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SAR COHERENCE MATRIX AS A TOOL TO UNDERSTAND BEHAVIOURS OF ICE APRONS

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ABSTRACT

This paper focuses on understanding the temporal behaviour of Ice Aprons (IAs) in the Mont-Blanc massif using high resolution SAR coherence matrix. InSAR coherence is estimated between all possible pairs of TerraSAR-X images acquired in 2009 and 2011 as well as between PAZ images acquired in 2020, both at 11-day interval. The results show that coherence values in summer are higher in 2020 than in 2009 and 2011. Coherence matrices are also computed for different regions of a glacial system. The results are compared with those of IAs to understand the differences in their temporal and physical behaviours. In summer, all IAs show an increase in coherence values, while other glacier regions show very low or no coherence. This information could be useful for automatic classification methods, where IAs could be classified separately as a different class from the other types of glaciers.

Index Terms— InSAR coherence, TerraSAR-X, PAZ, Ice apron, Mont-Blanc massif

1. INTRODUCTION

Glaciers in the Mont-Blanc massif (MBM) constitute a living subject in numerous studies using remote sensing [1] [2], because they are considered as important indicators of water resources and climate change. An increase in temperature directly results in permafrost warming [3] and usually increases glacier retreat. However, the local impact of global warming on the behaviour of ice aprons (IAs) is still not clear. The IAs are small ice features (less than 0.1 km²) located on very steep slope ($> 40^\circ$) and mostly in high altitude [4]. IAs correspond to likely oldest ice regions in the MBM and can thus be considered as a glacial heritage [5]. The number of IAs in the MBM is significant, but studies for understanding these IAs are complicated because of their small size, difficult access and complex links to local climate variables [6]. In fact, all major global glacier inventories even fail to consider the IAs as a specific sub-class of glaciers and often show them as part of larger glacial systems [7]. As a result, very few IAs over the world have been studied. Initial definitions of IAs

made the hypothesis that IAs are temporally stable ice bodies with no significant evolution along the year. But recent studies have shown a high sensitivity of IAs to climate change. [4] showed that IAs have been continuously losing their surface areas and thickness since the end of the Little Ice Age (LIA). But all previous studies have relied on historical photographs and recent high resolution optical images. Studies of IAs with advanced tools such as high resolution SAR images have never been attempted before and thus seem of particular interest.

In this paper, we aim to understand the temporal behavior of IAs in the MBM by means of high resolution SAR images. The interest of high resolution SAR images for studying IAs is twofold: 1) the high resolution (on the order of ≈ 2.5 m) allows efficiently capturing small areas covered by IAs; 2) SAR coherence matrix provides a useful way to survey the temporal evolution of targets under observation, since the coherence values constitute a relevant indicator of surface changes. We compute coherence matrices over IAs from TerraSAR-X images acquired in 2009 and in 2011 and PAZ images acquired in 2020. Since TerraSAR-X and PAZ have very similar acquisitions (in terms of wave frequency, revisit time, etc.), a joint analysis of both data sets enables us to consistently follow the temporal behaviors of IAs. Moreover, coherence matrices for other land classes in the glacial system such as accumulation zones, ablation zone, hanging glaciers, forest and urban areas are also computed in order to highlight the difference in behaviour of IAs compared to other glacier regions.

The main contribution of this paper lies on the first deployment of high resolution SAR images to understand temporal behaviors of IAs in the MBM, the considered targets being important for climate research but poorly studied until now. This study constitutes a preliminary step towards the physical interpretation of IAs. The paper is organised as follows: the study area and data processing are described in Section 2 and Section 3 respectively. Results and discussion are given in Section 4. Final conclusions are drawn in Section 5.

2. STUDY AREA

The MBM is spread over three countries, France, Italy and Switzerland. It is dominated by the Mont-Blanc summit

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(4809 m a.s.l) and composed of lots of glacier basins, but in this study we focus on the IAs spread across the entire massif. In the chosen study area, there are two main glaciers: Mer de Glace and Argentière glaciers (Fig. 1). The IAs are spread in the massif as shown in Fig. 1.

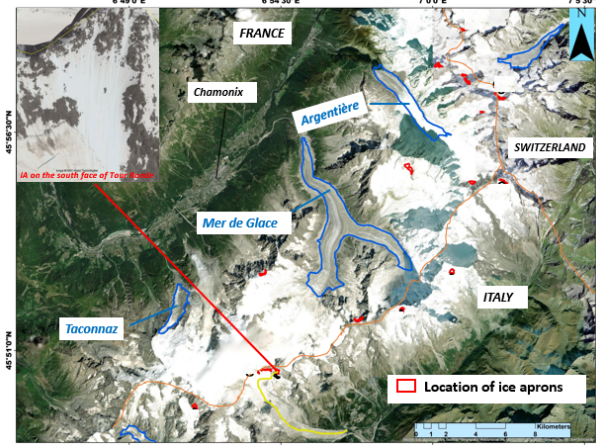


Fig. 1. Locations of the studied IAs in the MBM (in red). The background image is an ortho-photograph with 50 m resolution (source: IGN Geoportail).

3. DATA PROCESSING

Two high resolution X-band SAR image data sets are used for this study:

1. 51 TerraSAR-X images acquired in 2009 and in 2011, mostly during the 2 summer seasons,
2. 28 PAZ images acquired in 2020.

The revisit time of TerraSAR-X and PAZ satellites is 11 days.

The shapefiles of all IAs in the MBM are obtained by accurately digitizing the boundaries on very high resolution orthophotos (0.2 m resolution). Due to geometrical distortions (e.g. layover, shadow and foreshortening) related to the specific SAR acquisition geometry, all IAs cannot be studied. Only IAs avoiding these distortions have been selected by using a visibility map built from the Digital Elevation Model (DEM) obtained from Pleiades stereo image pairs and the temporal mean of the 28 SAR images acquired by PAZ in 2020 [8].

For each year and for each IA, coherence matrices are estimated between all image pairs of TerraSAR-X and of PAZ images. The coherence indicates the temporal correlation/decorrelation of IAs that is strongly related to stability/changes (as a result of melting or accumulation) of IAs' surface over time. A comparison is then performed between different years in order to highlight the IAs' surface changes

over time, even though there are gaps between the three considered years due to data availability. Further, the aim is to compare the behaviours of IAs with those of other regions commonly associated with the mountain environment. For this, we focus on the PAZ data set acquired in 2020 (because of the regular acquisitions) and compute the coherence matrices for different land cover classes such as ablation zone, accumulation zone, urban area, forest and hanging glaciers.

4. RESULTS AND DISCUSSIONS

4.1. Coherence matrix comparison between different years

An example of the coherence matrix obtained for an IA located on the North face of the Aiguille d'Argentière with PAZ data set in 2020 is shown in Fig. 2. A seasonal effect is observed, i.e. the coherence values are much higher in the summer months (from the beginning of June to the beginning of September 2020) than in other periods of the year. This is related to the melting of the IA cover, leading to the exposure of bedrock surfaces below the IA. In other periods of the year, coherence is lost due to regular snow covers. These high coherence values in summer make it possible to perform further analysis (e.g. elevation change, movement detection) with Interferometry SAR.

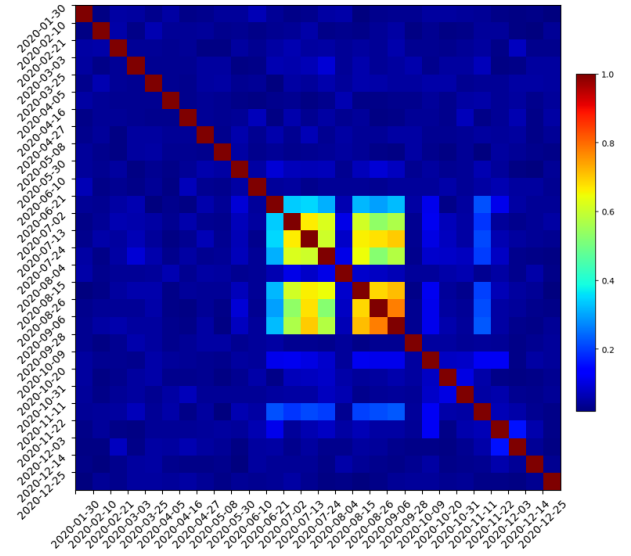


Fig. 2. Coherence matrix for the IA located on the North face of Aiguille d'Argentière with PAZ data set in 2020. A value of 1 shows highest coherence, while values close to 0 show no coherence.

Fig. 3 presents the coherence matrices for 7 IAs (named by their location) in the years of 2009, 2011 and 2020. Since we were limited with continuous data availability for TerraSAR-X in 2009 and 2011, a comparison of only the

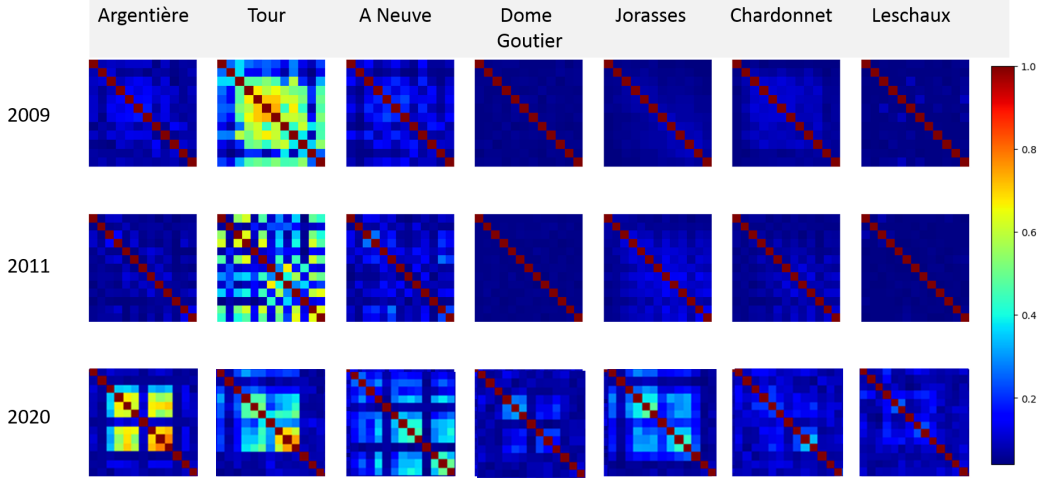


Fig. 3. Coherence matrix comparison for the years of 2009, 2011 and 2020 in case of 7 IAs. Each column corresponds to an IA named by its location.

three summers (2009, 2011 and 2020) is shown in Fig. 3, that is to say, the coherence matrices are built between image pairs from June to September. From this comparison, it is safe to say that coherence values have globally increased in 2020 compared to in 2009 and 2011 (except for the IA "Tour"). High coherence is observed for the IA "Tour" for the entire period of observation. The IAs, "Argentière", "A Neuve" and "Jorasses", present high coherence in 2020 but not in 2009 and 2011. This increased summer coherence is interesting, a plausible explanation for this could be attributed to the exposure of rock surfaces beneath the IAs as a result of the melting in summers. This is consistent with the fact that IAs have been continuously losing their surface areas and thickness since the end of the little ice age. This could further be a strong indicator of the rapid melting of IAs as a result of the changing climate.

4.2. Comparison of coherence matrices for IAs and other land classes

Coherence matrices for different land classes, including IAs, glacier ablation and accumulation zones, urban areas, forest and hanging glaciers, obtained with PAZ data set in 2020 are shown in Fig. 4. The ablation and accumulation zones present similar behaviors and always present very low coherence along the year, because of continuous surface change in these areas. As expected, long term and seasonal correlation is observed for urban area and forest, due to permanently and seasonally stable features. Global low coherence is observed for hanging glaciers, but seasonal correlation can still be observed, coherence values being slightly higher in summer. Regarding IAs, those presented in this study, always

show a higher coherence in summer and thus a relatively stable seasonal variation. Therefore, we can consider IAs, in general, as a separate class whose temporal behaviors are different from those of other zones in the glacial system, even though it happens that some IAs present low coherence along the year, similar to accumulation and ablation zones. Further investigations are necessary to relate the temporal behaviors of IAs to their physical characteristics such as location, orientation, morphology, etc. in order to better classify IAs and other glacial zones.

5. CONCLUSIONS

This paper deploys the high resolution SAR coherence matrix to understand the temporal behaviors of IAs in the MBM. According to the obtained results, we get the following conclusions: first, all IAs do not have the same temporal behaviors. Some of them stay weakly coherent over time, while others present high seasonal coherence. Besides the external climate conditions, their locations and orientations play an important part in their temporal evolution. Second, IAs do not always present temporal stability; they can present seasonal variations. In particular, in summer, high coherence is observed for a large number of studied IAs. This is related to the exposure of rock surfaces as IAs are melting. Considering that the thickness of IAs is of the order of a few meters, it is plausible that some IAs completely disappear in summer months and regain the mass again in winter. If this is the case, these ice features cannot be classified as IAs any more and further reconsideration of their definition needs to be contemplated. Third, different temporal behaviors of IAs from other land

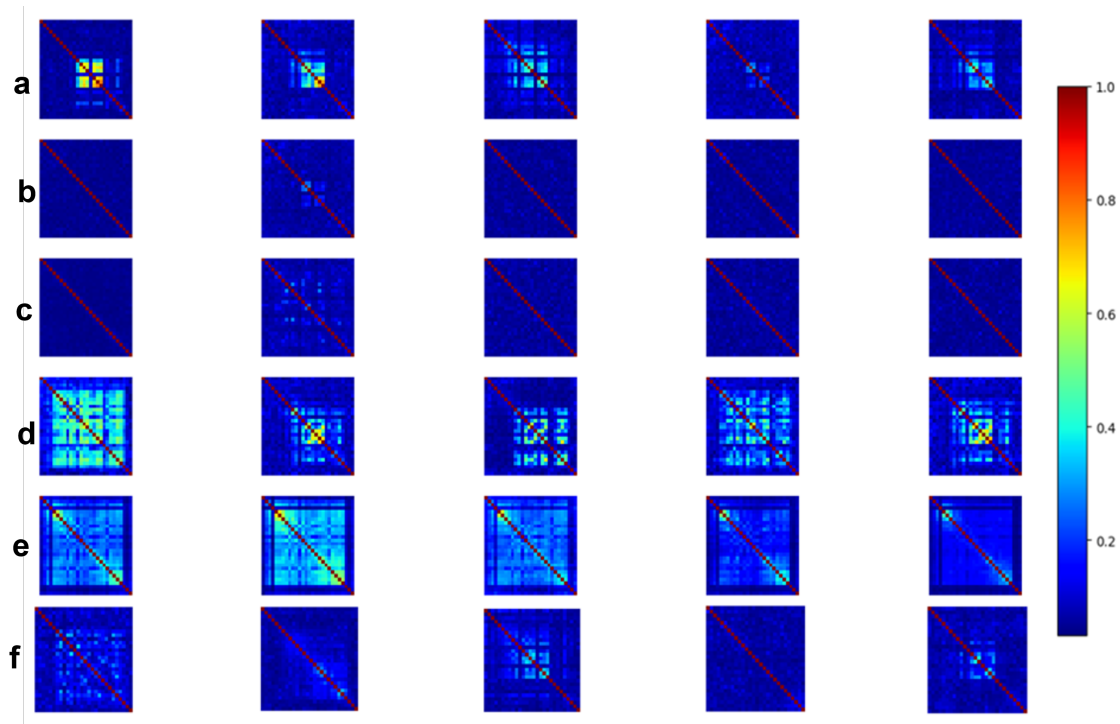


Fig. 4. Coherence matrix for different land classes with PAZ data set. a) Ice aprons, b) Ablation zones, c) Accumulation zones, d) Urban areas, e) Forest, f) Hanging glaciers. The different matrices represent different locations in the study area.

classes such as accumulation zones, ablation zones, hanging glaciers are observed. We can consider IAs as a separate class from other zones in a glacial system.

Future works include joint analyses of SAR coherence matrices and meteorological data (e.g. temperature, precipitation) in order to understand the physical behaviors of IAs and provide further evidences to prove their sensitivity to climate changes.

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