IMPROVED SNOW DARKENING COEFFICIENT FOR LARGE-SCALE SNOW ALBEDO MODELLING WITH CROCUS

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1 INTRODUCTION

Light-absorbing particles (LAPs) deposited at the snow surface significantly reduce its albedo and strongly affect the snow melt dynamics. The explicit simulation of these effects with advanced snow radiative transfer models can be associated with a large computational cost. Consequently, many albedo schemes used in snowpack models still rely on empirical parameterizations that do not account for the spatial variability of LAP deposition. In Gaillard et al. (2024), a new strategy of intermediate complexity that includes the effects of spatially variable LAP deposition on snow albedo was tested with the snowpack model Crocus. It relies on an optimization of the snow darkening coefficient that controls the evolution of snow albedo in the visible range. A global dataset of LAP-informed and spatially variable values of the snow darkening coefficient was constructed. The revised snow darkening coefficient improved snow albedo simulations at the ten sites considered in the study by 10%, with the largest improvements found in the Arctic (more than 25%). The uncertainties in the values of the snow darkening coefficient resulting from the inter-annual variability of LAP deposition on snow were also computed.

2 METHODOLOGY

The study detailed in Gaillard et al. (2024) relies on the version of the snowpack model Crocus that has recently been implemented as an additional option for snow simulations in the Soil, Vegetation and Snow version 2 (SVS-2) land surface scheme (Garnaud et al., 2019; Vionnet et al., 2022).

Snow albedo in Crocus is split between three spectral bands of incoming solar radiation (Brun et al., 1992; Vionnet et al., 2012). In the visible band, snow albedo depends mostly on the amount of LAPs, which is indirectly parameterized by the age of snow, and on the snow microstructure, represented by the optical diameter of snow:

$$
\begin{aligned}
&\alpha_{0.3-0.8\mu m} = \max(0.6, \alpha_i - \Delta\alpha_{age}) \\
&where: \alpha_i = \min(0.92, 0.96 - 1.58\sqrt{d_{opt}}) \\
&and: \Delta\alpha_{age} = \min(1, \max(\frac{P}{P_{CDP}}, 0.5)) \times 0.2\frac{A}{\gamma}
\end{aligned}
\tag{1}
$$

The impact of the deposition of light absorbing particles is parameterized from the age of snow through a snow darkening coefficient, γ (Equation 1). As shown on Fig.1, if γ is high, the albedo decreases slowly with the snow age, which is characteristic of a snowpack that receives low LAP deposition. In contrast, if γ is low, the effect of snow aging on albedo is larger, so that the snow albedo decreases more quickly, which can be associated with higher LAP concentrations at the snow surface. The default value of γ used until now in Crocus simulations is 60 days.

The narrowband albedo in the visible range also includes an empirical pressure term ($\min(1, \max(\frac{P}{P_{CDP}}, 0.5))$, where P_{CDP}=870 hPa is the mean pressure at the Col de Porte experimental site in the French Alps (1325 m)) that was initially designed to reflect the impact of elevation on the concentration of LAPs in the snow when applied in the French Alps for avalanche hazard forecasting. In the context of Gaillard et al. (2024), considering large scale applications of Crocus, the pressure term was not considered due to the large variability of the impact of elevation on the deposition of LAPs across the

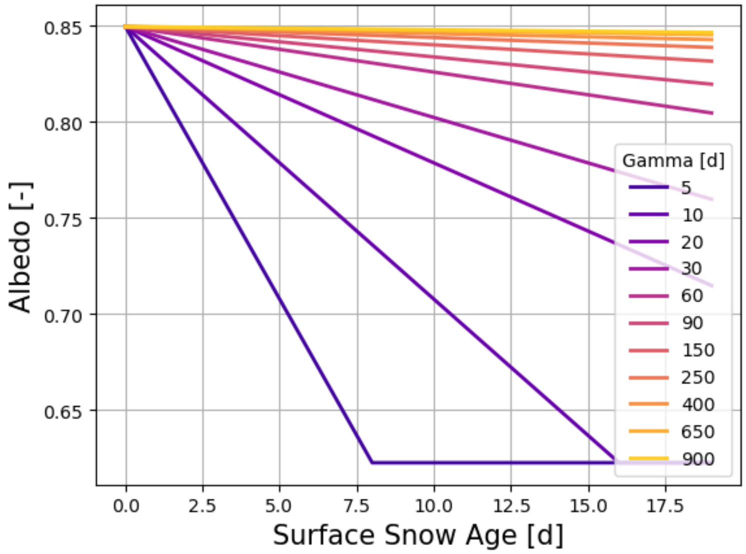

Figure 1. Graphic representation of the dependency of the snow albedo in the visible spectral band ($0.3-0.8\mu m$) to the snow age for different values of γ.

world.

The skills of snow albedo simulations with Crocus were first examined for different values of the snow darkening coefficient γ, at ten reference sites around the world, to find optimal ranges of γ for each site, taking into account observational uncertainties. Then, a global climatology of mean-annual LAP deposition rates (mineral dust and black carbon) on snow was computed, from which the values at each of the ten reference sites were extracted. Mineral dust and black carbon were summed in terms of equivalent black carbon. To quantify the strong inter-annual variability of LAP deposition on snow, similar climatologies were derived for a low and a high LAP year, respectively using the 25^{th} and 75^{th} percentiles of daily deposition rates. A cross analysis was then carried out to find a simple relationship between the LAP deposition rates and the optimal ranges of γ at the ten reference sites. This relationship was finally applied to the global climatology of LAP depositions, to obtain the global dataset of new and improved γ values presented here, which can be used for large scale applications of Crocus. The same relationship was applied to the values for low and high LAP years to quantify the uncertainty in the estimation of γ resulting from the inter-annual variability of LAP deposition on snow. A coefficient of variability for γ was computed:

$$C_{V,\gamma} = \frac{\gamma_{\text{low}} - \gamma_{\text{high}}}{\gamma_{\text{mean}}} \tag{2}$$

where γ_{mean} represents the mean values of gamma derived from the climatology of LAP deposition on snow and γ_{low} (γ_{high}) represents the value for a low (high) LAP year.

The spatial resolution of the final dataset of γ values is dependant on the resolution of the datasets used to create the climatology. The LAP deposition dataset (Zhao et al., 2018) limits the spatial resolution to a 50-km grid, but the dataset is presented interpolated on a finer 4-km grid inherited from the snow cover dataset (Romanov, 2017). Some regions of the world do not have a γ value in this dataset. This is inherited from the snow cover dataset (Romanov, 2017) which notably assumed no snowfall between -25°N and +25°N except in the Andes. However, these regions very seldom receive snowfall, and the snow stays on the ground for very little time, making the default value of 60 days sufficient in many cases for snowpack modelling in these regions. We also recommend that users fill the gaps presented over land and associated with the presence of lakes.

In Gaillard et al. (2024), the LAP deposition rates at the 5 mountain sites in the study were adjusted for elevation. To do this, a gradient of LAP deposition rates with altitude was computed around each of these sites. The elevations which were used here correspond to the altitude at which the LAP deposition data is given in Zhao et al. (2018), which is the ground altitude plus half of the thickness of first atmospheric layer ($\sim$ 15 m). This was done for the mean, low, and high LAP year values. Users wishing to obtain an elevation-adjusted value of gamma at a mountain site can use the LAP deposition values and altitudes included

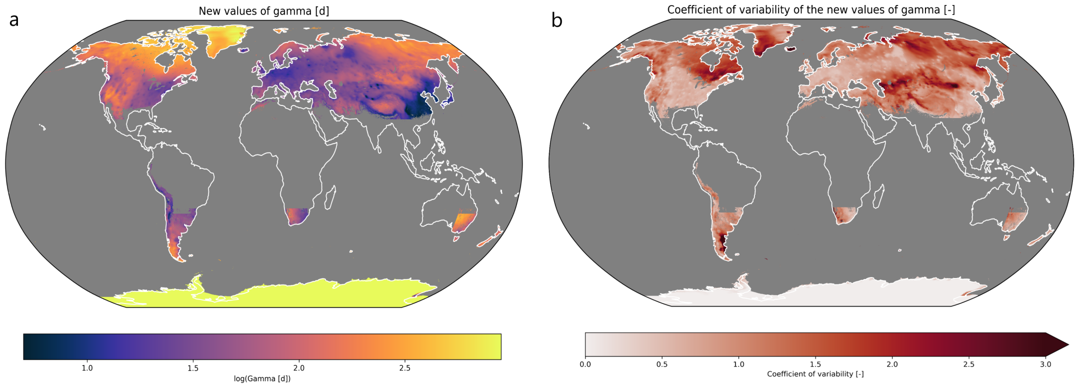

Figure 2. Global maps showing (a) the new LAP-dependant values of γ derived from this study and (b) their uncertainty linked to the inter-annual variability of LAP deposition.

in this dataset to compute an elevation-adjusted value of the LAP deposition rate at the site using the same methodology. By applying the log-linear relationship found in Gaillard et al. (2024), they will obtain a value of gamma adjusted for elevation.

3 FORMAT AND FILE ORGANIZATION

The file *gamma_tot_publish.nc* is provided in Netcdf format, and contains the dimensions and variables described below. The maps obtained by plotting γ and its coefficient of variability are shown Fig.2.

Name	Description	Unit	Type	Step
lon	Longitude	degrees E	float64	0.04° E
lat	Latitude	degrees N	float64	0.04° N

Table 1. Dimension variables contained in the file

Name	Description	Unit	Type	Range
GAMMA	Snow darkening coefficient	days	float64	5 to 900
GAMMACV	Coefficient of variability of the snow darkening coefficient	-	float64	0 to 7.9
GAMMA25	Snow darkening coefficient corresponding to the 25th percentile of total LAP deposition on snow	days	float64	5 to 900
GAMMA75	Snow darkening coefficient corresponding to the 75th percentile of total LAP deposition on snow	days	float64	5 to 900
LAPDEP	Average total LAP deposition on snow	kg m^{-2} d^{-1} black carbon equivalent	float64	0 to 3.5e-06
LAPCV	Coefficient of variability of total LAP deposition on snow	-	float64	0.22 to 23
LAPDEP25	25th percentile of total LAP deposition on snow	kg m^{-2} d^{-1} black carbon equivalent	float64	0 to 1.7e-6
LAPDEP75	75th percentile of total LAP deposition on snow	kg m^{-2} d^{-1} black carbon equivalent	float64	0 to 1.1e-5
ALT	Altitude of the GFDL dataset	m	float64	0 to 5535

Table 2. Variables contained in the file

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