**The role of dust, black carbon and algae**
**on the evolution of alpine glaciers in a changing climate**

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## Contexte and objectives

Mountain glaciers are shrinking rapidly, leading to drastic modifications on the availability of melt water and changes in natural hazards (e.g. Hugonnet et al., 2021). Alpine glaciers are very sensitive to minimal change in their surface energy balances, whether linked to variations in atmospheric forcings (changes in radiation or temperature, for example) or in their surface properties (reduced winter snow accumulation, increased detritic cover, etc.). Knowing the forcings that govern their evolution in the past, as well as for the current period, enables us to better constrain and predict their future evolution.

Glacier albedo is a key variable of the glacier surface energy balance and has a large impact on the glacier mass balance. Light absorbing particles such as black carbon, Saharan or local mineral dust, snow and ice algae, decrease glacier albedo when exposed at the surface, triggering several potent feedbacks (e.g. Di Mauro, 2020 ; Skiles et al., 2018). In the current context of climate change, temperature and precipitation changes control part of the acceleration of the mass balance changes since the 2000s (e.g. Hugonnet et al., 2021 ; Rounce et al., 2023). However, it is still unclear how much feedback related to the impact of light absorbing particles on snow and ice albedo contribute to these negative mass balances and how this will evolve in the future.

Several processes can lead to changes in the albedo of snow and ice. First, when glaciers are shrinking, more bare ice is exposed as the ablation area grows, with an albedo significantly lower than firn and snow leading to additional absorbed energy. It has also been hypothesized that an additional darkening of the ablation zone might occur due to accumulation of morainal debris (Oerlemans et al., 2009). Glaciers are highly sensitive to the ice albedo (e.g. Naegeli and Huss, 2017). However, trends in bare ice albedo in the ablation area have been investigated in over numerous swiss alps glaciers and found negative and significant only over a limited area (Naegeli et al., 2019). Second for the accumulation zone, several physical processes could lead to a darkening : (i) changes in surface deposits of both anthropogenic (e.g. black carbon) and natural impurities (e.g. Saharan dust and snow algae) or/and (ii) the enrichment of the accumulation zone in impurities due to the uncovering of layers from previous seasons during summers with a very negative mass balance (e.g. Gabbi et al., 2015). While these hypotheses have been tested on a very limited number of points and glaciers, regional assessments of the possible role of these processes on past and present glacier melt are missing.

**This PhD thus seeks to disentangle the respective contributions of meteorological drivers (temperature and precipitation) and light absorbing impurities in the decline of alpine glaciers.**

**The PhD project will be organized around the following scientific questions :**

**(i) What is the impact of light absorbing impurities such as black carbon, mineral dust and algae on the mass balance of the swiss and french glaciers ?**

**(ii) What are the physical processes and feedbacks in play ? How did they evolve in the past ? How will they potentially evolve in the future ?**

**Methodology**

This study will be based on the long series of observations of seasonal mass balances of Alpine glaciers (as part of SNO GLACIOCLIM for the French glaciers and VAW, Geibel et al., 2022). Satellite products calibrated using a first-of-its-kinds dataset of in situ dust measurement (Dumont, Gascoin et al., in press), e.g. from Sentinel- 2 (Gascoin et al., 2019 ; Dumont et al., 2020) will be used to document glacier albedo and light absorbing impurities at the surface of the glacier.

In addition, we will use the detailed snowpack model Crocus to model glacier mass balance at several locations on a subset of glacier explicitly accounting for light absorbing impurities (Vionnet at al., 2012, Tuzet et al., 2017 , Réveillet et al., 2022). For the French glaciers, the meteorological forcings will come from the SAFRAN reanalysis (Vernay et al., 2022) available over the period 1958-2023 and ADAMONT projections (Verfaillie at al., 2017) for the future

Black carbon and Saharan dust depositions over the period 1979-2023 will be taken from ALADIN-Climate reanalysis (Nabat et al., 2020) as in Réveillet et al., 2022. For future dust and black carbon deposition, we will investigate the sensitivity of mass balance to several scenaria (no change in deposition, increase deposition or decrease deposition). The evolution of the glacier geometry will be accounted for as in Vincent et al., 2019.

Additional field measurements might be planned if needed to document light absorbing particles mass on the studied glacier.

Since the extreme glacier melt in summer 2022 is highly documented (e.g. Cremona et al., 2023 ; Six et al., 2023) , the PhD will first focus 2021-2022 mass balance and to disentangle the role of heatwaves, lack of precipitations and successives massive Saharan dust depositions from February 2021 and March 2022 (Dumont, Gascoin et al., in press).

The work will be first performed on several pilot glaciers that are thoroughly documented : Argentière and Saint Sorlin glaciers in the French Alps, two glaciers in the Swiss Alps . The modeling will be then upscaled to the full mountain ranges and to the full period 1979-2050.

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**Expected start : end of 2023.**

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