

UMBERTO MINORA (*, **, ***), DANILO GODONE (*, ****), SANDRA LORENZINI (*),
CARLO D'AGATA (*, **), DANIELE BOCCHIOLA (*, ***), GONZALO SEPULVEDA BARCAZA
(*****), CLAUDIO SMIRAGLIA (*, **) & GUGLIELMINA ADELE DIOLAIUTI (*, **)

2008–2011 SNOW COVERED AREA (SCA) VARIABILITY OVER 18 WATERSHEDS OF THE CENTRAL CHILE THROUGH MODIS DATA

ABSTRACT: MINORA U., GODONE D., LORENZINI S., D'AGATA C., BOCCHIOLA D., BARCAZA G.S., SMIRAGLIA C. & DIOLAIUTI G.A., 2008–2011 snow cover area (SCA) variability over 18 watersheds of the central Chile through MODIS data. (IT ISSN 0391 – 9838, 2015)

Snowmelt contributes largely to water budget of several Chilean mountain watersheds. To describe snow covered area (SCA) variability within 18 watersheds in Central Chile during 2008–2011 we used MODIS data (i.e. MOD10A2-V5 maximum snow cover extent in eight-day periods). The study area was divided into three different zones (Northern, Central, and Southern), due to its large extent (~205,000 km²), and according to former studies performed by the Dirección General de Aguas (DGA) of the Chilean Government covering the time window 2000–2007. After georeferencing our data to the WGS84 Datum (UTM Projection, zone 19S), the scenes were cropped to fit the study area. We selected and set a threshold for cloud coverage (<30%) in order to discard the images with too cloud cover, so losing only 2% of the sample. Hypsographic and aspect analyses were performed using the SRTM3 elevation model. We found largest values of SCA during 2008–2011 in the Central Zone, while the topographic and climatic features (i.e. lower altitudes in the South, and a drier climate in the North) limit snow deposition elsewhere. Similarly, snow line is higher in the Northern zone (due to the presence of the plateau), and lower moving southwards. In the North the minimum SCA

is reached sooner than elsewhere, lasting for a longer period (November to March). West side showed the maximum of SCA in all zones throughout the study period. The present work extends in time the dataset of SCA in the Central Chile, adding information for statistic assessment, and trend analysis of snow cover in this area.

KEY WORDS: Snow covered area (SCA), Remote sensing, MODIS, Central Chile.

RESUMEN: MINORA U., GODONE D., LORENZINI S., D'AGATA C., BOCCHIOLA D., BARCAZA G.S., SMIRAGLIA C. & DIOLAIUTI G.A., *Estudio de la cubierta nival sobre 18 cuencas hidrográficas Chilenas nel periodo 2008-2011 con análisis de datos MODIS.* (IT ISSN 0391 – 9838, 2015)

La fusión nival contribuye en manera importante en el balance hidrológico en muchas cuencas de montaña Chilenas. Para describir la variabilidad de cubierta nival (SCA, o sea *snow covered area*) y aumentar el conocimiento de esta variable en 18 cuencas Chilenas, se analizaron datos MODIS (o sea MOD10A2-V5, la máxima cubierta nival en 8 días). El área de estudio (ca. 205 000 km²) se dividió en tres zonas (Norte, Sur, Centro), como se hizo en un estudio anterior, publicado por la Dirección General de Aguas (DGA) del gobierno Chileno, que ha analizado recientemente las mismas cuencas en el periodo 2000-2007. Los datos MODIS fueron geo-referenciados en el sistema WGS84 (UTM Projection, zona 19S). Se ha aplicado un umbral por la cubierta nubulosa (30%) para descartar las imágenes demasiado cubiertas, con reducción de la muestra utilizable de 2% sólo. Para analizar la cubierta nival encuentra de la topografía y de la exposición se usaron datos de levantación por el Modelo de Elevación Digital (DEM) SRTM3. Los resultados indican que los máximos valores de SCA por el 2008-2011 se vieron en el centro, mientras que factores topográficos y climáticos (o sea levantación en medio más bajas en el Sur y precipitaciones más reducidas en el Norte) limitan la cubierta nival en otros sectores. La línea de la nieve es más alta llendo hacia el Sur. En el Norte el SCA mínimo se encuentra primero que en los sectores Sur y Centro, además duran más tiempo. Exposición hacia el Oeste muestran el máximo de la cubierta nival en todas las zonas estudiadas y para todo el periodo analizado. Este estudio ha permitido de ampliar el banco de datos sobre la cubierta nival en 18 cuencas hidrográficas Chilenas y de ayudar el conocimiento de la variabilidad reciente de un parámetro hidrológico fundamental.

PALABRAS CLAVES: Área cubierta de nieve (SCA), Teledetección, MODIS, Chile.

(*) *Comitato EvK2CNR, Bergamo, Italy.*
(**) *Dipartimento di Scienze della Terra, Università degli Studi di Milano, Italy (guglielmina.diolaiuti@unimi.it)*
(***) *Politecnico di Milano, Italy.*
(****) *Research Centre on Natural Risks in Mountain and Hilly Environments (NatRisk), Università di Torino, Italy.*
(*****) *Dirección General de Aguas, Ministerio de Obras Públicas, Santiago, Chile.*
corresponding author: umberto.minora@unimi.it

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INTRODUCTION

In mountainous basins with temperate or mediterranean climate, large volumes of snow can be stored at higher elevations, and subsequently be released during Spring and Summer snowmelt events (Verbunt & *alii*, 2003). This natural process is critical for sustaining agricultural activities, hydropower production, urban water supplies and wildlife habitats. However, in the case of the Chilean Andes there is a lack of both meteorological input and hydrological validation data, which complicates the analysis of those hydrological processes (Sther & *alii*, 2009).

Here we try to fill this gap using the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor to estimate the snow cover variability during 2008–2011 within 18 catchments in Central Chile. This study furthers a previous work performed by the *Dirección General de Aguas* of the Chilean Government (DGA, 2008), which analyzed the same watersheds in the previous 2000–2007 time window with daily MODIS snow data. The use of MODIS imagery can provide a reasonable estimate of snow cover extent, especially in those areas where little ground-observed snow cover information is available (Ghanbarpour & *alii*, 2007). Godone & *alii* (2011) have shown that there is good agreement between snow cover extent and duration derived from

MODIS, and from in-situ measurements in the northwestern Alps. The snow covered area (SCA) is analyzed for temporal (with monthly and annual resolutions), and spatial variability (snow cover surface, snow hypsography and aspects, in altitude belts of 200, and 1000 m).

STUDY SITE

The study area stretches from North-to-South from the Copiapó River (in the Atacama Region), to the Petrohué River (Los Lagos Region), covering to 205,000 km² (fig. 1), and ca. 15° of latitude in the Southern Hemisphere (26°S–41°S). It includes 18 watersheds (fig. 1). Due to its shape, topography, and location, Chile presents contrasting climatic patterns. Mid-latitude Chile is characterized by a semiarid– mediterranean type climate controlled by the seasonal influence of the Southern Westerlies. Precipitation values at 33°S range between 400 mm/yr at the coast (Valparaíso) and 1000 mm/yr in the high Andes. To the north precipitation declines whereas southwards significantly higher values, and lower seasonality, occur in both coastal and mountain areas (Miller, 1976). Snow settles on the Chilean Andes, covering the eastern boundaries of the country.

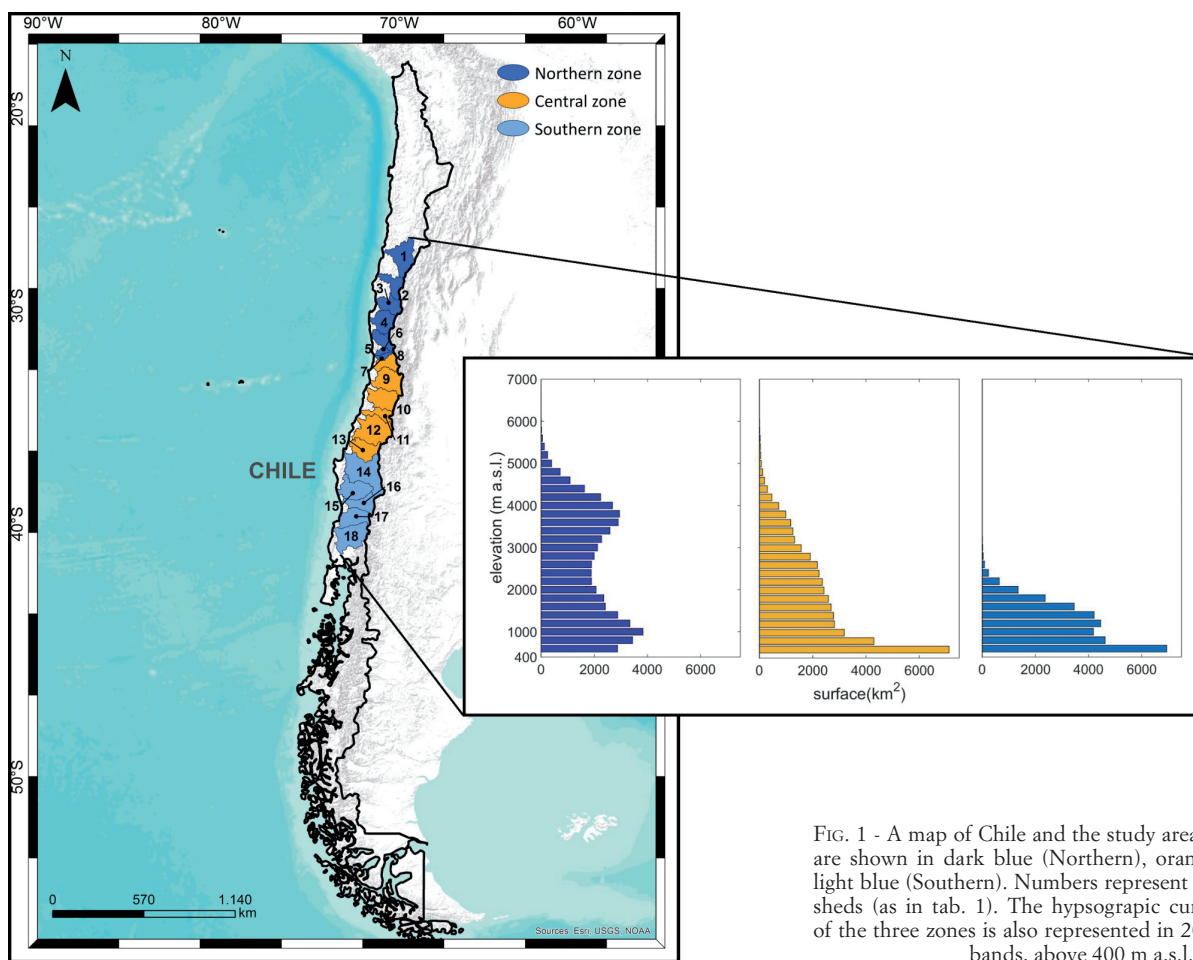


FIG. 1 - A map of Chile and the study area. The three zones are shown in dark blue (Northern), orange (Central), and light blue (Southern). Numbers represent the various watersheds (as in tab. 1). The hypsographic curve of the surface of the three zones is also represented in 200 meters altitude bands, above 400 m a.s.l..

MATERIALS AND METHODS

Given the study area size and the study period, a massive amount of data needed to be analyzed. Therefore we divided the area into three zones (i.e. Northern, Central, and Southern, see fig. 1 and tab. 1), to better show our findings. This choice is based on the previous DGA report (DGA, 2008), where the same zones were used. We used MODIS data, in particular the MOD10A2-V5 snow product (Hall & alii, 2006), already used in other studies concerning SCA in Chile (e.g. Favier & alii, 2009; Sther & alii, 2009). Data can be downloaded from the National Snow and Ice Data Center website (NSIDC, nsidc.org). The dataset contains information of maximum snow cover extent in an eight-day period (bundle), with 500 meters of resolution. We also used the DEM from the Shuttle Radar Topography Mission (SRTM90, see www2.jpl.nasa.gov/srtm), which features a resolution of 90 meters, to depict topography. The same MODIS sensor and DEM were used in the previous DGA report (DGA, 2008).

The MODIS scenes were first re-projected from the original sinusoidal format to the WGS84 Datum (Zones 19S and 18S). Then, the DEM was resampled to match the MODIS resolution. The MODIS images and the DEM were subsequently cropped to fit the area of the watersheds studied here. In this phase, we used the catchments' template provided by the Dirección General de Aguas (DGA) in the form of polygonal shapefiles as a base for clipping.

A pre-processing phase consisted in the selection of the images with low cloud coverage, necessary to attain unbiased SCA analysis. A threshold of 30% was set for cloud cover, to ensure the best tradeoff between image quality and number of scenes available for the analysis. So doing, only 2% of the data was discarded. The choice of this threshold was largely influenced by the high presence of cloud cover over the Bueno basin, where clouds were more frequent than all the other watersheds. Other studies (e.g. Gafurov & Bårdossy, 2009; Paudel & Andersen, 2011), developed an algorithm to remove cloud noise from the MODIS products. This was not necessary here because, being the MOD10A2 product a bundle of eight-day, the cloud coverage is much lower compared to the daily product, as a pixel needs to be cloud obscured for 8 days to be flagged as cloud. This makes this product preferable to the MOD10A1 daily product (Wang & alii, 2007), and does not require additional cloud correction to be used.

Further on, the DEM was reclassified into altitude belts of 200 meters to analyze SCA hypsography. Assignment of snow data to each watershed in the altitude belts was performed combining a script written in Python (python.org), and a Geographic Information System (GIS). Altitudes below 400 meters were excluded from the analysis, because no solid precipitation is expected here (DGA, 2008).

Finally, the study of the SCA divided per aspect and 1000 m altitude bins was performed by means of another reclassification of the DEM, and the aspect map derived from it. The workflow is summarized in figure 2.

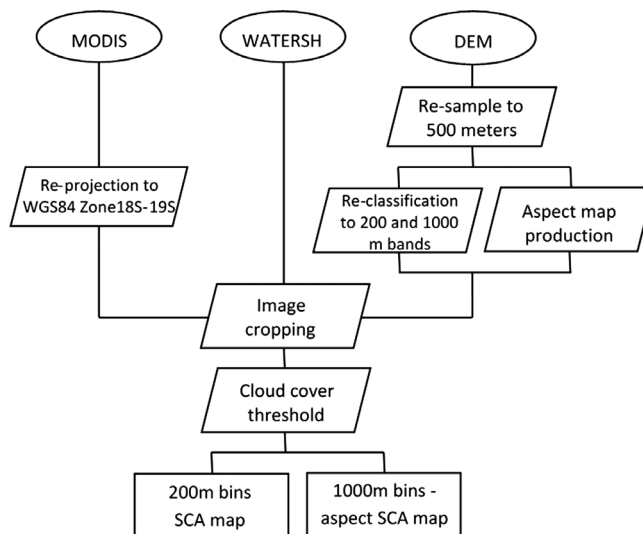


FIG. 2 - Data processing workflow.

RESULTS AND DISCUSSIONS

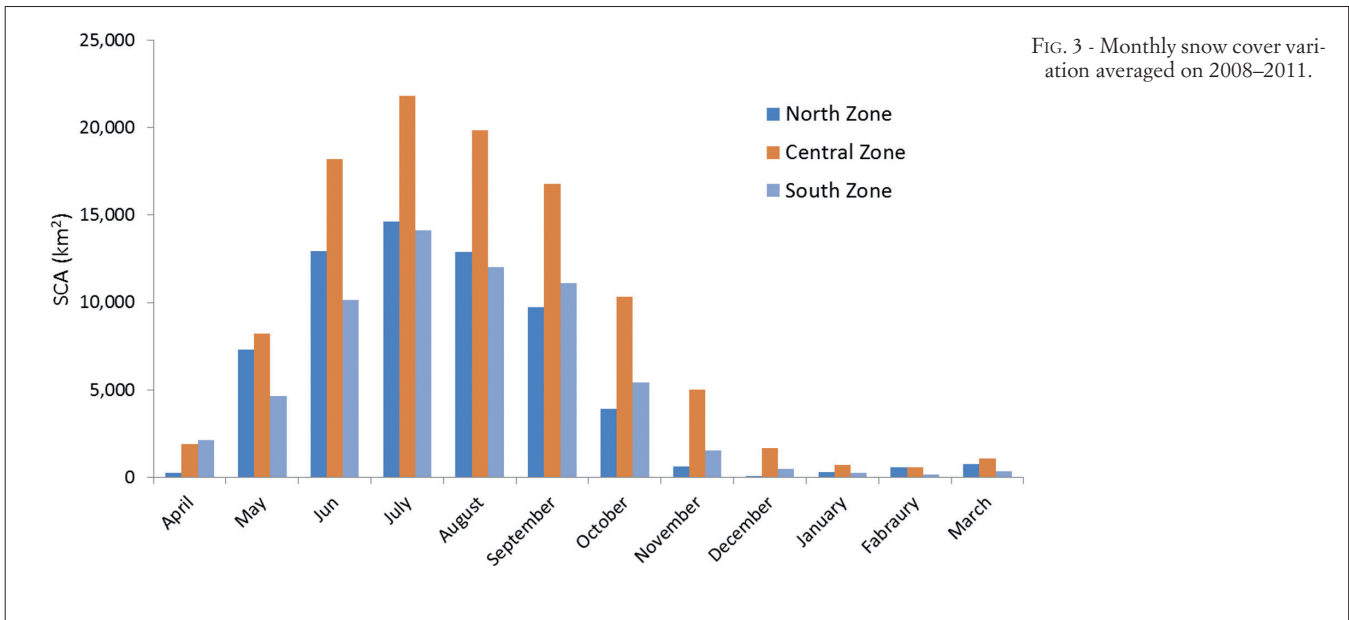
Figure 3 shows the summary results of the SCA analysis for all the three zones. Snow ablation starts in September, then SCA minima are reached in December in all the zones, while the maximum values are reached in July (i.e. at the end of the austral winter).

The Central zone has much higher values of SCA than the other zones. On the one hand, this is because the Central zone is the largest one (tab. 1). On the other hand, the low topography of the Southern zone and the drier climate towards the north are two major causes of this difference.

In figure 4 we report the SCA distribution per aspect (45° bins) and altitude (1000 m bins). Most of the snow cover shows prevalently westward aspects in all zones, both in Winter and Summer. The reason of such distribution is not straightforward. On the one hand, the Northern zone shows the most heterogeneous distribution of snow per aspect. Here the presence of glaciers and the plateau makes the recognition of a predominant orientation of snow difficult to be interpreted. In the Elqui and Choapa watersheds snow accumulates and persists more westwards due to the presence of transverse ridges (DGA, 2008). On the other hand, the other zones show much smaller variation of the distribution of snow per aspect, especially during winter. In summer, when snow melts, it tends to persist more on south aspects, due to the minor solar radiation received in the austral hemisphere.

Most of the snow of the Central and Southern zones is found in the 2000–3000 m a.s.l. belt in Winter (when SCA is at its maximum). In the same season, in the Northern zone the belt where most of the snow is found is 3000–4000 m a.s.l., higher than in the other zones, due to the presence of the plateau.

FIG. 3 - Monthly snow cover variation averaged on 2008–2011.



NORTHERN ZONE

The Northern zone shows highest variability of monthly SCA amongst the considered years. Snow cover ranges from the maxima of the winter season, up to 18,244 km² (in 2007–2008 hydrological year), to as little as 25 km² in Summer 2009. The percentage of snow cover over the entire zone at maximum snow extent is the lowest of the three considered zones (<30%). In general, SCA decreased during the four years here considered, and the maximum is always reached in July.

In the southernmost watersheds of this zone (*i.e.* Limarí, Choapa, Petorca, and Ligua basins), no snow is found in our analysis since the end of November until the beginning of the next hydrological year (in April). DGA (2008) depicts the same situation during 2000–2007. This is probably due to the less frequent precipitation than the other zones, and because the altitude is lower than the other watersheds of the same zone, thus consisting in the melt of all the snow accumulated during Winter.

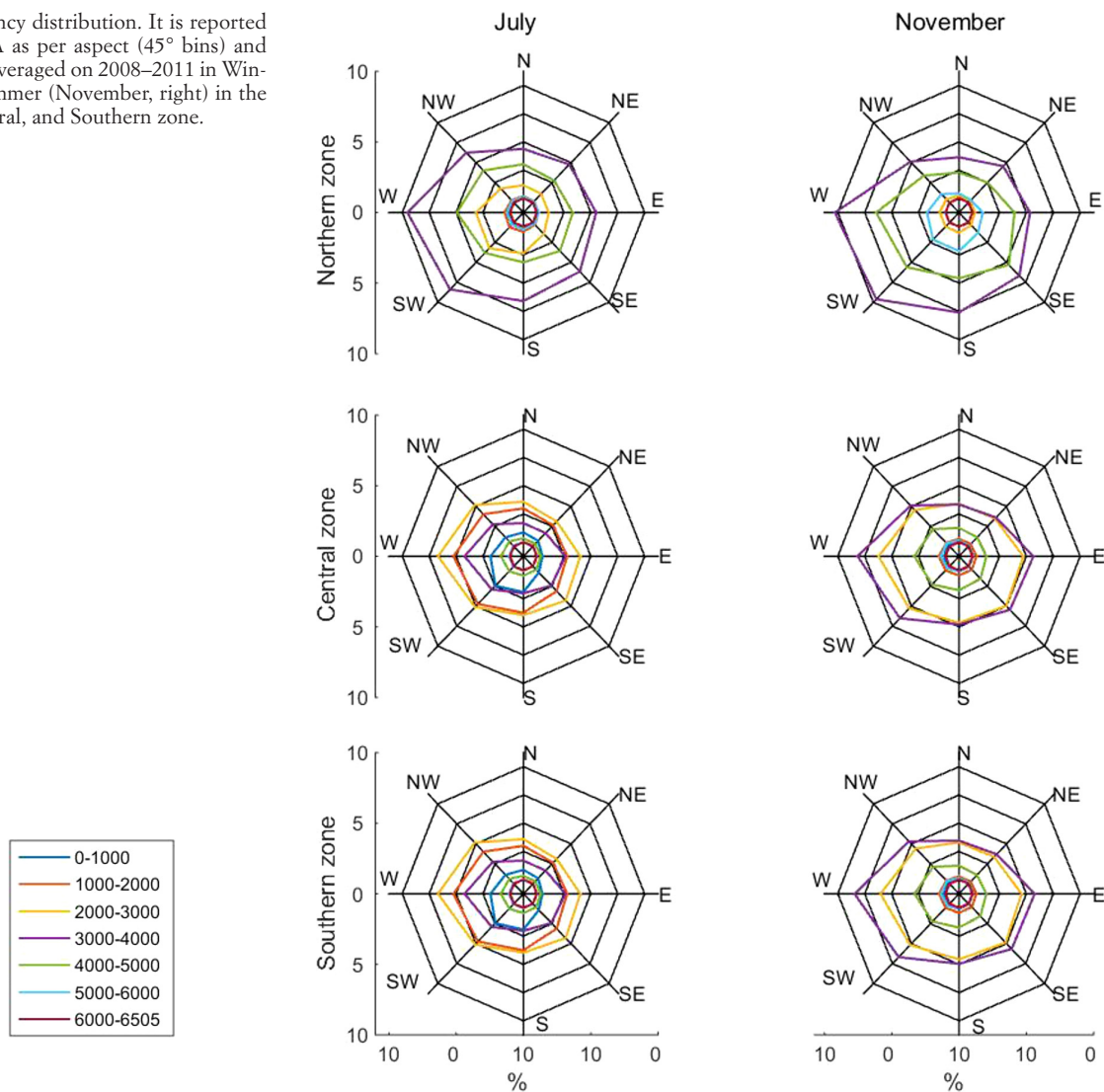
CENTRAL ZONE

SCA variability is almost constant in the Central zone during 2008–2011. Maximum values are much higher than the other zones (up to 29,106 km² in 2010 July), because i) this is the widest zone (tab. 1), ii) precipitation are higher than the Northern zone, and iii) maximum elevations are on average much higher than the Southern zone, thus facilitating snow accumulation. Glaciers are abundant in this zone. Ablation rates are less evident than the Northern zone, and the accumulation season extends to mid-September. This is in accordance with the previous DGA report (DGA, 2008). In general, SCA decreases through years during the study period, with the hydrological year 2010–2011 showing 10% less SCA than in 2008–2009. A decrease in precipitation (although not significant), was observed during 1970–2004 by Pellicciotti & *alii.* (2007) in the Aconcagua region and this might have caused a decrease in the snow cover in the same decades. Nevertheless, SCA values during 2008–2011 are higher than 2000–2007 on average (data from DGA, 2008).

TABLE 1 - The three zones we analyzed, and the respective watersheds (name of the rivers are provided, the numbers are referred to the watershed id code we assigned in fig. 1). Latitudes (in degrees) and surfaces (in km², square brackets) are also provide

Northern Zone (26°S–33°S)			Central Zone (33°S–38°S)			Southern Zone (38°S–41°S)		
1.	Copiapó	[18704]	8.	Aconcagua	[7334]	14.	Bío Bío	[24371]
2.	Huasco	[9814]	9.	Maipo	[15274]	15.	Imperial	[12669]
3.	Elqui	[9826]	10.	Rapel	[13767]	16.	Toltén	[8449]
4.	Limarí	[11696]	11.	Mataquito	[6332]	17.	Valdivia	[10245]
5.	Choapa	[7654]	12.	Maule	[21054]	18.	Bueno	[15367]
6.	Petorca	[1988]	13.	Itata	[11327]			
7.	Ligua	[1980]						
TOT zone		[61662]			[75088]			[71100]
TOT			[207851]					

FIG. 4 - Aspect frequency distribution. It is reported the percentage of SCA as per aspect (45° bins) and 1000 m altitude belts averaged on 2008–2011 in Winter (July, left), and Summer (November, right) in the Northern, Central, and Southern zone.



In particular, the maximum value found during 2000–2007 is $5,000 \text{ km}^2$, lower than the values found in Winter in our study period. Finally, maxima are observed between 2200 and 2600 m a.s.l. in July, while snow is still found even in the warmer season at the highest altitudes ($>4000 \text{ m a.s.l.}$, with the maximum represented by the Aconcagua, the highest peak of the Southern Hemisphere with its 6960 m a.s.l.). Note that only the Aconcagua, Maipo, and Rapel watersheds are higher than 4000 m a.s.l..

SOUTHERN ZONE

The annual variability of SCA during 2008–2011 is very high in the Southern zone. Maximum values are found since June to August, depending on the hydrological year. Also, SCA decreases on average during 2008–2010, only to increase in 2011. Thaw season begins in September as also reported in the previous DGA report (DGA, 2008), for

the period 2000–2007, with high rates leading to minimum cover already in November. The observed maximum value is $21,843 \text{ km}^2$ in August 2007. In general, the relatively low elevations limit snow accumulation here (elevation is often lower than 3000 m a.s.l.). However, precipitation is abundant (especially towards the coasts), and snow is found even below 3000 m. Unfortunately, we could not make a comparison with the previous DGA report, because the SCA analysis during 2000–2007 was made impossible by the massive presence of clouds in this zone. The use of the bundled (8-days) MODIS product against the daily product used in the previous report (MOD10A2 versus MOD10A1), allowed us to have a good dataset for this zone where precipitation (and thus clouds) is frequent throughout the year. As our study period is too short for assessing if SCA variation was significant, we refer to Bown & Rivera (2007), who studied the climate changes during the second half of the 20th century in the Chilean Lake District (38°S – 42°S , about the same latitudinal range of the Southern zone). The regional

rainfall data they collected from 1961 to 2000 showed an overall decrease with a maximum rate of -15 mm/year at Valdivia station ($39^{\circ}38'S/73^{\circ}05'W$). They speculated that this reduction in precipitation might be related to El Niño–Southern Oscillation (ENSO) phenomena which have been more frequent after 1976.

CONCLUSIONS

The present contribution aimed at showing SCA variability during 2008–2011 in the Central Chile, over 18 mountainous watersheds ($205,000$ km²). MODIS snow products from the NDSIC were used for the analysis. The dataset (consisting of eight-day bundles of maximum snow cover) was processed combining GIS tools and the Python programming language to automate the production of snow cover maps. We showed that SCA decreased during the four considered years. This is true also looking at a longer time window (*i.e.* since 2000), according to the previous DGA report (DGA, 2008), except for the Central zone, where SCA was higher in 2008–2011. The maximum SCA was found in the Central Zone, while the topographic and climatic features (*i.e.* lower altitudes in the South, and a drier climate in the North) limited snow deposition elsewhere. The snow line is higher in the Northern zone due to the presence of the plateau, and it decreases southwards. In the Northern Zone the minimum SCA is reached sooner than elsewhere, and lasts for a longer period (November to March), probably because the drier climate. West aspects showed the maximum of SCA in all zones throughout the study period. In the present work we showed how the MOD10A2 product can be used for studying snow covered areas over an extended domain. The spatial (500 m) and temporal (weekly) resolution of the MODIS sensor, its many bands (36 channels), and the availability of the data at no cost, makes it a reliable product to study SCA where few in-situ measurements are available.

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