Calculation Methods and Development Trends of Glacier Ice Storage Postprint

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Date: 2018-11-13T00:00:00+00:00

Abstract

Glacier ice volume constitutes not only a crucial attribute of glaciers, but also fundamental data for assessing glacier water resources and predicting glacier changes. Consequently, accurate calculation of glacier ice volume and its variations holds significant theoretical and practical importance. Currently, primary methods for glacier volume estimation include the empirical formula method, ice thickness modeling method, and ground-penetrating radar method; approaches for calculating relative changes in glacier volume comprise the field measurement method and the remote sensing monitoring method. This paper systematically analyzes and discusses the principles, current status, and existing challenges of each methodology, aiming to provide methodological references for glacier volume estimation. Research demonstrates that for glacier ice volume calculation, the empirical formula method is applicable to regional or global-scale glacier volume estimation; the modeling method is suitable for individual or small-scale glacier volume estimation; and the ground-penetrating radar method is appropriate for glacier volume estimation in readily accessible areas. Regarding the calculation of relative changes in glacier ice volume, the field measurement method is suitable for individual or medium-to-small sized glaciers requiring high precision and meeting fieldwork conditions, while the remote sensing monitoring method is applicable to global ice volume change estimation, though it necessitates algorithmic improvements and enhanced spatial resolution of data. Presently, the gradual application of unmanned aerial vehicle technology and the development of theoretical models such as glacier flow velocity provide new opportunities for advancing glacier ice volume estimation methodologies.

Full Text

A Review of Glacier Volume Calculation Methods

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Abstract: Glacier volume is not only a crucial glacier property but also foundational data for computing glacial water resources and predicting glacial change. Therefore, it is of vital theoretical and practical significance to accurately compute glacier volume and variation. In this paper, we analyze and discuss the principles, developments, and problems of existing methods in order to provide reference for the estimation of glacier volume. At present, major methods of estimating glacier volume include volume-area empirical formula method, ice thickness estimation models, and GPR, while computational methods to estimate relative change of glacier volume include mainly field measurement, estimation method based on remotely sensed data, and gravimetric method. The volume-area empirical formula method is used to estimate regional or global glacier volumes simply and fleetly; the method of ice thickness estimation models is suitable to estimate single or small-scale glacier volume and does not need the input of measured data. GPR is applied to estimate glacier volume where human beings can reach easily. Field measurement with the most accurate result fits to estimate glacier volume change specifically for single glacier as well as small or medium-sized glaciers that require high accuracy and meet the conditions of field measurement. The method based on remotely sensed data is applicable to estimate glacier volume change globally, so it needs to improve the algorithm and enhance the spatial resolution of the data. GRACE has the characteristic of wide coverage but has low spatial resolution, so it is necessary to modify the spherical harmonic domain and spatial domain and improve the spatial resolution when applied to small regional glaciers. With the emergence of new technology and theory, multi-disciplinary fusion provides new opportunities for the improvement of the estimation accuracy of glacier volume. The development of estimation models and continuous supplement of the glacier inventory data offer new chances and data support for estimation of glacier volume.

Keywords: glacier; glacier volume; glacier thickness; mass balance; calculation method

1. Introduction

Glacier volume represents one of the most fundamental parameters in glaciology, serving as essential input for assessing water resources, sea-level rise contributions, and climate change impacts. Accurate estimation of glacier volume and its temporal variations remains a critical challenge in cryospheric research. This paper systematically reviews existing methodologies for glacier volume calculation, analyzing their theoretical foundations, practical applications, and limitations to provide guidance for future research.

2. Volume-Area Empirical Relationships

2.1 Global and Regional Scaling Laws

The volume-area scaling approach provides a straightforward method for estimating glacier volume based on the empirical relationship:

$$V = k \cdot A^{\gamma}$$

where V represents glacier volume (km^3), A is glacier area (km^2), and k and γ are region-specific coefficients. Table 1 summarizes commonly used empirical formulas for different regions.

Table 1. Empirical formulas for ice volume estimation in different regions

Region	Formula	Source
Svalbard	$V = 0.027 \cdot A^{1.5}$	Erasov [9]
Svalbard	$V = 0.0361 \cdot A^{1.406}$	Shi et al. [10]
Svalbard	$V = 0.0597 \cdot A^{1.12}$	Macheret and Zhuravlev [11]
Svalbard	$V = 0.04 \cdot A^{1.25}$	Chizhov and Kotlyakov [12]
Svalbard	$V = 0.0371 \cdot A^{1.357}$	Macheret et al. [13]
Svalbard	$V = 0.03 \cdot A^{1.36}$	Zhuravlev [14]
Svalbard	$V = 0.0218 \cdot A^{1.124}$	Driedger and Kennard [15]
Svalbard	$V = 0.048 \cdot A^{1.186}$	Zhuravlev [16]
Svalbard	$V = 0.0298 \cdot A^{1.379}$	Macheret et al. [17]
Alps	$V = 0.0285 \cdot A^{1.357}$	Chen and Ohmura [18]
Global	$V = k \cdot A^{1.36}$	Meier and Bahr [19]
Global	$V = k \cdot A^{1.375}$	Bahr [20]
Global	$V = 0.0276 \cdot A^{1.36}$	Bahr et al. [21]
Global	$V = 0.0213 \cdot A^{1.375}$	Van de Wal and Wild [22]
Global	$V = 0.04 \cdot A^{1.35}$	Liu et al. [23]
Global	$V = k \cdot A^{[1.56-2.90]}$	Radic et al. [24]
Global	$V = 0.0365 \cdot A^{1.375}$	Radic and Hock [25]
Global	$V = [0.024-0.042] \cdot A^{[1.26-1.355]}$	Huss and Farinotti [2]
Global	$V = k \cdot A^{[1.38-1.46]}$	Adhikari and Marshall [26]
Global	$V = k \cdot A^{1.26}$	-

Region	Formula	Source
Global	$V = k \cdot A^{1.22}$	-
Global	$V = k \cdot A^{1.25}$	-
Global	$V = 0.0538 \cdot A^{1.25}$	-

Note: V *= ice volume (km*^{3}*);* A *= glacier area (km*^{2}*);* k *= scaling coefficient*

2.2 Ice Thickness Empirical Formulas

Ice thickness can be estimated through empirical relationships with glacier area, as shown in Table 2.

Table 2. Empirical formulas for ice thickness estimation in different regions

Region	Formula	Source
-	$H = -11.32 + 53.21A^{0.3}$	-
-	$H = 5.2 + 15.4A^{0.5}$	Chen [18]
-	$H = 34.4A^{0.45}$	[28]

Note: H *= ice thickness (m);* A *= glacier area (km*^{2}*)*

3. Ice Thickness Estimation Models

3.1 Model Classification

Various physical and empirical models have been developed to estimate glacier ice thickness distribution. These models typically require input data including surface topography, mass balance, and surface velocity. Table 3 presents a comprehensive list of current ice thickness models.

Table 3. Models for ice thickness estimation

Model Name	Input Data	Key Features
Macherth (GlabTop2) [7]	DEM, SMB	Physical-based
Linsbauer (GlabTop) [35]	DEM	Semi-empirical
RAAJ glabtop2 [27]	DEM, SMB	Physical-based
Farinotti (ITEM) [36]	DEM, SMB, Velocity	Inverse method
GC bedstress [37]	DEM, Mass balance	Stress-based
Maussion (OGGM) [38]	DEM, SMB	Flowline model
Huss (HF-model) [2]	DEM, SMB	Simplified physics
Morlighem [39]	DEM, SMB, Velocity	Mass conservation
Van Pelt Leclercq [40]	DEM, SMB	Inverse method
Brinkerhoff-v2 [41]	DEM, SMB	Higher-order physics
Fuerst [42]	DEM, SMB	Ice flow model

Model Name	Input Data	Key Features
Rabate1 [27]	DEM	Empirical
Gantayat [43]	DEM, SMB, Velocity	Inverse method
Gantayat-v2 [28]	DEM, SMB, Velocity	Improved inverse
RAAJ gantayat [27]	DEM, SMB	Modified empirical
Brinkerhoff [44]	DEM, SMB	Bayesian inference
GC neuralnet [45]	DEM, SMB	Machine learning

Note: DEM = Digital Elevation Model; SMB = Surface Mass Balance; Velocity = surface velocity

3.2 Model Principles

Most ice thickness estimation models are based on the principle of ice flow dynamics. The fundamental relationship derives from Glen’ s flow law [34], where ice deformation rate is proportional to the stress exponent:

$$\dot{\epsilon} = A\tau^n$$

where $\dot{\epsilon}$ is the strain rate, τ is the basal shear stress, A is the temperature-dependent rate factor, and n is the flow law exponent (typically ~3).

The basal shear stress can be estimated from surface slope and ice thickness:

$$\tau = f\rho g \sin(\alpha)$$

where f is the shape factor, ρ is ice density, g is gravitational acceleration, and α is the surface slope.

For steady-state conditions, the mass conservation equation relates ice thickness change to flux divergence:

$$\frac{\partial h}{\partial t} = \dot{b} - \nabla \cdot (\mathbf{u}h)$$

where h is ice thickness, $\dot{b}$ is mass balance, and $\mathbf{u}$ is velocity vector.

3.3 Ground-Penetrating Radar (GPR) Method

GPR provides direct measurements of ice thickness by emitting electromagnetic pulses and recording reflections from the ice-bedrock interface. The two-way travel time Δt of radar waves relates to ice thickness h through:

$$h = \frac{v \cdot \Delta t}{2}$$

where v is the electromagnetic wave velocity in ice (~0.168 m/ns). GPR surveys are typically conducted along longitudinal and transverse profiles, with interpolation methods used to construct three-dimensional bed topography.

4. Volume Change Estimation Methods

4.1 Field Measurement Approach

Field measurements provide the most accurate estimates of glacier volume change through repeated topographic surveys using differential GPS, total stations, or laser scanning. The geodetic method calculates volume change ΔV from elevation change Δz over area A:

$$\Delta V = \int_A \Delta z \, dA$$

This approach is suitable for small to medium-sized glaciers where high accuracy is required and field access is feasible.

4.2 Remote Sensing Methods

4.2.1 DEM Differencing Digital Elevation Models (DEMs) derived from satellite or aerial imagery enable regional-scale volume change estimation. The accuracy depends on DEM resolution and co-registration precision. Modern approaches combine multiple DEM sources (e.g., SRTM, ASTER, SPOT) to reduce uncertainties.

4.2.2 Altimetry Data ICESat and ICESat-2 laser altimetry data provide precise elevation measurements along orbital tracks. Volume changes are calculated by interpolating elevation differences between time periods:

$$\Delta V = \sum_{i=1}^{n} \Delta h_i \cdot A_i$$

where Δh_i is the mean elevation change in cell i and A_i is the cell area.

4.2.3 Gravimetric Method The GRACE (Gravity Recovery and Climate Experiment) mission measures temporal variations in Earth' s gravity field, which can be converted to mass changes. The spherical harmonic coefficients are used to estimate glacier mass balance:

$$\Delta M = \iint_{\text{region}} \Delta g \, dS$$

where ΔM is mass change and Δg is gravity anomaly. However, GRACE' s coarse spatial resolution (~300 km) limits its application to small glacierized regions.

4.3 Multi-Source Data Fusion

Combining multiple methods can improve accuracy. For example: - Integrating GPR measurements with ice flow models through data assimilation - Combining DEM differencing with mass balance models - Using machine learning algorithms to merge satellite observations with field data

5. Discussion and Future Directions

Current methods exhibit varying degrees of uncertainty. Empirical formulas provide quick estimates but lack physical basis and regional specificity. Ice thickness models require careful parameterization and validation. GPR offers high accuracy but limited spatial coverage. Remote sensing methods enable broad coverage but depend on data resolution and algorithm development.

Future improvements should focus on: 1. **Enhanced model physics**: Incorporating higher-order stress components and transient dynamics 2. **Data integration**: Multi-sensor fusion combining GPR, remote sensing, and field measurements 3. **Machine learning**: Neural networks trained on measured data to improve thickness estimates 4. **Uncertainty quantification**: Bayesian approaches for probabilistic volume estimates 5. **High-resolution data**: Utilizing emerging satellite missions (e.g., NISAR, CRISTAL)

The continuous update of glacier inventories and advancement of computational methods provide new opportunities for improving volume estimation accuracy. Multi-disciplinary integration represents the most promising path forward.

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