Changing Arctic snow cover: A review of recent developments and assessment of future needs for observations, modelling, and impacts

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Abstract Snow is a critically important and rapidly changing feature of the Arctic. However, snow-cover and snowpack conditions change through time pose challenges for measuring and prediction of snow. Plausible scenarios of how Arctic snow cover will respond to changing Arctic climate are important for impact assessments and adaptation strategies. Although much progress has been made in understanding and predicting snow-cover changes and their multiple consequences, many uncertainties remain. In this paper, we review advances in snow monitoring and modelling, and the impact of snow changes on ecosystems and society in Arctic regions. Interdisciplinary activities are required to resolve the current limitations on measuring and modelling snow characteristics through the cold season and at different spatial scales to assure human well-being, economic stability, and improve the ability to predict manage and adapt to natural hazards in the Arctic region.

Keywords Climate change · Ecosystem services · Human health · Societal costs · Indigenous · Snow

INTRODUCTION

Snow is a critically important element of the Arctic and is rapidly changing due to climate warming (Callaghan et al. 2011). Snow cover, stratigraphy, and physical characteristics are naturally changing throughout the seasons but are likely to be affected by climate warming with unexpected impacts for ecosystems and society. For example, Arctic snow-cover duration is decreasing rapidly (~3–5 days/decade), particularly due to earlier spring melt (20%/decade) and later onset of snow cover (Derkson et al. 2015). However, the Eurasian Arctic region has experienced larger declines in the duration of the snow-covered period (12.6 days), i.e. prolonged vegetation growing season, compared to the North American Arctic region (6.2 days) between 1982 and 2011 (Barichivich et al. 2013). In addition, climate warming increases the potential for unseasonal thaws, early snowmelt, and rain-on-snow events (ROS) (Liston and Hiemstra 2011). These changes impact snow properties and runoff (Semmens et al. 2013), which in turn affect Arctic ecosystems and societies (Meltote 2013; Cooper 2014; Hansen et al. 2014). However, changes in snow properties are not uniform across the Arctic and affected processes operate/respond at different temporal and spatial scales. Moreover, the various disciplines working on snow measure and evaluate its properties at different temporal and spatial scales. Therefore, there are potential mismatches on the availability and requirements of snow data between snow scientists, modellers, ecologists, and sociologists.

To address these issues, an interdisciplinary workshop was held to develop a road map to improve measurement, modelling, and prediction of changing snow characteristics and to collate developments in the field since the “Snow Water Ice and Permafrost in the Arctic” assessment of 2011 (Callaghan et al. 2011). This paper builds on the results presented at the workshop and presents an overview of recent developments in studies of changing Arctic snow cover and its consequences.
UNDERSTANDING THE IMPACTS OF CHANGING SNOW CONDITIONS ON SOCIETIES AND ECOSYSTEMS

Economy, human health, and well-being

The direct impact of snow temporal and spatial variability on economic development of the Arctic has to our knowledge not been comprehensively evaluated and quantified. Such a study would need to take into account among others: Snow clearing costs of transportation routes (Hanbali 1994; Riehm and Nordin 2012) (Fig. 1), which varies annually and is complicated by extreme snowfalls (Borzenkova and Shmakin 2012). The prevention of freezing damage to water pipes and drainage systems (Bjerke et al. 2015). Associated risks to winter-crops and forestry production due to changes in snow-season duration (Hanewinkel et al. 2011; Krenke et al. 2012), increased frequency of desiccation, exposure to snow moulds (Matsumoto and Hoshino 2009), and encasement in ground ice (Bjerke et al. 2014, 2015). Furthermore, ice-based construction procedures relying on firm-ice (e.g. winter roads) can be affected (Sosnovsky et al. 2014). Seasonal snow conditions are crucial for the way of life of indigenous people and local residents for reindeer herding practices and access to hunting grounds (Riseth et al. 2011), harvest yields of cultivated and wild berries (Bokhorst et al. 2011; Niemi and Ahlstedt 2012), and game animals (Stien et al. 2012; Hansen et al. 2013). Snow-season duration and snow-cover depth also affect the economy through changes in the magnitude and timing of spring runoff and floods. In Siberia, the frequency of dangerous river ice jams and spring river flooding events are increasing (Popova 2011; Semenov 2013), while decreased snow precipitation will affect the water supply for aquatic ecosystems, forestry, and agriculture (Jeelani et al. 2012; Clarke et al. 2015).

The increasingly wetter and milder Arctic climate can lead to increased frequency of avalanches threatening growing populations and infrastructure (Eckerstorfer and Christiansen 2012; Qiu 2014). When comparing snow avalanche risk assessments between regions, losses are often associated with an increase in land use, population density, and economic activities (Shnyparkov et al. 2012). Healthcare costs can rise due to increasing occurrence of bone fractures resulting from unusual snow and ice conditions (Bjerke et al. 2015). Snow can also become a health issue when supporting biological pathogens (Biedunkiewicz and Ejdys 2011; Shen and Yao 2013; Simon et al. 2013; Ejdys et al. 2014). The impacts of changing snow-melt dynamics on snow-pathogens for humans, livestock, and agriculture are unclear (Parham et al. 2015).

Ecosystems

Snow cover is an important determinant of community and ecosystem structure in polar regions (AMAP 2011) and winter temperatures are increasing in the Arctic more than those during summer (Walsh 2014). However, impacts of changing winter climate and snow regimes have received much less attention compared to the effects of climate change during summer. Different aspects of the snowpack play crucial roles in ecosystem processes and the life of Arctic organisms (e.g. Cooper 2014). Relevant snowpack characteristics include thermal insulation, snow depth, microstructure, temporal changes of these aspects, as well as snow-cover duration, all of which have been shown to be affected by climate change, with important consequences for Arctic ecosystems (AMAP 2011).
Terrestrial ecosystems

Snow acts as an insulating blanket against freezing Arctic temperatures for many organisms. Snow is also a major determinant of the mosaic of ecological communities through its uneven landscape distribution and the influence of snowmelt-driven spring flooding on wetland communities. Changes in snow quantity, quality, and seasonality can, therefore, result in changes in the distribution and composition of Arctic communities with resulting effects on their many inherent ecological processes, functions, and feedbacks. Extreme weather events (unseasonal warm temperatures and ROS see Fig. 2) can cause complete loss of snow cover, changes in the snow stratigraphy, snow hardness, and formation of ice layers with great impacts on plants (Bokhorst et al. 2011; Preece et al. 2012), herbivores (Bartsch et al. 2010; Ims et al. 2011; Stien et al. 2012; Bilodeau et al. 2013), soil organisms and CO₂ fluxes (Bokhorst et al. 2012, 2013), and agriculture (Bjerke et al. 2014, 2015). However, species responses to extreme weather events and snowmelt are dependent on the timing of events (Bokhorst et al. 2010, 2011), while the mechanisms behind species responses are unclear (Rumpf et al. 2014; Bowden et al. 2015) and processes are often inferred based on indirect correlative information (e.g. Ims et al. 2011). Furthermore, changing snow conditions can have wide-ranging indirect effects mediated by ecological interactions. For instance, shrub growth affects snow accumulation which in turn influences soil temperatures and ecosystem process rates (Myers-Smith and Hik 2013) highlighting the importance of interactions between vegetation structure and snow properties. Snow-induced changes in mortality and dynamics of reindeer and lemming (Hansen et al. 2013) affect predator populations (Schmidt et al. 2012) which in turn may shift to alternative prey (McKinnon et al. 2013; Nolet et al. 2013). These examples highlight the need to identify critical periods when species and ecosystems are vulnerable to winter climate change, especially with regard to periods of snowpack build-up, ROS and ground icing, and spring snowmelt.

Aside from the species-specific and ecosystem responses to changing snow conditions, there is a major research challenge in linking the predictions of snow changes to the scales that are relevant for the organisms or ecosystem that is being studied (Table 1). Specifically, there is a need for accurate predictions of the build-up and change in the snow stratigraphy across scales of a few square metres to landscapes covering several km².

Freshwater systems

Snow on lake and river ice affects the temperature and light transmission to the underlying ice and water. Changes in the snowpack can therefore affect the freezing regime, having consequences for the freshwater ecosystem with feedbacks to habitat structure, food availability, and survival of species (Prowse and Brown 2010; Prowse et al. 2011; Surdu et al. 2014). For shallow waters (< 3 m) and wetlands, the timing and duration of ice defines the open water, productive period and limits the active state of aquatic organisms by freezing to the bottom. Winter-dormancy allows species to survive such frozen conditions but the breaking of winter-dormancy depends on the photoperiod and temperature (Dupuis and Hann 2009) which is affected by the snow cover. Particularly the formation of ‘white ice’, formed when the snowpack exceeds the buoyance of the ice, affects the light transfer to the water column below (Dibike et al. 2012). Changing snow conditions affecting freshwater freezing and melting conditions may cause mismatches for organisms in terms of when winter-dormancy ends compared to peak food availability. Ecosystem phenology associated with ice and snow cover in freshwater systems is an area that needs more research.

Spring snowmelt is also an important conduit for transporting organic matter from the land into rivers and lakes. This pulse of organic matter into freshwater affects the clarity (light attenuation), nutrient and carbon cycling, primary productivity, and overall food web dynamics of aquatic ecosystems (Ask et al. 2009; Haukioja et al. 2011). Furthermore, dissolved and suspended concentrations of metals are highest in rivers and lakes during the spring freshet (Holemann et al. 2005) indicating that the snowpack acts as a reservoir for contaminants that are released as a pulse (Douglas et al. 2012). The timing of mercury (Hg) runoff, for example, is greatly affected by the spatial variability in hillslope flow paths and the magnitude of snowmelt inputs (Haynes and Mitchell 2012) indicating that predictions of mercury runoff in water streams need to be developed at small scales and that up-scaling will be challenging.

Sea ice and snow

Variations in snow-covered sea ice affect the Earth’s climate by affecting ocean–atmosphere interactions. Snow cover on top of sea ice has a high albedo that dominates the surface solar energy exchange, and a changing thermal conductivity that regulates ice/atmosphere heat transfer that greatly modifies the sea ice thermodynamic processes. The snow cover also modifies surface roughness with implications for the ice/air drag coefficient and sensible and latent heat fluxes. Snow depth and snow properties (e.g. thermal conductivity and density) on sea ice are thus of crucial importance, and must be accurately retrieved on a large scale.

Snow across sea ice influences algal communities with thin snow cover promoting productivity in the ocean.
This suggests that reduced snow precipitation or quicker melt out may promote higher primary production underneath sea ice with potential positive impacts higher up the food chain. Conversely, snow-cover removal from the sea ice surface can inhibit spring growth of Arctic ice algae through physiological and behavioural effects (Lund-Hansen et al. 2014).

Teleconnections and snow cover in Arctic amplification

Research has been dedicated to investigate the linkages between the changing Arctic snow cover and tropospheric processes (Cohen et al. 2014) and the impacts of Arctic amplification to temperature variability at low and high
Declining terrestrial spring snow cover in the Arctic is contributing to Arctic amplification (Serreze and Barry 2011; Matsumura et al. 2014). Changing snow on freshwater systems affects local climate conditions (Rouse et al. 2008; Brown and Duguay 2010). Observations of Arctic sea ice reduction in autumn are shown to be causing cold extremes (e.g. additional snowfall) in mid-altitude and northern continents/sub-Arctic areas (Cohen et al. 2013; Tang et al. 2013). Arctic amplification depends on heat-transport from lower latitudes but local factors on surface warming is still a matter of debate because it is difficult to isolate local forcings from simultaneously occurring external forcings and feedbacks (Screen and Simmonds 2012). Furthermore, high-latitude responses in the multiple types of forcing between models were broad, making it difficult to define the particular causes of Arctic temperature amplification (Crook et al. 2011). Improved process understanding, additional Arctic observations, and further modelling efforts in collaboration with observation data are required to elucidate the teleconnections with the Arctic (Cohen et al. 2014).

### Observations of Changing Snow Conditions

Quantifying snow-cover extent, thickness, and specific snow characteristics in the Arctic is challenging mainly due to the inclement weather conditions, polar night, and redistribution of snow by wind. In addition, the limited Arctic snow-observation stations challenge the up-scaling process to larger regions. However, there is a great need for accurate snow data at different spatial and temporal resolutions to address the challenges of changing snow conditions. We present an overview of recent advances in methods for quantifying and monitoring snow variables, and a summary of widely used ground-based snow observational methods is presented in Table 2. In addition, we indicate data/knowledge gaps where progress is required in terms of spatial and temporal resolution of snow variables.

#### Overview of Recent Advances in Methods and Findings in Arctic Snow Monitoring

##### Ground-based Snow-depth Monitoring

Several well-known methods for measuring snow depth exist (Table 2). Recent developments in snow-depth measurements include remote sensing methods that enable an objective monitoring of spatial distributions of snow depth. These methods include polarimetric phase differences (Leinss et al. 2014), ground-based laser scans (Deems et al. 2013), and electromagnetic wave technology (e.g. Koch et al. 2014; McCreight et al. 2014).

##### Spaceborne Snow-cover Monitoring

Snow-cover has high spatial and temporal variability and satellites provide observations at the hemispherical scale. Both passive and active remote sensing methods are used with sensors operating in the visible and microwave domains. Visible sensors observe snow-surface properties (with solar illumination, in cloud-free conditions), and are used for mapping snow-cover extent (e.g. Hall et al. 2002, 2006). Microwave sensors are sensitive to snow properties,
and operate independently from solar illumination with a weak sensitivity to the atmosphere. The main limitation of using microwave radiometers is the coarse resolution (i.e. tens of kilometres), whereas radars lack the appropriate frequencies. Existing radar sensors, which can provide information on snow-cover with fine resolution, are able to work only in the presence of wet snow.

**Snow water equivalent (SWE)**

Satellite algorithms have been developed to monitor SWE at the hemispherical scale since the 1980s (e.g. Kelly 2009). In the early 2000s, surface-based Frequency-Modulated Continuous-Wave (FMCW) radar measurements were used to estimate SWE to within 5% (Marshall et al. 2005). Furthermore, fixed radars installed underneath or above the snow cover have been used for deriving snow depth, density, bulk liquid water content, and for deriving SWE (Heilig et al. 2009; Schmid et al. 2014) and allow monitoring of the temporal evolution of the overlying snow. In addition, recent advances in SWE quantification have shown the benefit of combining passive microwave radiometer and ground-based synoptic weather station observations to provide robust information on hemispherical scale (Takala et al. 2011). Mobile measurements allow for monitoring spatial differences in SWE or liquid water content but only provide snapshots in time. Hence, there are major challenges to compare satellite-derived information with ground-based in situ data. In addition, further development on sensors for satellites and aircrafts is necessary including new technologies for data interpretation together with up-scaling methods for temporal continuous

| Target parameter(s) | Method(s) | Reference(s) |
|---------------------|-----------|--------------|
| Snow depth          | Simple (avalanche) or semi-automated probes (e.g. MagnaProbe) | e.g. Sturm et al. (2006) |
| Specific surface area (SSA) (i.e. the surface area of ice per unit mass) | Near-infrared photography and infrared reflectance methods | e.g. Matzl and Schneebeli (2006), Gallet et al. (2009) Arnaud et al. (2011), and Montpetit et al. (2012) |
| Penetration resistance and deviation of snow density, grain parameters, and SSA. | SnowMicroPen (Highly resolved measurements 250 measurements/mm) | Schneebeli and Johnson (1998) and Proksch et al. (2015) |
| Snowfall/new snow   | Snow board (i.e. new-snow observations are being conducted by placing a board (snow board) on the snow surface and revisiting it every 24 h to read the additional snow height | e.g. Fierz et al. (2009) |
| Liquid water content in snow | ‘Denoth capacity probe’ or ‘Finnish Snow Fork’ (e.g. used to deriving dielectric/conduction properties of the snow) | Denoth (1994) and Sihvola and Tiuri (1986) |
| Snow depth          | Acoustic snow-depth sensors, ultrasonic methods, lasers, manual readings at stakes, and automatic readings utilizing time-lapse cameras | |
| Snow density and snow bulk liquid water content | Upward-looking ground penetrating radar (upGPR) Combination of upGPR with buried GPS sensors (allows for direct conversion for density, SWE and liquid water content) | e.g. Mitterer et al. (2011), Avanzi et al. (2014), Heilig et al. (2015), Schmid et al. (2014, 2015), and Stacheder (2005) |
| Snow water equivalent (SWE) | Snow pillows or snow scales weigh the mass of the snowpack above the sensors and convert this to SWE | |
| Snow albedo         | Net radiometer | e.g. Michel et al. (2008) |
| Snow-cover fraction | Derived from hourly-daily digital photos acquired from automatic time-lapse digital cameras installed in terrestrial areas, e.g. near glaciers and ice fields | e.g. Bernard et al. (2013) |
| Avalanche hazard and activity | Seismic sensor Infrasound arrays | Reiweger et al. (2015) e.g. Van Herwijnen and Schweizer (2011), Havens et al. (2014) |
point measurements. Further investigations are required to convert satellite observations into accurate SWE retrievals and remote sensing of SWE is currently restricted to flat areas thereby excluding mountains.

**Snow microstructure (grain size, snow-specific surface area) and liquid water content (LWC)**

Snow microstructure is complex, but can be characterized by snow-specific surface area (SSA). SSA controls the snow albedo and is a more objective measure of snow’s complexity than grain size. SSA typically decreases with time with a rate depending on temperature and the shape of the initial snow grain (Hachikubo et al. 2014). SSA measurements have been successfully conducted in the field using near IR methods (Gallet et al. 2009; Arnaud et al. 2011; Montpetit et al. 2012). The SnowMicroPen, which uses highly resolved penetration resistance (250 measurements/mm), can be used to quantify snow density, grain size, and SSA (Proksch et al. 2015). Time-lapse X-ray micro-tomography methods provide a 3D reconstruction of the snow structure (Pinzer et al. 2012) and enable visualization of the recrystallization distribution on depth hoar crystals through time (Fig. 3). Recent development of SSA measurements led to implementation of SSA parametrizations in snow evolution modelling (Carmagnola et al. 2014). Advances in thermal and short IR remote sensing allow for determining surface snow types and surface temperature (Hori et al. 2014).

In snow hydrology, the onset and the total amount of runoff are essential for flood and reservoir management, and impact on terrestrial ecosystems. The change in dielectric permittivity of snow during melt highly influences remote sensing data from microwave to infrared, allowing us to monitor the extent of surficial melt (e.g. Steffen et al. 2004). Modelling of LWC and snowpack runoff is still very challenging and water transport schemes like a multi-layer bucket model or Richards equation underestimate observed maximum LWC in the course of a season (Heilig et al. 2015). LWC retention in the snow is important to improve modelled runoff performance (Essery et al. 2013; Heilig et al. 2015).

**Snow-surface albedo and light-absorbing impurities**

Impurities in the snowpack can affect the snowmelt rates through decreased surface albedo. Such light-absorbing snow impurities include organic carbon, mineral dust, and micro-organisms (Langford et al. 2010), and can be quantified in manually collected snow samples and by reflectance measurements. Algal communities have been associated with glacial melt and reducing snow-surface albedo (e.g. Tedesco et al. 2013; Lutz et al. 2014). Similar responses to deposits of black carbon (BC) on the snow surface are shown to cause accelerating snowmelt rates in Alaska, Norway, and Greenland (Doherty et al. 2013). Particle size of snow impurities can be used to identify their source and have been linked to peripheral snow-free areas or locations with early snowmelt and fires (Aoki et al. 2014; Dumont et al. 2014). A decreasing snow-cover extent may play a major role in the surface mass balance of Arctic ice bodies.

**Snow on sea, lake, and river ice**

Snow cover on sea ice influences the Earth’s climate and biology in the ocean. The only current snow-depth-on-sea-ice algorithm that uses satellite data is based on passive microwave observations (Cavalieri et al. 2012; Brucker and Markus 2013). Since 2009, NASA has supported the airborne Operation IceBridge mission, which operates multiple radars to retrieve snow depth on sea ice (Kurtz et al. 2013; Panzer et al. 2013). Recent work on IceBridge data and from drifting ice station indicates a substantial thinning of the snowpack in the western Arctic and in the Beaufort and Chukchi seas (Webster et al. 2014). This thinning is negatively correlated with the delayed onset of sea-ice freeze-up during autumn. Thin snowpack and sea ice increase the heat flux between the ocean and atmosphere with potential feedbacks for the Earths’ climate but are not thoroughly investigated. Although snow on lake ice has major implications for lake ecology, ice thickness, and the local climate (Brown and Duguay 2010), studies on these systems appear to be under-represented in the literature (Cheng et al. 2014; Duguay et al. 2015). Furthermore, there is currently little focus on quantifying changes in lake-ice snow cover. The most recent progress in remote sensing is summarized in Duguay et al. (2015).

**Avalanche detection**

Recent advances in avalanche detection include the use of seismic sensors and infrasound arrays (Table 2). Furthermore, Synthetic Aperture Radar (SAR), e.g. Radarsat-2, TerraSAR-X, and Cosmo-Skymed, have been shown useful in detecting avalanche activity. Especially, the SAR data properties as the spatial resolution (2–3 m), high temporal resolution (2–5 days), and their application during cloudy conditions make them ideal for this purpose (Caduff et al. 2015).

**Indigenous knowledge: Sámi snow observational methods and terminology**

Snow plays a central role in the cultures of indigenous Arctic people, notably for the reindeer herders of Eurasia.
They have developed a holistic snow terminology integrating the effects on the ecology, grazing opportunities, and management of the herd (Fig. 4) which differs from scientific standard terms (Eira et al. 2013). However, the combination of traditional ecological knowledge (TEK) of reindeer herders with natural science measurements and snow classification may guide future strategies for a sustainable future of reindeer herding in a changing climate (Riseth et al. 2011; Eira et al. 2013). TEK in general has been formally recognized by the Arctic Council as important to understanding the Arctic (Arctic-Council 1996) and the Ottawa traditional knowledge principles can be found here: http://www.arcticpeoples.org/images/2015/ottradknowlprinc.pdf.

**Extreme events**

Snow properties are increasingly impacted by extreme and anomalous events such as ROS (Rennert et al. 2009), icing (Bartsch et al. 2010; Hansen et al. 2013), and warming periods leading to unseasonal melt periods and isolated freeze–thaw cycles (Bokhorst et al. 2011; Semenchuk et al. 2013; Semmens et al. 2013; Wilson et al. 2013). These events are caused by different factors such as heavy rainfall (Rennert et al. 2009; Hansen et al. 2014) and movement of warm air masses through katabatic winds, e.g. Chinook (Fuller et al. 2009) and foehn winds (Pedersen et al. 2015). These extreme and anomalous events may be caused by different weather phenomena, but they all have the following in common: (1) they have an abrupt and sporadic nature, (2) they are unusual for the season in the geographical locations where they occur, (3) they cause changes in snowpack properties, and (4) they have immediate impacts on humans and ecosystems. Their temporal extent varies from a few hours to many days, and their spatial extent is controlled by the spatial scale of the driving weather phenomenon (e.g. synoptic).

The sparse distribution of meteorological stations and remoteness of areas across the Arctic region limit ground-based observation of extreme events, their effect on the
snowpack, and modelling efforts (e.g. Bulygina et al. 2010; Johansson et al. 2011; Hansen et al. 2014; Pedersen et al. 2015). However, Pedersen et al. (2015) quantified the spatially distributed snow property (SWE, snow depth, snow thermal resistance, and timing of snow-free date) changes associated with episodic snowmelt events through in situ snow observations, meteorological data, and snow modelling. Extreme events are also detectable through remote sensing using differencing 3-day averages of backscatter (Bartsch et al. 2010; Semmens et al. 2013; Wilson et al. 2013). Additionally, extreme events are detectable through modelling, e.g. by Liston and Hiemstra (2011) who showed an increased trend in ROS events over maritime regions of the Arctic since 1979. Observed (Hansen et al. 2014) and predicted (Bjerke et al. 2014) abrupt changes in snow properties and snow conditions associated with extreme events add complexity to the impacts of current warming in the Arctic (Walsh 2014). Quantification and prediction of these extreme events requires increased research focus.

MODELLING CHANGING SNOW CONDITIONS

Types and applications of snow models

Terrestrial snow-cover models are used to simulate the snow temporal evolution in multiple hydrological, meteorological, climatological, glaciological, and ecological applications. Depending on the snow-model sophistication (i.e. the complexity of parameterisations used to describe snow properties and the processes taking place within the snow and at the interfaces with the atmosphere and the soil), some models can also simulate snow stratigraphy (i.e. the vertical evolution of snow properties in the various layers forming the snowpack).
Simple (empirical) snow models have been widely used in impacts studies (e.g. Van Den Broeke et al. 2010; Saloranta 2012). These models have fewer data requirements (e.g. just temperature and precipitation) than physically based models, but require calibration. For example, Kumar et al. (2013) compared the impact of using a temperature index and a physically based snow model on streamflow simulations. They found that un-calibrated temperature-index models predict streamflow poorly. Therefore, simple empirical models need to be carefully calibrated in both time and space, whereas physically based snow and hydrological models provide better accuracy. In fact, even calibrated models may be unreliable outside their regions and periods of calibration (Bougamont et al. 2007). Moreover, models based on energy balance principles are essential when snow models are required to provide boundary conditions for atmospheric models in weather and climate prediction applications and physically based snow models therefore remain essential.

Three main categories of physically based snow models exist:
- Zero-layer (combined with soil) or single-layer snow models
- Intermediate complexity snow models accounting for some physical processes within the snowpack, typically with 2–5 model layers
- Detailed snowpack models

Snow models can be driven with measured or simulated meteorological data. Usually, the higher the snow model sophistication, the simpler the framework within which they are used. There are three main configurations in which snow models are run:
- Stand-alone models
- Coupled models with atmosphere, soil, and vegetation components
- Modules within Earth System Models (ESMs)

ESMs typically use zero- and single-layer snow models because they have few parameterisations leading to fast computations, but they have limitations. Successful attempts to couple intermediate complex snow models with atmospheric and soil models have been made (e.g. within numerical weather prediction (NWP) systems and ESMs such as HTESSEL (Dutra et al. 2010), RACMO (Kuipers Munneke et al. 2011), and CLM4 (Oleson et al. 2010). Detailed snowpack models are typically used in simple stand-alone configurations. Simulation results from these models provide the temporal evolution of snow properties with depth (Vionnet et al. 2012). It is possible to drive these sophisticated models either with weather station measurements or with atmospheric reanalyses (e.g. Brun et al. 2013). A similar approach is to use coarse-grid reanalyses or climate model fields downscaled to a fine scale grid in order to account for the strong horizontal variability caused, for example, by complex orography (Fiddes and Gruber 2014). The choice of input data depends on the application, and NWP data are used for snow prediction on large scales.

Recent developments within the NWP community have resulted in increased cooperation and interests among various disciplines (e.g. hydrology and ecology). The increased spatial resolution of NWP models increases their potential utility for user groups who depend on modelling regional- and local-scale processes. This is also supported by the development of off-line land-surface models which can be run stand-alone (e.g. Crocus snow physics model).

**Progress and key achievements in Arctic snow modelling**

Modelling snow cover accurately is important, particularly because of the crucial role it plays in energy transfer between the land and the atmosphere. Recent model inter-comparison projects have improved our understanding of how snow models perform and have prompted developments in individual models and parameterisations of snow processes. In this section, we highlight some achievements in snow modelling and look forward to upcoming inter-comparison experiments.

**Snow simulation achievements and limitations**

Phase 5 of the Coupled Model Inter-comparison Project (CMIP5: http://cmip-pcmdi.llnl.gov/cmip5/) provided an opportunity for assessing the simulation of snow in the current generation of climate models. Progress and limitations of CMIP5 models representing SWE, snow cover, and snowfall compared to observations and reanalyses have been identified (Brutel-Vuilmet et al. 2013; Kapnick and Delworth 2013; Terzago et al. 2014). A key result was that the decreasing trend in Northern Hemisphere spring snow-cover extent over the 1979–2005 period (Derksen et al. 2015) was underestimated by CMIP5 models (Brutel-Vuilmet et al. 2013). Snow-albedo feedbacks were modelled well but the spread in modelled snow-albedo feedback has not narrowed since CMIP3, probably due to the widely varying treatment of the masking of snow-covered surfaces by vegetation in the models (Qu and Hall 2014). Most CMIP5 models overestimate the contrast in albedo between snow-covered and snow-free land, but fewer models have large cold temperature or high snow-cover biases in CMIP5 than in CMIP3 (Fletcher et al. 2015). Because snow cover forms an interface between the atmosphere and the land surface, differences in simulations of the insulating effect of snow leads to disagreements in
modelled soil temperatures (Koven et al. 2013). Representation of snow properties may also affect the accuracy of air temperature calculated by climate models. Analysis of data from 48 CMIP5 models indicates that the calculated monthly-mean surface temperature for Northern Eurasia has the largest inter-model spread during the snowmelt period indicating that accurate representation of the snowmelt is needed to improve the overall performance of models and narrow the range of associated uncertainties in climate projections.

Large sets of simulations will soon be available from climate models and ESMs in CMIP6 (http://www.wcrpclimatemodels.org/wgcm-cmip/wgcm-cmip6) and from standalone land-surface models in GSWP3 (http://hydro.iis.u-tokyo.ac.jp/GSWP3/intro.html). The CliC ESM-SnowMIP project (http://www.climate-cryosphere.org/activities/targeted/esm-snowmip) has been initiated to assess the strengths and weaknesses of snow simulations in these experiments and to provide guidelines for the improvement of models.

**Snow model forcing data**

Improved simulations can result from improvements in the forcing data used to run snow models as well as from improvements in snow parameterizations. Snow-cover builds up due to solid precipitation and its properties are dramatically sensitive to liquid and mixed-phase precipitation. Though recent progress has been made (Marks et al. 2013; Mizukami et al. 2013), accurately partitioning precipitation into rain and snow remains a challenge. Multiple-year snow model forcing datasets with multiple evaluation data have recently been collated for several well-instrumented research sites in mid-latitude alpine locations (Brun et al. 2013), but there is a comparative lack of suitable data for the Arctic. For large-scale studies, global gridded forcing datasets available from reanalyses have been used successfully (e.g. Brun et al. 2013). ESM-SnowMIP includes comparisons between snow simulations at reference sites with in situ forcing data and large-scale simulations using reanalyses or coupled atmospheric models.

**Snow parameterizations**

Physical parameterizations of snow metamorphism are important because snow microstructure determines snow properties, including those controlling energy exchanges at the snow/soil and snow/air interfaces. Specific surface area (SSA) has attracted attention as a microstructural property that determines the physical, optical, and chemical properties of snow (Domine et al. 2008). It affects microwave remote sensing (e.g. Brucker et al. 2011; Roy et al. 2013; Picard et al. 2014) and it is now parameterized in some models (Carmagnola et al. 2014). SSA can now be measured in the field using observer-independent near-infrared sensors (Gallet et al. 2009; Arnaud et al. 2011; Montpetit et al. 2012). Process studies have identified weaknesses of snow models in simulating water percolation and ice-layer formation (e.g. Brucker et al. 2011; Weyer et al. 2014). However, physically based snow models may help in identifying ice layers in the snow (Vikhamar-Schuler et al. 2013; Bjerke et al. 2014). Snow water mass still varies widely (50 %) among models and datasets relying solely on satellite-derived information show approximately 40 % less total snow for the peak accumulation seasons, compared with retrievals combining satellite- and ground-based data (Mudryk et al. 2015).

**Modelling soil–snow–vegetation interactions**

Forests affect snow dynamics, and models have been developed to incorporate this (Essery 2013). However, there are still issues with simulated snow-albedo feedbacks and the transition from snow-covered to snow-free canopies when temperatures rise above freezing (Thackeray et al. 2014). Shrubs trap windblown snow thereby affecting snow distribution (Myers-Smith et al. 2011) and this effect may be accentuated by the expansion of shrubs in some Arctic regions (e.g. Pearson et al. 2013; Urban et al. 2014). The impact of snow-trapping by shrubs on soil temperatures and gas fluxes have been modelled (e.g. Lawrence and Swenson 2011; Menard et al. 2014), but these processes have not yet been included in dynamic vegetation models. Progress on modelling freeze–thaw processes has been made by increasing the numbers of layers and depth of soil models, but modelling of permafrost conditions is degraded by biases in snow-depth simulations (Slater and Lawrence 2013).

**Modelling contaminants in snow**

Models now parameterize the impacts of contaminants with different spectral properties on the snow-surface albedo (Qian et al. 2015), but it remains challenging to couple these parameterisations with the atmospheric transport and deposition of contaminants such as BC. Current aerosol models can simulate mean BC concentrations in snow reasonably well, but modelled distributions are poorly correlated with measurements; models generally underestimate BC concentrations in snow in northern Russia and Norway but overestimate BC elsewhere in the Arctic (Jiao et al. 2014). Algae and bacteria living in snow and ice are also considered contaminants, and the spectral properties of snow are affected by the species composition (Lutz et al. 2014).
| Gaps                                                                 | Recommendations                                                                 | Implementation strategy                                                                 |
|----------------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| A. Observations                                                                                                      |                                                                                |
| There are large spatial scaling issues that need to be resolved, from snow grain characteristics to the circumpolar Arctic region to the full Earth system. | (a) Increase the number of stations for manual and automatic recording            | INTERACT can provide additional measuring stations but needs information on methods and on making the data accessible |
|                                                                      | (b) Develop remote sensing tools that can detect snow-depth differences across small scale landscape topography | GEO Cold Regions Initiative, which coordinates existing in situ and remote sensing observations of snow can facilitate, through the Global Earth System of Systems (GEOSS), data sharing and method standardization |
| The temporal evolution of the Arctic snowpack throughout an entire cold season is poorly investigated, specifically, the evolution of ice crusts and soil properties (temperature and soil frost depth) | (a) Initiate year-round ground observations are needed at intervals of hours or day | INTERACT can provide year-round measuring stations but the number and location depends on whether or not the methods are manual or remotely controlled |
|                                                                      | (b) Improve methods to derive reliable information at a proper spatial and temporal resolution from remote sensing techniques from both optical and active (SAR) and passive (radiometer) microwave spaceborne sensors |                                                                                |
|                                                                      | (c) Resolve technological difficulties in microwave and SAR (Synthetic Aperture Radar) remote sensing techniques |                                                                                |
| The Arctic is vast but is sparsely populated and observing power is limited                                            | (a) Extend the number of human-based snow measurements to obtain a more detailed grid of snow parameters across the Arctic Region |                                                                                |
| Ground-based observations of impacts of extreme events on the snowpack are limited                                     | (b) Include citizen observations to extend the distribution of observations       |                                                                                |
| The effects of physical properties of the snowpack on sea ice have been measured but by out-dated methods and understanding of the snow-on-ice feedback is poor | (a) Improvement in the application and development of new and coordinated methodologies are required | INTERACT can provide Arctic-wide ground-validation of RS techniques over multiple topographies |
|                                                                      | (b) Develop remote sensing techniques to quantify snowpack on sea ice              | GEO Cold Regions Initiative can facilitate availability of remote sensing data through its Participant Organizations for inter-comparison and validation efforts |
| The accuracy of remote sensing of SWE is limited by topography and forest cover                                        | Develop and improve remote sensing techniques for quantification of SWE           |                                                                                |
| For modelling of snow precipitation, reliable measurements of total precipitation and solid precipitation fractions are crucial for properly driving snow models | (a) Increase the number of precipitation measuring stations to meet the needs of the modelling community | INTERACT can provide additional measuring stations but needs information on methods and on making the data accessible |
|                                                                      | (b) Equip automated weather stations with instrumentation to estimate precipitation phase—such as optical disdrometers (SPICE) | SPICE is evaluating current instrumentation (http://www.wmo.int/pages/prog/www/IMOP/intercomparisons/SPICE/SPICE.html) |
| There is great variety in methods used between different long-term measuring stations                                 | Share and compare techniques between monitoring teams to increase the support for long-term complete validation sites with sensors probing the atmosphere, snow, and soil | INTERACT is already compiling a list of methods used at research stations and will help implement new observations and methods |

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### Table 3 continued

| Gaps | Recommendations | Implementation strategy |
|------|----------------|------------------------|
| **B. Modelling** | | |
| The spread of model output needs to be reduced in relation to snow-albedo feedback, most models overestimate the contrast in albedo between snow-covered and snow-free land. Differences in simulations of the insulating effect of snow leads to disagreements in modelled soil temperatures | More accurate representation of the snowmelt is needed to improve the overall performance of the models and narrow the range of associated uncertainties in climate projections | WCRP CliC ESM-SnowMIP experiments under CMIP6 will be investigating sources of model spread in snow simulations and their influence on climate |
| Aerosol models can simulate mean Black Carbon (BC) concentrations in snow reasonably well, but modelled distributions are poorly correlated with measurements | Inclusion of particle transport from snow-free areas in GCM/regional snow models are needed and the simulation of surface albedo change due to dust deposition and microorganism growth | | |
| Potential feedbacks between snow and sea ice are of critical importance, but not experimentally investigated | The snow science community urgently needs to quantify these feedbacks and include them in models if relevant | INTERACT can provide facilities around the Arctic for observations and experiments on feedbacks and for validation of models |
| Potential feedbacks between snow and freshwater ice are likely to be important because of the spatial coverage of tundra lakes and ponds. However, this has not been investigated in the field or in the laboratory while snow manipulation experiments on lake ice are absent | The snow science community needs to quantify these feedbacks and include them in models if relevant. Also, processes should be identified and quantified using experimental manipulations of snow analogues to those deployed on land | | |
| Progress on modelling soil freeze and thaw processes has been made by increasing the numbers of layers and depth of soil models, but modelling of permafrost conditions is degraded by biases in snow-depth simulations | Snow-depth simulations need to be improved and coupling of snow and soil models is needed | WCRP CliC ESM-SnowMIP experiments under CMIP6 will be investigating sources of model spread in snow simulations and their influence on climate |
| Process studies have identified weaknesses of snow models in simulating water percolation and ice-layer formation | Physically based snow models may help in identifying ice layers in the snow | | |
| Impacts of changing snow conditions on teleconnections within the Arctic and with other regions of Earth require more research attention | Increase the modelling effort on how changing snow conditions impact on Arctic teleconnections | | |
| **C. Impacts studies** | | |
| Effects of earlier or late snowmelt impacts on human well-being, such as physical injuries and degree of exposure of people to pathogens from various sources transported in snow and melt water | (a) Initiate base-line studies to assess the current threats and where in the Arctic region large changes may be expected (b) Promote research and monitoring coordination across the Arctic for inter-comparability of methodologies | INTERACT can help monitor spread of pathogens and vectors throughout the Arctic and is developing a coordinated system to do this |
| Recent studies on avalanche risk assessments indicate that these may be inaccurate | Risk assessments need to be re-considered in light of changing snow conditions | GEO Cold Regions Initiative can provide the societal benefits assessment and awareness crossing the GEO societal benefits areas via the GEO new work programme for 2016–2025 |
| The direct impact of the temporal and spatial variability of snow on the economic development of the Arctic, especially expressed in monetary value, is hard to evaluate. Determining these impacts is difficult as snow conditions are changing at the same time as economic growth | Initiate an economic assessment on the cost of management and the costs associated with lack of appropriate management | |
Table 3 continued

| Gaps                                                                 | Recommendations                                                                 | Implementation strategy                                                                 |
|----------------------------------------------------------------------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| The detailed timing of changes in snow cover during the cold season is uncertain. These include periods of snowpack build-up, midwinter rain events, spring snowmelt, and timing as well as increased soil moisture deficits later in the growing season. | From an ecosystem perspective there is a pressing need to identify when the largest changes in snow conditions will occur, e.g., start, middle, or late winter. | INTERACT can facilitate to increase the number of appropriate observations. National funding agencies need to be made aware of the requirement of seasonal monitoring and experiments. |
| Impacts of changing snow conditions are species-specific both for plants and animals. However, species vary in the magnitude of their contribution to key ecosystem processes. | We need to identify which species are most responsive to snow changes and why, and how they will impact ecosystem processes and surface feedback to climate. | INTERACT can facilitate to start appropriate observations and host relevant experiments. Protocols for monitoring snow conditions and impacts in the same places and at the same scales need to be further developed in the frame of CPMP. |
| The influences of snow and ground ice on vegetation have been investigated in some models but these processes have not yet been included in large scale dynamic vegetation models. | Facilitate greater representation of snow-cover in all its complexity including ice layers needs to be developed in vegetation/ecosystem models. | GEO Cold Regions Initiative can initiate a dedicated aim that may bridge the ecosystem mapping and snow-cover interaction. |

D. Linking and communicating

Information exchange between science and society is generally poor with inadequate communication. Sometimes there is low relevance of the science for community needs. On the other hand, there are sometimes excessive expectations of governments on researchers and lack of understanding of science by policy makers.

(a) Facilitate information exchange between society and the science community
(b) Inform communities of ongoing and projected changes relevant at the local scale
(c) Design observation strategies for traditional science to work together with citizens

INTERACT offers a system for communication between field researchers and local communities and has outreach activities. GEO Cold Regions aims to establish a proactive framework for the development of information and related services over Cold Region: the Global Cold Regions Community Portal.

The Arctic science community is well integrated and coordinated by various organizations but their agendas for research and monitoring, for example of snow cover, are often implemented independently, even though there are numerous interactions within the Arctic and Earth systems.

(a) Improve the integration between activities—monitoring, modelling, and evaluating impacts—and between Earth system domains—terrestrial, marine, atmospheric, and freshwater.
(b) We need to establish archives (metadata portals) and/or a hub of in situ snow products that are relevant for the snow science disciplines and communicate awareness of the existence of these archives to other end-users (Policy makers and society).

GEO Cold Regions can help by bridging the different activities, domains, and communities (remote sensing and in situ) in the field of cold regions’ earth observations. GEO Cold Regions is promoting free access to the earth observations data over the Cold Regions, including the Global Observation System of Systems (GEOSS) products and GEOSS-DataCORE.

CURRENT GAPS AND RECOMMENDATIONS
FOR FUTURE RESEARCH
AND IMPLEMENTATION PLANS

Without duplicating recommendations suggested by other programmes (AMAP 2011), our intention was to review and up-date the perceived gaps in current research activities on Arctic snow changes as a contribution to the ICARP III process towards a roadmap for future research. To focus these developments, we identified key gaps, formulate recommendations, and seek commitments by stakeholders and major Arctic and Global organisations to implement these recommendations (Table 3). In addition, many detailed requirements exist which are listed in Supplementary material S1. A key limitation to progress on determining changes in Arctic snow cover and their consequences is a lack of integration among domains (land, sea, lakes, and atmosphere) and between approaches. Monitoring of snow identifies change but needs to be linked to manipulations of climate, environment, and ecosystems to understand the impacts. This understanding needs to be linked to modelling at relevant scales that project into the future (or past). With this predictive capability, knowledge-based management may be developed and implemented (Johansson et al. 2012). One possibility to improve integration of activities across domains and approaches is to develop coordinated activities, hosted by a regional or global organization.

Therefore, in order to develop ESM that can be used in the documentation and/or prediction of snow-cover...
changes and their impacts, there is a need for improved communication and cooperation between discipline-specific communities (ecologist/biologist, social scientists, and snow scientist) and between the approaches (monitoring/observers in the field/remote sensing and modellers) (Fig. 5). For instance, ecologists need to identify at which spatial and temporal resolutions snow-cover changes are relevant and make this known to the modelling community. This will assure that the outputs of modelled snow variables match the given resolution of ecosystem processes and dynamics. Conversely, modellers require validation data of snow variables on relevant scales (Table 1). Therefore, the timing, frequency, and spatial resolution of snow surveys and snow monitoring should match the snow-model resolution in order to generate useful snow outputs for the ecosystem scientists/snow-impact community (Fig. 5). For this interaction to be successful, detailed cross-disciplinary coordination of field campaigns, monitoring, research projects, and model development is required.

Since society and its infrastructure have to cope with the challenges of changing snow conditions (Fig. 1), it requires easy access to snow predictions. Therefore, an open dialogue needs to be established or expanded to facilitate information exchange between society and the science community. Implementation of these recommendations should ideally be considered by organizations, such as the Arctic Council, that span science and human dimensions. Integration between the different snow disciplines and communication to end-users could be achieved through the ICARP process and associated organizations IASC, INTERACT, CliC, GEO (GEOSS), and WMO (GCW). With this paper, we have attempted to provide a basis, and stimulus, for the implementation of key priorities (Table 3) to address the limitations in our understanding of Arctic snow conditions and how they may change in the near future.

Acknowledgments The writing of this paper was initiated by an IASC ICARP III Activity grant to TVC enabling a workshop hosted by the European Environment Agency. The authors acknowledge funding from their respective national and international funding bodies, which has enabled the contribution of all authors to this work.

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REFERENCES

Alou-Font, E., C.J. Mundy, S. Roy, M. Gosselin, and S. Agusti. 2013. Snow cover affects ice algal pigment composition in the coastal Arctic Ocean during spring. Marine Ecology Progress Series 474: 89–104.

AMAP. 2011. Snow, water, Ice and Permafrost in the Arctic (SWIPA): Climate change and the cryosphere, xii–538. Oslo: Arctic Monitoring and Assessment Programme (AMAP).
Deems, J.S., T.H. Painter, and D.C. Finnegan. 2013. Lidar measurement of snow depth: A review. Journal of Glaciology 59: 467–479.

Denoth, A. 1994. An electronic devise for long-term snow wetness recording. Annals of Glaciology 19: 104–106.

Derkson, C., R. Brown, L. Mudryk, and K. Luojus. 2015. Arctic: Terrestrial Snow. State of the Climate in 2014. J. Blunden and D. S. Arndt. Bulletin of the American Meteorological Society 96: 133–135.

Dibike, Y., T. Prowse, B. Bonsal, L. de Rham, and T. Saloranta. 2012. Simulation of North American lake-ice cover characteristics under contemporary and future climate conditions. International Journal of Climatology 32: 695–709.

Doherty, S.I., T.C. Grenfell, S. Forstrom, D.L. Hegg, R.E. Brandt, and S.G. Warren. 2013. Observed vertical redistribution of black carbon and other insoluble light-absorbing particles in melting snow. Journal of Geophysical Research—Atmospheres 118: 5553–5569.

Domine, F., M. Albert, T. Huthwelker, et al. 2008. Snow physics as relevant to snow photochemistry. Atmospheric Chemistry and Physics 8: 171–208.

Douglas, T.A., L.L. Loseto, R.W. Macdonald, et al. 2012. The fate of mercury in Arctic terrestrial and aquatic ecosystems: A review. Environmental Chemistry 9: 321–355.

Duguay, C.R., M. Bernier, Y. Gauthier, and A. Kouraev. 2015. Development of snow depth: A review. Journal of Hydroeteorology 11: 899–916.

Eckerstorfer, M., and H.H. Christiansen. 2012. Meteorology, topography and snowpack conditions causing two extreme mid-winter slush and wet slab avalanche periods in high Arctic maritime Svalbard. Permafrost and Periglacial Processes 23: 15–25.

Eira, I.M.G., C. Jaedicke, O.H. Magga, N.G. Maynard, D. Vikhamar-Dutra, E., G. Balsamo, P. Viterbo, P.M.A. Miranda, A. Beljaars, C. Dupuis, A.P., and B.J. Hann. 2009. Contribution of light-absorbing impurities in snow to Greenland’s darkening since 2009. Nature Geoscience 7: 509–512.

Dupuis, A.P., and B.J. Hann. 2009. Climate change, diapause termination and zooplankton population dynamics: An experimental and modelling approach. Freshwater Biology 54: 221–235.

Dutra, E., G. Balsamo, P. Viterbo, P.M.A. Miranda, A. Beljaars, C. Schär, and K. Elder. 2010. An improved snow scheme for the ECMWF land surface model: Description and offline validation. Journal of Hydrometeorology 11: 869–916.

Francis, J.A., and S.I. Vavrus. 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. Geophysical Research Letters 39: L06801.

Fuller, M.C., T. Geldsetzer, and J.J. Yackel. 2009. Surface-based polarimetric C-band microwave scatterometer measurements of snow during a Chinook event. IEEE Transactions on Geoscience and Remote Sensing 47: 1766–1776.

Galley, J.C., F. Domine, C.S. Zender, and G. Piccard. 2009. Measurement of the specific surface area of snow using infrared reflectance in an integrating sphere at 1310 and 1550 nm. Cryosphere 3: 167–182.

Hachikubo, A., S. Yamaguchi, H. Arakawa, et al. 2014. Effects of temperature and grain type on time variation of snow specific surface area. Bulletin of Glaciological Research 32(1): 33–45.

Hall, D.K., G.A. Riggs, and V.V. Salomonson. 2006. MODIS snow and sea ice products. In Earth science satellite remote sensing, vol. I: Science and Instruments, ed. J.J. Qu, W. Gao, M. Kafatos, R.E. Murphy, and V.V. Salomonson, 154–181. New York: Springer.

Hall, D.K., G.A. Riggs, V.V. Salomonson, N.E. DiGirolamo, and K.J. Bay. 2002. MODIS snow-cover products. Remote Sensing of Environment 83: 181–194.

Hanbali, R.M. 1994. Economic impact of winter road maintenance on road users. Transportation Research Record 1442: 151–161.

Hanewinkel, M., S. Hummel, and A. Albrecht. 2011. Assessing natural hazards in forestry for risk management: A review. European Journal of Forest Research 130: 329–351.

Hansen, B.B., V. Grott, R. Aanes, et al. 2013. Climate events synchronize the dynamics of a resident vertebrate community in the high Arctic. Science 339: 313–315.

Hansen, B.B., K. Isaksen, E. Benestad, et al. 2014. Warmer and wetter winters: Characteristics and implications of an extreme weather event in the High Arctic. Environmental Research Letters 9: 114021.

Havens, S., H.-P. Marshall, J.B. Johnson, and B. Nicholson. 2014. Calculating the velocity of a fast-moving snow avalanche using an infrasound array. Geophysical Research Letters 41: 6191–6198.

Haynes, K.M., and C.P.J. Mitchell. 2012. Inter-annual and spatial variability in hillslope runoff and mercury flux during spring snowmelt. Journal of Environmental Monitoring 14: 2083–2091.

Heilig, A., M. Schneebeili, and O. Eisen. 2009. Upward-looking ground-penetrating radar for monitoring snowpack stratigraphy. Cold Regions Science and Technology 59: 152–162.

Holemann, J.A., M. Schirmacher, and A. Prange. 2005. Seasonal variability of trace metals in the Lena River and the southeastern Laptev Sea: Impact of the spring freshet. Global and Planetary Change 48: 112–125.

Ims, R.A., N.G. Yoccoz, and S.T. Killengreen. 2011. Determinants of lemming outbreaks. Proceedings of the National Academy of Sciences of the United States of America 108: 1970–1974.

Jiao, C., M.G. Flanner, Y. Balkanski, et al. 2014. An AeroCom comparison of 1701 snow models using observations from an alpine site. Journal of Environmental Monitoring 16: 899–916.

Jeelani, G., J.J. Feddema, C.J. van der Veen, and L. Stearns. 2012. Variability of trace metals in the Lena River and the southeastern Laptev Sea: Impact of the spring freshet. Global and Planetary Change 48: 112–125.
Johansson, C., V.A. Pohjola, C. Jonasson, and T.V. Callaghan. 2011. Multi-decadal changes in snow characteristics in sub-Arctic Sweden. Ambio 40: 566–574.

Johansson, M., C. Jonasson, M. Soneson, and T.R. Christensen. 2012. The man, the myth, the legend: Professor Terry V. Callaghan and his 3M concept. Ambio 41: 175–177.

Kapnick, S.B., and T.L. Delworth. 2013. Controls of global snow under a changed climate. Journal of Climate 26: 5537–5562.

Kelly, R. 2009. The AMSR-E snow depth algorithm: Description and initial results. Journal of The Remote Sensing Society of Japan 29: 307–317.

Koch, F., M. Prasch, L. Schmid, J. Schweizer, and W. Mauser. 2014. Measuring snow liquid water content with low-cost GPS receivers. Sensors 14: 20975–20999.

Koven, C.D., W.J. Riley, and A. Stern. 2013. Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 earth system models. Journal of Climate 26: 1877–1900.

Krenek, A.N., E.A. Cherenkova, and M.M. Chernavskaya. 2012. Stability of snow cover on the territory of Russia in relation to climate change. Ice and Snow 1: 29–37.

Kuipers Munneke, P., M.R. van den Broeke, J.T.M. Lenaerts, M.G. Flanner, A.S. Gardner, and W.J. van de Berg. 2011. A new albedo parameterization for use in climate models over the Antarctic ice sheet. Journal of Geophysical Research: Atmospheres. doi:10.1029/2010JD015113.

Kumar, M., D. Marks, J. Dozier, M. Reba, and A. Winstral. 2013. Evaluation of distributed hydrologic impacts of temperature-index and energy-based snow models. Advances in Water Resources 56: 77–89.

Kurtz, N., J. Richter-Menge, S. Farrell, M. Stuhring, J. Padon, J. Sonntag, and J. Yungel. 2013. IceBridge airborne survey data support Arctic sea ice predictions. Eos, Transactions American Geophysical Union 94: 41–41.

Langford, H., A. Hodson, S. Banwart, and C. Boggild. 2010. The microstructure and biogeochemistry of Arctic cryoconite granules. Annals of Glaciology 51: 87–94.

Lawrence, D.M., and S.C. Swenson. 2011. Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming. Environmental Research Letters 6: 045504.

Leins, S., G. Farrella, and I. Hajnsek. 2014. Snow height determination by polarimetric phase differences in X-Band SAR data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 7: 3794–3810.

Liston, G.E., and C.A. Hiemstra. 2011. The changing cryosphere: Pan-Arctic snow trends (1979–2009). Journal of Climate 24: 5691–5712.

Lund-Hansen, L., I. Hawes, B. Sorrell, and M. Nielsen. 2014. Removal of snow cover inhibits spring growth of Arctic ice algae through physiological and behavioral effects. Polar Biology 37: 471–481.

Lutz, S., A.M. Anesio, S.E.J. Villar, and L.G. Benning. 2014. Variations of algal communities cause darkening of a Greenland glacier. FEMS Microbiology Ecology 89: 402–414.

Marks, D., A. Winstral, M. Reba, J. Pomeroy, and M. Kumar. 2013. An evaluation of methods for determining during-storm precipitation phase and the rain/snow transition elevation at the surface in a mountain basin. Advances in Water Resources 55: 98–110.

Marshall, H-P., G. Koh, and R.R. Forster. 2005. Estimating alpine snowpack properties using FMCW radar. Annals of Glaciology 40: 157–162.

Matsumoto, N., and T. Hoshino. 2009. Fungi in snow environments: psychrophilic molds—A group of pathogens affecting plants under snow. Enfield: Science Publishers Inc.

Matsumura, S., X. Zhang, and K. Yamazaki. 2014. Summer Arctic atmospheric circulation response to spring Eurasian snow cover and its possible linkage to accelerated sea ice decrease. Journal of Climate 27: 6551–6558.

Matzl, M., and M. Schneeberger. 2006. Measuring specific surface area of snow by near-infrared photography. Journal of Glaciology 52: 558–564.

McCreight, J.L., E.E. Small, and K.M. Larson. 2014. Snow depth, density, and SWE estimates derived from GPS reflection data: Validation in the western U.S. Water Resources Research 50: 6892–6909.

McKinnon, L., D. Berteaux, G. Gauthier, and J. Béty. 2013. Predator-mediated interactions between preferred, alternative and incidental prey in the arctic tundra. Oikos 122: 1042–1048.

Meltotto, H. 2013. Arctic biodiversity assessment. Status and trends in Arctic biodiversity. Akureyri: Conservation of Arctic Flora and Fauna.

Menard, C.B., R. Essery, and J. Pomeroy. 2014. Modelled sensitivity of the snow regime to topography, shrub fraction and shrub height. Hydrology and Earth System Sciences 18: 2375–2392.

Michel, D., R. Philipona, C. Ruckstuhl, R. Vogt, and L. Vuilleumier. 2008. Performance and uncertainty of CNR1 net radiometers during a one-year field comparison. Journal of Atmospheric and Oceanic Technology 25: 442–451.

Mitterer, C., A. Heilig, J. Schweizer, and O. Eisen. 2011. Upward-looking ground-penetrating radar for measuring wet-snow properties. Cold Regions Science and Technology 69: 129–138.

Mizukami, N., V. Koren, M. Smith, D. Kinn-mit, Z. Zhang, B. Cosgrove, and Z. Cui. 2013. The impact of precipitation type discrimination on hydrologic simulation: Rain–snow partitioning derived from HMT-West radar-detected brightband height versus surface temperature data. Journal of Hydroeteorology 14: 1139–1158.

Montpetit, B., A. Royer, A. Langlois, et al. 2012. New shortwave infrared albedo measurements for snow specific surface area retrieval. Journal of Glaciology 58: 941–952.

Mudryk, L.R., C. Derksen, P.J. Kushner, and R. Brown. 2015. Characterization of northern hemisphere snow water equivalent datasets, 1981–2010. Journal of Climate 28: 8037–8051.

Myers-Smith, I.H., and D.S. Hik. 2013. Shrub canopies influence soil temperatures but not nutrient dynamics: An experimental test of tundra snow–shrub interactions. Ecology and Evolution 3: 3683–3700.

Myers-Smith, I.H., B.C. Forbes, M. Wilmking, et al. 2011. Shrub expansion in tundra ecosystems: Dynamics, impacts and research priorities. Environmental Research Letters 6: 045509.

Niemi, J., and J. Ahsledt. 2012. Finnish agriculture and rural industries, 112a. Helsinki: Agrifood Research.

Nolet, B.A., S. Bauer, N. Feige, Y.I. Kokorev, I.Y. Popov, and B.S. Ebbinge. 2013. Faltering lemming cycles reduce productivity and population size of a migratory Arctic goose species. Journal of Animal Ecology 82: 804–813.

Olesen, K.W., D.M. Lawrence, B. Gordon, et al. 2010. Technical description of version 4.0 of the community land model (CLM). NCAR Technical Notes.

Panzer, B., D. Gomez-Garcia, C. Leuschen, et al. 2013. An ultrawideband, microwave radar for measuring snow thickness on sea ice and mapping near-surface internal layers in polar firm. Journal of Glaciology 59: 244–254.

Parham, P.E., J. Waldock, G.K. Christophides, et al. 2015. Climate, environmental and socio-economic change: weighing up the balance in vector-borne disease transmission. Philosophical Transactions of the Royal Society of London B: Biological Sciences 370: 20130557.

Pearson, R.G., S.J. Phillips, M.M. Loranty, P.S.A. Beck, T. Damoulas, S.J. Knight, and S.J. Goetz. 2013. Shifts in Arctic vegetation and associated feedbacks under climate change. Nature Climate Change 3: 673–677.
campaign. IEEE Transactions on Geoscience and Remote Sensing 44: 3009–3020.

Surdu, C.M., C.R. Duguy, L.C. Brown, and D. Fernández Prieto. 2014. Response of ice cover on shallow lakes of the North Slope of Alaska to contemporary climate conditions (1950–2011): Radar remote-sensing and numerical modeling data analysis. The Cryosphere 8: 167–180.

Tokala, M., K. Luojus, J. Pulliainen, et al. 2011. Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. Remote Sensing of Environment 115: 3517–3529.

Tang, Q., X. Zhang, X. Yang, and J.A. Francis. 2013. Cold winter extremes in northern continents linked to Arctic sea ice loss. Environmental Research Letters 8: 014036.

Tedesco, M., X. Fettweis, T. Mote, J. Wahr, P. Alexander, J.E. Box, and B. Wouters. 2013. Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data. Cryosphere 7: 615–630.

Terzaghi, S., J. von Hardenberg, E. Palazzi, and A. Provenzale. 2014. Snowpack changes in the Hindu Kush-Karakoram-Himalaya from CMIP5 global climate models. Journal of Hydrometeorology 15: 2293–2313.

Thackeray, C.W., C.G. Fletcher, and C. Derksen. 2014. The influence of canopy snow parameterizations on snow albedo feedback in boreal forest regions. Journal of Geophysical Research: Atmospheres 119: 9810–9821.

Urban, M., M. Forkel, J. Eberle, C. Huettich, C. Schmullius, and M. Herold. 2014. Pan-Arctic climate and land cover trends derived from multi-vari-ante -scale analyses (1981–2012). Remote Sensing 6: 2296–2316.

Van Den Broeke, M., C. Bus, J. Ettema, and P. Smeets. 2010. Temperature thresholds for degree-day modelling of Greenland ice sheet melt rates. Geophysical Research Letters 37: L18501.

Van Herwijnen, A., and J. Schweizer. 2011. Seismic sensor array for monitoring an avalanche start zone: Design, deployment and preliminary results. Journal of Glaciology 57: 267–276.

Vikhamar-Schuler, D., I. Hanssen-Bauer, T.V. Schuler, S.D. Mathiesen, and M. Lehning. 2013. Use of a multilayer snow model to assess grazing conditions for reindeer. Annals of Glaciology 54: 214–226.

Vionnet, V., E. Brun, S. Morin, et al. 2012. The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2. Geoscientific Model Development 5: 773–791.

Walsh, J.E. 2014. Intensified warming of the Arctic: Causes and impacts on middle latitudes. Global and Planetary Change 117: 52–63.

Webster, M.A., I.G. Rigor, S.V. Nghiem, N.T. Kurtz, S.L. Farrell, D.K. Perovich, and M. Sturm. 2014. Interdecadal changes in snow depth on Arctic sea ice. Journal of Geophysical Research-Oceans 119: 5395–5406.

Weyr, N., C. Fierz, C. Mitterer, H. Hirashima, and M. Lehning. 2014. Solving Richards Equation for snow improves snowpack meltwater runoff estimations in detailed multi-layer snowpack model. The Cryosphere 8: 257–274.

Wilson, R.R., A. Barsch, K. Joly, J.H. Reynolds, A. Orlando, and W.M. Loya. 2013. Frequency, timing, extent, and size of winter thaw-refreeze events in Alaska 2001–2008 detected by remotely sensed microwave backscatter data. Polar Biology 36: 419–426.

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