Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-357, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 20 September 2016

Snow cover dynamics in Andean watersheds of Chile (32.0-39.5°S) during the years 2000 - 2013

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Abstract. Andean watersheds present important snowfall accumulation mainly during the winter which is later melted during spring and part of the summer. The effect of snowmelt on the water balance can be critical to sustain agriculture activities, hydropower generation, urban water supply and wildlife. In Chile 25% of the territory between the Valparaiso and Araucanía Regions comprise areas where snow precipitation occurs. As in many other difficult-to-access regions of the world, in the Chilean Andes there is a lack of hydrological data like discharge, snow courses, snow depths, which complicate the analysis of important hydrological processes (e.g. water availability). Remote sensing provides a promising opportunity to enhance the assessment and monitoring of the spatial and temporal variability of snow characteristics, like Snow Cover Area (SCA) and Snow Cover Dynamic (SCD). In the above mentioned context the objectives of this study are to evaluate the suitability of MOD10A2 to estimate SCA and to assess SCD at five watersheds (Aconcagua, Rapel, Maule, Biobío and Toltén) located in the Chilean Andes, between latitude 32.0ºS and 39.5ºS. Those watershed were chosen because their importance in terms of number of inhabitants, and dependence of economic activities on water resources. SCA area was obtained from MOD10A2 for the period 2000 – 2013 and SCD was analysed through a number of statistical tests to explore observed trends. Prior of obtaining SCA for trend analysis, a validation of MOD10A2 product was done; comparing presence of snow predicted by MODIS with ground observations. Results indicate that there is an overall agreement from 81 to 98% between SCA -determined from ground observations, and MOD10A2, showing that MODIS snow product can be taken as a feasible remote sensing tool for SCA estimation in South-Central Chile. Regarding SCD no significant reduction in SCA area for 2000 -2013 was detected, with the exception of the Aconcagua and Rapel watersheds, although an important decline in SCA for the period of 2012 and 2013 was also evident, which is coincident with the rainfall deficit for the same years. Findings were compared against ENSO episodes occurring during 2010 – 2013, detecting that Niña years are coincident with maximum SCA during winter in all watersheds.

1 Introduction

Snowmelt-driven watersheds are systems highly sensitive to climate change, because the hydrologic cycle depends on both precipitation and temperature, and because water is already a scarce resource subject to an ever increasing pressure for its use (Barnett et al. 2005, Vicuña et al. 2010, Meza et al. 2012, Valdés-Pineda et al. 2014). Snowmelt controls the shape of the annual hydrograph and affects the water balance at monthly and shorter time scales (Verbunt et al., 2003, Cortés et al. 2011). The effect of snowmelt on the water balance can be critical to sustain agriculture activities, hydropower generation, urban water supply and wildlife habitat quality (e.g. Vicuña et al. 2011 and 2012).

Andean watersheds present important snowfall accumulation mainly during the austral winter, and snow melt during spring and usually also part of the summer, depending on relative altitude and ambient temperature. At higher elevations a snowpack stores significant volumes of water, which is released to surface runoff and groundwater when solar radiation increases.

In particular, 25% of the Chilean territory between Valparaiso and Araucanía Regions is contained in areas where snow precipitation occur (DGA, 1995). As in many other difficult-to-access regions of the world, in the Chilean Andes there is lack of hydrological data like discharge data, snow courses, snow depths (Ragettli et al., 2013), which complicates the analysis of important hydrological processes and the validation of water quantity prediction models.

Remote sensing provides a promising opportunity to enhance the assessment and monitoring of the spatial and temporal variability of different variables involved in the precipitation-runoff processes in areas where data availability for hydrological modeling is scarce (Simic et al., 2004; Boegh et al., 2004; Melesse et al., 2007; Montzka et al., 2008; Milzowa et al., 2009, Er-Raki et al., 2010; Stehr et al., 2009 and 2010).

Satellite derived snow cover area from products like e.g.: NOAA-AVHRR or MODIS, can be used to enhance the assessment and monitoring of the spatial and temporal variability of snow characteristics (Lee et al., 2006; Li & Wang, 2010; Marchane et al., 2015; Wang et al., 2015), especially when combined with field data and snowpack models (Kuchment et al., 2010).

Specific spectral reflectance of snow (higher reflectance in the visible compared to the mid infrared electromagnetic spectrum) allows SCA to be accurately discriminated from snow free areas using optical remote sensing methods (in the absence of clouds or vegetation canopies). Compared with other remote sensing techniques such as microwave which can be used to map snow water equivalent (SWE), optical remote sensing which is used to map snow areal extent (SAE) has a much higher spatial resolution (Zhou et al., 2005; Zeinivand & De Smedt, 2009).

Previous studies have compared MODIS snow maps with ground observations and snow maps produced by The National Operational Hydrologic Remote Sensing Center, USA (NOHRSC) (Hall et al., 2002; Klein & Barnett, 2003; Tekeli et al., 2005; Aulta et al., 2006). A validation done by Klein & Barnett (2003), in a study on the Upper Rio Grande River Watershed, USA, showed an 86% agreement between the MODIS and NOHRSC snow maps. Klein & Barnett (2003) compared MODIS and NOHRSC products with ground observations (SNOTEL measurements), obtaining an overall accuracy of 94% and 76%, respectively. MOD10A1 and MOD10A2 snow products are capable of predicting with good precision (over 90%) the presence of snow when the sky is clear (Zhou et al., 2005; Liang et al., 2008a; Wang et al., 2008; Huang et al, 2011). When clouds are present, however, the accuracy of MOD10A1 (daily) decreases to 34 - 50% (Zhou et al., 2005; Liang et al., 2008a,b).

Regarding snow cover dynamics, Zhang et al. (2012) using MOD10A1 and MYD10A have studied SCD of four lake watersheds located at the Tibetan Plateau in Central Asia. Results indicate that spatial distribution and pattern of snow covered days are from year to year very stable, and that there is no trend of snow cover change for each watershed, which are in agreement with the results from Gao et al. (2011) for the northwest pacific region, USA. However, Tang et al. (2013) found a high inter-annual variability of SCA during 2001 to 2011 for the Tibetan plateau, with parts of the studied area showing a declining trend in SCA, and other parts showing increasing trends in SCA. Dietz et al. (2012) in their study of snow cover characteristics in Europe found some abnormal events when comparing the mean conditions with single snow cover seasons. In particular, for the season 2005/2006 an increased snow cover with a later snow cover melt was detected. Maskey et al. (2011) studied the trends and variability of snow cover changes in the Himalayan region above the 3000 m, showing a decreasing trend of snow cover during January and increasing trends during March. Marchane et al. (2015) studied the SCD over the Moroccan Atlas mountain range from 2000 until 2013 concluding that SCA has a strong inter-annual variability and that there is no statistical evidence of trend in that period. Wang et al. (2015) evaluated trends in SCA at the Tibetan Plateau, showing a decrease of snow covered areas from 2003 until 2010.

From the literature review it is evident that SCD is site-specific and exhibit high variability among the different sites around the world. Since, the Andes are characterized by mean heights above 3000 m, with very steep slopes that produce an orographic effect that forces the rise of the western winds and condensation of moisture which is precipitated as rain or snow, SCD is difficult to assess even through remote sensing techniques whereby the validation process is strictly necessary. Indeed, one of the main sources of error in the classification of satellite images is the interpretation of topographic features especially in areas with rugged slopes. The irregular topography produces shading and lighting effects that change the radiometric response of the surface which depends on the local slope and its orientation (Riaño et al., 2003). As the climate controlling hydrologic processes in the Andes is influenced by El Niño events (Escobar y Aceituno 1993, Ayala et al. 2014), as well as warm winter storms (Garreaud 2013), assessment of SCD is of especial interest in this region. Pioneer studies have been presented in recent years for the Mataquito river watershed (De María et al. 2013, Vicuña et al. 2013). The aims of this study are to evaluate the suitability of MOD10A2 for estimation of SCA and to assess SCD at five watersheds located in the Chilean Andes, between latitude 32.0ºS and 39.5ºS.

2 Materials and methods

2.1 Study Sites

The study site includes five watersheds located in central and south Chile: Aconcagua, Rapel, Maule, Biobío and Toltén (figure 1). The watersheds were chosen considering their population, and dependence of economic activities on water resources.

The Aconcagua watershed is located in the Valparaiso region between the parallels 32°14′–33°09′S and 69º59′–71º33′W, with an area of 7340 km^2 and a maximum elevation of 5843 m a.m.s.l. Approximately 40% of the watershed lies above the snowline which is located at 2100 m (Garreaud, 1992). The climate in the watershed is temperate Mediterranean with a long dry season of 7 to 8 months, and a wet season of approximately 4 months (May–August) during which more than 80% of the precipitation occurs. The average annual precipitation is 529 mm. Principal economic activities at the watershed are agriculture, minning and industries, having a population of around 600000 inhabitants (4% of Chilean population).

The Rapel watershed is located in the General Libertador Bernardo O´Higgins region between the parallels 33°52′–35°00′S and 70º00′–71º53′W, having an area of 13695 km^2 and a maximum elevation of 5138 m a.m.s.l.. Approximately 30% of the watershed lies above the snowline which is located at 1500 m (Peña y Vidal, 1993). The climate in the watershed is temperate Mediterranean, with a dry season of 4 to 5 months (November–March), and a wet season of approximately 4 months (May–August) during which more than 75% of the precipitation occurs. The average annual precipitation is 960 mm. Main economic activities at the watershed are agriculture and minning, having a population of around 570000 inhabitants (3.8 % of Chilean population).

The Maule watershed is located in the Maule region between the parallels 35°05′–36°35′S and 70º18′–72º42′W, having an area of 20295 km^2 and a maximum elevation of 3931 m a.m.s.l.. Approximately 32% of the watershed lies above the snowline which is located at 1150 m (Peña y Vidal, 1993). The climate in the watershed is temperate Mediterranean, with a dry season of 6 months (November–April), and a wet season of approximately 4 months (May–August) during which more than 75% of the precipitation occurs. The average annual precipitation is 1471 mm. Main economic activity at the watershed is agriculture, having a population of around 410000 inhabitants (2.7 % of Chilean population).

The Biobío watershed is located in the Biobio region between the parallels 36°45′–38°49′S and 71º00′–73º20′W, having an area of 24264 km^2 and a maximum elevation of 3487 m a.m.s.l.. Approximately 41% of the watershed lies above the snowline which is located at 850 m (Peña y Vidal, 1993). The climate in the watershed is Mediterranean, with a dry season of 5 months (November–March), and a wet season of approximately 4 months (May–August) during which more than 55% of the precipitation occurs. The average annual precipitation is 1891 mm. Principal economic activities related to water resources at the watershed are agriculture, forestry and industries, having a population of around 630000 inhabitants (4.2 % of Chilean population).

The Toltén watershed is located in the Araucanía region between the parallels 38°32′–39°38′S and 71º21′–73º16′W, having an area of 8398 km^2 and a maximum elevation of 3710 m a.m.s.l.. Approximately 37% of the watershed lies above the snowline which is located at 750 m (Peña y Vidal, 1993). The climate in the watershed is temperate rainforest with Mediterranean influence, characterize by precipitation throughout the year but the having less rain during the summer months than the winter ones. The average annual precipitation is 2870 mm. Main economic activities related to water resources at the watershed are truism, agriculture and forestry, having a population of around 170000 inhabitants (1.1 % of Chilean population).

2.2 Ground observations of SCA

For validation of MOD10A2 ground observations at two specific sites were performed, including continuous monitoring of snow depth with meteorological stations, snow courses, and one-day observations of snow presence and depth at some mountain trails. Figure 2a shows the location of measuring sites.

2.2.1 Continuous monitoring of snow depth

In order to perform a continuous measurement of snow depth three meteorological stations were installed in the upper part of the Biobío watershed. The stations were Parque Tolhuaca, located at 900 m.a.s.l., Termas Malleco at 1190 m.a.s.l., and Laguna

Verde at 1410 m.a.s.l. Mean snow line elevation is around 850 m.a.s.l. (Peña &Vidal, 1993). Figure 2b shows the location of the meteorological stations.

Snow depth was measured using acoustic snow depth sensors (Campbell Scientific, SR50A) with a frequency of 15 min. Corrections for variation of the speed of sound in air were made considering the air temperature measured at the same time intervals as snow depth using the temperature and relative humidity probe (Vaisala, HMP60). The data were collected from April 2010 until December 2011 at Termas Malleco station and from July 2011 until December 2011 at Parque Tolhuaca and Laguna Verde stations. Snow data where grouped considering the average snow depth over 8 days (same 8 day period of MOD10A2) and then reclassify as snow (1) if the average snow depth was > 0 cm and no-snow (0) for snow depth = 0 cm.

2.2.2 One-day observation points

To cover a large spatial domain and thus achieve a better spatial and temporal representation of SCA a total of 114 different single measurements of snow depth were conducted during field campaigns at different mountain trails. Field measurements were taken from the end of June until the beginning of October 2011. The location of each observation point was recorded with a GPS and snow depth was measured with a Black Diamond QuickDraw Tour Probe 190. Figure 2c shows the location of the observation points and the date and number of observations for each day.

2.2.3 Snow courses

During six days of the winter season in 2011, eleven snow courses were conducted in the upper Malleco watershed. Figure 2d shows the location of snow courses. Each route was recorded with a GPS. Snow depth and density were measured with a Black Diamond QuickDraw Tour Probe 190 and Snow Sampling Tubes (3600 Federal Snow Tubes, Standard-Metric), respectively. Table 1 shows the dates and repetition times for each snow route conducted.

2.3 MODIS snow cover products

The Moderate Resolution Imaging Spectroradiometer (MODIS) is on the Earth Observing System, which employs a cross-track scan mirror and a set of individual detector elements to provide imagery of the Earth surface and clouds in 36 discrete and narrow spectral bands ranging in wavelength from 0.405 to 14.385 µm. It provides medium-to-coarse resolution imagery with a high temporal repeat cycle (1-2 days). The main purpose of MODIS is to facilitate the study of global vegetation and land cover, vegetation properties, global land surface changes, surface albedo, surface temperature as well as snow and ice cover, on a daily or nearly daily basis. The MODIS snow cover products are one of the many geophysical standard products derived from MODIS data. The MODIS snow cover products are provided both on a daily basis (MOD10A1) and as 8-day composites (MOD10A2) both at 500 m resolution over the Earth’s land surfaces. MOD10A1 consists of 1200 km by 1200 km tiles of 500 m resolution data gridded in a sinusoidal map projection and MOD10A2 is a composite of MOD10A1 especially produced to show maximum snow extent. For these study MOD10A2 were use. Classification of SCA using MODIS collected data is done based on the

Normalized Difference Snow Index (NDSI) (Hall et al., 1995, Klein et al., 1998, Riggs et al., 2006). Images were reprojected to WGS84 UTM 19S using the MODIS Reprojection Tool (MRT).

MODIS estimates of SCA were validated for the period between April 2010 and December 2011 by comparing them with ground observations. Eighty snow maps from MOD10A2 were analysed. Only cloud free observations for each cell of the map grid were used.

To validate the correspondence between the image classification and ground observations a confusion matrix was use (Congalton & Mead, 1983; Congalton, 1991; Foody, 2002). The confusion matrix is a simple cross tabulation of classified data versus observed ones providing a base for accuracy assessment (Campbell, 1996; Canters, 1997). This matrix will give the percentage of cases correctly allocated and the user's and producer's accuracy, depending on whether the calculations are based upon the matrix's row or column marginals (Campbell, 1996; Story & Congalton, 1986). The indexes are calculated as illustrated in figure 3.

2.4 Assessment of SCD

SCA variation in five selected watersheds was done using MOD10A2 for the period covering the years 2000 – 2013 using a total of 167 images. All images were processed in ArcGis reprojecting them to WGS84 19S and cutting the image according to the desired area, in this case for the Aconcagua, Rapel, Maule, Biobío and Toltén watersheds. SCA and clouds in was quantified in each image, and annual and seasonal averages of snow cover were calculated for each watershed.

SCD was analysed through a number of statistical tests to explore observed trends. The use of "nonparametric" statistical test was chosen, as they are more robust compared to "parametric" test. Mann-Kendall test was applied for determining existence of monotonic trends. Sen's method (Gilbert 1987) was applied to determine the rate of observed changes.

3 Results

The product MOD10A2 was validated for determination of SCA in the watersheds under study and the SCD was analysed.

3.1 Validation of MOD10A2 through ground observations

The composite images MOD10A2 where compared with ground observations. For the study period 23, 75, and 26 images where available for comparison with observations at Parque Tolhuaca, Termas Malleco, and Laguna Verde stations, respectively. Clouds were present in 2 (9%), 1 (1%), and 1 (4%) images for each aforementioned station, respectively. Table 2 shows the confusion matrix and indexes of agreement of the images with ground observations at Parque Tolhuaca, Termas Malleco, and Laguna Verde stations. For no-snow observations User's accuracy was higher (mean value at the three stations of 88%) than for snow observations (mean value at the three stations of 77%), while mean Producer's accuracy was 83% for no-snow observations, and 90% for snow observations. An overall accuracy of 86, 81, and 88% was observed at Parque Tolhuaca, Termas Malleco, and Laguna Verde stations, respectively, which meet the target of 85% (Thomlinson et al. 1999).

For comparison with one-day observations a total of 108 images corresponding to the study period were available, with none of them classified as covered by ‘clouds’. All ground observations were done over areas whit snow presence. When comparing it to MOD10A2 the agreement was of 96%. MODIS that did not coincide with ground observations occurred during the beginning of the snowfall season or the end of the melting period. In both cases, snow patches were observed in the field covering areas at the subpixel scale of the MOD10A2 image.

For comparison with snow-courses a total of 282 images were available during the study period, all of them without clouds. Ground observations were done on areas covered by snow only. The overall accuracy of MOD10A2 for predicting SCA was 98%.

Results indicate that MOD10A2 has a good agreement with ground observations, and thus the 8-days composite images are suitable for analysis of SCD in the Andean watersheds.

3.2 Assessment of SCD

Figure 4 shows the SCD at Aconcagua, Rapel, Maule, Biobío and Toltén watersheds for the period 2000-2013. All watersheds show the same SCD with more SCA in winter that the other seasons.

Figure 5 shows mean SCA for each season at Aconcagua, Rapel, Maule, Biobío and Toltén watersheds for the period 2000-2013. Northern watersheds i.e. Aconcagua and Rapel, present a higher SCA.

Figure 6 shows annual and seasonal trends of SCA at Aconcagua, Rapel, Maule, Biobío and Toltén watersheds. Trend analysis to the SCA series was performed with the nonparametric Mann-Kendall test. Decreasing trends in annual mean SCA are observed (p-value < 0.01) for the Aconcagua and Rapel watersheds, with a decreasing slope of 42 and 35 km^2/year, respectively (Figure 6a). No significant annual trend was observed for the other three watersheds. In autumn (Figure 6b) only the Aconcagua watershed shows a decreasing trend of mean SCA variation at a level of significance <= 0.05, with a decreasing slope of 65 km^2/year. In winter time (Figure 6c) only the Biobio watershed shows a trend of mean SCA variation at a level of significance <= 0.05, in this case the trend is positive with a slope of 157 km^2/year. At winter time no other watershed shows trend on SCA. At spring (Figure 6d) the Aconcagua and Rapel watershed have a decreasing trend at a level of significance <= 0.05, with a decreasing slope of 49 km^2/year and 53 km^2/year, respectively; data at the Maule watershed indicate a decreasing trend at a level of significance <= 0.1, with a decreasing slope of 86 km^2/year. At summer (Figure 6e) only the Aconcagua and Rapel watersheds shows some decreasing trends with level of significance <= 0.1 and 0.05, respectively and slopes of 17 km^2/year and 28 km^2/year. Important to remark is that both watersheds have important glacier areas. All above mentioned results are coincident with the outcomes given by the Pettitt homogeneity test which shows that both time series are not homogenous between two given times (p-value < 0.01).

Considering snow accumulation and melt seasons, data where grouped into two periods, i.e. autumn - winter (accumulation) and spring – summer (melt), for this two periods trend analysis was also done. Results indicated that there is a negative trend in mean SCA only for the Aconcagua watershed during the snow accumulation season (p-value < 0.01) with a decreasing slope of 28 km^2/year.

4 Discussion

In general terms we can say that MOD10A2 has a good agreement with ground observations, we found only some small disagreements between MOD10A2 and ground observations at Parque Tolhuaca station. This station is located close to the snowline where most of the time the soil is not covered by snow or is cover by snow for small time periods, in this case the presence of small snow patches is expected to be highly variable in time, even varying at the subdaily scale and thus reducing the capability of images to capture snow coverage when we are in the proximity of the snowline.

Regarding SCA, we can see on the results presented on Figures 4 and 5, that SCA has a similar behaviour in the different watersheds during the study period, i.e. all watersheds follow the same snow accumulation and melt dynamic and the maximum and minimum % of SCA are also coincident in time.

The SCA magnitude for each watershed was contrasted with historical data from El Niño/ La Niña Southern Oscillation (ENSO) episodes from 2000 – 2013[1]. Normal or neutral years correspond to historical conditions, as years Niño and Niña correspond to wet and dry years, respectively in the case of central and south of Chile. During 2000 and 2013 they were four episodes of El Niño (2002, 2004-2005, 2006 – 2007 and 2009) and three episodes of la Niña (1999 – 2000, 2007 – 2008 and 2010 – 2011).

Niña years are coincident with maximum SCA at winter time in all watersheds, with similar amounts of SCA between different Niña episodes. The 2007 Niña event is coincident with the highest % of SCA during winter for the study period (2000 – 2013) an all watersheds. Winter SCA for Niña and Niño episodes are all above or just at the mean SCA for the 14 years under study. Years under the mean of SCA area are all not coincident with Niña and Niño episodes, i.e. normal years are all under the mean SCA value.

During 2012 and 2013 an important decline in SCA can be perceived in most of the watershed, with exception of the Biobío watershed, where no difference can be seen. This decline is bigger at the Tolten watershed. Analyzing precipitation data we can see that in all watershed they was a rainfall deficit during 2012 and 2013, where deficit for 2012 and 2013 are in average the followings: Aconcagua 7% and 51%, Rapel 12% and 50%, Maule 28% and 36%, Biobío 22% and 38%, and finally at Toltén 35 % and 47 % (DGA, 2012, DGA, 2013, DMC, 2013, DMC, 2014).

5 Conclusions

The first validation of MODIS snow product MOD10A2 for estimation of snow covered areas (SCA) via remote sensing in watersheds located in the Southern Hemisphere is presented. Ground observations of SCA were conducted during the years 2010 and 2011 at six study sites including 3 meteorological stations, 116 one-day single-observation points, and 11 snow courses. The

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[1] http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

SCA was determined for 636 days from MODIS snow products and compared with the SCA measured in situ. The SCA estimated from MOD10A2 presented an overall agreement from 81 to 98% with SCA determined from ground observations, showing that MODIS snow product can be taken as a feasible remote sensing tool for SCA estimation in South-Central Chile.

By the other side we have analyze SCA trend for the period 2000 - 2013 in five of the most important watersheds of South-Central Chile in the context of water use and inhabitants, covering a longitudinal gradient from 32°14′S to 39°38′S, which implies different climates regarding precipitation, more drier in the northern part than at the south. Results indicate that all watersheds have the same SCD with more snow during winter time that decreases during spring and summer. Furthermore significant negative trend in annual mean SCA are observed for the Aconcagua and Rapel watersheds, which can have implication on water ability for summer time. In general we can see that there is no significant reduction in SCA for 2000 -2013, with the exception of the Aconcagua watershed. From the data we can appreciate an important decline in SCA for the period of 2012 and 2013, which is coextensive with the rainfall deficit we had for the same years.

The results where compare with ENSO episode during 2000 – 2013, we can conclude that for that period Niña years are coincident with maximum SCA at winter time in all watersheds, with similar amounts of SCA between different Niña episodes.

The results presented in this work are of importance and can be use as one feasible approximation to obtain SCA, particularly in Chilean Andes where there is lack of hydrological data like discharge data, snow courses, snow depths, etc., these can be a tool to improve the analysis of important hydrological processes and the validation of water quantity prediction models.

Acknowledgements

The present research was conducted in the framework of the FONDECYT 11100119 project and the FONDAP 15130015 project.

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Table 1: Dates and repetition times for each snow route

Snow route	Dates	Nº of times route was repeated
1	30-June	1
2	30-June	1
3	30-June, 19-July, 31-August, 14-September	4
4	1-July, 19-July, 31-August, 15-September	4
5	1-July	1
6	1-July	1
7	1-July	1
8	31-August, 15-September	2
9	1-September, 15-September	2
10	31-August, 14-September	2
11	31-August, 14-September	2

Table 2. Confusion matrix and indexes of agreement for Parque Tolhuaca, Termas Malleco and Laguna Verde Stations

		Ground observation								
		Parque Tolhuaca Station			Termas Malleco Station			Laguna Verde Station		
		snow	no-snow	User´s accuracy	snow	no-snow	User´s accuracy	snow	no-snow	User´s accuracy
MOD10A2	Snow	6	2	0.75	22	13	0.63	16	1	0.94
	no-snow	1	12	0.92	1	38	0.97	2	6	0.75
Producer´s accuracy		0.86	0.86		0.96	0.75		0.89	0.86	
Overall accuracy		0.86			0.81			0.88		

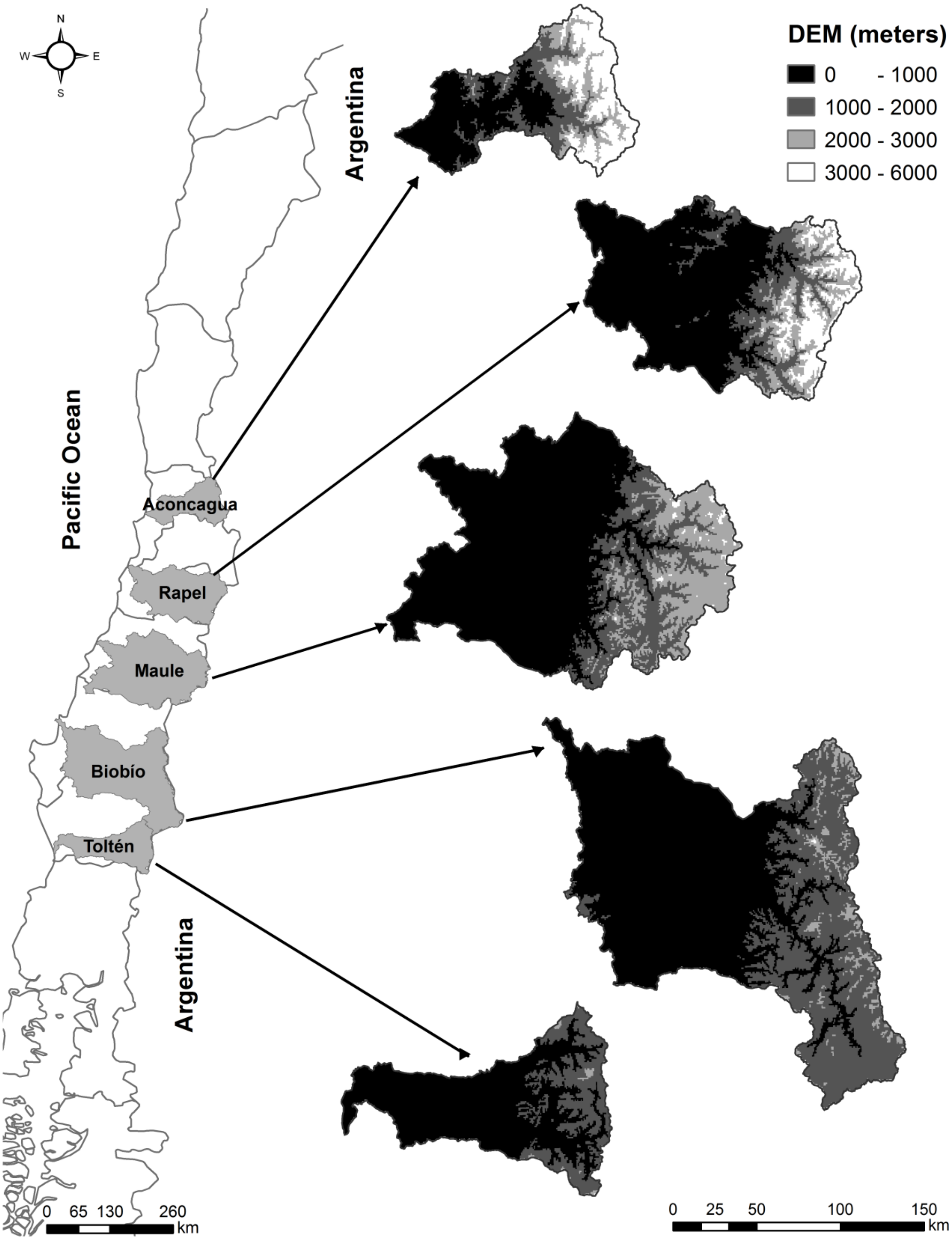
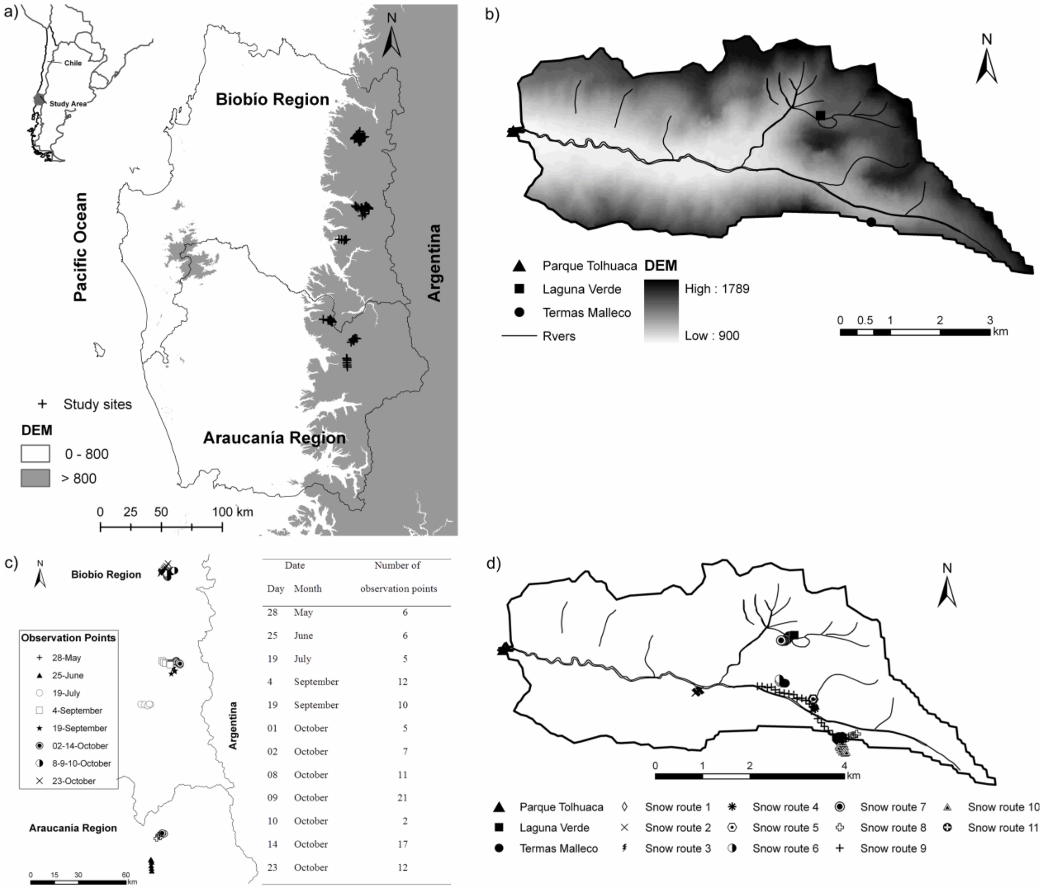


Figure 1: Study sites



Date		Number of
Day	Month	observation points
28	May	6
25	June	6
19	July	5
4	September	12
19	September	10
01	October	5
02	October	7
08	October	11
09	October	21
10	October	2
14	October	17
23	October	12

Figure 2: a) Study sites for MOD10A2 validation. b) Location of the meteorological stations for continuous monitoring of snow depth at Malleco watershed. c) Location and date of one-day observation points. d) Location of the snow courses.

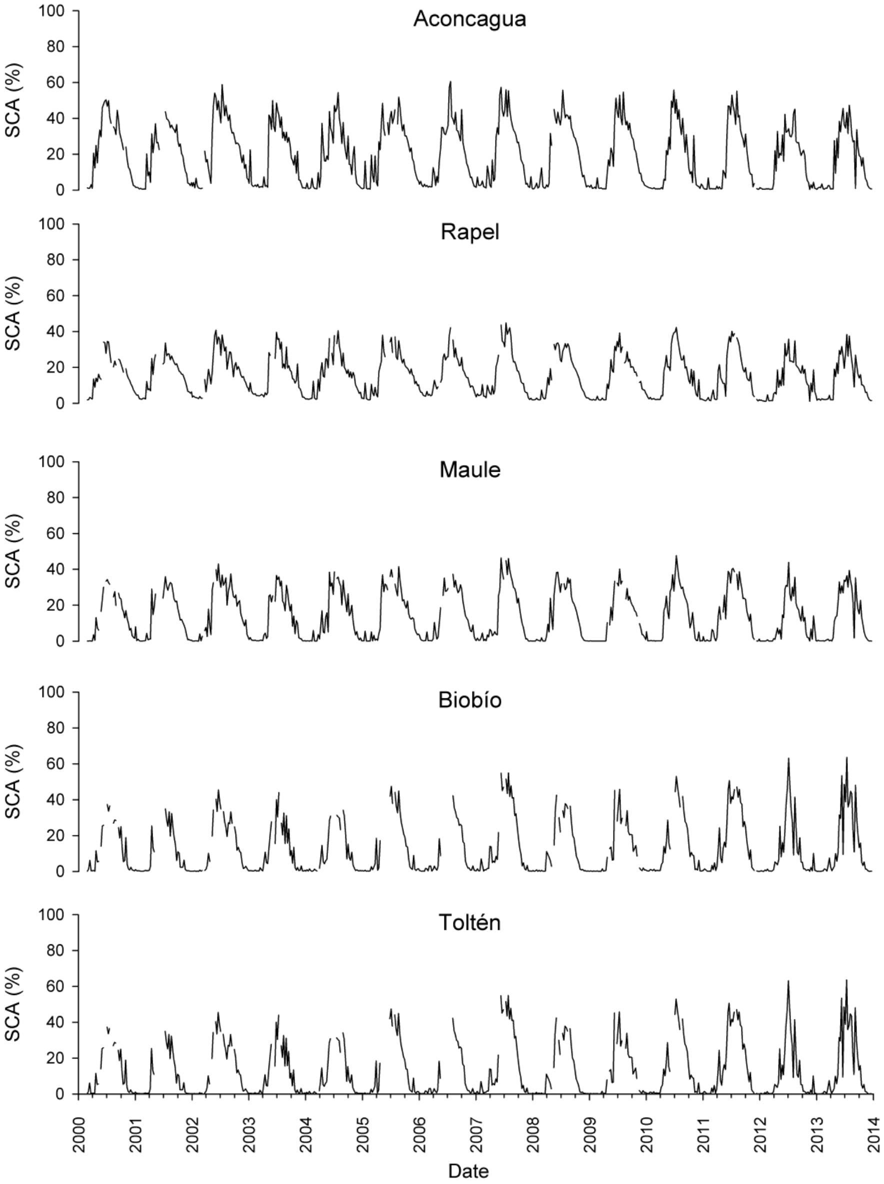
$$\begin{array}{c|cccccc}
k,k & A & B & C & \dots & q & \sum \\
\hline
A & n_{AA} & n_{AB} & n_{AC} & \dots & n_{Aq} & n_{A+} \\
B & n_{BA} & n_{BB} & n_{BC} & \dots & n_{Bq} & n_{B+} \\
C & n_{CA} & n_{CB} & n_{CC} & \dots & n_{Cq} & n_{C+} \\
\vdots & \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\
q & n_{qA} & n_{qB} & n_{qC} & \dots & n_{qq} & n_{q+} \\
\sum & n_{+A} & n_{+B} & n_{+C} & \dots & n_{+q} & n
\end{array}$$

$$\text{Percentage correct} = \frac{\sum_{k=1}^{q} n_{kk}}{n} \times 100$$

$$\text{User's accuracy} = \frac{n_{kk}}{n_{k+}} \times 100$$

$$\text{Producer's accuracy} = \frac{n_{kk}}{n_{+k}} \times 100$$

Figure 3: Confusion matrix and some indexes to measure classification accuracy.



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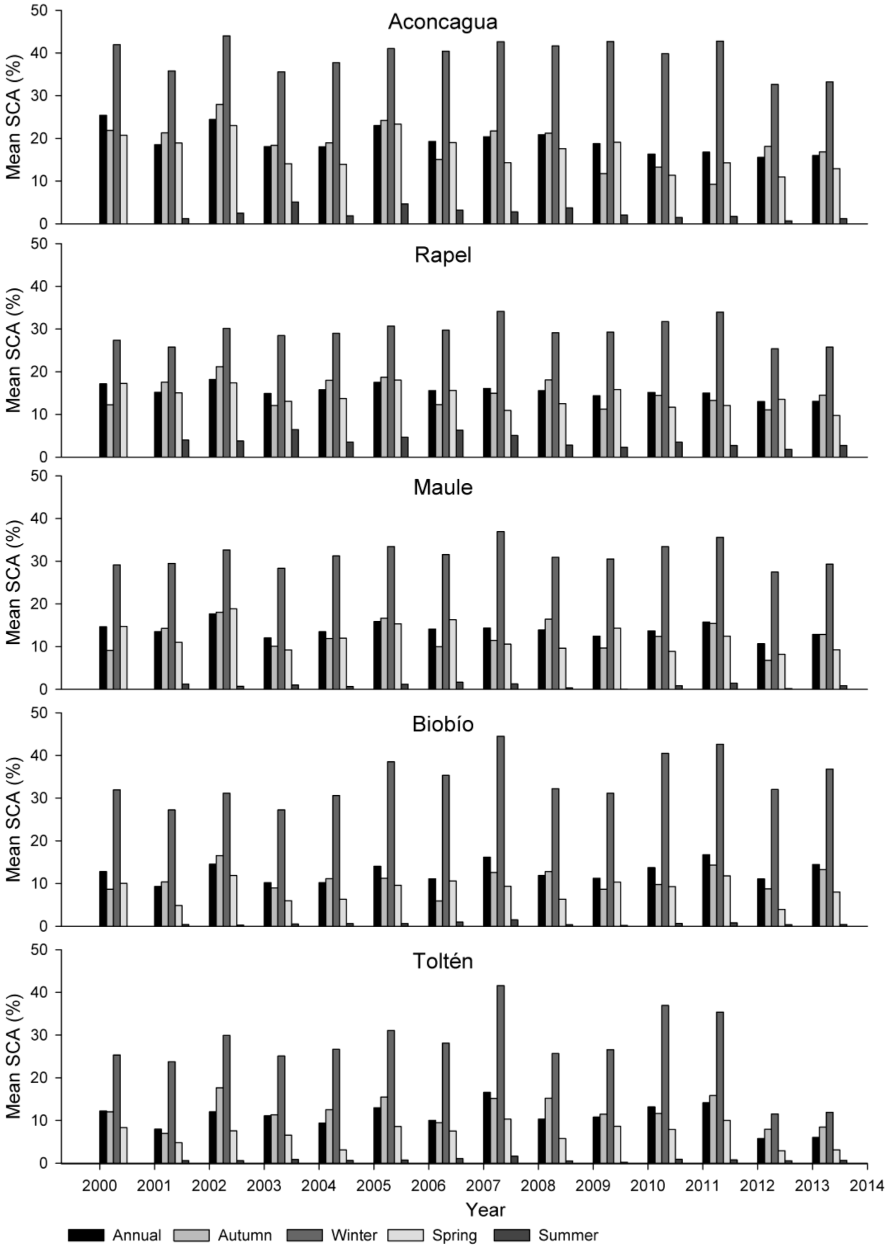
2 **Figure 4: SCD for the period 2000 – 2013 at Aconcagua, Rapel, Maule, Biobío and Toltén 6watersheds.**



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2 **Figure 5: Mean seasonal and annual SCA (%) in Aconcagua, Rapel, Maule, Biobío and Toltén watersheds during 2000–**
3 **2013.**

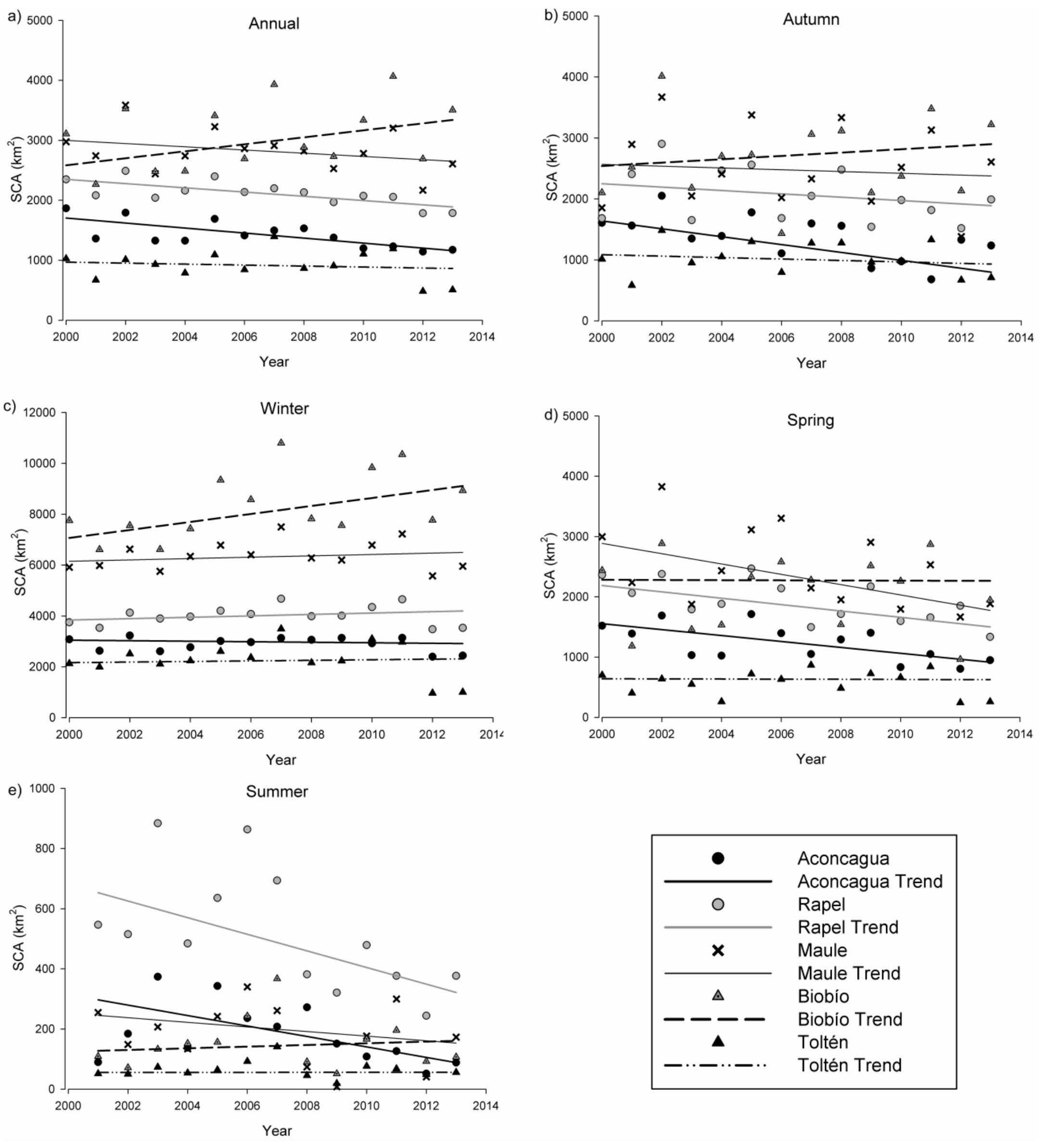

Figure 6: Annual and seasonal trend of SCA at Aconcagua, Rapel, Maule, Biobío and Toltén watersheds.