Frequency, timing, extent, and size of winter thaw-refreeze events in Alaska 2001–2008 detected by remotely sensed microwave backscatter data

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Abstract Creation of ice layers in snow due to thaw-refreeze events can lock away winter forage, preventing access by large mammals and causing population declines. Data are limited, however, on the frequency, timing, extent, and size of thaw-refreeze events in northern latitudes given the area's remoteness and paucity of weather stations. We used a remote sensing approach to detect thaw-refreeze events in Alaska during winter between 2001 and 2008. We also compared these results to a regional climate reanalysis dataset that identified rain events (freezing and non-freezing rain). All areas of the state, except high elevation sites, had ≥ 1 thaw-refreeze event during the study period. Southwestern Alaska had the highest frequency of thaw-refreeze events with an average of >4 events each winter, whereas northern Alaska had the lowest frequency with an average of <2 events. We observed substantial inter-annual variation in the distribution and frequency of thaw-refreeze events. For most of the state, thaw-refreeze occurred at similar rates each winter month, except in northern Alaska where thaw-refreeze events were most frequent in early and later winter. The median extent of individual thaw-refreeze events was 469 km^2, however, events in the interior of the state tended to be larger. Remotely sensed thaw-refreeze detections generally had low correspondence with observations from the climate reanalysis dataset. Our results support the use of remotely sensed data to identify thaw-refreeze events.

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Introduction

Winter thaw-refreeze events can form an impenetrable ice layer that restricts access to the underlying forage for wildlife. These ice layers can form through various means (i.e., rain-on-snow, temperatures above freezing, wind) and have the potential to cause population declines of grazing ungulates (Solberg et al. 2001; Hansen et al. 2011). Though the threat of winter thaw-refreeze events has been widely discussed (Forchhammer and Boertmann 1993; Miller and Gunn 2003; Rennert et al. 2009), the population-level effects remain unclear. To a large extent, this may be due to a lack of measurements of changes in snow characteristics at sites with ice layers and the subsequent reliance on thaw-refreeze proxies (e.g., days with temperatures above freezing; Tyler 2010). A poor quality or unrepresentative proxy would mask any signal, which is especially problematic when investigating infrequent or small thaw-refreeze events.

The remoteness of areas where the formation of ice layers are thought to play a role in ungulate population dynamics hinders our ability to obtain direct measures of snow characteristics for the detection of thaw-refreeze events. Weather station data are often used to serve as proxies for distant thaw-refreeze events. While weather stations may be sufficient for identifying ice layers adjacent to the site if temperature, precipitation, and snowfall are measured, they only offer limited spatial inference about ice conditions in the snow profile at distant sites. Given that weather stations are sparsely distributed in polar regions (Fleming et al. 2000), this limits our ability to understand thaw-refreeze conditions across the landscape or obtain estimates of the size of events. How a population is impacted by a thaw-refreeze event is largely determined by how widespread the event is and the movement potential of the population to find ice-free ranges (Stien et al. 2010). Thus, reliance on weather station data to detect thaw-refreeze events reduces our capacity to understand what impact they might have on wildlife.

Climate change has the potential to increase the frequency, distribution, and extent of events (Putkonen and Roe 2003; Rennert et al. 2009; Hansen et al. 2011). This could lead to longer periods each winter where forage is inaccessible, and a wider distribution of events could lead to greater impacts on local ungulate populations. Additionally, if thaw-refreeze events occur across areas larger than the movement ability of wildlife, they could have greater impacts to populations than observed today (Stien et al. 2010). The timing of events could also shift toward earlier in the winter, possibly causing longer periods of reduced forage access during winter. Knowledge of present-day thaw-refreeze conditions is therefore important for understanding the potential for thaw-refreeze events to impact ungulate populations and to serve as a baseline to judge future thaw-refreeze conditions against. Better detection of thaw-refreeze events will improve our understanding of conditions required for ice layer formation and how these will differ with global climate change (e.g., Rennert et al. 2009).

Recent advances in the detection of thaw-refreeze events with remotely sensed satellite data provide a potentially effective means of determining the size and timing of thaw-refreeze events across large areas and at spatial scales relevant to large mammals (Grenfell and Putkonen 2008; Bartsch et al. 2010a). While these approaches still serve as proxies to the actual presence of ice layers, they objectively measure changes in snow characteristics expected during a thaw-refreeze event. Thus, these measurements more closely approximate what would be measured with ground-based observations than proxies derived primarily from distant weather station data. The approach developed by Bartsch et al. (2010a) is particularly suited for documenting the size and timing of thaw-refreeze events because it is capable of detecting events daily and has successfully detected known events in Eurasia.

We used the method developed by Bartsch et al. (2010a) to document patterns in the frequency, timing, extent, and size of thaw-refreeze events across Alaska during the winters of 2001–2008. This provides an initial assessment of the potential for current thaw-refreeze conditions to affect Alaskan ungulate populations and serves as a baseline on which to compare future thaw-refreeze conditions. Although the satellite used to detect thaw-refreeze events ceased functioning in 2009, our analysis provides an important first assessment of thaw-refreeze conditions in Alaska and provides wildlife researchers a retrospective dataset with which to better understand wildlife spatial and demographic responses to ice layer formation. Because an alternative method is needed if we are to continue analyzing ice layer formation in the future, we compared detections based on the method of Bartsch et al. (2010a) for Alaska to events identified by the North American Regional Reanalysis climate dataset (NARR) during the same winters.

Materials and methods

Thaw-refreeze detection

To detect thaw-refreeze events, we relied on microwave backscatter measurements (13.4 GHz) obtained from the SeaWinds instrumentation on the QuikSCAT satellite (Jet Propulsion Laboratory, NASA, Pasadena, California). We followed the methods of Kidd et al. (2003) to process the backscatter data into a time series of regularly spaced points with a resolution of 12.5 km × 12.5 km.

We followed the methods outlined in Bartsch et al. (2010a) to detect thaw-refreeze events across the study area. For each grid point, we obtained the daily average of inner beam measurements within 12.5 km of a grid point. Because of Alaska's high latitude, each grid cell received 4–10 backscatter measurements per day (Kidd et al. 2003). When a thaw-refreeze event occurred, we expected higher levels of backscatter given the greater reflectance of the ice compared to the previous snow conditions. Thus, for each day during winter, we calculated the average backscatter value over the prior 3 days and over the following 3 days. If the average backscatter value 3 days after the day of interest was >1.5 dB larger than the average over 3 days prior, we classified that day as a thaw-refreeze event. While a large decrease in backscatter is expected during a period of thaw, Bartsch et al. (2010a) were unable to detect one for a known event (possibly due to the short duration thaw); thus, their algorithm is only calibrated to detect the

increase in backscatter as the surface refreezes. A 3-day average was found by Bartsch et al. (2010a) to be sufficient for detecting ice layer formation based on ground-based observations and the fact that backscatter values do not change much before or after an event. If a grid point had consecutive days with a value above the ice layer formation threshold, we only classified the first day of the series as a thaw-refreeze event. Changes in snow condition can also result from wind (Collins and Smith 1991), but it is unclear if wind-caused ice layer formation would be of significant magnitude to reach our detection threshold. Given this, our detections may also include some that were caused by wind rather than thawing or rain.

We restricted our analysis to all areas of Alaska north of 60° Latitude and along the Alaskan Peninsula to Unimak Island and north of Yakutat in southeast Alaska (Fig. 1). Additionally, we restricted our analysis to grid points occurring ≥12.5 km from the coastline to avoid contamination of the signal from ocean. We analyzed data for all available winters, 2001–2008; the satellite stopped collecting data in 2009 (Bartsch et al. 2010b). We defined winter as October through April. While the onset of the snow season is later than October in southern areas of the state (Liston and Hiemstra 2011), we wanted to ensure that we captured thaw-refreeze events in northern Alaska which occur earlier in winter.

We estimated the average annual number of events at each grid cell and for each month across all winters. We also calculated the sum of thaw-refreeze events at each grid cell for each winter. For each week of the study, we identified spatially continuous patches of thaw-refreeze detections with the SDMTools package in R (VanDerWal et al. 2012). We combined thaw-refreeze events by week because adjacent grid cells could be affected by the same event but have detections on slightly different days. Even if adjacent events occurred on separate days, occurrence within the same week would lead to a similar biological impact as if they occurred on the same day. We calculated the size (i.e., spatial extent) of each of these spatially continuous events and determined the median size of thaw-refreeze events that overlapped with each grid cell. We also determined the median and range of event sizes for each winter month across all winters.

Assessment of method

Although Bartsch et al. (2010a) vetted the detection algorithm with known thaw-refreeze events in Eurasia, we wanted to check that our detections in Alaska corresponded to climate conditions where ice layer formation was likely, given that we had no ground-based validation. We obtained daily maximum air temperature (T_{max}) measurements from SNOTEL weather stations (http://www.wcc.nrcs.usda.gov/snotel/Alaska/alaska.html; accessed 9 Jan 2012) across Alaska that were ≤10 km from a grid point with ≥1 thaw-refreeze event over the duration of the study. We assumed the majority of thaw-refreeze events occur when temperatures were initially above freezing; thus, we calculated the percent of weather stations that had $T_{max} \geq 0°$ C on the day of the corresponding thaw-refreeze event detection. We also determined the percent of weather stations that had $T_{max} \geq 0°$ C on any day within a ± 3 day window of the

Fig. 1 A map of the state of Alaska with major communities and geographic features depicted
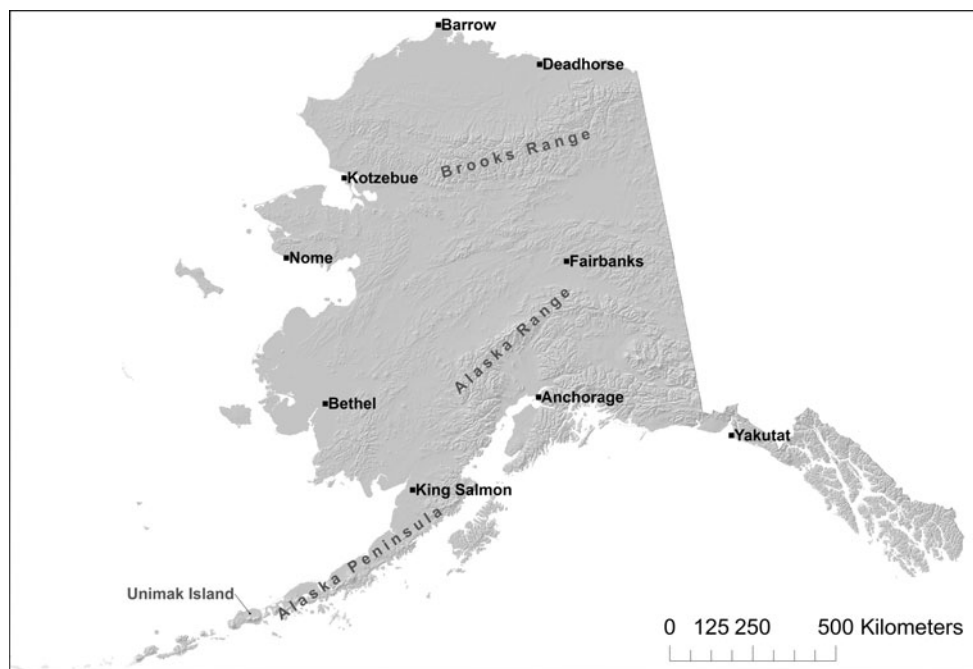
corresponding thaw-refreeze detection. We did not test for false detection rates of ice layer formation based on weather station data because thaw-refreeze events can also occur when $T_{max} < 0°$ C. At those same weather stations, we determined the amount of rain that fell 3 days prior and 3 days after our detections. If our detections corresponded with rain-on-snow events, then we expected rain to predominantly occur prior to the day of our thaw-refreeze detection. Finally, because a large snowfall event could cause a similar increase in backscatter as observed by a thaw-refreeze event, we wanted to ensure this was not a source of bias in this study. We therefore plotted the maximum snow depth at the weather stations 3 days before and 3 days after a thaw-refreeze event detection similar to Bartsch et al. (2010a). If changes in snow depth did not cause false detections of thaw-refreeze events, we expected a 1:1 relationship between snowfall measures before and after the event.

Comparison to reanalysis data

We compared thaw-refreeze events detected by QuikSCAT to detections of freezing rain and non-freezing rain from the NARR dataset (http://www.esrl.noaa.gov/psd/data/narr/; Mesinger et al. 2006). For more information on the NARR dataset, and how precipitation categories are derived, see Manikin et al. (2004). We identified large (i.e., ≥156,250 km^2, corresponding to 1,000 grid cells) thaw-refreeze events detected by the QuikSCAT or NARR data during 1-week periods across all years of the study. Our choice of 1,000 grid cells to define a large event was arbitrary, but based on our desire to compare events at a scale most likely to have an effect on wildlife. We then compared overlap of large QuikSCAT events to all NARR events, regardless of size, for the same 1-week period as the large QuikSCAT event. Similarly, we compared large NARR events to all QuikSCAT events for the same 1-week period as the large NARR event. This helped to show if the NARR dataset detected thaw-refreeze evens that were not indicated by the QuikSCAT dataset.

Results

The annual number of thaw-refreeze events at each grid point ranged from 0 to 16. Most areas of the state had ≥1 thaw-refreeze event during the winters studied (Fig. 2). Only high elevation areas (ca. >1,500 m) lacked any detection across the 7 winters (Fig. 2). We observed substantial spatial variation in the frequency of thaw-refreeze events across the state with thaw-refreeze events being most frequent in southwestern Alaska (Fig. 2). The areas in southwestern Alaska with the highest frequency of
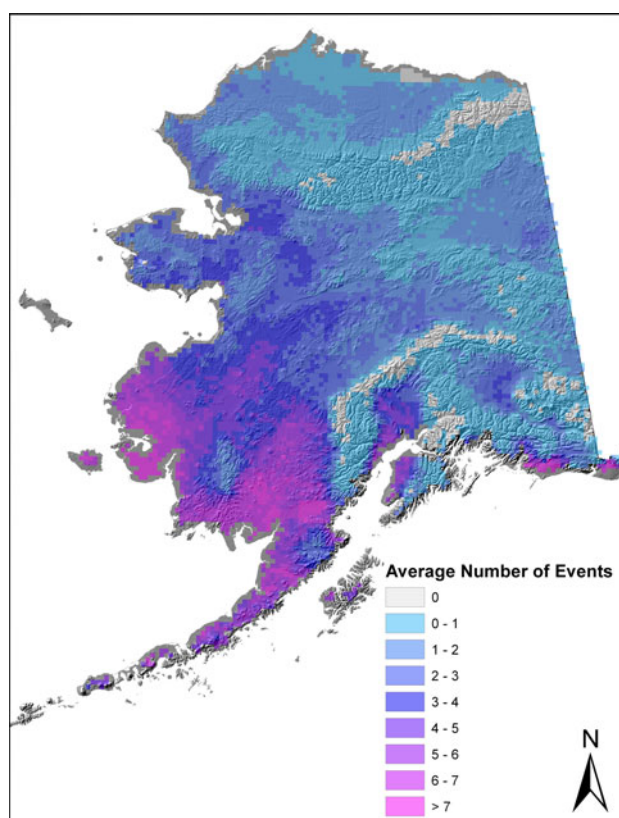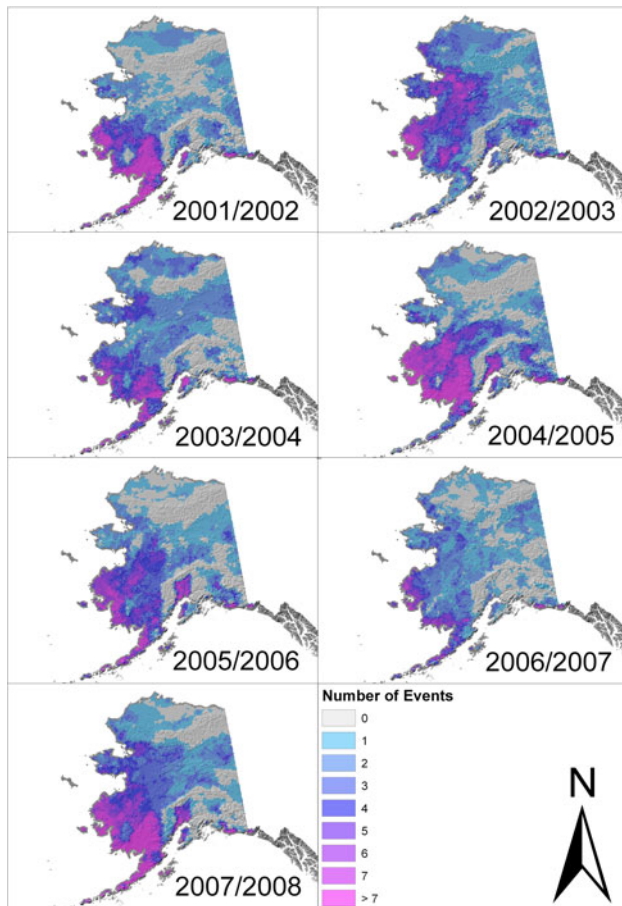

Fig. 2 Average number of thaw-refreeze events each winter (Oct–Apr) in Alaska from 2001 to 2008. *Dark gray shading* on periphery of map represents areas where data were censored due to their proximity to the coastline. Data were derived from changes in backscatter data detected from the SeaWinds instrumentation on the QuikSCAT satellite

detections tended to be in low elevation areas adjacent to the coastline (Fig. 2). Conversely, the least frequent occurrence of ice layer formation (aside from high elevation sites) occurred in northern Alaska, primarily north of the Brooks Mountain Range and in the central interior of the state (Fig. 2).

On average, 73 % (SE = 3) of the state had ≥1 thaw-refreeze event annually. There was, however, considerable inter-annual variation in the frequency and distribution of thaw-refreeze events (Fig. 3). In particular, the winter of 2002–2003 had the most widespread distribution of thaw-refreeze events across the state (Fig. 3). Northern Alaska had few events most years, and only in winters 2002–2003 and 2003–2004 did a large portion northern Alaska receive frequent (1–4 events) ice layer formation (Fig. 3). Conversely, southwestern Alaska had events each year, but during the winters of 2001–2002, 2004–2005, and 2007–2008, events were more frequent (Fig. 3).

The percentage of the state where ≥1 thaw-refreeze event occurred was similar between months across all winters except April when a significantly greater proportion of the
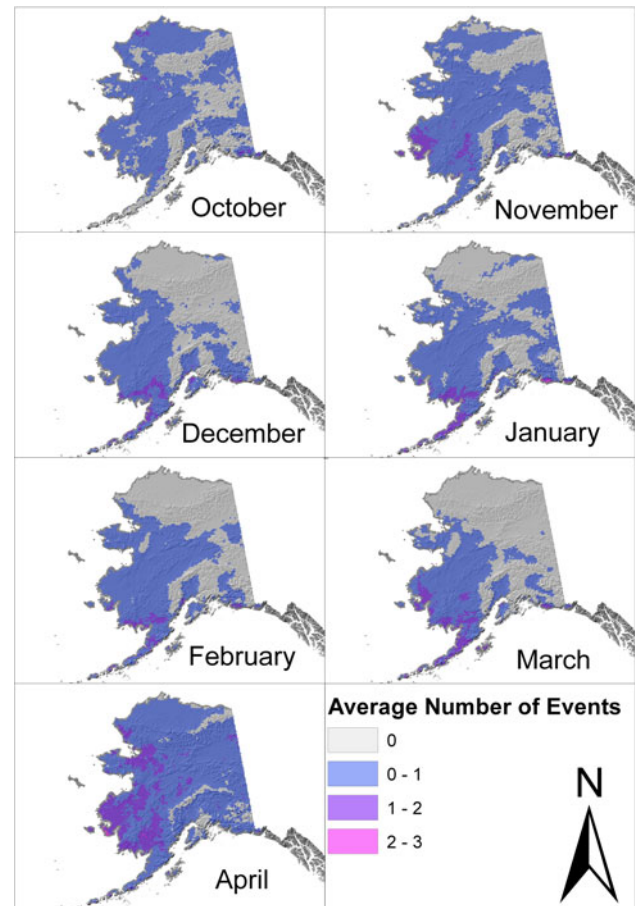
Fig. 3 Sum of thaw-refreeze events each winter (Oct–Apr) in Alaska from 2001 to 2008. *Dark gray shading* on periphery of map represents areas where data were censored due to their proximity to the coastline. Data were derived from changes in backscatter data detected from the SeaWinds instrumentation on the QuikSCAT satellite

Fig. 4 Average number of thaw-refreeze events each month of winter (Oct–Apr) across all study years (2001–2008). *Dark gray shading* on periphery of map represents areas where data were censored due to their proximity to the coastline. Data were derived from changes in backscatter data detected from the SeaWinds instrumentation on the QuikSCAT satellite

state had ice layer formation: October 23 % (SE = 2), November 24 % (7), December 20 % (4), January 20 % (7), February 21 % (5), March 18 % (4), and April 50 % (5). The period of winter when thaw-refreeze events were most frequent differed between regions of the state. In southwestern Alaska, ice layer formation was frequent during all winter months, but tended to be most frequent during November, March, and April (Fig. 4). In northern Alaska, events tended to be most frequent during early (October and November) and late winter (April) and mostly absent the rest of winter (Fig. 4).

The size of thaw-refreeze events ranged from 156 km^2 (i.e., the size of 1 grid cell and the minimum size capable of being detected) to 737,500 km^2, with the median size of an event being 469 km^2 (3 grid cells). The size of thaw-refreeze events were highly skewed toward smaller events with very few medium or large events (Table 1). October and November had the smallest maximum event sizes

compared to April which had the largest (Table 1). Areas in the interior of the state tended to have larger thaw-refreeze events than other regions of the state (Fig. 5).

Assessment of method

We obtained data on T_{max} from 29 SNOTEL weather stations across the state that corresponded to 109 thaw-refreeze events. Of those 109 thaw-refreeze events, 83 % (n = 90) corresponded to days with $T_{max} \geq 0°$ C, and 93 % (n = 101) had ≥1 day with $T_{max} \geq 0°$ C around a 3 day window of the event. On average, 1.0 cm (SE = 0.1) of rain fell during the 3 days before the day of our detection of a thaw-refreeze event, compared to 0.4 cm (0.1) during the 3 days after. When we plotted the maximum snow depth 3 days before and after our detected event, there was a clear 1:1 relationship indicating no evidence of large snowfall events causing false detections of thaw-refreeze events (Fig. 6).

Table 1 Median and range of the size (km^2) of spatially contiguous thaw-refreeze events each month of winter in Alaska from 2001 to 2008

| Month	Size of Event (km^2)		
	Median	Min	Max
October	469	156	96,875
November	469	156	105,156
December	469	156	221,875
January	469	156	362,813
February	469	156	360,000
March	469	156	242,343
April	313	156	737,500

Data were derived from changes in backscatter data detected from the SeaWinds instrumentation on the QuikSCAT satellite
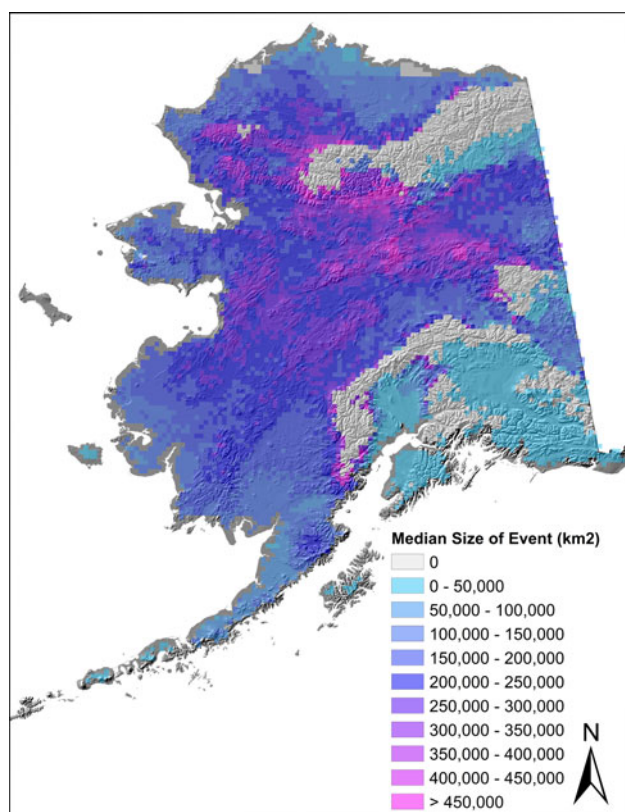
Fig. 5 Median size (km^2) of thaw-refreeze events impacting each grid cell across all years of the study (2001–2008). If a cell only had 1 thaw-refreeze event during the course of the study, we did not calculate a median value and instead classified its median size as 0. *Dark gray shading* on periphery of map represents areas where data were censored due to their proximity to the coastline. Data were derived from changes in backscatter data detected from the SeaWinds instrumentation on the QuikSCAT satellite

Comparison with NARR data

We detected 18 large thaw-refreeze events with the Quik-SCAT dataset. On average, the QuikSCAT detections had a
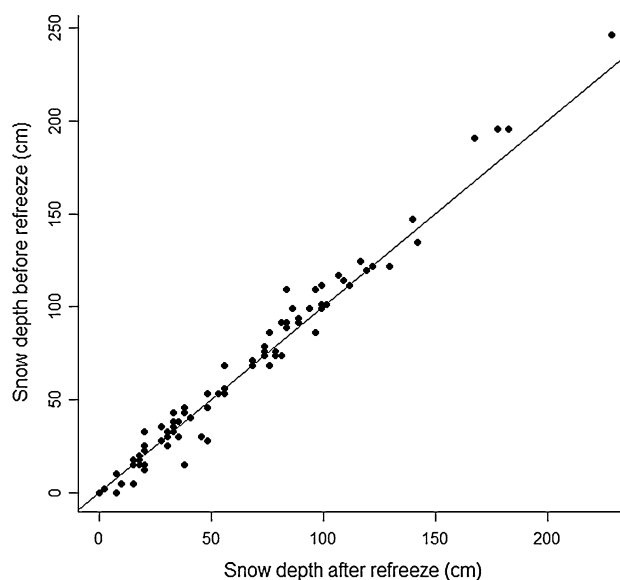
Fig. 6 Relationship between maximum snow depth within the 3 days before and the 3 days after a thaw-refreeze event detected by backscatter data from the SeaWinds instrumentation on the Quik-SCAT satellite. Snow depth data were obtained from SNOTEL weather stations in Alaska that corresponded to a grid point with a thaw-refreeze detection within 10 km. The *solid black line* represents a 1:1 relationship with a slope equal to 1 and intercept equal to 0

51 % (SE = 7) overlap with freezing rain and 2 % (1) overlap with non-freezing rain from NARR during the same 1-week period. The range of overlap between freezing rain and detections by QuikSCAT was quite large, with some events overlapping as much as 96 % and others as little as 2 %. The amount of overlap with QuikSCAT detections did not change, with a 52 % (7) overlap when compared with any area that had either freezing or non-freezing rain during the same 1-week period. We identified 24 large events detected by the NARR dataset after combining the freezing and non-freezing rain metrics. When compared to QuikSCAT detections during the same 1-week period, there was 34 % (5) correspondence, ranging from 0 to 88 % for individual weeks.

Discussion

This retrospective analysis provided novel information about frequency, timing, and extent of thaw-refreeze conditions in Alaska. In particular, estimates of the size of individual thaw-refreeze events have not been documented before and provide insight into the different climate mechanisms that likely lead to ice layer formation across the state. We found that mountainous areas (excluding the highest elevation sites in the Alaska) tended to have larger thaw-refreeze events than adjacent sites at lower elevations, even though mountainous areas had fewer events overall. While

this may seem counterintuitive, if conditions were suitable for the formation of an ice layer at high elevations, then adjacent areas at lower elevations would also typically experience suitable conditions. Therefore, when an event was detected in mountainous areas, it was likely to have inherently occurred within a larger thaw-refreeze event. Similarly, we observed a bias toward larger events detected in interior Alaska compared to the southwestern portion of the state. Thaw-refreeze events in southwestern Alaska can result from more transient weather systems that only take 1–2 days to form (Rennert et al. 2009). Elsewhere, storms capable of ice layer formation require nearly a week for conditions to materialize (Rennert et al. 2009) and large warm air masses typically must be present to melt snow in interior Alaska (Shulski and Wendler 2007). Thus, thaw-refreeze events would be expected to occur over larger areas in interior Alaska. Clearly, some areas of the state had median event sizes biased small due solely to the amount of area where icing could occur. For example, the Alaska Peninsula and the area just north of Anchorage are bounded by the ocean and a high elevation mountain range, respectively, that restrict how large events in those areas can be.

Our results generally match the distribution of thaw-refreeze events previously documented from reanalysis and modeled datasets (Putkonen and Roe 2003; Rennert et al. 2009; Liston and Hiemstra 2011). Similar to our results, Liston and Hiemstra (2011) and Rennert et al. (2009) both observed the most frequent ice layer formation in southwestern Alaska and infrequent icing in interior and northern portions of the state. The high frequency of events in southwestern Alaska was likely due to the area's maritime climate which results in more frequent thaw-refreeze events due to temperatures consistently near freezing and frequent storms capable of significant amounts of rain (Shulski and Wendler 2007; Rennert et al. 2009).

It should be noted that our methodology was incapable of determining the severity of a detected event. Given that thin layers of ice do not provide an impenetrable barrier to caribou given their sharp hooves (Hansen et al. 2010), it would be nice to use the magnitude of the change in backscatter as an index of the severity of thaw-refreeze events. Unfortunately, this is not possible because the magnitude of backscatter is partially dependent on the snow depth and structure of the snow and ice prior to a thaw-refreeze event. Thus, the magnitude of backscatter change due to the creation of a thin layer of ice may be indistinguishable from a thick layer created on top of multiple other ice layers. This was acknowledged by Bartsch et al. (2010a) as a limitation of their method but an area ripe for research if an alternative platform to replace QuikSCAT is found.

We were unable to compare remotely detected events to observed events given a lack of ground-based observations of ice layer formation. The method, however, produced results that were consistent with weather conditions measured at SNOTEL sites that are expected during ice formation (i.e., temperatures above freezing, rainfall). The high correspondence between days with ambient temperature above freezing and rainfall with the detection of ice layer formation by this method also highlights the technique's capacity to detect ice conditions remotely over a large area. It is therefore important that an alternative platform to QuikSCAT is found if continued remote monitoring of ice conditions in Alaska and elsewhere is desired.

The results of our comparison between QuikSCAT detections and those from the NARR dataset revealed the limited potential for continued monitoring of icing conditions in Alaska derived from the NARR data. Despite high correspondence for numerous thaw-refreeze events detected by both datasets, there were a number of events detected by QuikSCAT that had low correspondence with the NARR dataset even when multiple metrics (i.e., freezing and non-freezing rain) were combined. It is unclear why large events identified by the NARR dataset had even lower correspondence to QuikSCAT detections. Given that the QuikSCAT data should detect all forms of icing, one would expect higher correspondence with large NARR-detected events. Lower correspondence could be the result of NARR not being able to adequately distinguish between snow and rain (Rennert et al. 2009). Because QuikSCAT detections are generally insensitive to snowfall and do not indicate icing with increased snowfall (Bartsch et al. 2010a), this could also account for some of the discrepancy. There is also likely greater uncertainty in whether an icing event truly occurred with the NARR dataset given that it is partially derived from the limited network of weather stations in Alaska and has a lower spatial resolution. At present, the level of overlap between QuikSCAT and NARR detections is inadequate for supporting NARR as an alternative platform for continued monitoring.

An alternative to NARR is the ASCAT scatterometer on the MetOp-A satellite. This satellite will be in orbit until at least 2020 and might allow for continued remote monitoring of thaw-refreeze events (Bartsch et al. 2010b). The two datasets have 1 year of overlap, so more research is needed to determine how results compare to those obtained with the QuikSCAT given the lower sensitivity of the ASCAT data to detect ice layer formation (Bartsch et al. 2010b). The ASCAT dataset has the added benefits over the NARR dataset and other modeled data products of allowing for near real-time assessment of ice conditions (Bartsch et al. 2010b), rather than ≥ 6 month delay required for NARR products. Additionally, ASCAT measurements are higher resolution (625 km^2) than NARR data ($1,024 \text{ km}^2$) and are

available worldwide, therefore potentially providing a unified approach around the circumpolar north.

Our results are of too short duration to document long-term trends in ice layer formation across Alaska but still provide an informative snapshot of recent thaw-refreeze conditions and help wildlife managers better understand the potential for thaw-refreeze events to impact ungulate populations. When our data are combined with wildlife movement and demographic data, we can gain an even better understanding of the population-level impacts ice layer formation have on ungulate populations in Alaska (e.g., Stien et al. 2010; Hansen et al. 2011). Further, our results can help improve ground-based snow monitoring efforts that are currently underway by identifying areas to place monitoring plots that are likely to receive frequent thaw-refreeze events. In addition to providing information to wildlife managers, our results can be used to better understand the synoptic conditions associated with thaw-refreeze events. Lack of known thaw-refreeze events to associate with climatic data has been a factor-limiting projections of future thaw-refreeze conditions (Rennert et al. 2009), as is the lack of adequate statewide climate data.

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