EVOLUTION, ORIENTATION, AND EFFECTS OF CLIMATE CHANGE ON ICE APRONS IN THE WESTERN EUROPEAN ALPS

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1. INTRODUCTION

The impacts of climate change on mountain environments are a great concern to the scientific community. However, most research is focused primarily on large systems like glaciers. The scientific community has overlooked small geomorphic features like Ice Aprons (IA) until now; hence very few studies have been dedicated to their existence and consequent disappearance. Guillet and Ravanel, 2020 defined IAs 'as a very small (typically smaller than 0.1 km^2 in extent) ice bodies of irregular outline, lying on slopes $> 40°$, regardless of whether they are thick enough to deform under their own weight'. One of the primary reasons for the disregard towards IAs could be attributed to their small size; hence their disappearance as an effect of global warming does not drastically affect the water resource availability. Studies of (Guillet and Ravanel, 2020) showed that IAs has been losing volume since the end of the Little Ice Age (LIA). This is of grave concern for mountaineers, as the presence of IAs is considered as a necessary condition for defining many mountaineering routes in the Mont Blanc Massif (MBM) ((Mourey et al., 2019)). Carbon 14 dating analysis of an ice core extracted from the IA on the Triangle du Tacul showed the ice's age to be around 2640 +- 130 years. Considering the old age of the ice preserved in the IAs, their shrinkage and eventual disappearance by the next century can also be regarded as a loss of an important glacial heritage. Keeping this into perspective, the article's main aim is to identify the locations and orientations of IAs in the Mont Blanc Massif. Understand their evolution and assess the impacts of global warming and topographic factors on the area lost by IAs over the past two decades.

2. DATASET AND METHODOLOGY

The datasets used in this study are summarized in Table 1.

Data	Resolution (m)	Acquisition
ALOS World 3D DEM	30	31/03/2015
Pleaides stereo pair	0.5	25/08/2019
Orthophotos (IGN)	0.2	2015
Orthophotos (IGN)	0.5	2001
Pleaides 1B PAN/XS	0.2/2	19/08/2012

Table 1. Datasets used for the study.

Considering the theme of our work, and the small dimensions of the objects we are analyzing, a high spatial resolution DEM was prepared using the stereoscopic sub-meter optical images from Pleiades constellation over the Mont-Blanc massif. For each acquisition, a 4m DEM was computed from a pair of stereo images of 0.5m resolution using the Ames Stereo Pipeline (Shean et al., 2016). The DEM was then accurately co-registered with a LiDAR DEM at 2m resolution available for Argentière glacier (Nuth and Kääb, 2011). The gaps in the generated DEM was filled using a re-sampled ALOS world 3D DEM. An inventory of different glacier types was prepared using very high-resolution orthophotos (20 cm resolution) from 2015. Boundaries of ice aprons were defined by accurately digitizing the area using orthophotos from 2001, the Pleiades panchromatic (PAN) and XS images from 2012 and a combination of Pleiades PAN, Spot 7 PAN and high-resolution images from Google Earth from 2019. To avoid an overestimation or miscalculation of areas, all images were selected at the end of the summer. After delineating the IAs accurately from 2001, 2012 and 2019, an area change comparison was performed, and the effects of topographic factors like slope, aspect, curvature, elevation and Topographic Ruggedness Index (TRI) on area loss of IAs was assessed.

3. RESULTS AND DISCUSSION

3.1 Location and orientation of Ice Aprons in Mont Blanc Massif

A total of 362 ice aprons were identified in the Mont Blanc Massif (MBM) by visual interpretation and accurately digitized in a GIS environment using a combination of high-resolution images from 2019. The total area occupied by IAs in 2019 in the Mont Blanc massif is 2.404 km^2, which is 0.40 % of the massif's area. An analysis of the location of IAs with altitude shows around 83 % of the existing IAs are present above the ELA, while 17 % exist below the ELA. We fixed the ELA line very conservatively at 3200 m a.s.l based on past research. An analysis with the aspect shows that the Northern aspects (north, northwest, northeast) are most favourable for the existing IAs with almost 52 % of all the IAs in MBM existing here while the East and West aspects are the least favourable. The trend is similar to the glaciers in MBM with most major glaciers found on the NW aspect, while smaller glaciers found on the SE aspect. Another vital factor to characterize the location of IAs is the slope. Since we have already restricted our criteria for selecting IAs to steep slopes (slope over 40°), we classified the IAs on slopes higher than 40°. We observed that most IAs in MBM exist on slopes between 50-70° (70 %).

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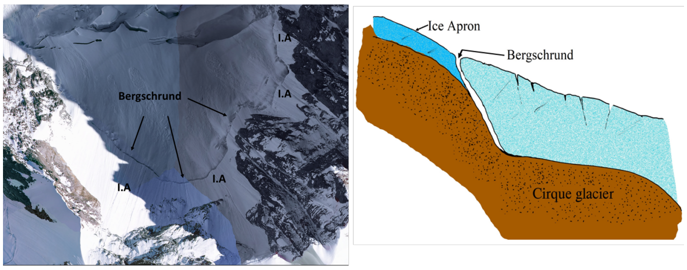

Figure 1. Evolution of Ice Aprons on the headwalls of steep glaciers

3.2 Evolution of Ice Aprons

Using the inventory of glaciers we prepared on very high-resolution orthophotos from 2015, and the locations of IAs identified previously, we tried to understand the evolution of IAs concerning other glacier systems. We observed that around 85 % of the total IAs exist above a steep slope glacier or on the top walls of a cirque glacier. These IAs were part of large glacial systems in the past, but are separated today to form a new glacial entity by the presence of a bergschrund. Bergschrund is defined commonly as a deep crack near or at the top of a glacier, separating moving ice (glacier below) from ice that is not moving (IA above) (figure 1). There are many possible reasons for the development of a bergschrund, the primary of which is the difference in flow velocities, both tangential to the surface and vertical from the upper rim (which has lower flow velocities) to the lower rim (higher flow velocities). Thus, the headwall's upper part is separated from the main glacier body and forms an IA. One of the contributing factors for the increasing disparity in the flow velocities leading to the forming a bergschrund is the increased melting due to global warming effects.

3.3 Effect of climate change and topographic factors on area loss of Ice Aprons

Similar to 2019, IAs were identified accurately and delineated for the years 2001 and 2012 using a combination of very high-resolution optical images mentioned in 1. The total area of IAs in 2001 was 3.621 km^2, which dropped to 2.624 km^2 in 2012 and then to 2.404 km^2 in 2019. This implies from 2001 to 2012 IAs lost 19% of its original area, while in 2019 % around 26 % of the original area of IAs had been lost. This is significant because, on comparison with the glaciers in the MBM, the IAs are losing area at a much alarming rate. Understandably, the smaller size of IAs makes them more susceptible to the impacts of global warming compared to large glaciers. Also, topography and local climate conditions effects are far more pronounced for IAs compared to glaciers. Guillet and Ludovic (2020) explained the effect of air temperature and precipitation on area change of IAs. Their study involved a time series analysis of six different IAs in the MBM, to assess the variations in climate forcing on the area loss of IAs. However, their study did not focus on the impact of topographic factors on the rate of area loss. Since topographic factors are non-dynamic that remain constant over time, their impacts can be modelled accurately. We assess the impacts of standard topographic parameters like the slope, aspect, elevation, curvature, topographic ruggedness index (TRI) on the area loss of IAs in the Mont Blanc Massif. Results presented in figure 2 shows that as a general rule IAs present on western aspects, low altitudes, steeper slopes, convex aspects, and higher TRI values have lost more area relative to the original area in 2001 as compared to other factors

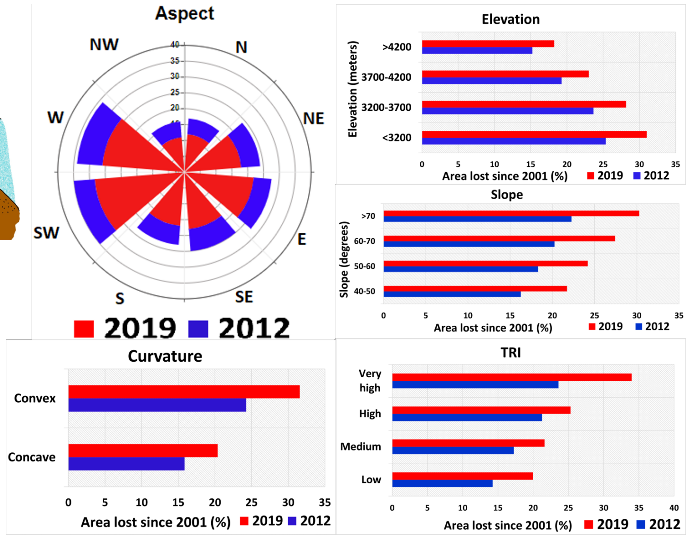

Figure 2. Influence of topographic factors on relative area loss of Ice Aprons in the Mont Blanc Massif

and are hence most vulnerable to global warming. The results are consistent for analysis of 2012 and 2019. Conversely, IAs present on slopes with northern aspects, at higher altitudes, low slope steepness, concave curvatures, and low TRI values are most protected by global warming. This shows the significant influence topography has along with climate variables on the area loss of Ice Aprons in the Mont Blanc Massif.

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