RC2: 'Comment on egusphere-2025-1614', Anonymous Referee #2, 01 Oct 2025

General comments:

This study presents comprehensive work done on the Gangotri glacier in Himalaya.

The study has three to four branches:

1. Comparing different methods for velocity mapping
2. Calculating ice thickness using two different inversion approaches one based on a known DEM and velocity field and one on a stress-based approach
3. Calculating thinning rates based on dem differencing
4. Apparent thermal inertia: but this is not well described

While a lot of solid work clearly forms the basis of the manuscript, I found the 40-page manuscript quite hard to follow, and a major revision of the text as well as a discussion of the velocity maps is required. I agree with Referee #1 on all comments, and I hope my general and line-by-line comments below can help identify the main issues to address before it can be considered for publication.

We sincerely thank the reviewer for their valuable time and thoughtful comments on our manuscript "Understanding the Gangotri glacier dynamics: Implications from a fully distributed inversion of water equivalent volume change." The comments and suggestions provided have been significantly beneficial in improving the clarity, rigor, and overall quality of the work. We have carefully considered each comment and intend to revise the manuscript accordingly while addressing the concerns and enhancing the presentation of our findings. The responses and revisions are mentioned in different colors in the following.

Main concerns:

The title: Understanding the Gangotri glacier dynamics: Implications from a fully distributed inversion of water equivalent volume change.

I think that the title might refer to glacier changes and not actual dynamics, since it is the changes in mass/volume and not the glacier dynamical changes that are in focus of the paper.

We thank the reviewer for their insightful remarks. We have accordingly revised the title as follows:

"Understanding the Gangotri glacier: Implications from a remote sensing based fully distributed inversion of equivalent water-volume change"

There is a strong focus on the ice volume calculations and as far as I understand the velocity mapping is done with the purpose to create an input for the thickness and volume change inversions. Maybe with the focus of ending up with mass balance estimates, the velocity mapping descriptions could be shortened throughout or maybe moved to supplementary, making room for a stronger discussion of the quality of the velocity maps and the different time periods.

We thank the reviewer for their remarks. The glacier surface velocity is one of the critical inputs in the velocity based inversion of ice-thickness and the focussed model VWDV. Additionally, we compared different tools for velocity inversion from remote sensing data. Following this, we believe that sufficient depth to details on velocity estimation, and associate discussion is needed in the manuscript as conducted. We agree that in the original write-up the clarity was lacking. To account for this, we have merged section 3.1. Image Processing and Ice Masking and section 3.2. Glacier velocity estimation as a single section 3.1. Glacier velocity estimation. We have also added further details to clarify the data selections and methods. We have also revised section 6.1. to improve the discussion on comparison of velocities as per glacier sub-zones, different methods and other studies. These two sections can now be read as follows.

"3.1. Glacier ice velocity estimation

A total of 152 Sentinel-2 RGB images, spanning the years 2016 to 2023, were used for Glacier Image Velocimetry (GIV)-based velocity estimation (Van Wyk De Vries & Wickert, 2021). The RGB images were processed in Google Earth Engine (GEE) with a cloud-masking filter to enhance feature-tracking accuracy. Additionally, for comparison single-band near infrared (NIR) grayscale images, free of clouds and snow were utilized for velocity estimation using the Co-registration of Optically Sensed Images and Correlation (COSI-Corr) tool (Leprince et al., 2007) and Image georectification and feature tracking toolbox (ImGRAFT) with time-series image pairs from 2016 to 2023. Sentinel-2 NIR single-band images for the snow-free months of July to October, were downloaded from the Sentinel Data Hub for velocity estimation using Cosi-Corr and ImGRAFT tools. The three methods used for glacier surface velocity estimation rely on tracking persistent surface features between multi-temporal satellite images using different correlation algorithms and windowing strategies, were employed to cross-validate results and assess the consistency and reliability of velocity estimations derived from different algorithms. The resulting velocity maps were carefully refined by applying a glacier mask based on the manually derived glacier outline based on high resolution imagery and RGI 6.0 glacier boundaries.

Sentinel-2 RGB images were used for a pair-wise velocity estimation based on the GIV tool using multi pass feature tracking frequency domain image correlator (Van Wyk De Vries & Wickert, 2021). Image pairs with temporal intervals ranging from 9 days to 1 year were used to derive annual surface displacement and velocity fields of the glacier. Total pairs were generated for this glacier with all years 151 for this study covering an 8-year time period (2016 - 2023). For each Sentinel-2 RGB image pair, displacements were estimated iteratively using a multipass template matching following the standard GIV workflow. The GIV approach follows an iterative multi-pass approach in which displacement is first estimated using larger window sizes, followed by smaller windows in subsequent passes to refine the estimated velocity. We used the standard GIV reference window sizes of 400 m, 200 m, and 100 m and a 50% window overlap, resulting in a final glacier surface velocity map with a spatial resolution of 30 m (Van Wyk De Vries & Wickert, 2021). The overlap refers to the percentage of each template window that overlaps with adjacent windows during feature matching in the Glacier Image Velocimetry (GIV) process, where a 50% overlap is used to significantly reduces noise in the resulting velocity field and ensure consistency. Signal to noise ratio lower than 5 and peak ratio less than 1.3 were considered during multi-pass template matching with sub-pixel estimator (a correlation refinement technique used to improve the accuracy of displacement measurements beyond the spatial resolution of the input imagery) (Van Wyk De Vries & Wickert, 2021). To enhance the quality of estimated displacements, three pre-processing filters were applied including, the Contrast Limited Adaptive Histogram Equalization (CLAHE), a high-pass filter , and the Near-Anisotropic Orientation (NAO) Filter (Van Wyk De Vries & Wickert, 2021). The CLAHE filter was applied to the satellite images to enhance local contrast in the images aiding in feature tracking. The high pass Sobel filter was applied to the images for improved identification of features for tracking, and the NAO filter was applied to the resulting displacement map. Further, to remove outliers arising from mismatches or noisy correlations in feature tracking, an upper velocity threshold of 200 m a^{-1} was applied to the resulting displacement map and thresholded pixels were interpolated. The threshold was selected based on prior studies in the region and is consistent with expected velocity ranges for Gangotri glacier (Bhushan et al., 2017; Gantayat et al., 2014). The resultant displacement map represents the annual velocity maps with velocity values expressed in meters per annum (ma^{-1}).

Through the Cosi-Corr, a single-pass feature-tracking approach was implemented to evaluate glacier surface displacement using Sentinel-2 NIR band imagery, primarily acquired during July–October (2016 to 2023) to ensure minimal cloud cover over the Gangotri Glacier (Table S1). The surface displacement was estimated for consecutive study intervals (2016–2017, 2017–2018, ..., 2022–2023)(Leprince et al., 2007). The COSI correlation module provides two correlation algorithms frequency-based and statistical approach. This study used the frequency method, which is better for reliable results using an optical dataset (Bhushan et al., 2017). The correlation window, commencing with an initial window dimension of 64 × 64, progressively decreases to a final size of 32 × 32, employing a step size of 2, as specified by Bhushan et al., 2017. First, the displacement output is derived at resolution at 160 meters, containing displacements in the east-west (EWD) and north-south (NSD) direction, as well as the associated signal-to-noise ratio (SNR). Pixels with low correlation are eliminated by applying a limit value of SNR < 0.9. Finally, surface displacements were determined by the Eulerian distance using the two displacement vectors east-west (E - W) and north–south (N - S). The velocity vector area was verified and synchronized before generating the Velocity map. The time interval between the two images (about 1 year for each study period) is utilized to estimate the ice velocity meter per annum (ma-1). The velocity (u) is estimated from the North-South (y) component (NSD) and the East-West (x) component (EWD) over the time interval t over which displacements occur as follows.

$$u = \frac{\sqrt{(NSD)^2 + (EWD)^2}}{t} \quad (1)$$

For the ImGRAFT based velocity estimation, seven NIR band images acquired in July-October of each year were used as input (Table S1). The ImGRAFT (Messerli & Grinsted, 2015) was used iteratively in a multi-pass tracking framework by considering sequential mean displacements from consecutive iterations for each of the satellite image pairs in the ascending order of their sensing dates. The CLAHE filter was used as a pre-processing step to enhance image contrast and a statistical normalization was carried out for each image pair prior to template matching. The ImGRAFT algorithm uses template matching to detect displacement vectors between corresponding features, and a regular grid was created with a defined spacing to sample motion within the region of interest defined by the glacier boundaries. The displacement vectors were converted into ground units through pixel-to-meter scaling, and velocity components (x, y) were computed alongside the total surface velocity (u) after applying a temporal normalization factor to retrieve annual velocities. If the mass changes calculated in this study are not significant over the relatively short period of this study, then maybe they can be put into longer time trends by comparing to other studies.

This study conducted the mass balance based on modelled thickness change according to VWDV model which considered the glacier periodic velocity and surface slope of the glacier with SIA equation as per (Cuffey & Paterson, 2010). The calculated mass balance indicates negative mass wastage, showing good agreement with previous studies conducted using energy balance, geodetic, and glaciological methods on the Gangotri Glacier and surrounding benchmark glaciers (Azam et al., 2018; Dobhal et al., 2021). Therefore, our estimated glacier mass balance reliably represents the surface mass balance over the short period of 2016–2023.”

“**6.1**. **Glacier velocities**

6.1.1. Comparative assessment with ITS_LIVE

This study investigates the ice surface velocity of the Gangotri Glacier using three different feature-tracking approaches: GIV, COSI-Corr, and ImGRAFT. To evaluate the internal consistency of these methods, we compared their outputs with the Inter-mission Time Series of Land Ice Velocity and Elevation (ITS_LIVE) dataset (Gardner et al., 2022) over a common period (2016–2023). While this comparison does not validate the absolute accuracy of the methods—since all are remote-sensing-based and lack in situ ground-truth data—it provides insights into the relative spatial variability of different approaches across various glacier zones. It is important to note that such inter-comparisons primarily reflect the comparability of methodologies, not their absolute correctness. To ensure a robust assessment, we analysed velocity estimates along the central flow line and in glacier sub-zones (ablation, equilibrium line, accumulation), minimizing lateral variability (Fig. 3e & 6a). Further, recent Sentinel-1-based velocity data (Bhattacharjee & Garg, 2024) and earlier feature-tracking results (Gantayat et al., 2014; Saraswat et al., 2013) were used for contextual comparison. Statistical comparisons were performed using a Least Absolute Residuals (LAR) fit with 95% prediction bounds. The ITS_LIVE data were resampled from their native 120 m resolution to 30 m to match the resolution of GIV, ImGRAFT, and resampled COSI-Corr (originally 60 m) Fig 6.

Across the whole glacier, ITS_LIVE velocities showed strong statistical correlations with COSI-Corr (r = 0.857), GIV (r = 0.755), and ImGRAFT (r = 0.755), indicating overall consistency (Fig. 6a & 6b). In the ablation zone, velocity agreement was highest with COSI-Corr (r = 0.872). At the same time, GIV and ImGRAFT exhibited slightly lower correlations (0.738 and 0.753, respectively), likely due to localized effects such as surface melt, debris cover, and ice deformation. In the accumulation zone, while high correlations were also observed (e.g., COSI-Corr = 0.977), these must be interpreted cautiously, as this region is prone to featureless snow cover and frequent image decorrelation. These issues are known to reduce tracking accuracy, and the stronger agreement here may reflect limited feature variability rather than true velocity accuracy.

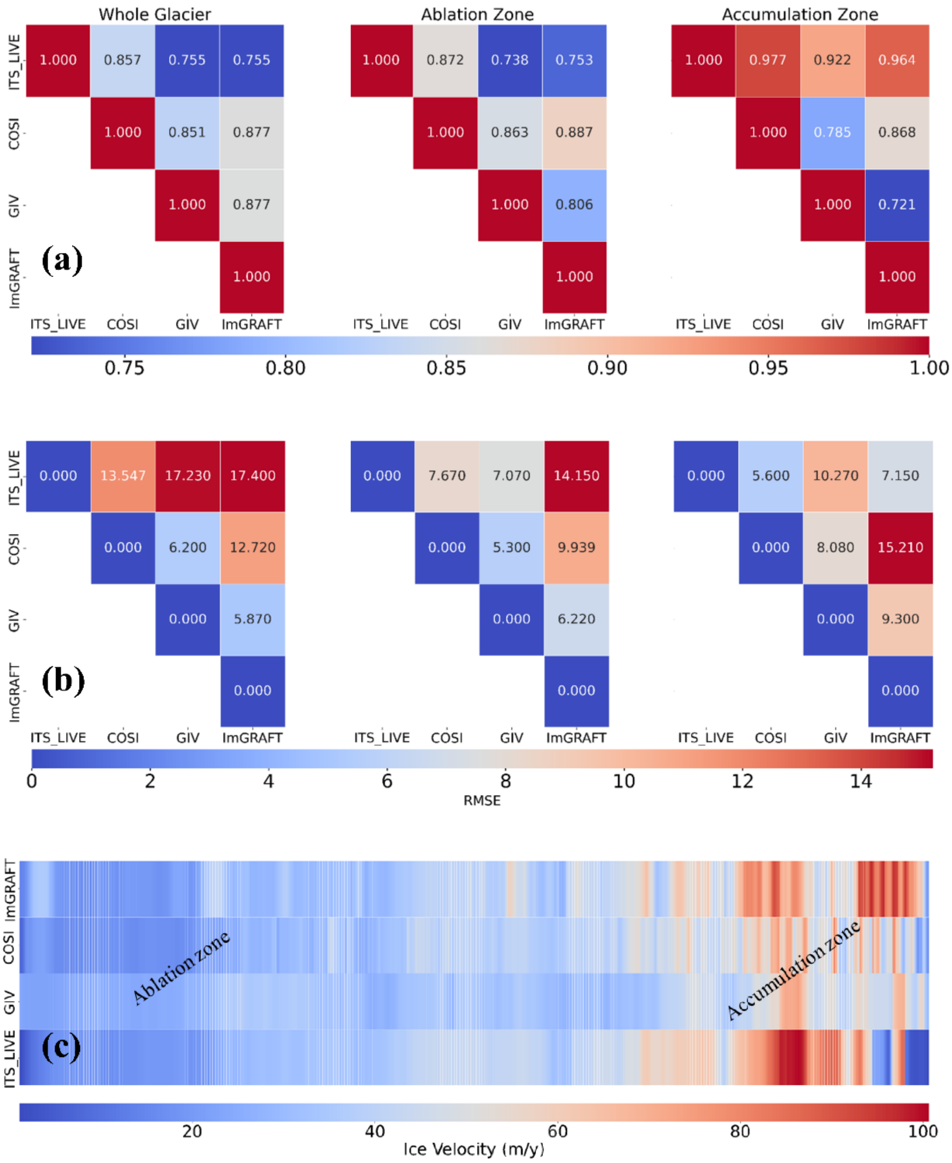

Figure 6: a) Illustrates the correlation between different glacier velocity estimation approaches for the Gangotri Glacier across various zones; b) Root Mean Square Error (EMSE) of the ice velocity between different approach and c) Depicts the distribution of glacier velocity along the central flow line, extending from the glacier terminus to the accumulation peak (A–A').

In the ablation zone, ITS_LIVE shows a higher correlation with COSI Corr (0.872) and about similar correlation with GIV (0.738) and ImGRAFT (0.753), reflecting the influence of surface melting, crevassing, and ice deformation, which can introduce uncertainties in velocity retrieval (Fig. 6b). In contrast, the accumulation zone presents the strongest correlations, with ITS_LIVE aligning closely with COSI Corr (0.977), GIV (0.922), and ImGRAFT (0.964), suggesting more stable ice dynamics in this region due to reduced surface melting and a more consistent ice mass flow (Fig. 6b).

Fig. 3e & 6c represents the glacier velocity distribution along the central flow line from the terminus to the accumulation zone, highlighting distinct spatial variations in ice motion. The velocity remains relatively low near the terminus due to high frictional resistance from bedrock and debris cover, gradually increasing in the ablation zone where ice thinning and gravitational flow enhance movement (Nicholson et al., 2018). In the accumulation zone near the ELA, the velocity reaches its peak, attributed to the increased ice mass and steep surface gradients (Vatsal et al., 2025). The observed variations of the entire glacier velocity reflect the combined effects of topography, ice thickness, and surface conditions, with the ELA emerging as a critical zone for maximum ice movement. The strong correlation suggests that all the remote sensing methods effectively capture glacier dynamics with consistent ice movement along the central flow line. These results demonstrate the compatibility of remote sensing based feature tracking techniques with well-established satellite datasets. As delineated in Fig. 6a, the ITS_LIVE velocity captures these patterns of decreasing velocity from accumulation to the ablation zone, followed by ImGRAFT, which also captures similar pattern, however, with higher velocity in some accumulation zones in contrast to ITS_LIVE. These differences in the velocity patterns are also statistically observed in the higher RMSE for ImGRAFT compared with ITS_LIVE (Fig. 6b). It is worth mentioning here that for the statistical comparison, the ITS_LIVE and the COSI-Corr velocities were resampled to 30m from 120m and 60m, respectively. The relatively higher agreement between the COSI-Corr velocity and the ITS_LIVE product may be attributed to the coarser resolution compared with the GIV and ImGRAFT where the source spatial resolution of the velocity product was 30m. Fig. 6c shows that the GIV and ImGRAFT methods largely underestimate the velocity in some zones of the accumulation region along the central flow line.

While the velocity estimates are broadly consistent across all remote sensing methods, this comparison emphasizes spatial reliability more than validation. The methods appear most robust in the ablation zone, where clear surface features persist throughout the season. In contrast, estimates in the accumulation zone carry higher uncertainty, and results in this region should be interpreted conservatively. These findings highlight the importance of considering glacier zone-specific reliability when applying and comparing remote sensing velocity products.

6.1.2. Assessment with other studies

Due to the harsh climatic conditions in the Gangotri Glacier region, in-situ field-based velocity measurements through stake installations remain challenging. Therefore, we compared our velocity estimates with existing studies based on optical and microwave remote sensing techniques. To ensure meaningful comparison, we focused on specific glacier zones—particularly the snout and ablation areas—where earlier studies have discussed glacier surface velocity quantitatively. In this study, the surface velocity (2019) near the central flowline in the near the terminus zone was estimated to range between 18 ± 3.6 and 31 ± 5.78 m a^{-1}, which aligns well with the findings of (Thakur et al., 2023; Gantayat et al., 2014), who reported velocities between 20 and 30 m a^{-1} in period of 2019. Similarly, (Saraswat et al., 2013) documented velocities between 24.8 ± 2.3 and 28.9 ± 2.3 m a^{-1} in the snout region in the period of (2004-2010). A more recent study by Bhattacharjee & Garg, (2024) , based on Sentinel-1 offset tracking for 2017–2022, estimated a mean glacier velocity of 32.85 ± 2.25 m a^{-1}, closely matching the average values along the central flow line observed in our results. Our results identified the mean surface velocity along the central flow line as 30.20 ± 5.60 m a^{-1} for 2017-2022.

In the study period, we observed a downslope acceleration in the Gangotri Glacier's surface velocity as per time-series investigations based on the GIV tool. However, the distribution of the surface velocity varied across the glacier. The marginal regions of the glacier exhibited a decreasing trend in surface velocity which may be due to debris accumulation, which increases friction and inhibits ice flow (Fig. S2). Additionally, the presence of stagnant ice and reduced ice thickness in marginal areas further contributes to slower movement, as the driving stress diminishes near the margins, whereas the central trunk of the glacier displayed an increasing trend during the study period."

Abstract:

The abstract needs to be revised and some of the details left out. See line by line comments for details.

We thank the reviewer for noticing the issues in the abstract. We have revised the same accordingly as follows.

"Evidence of rapidly increasing temperatures with climate change is clearly visible in the concerning mass changes of Himalayan glaciers. Subsequently, monitoring glacier volumes is critical for managing regional water resources and predicting glacier dynamics. The Gangotri Glacier remains a subject of scientific debate due to limited field data on its dynamics, ice thickness, volume, and mass balance, leading to uncertainties in understanding its behavior and changes. The Gangotri glacier, a significant water resource for northern India, is experiencing significant changes due to climate change. The ice thickness and mass balance of Gangotri glacier during 2016–2023 was analyzed using a velocity and shear stress-based framework. A laminar flow-based approach is applied to determine the ice thickness of the Gangotri Glacier, while glacier surface velocity was estimated from Sentinel-2 multispectral imagery using three independent feature-tracking methods. The thickness change of the study period is used to estimate the mass balance and equivalent water volume change of the glacier. The analysis revealed a pronounced spatial variability in glacier flow and ice thickness, with faster movement and greater ice depth in the accumulation and upper ablation zone that gradually diminished toward the snout. The Gangotri Glacier exhibited a consistent thinning trend and negative mass balance, reflecting significant ice loss during the study period. We observed the volumetric change is a declining pattern of the study period 2017 to 2023 gradually. The climatic parameters observed an increasing trend over the last two decades. We also found that the Apparent Thermal Inertia (ATI) increased which determined the debris accumulation over the ablation zone significantly from the side wall and transported from the accumulation and emerges in the ablation zone of the glacier due to fluctuation of the temperature differences (Thaw-freezing). These changes denote a significant reduction in the water storage capacity of the Gangotri Glacier."

Description of methods and data:

The Apparent Thermal Inertia is mentioned in the abstract, but no information can be found about this in the introduction, method and data or results section.

We are grateful for this observation. We have included in the introduction literature focusing on the critical influences of climate forcing on Himalayan glaciers.

"Glacier dynamics are critically governed by interconnected climatic forcing that drive surface ablation, ice flow acceleration, and irreversible thinning (Immerzeel et al., 2020). Declining winter precipitation and snowfall reduce accumulation zones, lowering albedo and shifting melt-runoff timing, with snowmelt contributions dropping in High Mountain Asia (Jouberton et al., 2025; Kraaijenbrink et al., 2021). Enhanced runoff from intensified summer melt alters downstream hydrology, amplifying flood risks while depleting late-season baseflow (Pritchard, 2019). The thermal properties as identified from the ATI of snow, ice, and debris of a glacier play a vital role in determining its thermal resistance and its melting processes. ATI quantifies the resistance to temperature change in the upper layers of ice/snow, revealing enhanced ablation on debris-free tongues where diurnal temperature shifts are high and consequentially low ATI facilitates frequent melt–freeze cycles (Brenning et al., 2012). Thus, the combined effects of changing precipitation, runoff, ATI, and aerosol-induced albedo reduction collectively drive enhanced glacier surface lowering across the Himalaya (Bolch et al., 2019)."

A new sub-section 3.6. Analysis with key influencing parameters is added in the methodology section.

"**3.6. Analysis with key influencing parameters**

The Gangotri glacier ice thinning was analysed corresponding climatic factors such as precipitation, runoff, snowfall, ATI, PM2.5 concentrations, and aerosol optical depth. The various satellite and reanalysis products used for the extraction of these factors are listed in Table 1, and these were used at their native spatial resolution to derive mean annual magnitudes to assess their impact on Gangotri glacier thinning. One of the critical parameters used in this study, is the ATI, which is primarily based on the diurnal melt–freeze cycles is derived from MODIS LST (MOD11A1) and MODIS Albedo (MCD43A3). The diurnal melt–freeze cycles in temperate/polythermal glaciers exert a strong influence on the seasonal pattern of surface mass loss, as daily fluctuations in surface temperature directly control melting and refreezing intensity (Irvine-Fynn et al., 2011; Steiner et al., 2021). The ATI is a key parameter used to evaluate the thermal response and heat retention capacity of glacier surfaces, reflecting variations in surface composition, moisture content, and debris thickness (Foster et al., 2012; Van Doninck et al., 2011). ATI was calculated using Equation (18) following the formulation of Van Doninck et al., (2011), where it is derived from the combination of diurnal temperature amplitude and the albedo to represent the apparent resistance of the surface to temperature change. The ATI was analysed to infer thermal heterogeneity and surface energy exchange characteristics across the glacier, thereby linking surface thermodynamics with observed mass-balance variations.

$$ATI = C\frac{(1-\alpha)}{\Delta T} \quad (18)$$

where α represents the surface albedo, and C = 0.84 is the solar correction factor, which accounts for variations in incoming solar radiation calculated according to (Nicholas & Locke, 1982) and ΔT is the diurnal temperature range. This equation highlights the fundamental relationship between surface reflectivity, thermal variation, and energy retention, making ATI an effective indicator of glacier melt dynamics."

In particularly, the velocity data used as input needs to be better described to understand the effect of potentially different input data to the velocity mapping. And an analysis of the seasonal and year to year evolution of the surface velocity would be both interesting and aid the understanding of uncertainties in the thickness calculations.

We thank the reviewer for their observation. We have revised the sections to add more details and clarity to velocity inversion process and datasets and their discussion.

Although it would be interesting to compare the seasonal velocities and annual velocities, due to limited availability of cloud-free satellite images, seasonal velocity estimation is not possible with optical remote sensing data, particularly in very high elevation glaciers.

Using the Shallow Ice Approximation on a valley glacier needs to be justified, maybe with references to other studies? Also, I would be really interested in seeing the seasonal evolution of the velocity (even though that might be out of the scope for this study).

We thank the reviewer for their remarks. Reviewer-1 had also suggested improving clarity and justifications for the same. We have revised the section as follows.

"**3.2. Glacier Ice thickness estimation**

Ice thickness is determined using the glacier surface velocity and the ice surface slope through the shallow ice approximation (SIA) method (Cuffey & Paterson, 2010; Hutter & Morland, 1984; Le Meur et al., 2004). The laminar flow-based SIA method is commonly used globally for estimating glacier ice thickness. This approach combines the principles of glacier flow with the shallow-ice approximation to estimate ice thickness under the assumption of a hard, non-deforming bed (Cuffey & Paterson, 2010; Farinotti et al., 2019; Frey et al., 2014; Maussion et al., 2019; Millan et al., 2022; Nela et al., 2023). The SIA method utilizes basal shear stress for defining the glacier motion as compared to the full driving stresses, and assumes that the local stresses inducted are much greater than the stresses arising from the lateral coupling between adjacent columns (Cuffey & Paterson, 2010). Many glaciers in the Himalaya and Andes are characterized by relatively thin ice in their upper reaches and moderate to steep surface slopes. These conditions exhibit the dominance of basal shear stress within the total driving stress, thereby justifying the application of the SIA for estimating ice thickness and glacier dynamics (Schotterer et al., 2003; Thouret et al., 2007). Several studies employed the glacier surface velocity based approach (Farinotti et al., 2017; Gantayat et al., 2014; Van Wyk De Vries & Wickert, 2021), while others utilize the basal shear stress approach for the retrieval of glacier ice thickness (Farinotti et al., 2017, 2019; Haeberli & Hoelzle, 1995; Kumari et al., 2021; Linsbauer et al., 2012). These methods were carefully selected to provide comprehensive estimates of glacier ice thickness by leveraging different glaciological principles.

3.2.1. Velocity-based ice thickness

Glaciers primarily move as the ice deforms under the force of gravity. This flow occurs through three main mechanisms: internal ice deformation, sliding at the base, and deformation of the subglacial bed (Hambrey & Glasser, 2012). The glacier ice surface velocity u is a result of two component glacier internal deformation u_d and basal velocity u_b (sum of basal sliding and subglacial sediment deformation) (Cuffey & Paterson, 2010), as shown in equation 2.

$$u(H) = u_d(H) + u_b \tag{2}$$

where, the internal deformation u_d and glacier ice surface velocity are functions of the ice-thickness H that are evaluated at the ice surface. The deformation velocity is related to the basal shear stress and the ice thickness as follows (Cuffey & Paterson, 2010).

$$u_d(H) = \frac{2A_c}{n+1}\tau_b^n H \tag{3}$$

where A_c is the Arehenius creep parameter, τ_b represents basal shear stress, n is the Glen's flow exponent ($n = 3$) (Glen, 1958). The glacier surface velocity as shown in equation 2 can then be represented as shown in equation 4 (Glen, 1958; Van Wyk De Vries et al., 2022).

$$(1-\beta)u(H) = u_d(H) = \frac{2A_c}{n+1}\tau_b^n H \tag{4}$$

where, β is the basal sliding correction factor (Van Wyk De Vries et al., 2022). The laminar flow law (King, 1983) accounts for both surface and basal velocities of the glacier. However, determining basal sliding velocity through remote sensing is not feasible.

Some benchmark studies assumed the subglacial deformation to be negligible and have considered basal sliding to represent the major contributions to the glacier's surface velocity (Farinotti et al., 2009, 2017; Linsbauer et al., 2012). In other studies, the basal velocity was typically considered as one-fourth (25%) of the surface velocity of the glacier (Bhushan et al., 2017; Gantayat et al., 2014; Nela et al., 2023; Remya et al., 2019). In contrast, van Wyk et al., (2022) employed a basal sliding correction factor to account for the fraction of glacier motion corresponding to basal sliding. The basal shear stress, τ_b, is expressed in terms of measurable parameters following equation 5 (Frey et al., 2014; Linsbauer et al., 2012; Van Wyk De Vries et al., 2022).

$$\tau_b = f\rho_i g H \sin(\alpha) \tag{5}$$

where f is the shape factor (Gantayat et al., 2014; Haeberli & Hoelzle, 1995), ρ_i is the snow/firn/ice density, g is acceleration due to gravity, α is the ice-surface slope angle (derived from the DEM) and H is ice-thickness. We follow the velocity-based ice thickness estimation by Van Wyk De Vries et al., (2022), as shown in equation 6.

$$H = \left(\frac{n+1}{2(f\rho_i g)^n A_c^* \exp\left(\frac{Q_c}{R}\left[\frac{1}{T} - \frac{1}{T^*}\right]\right)}\right)^{\frac{1}{n+1}} \left(\frac{u(H)(1-\beta)}{\sin(\alpha)^n}\right)^{\frac{1}{n+1}} \tag{6}$$

where the Arrhenius creep constant A_c as defined in Cuffey & Paterson, (2010), was determined using glacier ice surface temperature based on the following temperature-dependent relation.

$$A_c = A_c^* \exp\left(\frac{Q_c}{R}\left[\frac{1}{T} - \frac{1}{T^*}\right]\right) \tag{7}$$

where the constants being $A_c^* = 2.4 \cdot 10^{-24}, Q_c = 115\ \mathrm{kJ\ mol^{-1}}, R \approx 0.0083145$ (the ideal gas constant), and $T^* = 273\ \mathrm{K}$ (Cuffey & Paterson, 2010). To estimate the ice surface temperature T of the Gangotri Glacier, MODIS MOD11A1 LST data was utilized. Further details regarding the temperature extraction and processing are provided in Table S2 and S3, and Fig S1.

The glacier ice thickness inversion as described in equation 6, involves several parameters typically assumed as constant such as g, β, ρ_i, f, A_c and n. In equation 6, the spatially varying components include α, $u(H)$, and A_c. The parameter A_c varies spatially corresponding to the ice surface temperature determined by MODIS LST data, α as per the DEM and the surface velocity $u(H)$ as defined in the previous sub-section. Recent studies (Sinha et al., 2024; Van Wyk De Vries et al., 2022; Yang et al., 2024) as compared to previous literature (Bhattacharjee & Garg, 2024; Frey et al., 2014; Nela et al., 2023; Ramsankaran et al., 2018) vary the constant parameters based on a Monte Carlo simulation for improving the ice-thickness estimates. Following these recent studies, to account for the spatial and thermal variability of the Gangotri Glacier, which exhibits polythermal and temperate characteristics, the basal sliding correction factor β was varied from 0 to 0.4 in the inversion simulations as per previous studies in a Monte Carlo simulation framework. This approach provides a more realistic representation of basal motion compared to the conventional assumption of a constant sliding coefficient. the shape factor f was varied between 0.7 (ablation) and 0.9 (accumulation) instead of being held constant, to account for the influence of valley geometry and lateral drag effects across different sections of the glacier (ablation and accumulation) (Gantayat et al., 2014; Linsbauer et al., 2012; Sinha et al., 2024; Van Wyk De Vries et al., 2022). This range reflects the realistic variability between narrow, deep valley segments and wider glacier, thereby improving the physical representation of ice flow in the inversion modelling. The snow–firn–ice density was varied between 850 and 917 kg m^{-3} to account for glacier surface (Sinha et al., 2024; Van Wyk De Vries et al., 2022; Yang et al., 2024)."

Regarding the seasonal velocities, we agree it would be very interesting, yet it is not possible with optical remote sensing due to insufficient cloud-free images.

Mass balance estimates from thickness change, require some consideration of density which is not described to a high enough detail.

We thank the reviewer for pointing out this issue. We have revised sentences in the section 3.5. Mas balance estimation. The revisions are as follows.

"The mass balance and the change in the total volume ΔV was determined by summing the change in the ice thickness Δh_i at an individual pixel using the equation 13.

$$B = \frac{\Delta V}{S} \times \frac{\rho_{ice}}{\rho_{\text{water}}} = \Delta \bar{H} \times \frac{\rho_{ice}}{\rho_{\text{water}}}\ ;$$
$$\Delta V = \sum_{i=1}^{N} r^2 \Delta \bar{h}_i;\ S = \sum_{i=1}^{N} r^2 \tag{13}$$

where B is given in m.w.e, Δh_i is the mean ice thickness change of the ith pixel, ΔH is the mean glacier ice thickness change in meters, ρ_{ice} is the density of glacier ice, ρ_{water} is the density of water, r is the pixel resolution in meters, $S = \sum_{j=1}^{n} r^2$ is the average area of glacier during the study period, N is the number of pixels covering the glacier ice at its maximum extent. The density of ice was considered as 850 kgm^{-3} following previous studies (Cogley, 2011; Hubbard et al., 2000; Zemp et al., 2013). A standard water density of 997 kg m^{-3} was used to convert the derived ice volume changes into m w.e., following commonly adopted glaciological practices (Huss, 2013; Zemp et al., 2013)."

Line by line comments

Abstract:

I would move the first sentence two sentences down to keep the structure natural: First general trends then Gangotri specifically

Thank you for your suggestion. We have moved and revised the sentence as follows.

"The Gangotri Glacier remains a subject of scientific debate due to limited field data on its dynamics, ice thickness, volume, and mass balance, leading to uncertainties in understanding its behavior and changes."

Line 21 – 25: Restructure for better reading flow.

Thank you for the suggestion. We have revised the sentences as follows for improving readability.

"The ice thickness and mass balance of Gangotri glacier during 2016–2023 was analyzed using a velocity and shear stress-based framework. A laminar flow-based approach is applied to determine the ice thickness of the Gangotri Glacier, while glacier surface velocity was estimated from Sentinel-2 multispectral imagery using three independent feature-tracking methods."

27 – 29: Leave the specific numbers on thinning out of the abstract and mention only the interpretation of these numbers and the final mass wastage

Thank you for the comment. We have revised the sentences as follows.

"The analysis revealed a pronounced spatial variability in glacier flow and ice thickness, with faster movement and greater ice depth in the accumulation and upper ablation zone that gradually diminished toward the snout. The Gangotri Glacier exhibited a consistent thinning trend and negative mass balance, reflecting significant ice loss during the study period."

31: leave out the sentence with the volume number

We thank the reviewer for their remarks. We have now removed the sentence as suggested.

Introduction:

43: What is HKH?

Thank you for your observation. The abbreviation HKH refers to the Hindu Kush Himalaya, which has now been added. The sentences now read as follows.

"The Hindu Kush Himalaya (HKH), also referred to as the "Water Tower of Asia," are home to one of the largest mountain glacier networks on Earth (Bolch et al., 2012). The HKH region hosts a total of 54,252 glaciers covering approximately 60,054 km² and holding an estimated ice reserve of 6,127 km3 (Bajracharya et al., 2015)."

45: What is meant by largely significant?

We thank the reviewer for the observation. The phrase has now been omitted for clarity, and a new sentence has been added as follows.

"The HKH region is the source of 10 major river basins — the Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, Yellow, Amu Darya, and Tarim — making it one of the most important water resource of the world. Among these, the Indus, Ganga, and Brahmaputra basins together contain the majority of the region's glacierized area (Mukherji et al., 2015; Singh et al., 2025)."

52: What is meant by when? Is it the glaciers that are not covered in debris so: Particularly those glaciers that are not covered…

We have revised the sentence as follows.

"Glaciers that are entirely situated below 5700 m elevation are mostly sensitive to climate change, particularly those glaciers that are free from thick debris cover and are directly exposed to atmospheric conditions (Bajracharya et al., 2015)."

63 – 64: does ice velocity provide any insights into retreat or advance of glaciers in general?

We thank the reviewer for pointing this out. We have revised the sentence as follows.

"It provides insights into glacier movement patterns and indirectly glacier mass change (Herman et al., 2011)."

In general, the ice velocity provides valuable insights into glacier dynamics. Increased velocities may indicate mass gain and possible glacier advance, whereas decreasing velocity may reflect mass loss and glacier retreat (Herman et al., 2011). However, understandably, glacier behaviour is influenced by a complex interplay of climatic, geological, topographical and environmental factors (Dobreva et al., 2017; Nagai et al., 2014).

64: I don't think it is correct to say that velocity provides any predicting factor for GLOFs. As far as I understand the reference, it is surging that poses an increased risk of GLOFs.

We thank you for your insightful observation. We agree, Glacier velocity itself does not directly predict GLOF occurrence. Instead, surging glaciers, which exhibit episodic increases in velocity, can destabilize ice-dammed or moraine-dammed lakes and thereby increase the risk of GLOFs. We have revised the sentence as follows.

"In the case of surging glaciers (velocity spiking glacier), glacier velocity can highlight periods of increased instability which connected with a dammed lake may potentially increase GLOF risk. (Bhambri et al., 2020; Scherler et al., 2011)."

88-89: "It has been generally observed…" By whom?

We thank the reviewer for their comment. We were referring to Sinha et al. 2024. However, we have revised this paragraph (for lines 85-117 in original submission) following also the comments by Reviewer-1 as follows.

"The collection of in situ observations using intrusive or extrusive methods, such as hot water drilling, seismic or radar measurements, and gravimetry, poses significant challenges on glaciers with rugged terrain and are often impractical for complete glacier surfaces (Murray et al., 2007). Some glaciers are often inaccessible or have restricted access due to their geopolitical sensitivity rendering no potential opportunities for on-site data collection (Ambinakudige, 2010). As a result, remote sensing-based techniques are widely employed. Models using digital elevation model (DEM) data, glacier boundary, and boundary of ice-flow catchments—such as the mass conservation approach by (Farinotti et al., 2009; Huss & Farinotti, 2012)—have become particularly prominent for estimation of glacier ice thickness. Other methods are based on surface slope , velocity and basal shear stress (Bhushan et al., 2017; Gantayat et al., 2014, 2017; Linsbauer et al., 2012; Michel et al., 2013; Zorzut et al., 2020). An extension of the ice-velocity based approach based on SIA (VWDV) was proposed by (Van Wyk De Vries et al., 2022), which showed significant glacier ice-thickness estimates compared with in-situ measurements. Sinha et al., (2024) proposed an ensemble modelling approach to account for overestimation and underestimation of different ice-thickness inversion models. In practical applications, these modelling techniques effectively determine ice thickness for most glaciers, though they tend to exhibit greater uncertainties when applied to small glaciers unlike the Gangotri glacier with gentle topography (Linsbauer et al., 2012; Rabatel et al., 2018)."

107: What is meant by "less"?

We thank the reviewer; we have removed the sentence following the comments by Reviewer-1.

121: With theoretical knowledge – do you perhaps actually mean observations?

We thank you for your for pointing out this mistake. The purpose of the sentence was to highlight the intercomparison of velocity and shear stress based ice-thickness estimates. However, in the absence of field data it is not exactly possible. Hence, we have removed this phrase. The sentences now read as follows.

"This study aims to conduct a comprehensive investigation on understanding the ice-thickness and mass balance changes of the Gangotri glacier through a comparative integration of model-based analysis with remote sensing data. **The ice-thickness is modelled using both velocity and shear stress-based approaches.** We have also investigated the annual ice-thinning rates compared with the geodetic method and their implications in retrieving the equivalent water volume variations."

128-137: It is a good idea to have an overview of the study aims, they are just not easy to understand

We thank you for your suggestion. We have revised the study aims to improve clarity and readability as follows.

"In summary, the current study aims to perform:

1) an intercomparison of different glacier surface velocity determination methods using time-series Sentinel-2 imagery;
2) a comparison of the ice-velocity and basal shear stress-based ice-thickness estimates;
3) estimation of the glacier ice thinning rate based on the annual ice thickness changes;
4) estimation of the mass balance and the equivalent water volume changes of the Gangotri glacier using annual ice thinning data for the study period 2016-2023;
5) an assessment of the influence of different climatic parameters such as precipitation, runoff, snowfall, etc. on glacier thinning and surface mass balance."

Study area and data

158: You should cite Sentinel data properly.

Cited in the revised text as follows

"The datasets used in this study primarily include remote sensing satellite optical imagery, particularly Sentinel-2 (European Space Agency, 2018) RGB and Near-Infrared band imagery (2016 – 2023) with a spatial resolution of 10 meters, which was essential for estimating glacier velocity and capturing temporal trends in glacier motion."

176: Describe why are you using ITS LIVE data at 120m resolution, when you have your own velocity maps from this study and what is velocity model output?

We thank you for the comment. We used the ITS LIVE data for independent comparison and considering that it is derived from a combination of optical and SAR remote sensing, where the latter is unaffected by cloud cover. We have revised as follows.

"ITS LIVE velocity data (Gardner et al., 2022), with a resolution of 120 meters, was employed to enable a comparative assessment with the ice velocity datasets derived in this study. This comparison provides an independent reference to evaluate the consistency of the estimated velocities, helping to identify potential deviations , while the widely used ice thickness dataset by Farinotti et al., (2019), with a 50-meter resolution, was used for comparative analysis with thickness model outputs. The ITS LIVE velocity data is based on an integrated combination of optical and SAR remote sensing data, where the latter provides gap-free all weather capabilities for velocity estimation, the drawback of the integration, however, is the reduced spatial resolution of 120 m."

204-205: This subsection is not about the ice velocity mapping

We thank the reviewer for pointing this out. We have merged section 3.1 and 3.2 as single section 3.1. glacier velocity estimation (provided in response to your comments under **Main Concerns**). Approximately, the entire section has been revised.

242: I don't understand what is meant by comprehensive. How many IV maps do you end up with? Only 1 per year? And have you considered variability in flow from year to year?

We thank the reviewer for pointing out these issues. We have revised the section as mentioned earlier. For the 8 years (2016-23), we generate annual velocity maps. The objective of the ice-velocity estimation was to gather the needed inputs for velocity based inversion of ice thickness hence, we have not considered the variability in glacier surface velocity for discussion, and focus on the mean velocity for further analysis. However, our discussion now focuses on the spatial variability of the surface velocity in different glacier zones (provided in response to your comments under **Main Concerns**).

Section 3.2: It is unclear to me what the purpose of applying these three different velocity mapping methods is.

We thank the reviewer for their comment. The three methods are used for intercomparison, where all three use different feature tracking approaches. Further details of the methods are given in the revised section 3.2. glacier velocity estimation (provided in response to your comments under **Main Concerns**).

234: Here the term sub-pixel estimator is used but not explained, only with a reference to the same study that we know the whole approach is based on. Please explain what is meant, this is also the case in line 236 and 240.

We thank the reviewer for notifying this. The sub-pixel estimator refers to correlation at sub-pixel level leading to improved displacement accuracy and provides robust sub-pixel correlation and error minimization procedures for glacier motion detection by optical imageries. We have revised the sentence as follows to improve clarity (Van Wyk De Vries & Wickert, 2021).

"Signal to noise ratio lower than 5 and peak ratio less than 1.3 were considered during multi-pass template matching with sub-pixel estimator (a correlation refinement technique used to improve the accuracy of displacement measurements beyond the spatial resolution of the input imagery) (Van Wyk De Vries & Wickert, 2021)."

244: It is difficult to understand what this paragraph is going to be about. Please add a sentence to explain what is coming.

We thank the reviewer for pointing this out. We have revised the entire section for improved readability and clarity (provided in response to your comments under **Main Concerns**).

Paragraph 251 to 264: You state just above that algorithms are explained in the reference, and then you add this whole paragraph explaining part of it. It is unclear what the purpose if this is?

We thank the reviewer for pointing this out. We have revised the entire section for improved readability and clarity (provided in response to your comments under **Main Concerns**).

3.3 Glacier ice thickness estimation

Please add a paragraph and references to why the SIA approach is suitable for this.

We thank the reviewer for pointing this out. We have revised the entire section for improved readability and clarity (provided in response to your comments under **Description of Methods and Data**).

300: What is meant by corresponds?

We thank the reviewer for pointing this out. It should have been "refers to". We have revised the entire section for improved readability and clarity (provided in response to your comments under **Description of Methods and Data**).

228-2029: I don't understand what is meant by this sentence. Is it a reference to the velocity maps described earlier?

We thank the reviewer for pointing this out. Feature tracking algorithms use multi-date satellite images for determining surface displacement (referred to as velocity). As per the GIV algorithm a minimum of 9 day gap and a maximum of 1 year (365 days) comprise the boundary conditions for the algorithm to estimate displacements. Cosi-Corr and ImGRAFT use only bi-temporal images, and hence for them we use images at a year difference. To avoid snow, typically, images are only considered between July-October, where often fewer images are available. Hence, the comparison with ITS LIVE also becomes critical, which is considered as a robust velocity product in the scientific community.

We have revised the entire section for improved readability and clarity (provided in response to your comments under **Main Concerns**).

334-336: I don't understand what is meant here at all.

We thank the reviewer for pointing this out. We have revised the entire section for improved readability and clarity (provided in response to your comments under **Description of Methods and Data**).

357: Use proper data citation

Cited as (OpenTopography, 2013).

383: cite Landsat correctly (Should probably be mentioned in the data section)

We thank the reviewer for pointing this out. The datasets section is revised as follows.

"**2.2. Datasets**

The datasets used in this study primarily include remote sensing satellite optical imagery, particularly Sentinel-2 (European Space Agency, 2018) RGB and Near-Infrared band imagery (2016 – 2023) with a spatial resolution of 10 meters, which was essential for estimating glacier velocity and capturing temporal trends in glacier motion. To derive the glacier surface slope, we used the Cartosat digital elevation model (DEM) v3 from 2018, with a 30-meter spatial resolution. This DEM product provides relatively better elevation accuracy, making it suitable for glacier slope and ice thickness modelling during the 2016–2023 study period (Talchabhadel et al., 2021). The SRTM DEM used in this study (data year 2000), with a spatial resolution of 30 meters, was derived from C-band radar interferometry data and has an accuracy of ±16 meters (Farr et al., 2007). The vertical accuracy of SRTM DEM varies significantly depending on terrain. Rodríguez et al., (2006) reported a general vertical error of less than 9 meters for the SRTM DEM in mountainous regions. Kolecka & Kozak, (2014) observed a mean vertical error of 4.31 meters, and root mean square error (RMSE) of ±14.09 meters in mountainous terrain. The Copernicus DEM which is based on the TanDEM-X mission data, with a spatial resolution of 30 meters and an absolute vertical accuracy better than 4 meters (90% linear error) was used for year 2015 (European Space Agency & Airbus, 2022). The Copernicus DEM was used in combination with the SRTM DEM (data year 2000) to assess surface elevation changes between 2000-2015 over the Gangotri Glacier after penetration depth correction based on Landsat-7 satellite images with normalized difference snow index (NDSI) (Millan et al., 2015; Purinton & Bookhagen, 2018; Carturan et al., 2020; Guillet & Bolch, 2023). The selection of the Copernicus DEM and the SRTM DEM stems from the fact that both these are technically DSMs generated from radar remote sensing data, as compared to the Cartosat DEM which is generated from stereo-optical imagery.

The Gangotri glacier boundary was derived from the RGI 6.0 dataset (RGI Consortium, 2017) and subsequently refined using high-resolution satellite imagery in Google Earth Pro. On-screen digitization during snow-free periods allowed for accurate updates of the terminus and lateral boundaries, especially where RGI 6.0 outlines were inconsistent compared with recent imagery. ITS LIVE velocity data (Gardner et al., 2022), with a resolution of 120 meters, was employed to enable a comparative assessment with the ice velocity datasets derived in this study. This comparison provides an independent reference to evaluate the consistency of the estimated velocities, helping to identify potential deviations , while the widely used ice thickness dataset by Farinotti et al., (2019), with a 50-meter resolution, was used for comparative analysis with thickness model outputs. The ITS LIVE velocity data is based on an integrated combination of optical and SAR remote sensing data, where the latter provides gap-free all weather capabilities for velocity estimation, the drawback of the integration, however, is the reduced spatial resolution of 120 m.

To assess the climatic and environmental variability influencing the Gangotri Glacier, multiple datasets were utilized. MODIS (Yu et al., 2022) Land Surface Temperature (LST) data (MOD11A1) from 2016 to 2023, at a 500-meter resolution from Aqua and Terra satellites, was applied to derive ice surface temperature (IST). The MODIS MCD43A3 dataset provided surface albedo estimates essential for analysing the apparent thermal inertia (ATI) of the glacier ice surface. TerraClimate data was employed to examine maximum temperature, precipitation, and runoff trends across the glacier basin. ERA5-Land reanalysis data supplied estimates of snowfall parameter. The MODIS MCD19A2 product was used for aerosol optical depth (AOD) analysis, contributing to the assessment of radiative forcing impacts. Further, the Global Annual Weighted PM2.5 dataset (GWRPM25) was used to evaluate long-term atmospheric pollution trends over the region and their potential effects on glacier melt dynamics. The MODIS products have been widely used in the literature for climatic investigations in mountainous regions (Hassan et al., 2023; Thanveer et al., 2024; Varade et al., 2023; Varade & Dikshit, 2020). Table 1. summarizes the various datasets used in this study for modelling, comparative assessment and complementary analysis.

Table 1. Satellite and other ancillary data used in this study.

Data	Time period	Spatial Resolution	Purpose	Source
Sentinel – 2	2016 - 2023	10 m	Glacier velocity estimation	(European Space Agency, 2018)
Cartosat – 1 DEM	2018	30 m	Slope and thickness estimation	(Muralikrishnan et al., 2013)
SRTM DEM	2000	30 m	DEM differencing	(OpenTopography, 2013)

Copernicus DEM	2015	30 m	DEM differencing	(European Space Agency & Airbus, 2022)
RGI 6.0	2017		Glacier ice masking	(RGI Consortium, 2017)
MODIS LST (MOD11A1) (Aqua and Terra dataset)	2016 - 2023	500 m	Derived ice surface temperature	(Yu et al., 2022)
ITS_LIVE	2016 - 2023	120 m	Correlation with velocity model output	(Gardner et al., 2022)
Global Ice Thickness Dataset	2019	50 m	Correlation with thickness model output	(Farinotti et al., 2019)
Google Earth Pro			Glacier outline modification	-
Landsat – 7 and 8	2000 and 2022	30 m	NDSI for snow cover delineation and IST determination for validation of MODIS derived LST	(Earth Resources Observation and Science (EROS) Center, 2013)
MODIS (MCD43A3)	2000 - 2023	500 m	Ice Surface Albedo	(Schaaf & Wang, 2021)
TerraClimate	2000 - 2023	4.56 km	Max. temperature, Precipitation, Runoff	(Abatzoglou et al., 2018)
ERA 5 Land	2000 - 2023	9 km	Snowfall estimation	(C3S, 2018)
MCD19A2	2000 - 2024	500 m	Aerosol Optical Depth (AOD) estimation	(Lyapustin & Wang, 2018)
GWRPM25	1998 - 2021	1.13 km	PM 2.5 trend analysis	(Van Donkelaar et al., 2021)

388: What is meant by each period?

Thank you for your observation. The phrase “each period” referred to the different years between 2016 and 2023. However, to avoid confusion, we have omitted this phrase from the revised manuscript for clarity.

“This study employed two approaches to estimate the glacier ice volume. The first method calculates the volume by multiplying the glacier area by its estimated ice thickness for 2016 - 2023, as expressed in Equation 11.

$$V_i = H.A_g \qquad (11)$$

where V_i is the glacier ice volume, H is Monte-Carlo-derived mean ice thickness, as described by van Wyk de Vries et al. (2022), and A_g denotes area of the glacier.”

472: I think some considerations on what seasons the velocity data covers might be appropriate here. Maybe the difference is not due to different methods, but simply different timing or inability to get velocities over certain time periods.

Thank you for your observation. As already mentioned that in one of the previous responses, the duration for acquiring images for velocity estimation is from July-Oct. GIV requires multiple images (minimum 4) for velocity retrieval while Cosi-Corr and ImGRAFT require minimum 2 images. From the image dataset for GIV, we supplied the images at a year gap to the other two methods.

523: I don't think we need abbreviations for left/right hand side.

Removed as suggested.

541: I don't think I have read anywhere anything about density considerations.

We thank the reviewer for pointing this out. We have now illustrated the computation of mass balance in the Methodology section (details provided in response to similar comment in **Study Area and Data**)

694-695: Volume estimates from other studies need to be discussed in the relation to this study's estimate – here it is only area mentioned?

Thank you for your observation we have revised the text and indicated the glacier ice volume with area during the study period 2016 - 2023.

"The Gangotri glacier ice volume was estimated by Gantayat et al. (2014) using velocity-based determined thickness of 23.4 ± 4.2 km³ in 2009 and 2010. Haq et al. (2014) estimated the ice volume using artificial neural networks (ANN) and perfect plasticity to be 21.559 km³. Fig. 8 illustrates the time-series volumetric changes in Gangotri ice volume (pixel area × depth) and the corresponding equivalent water volume of the Gangotri Glacier from 2016 to 2023. **In the present study, the Gangotri Glacier area, delineated from the updated glacier boundaries, was determined to be 141.9 km², with a mean ice volume of 19.70 ± 2.64 km³ for the period 2016–2023. This estimate shows good agreement with the values reported in earlier studies, reflecting consistency in the glacier's overall volumetric characteristics despite methodological differences and temporal variations.**"

Table 4: It is quite important to state what period the volume estimate is based on in this table. Then it becomes clear that volume has decreased since the first observation maybe?

Thank you for your valuable suggestion. We have revised the table captions as follows.

"Table 4. Comparison of the Gangotri Glacier ice volume and estimated mean thickness as reported by Frey et al., (2014) for the period 2000–2010, and as obtained in the present study 2016–2023."

724-727: you have the observations to explain this if you want. At least you could say something about which zone the thinning was more severe.

Thank you for your insightful observation. In section 5.3. we have described the zonal characteristics in terms of thinning and equivalent water volume change. Here, we have added a sentence as follows.

"As described in section 5.3., the particularly dominant thinning in the ablation zone may also be assessed as increased equivalent water loss in this zone. In contrast, in the accumulation zones particularly in the tributary glaciers, there is an increase in the equivalent water volume."

729-731. so, what you are basically saying is that the mass wastage rate has been the same since 1985 to present?

Thank you for your insightful comment.

While the comparison shows similar magnitudes of mass wastage from 1985 to the present, we do not imply that the rate has remained constant over time. The consistency in the average values primarily reflects the long-term negative mass balance trend of the Gangotri Glacier under persistent climatic forcing. However, short-term variations in melt intensity, accumulation, and climatic conditions likely exist between different study periods. We have revised the manuscript to clarify that the apparent similarity indicates a sustained pattern of glacier mass loss rather than a constant rate through time.

The following lines have been added and revised to the end of this section

"These comparisons collectively indicate a persistent negative mass balance trend in the region over the past several decades, although short-term variability in melt intensity and climatic forcing likely occurred between different study periods. The overall consistency in long-term averages highlights sustained glacier mass loss rather than a uniform rate through time. Details of these comparisons are provided in Section 2 of the supplementary material (Table S4)."

Data availability:

It would be of great interest to the community if also the datasets produced in this study were published.

We thank the reviewer for their remarks. In the next phase of the peer review process, we will provide the georeferenced raster maps through open source repositories like Zenodo.

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