SNOW ALBEDO REDUCTION IN CENTRAL ANDES BY ATMOSPHERIC AEROSOLS: CASE STUDY ON THE TUNUYÁN BASIN (ARGENTINA)

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ABSTRACT:
Changes in snow albedo (SA) on several basins of the central Andes of Argentina are associated with the possible deposition of light-absorbing particles (LAP) in the austral spring. To demonstrate this possibility, we correlate SA with daily data of snow cover (SC), aerosol optical depth (AOD) and land surface temperature (LST) available from the Moderate-Resolution Imaging Spectroradiometer (MODIS) on board NASA Terra satellite during 2000-2016, and other derived parameters such as days after albedo (DAS) and snow precipitation (SP) from the Tropical Rainfall Measuring Mission (TRMM). We used satellite pixels with 100% snow cover to obtain monthly average value of SA, LST, AOD, DAS and SP performing multiple regression analysis. Further, we analysed biomass burning emissions in northern Argentina using MODIS products MCD64 collection C6 as possible source for snow pollution. Aerosol deposition and trajectories were analysed using WRF-Chem atmospheric numerical prediction model, with inventories of regional anthropogenic emissions of own elaboration (lat. 0.025° x long. 0.025°) and the estimation of open burning emissions from the FINN global inventory (Fire INventory from NCAR).

1. INTRODUCTION

Snow albedo is a parameter of great importance to determine the amount of solar radiation adsorbed in the cryosphere and is defined as a relationship between incoming and reflected solar radiation by a surface. Snow albedo variations are influenced, among others by the surface temperature, snowfall, snow age and snow impurities (Warren SG. et al. 1980; Levy RC. et al. 2007; Lee W. et al. 2012; Qian Y. et al. 2015).
Snow impurities (LAP) reduces the snow albedo and absorb more solar radiation (snow darkening effect — SDE), which further accelerates the snow aging process and the melting rate of the layer of snow (Clarke AD. et al. 1985; Hansen JE. et al 1997; Hansen JE. et al. 2001; Menon S. 2002; Pepin N. et al. 2015). LAP and its SDE were identified as the main forcing agents that affect climate change (Griggs DJ. et al. 2002; IPCC 2007).

Estimating the snow darkening effect (SDE) through the presence of snow impurities requires a great effort of in situ measurements covering large snowy areas in many cases hardly accessible. Therefore, retrieved satellite remote sensing data are a good alternative to analyse data with acceptable spatial and temporal distribution covering large regions.

In the Central Andes, satellite products [mainly Moderate Resolution Imaging Spectroradiometer (MODIS)] have also been used to analyse the snow cover in the Mendoza River Basin (Argentine eastern slope of Central Andes) (Cara L. et al. 2016). Recently, it was established that the cover, albedo and duration of snow decreased by $13.4 \pm 4\%$, $7.4 \pm 2\%$ and 43 ± 20 days, respectively (Malmros JK et al. 2018). A case study in the area of the sky complex in Portillo (32.83°S, 70.13°W) showed a negative relationship between local vehicle emissions and the snow albedo measured in situ. However, it could not quantify the SDE from vehicular emissions (Cereceda-Balic F. et al. 2018).

The main objective of this study was to investigate the aerosols effect on the snow albedo reduction in Central Andes of Argentina (CAA) during the spring season, based on satellite remote sensing data for the years 2000–2016. The role that aerosols play in the negative trend of snow albedo (Malmros JK. et al. 2018), and their relationship with the distribution and local deposition of aerosols in snow has been identified in previous studies for this region (Cereceda-Balic et al. 2012; Bolaño-Ortiz et al. 2017; Cereceda-Balic et al. 2018; Bolaño-Ortiz et al. 2018).

2. DATA AND METHODOLOGY

We selected the Tunuyán basin (Tyn) of Central Andes of Argentina to analyse the reduction of albedo in the CAA as shown in Figure 1.

The Global Digital Elevation Model (GTOPO30) developed by the Data Center of the National Center for Earth Observation and Science (EROS) of the United States Geological Survey (USGS) was used as a surface topography ((https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30).

Daily satellite data of snow cover (SC), snow albedo (SA), land surface temperature (LST), optical aerosol depth (AOD) and precipitation (P) were analysed (Table 1). SC and SA were recovered from MODIS images (Klein AG et al. 2002; Hall DK et al. 2002; Riggs GA et al. 2006). MODIS products consider slopes and snow cover on mountainous surfaces (Klein AG. et al. 2002; Pu Z et al. 2007).

Parameter	*Satellite product*	*Spatial resolution (km)*	*Pixels*
SC	MOD 10	0.5	100%
SA	MOD 10	0.5	All pixels with 100% snow cover
LST	MOD 11	1	
AOD	MOD 04	10	
P	3B42	25	

Table 1. Satellite products used

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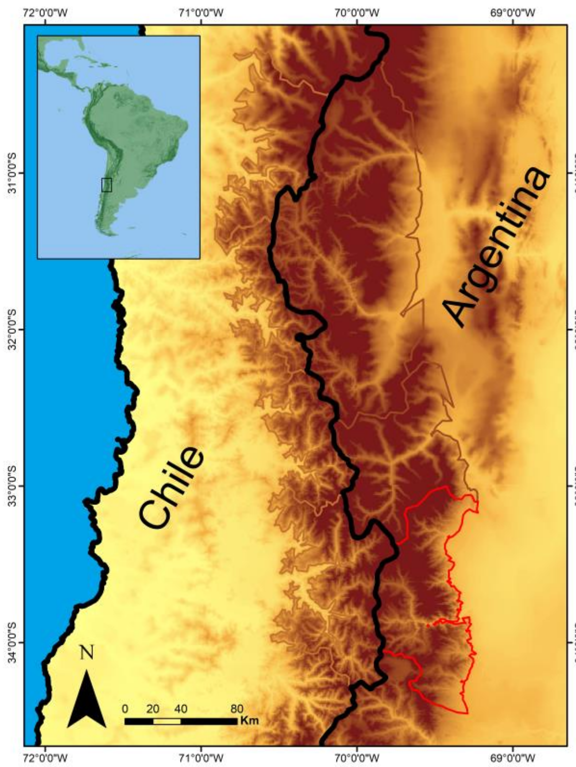

Figure 1. Study area in South America and the Central Andes. Red line encloses the Tunuyán basin on the eastern side of the Andes mountain of CAA.

The LST product used (Wan Z. et al 1997; Pepin N. et al. 2015) has been shown to be suitable for mountainous areas with an agreement of 86% (Klein AG. et al 2003). The AOD aerosol product was recovered from MOD04 (Levy R. et al 2015) with a wavelength of 0.55 μm, where snow albedo showed the greatest variability due to light absorbing particles (Qian Y et al 2015; Cereceda-Balic et al. 2018; Skiles SMK et al. 2018). Precipitation was obtained from the Tropical Rain Measurement Mission (TRMM) (Adler RF et al 2000; Huffman GJ et al. 2007a; Huffman GJ et al 2007b) that provided spatial information and vertical precipitation profiles (Hong Y et al. 2006).
The presence of clouds frequently produced missing satellite data (daily), to minimize the gaps and produce a more reliable statistic we worked with a 17-year series of daily data from the southern spring (September to November 2000 to 2016).
Since TRMM detects only liquid precipitation, a parameter was generated to estimate the days where precipitation was snow (SP), by detecting temperatures below the freezing level at −4 °C, taking the uncertainties of MOD11 measurements into account (Seemann SW et al 2006). The number of days between snowfalls was also estimated by another parameter: days after snow (DAS).
To estimate the effect of aerosol deposition on the SA reduction in each basin, the correlation of SA to LST, AOD, snow precipitation (SP) and DAS was investigated by means of a multiple regression analysis for all available data sets.
Finally, the Weather Research and Forecasting with Chemistry (WRF-Chem) numerical prediction model (Flanner MG et al 2007) was run for selected days and we compared them with the average snow albedo (SA) and the AOD data recovered in the basin. To estimate the regional source of black carbon (BC), we studied the winds that drag air masses toward the high areas of the basin studied using WRF-Chem and backward trajectories using NOAA HYSPLIT (Stein AF et al. 2015; Rolph G et al. 2017).

3. ANALYSIS AND DISCUSSION

3.1. Observational data

Table 2 shows the linear correlation r among all the variables. It is observed that the LST, ODA, and DAS contribute negatively to the SA, while the SP increases the SA. This can also be seen in the r of -0.6487, which correlates SP and LST, which means that when the snow increases, the surface temperature decreases.

	SA	LST	AOD	SP	DAS
SA	1				
LST	-0.8565	1			
AOD	0.1705	-0.2165	1		
SP	0.5881	-0.6487	0.1019	1	
DAS	-0.4146	0.5863	-0.2097	-0.2165	1

Table 2. Correlation coefficient between all variables

To analyse the relationship between SA and LST, AOD, DAS and SP, we calculated the correlation coefficients (r) using their monthly averages from September to November during 2000–2016, as shown in Table 3. These correlations show that the LST has the greatest impact on the SA. Furthermore, the sign coincides with the expected effect on the snow albedo: SA decreases with LST, AOD, DAS and increases with the SP (Grell GA et al 2005; Flanner MG et al 2006; Qian Y et al 2015; Skiles SMK et al 2018).

Cuenca	LST	AOD	SP	DAS
Tyn	-0679	-0.388	0.337	-0.280

Table 3. Correlation coefficient r with SA

The correlation coefficients analysis (r) shows that LST, AOD, DAS and SP are not linearly independent. However, sometimes the relationship is not linear using only one parameter. Therefore, we utilized a multiple linear regression technique to evaluate the AOD impact on the SA decrease (Lee W et al 2012). We used a multiple linear regression technique, standardizing the data with its standard deviations, for the austral spring months (2000–2016) for each parameter obtaining the following relation: (shown in Eq. 1). Confidence Level: 95%

$$SA = -0.019 \times 10^{-16} - 0.596LST - 0.143AOD + 0.161SP - 0.013DAS \qquad R^2 = 0.62 \tag{1}$$

The Eq. 1 show that a larger LST, AOD and DAS lead to a lower surface albedo (SA), which coincides with the physical behaviour of melting snow. When surface temperature (LST) increases, it also increases the snow grains. Impurities on the snow increase the absorbed radiation, and since older snow is darker, this leads to a lower SA

To estimate the LST, AOD, PS and DAS contributions to the behaviour of SA, we used the difference of the normalized mean values of LST, AOD, DAS and SP for the spring months (September to November, years 2001–2016). Table 4 shows the contribution percentage of each parameter to SA.

Cuenca	%LST	%AOD	SP	%DAS
Tyn	89.1	8.58	2.29	0.02

Table 4. Contribution percentage to SA of each parameter for the data sets and basins analysed using the multiple regression model

The multiple regression model predicts that the AOD is the second parameter that most contributes to SA decrease after LST. AOD and SP have a significant contribution to the SA of the study area (8.58% and 2.29% respectively).

3.2. Case study using WRF-Chem model

Temporal distribution observed on the Tunuyan basin from September 26 to 30, 2016, shows that with a 1-day AOD delay over the SA (Figure. 2), the expected behaviour of the AOD over the SA coincides with what is expected intuitively and predicted by the multiple regression model. We consider that the 1-day delay of AOD with respect to the SA is a consequence of transport time and deposition rate (Xu R et al 2018). Moreover, the measuring satellite passes by the study area early on the day, and, therefore, the effect of the aerosol deposited would occur in the course of the day when the snow cover receives radiation from the sun. For the particular analysed days, the sunrise and sunset were at 6:24 and 18:44 local time, respectively (i.e., 12.3 h of solar irradiation). However, the satellite that captured the AOD measurement passed at 10:45 and 9:45 local time on September 28 and 29, respectively; therefore, the effect of the measured AOD on the SA (during the rest of the solar day: 8 and 9 h, respectively) will be better observed on the next day.

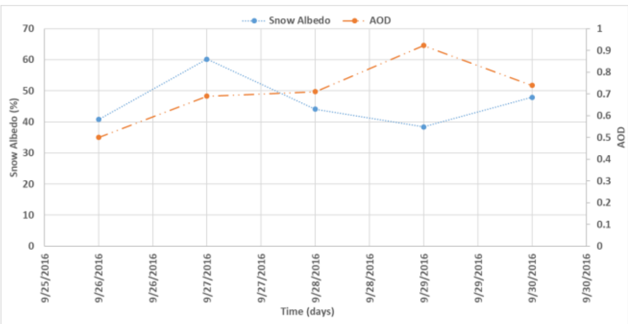

Figure 2. Daily average of snow albedo and optical depth of aerosols for pixels with 100% snow cover to each basin during 4 consecutive days in September 2016 on Tunuyán basin.

3.2.1. WRF-Chem modelling

To analyse the contribution of aerosol to the studied basin, we run a numerical meteorological prediction model, the Weather Research and Forecast with Chemistry (WRF-Chem) (Grell GA et al 2005). This model was used with a parametrization shown in Table 5, which was already tested in this region (Morata D et al 2008; Puliafito SE et al 2015; Mulena GC et al 2016; Cremades PG et al 2017; Bolaño-Ortiz et al 2019).

Parameterization	Scheme
Input data	
Ground elevation	SRTM3
LULC	GLOBCOBER+DMPS-OLS
Meteorology IC/BC	Re-analysis NCEP-GFS
SST	NCEP_daily
Chemistry	
Gas phase	CBM-Z
Aerosols	MOSAIC 4 bin module
Chemistry IC/BC	MOZART-4
Global emissions inventory	EDGAR
Regional Emissions Inventory	Local inventory - GEAA
Physical	
Microphysics	Morrison double-moment
Cumulus	Grell Devenyi
Long wave radiation	RRTM
Short wave radiation	Goddard Dudhia
Surface	Noah Land Surface Model
PBL	YSU
Resolution	
Temporary	Δt (seg)= 90
Spatial	Δx, Δy (km)= 36, 12, 4
Vertical	Δz (ETA levels) = 50

Table 5. Details of the parameterization used in the WRF-Chem simulation

WRF-Chem model was run using three nested domains and was verified using vertical profiles of several meteorological variables for September 28 and 29, 2016. Aerosol deposition as light-absorbing particles (BC) is very efficient to decrease the snow albedo (Keegan KM et al 2014; Zhang Y et al 2017; Skiles SMK et al 2018), and we used BC to simulate and estimate the distributions over the basin of the study area (Figure. 1).

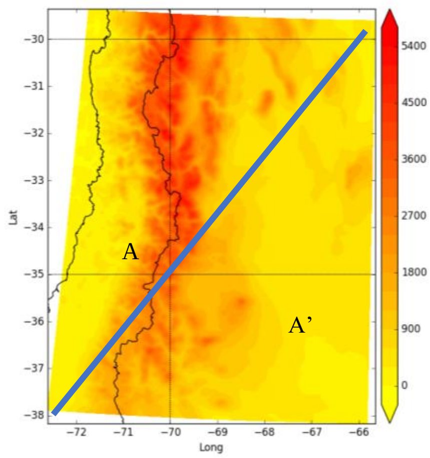

Figure 3. Terrain elevation and cross section (blue line) to observe the vertical behavior of BC concentrations for the Tunuyán basin (A-A’)

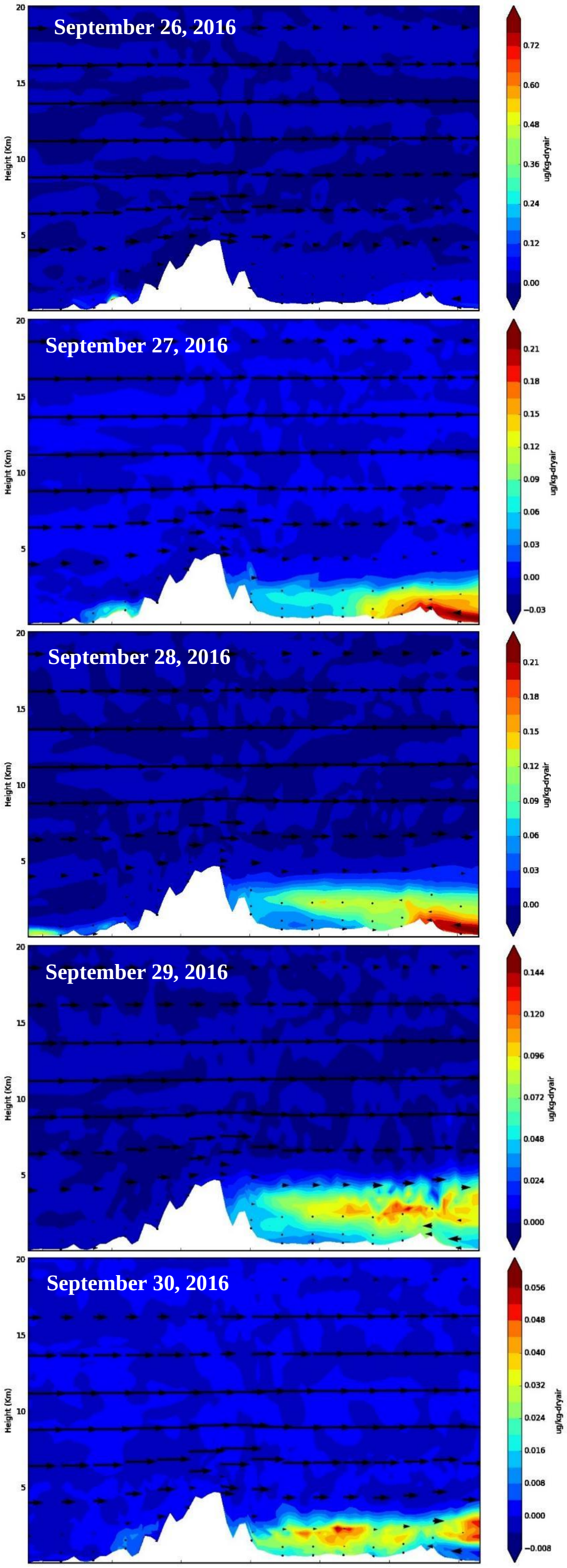

Figure 4. Vertical profile to BC average concentration for cross section A-A' shown in Figure 3 over the Tunuyán basin on September 26-30, 2016. Arrows indicate direction of zonal winds.

The snowpack in the studied area is a very important source of water supply in central Argentina because snow stores fresh water during the cold and wet season and then gradually releases water during warm season, representing an important contribution to the river flows of this region (Masiokas MH et al 2006; Masiokas MH et al 2016). In addition, several studies suggest that a snowpack reduction in this mountain area has impacts on the hydrological cycle and the water supply for the region (Mernild SH et al 2017; Meza FJ et al 2012). The variations and high absorbent aerosols deposited in the snow analyzed in this study suggest that the sources of anthropogenic aerosols may be playing a role in the availability of water through a positive effect with solar radiation.

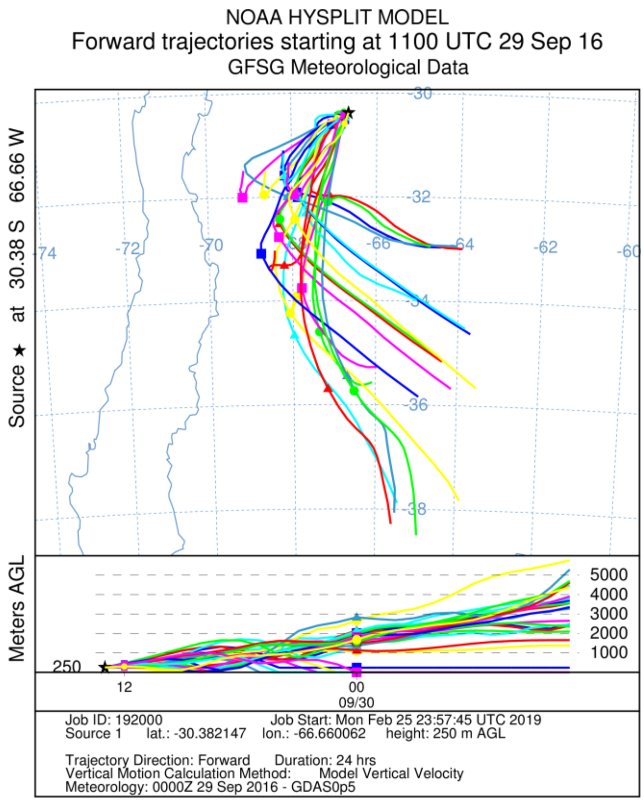

Figure 5. Trajectory from the emission source estimated for the day of higher BC antibodies on the Argentine side (September 29, 2016) by NOAA HYSPLIT.

The differences simulations (Fire_ON - Fire_OFF) indicate BC source only by Biomass Burning, also show than from September 26 start to increase BC values over the Tunuyán basin (the eastern side of the Andes mountains) up the highest values on September 29, later start to decrease to low altitude (shown in Figure 4). This behaviour has been observed too on AOD variations to same days (Figure 2). The estimated maximum values of BC were explained by higher AOD and air mass transport patterns by the NOAA HYSPLIT model (Figure 5). The AOD peak originated from the northeast of Argentina with emission source of AOD in the areas where many biomass burning situations are present.

4. CONCLUSIONS

Our results suggest that the decrease in SA due to AOD, in the case of study, originated due to BC generated by the burns that commonly occur at that time of year in Argentina and South

America, which produces an impact negative in snow and hydrological resources generated in the Central Andes. In special, our case study on the Tunuyán Basin show results showed a reasonable representation of the smoke sources observed in images of the WRF-Chem output.

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