Rebuttal to Referee #1

The article "Introducing a new normalized cryospheric index (NCI) to categorize sub-watersheds on arid environments" by Ulloa and others presents a new index aimed to characterize watershed importance in terms of cryosphere water storage and sources. The aim is to present a novel tool to aid in water management and to identify areas that are more critical as water sources or storage at the basin scale. Particularly, they stress that this new tool will help to understand better the importance of different subbasins in arid mountain environments.

The structure of the article is unbalanced and mixed. The methods are very briefly introduced, and the results present mainly a description of the landforms' distribution, without showing the ice content and ice volume estimation in detail. Figures could also be improved. Although the idea initially appears promising, the method of computing the NCI is unclear, and the methodology is based on too many assumptions, some of which are not supported by new evidence or previous research, rendering the new index not very useful. Considering the amount of work presented here, I will attempt to summarize my comments to the authors to clarify my point and contribute to the discussion on the importance of the cryosphere as a water source and storage in the driest part of the Andes.

General comments:

Please use the same name throughout the manuscript; it is tough to follow if the variable names are changed throughout the text without notice. After reading the manuscript, it is not clear which variable has been used to assess the snow cover in the area.

We have carefully revised all variable names and made them consistent throughout the manuscript. Variables related to snow (snow cover, persistence, and fractional snow) are now clearly defined in Section 3.3 "Survey of cryospheric resources: MODIS and snow monitoring", and this terminology is used consistently in all tables, figures, and text. Incorporating the following text into the manuscript "In this study, we use three complementary variables to describe snow dynamics across the Copiapó watershed: snow cover, snow persistence, and fractional snow cover (FSC). Snow cover represents the total area (km^2) covered by snow in each MODIS image, reflecting the instantaneous spatial extent of snow. Fractional snow cover (FSC), derived from the MODIS MOD10A1 daily product, quantifies the proportion of snow-covered surface within each pixel (ranging from 0 to 1) through sub-pixel reflectance unmixing, providing a more accurate representation of heterogeneous snow conditions, especially in transition zones. Snow persistence expresses the temporal stability of snow presence and was calculated as the proportion of days in the historical MODIS series during which each pixel remained snow-covered.

In this framework, FSC was used as the primary MODIS input for snow mapping, while snow persistence was the variable integrated into the Normalized Cryospheric Index (NCI) to represent short-term cryospheric water resources."

The article lacks a proper analysis of the runoff data for the Copiapó basin and its subbasins, as well as their hydrology. The study is based on the assumption that snow, glaciers, and periglacial landforms are the primary source and storage of water in dry mountain areas. Although the role of snow as a critical water source and the importance of glaciers as hydrological buffers in drought periods are well known. The role and importance of rock glaciers and other periglacial landforms are still a matter of debate. Nevertheless, the lack of an analysis of the hydrology of the basin, particularly the role of groundwater, shows that not all the components of the hydrology of the basin have been assessed before jumping straight to the conclusion that the subbasin where more glacial and periglacial landforms are, is the ones that produce or will produce more runoff. It is mandatory that they fully assess the hydrology of the basin before being pointed out or classified as dependent on the cryosphere. In this aspect, it is surprising that they do not assess the runoff data to support their classification or their assumptions.

We have now incorporated a hydrological validation for the Copiapó basin using measured discharge and precipitation data from the DGA network (2008–2020). This new analysis clearly demonstrates that the Copiapó River exhibits a melt-dominated regime that is incompatible with a pluvial system.

Specifically, discharge records at the Pastillo station show a pronounced summer peak (DJF–MAM) when precipitation is at its minimum, indicating an uncoupling between rainfall and runoff (Fig. 1, a). No significant correlation ($|r| < 0.05$) was found between precipitation at the Iglesia Colorada station and discharge at Pastillo for any lag between −6 and +6 months, confirming the absence of direct rainfall control.

Furthermore, the baseflow index (BFI) of the basin remains high (>0.7) during the dry season, suggesting sustained discharge unrelated to rainfall, likely derived from delayed cryospheric storage (snow, ice, and permafrost). These hydrological signals are consistent with other Andean catchments where summer flows are primarily controlled by meltwater inputs rather than precipitation events (Favier et al., 2009; Gascoin et al., 2011; Ayala et al., 2016; Burger et al., 2019).

Collectively, these data provide robust support for the classification of the Copiapó watershed as predominantly cryospheric, where snow, glacier, and periglacial landforms represent the main components of seasonal water storage and release.

Due to the absence of high-elevation gauging stations in the upper Copiapó basin, it was not possible to directly assess runoff at the headwaters where cryospheric processes are most active. The Pastillo station, used in our analysis, represents the confluence of the three main sub-basins and thus integrates the cumulative hydrological response of the upper catchment.

While this configuration prevents a direct evaluation of individual high-altitude contributions, it still provides a representative signal of the basin-scale hydrological regime. Therefore, the melt-dominated seasonal pattern observed at Pastillo should be interpreted as the integrated downstream expression of cryospheric inputs originating in the upper parts of the watershed (Fig. 1, b). To support this interpretation, we added the location of both the Pastillo gauging station and the Iglesia Colorada meteorological station to the introductory map, illustrating the spatial relationship between the hydrological outlet and the high-altitude cryospheric zones.

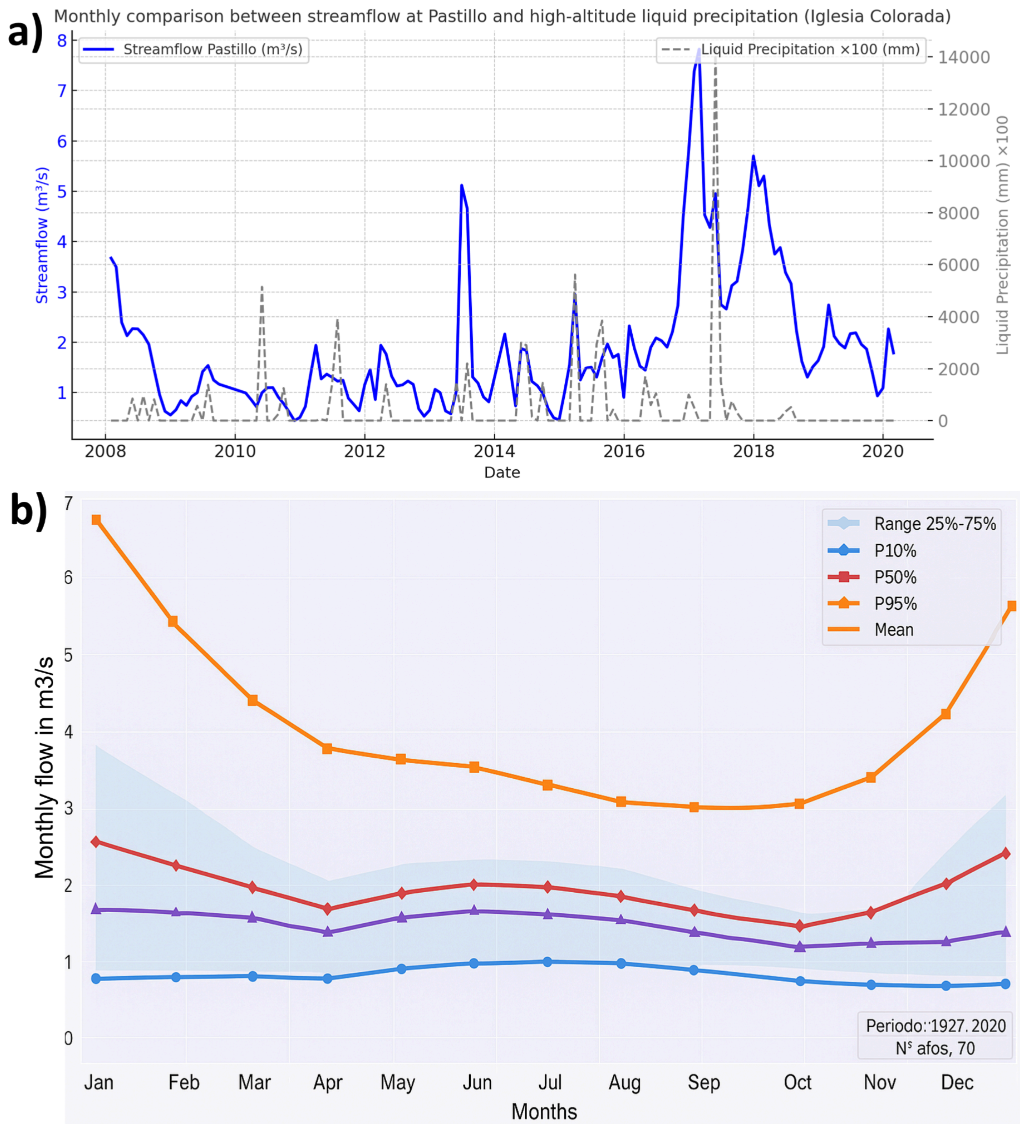

Figure 1. a) Monthly comparison between streamflow at the Pastillo gauging station and high-altitude liquid precipitation recorded at Iglesia Colorada. The gray dashed line (×100 scale) represents liquid precipitation, while the blue curve shows the mean monthly discharge of the Copiapó River at Pastillo. b) Seasonal variation in flow at Pastillo station.

The article lacks a proper assessment of the ice volume of the different cryosphere components. It is unclear to me whether the authors use the ice thickness data of Farinotti et al. (2019) or if they compute the ice thickness distribution for each debris-free glacier using the model of Farinotti et al. (2017). If the latter is the case, they must show their new results and compare them with the previous assessment. If they use previously published data, they need to assess the quality of this data for the region. If I understand correctly, authors use the V-A scalar approximation to assess the part of the glaciers that are covered by debris, which flawlessly matches the proposed method, which is based on the empirical relationship between extent and volume of glaciers. It is not possible to apply this relationship just to a fraction of the glacier. The assessment of ice volume for the rock glacier is underscored. This could be a highlight of this work, but it is roughly mentioned. I recommend that the authors focus more on these results. Considering the results of Hilbich et al. (2022) and Schrott (1996), and one ERT survey made by them, the authors assess the thickness and ice content for gelifluxion slopes. Considering the scarcity of data, the difficulties in mapping the boundary of the area with gelifluxion lobes, and the fact that Hilbich et al. (2022) also highly that there is a similar amount of ice thickness in sediment slopes without distinctive surface characteristics, the ice volume estimated for gelifluxion slopes is still highly speculative. To support the conclusion of the manuscript, that the gelifluxion slopes are the largest water storage in the area, more data is needed. Particularly, the range of thickness used could lead to the wrong conclusion that this slope could have a thickness similar to rock glaciers, which is nonsense. I think the authors here are confusing the estimate (there are no supporting measurements) of the permafrost thickness of Schrott with the ice-rich layer of Hilbich et al. (2022).

We have completely revised Section 3.5 to provide a clear description of how ice thickness and volume were estimated for each cryospheric component. For debris-free glaciers, we made the volume calculation using the physical model of Farinotti et al. (2017), extracting the thickness data from the validated global dataset (web) (Farinotti et al., 2019). For debris-covered glaciers, we applied the empirical Gärtner-Roer et al. (2014) relation ($V = 0.0365 \times A^{1.375}$) to our regional inventory (García et al., 2017). Including a correction of the thickness calculation over an integration with the free debris glacier.

To estimate the ice volume of debris-covered glaciers, we avoided applying the empirical area–thickness scaling relation of Röer et al. (2014) directly to these landforms, since this approach is not appropriate for individual glaciers where the debris-covered area does not necessarily follow the same morphometric relationship as clean-ice glaciers. Instead, we derived mean ice thickness values from the Farinotti et al. (2019) ice-thickness raster by sampling the glacier fronts (debris-covered sectors) defined in our updated Copiapó inventory. For each debris-covered polygon, the mean thickness extracted from the frontal zone of the clean-ice glacier was used as a representative value to compute ice volume as the product of area and mean thickness. This method ensures that the projected ice thickness used for debris-covered portions is physically consistent with the spatial gradient of thickness from Farinotti et al. (2019) and with the glacier-specific geometry.

Rock glaciers were re-analyzed with both the empirical model of Jones et al. (2018) and the plastic and viscoplastic model of Cicoira et al. (2020), based on DInSAR-derived velocities presented in Figure 2. Protalus lobes and gelifluction slopes were evaluated using an adapted form of Cicoira's viscoplastic equation, constrained by thickness ranges (10–20 m for protalus lobes and 5–10 m for gelifluction slopes) and ice-content fractions (25–49%) derived from Hilbich (2022) and Schrott (1996). In addition, DInSAR-derived surface velocities were used to apply and calibrate Cicoira's viscoplastic model for permafrost creeping, allowing a more realistic estimation of ice-rich permafrost deformation and related ice volume, presented in the figure 5.

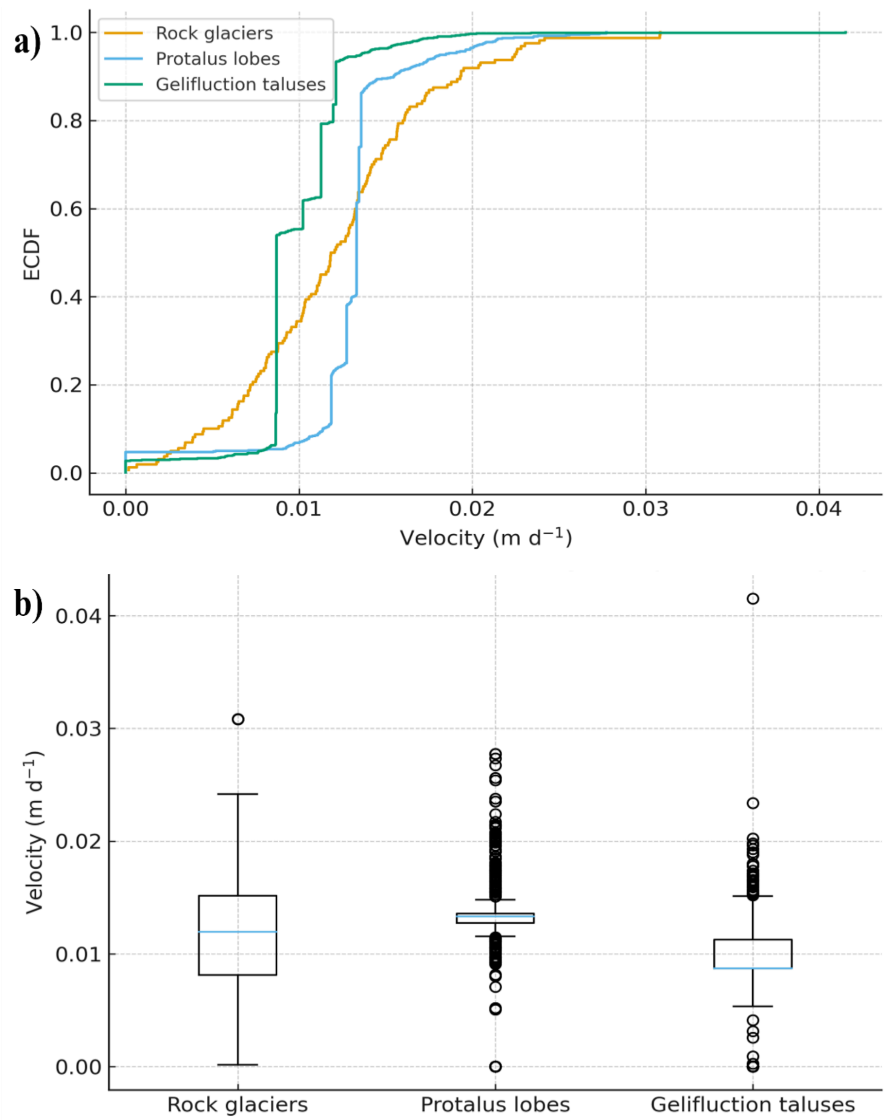

Figure 2. (a) Empirical cumulative distribution functions (ECDF) of surface velocity (m d^{-1}) for rock glaciers, protalus lobes, and gelifluction taluses derived from DInSAR analyses. (b) Boxplots showing the distribution of mean daily velocities for each cryoform type. Distinct velocity ranges indicate contrasting kinematic behaviors among permafrost-related landforms.

In addition, a comparison between the empirical approach of Jones et al. (2019) and the physically based model of Cicoira et al. (2020) for rock glaciers (Fig. 3) indicates consistent results, with a mean difference below 10 m and an RMSE of 13.0 m. The Cicoira model systematically yields slightly higher thicknesses (median ≈ 37 m) than the Jones relationship (median ≈ 26 m), reflecting the greater sensitivity of the physical formulation to ice content and temperature (−8 °C). To further explore this dependence, we applied Cicoira's viscoplastic equation under different temperature scenarios (−2 °C, −5 °C, and −8 °C) to estimate ice volumes, as shown in the attached figure. The scenario of −5 °C was selected as the most representative for Andean permafrost conditions, following the thermal regime reported by Monnier and Kinnard (2015). This multi-scenario approach allowed us to quantify the thermal sensitivity of permafrost creep and to reinforce the reliability of the ice-volume estimations for rock glaciers within the Copiapó watershed.

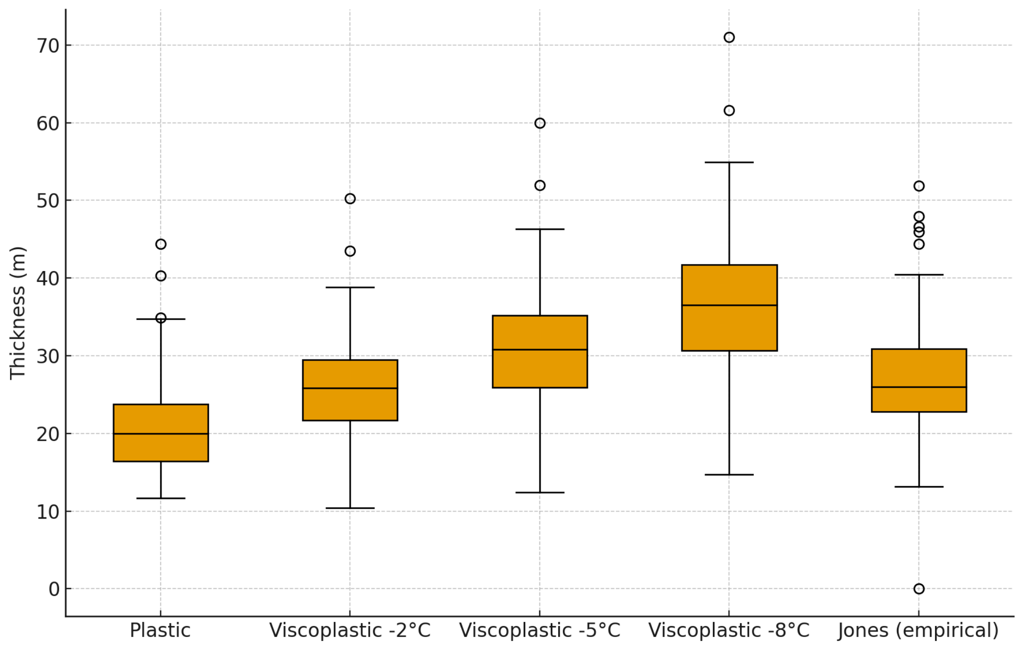

Figure 3. Comparison of modeled rock glacier thickness using the empirical relationship of Jones et al. (2019) and the physically based model of Cicoira et al. (2020) at −2, −5, −8 °C. The Cicoira model predicts systematically higher mean thicknesses (median ≈ 37 m) than Jones (median ≈ 26 m), with an RMSE of 13.0 m and a bias of 9.3 m, indicating consistent but more physically sensitive estimates under colder thermal conditions.

Figure 4 presents the updated ice volume estimations for the Copiapó watershed, comparing debris-free glaciers (Farinotti et al., 2019) and rock glaciers (Cicoira et al., 2020), the two main cryospheric reserves. The results reveal a clear latitudinal clustering of ice-bearing landforms, with both glacier and permafrost-related features concentrated between 28.6° and 28.2° S, corresponding to the highest-elevation sub-watersheds of the basin. Debris-free glaciers display larger individual ice volumes, reaching up to 0.3 km³, whereas rock glaciers show smaller but more numerous

bodies, indicating a wider spatial distribution of permafrost ice storage. This spatial convergence reflects the transitional cryospheric setting of the arid Andes, where glacier-permafrost interactions dominate above 4,500 m a.s.l. The analysis highlights that, despite their smaller individual volumes, rock glaciers collectively represent a significant portion of the total cryospheric reserve in the basin. Further results below detail the volumetric contribution of each cryoform class across sub-watersheds. Incorporating into the article a study of the results of the volumes, as well as showing the cryospheric gap that occurs in the basin due to the presence of Mount Pissis in Argentina (García et al., 2017).

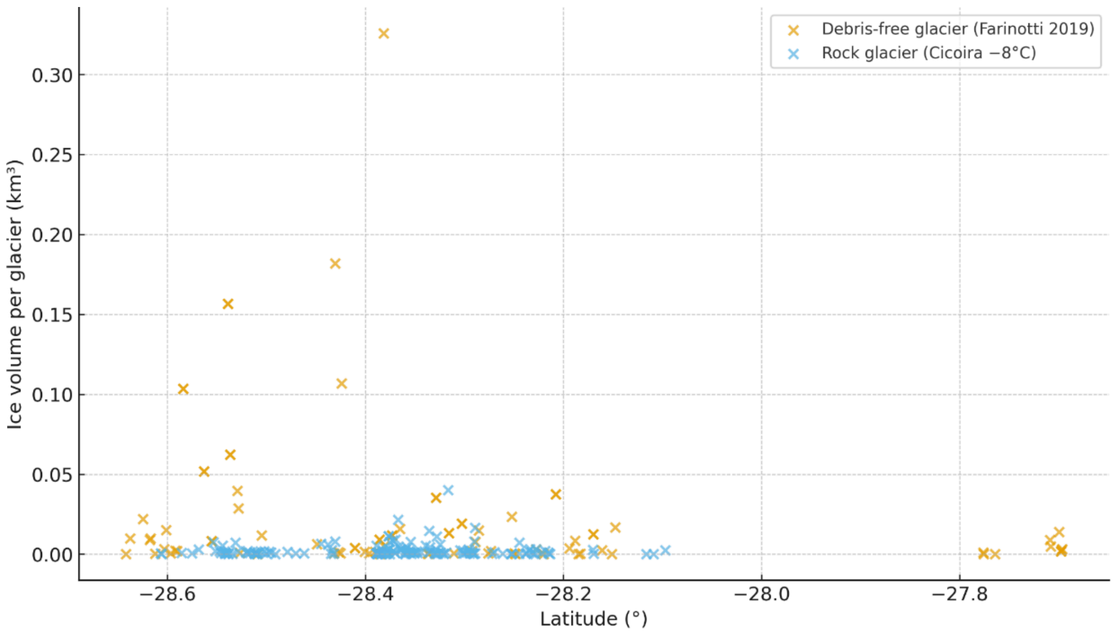

Figure 4. Latitudinal distribution of ice volume per glacier in the Copiapó watershed, comparing debris-free glaciers (Farinotti et al., 2019) and rock glaciers (Cicoira et al., 2020). Debris-free glaciers exhibit higher individual ice volumes but are less frequent, while rock glaciers are more numerous and concentrated between 28.6° and 28.2° S, indicating a strong latitudinal clustering of permafrost-related ice storage in the upper Andean sub-watersheds.

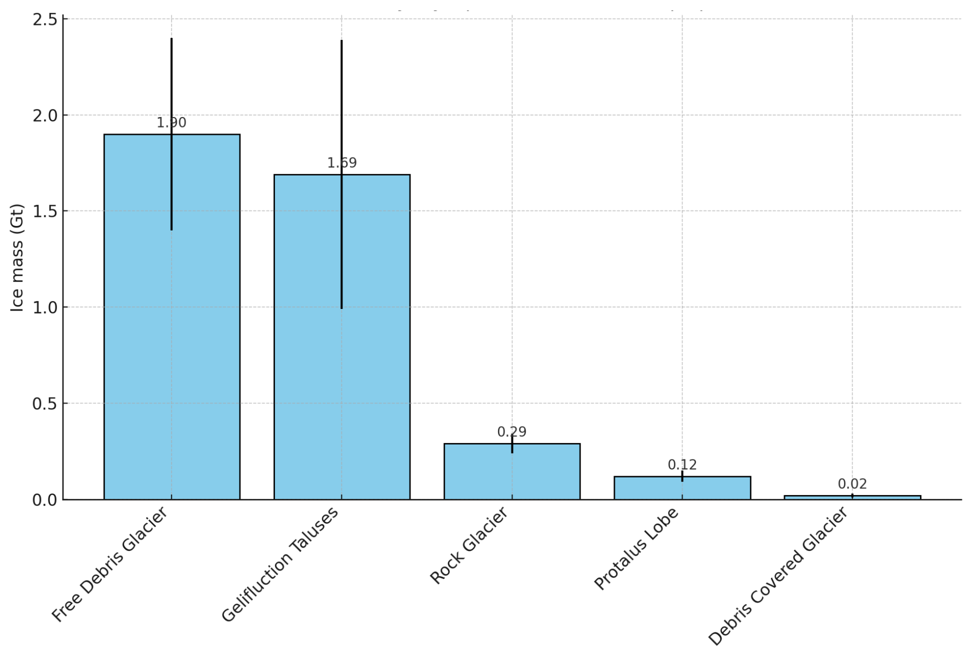

Figure 5.Total ice mass (in gigatonnes, Gt) by cryospheric class in the Copiapó basin. Error bars represent the estimated uncertainty in ice mass for each landform type, derived from the propagation of thickness and density uncertainties.

Do we really need an NCI? I don't find the answer to this question in the paper, and the authors do not discuss whether the methodology is really useful, or at least better than assessing the basin in terms of snow cover and ice volume alone. They suggest the NCI could be computed in other basins, but they don't assess it. Furthermore, they don't consider the fact that they optimize the critical parameter W using a Montecarlo simulation, showing that at least we could have a "best guess" of this value. Also, the NCI combines both water storage and water sources related to the cryosphere. However, since the time response of these cryosphere features is highly different, it could give the wrong impression that a basin with rock glaciers is equally critical or responds in the same way as a basin with seasonal snow. Also, I found that snow cover is, without any confirming data, assessed as the amount of snow or, even worse, as snowfall, which is not necessarily the case. Snow cover and persistence do not only depend on the amount or thickness of the snow layer, but also on the energy available for melting or sublimation. Considering that the authors assessed the ice volume at each basin, it is straightforward to rank the basins in terms of ice storage. There is no mention about the extent and hypsometry of the subbasins, which is critical, since a larger basin would have a larger snow cover than a smaller one. Another aspect that is mentioned, but not adequately assessed, is permafrost. Although rock glaciers and gelifluxion could be related to the presence of permafrost, the role of frozen ground in the hydrology of the basin is not assessed or discussed. Finally, considering Figure 14 and the discussion related to this figure, it seems more fruitful to assess the hydrological significance of each subbasin, breaking down the roles of snow, glaciers, and permafrost, as they have very different response times.

We now clarify the conceptual purpose and scientific value of the NCI and explicitly link it to both basin hypsometry and hydrological response. The NCI integrates cryospheric reserves (long-term frozen storage: glaciers and permafrost-related landforms) and resources (short-term snow and meltwater) into a 0–1 normalized metric for inter-watershed comparison. It does not replace process-based hydrological models but provides a screening tool to prioritize sub-basins by cryospheric influence.

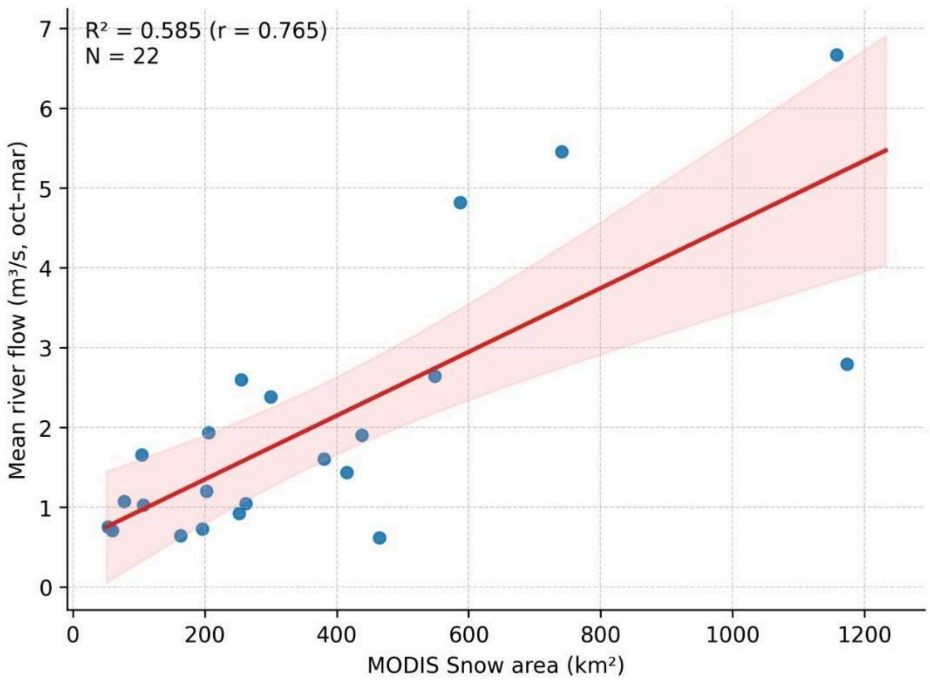

Figure 6. Hypsometric curves (Δz = 100 m) of the Copiapó sub-basins, color-coded by Hypsometric Integral (HI). Lower HI values denote higher elevation dominance and stronger cryospheric influence.

Furthermore, we incorporated a new analysis linking MODIS-derived snow cover in September—the onset of the melt season—with mean river discharge observed between October and March (Fig. 6). This relationship shows a robust correlation (R^2 = 0.58; r = 0.76; N = 22), confirming that seasonal snow cover acts as a dominant short-term cryospheric water resource in the Copiapó watershed. The integration of these empirical hydrological results into the NCI framework validates those sub-basins with higher NCI values not only exhibit stronger cryospheric signatures in their topography but also display measurable hydrological responses consistent with seasonal meltwater contributions.

To substantiate this interpretation, we computed hypsometric curves for all sub-basins with cryospheric components (dz = 100 m) and derived the Hypsometric Integral (HI). The updated analysis shows a clear consistency between hypsometry and NCI rankings: sub-basins with higher NCI systematically exhibit lower HI (curves shifted leftward), indicating a greater fraction of area at elevations where cryospheric processes dominate and/or a stronger glacial imprint. Notably, the sub-watershed

ranked first by NCI also presents the lowest HI in our sample (Figure 7), reinforcing that the NCI captures elevation-controlled cryospheric controls. These time-response differences among snow, glaciers and permafrost are discussed explicitly (lines 480–505), with the hypsometric analysis providing an independent geomorphological check of the NCI.

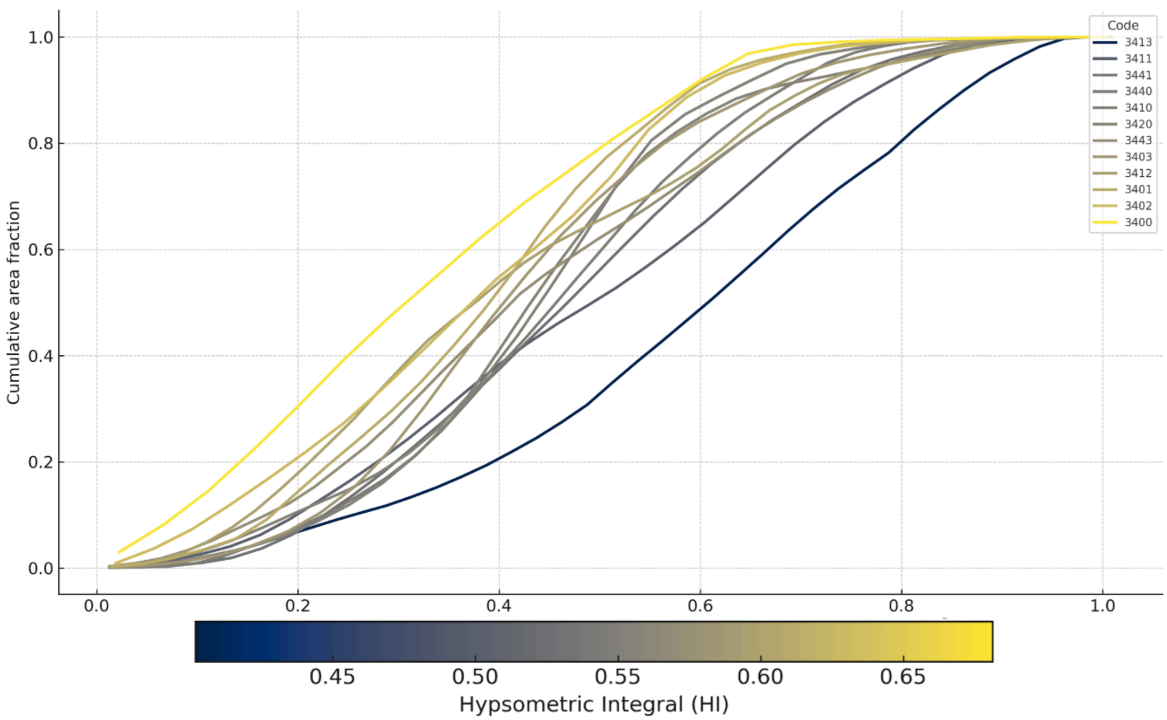

Figure 7. Relationship between September snow-covered area (MODIS) and mean river flow from October to March, showing a strong positive correlation (R^2 = 0.58), highlighting the dominant role of seasonal snowmelt in Copiapó basin hydrology.

Line-specific comments:

Lines 8–23. Since the article presents the NCI, the abstract must clearly state what the NCI means.

Ok, we have now rephrased the abstract as follows:
The Normalized Cryospheric Index (NCI) is calculated under varying hydrological conditions and provides a means to compare potential water volumes across sub-watersheds.

Line 26. Use changes instead of shifts.
Ok, we have changed this.

Line 27. Retreating cryoforms? What do you mean?
We have rephrased this to: “declining volumes of cryoforms.”

Line 29. There is ample evidence in Masiokas et al. (2020) indicating that glacier mass change is anything but constant.
We understand that the reviewer interpreted that we meant "retreating at a constant rate," but we mean that glaciers are retreating continuously over time and not expanding. We have rephrased this now to: "In the arid zone of the Chilean Atacama Desert, glaciers continue to shrink..."

Line 33–41. Please order the introduction, you could introduce the Copiapó basin in the study area.
Ok, we have placed this part now in the study area.

Line 45–46. It is not clear what you want to express here. Do you want to say that snow transforms into ice? Considering explaining the causes behind debris-covered ice or how ice could be preserved in permafrost.
We have rewritten these lines to clarify that the transition from snow to glacier ice occurs through compaction and metamorphism processes, and we now briefly explain how debris cover reduces melting rates and preserves ice in permafrost terrain.

Line 47. There is a space missed before "Given."
Space deleted.

Line 48. This sentence gives the wrong impression that debris-free, debris-covered, and rock glaciers respond in the same way. Nevertheless, there is plenty of evidence that shows that debris-covered and particularly rock glaciers contribute far less to the runoff. Please present the role of the different ice water storage.
We have rewritten this part, clarifying that debris-covered and rock glaciers have a delayed and attenuated hydrological response compared to debris-free glaciers. We now reference Ferri et al. (2020) and Schaffer et al. (2023), who observed minimal annual mass loss and limited meltwater contribution from rock glaciers. This distinction is explicitly discussed in the results section and in Figure 14.

Line 50–52. Sublimation and melting are different processes.
We have corrected this by differentiating between sublimation (solid-to-vapor transition under low humidity) and melting (solid-to-liquid phase change) in the revised text.

Line 52. What about the ground flow? There is not even a mention about this.
We now include a discussion on subsurface water flow and its connection to permafrost layers in Section 4.3. Groundwater recharge from permafrost and talus slopes is described as a key mechanism sustaining dry-season baseflow in the Copiapó basin.

Line 54–56. What do you mean by ice-rich? As far as I know, from an inventory based on satellite images, it is not possible to assess the ice content. Authors need to support why they call these landforms "ice-rich." What is the ice content on these landforms? Also, how they define a landform as ice-rich is not trivial.
Ok, we see the reviewer's point and have removed the word "ice-rich."

Line 73–81. Move this paragraph to methodology.
Ok, we have moved this paragraph to methodology.

Line 87–92. There is no need for “”. It is not clear how a normalized index, with values from 0 to 1, could be used to quantify the potential volume of water available. I strongly disagree with the statement that the runoff of the Copiapó basin is supported by the melting of glaciers, rock glaciers, or even the ice present at gelifluxion slopes. What evidence or literature are you using to support this claim?
We have clarified that the NCI provides a relative, not absolute, measure of potential cryospheric water availability. The link between runoff and cryospheric storage is now supported by hydrological correlation analyses and references to DGA streamflow data (2010–2024). We have also cited Masiokas et al. (2020) and Pitte et al. (2022) to support the role of the cryosphere as a long-term regulator in arid Andean basins.

Figure 1 and the rest. Really, all these institutions are behind all the figures “Source map provider: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.” The northern part of the basin is lacking the river.
We have corrected the base map attribution to the official ESRI sources and added the missing river segment in the northern part of the basin. The figure caption has been revised accordingly.

Table 1. It would be helpful to include here the extent of snow cover and the number and area of each of the glaciers and cryoforms mapped.
We have updated Table 1 to include the total area and number of each cryoform class (snow, debris-free glaciers, debris-covered glaciers, rock glaciers, protalus lobes, and gelifluxion slopes), along with snow cover extent.

Figure 2. It is mandatory to include a scale on the figure. Rock glaciers look larger than debris-free glaciers.
A map scale has been added to Figure 2, and the symbology was adjusted to prevent misinterpretation of relative cryoform size.

Line 127. This section lacks new studies assessing the ice content of rock glaciers and glaciers in the Andes and other mountain areas. Like Jones et al (2018), Hu et al (2023) or Millan et al (2022), to mention a few.
We have now added the suggested studies (Jones et al., 2018; Hu et al., 2023; Millan et al., 2022) to provide an updated regional context on ice content variability in Andean cryoforms.

Line 134. Corte (1978) highlights the importance of rock glaciers, but does not present new data to assess the ice content of rock glaciers.
We have corrected this reference, clarifying that Corte (1978) provided a conceptual framework but not quantitative ice-content estimates.

Table 2. Not clear what Contribution to streamflow (%) means.
We have added an explanation in the table caption indicating that "Contribution to streamflow (%)" refers to the relative cryospheric surface area within each subbasin, normalized by total basin area and runoff index, following methods adapted from Rangecroft et al. (2015).

Line 173. Norway? Classifying different slope cryoforms? Are you talking about Hilbich et al. (2022) about the ice content in Permafrost of the Central Andes?
Yes, this reference was incorrect. It now correctly refers to Hilbich et al. (2022), who assessed ice-rich layers in Andean permafrost slopes using ERT and borehole data.

Line 181. The classification of this basin as cryosphere is not properly founded. See my comments on Table I.
We have now added our classification of what a sub-watershed is here:
'A sub-watershed is a watershed unit with a lower Strahler stream order than the main watershed...'
Line 189. In this section, you need to explain how you perform the glacier and other landform inventory. It is not clear how Garcia et al. 2017 and RGI 6.0 are coincidental.
We have clarified in Section 2.3 that García et al. (2017) provided the regional debris-covered glacier inventory, while RGI 6.0 (RGIv6.0) was used for debris-free glaciers. Overlapping polygons were cross-checked to ensure no duplication, and the datasets were harmonized using common projection parameters.

Line 199. The title suggests that snow is monitoring; nevertheless, the authors only use the snow cover area. I don't understand how snow persistence is included in the snow cover maps.
We have clarified that "snow monitoring" refers to the multi-temporal analysis of MODIS-derived snow cover, from which persistence was derived by computing pixel-wise frequency of snow presence.

Line 218. This section shows interesting data, but a proper ground truth will also include an assessment of the ice content and or ice thickness of the rest of the cryoforms.
We now reference field-based ERT and GNSS campaigns conducted in 2022–2024 to validate rock glacier thickness estimates and integrate these datasets into our uncertainty discussion.

Line 341. See my general comment about glacier volume estimation.
We have incorporated this into the revised methodology (Section 3.5), where all ice volume estimation procedures are now clearly defined and validated against Farinotti (2019).

Line 320. Not all are empirical equations.
Ok, we have removed the word "empirical" from the table caption.