



D4.3 Snow coverage map

*Connecting Europe and Latin America
Transforming Today's Data into
Tomorrow's Solutions*



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Table of content

Project Summary.....	4
Acknowledgement.....	5
Copyright Statement.....	5
Executive Summary.....	6
Introduction.....	7
1. Snow Cover Map.....	8
Conclusion.....	17
References.....	18



Project Summary

The COMUNIDAD project, led by Lesprojekt, utilises Copernicus satellite data and the European Global Navigation Satellite System (EGNSS), along with Artificial Intelligence (AI), Big Data technologies and numerical modelling to transfer technologies and know-how to Latin America. The COMUNIDAD project focuses on improving agricultural and forestry management in Chile and Colombia through infrastructure development and a basic platform for creating applications that enhance precision, efficiency, and sustainability. The South American region benefits from this initiative by contributing to its socio-economic growth. Technological advancements are expected to lead significantly to practical applications due to the open-source approach in development.

Lesprojekt, the project coordinator, draws on its expertise in technology applications in agriculture and forestry to guide the consortium. The project provides actionable insights by employing advanced techniques to incorporate Copernicus services, EGNSS and other spatial datasets. These insights help stakeholders, including farmers, advisors, policymakers, and land managers, make informed decisions that support sustainable practices. Essential data on crop health, land use, and forestry conservation are provided, enhancing land management practices and boosting agricultural productivity.

In the COMUNIDAD project, experiences and knowledge are transferred through developing and using technological components, infrastructure, and training materials.

The COMUNIDAD project aims to transform agricultural and forestry management in South America through technological innovation and international collaboration based on experiences and know-how from European partners and based on international cooperation with partners from Latin America. The integration of cutting-edge technologies with strategic data analysis is set to improve different domains and promote environmental sustainability in the region.



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Executive Summary

The primary objective of WP4 is to develop the pilots and deliver specialized downstream services as part of the COMUNIDAD Project tasks under COPERNICUS program, aimed at enhancing decision-making capabilities in key regions of Chile and Colombia. Integrated into the COMUNIDAD platform, these services will combine high-resolution Earth Observation data, climate services, IoT, and VGI (Volunteered Geographic Information) solutions to support various applications across sectors. In Colombia, these tools will benefit daily farming operations, while in Chile, the focus is on forest management and developing agro-climatic indicators crucial for risk mitigation and informed policy recommendations.

In Chile, a significant aspect of the project is the estimation of snow climatology through remote sensing, using Copernicus data and the Normalized Difference Snow Index (NDSI) to generate precise snow cover maps. Employing a System Dynamics approach, the project will assess the impact of snow cover on economic activities such as agriculture and forestry, with a particular emphasis on native forest restoration and water management. This analysis is especially relevant for forest management practices, where reliable snow cover data supports the sustainable management of water resources essential for ecosystems and agricultural productivity.

A key case study within the Chilean pilot focuses on the Campos de Hielo Norte region in Aysén, where glacier calving is monitored through satellite imagery. This initiative aims to strengthen national park management, enhance tourist safety, and support academic research. Presently, a snow cover estimation algorithm is being implemented to improve snow cover mapping, particularly around Coyhaique and the "El Fraile" area. Initial testing on a low-cloud image has provided a basis for variogram estimation and image selection. Once fully automated, this system will allow users to access dynamic maps with multiple layers and filters, greatly enhancing decision-making capabilities across diverse applications and promoting informed responses to environmental and economic challenges in the region.



Introduction

The primary goal of WP4 is to implement pilot projects both in Colombia's Eje Cafetero region and in the Aysén region of Chilean Patagonia, along with related applications. These pilots will be leveraged directly by end users or indirectly through smart decision-making tools developed for the pilots and operated via the COMUNIDAD Platform. The tools will be structured and tested in collaboration with project partners and local stakeholders. Key activities include the development of high-resolution downstream services to enhance the use of Earth Observation data, IoT, VGI, and climate services; the creation of tailored solutions for daily farm management in Colombia and sustainable forest management in Chile; and the generation of agro-climatic indicators to support climate risk mitigation and inform policy recommendations.

A key methodology in WP4, in the case of Chilean Pilot, involves estimating snow/no-snow climatology through a synergy of optical and, if the data sets are available, radar remote sensing. Using Copernicus data, from Sentinel missions, seasonal snow composites will be generated at various spatial resolutions, with the Normalized Difference Snow Index (NDSI) identifying snow-covered areas. To address cloud cover gaps, a stochastic algorithm will estimate obscured regions accurately. The project will also adopt a System Dynamics approach to link snow cover with key economic activities, such as agriculture and forestry, by identifying feedback loops and evaluating policy implications using Dynamic Performance Management. In Chile, WP4 will prioritize forest management, focusing on restoring native forests and mitigating stress on natural ecosystems. Agroclimatic variables will support more effective crop management and inform strategies for water supply and productive activities. Collaboration with institutions such as FIA and CONAF will be essential to promote technology transfer and explore deployment opportunities for sustainable land-use practices.



1. Snow Cover Map

To introduce and present the snow cover maps analyzed using the Sentinel-2 MSI mission, it is essential to understand why snow cover data is critical in the Aysén region. Snow cover significantly influences climatic patterns, water resources, and agricultural planning.

The value of snow cover data extends beyond its technical significance; it provides decision-makers with real-time information that facilitates risk anticipation and resource management. Snow cover directly impacts water availability, a critical factor for agriculture and hydroelectric power generation in Aysén. Additionally, in a region with limited studies on snowfall trends and their influence on river flow and hydroelectric feasibility, these data address key knowledge gaps, allowing for future scenario planning to mitigate potential water scarcity issues.

Remote sensing offers a practical solution to the challenges posed by Aysén's rugged terrain, enabling frequent and accurate snow cover monitoring even in remote areas. This approach is essential for developing sustainable management strategies, addressing data gaps caused by cloud cover, and overcoming obstacles posed by clouds in interpreting optical data. Advanced algorithms, employing spatial interpolation and machine learning, enhance snow cover estimates under cloudy conditions, which is crucial for agriculture, forestry, and environmental conservation applications.

Using Copernicus data thus supports a more resilient Aysén region, bolstering critical sectors in changing climatic patterns and ensuring sustainable resource use through informed decision-making.

For the Aysén region, several polygons are being defined to validate case studies within this pilot project. Key areas of interest include Campos de Hielo Norte, Coyhaique, Ñirehuao, and other critical locations aligned with the study's objectives. During this initial phase, the focus area includes the Fraile sector and the city of



Coyhaique. Its extent is delineated using a bounding box (BBOX) based on geographic coordinates in the WGS84 CRS system, bounded by the coordinates: (-72.083847, -45.662527) to (-71.862877, -45.520421), providing precise dimensions for the area, as illustrated in Figure 1.

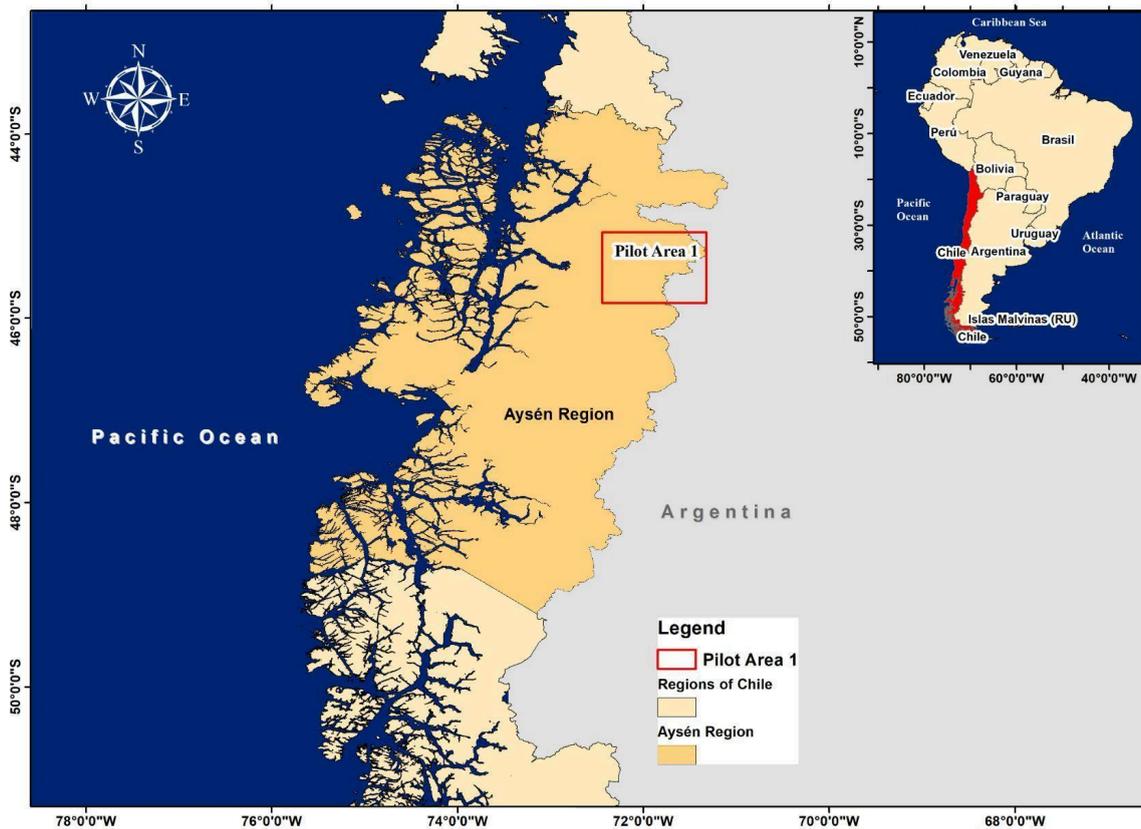


Figure 1. Location of the Coyhaique pilot area

The development of the snow cover algorithm utilizes satellite imagery obtained through the Sentinel Hub API, a programmable interface compliant with Open Geospatial Consortium (OGC) standards. This API provides efficient access to satellite data, enabling integration into custom applications on both online platforms and desktop environments. Through it, Sentinel-2 L2A images from the Copernicus program were accessed, offering a resolution of 10 to 20 meters and surface reflectance data optimized through atmospheric correction.

To enhance processing capabilities, resolution, and coverage area, the development of this map and algorithm will be transitioned to the COMUNIDAD platform. This shift will enable the structuring of services based on snow cover estimation, facilitating implementation across various use cases.

The areas of interest (AOI) were defined using the Copernicus Request Builder tool, which generated requests in both CURL and Python formats, simplifying the acquisition of the imagery. These images were downloaded in GeoTIFF format, crucial for analysis in GIS systems, with an initial resolution of 100x100 pixels to optimize computational resources during the preliminary stages of analysis.

From the GeoTIFF files containing multiband data, the relevant spectral bands were processed to enhance visualization. Each band was normalized by stretching its values to the range between the 2nd and 98th percentiles, thereby improving visual interpretation. Subsequently, the bands were scaled to a 0-255 range to generate an RGB composite image, represented in both true color (red, green, and blue) and false color (NIR, red, and green) for the area of interest (see Figure 2).

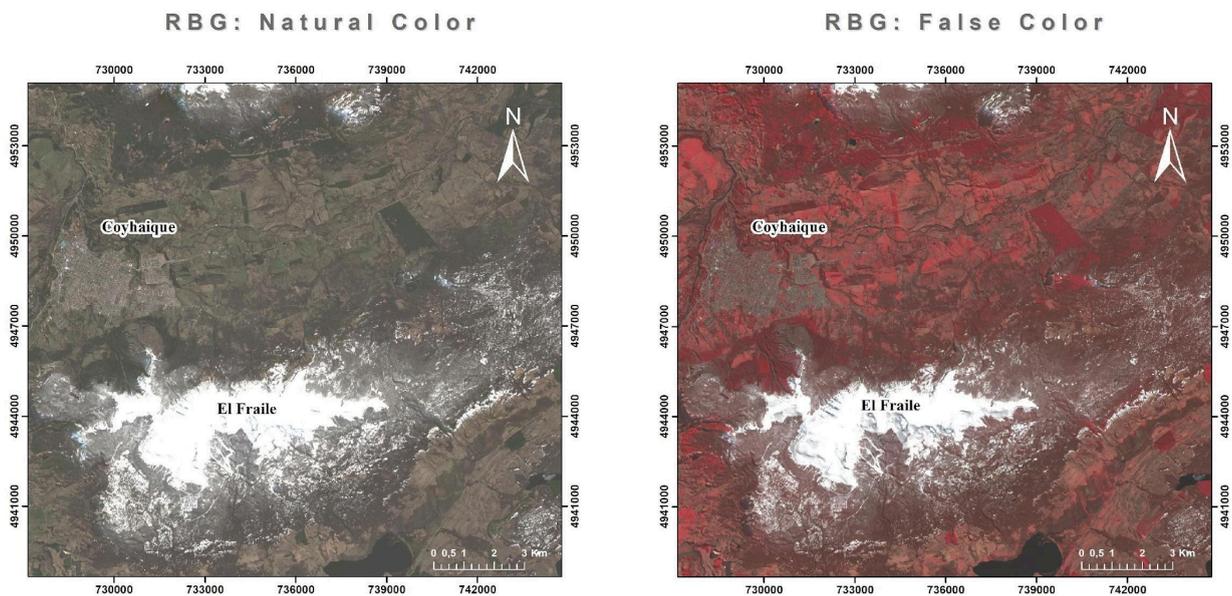


Figure 2: RGB composition in true color (A) and false color (B), highlighting the initial distribution of snow within the pilot polygon area.



Subsequently, the Normalized Difference Snow Index (NDSI) is calculated using two spectral bands: one in the visible region of the electromagnetic spectrum and the other in the shortwave infrared (SWIR). This index leverages the optical properties of snow, characterized by high reflectance in the visible region and strong absorption in the SWIR (Hall & Riggs, 2010). The NDSI is calculated using the following mathematical expression:

$$NDSI = \frac{\rho_{GREEN(0.54-0.58 \mu m)} - \rho_{SWIR(1.57-1.66 \mu m)}}{\rho_{GREEN(0.54-0.58 \mu m)} + \rho_{SWIR(1.57-1.66 \mu m)}} \quad (\text{Ec. 1})$$

Where ρ_{GREEN} and ρ_{SWIR} represent the reflectance in the green band (Band 3) and the shortwave infrared band (Band 11), respectively. The generated index is shown in Figure 3 below.

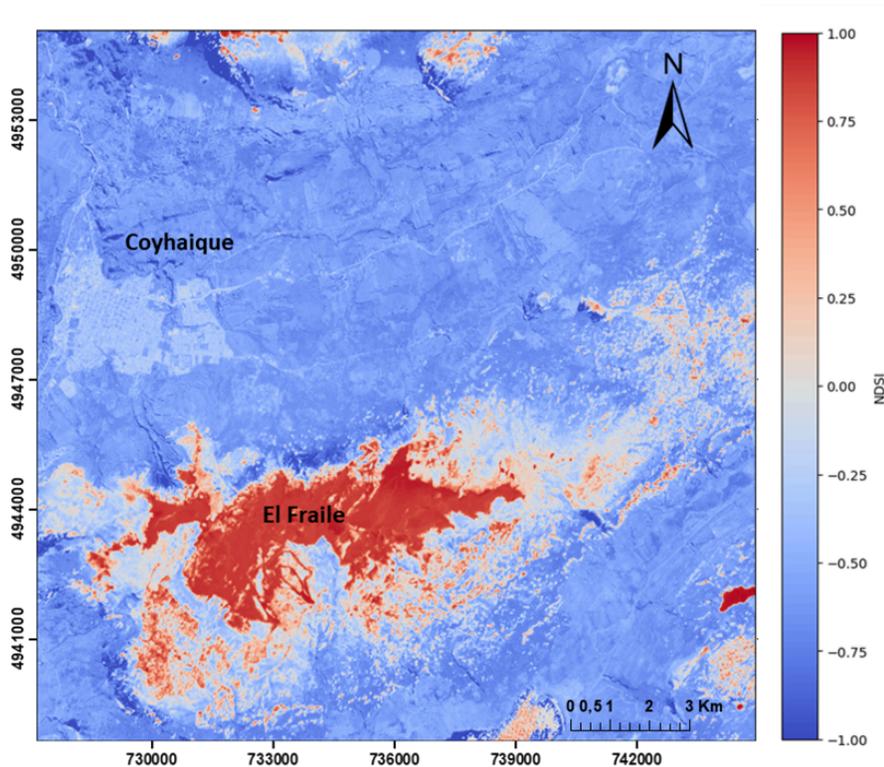


Figure 3: Normalized Difference Snow Index (NDSI).

From the NDSI, a mask is generated by applying a threshold to discriminate snow cover, as indicated in Equation 2:

$$NDSI \geq 0.4 \quad (\text{Ec. 2})$$

This threshold, established by Cea López et al. (2007), has proven effective as an initial approach for identifying snow cover. These authors, as in this study, calculated the threshold using radiometrically corrected images. However, previous studies (Riggs et al., 2006) have utilized uncorrected radiometric images, benefiting from the fact that, being a normalized index, atmospheric effects are partially mitigated. Nevertheless, in such cases, the 0.4 threshold is not universally applicable, with adjustments down to a value of 0.3 reported for certain images.

The Normalized Difference Snow Index (NDSI) threshold of 0.4 has been widely recognized as an effective criterion for identifying snow cover across diverse geographical contexts (Hall & Riggs, 2007). This threshold has been validated in numerous studies using radiometrically corrected satellite images, particularly in regions where snowpack dynamics are influenced by high latitudes and complex topography. In the Aysén Region of Chile, characterized by a mix of Patagonian ice fields, seasonal snow cover, and variable atmospheric conditions, the 0.4 threshold provides a reliable initial approach for snow detection. Given the region's heterogeneous land cover, including glaciers, forests, and high-altitude plateaus, applying this standardized threshold ensures consistency in snow mapping while mitigating potential false detections associated with lower values (Gascoin et al., 2019).

As the project progresses, further validation efforts will be conducted in prioritized areas to assess the threshold's effectiveness under local environmental conditions. Studies have shown that regional factors such as vegetation density, cloud contamination, and variations in snow grain size can affect NDSI performance, potentially requiring threshold adjustments. By implementing ground-truthing campaigns and integrating high-resolution Sentinel-2 data, the study aims to refine snow detection accuracy across different landscape types in Aysén. The validation process will also include comparisons with in situ snow depth measurements and meteorological records, ensuring that the applied threshold aligns with actual snow



presence on the ground.

To enhance the algorithm's precision over time, an automated feedback mechanism will be developed, enabling dynamic updates to the NDSI threshold based on real-time validation results. By leveraging machine learning techniques and time-series analyses, the model will adapt to seasonal and interannual variations in snow cover, improving its classification accuracy in response to environmental changes (Härer et al., 2018). This iterative approach will allow for continuous refinement, ensuring that the algorithm remains robust in detecting snow across Aysén's diverse terrain. Ultimately, this adaptive framework will contribute to a more accurate and reliable snow monitoring system, supporting regional water resource management and climate change studies.

In this study, for Pilot 1, areas with an NDSI value equal to or greater than 0.4 were classified as snow, represented in cyan to facilitate differentiation. The resulting snow cover layer is overlaid on the RGB composite image, combining the original view of the area with a modified version that highlights snow cover, providing a clear visual interpretation of its distribution (Figure 4).

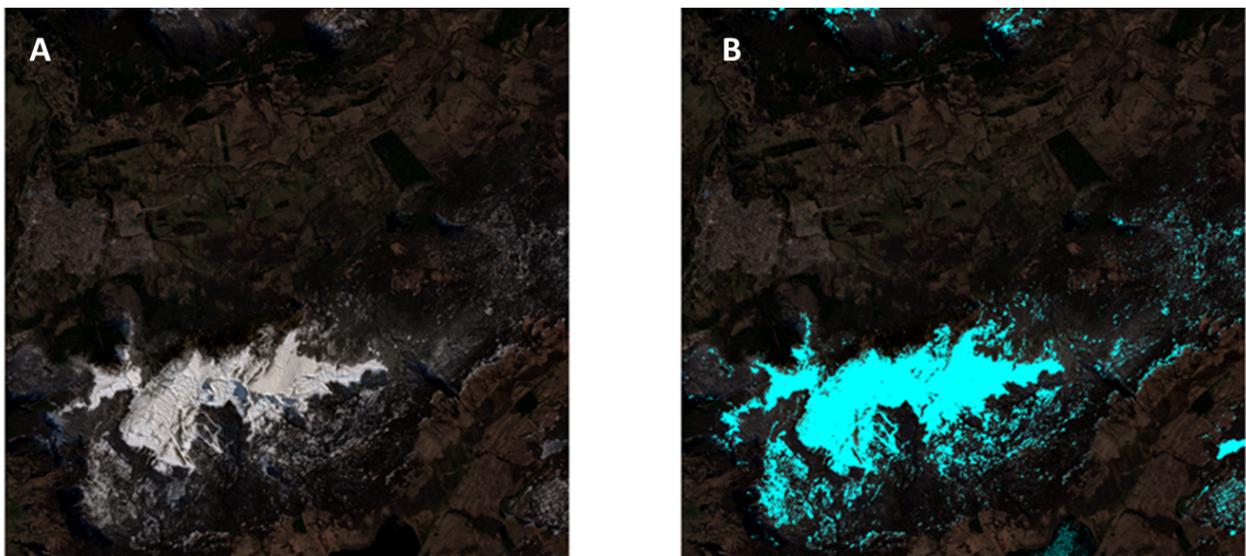


Figure 4: The right panel "A" displays a true-color image, while the left panel "B" shows an image highlighting areas with snow cover calculated using the threshold proposed by Cea López et al. (2007).

The initial snow coverage map is available on the COMUNIDAD website and once the COMUNIDAD platform is released, updated versions of the snow cover map will be available on the COMUNIDAD platform.¹ Figure 5 shows the map on the COMUNIDAD website.

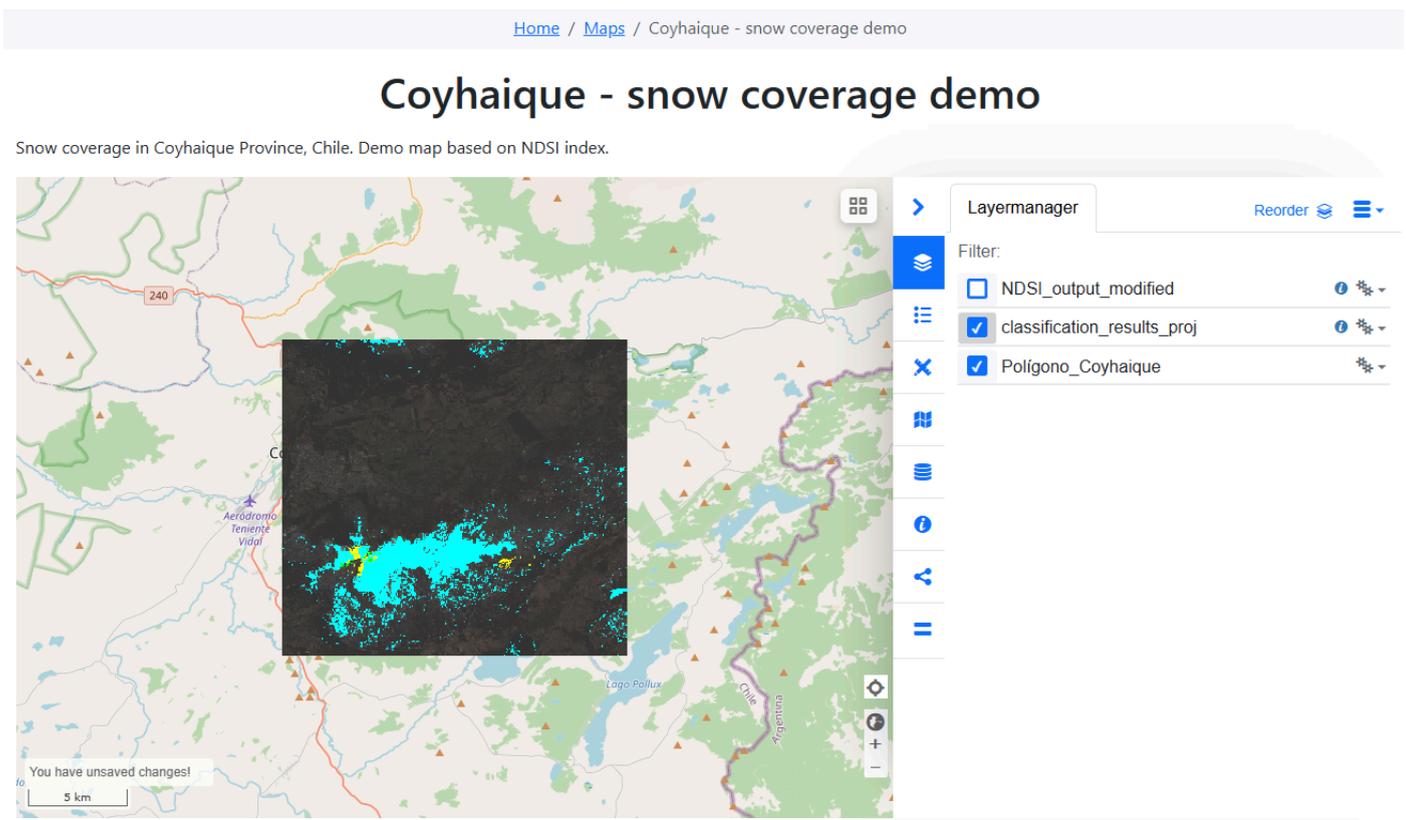


Figure 5. Screenshot of the map window on the COMUNIDAD website.

A cloud mask is implemented. To obtain a binary mask indicating the presence of clouds, bands B01 to B12 of the LIC product are processed using the Sentinel-2 Cloud Detector cloud detection algorithm provided by the SentinelHub service.

The workflow of this stage of the algorithm is described in figure 6 and follows the steps below:

¹ <https://comunidad-project.eu/map/coyhaique-snow-coverage-demo>

1. **Definition of the area of interest:** The user enters the coordinates of the corresponding polygon and specifies the coordinate system used.
2. **Data download:** The LIC catalog bands of the Sentinel-2 mission are obtained, together with the dataMask band, which is a binary mask indicating the presence of valid data (value = 1) or the absence of valid data (value = 0).
3. **Initialization of the cloud detector:** The cloud detector object is configured with the following key parameters:
 - a. **threshold:** All pixels with a cloud probability higher than the set threshold are considered cloudy. A value of 0.6 (60%) is defined.
 - b. **average_over:** Size of the disk (in pixels) used to apply a convolution and smooth the probability of clouds over adjacent areas. A value of 4 pixels is used.
 - c. **dilation_size:** Size of the disk (in pixels) used for the dilation operation, which expands the areas detected as cloudy to include the cloud edges. A value of 2 pixels is used.
 - d. **all_bands:** Boolean parameter (True or False) indicating whether the input image will include all 13 bands of the Sentinel-2 satellite. Since all bands of the spectrum are downloaded, it is set to True.
4. **Generation of the cloud mask:** From the downloaded bands and the defined parameters, the probability of cloud presence is calculated and a binary mask is generated. All pixels with a probability higher than 60% are considered as cloudy.
5. **Application of the mask:** The binary mask is superimposed on the previously calculated NDSI raster, eliminating the areas affected by the presence of clouds.
6. **Generation of the final product:** As a result, a raster of the NDSI is obtained with empty values in the areas where the presence of clouds was detected.

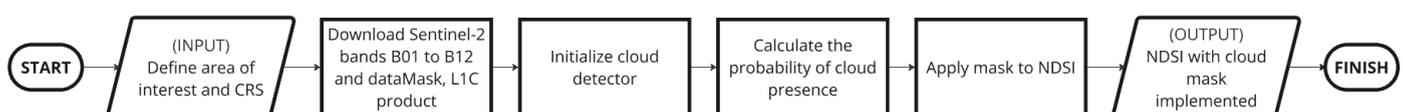


Figure 6. Workflow of the cloud detection algorithm.

Following this visual analysis, spatial patterns can be further investigated through a variogram. The variogram serves as a key tool to describe the spatial dependency of observations as distance increases between them. This measure reflects that

observations closer in proximity generally share similar values. The variogram calculates this spatial correlation by assessing separation distances between observation pairs, grouping them into distance classes (e.g., 10 to 20 meters) to estimate semivariance. In this approach, the semivariance represents a (dis)similarity metric, giving insight into the degree of spatial correlation within the data.

This initial snow cover map, although a static visualization, provides a foundational representation of what the final application aims to achieve. It first approximates the snow coverage and spatial relationships within the pilot area, laying the groundwork for a more refined implementation of the snow detection algorithm and additional spatial analysis techniques.

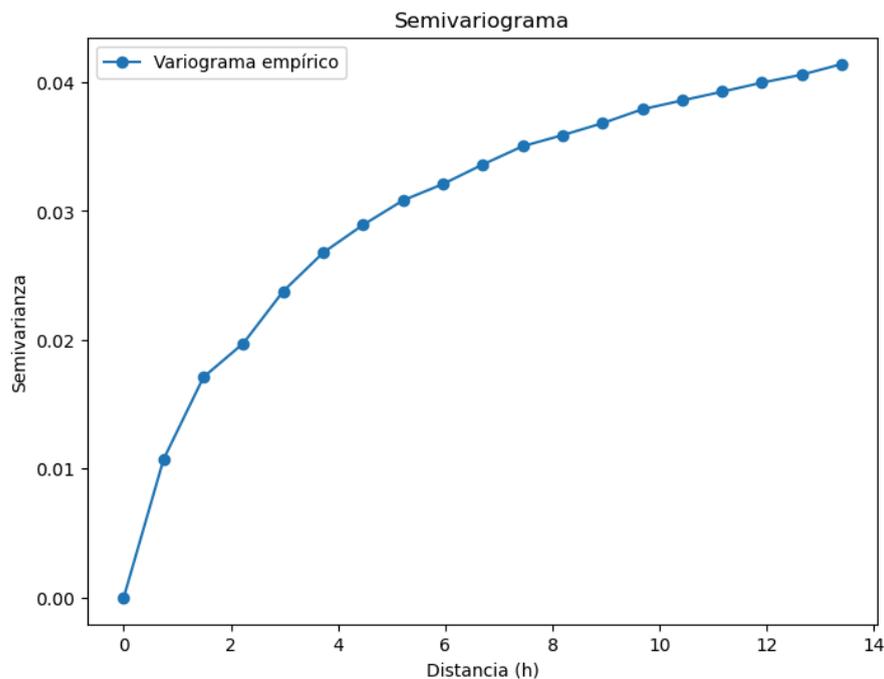


Figure 7: Variogram illustrating the spatial dependency of snow cover observations across varying separation distances.

In this phase, the snow cover map provides a static representation of snow distribution within the pilot area, serving as a valuable first step in assessing the feasibility and functionality of the snow monitoring process. However, once the snow cover detection algorithm is fully implemented through the COMUNIDAD infrastructure, the platform will shift from static visualization to a dynamic, real-time snow monitoring tool. This

dynamic system will allow users across sectors—particularly in agriculture and tourism—to access continually updated data, empowering them to make timely, data-driven decisions.

The platform will integrate environmental indicators such as seasonal streamflows, precipitation, and temperature variations for snow cover monitoring. Government agencies and local authorities will collaborate to incorporate this data into broader water resource planning, supporting agriculture and energy needs. Through interactive maps and charts accessible on the platform, users can explore trends in water availability and assess how snow cover changes impact local water resources, directly informing agricultural and land management practices.

The tourism sector, particularly in areas like the Exploradores Glacier, will benefit significantly from this dynamic platform. Real-time monitoring of snow cover and glacier retreats provides critical information to tourism operators and local governments, enabling them to manage visitor access, implement safety measures, and communicate effectively with tourists about potential risks or route closures. With features like real-time alerts and risk zone maps, the platform will be a valuable tool for maintaining tourist safety and sustainable tourism practices.

As the COMUNIDAD project infrastructure continues to develop, executing pipelines for data processing and deployment will enable an integrated, dynamic experience. Users will not only have access to historical data but also real-time updates, making the platform an essential tool for effective snow cover monitoring and informed decision-making across multiple sectors. This evolution from a static to a dynamic platform marks a significant advancement in the region's capability to monitor and manage snow cover, supporting resilience in agriculture, tourism, and resource management.

Conclusion

The initial development of static snow cover maps within the COMUNIDAD project provides a valuable foundation for understanding snow distribution in critical areas such as Aysén. This preliminary visualization allows stakeholders to assess snow coverage across regions of interest, particularly relevant to water resource



management and environmental planning. However, integrating a fully implemented snow detection algorithm will transition the platform into a dynamic, real-time monitoring tool as the project advances. This enhancement will enable local stakeholders, especially agriculture and tourism, to make data-driven decisions based on up-to-date snow cover information, vastly improving planning and risk management.

The COMUNIDAD platform will further support collaborative resource management efforts across sectors by incorporating additional environmental indicators, such as seasonal streamflows, precipitation, and temperature. This data integration empowers government agencies, local authorities, and agricultural users to anticipate and plan for fluctuations in water availability, an essential component for optimizing agriculture and supporting energy requirements in Aysén. With real-time snow cover maps, stakeholders gain a more holistic understanding of regional climate and water dynamics, allowing them to make informed decisions that enhance resource sustainability and mitigate risks associated with water scarcity.

In the tourism sector, especially in high-traffic areas like the Exploradores Glacier, the platform's real-time snow cover monitoring will allow operators and local authorities to improve safety measures and manage visitor access more effectively. Equipped with dynamic alerts and risk maps, tourism managers can make timely adjustments to visitor guidelines and route accessibility, ensuring safe and sustainable operations in response to glacier and snow conditions. This dynamic monitoring represents a significant advancement toward supporting a resilient tourism sector in Aysén that prioritizes visitor safety while promoting responsible tourism practices that align with environmental conservation objectives.

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