Journal of Hydrology 484 (2013) 63–73

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

Spatial and temporal variability in seasonal snow density

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ARTICLE INFO

Article history:
Received 17 November 2012
Received in revised form 9 January 2013
Accepted 13 January 2013
Available online 4 February 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief

Keywords:
Snow density
Snow densification
Climate variability
Spring snow density
Snow hydrology

SUMMARY

Snow density is a fundamental physical property of snowpacks used in many aspects of snow research. As an integral component in the remote sensing of snow water equivalent and parameterisation of snow models, snow density may be used to describe many important features of snowpack behaviour. The present study draws on a significant dataset of snow density and climate observations from the United States, Australia and the former Soviet Union and uses regression-based techniques to identify the dominant climatological drivers for snow densification rates, characterise densification rate variability and estimate spring snow densities from more readily available climate data. Total winter precipitation was shown to be the most prominent driver of snow densification rates, with mean air temperature and melt-refreeze events also found to be locally significant. Densification rate variance is very high at Australian sites, very low throughout the former Soviet Union and between these extremes throughout much of the US. Spring snow densities were estimated using a statistical model with climate variable inputs and best results were achieved when snow types were treated differently. Given the importance of snow density information in many snow-related research disciplines, this work has implications for current methods of converting snow depths to snow water equivalent, the representation of snow dynamics in snow models and remote sensing applications globally.

1. Introduction

Snow density is an important physical feature that influences the thermal, mechanical and optical properties of snow layers. It is therefore a prominent variable in snow related research, including snow load estimation (Meløysund et al., 2007), slope stability calculations for avalanche prediction (Hirashima et al., 2009; Brun et al., 1989), assessment of snow trafficability (Lee and Wang, 2009), snow representation in land surface schemes and climate models (Pitman et al., 1991; Koren et al., 1999; Livneh et al., 2010), and snow hydrology (Rango and Martinec, 1995; Jonas et al., 2009; Sturm et al., 2010). These studies show that snow density is a complex parameter that can vary spatially, temporally and vertically within the snow pack profile.

Snow density has, therefore, been examined regionally in a variety of locations, most of which are in the large northern hemisphere snowfields (Bilello, 1984; Onuchin and Burenina, 1996; Sturm and Holmgren, 1998; Kershaw and McCulloch, 2007; Meløysund et al., 2007). In these studies, high snow densities are typically associated with high precipitation, warm air temperatures, strong winds and long season duration. These climate factors are well accepted influences for the spatial distribution of mean seasonal snow density however snow densities can increase considerably during individual seasons (Ruddell et al., 1990) at varying densification rates.

Seasonal densification of the snowpack over time may cause significant differences between early and late season snow densities which can deviate greatly from regional mid-season means. Linear density–time curves are commonly used to approximate seasonal snow densification (Jonas et al., 2009; Sturm et al., 2010) and although the density increases are relatively linear with time, these simple density–time relationships have limited spatial applicability, do not allow for interannual variability in densification rates nor provide links to physical processes or influences. Whilst the influences of climate on mid-season snow densities and regional density–time curves has been a focus for previous studies (Jonas et al., 2009; Sturm et al., 2010), less understood are seasonal densification rates themselves and their variability.

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http://dx.doi.org/10.1016/j.jhydrol.2013.01.032

Seasonal densification of snow packs is caused by wind erosion, melt-refreeze events, compaction and snow metamorphisms acting in response to internal temperature and moisture gradients (Sommerfeld and LaChapelle, 1970; Colbeck, 1982). Wind erosion, for example, physically reshapes snow crystals to more sphere-like grains that can pack closer together. Similarly, the presence of liquid water (Brun, 1989a; Marshall et al., 1999) and destructive snow metamorphisms occurring when vertical temperature gradients are weak (Colbeck, 1982), also result in smaller, rounded grains. Conversely, strong vertical temperature gradients through dry snow layers result in the formation of larger faceted grains through constructive metamorphisms (Colbeck, 1982). These larger grains cannot pack closely together and consequently low densification rates are observed in cold regions where temperature gradients are prominent. Regardless of internal snow metamorphisms, the weight of new snow bears down on those below, densifying through compaction (Kojima, 1967; Anderson, 1976). Melt-freeze processes (Gray and Male, 2004) have long been implicated in snow densification, but no studies have established the link unequivocally. It is unclear which of these densification processes most influences densification rate and how dominant processes may differ between regions.

The relationship between snow densification processes and climate variability is not well understood. Limited studies in the US have linked air temperature, liquid water content and grain size to snow densification (Sturm and Holmgren, 1998), but report low interannual variability, perhaps due to the very cold climates in the study region, Alaska and Canada. Some correlation between densification rate and site characteristics such as elevation and proximity to the ocean has also been observed, with densification rate increasing during spring (Mizukami and Perica, 2008). Spatial variability in snow densification rate both regionally and between types of snow have been reported (Sturm et al., 2010) but interannual variability is generally considered negligible. As interannual climate variability is observed in snow affected regions, it is logical to also expect interannual variability in snow densification rates, particularly in highly variable climates.

Seasonal snowfields provide fresh water resources to large populations (Barnett et al., 2005) of which the accumulation and melt of snow in watersheds is critically important. Snow models show significant spread in simulations of snow water resources, even at sites with comprehensive observations (Essery et al., 2012), indicating that more research into understanding snow behaviour is required. Snow density may be used to parameterise energy flux and liquid water retention parameterisations in snow models (Essery et al., 2012), which are likely to affect runoff rates and late season SWE estimation (Dutra et al., 2010). Uncertainty in snow densification parameterisations is one of several potential sources of error contributing to snow model disagreement with SWE observations (Livneh et al., 2010; Fox et al., 2008). Snow density observations are somewhat limited even in well studied regions (Jonas et al., 2009), and often completely absent in less monitored locations. Snow research in these regions stands to benefit largely from methods of estimating important snow properties from more readily available data.

The present study therefore aims to capture the full range of snow densification variability across a large number of sites by (1) characterising interannual and spatial variability in snow densification rates; (2) identifying the dominant climatological drivers for snow densification rates; and (3) developing relationships between spring snow densities and climate variables. The study examines a wider range of sites, snow types and geographical conditions than previous work, including the southern hemisphere, using data from approximately 1700 snow years across 96 locations throughout the US, the former Soviet Union and Australia.

2. Data

2.1. Sourcing the data

Snow depth, snow water equivalent (SWE), air temperature (minimum, maximum) and precipitation observations were collected for sites in the US, Australia and the former Soviet Union. The three main sources of data are outlined below.

- Daily data from the US for all variables listed above were obtained from the SNOwpack TELemetry (SNOTEL) network via the National Water and Climate Center website (www.wcc.nrcs.usda.gov/snow/). Snow depth measurements from the SNOTEL network are typically available from the mid 1990s to present.
- Data from Australia of snow density, snow depth and SWE, at weekly to twice monthly intervals, were collected from the hydro-electric scheme operators, Snowy Hydro Pty Ltd. and Southern Hydro Pty Ltd. Snow data are available from the late 1950s to present.
  - Daily temperature and precipitation data were compiled from collocated or nearby Snowy Hydro station sources.
  - Missing periods in the climate data were supplemented with Australian Bureau of Meteorology (BoM) station values where required. A lapse rate of 5.5 °C/km was used to adjust temperature observations to account for elevation differences between climate stations and snow observation sites.
- Former Soviet Union snow depth and SWE data, available at 5 day intervals, were obtained from the former Soviet Union Hydrological Snow Surveys (FSUHSS) dataset. This dataset is archived at the National Snow and Ice Data Center website (NSIDC www.nsidc.org/) and contains data from the mid 1960s to the 1990s. Corresponding climate data were sourced from the Daily Temperature and Precipitation Data from 223 former-USSR Stations dataset (Razuvaev et al., 1993) held at the Carbon Dioxide Information Analysis Center (CDIAC <http://www.cdiac.ornl.gov/ndps/ndp040.html>).

2.2. Criteria for site selection

Suitable sites for study were selected based the continuity of the data. A minimum record of 10 years was required with a sampling frequency that captured the seasonal evolution of the snow pack. The time span was allowed to vary between sites to maximise the number of snow seasons in the data pool. Whilst all eligible sites in the US and Australia were included, the large number of eligible sites throughout the former Soviet Union required further screening. The FSUHSS dataset provided 618 sites that satisfied the criteria, of which the 40 with the highest number of snow observations over the longest period were selected as possible study sites. From these 40 sites, three were rejected due to poor or missing collocated temperature and precipitation data. The resulting 37 sites throughout the former Soviet Union are spatially distributed across the region and were considered representative of the full dataset. From the available data, four sites in Australia, 55 sites in the western US and 37 sites throughout the former Soviet Union were selected.

Fig. 1 shows the locations of the 96 observation sites across two hemispheres and three continental zones. The marker colour and type represents snow type classification. The Australian snowfields cover the smallest area of those investigated, but represent sites with demonstrated high interannual variability (Bormann et al., 2012).