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1	Snow cover and snow albedo changes in the central Andes of Chile and Argentina
2	from daily MODIS observations (2000–2016)
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35 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 (EYE) weather station) 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 $\sim 13 \pm 2$ % and 43 ± 20 days respectively, over the study period. Analysis of spatial pattern of SCE indicates a slightly greater reduction on the eastern side ($\sim 14 \pm 2$ %) of the Andes Cordillera compared to the western side ($\sim 12 \pm 3$ %). 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. Keywords: Andes; Argentina; Chile; climate change; ENSO; MOD10A1; MODIS; snow albedo; snow cover extent; time series analysis.

65 **1. Introduction**

66 Snow in the semi-arid mountain regions of the central Andes of Chile and Argentina provides important water resources to more than 10 million people and is of major importance for agriculture in 67 68 this area (Masiokas et al. 2006). Moreover, snow constitutes a key seasonal component in the surface 69 energy and hydrosphere budgets, reflecting incoming solar shortwave radiation (e.g., Konzelmann and 70 Ohmura 1995). Hydrological balance in the cryosphere is highly influenced by the amount of snow 71 precipitation and the spatiotemporal variability of seasonal snow cover extent (SCE). The combined 72 variability of snow precipitation, SCE, and snow cover duration (SCD) directly influences river-runoff 73 variabilities and glacier surface-mass balance conditions (Ragettli et al. 2016; Wilson et al. 2016).

74 On high mountain glaciers, energy availability for snow and ice melt is regulated by surface 75 albedo which is defined as the ratio of incoming solar radiation reflected by a surface (Cuffey and 76 Paterson 2010). Fresh snow, for example, acts as a near perfect reflector with albedo values of up to 77 0.98. However, snow albedo (SAL) diminishes over time as a result of snow metamorphism, 78 decreasing to as low as 0.46 (Cuffey and Paterson 2010). Rainfall can further enhance this natural 79 lowering of SAL through the addition of latent energy, which can initiate melting (Benn and Evans 80 2010) and cause downwasting and thinning of glaciers (Neckel et al. 2017). Snow and ice albedo can 81 also be reduced by the surface deposition of dust and/or anthropogenic soot (Hansen and Nazarenko 82 2004; Cereceda-Balic et al. 2012). In the central Andes, an additional factor which influences SAL is 83 the seasonal formation of penitents. Often forming in areas of low humidity and high solar elevation, 84 snow penitents can result in significant changes in the surface roughness of snow-covered terrain, 85 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 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, snowsublimation, 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).

93 Spatiotemporal trends in SCE and SAL interpolated from point measurements often include
 94 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

97 measurements and have been successfully used as key inputs in climate, atmospheric and hydrological

98 models (Farr et al. 2007; Mernild et al. 2008; Vuille et al. 2008; Mernild et al. 2015a). Remote sensing

99 systems acquiring data from the visible (VIS) to shortwave infrared (SWIR) spectrum with a high

100 temporal resolution are well suited for monitoring SCE and SAL over large areas, providing good

101 spatial and temporal coverage (Wiscombe and Warren 1980; Dozier and Frew 1981; Dubayah 1992;

102 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 2002a). 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.

110 To compensate for extensive cloud cover, compromises are often made by conducting satellite 111 analysis based on composite products such as the MODIS (Moderate Resolution Imaging 112 Spectroradiometer) 8 day snow cover MOD10A2 product (Hall et al. 2002), which can mask subtle 113 changes in SCE and SAL over time. In order to avoid this limitation, the MODIS MOD10A1 114 Collection 6 (C6) dataset was used this study. MOD10A1 provides daily SCE and SAL values globally 115 at a spatial resolution of 500 m, making it suitable for evaluating seasonal trends in SCE and SAL (Hall 116 et al. 2002; Liang et al. 2005; Marchane et al. 2015; Hall and Riggs 2016; Saavedra et al. 2016; Li et al. 117 2017; Huang et al. 2017; Dariane et al. 2017), snow cover phenology (Xu et al. 2017) and the relation 118 between SCE and climate (Gurung et al. 2017; Li et al. 2017). Using MOD10A1 data, this study 119 analyses spatiotemporal changes in SCE and SAL in the central Andes of Chile and Argentina by 120 parameterizing a time series of seasonal SCE and SAL metrics at the per-pixel level. Furthermore, this 121 study examines the large-scale influence of ENSO events on SCE and SAL as well as the more 122 localized effect of climatic variability (utilizing meteorological data from the El Yeso Embalse (EYE) 123 weather station) and elevation.

125 2. Study area

126 The Andes of central Chile and Argentina (31°S and 40°S) contain some of the highest peaks of 127 the entire Andes Cordillera, reaching altitudes above 6,000 m above sea level (a.s.l.) (Fig. 1). Covering an area of ~1,730 km², the study area chosen is located immediately west of Santiago de Chile 128 (32°50'- 34°50'S; 69°20' - 70°40'W). This study area includes several river basins which supply 129 130 freshwater to large downstream populations (10+ million people in Chile and 2+ million in Argentina), 131 hydro-power stations, and agricultural lands on both sides of the cordillera (Corripio and Purves 2006). 132 This area of the central Andes also includes the largest glaciated areas in South America outside 133 southern Patagonia (Saavedra et al. 2016). River runoff in this central region originates primarily from 134 snowmelt (Masiokas et al. 2006), with snowfall contributing up to \sim 85 % of runoff from specific 135 catchments (Mernild et al. 2016b). The availability of snow as a freshwater resource is therefore of 136 vital socio-economic importance in this semi dry region (Peña and Nazarala 1987; Meza et al. 2012; 137 Carey et al. 2017).

138 The intra-annual variability of precipitation in central Andes is highly influenced by the 139 placement of an atmospheric high-pressure cell over the southeastern Pacific Ocean. This cell normally 140 inhibits precipitation in the Austral summer (December – February) and allows for the passage of 141 westerlies and frontal precipitation during Austral winters (June – August) (Garreaud et al. 2009). 142 Precipitation events are usually concentrated between April and October, providing ~95 % of the mean 143 annual totals, peaking in June or July (Masiokas et al. 2016). The strength of El Niño Southern 144 Oscillation (ENSO) influences inter-annual variability in precipitation, with higher/lower precipitation 145 occurring during El Niño/La Niña events (Rutllant and Fuenzalida 1991; Escobar et al. 1995; Leiva 146 1999; Montecinos and Aceituno 2003; Garreaud et al. 2009). During El Niño events, precipitation 147 increases predominantly during the austral winter (Masiokas et al. 2006; McClung 2013). Whilst El 148 Niño events do influence precipitation amounts, these events shows little or no significant signal in 149 annual mass balance measurements of glaciers located in the central Andes but has been linked to the 150 Pacific Decadal Oscillation (PDO) rather than the ENSO (Mernild et al. 2015a).

Along the central Andes, annual accumulation of snow is highest at 4,000 – 5,000 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 easternCordillera 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°Cisotherm for the western side of the cordillera (40 km northeast of Santiago de Chile), was located at 3,385 m

161 a.s.l. between 2009 and 2014 (Mernild et al. 2016c).



163

164 Figure 1: (a) The central Andes of Chile and Argentina; and (b) including the area of interest west and 165 east snow cover regions delineated by red and blue lines, respectively. The divide between the western

and eastern Andes also represents the natural border (continental divide) between Chile and Argentina.
Blue areas represents glaciers. The red star in the center of the study area represents the location of the
El Yeso Embalse (EYE) weather station.

- 169
- 170 **3. Data**
- 171
- 172 *3.1 MODIS data*

173 The MOD10A1 C6 (henceforth MOD10A1 unless other version is implied) snow product is 174 derived from daily data acquisitions by the MODIS sensor aboard the Terra spacecraft (Riggs et al. 175 2017). The MODIS global daily snow cover product MOD10A1 (MODIS/Terra Snow Cover Daily L3 176 Global 500m Grid) is derived from cloud free observations and is well suited for regional snow cover 177 and albedo mapping (Hall et al. 2002; Liang et al. 2005; Dozier et al. 2008; Rittger et al. 2013; Fausto 178 et al. 2015; Mernild et al. 2015b). The latest MOD10A1 product was released in the spring of 2016 and 179 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). 180 181 Importantly, the algorithms used to compile the MOD10A1 snow product are modified to include only 182 the best quality observations from the atmospherically corrected MOD10GA product (Hall et al. 2002). 183 Individual MOD10A1 product parts include NDSI, NDSI snow cover (SCE), SAL and corresponding 184 quality control flags. The MOD10A1 NDSI SCE calculated is produced from an empirical relationship 185 with NDSI values, where NDSI values are multiplied by a constant (Dozier et al. 2008; Hall and Riggs 186 2016). By using only full snow cover pixels, the accuracy of the MOD10A1 SAL product is improved 187 in terms of ground truth comparisons (Sorman et al. 2007; Mernild et al. 2015b). The overall error of 188 the MOD10A1 SAL product can vary substantially but is found to be in the order of 1-10 % for good 189 observations with low atmospheric disturbances across the Greenland ice sheet (Klein and Stroeve 190 2002b). The overall error at this location is likely to be higher due to the complex terrain of the Andes 191 Mountains. However, changes in albedo can still be quantified and here we opted for a per-pixel 192 temporal change analysis that is expected to mitigate the influence of topography to some degree by 193 avoiding direct inter-comparison of pixels influenced by different slope/aspect. 194 MOD10A1 data used in this study was obtained from the NASA Earth Observation System

195 Data and Information System (EOSDIS) Reverb ECHO website (<u>https://reverb.echo.nasa.gov/</u>). Out of

196 the 5,844 potential scenes available between March 1 2000 and Feb 29 2016, only 121 (~2 %) were 197 missing in the archive, with a maximum temporal gap of 17 days. The snow cover year (season) was 198 set to start 1 March and end February 28 (29) based on analysis of the data set. Pixels with cloud cover 199 or poor retrievals were omitted as determined from QA flags and only pixels flagged as "best quality" 200 were included in the further analysis (see section 4.1). Out of all pixels in the data series 74.8 % 201 contained "best quality" data (supplementary material S1). 202 203 204 3.2 Ancillary data 205 Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) v.3. SRTM 206 provides elevation data at a spatial resolution of 30 meters with an overall vertical accuracy of ~ 10 m 207 and geo-position error of ~9 m (Farr et al. 2007). Multivariate El Niño index (MEI) ranks were 208 obtained from the National Oceanic and Atmospheric Administration (NOAA) website 209 (http://www.esrl.noaa.gov/psd/enso/mei/table.html). The MEI provides a ranked index of the strength 210 of El Niño and La Nina events. MEI values are normalized for each bimonthly season (Wolter and 211 Timlin 2011) and cover the 16-year study period of snow cover and snow albedo observations. 212 We acquired mean monthly air temperature (MMAT), mean annual air temperature (MAAT), 213 and monthly precipitation sums (2000–2016) from the El Yeso Embalse meteorological station (EYE) 214 (location in Fig. 1; data shown in supplementary material S2) from Dirección General de Aguas (DGA; 215 www.dga.cl). Finally, glacier outlines were obtained from the Randolph glacier inventory v. 5.0 216 (Pfeffer et al. 2014) in combination with updated glacier shapes from 2013/2014 (Malmros et al. 2016). 217 4. Methods

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- 219

220 4.1 Time series preprocessing

221 The MOD10A1 time series was preprocessed and analyzed using the program TIMESAT 222 (Jönsson and Eklundh 2002, 2004; Eklundh and Jönsson 2015). TIMESAT originally developed to 223 analyze vegetation seasonality can be applied to all remote sensing data containing seasonal variability. 224 We applied a Savitzky-Golay filter within TIMESAT which allows for a smoothening of the 225 MOD10A1 time-series by applying polynomial fitting to the data points within a moving window of a

226 certain width (Savitzky and Golay 1964; Jönsson and Eklundh 2004). Missing dates were filled with 227 blank scenes before smoothing (Jönsson and Eklundh 2002) in order to compose a complete time 228 series. Pixels not flagged as "best quality", as determined from QA flags, were given a weight of zero 229 in the fitting algorithm to allow only pixels of best quality to be included. The width of the moving 230 window influences the degree of smoothing and the ability of the filter to cope with rapid changes 231 (parameters used in the TIMESAT preprocessing are shown in Table 1). The polynomial fitting was 232 iterated and adapted to the upper part of the curve by assigning weights to data points above and below 233 the result of the previous step (Jönsson and Eklundh 2004). SCD was extracted in TIMESAT for SCE, 234 and the seasonal snow cover integral (SCI) (defined as the integral under the curve between onset and 235 end of seasonal snow cover) was extracted to evaluate the accumulated seasonal SCE for each season. 236 Areas characterized by limited seasonal variability were masked out due to the inability of the 237 TIMESAT algorithm to estimate SCD for such conditions. The mask was created from the median of 238 the 16 seasons and excluded areas with less than 16 days in the SCD dataset. Most excluded areas were 239 located in glacier accumulation zones where constant snow cover prevents seasonal variability in SCE. 240

2	4	U	

Parameter	NDSI Snow Cover	Snow Albedo
Seasonal parameter	0.7	0.7
Number of envelope iterations	3	3
Adaptation strength	2	2
Savitzky-Golay window size	15	15
Spike Method	Median filter	Median filter
Amplitude season start (%)	70	65
Amplitude season end (%)	20	46

241 Table 1: Input parameters for use in TIMESAT.

242

243 4.2 Trend estimation

244 We conducted linear temporal trend analysis to estimate the magnitude and direction of changes 245 in SCE, SAL, SCD, SCI, MAAT, and annual precipitation. We calculated per-pixel trends by applying a nonparametric linear regression model with time as the independent variable and the abovementioned 246 247 variables as dependent variables. Since time series of the variables analyzed often do not meet

248 parametric assumptions of normality and homoscedasticity, a median trend (Theil–Sen, TS) procedure 249 was applied using the Theil-Sen slope estimator (median trend) which has proven robust against 250 outliers (Eastman 2009). Uncertainty estimates of trends are calculated from standard deviations of the 251 calculated metrics and are provided as \pm values to all trends reported. The significance of the trends 252 was determined using the nonparametric Mann-Kendall test of significance (Mann 1945; Kendall 253 1975). The Mann–Kendall significance test is commonly used as a trend test for the TS median slope 254 operator (Eastman 2009) and produces outputs of z-scores that allow for the assessment of both the 255 significance and direction of trends. The trends were considered significant at p < 0.05 (where p 256 denotes the probability that there is no significant difference between observations over time). Trends 257 in SCE, SCD, and SCI were extracted from the area of maximum values (minimum of 75% at any 258 given time) for the entire study period and similar for SAL.

259

260 **5. Results**

261 5.1 Spatio-temporal patterns in snow cover extent

262 Statistical analysis of the MODIS time series revealed that the minimum, median, and maximum SCE for the entire observation period and area (Fig. 2) was 2 %, 43 %, and 74 %, 263 264 respectively. SCE showed the presence of a clear linear relationship with elevation (coefficient of determination $(r^2) = 0.95$, p < 0.01; Fig. 2d). However, the relationship was imperfect $(r^2 = 0.34)$ above 265 4,000 m a.s.l due to increased scattering in the accumulation zone of the glaciers. At its maximum, SCE 266 covered 1,730 km² (74%) of the study area, only being present at elevations above 1,250 m a.s.l. SCE 267 268 area was normally distributed with highest consentration of SCE observed between 3,250 and 4,000 m 269 a.s.l. (Fig. 2e). SCE was on average ~11 % less on the eastern side of the Cordillera compared to the 270 west (Fig. 2a-c).



Figure 2: a) Median snow extent; b) maximum snow cover extent; c) minimum snow cover extent for
the 16 snow seasons observed (2000–2016) (glaciers are delineated by black); d) Mean SCE change
with elevation; and e) Snow covered area distribution with elevation.

- 277 5.2 Inter- and intra-annual variability in snow cover extent (SCE) and snow albedo (SAL)

The mean SCE over the study area between 2000 and 2016 was approximately ~25 % in austral 279 summer and ~68 % in austral winter, reaching a maximum between July 24th and 25th October and a 280 minimum in autumn between March 6th and June 6th (Fig. 3). Overall, spatial trends for SCE and SAL 281 282 showed widespread downward tendencies (Fig. 4). For SCE, downward trends dominated, with medium SCE decreasing by 13.4±4.0.x % between 2000 and 2016 (0.35 % yr⁻¹). Demonstrating spatial 283 284 variabilities, the downward trends in SCE were found to be more pronounced for the the eastern side of the Cordillera (13.9±4.0 %, 0.9 % yr⁻¹) compared to the west (12.4±3.1 %, 0.8 % yr⁻¹). The eastern side 285 286 of the Cordillera also showed lower SCE but higher SCE variability compared to the western side, this 287 despite the eastern side being more elevated (mean elevation for the western and eastern sides is 3,115 288 m a.s.l and 3,720 m a.s.l, respectively) (Fig. 2d). Median SAL trends from March 2000 to Feburary 2016 were also downward with mean values decreasing by 7.4 ± 2.2 % (0.5 % yr⁻¹). Downward trends in 289 290 SAL were shown to be more widespread in the southern parts of the study area compared to northern 291 parts. However, we found no significant differences between the eastern and western sides of the 292 Cordillera.

293



294

Figure 3: Variation in daily median SCE (blue) and median SAL (red) percentage and the bi-monthly
multivariate ENSO index (MEI) (dark dashed line) in 1/1000 standard variations (Wolter and Timlin
2011).



Figure 4: Linear median trend (p < 0.05) in: SCE (a) and SAL (c) from Mar 2000 through Feb 2016, and the corresponding significance level of each trend (b, d).

299

Comparisons with SRTM data, the SAL trends observed showed negative correlations below ~4,600 m a.s.l. (-1.1 \pm 0.8 % yr⁻¹, r=0.84, *p* < 0.01). Above ~4,600 m a.s.l., however, a distinct shift is observed, with increasing correlations as a function of elevation (0.2 \pm 0.01 % yr⁻¹, r=0.83, *p* < 0.01) (Fig. 5). In regards to intra-annual variability, SCE showed pronounced downward trends (<-1 % yr⁻¹) during the onset (April, May, and June) and offset (October, November, December, and January) of the snowy season. In comparison to SCE, SAL showed slightly less intra-annual variability with most downward trends occurring during the onset of the snowy season (Fig. 6).



Figure 6: Intra-annual linear trends (blue and red lines), monthly mean values (dotted lines) and spread
(colored areas; monthly minimum and maximum values)) in: (a) snow cover extent (SCE); and (b)
snow albedo (SAL) between 2000 and 2016.

320 5.3 Snow cover duration (SCD) and seasonal snow cover integral (SCI)

The seasonal SCD values ranged between 0 and 280 days and the seasonal mean SCD ranged between 203 days in the 2005–2006 to 130 days in 2011–2012, with an overall median of 173 days (Fig. 7a). We observed a strong correlation between SCD and elevation (excluding glacier areas). SCD,

324 for example was shown to increase by an average of ~6 days for every 100-meter increment within the

2,000 to 4,600 m a.s.l. elevation range ($r^2=0.80$, p<0.01) (Fig. 7a). Overall, the trends in SCD were 325

- 326 downward, showing a mean reduction of 43 ± 20 days for the study period (-2.7 ± 1.3 days yr⁻¹) (Fig.
- 327 8a). Trends were especially negative on the eastern side of the Cordillera, with a reduction of 52 ± 36
- days $(3.3 \pm 2.3 \text{ days yr}^{-1})$, whereas on the western side SCD reduced by 35 ± 33 days $(2.2 \pm 2.0 \text{ days yr}^{-1})$ 328 ¹).
- 329
- 330



332 Figure 7: a) Median snow cover duration (SCD, days) 2000–2016 (dark grey areas represent locations 333 where the model failed to determine seasonality); and (b) Mean snow cover duration with elevation for 334 the 2000–2016 period (grey bars show the spread between minimum and maximum values of SCD as a 335 function of elevation).

336

Figure 8: (a) Per pixel yearly snow cover duration (SCD) trend 2000–2016, and (b) corresponding
significance of trend. Dark gray masked areas represent the mask where SCD values are erroneous and
black lines represent glaciers.

341

The SCI for the entire study area declined by $1.5 \pm 0.5 \%$ yr⁻¹ (median trend), corresponding to 25 ± 8 % during the full period of 16 snow seasons. The SCI also shows substantial inter-annual variation (Fig. 9), especially on the eastern side of the Cordillera, where SCI is on average 17 % smaller and trends are substantially more downward ($1.8 \pm 0.5 \%$ yr⁻¹) than for the western side ($1.2 \pm 0.4 \%$ yr⁻¹).

346





Figure 9: Mean snow cover duration (SCD, bars) and seasonal snow cover integral (SCI, lines) for the entire study area and for the western (SCD-W) and eastern (SCD-E) sides of the cordillera separately.

350

5.4 Impact of changes in temperature, precipitation, and El Niño Southern Oscillation (ENSO) on snow
 cover duration and snow albedo



MAAT of 0.05°C yr⁻¹ between 2000 and 2016. Between 2000 and 2009, nine extreme precipitation 355 events (>200 mm month⁻¹) were identified, with the 2003-2004 season (March-February) receiving a 356 357 maximum of 1,259 mm. These 'extreme' events occurred mostly during austral winters and account for 358 large differences in inter-annual precipitation amounts, SCE and SCD sums. Post 2009, no extreme 359 precipitation events occurred, however a minimum of 317 mm was observed for the 2014-2015 season. 360 The mean annual precipitation sum for the 2000 to 2016 observation period was 677 mm. MAAT for 361 this observation period was 9.0°C, with maximum and minimum values of 10.3°C and 7.3°C measured 362 for the 2003-2004 and 2011-2012 seasons, respectively.

Statistical comparisons between the MODIS-derived snow data and the observed EYE meteorological data revealed that monthly SCE and SAL averaged over the study area correlated strongly with MMAT (r²-values of 0.74 and 0.84, respectively) (Fig. 10a-b). Mean monthly SCE and SAL also correlate with monthly precipitation sums, but to a lesser extent (r²-values of 0.20 and 0.28) (Fig. 10c-d). In comparison, SCI correlated more strongly with annual precipitation sums (r²-value of 0.84) (Fig. 10e).



370

Figure 10: Relationships between monthly meteorological data (EYE station; Fig. 1) and monthly SCE,
monthly SAL, and SCI averaged over the study area. a) Monthly SCE against MMAT; b) monthly SAL

373 against MMAT, c) Monthly SCE against monthly precipitation sums, d) Monthly SCE against monthly 374 precipitation sums, e) SCI against annual precipitation sums, and f) SCI against MAAT.

375

376 ENSO events (MEI) (plotted in Fig. 3) show significant correlations with mean SCE and SAL 377 values for the study area (Fig. 11). Mean correlation coefficient values (r) between MEI and SCE/SAL 378 were strongest when a lag of one month (L1) was applied to the SCE/SAL time series (mean r-values 379 of 0.21 for the study area).

380 Generally, glaciated areas where snow cover is already present are characterized by negative 381 SCE and ENSO correlations for shorter lag periods (L1), which is in contrast to the surrounding snow 382 covered areas. This pattern is reversed for longer lag periods (e.g., five months), when glaciated and 383 higher elevated areas significantly correlate with ENSO, whereas surrounding lower altitude areas are 384 characterized by negative correlations.

385



El Niño southern oscillation (ENSO)

Figure 11: Per-pixel correlations and significance of SCE/SAL with the ENSO index (MEI) including 387

- 388 one-, three- and five-month lag time (L1, L3, and L5). Red line demarks the east west divide.
- 389
- 390 6. Discussion

392

6.1 Monitoring and assessment of snow cover and snow albedo

393 Spatio-temporal analysis of MODIS-derived SCE, SAL, SCD, and SCI data revealed significant 394 changes during the observation period of this study. Key to the interpretation of these results is the 395 quantification of sensor related errors and their influence on the trends observed (2000–2016). 396 Unfortunately, only a few validation studies of the MOD10A1 C6 products have been published to 397 date. Recent studies using MOD10A1 collection C6 for the Greenland ice sheet however found that 398 v.C6 corrects for the C5 temporal trend bias in dry snow areas and that albedo retrieval accuracy in C6 399 is substantially improved over C5 (Box et al. 2017; Casey et al. 2017). Therefore, the accuracy of this 400 product is expected to be better than or at least as good as the C5 product, which has been evaluated in 401 several previous studies (Tekeli et al. 2005; Hall and Riggs 2007; Gao et al. 2010; Arsenault et al. 402 2014; Marchane et al. 2015). These studies estimate an overall detection error ranging from ~ 5 % to 403 ~48 %, depending on locational properties and type of 'ground truth' observations used. In general, 404 spatially homogeneous locations with flat terrain produces less error than in complex terrain with 405 mixed surface as being the case for this study (Wang et al. 2014; Burakowski et al. 2015; Moustafa et 406 al. 2017). By applying a per-pixel temporal change analysis approach in the current study, thereby 407 avoiding direct inter-comparison of pixels characterized by different slope/aspect, the influence of 408 topography is expected to be reduced to some degree. This should also be seen in the context of the latitudinal location of the study area (32°50'- 34°5050' S), characterized by an annual range in solar 409 410 zenith angles of 28-60 for MODIS overpass times. This makes the region less prone to influences from 411 mountain shadowing as compared to complex terrain of higher latitudes of the northern/southern 412 hemisphere. Snow detection in v.6 is expected to show improvements in comparison to previous 413 versions especially above 1.300 m a.s.l., where the surface temperature screen used in the product 414 algorithm (which has previously caused false negatives) has been rolled back leaving fewer gaps in the 415 data (Hall and Riggs 2016).

The smoothed and gap-filled MOD10A1 C6 dataset produced with TIMESAT is assumed to correctly represent the seasonal snow distribution for the area. Here, only the best quality MOD10A1 C6 observations (by including information available from the QA flags; 0="best quality") were used for the Savitzky-Golay function fitting in TIMESAT. By adjusting the data fitting to the upper envelope of the daily observations, we ensured that the SCE and SAL values follow rapid changes,

421 which can occur in snow cover extent and albedo. The TIMESAT model uses local function fitting, 422 where values before and after in the time series are considered. This local function fitting reduces the 423 chance of error occurrence in the MOD10A1 observed snow cover (Tekeli et al. 2005). For the upper 424 ablation zones of glaciers, characterized by limited seasonal variability or year round snow SCE, it is 425 not possible to accurately assess seasonality variables and thereby SCD. In this case, a glacier mask 426 was applied based on SCE seasonal variability, in doing so, restricting the SCD analysis to non-427 glaciated areas (Fig. 7a). Out of all the pixels in the data series 24.2 % was filled with modeled data 428 from TIMESAT.

429 Snow albedo detection in mountainous environments from remotely sensed imagery can contain 430 large errors when measured on terrain with steep slopes. Validation of satellite or aerial imagery based 431 data using stationary point albedometers can also be challenging because of pronounced mixed pixel 432 and geolocation issues (Liang et al. 2005; Sorman et al. 2007; Mernild et al. 2015b; Box et al. 2017). 433 However, these issues are not likely to have significantly influenced the trends observed in this study as 434 the MOD10A1 pixels are measured in the same pixel location from year to year in a location where 435 seasonal variation in solar zenith angle influence is relatively low (annual range between 28-60 436 degrees) compared to higher latitudes of the northern/southern hemisphere. MOD10A1 snow albedo is 437 produced only for cloud free pixels with full snow cover (+50 %) indicating that for pixels 438 characterized by limited full snow cover observations seasonal fitting could have influenced the 439 accuracy of the TIMESAT generated data.

440

441 6.2 Analysis of climate variables

442 The analysis of the effect of local scale climatic variability presented in this study made use of 443 the only existing weather station EYE in the study area. Indeed, the use of a single station is not ideal 444 when comparing measurements with the spatially large-scale MOD10A1 dataset. Furthermore, given 445 the location of this weather station on the western side of the cordillera and the presence of distinct 446 climatic gradients (e.g. Mernild et al. 2016a), the data recorded is unlikely to be fully representative of 447 the study area as a whole. However, this scarce coverage of ground observations reflects the general 448 conditions for mountainous areas of the Andes and underlines the need for remotely sensed monitoring 449 methods.

Upward trends in MAAT have higher impact the lower the altitudes (mostly noticeable in the southern part of the study area) causing changes in onset and offset of snow seasons to be more sensitive to even small changes in temperature (Fig. 4). Low areas with small slope gradient show higher sensitivity to upward changes in MAAT in regards to snow accumulation. Especially the low elevated areas on the eastern side of the cordillera show the effect of increased MAAT.

Above 4,600 m a.s.l., SCD shows a considerable increase in variability (Fig. 7b). This however is not surprising as, in highly elevated zones where SCD can be dependent on localized terrain (slope and area of topographical shadow) and weather conditions. High wind speeds, for example, often make it less likely for snow cover to persist in certain areas despite high levels of solid precipitation.

459

460 *6.3 Drivers of change on snow cover variables*

461 Studies based on modeling, field measurements and remote sensing have provided insights into 462 the past, current, and future impacts of climate change on snow conditions and runoff in the Andean 463 river catchments of central Chile and Argentina (Pellicciotti et al. 2007; Apaloo et al. 2012; Delbart et 464 al. 2015; Mernild et al. 2015a, 2016a, 2016c; Ragettli et al. 2016). A number of these studies have 465 predicted that air temperatures in the central Andes will continue to increase. An increase in air 466 temperature, together with seasonal changes in precipitation patterns, will likely result in a decrease in 467 the amount of runoff from snow melt and an increase in the amount of runoff from rain (Cai et al. 468 2014; Mernild et al. 2016a, 2016c; Ragettli et al. 2016). Since the 1970's, precipitation events have 469 generally become more intense but less frequent in central Chile (Falvey and Garreaud 2007; Garreaud 470 et al. 2009). The EYE precipitation data, for example, shows a number of intense precipitation events 471 (above 200 mm m⁻¹) during the 2000–2009 period. Interestingly, none of these 'intense' events 472 occurred during the 2010–2016 period.

473 Per-pixel correlations between SCE/SAL and the Multivariate El Niño index (MEI) show that 474 MEI has a strong and significant impact on inter-annual SCE/SAL variability in the region (Fig. 11). 475 Although El Niño events are often associated with increases in precipitation, they can also be 476 associated with increases in air temperature (Cai et al. 2014) which, together, can have a pronounced 477 altitude dependent effect on snow cover during spring and autumn. An increase in air temperature, for 478 example, causes the 0°C isotherm to ascend to higher elevations resulting in a larger proportion of 479 precipitation falling as rain as opposed to snow. Mernild et al. (2016c) observed this phenomenon for

the Olivares basin (33°12' S; 70°09' W) between 1979 and 2014, where precipitation has been increasingly falling as rain in recent years. This change in the partitioning of precipitation over mountainous areas can offset the positive effects of increased precipitation on snow accumulation, with rainfall often enhancing snow and ice melt rates on glacier surfaces. The significant spatial variation in correlation between MEI and SCE for one-month lag, we suspect is caused by the presence of snow cover on glaciers giving negative or no correlation on short term but increasing correlations with time.

486 Reduction in SCE in this study has also been studied in modelling studies based on MERRA 487 satellite data (Mernild et al. 2016b, 2016c) which estimate that snow cover extent in the central Andes 488 has reduced ~1.3% per decade 2000–2014 (linear trend, for the b1 window in Fig. 1) (Mernild et al. 489 2016b). Mernild et al. (2016c) suggest that the largest decreases in snow cover have occurred within 490 the 3,000–5,000 m a.s.l. elevation range, where more than 70 % of seasonal precipitation falls as snow. 491 In comparison, the rate of SCE change observed in this study for the same period and area is 492 significantly higher, with per decade reductions equating to $\sim 2.8\%$. This difference between the results 493 presented here and in Mernild et al. (2016c) may either be an indicator of faster SCE reduction during 494 the 2000–2016 period or highlight possible SCE overestimations in the MERRA model utilized by the 495 latter. For other regions of the world snow cover reductions are well documented. In the Arctic, for 496 example, a general decease in the amount of snow has been observed between 1999 and 2009, together 497 with reductions in maximum winter snow water equivalent, a later snow-cover onset in autumn and earlier snow-free date in spring, and a decreasing snow-cover duration (Liston and Hiemstra 2011). 498 499 To sustain all year runoff, rivers of the central Andes rely on substantial contributions from snow and 500 ice-melt, and river discharge here is strongly linked to snow cover changes (Delbart et al. 2015). 501 Decreases in SCE at the magnitudes shown in this study has the potential to cause a substantial 502 redistribution in seasonal runoff for this region, where ~21 % of river runoff originates from snow- and 503 ice- melt (increasing to ~85 % during dry summers) (Peña and Nazarala 1987; Mernild et al. 2016a). 504 Glaciers in the central Andes are shrinking and down wasting as a consequence of climate warming and 505 changes in precipitation patterns (Masiokas et al. 2006; Bodin et al. 2010; Gacitua et al. 2015; Malmros 506 et al. 2016). Although initially increasing, ice melt runoff will begin to reduce in the future as lowest 507 elevation land ice disappears. If these ice/snow cover trends continue, runoff conditions will likely 508 change, especially during spring, dry summers and periods of drought, affecting the future 509 sustainability of freshwater resources in areas downstream of the central Andes (Peña and Nazarala

510 1987; Delbart et al. 2015; Saavedra et al. 2016; Carey et al. 2017; López-Moreno et al. 2017). Whether
511 this change in runoff will cause the low lying areas in the catchment to become wetter or drier is
512 largely determined by local topography (Polk et al. 2017, López-Moreno et al. 2017).

513 Directly influencing the surface energy balance, the downward trends in SAL revealed in this 514 study (Fig. 4) may possibly result in positive feedbacks in regards to snow and ice melt. This trend of 515 darkening surfaces, either from reduced snow cover or from enhanced melt conditions, is likely to be 516 reinforced by increasing air temperatures and decreasing precipitation (e.g., Mernild et al. 2016c). 517 Another positive feedback could be initiated by the accumulation of dust and debris on glacier surfaces 518 leading to more energy being absorbed and further melt conditions, especially on lower parts of 519 glaciers (Hansen and Nazarenko 2004; Oerlemans et al. 2009; Arenson et al. 2015). Minimum glacier-520 wide albedo has shown to be a good predictor for glacier mass balances conditions for temperate 521 glaciers (López-Moreno et al. 2017; Polk et al. 2017), which suggests that glaciers in the study area 522 may have positive mass balances, at least for some of the years analyzed. Decreases in surface albedo 523 have also been observed for many other glaciated parts of the world (Box et al. 2012; Tedesco et al. 524 2013; Abermann et al. 2014; Fausto et al. 2015; Mernild et al. 2015b). The mean albedo for the 525 Greenland ice sheet ablation area (June-August), for example, declined by 22.9 % from 2000 to 2016 526 while dry snow areas only decreased by 1.2 % (Box et al. 2017). Increasing albedo values seen above 527 4.600 m a.s.l. (Fig. 5.) are likely contributed to by the increase in precipitation and the presence of dry 528 snow conditions at high altitudes (Box et al. 2017).

The central Andes are dominated by two distinctly different climate systems. On the western side of the Cordillera the climate is influenced by oceanic atmospheric interactions, whereas on the eastern side the climate can be considered continental in type (Prohaska 1976). This difference in climate is highlighted in this study by the relatively weak correlation between SCE/SAL and MEI on the eastern side of the Cordillera compared to the west. A higher inter-annual variability in SCE and SCI and more downward trend on the eastern part may be contributed to continental climate conditions (Fig. 9) as also observed in Saavedra et al. 2017.

536

537 7. Conclusions and outlook

538 Overall, snow cover extent (SCE) and snow albedo (SAL) decreased by 13.4 ± 4 % and 7.4 ± 2 539 %, respectively, between 2000 and 2016. SCE showed more downward trends on the eastern side of the 540 Andes Cordillera (13.9 \pm 4 %), while SAL showed a uniform decline thrughout the area. A seasonal 541 analysis revealed downward trends in SCE and SAL for all months of the year, with the largest 542 decreases occuring during the onset (for SCE and SAL) and at the end of the snow seasons (for SCE) 543 $(> 1\% \text{ yr}^{-1})$. SCE showed a near linear increase with elevation (r²=0.96, p < 0.01), and largest relative 544 losses occuring at elevations above 4.600 m a.s.l. outside glaciated areas. Spatial analysis of the SAL 545 data revealed increasingly downward trends up to \sim 4,600 m a.s.l. in elevation. Above \sim 4,600 m a.s.l. 546 this trend is reversed, likely because of permanent or semi-permanent dry snow conditions present in 547 glacier accumulation zone. Snow cover duration (SCD) decreased on average by 43 ± 20 days 548 throughout the study area between 2000 and 2016 with largest changes occuring at elevations below 549 4.500 m a.s.l. on the eastern side and 3.500 m a.s.l. on the western side.

TIMESAT was unable to extract SCD for glacier areas that were covered with snow for most of the year due to the lack of seasonal variation. Additionally, in situations of large variations in snow conditions occuring over a very short time period the Savitzky-Golay seasonal fitting process applied may introduce some errors. SCD trends for the study area indicate a shortening of the snow season between 2000 and 2016. SCI trends for the included glacial areas were also shown to be downward during this 16-year observation period (these being more pronounced on the eastern side of the Cordillera).

557 The impact of ENSO events, which influence largescale precipitation and temperature patterns 558 in the study area, on the SCE, SCD, and SAL was shown to be evident. Per-pixel analyses revealed that 559 ENSO positively influences SCE/SAL values most strongly with a one-month time-lag. Data available 560 from the EYE meteorological station, between 2000 and 2016, reveals that the monthly SCE and SAL 561 values are primarly determined by variations in temperature, whilst monthly SCI values are determined 562 mostly by precipitation. If the observed decline in SCE persist in the coming years, it will likely result in a a seasonal redistribution of avaliable downstream freshwater which may cause future problems for 563 564 people and agriculture in the region.

565

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573 **References**:

- Abermann, J., Kinnard, C., & MacDonell, S. (2014). Albedo variations and the impact of clouds on
 glaciers in the Chilean semi-arid Andes. *Journal of Glaciology*, 60, 183-191
- Apaloo, J., Brenning, A., & Bodin, X. (2012). Interactions between Seasonal Snow Cover, Ground
 Surface Temperature and Topography (Andes of Santiago, Chile, 33.5°S). *Permafrost and Periglacial Processes*, 23, 277-291
- Arenson, L.U., Jakob, M., & Wainstein, P. (2015). Effects of Dust Deposition on Glacier Ablation and
 Runoff at the Pascua-Lama Mining Project, Chile and Argentina. In G. Lollino, A. Manconi, J.
- 581 Clague, W. Shan, & M. Chiarle (Eds.), *Engineering Geology for Society and Territory Volume*
- 582 *1: Climate Change and Engineering Geology* (pp. 27-32). Cham: Springer International
 583 Publishing
- Arsenault, K.R., Houser, P.R., & De Lannoy, G.J.M. (2014). Evaluation of the MODIS snow cover
 fraction product. *Hydrological Processes, 28*, 980-998
- 586 Benn, D.I., & Evans, D.J.A. (2010). *Glaciers and glaciation*. London: Hodder Education
- Bodin, X., Rojas, F., & Brenning, A. (2010). Status and evolution of the cryosphere in the Andes of
 Santiago (Chile, 33.5 degrees S.). *Geomorphology*, 118, 453-464
- Box, J.E., Fettweis, X., Stroeve, J.C., Tedesco, M., Hall, D.K., & Steffen, K. (2012). Greenland ice
 sheet albedo feedback: thermodynamics and atmospheric drivers. *The Cryosphere*, *6*, 821-839
- Box, J.E., Van As, D., Steffen, K., Fausto, R.S., Ahlstrøm, A.P., Citterio, M., & Andersen, S.B. (2017).
 Greenland, Canadian and Icelandic land-ice albedo grids (2000–2016). *Geol. Surv. Den. Greenl. Bull, 38,* 53-56
- Brock, B.W., Willis, I.C., & Sharp, M.J. (2000). Measurement and parameterization of albedo
 variations at Haut Glacier d'Arolla, Switzerland. *Journal of Glaciology*, *46*, 675-688
- 596 Burakowski, E.A., Ollinger, S.V., Lepine, L., Schaaf, C.B., Wang, Z., Dibb, J.E., Hollinger, D.Y., Kim,
- 597 J., Erb, A., & Martin, M. (2015). Spatial scaling of reflectance and surface albedo over a mixed-

- use, temperate forest landscape during snow-covered periods. Remote Sensing of Environment,
 158, 465-477
- 600 Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A.,
- 601 Santoso, A., McPhaden, M.J., Wu, L., England, M.H., Wang, G., Guilyardi, E., & Jin, F.-F.
- 602 (2014). Increasing frequency of extreme El Nino events due to greenhouse warming. *Nature*
- 603 *Clim. Change, 4*, 111-116
- Carey, M., Molden, O.C., Rasmussen, M.B., Jackson, M., Nolin, A.W., & Mark, B.G. (2017). Impacts
 of Glacier Recession and Declining Meltwater on Mountain Societies. *Annals of the American Association of Geographers*, 107, 350-359
- Casey, K.A., Polashenski, C.M., Chen, J., & Tedesco, M. (2017). Impact of MODIS sensor calibration
 updates on Greenland Ice Sheet surface reflectance and albedo trends. *The Cryosphere*, *11*,
- 609 1781-1795Cereceda-Balic, F., Palomo-Marín, M.R., Bernalte, E., Vidal, V., Christie, J., Fadic,
- K., Guevara, J.L., Miro, C., & Pinilla Gil, E. (2012). Impact of Santiago de Chile urban
 atmospheric pollution on anthropogenic trace elements enrichment in snow precipitation at
 Cerro Colorado, Central Andes. *Atmospheric Environment*, 47, 51-57
- Cornwell, E., Molotch, N.P., & McPhee, J. (2016). Spatio-temporal variability of snow water
 equivalent in the extra-tropical Andes Cordillera from distributed energy balance modeling and
- 615 remotely sensed snow cover. *Hydrology and Earth System Sciences*, 20, 411-430
- 616 Corripio, J.G., & Purves, R.S. (2006). Surface Energy Balance of High Altitude Glaciers in the Central
 617 Andes: The Effect of Snow Penitentes. *Climate and Hydrology in Mountain Areas* (pp. 15-27):
 618 John Wiley & Sons, Ltd
- 619 Cuffey, K.M., & Paterson, W.S.B. (2010). The Physics of Glaciers. Elsevier Science
- Dariane, A.B., Khoramian, A. & Santi, E. (2017). Investigating spatiotemporal snow cover variability
 via cloud-free MODIS snow cover product in Central Alborz Region. *Remote Sensing of Environment*, 202, 152-165.
- Delbart, N., Dunesme, S., Lavie, E., Madelin, M., & Goma, R. (2015). Remote sensing of Andean
 mountain snow cover to forecast water discharge of Cuyo rivers. *Journal of Alpine Research*,
 15
- Dozier, J., & Frew, J. (1981). Atmospheric Corrections to Satellite Radiometric Data over Rugged
 Terrain. *Remote Sensing of Environment*, 11, 191-205

- Dozier, J., Painter, T.H., Rittger, K., & Frew, J.E. (2008). Time-space continuity of daily maps of
 fractional snow cover and albedo from MODIS. *Advances in Water Resources*, *31*, 1515-1526
- Dubayah, R. (1992). Estimating Net Solar-Radiation Using Landsat Thematic Mapper and Digital
 Elevation Data. *Water Resources Research*, 28, 2469-2484
- Dumont, M., Gardelle, J., Sirguey, P., Guillot, A., Six, D., Rabatel, A., & Arnaud, Y. (2012). Linking
 glacier annual mass balance and glacier albedo retrieved from MODIS data. *The Cryosphere*, *6*,
 1527-1539
- Eastman, J.R. (2009). IDRISI Taiga guide to GIS and image processing. *Clark Labs Clark University*,
 Worcester, *MA*
- Eklundh, L., & Jönsson, P. (2015). TIMESAT: A Software Package for Time-Series Processing and
 Assessment of Vegetation Dynamics. In C. Kuenzer, S. Dech, & W. Wagner (Eds.), *Remote Sensing Time Series: Revealing Land Surface Dynamics* (pp. 141-158). Cham: Springer
 International Publishing
- Escobar, F., Casassa, G., & Pozo, V. (1995). Variaciones de un glaciar de Montaña en los Andes de
 Chile Central en las últimas dos décadas. *Bulletin de l'Institut français d'études andines, 24*,
 683-995
- Falvey, M., & Garreaud, R. (2007). Wintertime Precipitation Episodes in Central Chile: Associated
 Meteorological Conditions and Orographic Influences. *Journal of Hydrometeorology*, *8*, 171 193
- Falvey, M., & Garreaud, R.D. (2009). Regional cooling in a warming world: Recent temperature trends
 in the southeast Pacific and along the west coast of subtropical South America (1979-2006). *Journal of Geophysical Research-Atmospheres*, 114
- Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M.,
 Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M.,
 Burbank, D., & Alsdorf, D. (2007). The Shuttle Radar Topography Mission. *Reviews of Geophysics*, 45, n/a-n/a
- Fausto, R.S., van As, D., Antoft, J.A., Box, J.E., Colgan, W., & Team, P.P. (2015). Greenland ice sheet
 melt area from MODIS (2000-2014). *Geological Survey of Denmark and Greenland Bulletin*,
 57-60

- Gacitua, G., Uribe, J.A., R., W., Loriaux, T., Hernandez, J., & Rivera, A. (2015). 50MHz helicopterborne radar data for determination of glacier thermal regime in the central Chilean Andes. *Annals of Glaciology*, 56
- Gao, Y., Xie, H.J., Yao, T.D., & Xue, C.S. (2010). Integrated assessment on multi-temporal and multi sensor combinations for reducing cloud obscuration of MODIS snow cover products of the
 Pacific Northwest USA. *Remote Sensing of Environment*, 114, 1662-1675
- Gardner, A.S., & Sharp, M.J. (2010). A review of snow and ice albedo and the development of a new
 physically based broadband albedo parameterization. *Journal of Geophysical Research-Earth Surface, 115*
- Garreaud, R.D., Vuille, M., Compagnucci, R., & Marengo, J. (2009). Present-day South American
 climate. *Palaeogeography Palaeoclimatology Palaeoecology*, 281, 180-195
- Gurung, D. R., Maharjan, S. B., Shrestha, A. B., Shrestha, M. S., Bajracharya, S. R. and Murthy, M. S.
 R. (2017). Climate and topographic controls on snow cover dynamics in the Hindu Kush
 Himalaya. *Int. J. Climatol.*, 37: 3873–3882.
- Hall, D.H., & Riggs, G. (2016). MODIS/Terra Snow Cover Daily L3 Global 500m Grid, Version 6. In
 National Snow and Ice Data Center (NSIDC) (Ed.). Boulder, Colorado USA: NASA
- Hall, D.K., & Riggs, G.A. (2007). Accuracy assessment of the MODIS snow products. *Hydrological Processes, 21*, 1534-1547
- Hall, D.K., Riggs, G.A., & Salomonson, V.V. (1995). Development of methods for mapping global
 snow cover using moderate resolution imaging spectroradiometer data. *Remote Sensing of Environment, 54*, 127-140
- Hall, D.K., Riggs, G.A., Salomonson, V.V., DiGirolamo, N.E., & Bayr, K.J. (2002). MODIS snowcover products. *Remote Sensing of Environment*, 83, 181-194
- Hansen, J., & Nazarenko, L. (2004). Soot climate forcing via snow and ice albedos. *Proceedings of the National Academy of Sciences of the United States of America, 101*, 423-428
- Hock, R. (2005). Glacier melt: a review of processes and their modelling. *Progress in Physical Geography*, 29, 362-391
- Huang, X., Deng, J., Wang, W., Feng, Q. & Liang, T. (2017). Impact of climate and elevation on snow
 cover using integrated remote sensing snow products in Tibetan Plateau. *Remote Sensing of Environment*, 190, 274-288.

- Jönsson, P., & Eklundh, L. (2002). Seasonality extraction by function fitting to time-series of satellite
 sensor data. *Ieee Transactions on Geoscience and Remote Sensing*, 40, 1824-1832
- Jönsson, P., & Eklundh, L. (2004). TIMESAT a program for analyzing time-series of satellite sensor
 data. *Computers & Geosciences*, 30, 833-845
- Justice, C.O., Vermote, E., Townshend, J.R.G., Defries, R., Roy, D.P., Hall, D.K., Salomonson, V.V.,
- 692 Privette, J.L., Riggs, G., Strahler, A., Lucht, W., Myneni, R.B., Knyazikhin, Y., Running, S.W.,
- 693 Nemani, R.R., Wan, Z.M., Huete, A.R., van Leeuwen, W., Wolfe, R.E., Giglio, L., Muller, J.P.,
- 694 Lewis, P., & Barnsley, M.J. (1998). The Moderate Resolution Imaging Spectroradiometer
- 695 (MODIS): Land remote sensing for global change research. *Ieee Transactions on Geoscience* 696 *and Remote Sensing*, *36*, 1228-1249
- 697 Kendall, M.G. (1975). Rank Correlation Methods. London: Griffin
- Klein, A.G., & Stroeve, J. (2002a). Development and validation of a snow albedo algorithm for the
 MODIS instrument. *Annals of Glaciology, Vol 34, 2002, 34*, 45-52
- Klein, A.G., & Stroeve, J. (2002b). Development and validation of a snow albedo algorithm for the
 MODIS instrument. *Annals of Glaciology*, *34*, 45-52
- Knap, W.H., Brock, B.W., Oerlemans, J., & Willis, I.C. (1999). Comparison of Landsat TM-derived
 and ground-based albedos of Haut Glacier d'Arolla, Switzerland. *International Journal of Remote Sensing*, 20, 3293-3310
- Konzelmann, T., & Ohmura, A. (1995). Radiative Fluxes and Their Impact on the Energy-Balance of
 the Greenland Ice-Sheet. *Journal of Glaciology*, *41*, 490-502
- Leiva, J.C. (1999). Recent fluctuations of the Argentinian glaciers. *Global and Planetary Change*, 22,
 169-177
- Li, C., Su, F., Yang, D., Tong, K., Meng, F. and Kan, B. (2017). Spatiotemporal variation of snow
 cover over the Tibetan Plateau based on MODIS snow product, 2001–2014. *Int. J. Climatol.*doi:10.1002/joc.5204
- Li, X., Fu, W., Shen, H., Huang, C. & Zhang, L. (2017). Monitoring snow cover variability (2000–
- 2014) in the Hengduan Mountains based on cloud-removed MODIS products with an adaptive
 spatio-temporal weighted method. *Journal of Hydrology*, *551*, 314-327.
- Liang, S.L., Stroeve, J., & Box, J.E. (2005). Mapping daily snow/ice shortwave broadband albedo from
 Moderate Resolution Imaging Spectroradiometer (MODIS): The improved direct retrieval

- algorithm and validation with Greenland in situ measurement. *Journal of Geophysical Research-Atmospheres*, 110
- Liston, G.E., & Hiemstra, C.A. (2011). The Changing Cryosphere: Pan-Arctic Snow Trends (1979–2009). *Journal of Climate*, *24*, 5691-5712
- López-Moreno, J.I., Valero-Garcés, B., Mark, B., Condom, T., Revuelto, J., Azorín-Molina, C., Bazo,
 J., Frugone, M., Vicente-Serrano, S.M., & Alejo-Cochachin, J. (2017). Hydrological and
 depositional processes associated with recent glacier recession in Yanamarey catchment,
 Cordillera Blanca (Peru). *Science of the Total Environment*, *579*, 272-282
- Lyapustin, A., Wang, Y., Xiong, X., Meister, G., Platnick, S., Levy, R., Franz, B., Korkin, S., Hilker,
 T., Tucker, J., Hall, F., Sellers, P., Wu, A., & Angal, A. (2014). Scientific impact of MODIS C5
- calibration degradation and C6+ improvements. *Atmos. Meas. Tech.*, 7, 4353-4365
- Male, D.H., & Granger, R.J. (1981). Snow Surface-Energy Exchange. *Water Resources Research*, 17,
 609-627
- Malmros, J.K., Mernild, S.H., Wilson, R., Yde, J.C., & Fensholt, R. (2016). Glacier area changes in the
 central Chilean and Argentinean Andes 1955-2013/14. *Journal of Glaciology*, *62*, 391-401

732 Mann, H.B. (1945). Nonparametric Tests Against Trend. Econometrica, 13, 245-259

Marchane, A., Jarlan, L., Hanich, L., Boudhar, A., Gascoin, S., Tavernier, A., Filali, N., Le Page, M.,
Hagolle, O., & Berjamy, B. (2015). Assessment of daily MODIS snow cover products to
monitor snow cover dynamics over the Moroccan Atlas mountain range. *Remote Sensing of Environment*, 160, 72-86

Masiokas, M.H., Christie, D.A., Le Quesne, C., Pitte, P., Ruiz, L., Villalba, R., Luckman, B.H.,
Berthier, E., Nussbaumer, S.U., González-Reyes, Á., McPhee, J., & Barcaza, G. (2016).
Reconstructing the annual mass balance of the Echaurren Norte glacier (Central Andes, 33.5° S)

vising local and regional hydroclimatic data. *The Cryosphere*, *10*, 927-940

- Masiokas, M.H., Villalba, R., Luckman, B.H., Le Quesne, C., & Aravena, J.C. (2006). Snowpack
 variations in the central Andes of Argentina and Chile, 1951-2005: Large-scale atmospheric
 influences and implications for water resources in the region. *Journal of Climate, 19*, 63346352
- McClung, D.M. (2013). The effects of El Niño and La Niña on snow and avalanche patterns in British
 Columbia, Canada, and central Chile. *Journal of Glaciology*, *59*, 783-792

- 747 Mernild, S.H., Beckerman, A.P., Yde, J.C., Hanna, E., Malmros, J.K., Wilson, R., & Zemp, M.
- (2015a). Mass loss and imbalance of glaciers along the Andes Cordillera to the sub-Antarctic
 islands. *Global and Planetary Change*, *133*, 109-119
- Mernild, S. H., Liston, G. E., Hiemstra, C. A., Beckerman, A. P., Yde, J. C., and McPhee, J. (2016b).
 The Andes Cordillera. Part IV: Spatiotemporal freshwater runoff distribution to adjacent seas
 (1979–2014). *International Journal of Climatology*, 37(7), 3175–3196
- Mernild, S. H., Liston, G. E., Hiemstra, C. A., Malmros, J. K., Yde, J. C., and McPhee, J. (2016a). The
 Andes Cordillera. Part I: Snow Distribution, Properties, and Trends (1979–2014). *International Journal of Climatology*, 37(4), 1680–1698
- Mernild, S. H., Liston, G. E., Hiemstra, C. A., Yde, J. C., McPhee, J., and Malmros, J. K. (2016c). The
 Andes Cordillera. Part II: Rio Olivares Basin Snow Conditions (1979–2014), Central Chile.
 International Journal of Climatology, 37(4), 1699–1715.,
- Mernild, S.H., Liston, G.G., Kane, D.L., Knudsen, N.F., & Hasholt, B. (2008). Snow, runoff, and mass
 balance modeling for the entire Mittivakkat Glacier (1998-2006), Ammassalik Island, SE
 Greenland. *Geografisk Tidsskrift-Danish Journal of Geography*, 108, 121-136
- Mernild, S.H., Malmros, J.K., Yde, J.C., Wilson, R., Knudsen, N.T., Hanna, E., Fausto, R.S., & van
 As, D. (2015b). Albedo decline on Greenland's Mittivakkat Gletscher in a warming climate.
 International Journal of Climatology, 35, 2294-2307
- Meza, F.J., Wilks, D.S., Gurovich, L., & Bambach, N. (2012). Impacts of Climate Change on Irrigated
 Agriculture in the Maipo Basin, Chile: Reliability of Water Rights and Changes in the Demand
 for Irrigation. *Journal of Water Resources Planning and Management, 138*, 421-430
- Montecinos, A., & Aceituno, P. (2003). Seasonality of the ENSO-related rainfall variability in central
 Chile and associated circulation anomalies. *Journal of Climate, 16*, 281-296
- Moustafa, S.E., Rennermalm, A.K., Román, M.O., Wang, Z., Schaaf, C.B., Smith, L.C., Koenig, L.S.,
 & Erb, A. (2017). Evaluation of satellite remote sensing albedo retrievals over the ablation area
 of the southwestern Greenland ice sheet. *Remote Sensing of Environment*, *198*, 115-125
- Oerlemans, J., Giesen, R.H., & Van den Broeke, M.R. (2009). Retreating alpine glaciers: increased
 melt rates due to accumulation of dust (Vadret da Morteratsch, Switzerland). *Journal of*
- 775 *Glaciology*, *55*, 729-736

- Neckel, N., Loibl, D., & Rankl, M. (2017). Recent slowdown and thinning of debris-covered glaciers in
 south-eastern Tibet. *Earth and Planetary Science Letters*, 464, 95-102
- Pellicciotti, F., Burlando, P., & Van Vliet, K. (2007). Recent trends in precipitation and streamflow in
 the Aconcagua River basin, central Chile Glacier mass balance changes and meltwater
 discharge. In, *Foz do Iguaçu*. International Association of Hydrological Sciences: IAHS
- Peña, H., & Nazarala, B. (1987). Snowmelt-Runoff Simulation Model of a Central Chile Andean Basin
 with Relevant Orographic Effects. In, *International Association of Hydrological Sciences (IAHS).* Vancouver, Canada: IAHS
- Pfeffer, W.T., Arendt, A.A., Bliss, A., Bolch, T., Cogley, J.G., Gardner, A.S., Hagen, J.-O., Hock, R.,
- Kaser, G., Kienholz, C., Miles, E.S., Moholdt, G., Mölg, N., Paul, F., Radi, Valentina, Rastner,
 P., Raup, B.H., Rich, J., & Sharp, M.J. (2014). The Randolph Glacier Inventory: a globally
 complete inventory of glaciers. *Journal of Glaciology*, *60*, 537-552
- Polk, M.H., Young, K.R., Baraer, M., Mark, B.G., McKenzie, J.M., Bury, J., & Carey, M. (2017).
 Exploring hydrologic connections between tropical mountain wetlands and glacier recession in
 Peru's Cordillera Blanca. *Applied Geography*, 78, 94-103
- Prohaska, F. (1976). The climate of Argentina, Paraguay and Uruguay. In W. Schwerdfeger (Ed.),
 World Survey of Climatology (pp. 13 112). New York: Elesevier
- Ragettli, S., Immerzeel, W.W., & Pellicciotti, F. (2016). Contrasting climate change impact on river
 flows from high-altitude catchments in the Himalayan and Andes Mountains. *Proceedings of the National Academy of Sciences of the United States of America*, 113, 9222-9227
- Riggs, G.A., Hall, D.K. & Román, M.O. (2017) Overview of NASA's MODIS and Visible Infrared
 Imaging Radiometer Suite (VIIRS) snow-cover Earth System Data Records. *Earth Syst. Sci. Data*, 9, 765-777.
- Rittger, K., Painter, T.H., & Dozier, J. (2013). Assessment of methods for mapping snow cover from
 MODIS. *Advances in Water Resources*, *51*, 367-380
- Rutllant, J., & Fuenzalida, H. (1991). Synoptic Aspects of the Central Chile Rainfall Variability
 Associated with the Southern Oscillation. *International Journal of Climatology*, 11, 63-76
- Saavedra, F.A., Kampf, S.K., Fassnacht, S.R., & Sibold, J.S. (2016). A snow climatology of the Andes
 Mountains from MODIS snow cover data. *International Journal of Climatology*

- Saavedra1, F.A., Kampf, S.k., Fassnacht, S.R., and Sibold, J.S. Changes in Andes Mountains snow
 cover from MODIS data 2000-2014. *The Cryosphere Discuss.*, https://doi.org/10.5194/tc-201772, in review, 2017.
- Savitzky, A., & Golay, M.J.E. (1964). Smoothing and Differentiation of Data by Simplified Least
 Squares Procedures. *Analytical Chemistry*, *36*, 1627-1639
- Sirguey, P., Still, H., Cullen, N.J., Dumont, M., Arnaud, Y., & Conway, J.P. (2016). Reconstructing the
 mass balance of Brewster Glacier, New Zealand, using MODIS-derived glacier-wide albedo. *The Cryosphere*, 10, 2465-2484
- Sorman, A.U., Akyurek, Z., Sensoy, A., Sorman, A.A., & Tekeli, A.E. (2007). Commentary on
 comparison of MODIS snow cover and albedo products with ground observations over the
 mountainous terrain of Turkey. *Hydrology and Earth System Sciences*, 11, 1353-1360
- Tedesco, M., Fettweis, X., Mote, T., Wahr, J., Alexander, P., Box, J.E., & Wouters, B. (2013).
 Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional
 climate model and reanalysis data. *The Cryosphere*, 7, 615-630
- Tekeli, A.E., Akyürek, Z., Arda Şorman, A., Şensoy, A., & Ünal Şorman, A. (2005). Using MODIS
 snow cover maps in modeling snowmelt runoff process in the eastern part of Turkey. *Remote Sensing of Environment*, 97, 216-230
- Vuille, M., Kaser, G., & Juen, I. (2008). Glacier mass balance variability in the Cordillera Blanca, Peru
 and its relationship with climate and the large-scale circulation. *Global and Planetary Change*,
 62, 14-28
- Wang, Z., Schaaf, C.B., Strahler, A.H., Chopping, M.J., Román, M.O., Shuai, Y., Woodcock, C.E.,
 Hollinger, D.Y., & Fitzjarrald, D.R. (2014). Evaluation of MODIS albedo product (MCD43A)
 over grassland, agriculture and forest surface types during dormant and snow-covered periods. *Remote Sensing of Environment*, 140, 60-77
- Warren, S.G., & Wiscombe, W.J. (1980). A Model for the Spectral Albedo of Snow. II: Snow
 Containing Atmospheric Aerosols. *Journal of the Atmospheric Sciences*, *37*, 2734-2745
- Wilson, R., Mernild, S.H., Malmros, J.K., Bravo, C., & CarriÓN, D. (2016). Surface velocity
 fluctuations for Glaciar Universidad, central Chile, between 1967 and 2015. *Journal of Glaciology*, 62, 847-860

- Wiscombe, W.J., & Warren, S.G. (1980). A Model for the Spectral Albedo of Snow. I: Pure Snow. *Journal of the Atmospheric Sciences*, *37*, 2712-2733
- Wolter, K., & Timlin, M.S. (2011). El Niño/Southern Oscillation behaviour since 1871 as diagnosed in
 an extended multivariate ENSO index (MEI.ext). *International Journal of Climatology, 31*,
 1074-1087
- Xu, W., Ma, H., Wu, D. & Yuan, W. (2017). Assessment of the Daily Cloud-Free MODIS Snow-Cover
 Product for Monitoring the Snow-Cover Phenology over the Qinghai-Tibetan Plateau. *Remote Sensing*, 9, 585.