis to determine the magnitude of snow transported by the wind annually and the predominant transport directions.
3. To understand the nature and severity of the drift problems at Summit Station.
4. To outline a way forward for developing a snowdrift assessment and management strategy at Summit.

1.3 Approach

This study met these objectives by reviewing and analyzing existing survey data, by reviewing existing satellite and ground imagery, and by analyzing existing meteorological data.

2 Weather and Snow Transport

Figure 2 provides a summary of the wind data at the site for 2009–13. A review of the yearly wind roses from 2008 to 2015 (Appendix A) determined that the wind rose in Figure 2 captures the overall trend in the wind data at Summit: on average, the winds are out of the south and generally range from southeast (SE) to southwest (SW). However, from year to year, the range can be wider than that; and for any given year, the highest probability of wind direction can range from south to west (e.g., 2010) or from east to southwest (2013). The monthly data show that the wind direction varies widely throughout the year and that, though on average the highest probability of winds are from the southerly quadrant, major wind events can come from any direction and that strong winds (greater than 10 m/s or 19 knots) can occur year round.

To understand the amount of drifting snow that needs to be managed annually, it is beneficial to estimate the amount of snowdrift transported by the wind into a region. Tabler (1994) provides an estimate of the snow transport, q, as a function of wind speed:

$$q\left(\frac{kg}{m-s}\right) = \frac{U_{10}^{3.8}}{233846} \tag{1}$$

where U_{10} is the wind speed reported at the 10 m height (this is the standard height at which most weather data reports wind speed). Equation (1) shows that the snow transport grows with almost the fourth power of the wind speed; therefore, small increases in wind speed yield large increases in snow transport, and the frequency of the wind observations plays a big role in the accuracy of estimating the snow transport using Equation (1). For example, a daily average report of the wind speed ignores the peak wind data for the day, which is responsible for transporting most of the snow. Thus, shorter reporting intervals are better as they improve accuracy, and hourly data provide a reasonable compromise between accuracy and data volume.

CRREL was able to obtain three sets of weather data for Summit Station. The Air Force 557th Weather Wing, formally the Air Force Weather Agency (AFWA), had records for two meteorological stations: 44160 and 44180. The National Oceanic and Atmospheric Administration (NOAA) provided records for a third station. Table 1 provides a summary of these data sets. Figure 3 shows the locations of these weather stations relative to Summit Station. The weather station furthest from Summit is SUM (the NOAA site); it is located about 2.5 km north-northeast (NNE) of Summit Station.

Table 1. Summary of weather data sources for Summit Station.

Station	Period of Record	Frequency	Location	Elevation (m)	Source
44160	June 1999–present[*]	3 Hour	72.583° N, 38.45° W	3207	557th
44180	Feb 2011–Feb 2013[†]	3 Hour	72.583° N, 38.5° W	3198	557th
SUM	June 2008–present[‡]	Hourly	72.60° N, 38.42° W	3209	NOAA

[*] Though the record starts in 1998, the wind data for that year is extremely high (100–150 knots) and is therefore suspect and not included in this study. There are large gaps in data for 2002–04. Following this, generally the gaps in data occur during the winter.

[†] Gap in data October 2011–March 2012.

[‡] Gap in data 14 July–27 August 2013.

Figure 3. Location of weather stations relative to Summit Station, Greenland. (Image taken 15 June 2014 by Digital Globe.)

Equation (1) provides the amount of snow transported per unit time. What is of more interest is the total amount of snow transported, Q, during a period of interest (e.g., a storm or a season). This is computed using Equation (2) (Haehnel and Weatherly 2014):

$$Q\left(\frac{kg}{m}\right) = \Delta t \sum_{i=1}^{n} q_i \tag{2}$$

where Δt is the reporting time interval (e.g., 1 hour) and n is the number of observations over a period of interest.

However, some snow is lost due to sublimation while it is airborne so that not all of the transported snow is deposited on the ground. The amount of snow that sublimes away is a function of how far a snow particle might travel. Tabler (1994) indicates that any snow that is carried aloft more than 6000 m will evaporate before it reaches the ground. The following expression provides an estimate of the amount of deposited snow, Q_{dep}, as a function of fetch length, F (Tabler 1994):

$$Q_{dep} = 0.7\,Q\,(1 - 0.14^{F/3000\ \mathrm{m}}) \tag{3}$$

where a fetch is the length of the unobstructed distance upwind of the region of interest (i.e., a region where drift might form). For all intents and purposes, the fetch surrounding Summit Station is infinite; and Equation (3) reduces to

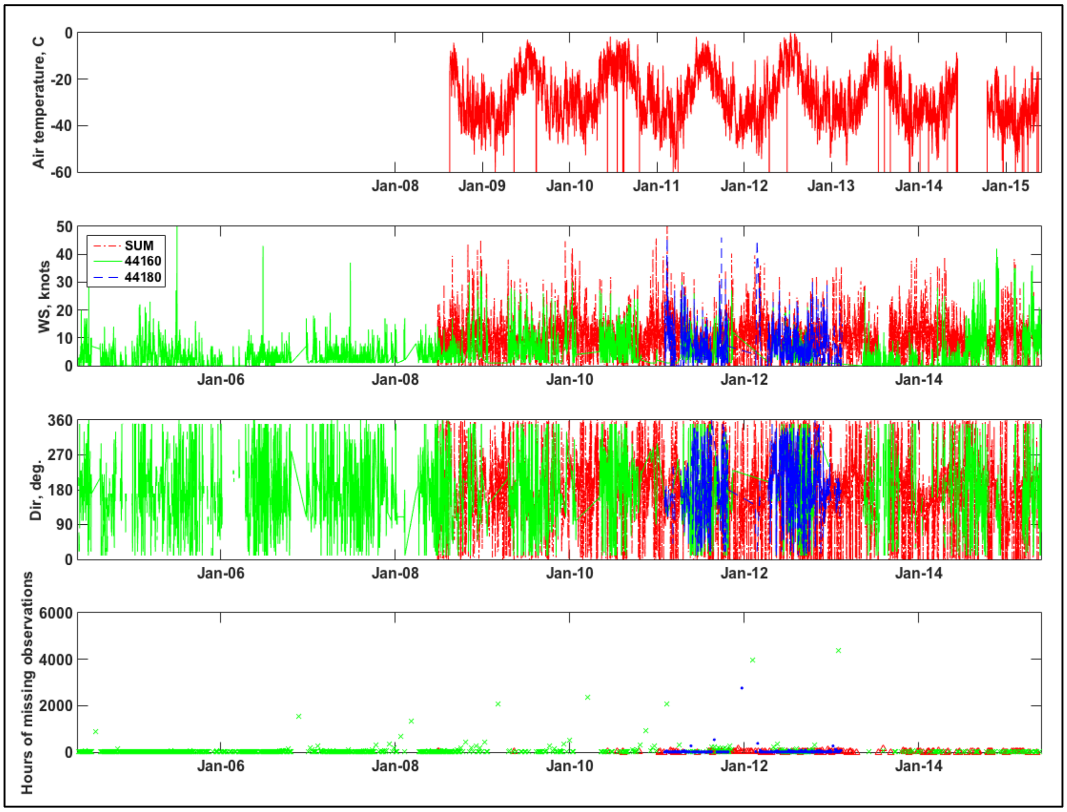
$$Q_{dep} = 0.7\,Q. \tag{4}$$

This study used Equations (1), (2), and (4) to estimate the deposited snow at Summit Station by using available wind data records.

Figure 4 shows that the average hourly air temperature never rises above freezing. In general, little melting occurs though we expect that localized melting can occur on warm days when the insolation raises the surface temperature above freezing in localized points. More to the point, owing to the subfreezing temperatures throughout the year, we expect all precipitation will be frozen and will likely fall as snow. Furthermore, once the snow deposits in drifts or otherwise, no substantial melting will occur; and the snow will be removed only through maintenance operations, not through melting.

The estimated wind speed required to move freshly deposited snow (i.e., fresh snow precipitation) is in the range of 3–7 m/s (6–14 knots). Consequently, we can see from Figure 4 that the wind speed is above this threshold range the majority of the time; therefore, we expect that any available snow is transported by the wind and is available to form drifts.

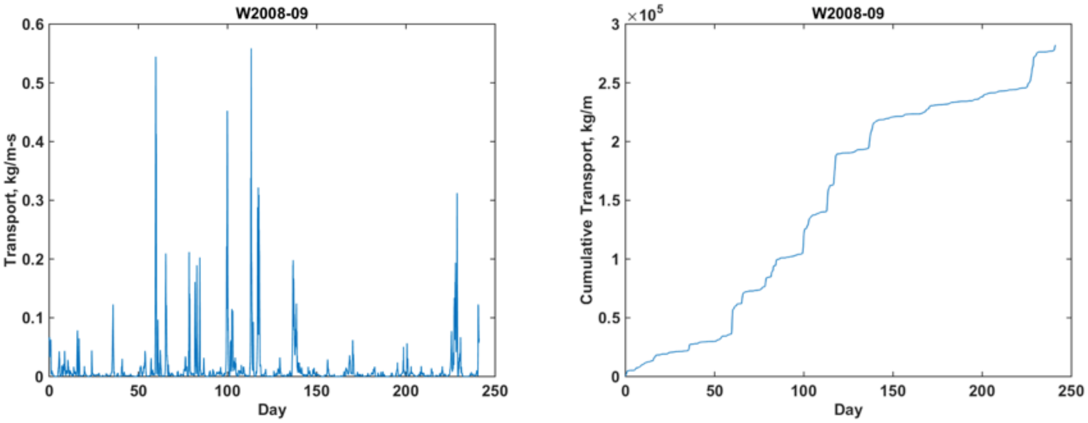
Figure 4. Summary of temperature and wind data available at Summit Station, Greenland. The bottom pane provides information on the data missing data for each data set. Note, as indicated in the legend, the *red* data is from the SUM station (NOAA), while station 44160 is indicated in *green* and 44180 is *blue*.



This study used the NOAA dataset to make transport calculations because it provides hourly reporting and contains the fewest gaps. Though the period of record for the NOAA data is shorter than station 44160, the gaps in data and the longer sampling interval made the 44160 data record less desirable. Nevertheless, we computed transport using both data sets to estimate the magnitude of error introduced by using the lower frequency (3 hour) data.

Figure 5 shows example transport calculations for a season. The left frame shows the daily variation in transport that occurs through the season, and the right frame shows the cumulative transport during the same season.

Figure 5. Estimated snow transport for the winter of 2008–09 (1 September 2008–30 April 2009). The *left* frame shows the calculated transport using Equation (1), while the *right* frame provides the cumulative transport (Equation 2) over the season.



Tables 2 and 3 give the estimated snow transported by the wind during the winter (1 September–30 April) and summer (1 May–31 August), assuming there is an unlimited snow supply anytime the wind is blowing. Any years missing a significant amount of data points that would affect the calculation were not included in the tables. Thus, there are some years without an estimate of the amount of potential snow that could be deposited.

From a comparison of the data provided in Tables 2 and 3, we find that the amount of potential deposited snow during the winter period is about 4–7 times as much as during the summer months. Furthermore, we see that the estimated snow amount using 3-hour observations (station 44160) is about one-third to one-half of the amount estimated from hourly observations because averages over a longer time interval tends to reduce the magnitude of the reported average wind speed.

Table 2. Estimated winter (1 September–30 April) snow deposits from drifting snow at Summit Station, Greenland.

	Potential Deposited Snow (t/m)* per Station	
Year	SUM	44160†
2008–09	197.5	
2009–10	206.0	
2010–11	271.0	
2011–12	183.1	
2012–13	115.5	
2013–14	183.0	
2014–15	180.5	134.2
Mean	190.9	

* Note that t is metric tonnes: 1 t = 1204 lb.

† There were larges gaps in the data in years for which no data was reported.

Table 3. Estimated summer (1 May–31 August) snow deposits from drifting snow at Summit Station, Greenland.

Year	Potential Deposited Snow (t/m) per Station	
	SUM	44160
2009	44.49	28.27
2010	40.00	22.23
2011	30.74	14.39
2012	34.56	9.10
2014	27.77	14.85
Mean	35.51	17.77

Based on the snow drift severity classification provided in Tabler (1994), the wintertime snow transport falls into a classification of "severe" while the amount of snow transported during summer is classified as "moderate."

As a check on the transport numbers provided in Tables 2 and 3, we provide an alternate method for obtaining a gross estimate of the maximum possible snow transport at a given site (Haehnel and Weatherly 2014)

$$Q_{dep} = 0.7\rho F S_{we} \tag{5}$$

where $\rho = 1000$ kg/m^3, the density of water, and S_{we} is the water equivalent depth of the snow (i.e., the depth of snow, converted to water depth, that has accumulated over a period of time). For example, the average annual accumulation of snow in the region near Summit is about 65 cm (Dibb and Fahnestock 2004) (depth away from buildings or other obstructions that may cause a bias). The average surface density of the snow at Summit is about 320 kg/m^3 (Haehnel and Knuth 2011), so the annual $S_{we} \approx (320\ \text{kg/m}^3 \div 1000\ \text{kg/m}^3) \times 0.65\ \text{m} = 0.21$ m. Applying Equation (5) with a maximum fetch length, $F = 6000$m, $Q_{dep} = 874$ t/m. This is about four times higher than the combined summer and winter average estimated potential snow deposited as given in Tables 2 and 3. Though the amount of estimated snow potential that may be deposited as drifts is severe by standards for the continental United States, it is significantly less than the maximum potential snow transport estimated via Equation (5). That is, the annual snow-transport estimates provided in Tables 2 and 3 seem realistic and may not be overly conservative.

Tables 2 and 3 present the amount of snow potentially transported by wind, irrespective of wind direction. The capture efficiency of the structures that the blowing snow encounters determines how much snow actually is deposited. Therefore, the locations where snow is deposited depend on the direction of the wind during the blowing snow event. Because of the wide variation in wind direction, one would expect that snowdrifts formed on buildings at Summit Station are distributed over a large angle around the structures. To appreciate the variability in location of the deposited drifts, we computed a transport rose, a variant of a wind rose that includes the wind direction and amount of snow transported from that direction. Figures 6 and 7 are example transport roses.

A transport rose will often differ in shape from a wind rose. Because the snow transport is a function of almost the fourth power of wind speed, the transport rose accentuates the high velocity wind periods and diminishes the low wind speed periods. Thus, the dominant directions highlighted by a transport analysis may be quite different than a wind rose.

Figure 6. Some example transport roses for Summit Station for the winter (1 September–30 April).

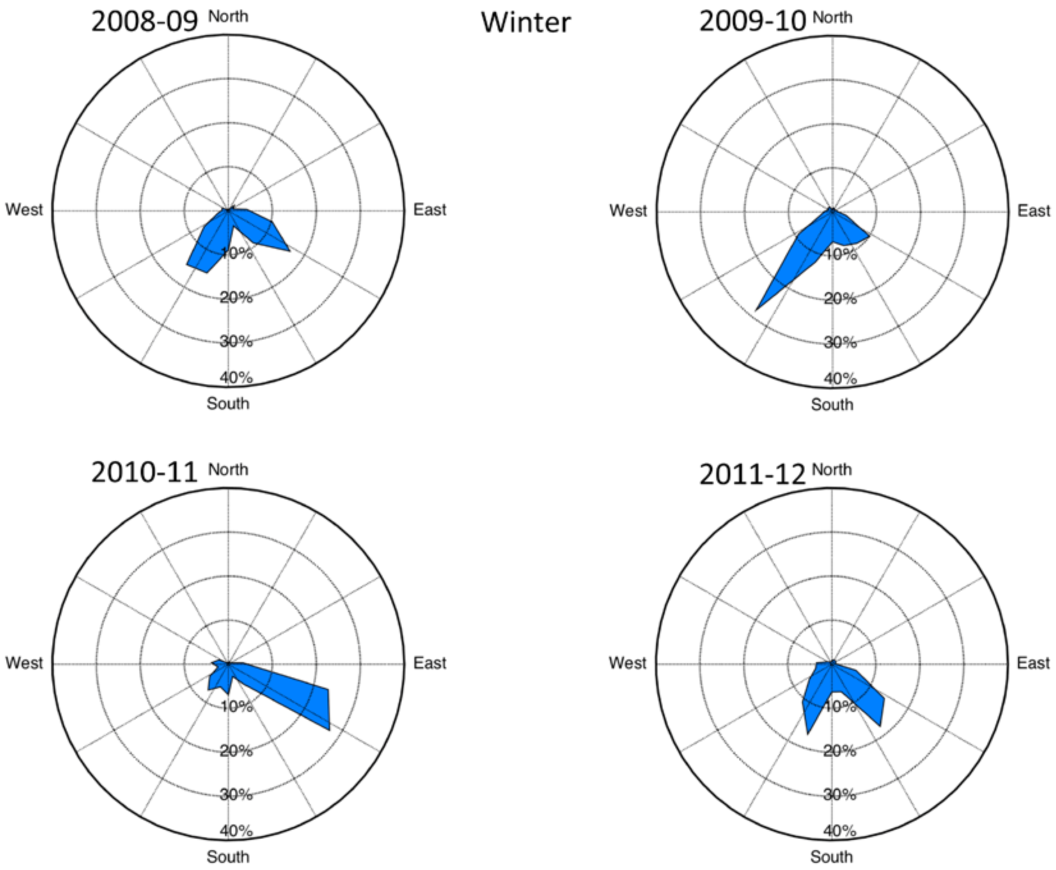
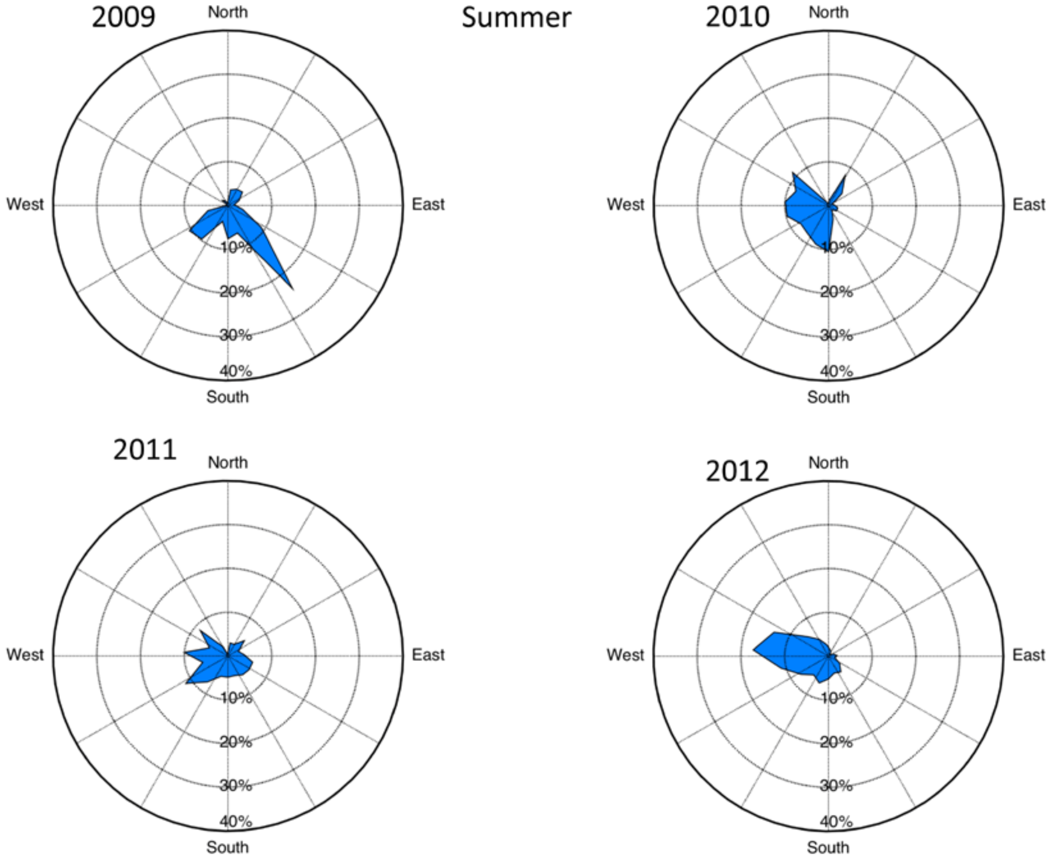


Figure 7. Some example transport roses for Summit Station for the summer (1 May–31 August).



The main direction from which the snow is transported varies from season to season and year to year at Summit. For example, during the summer of 2009, the transport was principally out of the SE, while during the summer of 2012, the transport was principally out of the west. This wide variation makes it difficult to plan which direction to orient a building to minimize drifting. In the winter, however, the variation in wind direction appears to be reduced to mainly two directions (Figure 6), SE and SW. Because these two directions are orthogonal, it is likely that buildings are correctly oriented for only about 50% of storm events.

Tables 4 and 5 summarize the estimated potential snow volume transported from the principle directions identified during both winter and summer. Table 4 shows that during the winter periods of 2008–15, the drifting snow was most often from the SE; yet significant amounts of snow still was also transported from SSW or SW. During one winter (2009–10), over 50% of all of the blowing snow came from the SW. This suggests that although the snow is most generally transported from the SE, one still needs to account for a significant amount of snow coming from SSW to SW direction. Furthermore, one-quarter to one-half of all the snow transported annually originates from other directions during the winter, though the percentage transported in any one direction is relatively small (e.g., less than 5%).

Table 4. A breakdown of estimated potential winter snow transport by dominate transport directions. Total amount is brought down from Table 2.

Year	Potential Deposited Snow (t/m)					
	Total	ESE*	SE	SSW	SW	Other Direction
2008–09	197.5		73.1		67.2	57.3
2009–10	206.0		41.2		107.1	57.7
2010–11	271.0	135.5			13.6	121.9
2011–12	183.1		95.2			87.9
2012–13	115.5		60.1		23.1	32.3
2013–14	183.5		68.0	34.9		80.7
2014–15	180.5		45.1	41.5		93.9

* East-southeast

Table 5. A breakdown of estimated potential summer snow transport by dominate transport directions. Total amount is brought down from Table 3.

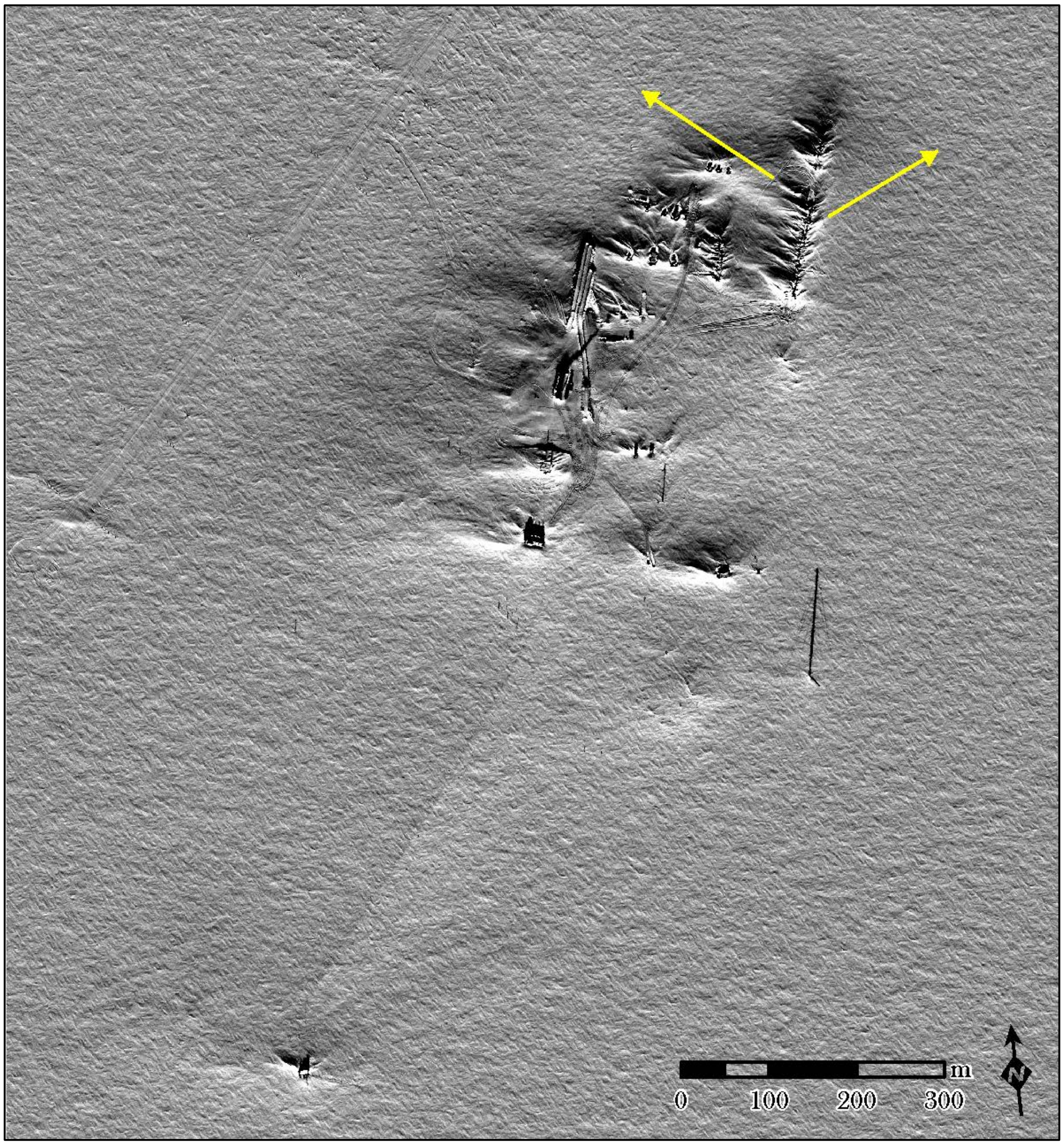
Year	Potential Deposited Snow (t/m)							
	Total	NE*	SE	S*	SW	W*	NW*	Other Direction
2009	44.49		10.7	3.6	8.9			21.4
2010	40.00	3.2		4.0	6.0	8.0	4.4	14.4
2011	30.74		3.1		3.4	3.1	2.8	18.4
2012	34.56					15.6		19.0
2014	27.77				6.7	7.5		13.6

* NE, S, W, and NW stand for northeast, south, west, and northwest, respectively.

Table 5 shows that while the total amount of snow transported during the summer is classified as moderate, the amount of snow from any one direction is generally quite small (i.e., classified as light [10–20 t/m] to very light [<10 t/m] per Tabler 1994). This suggests that though there are drifting snow events during the summer, they are generally small and that the size of the drifts formed would likely be easily managed. Therefore, snowdrift management strategies should focus mainly on winter transport and the resulting drifts formed during that time.

For comparison, an example satellite image of Summit in early spring in Figure 8 demonstrates the veracity of the transport calculations provided in Table 4; the image shows that the snow drifts extend approximately to the WNW (west-northwest) and NE, consistent with the dominate wind transport directions being from the ESE and SW as indicated in Table 4. This trend is most evident around the cargo berms (upper right) but can also be seen on the other structures located at Summit.

Figure 8. Satellite image of Summit Station taken 2 April 2011 showing the drift patterns around the buildings and cargo berms at the end of the winter (World View 1). The *yellow arrows* highlight the direction of the drifts extending from the cargo berms.



3 Summit Snow Survey Data

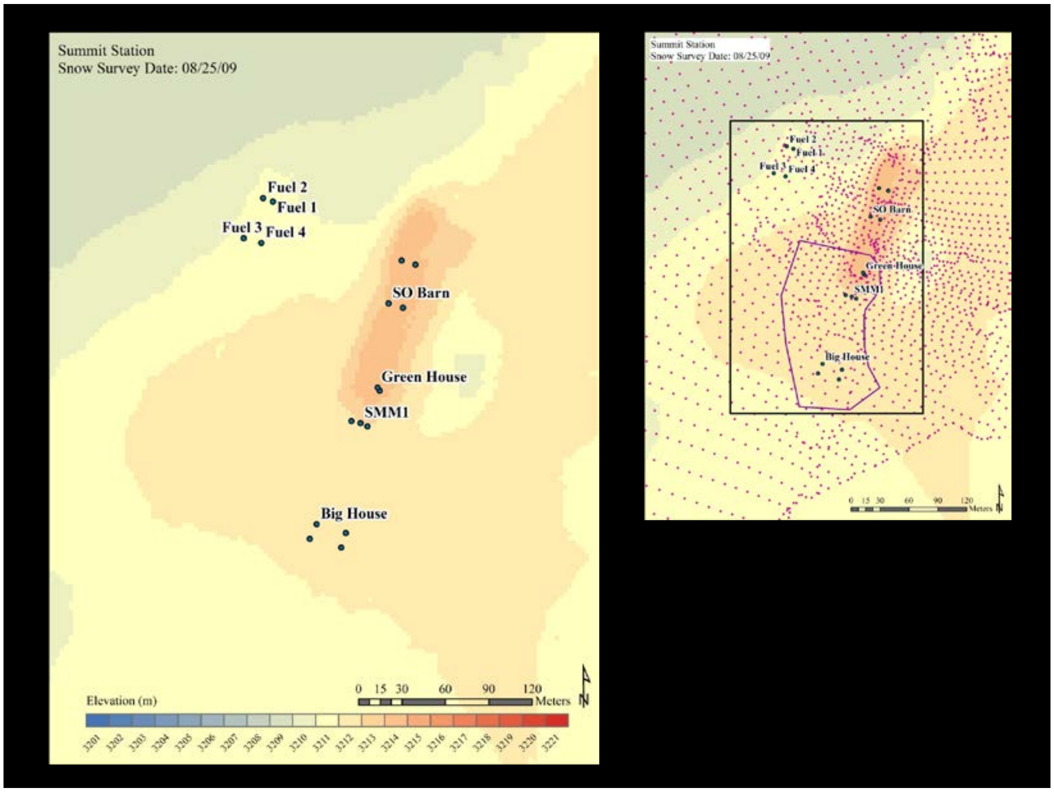
Personnel stationed at Summit took several snow surveys from 2006 to the present around the Big House, Green House, Science and Operation (SO) Barn, and fuel bladders (collectively referred to as the “main buildings”); temporary automatic weather observation (TAWO) structure; and the snow pile. This report focuses on data collected around the main buildings to understand the quality and usefulness of those surveys. Note that several of the Trimble™ (a 3-dimensional geographic positioning system) survey files provided to CRREL could not be processed and used in this analysis. Table 6 provides a list of all of the surveys taken, remarking as to why some of the surveys could not be used and summarizing the results from surveys with quality data.

Table 6. Summary of snow survey data collected around the main buildings (Big House, Green House, SO Barn and fuel bladders) at Summit Station, Greenland.

Survey date	Net Survey Area, A (m^2)	Net Increased Snow Volume, V_c (m^3)	Average Added Snow Depth, V_c/A (m)	Estimated capture efficiency
1 Dec. 2006	Missing job file (no quality control data)			
21 Feb. 2007	Missing job file (no quality control data)			
16 Oct. 2007	27,615	0	0	
15 Feb. 2008	27,615	12,817	0.46	
13 Apr. 2008	27,615	18,423	0.67	
28 Aug. 2008	35,980	0	0	
3 Nov. 2008	35,980	57,601	1.60	
25 Jan. 2009	35,980	59,440	1.65	
19 Mar. 2009	35,980	86,424	2.40	
25 Aug. 2009	14,099	0	0	
1 Feb. 2010	14,099	−4,610	−0.33	
27 Oct. 2010	Data good, but no valid associated spring data			
9 Mar. 2011	No valid data in Trimble files			
14 Sep. 2011	Data good, but no valid associated spring data			
20 Mar. 2012	No valid data in Trimble files			
29 Sep. 2012	46,000	0	0	
13 Mar. 2013	46,000	21,865	0.48	0.21
12 Mar. 2014	Not processed (no associated Aug./Sep. data)			
17 Sep. 2014	50,990	0	0	
27 Mar. 2015	50,990	46,335	0.91	0.29

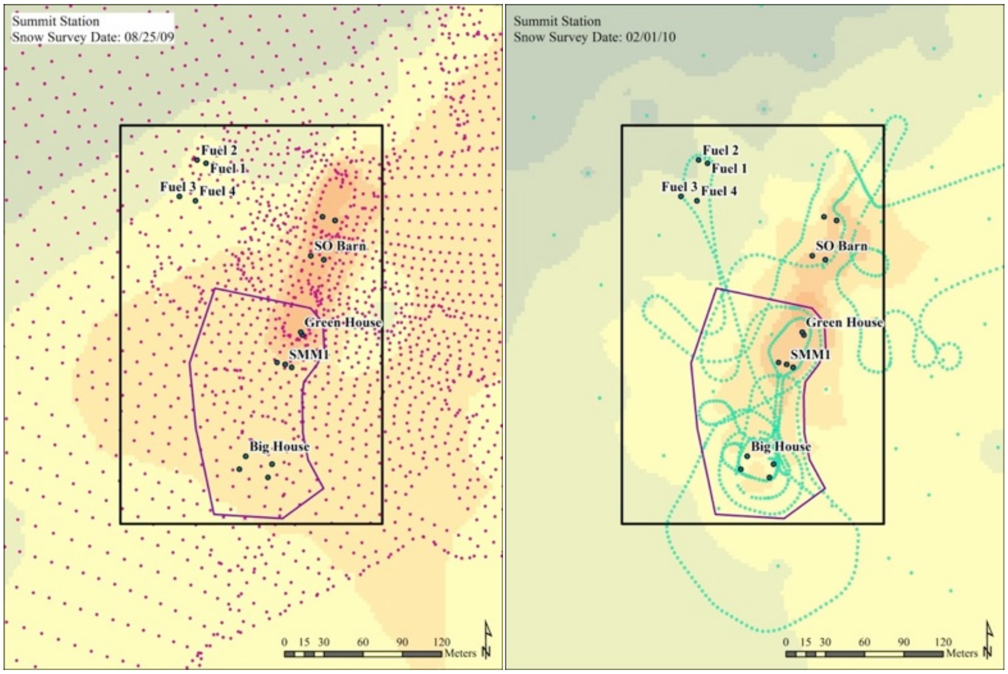
The data were collected as an irregularly spaced point cloud. CRREL converted the data to gridded raster format wherein the irregularly spaced data was interpolated to form a regularly spaced grid. This enabled comparison of one survey data set with another. Figure 9 shows typical processed survey data.

Figure 9. Processed snow survey data for 25 August 2009. The figure on the *right* shows the survey points (*magenta dots*), while the figure on the *left* shows the interpolated snow surface computed from the survey data. The color shading indicates the elevation above sea level (modified from Burzynski and Newman 2013).



However, some surveys covered a larger area and some a smaller one. Additionally, some portions of an individual survey were spaced too far apart to provide a meaningful result. Figure 10 illustrates the disparities by using data acquired during the 2009–10 winter season as an example. These issues made it difficult to directly compare each survey. To account for this for each sequence of surveys that progressed from the fall to spring (roughly August through March or April), we used the intersection of the usable survey region from each individual survey as the area used to compare drift accumulation through a winter season. Table 6 refers to this intersection of regions as the net survey area.

Figure 10. Snow surface surveys taken at Summit Station, Greenland, spanning the 2009–10 winter season. The first survey (*a*) was taken 28 August 2009; the *magenta points* show each survey data point. The second survey (*b*) was taken on 2 February 2010; the *cyan dots* indicate the survey points. The *magenta polygon* shown in both plots indicates the intersection of the usable data from both surveys. This is the net survey area reported in Table 6 for that data set. The color shades indicate the variation in elevation across the domain interpolated from the survey data.



(a) (b)

We made a difference calculation for each sequence of surveys that spanned a winter season, using the fall survey as the initial condition. The elevations of the fall data set (e.g., August or September) were set as the initial condition and subtracted from the snow elevations in subsequent surveys. Then the increase in snow volume in the net survey area could be computed, and Table 6 reports the results. In each case, the fall survey is reported as having zero increased snow volume as this is the starting point (i.e., the point entering the winter season when all of the drifted snow from the prior year has been removed during summer maintenance activities). Subsequent surveys will indicate a net deposition of snow resulting from winter storms.

The next to last column on the right in Table 6 provides the average increase in snow depth over the net survey area as a cursory check. This is simply computed by dividing the increased snow volume by the net survey area.

As mentioned previously, the average annual increase in snow depth at Summit Station is approximately 0.65 m with a standard deviation, σ = 0.045 m (Dibb and Fahnestock 2004). Though there may be localized increased snow accumulation or scouring due to buildings or other structures on the snow surface, one would expect if the survey is taken over a reasonably large area that the spatially averaged increased snow depth due to drifting at Summit Station would be approximately within 3σ of this mean value (i.e., 0.52–0.79 m). For smaller regions, the influence of the buildings on accumulation will have a strong effect on the average accumulation depth; and for that case, the range may be a bit larger.

The survey data from the 2007–08, 2012–13, and 2014–15 winters show an average snow accumulation between October and April of 0.67 m, 0.48 m, and 0.91, respectively, which is close to the range in average annual accumulation at Summit (the upper and lower values are +5.8σ and −3.8σ). The lower average depth associated with the 2012–13 season seems reasonable as the estimated transport for that season was lower than typical as indicated in Table 2. However, the winters of 2008–09 and 2009–10 show average added snow depths of 2.4 m and −0.33 m, respectively. Considering these deviate from the mean by +39σ and −21σ, respectively, these seem unreasonable, the first being over 3.6 times the expected value and the latter showing a net decrease in snow depth over the winter. Discussions with station personnel indicate that there was nothing unusual during the winter of 2009–10 such as a notable reduction in drifting snow that needed to be managed during the spring of 2010. Consequently, the survey data from that year is highly questionable. The data from 2008–09 is similarly questionable because it is so high relative to the norm and also because the estimated snow transport for that winter of 197.5 t/m (Table 4) is typical for Summit, Greenland, and certainly is not the peak estimated winter transport for the period of record (e.g., 2010–11).

For the three years with reasonable winter added snow volumes, 2007–08, 2012–13, and 2014–15, only the last two have good quality weather data from which to calculate an estimate of the wintertime snow transport (Table 4). For those years, snow deposition (Table 6) was compared with the estimated quantity of snow transported by the wind (Table 4) (i.e., a snow capture efficiency, η_c):

$$\eta_c = \frac{V_c}{V_{dep,A}} \tag{6}$$

where V_c is the volume of snow deposited around, or captured by, the buildings and terrain—the net increase in snow volume reported in Table 6—while $V_{dep,A}$ is the total volume of snow that is transported across the net survey area, A (reported in Table 6). The quantity $V_{dep,A}$ is computed by

$$V_{dep,A} = \frac{0.7}{\rho_{snow}} \sum_{i=1}^{n} q_i L_i \Delta t_i \tag{7}$$

where q_i is the transported snow for each time increment, Δt_i, and L_i is the length of the edge of the survey area that is perpendicular to the wind during that time increment. The density of the snow on the ground is ρ_{snow}; the coefficient 0.7 is the fraction of blowing snow that is deposited (Equation 4). Therefore, Equation 7 accounts for the amount of snow that will be lost to sublimation; and $V_{dep,A}$ is the amount of snow that is transported by the wind and that has the potential to be deposited.

For the years it was possible, Table 6 provides the estimated capture efficiency in the last column. This indicated that for the two seasons that sufficient data are available, on average about one-quarter of the transported snow is deposited on the terrain and around buildings. The fraction of snow deposited that will need to be removed from around structures is not clear at this point but is explored in the next section.

The quality of the data sets for some of the earlier surveys (prior to 2013) varied greatly. As noted in Table 6, some of the quality control data were missing from the earliest files, making those survey data unusable. For some of the later surveys, the reference geoid used was not the same for all of the files in a fall/spring sequence; and adjustments were required to account for the resulting elevation shift. Despite these errors in data collection, we were able to salvage some of the earlier data and to get some useful information from them. The quality of the survey data for the later datasets (2013 and newer) is very good; and for these later years with fall/spring survey pairs, we were able to obtain good estimates of the amount of snow deposited in the region around Summit Station.

4 Comparison of Survey Data and Satellite Imagery

In addition to calculating deposited drift volume by using the survey data, it is also worth comparing the drift patterns observed from the survey data with those seen in the satellite imagery. As shows in the top image in Figure 11, the color shading in the presentation of the survey data was controlled such that blue indicates a loss of snow, red indicates an addition of snow, and white indicates no change. In Figure 11, the red shading in the central portion highlights the approximate location of drifts identified from the survey data. Also, when the sun angle is low, satellite imagery readily shows the snowdrifts (e.g., lower panes in Figure 11), allowing comparison of where the survey data identifies the drifts in comparison with the satellite observations.

The survey data shows clear snow accumulation on the entire fuel storage area, and the satellite imagery clearly shows that the fuel storage in the upper left is buried by snow with just the outline of the storage area visible above the snow. The survey data show that the snow accumulation on the east side of the SO Barn is substantial while on the west side there is little to no accumulation. This trend is not as evident in the satellite imagery, from which one might conclude that the deposition is about the same on the east and west sides of the SO Barn. In both the survey and satellite imagery, one can see considerable accumulation in the vicinity of the Green House. The survey data seem to show that the bulk of the deposition associated with the Big House is north of the structure, yet the satellite imagery shows that there is an obvious wing drift to the west and a drift in front (south) of the Big House. Both of these features show up faintly in the survey data. So it appears that generally the survey data faithfully capture what is seen by satellite and in some cases provide better detail.

The color shading provided in Figure 11 appears to show that the majority of snow deposited for the 2012–13 season was associated with the buildings and structures at the site and that little snow was deposited on the terrain immediately surrounding these structures. There were a couple locations on the south and west edges of the survey area where there appears to be a net erosion of snow (light blue shading).

Figure 11. Comparison of 2013–13 survey data (*top*) with satellite imagery on 12 March 2013 (*left*, World View 2) and 18 March 2013 (*right*, World View 1). Note that for the snow survey results, the inner rectangular region is the interpolated difference between the surveys taken on 29 September 2012 and 13 March 2013 while the outer region shows the topography of the survey taken on 29 September 2012.

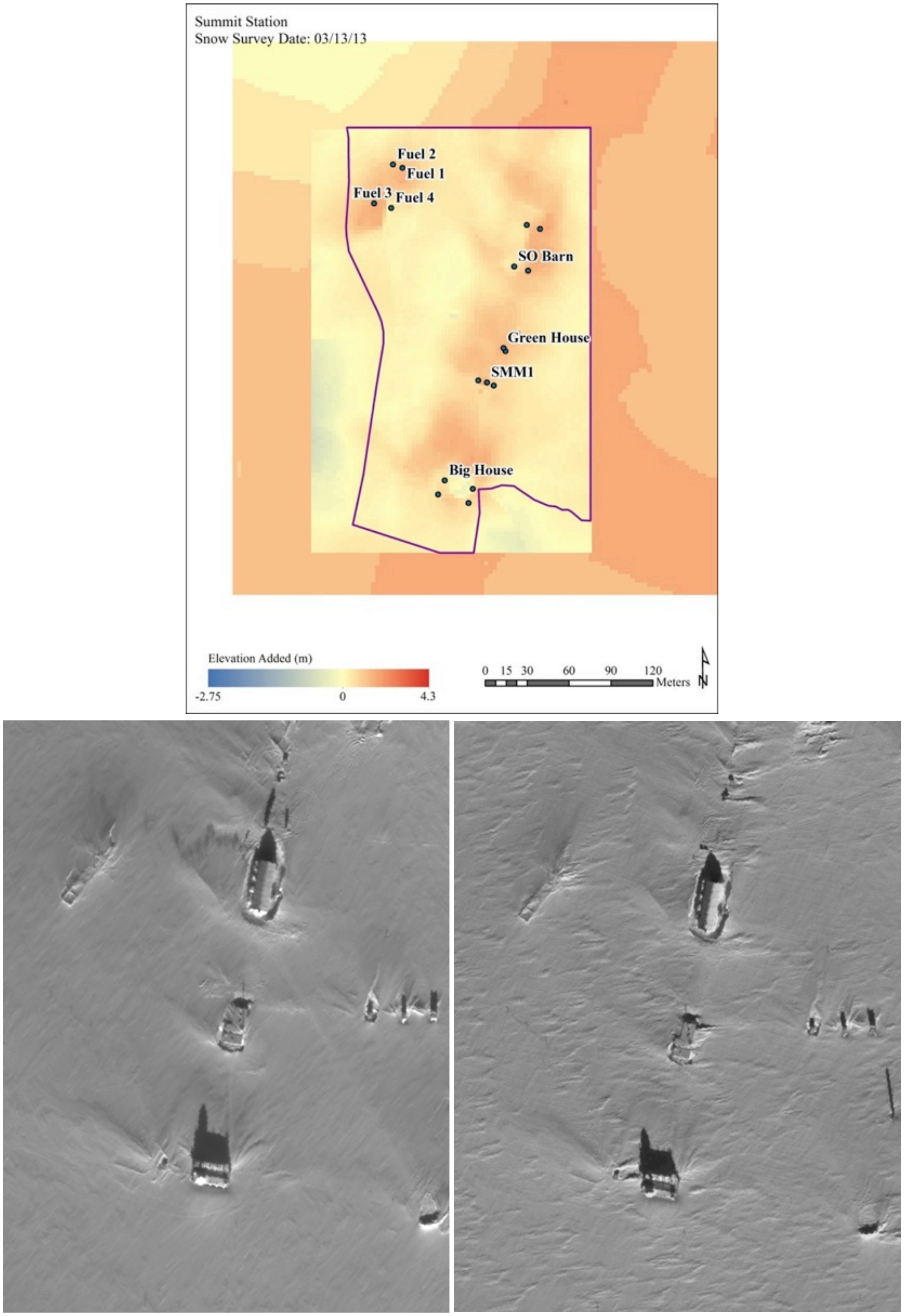
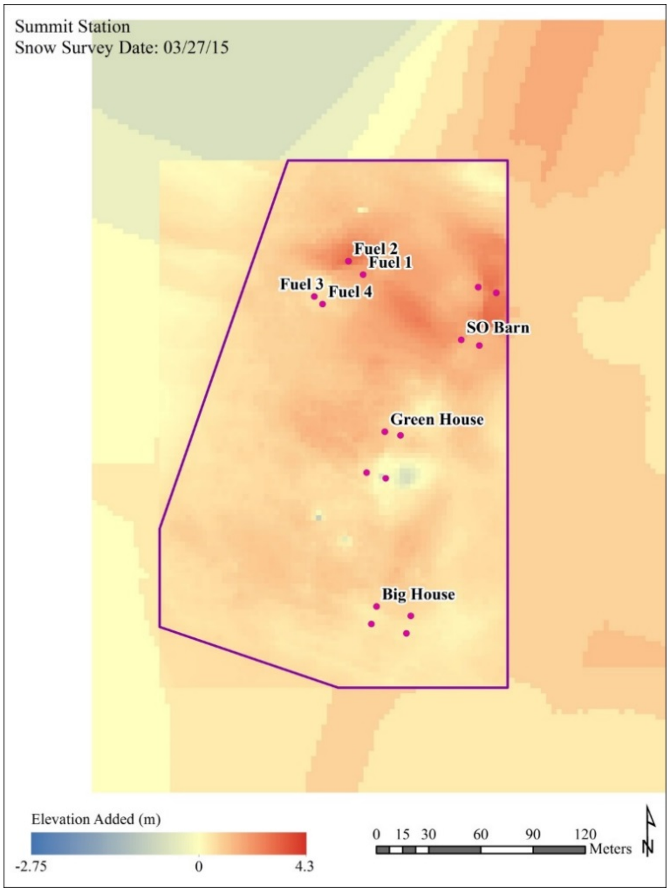


Figure 12 shows the survey results for the 2014–15 season. Unfortunately, we do not have accompanying satellite data for spring 2015 to provide a comparison; this newer imagery was not available at the time of the satellite data request in July of 2015. Still, the data provide interesting insight into the 2014–15 drift accumulation. Of note, most of the region is red, indicating that there was a general accumulation on the terrain and around the buildings during the winter of 2014–15. This made it harder to pick out the drifts that accumulated around just buildings. Still, it was clear that there was more drift accumulation around the SO Barn and fuel tanks than on the surrounding terrain. The drift accumulation around the Green House and Big House is less obvious. Also, it is hard to explain the apparent erosion of snow just east of the Green House as this is an area of perennial accumulation. Further information is required to understand this anomaly, such as records of a mid-winter or early spring removal of snow in that region.

Figure 12. Survey results for the 2014–15 winter season. The inner rectangular region is the interpolated difference between the surveys taken on 16 September 2014 and 27 March 2015 while the outer region shows the topography of the survey taken on 16 September 2014.



5 Conclusions and Recommendations

This analysis found that the bulk of the drifting snow at Summit Station, Greenland, occurs in the winter. Because of the mild drifting and extreme variability in the drifting direction in the summer, there is little benefit in trying to design for summer drift events. The main focus should be optimizing station design and drift management strategies for winter drifting.

An important finding is that though the winds tend to come most prominently from the southern sector, the dominant snow-transport direction varies widely throughout a winter and from one winter to the next. Because of the wide range of wind directions, it is difficult to orient the Station based on the long-term prevailing wind (the average wind direction taken over many years) (Figure 2). Table 4 shows that most winters, the dominant snow-transport direction is from the SE; yet some winters, the dominant direction is from the SW, approximately coincident with the prevailing wind: SSW (Figure 2). Because these directions are orthogonal, a camp layout designed to minimize drifting for one direction will result in large drift accumulations when transport is from the orthogonal direction in any given winter.

A review of the survey data taken by Summit Station personnel from 2006 onward identified significant issues with many pre 2012–13 data such that most of them were unusable. One exception was 2007–08. The data quality improved dramatically beginning in 2012–13 and was more useful for locating drift formations and computing drift volumes. Furthermore, the overlap of the good-quality survey data with hourly meteorological data allows a comparison of the surveyed drift volumes with the estimated transported snow volumes, which, in turn, enables calculation of a drift capture efficiency for the structures at Summit.

Based on the 2012–13 and 2014–15 data, it appears that on average about 25% of the estimated snow transport is deposited to form snowdrifts and that the bulk of the deposition appears to be around the buildings. This information provides the opportunity to predict the amount of snow that needs to be managed following a winter season. The meteorological data can be used to estimate the snow transport at the site during the winter. The conclusion here is that approximately one-quarter of the computed winter transported snow will need to be “managed” during the summer to dig out buildings from the prior winter and to level the ground in preparation for the ensuing winter.

Based on this study, we recommend that the current snow survey techniques continue with annual surveys taken in the fall (September, following the completion of the annual snow maintenance) to establish a "baseline" and a spring survey (late March to early April before snow maintenance commences) to determine the winter drift volume deposited at Summit. Concurrently, a transport analysis as described herein should be performed to obtain additional information on the capture efficiency (fraction of transported snow deposited around the buildings at Summit). With additional data, we can improve our certainty in the average snow capture efficiency at Summit and use the weather data, rather than snow surveys, to estimate the annual level of effort needed for snow maintenance activities for the existing station. Note that the current analysis is confined to the core set of buildings around which the survey is taken annually. Further work is needed to apply this to the broader station that includes the cargo berms and other buildings that are further removed from the central station.

It will take additional drift analysis and work to determine the optimal station layout for what is essentially a bi-modal snow transport distribution with the primary lobes being orthogonal to each other. Conventional designs for minimizing drifting around surface buildings rely on wind originating from one predominate direction (Tabler 1994; Haehnel and Weatherly 2014) and will not perform as well in the conditions present on Summit. Where possible, elevated and equi-axis (e.g., square) buildings will perform better in locales that are subjected to omni- or multi-directional winds. Larger, multi-function buildings tend to accumulate less snow than many smaller buildings that occupy the same volume as a single larger building. Further work is also required to understand the best cargo berm design in this environment.

References

Burzynski, A., and S. Newman. 2013. Snow Drift Surveys: Summit Station, 2007–2012. Presentation prepared for the National Science Foundation, Office of Polar Programs, Arctic Research and Logistics Support. Hanover, NH: U.S. Army Engineer Research and Development Center.

Dibb, J. E., and M. Fahnestock. 2004. Snow Accumulation, Surface Height Change, and Firn Densification at Summit, Greenland: Insights from 2 Years of In Situ Observation. *Journal of Geophysical Research* 109:D24113.

Haehnel, R. B., and M. A. Knuth. 2011. *Potable Water Supply Feasibility Study for Summit Station, Greenland*. ERDC/CRREL TR-11-4. Hanover, NH: U.S. Army Engineer Research and Development Center.

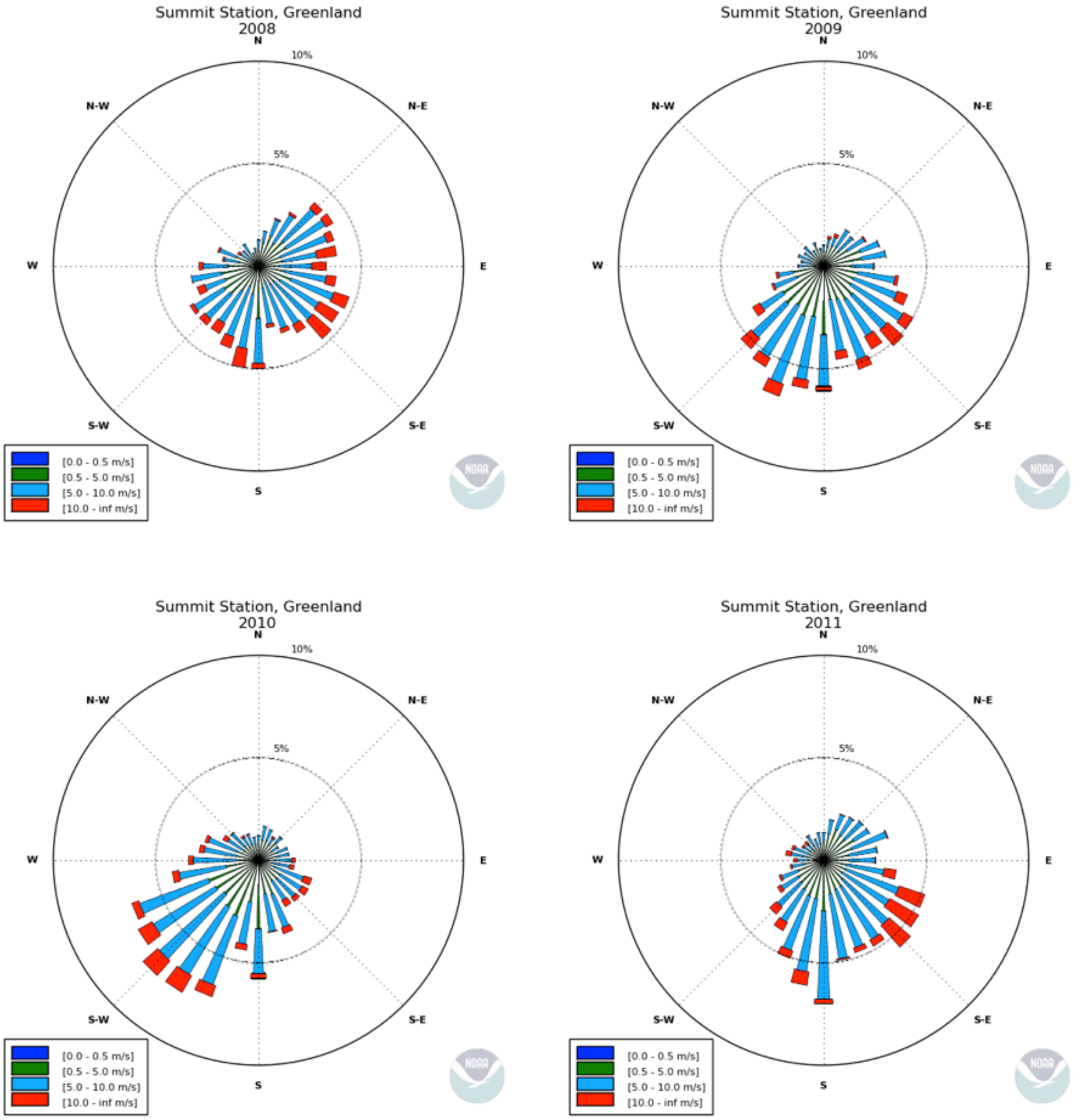
Haehnel, R. B., and J. Weatherly. 2014. *Antarctic Camps Snow Drift Management Handbook*. ERDC/CRREL TR-14-21. Hanover, NH: U.S. Army Engineer Research and Development Center.

Scannellio, J. 2015. *Summit Station Greenland: Summit Station Layout*. Centennial, CO: Antarctic Support Contract.

Tabler, R. D. 1994. *Design Guidelines for the Control of Blowing and Drifting Snow*. SHRP-H-318. Washington, DC: Strategic Highway Research Program, National Research Council.

Appendix A: Wind Roses

Figure Wind roses for Summit Station, Greenland, obtained using the NOAA web site.

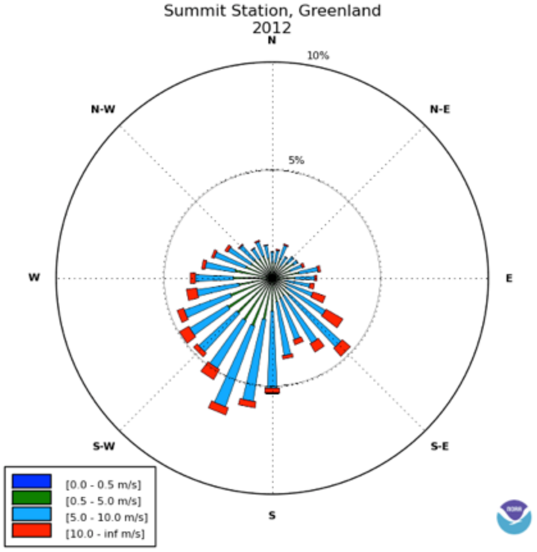


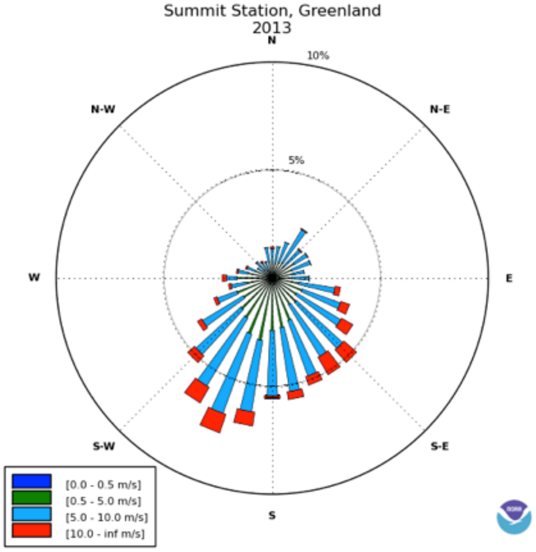
Summit Station, Greenland 2008

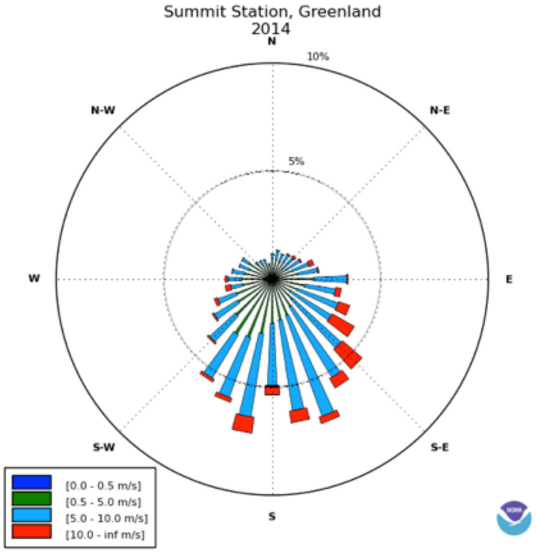
Summit Station, Greenland 2009

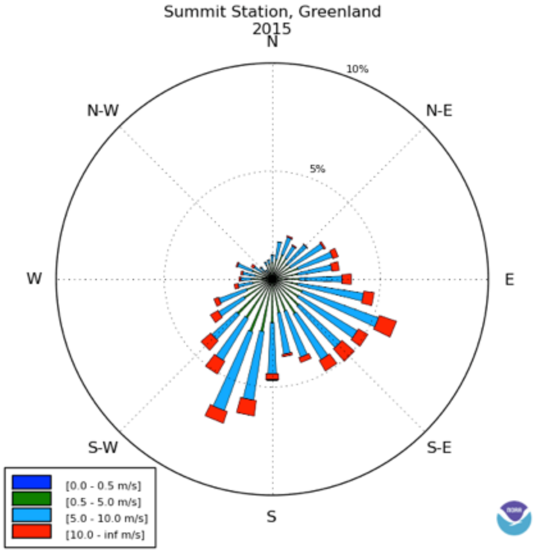
Summit Station, Greenland 2010

Summit Station, Greenland 2011


Summit Station, Greenland
2012
N
10%
5%
N-W
N-E
W
E
S-W
S-E
S
[0.0 - 0.5 m/s]
[0.5 - 5.0 m/s]
[5.0 - 10.0 m/s]
[10.0 - inf m/s]


Summit Station, Greenland
2013
N
10%
5%
N-W
N-E
W
E
S-W
S-E
S
[0.0 - 0.5 m/s]
[0.5 - 5.0 m/s]
[5.0 - 10.0 m/s]
[10.0 - inf m/s]


Summit Station, Greenland
2014
N
10%
5%
N-W
N-E
W
E
S-W
S-E
S
[0.0 - 0.5 m/s]
[0.5 - 5.0 m/s]
[5.0 - 10.0 m/s]
[10.0 - inf m/s]


Summit Station, Greenland
2015
N
10%
5%
N-W
N-E
W
E
S-W
S-E
S
[0.0 - 0.5 m/s]
[0.5 - 5.0 m/s]
[5.0 - 10.0 m/s]
[10.0 - inf m/s]

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
May 2016

2. REPORT TYPE
Technical Report/Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Snow Drift Management: Summit Station Greenland

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Robert B. Haehnel and Matthew F. Bigl

5d. PROJECT NUMBER

5e. TASK NUMBER
EP-ARC-15-33

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CRREL TR-16-6

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Science Foundation, Division of Polar Programs,
Research Support and Logistics
Arlington, VA 22230

10. SPONSOR/MONITOR'S ACRONYM(S)
NSF

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Engineering for Polar Operations, Logistics, and Research (EPOLAR)

14. ABSTRACT

At the request of the National Science Foundation, the U.S. Army Cold Regions Research and Engineering Laboratory reviewed available snow survey data and conducted a drifting snow transport analysis for Summit Station, Greenland, to assess the nature of the drifting problems at this site. The severity of drifting during the winter was significantly greater than during summer months; therefore, snowdrift management strategies should focus on minimizing winter accumulations. The transport analysis showed that the snow is conveyed from two dominant directions, southeast and southwest, which satellite imagery of snowdrifts confirmed.

Computing the elevation difference between fall and spring surveys allowed estimates of the accumulated drift volume during a winter at Summit. Comparing these computed volumes to the snow transport analysis showed that about 25% of the estimated snow that the wind transports to Summit each winter is deposited and forms drifts, mostly in close proximity to the structures. This analysis demonstrates that weather data (wind speed and direction) and a transport analysis can aid in estimating the volume of snowdrifts needing to be managed at Summit.

Further work is required to determine the optimal station layout and building design at Summit to minimize drifting in the bi-modal transport environment present there.

15. SUBJECT TERMS

Building design
EPOLAR
Greenland
Snow drift
Snow management
Snow surveys
Transport analysis
Winds -- Speed

16. SECURITY CLASSIFICATION OF:

a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
Unclassified	Unclassified	Unclassified	SAR	36	**19b. TELEPHONE NUMBER** *(include area code)*