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Snow cover and snow albedo changes in the central Andes of Chile and Argentina from daily MODIS observations (2000–2016)

Jeppe K. Malmros[a,*], Sebastian H. Mernild[b,c,d], Ryan Wilson[e], Torbern Tagesson[a], Rasmus Fensholt[a]

[a] Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark
[b] Nansen Environmental and Remote Sensing Center, Bergen, Norway
[c] Direction of Antarctic and Sub-Antarctic Programs, Universidad de Magallanes, Punta Arenas, Chile
[d] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Sogndal, Norway
[e] Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, UK

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ABSTRACT

The variables of snow cover extent (SCE), snow cover duration (SCD), and snow albedo (SAL) are primary factors determining the surface energy balance and hydrological response of the cryosphere, influencing snow pack and glacier mass-balance, melt, and runoff conditions. This study examines spatiotemporal patterns and trends in SCE, SCD, and SAL (2000–2016; 16 years) for central Chilean and Argentinean Andes using the MODIS MOD10A1 C6 daily snow product. Observed changes in these variables are analyzed in relation to climatic variability by using ground truth observations (meteorological data from the El Yeso Embalse and Valle Nevado weather stations) and the Multivariate El Niño index (MEI) data. We identified significant downward trends in both SCE and SAL, especially during the onset and offset of snow seasons. SCE and SAL showed high inter-annual variability which correlate significantly with MEI applied with a one-month time-lag. SCE and SCD decreased by an average of ~13 ± 2% and 43 ± 20 days respectively, over the study period. Analysis of spatial pattern of SCE indicates a slightly greater reduction on the eastern side (~14 ± 2%) of the Andes Cordillera compared to the western side (~12 ± 3%). The downward SCE, SAL, and SCD trends identified in this study are likely to have adverse impacts on downstream water resource availability to agricultural and densely populated regions in central Chile and Argentina.

1. Introduction

Snow in the semi-arid mountain regions of the central Andes of Chile and Argentina provides important water resources to > 10 million people and is of major importance for agriculture in this area (Masiokas et al., 2006). Moreover, snow constitutes a key seasonal component in the surface energy and hydrosphere budgets, reflecting incoming solar shortwave radiation (e.g., Konzelmann and Ohmura, 1995). Hydrological balance in the cryosphere is highly influenced by the amount of snow precipitation and the spatiotemporal variability of seasonal snow cover extent (SCE). The combined variability of snow precipitation, SCE, and snow cover duration (SCD) directly influences river-runoff variabilities and glacier surface-mass balance conditions (Ragettli et al., 2016; Wilson et al., 2016).

On high mountain glaciers, energy availability for snow and ice melt is regulated by surface albedo which is defined as the ratio of incoming solar radiation reflected by a surface (Cuffey and Paterson, 2010). Fresh snow, for example, acts as a near perfect reflector with albedo values of up to 0.98. However, snow albedo (SAL) diminishes over time as a result of snow metamorphism, decreasing to as low as 0.46 (Cuffey and Paterson, 2010). Rainfall can further enhance this natural lowering of SAL through the addition of latent energy, which can initiate melting (Benn and Evans, 2010) and cause downwasting and thinning of glaciers (Neckel et al., 2017). Snow and ice albedo can also be reduced by the surface deposition of dust and/or anthropogenic soot (Hansen and Nazarenko, 2004; Cereceda-Balic et al., 2012). In the central Andes, an additional factor which influences SAL is the seasonal formation of penitents. Often forming in areas of low humidity and high solar elevation, snow penitents can result in significant changes in the surface roughness of snow-covered terrain, which, in turn, influences SAL and sublimation conditions (Corripio and Purves, 2006).

The overall variability of SAL is influenced by a variety of factors: snow grain size, levels of contamination, solar zenith angle, cloud cover, snow metamorphism, surface roughness, age factor, and liquid

* Corresponding author at: Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen, Denmark.
E-mail address: vwh636@alumni.ku.dk (J.K. Malmros).

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water content, amongst others (Warren and Wiscombe, 1980; Mernild et al., 2015a). Since SAL is a key parameter determining the amount of energy available for surface melting snow and ice, snow-sublimation, and metamorphosis, spatiotemporal variability in SAL is important when determining snow ablation conditions (Male and Granger, 1981; Brock et al., 2000; Hock, 2005; Gardner and Sharp, 2010; Mernild et al., 2016a).

Spatiotemporal trends in SCE and SAL interpolated from point measurements often include large errors, especially in remote mountainous regions characterized by limited ground observations, localized climate conditions and complex terrain. In comparison, satellite-based remote sensing and satellite derived snow cover products provide opportune sources of large-scale SCE and SAL measurements and have been successfully used as key inputs in climate, atmospheric and hydrological models (Farr et al., 2007; Mernild et al., 2008; Vuille et al., 2008; Mernild et al., 2015a). Remote sensing systems acquiring data from the visible (VIS) to shortwave infrared (SWIR) spectrum with a high temporal resolution are well suited for monitoring SCE and SAL over large areas, providing good spatial and temporal coverage (Wiscombe and Warren, 1980; Dozier and Frew, 1981; Dubayah, 1992; Knap et al., 1999).

Several remote sensing based snow cover products are currently available, most of which apply either the normalized difference snow index (NDSI) (Hall et al., 1995), empirical relationship assumptions or spectral un-mixing models (Klein and Stroeve, 2002). Optical sensor systems, however, are unable to acquire useful information during cloudy conditions (Justice et al., 1998; Marchane et al., 2015). Therefore, frequent satellite observation revisits are essential to study changes in SCE and SAL, since surface conditions can vary rapidly and may change considerably over a few days.

To compensate for extensive cloud cover, compromises are often made by conducting satellite analysis based on composite products such as the MODIS (Moderate Resolution Imaging Spectroradiometer) 8 day snow cover MOD10A2 product (Hall et al., 2002), which can mask subtle changes in SCE and SAL over time. In order to avoid this limitation, the MODIS MOD10A1 Collection 6 (C6) dataset was used this study. MOD10A1 provides daily SCE and SAL values globally at a spatial resolution of 500 m, making it suitable for evaluating seasonal trends in SCE and SAL (Hall et al., 2002; Liang et al., 2005; Marchane et al., 2015; Hall and Riggs, 2016; Saavedra et al., 2016; Li et al., 2017a, 2017b; Huang et al., 2017; Dariane et al., 2017), snow cover phenology (Xu et al., 2017) and the relation between SCE and climate (Gurung et al., 2017; Li et al., 2017a, 2017b). Using MOD10A1 data, this study analyses spatiotemporal changes in SCE and SAL in the central Andes of Chile and Argentina by parameterizing a time series of seasonal SCE and SAL metrics at the per-pixel level. Furthermore, this study examines the large-scale influence of ENSO events on SCE and SAL as well as the more localized effect of climatic variability (utilizing meteorological data from the El Yeso Embalse (EYE) and Valle Nevado (VN) automatic weather stations (AWS)) and elevation.

2. Study area

The Andes of central Chile and Argentina (31°S and 40°S) contain some of the highest peaks of the entire Andes Cordillera, reaching altitudes above 6000 m above sea level (a.s.l.) (Fig. 1). Covering an area of ~1730 km^2, the study area chosen is located immediately west of Santiago de Chile (32°50′–34°50′S; 69°20′–70°40′W). This study area includes several river basins which supply freshwater to large downstream populations (10 + million people in Chile and 2 + million in Argentina), hydro-power stations, and agricultural lands on both sides of the cordillera (Corripio and Purves, 2006). This area of the central Andes also includes the largest glaciated areas in South America outside southern Patagonia (Saavedra et al., 2016). River runoff in this central region originates primarily from snowmelt (Masiokas et al., 2006), with snowfall contributing up to ~85% of runoff from specific catchments (Mernild et al., 2016b). The availability of snow as a freshwater resource is therefore of vital socio-economic importance in this semi dry region (Peña and Nazarala, 1987; Meza et al., 2012; Carey et al., 2017).

The intra-annual variability of precipitation in central Andes is highly influenced by the placement of an atmospheric high-pressure cell over the southeastern Pacific Ocean. This cell normally inhibits precipitation in the Austral summer (December–February) and allows for the passage of westerlies and frontal precipitation during Austral winters (June–August) (Garreaud et al., 2009). Precipitation events are usually concentrated between April and October, providing ~95% of the mean annual totals, peaking in June or July (Masiokas et al., 2016). The strength of El Niño Southern Oscillation (ENSO) influences interannual variability in precipitation, with higher/lower precipitation occurring during El Niño/La Niña events (Rutllant and Fuenzalida, 1991; Escobar et al., 1995; Leiva, 1999; Montecinos and Aceituno, 2003; Garreaud et al., 2009). During El Niño events, precipitation increases predominantly during the austral winter (Masiokas et al., 2006; McClung, 2013). While El Niño events do influence precipitation amounts, these events shows little or no significant signal in annual mass balance measurements of glaciers located in the central Andes but has been linked to the Pacific Decadal Oscillation (PDO) rather than the ENSO (Mernild et al., 2015a).

Along the central Andes, annual accumulation of snow is highest at 4000–5000 m a.s.l., where glacier accumulation zones are also present (Cornwell et al., 2016; Mernild et al., 2016b; Mernild et al., 2016c). Precipitation differences observed between the western and eastern sides of the Andes Cordillera occur due to the combination of orographic effects of the mountain relief and the dominating westerly wind direction which results in precipitation amounts and humidity being lower on the eastern Cordillera slopes (Cornwell et al., 2016; Mernild et al., 2016b).

For the central Andes, mean surface air temperatures are normally highest between December and March and lowest in July and August (Masiokas et al., 2016) and temperatures in the Andes showed increasing trends from 1975 to 2006 (~0.25 °C/decade) (Falvey and Garreaud, 2009). The 0 °C isotherm for the western side of the cordillera (40 km northeast of Santiago de Chile), was located at 3385 m a.s.l. between 2009 and 2014 (Mernild et al., 2016c).

3. Data

3.1. MODIS data

The MOD10A1 C6 (henceforth MOD10A1 unless other version is implied) snow product is derived from daily data acquisitions by the MODIS sensor aboard the Terra spacecraft (Riggs et al., 2017). The MODIS global daily snow cover product MOD10A1 (MODIS/Terra Snow Cover Daily L3 Global 500 m Grid) is derived from cloud free observations and is well suited for regional snow cover and albedo mapping (Hall et al., 2002; Liang et al., 2005; Dozier et al., 2008; Rittger et al., 2013; Fausto et al., 2015; Mernild et al., 2015b). The latest MOD10A1 product was released in the spring of 2016 and includes a range of improvements to the previous version including, amongst others, the removal of Terra sensor degradation issues and improvements in atmospheric calibration (Lyapustin et al., 2014). Importantly, the algorithms used to compile the MOD10A1 snow product are modified to include only the best quality observations from the atmospherically corrected MOD10GA product (Hall et al., 2002). Individual MOD10A1 product parts include NDSI, NDSI snow cover (SCE), SAL and corresponding quality control flags. The MOD10A1 NDSI SCE is produced by using an empirical relationship with NDSI values, where NDSI values are multiplied by a constant (Dozier et al., 2008; Hall and Riggs, 2016). By using only full snow cover pixels, the accuracy of the MOD10A1 SAL product is improved in terms of ground truth comparisons (Sorman et al., 2007; Mernild et al., 2015b). The overall error of the MOD10A1 SAL product can vary substantially but is

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