Remote Sensing of Environment 189 (2017) 84–95

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Detection of rain-on-snow (ROS) events and ice layer formation using passive microwave radiometry: A context for Peary caribou habitat in the Canadian Arctic

A. Langlois [a,b,*], C.-A. Johnson [c], B. Montpetit [a], A. Royer [a,b], E.A. Blukacz-Richards [d], E. Neave [c], C. Dolant [a,b], A. Roy [a,b], G. Arhonditsis [e], D.-K. Kim [e], S. Kaluskar [e], L. Brucker [f]

[a] *Centre d'Applications et de Recherches en Télédétection, Université de Sherbrooke, Québec, Canada*
[b] *Centre d'Études Nordiques, Université Laval, Québec, Canada*
[c] *Landscape Science & Technology, Environment and Climate Change Canada, Ottawa, Ontario, Canada*
[d] *Climate Research Division, Environment and Climate Change Canada, Toronto, Ontario, Canada*
[e] *Department of Physical and Environmental Sciences, University of Toronto, Ontario, Canada*
[f] *NASA Goddard Space Flight Center, Cryospheric Laboratory, Code 615, Greenbelt, MD, USA*

ARTICLE INFO

Article history:
Received 12 April 2016
Received in revised form 8 September 2016
Accepted 11 November 2016
Available online xxxx

Keywords:
Rain-on-snow
Ice layers
Snow
Arctic
Passive microwave
Peary caribou

ABSTRACT

Over the past four decades, amplified warming in the Arctic has led to numerous consequences. Of particular relevance, negative anomalies of snow and sea ice cover, glacier retreat, and the extended melt of Greenland combined with increasing temperature at double the rate of the rest of the planet have been observed in the Arctic. Several studies have suggested that another response to the current arctic warming could be an increase in rain-on-snow (ROS) events followed by subsequent freezing and the creation of ice layers. We use recently developed detection algorithms of ROS and ice events using passive microwave retrieval approaches to examine the spatial and temporal trends in rain-on-snow and ice layer creation for 18 islands across the Canadian Arctic Archipelago (CAA) over the last two decades. Results show that both icing and ROS event occurrence tripled between the periods of 1979–1995 and 1996–2011, with very active years in winters 1993–1994, 1998–1999 and 2002–2003. The areas with the most combined occurrences are the Boothia Peninsula and Axel Heiberg, Cornwallis, Banks and Victoria Islands. We then compare the rain-on-snow and icing events to Peary caribou estimates to test whether the algorithms can detect weather events associated with population declines. There has been an important reduction in population numbers of Peary caribou, the northernmost caribou population in Canada, over the last three generations. The major hypothesis for the decline is that severe weather events lead to more difficult winter grazing conditions. The comparison with the Peary caribou population estimates suggest that caribou numbers decrease with increased occurrence of ROS and icing events, where 3–4 ROS events and 1–2 icing events in one winter season are sufficient to have a negative impact on Peary caribou.

1. Introduction

Significant climate variability and warming has been observed in the arctic over the past four decades (Serreze et al., 2009; Derksen and Brown, 2012; IPCC, 2014). Over that period, the Arctic has experienced 1.9 times the warming than the rest of the Earth (Winton, 2006; IPCC, 2014), leading to negative trends in snow cover (e.g. Derksen and Brown, 2012) and water equivalent (e.g. Liston and Hiemstra, 2011), sea ice coverage (e.g. Steele et al., 2008; Parkinson, 2014), glacier mass balance (e.g. Papasodoro et al., 2015) and permafrost duration (e.g. Romanovsky et al., 2010). The main reason for the 'Arctic amplification' in global warming is explained by the decreased albedo through the sea ice albedo feedback, but recent studies have shown that this amplification is also caused by the alteration of heat flux exchanges between the ocean and the atmosphere, changes in cloud cover and atmospheric water vapour, soot on snow and atmospheric black carbon (Serreze and Barry, 2011). Given the state of these causative factors, it is expected that the Arctic amplification will become stronger in the near future.

A significant consequence of such warming is the increased occurrence of rain-on-snow (ROS) events (Rennert et al., 2009; Liston and Hiemstra, 2011). Very little is known about ROS in northern regions, and even less about their cumulative impact on the surface energy balance. The water percolation from ROS leads to an accumulation of a significant amount of water at the bottom of the snowpack, which can refreeze (Riseborough et al., 2008; Weismüller et al., 2011. Given the

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* Corresponding author at: Centre d'Applications et de Recherches en Télédétection (CARTEL), Département de Géomatique Appliquée, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada.
E-mail address: a.langlois2@USherbrooke.ca (A. Langlois).

http://dx.doi.org/10.1016/j.rse.2016.11.006

current Arctic amplification, ROS events are projected to be more frequent and over a wider spatial extent (Semmens et al., 2013). For instance, Liston and Hiemstra (2011) modeling work suggests an increase in ROS days of + 0.03 days/decade and an increase in air temperature of + 0.17 °C/decade. However, they did not provide any specific trend for the Canadian Arctic Archipelago (CAA). Furthermore, Putkonen and Roe (2003) modeled a 40% increase in areas impacted by ROS by 2080 by doubling the atmospheric CO_2 levels. Although simulations suggest that ROS and icing events will increase in future, there have been very few studies that have quantified whether there is evidence showing that events have increased at present compared to historical data.

Severe snowpack conditions are hypothesized to decrease forage accessibility or completely prevent foraging by Peary caribou (*Rangifer tarandus pearyi*) (Miller et al., 1982; Aanes et al., 2000; Larter and Nagy, 2001) by creating "locked pastures", a situation where the forage is present but not accessible because it is locked under snow or ice (Vors and Boyce, 2009; Stien et al., 2010). Prolonged and severe weather events have been linked to poor body condition, malnutrition, high adult mortality and calf losses, and major population die-offs in Peary caribou (Parker et al., 1975; Miller and Gunn, 2003). Ouellet et al. (2016) showed that a snow density threshold value can be linked to decreased Peary caribou observations in the Canadian Arctic Archipelago (CAA). This is of particular relevance given that the main cause for reported declines in Peary caribou populations is hypothesized to be linked to snow conditions (COSEWIC, 2004; Johnson et al., 2016). In a similar context, Kohler and Aanes (2004) demonstrated that ROS events explain most of the population variability in growth rate for Svalbard reindeer.

The development of tools such as a satellite approach to monitor ROS and ice layers that would allow for the estimation of the frequency and spatial extent of severe weather events is needed to improve the ability to quantify the magnitude of the effects on Peary caribou populations and consider the potential consequences of future changes in climate on population persistence (Johnson et al., 2016). This was identified as a priority research need for informing Peary caribou management and recovery (Johnson et al., 2016). Given the sensitivity of passive microwave brightness temperatures to wet snow and ice (or snow density), recent studies have attempted to track ROS events and ice layers (e.g. Grenfell and Putkonen, 2008; Rees et al., 2010), but it was concluded that more robust detection algorithms using statistical approaches should be explored. This motivated recent work on the detection of ROS (Dolant et al., 2016) and ice layers (Montpetit et al., 2013) using passive microwave radiometry that now allows the use of satellite remote sensing to track event occurrence since 1979 (a detailed description of both approaches is provided in Section 2.3).

Specifically, we intend to 1) retrieve ROS and ice occurrence for 18 islands of the Canadian Arctic Archipelago for which caribou population counts are available; 2) examine changes in frequency of ROS and ice occurrence across the islands from 1979 to 2011; 3) compare event occurrence with Peary caribou population data; and 4) provide future insight on ROS and ice layer conditions. This worked is centred on two main hypotheses: 1) ROS and icing event occurrence increased since 1979 across the CAA and 2) large caribou numbers are found in years with less occurrence in ROS and icing events. One should not that the ice layers detected by our algorithm can either be from a ROS or a melt event as there are currently no ways to distinguish both types of ice layers.

2. Data and methods

2.1. Study sites

In Canada, caribou are divided into 12 designatable units allowing for a better representation of the species with regards to their habitat (COSEWIC, 2011). Peary caribou are the northernmost designatable unit in Canada. The study area is located in the Canadian Arctic Archipelago (CAA), where Peary caribou are distributed (Johnson et al., 2016). For this study, a total of 18 islands where caribou survey counts are available were analyzed (Fig. 1).

2.2. Passive microwave algorithm details

2.2.1. Rain-on-snow

The rain-on-snow detection approach used in this study was developed by Dolant et al. (2015), where the full details can be found. The algorithm uses passive microwave brightness temperatures (T_B) at 19 and 37 GHz in both horizontal (H) and vertical (V) polarizations, hereinafter referred to as 19H, 19V, 37H and 37V. The method uses the gradient ratio (GR) in both polarizations such that:

$$GR\left(pol_{(37,19)}\right) = \frac{[T_B\ (pol,37) - T_B\ (pol,19)]}{[T_B\ (pol,37) + T_B\ (pol,19)]}, \tag{1}$$

Their results have shown that under a ROS event $T_B37H > T_B19H$ and $T_B37V < T_B19V$, which was explained by warmer, wetter and higher emissivity of the snow-air interface at 37H (horizontal polarization being more affected than vertical polarization). They suggested a ratio (GRP) between GR-V and GR-H:

$$GRP = \frac{GR - V\ pol}{GR - H\ pol}, \tag{2}$$

where a threshold on GRP indicates the presence of ROS (a clear distinction in ROS for $GRP < -5$ was shown) with lower threshold applied in dense snow (see Results). Since the GRP is calculated using two ratios, noise in the temporal evolution is small, thus no correction is required between the different satellite sensors. Furthermore, it was showed in Dolant et al. (2016) that a melt event was not sufficient to trigger the reversal on which the ROS detection algorithm is based. Furthermore, the amount of water added to the snowpack from a ROS event is far greater, and over a shorter period, which is needed to create the inversion.

2.2.2. Ice detection index

Rain-on-snow events will lead to subsequent ice layer formation, which may be located at the surface, within the snow cover or at the soil/snow interface. Ice layers can be detected using passive microwaves for which an ice detection index (IDI) was developed by Montpetit (2015). The IDI is based on a sensitivity analysis of the Microwave Emission Model of Layered Snowpacks (MEMLS, Wiesmann and Mätzler, 1999) for the effects of the presence of ice lenses within a snowpack. Montpetit et al. (2013) showed that the microwave T_B is very sensitive to the presence of an ice layer and its position within the snowpack due to the very different dielectric contrast between the different layer interfaces (i.e. ice-soil, ice-snow and ice-air) (Fig. 2).

Grenfell and Putkonen (2008) showed that the polarization ratio (PR, Eq. (3)) at 19 and 37 GHz was very sensitive to the presence of ice lenses in the snowpack. This is because the horizontal polarization (H-pol) T_B is more sensitive to layering than the vertical polarization T_B (V-Pol); hence, an increased difference between the T_B in both polarizations results in an increased PR for a given frequency.

$$PR(f) = \frac{T_B(f, V{-}Pol) - T_B(f, H{-}Pol)}{T_B(f, V{-}Pol) + T_B(f, H{-}Pol)} \tag{3}$$

Montpetit (2015) simulated the T_B for 23 measured snowpacks to reproduce realistic snowpack conditions. Next, the simulations were re-run adding ice layers at different positions within the snowpack (at the snow-soil, snow-snow and snow-air interfaces) to examine the effects on the T_B to the presence of ice lenses. Spatial variability was