



Landsat-based snow persistence map for northwest Alaska



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ABSTRACT

Landsat imagery for northwest Alaska from 1 February to 31 August, 1985–2011 was used to map snow persistence at high spatial resolution. We analyzed 11,645 scenes covering 505,800 km², including five Arctic National Park units and the range of the Western Arctic caribou herd (85 Landsat path/rows). A cloud mask was created using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS). Terrain shadows were calculated from ASTER G-DEM2 and solar incidence angle. The presence of snow cover was determined using separate Snowmap algorithms for non-shadowed and shadowed pixels. Resulting snow cover data were reformatted into 562 30 × 30 km tiles, with an average sample size per pixel of 216 cloud-free observations. A binary classification tree was used to successfully determine the day of the year that best marked the change from snow to snow-free conditions for 99.8% of the study area. An internal consistency check evaluating the occurrence of snow-free data earlier than that day or snow data later than that day, showed that 98.7% of the land pixels were consistently classified ≥90% of the time. Comparison with MODIS end of snow season data showed an average difference of 4.2 days. The snow persistence map was strongly correlated with the few SNOTEL stations in the study area ($r^2 = 0.856$). Broadly, most snowmelt over the study area occurs from late April through early June, with timing delayed farther north and at higher elevations. Many local-scale snow patterns are evident in the detailed, 30-m product. The snow persistence map was co-registered to Landsat land cover mapping, creating a powerful, publicly available resource for ecosystem and land use analyses (<https://irma.nps.gov/App/Reference/Profile/2203863>).

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1. Introduction

Snow persistence and snow depth patterns affect important aspects of northern ecosystems. Snow cover protects plants from desiccation, wind abrasion, and herbivory (Tape, Lord, Marshall, & Ruess, 2010; Walker, Billings, & De Molenaar, 2001). Approximately 30 cm of snow provides the hiemal threshold needed to insulate the surface from daily fluctuations in air temperature, creating the subnivean environment in which invertebrates and small mammals survive through the winter (Aitchison, 2001). Snow insulates plants and the soil, and can facilitate shrub growth and expansion (Sturm et al., 2001). In return, vegetation protruding above snow has been shown to decrease albedo, speeding up spring snowmelt (Cohen et al., 2013). Snowbed plant communities often include unique species assemblages, have delayed phenology, and melt from late-lying snowbeds can help support stream flow during dry summers (Walker et al., 2001). Deep snow areas also provide drifts for dens of large animals such as wolverines and bears (McKelvey et al., 2011). Conversely, many wildlife species use

shallow-snow and snow-free areas that are exposed early in the season for grazing and nesting (e.g., Hupp et al., 2001).

Caribou (*Rangifer tarandus*) are an iconic species of the Arctic. Snow influences caribou winter distribution and habitat availability by impacting the energy required for traveling and foraging for food. Snow depth patterns on the landscape also affect the distribution of preferred forage species. Access to lichens is particularly important for caribou when the land is snow-covered (approx. October–April in our study area), as lichens form a major part of their winter diet (Boertje, 1984). Lichens are most common and abundant on sites with moderate snow cover (Flock, 1978). Areas that are wind-scoured during winter are often snow-free or melt in very early spring. These sites may have many species of lichens growing on rocks but they do not produce abundant biomass and are generally not preferred caribou forage (Flock, 1978). Very deep snow makes winter travel and foraging more difficult for caribou (Fancy & White, 1985). Sites with shallow snow provide protection for vegetation, including lichens, easier travel and minimal costs for digging for winter forage. These sites tend to melt earlier than average in the spring, making a snow-persistence map an ideal tool for examining caribou habitat.

Maps of snow characteristics are valuable tools for monitoring changes caused by widespread warming and increased precipitation

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in the Arctic. North America has experienced decreases in snow cover and snow depth since the 1950s, with northwest Alaska showing no change in fall onset of snow cover, but a decrease of four days in the snow melt date between the 1972/1973 and 2008/2009 snow seasons (Callaghan et al., 2011). Physical modeling techniques (e.g. Liston & Hiemstra, 2011; Liston & Sturm, 2002) have been used to simulate global and regional snow characteristics. Remote sensing methods have been used to map snow cover since the 1960s (Dozier, 1989; Matson, 1991). While Landsat data provided needed spatial resolution (30-m pixels) (Rosenthal & Dozier, 1996), the 16-day imaging interval is too coarse to portray snow dynamics. Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) data come from satellites with more frequent passes (1–2 days globally, more frequent at high latitudes), but have coarser spatial resolution (≥ 250 -m pixels). The MODIS snow products, built on the work done with Landsat (Brozdik, Armstrong, & Savoie, 2007; Hall, Riggs, Salomonson, DiGirolamo, & Bayr, 2002; Sirguey, Mathieu, Arnaud, Khan, & Chanussot, 2007) provide information on snow cover at daily to monthly timescales, and at spatial resolutions as fine as 500 m. However, much of the variability in snow cover occurs at much finer spatial scales, particularly for mountain and tundra snow-packs (Liston & Sturm, 2002; Sturm, Holmgren, & Liston, 1995). Some work has been done using Landsat snow cover patterns to downscale MODIS fractional snow cover data (Selkowitz, 2011).

In this study, we used a combination of image interpretation and statistical modeling to describe patterns of snow persistence on the landscape at 30-m spatial resolution to help characterize winter and spring caribou habitat conditions related to snow depth across northwest Alaska. To accomplish this we compiled and analyzed an extensive time series of over 10,000 Landsat images (1985–2011) that covered the study area. We used the results of this analysis to map the typical date when areas became snow-free across the range.

2. Methods

2.1. Study area

The study area covers the northwest portion of Alaska, including portions of the North Slope, Brooks Range, Yukon Basin, Seward Peninsula and Yukon–Kuskokwim Delta, with a focus on the range of the Western Arctic caribou herd (Fig. 1). The study area encompasses the winter range, calving grounds, summer range, migratory areas, and outer range (areas on the periphery of the herd's range that get occasional use). The status, distribution, movements and trends in the condition of caribou are monitored as part of the US National Park Service's Arctic Network Inventory and Monitoring Program. Data on snow cover within the range of the Western Arctic caribou herd are important to understanding movement patterns and timing of caribou migrations. There are five Arctic National Park Service units (Gates of the Arctic National Park and Preserve, Noatak National Preserve, Kobuk Valley National Park, Cape Krusenstern National Monument, and Bering Land Bridge National Preserve), three National Wildlife Refuges (Selawik, Kanuti and Koyukuk) and the National Petroleum Reserve–Alaska in northwestern Alaska that are wholly contained by the study area. The extent of the area for which Landsat data were downloaded and analyzed was somewhat larger than the Western Arctic caribou herd's range to accommodate possible range expansion and to include the full extent of some conservation units, for a total area of 505,800 km² (Fig. 2).

2.2. Landsat image acquisition

A total of 89 path/row locations (footprints of individual satellite scenes as defined by the Landsat Worldwide Reference System-2 (WRS-2)) covered the study area (Fig. 3). Four of these were excluded because they were mostly ocean and contained no land that was not

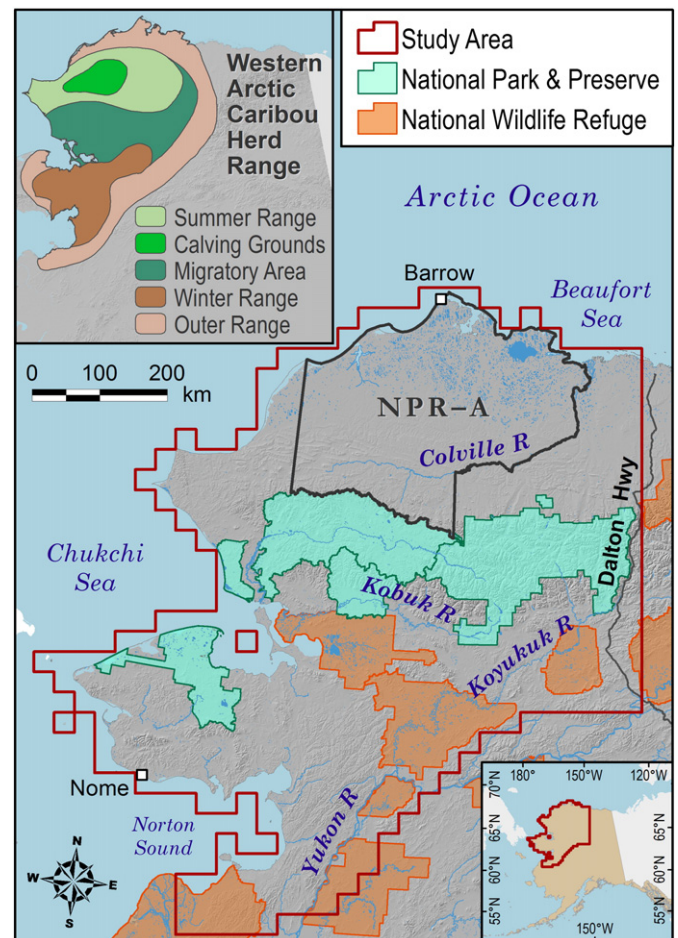


Fig. 1. Study area overview, Western Arctic caribou herd range, northwest Alaska.

also included in the adjacent row. All browse images available by September 2011 for Landsat 4-TM, Landsat 5-TM, and Landsat 7-ETM+ for the remaining 85 WRS-2 path/rows were downloaded, along with the associated metadata text records. The browse images were georeferenced by creating a GIS-readable world file from the information in the metadata file using a custom Python script. Each Landsat path/row was reviewed manually and browse images which contained useful information about ground conditions over at least 10% of the scene were identified.

A total of 11,811 scenes of interest were selected, and the list was submitted to the U.S. Geological Survey (USGS) Earth Explorer website (<http://earthexplorer.usgs.gov>) for processing. Some of the scenes (166) could not be processed, though the USGS indicates that it is possible that these may be processed in the future (11,645 scenes downloaded).

The number of images from each path/row was fairly uniform (Fig. 4), with well over 100 scenes with useable imagery for each path/row except some path/rows at the edge of the study area, which were often mostly ocean and sea ice. Few Landsat scenes are collected for path/rows that are mostly ocean, since the satellites are focused on land-surface studies. There are more scenes available towards the east of the study area. There were fewer scenes available towards the north because the daylight acquisition window is reduced with latitude.

While there were some Landsat TM scenes from as early as September 1984, the number of early season (February–May) images was very limited prior to the launch of Landsat 7 in late 1999. The current analysis was heavily weighted by data available in the 2000 to 2011 period (97% of February–May scenes and 90% of June scenes were from the 2000–2011 period) (Supplement Table S1).

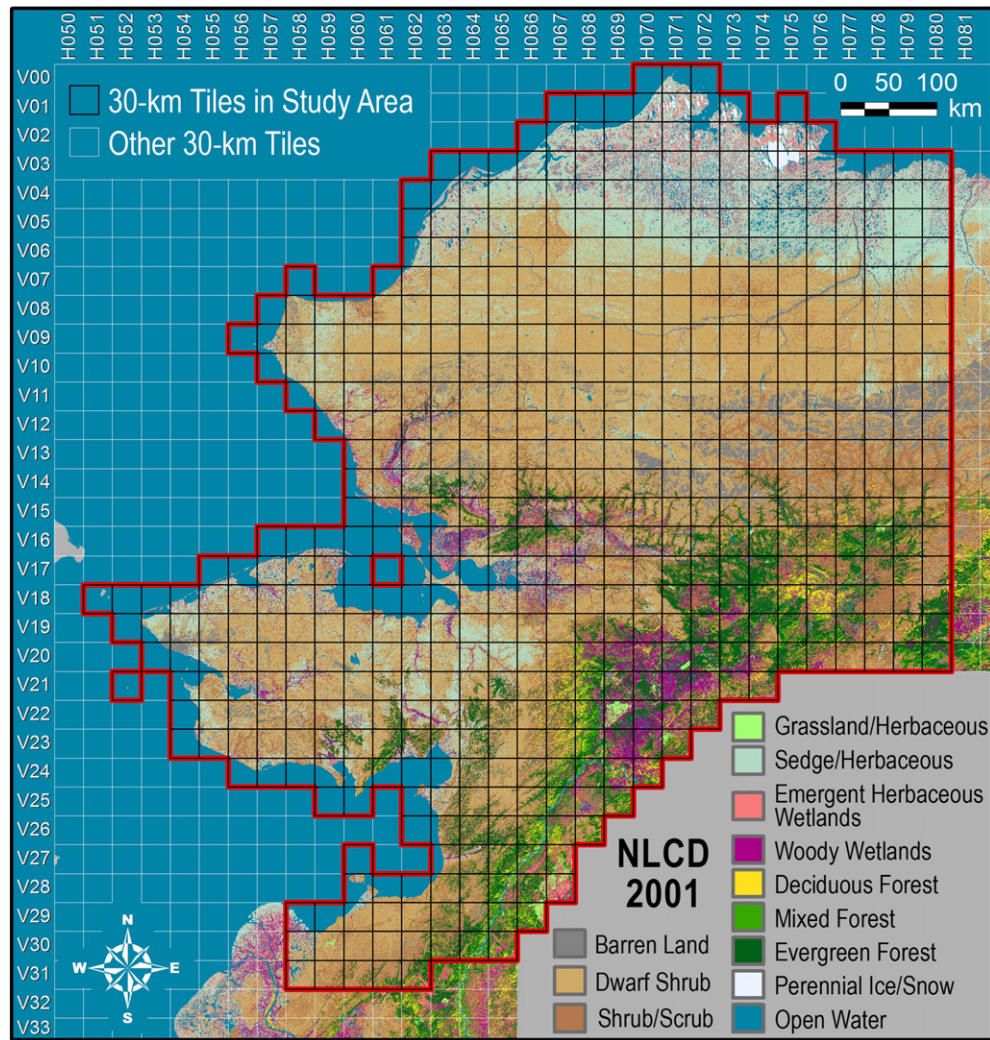


Fig. 2. Tiling scheme for Landsat data in northwest Alaska, encompassing the Western Arctic caribou herd range.

2.3. Landsat image preprocessing

Only the scenes successfully processed to the systematic terrain corrected (L1T) product were used for the snow persistence analysis (10,913 of 11,645). Extraction of relevant metadata was performed using LEDAPS scripts (Masek et al., 2006). We standardized each scene to top of atmosphere reflectance using the LEDAPS *Indcal* algorithm, but had to omit seven scenes from November or December from the analysis, as these could not be calibrated because solar elevation was below zero (i.e. the sun was below the horizon at the scene center).

The LEDAPS *Indcsm* algorithm was used to calculate a cloud mask using the Automated Cloud-Cover Assessment (ACCA) algorithm for the remaining 10,906 scenes (Irish, Barker, Goward, & Arvidson, 2006). Visual assessment of the cloud mask showed that it performed well for optically thick clouds. The cloud mask algorithm also reliably flagged data gaps at image edges. Some observed limitations of the cloud mask algorithm were: cloud shadows were not identified, clouds were sometimes not identified when saturation occurred in one or more spectral bands due to the calibration setting of the sensor, thin clouds were not reliably identified, some patchy snow was misinterpreted as cloud, and occasionally spurious clouds were detected in pixels adjacent to the SLC_OFF gaps. The frequency and effect of these limitations was not assessed directly for the current effort, but the accuracy of the final product was assessed (see Section 3.2). The saturation issue is likely the most important limitation of the ACCA

algorithm. The false detection of clouds over some patchy snow pixels (i.e. pixels close to 50% snow-covered) does remove good observations near the critical window of snow-melt, but since we are interested in a binary response (snow-covered vs. snow-free) the masking of some of these transitional pixels does not seriously affect our analysis. Improved cloud-masking algorithms such as the *fmask* algorithm (Zhu & Woodcock, 2012), now available as a product from the USGS, should be strongly considered for future analyses.

2.4. Shadow model

The study contains extensive areas of hilly and mountainous terrain which created dark, shadowed terrain in satellite images. Sun angles are low at high latitudes, particularly in non-summer months, increasing the extent of shadowing. Terrain modeling, described below, was used to identify the areas in each Landsat scene that were potentially affected by terrain shadowing. Within these areas, a modified snow mapping algorithm was applied. This modeling did not correct for cloud shadow areas.

2.4.1. Digital Elevation Model (DEM)

DEM data are required inputs for calculation of solar incidence angle and terrain shadowing.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (G-DEM2)

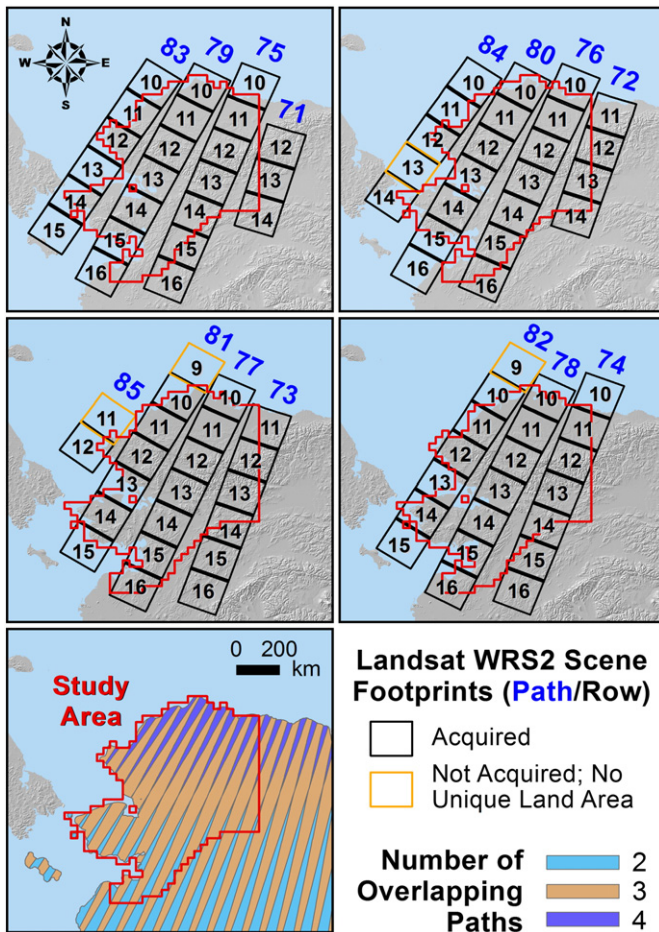


Fig. 3. Landsat path/row coverage in northwest Alaska, encompassing the Western Arctic caribou herd range. Numbering is according to the Landsat Worldwide Reference System-2 (WRS-2).

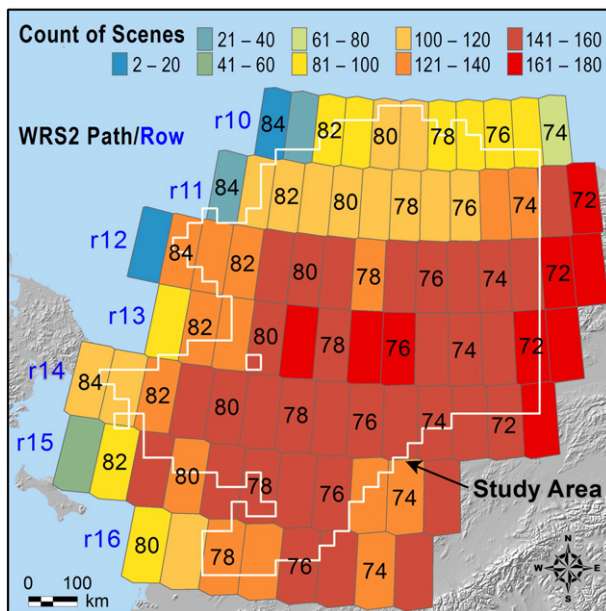


Fig. 4. Number of Landsat scenes downloaded for each path/row for northwest Alaska (Feb 1–Aug 31, 1985–2011). The “Thiessen polygons” for the nominal center point of each WRS-2 path/row are shown; these are constructed with no overlap or gaps and are much smaller than the actual footprints.

(ASTER GDEM ASTER GDEM Team, 2011) and the USGS National Elevation Dataset (NED) were evaluated for the terrain shadow modeling. The ASTER G-DEM2 was selected because it has higher spatial resolution, is based on more recent data, and was observed to be more accurate than the NED in areas of high relief based on visual comparisons of modeled mountain shadows to the mountain shadows visible in the imagery.

The G-DEM2 data were mosaicked and reprojected to 30-m resolution using a cubic convolution kernel into UTM zones that covered the extent of the Landsat imagery. The cubic convolution kernel was used because it better preserves the peaks and valleys of the input data; the peaks in particular were important factors controlling terrain shadows. Terrain slope (degrees) and aspect (degrees) were calculated from the reprojected G-DEM2 data.

Abundant artifacts (artificial bumps and valleys) created some modeled shadows that did not actually occur. Such artifacts probably covered <1% of the area, though the shadows cast by artifacts may have approached or exceeded 1% of the area when sun elevation was low. However, the only consequence was to cause the more conservative shadow snow mapping algorithm to be applied to areas that were not actually shadowed (see Section 2.5 below).

2.4.2. Solar incidence angle and terrain shadows

The solar incidence angle was calculated for each pixel in each scene using the G-DEM2 slope and aspect rasters, combined with the scene center solar geometry values from the scene metadata:

$$i = \arccos[\cos \theta \cos e + \sin \theta \sin e \cos(\varphi_m - \varphi_s)]$$

where i = solar incidence angle, θ = solar zenith angle, e = terrain slope, φ_m = terrain aspect, and φ_s = solar azimuth.

The results of the solar incidence angle were reviewed interactively and a threshold of 80° was determined as best identifying pixels that were generally dark and considered as shadows for the snow mapping. The selected threshold of 80° was somewhat liberal for shadow mapping (i.e. it tended to map shadows aggressively, including some areas without visible shadowing, but missing few real shadows). A liberal threshold was used because the shadow snow map algorithm is likely to be more resistant to error in non-shadow conditions compared to the standard snow map algorithm in shadow conditions (see Section 2.5).

The shadowing in mountainous terrain is pronounced by late August due to low sun angle. Shadows are also darker in August than in mid-winter because the surrounding terrain lacks bright snow which can reflect light into shadowed areas. The extreme shadowing could contribute to errors in the snow mapping for mid- to late-summer shadowed terrain because the signal to noise ratio in the satellite signal is particularly low.

Additional shadows occur on surfaces that are facing the sun but have intervening terrain blocking the sun. The ArcGIS Hillshade tool was run for each scene using the G-DEM2 and solar geometry from the metadata as inputs, and pixels in shadow from adjacent terrain were identified.

2.4.3. Shadow rasters

A shadow raster was calculated for each scene by combining the shadows identified by the solar incidence angle and by the terrain shadow (Hillshade). If a pixel was in a terrain shadow, the shadow raster was set to a value outside the range of the solar incidence angles (200); otherwise, the value of the shadow raster was set to equal the solar incidence angle raster.

2.5. Snowmap algorithms

The Snowmap algorithm (Hall, Riggs, & Salomonson, 1995; Hall et al., 2002) was used to generate a binary map of the presence or

absence of snow for all non-missing, non-shadow pixels. Snow is one of the only natural materials that is both highly reflective in visible wavelengths and absorbs light in the middle infrared wavelengths. The Normalized Difference Snow Index (NDSI) is calculated from the visible and short-wavelength infrared wavelengths as follows:

$$\text{NDSI} = (\text{VIS} - \text{SWIR}) \div (\text{VIS} + \text{SWIR})$$

where VIS = top-of-atmosphere reflectance in the visible wavelength, 0.52–0.6 μm for Landsat band 2; and SWIR = top-of-atmosphere reflectance in the short-wavelength infrared, 1.55–1.75 μm for Landsat band 5.

The Snowmap algorithm classifies pixels as snow if the following conditions are met: NDSI is greater than 0.4, visible reflectance (Landsat band 3) is greater than 0.10, and near-infrared reflectance (Landsat band 4) reflectance is greater than 0.11. The MODIS snow product (Hall et al., 2002) incorporates an additional test intended to reduce false snow-free classification in forests. The test uses a combination of Normalized Difference Vegetation Index (NDVI) values and NDSI values to identify some cases when snow is present even though NDSI is less than 0.4 (Klein, Hall, & Riggs, 1998). We did not incorporate the forest cover test because the primary habitats of interest were tundra; the forest cover test would have added complexity and the parameters to implement it were not available—they are only represented in graphical form. Based on the 2001 National Land Cover Database (NLCD 2001) product (Homer et al., 2007; Selkowitz & Stehman, 2011), 15% of the study area is covered by Forest classes or Woody Wetlands, concentrated along the southeast edge of the study area (Fig. 2). The forested areas are mostly at the periphery of the Western Arctic caribou herd range, and much of the forest cover that does occur is sparse.

The standard Snowmap algorithm frequently misclassified shadowed pixels as snow-free. The visible reflectance and near-infrared tests are intended to prevent dark materials such as water from being mistakenly mapped as snow. However, all surfaces in deep shadows may be dark, and hence one or both of the reflectance tests fail and the shadowed pixel is classified as snow-free. To prevent shadows from being misclassified as snow-free, the two reflectance tests were dropped for pixels where modeled shadows were present. Only the NDSI test was applied. The Shadow Snowmap algorithm classifies pixels as snow if the following condition is met: NDSI is greater than 0.4.

2.6. Time series analysis of snow persistence

The *Indcsm* algorithm identified each pixel as cloud, cloud-free, or gap (missing data). The terrain shadow model classified each pixel as shadow or illuminated. The Snowmap and Shadow Snowmap algorithms identified each pixel as snow or snow-free. The results from these four models were combined to calculate the cloud, shadow and snow status of each pixel in each scene (Supplement Table S2). The outputs were visually examined in detail to assess the performance of the cloud and snow algorithms (Supplement Fig. S1). For the time series analysis of snow persistence, only the cloud-free pixels were utilized, and only the snow status (snow or snow-free) was extracted.

2.6.1. Landsat 30-km tiles of snow cover

We developed a statewide tiling scheme in the Alaska Albers (NAD 1983) coordinate system (Fig. 2) to facilitate the creation of time-series stacks from overlapping Landsat paths. The final study area included 562 30 $\times$ 30 km tiles (1000 $\times$ 1000 30-m pixels). The compilation for each tile was performed by a Geospatial Data Abstraction Library (GDAL) script. The script reprojected the cloud/shadow/snow raster from the default UTM projection to Alaska Albers (NAD 1983); clipped the imagery to the extent of each tile; and, if necessary, mosaicked adjacent Landsat rows from the same acquisition date together. The nearest neighbor resampling method was used during

reprojection and the 30-m pixel size was maintained. The product was co-registered with another Landsat-derived product, the NLCD 2001 land cover product (Fig. 2) (Homer et al., 2007; Selkowitz & Stehman, 2011). Our tiling approach was similar to that used by the Web Enabled Landsat Data project (WELD) (Roy et al., 2010). The results of the cloud/shadow/snow combined mapping model were compiled for each of the 562 30 $\times$ 30 km tiles in the study area. A Python script was run to calculate the number of valid pixels (illuminated snow, shadowed snow, illuminated snow-free, and shadowed snow-free) for each tile and scene.

2.6.2. Landsat time series preparation

The set of cloud/shadow/snow maps for each tile was filtered to select all scenes with valid data and acquisition dates between February 1 and August 31 (Julian day of year 60–244, *doy*). Due to cloud cover and slight shifts in the location of Landsat paths, some tiles contained no data from a particular scene and these were excluded from further analysis. Dates after August 31 were more likely to have recent autumn snow, so were not helpful in the detection of the spring snow-free date. The resulting set of cloud/shadow/snow maps (*css*) for each tile was stacked into a virtual dataset (VRT) using the Geospatial Data Abstraction Library (GDAL).

The sample size for each pixel in the study area averaged 216 cloud-free observations (s.d. = 33.6). Pronounced wedge shapes in the spatial distribution of sample size were caused by the overlap pattern of adjacent Landsat paths (Fig. 3). In mountainous areas, there were more cloud-free observations in valleys than at higher elevations, likely due to orographic effects (Supplement Fig. S2). Many of the highest sample sizes were in the east, where more Landsat images were collected (Fig. 4). The lowest sample sizes occurred offshore in the northern and western portions of the study area. Overall the high sample sizes provided adequate data for a robust analysis of snow persistence patterns on the landscape.

2.6.3. Snow persistence algorithm

To identify the day of year that best separated the snow-covered from the snow-free season, we analyzed the *css* stack and *doy* vector in “R” (R Core Team, 2012) using a binary classification tree (*rpart*), which was constrained to one split. We chose classification tree over logistic regression because it is less influenced by outliers. For each pixel, the split value (Julian date) that provided the best split between the snow-covered (1) and snow-free (0) season was extracted. The direction of the split (left or right) was extracted; a right split corresponded to the unusual circumstance when the best split was from a snow-free condition to a snow-covered condition and was stored as a negative number.

When there was no split, or when the split date was a negative number (indicating snow-free to snow-covered), the proportion of snowy days (*p_snow*) was calculated by dividing the number of days between February 1 and August 31 by the count of cloud-free observations with snow. If *p_snow* $\leq$ 0.25, the condition was defined as “usually snow-free” and the split date value was set to 1. If *p_snow* $\geq$ 0.75 the condition was defined as “usually snow-covered” and the value was set to 254. If 0.25 < *p_snow* < 0.75, the condition was defined as “no pattern” and the value was set to 0.

2.7. Assessment and validation

The internal consistency of the snow-free date algorithm was assessed by calculating the proportion of correct classifications for each pixel, based on the modeled snow-free date and the input stack of snow/snow-free/no-data observations by day of year. The sum of snow observations before the snow-free date, and snow-free observations on or after the snow-free date was divided by the total number of cloud-free observations. The snow mapping algorithm will correctly map snow that occurs on ice over water bodies, but it can perform

unreliably over snow-free ice, flooded ice, and turbid water. The analysis was performed over the entire study area of 562 tiles, which includes many lakes and rivers and extensive coastal and offshore waters around the edge of the study area. The internal consistency assessment was summarized using the full study area, and was also summarized for only the land portion of the study area. For the land portion, water was masked by excluding the Open Water class as mapped by the Landsat-based NLCD 2001 (Homer et al., 2007; Selkowitz & Stehman, 2011).

The dates were compared with MODIS snow metrics (Zhu & Lindsay, 2013) derived from the MODIS Terra Snow Cover Daily L3 Global 500 m Grid data (MOD10A1, Riggs, Hall, & Salomonson, 2006). The median date for the last day of the longest continuous snow segment (longest_css_last_day) was calculated for the MODIS data series (2001–2012) and compared for 10,000 randomly selected pixels within the study area with the zonal median of the Landsat snow-free date for each MODIS pixel. In addition, the range and standard deviation of snow-free date from these MODIS data were summarized to characterize the interannual variability in snowmelt data in the study area.

In situ data were compiled from SNOWpack TElemetry (SNOTEL) sites operated by the Natural Resource Conservation Service within the study area (<http://www.wcc.nrcs.usda.gov/snow/snotel-wedata.html>). These sites are not intended to be representative of snow conditions in their vicinity, but do provide detailed snow condition data for their locations (Schaefer & Werner, 1996). The snow-free date in spring was calculated for each site and for each available year for sites with snow depth and/or snow water equivalent data. For snow depth, the snow-free date was identified as the first date with zero inches snow depth. Similarly, for water equivalent data, the first date with zero inches water equivalent was identified as the snow-free date. If both snow depth and water equivalent data were available for a particular winter, the water equivalent data was used to determine the snow-free date. The mean snow-free date for each site was calculated from all years with SNOTEL data during the snowmelt season. The results from the SNOTEL data and the Landsat analysis were compared using the value of the Landsat pixel that intersected the SNOTEL location.

3. Results

The cloud, shadow and Snowmap algorithms produced tiled data of snow/no-snow (or missing data). In midwinter, it captures the landscape pattern of complete or near-complete snow cover, with only scour areas exposed. During spring, the snow-free area increases as lower elevation and shallower snow areas are exposed. Finally, in late spring/early summer only snow drifts remain; some drifts may persist well into late summer or remain as permanent snow fields.

3.1. Snow persistence

The binary classification tree returned a snow-free date (the day of year that split the snow season from the snow-free season) for 99.8% of the study area (Fig. 5). Broadly, most snowmelt over the study area occurs from late April through early June, with timing delayed farther north and at higher elevations. Many local-scale snow patterns are evident in the results (Supplement Fig. S3). Wind redistribution of snow frequently results in snowdrifts in the lee of terrain breaks that melt much later than surrounding areas. In rounded terrain without terrain breaks, snow redistribution can result in snow accumulating in valley bottoms. Windswept, scoured patches that melt out earlier than the surrounding landscape often occur near snow drifts. Early melt as a result of dust on the snow surface is observable from both riparian dust and road dust. Overall, the time series analysis captures the sometimes dramatic spatial variability of the landscape snow regime.

Striping artifacts are apparent throughout the map, the result of including Landsat 7 ETM+ SLC-OFF data with striped data gaps in each scene. The analysis is affected when an influential scene at a time

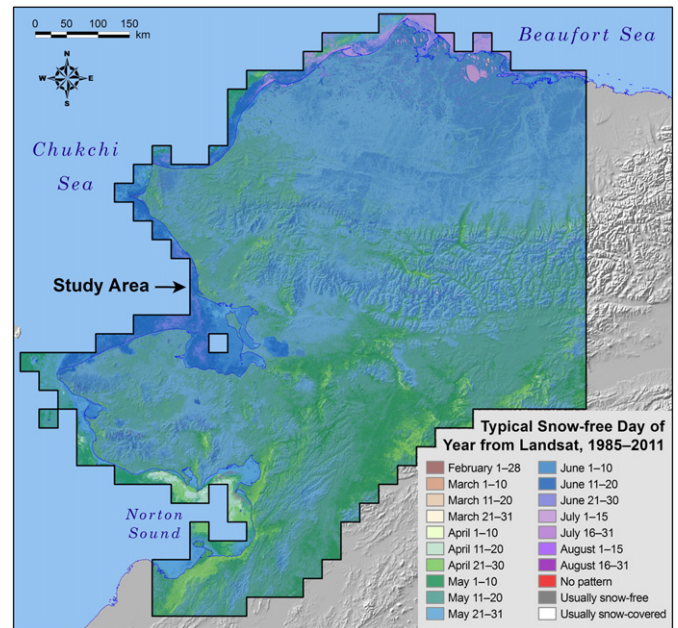


Fig. 5. Typical snow-free day of year based on Landsat time series analysis (Feb 1–Aug 31, 1985–2011), northwest Alaska.

close to the snow-free date has stripes of missing data. The snow-free dates from the areas with and without missing data generally differ by only a few days.

The “no split” condition occurred for 0.16% of the study area and was usually associated with situations where the pixel was nearly always snow-covered or nearly always snow-free. Each accounted for 0.08% of the study area. Most of the “usually snow-covered” pixels occurred in rugged mountainous terrain, mainly in the Brooks Range. Most occurred on permanent snowfields, though some did become snow-free during some summers. The only other location with sizeable patches of the “usually snow-covered” class occurred in some lakes east of Teshekpuk Lake; in this case the result appears to be spurious due to the highly variable sediment concentrations in the lakes, which confused the snow mapping algorithm.

3.2. Assessment and validation

The internal consistency of our snow persistence model was estimated from the proportion of observations that was correctly classified by the snow-free date at each pixel (i.e., the sum of snow observations before snow-free date and snow-free observations on or after the snow-free date, divided by the total number of observations). The land portion of the study area, derived from the NLCD 2001, is about 429,863 km² (85% of the total study area). Some snow-covered sea ice and lake ice in the far north of the study area is included as land by this approach because it was not classified as “Open Water” in the NLCD 2001. Our snow mapping algorithm is expected to perform better over land, so the summary statistics focus on results for the land portion of the study area.

The internal consistency analysis showed that 69.2% of the land pixels in the study area were correctly classified 95% or more of the time and an additional 29.5% between 90 and 95% of the time (Fig. 6). The remaining 1.2% was correctly classified over 75% of the time. These results demonstrate the strong internal consistency of the model results over land. Results were much less consistent for rivers, lakes and ocean; only 63.7% of the water in the study was correctly classified 90% of the time. Higher elevations were less consistent than lower land elevations, as expected due to their highly variable snow cover.

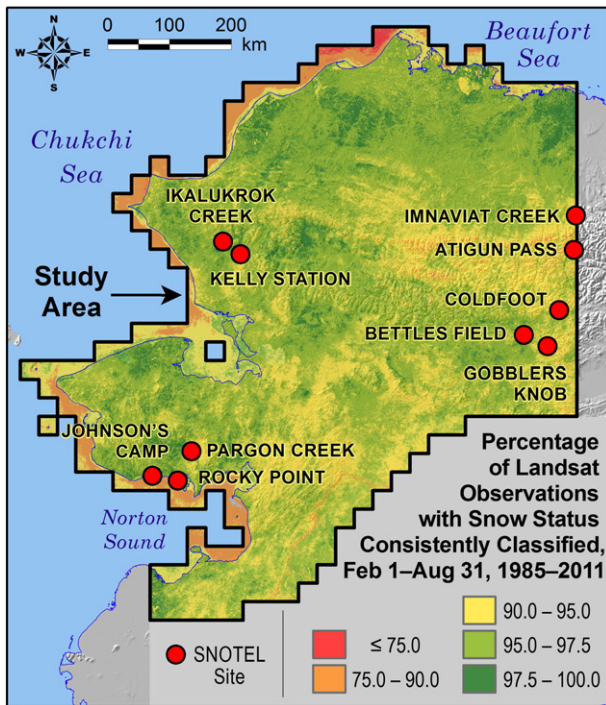


Fig. 6. Percentage of cloud-free Landsat observations consistently classified by typical snow-free day algorithm, northwest Alaska. The sum of snow observations before the snow-free date, and snow-free observations on or after the snow-free date was divided by the total number of cloud-free observations. Many inconsistencies are a result of normal inter-annual variation.

Inconsistent pixels can be caused by several different factors. Due to normal inter-annual variation in snowfall and snow redistribution, some years will lack snow on dates prior to the typical snow-free date, and some years will have snow on dates after the typical snow-free date. Occasional summer snow events (especially at high elevations) can cause unusually late snow cover. This type of normal variability decreased the number of consistent pixels. Finally, snow mapping errors due to missed cloud cover, cloud shadows, or other factors also contributed to incorrectly classified observations.

The comparison of the median MODIS date “end of longest continuous snow segment” to the Landsat snow-free date showed that the average MODIS date was 3.4 days earlier than the Landsat snow-free date calculated in this study. The mean absolute difference between the two data sets was 4.2 days (root mean square difference = 5.6 days) (Fig. 7). The coarser MODIS data could not pick up many of the differences in snow persistence due to landscape topography seen in the Landsat data (Fig. 7a, b).

The MODIS data also provided information on the inter-annual variability of the snow-free date over the 2000–2012 period (Supplement Fig. S4). 2001 was late melting almost everywhere, while in 2004 early melting was extensive, but most years had a mixture of early, normal, and late melting within the study area. The MODIS snowmelt date was less variable on the North Slope of Alaska compared to areas further south, based on the range and standard deviation of annual MODIS snowmelt dates. The range and standard deviation of the snow-free date on the North Slope were ≤ 3 weeks and ≤ 1 week, respectively; the range of snow-free date was > 1 month for much of the southern portion of the study area. The standard deviation of the MODIS snowmelt date was ≤ 1 week for most of the study area, with the exception of portions of the northern Brooks Range and coastal areas.

Of the ten SNOTEL stations in the study area (Fig. 6), nine collected suitable data (water equivalent and/or snow depth) during the snowmelt season for one or more years. The number of years with

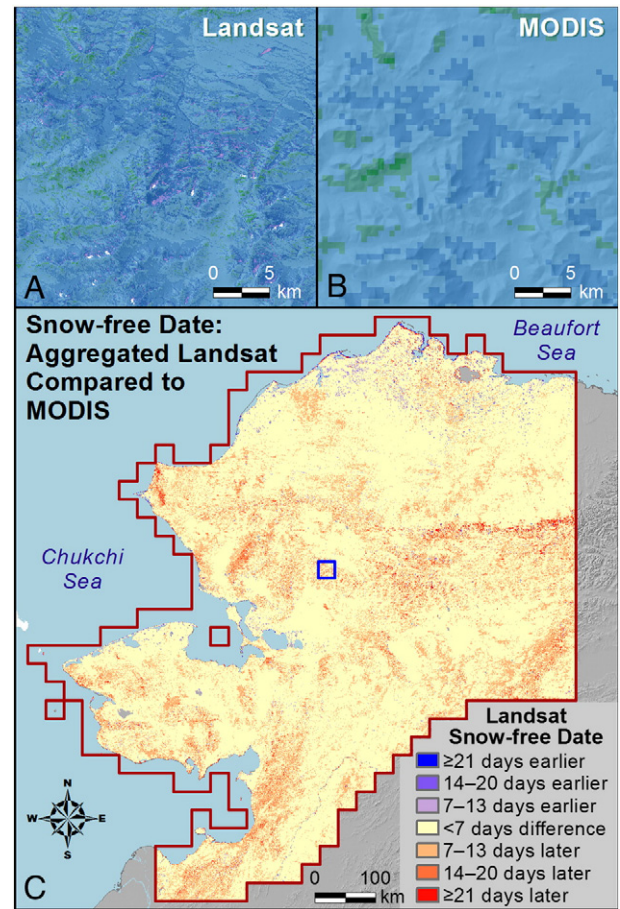


Fig. 7. Comparison of Landsat and MODIS snow-free date for northwest Alaska: A—detail of Landsat snow-free date for region outlined in blue (see Fig. 5 for legend); B—median MODIS “end of longest continuous snow segment” date for same area as A; C—difference between Landsat (aggregated to 500 m pixels) and MODIS snow-free dates for northwest Alaska.

data ranged from 1 year at Imnavait Creek to 32 years at Bettles Field. Coldfoot had a 17-year record, while the remaining six stations had record lengths of 4–8 years. Gobbler's Knob had six years of data but the data quality was problematic. There were extremely early melts recorded in two of the years (February or March) but examination of the Landsat data from those years indicated that snow was present after the SNOTEL-derived snow-free dates. There were also many gaps in the Gobbler's Knob data record, suggesting an unreliable snow depth sensor. For these reasons the Gobbler's Knob station data were excluded from the comparison.

The mean snow-free dates from the eight remaining SNOTEL sites ranged from 13 May to 7 June although the dates were not evenly distributed. Six of the sites had SNOTEL snow-free dates between 13 May and 17 May, while the other two (Atigun Pass and Imnavait Creek) had SNOTEL snow-free dates of 3 and 7 June, respectively. A comparison of the SNOTEL snow-free dates and the Landsat time-series results (Fig. 8) demonstrates very good agreement between the two estimates ($r^2 = 0.856$). The slope of the regression line was somewhat steeper than 1.0, suggesting a bias, though the influential late-melting sites at Atigun Pass and Imnavait Creek had few years of SNOTEL data (4 and 1 years, respectively).

4. Discussion

The Landsat time-series modeling and analysis proved a very efficient method for quantifying snow persistence over a wide area.

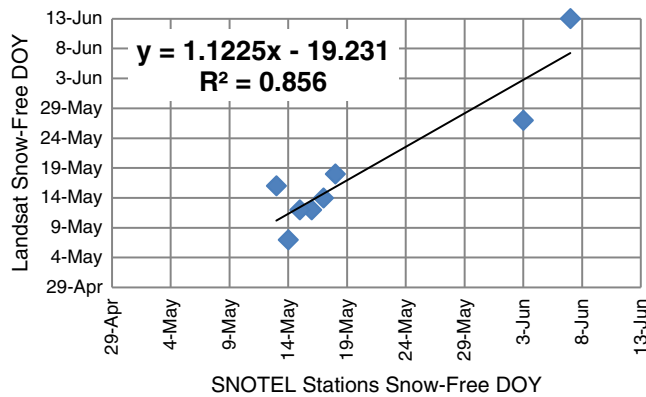


Fig. 8. Comparison of Landsat-derived snow-free day of year and SNOTEL derived snow-free day of year, northwest Alaska.

The SNOTEL sites provide detailed data for specific locations, while the Landsat time series method used freely available archived imagery to estimate the snow-free dates for 562 million pixels in the study area. The good agreement between the two methods provides confidence in the spatially detailed results from the Landsat analysis. Additional validation data could be obtained by compiling other records of annual snow-free dates in the study area, such as field observations from the Imnavait Creek site in the Toolik Lake Research Natural Area. If the study area was expanded to the west and south to include the Fairbanks area, then available SNOTEL records for snow-free date become much more extensive for both number of sites and length of record. With more extensive and denser forests in interior Alaska, we would need to incorporate improvements in the mapping of snow under forest canopy (e.g. Klein et al., 1998). Finally, opportunistically collected oblique landscape images, especially those acquired during the active snowmelt period, could be compared to simulated views generated by the Landsat snow-free date algorithm draped over the terrain.

Change in the average snow-free date over time was not a focus of the current analysis, and could be a potential source of error. Although the input data were nominally from 1985 to 2011, 99% of the February–May scenes and 90% of the June scenes were from 2000 to 2011. This shorter time period minimized the impact of changes over time in the snow regime. The 1985–1999 data were included in the analysis to increase the sample size of data available for the analysis, improving the ability to capture patterns of snow persistence on the landscape. In addition, all of the earlier data are gap-free, unaffected by the May 2003 scan-line corrector malfunction on Landsat 7. The additional gap-free data reduced the occurrence of striping artifacts. These artifacts limit the usefulness of the map for characterizing snow-free differences to a temporal resolution finer than 3–4 days in areas where they occur. If a future analysis is conducted to extend the mapped area we recommend including a sensitivity analysis by running the algorithm with and without the 1985–1999 data.

The comparison of the Landsat and MODIS end of snow season dates showed the MODIS dates to be 3.4 days earlier on average than the Landsat dates. This would be expected given the fact that the Landsat analysis included data from earlier years than the MODIS data. The documented trend towards earlier snowmelt (Callaghan et al., 2011) would lead one to expect later snow-melt dates in these earlier years. The map showing the differences between the MODIS and Landsat dates may indicate portions of the landscape where snow persistence dates are changing most rapidly (Fig. 7). Snow models to 2050 for northwest Alaska predict little change in snow-water-equivalent (SWE), but a 20–30% decrease in snow-covered days (SCD) (Callaghan et al., 2011). Unfortunately, the sparseness of 1985–1998 Landsat imagery in Alaska, and the challenges of cloud-masking and snow-mapping using 1972–1984 Multispectral Scanner, make it difficult to envision

how the full Landsat record could be utilized to assess changes in snow-free date over the past four decades.

The snow-free date analysis at 30-m resolution readily identified early- and late-melting terrain within landscapes (Fig. 5, Supplement Fig. S3). Within a given area, earlier melting areas generally have shallower snow than areas that melt later. However, the snowmelt date is not directly correlated to the depth of winter snow pack, as the rate of snow melt is affected by elevation, latitude, and region (which all affect temperature). Focal analysis to determine the difference between the snow-free date for a pixel, and the mean snow-free date for a surrounding window, could provide a systematic measure of “early”, “normal”, and “late” that corresponds to “shallow”, “moderate”, and “deep” snow for a given area. Stratification based on elevation should be applied because colder temperatures at higher elevations delay snowmelt. Other stratification categories could include aspect and vegetation class. This product is co-registered with the NLCD 2001 land cover product to facilitate stratification by vegetation class (Homer et al., 2007; Selkowitz & Stehman, 2011). For areas with highly variable snow cover, the Landsat-derived snow-free date can be correlated with detailed field survey observations such as those collected by Liston and Sturm (2002) to improve snow distribution models. Much of the local variation in snow depth and snow water equivalent is shown in the snow persistence patterns captured by the Landsat analysis (Supplement Fig. S3).

A GeoTIFF version of the map of typical snow-free day of the year for northwest Alaska is publicly available through the US National Park Service (<https://irma.nps.gov/App/Reference/Profile/2203863>).

5. Conclusions

The Landsat image inventory freely available for download from the USGS is a very valuable resource. We downloaded and analyzed 11,645 Landsat scenes covering northwest Alaska. The satellite data provided high sample sizes per pixel for a robust analysis of snow persistence patterns on the landscape. A combination of cloud screening and shadow identification was used to generate a time series of snow cover maps. Snow persistence analysis of this time series produced a map of typical snow-free date for the study area, with Landsat's high spatial resolution (30 m) (<https://irma.nps.gov/App/Reference/Profile/2203863>). The map showed very high accuracy, especially over land areas, when checked for internal consistency and compared to SNOTEL station data and MODIS snow metrics. The map captures the fine-scale spatial variation that occurs in snow-persistence at the landscape scale. It identifies areas that have low, average or deep snow cover during the winter. The snow persistence map was co-registered to the Landsat land cover mapping (NLCD 2001), creating a very powerful combination of maps useful for ecosystem analyses of all types, including hydrology, vegetation and habitat studies. The snow data can be correlated with detailed caribou location data from satellite telemetry to better characterize winter caribou habitat, both in terms of spatial variability and temporal variability, and the relationship to snow persistence. The map can also be used for development applications, such as mapping low-snow areas that would be sensitive to winter traffic, or drift areas that would pose road maintenance problems.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.rse.2015.02.028>.

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