

QGIS

EVOLVING SNOW MAPPING IN FRANCE (2005-2025)



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0. INTRODUCTION

The rapid evolution of the alpine cryosphere represents a critical environmental challenge for the European ecosystem. This report presents the technical implementation of a geospatial analysis project aimed at quantifying the dynamics of snow cover in the French Alps between 2005 and 2025.

Relying on High Resolution Snow & Ice (HRSI) products from the Copernicus programme, we conducted a comparative analysis at the Massif level to ensure relevant spatial clarity. This document details the entire processing chain, from automated satellite data acquisition via Python to the production of cartographic visualizations in QGIS, highlighting a systemic decline in snow coverage.

1. CONTEXT AND OBJECTIVES

1.1. Context

The retreat of alpine snow cover constitutes a significant structural signal of climate change. To monitor this phenomenon, the reference data used is the Fractional Snow Cover (FSC) product provided by the Copernicus Data Space Ecosystem. This specific metric measures the percentage of ground covered by snow at a high spatial resolution, offering a precise view of the cryosphere's state rather than a simple binary presence/absence observation.

From a data analysis perspective, processing this information at the raw raster pixel level presents a readability challenge. With high-resolution satellite imagery covering thousands of square kilometers, a raw visualization becomes dense and difficult to interpret quantitatively. Therefore, to produce a relevant territorial analysis, it is necessary to perform a spatial aggregation by "Massif" (e.g., Mont Blanc, Écrins, Vercors). This approach reduces the complexity to 10 distinct morphological entities, offering a much clearer view of regional climate impacts.

1.2. Main Objective

The primary goal of this project is to produce a comparative cartographic visualization. The purpose is not merely to display static satellite imagery, but to clearly identify the massifs most affected by the decline in snow cover. Furthermore, the project aims to analyze the temporal dynamics of the situation by quantifying the absolute and relative evolution of snow percentage between January 2005 and January 2025.

1.3. Expected Results

The project is structured to deliver specific outputs that facilitate a direct "Before/After" comparison:

- ⇒ Map A: A thematic map of snow coverage across the 10 massifs for January 2005.
- ⇒ Map B: A thematic map of snow coverage across the 10 massifs for January 2025.

2. RESOURCES AND TECHNICAL ENVIRONMENT

This section outlines the data architecture and the software ecosystem selected to carry out the project, ensuring both the accuracy of snow cover indicators and the reproducibility of the geospatial analysis.

2.1. Data Sources

The analysis relies on the cross-referencing of three distinct types of data: attribute data (satellite imagery), spatial data (geometry), and temporal data (periods).

- ⇒ Satellite Data (Attribute Data): The core statistical data is provided by the Copernicus Data Space Ecosystem (CDSE).
 - ◆ Files: We utilized the HRSI FSC (High Resolution Snow & Ice – Fractional Snow Cover) products. These indicators measure the percentage of ground covered by snow.

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- ◆ Format: The data was acquired in Cloud Optimized GeoTIFF (COG) format via the STAC API.
 - ◆ Granularity: The raw data is defined at the pixel level with values ranging from 0 to 100%. Since this level is too fine for a legible regional map, these values serve as the input for zonal statistical aggregation.
- ⇒ Geographic Data (Spatial Data): To visualize the data on a map, we used specific boundary definitions for the mountain ranges.
- ◆ File: The specific geometry used is `alpine_massifs.geojson`, containing the boundaries for 10 major massifs (e.g., Mont Blanc, Vercors, Écrins).
 - ◆ Format: The map data is in GeoJSON (MultiPolygon) format, a standard vector format compatible with GIS software and web mapping.
 - ◆ Coordinate System: The data utilizes the WGS84 (EPSG:4326) reference system.
- ⇒ Temporal Configuration (Time Series): A specific timeframe was selected to establish the "Before/After" comparison.
- ◆ Periods: The analysis compares a reference period (January 2005) against a recent period (January 2025) to quantify the evolution over 20 years.
 - ◆ Filtering: Data was filtered to exclude images with more than 20% cloud cover to ensure data quality.

2.2. Technical Stack

The project utilizes a modern open-source stack to automate data processing and produce high-quality maps.

- ⇒ Data Preparation (ETL): Python 3.9 is used for all data extraction, transformation, and ingestion tasks. Specifically, the rasterio and rasterstats libraries are employed to handle raster processing and zonal statistics, enabling the automation of snow percentage calculations that would be prone to error if done manually.
- ⇒ Database & Infrastructure: Docker is used to containerize the database environment, ensuring consistency across different machines. The core storage engine is
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PostgreSQL 16 with the PostGIS 3.4 extension, which stores the processed temporal geospatial data and facilitates complex spatial queries.

- ⇒ Geographic Information System (GIS): QGIS 3.4 serves as the central tool for spatial analysis and visualization. It is used to connect to the PostGIS database, apply graduated color symbology based on snow percentage, and design the final cartographic layouts (maps snow2005 and snow2025).

3. DATA PROCESSING AND TRANSFORMATION (PYTHON WORKFLOW)

This section details the automated processing chain designed to handle satellite imagery. By using a modular Python pipeline (`etl_pipeline.py`), we ensure reproducibility and efficiency in handling large raster datasets. The workflow is divided into three sequential stages: acquisition, processing, and storage.

3.1. Processing Algorithm

The global architecture is orchestrated by a main script that triggers specific modules for each step of the ETL (Extract, Transform, Load) process.

- ⇒ **Step 1:** Automated Acquisition (`acquire_data.py`): The first module interfaces with the Copernicus Data Space Ecosystem. It utilizes the `pystac_client` library to query the STAC API, filtering images based on a specific bounding box and date range. A critical filter is applied to exclude unsuitable data: only images with a cloud cover percentage lower than 20% (configurable via `CLOUD_COVER_MAX`) are downloaded. The script handles OAuth2 authentication automatically to retrieve the necessary access tokens for downloading high-resolution COG (Cloud Optimized GeoTIFF) files.
- ⇒ **Step 2:** Raster Analysis (`process_raster.py`): Once the data is locally available, the second module performs the geospatial analysis. The script dynamically checks the Coordinate Reference System (CRS) of the massifs and reprojects them to match the satellite raster if necessary, ensuring spatial alignment. The core logic overlays the massif polygons onto the raster grid to compute key metrics: the mean pixel value

(snow percentage) and the pixel count. Snow-covered area can be derived by multiplying the sum of snow fractions by the pixel resolution squared, then converting the result to square kilometers. However, for this project, the interpretation focuses on fractional snow percentages, which are less sensitive to projection distortions.

- ⇒ **Step 3:** Database Ingestion (`ingest_to_db.py`): The final step persists the results in a persistent storage engine. The script establishes a connection to the PostgreSQL container using SQLAlchemy and psycopg2. The processed GeoDataFrame is pushed to the `snow_analysis` table, and spatial indexes (GIST) are automatically created to optimize future geometric queries in QGIS.

3.2. Technical Constraints

To ensure the scientific validity of the results, specific technical constraints were implemented within the Python code.

- ⇒ Satellite rasters often contain border pixels or invalid data marked with a specific integer (255). In `process_raster.py`, the `zonal_stats` function is configured with `nodata=255`. This ensures that these invalid pixels are strictly excluded from the mean calculation, preventing them from skewing the snow coverage percentage.
- ⇒ Mountain peaks often fall on the edge of raster pixels. The parameter `all_touched=True` is enabled. This ensures that any pixel touched by the massif geometry (even partially) is included in the statistics, providing a more comprehensive assessment of the snow cover.
- ⇒ Dates in file names or STAC metadata can vary in format. The pipeline explicitly casts the observation date (`date_obs`) to a standard Python `datetime` object before ingestion, ensuring that temporal queries in the database (e.g., "Select all data from 2025") function correctly.

3.3. Database Schema

To ensure data integrity and high-performance querying, the processed statistics are stored in a structured PostGIS table named `snow_analysis`. This table is defined with strict data types and constraints, utilizing columns for `massif_name` (VARCHAR), `date_obs` (DATE), and `snow_percent` (FLOAT). Crucially, a unique constraint on the composite key (`massif_name`, `date_obs`) is implemented to prevent duplicate entries for the same massif on the same date, ensuring the time series remains clean.

The spatial component is handled by a geometry column using the MultiPolygon type with the WGS84 reference system (SRID 4326). To optimize performance for geospatial operations in QGIS, a Generalized Search Tree (GIST) index named `sidx_snow_geom` is automatically created on the geometry column. Additionally, standard B-tree indexes are applied to the date and name columns to accelerate temporal filtering and retrieval operations.

3.4. Code Implementation

The core analytical logic is encapsulated within the `calculate_zonal_stats` function in the `process_raster.py` module. This function implements the zonal statistics algorithm using the `rasterstats` library to overlay vector massifs onto the satellite raster grids. A critical technical detail is the handling of the `nodata` parameter, which is explicitly set to 255. This ensures that the borders of the satellite imagery, often containing invalid or missing values, do not corrupt the statistical mean of the snow cover.

Furthermore, the `all_touched=True` strategy is employed to include any pixel intersected by the massif geometry, preventing the underestimation of snow cover in narrow mountain ridges that might otherwise be excluded by a strict centroid-based approach. The function calculates the total snow area by multiplying the verified pixel count by the square of the raster resolution, converting the result into square kilometers before packaging the data into a `GeoDataFrame` for database ingestion.

4. GIS IMPLEMENTATION IN QGIS

This section details the cartographic production phase, where the processed geospatial data is transformed into visual information. QGIS 3.4 was used as the central interface to connect to the database, style the layers, and generate the final comparative maps.

4.1. Import and Connection

Unlike traditional workflows that require manual file imports (e.g., Shapefiles), this project leverages the direct connectivity between QGIS and the PostGIS database container

- ⇒ Database Connection: We established a direct connection to the local PostgreSQL instance running on port 5432 via Docker. The connection utilizes the standard postgres user and the snowdb database defined in the environment variables.
- ⇒ Layer Loading: The snow_analysis table was loaded as the primary vector layer. QGIS automatically recognized the MultiPolygon geometry type and the EPSG:4326 coordinate reference system stored in the database.

4.2. Symbology and Thematic Analysis

To visually communicate the quantitative decline in snow cover, a specific thematic styling was applied to the massif polygons.

- ⇒ Classification Method: We utilized a "Graduated" symbology renderer based on the numerical field snow_percent. The data was divided into distinct classes to represent different levels of snow saturation, ranging from 0% to 100%.
- ⇒ Color Ramp: A custom color ramp was selected to intuitively represent snow depth. The ramp transitions from warm tones (red/orange) representing low snow coverage to cool/white tones representing high snow coverage. This visual hierarchy makes the "browning" of the Alps immediately apparent when comparing years.

4.3. Layout (Print Layout)

The final step involved creating publication-ready maps to document the environmental changes.

- ⇒ Temporal Comparison: A specific layout was generated for the January 2005 data (snow2005.pdf), showing high snow percentages across most massifs. A corresponding layout was generated for January 2025 (snow2025.pdf), utilizing the exact same scale and symbology to ensure a valid visual comparison.
- ⇒ Project Files: The entire configuration, including layer styles and print layouts, is saved in the snow.qgz project file, allowing for easy reproduction of the maps.

5. ERROR MANAGEMENT AND ENCOUNTERED ISSUES

The implementation of a geospatial ETL pipeline involving remote satellite APIs and containerized databases inevitably presents technical challenges. This section details the specific hurdles encountered regarding data acquisition and infrastructure, ensuring the robustness of the final workflow.

5.1. Data Acquisition and Integrity

The interface with the Copernicus Data Space Ecosystem presented the first major technical hurdle. Mastering the STAC API syntax and the OAuth2 authentication flow was essential to securely retrieve High Resolution Snow & Ice products. Furthermore, ensuring data integrity required strict handling of coordinate reference systems and "nodata" values. We implemented dynamic reprojection logic to align massifs with rasters and explicitly excluded the specific 255 value from zonal statistics to prevent statistical skewing.

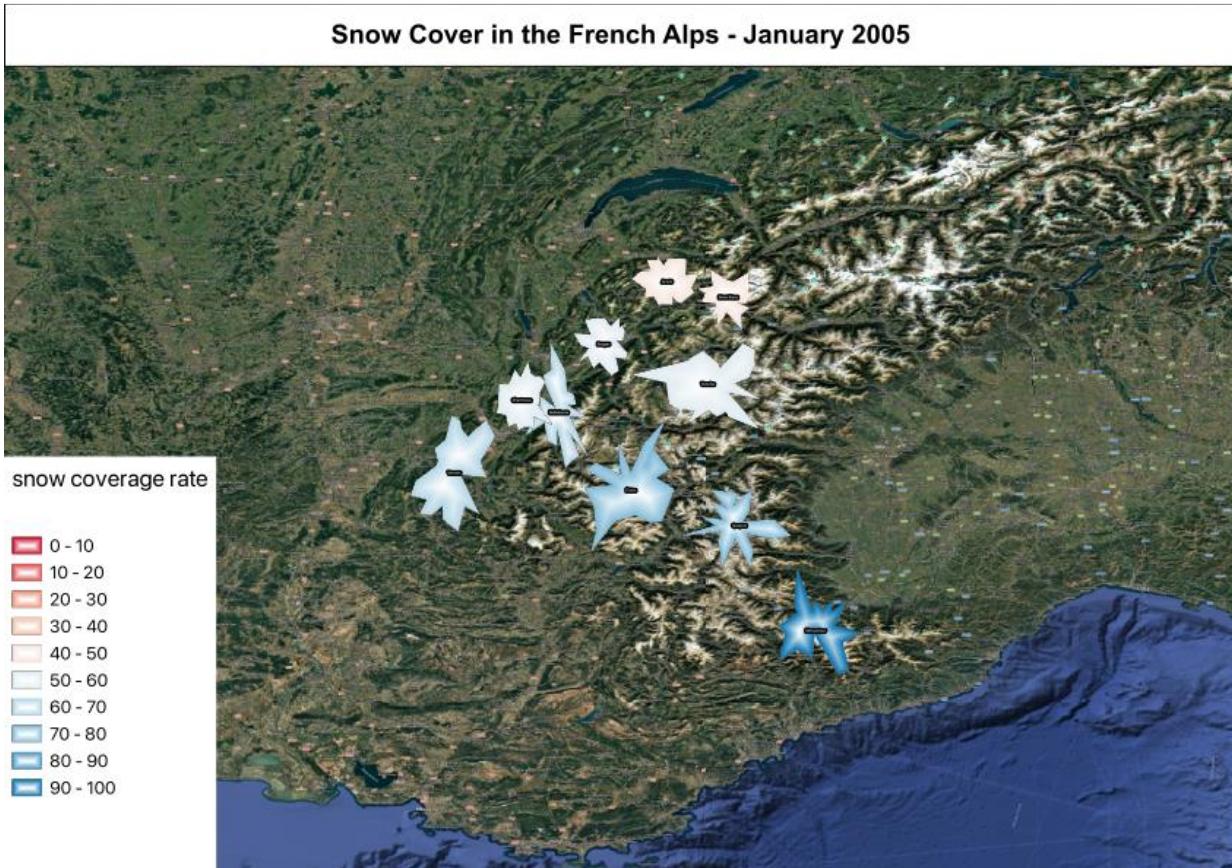
5.2. Infrastructure and Performance

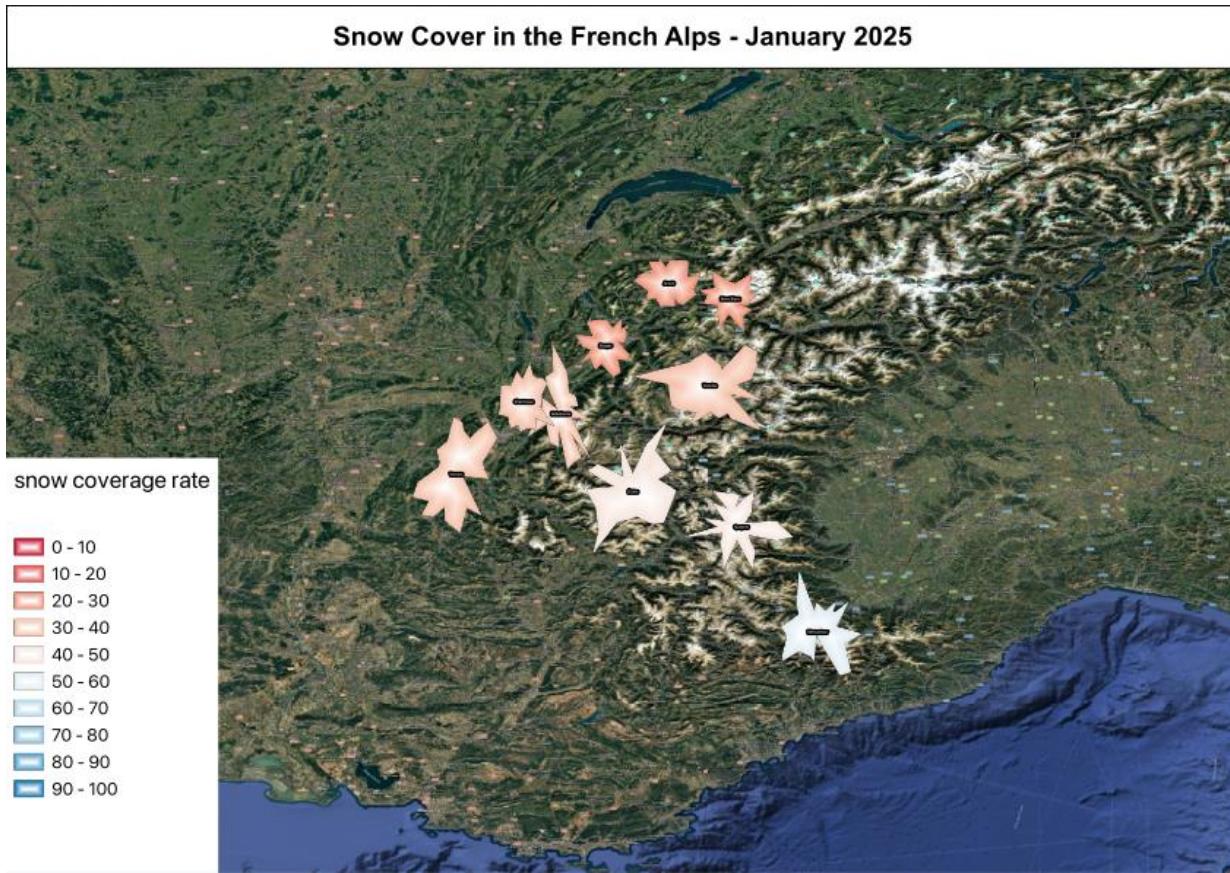
On the infrastructure side, integrating the Python environment with a Dockerized database required network configuration. Establishing stable communication between host scripts and the PostGIS container necessitated port mapping to ensure the database was accessible

via localhost. Additionally, the sheer size of satellite imagery files demanded memory management, which we addressed by implementing streaming downloads to handle high-resolution raster data without exhausting system resources.

6. COMPARISON OF RESULTS AND ANALYSIS

This section presents the quantitative findings derived from the processing of satellite imagery, highlighting the evolution of snow coverage across the French Alps between January 2005 and January 2025. The analysis combines statistical aggregation at the massif level with spatial distribution patterns to assess the magnitude of the decline.





6.1. Statistical Analysis (Min/Max Evolution)

The data reveals a severe and generalized reduction in snow availability, characterized by a sharp drop in fractional snow cover percentages across all studied areas.

- ⇒ Overall Trends: The mean snow coverage across all ten massifs dropped significantly, falling from approximately 63% in 2005 to 35% in 2025. This represents a relative decrease of roughly 45% in just two decades, indicating a rapid environmental shift rather than a slow, linear degradation.
- ⇒ Extreme Values (Maximum Impact): The Mercantour massif experienced the most dramatic absolute decline. In 2005, it held the highest coverage at 93.59%, but this figure plummeted to 51.70% in 2025, a loss of nearly 42 percentage points. Similarly affected, the Queyras massif saw its coverage drop from 78.75% to 43.02%, confirming that even high-altitude southern massifs are not spared.

⇒ Resilience Factors (Minimum Impact): While still declining, the Aravis massif showed the smallest absolute drop (-18.95 points). However, this "resilience" is deceptive, as the massif already started with a low coverage of 42.12% in 2005, leaving less snow to lose. The Mont Blanc massif, the highest massif in the Alps, also lost roughly 20 percentage points (44.00% to 24.26%), suggesting that elevation alone is no longer a complete buffer against winter warming.

6.2. Spatial Analysis

Beyond the raw numbers, the spatial distribution of the decline offers critical insights into the systemic nature of the phenomenon.

- ⇒ Uniformity of the Decline: The relative decline is remarkably consistent across the entire study area. Regardless of latitude or specific microclimates, almost every massif lost close to 45% of its snow cover relative to the 2005 baseline. This uniformity strongly suggests a large-scale, systemic climate driver, likely rising global temperatures, rather than localized weather anomalies or precipitation deficits specific to one valley.
- ⇒ No Sanctuary Areas: No single massif maintained its 2005 levels. From the Northern Alps (Bauges, Aravis) to the southern ranges (Mercantour, Écrins), every zone recorded a double-digit drop in percentage points. The notion of "sanctuary" zones where snow cover remains stable is contradicted by the data. The impact is comprehensive and geographically ubiquitous across the French Alps.

6.3. Detailed Results Table

To provide a granular assessment of the cryospheric retreat, the following table details the specific fractional snow cover evolution for each of the ten studied massifs. The data compares the mean snow coverage percentage recorded in January 2005 against the values from January 2025, sorted by the magnitude of the absolute decline.

Massif Name	2005 Snow Cover (%)	2025 Snow Cover (%)	Absolute Change (pp)	Relative Change (%)
Mercantour	93.59%	51.70%	-41.89	-44.8%
Queyras	78.75%	43.02%	-35.73	-45.4%
Écrins	72.76%	40.11%	-32.65	-44.9%
Vercors	68.95%	38.17%	-30.79	-44.6%
Belledonne	61.69%	33.59%	-28.11	-45.6%
Chartreuse	59.79%	32.70%	-27.09	-45.3%
Vanoise	57.12%	31.38%	-25.74	-45.1%
Bauges	50.91%	27.89%	-23.02	-45.2%
Mont Blanc	44.00%	24.26%	-19.74	-44.9%
Aravis	42.12%	23.17%	-18.95	-45.0%

This tabulation confirms the systemic nature of the decline. While the Mercantour massif experienced the most severe absolute loss (dropping nearly 42 percentage points), the relative change remains remarkably consistent across the entire region, with every massif losing approximately 45% of its initial snow coverage regardless of its starting baseline. The Aravis and Mont Blanc massifs appear statistically more resilient in absolute terms only because their initial snow coverage in 2005 was already significantly lower than the southern ranges.

6.4. Impact on Ski Infrastructures

The intersection of climatological data with recreational infrastructure reveals the economic vulnerability of the French Alps. By overlaying the vector network of ski pistes onto our massif geometries, as visualized in the supplementary map, we can spatially correlate the areas of steepest snow decline with the density of winter sports facilities.

This spatial analysis highlights a critical "fixed asset" risk. Unlike the snow cover, which is retreating upward and diminishing in volume, the ski lifts and slopes represented by the colored vector lines are geographically static. The data indicates that massifs like the Vercors and Chartreuse, which host significant low-to-medium altitude ski networks, have experienced a drastic reduction in fractional snow cover. This mismatch implies that a significant portion of the infrastructure shown in the visualization is becoming increasingly non-viable without heavy reliance on artificial snow production, transforming what was once a guaranteed natural resource into a precarious management challenge.



(Lines represent ski slopes)

7. CONCLUSION

This project successfully demonstrated the power of a modern geospatial technology stack in quantifying the impact of climate change on the Alpine cryosphere. By orchestrating an automated ETL pipeline with Python, PostGIS, and QGIS, we were able to process high-resolution satellite imagery and reveal a severe reduction in snow availability across the French Alps. The analysis highlights a dramatic and consistent decline, with the average fractional snow cover dropping from approximately 63% in January 2005 to just 35% in January 2025. This 45% relative decrease across all ten massifs confirms that the phenomenon is systemic, affecting high-altitude southern ranges like Mercantour just as severely as the northern massifs.

While these results provide a compelling snapshot of environmental change, it is important to acknowledge certain limitations inherent in this specific methodology. The comparison relies on two distinct temporal data points (January 2005 and January 2025) which, while sufficient to demonstrate the pipeline's capability and the general trend, does not constitute a continuous climatological time series. A more robust analysis would require processing monthly intervals over the entire twenty-year period to smooth out inter-annual weather variability and isolate long-term climate trends from short-term meteorological anomalies. The analysis prioritized fractional percentages for interpretation, since raw area calculations can be sensitive to coordinate system projections in high-relief terrain.

Looking forward, this project establishes a solid foundation for more advanced geospatial applications. Future development should prioritize increasing the temporal resolution to a monthly or weekly cadence, which would allow for the monitoring of seasonal shifts such as the timing of snowmelt. Additionally, integrating Digital Elevation Models (DEM) would enable a vertical analysis to track the upward migration of the snow line. Finally, the current workflow could be scaled to cover other critical mountain ranges, such as the Pyrenees, or deployed as an interactive web dashboard to make these vital environmental insights accessible to the broader public.

8. REFERENCES

The following technical documentation and data sources were utilized in the development of this project:

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