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Review article: Remote sensing methods for snowline dynamics detection in the Andes: a critical review

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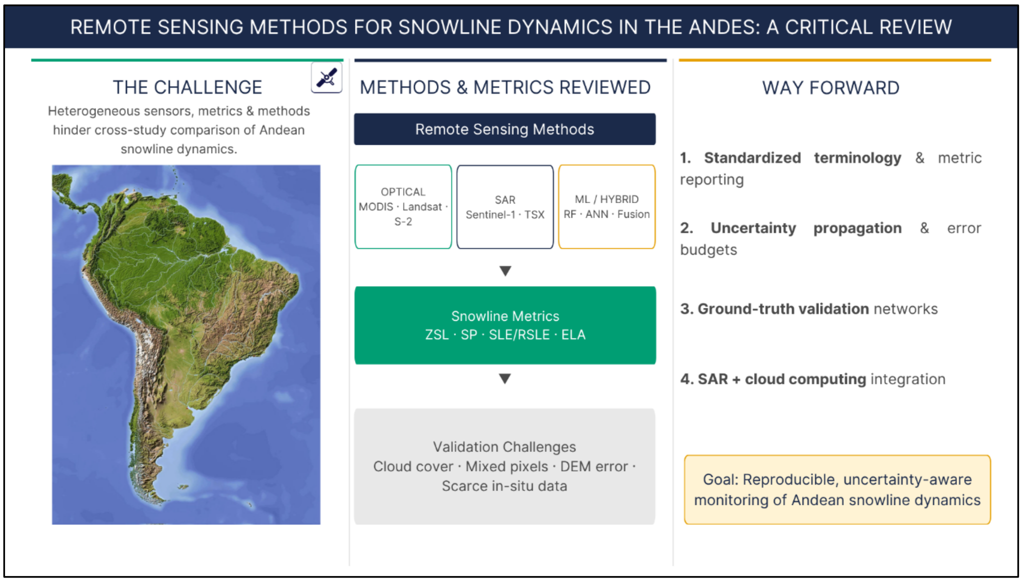
Graphical Abstract



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Abstract

Remote sensing has become a key tool for monitoring snowline dynamics in the Andes, yet cross-study comparison remains limited by heterogeneous definitions, sensors, classification schemes and spatial scales. Drawing on more than 60 studies covering satellite data from 1984 to 2025, spanning optical, SAR and hybrid approaches, and following a PRISMA-informed structure, this review examines how snowline-related metrics are defined, applied and interpreted in Andean research, with emphasis on local snowline altitude, snow persistence and catchment- to regional-scale snowline elevation. Andean applications rely predominantly on MODIS-derived snow products and snow-persistence approaches, whereas fewer studies exploit Landsat, Sentinel-2 or SAR workflows to derive transferable metrics or uncertainty-aware frameworks. Reported trends in the extratropical Andes (29° - 37° S) range from 10 to 30 m yr^{-1}, but these estimates are not directly comparable because they derive from different metrics, sensors, temporal windows and aggregation rules. Comparability is further constrained by inconsistent terminology, variable thresholding, limited treatment of digital elevation model and mixed-pixel effects, and scarce in situ validation. Rather than identifying a single optimal metric, the evidence indicates that different approaches suit different objectives: local metrics for event-scale analyses, snow persistence for climatological zonation, and regional snowline elevation for basin-to-regional trend assessment. We identify four priorities: standardized terminology and metric reporting; explicit propagation of uncertainty; systematic ground-truth validation; and stronger integration of SAR and cloud-computing workflows. Reframing snowline monitoring as a problem of metric selection, scale, uncertainty and application provides a basis for more reproducible and hydrologically meaningful assessments of Andean snowline dynamics.

Keywords: *Andes; Snowline elevation; Snow persistence; Mountain hydrology; Climate change.*

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1. Introduction

Mountain snow, and particularly the position of the snowline, exerts a first-order control on the timing and magnitude of meltwater delivery to downstream basins worldwide, not only in South America (Masiokas et al., 2020; Schauwecker et al., 2022). The Andean cryosphere spans seasonal snow cover, glaciers, mountain permafrost and specialized ice forms such as penitentes, making it one of the most diverse cryospheric settings on Earth (Masiokas et al., 2020; Dussaillant et al., 2019). In semi-arid catchments, where precipitation falls in only a handful of winter storms, the altitude of the snowline and its seasonal evolution determine how much water is stored as snow and subsequently released during the spring and summer melt (Masiokas et al., 2020).

This hydrological role is most acute in central Chile and western Argentina, where snow and ice underpin urban supply, irrigation and hydropower (Masiokas et al., 2006; Masiokas et al., 2020; McCarthy et al., 2022). Between roughly 30° and 37°S, winter snow accumulation explains more than 85% of the interannual variability in mountain river discharge, a striking measure of how completely regional water security depends on seasonal snow storage (Masiokas et al., 2006). The recent central-Chile drought has exposed both sides of this dependence: the cryosphere buffers supply yet is itself highly vulnerable, and snow-dominated basins in the extratropical Andes display a long hydrological memory that prolongs runoff deficits under sustained precipitation shortfalls (Garreaud et al., 2017; McCarthy et al., 2022; Álvarez-Garretón et al., 2021).

Against this backdrop, satellite remote sensing has become the primary source of information on snow cover and snowline dynamics in the Andes, especially in data-scarce mountain regions (Dietz et al., 2012; Masiokas et al., 2020; Gascoin et al., 2024). Andean studies nonetheless diverge widely in their choice of sensors, spectral indices, cloud treatment, elevation models, thresholds and snowline metrics, which makes cross-study comparison difficult and often methodologically ambiguous (Dietz et al., 2012; Gascoin et al., 2024). This heterogeneity is not merely technical but conceptual: terms such as ZSL, SLA, TSL, SLE, RSLE, snow persistence, ELA and even the 0 °C isotherm is frequently treated as interchangeable despite denoting different processes, spatial supports and temporal meanings (Schauwecker et al., 2022; Hu et al., 2019; Dietz et al., 2025).

Existing reviews offer valuable overviews of snow remote sensing, ranging from early syntheses of remote sensing, GIS and GPS in glaciology (Gao and Liu, 2001) and of global satellite-derived snow products (Frei et al., 2012) to more recent assessments of mountain-snow methods (Dietz et al., 2012; Nolin, 2010; Hammond et al.,2018; Gascoin et al., 2024). They tend, however, to emphasize sensors or broad cryospheric change rather than systematically comparing how individual snowline metrics perform under Andean conditions. The unresolved problem is therefore not a shortage of studies but the absence of an explicit methodological framework for comparing robustness, reproducibility, uncertainty, scalability and operational relevance across snowline approaches. That gap is especially consequential in the Andes, where high relief, aridity, cloud contamination, mixed pixels, DEM sensitivity and scarce in situ validation strongly condition the interpretation of snowline products (Dietz et al., 2012; Choubin et al., 2019; Gascoin et al., 2024).

This review addresses that gap by positioning itself explicitly as a methodological review of Andean snowline monitoring rather than a general cryospheric or climatic overview.

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Following a PRISMA-informed reporting structure, we make the identification, selection and synthesis of studies transparent, and we compare snowline-related metrics and remote-sensing methods by their definitions, scale dependence, uncertainty sources, validation requirements and fitness for different hydrological and climatic objectives (Page et al., 2021). Three questions organize the review: (1) how do local snowline altitude, snow persistence and SLE/RSLE-type metrics differ in conceptual meaning and robustness; (2) what methodological limitations affect optical, SAR and hybrid approaches in the Andes; and (3) what elements would constitute a more reproducible, uncertainty-aware and operationally relevant multi-sensor framework for Andean snowline monitoring (Page et al., 2021; Masiokas et al., 2020; Gascoin et al., 2024).

2. Materials and methods.

This review was structured using a PRISMA-oriented approach to improve transparency, reproducibility, and consistency in the identification, screening, classification, and synthesis of studies addressing snowline monitoring in the Andes and comparable mountain environments (Page et al., 2021). In this context, the review was designed not only to compile Andean case studies, but also to compare the methodological performance of snowline-related metrics and sensors under the specific environmental constraints of high-relief, data-scarce mountain regions (Masiokas et al., 2020; Gascoin et al., 2024).

2.1 Literature search strategy.

The literature search was conducted using major scientific databases such as Web of Science, Scopus, and Google Scholar, which together provide broad coverage of remote-sensing, cryosphere, hydrology, and mountain-environment studies. Search strings combined geographic, methodological, and metric-related terms, including “Andes”, “snowline”, “snowline elevation”, “regional snowline elevation”, “snow persistence”, “remote sensing”, “optical”, “SAR”, “Sentinel-2”, “Landsat”, and “MODIS”, together with commonly used metric variants such as ZSL, SLA, TSL, SLE, and RSLE (Hu et al., 2019; Dietz et al., 2025; Schauwecker et al., 2022). Because snowline terminology is not standardized across the literature, the search strategy explicitly incorporated synonymous or partially overlapping expressions to avoid excluding relevant studies that use different conceptual labels for similar snow-no snow interface metrics.

2.2 Screening and eligibility criteria

The search was designed to capture both Andean applications and methodological studies from other mountain regions, provided the latter offer transferable approaches to snowline detection, uncertainty assessment or metric evaluation (Tang et al., 2014; Hu et al., 2020; Liu et al., 2021). This broader inclusion is warranted because several methods now applied in the Andes, regional snowline elevation, scene-based optical delineation and snow-persistence zoning, were first developed or comparatively tested in other mountain settings before being adapted to Andean conditions (Krajčí et al., 2014; Moore et al., 2015; Aranda et al., 2023). The regional snowline-elevation approach, for instance, has been extended to characterize snowmelt-runoff events across European basins (Parajka et al., 2019) and combined with snow persistence to map snow regimes in the Himalaya (Dixit et al., 2024), illustrating the cross-regional transferability that this review exploits. The exact search period, the date of the last search and any language restrictions applied are reported in accordance with PRISMA principles (Page et al., 2021).

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Study selection was performed in two consecutive stages: an initial title and abstract screening, followed by full-text assessment of potentially relevant records (Page et al., 2021). Studies were included when they: (i) address snowline, snow-cover dynamics, or snow persistence in mountain environments; (ii) use remote sensing, DEM-based analysis, or related geospatial methods; (iii) report or enable interpretation of metrics such as ZSL, SLA, TSL, SLE, RSLE, or SP; and (iv) either focus directly on the Andes or provide methods that are demonstrably transferable to Andean mountain conditions. Studies were excluded when they are purely climatological without a snowline-related metric, when they lack sufficient methodological detail, when they are duplicates, or when their scope does not contribute to the comparative methodological objectives of the review. Additionally, prior to formal title and abstract screening, 1,227 records retrieved by the database queries were excluded at a pre-screening stage because they addressed snowlines in non-terrestrial contexts (planetary bodies, comets, and stellar astrophysics), which fall outside the scope of this review. This pre-screening step reduced the de-duplicated pool from 1,781 to 554 records that underwent formal title and abstract assessment (see Figure 1 and Table 1).

This screening logic is particularly important in the present review because the review distinguishes among multiple non-equivalent concepts, including ZSL, SLA, Transient Snowline (TSL), SLE, RSLE, ELA, and the 0 °C isotherm altitude, which are sometimes used inconsistently in the literature (Schauwecker et al., 2022; Hu et al., 2019; Dietz et al., 2025). A PRISMA flow diagram (Figure 1) summarizes the number of records identified, screened, excluded, and finally included, thereby making the literature selection process explicit and reproducible.

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167 **Table 1. Literature search and screening summary**

Database	Search date	Time window	Search string / keywords	Records retrieved	Duplicates removed	Records screened	Full-text assessed	Full-text excluded	Final included studies
Web of Science	January-2026	2000-2026	(“snowline” OR “snow line” OR “snowline elevation” OR “regional snowline elevation” OR “snow persistence”) AND (“Andes” OR “Andean” OR mountain) AND (“remote sensing” OR optical OR SAR OR MODIS OR Landsat OR Sentinel)	1773	0	546	464	446	18
Scopus	January-2026	2000-2026	(“snowline” OR “snow line” OR “snowline elevation” OR “regional snowline elevation” OR “snow persistence	362	354	8	8	0	8

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			" AND (Andes OR Andean OR mountain) AND ("remote sensing" OR optical OR SAR OR MODIS OR Landsat OR Sentinel))						
Google Scholar	March 2026	2000-2026	"Snowline" OR "snow persistence" OR "regional snowline elevation" Andes "remote sensing" (MODIS OR Landsat OR Sentinel OR SAR)	664	664	0	0	0	0
Total	**2026**	**26**		**2799**	**1018**	**554**	**472**	**446**	**26**

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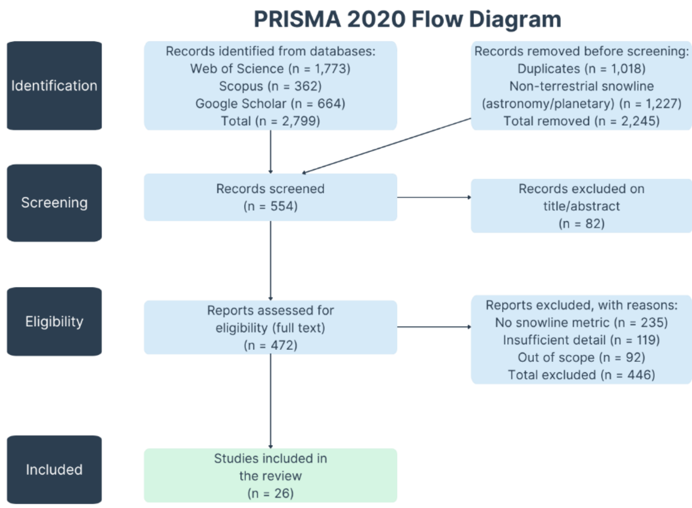

Figure 1. PRISMA 2020 flow diagram for the identification, screening, eligibility assessment, and inclusion of studies on remote sensing methods for Andean snowline monitoring. Records were retrieved from Web of Science (*n* = 1,773), Scopus (*n* = 362), and Google Scholar (*n* = 664) in January-March 2026. Prior to formal title/abstract screening, 1,227 records addressing non-terrestrial snowlines (astronomy and planetary science) were excluded at a pre-screening stage. A total of 26 studies met all inclusion criteria and are synthesized in this review. Full search strings and record counts by database are provided in Table 1.

2.3 Study classification framework

After screening, the selected studies were classified using a structured framework that reflects the analytical goals of this review rather than purely chronological or regional ordering. At minimum, the classification includes the following dimensions: (i) metric type, including local snowline metrics and temporally integrated metrics; (ii) satellite platform or sensor, such as MODIS, Landsat (sensors MSS/TM/ETM+/OLI), Sentinel-2 (sensor MSI), SAR, or multi-sensor fusion; (iii) spatial scale, from slope or glacier scale to basin and regional scale; (iv) validation approach, including in situ observations, photographs, reanalysis products, or indirect hydrological consistency; and (v) uncertainty treatment, including threshold sensitivity, DEM sensitivity, cloud contamination, mixed pixels, and cross-sensor inconsistencies (Dietz et al., 2012; Choubin et al., 2019; Gascoin et al., 2024).

An additional classification level distinguishes studies according to their primary application objective, such as event-based snowline detection, climatological zonation, long-term trend analysis, or operational hydrological support. This distinction is necessary because there is no single universally best method for determining the snowline; rather, metric suitability depends strongly on the temporal scale, spatial scale, and decision context of the analysis.

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Table 2. Classification framework of reviewed studies

Author (Year)	Region / sector	Metric type	Satellite (sensor) / data source	Resolution	Validation	Uncertainty treatment	Reported trend / change	Primary application
Saavedra et al. (2017)	Andes (tropical-Patagonia), Andes (8-55°S)	SP	MODIS	500 m / Daily → seasonal	Climatological consistency	Cloud gaps, temporal sampling	-	Climatological zoning
Saavedra et al. (2018)	Extratropical Andes, Andes (south of 29°S)	SP / SLE	MODIS	500 m / 2000-2016	Indirect / climatological	Limited explicit propagation	+10-30 m yr⁻¹ SLE	Trend
Aranda et al. (2023)	Central Andes (~33°S), Yeso River basin	SP / SLE	MODIS	500 m / 2000-2021	Basin consistency	Cloud, DEM	+21 m yr⁻¹ SLE	Trend
Dietz et al. (2025)	Central Chilean Andes, Aconcagua-Maipo	SLE	Landsat	30 m / 1985-2024	Noted in study	Method-dependent	+9.8-15.6 m yr⁻¹ SLE	Trend
Saavedra et al. (2026)	Andes (Chile)	SP / SCA	MODIS	500 m / 2000-2025	Cloud-reduction validation	Cloud (49→29 %)	Continued snow decline	Zoning / trend
Schauwecker et al. (2022)	Dry subtropical Andes, Subtropical Chilean Andes	ZSL / Z0°	Sentinel-2 + stations + ERA5	10-20 m / 2011-2021 events	Citizen science + stations	Event-scale	ZSL below Z0°	Event
Cordero et al. (2019)	Andes (tropical-extratropical), Andes (18-40°S)	SCA (ZSL proxy)	Landsat / MODIS	30-500 m / 1986-2018	Limited	Fixed-threshold bias	Declining snow-cover extent	Trend
Cortés et al. (2014)	Extratropical Andes (32-38°S)	FSC (sub-pixel)	Landsat 5/7	30 m / 1986-2013	High-resolution imagery	Unmixing / endmember	Declining min. snow/ice	Trend
Cortés and Margulis (2017)	Extratropical Andes	SWE (assimilation)	Landsat + reanalysis	~100-500 m / 1985-2015	Reanalysis / in situ	Model + observation error	-	Hydrology

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Veettil et al. (2016)	Tropical Andes (Peru), Cordillera Blanca	Annual max snowline (TSL)	Landsat	30 m / 1984-2015	Glacier records	Scene availability	Rising end-of-summer snowline	Trend
Klein and Isacks (1999)	Tropical Andes (Bolivia/Peru), Zongo / Quelccaya	TSL (spectral unmixing)	Landsat TM	30 m / Event	Mass-balance ELA	Endmember selection	-	Event
Rabatel et al. (2012)	Tropical Andes, Outer tropics	TSL → ELA	Landsat / SPOT	10-30 m / Annual	Glacier mass balance	Snowline-ELA offset	-	Zoning
Carrasco et al. (2008)	Southern Andes, western side	ELA (0 °C isotherm)	Radiosonde + surface	-	Surface stations	-	Rising ELA (secular)	Trend (atmospheric proxy)
MacFee et al. (2025)	SH glaciers (incl. Andes)	Glacier snowline altitude	MODIS	500 m	-	-	Broadly rising SLA	Trend (hemispheric)
Krajčí et al. (2014)	Analogue (Europe) Carpathians	RSLE	MODIS	500 m / Daily	Runoff consistency	DEM, classification	-	Trend
Parajka et al. (2019)	Analogue (Europe) European basins	RSLE	MODIS	500 m / Daily (events)	Runoff	DEM, clouds	-	Hydrology
Hu et al. (2019)	Analogue (Europe) European mountains	RSLE	Landsat	30 m / 1984-2018	-	DEM, classification	-	Trend
Hu et al. (2020)	Analogue (Alps) European Alps	RSLE	Landsat	30 m / 1985-2018	-	DEM, clouds	-	Trend
Tang et al. (2014)	Analogue (HMA), Tibetan Plateau	SLA	MODIS FSC	500 m / 2001-2013	-	Cloud, DEM	-	Trend
Liu et al. (2021)	Analogue (HMA), Eastern Tibetan Plateau	SLA	Landsat (GEE / Otsu)	30 m / 1995-2016	-	Threshold, geometry	-	Trend
Dixit et al. (2024)	Analogue (HMA), Indus-Ganga-	SP / RSLE	MODIS	500 m / 2003-2021	Köppen zones	Cloud, threshold	-	Zoning / trend

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	Brahmaputra							
Racoviteanu et al. (2019)	Analogue (HMA), Karakoram-E. Himalaya	SLA (automated)	Landsat / ASTER	15-30 m / End-of-season	DEM / visual	DEM, clouds	-	Event
Wu et al. (2014)	Analogue (HMA), Tien Shan	SLA → ELA	HJ-1	30 m / 2009-2010	In situ ELA	SLA-ELA mismatch	-	Event
Hammond et al. (2018)	Analogue (global)	SP	MODIS	500 m / 2001-2016	-	Gap-filling	-	Zoning / trend
Callegari et al. (2016)	Analogue (Alps), European Alps	TSL (PolSAR)	SAR (RADARSAT-2)	~10 m / Event	Reference maps	Geometry, classification	-	Event
Snauffer et al. (2018)	Analogue (N. America), British Columbia	SWE (ML fusion)	Multi-source + ML	Gridded / Annual	Station SWE	Training bias	-	Hydrology
Bonnell (2024)	Analogue (N. America), Western US	SWE (L-band InSAR)	Airborne / UAVSAR	<500 m / Weekly	In situ / GPR	Phase, snow density	-	Snow-state
Portenier et al. (2022)	Analogue (Alps), Swiss Alps	RSLE (webcams)	Public webcams	Variable / Sub-daily	DEM-projected	Viewpoint, mapping	-	Event

2.4 Evidence synthesis criteria

The synthesis of evidence was guided by a comparative methodological perspective focused on robustness, reproducibility, uncertainty, scalability, and suitability for trend detection. In practical terms, each study was assessed according to its sensitivity to cloud contamination, topographic shadowing, DEM quality, threshold choice, mixed-pixel effects, temporal compositing strategy, and validation support, because these factors strongly affect the interpretation of snowline products in the Andes (Dietz et al., 2012; Harer et al., 2018; Choubin et al., 2019; Gascoin et al., 2024).

Within this framework each metric is treated as a distinct analytical tool rather than a label for a single phenomenon; the metric-by-metric comparison is developed in Section 4, and the classification dimensions are summarized in Table 2. Where persistent cloud cover limits optical products, SAR and optical-SAR fusion is noted as complementary sources, although their Andean use remains comparatively limited. The aim of overarching is to identify which combinations of metrics, sensors and processing strategies are most reproducible and operationally meaningful for Andean snowline monitoring.

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3. Conceptual framework: Andean cryosphere and snowline metrics.

3.1 The Andean cryosphere and its hydrological role

The Andean cryosphere encompasses every component of the Earth system in which water occurs in solid form, seasonal snow, glaciers, permafrost and other frozen materials in the atmosphere, on land and in the oceans (Masiokas et al., 2020). Spanning more than 60° of latitude, this domain is exceptionally diverse, ranging from tropical high-elevation glaciers through the extensive temperate ice fields of Patagonia, where twentieth-century glacier recession is well documented (Masiokas et al., 2008), to the seasonally snow-covered mountains of the semi-arid sectors (Masiokas et al., 2020; Dussaillant et al., 2019). The resulting latitudinal and altitudinal gradients generate a strongly heterogeneous cryospheric mosaic in which snow and ice regimes change markedly both along and across the range (Masiokas et al., 2020). In the tropical Andes this gradient is also ecological: the snowline and the treeline together bound the habitable mountain landscape and respond jointly to climate variability (Young et al., 2016).

Hydrologically, the Andean cryosphere acts at once as a seasonal snow reservoir and as a longer-term ice store that buffers downstream flow (Masiokas et al., 2020). This dependence is strongest in the semi-arid sectors of central Chile and western Argentina, where solid precipitation above the snowline governs most of the interannual variability in river discharge (Masiokas et al., 2006). Changes in snow and ice storage therefore propagate directly to urban supply, irrigation, hydropower and other water-dependent sectors in the adjacent lowlands (Masiokas et al., 2020; McCarthy et al., 2022).

The recent central-Chile drought has laid bare the vulnerability of this system: as snowfall declined, glacier melt became a non-negligible contributor to river flow during prolonged precipitation deficits (Garreaud et al., 2017; McCarthy et al., 2022). Snow-dominated catchments between about 30° and 35°S likewise reveal a long hydrological memory, in which groundwater-supported baseflow and carry-over snowmelt amplify runoff deficits during extended dry spells (Álvarez-Garretón et al., 2021). Within this setting, the altitude of the snowline and its seasonal evolution emerge as sensitive indicators of both climate forcing and hydrological response in Andean basins (Masiokas et al., 2020).

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3.2 Snowline, freezing level and equilibrium line altitude

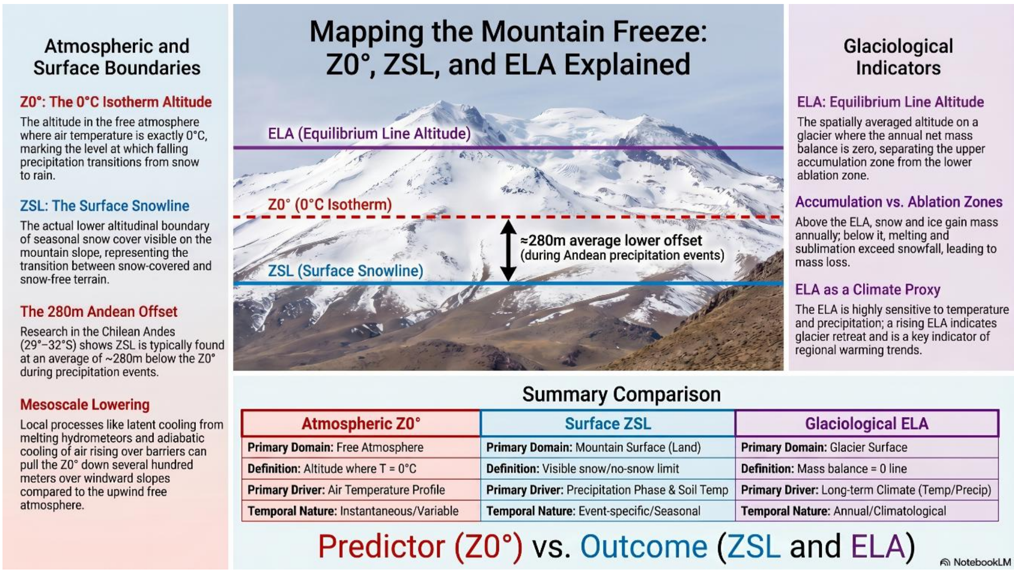

Figure 2. Conceptual diagram illustrating the vertical relationships among three key mountain cryosphere metrics over the central Chilean Andes (29°-37°S). The Equilibrium Line Altitude (ELA, purple line) marks the glacier surface where annual mass accumulation equals ablation. The 0°C isotherm altitude (Z0°, red dashed line) represents the altitude in the free atmosphere where air temperature is exactly 0°C, marking the level at which falling precipitation transitions from snow to rain. The Local Snowline Altitude (ZSL, blue line) is the actual lower boundary of visible seasonal snow cover on the mountain slope. During precipitation events, ZSL is observed at an average of ≈280m below Z0° due to mesoscale cooling from melting hydrometeors and adiabatic cooling of orographically lifted air (Schauwecker et al., 2022). The vertical arrow indicates this mean offset. The summary table (bottom) compares the three metrics by domain, definition, primary driver, and temporal scale.

The snowline is most defined as the lower altitudinal limit of seasonal snow cover on a mountain slope after a precipitation or melt event, that is, the visible surface boundary between snow-covered and snow-free terrain (Schauwecker et al., 2022). Its position integrates the atmospheric and surface controls operating during storm and melt episodes, precipitation phase, advection, radiative exchange and terrain-controlled microclimates (Schauwecker et al., 2022). Importantly, the climatic sensitivity of this boundary is not fixed but varies with the moisture regime. In the central Andes, Klein et al. (1999) showed that snowlines in the humid eastern cordillera lie close to the mean annual 0 °C isotherm and respond mainly to temperature, whereas in the more arid western cordillera they rise far higher and are governed primarily by accumulation. ZSL therefore captures an instantaneous, event-specific boundary whose very drivers are spatially variable, whereas snow-persistence and regional-elevation metrics integrate this signal over longer windows and broader spatial supports.

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The altitude of the 0 °C isotherm (Z0°) is frequently used as a proxy for the rain-snow transition, yet it is not equivalent to the surface snowline (Minder et al., 2011; Minder and Kingsmill, 2013; Schauwecker et al., 2022). Mesoscale processes, isothermal layers, variable lapse rates, windward -leeward contrasts and cold-air pooling, can displace the freezing level from the actual surface snowline by several hundred meters, particularly in the steep, narrow valleys typical of the Andes (Minder et al., 2011; Minder and Kingsmill, 2013; Schauwecker et al., 2022). This offset is not merely theoretical: in the dry subtropical Chilean Andes, Schauwecker et al. (2022) found that event snowlines typically lie below the 0 °C isotherm, so substituting Z0° directly for snowline position introduces systematic conceptual and operational mismatches.

The snowline is likewise related to, but not interchangeable with, the equilibrium-line altitude (ELA) of glaciers. Whereas ZSL marks an instantaneous lower boundary of seasonal snow, the ELA is the spatially averaged altitude at which glacier surface mass balance is zero over a defined interval, separating the accumulation and ablation zones (Masiokas et al., 2020). The two are physically coupled: Condom et al. (2007) reconstructed the ELA across the entire Andes (10°N-55°S) from the 0 °C isotherm altitude and precipitation, and the end-of-summer transient snowline is widely treated as a proxy for the ELA on individual glaciers. That proxy relationship is not universal, however. Wu et al. (2014) demonstrated in the Tien Shan that the optically derived snowline can depart substantially from the in-situ ELA where accumulation and ablation occur simultaneously throughout the year, a caveat that is directly relevant to the semi-arid Andes. In the central Chilean Andes, ELA reconstructions from atmospheric variables reveal upward shifts consistent with regional warming since the late twentieth century (Carrasco et al., 2005, 2008; Barría et al., 2019). Hydrologically, the snowline and the ELA jointly govern the altitudinal distribution of seasonal snow and perennial ice, and hence the timing and magnitude of meltwater delivery to rivers (Masiokas et al., 2006; McCarthy et al., 2022).

Throughout this review, ZSL denotes local, scene-based estimates of the lower snow boundary, whereas SLE and RSLE are reserved for catchment- and regional-scale metrics derived from the joint elevation distribution of snow-covered and snow-free pixels (Hu et al., 2019; Dietz et al., 2025). The distinction matters because the single term "snowline" can denote different spatial supports and aggregation rules depending on the method applied. Table 3 fixes these conceptual differences before the methodological comparison developed in Section 4.

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Table 3. Conceptual distinctions among snowline-related metrics used in this review

Concept / metric	Operational definition	Spatial scale	Temporal scale	Relation to snowline	Main sensitivity	Best suited use
Local Snowline Altitude (ZSL)	Lower boundary of visible seasonal snow in a single scene, derived from direct delineation or thresholding of the snow-land transition.	Hillslope / sub-basin / single glacier	Event / instantaneous	Direct surface snowline estimate	Clouds, shadows, subjective delineation, sub-pixel heterogeneity	Event-based monitoring and individual storm or melt episodes
Snowline Altitude / Transient Snowline (SLA / TSL)	Snowline extracted from an individual optical image, often after cloud masking and elevation filtering.	Hillslope / glacier / small catchment	Event / seasonal	Direct but scene-specific snowline estimate	Viewing geometry, cloud contamination, pixel mixing	Short-term snowline dynamics and seasonal melt evolution
0 °C Isotherm Altitude (Z0°)	Altitude in the free atmosphere where air temperature reaches 0 °C.	Atmospheric column / basin	Hourly to daily	Proxy, not equivalent to surface snowline	Lapse rate variability, cold-air pooling, terrain effects	Meteorological context for rain-snow transition
Equilibrium Line Altitude (ELA)	Altitude where glacier mass balance is zero over a defined period, separating accumulation and ablation zones.	Glacier / glacierized basin	Annual to multiyear	Related to snowline, but not equivalent	Climate forcing, glacier geometry, accumulation-ablation balance	Glacier-climate studies and long-term mass-balance interpretation
Snowline Elevation (SLE) / Regional Snowline Elevation (RSLE)	Catchment- or region-scale snowline derived from the elevation distribution of snow-covered and	Catchment / regional	Seasonal / multiyear	Regional snowline metric	DEM quality, classification errors, topographic heterogeneity	Trend detection and inter-basin comparison

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	snow-free pixels.					
Snow Persistence (SP)	Fraction of a period during which a pixel remains snow covered.	Pixel / grid-cell / region	Seasonal / annual	Indirect snowline descriptor through snow zoning	Cloud gaps, temporal sampling, gap-filling assumptions	Snow-climate zonation and climatological snow distribution

3.3 Recent snowline changes: climatic drivers and global context

Snowline variability in the Andes is governed by regional and large-scale climate models that modulate both precipitation and temperature. The El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) strongly condition snow accumulation by shifting storm tracks, moisture transport and freezing-level heights (Garreaud, 2009; Masiokas et al., 2020). South of about 35°S, the extratropical westerlies dominate, delivering abundant snowfall on the windward Chilean flank while casting a heavy rain shadow over leeward Argentina (Viale et al., 2019b). Over recent decades a positive SAM trend has pushed the westerlies poleward, reducing cold-season precipitation and raising freezing levels across central Chile (Cordero et al., 2019; Garreaud et al., 2017).

These circulation changes coincided with the onset, since 2010 of the unprecedented central-Chile megadrought-sustained precipitation deficits, elevated temperatures and a marked decline in low-elevation snow events (Cordero et al., 2019; Garreaud et al., 2017). Under such conditions the snowline migrates upward, the snow season shortens and the extent of seasonal snow contracts, most sharply in basins whose climatological snowline already sits close to the 0 °C isotherm (Masiokas et al., 2020). The consequences are amplified in semi-arid basins, where snow storage carries a disproportionate share of the seasonal water supply and small upward shifts in snowline position translate into large changes in meltwater availability.

Satellite-based analyses for the extratropical Andes between roughly 29° and 36°S have reported upward trends in snowline metrics on the order of 10-30 m yr^{-1} over recent decades, consistent with regional warming and rising freezing-level heights (Saavedra et al., 2018; Dietz et al., 2025). However, these rates should be interpreted cautiously because they are not directly comparable across metrics, sensors, time periods or aggregation rules. For that reason, this review treats the reported trends as evidence of a persistent upward tendency rather than as a single uniform rate for the entire Andes.

Comparable patterns of rising snowlines and shortening snow seasons have been documented across other mountain ranges, including the European Alps and High Mountain Asia, where regional snowline-elevation metrics prove especially sensitive to warming in mid-latitude and maritime-influenced settings (Hu et al., 2020; Prein and Heymsfield, 2020; Liu et al., 2021; Bernat et al., 2025). Indeed, the upward migration of the high-mountain snowline has been characterized as a global imprint of atmospheric warming (Li et al., 2026), while snow droughts have lengthened and intensified across several hotspots over recent decades (Huning and AghaKouchak, 2020). These analogues situate the Andean signal within a

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broader global pattern and reinforce the value of robust, regionally consistent metrics such as SLE and RSLE for detecting and comparing change across climatic regimes.

4. Remote sensing methods for snowline detection

Remote sensing products such as MODIS were designed to provide automated, consistent inputs for climate studies, with improved snow-cloud discrimination and quality-assessment information compared with earlier operational products (Hall et al., 2002). Building on this foundation, Krajčí et al. (2014) introduced Regional Snowline Elevation (RSLE) as a catchment-scale metric derived from MODIS imagery for seasonally snow-covered mountain basins. Their method identifies the elevation at which the number of snow-covered pixels below a given altitude equals the number of snow-free pixels above it, thereby maximizing the correspondence between topography and snow-cover patterns. RSLE therefore provides a topography-aware snowline metric that integrates information from many pixels and reduces sensitivity to local cloud contamination and small-scale terrain effects.

4.1 Historical development of optical snowline metrics

The most widely used technique for snow cover mapping from optical satellite sensors is the Normalized Difference Snow Index (NDSI), which exploits the high reflectance of snow in visible wavelengths and its strong absorption in shortwave infrared bands. Salomonson and Appel (2004) showed that MODIS-based NDSI, when combined with threshold tests, provides robust automated binary mapping of snow cover and established relationships between NDSI values and fractional snow cover within 500 m pixels. This work extended the binary snow-mapping approach underlying operational products such as MOD10A1 (Hall et al., 2002) and marked a transition from binary snow/no-snow classification toward sub-pixel representations of snow cover that are essential for snowline detection in heterogeneous terrain.

Binary snow maps alone, however, do not resolve the geometry of the snowline, especially in narrow valleys, complex topography, and partially cloud-covered scenes. This limitation motivated the development of metric-specific approaches such as Regional Snowline Elevation (RSLE), snowline altitude (SLA) and transient snowline (TSL), which use elevation information to translate snow-cover distributions into snowline estimates.

Complementary scene-based approaches extract snowline altitude from individual optical images, typically combining cloud-filtered fractional snow-cover products with digital elevation models. An early Andean example is the spectral mixture analysis of Klein and Isacks (1999), who unmixed Landsat TM imagery to locate the transient snowline on tropical glaciers in Bolivia and Peru and showed that the end-of-summer snowline approximates the equilibrium line. Subsequent work has automated the delineation: Tang et al. (2014) derived a snowline-altitude field over the Tibetan Plateau for 2001-2013 from cloud-removed MODIS fractional snow cover and a DEM, revealing strong seasonal and interannual SLA variability and high correlations with melt-season temperature, while Racoviteanu et al. (2019) developed an automated algorithm to estimate snowline altitudes from optical imagery across High Mountain Asia. Comparable automated pipelines have been built specifically for glaciers: Rastner et al. (2019) mapped glacier snow cover and computed snowline altitudes from multi-temporal Landsat, and Shea et al. (2013) derived regional snow

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lines from MODIS to constrain glacier mass change in western North America; earlier still, Turpin et al. (1997) used satellite-observed snowline rise to calibrate a glacier runoff model, an early demonstration of the metric's hydrological value. Together these developments mark the shift from mapping snow presence alone toward deriving standardized, comparable snowline metrics across seasons, basins and climate regimes.

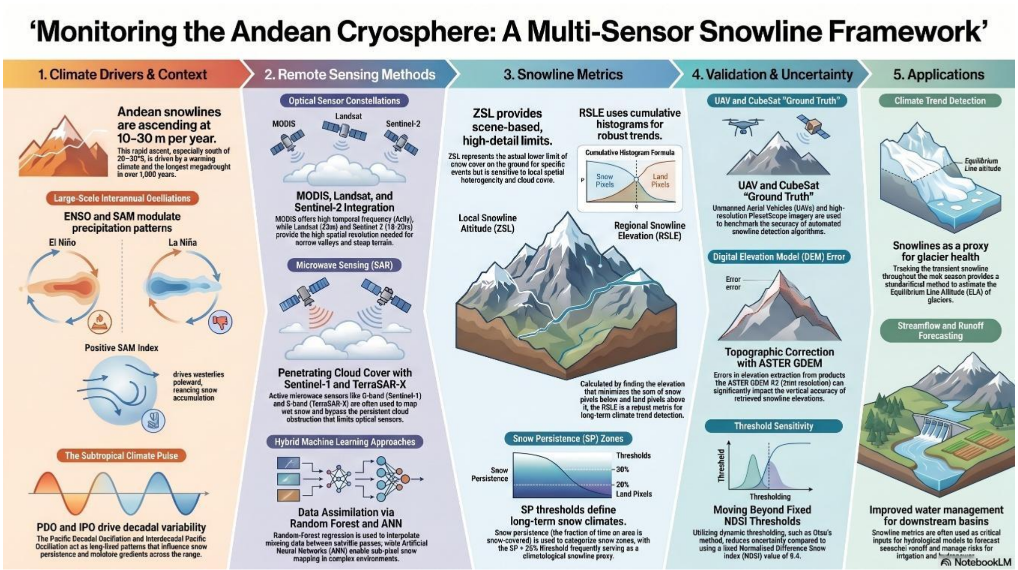

Figure 3. Integrated multi-sensor framework for Andean snowline monitoring, organized into five thematic blocks: (1) climate drivers and context (ENSO, SAM, PDO/IPO and the subtropical megadrought); (2) remote-sensing methods (optical constellations, microwave/SAR sensing and hybrid machine-learning approaches); (3) snowline metrics (ZSL, RSLE and snow-persistence zones); (4) validation and uncertainty (UAV/CubeSat ground truth, DEM error and threshold sensitivity); and (5) applications (climate-trend detection and streamflow forecasting).

4.2 Snowline metrics and their robustness under Andean conditions

Although several remote-sensing metrics are used to characterize the snowline, they are not methodologically equivalent and should not be interpreted as interchangeable under Andean conditions (Krajčí et al., 2014; Hu et al., 2019; Dietz et al., 2025). A central issue for this review is therefore not only how each metric is calculated, but also how each one responds to the main sources of uncertainty that affect snowline monitoring in the Andes, including cloud contamination, mixed pixels, DEM quality, threshold dependence and limited ground validation (Dietz et al., 2012; Choubin et al., 2019; Gascoin et al., 2024). From this perspective, the robustness of a snowline metric depends on its sensitivity to local noise, its capacity to scale across basins and climatic sectors, and its suitability for detecting long-term changes rather than isolated events.

Local snowline altitude (ZSL) is the most intuitive metric because it attempts to delineate the visible transition between snow-covered and snow-free terrain in individual scenes (Schauwecker et al., 2022; Tang et al., 2014). This makes ZSL useful for event-based analyses, storm reconstruction and high-resolution interpretation of hillslope-scale

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variability, particularly when Landsat or Sentinel-2 imagery is available (Tang et al., 2014; Xiao and Liang, 2024). However, its apparent simplicity masks substantial methodological fragility: ZSL is highly sensitive to partial cloud cover, terrain shadows, viewing geometry, sub-pixel heterogeneity and operator decisions regarding which boundary pixels represent the actual snowline (Dietz et al., 2012; Choubin et al., 2019; Gascoin et al., 2024). In steep Andean terrain, these factors can introduce strong scene-to-scene noise and limit the reproducibility of multi-decadal time series based on local delineations alone (Dietz et al., 2012; Choubin et al., 2019).

Catchment- and regional-scale metrics such as SLE and RSLE were developed to reduce this sensitivity to local noise by aggregating snow-cover information across many pixels and explicitly linking snow distribution to elevation (Krajčí et al., 2014; Hu et al., 2019; Dietz et al., 2025). In RSLE, the objective is not to trace a visible line on a single slope, but to identify the elevation that best separates snow-covered terrain below from snow-free terrain above at the basin or regional scale (Krajčí et al., 2014). This aggregation reduces the influence of local cloud contamination, isolated misclassified pixels and small-scale terrain heterogeneity, making SLE/RSLE more suitable for interannual comparison and trend detection across multiple basins (Krajčí et al., 2014; Aranda et al., 2023; Dietz et al., 2025). Even so, these metrics are not uncertainty-free, because their performance depends strongly on DEM resolution, vertical accuracy and the way snow/no-snow classifications are generated from optical data (Choubin et al., 2019; Dietz et al., 2012). In the Andes, where slopes are steep and relief is high, DEM errors and threshold choices can propagate into vertical snowline uncertainties of tens to hundreds of metres if they are not explicitly evaluated (Choubin et al., 2019; Harer et al., 2018). A recent Andean refinement of this family is the Maximum Dissimilarity Method (MDM) of Aranda et al. (2023), which retrieves SLE from MODIS even on cloudy days and over largely snow-covered basins by selecting the elevation that maximizes the statistical dissimilarity between snow and snow-free bands. Benchmarked against the regional snow-line elevation estimation method in a snowmelt-driven basin of the central Chilean Andes, the MDM recovered a coherent 22-year series and an upward SLE trend of about 21 m per year, illustrating how Andean studies are beginning to adapt, rather than merely import, regional snowline algorithms.

Snow persistence (SP) metrics provide a different but complementary perspective by integrating snow occurrence through time rather than estimating a snowline from a single image (Moore et al., 2015; Saavedra et al., 2017; Hammond et al., 2018). In this framework, the relevant variable is the fraction of a season or year during which each pixel remains snow-covered, allowing the delineation of intermittent, transitional and persistent snow zones (Moore et al., 2015; Saavedra et al., 2017). Because SP reduces dependence on individual scenes, it is less vulnerable than ZSL to transient cloud conditions and isolated classification errors, and it is especially useful for climatological zonation and long-term regional comparison (Saavedra et al., 2017; Hammond et al., 2018; Aranda et al., 2023). This is particularly relevant in the Andes, where SP-based approaches have been used to define snowline elevation from persistence thresholds and to detect upward migration of snow zones over recent decades (Saavedra et al., 2017; Saavedra et al., 2018). Nevertheless, SP is not a direct event-scale snowline metric, and its interpretation depends on the selected temporal window, gap-filling strategy and persistence threshold, so comparisons across studies can also become inconsistent when reporting standards are weak (Hammond et al., 2018; Aranda et al., 2023; Dietz et al., 2025).

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Taken together, these contrasts show that metric selection should follow the research objective rather than convention: ZSL suits event-scale or slope-specific analyses, SLE/RSLE basin- to regional-scale trend assessment, and SP climatological zonation and temporally integrated monitoring (Krajčí et al., 2014; Saavedra et al., 2017; Hu et al., 2019; Dietz et al., 2025). Because each metric operates on a different spatial and temporal support, the resulting Andean trends are not directly comparable even when all are labelled "snowline change"; they must be treated as distinct analytical tools with their own uncertainty structures, scaling properties and interpretive limits. This principle, developed once here, underpins the methodological reading of observed trends in Section 5 and the recommendations in Section 6. The consolidated metric- and approach-level comparison is presented in Table 4 (Section 4.5).

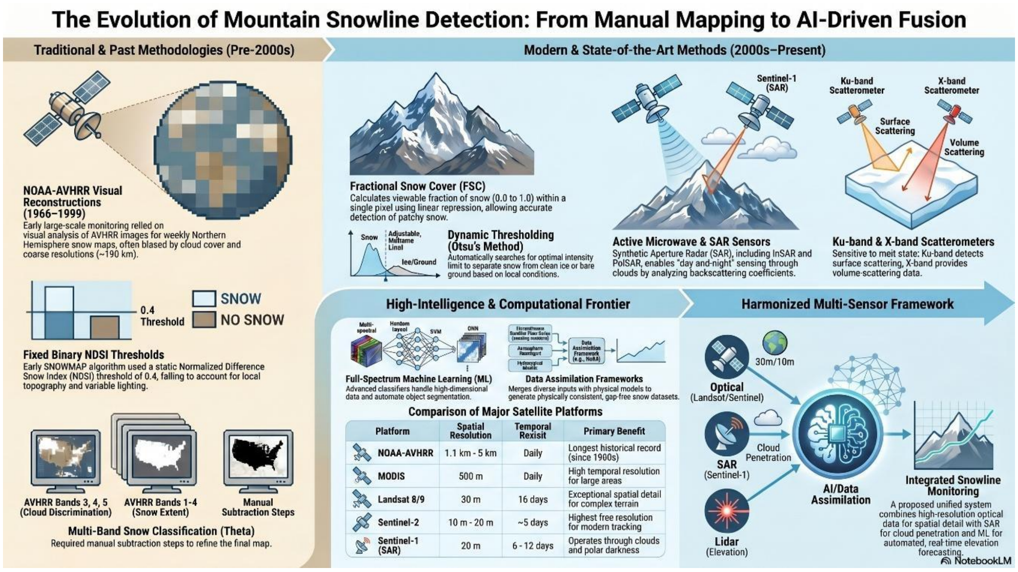

Figure 4. Evolution of mountain snowline detection, from traditional manual interpretation of coarse NOAA-AVHRR imagery and fixed NDSI thresholding (pre-2000s) toward fractional snow cover, dynamic (Otsu-type) thresholding, active microwave and SAR sensing, and AI-driven multi-sensor data assimilation (2000s-present). The lower table compares the main satellite platforms (NOAA-AVHRR, MODIS, Landsat 8/9, Sentinel-2 and Sentinel-1) in terms of spatial resolution, temporal revisit and principal benefit for snowline monitoring.

4.3 Optical methods and snow indices under Andean constraints

Optical methods remain the backbone of snowline monitoring in the Andes because they provide long time series, relatively high spatial detail, and direct sensitivity to surface snow cover conditions (Salomonson and Appel, 2004; Saavedra et al.,2017; Hall et al., 2002). However, their performance in the Andes is constrained by persistent cloud cover, strong topographic shading, aridity, and high surface reflectance from bare rock and soil, all of which complicate the interpretation of snow masks and the derivation of snowline metrics (Dietz et al., 2012; Gascoin et al., 2024). For this reason, optical methods should be treated not as a single universal solution, but as a family of approaches whose suitability depends on

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the metric being estimated, the spatial scale of the analysis, and the level of uncertainty that can be tolerated.

Traditional applications commonly use fixed NDSI thresholds to derive binary snow maps from MODIS, Landsat, or Sentinel-2 data, but these thresholds can be problematic in semi-arid Andean environments where bright non-snow surfaces are frequent (Dietz et al., 2012; Salomonson and Appel, 2004; Saavedra et al.,2017). Threshold choice should not be treated as a minor technical detail, because it directly affects robustness, reproducibility, and comparability across studies. In steep terrain, small shifts in classification can translate into large changes in estimated snowline elevation, so threshold sensitivity should be treated explicitly as a source of methodological uncertainty rather than as a background issue (Choubin et al., 2019; Harer et al., 2018).

Adaptive approaches such as Otsu-based thresholding and multi-index classification can reduce some of these biases by allowing thresholds to respond to local scene conditions rather than imposing a fixed global cutoff (Otsu, 1979; Masson et al., 2018; Bhardwaj et al., 2015). This is particularly relevant in the Andes, where illumination, land cover, and snow properties vary strongly with elevation and exposure, and where a single binary threshold may not transfer well across catchments or seasons. At the same time, adaptive methods introduce their own challenges, because they may improve local classification while reducing direct comparability across time or between basins if the decision rules are not reported transparently.

4.3.1 Fractional snow cover approaches

Fractional snow-cover (FSC) products provide a firmer basis for snowline analysis than binary snow/no-snow maps because they resolve the sub-pixel heterogeneity that pervades mountain terrain (Salomonson and Appel, 2004; Rittger et al., 2013). This is critical in the Andes, where the snowline frequently falls within mixed pixels, in narrow valleys, on steep slopes and across the transition between persistent snow and exposed ground (Saavedra et al.,2017). Cloud-removed MODIS FSC data have been used to derive snowline-altitude fields and quantify seasonal variability over large mountain regions, a useful analogue for Andean applications (Tang et al., 2014). The approach has also been demonstrated directly in the Andes: Cortés et al. (2014) applied spectral unmixing to the historical Landsat archive to retrieve sub-pixel snow and ice extent over the extratropical Andes, validating the retrievals against high-resolution imagery and extracting multidecadal trend evidence that FSC unmixing is viable for long-term Andean snowline monitoring.

Fractional snow cover is also helpful for connecting local snowline estimates with regional metrics such as SLE and RSLE, because it provides a more continuous representation of the snow-no snow transition than binary classification alone. Recent assessments of snow-cover mapping algorithms indicate that multi-index and fractional approaches generally outperform simple fixed-threshold methods in heterogeneous terrain, especially when forests, shadows, or bright rock surfaces are present (Masson et al., 2018; Teleubay et al., 2022). For the Andes, this suggests that FSC-based workflows should be prioritized where the goal is methodological robustness rather than simply maximizing operational simplicity.

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4.3.2 DEM dependence and topographic sensitivity

The estimation of snowline elevation from optical imagery depends strongly on the quality of the underlying DEM because elevation is the vertical reference used to locate the snowline boundary (Choubin et al., 2019). In steep Andean terrain, even moderate vertical errors can produce substantial horizontal displacement of the snowline boundary, which affects both ZSL and elevation-based metrics such as SLE and RSLE. This issue is central to a rigorous treatment of uncertainty propagation, encompassing DEM sensitivity, mixed pixels, and threshold effects.

The manuscript should therefore avoid presenting DEM use as a routine preprocessing step and instead describe it as a source of structural uncertainty that must be documented, tested, and, where possible, propagated into the final snowline estimates (Choubin et al., 2019). Studies in high-relief environments show that DEM errors, terrain ruggedness, and the choice of elevation binning rules can alter reported snowline values enough to affect multi-year trend interpretation, particularly when the analysis seeks to compare basins or sensors. This is one of the reasons why RSLE and SP-based metrics are often more defensible for long-term comparisons than single-scene ZSL estimates.

4.3.3 Cloud gaps and compositing

Cloud contamination is one of the principal limitations of optical snowline detection in the Andes because it reduces the number of usable scenes and increases the risk of biased snowline estimates in storm-prone or persistently cloudy seasons (Dietz et al., 2012; Saavedra et al.,2017; Gascoin et al., 2024). Temporal compositing, cloud masking, and gap-filling strategies can partially alleviate this problem, but they also introduce assumptions that should be stated explicitly in any scientific studies. Snowline studies should not overstate the precision of optical snowline estimates without acknowledging that scene availability itself can control the reliability of the resulting trend analysis.

Recent work in the tropical Andes shows that MODIS MOD10A1 products processed in Google Earth Engine can yield long snow-cover-area time series when paired with Landsat-based validation masks, underscoring the value of cloud-based workflows for large-scale monitoring (Calizaya et al., 2023). Cloud contamination itself can be mitigated rather than merely tolerated: Saavedra et al. (2026) applied multi-step spatio-temporal gap-filling to MODIS snow products over the central Andes, substantially increasing the number of cloud-free observations available for trend analysis and reducing the bias that intermittent cloud cover imposes on snowline estimates. These results indicate that operational optical workflows in the Andes are most effective when they couple automated processing and explicit cloud reduction with a metric that absorbs residual missing-data effects, such as SP or RSLE. Optical methods are therefore best framed not as a standalone solution but as a core component of a multi-metric monitoring system.

4.4 SAR and microwave methods for snowline detection

Synthetic Aperture Radar (SAR) is a valuable complement to optical methods because it can acquire data regardless of daylight and cloud cover, which is a major advantage in mountainous environments with frequent winter cloud contamination (Tsai et al., 2019). Its signal is sensitive to snow dielectric properties, grain structure, and especially liquid water content, meaning that wet snow typically produces much lower backscatter than dry snow or bare ground, which can be exploited to identify the transient snowline (TSL) (Tsai et al.,

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2019). In a review focused on the Andes, this advantage should be framed carefully: SAR is not universally superior, but it is particularly useful when optical observations are incomplete or temporally sparse.

The main methodological challenge is that SAR interpretation in steep terrain is strongly affected by geometric distortions such as layover and foreshortening, as well as by shadowing, incidence angle variability, and coherence loss (Callegari et al., 2016; Tsai et al., 2019). These effects are especially relevant in the Andes because extreme relief can distort the radar geometry enough to complicate the separation between snow, ice, rock, and vegetation. For that reason, SAR-based snowline products should always be presented together with a clear discussion of topographic correction and scene geometry, otherwise the method can appear more robust than it really is

Polarimetric SAR improves snowline detection by adding scattering information that helps separate wet snow from other surfaces. Li et al. (2012) proposed glacier snowline detection using polarimetric SAR and Support Vector Machine (SVM) classification, defining the TSL as the boundary between wet snow and ice on the classification map. Callegari et al. (2016) showed that topographic correction and polarimetric decomposition features improve classification performance, with accuracy gains over backscatter-only methods and higher performance for fully polarimetric configurations than for simpler dual-pol setups. Although these examples are not Andean, they are methodologically relevant because they show that SAR is most effective when geometry, scattering mechanism and surface state are handled explicitly rather than treated as secondary details. Beyond mapping, the transient snowline retrieved from such imagery can itself constrain glacier mass balance: Barandun et al. (2018) reconstructed multi-decadal mass-balance series for Kyrgyz glaciers in the Tien Shan from transient-snowline observations, illustrating how snowline products feed directly into climate-relevant variables in data-sparse high mountains.

Interferometric SAR (InSAR) has been explored for snow-depth and snow-water-equivalent (SWE) retrieval, which can indirectly support snowline analysis by improving snow-state characterization in space and time (Schaffhauser et al., 2008). Interest has intensified with longer-wavelength sensors: L-band InSAR penetrates the snowpack more effectively and has emerged as a promising route to spatially distributed SWE, although retrievals still hinge on phase-unwrapping accuracy and on changes in snow density and stratigraphy between acquisitions; assessments over shallow, heterogeneous snowpacks confirm both the promise and the strong sensitivity of these retrievals to snow state (Bonnell, 2024; Palomäki and Sproles, 2023). These applications nonetheless remain difficult, because temporal decorrelation, variable snow metamorphism and complex scattering reduce retrieval stability, particularly in operational settings. In the Andes, InSAR is therefore best presented as an emerging complement rather than a routine snowline-monitoring solution, pending further validation and a stronger empirical record in steep mountain terrain gap that upcoming L- and S-band missions are well placed to fill.

Overall, SAR is best treated in this review as the most promising all-weather alternative for cloud-prone periods, but also as a method whose usefulness depends heavily on terrain correction, acquisition geometry, and the snow condition being observed (Tsai et al., 2019). In practical terms, SAR is most valuable when it is used to support optical snowline metrics, not to replace them entirely, and when the review explicitly distinguishes wet-snow detection, dry-snow ambiguity, and geometry-driven uncertainty.

4.5 Hybrid, data-assimilation and machine-learning approaches

Hybrid approaches combine optical, microwave, atmospheric, and model-based information to infer snowline behavior indirectly through snow cover depletion, snow water equivalent, or snow-state transitions when direct optical detection is limited by cloud cover or complex terrain (Dietz et al., 2012; Cortés and Margulis, 2017). In the Andes, this type of integration is especially relevant because snowline monitoring is constrained by persistent cloud contamination, strong topographic gradients, limited in situ validation, and the coexistence of multiple non-equivalent metrics such as ZSL, SLE/RSLE and SP. Rather than replacing snowline metrics, hybrid systems should be understood as frameworks that improve their consistency, spatial continuity and operational usability across time and space.

Cortés and Margulis (2017) illustrated this logic by assimilating Landsat-derived snow depletion information into a high-resolution SWE reanalysis over the extratropical Andes, showing that remote sensing can effectively constrain model estimates in data-sparse basins. This is important for the present review because it demonstrates that snowline-related observations can play a role beyond mapping: they can also serve as boundary conditions, validation layers, or calibration targets for hydrological and land-surface models. In that sense, hybrid methods are not merely technical add-ons, but an avenue for connecting snowline monitoring with runoff prediction and climate-impact assessment.

Data-assimilation and data-fusion approaches are particularly useful when the snowline is intermittently obscured or when the objective is a continuous basin-scale variable rather than a scene-based boundary. Merging Landsat, MODIS, reanalysis and land-surface-model outputs reduce uncertainty relative to any single source, especially where cloud gaps, spatial aliasing or sensor-specific biases would otherwise dominate the signal. Spatio-temporal fusion offers a complementary route to the same end: Yang et al. (2024) fused polar-orbiting Sentinel-3 with geostationary Himawari-9 imagery and found that an enhanced spatio-temporal adaptive reflectance fusion model (ESTARFM) reconstructed cloud-gap snow cover in mountainous terrain more faithfully than a simpler multi-temporal scheme, recovering sub-daily snow dynamics that any single sensor would miss. Such methods nonetheless demand care: they add robustness only when the target variable, the error structure and the validation strategy are explicitly defined.

Machine-learning methods extend this logic by learning relationships among optical, SAR, topographic, and climatic predictors, with the goal of improving snow classification, gap-filling, or sub-pixel snow-cover retrieval. Snauffer et al. (2018) showed that neural-network fusion of multiple SWE products and covariates can outperform individual products and simpler regression approaches, suggesting a potentially valuable pathway for Andean applications where complex terrain and sparse observations limit conventional calibration. At the same time, the Andes still lack dense high-elevation training and validation datasets, which means that machine-learning outputs should be interpreted as model-assisted estimates rather than direct observations.

From a methodological standpoint, the most promising hybrid workflow for the Andes is not a fully generic "black box" fusion system, but a tiered framework in which optical ZSL/SLE/RSLE or SP products are first derived, then corrected or complemented using SAR and model-based information and finally evaluated against any available in situ or photographic evidence. This tiered logic responds directly to the need for a more operational

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and reproducible framework, because it links metric selection, uncertainty handling and data fusion within a single methodological pathway (Dietz et al., 2012; Gascoin et al., 2024). In this review, hybrid approaches are therefore positioned as the most flexible route toward near-real-time, cloud-resilient and basin-scale snowline monitoring, if uncertainties are explicitly propagated and the limits of each input source are documented.

To compare the available snowline monitoring approaches in a meaningful way, the review organizes them according to the criteria most relevant to a methodological assessment: spatial scale, temporal scale, principal strengths, key limitations, dominant sources of uncertainty, and best-suited analytical objective.

As Table 4 makes explicit, these approaches are complementary rather than interchangeable: local optical estimates give the most direct but least reproducible boundary, SP best captures regime zonation, SLE/RSLE are most robust for multi-decadal trends, and SAR and fusion extend observation under persistent cloud (Krajčí et al., 2014; Saavedra et al., 2017; Hu et al., 2019; Dietz et al., 2025).

The comparison also makes clear that sensor choice cannot be separated from metric choice. Optical approaches offer higher geometric fidelity and direct boundary visualization, but they are constrained by aridity, cloud cover and threshold sensitivity; SAR adds all-weather capability, yet introduces its own geometric and interpretive uncertainties in steep Andean terrain; and hybrid or data-assimilation approaches improve continuity and operational relevance only when their input data, target variable and uncertainty structure are explicitly defined (Tsai et al., 2019; Hu et al., 2019; Gascoin et al., 2024). In that sense, the table is not only a summary of methods, but a decision framework for matching each approach to a specific monitoring objective.

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679 **Table 4. Comparative evaluation of snowline metrics and monitoring approaches in the**
680 **Andes**

Approach	**Metric / output**	**Main data sources**	**Spatial scale**	**Temporal scale**	**Main strengths**	**Main limitations**	**Key uncertainty sources**	**Best suited for**	**Relative robustness**
Local optical snowline	ZSL / SLA / TSL	Landsat, Sentinel-2, MODIS FSC	Hillslope, glacier, sub-basin	Event to seasonal	High spatial detail, direct boundary observation	Sensitive to clouds, shadows, subjective delineation, mixed pixels	Cloud gaps, threshold choice, DEM quality, sub-pixel heterogeneity	Event-scale snowline mapping, storm response	Low to moderate
Snow persistence	SP zones	MODIS, Landsat time series, Sentinel-2 composites	Pixel, basin, regional zonation	Seasonal to multiannual	Integrates snow dynamics through time, useful for snow regime zonation	Not a direct elevation metric, depends on compositing and data continuity	Temporal gap filling, cloud masking, compositing rules	Climatic zoning, snow regime classification	Moderate to high
Regional snowline elevation	SLE / RSLE	MODIS, Landsat, Sentinel-2, DEM	Catchment to regional	Seasonal to multiannual	More stable for trend detection, less sensitive to local clouds and heterogeneity	Depending on DEM accuracy, may smooth local variability	DEM vertical error, elevation binning, classification error	Long-term trend detection, basin comparison	High
Fixed-threshold optical	Binary snow map	MODIS, Landsat, Sentinel-2	Scene to regional	Daily to seasonal	Simple, operational, long archives	Threshold transferability poor in arid/high	NDSI threshold sensitivity, brightness confusio	Broad snow cover mapping	Low

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						-relief terrain	n, shadow effects		
Dynamic optical	Adaptive snow map / FSC	Landsat, Sentinel-2, MODIS FSC	Scene to regional	Daily to seasonal	Better scene adaptation, improved snow discrimination	More complex and less standardized	Algorithm choice, training data, validation scarcity	Complex terrain, heterogeneous land cover	Moderate
SAR backscatter	Wet-snow / snow state map	Sentinel-1, TerraSAR-X	Scene to regional	Event to sub-weekly	All-weather, day/night capability	Dry snow ambiguity, geometry distortions, interpretation complexity	Layover, foreshortening, incidence angle, coherence loss	Cloud-prone periods, wet-snow detection	Moderate
PolSAR	Wet snow / TSL	Fully polarimetric SAR	Scene to glacier / basin	Event to seasonal	Stronger surface discrimination than backscatter-only	Limited availability, higher processing burden	Polarimetric decomposition, topographic correction, classification error	Research-focused snowline mapping	Moderate
InSAR	Snow depth / SWE proxy	Interferometric SAR	Scene to basin	Event to seasonal	Indirect snow-state information, complementary to other data	Temporal decorrelation, complex interpretation	Phase noise, coherence decay, snow metamorphism	Experimental snow-state estimation	Low to moderate

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Hybrid assimilation	Continuous snow state	Optical + SAR + reanalysis + models	Basin to regional	Continuous or gap-filled	Best continuity, supports forecasting and calibration	Model dependence, calibration burden	Model structure error, observation error, forcing uncertainty	Operational hydrology, forecasting	High if well validated
Machine learning fusion	Gap-filled snowline / FSC / SWE proxy	Optical + SAR + terrain + climate covariates	Basin to regional	Continuous or near-real-time	Nonlinear integration of predictors, gap filling	Training-data scarcity, interpretability issues	Training bias, overfitting, domain transfer	Regional mapping and automation	Moderate to high

No single approach is therefore optimal across all Andean applications; the practical mapping of method to objective is summarized in Table 4 and revisited as operational guidance in Table 6 (Section 6.6).

5. Observed snowlines change in the Andes and global context

Satellite remote sensing has revealed coherent evidence of upward snowline shifts across large portions of the Andes, together with shorter snow seasons and a lower frequency of snow occurrence at low elevations (Saavedra et al., 2018; Cordero et al., 2019; Masiokas et al., 2020). In the extratropical Andes between about 29° and 36°S, MODIS- and Landsat-based analyses indicate increases in snowline-related metrics on the order of 10-30 m yr^{-1}, although the magnitude and interpretation of these trends depend on the metric, study period, and analytical approach used (Saavedra et al., 2018; Dietz et al., 2025). This distinction is essential for the present review, because a trend derived from SP-based snow zones is not directly equivalent to a trend based on scene-scale ZSL or basin-scale RSLE (Saavedra et al., 2017; Hu et al., 2019; Dietz et al., 2025).

5.1 Observed changes across the Andes

Across the central and extratropical Andes, the dominant signal is an upward displacement of the snowline, particularly in semi-arid sectors where the seasonal snow cover is highly sensitive to changes in freezing level and precipitation phase (Masiokas et al., 2020; Dietz et al., 2025). In these regions, reductions in low-elevation snow occurrence and contractions of intermittent snow zones have been documented using both persistence-based and elevation-based metrics, indicating that the most climate-sensitive portions of the snow regime are shifting upslope (Saavedra et al., 2017; Saavedra et al., 2018; Aranda et al., 2023). Reported changes are nevertheless spatially heterogeneous, reflecting differences in latitude, relief, storm exposure, basin size and sensor availability across the Andes (Masiokas et al., 2020; Gascoin et al., 2024).

The tropical Andes and Patagonia likewise show snow-cover and snowline changes, but their observational density, sensor strategies and climatic interpretation differ from those of the

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semi-arid central Andes, making direct comparison less straightforward (Masiokas et al., 2020; Gascoin et al., 2024). In the tropical Andes, glacier-scale studies report rising end-of-summer snowlines against a broader, multi-decadal decline of tropical snow and ice (Rabatel et al., 2013; Vuille et al., 2018): Veettil et al. (2016), for example, documented an upward shift of the annual maximum snowline on Cordillera Blanca glaciers (Peru) between 1984 and 2015. At the extratropical end, the Landsat-based sub-pixel record of Cortés et al. (2014) revealed widespread declines in minimum annual snow and ice extent over 1986-2013. Even so, the strongest synthesis currently available concerns the extratropical Andes, where longer time series and more consistent use of MODIS-based products have enabled clearer identification of multi-decadal tendencies (Saavedra et al., 2018; Aranda et al., 2023; Dietz et al., 2025). This uneven regional evidence base reinforces the need to distinguish a robust regional pattern of rising snowlines from the far more variable confidence attached to local magnitudes and specific trend estimates.

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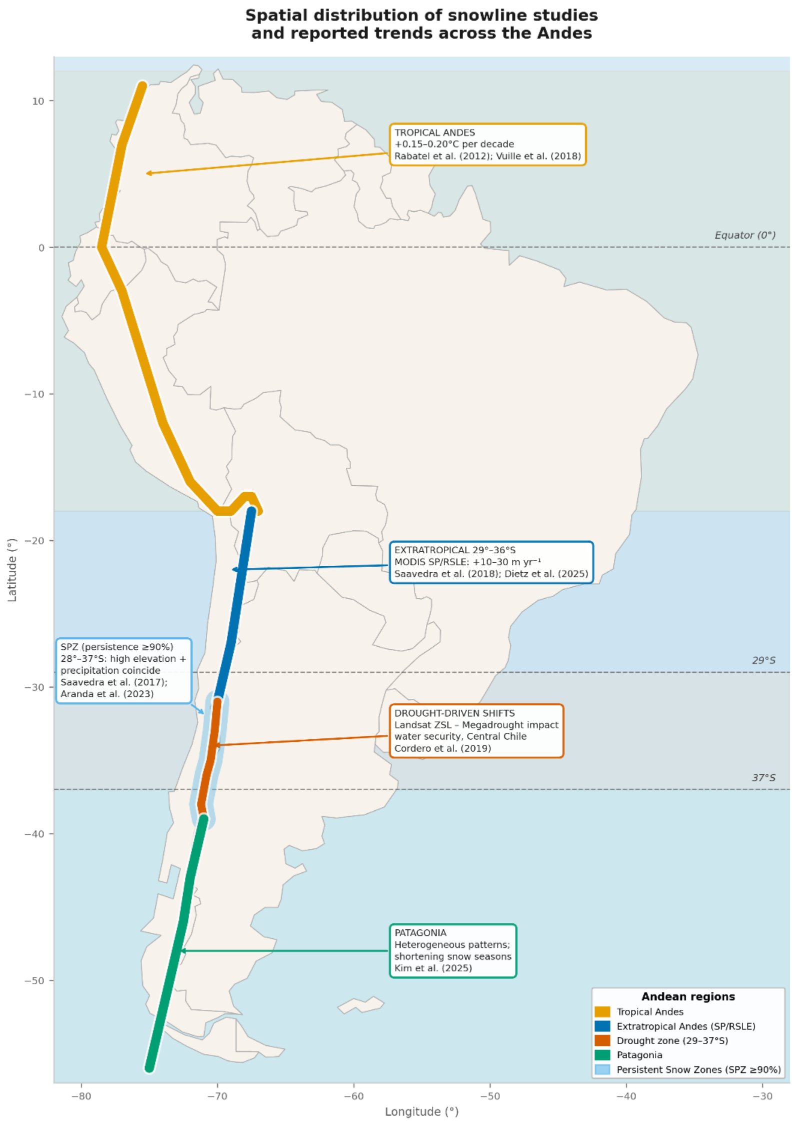

Figure 5. Spatial distribution of snowline studies and reported trends across the Andes. Key patterns include the rapid decline of tropical snow and ice, MODIS SP/RSLE increases of 10-30 m yr^{-1} in the extratropical Andes (29-36°S), drought-driven snowline shifts associated with the central-Chile megadrought, persistent snow zones (SP $\geq$ 90%) concentrated between 28° and 37°S, and heterogeneous snow-season patterns across Patagonia.

5.2 Drivers and regional contrasts

The main climatic controls on Andean snowline change are temperature, precipitation amount, precipitation phase and large-scale circulation variability, especially through ENSO, PDO and SAM influences on storm tracks, atmospheric-river activity and freezing-level altitude (Garreaud, 2009; Garreaud et al., 2017; Masiokas et al., 2020; Viale et al., 2018, 2019a). In central Chile, the persistent megadrought since 2010 has been associated with warmer conditions, reduced cold-season precipitation and fewer low-elevation snowfall events, all of which favor upward migration of the snowline (Garreaud et al., 2017; Cordero et al., 2019; Masiokas et al., 2020). These mechanisms are especially important in basins where climatological snowlines lie close to the freezing-level transition zone, because relatively small atmospheric shifts can produce strong altitudinal responses in snow occurrence (Masiokas et al., 2020; Pepin et al., 2015).

At the same time, the expression of these drivers depends on the metric used to summarize snowline behavior (Hu et al., 2019; Dietz et al., 2025). SP-based approaches tend to emphasize persistent changes in the temporal frequency of snow cover, whereas ZSL-type products are more sensitive to event-scale conditions and RSLE-type metrics capture integrated basin- or region-scale elevation responses (Saavedra et al., 2017; Saavedra et al., 2018; Krajčí et al., 2014; Hu et al., 2019). As a result, the same underlying climatic forcing may appear as a contraction of intermittent snow zones, an upward migration of a local snow boundary, or a gradual increase in regional snowline elevation depending on the observational framework adopted (Saavedra et al., 2018; Aranda et al., 2023; Dietz et al., 2025).

5.3 Global comparison

The Andean evidence is broadly consistent with findings from other mountain systems. In the European Alps, snow cover is receding and snow seasons are shortening (Beniston, 2012; Hu et al., 2020), while in High Mountain Asia satellite analyses report upward snowline shifts and reduced snow persistence (Prein and Heymsfield, 2020; Liu et al., 2021; Pandey et al., 2024; Bernat et al., 2025). The pattern extends to the Mediterranean mountains, where snow is a critical but increasingly stressed water resource (Fayad et al., 2017), and to the Southern Hemisphere, where four decades of observations in the New Zealand Southern Alps reveal a rising snowline and coherent glacier-climate responses (Lorrey et al., 2022), and a satellite census of Southern Hemisphere glaciers documents broadly rising snowline altitudes from 2000 to 2023 (MacFee et al., 2025). On the global scale, satellite records document a broad decline in snow cover over recent decades (Young, 2023). This convergence supports interpreting Andean snowline rise as part of a wider pattern of elevation-dependent warming on mountain cryospheres (Pepin et al., 2015; Arias et al., 2021). Cross-regional comparison must nonetheless remain cautious, because snowline sensitivity reflects not only climate forcing but also relief, cloud regime, precipitation seasonality, sensor selection and the metric chosen to define snowline change (Hu et al., 2019; Gascoin et al., 2024; Dietz et al., 2025).

For this reason, the global comparison is useful primarily as contextual support rather than as proof of strict equivalence between regional trends. The Andes share the general direction of change reported elsewhere, but the interpretation of magnitude remains conditioned by uneven validation, high-relief terrain, data scarcity and methodological heterogeneity (Masiokas et al., 2020; Gascoin et al., 2024). Cross-regional comparability thus depends as

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much on metric standardization as on shared climatic signals (Hu et al., 2019; Dietz et al., 2025).

Because the metrics summarized above operate on different spatial and temporal supports (Section 4.2), the trends they yield cannot be pooled into a single value. Accordingly, the most defensible conclusion from the available evidence is not that a single number summarizes Andean snowline change, but that multiple snowline formulations consistently indicate an upward tendency, while differing in the magnitude, uncertainty and interpretation of that change (Saavedra et al., 2018; Aranda et al., 2023; Dietz et al., 2025).

6. Methodological gaps and future directions

The current Andean literature demonstrates substantial progress in satellite-based snowline monitoring, but it still falls short of a fully standardized, reproducible and operational framework for comparing snowline dynamics across basins and sensors (Masiokas et al., 2020; Gascoin et al., 2024). The main limitation is not the absence of observations, but the lack of methodological harmonization in how snowline metrics are defined, extracted, validated and interpreted (Saavedra et al., 2018; Hu et al., 2019; Dietz et al., 2025). For that reason, future work should prioritize conceptual clarity, consistent reporting and explicit uncertainty treatment rather than simply expanding the number of case studies.

6.1 Harmonizing snowline definitions and reporting

A first priority is to standardize snowline terminology and report metrics so that studies remain comparable across the Andes and beyond (Krajčí et al., 2014; Saavedra et al., 2017; Hu et al., 2019). Existing studies deploy ZSL, SLA, TSL, SLE, RSLE and SP-based zones in ways that are sometimes operationally similar yet conceptually distinct, which hampers synthesis and invites incorrect cross-study comparisons (Saavedra et al., 2018; Choubin et al., 2019; Dietz et al., 2025). Progress toward standardization is feasible: Wayand et al. (2018) defined a set of globally scalable alpine snow metrics computed automatically from Landsat-8 and Sentinel-2 in Google Earth Engine, showing that consistent, transferable definitions can be applied across disparate mountain ranges. Building on such efforts, this review recommends that every study explicitly reports the metric definition, spatial aggregation unit, temporal window, snow-map source and elevation reference used to derive its snowline products (Hu et al., 2019; Dietz et al., 2025).

In practice this means avoiding generic statements such as “the snowline rose” unless the underlying metric, sensor and uncertainty are specified, so that a ZSL trend is never equated with an SP or RSLE trend. Standardized terminology is, in this sense, a prerequisite for any credible benchmarking effort in the Andes.

6.2 Formal uncertainty propagation

A second priority is the explicit quantification and propagation of uncertainty, which remains underdeveloped in most Andean studies despite being central to the interpretation of snowline trends (Choubin et al., 2019; Gascoin et al., 2024). Optical snowline products are affected by cloud contamination, shadowing, mixed pixels and threshold sensitivity, while RSLE and SLE add DEM-related uncertainty and sensitivity to elevation binning (Dietz et al., 2012; Harer et al., 2018; Choubin et al., 2019). SAR-based methods face a different uncertainty structure, dominated by layover, foreshortening, incidence-angle effects, wet-snow ambiguity and coherence loss in steep terrain (Tsai et al., 2019; Callegari et al., 2016).

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The review should therefore encourage studies to report uncertainty budgets rather than only final snowline values or trends. At minimum, this includes sensitivity tests for thresholds, DEM quality, cloud masking choices and pixel aggregation rules, together with error propagation derived into trend estimates (Dietz et al., 2012; Choubin et al., 2019; Gascoin et al., 2024). For Andean applications, uncertainty reporting is particularly important because small vertical changes can produce large apparent shifts in snowline position in steep slopes and narrow valleys.

Table 5. Main uncertainty sources across snowline methods

Uncertainty source	Affects most strongly	Effect on result	Typical mitigation
Cloud contamination	Optical ZSL, FSC, SLE/RSLE	Missing or biased snow boundaries	Cloud masking, compositing, SAR fusion
DEM vertical error	SLE, RSLE, ZSL	Elevation bias, boundary displacement	Higher-quality DEMs, sensitivity analysis
Threshold choice	Optical binary and fractional products	Snow over/underestimation	Adaptive thresholds, multi-index schemes
Mixed pixels	Optical ZSL, FSC	Boundary smoothing, uncertainty in transition zone	High-resolution data, fractional products
Topographic shadow	Optical methods	False snow/no-snow classification	Terrain correction, illumination normalization
Layover / foreshortening	SAR	Geometric distortion of terrain response	Terrain correction, acquisition planning
Coherence loss	InSAR	Reduced retrieval stability	Short revisit times, scene selection
Cross-sensor inconsistency	Multi-sensor fusion	Non-comparable outputs	Harmonized preprocessing and validation

6.3 Improving validation and ground truth

Validation remains one of the weakest parts of the current literature, largely because in situ observations near the seasonal snowline are sparse and unevenly distributed across the Andes (Masiokas et al., 2020; McCarthy et al., 2022). Most studies report trends but do not provide systematic pixel-level validation against independent field data, high-resolution imagery or UAV surveys, which limit confidence in their derived products (Dietz et al., 2012; Gascoin et al., 2024). This remains a key gap for improving validation, reproducibility and operational credibility.

Future work should combine station observations, snow courses, UAV mapping, very-high-resolution satellite imagery and, where available, airborne data to validate ZSL, SLE and RSLE products across representative elevation bands (Rittger et al., 2013; Choubin et al., 2019; Özen et al., 2024). Emerging Andean datasets already point the way: satellite tri-stereo photogrammetry has been used to map high-elevation snow depth in the central Chilean Andes (Shaw et al., 2020), providing a spatially distributed reference against which snowline retrievals can be checked, while networks of public webcam images have been shown to yield regional snowline-elevation estimates at low cost (Portenier et al., 2022), a particularly attractive option for the data-scarce Andes. A practical strategy is to locate validation sites around the climatological snowline and to report standard performance metrics, overall

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accuracy, precision, recall, Dice coefficient and F1-score, rather than relying on visual agreement alone (Gascoin et al., 2024; Özen et al., 2024).

6.4 Strengthening SAR and multi-sensor workflows

SAR remains underused in the Andes despite its clear potential under cloudy conditions and its ability to complement optical observations when cloud cover limits scene availability (Tsai et al., 2019; Gascoin et al., 2024). The current challenge is not whether SAR is useful in principle, but how to adapt its processing to steep Andean terrain without overclaiming robustness. Future studies should address geometry correction, wet-snow classification and cross-sensor harmonization more explicitly, especially when comparing SAR backscatter with optical snow indices and elevation-based metrics (Callegari et al., 2016; Tsai et al., 2019).

A promising direction is the construction of multi-sensor workflows that integrate optical snow extent, SAR wet-snow information, DEM constraints and meteorological forcing into a single reproducible processing chain (Lievens et al., 2019; Gascoin et al., 2024). Such workflows are especially relevant for cloud-prone periods and for basins where operational snow monitoring is required at near-real-time cadence.

6.5 Toward operational and reproducible monitoring

The final gap concerns operationalization. The review shows that many studies remain research-oriented and do not yet provide workflows that are easily transferable to water management, drought monitoring or forecasting applications (Cortés and Margulis, 2017; Saavedra et al., 2018; Gascoin et al., 2024). This is important because the hydrological relevance of snowline change in the Andes depends not only on scientific accuracy, but also on how readily the output can be used in seasonal runoff forecasting and adaptation planning (Masiokas et al., 2006; McCarthy et al., 2022).

To move in that direction, future studies should favor transparent code, cloud-computing platforms, reproducible preprocessing and explicit documentation of all thresholds and parameters used (Gascoin et al., 2024; Altemus Cullen, 2023). Google Earth Engine and similar environments can support this transition, but only if they are used within a clearly defined methodological framework that links data ingestion, classification, validation and uncertainty reporting. In short, operational relevance in the Andes will come from reproducible methods and consistent metrics, not simply from more satellite data.

6.6 Synthesis

The most robust path for Andean snowline monitoring combines standardized metric definitions, explicit uncertainty propagation, stronger validation and multi-sensor integration. Table 6 condenses the four priorities of this section into operational guidance, mapping each analytical objective to its best-suited metric and method (Saavedra et al., 2018; Hu et al., 2019; Dietz et al., 2025).

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Table 6. Recommended method by analytical objective

Objective	Recommended metric / method	Why
Event-scale storm analysis	ZSL / SLA with high-resolution optical imagery	Captures the actual snow boundary at fine spatial detail
Seasonal regime characterization	SP zones	Integrates snow presence through time
Long-term trend detection	SLE / RSLE	More robust to clouds and local terrain effects
Cloud-dominated conditions	SAR or optical-SAR fusion	Maintains observations when optical data fail
Operational hydrology	SLE / RSLE + SP + model assimilation	Links snowline dynamics to runoff and forecasting
Research on snow state processes	PolSAR / InSAR	Useful where detailed scattering or phase information is needed

7. Conclusions

The main contribution of this review is methodological. Across the Andes, snowline monitoring is best understood not as a single measurement but as a choice among non-equivalent metrics, each tied to a particular scale, definition and uncertainty structure. This distinction matters beyond methodology. In a cordillera where seasonal snow sustains the water security of tens of millions of people, the snowline is a decision-relevant indicator, and the way it is measured shapes what water managers, forecasters and policymakers can act upon.

For the study region of this work, the semi-arid and Mediterranean Andes between roughly 29° and 36° S, these distinctions point to a clear preference. The combination of steep terrain and persistent winter cloud cover makes scene-based local snowline altitude too noisy for reliable multi-decadal trends, so a regional, elevation-aggregated metric such as the regional snowline elevation (RSLE) is better suited as the primary indicator of change, with ZSL reserved for event-scale analysis. No single sensor is sufficient either: a continuous MODIS record provides the long baseline, Landsat and Sentinel-2 add spatial detail, and Sentinel-1 SAR fills the winter cloud gaps that most affect this latitude band. The strongest configuration for 29 - 36° S therefore couples RSLE-type metrics with optical-SAR fusion in a reproducible cloud-based workflow, ideally assimilating the resulting snow-depletion information into a snow water equivalent reanalysis, so that the snowline is tied directly to the volume and timing of meltwater, the variable that matters most for water management in this drought-exposed region.

This framing has direct operational value. In the semi-arid central Andes, where the recent megadrought showed how abruptly snow storage can fail, snowline and snow-persistence products can inform reservoir operation, irrigation scheduling, hydropower planning and drought early warning, provided their uncertainty is quantified rather than hidden. Because a rising snowline translates almost directly into a shorter, earlier melt season and a smaller seasonal reservoir, consistent regional metrics give water agencies a spatially explicit early signal of change that sparse station networks cannot provide on their own.

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Turning this potential into practice requires embedding snowline products in climate services and in durable monitoring infrastructure. Snowline elevation is a sensitive, physically interpretable climate indicator, and it can be assimilated into national water and climate services, seasonal forecasts and adaptation planning, narrowing the gap between satellite research and operational decisions. What is needed is a coordinated, multi-sensor Andean snowline observatory built on harmonized, openly documented processing chains, which cloud platforms such as Google Earth Engine now make increasingly feasible. Such a system would fuse optical and SAR observations, anchor them to in-situ, UAV and even citizen-science or webcam references, and deliver near-real-time products with explicit error bounds. Infrastructure of this kind would turn the standardization advocated here into shared regional practice rather than a study-by-study choice.

The methods reviewed here, including automated snowline delineation, optical-SAR fusion and L-band interferometry for snow water equivalent, are arriving alongside a new generation of L-band SAR missions such as NISAR and ROSE-L, which should markedly improve all-weather monitoring of the steep, cloud-prone Andes. Detecting snowline change is, for the most part, no longer the obstacle. The harder task is for the Andean scientific and operational community to build the shared metrics, validation networks and reproducible pipelines needed to monitor that change consistently and to feed it into water-security and climate-adaptation decisions. How well the region meets that task will determine the value of snowline remote sensing for the Andes.

8. Code and data availability

This review article did not generate new code or datasets. All data and studies discussed derive from previously published literature and publicly available satellite products (MODIS, Landsat, Sentinel-2, Sentinel-1) accessible through their respective distribution platforms and from the original publications listed in the reference list. No new data were created or analysed in this study.

9. Author contributions

CR conceptualized the review, performed the literature search and synthesis, and wrote the original draft. FS supervised the work, contributed to the conceptual framework and methodology, and reviewed and edited the manuscript. PCP co-supervised the work and reviewed and edited the manuscript. All authors have read and agreed to the submitted version of the manuscript.

10. Competing interests

The authors declare that they have no competing interests.

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