Project of strategic interest NEXTDATA

Deliverables

WP 1.4 – Climatic and environmental data from non-polar ice cores

WP.2.3: Archive of data from non-polar ice cores

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Deliverables WP2.3 B. Report on quantitative methodologies for the evaluation of glacial sites suitable for drilling, containing maps of suitability for drilling for the Alpine chain and other mountain sites and information on drilling technologies

A novel methodology to identify suitable areas for non-polar ice-core drilling that can be applied in unexplored areas for a preliminary identification of potential drilling sites has been developed in the WP2.3B. For this purpose, initially the morphometric and climatic variables associated to glacier suitability for ice-core drilling based on the characteristics of already drilled sites in Alpine and Asian High Mountain glaciers have been identified. Then, a statistical approach to map the Suitability for Ice-Core Drilling (SICD) for these areas has been developed. Assuming that in the European Alps all available drilling sites have been already exploited, this area has been used to create and evaluate the model. Finally, the model has been applied in the Asian High Mountains, and several new drilling sites are proposed and discussed providing important constraints in this poorly explored area.

1 Data collection and methodology

The overall study area is shown in Figure 1. The European Alps are a complex mountain system that extends about 1000 km (from East to West) throughout south-central Europe, reaching a maximum elevation of 4800 m (at the Mont Blanc summit). The Alps are affected by different climatological regimes and can be divided into three geographical regions with different characteristics. The Western Alps are the most elevated and they are primarily influenced by air masses that flow from the Atlantic Ocean. This region presents several drilled sites (e.g., in the Monte Bianco and Monte Rosa massifs). The glaciers of the Central Alps are less elevated compared to those in the Western Alps and they are threatened by rapid melting. In this region, drilled sites are limited in the area of the Ortles massif. Although the eastern part of the Alpine chain is influenced by cold air from Siberia, the presence of drilled sites is very low.

The Asian High Mountains correspond to the regions of Himalaya, Karakoram, Tibet, Pamir, Tien Shan and Altay Shan. The main weather systems that influence the Asian High Mountains are the westerlies and the Indian monsoon. These systems produce regional climate patterns affecting glacier behaviour differently across the Asian High Mountains. The Indian monsoon supplies high amounts of precipitation from the Indian Ocean over the Himalaya. The westerlies system becomes more important in the Western Himalaya and the Karakoram. The northern and western air masses that flow from Siberia and Central Asia to the Tien Shan and Pamir Mountains dictate the continental climate of these regions.

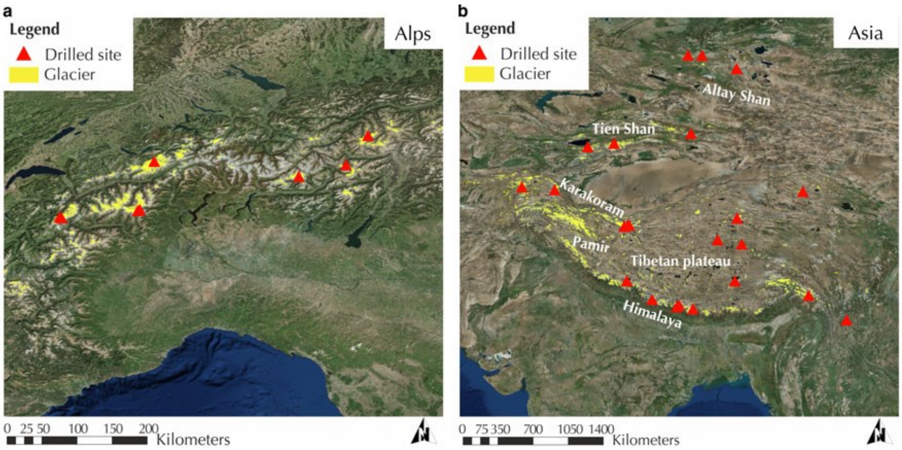

Fig. 1. Study area: the European Alps (a) and the Asian High Mountains (b). The yellow polygons show the extent of glaciers, with the position of the ice-core drilled sites (red triangles) retrieved from the Ice Core Database (IDB).

1.1 Glacier outlines

The Randolph Glacier Inventory was used to define glacier outlines within the study area. This inventory is a globally complete collection of glacier outlines supplemental to the Global Land Ice Measurements from Space. The European Alps contain 3812 glaciers, covering a total surface area of about 2052 km^2, with a vertical altitudinal range from about 1500 to 4800 m. The Asian High Mountains include 85492 glaciers covering about 120070 km^2, with an elevation range from 2500 to 8800 m.

1.2 Digital Elevation Model

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (ASTER G-DEM), characterized by 30 m spatial resolution (~1 arc-second) and ~15-30 m vertical accuracy, was chosen in order to obtain global coverage with a homogenous spatial resolution. This digital elevation model offers great geomorphologic detail in areas with a complex topography.

1.3 Climate data

Climate data were sourced from the WorldClim database. WorldClim is a set of global climatic data layers, with a spatial resolution of ~1 km^2, generated through interpolation of average monthly data from weather stations (1960-90 period; Hijmans and others, 2005). The most relevant variables for this study are monthly and annual precipitation, monthly mean, minimum and maximum temperature and some derived variables (e.g., mean diurnal range, mean temperature of warmest season, precipitation seasonality, precipitation of warmest season).

1.4 Selected morphometric and climatic variables

The most relevant morphometric and climatic variables to be used as input of the SICD model were identified based on a literature review combined with a preliminary analysis of the Cumulative Distribution Functions (CDF) of the variables characterising the drilled sites present in the IDB database. The values of each variable map were extracted from drilled sites (area of 5×5 pixels around the drilled point, ~150 m × 150 m) and from RGI glacier polygons. Differences between the CDF of already drilled sites and the CDF of the whole glacier area were evaluated to characterize drilled sites. The following variables were selected:

- **Slope** (°). Degree of surface inclination from the horizontal plane generated from DEM using a GIS (Geographic Information System) function. In areas with lower slope gradients, the preserved stratigraphy shows parallel layers that can easily refer to climate history. These sites are also suitable for technical drilling operations (e.g., location of drilling camp, drill requirements).
- **Local relief** (m). Vertical difference in elevation between the highest and lowest points of a land surface within a specified horizontal distance (computational window of 9×9 pixels). Higher values indicate the presence of steepest slopes that correspond to a major glacier flow velocity. These areas do not favour ice-core drillings because these elements can modify the original stratigraphy. In addition, steep slopes are also predisposing factors for avalanches, which disrupt the layers and constitute a risk for the technical operations.
- **Mean temperature of warmest season** (°C). Average temperature of the three warmest months. The suitable areas for ice-core drilling are characterized by below freezing temperature throughout most of the year. As temperature is inversely correlated with elevation, drilling sites are generally chosen in more elevated areas. Conversely, positive temperatures (higher than 0 °C) favour snow melting that can modify the ice-core stratigraphy. The mean temperature of warmest season was chosen from the WorldClim dataset in order to evaluate the mean higher temperature at the site.
- **Direct solar radiation** (W m^{-2} d^{-1}). A raster map of solar direct radiation was calculated using the GIS software Geographic Resources Analysis Support System (GRASS) for a given day, latitude, surface and atmospheric condition (i.e., r.sun function; Hofierka and Šúri, 2002). This variable was computed considering topographic exposure and shadows and allows evaluation of temperature difference at local scale. The function was

evaluated on 15 August. In this period, the mean temperatures are usually high in both study areas, and heat accumulation in the glacier body causes ice melting. Suitable areas for ice-core drilling are ideally those that are less exposed to high-intensity solar radiation.

1.5 Weight of Evidence and derivation of the SICD index

The SICD of mountain glaciers was defined here as the possibility of extracting an ice core with preserved stratigraphy suitable for reconstructing past climate conditions. SICD index was derived from a combination of the environmental variables described in Section 3.1.5 based on a Spatial Multi-criteria Analysis. Assuming that areas suitable for future drilling have similar conditions (i.e., combination of variables) to already drilled areas, the Weight of Evidence (WoE) method was proposed for analysing the drilling suitability of different sites. In order to apply the spatial analysis, each variable was divided into eight uniform intervals on the basis of the CDF.

1.5.1 SICD index derivation

The SICD index was calculated using a linear combination of weights defined for the selected variables:

$$SICD_{WoE} = S_{W^t} + R_{W^t} + T_{W^t} + D_{W^t}$$

where S, R, T, D are the four variables (Slope, local Relief, Temperature, Direct radiation) and W^t is the total weight corresponding to the variable interval calculated using the WoE method. All variable maps were combined in a GIS environment (i.e., GRASS). The SICD index maps were created for the European Alps and for the Asian High Mountain glaciers. Higher values of SICD indicate a better site for ice-core drilling. Normalization (between 0 and 1) was performed for the maps of SICD to evaluate the model. Finally, the first indications of potential glaciers suitable for ice-core drilling were established by ranking the sum of pixels with values of SICD >0.7 of a glacier.

1.6 Model evaluation

The root-mean-square error (RMSE) was computed to evaluate the generated maps. It was calculated using the values of SICD estimated at the drilled sites and considering 1 the expected value of SICD at these points. Furthermore, the ability of the proposed method to indicate suitable areas for ice-core drilling was verified using the success rate curve to evaluate the goodness of fit of the model. The success rate curve indicates how well the model fits the occurrences by calculating the percentage of drilled sites that occur in the areas classified with higher values of SICD. If the curve and the diagonal coincide, the model should be deemed equivalent to a totally random model. Likewise, greater slope in the first part of the curve indicates higher model quality. The curve was created by cross-checking the distribution of the total set of drilled sites with the SICD maps: after sorting SICD values of each pixel in descending order, the cumulative percentage of drilled sites was plotted against the cumulative percentage of the total study area. The Area Under the Curve (AUC) represents the quality of the model to reliably fit the occurrence: the larger the area, the greater is the goodness of fit of the model. The AUC allows the comparison of different success rate curves. A total area equal to 100 denotes perfect accuracy, whereas values below 50 represent a random fit.

2 Results

2.1 Spatial variability of the selected variables

The spatial variability of the selected variables is shown in Figure 2, focusing on the Monte Rosa massif (European Alps). Low slope values (0–20°) are present in glacier tongues but also in more elevated areas in the accumulation basins suitable for ice-core drilling (Fig. 2a). High local relief values (higher than 70 m) are found along the mountain ridges and in the vicinity of northern sides (Fig. 2b). Those steep slopes are generally associated with stratigraphic deformation of seasonal depositions. The mean temperature of the warmest season (Fig. 2c) shows an inverse relation with elevation, with negative temperatures in the more elevated summit areas. The local variability typical of complex mountain ranges is better resolved in the direct solar radiation map (Fig. 2d, 30 m spatial resolution) with respect to the temperature map (Fig. 2c, 1 km spatial resolution). The highest values of solar radiation are observed on elevated flat areas and southern slopes because they are not shielded by the effect of topography (i.e., prevailing exposure and shadows).

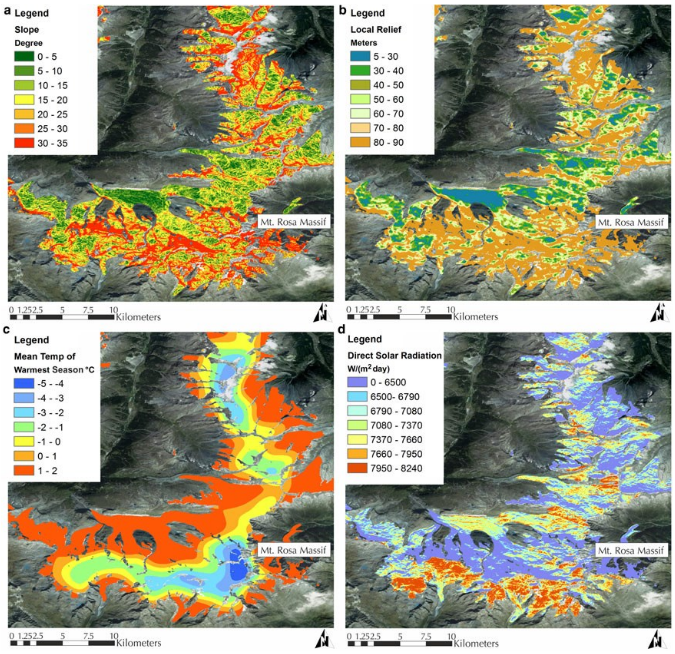

Fig. 2. Environmental variables included in the model: (a) slope; (b) local relief; (c) mean temperature of warmest season; (d) direct solar radiation. Example for the Monte Rosa massif, European Alps.

The CDF curve enables us to determine which values characterize the drilled sites. Based on the CDF, each variable was divided into the same uniform intervals used in the WoE model. CDF plots of slope and local relief show similar behaviour between the Alps and the Asian High Mountains, whereas some differences are present for mean temperature and direct solar radiation. Regarding the slope, we observe that 80% of the drilling sites are characterized by values lower than 20°. Local relief CDF shows that the drilled sites are mainly characterized by low values of local relief. Mean temperature of warmest season in the drilled Alpine sites ranges from -4 to 2 °C, with 85 % of the sites having a mean temperature lower than 0 °C, while for the Asian glaciers the temperature CDF shifts to higher values ranging from -2 to 4 °C. Similar differences can be observed for direct radiation. These can be ascribed to geomorphological differences between the Alps and the Asian High Mountains. The latter, in fact, cover a broader altitudinal and latitudinal range, resulting in higher temperature and direct radiation than in the European Alps. These differences were considered in order to adjust the intervals used for these variables in the two study areas.

2.2 Weight definition

The results of the WoE model parameters (positive, negative and total weight) were assigned to each interval of the selected variables (slope, local relief, mean temperature of warmest season, direct solar radiation) to map more suitable drilling site. Variable intervals with negative weights are negatively associated with SICD, while positive values indicate that the identification of variables within the specified intervals favours ice-core drilling. Weights close to zero reveal a slight relation between the interval and SICD. Weight values between the Alps and the Asian region show good agreement. Low slope values (0–15°) have positive weights, indicating that these intervals are suitable for ice-core drilling, whereas values above 25° are negatively related with SICD. Local relief shows that values from 30 to 50 m are positively associated with SICD while high values (> 70 m) are less favourable (negative weights) to ice-core drilling. The WoE model shows that areas more exposed to solar radiation evidence a positive relation with SICD. Finally, temperature is the most important variable with the highest weights for low temperature values.

2.3 SICD maps and model evaluation

Figure 3 shows a focus of the SICD map on the Monte Rosa Massif (Central Alps) and on Dasuopu and Yala glaciers (Central Himalaya). Green colour indicates areas not suitable for ice-core drilling; yellow and orange colours evidence sites with moderate SICD; red indicates potential drilling sites corresponding to high values of suitability for ice-core drilling (i.e., 0.7–1). Blue triangles in the maps show the locations of already drilled sites. Areas suitable for ice-core drilling, identified with red colour on the map, are mostly located in elevated flat areas, whereas southern-exposed glaciers and steep northern slopes are usually characterized by lower SICD values. The evaluation of model performances was separately conducted for the two study areas. The mean values of SICD in the already drilled sites are equal to 0.75 and 0.70 in the Alps and in Asia, respectively. The RMSE values are 0.29 for the Alps and 0.35 for Asia. The AUC, representing the quality of the model to reliably fit the occurrence, assumes values of 95.86 in the Alps and 89.77 in the Asian region. More in detail, the success rate curve (Fig. 4) shows that 13% of the study area classified as more suitable for ice-core drilling (i.e., higher SICD values) contains 90% of the already drilled sites (red line) in the Alps while, for the Asian High Mountains, 21% of the most suitable area contains 90% of the drilled sites (blue line).

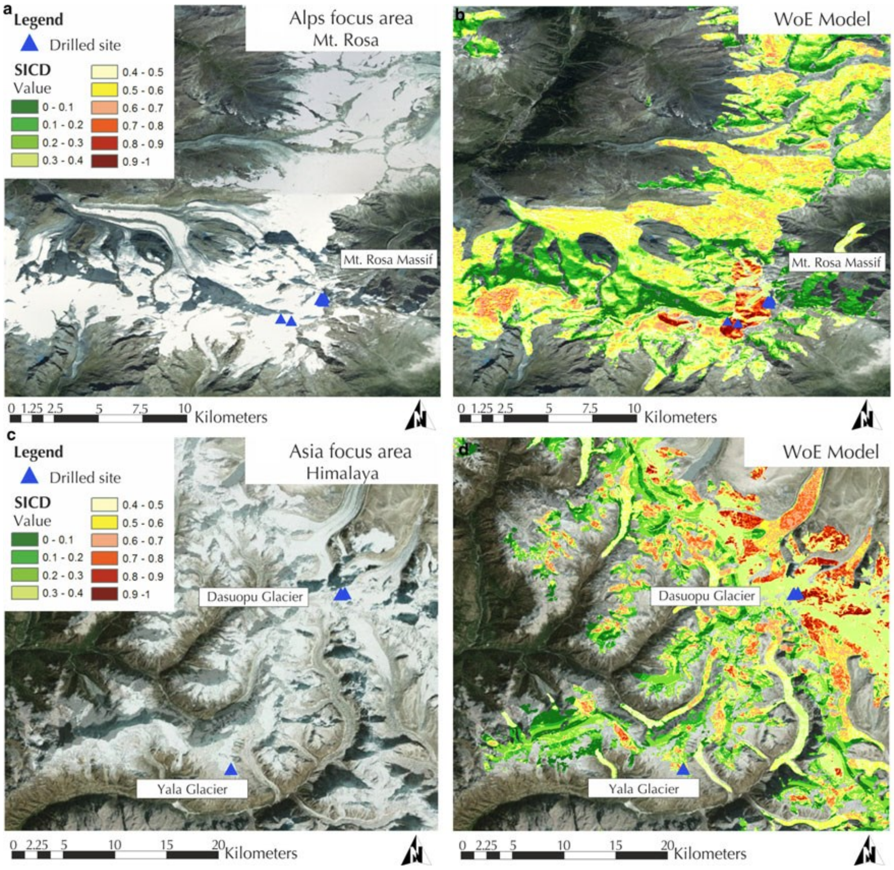

Fig. 3. Focus of true colour Landsat 8 images (left column) and related suitability for ice-core drilling maps (right column) in Alpine and Asian regions. (a) Focus on Monte Rosa Massif (Col du Lys and Colle Gnifetti drilling site) in the European Alps; (b) WoE SICD map of Monte Rosa Massif; (c) Focus on Dasuopu and Yala glaciers in Himalaya; (d) WoE SICD map of Dasuopu and Yala glaciers. Green is associated with areas unsuitable for ice-core drilling, yellow and orange colours show moderate SICD, and red indicates potential drilling sites, corresponding to high values of suitability for ice-core drilling (0.7–1). Blue triangles show the locations of already drilled sites.

All these results suggest that the model performs well in both study areas, with slightly better performances in the Alps compared to the Asian mountains. In the European Alps, hotspots of high SICD values correspond to the areas where the already drilled sites are located. This result confirms that all the potential drilling sites have been already exploited in the Alps and allows to verify the reliability of the proposed method in providing SICD maps. In contrast, in the Asian region, hotspots of high SICD values are located both in correspondence to already drilled sites and in still unexplored areas, suggesting that several new potential drilling sites can be identified in the High Asian Mountains using the model proposed in this study.

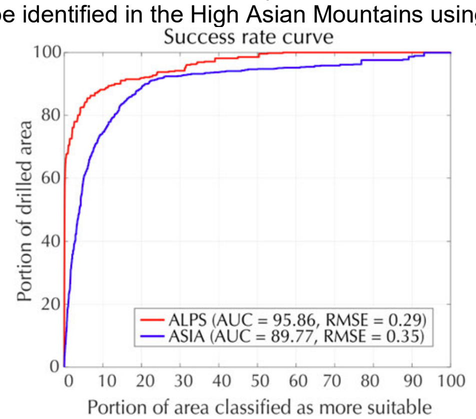

Fig. 4. Success-rate curves, area under the curve (AUC) values and root-mean-square error computed for the Alps (red line) and the Asian High Mountains (blue line).

As examples of potential drilling areas in the Asian High Mountains, Figure 5 shows true colour Landsat 8 images and the SICD map zoomed respectively in Central Himalaya (Fig. 5a), Karakoram (Fig. 5b) and Altay mountains in Tien Shan (Fig. 5c). Red colours indicate SICD values ranging from 0.7 to 1 and represent most suitable drilling areas.

The proposed methodology combines morphometric and climatic variables that are globally and freely distributed from online repositories. Some limitations of the model could be caused by the accuracy of the ASTER G-DEM and RGI glacier outlines. ASTER G-DEM shows a vertical accuracy of ~15-30 m that can introduce errors in the morphometric variables. This product was chosen in order to have a global DEM with high spatial resolution. DEM artifacts (e.g., spikes, holes etc.) can in principle affect the SICD analysis. We overcome this issue by considering an area of 9x9 pixels when calculating morphometric variables. Furthermore, when evaluating SICD maps, we considered as potential drilling sites only parts of the glacier characterized by a cluster of high SICD values.

Model inaccuracies can arise also from the use of the RGI dataset to define glacier outlines. Artifacts such as internal rocks or snow-covered bedrock are included in the RGI dataset. However, despite this limitation, the RGI was chosen because it is the most complete database of glacier outlines. Another limitation of our model is the possibility of identifying high SICD values in large ablation zones (e.g., see Fig. 5a for the Central Himalaya). To overcome these issues, the selection of potential drilling sites was supported by the inspection of optical satellite images.

Other variables, such as glacier thickness, snow accumulation, wind erosion and warming trend, can also have an effect on the SICD definition. They are not included in the model because they are not globally distributed. These variables should be further investigated at regional or local scale to support the accurate location of a drilling site within a suitable area. For example, glacier thickness is a very important variable because it is directly related to the stratigraphic resolution and it is traditionally explored using ground penetrating radar soundings or with physical methods based on surface slope and driving stress.

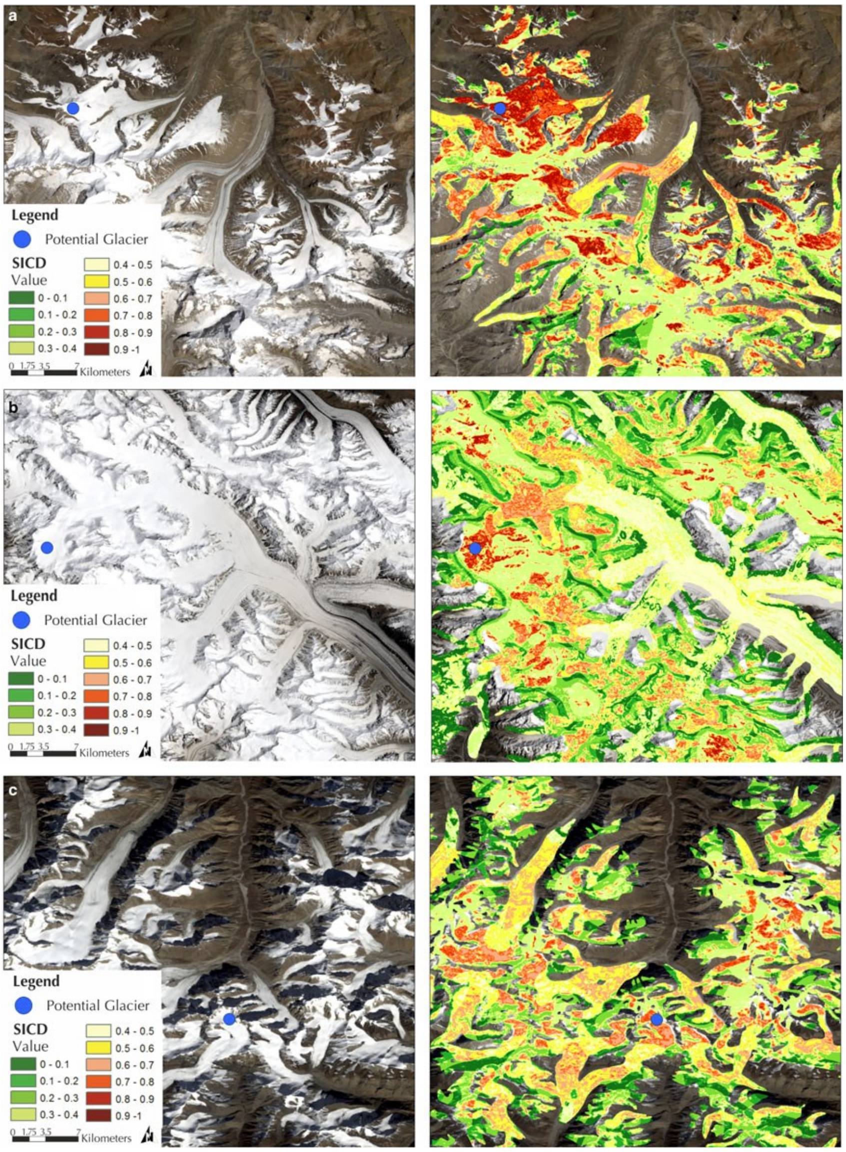

Fig. 5. True colour Landsat 8 images (left column) and maps of suitability for ice-core drilling (SICD) (right column) for the Asian High Mountains glaciers: (a) Central Himalaya, (b) Karakoram region and (c) Altay mountains in Tien Shan. The areas with drilling potential (blue dots) correspond to high values of SICD (red colours).

2.4 Potential drilling sites

Glaciers with most potential for ice-core drilling were identified by summing SICD values higher than 0.7 for glacier polygons in the following geographic regions: Central Himalaya, Hengduan Shan, East Himalaya, Hindu Kush, West Himalaya, Central

Himalaya, Karakoram, Pamir, South and Est Tibet, Inner Tibet, East Kun Lun, East Tien Shan, West Kun Lun, West Tien Shan, Alps (Mt. Rosa), Alps (Bernina), Alps (Aletsch), Alps (Mt. Bianco) and Alps (Grossfiescherhorn).

The SICD map highlights the presence of unexplored glaciers suitable for ice-core drilling in the Asian High Mountains that should be exploited in the next years for collecting fundamental climatic and environmental data. Figure 6 shows the location of the most suitable glaciers (blue dots) and the already drilled sites (red triangles) for each geographic region of the Asian High Mountains as defined in the RGI dataset.

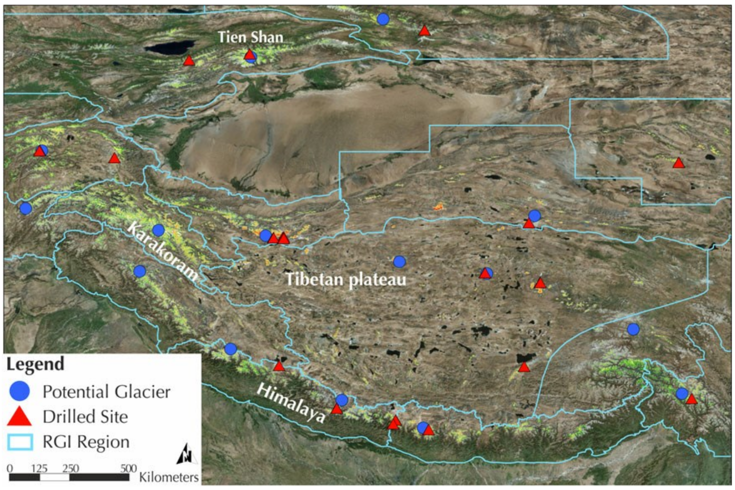

Fig. 6. Glaciers with the highest potential for ice-core drilling (blue dots), and position of the already drilled sites (red triangles) for each geographic region of the Asian High Mountains as defined in the RGI dataset.

Bibliography

Garzonio, R., Di Mauro, B., Strigaro, D., Rossini, M., Colombo, R., De Amicis, M., et al. (2018). *Mapping the suitability for ice-core drilling of glaciers in the European Alps and the Asian High Mountains*. THE JOURNAL OF GLACIOLOGY, 64(243), 12-26.