ATBD

Algorithm Theoretical Basis Document

MapBiomas Argentina

Glaciers — Collection 1

Cross-cutting class of the Land Cover and Land Use map of Argentina (Col. 3)

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Version 1

Team

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1. Introduction

1.1 Scope and Content

The objective of this document is to describe the theoretical basis, justification, and methods applied to produce annual maps of the class 'Clean-ice glaciers and perennial snow' in Collection 1 of the MapBiomas Glaciers Argentina maps. This class is integrated into the land use and land cover (LULC) maps of MapBiomas Argentina.

The dataset provides a consistent 41-year time series (1985–2025) of clean-ice glacier and perennial snow extent at 30 m spatial resolution, mapped annually across six Argentine glaciological regions: Andes Desérticos, Andes Desérticos Orientales, Andes Centrales, Andes del Norte de la Patagonia, Andes del Sur de la Patagonia, and Andes de Tierra del Fuego e Islas del Atlántico Sur. The classification algorithms are available on the MapBiomas Argentina GitHub.

1.2 Methodological Overview

The methodology combines multitemporal compositing of satellite imagery, an empirical decision tree for the generation of training samples, supervised classification through Random Forest, and a chain of temporal and spatial post-processing, in order to discriminate clean-ice glaciers and perennial snow from seasonal snow, rock, and other land surfaces. From annual dry-season Landsat mosaics —built to prioritize the minimum annual glacier extent— the dry years of each region are classified independently, acting as temporal anchors of the series. On these stable classifications, pixels of constant class are identified and filtered against the Inventario Nacional de Glaciares (IANIGLA) as a reference dataset, in order to generate the sample set that trains the classifier and extends the classification to the full annual series 1985–2025. A chain of filters applied after classification enforces physical consistency across the time series, ensuring that the detected gains and losses of glacier surface reflect real cryospheric dynamics rather than interannual classification noise associated with seasonal snow or cloud contamination.

1.3 Mapped Classes

The first collection of MapBiomas Glaciers Argentina maps exclusively the two geoforms that present exposed ice or snow at the surface: clean-ice glaciers (glaciares descubiertos) and perennial snowfields (manchones de nieve perenne). Both classes have a distinguishable spectral signature, with high reflectance in the visible and low reflectance in the short-wave infrared (SWIR), which enables their automatic, multitemporal, and reproducible identification and classification from optical Landsat imagery (30 m resolution) for the period 1985–2025. Together, these geoforms represent approximately 85% of the country's inventoried ice surface.

Other geoforms that make up the glacial and periglacial environment fall outside the automatic mapping: debris-covered glaciers and rock glaciers. These geoforms, of great hydrological relevance —particularly in the Andes Desérticos and Andes Centrales, where rock glaciers constitute a strategic water reserve— have a spectral response that is difficult to distinguish from that of the surrounding debris and rock. For this reason, rather than classifying them, MapBiomas incorporates the Inventario

Nacional de Glaciares as an auxiliary layer on the platform, in order to represent the full set of glacial and periglacial geoforms of the country and to contextualize the clean ice that is effectively mapped.

1.4 Key Applications

The glacier time series supports the long-term monitoring of glacier area change at the national and regional scale, the assessment of water-resource contributions from glacial ice, the validation and calibration of glaciological and hydrological models, reporting on national and international cryosphere indicators, and integration with the broader MapBiomas land cover and water datasets of Argentina.

2. Background

2.1 Context

For the delimitation and organization of the analysis, the glaciological zoning established by the Instituto Geográfico Nacional (IGN) —used in the national glacier inventory— was adopted, each region having similar climatic, topographic, and glaciological characteristics (IANIGLA-CONICET, 2018):

Table 1. Glacier regions of Argentina (IANIGLA-CONICET, 2018).

Great region	***Region***	***Subregion***	***Argentine provinces included***	***Approx. latitude***
Andes del Sur o Extratropicales	***ANDES SECOS***	***Andes Desérticos***	*Jujuy, Salta, Catamarca, La Rioja and San Juan*	*21°–31° S*
		Andes Centrales	*San Juan and Mendoza*	*31°–35° S*
	ANDES HÚMEDOS	***Andes del Norte de la Patagonia***	*Neuquén, Río Negro and Chubut*	*35°–45° S*
		Andes del Sur de la Patagonia	*Santa Cruz*	*45°–54° S*
		Andes de Tierra del Fuego e Islas del Atlántico Sur	*Tierra del Fuego, Islas Malvinas, Islas Georgias del Sur and Sandwich del Sur*	*54° - 60,5°S*

- **Andes Desérticos (AD):** The Cordillera is very high, with cold and arid conditions; ice bodies are small and located above 5,000 m a.s.l. Extreme aridity limits the development of large conventional ice masses: rock glaciers largely predominate, together with small niche glaciers and snowfields on the highest summits. For this initiative, the region was subdivided by separating the ranges toward the east (Desiertos Orientales, ADO), as they present summer precipitation regimes.
- **Andes Centrales (AC):** Presents a Mediterranean regime with winter precipitation and a wide variety of ice bodies, of great hydrological importance. Rock glaciers are the most numerous bodies (approximately 68% of the inventoried bodies according to the ING) but conventional glaciers, mainly valley and niche glaciers, dominate in area (approximately 65% of the total area);

these clean-ice bodies appear at around 2,910 m a.s.l. Debris-covered ice is also very abundant: around 59% of the total area presents some level of debris cover.

- **Andes del Norte de la Patagonia (PN):** Marks the transition toward the Patagonian regime, under an increasingly humid climate. Glaciers are generally smaller and concentrated on isolated Andean peaks and stratovolcanoes, where they form small ice caps; clean-ice glaciers appear above 1,700 m a.s.l. Rock glaciers are found mainly on the eastern, drier margins, owing to the rain-shadow effect of the Andes.
- **Andes del Sur de la Patagonia (PS):** The Cordillera is lower but precipitation is substantially higher, favoring the development of large glaciers whose fronts may reach 200 m a.s.l. Large continuous icefields and outlet glaciers predominate, mostly temperate, with high flow velocities and both lacustrine and marine calving fronts. On the drier eastern Argentine slope —owing to the Andean rain shadow— smaller accumulations of niche glaciers and marginal rock glaciers are found.
- **Andes de Tierra del Fuego e Islas del Atlántico Sur:** Covers the southern tip of the continent on Isla Grande de Tierra del Fuego, as a continuation of the cordillera with a change of orientation W–E and Pacific precipitation; its glaciers, of smaller size, are found at around 940 m a.s.l. According to the Atlas de Glaciares de la Argentina, clean-ice glaciers predominate (57% of the surface), followed by rock glaciers (25%) and snowfields (18%), with a greater concentration of glacier bodies around Lago Fagnano; north of the lake, rock glaciers and some snowfields predominate. The region also includes the South Atlantic islands. In this collection, only Georgias del Sur islands are included, where the presence of mountains above 2,000 m a.s.l. together with a cold and humid climate, favors the development of large glaciers.

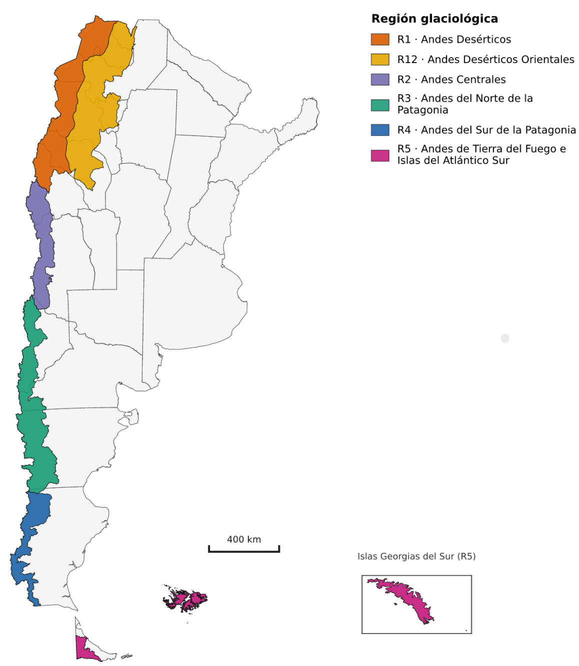

Figure 1. Glacier regions used in MapBiomas Glaciers Argentina.

2.2 Reference Inventory

As a reference for contextualizing the mapping, the Inventario Nacional de Glaciares (ING) was used, produced by IANIGLA–CONICET within the framework of Law 26,639. The ING constitutes the first systematic survey of the glaciers and periglacial geoforms of Argentina, including clean-ice bodies, snowfields, debris-covered glaciers, and rock glaciers, and provides, for each geoform, its delineation and classification derived from high-resolution satellite imagery with field validation. The ING was built from satellite imagery of the 2003–2017 period, selecting for each basin the most suitable scene, in order to generate a single reference classification of the state of the glaciers and periglacial geoforms of the country. To date, the Andes Desérticos region has been updated (Resolución 142/2024), and updates of the other regions are underway.

In this work, the ING is used to delimit the classification area and, in turn, as a reference layer for the calibration of thresholds, the filtering of samples, and the representation of the non-mapped geoforms (debris-covered and rock glaciers).

3. Algorithm Description

The classification pipeline is organized into the following main stages: image compositing and mosaic generation, generation of the training-sample set, supervised classification, and temporal and spatial post-processing, followed by national integration. All processing was carried out within Google Earth Engine (GEE).

3.1 Image Compositing and Mosaic Generation

3.1.1 Classification Area

In this work, the ING was used to delimit the classification area. On the polygons of the 'Glaciar descubierto' (clean-ice glacier) and 'Manchón de nieve perenne' (perennial snowfield) classes of the ING, a buffer of 1 and 2 km was applied, in order to consider an enlarged classification area that captures the glacier surface from 1985 to the present.

3.1.2 Landsat Archive

Surface Reflectance (SR) composites were derived from the Landsat Collection 2 Tier 1 archive (Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI, Landsat 9 OLI-2), accessed via GEE. Coverage spans 1985 to 2025 across the AD, ADO and AC regions, whereas for PN, PS and TDF-I there is a gap in 1985 and between 1987 and 1997 without images (images exist for 1986). For each year, images were filtered by acquisition date according to two temporal windows defined by regional precipitation seasonality: January–March for the AD, AC, PN, PS and TDF-I regions, where the summer melt season (dry season) exposes bare ice; and August–October for ADO, where the dry season occurs in winter.

3.1.3 Image Mosaic

For the glacier classification, annual mosaics generated from Landsat SR (Surface Reflectance) imagery were used, without applying pixel-level cloud and shadow masking. A scene-level cloud-cover filter was applied, discarding images whose cloud percentage reported in the metadata exceeds 70%. For each year, a mosaic was built by temporal median reduction of the previously filtered Landsat collection, prioritizing the condition of minimum snow cover. For each pixel, the observations with the lowest values of the Normalized Difference Snow Index (NDSI ≤ 25th percentile of the dry-season series) are retained and, over that subset, the median is computed. In this way, the mosaic represents the minimum annual glacier extent, when seasonal snow has melted and only perennial ice remains.

In order to mitigate the interannual variability in snow and ice cover caused by the alternation between dry and wet periods, previously identified dry-year mosaics were used as a baseline.

3.1.4 Definition of Dry Years

The selection of dry years was carried out from an analysis of the snow-precipitation conditions corresponding to each year of the study period. This criterion responds to the need to mitigate the interannual variability in snow and ice cover, as well as to maximize the availability of cloud-free satellite imagery. To this end, a reference temporal interval of between 5 and 7 years was established for the search and selection of imagery, which made it possible to define, for each region, the years most representative of minimum snow-cover conditions, detailed in Table 2. It should be noted that image availability was largely conditioned by the presence of cloud cover, particularly in the Patagonia Sur and Tierra del Fuego e Islas regions.

Table 2. Dry years with good imagery identified.

AD	ADO	AC	PN	PS	TDF-I
1986	**1986**	**1986**	**1986**	**1998**	**2004**
2001	**1991**	**1991**	**1999**	**2007**	**2017**
2004	**1996**	**1999**	**2005**	**2012**	
2008	**2000**	**2005**	**2009**	**2016**	
2014	**2005**	**2010**	**2014**	**2021**	
2020	**2010**	**2015**	**2021**		
2024	**2015**	**2019**	**2024**		
	2019	**2024**			
	2024				

3.2 Training-Sample Set

3.2.1 Generation of Stable Pixels (Decision Tree)

The initial classification that enabled the generation of stable pixels was performed by means of an empirical decision tree based on spectral thresholds, applied over dry-season Landsat mosaics (Surface Reflectance, without cloud and shadow masking) only for the dry years. This approach identifies candidate glacier pixels through the combination of four conditions:

- **NDSI snow index:** the minimum NDSI value of the pixel must exceed a threshold (ndsi_min), capturing the characteristic signature of ice and snow.
- **Near-infrared reflectance (NIR):** the dry-season median must exceed a threshold (nir_dry), which helps to distinguish ice from other bright surfaces.

- **Red reflectance (RED):** the dry-season median must exceed a threshold (red_dry).
- **NDSI frequency:** the number of images in the period in which the pixel exceeds the NDSI threshold must reach a minimum (frec_ndsi), which provides temporal robustness and discards spurious single-date detections.

The decision-tree thresholds (ndsi_min, nir_dry, red_dry, frec_ndsi) are not fixed but were adjusted by region and by period through an optimization process. Using the samples filtered against the ING as ground truth, multiple decision trees were run varying the thresholds (a grid-search process) for all years 2000–2024, and those that maximize classification performance —measured with the F0.5 precision metric— were selected. The use of F0.5 prioritizes precision over recall, an appropriate criterion for minimizing glacier false positives (the model is penalized more if it predicts false positives, and it matters less to lose some true positives). This period-differentiated adjustment (distinct parameters for 2000–2019 and 2020–2024 in each region) responds to the changes between Landsat sensors and to changing surface conditions, and produces the threshold sets that are finally applied to generate the base classifications of each dry year.

The cut-off thresholds for the parameters obtained from the optimization resulted in the values in Table 3:

Table 3. Cut-off thresholds for the parameters obtained from the optimization.

Region	Period	NDSI	NIR	RED
AD, ADO	early (2000–2019)	0.35	1800	900
	recent (2020–2024)	0.15	1700	900
AC	early	0.05	1800	900
	recent	0.15	1000	900
PN	early	0.15	1800	900
	recent	0.15	1800	900
PS	early	0.15	1800	1100
	recent	0.15	1700	900
TdF-I	early	0.05	1700	900
	recent	0.15	1000	900

Pixels that meet all conditions are labeled as glacier (34); the rest are classified as non-glacier (25), reserving the No-observation code (27) for areas without data.

3.2.2 Stable Samples

From the stable pixels —those that keep the same class throughout the entire dry-year series of each region— the training samples were generated. From the multi-year stack of dry-year classifications, the pixels whose class (glacier or non-glacier) remains constant across all years were identified, under the premise that temporal coherence is an indicator of reliable classification. These stable pixels were masked to the working region and additionally filtered against the ING: stable glacier pixels were retained only inside the inventory, and non-glacier pixels only outside it, thereby reducing false positives in both classes. On this refined set, a stratified sampling with a fixed total of 5,000 samples was applied, balanced between the two classes (glacier or non-glacier) by region according to the relative glacier surface in the classification area.

3.2.3 Complementary Samples

To correct localized errors that stable sampling did not capture (areas of orographic shadow or underrepresented small glaciers), the reviewers incorporated complementary samples through manually drawn polygons. At this step, the aim is to capture the most general errors possible, useful for improving the overall classification. Each polygon is associated with a reference class (glacier or non-glacier) that is stable over the period, and from it the spectral signature of the mosaic of the corresponding year is extracted. These complementary samples are combined with the stable samples before training, allowing the signal in problematic areas to be reinforced without altering the rest of the model. This mechanism is optional and is activated only when complementary polygons exist for the region and year being processed.

The complementary samples were chosen so as to belong to a single class (glacier or non-glacier) for the 1985–2025 period; in addition, some complementary samples were incorporated only for a Period 1 (1985–2004) and for a Period 2 (2005–2025).

3.3 Supervised Classification — Random Forest

3.3.1 Classification of Dry Years

The classification of each dry year was performed with the Random Forest algorithm, training an independent model per year. For each year, the training set was built by combining the filtered stable samples with the eventual complementary samples, and the spectral information was extracted from the corresponding dry-season Landsat mosaic. The classifier was configured with 100 trees and one variable per split, operating over a feature space that includes the attributes:

'swir1_median', 'nir_median', 'red_median', 'blue_median_dry', 'green_median_dry', 'red_median_dry', 'nir_median_dry', 'swir1_median_dry', 'swir2_median_dry', 'ndwimf_median_dry', 'ndsi_median_dry', 'ndsi_median_wet', 'ndsi_min', 'slope', 'gv', 'npv', 'soil', 'cloud', 'snow', 'shade'.

The result is a binary classification (glacier 34 / non-glacier 25) for each dry year of the region, and the No-observation class (27) for those pixels not classified.

3.3.2 Filters on Dry Years

A series of both spatial and temporal filters was applied to the classification obtained with the Random Forest for the dry years, ensuring temporal and spatial consistency:

1. **Gap filter:** fills pixels with value 27 (No-observation) using the classification of the previous year. For the first dry year, it fills with the next available year.
2. **Glacier frequency filter:** a pixel is considered glacier only if it appears as glacier in at least two dry years of the series. Exception: the first dry year of the region is admitted with a single occurrence.

3. **Non-glacier frequency filter:** a non-glacier pixel must be coherent with at least one neighboring dry year to remain as such.
4. **Spatial filter:** removes glacier patches smaller than 11 connected pixels or with a bounding box smaller than 2×2 pixels. It includes a bypass mechanism for large icefields, where the connected-pixel count saturates at 1024 and is interpreted as legitimate ice.
5. **Hole-filling filter:** completes small non-glacier gaps within glacier patches by morphological closing (dilation followed by erosion, kernel of radius 2).

For Region 5 (Andes de Tierra del Fuego e Islas Georgias del Sur), given that only 2 dry years with good imagery were identified (2004 and 2017), the frequency filters (2 and 3) have no statistical meaning and are omitted. Therefore, the Gap (1), Spatial (4), and Hole-filling (5) filters are applied, and an additional filter specific to this region is included:

6. **LCLU exclusion filter:** excludes pixels where the land-cover classification of the MapBiomas Patagonia Collection 2 group indicates class 33 (water) or 27 (no observation).

3.3.3 Extension of the Time Series

From the refined dry-year classification, the full annual series 1985–2025 was generated. The extension relies on a Random Forest retrained over the combined set of all dry years, then applied to the mosaics of each intermediate year. To reinforce temporal consistency, a temporal anchor was incorporated: a pixel is considered glacier in a given year only if it was also classified as glacier in the immediately preceding or following dry year, which limits the appearance of spurious glacier in years without support from the stable classifications. The product of this stage is a multi-band asset per region with one classification band per year.

3.3.4 Classification Output and Post-Processing

The output consists of the extended classifications for the 1985–2025 period as a multi-band asset per region, with one year per band. There are three values: 34 (glacier), 25 (non-glacier), and 27 (no observation). Over this extended series, the following post-processing steps are applied:

1. **Gap fill:** fills pixels with value 27 (No-observation) using the classification of the previous year. The first year of the series (1986) is completed with the next available year.
2. **Moving-window temporal filter:** corrects gaps of one to three years surrounded by the same class at both ends. It applies windows of size 3, 4 and 5, first to the glacier class (34) and then to non-glacier (25). Remaining no-data pixels are reassigned to No-observation (27).
3. **Spatial and morphological:** applies the spatial connectivity and bounding-box filter, followed by the morphological hole-filling. It incorporates a special-zone correction for the icefields of Patagonia Sur (R4) and the Sandwich del Sur islands (R5), where the spatial filter is omitted so as not to clip extensive, legitimately connected glacier surfaces.

3.4 National Integration

The classifications of the 6 regions were spatially merged and clipped using the political-boundary mask of Argentina (IGN). Class 34 (glacier), in each annual map, is overlaid on the annual national LULC maps of Argentina.

4. Results and Comparison with Reference Data

4.1 Reporting of Results

To evaluate the product, the surface mapped by MapBiomas Glaciers (Collection 1) was compared with the surface inventoried by the ING (IANIGLA-CONICET) for the same geoforms (clean-ice glacier and perennial snowfields). Given that the ING constitutes a single-date reference state per basin, the comparison was carried out against the year of the MapBiomas series temporally closest to the inventory's reference date in each region (2005–2012 for the AD, AC, PN and PS regions, and 2012–2017 for TdF-I).

At the national level, MapBiomas reproduces the surface inventoried by the ING with a difference of +1.7% at the glaciological-region level (7,331.10 km² versus 7,212.00 km²). The comparison by region (Table 4) shows differences below 8% in all glaciological regions, with MapBiomas estimating slightly larger surfaces in the continental sector (AD +4.4%, AC +5.5%, PN +2.8%, PS +7.1%) and somewhat smaller ones in Tierra del Fuego e Islas (−6.4%). This level of agreement, sustained across three orders of magnitude of glacier surface, indicates a high consistency between the automatic mapping for the 40-year period and the official reference inventory.

Table 4. Comparison of clean-ice surface (km²) by glaciological region: MapBiomas Glaciers (Col. 1) vs. ING (IANIGLA-CONICET).

Region	MapBiomas Glaciers Col-1 (km²)	ING IANIGLA-CONICET (km²)	Reference time period
AD	183,80	176,00	2005-2012
AC	799,00	757,00	2005-2012
PN	282,60	275,00	2005-2012
PS	3.551,00	3.317,00	2005-2012
TdF-I	2.514,70	2.687,00	2012-2017
TOTAL	7.331,10	7.212,00	

4.2 Limitations and Known Issues

- **Non-mapped geoforms:** debris-covered glaciers and rock glaciers fall outside the automatic mapping because their spectral signature is indistinguishable from that of debris and rock. The product captures approximately 85% of the inventoried ice surface but underestimates the total ice reserve, particularly in the Andes Desérticos and Andes Centrales, where rock glaciers predominate. The mapping of this type of glacier (IANIGLA, 2014) is added as an auxiliary layer on the MapBiomas platform.
- **Overestimation in the first decade:** at the beginning of the series, an overestimation of the class is estimated. The highest product accuracy occurs in the 1998–2025 period.

- **Image availability in the south of the country:** in the PN, PS and TDF-I regions there is a gap in 1985 and between 1987 and 1997 without usable images; together with the lower scene density of the early period, this increases uncertainty and the time series remains static in these regions during that interval.
- **Perennial snow:** the class includes snowfields that persist for at least two years; however, snowfields must appear in one of the dry years to enter the classification. This leads to an underestimation of some perennial snowfields.
- **Detection of small glaciers:** identification was not homogeneous across the whole territory, and some smaller glaciers were not detected by the classification algorithms.
- **Cloud cover:** in Patagonia Sur and Tierra del Fuego e Islas, cloud cover strongly limits valid observations and reduces the number of available dry years (in the TDF-I region only two dry years with good imagery were identified, 2004 and 2017), which restricts the temporal frequency filters.
- **Moraines:** moraines with surface debris are frequently not recognized as glaciers by the algorithm, given their spectral similarity with other land covers.
- **Edge resolution:** using Landsat imagery as the primary source, the spatial resolution conditions the definition of glacier boundaries, which do not present an optimal level of refinement.

5. Concluding Remarks and Perspectives

Collection 1 of MapBiomas Glaciers Argentina provides a consistent, automatic, and reproducible 40-year annual series (1985–2025) of clean ice (clean-ice glaciers and perennial snowfields) at 30 m resolution for the entire continental Argentine territory and part of the South Atlantic islands, with the code available on the MapBiomas Argentina GitHub. The product is integrated as a cross-cutting class in the land cover and land use maps of MapBiomas Argentina (Collection 3) and uses the ING as a reference and auxiliary layer, preserving the independence of the classification and offering, on the platform, the complete picture of glacial and periglacial geoforms. The series makes it possible to quantify the retreat of clean ice at the national and regional scale over four decades.

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