Alaskan North Slope Oil & Gas Transportation Support: Final Technical Report

Ice road leading to a winter exploration well, North Slope, Alaska.

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DISCLAIMER

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 (m)
mile (mi)	1.609	kilometer (km)
	Area	
Acre	43560	square feet (ft^2)
Acre	0.4047	hectare (ha)
Square foot (ft^2)	$3.587X10^{-8}$	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)	.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)

Units

For the purposes of this report, both US Customary and Metric units were employed. Common regulations related to tundra travel and water use on the North Slope, Alaska, uses combinations of both US Customary and Metric units. The choice of "primary" units employed depended on common reporting standards for a particular property or parameter measured. Whenever possible, the approximate value in the "secondary" units was also provided in parentheses. Thus, for instance, snow depth was reported in inches (in) followed by the value in centimeters (cm) in parentheses.

Physical and Chemical Water-Quality Units:

Temperature:

Water and air temperature is given in degrees Celsius (°C) and in degrees Fahrenheit (°F). Degrees Celsius can be converted to degrees Fahrenheit by use of the following equation:

°F = 1.8(°C) + 32

Snow Water Equivalent (SWE):

Water content of a given column of snow is determined by knowing the depth of the snowpack and density.

$$SWE = d_s * \rho_s / \rho_w$$

where:

d_s = snow depth

ρ_s = snow density

ρ_w = density of water.

Electrical Conductance (Actual Conductivity and Specific Conductance):

In this report conductivity of water is expressed as Actual Conductivity [AC] in microSiemens per centimeter (µS/cm). This unit is equivalent to micromhos per centimeter. Elsewhere, conductivity is commonly expressed as Specific Conductance at 25°C [SC25] in µS/cm which is temperature corrected. To convert AC to SC25 the following equation can be used:

Error! Bookmark not defined. $$SC25 = \frac{AC}{1 + r(T - 25)}$$

where:

SC25 = Specific Conductance at 25°C, in µS/cm

AC = Actual Conductivity, in µS/cm

r = temperature correction coefficient for the sample, in °C

T = temperature of the sample, in °C

Milligrams per liter (mg/l) or micrograms per liter (µg/l):

Milligrams per liter is a unit of measurement indicating the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/l, the numerical value is the same as for concentrations in parts per million (ppm).

Millivolt (mV):

A unit of electromotive force equal to one thousandth of a volt.

Vertical Datum:

"Sea level" in the following report 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*.

Horizontal Datum:

The horizontal datum for all locations in this report is the North American Datum of 1983 or North American Datum of 1927.

Abbreviations, Acronyms, and Symbols

AC	Actual conductivity
ADOT&PF	Alaska Department of Transportation and Public Facilities
ADNR	Alaska Department of Natural Resources
ASTM	American Society for Testing and Materials
atm	Atmospheres
ATN	Arctic Transportation Networks
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
C	Celsius (^{o}C)
cm	Centimeters
DO	Dissolved oxygen
DVM	Digital voltage multi-meter
F	Fahrenheit (^{o}F)
ft	Feet
GWS	Geo-Watersheds Scientific
in	Inches
kg	Kilograms
km^2	Square kilometers
kPa	Kilopascal
lb/in^2	Pounds per square inch
m	Meters
mg/l	Milligrams per liter
μg/l	Micrograms per liter
mi^2	Square miles
mm	Millimeters
μS/cm	Microsiemens per centimeter
mV	Millivolt
NGVD	National Geodetic Vertical Datum
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
ORP	Oxygen-reduction potential
ppm	Parts per million
QA	Quality assurance
QC	Quality control
Sag	Sagavanirktok River
SC25	Specific conductance at 25^{o}C
SWE	Snow water equivalent
UAF	University of Alaska Fairbanks
USACE	U.S. Army Corps of Engineers, Alaska District
USGS	U.S. Geological Survey
WERC	Water and Environmental Research Center
WWW	World Wide Web
YSI	Yellow Springs Instruments

ACKNOWLEDGEMENTS

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Alaskan North Slope Oil & Gas Transportation Support: Final Technical Report

EXECUTIVE SUMMARY

North Slope oil and gas resources are a critical part of US energy supplies and their development is facing a period of new growth to meet increasing national energy needs. While this growth is taking place in areas active in development for more than 20 years, there are many increasing environmental challenges facing industry and management agencies. A majority of all exploration and development activities, pipeline maintenance and other field support activities take place in the middle of winter, when the fragile tundra surface is more stable. The window for the critical oil and gas winter operational season has been steadily decreasing over the last 25 years. The number of companies working on the North Slope is increasing. Many of these companies are smaller and working with fewer resources than the current major companies. The winter operations season starts with the tundra-travel opening, which requires 15 cm of snow on the land surface in the coastal management areas and 23 cm in the foothills management areas. All state managed areas require -5°C soil temperatures at a soil depth of 30 cm. Currently there are no methods to forecast this opening date, so field mobilization efforts are dependent on agency personnel visiting field sites to measure snow and soil temperature conditions. Weeks can be easily lost in the winter operating season due to delays in field verification of tundra conditions and the resulting mobilization. After the season is open, a significant percentage of exploration, construction, and maintenance do not proceed until ice roads and pads can be built. This effort is dependent on access to lake ice and under-ice water. Ice chipping is a common ice-road construction technique used to build faster and stronger ice roads. Seasonal variability in water availability and permitting approaches are a constant constraint to industry. At the end of the winter season, projects reliant on ice-road networks are often faced with ending operations early or risk being caught on ice roads with flooded stream crossings, or unusable sections of ice road due to local melt. These challenges result in higher oil and gas field exploration and operational costs.

Much of the scientific understanding to address transportation issues for oil and gas development on the North Slope exists, but has not been placed into a set of tools and data sets useful for industry and management agencies. Optimizing North Slope transportation networks during winter operation seasons is critical in managing increasing resource development and will provide a framework for environmentally-responsive development. Understanding the physical environment (such as snow, water, ice, soils) is necessary to ensure protection of fisheries and other natural resources on the sensitive tundra landscape. Solutions also have to do more than just describe current conditions, they need the ability to forecast short-term conditions. This will allow management agencies to respond to future variability in snow cover, soil temperature, and water availability more effectively. In turn, industry will then have more time to plan the significant mobilization taking place every winter season.

GOAL

The primary objectives of this project are to develop analysis and management tools related to Arctic transportation networks (e.g., ice and snow road networks) that are critical to North Slope, Alaska oil and gas development.

PERFORMERS

Geo-Watersheds Scientific, Fairbanks, AK 99708
University of Alaska Fairbanks, Fairbanks, AK 99775
Idaho National Laboratory, Idaho Falls, ID 83415

BACKGROUND

The objective of this project is to improve winter oil and gas transportation operations on the North Slope, Alaska (Figure 1). This includes providing data, methods, and tools to develop forecast models for environmental conditions related to tundra-travel management, and winter water use. The operational period for oil and gas transportation network are typically referred to as the tundra-travel season (Figure 2). The management methods have changed over time as industry developed methods for snow transportation and building ice roads and management agencies developed methods of limiting potential damage from these activities. Warming winters and variable snow conditions resulted in a shortening of tundra travel seasons over time, though adaptive construction techniques, such as adding snow and ice chips to the tundra, pre-packing snow to enhance soil freezing and other methods helped address the shortening season in some cases (Figure 3).

Snow-depth data are being measured and evaluated to further test and improve standard methods. The snow data will also be used for the analysis objectives of the project. Field trips begin by driving from Fairbanks to Toolik Research Camp in the northern foothills of the Brooks Range. This is approximately the southern extent of current exploration activities related to oil and gas development in the foothills and serves as a southern boundary for the project focus. The Toolik Research Camp meteorological station collects many of the parameters required by this project and is reported online. Field staff collects specific information such as snow-course and lake-ice measurements to help meet project interpretative goals. Data sites along the Dalton Highway are co-located with ADNR snow-course sites. A subset of the ADNR sites is measured each winter field trip to help compare cumulative use of project data with ADNR data. Additional snow data is collected at ADNR sites and climate stations from Duck Island in the eastern Prudhoe Bay fields, and to the west in the Kuparuk and Alpine field areas. Primary field data collection sites are located near roads, facilities, or drilling pads. Work in remote field areas is conducted when field logistics and weather allow access. The total extent of the data collection takes place over a route approximately 320 kilometers (200 miles) long. Field trips vary from 7 to 12 days and involve working in wind chill conditions down to -50°C. Whiteout and blizzard conditions can limit field work at warmer temperatures. Electrical wiring on weather stations is difficult to work with when wind-chill factors are colder than -40°C, common for most of the early and mid-winter months.

Climate stations used by the project extend from Duck Island and Badami on the east, into NPRA on the west. Climate sites directly supported by the project and those managed by cooperating projects provide data that will be used by various project task teams, such as snow and soil temperature modeling groups.

Data collected from surveys, meteorological stations, and historical records are used to improve soil temperature, watershed delineation, and ice development models. Some models include: The University of Alaska Fairbanks, Geophysical Institute Permafrost Laboratory (GIPL) thermal models to hindcast soil temperature conditions; RiverTools, a watershed analysis program; and Stefan and Modified Stefan equations for lake ice growth calculations.

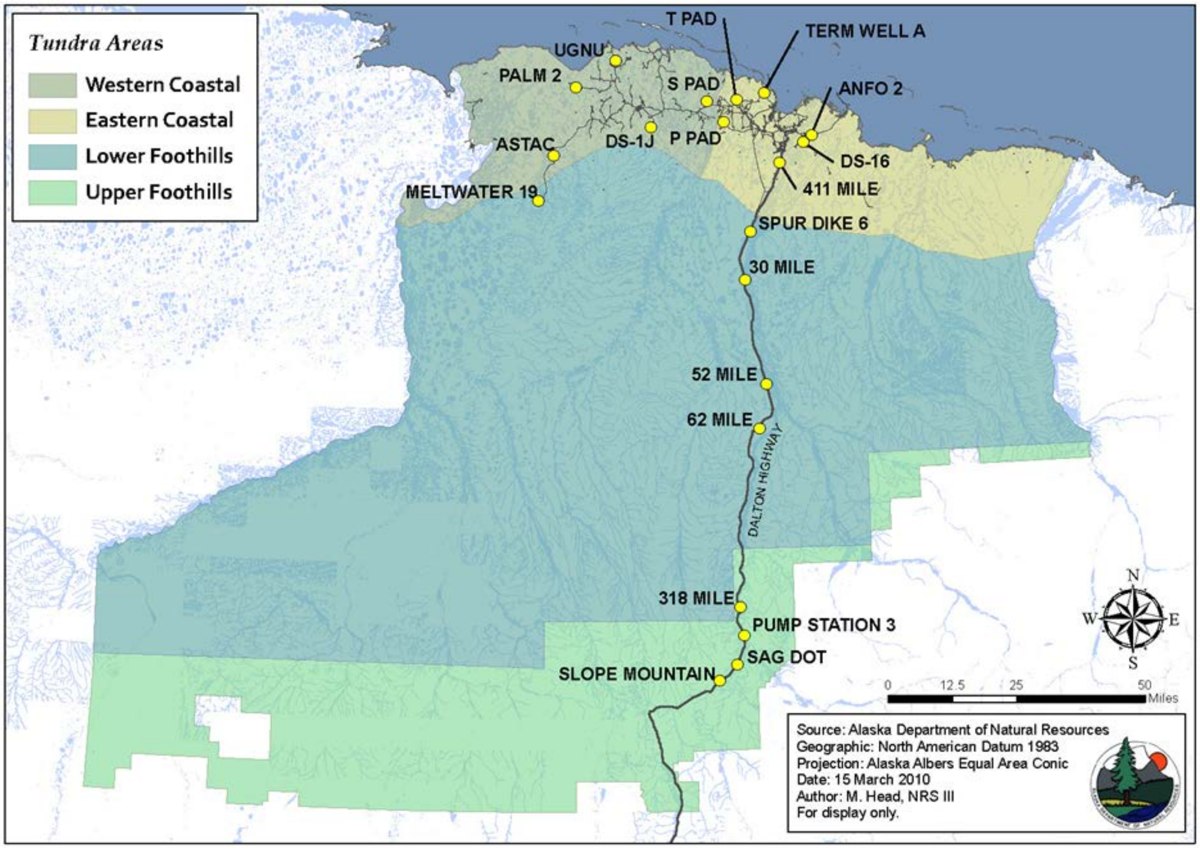

Figure 1. Map of the North Slope, Alaska, study area.

Improving oil and gas transportation management for the winter operations period requires the evaluation of lake and reservoir water use, snow and freezing soils, and water use patterns and variability. The combination of improved methods in any of these areas can result in a significant benefit to the annual arctic transportation networks developed to support North Slope oil and gas operations. These networks are often re-established each year depending on the different exploration, development and maintenance activities that take place annual, for the life of each oil and gas field on the North Slope.

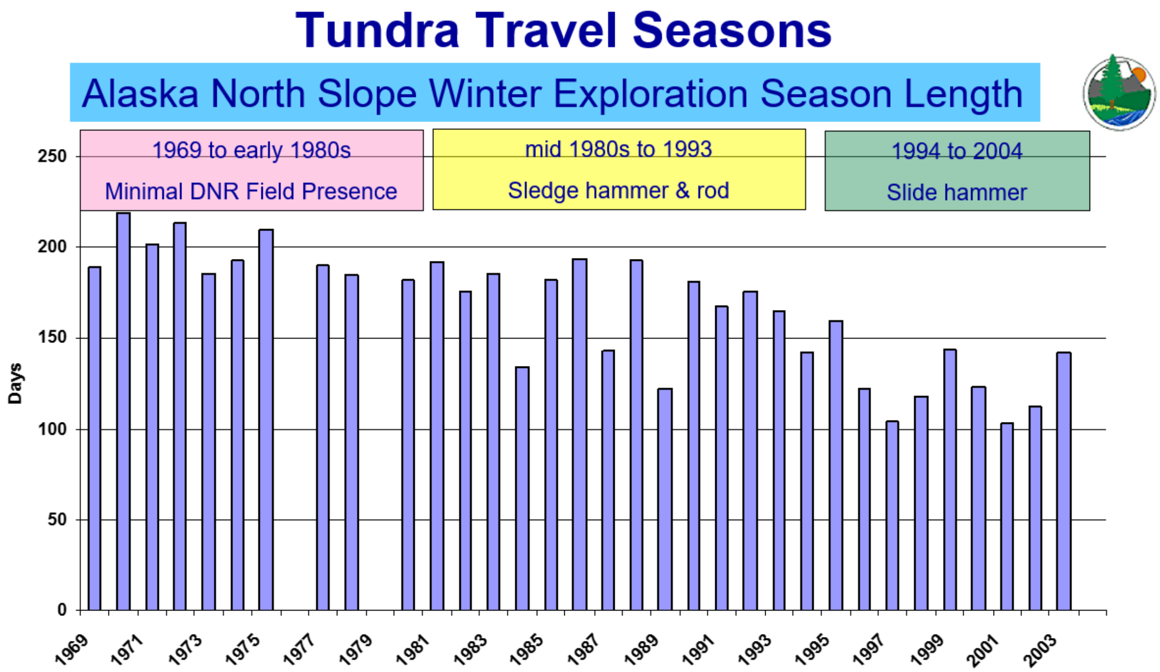

Figure 2. Early tundra-travel seasons and management by the Alaska Department of Natural Resources.

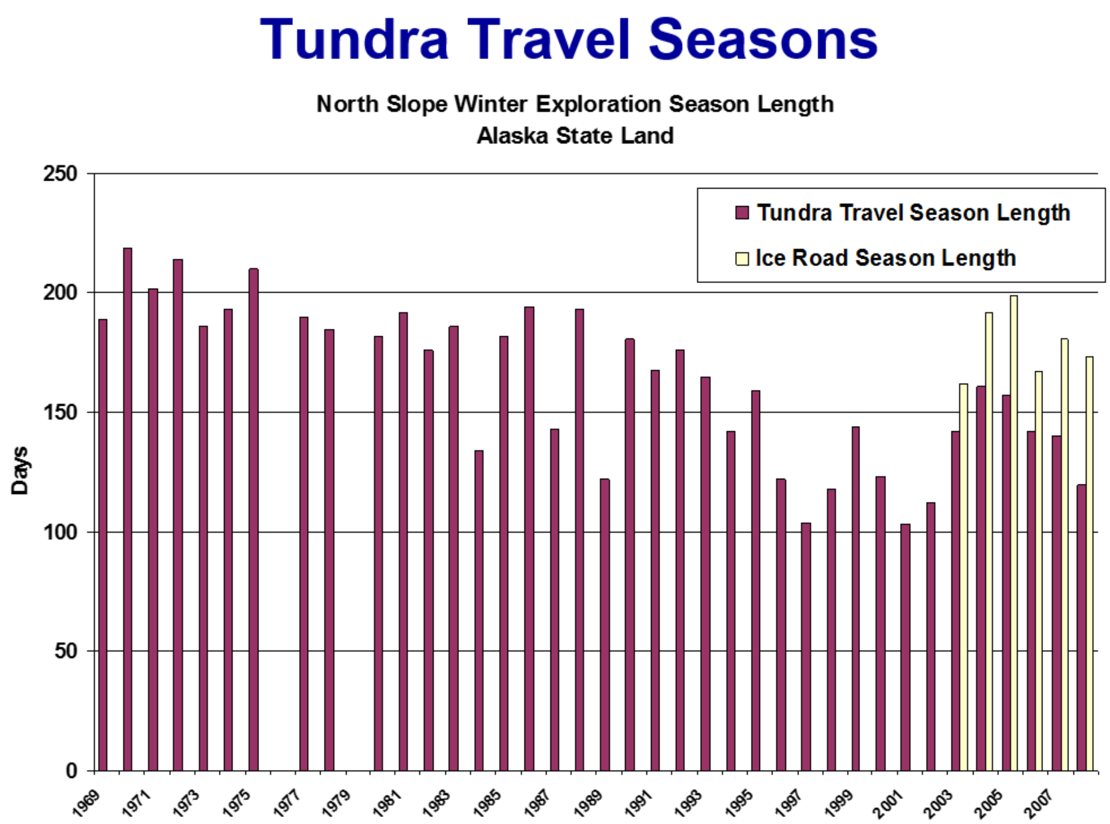

Figure 3. Early tundra-travel and ice-road seasons. Ice road seasons were lengthened by using adaptive construction techniques such as end-dumping snow and/or ice chips and pre-packing snow to promote faster ground freezing.

APPROACH

The project team involved a multidisciplinary approach and divided the major topics of the project into six focus areas of study: snow distribution, water use, soil strength, soil temperature, adaptive management, and Nowcast/Forecast tools.

Snow Distribution

Snow distribution is important for several reasons. There must be adequate snow on the tundra surface to support vehicle traffic without damaging the fragile tundra surface. Snow on the North Slope is significantly affected by wind and can be redistributed after initial snowfall causing adequate conditions to change rapidly. Snow is also the primary recharge source for lakes, reservoirs which are the primary source of water used for ice roads. One of the key issues identified early in the study was the need for standard practices in measuring snow depths by industry and management agencies.

Water Use

Permitting methods, timing and reasons for water use, relationship to ice and snow covered lakes and the annual hydrologic cycle of lakes had been management approaches developed to provide safe water use. Agencies adopted conservative approaches due to the lack of data on lake and reservoir hydrology. The reasons why water use varied by operational needs was also not well understood. Prior DOE studies had demonstrated that current water use and management practices were both conservative and not creating problems for fisheries resources (Chambers and others, 2008; Cliverd, White and Lilly, 2009; Hinzman and others, 2006; White and others 2008a, b). These studies also helped indicate that with more understanding, water use could be safely increased in a variety of hydrologic conditions and water-use scenarios. Information on water use patterns were collected, watershed mapping approaches were demonstrated and test permits were developed with industry and agencies to help show how additional information and management approaches could safely increase water availability on the North Slope.

Soil Strength

Soils types vary on the North Slope and it is generally understood that freezing soils that are ice rich have greater soil strengths than unfrozen soils. Soil strength though is not taken into account when managing tundra travel or the design of ice-road networks. The study approach was to demonstrate basic soil strength characteristics found on the North Slope so future tundra-travel management could take soil strength properties into account, where it made economic sense for industry to collect and use this type of information.

Soil Temperature

Soils temperature at a 30 cm depth is a key tundra-travel management criteria. Agencies and industry measure and wait for permit conditions to be met for soil temperatures before fully opening up tundra travel in different management areas on the North Slope (Figure 1). Developing methods to forecast soil temperatures were explored as well as developing more real-time reporting of soil temperature data on the North Slope by various data networks. The benefits of better predications of soil temperatures and knowing current conditions are related to the time and costs of mobilizing work force efforts on the North Slope for the construction of ice and snow roads and following exploration, development and maintenance project. Either delays in mobilization, or mobilizing too soon can be significant costs to industry.

Adaptive Management

The natural environment (ice, snow, water, freezing tundra) and transportation routes, water use and project activities can all vary from year to year. Fixed water-use and tundra-travel management approaches that do not provide any flexibility to adapt to these changes conditions and needs result in excessive costs to industry each year over the decades oil and gas fields may operate. The development of adaptive management approaches can help reduce these long-term costs and still meet environmental protection needs. Various examples were identified to show how adaptive management approaches could be incorporated into various aspects of arctic transportation networks. Not every method is needs in every case, so approaches that allow industry and agencies to use the right combination of approaches provides a “toolbox” approach to improving management methods.

Nowcast/Forecast Tools

The original focus of Nowcast/Forecast modeling tools was to improve regional models used for weather predications, with NOAA models as the main end objective. Successful evaluations were conducted to look at issues such as blowing-snow model enhancements to forecast models. While improved understanding was gained in this area, the near term application to industry and agencies was limited by the state of the science in the forecast models, and general availability of data in the region to further develop and operate models with these increased applications. More detailed discussion on the modeling efforts is provided in Appendix B.

SELECTED RESULTS

The following sections show various highlights for each or the technical focus areas of the project. The combined efforts of the multi-disciplinary team and the many project partners (industry and agencies) in reaching the results and concluding recommendation for the project.

Snow Distribution

At the beginning of the project there were no uniform methods for collecting and reporting snow depth and density on the North Slope. Studies by the UAF Water and Environmental Research Center had demonstrated methods for measuring snow depth and density in the region of interest and addressed the predominant wind-blown snow conditions. Appendix A show an example blank form and one that is filled out for a site that has been suggested to industry and agencies. BLM has adapted this approach in NPR-A and training programs were conducted with Conoco Phillips survey crews in both the Alpine and Kuparuk fields. Comparison were made at similar sites between project field staff and ADNR tundra-travel management staff to show the difference between methods used at the time by ADNR and those recommended by the project (Figure 4). To help demonstrate the benefits of a common approach, duplicate sampling results with surveyors is shown in Figure 5. The results indicate the surveyors could collect comparable measurements to project staff. The recommend method collected 50 sample depths at a location, in an L-shape pattern with 25 points on each leg, with a spacing of approximately 3 feet, or 1 meter. While not used for tundra travel management, the density is also important in understanding differences between loose snow and wind-blown snow and later recharge to lakes and reservoirs.

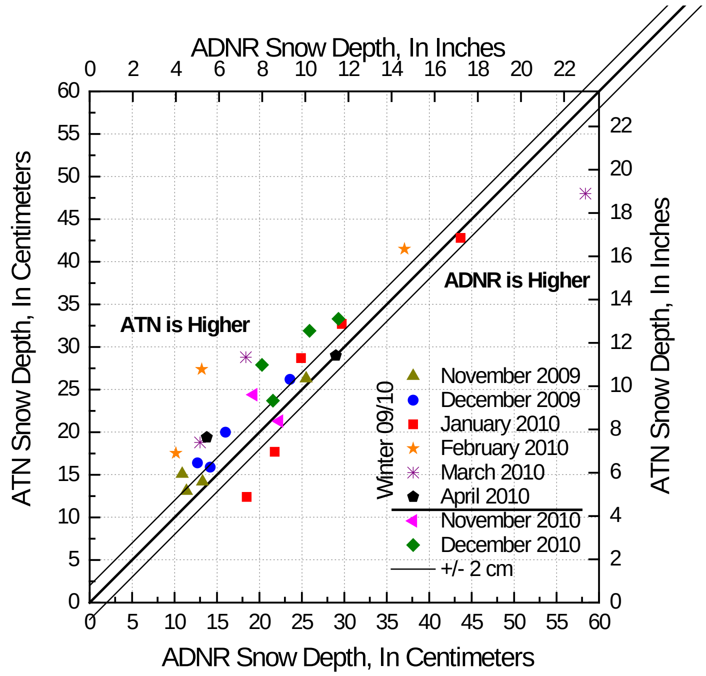

Figure 4. Comparative snow depth sampling between project staff and ADNR tundra-travel management staff.

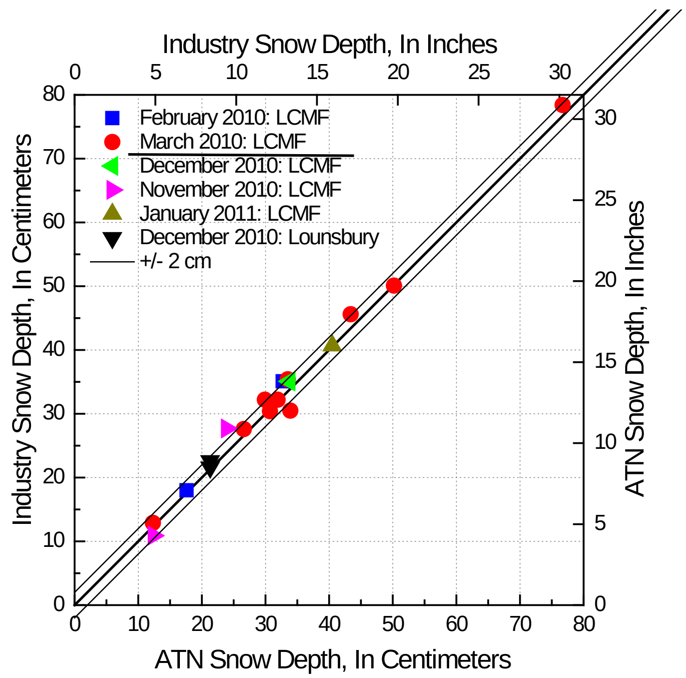

Figure 5. Comparative snow depth sampling between project staff and industry surveying staff.

Water Use

Industry commonly permits more water than they use. This is important to provide operational flexibility, emergency fire response and allow adequate time for developing and reviewing permits. Reducing the excess permitting volumes would wind up with more rushed permitting requirements and added workloads on agency permitting staff. This need is not unique to the oil and gas industry in Alaska, but most industrial and public drinking water providers across the country. Figure 6 shows an example of permitted versus used water in the Prudhoe Bay field by B Exploration. When only permit volumes are reported to the public, and not actual volumes, it leads to an incorrect perception of water use. Making available both permit volumes and actual volumes has helped correct incorrect perceptions.

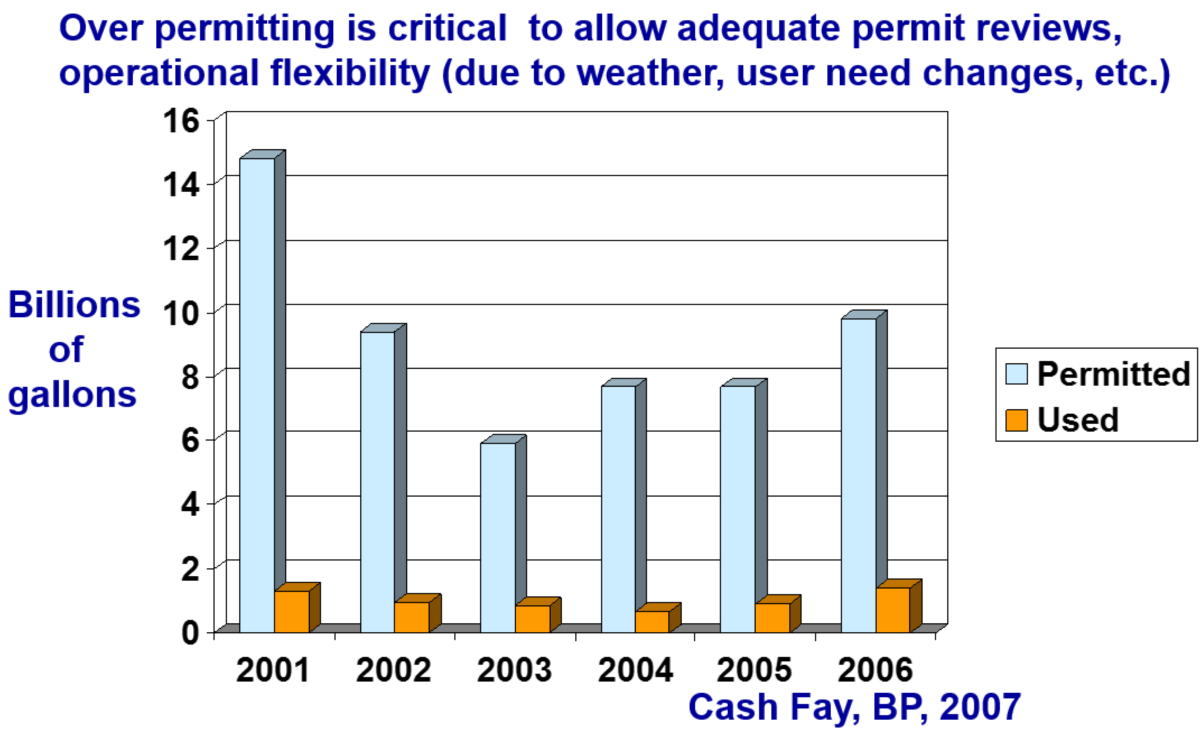

Figure 6. The amount of permitted versus used water is significantly different. The permit process takes time, and numerous factors require industry to permit excess water to address emergency response, changing plans due to winter conditions, variation in exploration and water use needs.

Understanding why water is used also helps in the improvement of water-use management practices and evaluate future needs and changes in management practices and supporting data. Figure 7 shows an example of water use changes over three years in the Prudhoe Bay fields by BP Exploration. Camp and utility needs were fairly constant over this period, while drilling support for infield exploration and enhance oil recovery were more variable. Enhanced oil recovery is an important future need related to maintaining adequate flow in the Trans-Alaska Pipeline System (TAPS).

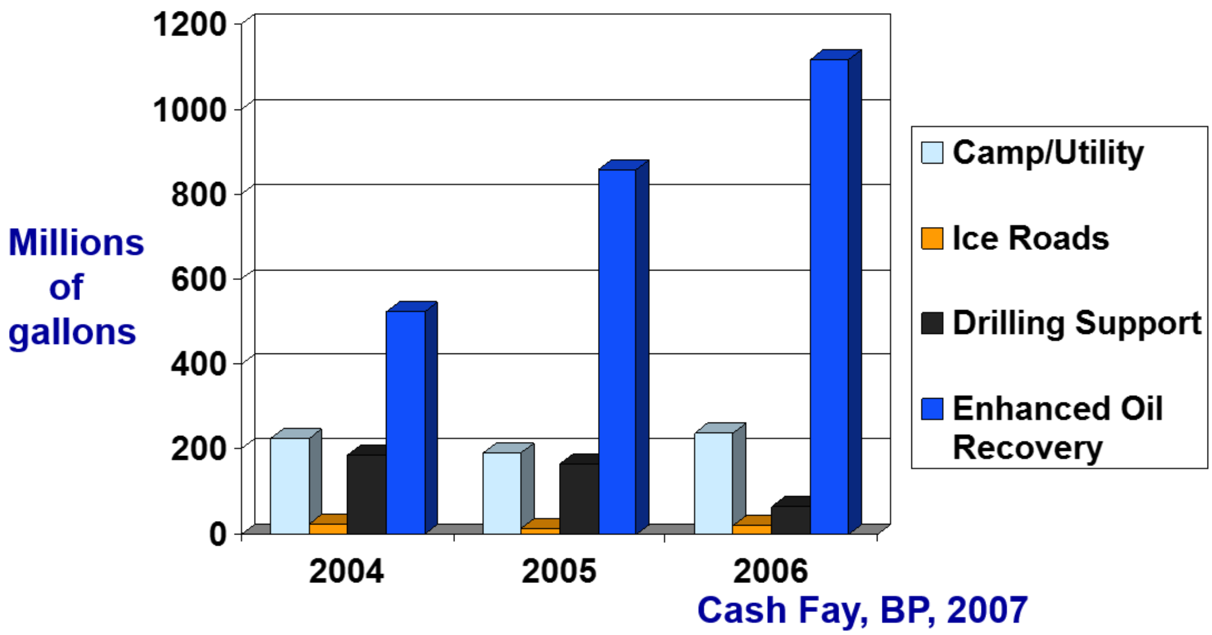

Figure 7. BP Exploration water-use data illustrates differences between various water uses in the Prudhoe Bay Field. Enhanced oil recovery is one uses that may continue to increase water demands in the future.

Evaluating the water use at a variety of lakes used for ice roads, drilling support and/or facility operations is important in developing water management practices that allow water to be used when needed, but also to address environmental protection needs related to fisheries and seasonal hydrologic and ecosystem functions. L9817 is a lake in NPR-A which was used for an exploration ice road for three years (Figure 8). Water and ice were used for both construction (early season) and ongoing maintenance (throughout season) of the ice road. More water was used for maintenance during the winter of 2004/05 and 2007/08. In this example, most of the water is taken in a short period, in mid-winter, at the beginning of the ice-road construction season. The timing of water use for lakes used for ice road construction also depends on location, with lakes near the beginning of an ice road construction route used early than lakes near the end of the route. In comparison, L9322 is located near the Alpine field main facility and can be used each year for the annual ice road built to the facility to connect it to the Kuparuk field each winter (Figure 9). The lake also serves as a backup for facility and drilling support, so is not used each year for ice road construction.

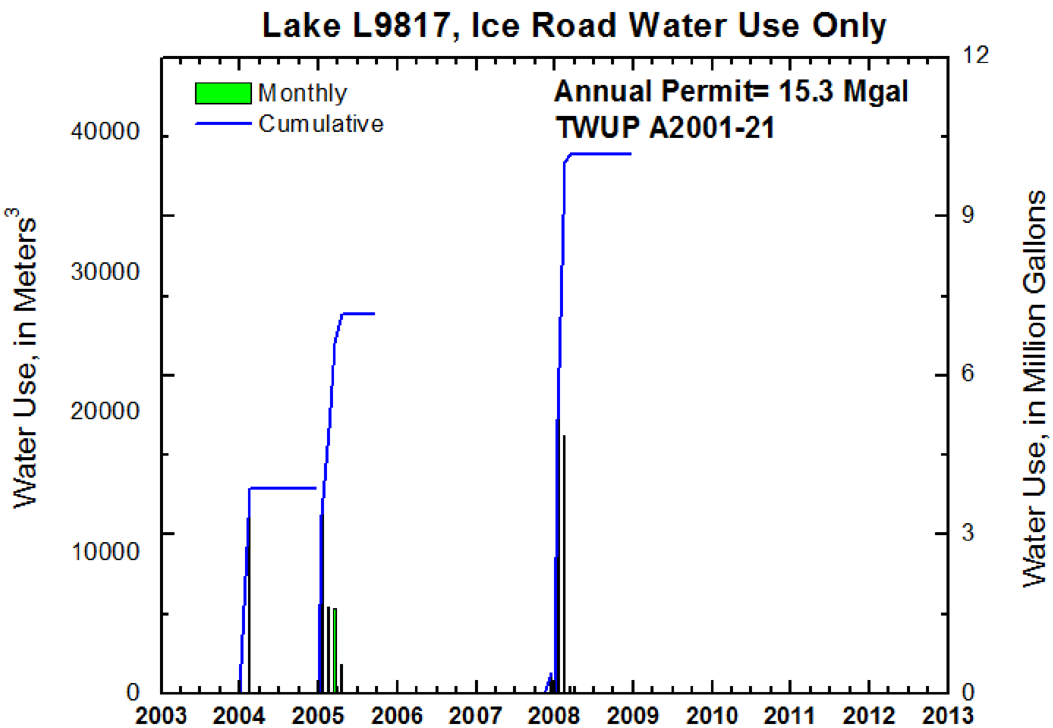

Figure 8. L9817 water use representing a lake used for exploration ice roads in NPR-A.

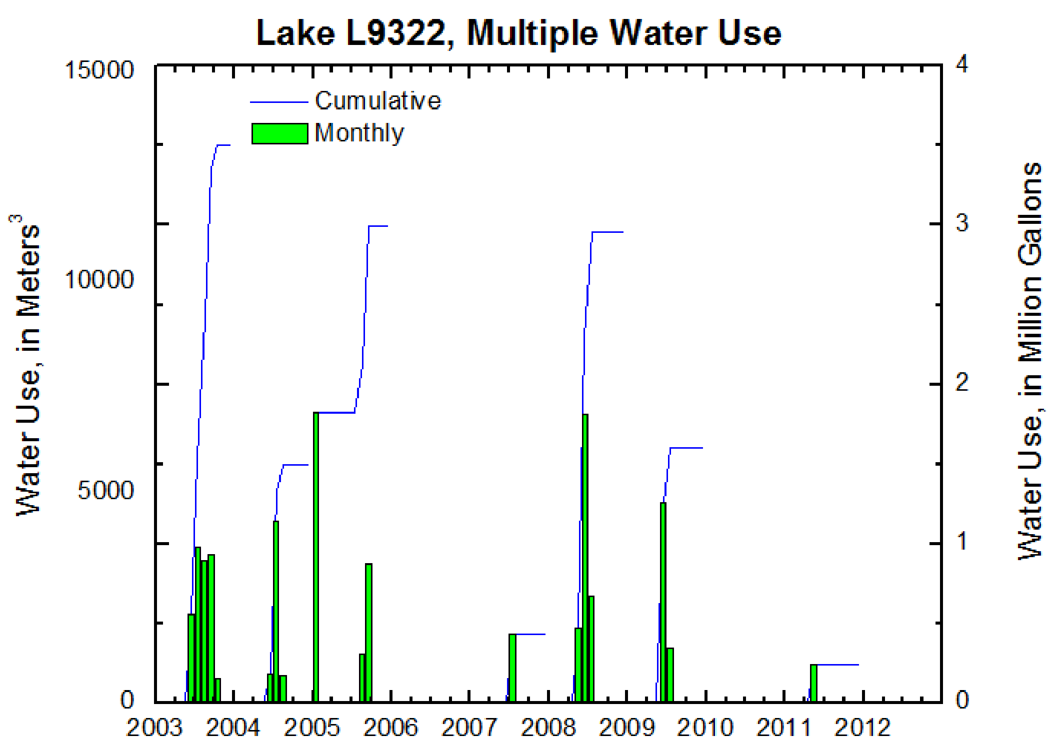

Figure 9. L9322 water use representing a lake used for annual ice roads in the Alpine Field area. Water use varied due to other lakes being used in the same area.

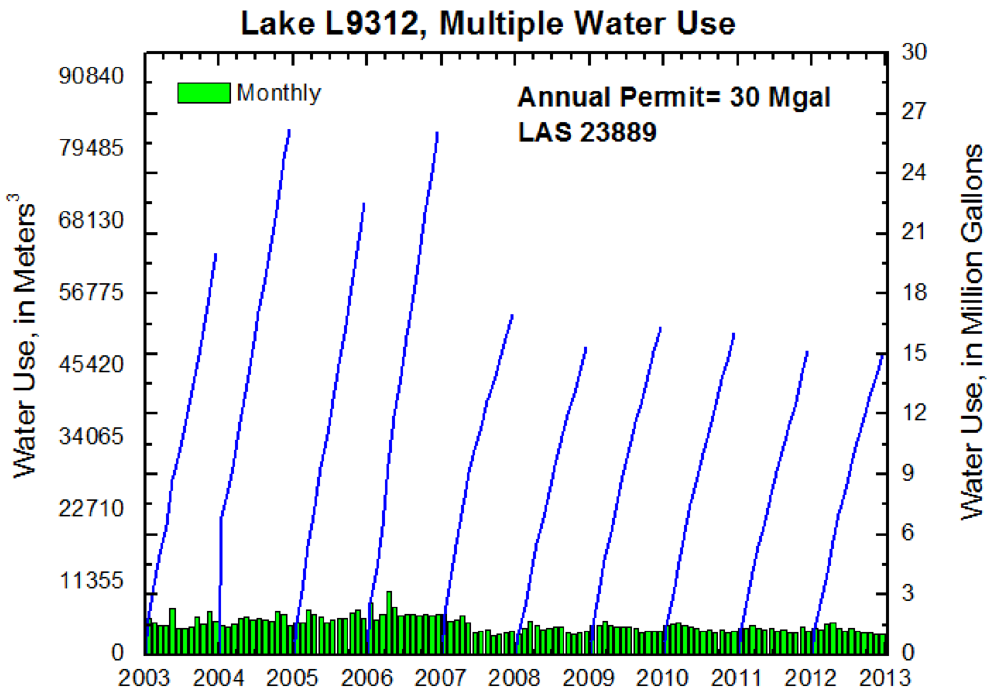

Figure 10. L9312 water use representing a lake used for year-round Alpine facility use and drilling support.

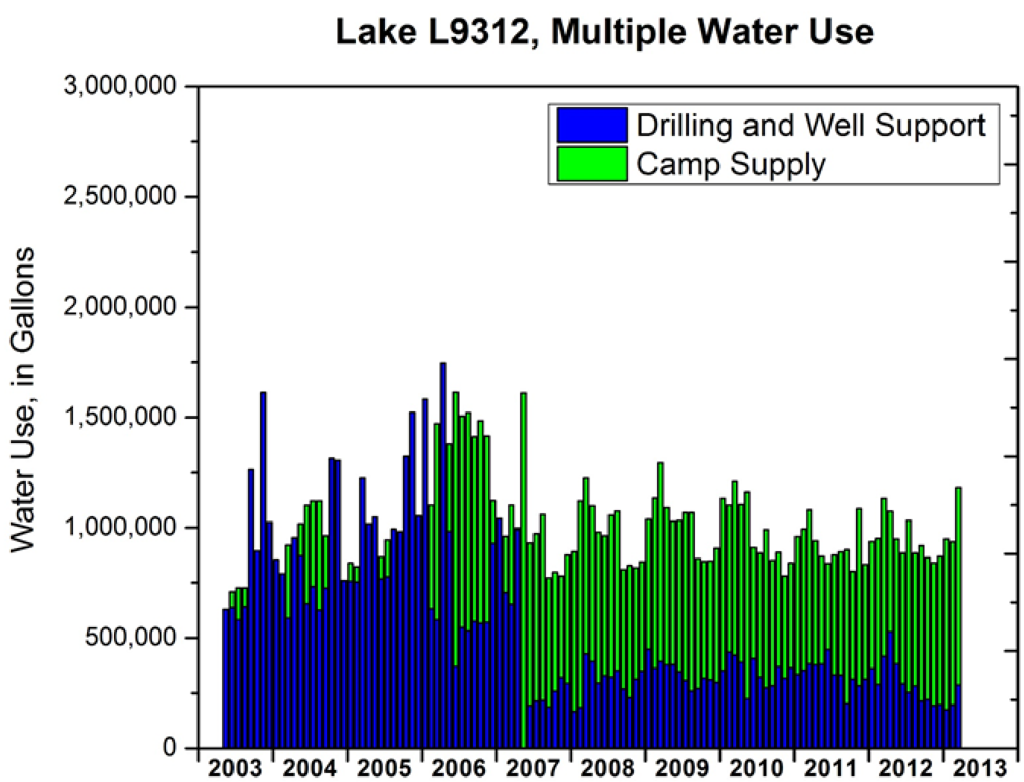

Figure 11. L9312 water use break-down for Alpine facility use and drilling support. In-field drilling at the Alpine facility and nearby drilling pads accounts for significant water use in the early development of the Alpine field.

Water-use lake L9312, located by the Alpine facility helps show a different pattern of use that shows the early development of the facility and drilling of wells at the location, followed by increased facility water use activities and continued drilling support (Figure 10). The lake is used year round and water use is through a pump house and piped system to the water plant at the Alpine facility (Figure 11). This lake served as a key study lake due to its proximity to the Alpine facility.

Watershed areas to lakes and reservoirs and contributing recharge were not considered in water management practices before this project. L9817 in NPR-A was chosen to help illustrate how to calculate watershed areas. The terrain is relative flat around L9817 (Figure 12), and outlets may be fairly small. L9817 is an example of an isolated thaw lake with no inlet streams and it drains into the open tundra. The watershed for this lake is illustrated in Figure 13. A digital elevation model (DEM) was used to calculate the drainage patterns and watershed boundary using an inexpensive terrain analysis software package. Defining the watershed boundary and end of season snowpack in the watershed helped explain why the lake recharged each year.

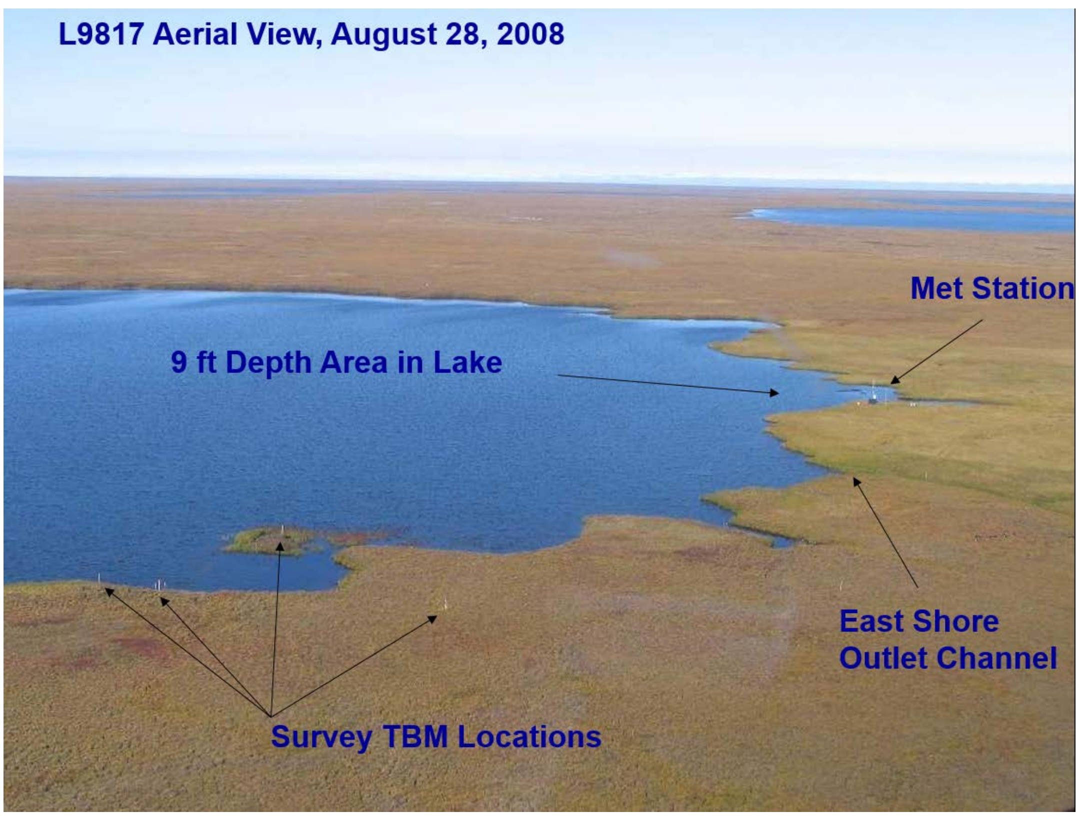

Figure 12. L9817 was one of the study lakes in the NPR-A, which was used by Conoco-Phillips for as an exploration ice road construction and maintenance water and ice source.

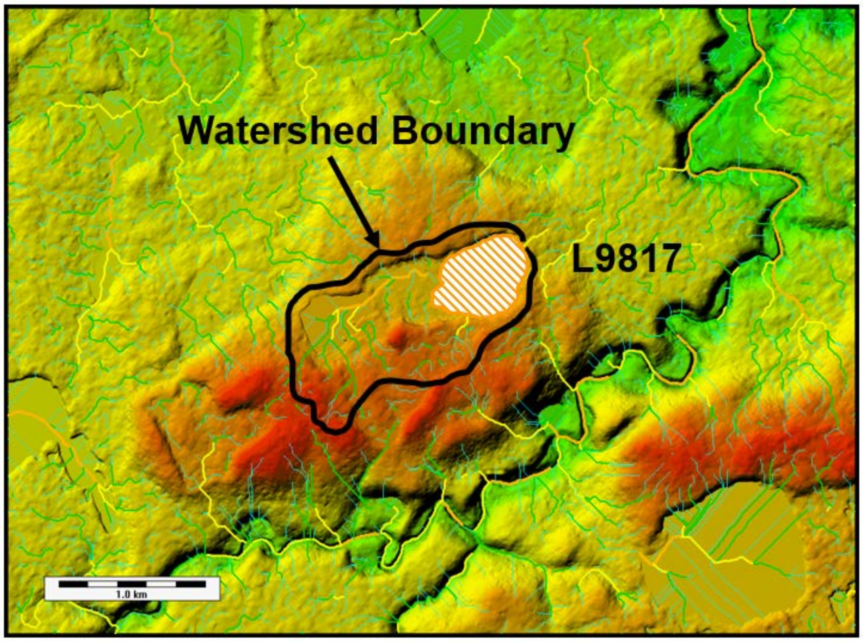

Figure 13. Example of identifying watershed boundaries for a water supply lake in the NPR-A, with drainage patterns and topography shown.

The primary goal of lake and reservoir management on the North Slope has been the protection of fish that overwinter in lakes. A general lake volume is taken into account, but the timing and development of ice and snow cover, and how it relates to winter and summer measurements of lake water levels was not well understood. Figure 14 helps show how ice cover, snow accumulation and loading and under-ice volumes change in L9817 over the winter. As water is removed from the lake in the winter, snow may also accumulate at the top. While grounded along the lake shoreline, lake is generally free-floating in the center of lakes where water depth is greater than end of season ice thickness. Measured water levels taken during the winter reflect what the water level would be if all ice and snow were melted (if taken out in the free-floating portion of the lake). Where industry needs warrant the collection of more data, taking these additional features into account can result in more water being available in winter months, if the result is a certain under-ice volume remaining at end of winter.

The variation in lake ice thickness is also important to consider. In the lack of long-term records and area-wide data reporting, water management approaches have assumed 7 feet of ice thickness at end of winter. Figure 15 illustrates that this is a conservative estimate. Even adopting a lower thickness of 6.5 feet can result in significant more water and savings to industry. Where water may be needed throughout the winter season, monitoring lake ice thickness may allow additional volumes to be taken of water management allowed an adaptive approach to use this information and not assume a fixed value for lake ice thickness. One of the challenges in using variable ice thickness is the timing of water use, versus the timing of lake ice growth. For lakes like L9817 where water may be needed in the beginning of the season, and total ice thickness is months from being developed, conservative estimate may need to be made about ice growth over the winter season. Improving the collection, reporting and archiving of lake ice thickness would help make better predictions of lake ice thickness and reduce risks associated with more adaptive management practices. This would also allow applications, such as the use of the Stephen Equation (for lake ice growth predication) to be used as a simple forecast tool.

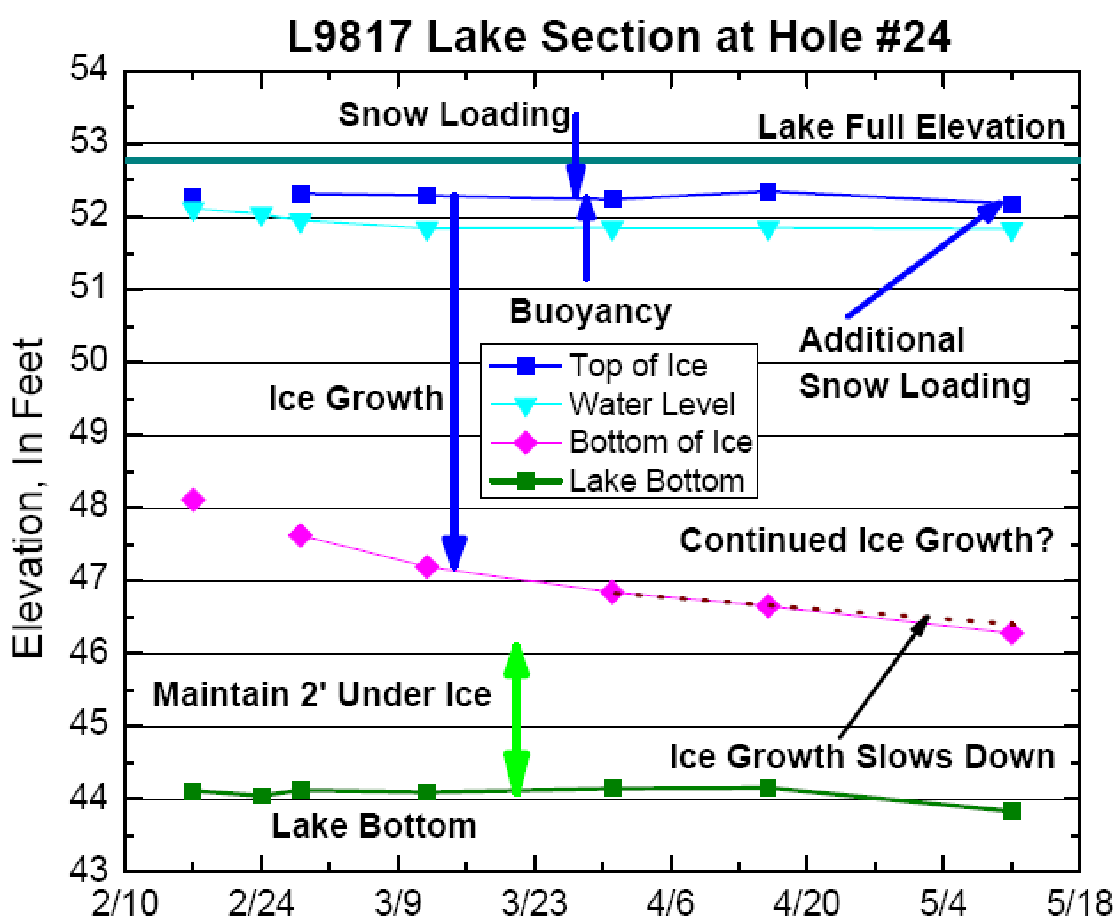

Figure 14. Water-supply lake L9817 is located in the Alpine field area. The figure shows the relationships between lake-ice cover, snow loading on ice, lake-bottom elevations and water management goals of leaving 2' of water below ice at end of winter to prevent impacts to fish that overwinter in the lake.

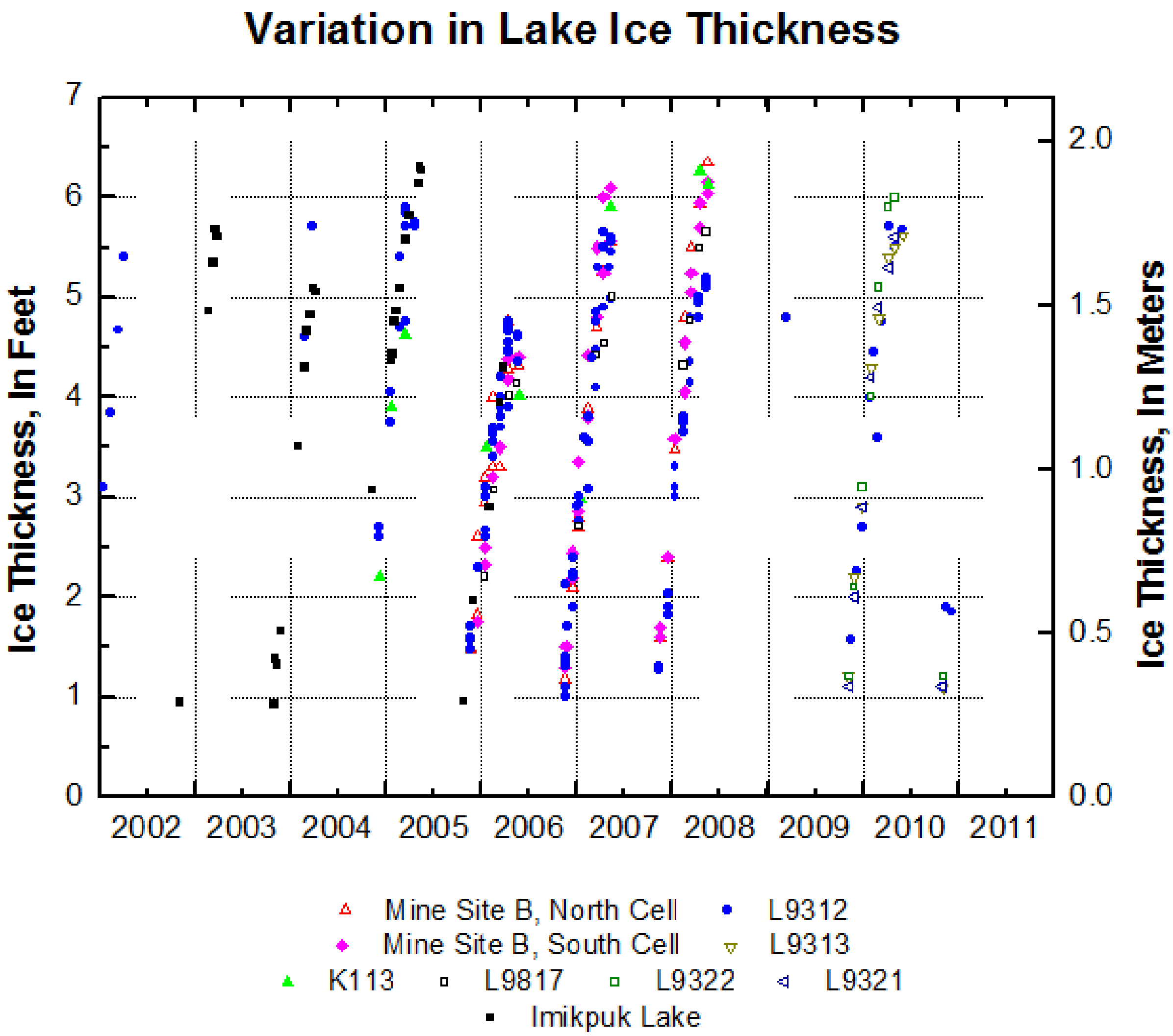

Figure 15. Examples of ice thickness at a sample of lakes and water reservoirs sampled over several years.

Soil Strength

Soil strength studies were carried out in special cold chambers at the University of Alaska Fairbanks, Institute of Northern Engineering facilities. The goal of the study was to show the range of soil strengths for various soils and freezing temperatures. Figure 16 illustrates some of the test chamber used and the associated monitoring equipment. Figure 17 shows a test sample undergoing unconfined compression testing at a strain-rate of 1%/min. Results of the soil strength testing are illustrated in Figure 18 for a variety of index soils tested and values found in the literature.

Figure 16. Soil-strength studies were conducted in University of Alaska Fairbanks cold chambers and measured at conditions representative for field conditions on the North Slope, Alaska.

Figure 17. A frozen-silt sample undergoing unconfined compression testing at a strain-rate of 1%/minute.

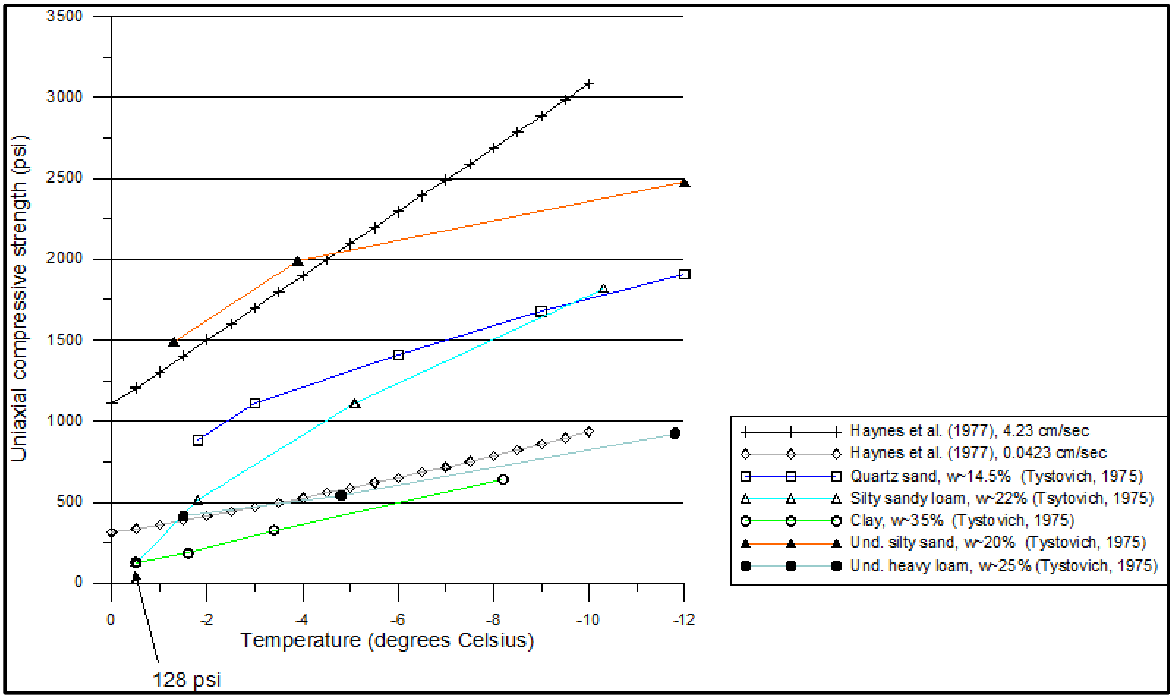

Figure 18. Results of soil-strength tests over various temperature ranges.

Soil Temperature

Soil temperature is directly used in tundra travel management, though selected at a standard 30 cm. depth. One of the issues industry has faced was the availability of real-time data for both industry use and agency use to use to evaluate the initial opening of tundra travel operational periods. Various models were investigated to forecast freezing soil temperatures. Hindcasting temperature conditions, where air temperature and snow cover where known was generally accurate (Figure 19). Forecasting soil conditions was not as accurate due to the uncertainty in forecast simulations of air temperature and snow cover (Figure 20).

The real-time reporting examples from stations setup by the project did help demonstrate the benefits of have more data available to show current conditions. This helped lead to other networks, such as those operated by the UAF Geophysical Institute to report data online for industry and agency use.

- http://permafrost.gi.alaska.edu/content/data-and-maps

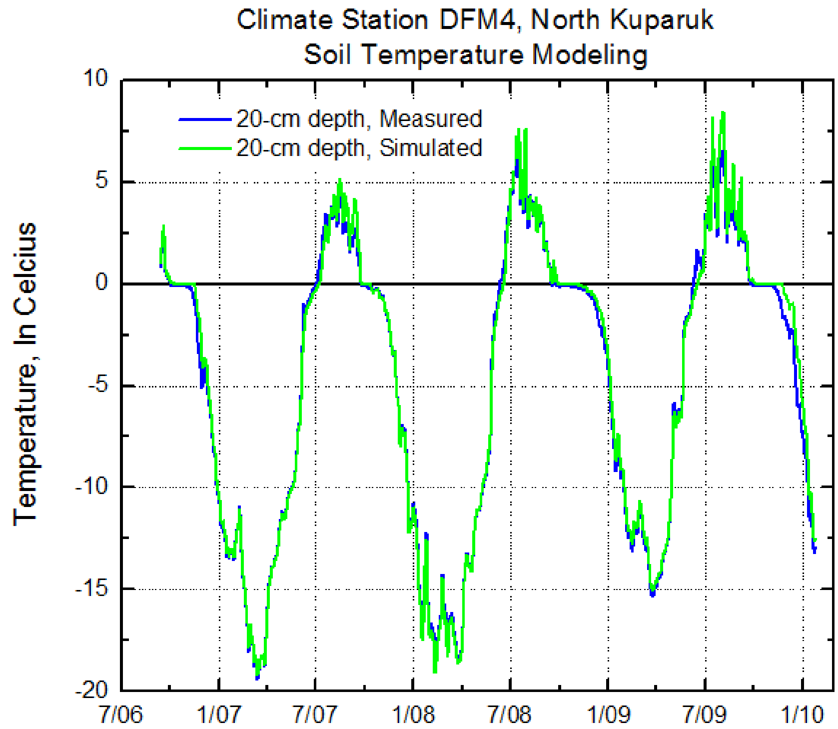

Figure 19. Results of soil-temperature modeling at a climate station south of the Kuparuk Field area.

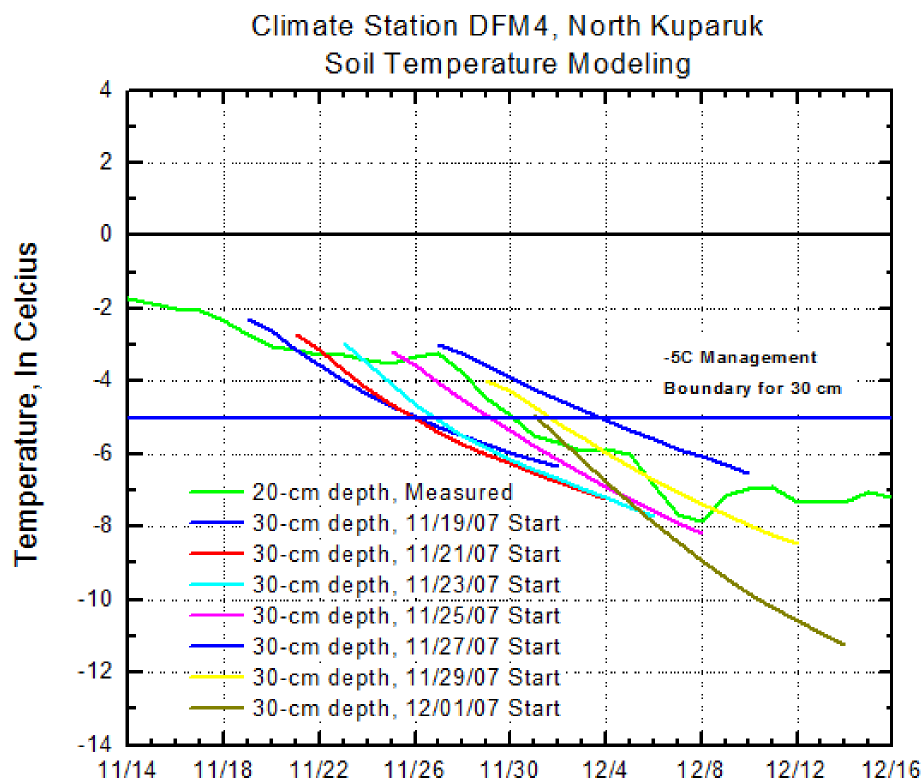

Figure 20. Variations in soil-temperature modeling using various starting dates at a climate station south of the Kuparuk Field area.

Adaptive Management

Some of the examples recommended by the project and put into practice by water-management agencies are shown in Figure 21 through Figure 24. A typical thaw lake example is shown with an estimate of 7 feet of ice growth at end of winter and the relative volumes of lake ice and under-ice lake water. This under-ice water volume has to sustain over-wintering fish through the duration of winter until spring snowmelt and runoff recharges the lake. In the example shown, 29% of the total lake volume is unfrozen at end of winter. Figure 22 show how this under-ice water volume can be further divided up into a permitted volume industry can use, an ecosystem volume needed for supporting over-wintering fish, and a buffer volume which is needed to limit risk to fish, as well as industry. The water management levels vary depending on type of fish present in a lake, where sensitive fish species require more water, which allows industry to generally use 15% of the under-ice volume (assuming 7 feet of ice growth) or 50% of the under-ice volume for non-sensitive fish species (Figure 23). Before the project made recommendation to improve water-management practices, ice chips taken off the lake ice surface (for safety reasons generally on grounded (frozen to lake bottom) ice), the ice chip volume was counted against the under-ice withdraw limit. This approach did not fit the natural conditions of lakes and over-estimated the withdraw of water from the under-ice volume limits. By separating out the surface-ice removal industry gained by potential water to use, without having negative impacts on the volume of water required for overwintering fish habitat. The key issue is will the lake fully recharge during spring snowmelt. By looking at these simple illustrations of different end-of winter volumes, and management volumes, improvement in the assumptions of total lake ice thickness and how much water is needed to support over-wintering fish could further increase the safe limits for industry water use of lakes during the winter season.

Figure 25 and Figure 26 show another way of looking at the different lake volumes for winter conditions. A test permit recommendation was developed to illustrate the gains that could be made by improving the understanding of the under-ice volumes developing permitting approaches to use this information The water permit limits at the time (labeled current) were 1.77 million gallons. By understanding the buffer volume in the lake and variable ice thickness, a recommended test permit limit of 3.5 million gallons was recommended, which still used a very conservative ice thickness of 8 feet. Given that the general ice thicknesses measurement in lakes in this area were around 6 feet, there was still a large buffer volume available.

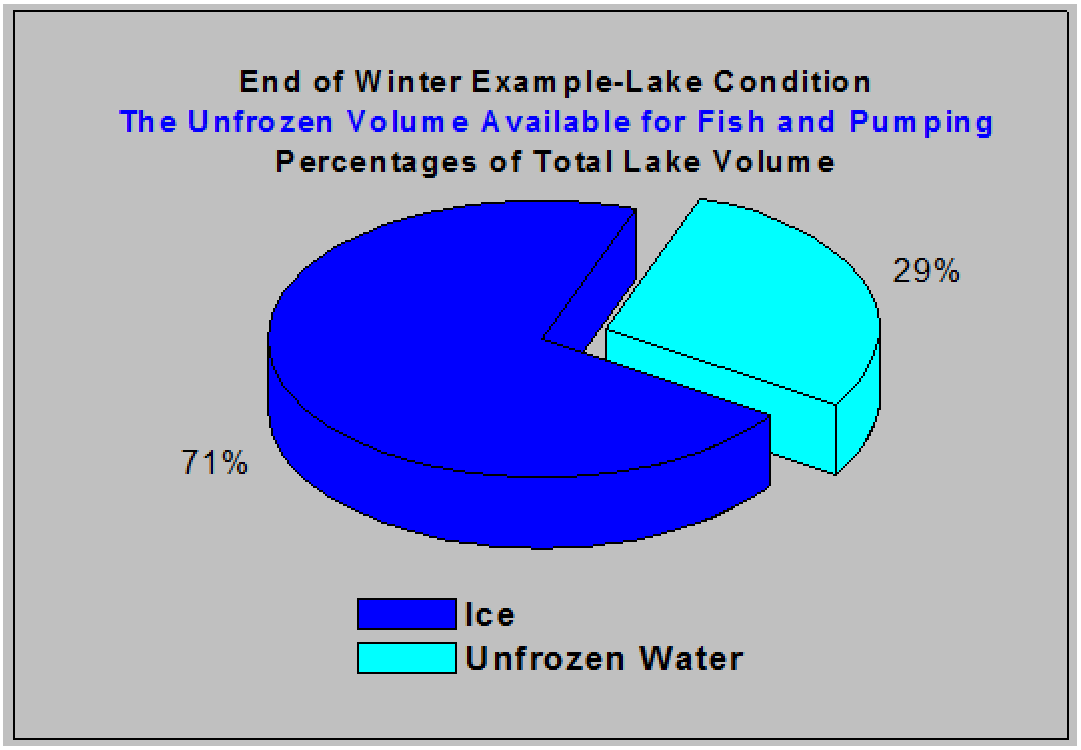

Figure 21. An example of a typical North Slope lake and volumes available at end of winter, which is the management design period for lake with over-wintering fish populations.

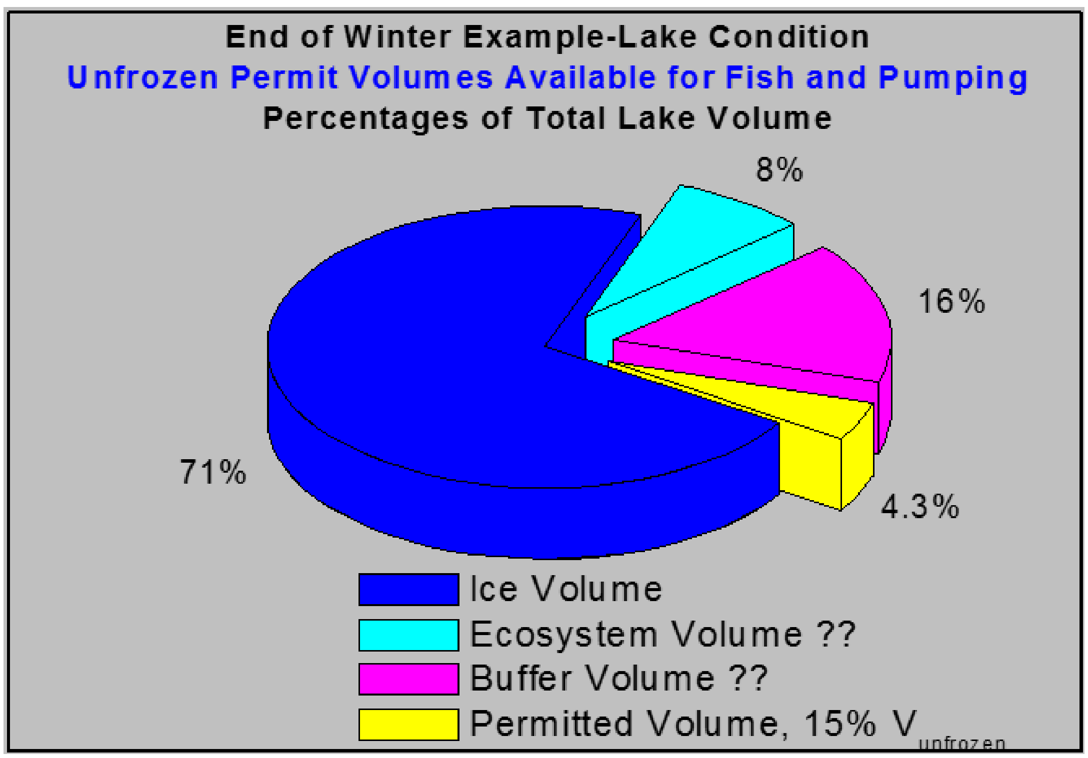

Figure 22. The lake example showing the water volume left unfrozen at end of winter, broken up between different management volumes. The 15% volume assumes sensitive fish species.

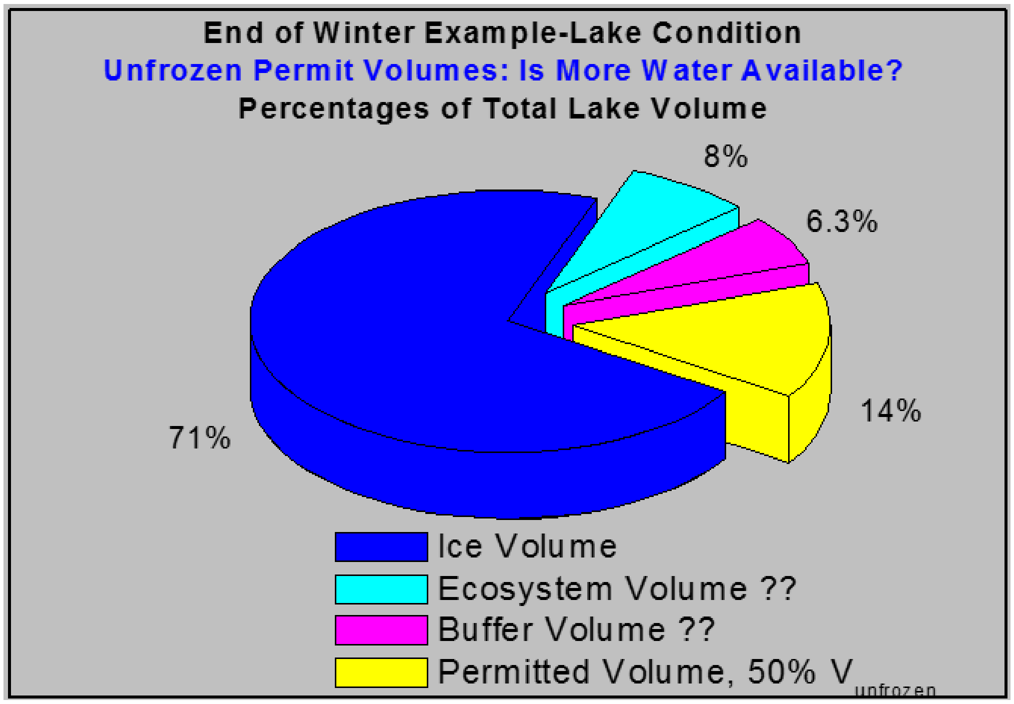

Figure 23. The lake example showing the water volume left unfrozen at end of winter, broken up between different management volumes. The 50% volume assumes non-sensitive fish species. The 50% under-ice volume in this example equals 14% of the total lake volume.

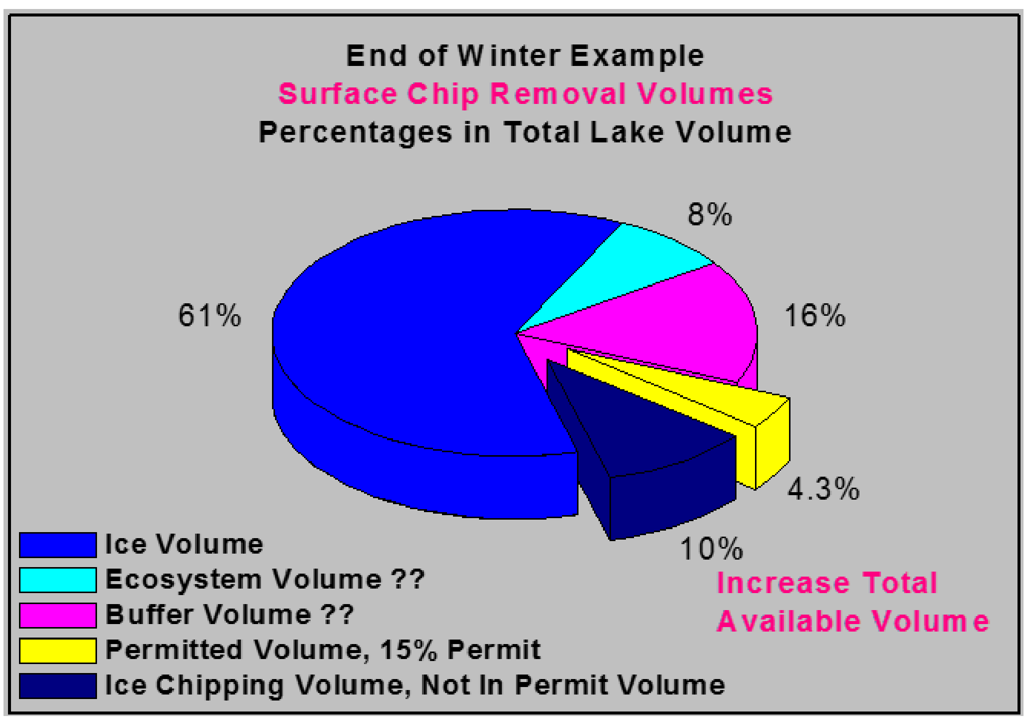

Figure 24. The lake example now showing separating out water taken in the form of ice chips (from grounded portions of the lake) and not accounting this volume against the under-ice liquid water volume limit. The adaption of this approach resulting in a 10% of total lake volume increase in total water use.

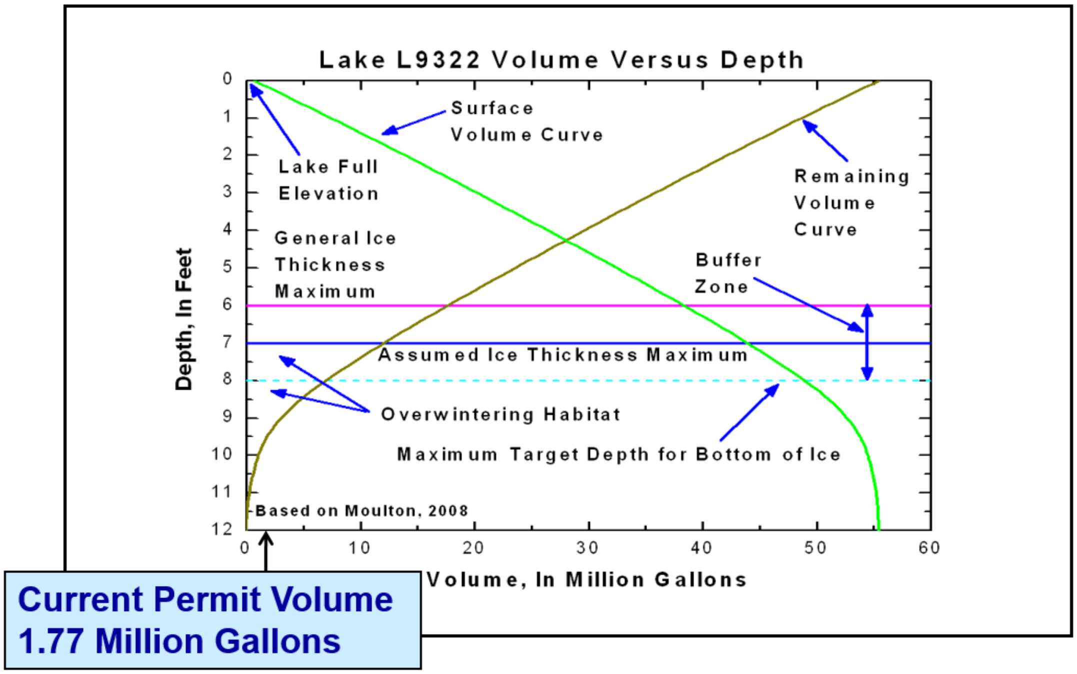

Figure 25. An example of an adaptive management approach to winter lake water use for study lake L9322 showing major water-management concepts. The regular permit volume was 1.77 million gallons.

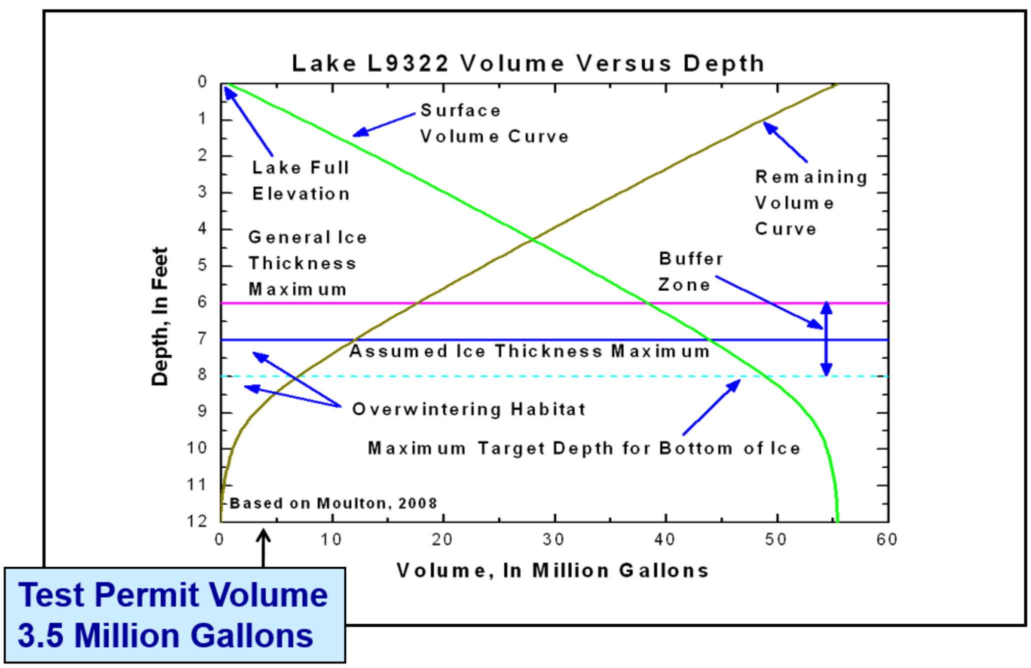

Figure 26. An example of an adaptive management approach to winter lake water use for study lake L9322 showing major water-management concepts. The test permit volume was 3.5 million gallons takes into account more accurate lake parameters.

Nowcast/Forecast Tools

The use of regional Nowcast/Forecast models were explored and improvements that would relate to arctic transportation. Wind has a significant effect on snow distribution and depth, but was not part of any NOAA forecast model outputs. An example of a simulation is shown in Figure 27. The results of this portion of the study indicated further research and more data collection stations in the region (more weather stations reporting wind and snow conditions) are needed before this can be a practical consideration for NOAA to implement or industry and management agencies to use. A more detailed report of these evaluations is reported in Appendix B.
Figure 28 illustrates some of the field and blowing snow conditions that model simulation tools would have to improve to meet the operational needs of arctic transportation users and managers.

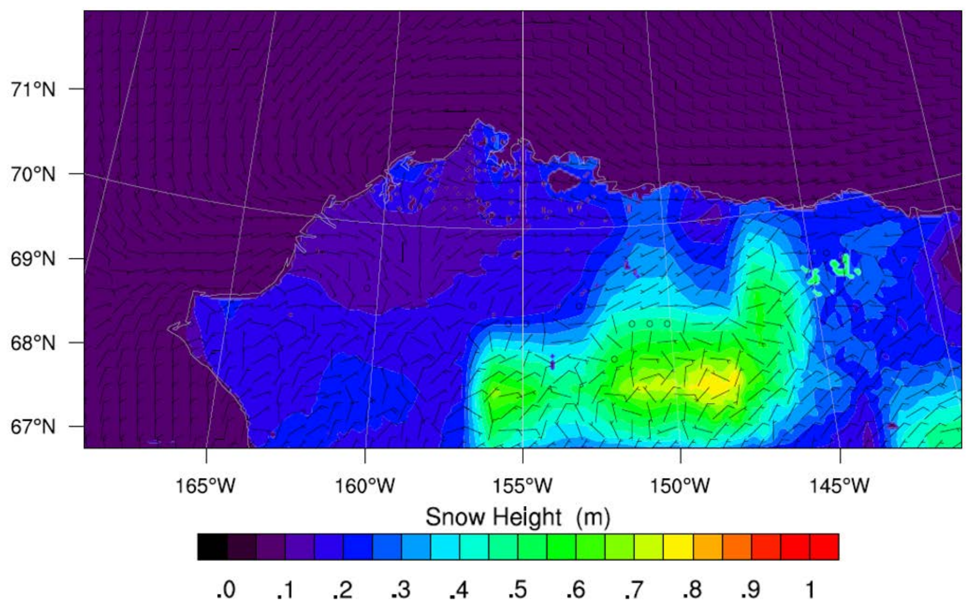

Figure 27. An example of a regional blowing snow model for the North Slope region.

Figure 28. Field crews measuring snow depth in the Alpine Field area. Blowing snow conditions often result in wind slabs and variable snow depth patterns.

IMPACT

The scientific knowledge needed to address the transportation issues for oil and gas development on the Slope exists, but has not been developed into a set of tools useful to industry and management agencies. Optimizing North Slope transportation networks during winter operations will be critical for addressing increasing development pressures, while maintaining a framework for environmentally-sensitive development. Understanding physical conditions is necessary to ensure protection of tundra, fisheries, and other natural resources on the sensitive tundra landscape. These tools do more than describe the current conditions, they help provide the ability to forecast physical and environmental conditions so that management agencies can respond to snow cover and soil temperature audits more effectively, and industry can better plan water-use activities and the significant mobilization efforts which take place every winter season. A project focus has been to generate tools that will have a higher probability of use after project activities are complete.

TECHNOLOGY EXCHANGE

The following are selected technology exchange activities that took place during the project. Figure 29 and Figure 30 show additional technology exchange during the project period through the project website.

- North Slope Borough Planning Committee - Presentation on Lake Water Use and Management
- March Arctic Ice and Snow Roads 2010 Conference: Advancements and Future Needs
  - ATN Project was a sponsor
  - More than 130 registrants
  - http://www.itsalaska.org/Ice2010_Program.html
- December 2010 US/Canada Northern Oil and Gas Research Forum Presentations: Overview Presentation, Three Topical (Snow, Soil, Water) Posters
- Special Sessions at Alaska Section, AWRA, Annual Water Resource Conferences – 2002 to 2013
- Intelligent Transportation Technologies!
  - Agency Smartphone Management Interface
  - Save Agencies Time, Faster Updates to Industry
- February 2011 Alaska/Canada Ice Road Workshop
  - ~40 Industry, Contractor, Agency Representatives
  - Discussion of Best Management and Construction Practices
  - Alaska vs. Canada Practices, Adaptation Needs & Climate Change
- 2012 Tenth International Conference on Permafrost
  - Northern Russia Oil Provence, Salekhard
  - Soils, Hydrology, Students
- Adaptive water management and water use information provided to other projects (NSDSS, Snow Fences)
- Project is identifying Industry key priorities and challenges with respect to water management and supply, and communicating those findings to related projects
- 2010 Ice Roads Conference material continues to serve as training for other project teams
- Facilitating Industry Connections
- Coordinating activities designed to create synergies between Industry and DOE projects in Alaska

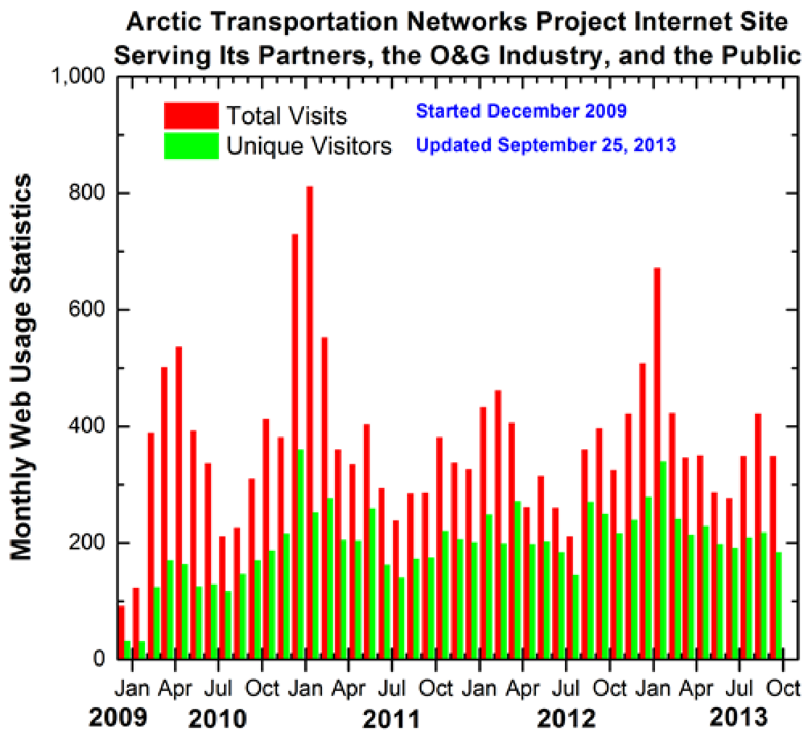

Figure 29. Usage statistics of the project website during the project period.

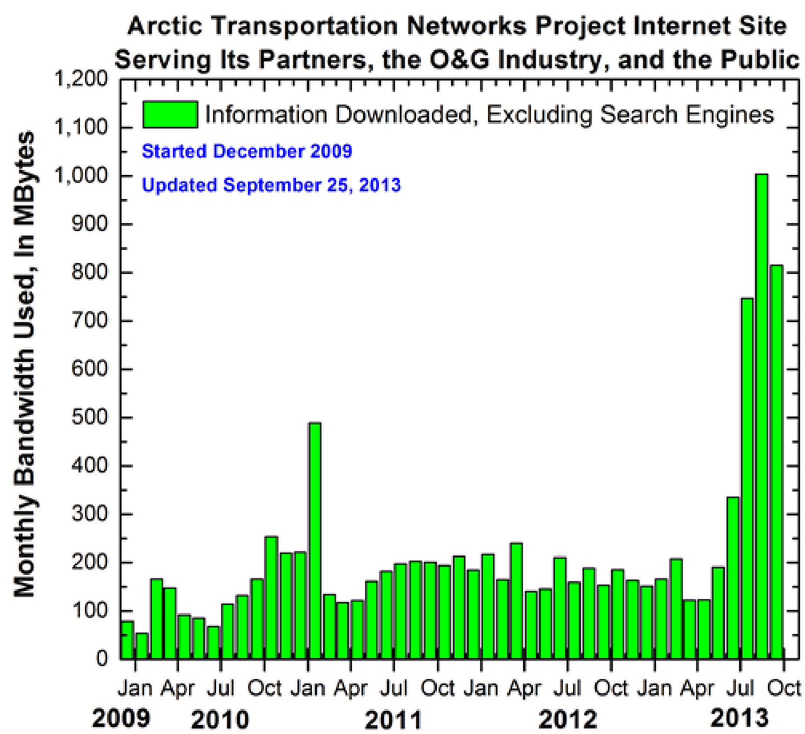

Figure 30. V Usage statistics of the project website during the project period.

Some additional notes of interest for the project website.

- arctic-transportation.org
- Content on project website results in ongoing Tech Transfer !
- Over 17,000 total visits
- Over 9 Gigabytes served
- Data, Reports, Methods, References, Photos

SUMMARY AND RECOMENDATIONS

The following are key highlights from the project and issues that will lead to increased water needs for industry and further needs to improve and optimize water use and tundra travel permitting.

- **Increasing Needs for Water**
  - Low-Sal Water Flooding for Heavy Oil
  - Ice Roads in More Remote, Rougher Terrain
  - Increased Users, BUT Smaller Companies and E&D Projects
  - Shale Development?
  - Areas of Lower Availability
  - Access to NPR-A? ANWR?
  - New Reservoir Development Technologies
  - Competing Uses, Users
- **Increased Needs for Better Transportation**
  - Marginal Field Further Away from Permanent Road Systems
  - State Maintained Seasonal Winter Roads?
  - Life of Field Maintenance Activities

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Clilverd, H. White, D., and Lilly, M. 2009. Chemical and Physical Controls on the Oxygen Regime of Ice-Covered Arctic Lakes and Reservoirs. Journal of the American Water Resources Association (JAWRA) 45(2): 500-511.

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Kane, D., White, D., Lilly, M., Toniolo, H., Berezovskya, S., Schnabel, W., Youcha, E., Derry, J., Gieck, R., Paetzold, R., Trochim, E., Remillard, M., Busey, R., and Holland, K., 2009. Meteorological and Hydrological Data and Analysis Report for Bullen Point and Foothills Projects: 2006–2008. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 08.18, Fairbanks, Alaska, 180 pp.

White, D.M., Clilverd, H.M., Tidwell, A.C., Little, L., Lilly, M.R., Chambers, M.K., and Reichardt, D., 2008, A tool for modeling the winter oxygen depletion rate in Arctic lakes. Journal of the American Water Resources Association (JAWRA) 44(2):1-12. DOI: 10.1111/j.1752-1688.2007.00162.x

White, D.M., Prokein, P., Chambers, M.K., Lilly, M.R., and Toniolo, H., 2008, Use of synthetic aperture radar for selecting Alaskan lakes for winter water use. Journal of the American Water Resources Association (JAWRA) 44(2):1-10. DOI: 10.1111/j.1752-1688.2007.00160.x

APPENDIX A. SNOW DEPTH FIELD EXAMPLE FORM (BLANK & FILLED OUT)

Arctic Transportation Networks Project

Form F-012: Snow Survey Form

Project ID:		Site Location/Lake ID:	
Survey Purpose:		Date:	Time:

Location Description:	On tundra on staked course, adjacent and north of L9312 weather station.				
Survey objective:	Determine snow depth and density for application to lake recharge studies, and tundra travel management.			Weather Observations:	Very Cold (-40s), Breeze, Light
Latitude:		Longitude:		Datum:	
Elevation:		Elevation Datum:		Reference Markers:	
Drainage Basin:		Slope Direction:		Vegetation Type:	
Slope Angle:		Access Notes:		Other:	
Snow Depth Probe Type:		T-probe		Snow-Survey Team Names:	
Snow Tube Type:					

Snow Course Depths (cm)

	1	2	3	4	5
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

	(cm)
Average snow depth =	
Maximum snow depth =	
Minimum snow depth =	
Standard variation =	

	(inches)
Average snow depth =	
Maximum snow depth =	
Minimum snow depth =	
Standard variation =	

Snow Sample Depths and Weights

Bag #	Snow Depth (cm)	Weight (g)	Volume (cm^3)	Density (g/cm^3)	Organic Plug (cm)

Average Density =

Average Snow Water Equivalent (SWE) = ________ cm H2O

Average Snow Water Equivalent = ________ inches H2O

Average Snow Water Equivalent = ________ feet H2O

SWE = avg. snow depth*(density snow/density water)

Data entered by: Date:

Data QA/QC by: Date:

Arctic Transportation Networks Project

Form F-012: Snow Survey Form

Project ID:	**ATN**	Site Location/Lake ID:	**L9312 - Tundra**
Survey Purpose:	**Determine snow depth, SWE**	Date: 1/19/2010	Time: 12:30

Location Description:	On tundra on staked course, adjacent and north of L9312 weather station.				
Survey objective:	Determine snow depth and density for application to lake recharge studies, and tundra travel management.			Weather Observations:	Very Cold (-40s), Breeze, Light
Latitude:	N 70° 19.995'	Longitude:	W 150° 56.918'	Datum:	NAD 83
Elevation:	7 ft	Elevation Datum:	BPMSL	Reference Markers:	Orange stakes
Drainage Basin:	Colville River	Slope Direction:	Flat	Vegetation Type:	Lowland Wet Sedge Tundra
Slope Angle:	Flat	Access Notes:	Haggland	Other:	Snow pack was fairly uniform, some slabbing
Snow Depth Probe Type:		T-probe		Snow-Survey Team Names:	
Snow Tube Type:	Adirondack Snow Tube			Jeff Murray, Chris (LCMF)	

Snow Course Depths (cm)

	1	2	3	4	5
1	22.0	29.0	39.0	10.0	15.0
2	15.5	29.5	36.5	47.5	23.5
3	30.0	27.0	30.0	43.0	36.0
4	25.0	28.5	31.0	13.0	46.0
5	25.0	15.0	29.0	23.0	48.0
6	52.5	21.5	27.0	41.0	47.5
7	32.0	19.0	26.5	43.5	29.0
8	17.0	25.0	22.0	43.0	22.0
9	26.0	30.0	48.0	41.0	16.0
10	27.0	27.5	48.5	30.0	27.0

	(cm)
Average snow depth =	**30.1**
Maximum snow depth =	52.5
Minimum snow depth =	10.0
Standard variation =	10.7

	(inches)
Average snow depth =	**11.9**
Maximum snow depth =	**20.7**
Minimum snow depth =	**3.9**
Standard variation =	**4.2**

Snow Sample Depths and Weights

Bag #	Snow Depth (cm)	Weight (g)	Volume (cm^3)	Density (g/cm^3)	Organic Plug (cm)
ZOE4	26	256.9	928.2	0.28	
BL(5)	17	73.9	606.9	0.12	
BL(1)	14	92.1	499.8	0.18	
B5	36	381.3	1285.2	0.30	
B2	35	310.3	1249.5	0.25	

Average Density = **0.226**

Average Snow Water Equivalent (SWE) = **6.8** cm H2O

Average Snow Water Equivalent = **2.68** inches H2O

Average Snow Water Equivalent = **0.22** feet H2O

SWE = avg. snow depth*(density snow/density water)

Data entered by: Jeff Murray Date: 12/8/09

Data QA/QC by: Jeff Derry Date: 12/14/09

APPENDIX B. UNIVERSITY OF ALASKA FAIRBANKS BLOWING SNOW MODEL REPORT

The Challenges of Forecasting Blowing Snow Probability on Alaska's North Slope

Jessica Cherry[1,2], Don Morton[3,4], Vladimir Alexeev[1]

1. International Arctic Research Center, University of Alaska Fairbanks
2. Institute of Northern Engineering, University of Alaska Fairbanks
3. Arctic Region Supercomputing Center, University of Alaska Fairbanks
4. Borealis Computing, LLC

Submitted December 29, 2013

Alaska's North Slope, that is the area North of the Brooks Mountain Range, is an important region for the Oil and Gas industry, as it is for all of the logistics and support entities that make that industry possible. There are also a number of coastal and inland communities on the North Slope where residents—many of them Alaska Natives--participate in both subsistence living and wage economies. For most of these people, the safety of transportation in and around their communities and work camps, be it over the tundra, on ice roads, or by sea or air, depends on atmospheric visibility conditions. During the cold season, blowing snow is a key factor for visibility conditions and helps determine what the Oil and Gas industry has termed 'Phased Driving Conditions'. One problem, however, is that weather forecast models used by the National Weather Service (NWS) do not directly forecast or simulate blowing snow as a visibility factor. This leads forecasters and industry specialists to rely on simpler and potentially inaccurate rules of thumb about the likelihood of 'Phased Driving Conditions.'

The purpose of the present study is to explore a possible modeling framework from which to generate a simple but accurate measure of the likelihood of blowing snow, such as an index. We explore two different modes of model operation: one that is more convenient but theoretical because it is a single, cold season-long simulation with the Weather Research and Forecasting model (WRF); the other is a realistic forecasting-type run with the High Resolution Rapid Refresh for Alaska model (HRRR-AK), that involves routine model restarts with new initialization data. After a discussion of blowing snow physics, both methods will be used to test the concept of a Blowing Snow Probability Index (BSPI). Observational data from the National Weather Service station at Deadhorse Airport, Prudhoe Bay, AK will be used to evaluate the model simulations. Results show that the simple BSPI used here--a function of air temperature, windspeed, and snow age--effectively predicts low visibility conditions at Deadhorse in both model simulations.

1. The Physics of Blowing Snow

Much has been written about the measurement of snow and its tendency to be transported by wind (Cherry et al., 2005 provides a review). Alaska's North Slope is, in some ways, similar to the American Prairies: an open, treeless, windswept region. For this reason, blowing snow models developed for the Prairies, such as those by Pomeroy and Li (2000) are likely to be appropriate. Sophisticated, three-dimensional transport models have been developed for snow (Liston et al., 2007) but have had limited success in coupling with forecasting models (Bernhardt et al., 2008) and none yet in an operational framework. The development teams behind the land surface schemes in the mesoscale weather forecasting models simply have not focused on the problem of snow redistribution, in part because it is computationally intensive.

A Master's thesis by Byam (2012) and supervised by Cherry and Morton evaluated the ability of various land surface models in WRF to represent snow conditions on Alaska's North Slope and whether depth discrepancies between the model and observations could be explained by snow redistribution. Using equations from the SnowTran3D model (Liston et al., 2007), snow redistribution did appear to be the most plausible mechanism for model underestimates of snow in the Barrow area. This suggests that for estimates of snow on the ground, implementation of a snow transport model would be quite valuable. For estimating and forecasting variability, however, a simpler approach, such as use of an index based on wind speed, temperature, and snow depth and age may be equally useful.

We followed the approach of Essery et al. (1999), Li and Pomeroy (1997), and Pomeroy and Li (2000) based on their work in the Canadian Prairies. They used the following equations to represent the probability of blowing snow occurrence as a function of windspeed at ten meters (u_{10}), as follows:

$$P(u_{10}) = \frac{1}{\sqrt{2\pi}\delta} \int_0^{u_{10}} \exp\left\{-\frac{(\bar{u}-u)^2}{2\delta^2}\right\} du, \tag{1}$$

where, for dry snow of age A (in hours), the parameters of the distribution are given by

$$\bar{u} = 11{\cdot}2 + 0{\cdot}365T + 0{\cdot}00706T^2 + 0{\cdot}9\ 1\text{n}(A) \tag{2}$$

and

$$\delta = 4{\cdot}3 + 0{\cdot}145T + 0{\cdot}00196T^2. \tag{3}$$

Where T is air temperature in °C. Essery et al. (1999) suggest the following approximation:

$$P(u_{10}) = \left[1 + \exp\left\{\frac{\sqrt{\pi}(\bar{u}-u_{10})}{\delta}\right\}\right]^{-1} \tag{4}$$

In both of the modeling approaches tested here, these equations were applied by using model wind and air temperature values at the grid cell nearest to Deadhorse Airport at Prudhoe Bay, AK. Snow age was determined by tracking positive changes in snow depth in access of 1 mm. Figure 1 (a-c) explores the behavior of Equation 4, mathematically, so the reader can see clearly how changes in temperature, windspeed and snow age impact the probability of blowing snow.

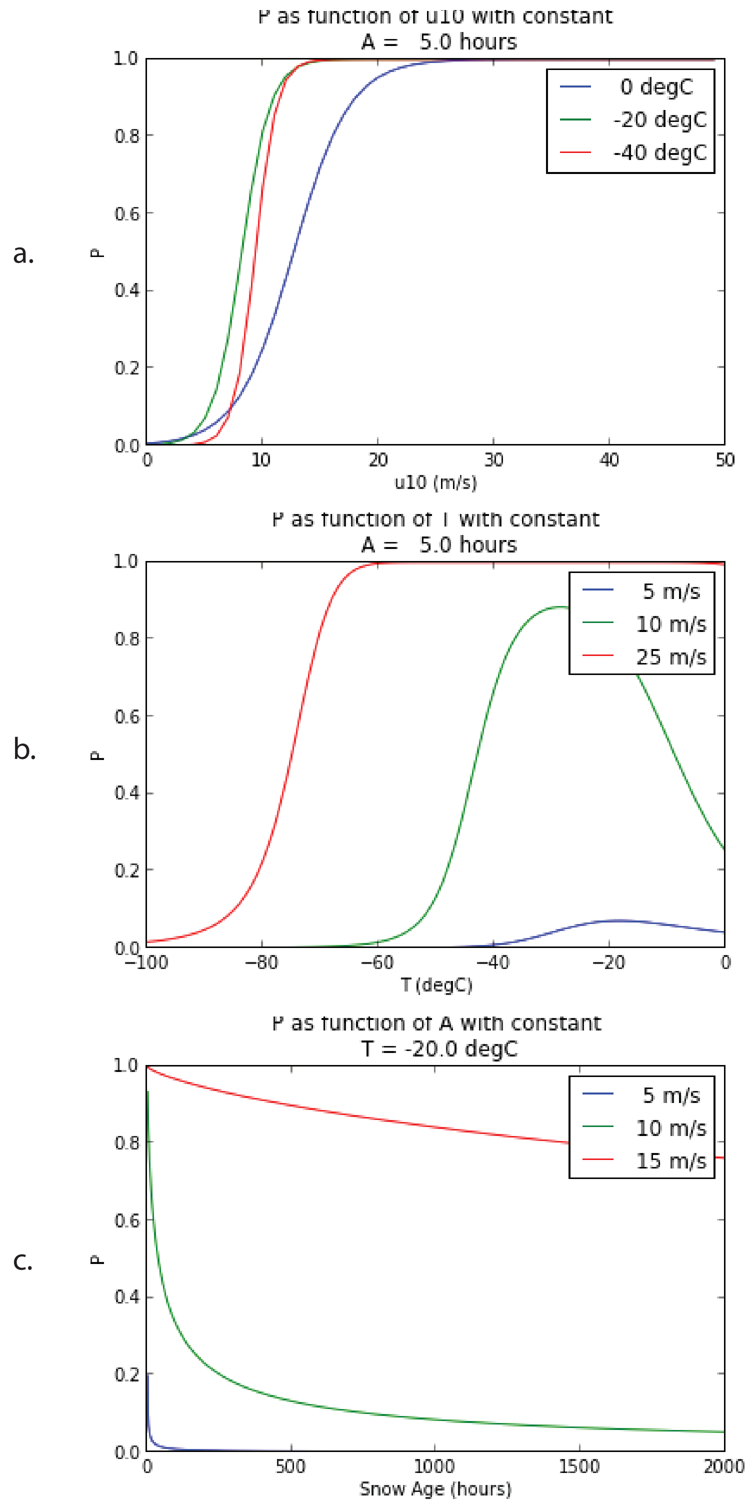


Figure 1a: shows how the probability of blowing snow varies with temperature, according Equation 4; 1b: the same but for windspeed; 1c: the same but for snow age.

2. First Approach at BSPI: Continuous WRF Simulations

In the first set of simulations, the WRF model was run as a continuous simulation from September 2012 through May 2013 so that a snow pack could develop in the model as it would in the real world. The domain of the simulation was for Northern Alaska and the adjacent seas, as shown in Figure 2. The boundaries were forced with the National Center for Environmental Prediction North American Model (NAM) for this period. The following options were selected for the WRF model: the Morrison 2-moment scheme for microphysics, RRTM long-wave radiation, Dudhia scheme for shortwave radiation and the NOAH LSM surface scheme. The horizontal resolution of the model was 3km.

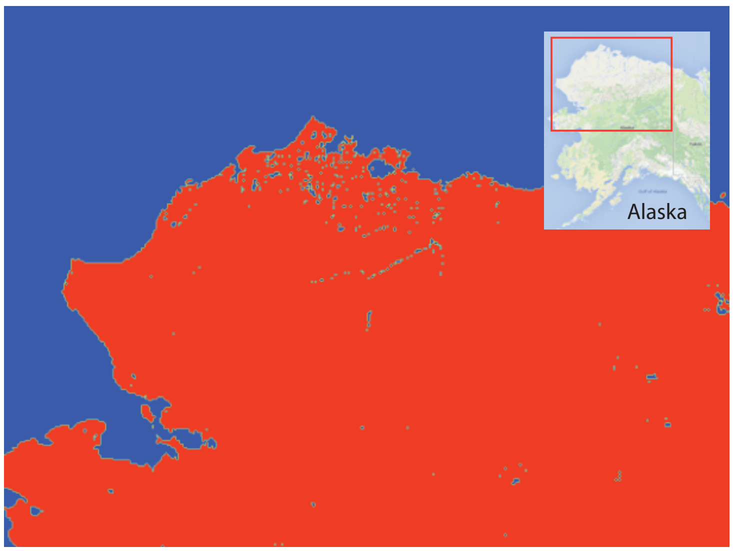


Figure 2: WRF model simulation domain.

Simulations show spatial distributions of wind and the calculated BSPI at each model time step, calculated according to Equation (4) above. Examples of this output are show here in Figure 3 (a,b). At this random time slice, windspeeds and BSPI are both shown to be greatest not only in the Brooks Range, but also in the Central and Western Slope areas and in Barrow. This simulation also shows a strong probability of blowing snow offshore of Barrow.

Figure 4 (a-d) shows how model output compares to observations at Deadhorse Airport. For several variables, the temporal changes in model values were similar to the observations, but the magnitudes were off. WRF output in this simulation was uniformly too cold (by about 4 C) and winds were too light (by a factor of 2) for this period. These offsets and multipliers were applied to 'bias-correct' WRF for the purposes of comparison with observations. These biases are likely to be a combination of shortcomings in the model physics with biases in the boundary conditions coming from the NCEP NAM product. Regardless, the calculated BSPI matches closely to changes in visibility at the airport: as the BSPI goes up, visibility goes down. Discrepancies may be due to other phenomena affecting visibility besides blowing snow, such as low cloud and fog.

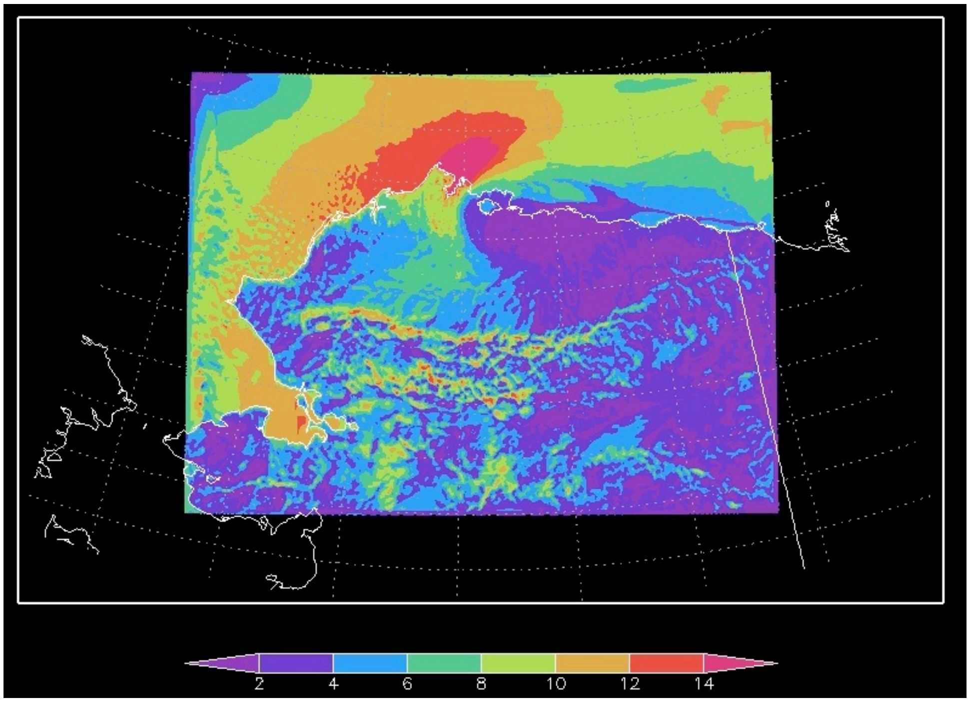


Figure 3a: spatially explicit model output for windspeed near surface, for a random time slice during the winter of 2012-2013.

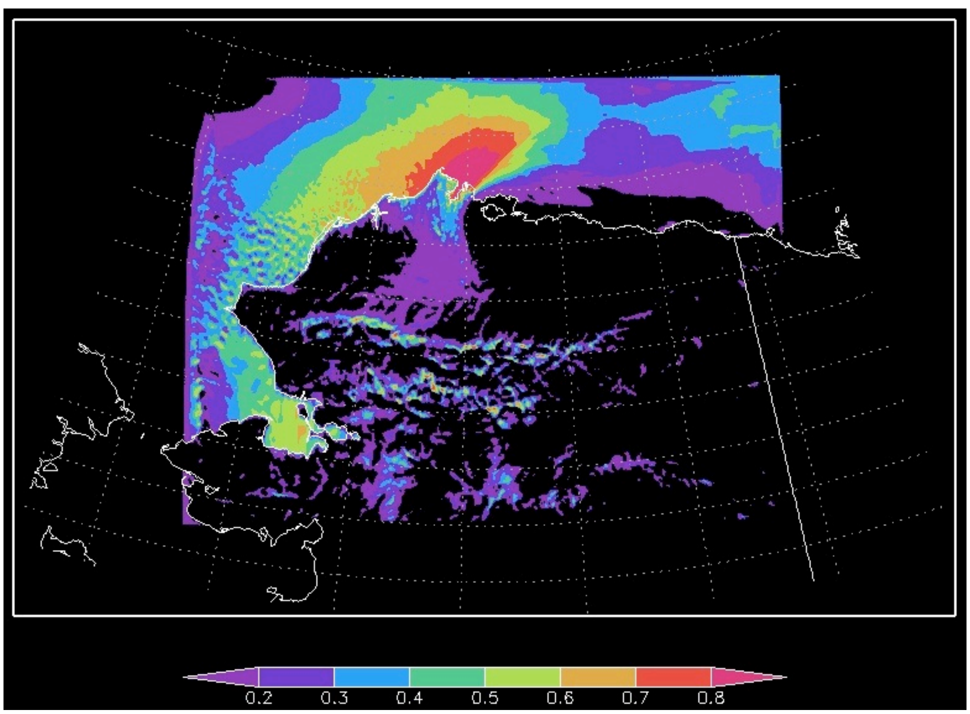


Figure 3a: the spatial distribution of the Blowing Snow Probability Index (BSPI) calculated from model fields according to Equation (4) above, for a random time slice during the winter of 2012-2013.

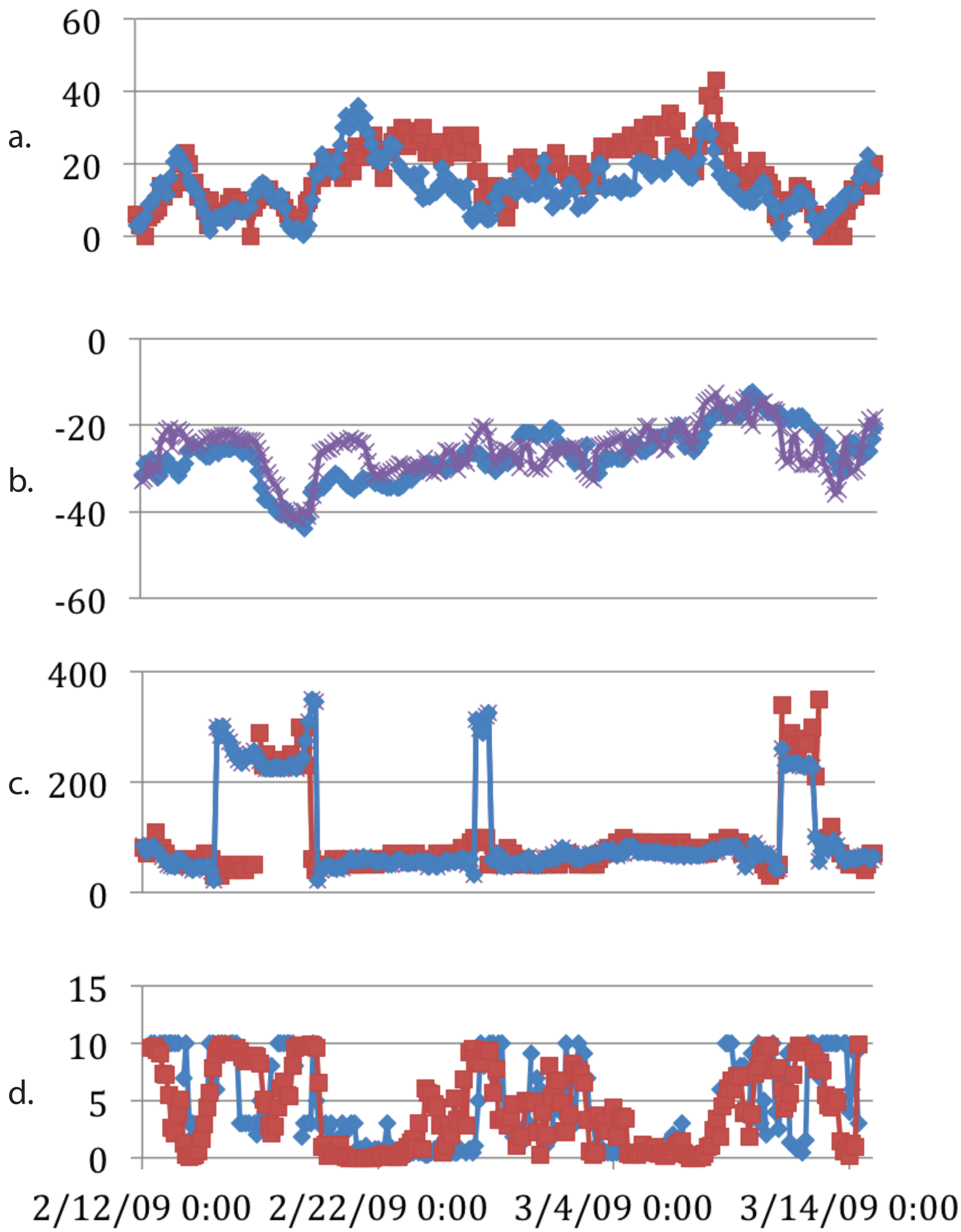


Figure 4a: Windspeed measured at Deadhorse (blue diamonds) and WRF simulated (crosses) for Feb-Mar 2013, miles/hour. WRF windspeeds were 'bias-corrected' by multiplying by a factor of 2: it was uniformly too weak at Deadhorse. 4b: Dew point temperature measured at Deadhorse (blue diamonds) and WRF simulated (crosses) for Feb-Mar 2013, deg. C. Units of X-axis is a snapshot number (output was produced every three hours). WRF temperature was 'bias-corrected' by +4C: it was uniformly too cold at Deadhorse. 4c: Wind direction measured at Deadhorse (blue diamonds) and WRF simulated (red squares) for Feb-Mar 2013. 3d: Visibility recorded at Deadhorse (blue diamonds) and WRF simulated for Feb-Mar 2013, miles. 'Visibility' was calculated as 10*(1-P), where P is the probability of blowing snow as calculated by Equation 4, above.

3. Second Approach at BSPI: Realistic Forecast Mode Simulations with HRRR-AK

The High Resolution Rapid Refresh for Alaska (HRRR-AK) has been running operationally at the Arctic Region Supercomputing Center (ARSC) since late 2009. It has undergone a number of transformations, but is currently set up at 3km horizontal resolution over the Alaska region, running two 48-hour forecasts per day, with start times of 00Z and 12Z. The forecasts use 256 processing elements on ARSCs supercomputers almost 24 hours per day to pre-process, execute the model, and post-process a number of output products.

Initialization comes from the 13km NOAA ESRL Rapid Refresh (RAP) model, run hourly for fifteen forecast hours. Since the RAP data only goes out to fifteen hours, lateral boundary conditions are obtained from NCEPs 11km Alaska NAM and ramped down to the RAP initial conditions. Raw output from the HRRR-AK forecasts are produced at hourly intervals and are available as soon as the hourly timestamp has passed, in a native NetCDF format and in a transformed GRIB2 format delivered to NOAA NWS Alaska Region forecast office Advanced Weather Interactive Processing System AWIPS systems.

3.1 Data Preprocessing

Computing a BSPI according to Equation 4 depends on temperature and windspeed - both of which are readily available from the HRRR-AK NetCDF output files, and snow age (in hours). The definition of snow age is not well-stated, so we have made the assumption that an hourly snow accumulation of at least 1mm constitutes new snow, and has an age of 0 hours, and then ages until there is, again, new snow. Computing snow age fields from the HRRR-AK forecasts requires several steps.

- First, because an hourly HRRR-AK output file is 6 GBytes in size, we chose to extract a small subset of the fields needed for snow analysis, writing these into 66 MByte files.

- Each HRRR-AK forecast is a separate entity, with a cold-start initialization from a RAP forecast. Therefore, there is no natural continuity from one forecast to the next. Because the age of snow at a particular grid point might accumulate through a number of forecasts, we choose to take our twice-daily 48-hour forecasts and build a continuous hourly stream of forecast files across a number of forecasts. This was accomplished by starting with an initial forecast at Forecast Hour 6 (FH06) (FH06 was chosen in order to allow the forecast six hours spin-up time), and using each hourly file up through FH18. FH18 corresponded to the same time as FH06 of the next forecast, so we averaged the FH18 and FH06 outputs of two forecasts, then started using hourly files from FH07 of the next forecast, and so on. This allowed us to build a single stream of hourly forecast outputs for our time period of interest. Unfortunately, the HRRR-AK has exhibited a number of outages, and that leaves us with gaps in this stream of hourly forecast outputs. There is no way to resolve this.

- With the stream of hourly forecasts, the next step was to build a two-dimensional SNOWAGE field for each hourly forecast. This was accomplished by initializing the first hourly file as having undefined SNOWAGE. For each subsequent hour, and at each grid point, if the accumulated snow height (from the SNOWH variable) increased by 1mm, we assigned a SNOWAGE of zero hours. At subsequent forecast hours, if grid point had a defined SNOWAGE, but no additional accumulation, the age was incremented by one hour. If there was additional accumulation at a grid point, the SNOWAGE was reset to zero hours. Although this was fairly logical, the method suffered due to gaps in the forecasts. For each gap encountered, the next available forecast file had SNOWAGE again set to 'undefined', and the process started over. This is an unavoidable issue as long as we have gaps in our forecasts, unless we want to start making other assumptions that allow all snow to age through the gaps. Once a SNOWAGE field had been derived, it was added to the existing NetCDF forecast file, allowing us to keep track of SNOWAGE along with all the other snow-related variables.

The methods we used were for forecasts over the winter of 2012-2013 (specifically, 01 Dec 2012 to 31 Mar 2013), using archived forecast files. The same approach could be employed for real-time operational forecasts, creating and maintaining snow age fields for each forecast output file. These could then be used to generate the blowing snow probability index as described below.

3.2 Calculating BSPI from Operational Model Fields

Python routines were developed to extract key variables from specified location in HRRR-AK domain and compute and plot a time series of the BSPI, along with other key variables. The initial test case comes from Deadhorse, with plots shown in Figure 5 (a-c).

With temperature, wind speed, and snow age, all three contributing to the BSPI, it can be difficult to determine how the individual variables affect the BSPI. Therefore, another set of graphics was produced, plotting the BSPI computed by variations in each variable (Figure 6). For example, BSPI was computed with the normal varying snow age (labeled as observed in the plots), and value of constant snow age (allowing temperature and wind speed to vary normally). This allows us to determine that snow age does, indeed, play a significant role in the calculation of BSPI. Likewise, similar plots were made to explore how temperature and windspeed affect the BSPI. In all cases, it is apparent that each variable plays a significant role.

Finally, in Figure 7, we provide a snapshot of the wind, temperature, snow age, and derived BSPI fields from a HRRR-AK forecast. In an operational environment these fields would be produced hourly, and would be available in a time-sequenced graphics viewer.

a.
b.
c.

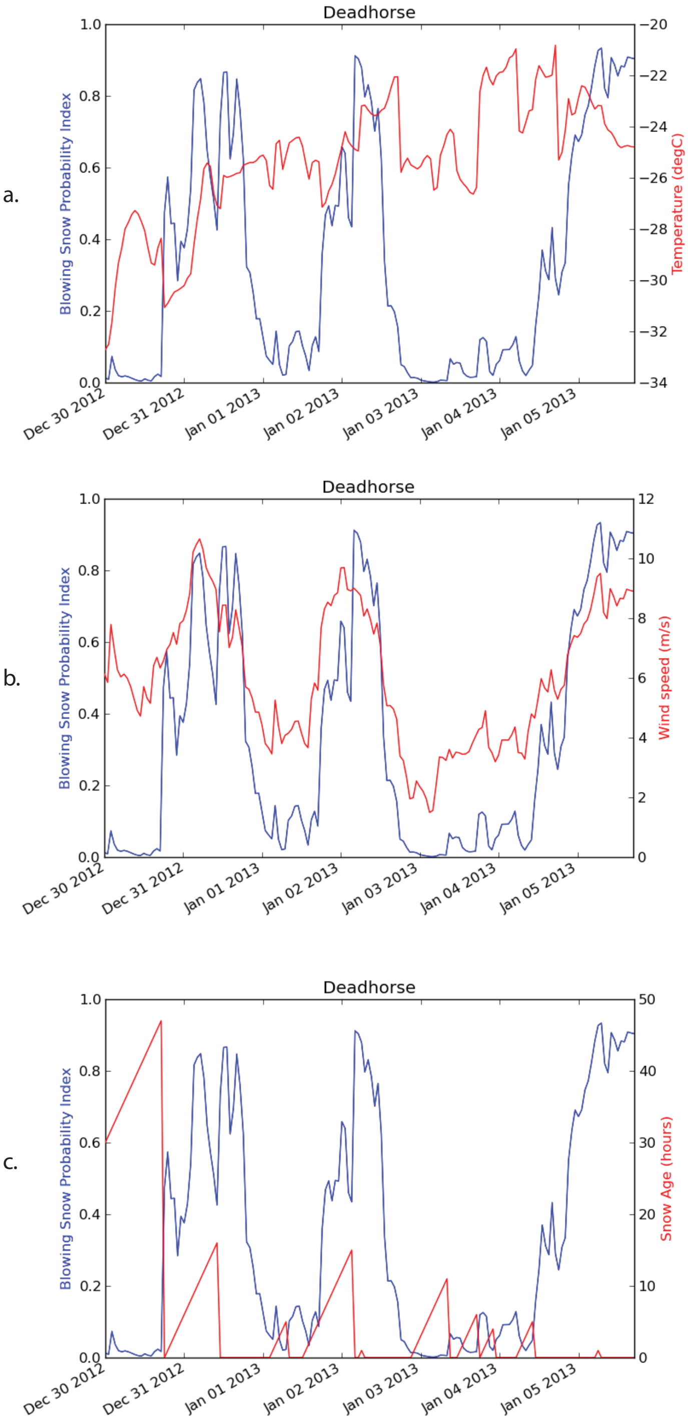
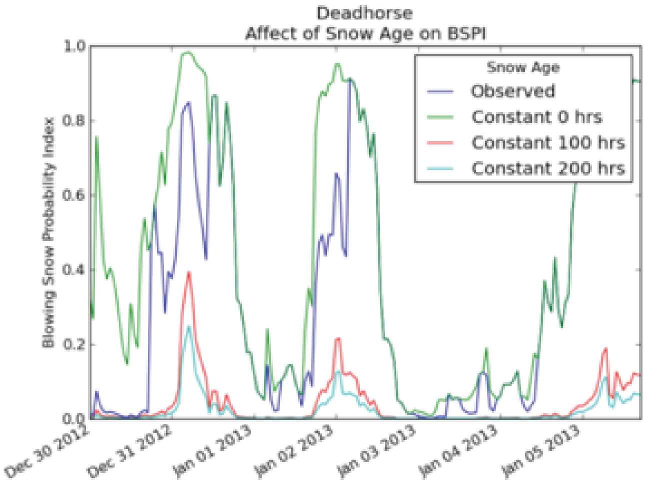


Figure 5a: shows temperature plotted with BSPI for the 2012-2013 test case at Deadhorse; 5b: same but for windspeed; 5c: same but for snow age.

a.



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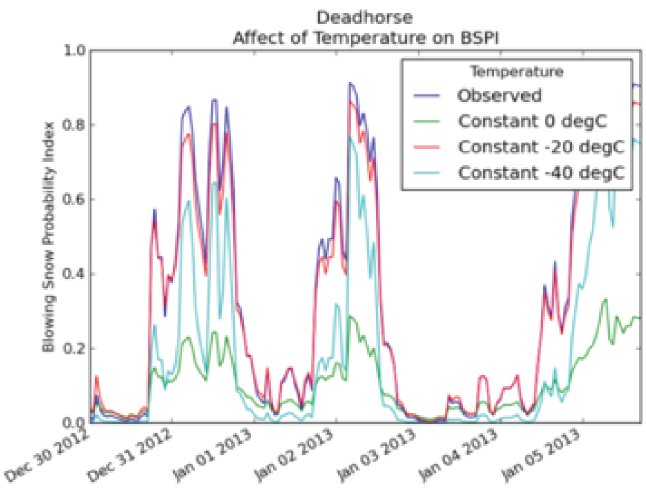

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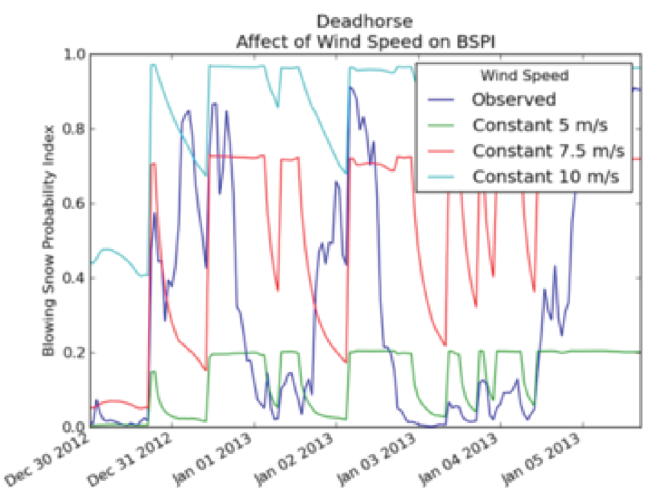


Figure 6a: effects of changing model snow age on BSPI; 6b same but for temperature; 6c same but for windspeed. The term 'observed' here refers to observed in the model run, not from actual measurements.

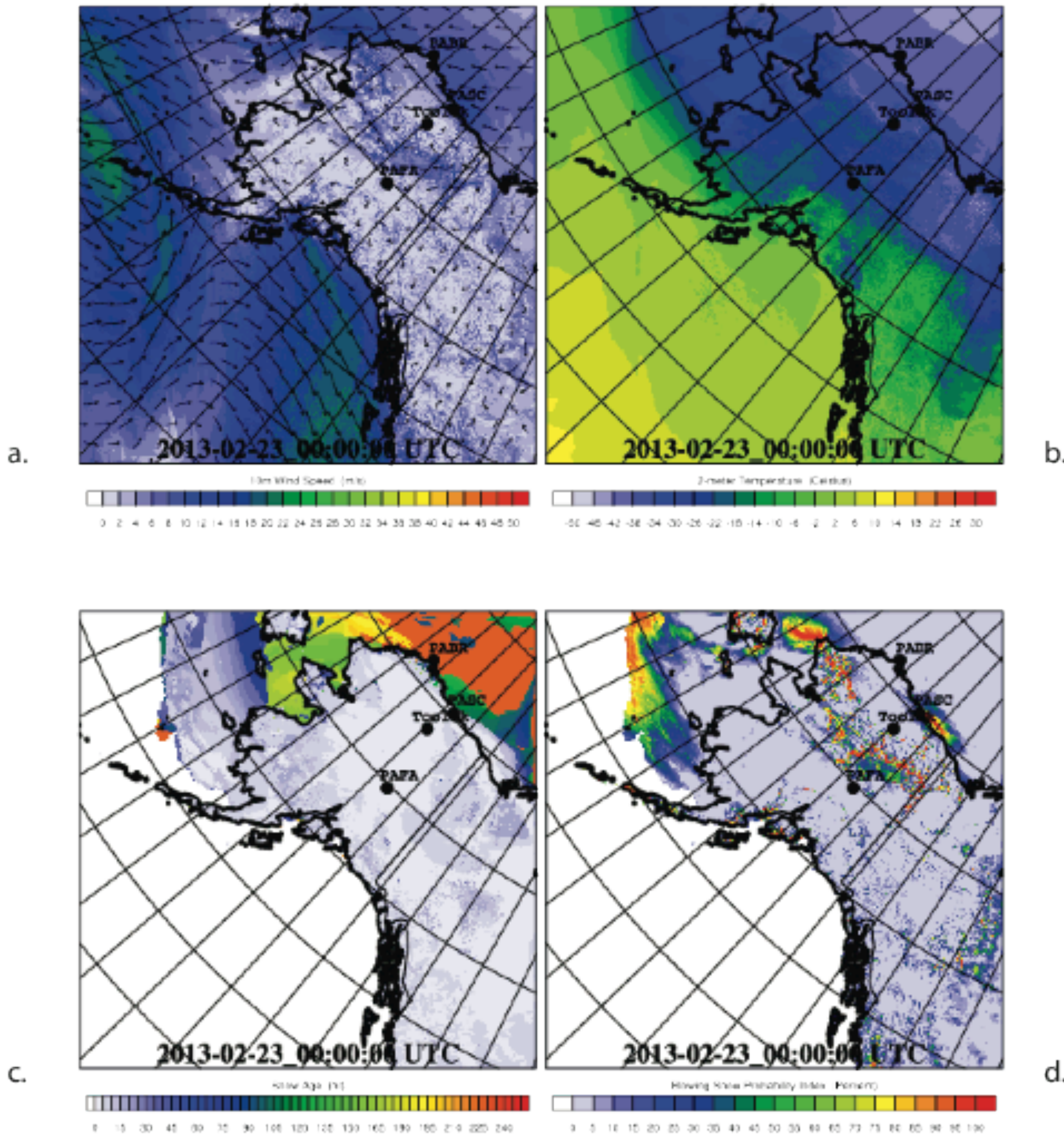
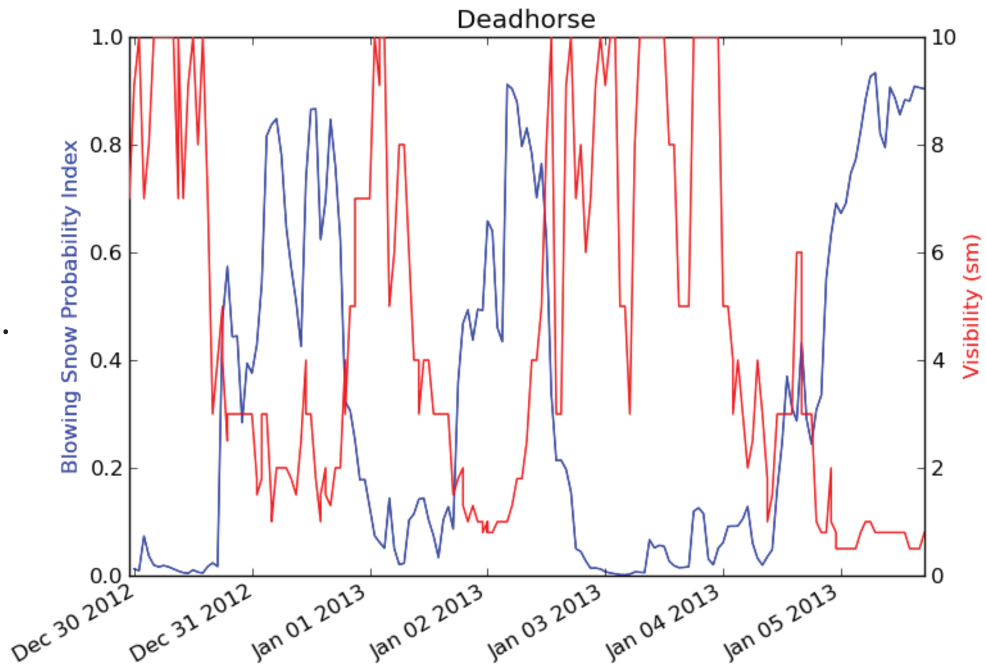


Figure 7a: 10 m windspeed output from HRRR-AK; 7b: same but for temperature; 7c: same but for snow age; 7d: BSPI calculated from these fields.

3.3 Comparison with Observations

A number of persistent low visibility periods were identified for Deadhorse during the 2012-2013 test period using the NWS data from the National Climate Data Center. Two of these periods were chosen for comparison with the model runs based on the availability of archived forecasts. These results are shown in Figure 8. A review of the figures shows a number of situations where a transition in forecast BSPI is matched with an appropriate transition in observed visibility. This suggests potential in using high resolution weather forecasts to compute an accurate blowing snow probability index.

a.



b.

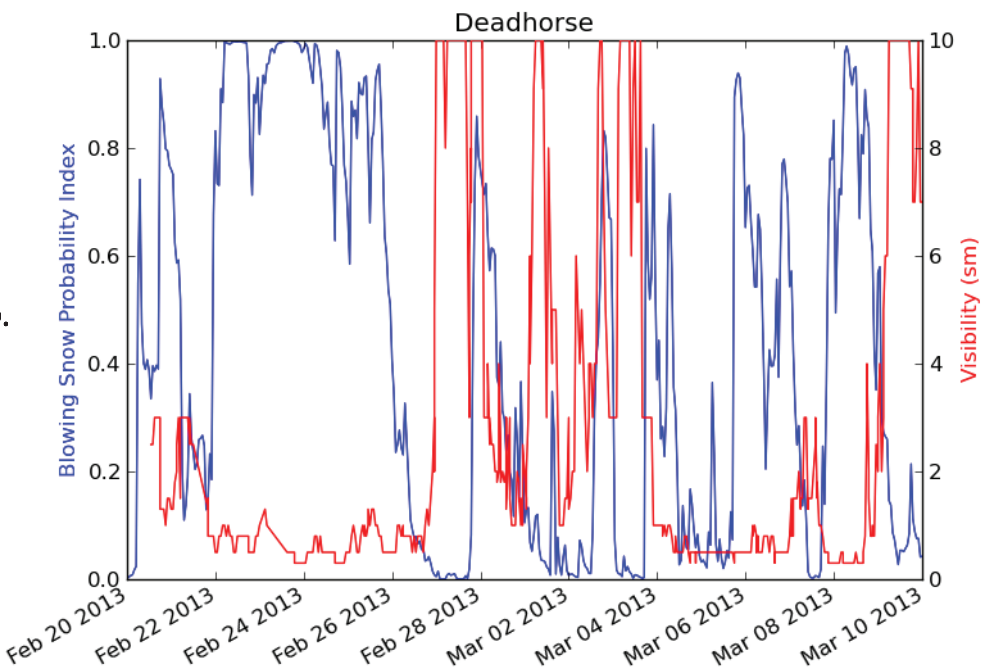


Figure 8a: comparison between modeled BSPI and measured visibility at Deadhorse Airport for late December, 2012-early January, 2013; 8b: same but for late February, 2013-mid March, 2013. A high BSPI is associated with low visibility.

4. Conclusions and Future Work

The BSPI looks to be a promising tool for forecasters to predict low visibility and 'Phased Driving Conditions' on Alaska's North Slope. Our method illustrates a number of challenges, however. By design, the algorithm we tested depends on air temperature, windspeed and the age of snow sitting on the ground. To get an accurate forecast for blowing snow, the air temperature and windspeed need to be accurate. The first set of our simulations showed biases in these fields in WRF forced with the NAM for the cold season 2012-2013. Once these air temperature and windspeeds were corrected, the calculated BSPI matched well with poor visibility events at Deadhorse. However, this suggests there are problems in the model physics or boundary conditions during the simulation, relative to actual observations.

Snow age is a harder parameter to get right. It depends on two things: solid precipitation and snow transport. We already know that later snow transport is not simulated in WRF or HRRR-AK. So what is shown here is only the new age, calculated from precipitation events. Precipitation needs to be accurate then, to get accurate snow age. Measurements of solid precipitation are notoriously poor (Cherry et al., 2005, 2007, 2013 and references therein) and so verifying the precipitation forecast is going to be difficult, particularly because errors in measurement are typically a function of wind (with high winds resulting in greater error). We also used a 1 mm threshold to define a new snow event (and therefore resetting the snow age clock). This may or may not be reasonable. So there are several errors that are not quantified with respect to snow age in the continuous WRF run: the role of mobile snow that is laterally transported, the accuracy of the precipitation forecast, and the amount of new snow that is needed to generate low visibility conditions. Attempts to quantify these factors may be pursued in future work.

Finally, snow age is relatively easy to track in a continuous model run. In an operational forecast mode, however, information about the condition of the snowpack and new solid precipitation must be passed from forecast period to forecast period in order to calculate snow age. This is somewhat computationally intensive and more difficult if there are breaks in forecast system or when the land surface conditions in the forecast start to drift from reality without any assimilation or verification. There may, in fact, be value in generating a BSPI from a reanalysis product because this includes the known observations from the past and may lessen the drifting issues or overall model biases. Unfortunately some of the current atmospheric reanalysis have problems in their representation of snowpacks, a problem that would need correcting to calculate snow age.

Future work will attempt to correct model biases and quantify some of the uncertainties described here. There are also other meteorologic and anthropogenic causes for low visibility on Alaska's North Slope. These include low clouds, fog, mist, and local and regional atmospheric pollution. To tease apart each of these factors would require additional modeling work and observational analysis but could improve the utility of future forecasts for travel across Alaskan and other Arctic transportation networks.

5. Acknowledgements

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