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Water Resources Research

RESEARCH ARTICLE

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Key Points:

- Globally 53%–71% of snowmelt runs off, while 29%–47% contributes to evaporation
- Snowmelt partitioning exhibits distinct latitudinal, elevational, and climatic patterns
- Our findings redefine snowmelt as a key eco-hydrological resource, vital for both freshwater supply and ecosystem demands

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Fate of Snowmelt: Global Partitioning Into Runoff and Evaporation

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Abstract Snowmelt is a critical component of the global water cycle and a vital freshwater source for both ecosystems and human societies. Yet the global partitioning of snowmelt into runoff and evaporation remains poorly quantified. Here, using a process-based hydrological model (FLEX-Global) forced by meteorological data from 1980 to 2014 and validated against observed streamflow and snow water equivalent, we present a comprehensive assessment of global snowmelt partitioning. The model results are independently supported by two additional approaches: an empirical partitioning equation and inverse estimations from three global hydrological models. We show that 53%–71% of snowmelt runs off globally (excluding Antarctica and Greenland), while 29%–47% contributes to evaporation. Snowmelt partitioning exhibits distinct latitudinal and climatic patterns: contributions of snowmelt to both runoff and evaporation increase with latitude. In cold–humid high-latitude regions, more than 60% of snowmelt becomes runoff, whereas in mid-latitude arid regions, 63%–91% is released from the terrestrial ecosystems as evaporation. Elevation further modulates snow hydrology in mid-latitude mountains, where snowmelt generates 58%–74% of total runoff and 51%–66% of total evaporation—significantly higher than contributions at lower elevations. The traditional definition of snowmelt runoff (snowfall/total runoff) estimates that snowfall accounts for 38% of total runoff, whereas our snowmelt-partitioning approach (snowmelt runoff/total runoff) yields a much lower contribution of 11%–18%. Our results underscore snowmelt's dual role in sustaining freshwater availability and supporting vegetation water demand, redefining its importance in the global hydrological cycle and associated ecosystem services.

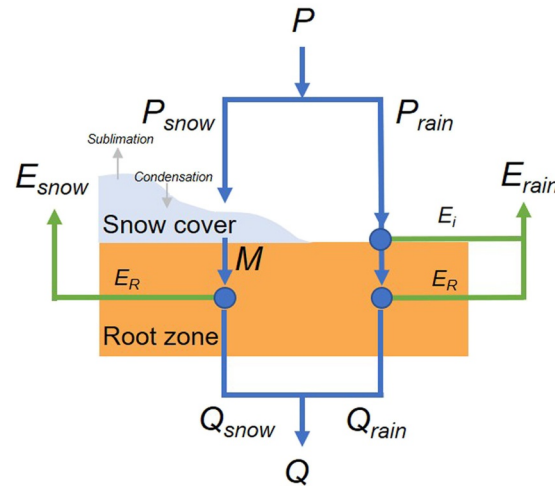
1. Introduction

The fate of precipitation in terrestrial ecosystems is dictated by a fundamental hydrological dichotomy. It is either directly or via aquifers released into rivers, leaving the system as runoff, or it feeds back into the atmosphere as evaporation. Here, we use the term “evaporation” throughout this paper to represent all the different types of evaporative fluxes (e.g., interception, sublimation, soil evaporation, and transpiration) (Miralles et al., 2020; Savenije, 2004). Previous studies suggest that about 60% of precipitation is used by terrestrial ecosystems through evaporation, while the remaining 40% provides water resources for human societies and freshwater aquatic ecosystems (Abbott et al., 2019; Dorigo et al., 2021; Gao et al., 2023).

Precipitation ($111 \times 10^3 \text{ km}^3/\text{y}$) consists of rainfall and snowfall, with snowfall accounting for about 11% ($12.5 \times 10^3 \text{ km}^3/\text{y}$) of the global total (Oki & Kanae, 2006). Unlike rainfall, snow acts as a natural reservoir, storing as snowpack during autumn and winter (Beria et al., 2018), and releasing it gradually during spring and summer either as water supply to satisfy root zone deficit and transpired by vegetation through root water uptake or as runoff generation (Li et al., 2017; Marshall et al., 1994). Runoff from snowmelt is a vital component of global streamflow, sustaining over a billion people worldwide who rely on snowpack and glacier meltwater (Barnett et al., 2005; Mankin et al., 2015; Qin et al., 2020). Beyond its hydrological impacts, snowmelt also plays crucial ecological roles as part of a coupled snow–vegetation–hydrology system with multiple linkages and feedbacks (Yang & Kane, 2021). Studies have shown that snowmelt can alleviate plant water stress before the onset of summer rainfall, thereby enhancing vegetation productivity (Harpold et al., 2014; Hu et al., 2013; Zhu et al., 2022). Thus, snowmelt is a key driver of root zone soil moisture availability and significantly influences terrestrial evaporation processes, highlighting its importance for ecosystem health and stability (Blankinship & Hart, 2012; Stewart, 2009; Vavrus, 2007; Wu et al., 2015).

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Traditional definition

$$f_{SR_old} = \frac{P_{snow}}{Q} = \frac{P_{snow}}{Q_{snow} + Q_{rain}} \quad (1)$$

New definitions

$$f_{SR} = \frac{Q_{snow}}{M} = \frac{Q_{snow}}{Q_{snow} + E_{snow}} \quad (2)$$

$$f_{SE} = \frac{E_{snow}}{M} = \frac{E_{snow}}{Q_{snow} + E_{snow}} \quad (3)$$

$$f_{Q_{snow}} = \frac{Q_{snow}}{Q} = \frac{Q_{snow}}{Q_{snow} + Q_{rain}} \quad (4)$$

$$f_{E_{snow}} = \frac{E_{snow}}{E} = \frac{E_{snow}}{E_{snow} + E_{rain}} \quad (5)$$

Figure 1. Conceptual diagram of the partition of snowfall and rainfall into runoff and evaporation. P , P_{snow} , P_{rain} , M , E_{snow} , E_i , E_R , E_{rain} , Q_{snow} , Q_{rain} , and Q represents precipitation, snowfall, rainfall, snowmelt, evaporation after snowmelt, rainfall interception, root zone evaporation, total evaporation after rainfall, snowmelt generated runoff, rainfall generated runoff, and the total runoff, respectively. Q_{snow} and Q_{rain} represent all liquid water that is infiltrated and eventually released to the stream, without any assumption on the flow paths involved. f_{SR_old} correspond to the traditional definition of snowmelt runoff; f_{SR} , and f_{SE} represent the new proposed definitions in this study: the proportion of snowmelt contributing to runoff and the proportion of snowmelt contributing to evaporation. $f_{Q_{snow}}$ and $f_{E_{snow}}$ represent the proportion of snowmelt-derived runoff in the composition of total runoff, and the proportion of snowmelt-derived evaporation in the composition of total evaporation.

However, despite importance of snow, most previous global studies have primarily focused on rainfall–runoff processes (Ban et al., 2023; Cui & Li, 2006; Love et al., 2010; Marin et al., 2000), while the partitioning of snowmelt between runoff and evaporation—a key hydrological process—has received less attention, leaving a critical gap in our understanding of the role of snowmelt in the global water cycle.

Previous studies have largely focused on snowmelt's contribution to runoff (Barnett et al., 2005; Kapnick & Delworth, 2013; Kesting & Allen, 2024; Kirchner & Allen, 2020; Li et al., 2017). Such studies generally rely on indirect metrics to estimate the proportion of runoff derived from snowmelt, such as the ratio of snowfall (P_{snow}) to precipitation (P), the ratio of snowfall (P_{snow}) to total runoff (Q), and the ratio of runoff during the snowmelt season to total runoff. Among them, the ratio of snowfall to total runoff (f_{SR_old}) is the most widely used traditional definition of snowmelt runoff, which implicitly assumes that all snowfall contributes to runoff. As pointed out by Serreze et al. (1999), while such metrics offer useful approaches for estimating the fraction of snowmelt in runoff, they largely neglect critical physical processes affecting the transformation from snowmelt to runoff. The normalized melt index (NMI, defined as the ratio of upstream snow and glacier melt runoff to downstream natural runoff) employed in the Indus Basin essentially compared pre-runoff snowmelt amounts with total runoff, without representing the intermediate storage processes and resulted in values exceeding 100% (Immerzeel et al., 2010). As a result, these approaches primarily address the question of how much snowmelt is in the runoff (“component of” perspective) (Weiler et al., 2018), but do not explicitly resolve how snowmelt is partitioned between runoff and evaporation.

To address this limitation and move beyond the “component of” perspective, a process-based framework is required to explicitly track the pathways through which snowmelt is partitioned. To this end, Figure 1 demonstrates the conceptual diagram of the partition of snowfall and rainfall into runoff and evaporation. Precipitation is partitioned into rainfall and snowfall, with snowfall stored as snowpack and undergoes melting during the warm season. Snowmelt, together with rainfall, infiltrates into the unsaturated root zone to replenish soil moisture deficits and then returns to the atmosphere through evaporation, with the remaining portion generating runoff (Q), which here represents the combined total of all liquid fluxes that are not stored in the subsurface and which are eventually released to the stream irrespective of the individual flow paths they follow such as overland flow, lateral subsurface flow or groundwater flow. Stable isotope studies have provided evidence that rainfall and

snowmelt signals are often mixed within the soil and subsurface storage before contributing to different hydrological fluxes (Beria et al., 2018; Jeelani et al., 2010). Based on this experimental conclusion, we assume that rainfall and snowmelt are fully mixed. Under this assumption, we isolate the snowmelt component from the combined water input (rainfall plus snowmelt) and quantify its partitioning pathways independently.

In applying this framework within a modeling context, two additional assumptions have implicitly been made which may have impacts on our results. First, vapor fluxes from the snow surface (including sublimation and possible evaporation of meltwater) and the reverse process of condensation as vapor deposition are not taken into account explicitly. They are still problematic to determine at global level and, moreover, may partly compensate for each other (Hughes et al., 2021). As a result, in this study, the combined effect of sublimation and condensation is included in E_{snow} . Second, the direct evaporation by canopy interception (E_i) is combined with root zone evaporation (E_R) and included in E_{rain} . Transpiration and soil evaporation are not treated separately but are jointly represented as root-zone evaporation (E_R). Accordingly, we define root zone from soil surface to the root zone bottom (Gao et al., 2024; Wyatt et al., 2021). Although interception can be considered separately by a hydrological model, in snow dominated areas, during the snowmelt season, the contribution of interception to total evaporation is considered to be minor and hence is considered jointly with the evaporation from soil (Gustafsson et al., 2009).

It is important to distinguish between snowmelt and snowmelt runoff. A portion of snowmelt infiltrates into the root zone and is stored as soil moisture, which subsequently supports evaporation. Only the surplus exceeding the root-zone storage capacity contributes to runoff.

Based on the above analysis of the physical processes and the assumptions made this study adopts a “*contribution to*” perspective to explicitly quantify the actual partitioning of snowmelt—that is, how much snowmelt replenishes the root zone and subsequently supports vegetation evaporation, and how much generates runoff. Drawing on Falkenmark’s blue–green water framework (Falkenmark, 2000), we propose a novel, process-based definition to characterize snowmelt partitioning: the blue-water fraction refers to snowmelt contributing to runoff (Q_{snow}), while the green-water fraction refers to snowmelt infiltrating into the soil contributing to ecosystem evaporation (E_{snow}). By directly quantifying the individual fractions of snowmelt contributing to runoff (Q) and evaporation (E)—(f_{SR} and f_{SE} , as illustrated in Figure 1)—we move beyond previous reliance on indirect proxies. This perspective not only clarifies the hydrological contribution of snowmelt to runoff but also highlights its ecological role in supporting vegetation and ecosystem processes.

However, the partitioning process is inherently unobservable as it largely occurs below the surface. Although methods such as isotope analysis can provide useful insights, they are generally limited to small catchments and remain associated with substantial uncertainty (Kesting & Allen, 2024). Consequently, at large spatial scales where direct observations are sparse, hydrological models are commonly used as a practical tool to explore potential snowmelt partitioning patterns, while recognizing the uncertainties inherent in model-based estimates.

Several studies have attempted to trace snowmelt partitioning at regional scales. For example, the tracking model proposed by Liu et al. (2023) is applied in a small catchment on the Tibetan Plateau. Besides, Li et al. (2017) quantified the critical role of snow in water supply by using the ratio of snowmelt-derived runoff to total runoff in the western United States through a new snowmelt tracking algorithm. Similarly, Kirchner and Allen (Kirchner & Allen, 2020) used the “end-member splitting analysis”, with isotopic tracers and water flux measurements, to partition both rainfall and snowmelt into evaporation and streamflow in snowy- and rainy-seasons.

Despite these advances, these studies are largely limited to regional scales. The global-scale partitioning and underlying mechanisms remain largely unexplored. This study aims to fill this critical gap in the understanding of the water cycle and complement previous studies by disentangling the dual pathways of snowmelt.

Specifically, the present work aims to (a) simulate the global partitioning of snowmelt into runoff and evaporation for the 1980–2014 period using the distributed conceptual hydrological model FLEX-Global (excluding Antarctica and Greenland) (Fenicia et al., 2008; Gao, Hrachowitz, Fenicia, et al., 2014; Kavetski & Fenicia, 2011; Savenije, 2010; Wang et al., 2021); (b) verify the rationality of our framework using two independent approaches (i.e., the empirical infiltration method and the inverse estimation method); (c) quantify the fractions of global total runoff and evaporation sustained by snowmelt. By introducing this novel perspective and providing new insights, our study does not only establish a foundation for assessing the role of snowmelt in global hydrological processes but also advance understanding of its implications for water resources and ecosystems in snow-covered regions,

thereby offering a scientific basis for water resource management and allocation under climate change and intensifying human activities.

2. Data and Methods

2.1. Climate Data Inputs

We used outputs from four CMIP6 (Coupled Model Intercomparison Project Phase 6) Global Climate Models (GCMs) from the historical experiment (1980–2014) as climate forcing data of FLEX-Global, including GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. The IPSL-CM data set was excluded due to its pronounced warm and dry bias, which tends to distort snow-related hydrological processes (Cheruy et al., 2020; Lalande et al., 2021). The data sets are centrally bias-adjusted and downscaled by the ISIMIP framework to provide climate input data sets on a daily regular $0.5^\circ \times 0.5^\circ$ global grid. The four GCMs are structurally independent in terms of their ocean and atmosphere model components and they represent the range of equilibrium climate sensitivity (ECS) across the full CMIP6 ensemble, including three models with below-average ECS (i.e., GFDL-ESM4, MPI-ESM1-2-HR and MRI-ESM2-0) and one model with above-average ECS (i.e., UKESM1-0-LL).

The daily hydro-meteorological forcing data at a 0.5° spatial resolution that are used as input for the FLEX-Global models include daily mean, minimum, and maximum 2 m air temperature (T , $T_{\min}$, and $T_{\max}$, respectively ($^\circ\text{C}$)), and daily total precipitation (P (mm)).

2.2. FLEX-Global Model and Validation

2.2.1. FLEX-Global Model

The FLEX-Global model was well tested by streamflow observation at global scale (Wang et al., 2021). It was developed based on a basin-scale hydrological model, the FLEX, containing a snow module, a rainfall-runoff generation module MCT-HSC (Gao et al., 2019; Gao, Hrachowitz, Schymanski, et al., 2014), fast response module, and slow response module. While the original model accounts for subsequent runoff routing processes (fast and slow recession) following root zone runoff generation, the present study focuses on the partitioning of snowmelt into runoff and evaporation. Therefore, we employed a simplified version of the model with three conceptual reservoirs representing the partition of runoff and evaporation: S_w is the snow reservoir describing snow accumulation and melt; S_i is the interception reservoir describing canopy interception processes; and S_u is the unsaturated root zone reservoir describing water storage and runoff generation in the root zone. The CaMa-Flood model was used with default parameter settings in the present study for routing calculation (Yamazaki et al., 2011). The FLEX-Global model was driven by daily precipitation and daily temperature data from CMIP6 products at a spatial resolution of 0.5° . Also, all simulations were performed at daily resolution and the simulation period spans 1980–2014. It should also be noted that the 0.5° spatial resolution may smooth complex topography in mountainous regions, potentially introducing uncertainties in representing snow accumulation and melt processes in high-altitude areas. However, this resolution is widely used in global hydrological modeling and represents a necessary compromise between computational feasibility and global coverage. Given that the focus of this study is on large-scale patterns of snowmelt partitioning, the chosen resolution is considered appropriate for the objectives of this study. The equations and a schematic diagram of the FLEX-Global model structure are provided in Table 1 and the (Table S1; Figure S1 in Supporting Information S1).

2.2.1.1. Snow Module

Snow accumulation and melt are controlled by a temperature threshold T_i ($^\circ\text{C}$). When the air temperature (T) is below the threshold, precipitation P (mm day^{-1}) falls as snow (P_s) and is added to the storage in S_w (Equation 6). When temperature exceeds T_i , snow starts to melt. The snowmelt amount (M) is calculated using a degree-day factor (F_{DD} , $\text{mm}/(^\circ\text{C}\cdot\text{day})$) (Equation 7), which is a regionalized value obtained from Beck et al. (2013, 2016).

2.2.1.2. Interception Module

Intercepted evaporation E_i (mm/day) after rainfall is calculated from the potential evaporation E_p (mm/day), which is calculated through Hargreaves equation (Samani, 1982), the amount of water stored in the interception reservoir S_i (mm), and the maximum interception capacity $S_{i\text{Max}}$ (mm) (Equations 8–5). $S_{i\text{Max}}$ is estimated by

Table 1
Water Balance Equations and Constitutive Equations

Sub-module	Water balance equations	Constitutive equations
Snow module	$\frac{dS_w}{dt} = \begin{cases} -M, & T > T_t \\ P_{\text{snow}}, & T \leq T_t \end{cases} \quad (6)$	$M = \begin{cases} \min(S_w, F_{DD}(T - T_t)), & T > T_t \\ 0, & T \leq T_t \end{cases} \quad (7)$
Interception module	$\frac{dS_i}{dt} = P - E_i - P_e \quad (8)$	$E_i = \min(E_p, S_i) \quad (9)$ $S_{i\text{Max}} = 0.2\text{LAI} \quad (10)$ $P_e = \begin{cases} P - (S_{i\text{Max}} - S_i), & S_i < S_{i\text{Max}} \\ P, & S_i = S_{i\text{Max}} \end{cases} \quad (11)$
Root zone module	$\frac{dS_u}{dt} = P_e + M - E_a - Q \quad (12)$	$E_a = \frac{S_u}{C_e \cdot S_{R\text{max}}} (E_p - E_i) \quad (13)$
Snowmelt partition module		$\alpha = f(S_u, S_{R\text{max}}, \text{HAND}) \quad (14)$ $Q_{\text{snow}} = M * \alpha \quad (15)$ $Q_{\text{rain}} = P_e * \alpha \quad (16)$ $E_{\text{snow}} = M - Q_{\text{snow}} \quad (17)$ $E_{\text{rain}} = P_e - Q_{\text{rain}} \quad (18)$

Equation 11 and it represents maximum interception capacity, where *LAI* is the leaf area index. *P_e* represents effective precipitation into root zone after interception.

2.2.1.3. Root Zone Module

The root zone reservoir plays a key role in runoff generation. The root zone water storage capacity (*S_{Rmax}*) determines the distribution of runoff and infiltration. Mass Curve Technique (Gao, Hrachowitz, Schymanski, et al., 2014) was utilized to derive *S_{Rmax}* based on rainfall patterns and the water requirements of ecosystem vegetation. We applied a topography-driven runoff generation module, the HSC (HAND-based Storage Capacity curve, HAND means height above the nearest drainage), to map the landscape-scale spatial distribution of root zone water storage capacity (Gao et al., 2019), which was verified with a large amount of watershed data in the United States and around the world (Biswal et al., 2024; Wang et al., 2021; Zhang et al., 2021). The net rainfall (*P_e*) (i.e., rainfall after interception) and snowmelt first replenishes the unsaturated root zone without runoff generation, until the local root zone storage is above its holding capacity. The variable source area for runoff generation was determined by identifying the portion of water storage volume (*S_u*) exceeding its local *S_{Rmax}*, after which the runoff was calculated (Equation 12). Then this module isolates the snowmelt-derived blue water based on the proportion of snowmelt in the net precipitation. In the formula, *E_a* represents actual evaporation (i.e., transpiration plus soil evaporation) and *C_e* is a regionalized threshold value obtained from Beck et al. (2013, 2016), which represents the soil water content when actual evaporation is equal to potential evaporation. *Q* represents the amount of generated runoff. *α* represents the splitter that determines the partition of snowmelt (*M*) and effective rainfall (*P_e*) to runoff. *f(S_u, S_{Rmax}, HAND)* represents the dual-pathway process of snowmelt induced by the runoff-evaporation partitioning mechanism in the root zone, which is related to the water storage volume of root zone, maximum root zone water storage capacity, and topography. *Q_{snow}* is runoff generated by

snowmelt, and E_{snow} is the portion of snowmelt partitioned to evaporation. Q_{rain} is runoff generated by effective rainfall, and E_{rain} is the portion of effective rainfall partitioned to evaporation.

A key advantage of the FLEX-Global model over other global hydrological models lies in its streamlined modeling framework, particularly the concise and process-based parameterization used to distinguish runoff generation (blue water) from infiltration that replenishes root zone soil moisture deficit (green water). It should be noted that runoff is represented as an integrated flux in the model, without explicitly separating infiltration-excess overland flow and subsurface runoff processes. The model framework's flexibility and parsimony, with merely three free parameters (T_i , F_{DD} , C_e), enables a focused investigation of vertical snow hydrology and associated partitioning processes.

2.2.2. Proportion of Snowmelt Contributing to Runoff and Evaporation

Based on the above fluxes and the runoff-evaporation partitioning mechanism of snowmelt, we can calculate the proportion of snowmelt contributing to runoff (f_{SR}) and that to evaporation (f_{SE}):

$$f_{\text{SR}} = \frac{\sum_{i=1}^N Q_{\text{snow},i}}{\sum_{i=1}^N M_i} \quad (19)$$

$$f_{\text{SE}} = 1 - f_{\text{SR}} = \frac{\sum_{i=1}^N E_{\text{snow},i}}{\sum_{i=1}^N M_i} \quad (20)$$

where, $Q_{\text{snow},i}$, $E_{\text{snow},i}$, and M_i represent the runoff generated by snowmelt, the evaporation generated by snowmelt, and snowmelt in the year i .

2.2.3. The Fraction of Snowmelt-Derived Runoff (Evaporation) in Total Runoff (Evaporation)

We also analyzed the fraction of snowmelt-derived runoff in total runoff ($f_{Q_{\text{snow}}}$) through dividing the runoff from snowmelt by the total runoff (Equation 21). Similarly, the fraction of snowmelt-derived evaporation in total evaporation ($f_{E_{\text{snow}}}$) was calculated through dividing the evaporation from snowmelt by the total land evaporation (Equation 22). $f_{Q_{\text{snow}}}$ corresponds to the concept of “component of”, the same as the traditional view of snowmelt runoff ($f_{\text{SR_old}}$). Unlike previous indirect metrics (Barnett et al., 2005; Kapnick & Delworth, 2013; Li et al., 2017), our analyses explicitly consider the dual pathways of snowmelt—runoff and evaporation—rather than simply substituting snowfall for the runoff.

$$f_{Q_{\text{snow}}} = \frac{\sum_{i=1}^N Q_{\text{snow},i}}{\sum_{i=1}^N Q_i} \quad (21)$$

$$f_{E_{\text{snow}}} = \frac{\sum_{i=1}^N E_{\text{snow},i}}{\sum_{i=1}^N E_i} \quad (22)$$

where, $Q_{\text{snow},i}$ and $E_{\text{snow},i}$ represent runoff and evaporation generated by snowmelt in the year i , Q_i and E_i represent the total global runoff and evaporation in the year i .

2.2.4. Ensemble Model and Uncertainty Analysis

In the FLEX-Global model, parameters related to snowmelt include F_{DD} and T_i , and parameters related to the partition of blue water and green water from snowmelt include $S_{R_{\text{max}}}$ and C_e . The base values of T_i , F_{DD} and C_e are obtained from Beck's research (Beck et al., 2020; Wang et al., 2021), and are increased and decreased by 20% respectively as uncertainty range. $S_{R_{\text{max}}}$ was selected three different recurrence periods of 10 years, 20 and 40 years in Wang-Erlandsson's research (Wang-Erlandsson et al., 2016). By permutation and combination, we can get 81 parameter combination settings and with four sets of GCMs input data. Hence, we conducted a total of 324 simulations to provide an uncertainty range. The detailed 81 parameter settings are described in the (Table S1 in Supporting Information S1).

2.3. Snowmelt Partitioning Based on Two Independent Methods

2.3.1. Empirical Infiltration Equation

Granger et al. (1984) provide the following empirical equation to calculate snowmelt infiltration (INF) into root zone to satisfy water deficit, and used for evaporation afterward:

$$\text{INF} = f_{\text{SE}} \text{SWE} = 5(1 - \theta) \text{SWE}^{0.584} \quad (23)$$

Here, we assume that the infiltration amount calculated by this infiltration equation is the part that is used to meet the water deficit in the root zone, which is equivalent to green water in this paper. The parameter θ is degree of soil pore saturation ($\text{mm}^3 \text{mm}^{-3}$).

Then we can obtain the runoff from snowmelt (Q_{snow}) by subtracting snowmelt (M) and infiltration (INF):

$$Q_{\text{snow}} = M - \text{INF} \quad (24)$$

With the Q_{snow} obtained, we can calculate f_{SR} using Equation 19.

Their underlying assumption is that snowmelt infiltration into unsaturated soils varies with the Snow water equivalent (SWE) of the snow cover. Here, we use the 95% percentile of the annual SWE simulated by FLEX-Global model to calculate infiltration through Equation 23. We did not use the annual maximum SWE in order to avoid the error influence of extreme values. Regarding the selection of the θ value, we adopted the three values of 0.4, 0.5, and 0.6 as provided by the original study, in order to quantify the associated uncertainty.

2.3.2. Inverse Estimation Method Using ISIMIP Model Outputs

The Inter-Sectoral Impact Model Intercomparison Project phase 3a (ISIMIP3a) provides harmonized simulations from multiple global hydrological models under consistent climate forcing. These outputs include key hydrological variables such as SWE, runoff, evaporation. Although ISIMIP3a does not explicitly trace the pathways of snowmelt, it enables the indirect estimation of snowmelt partitioning by leveraging output data.

In this study, we utilized outputs from three widely used hydrological models—H08, HydroPy, and WaterGAP2. Despite differences in implementation, these three models share a common hydrological representation of snowmelt processes with the FLEX-Global model: snowmelt water infiltrates into the soil to compensate for the water deficit in the root zone, and runoff is generated as all excess water beyond the soil storage capacity together with overland flow. In addition, the relatively better performance of these three models, particularly in cold regions (Wang et al., 2021) was one of the reasons for their selection. This conceptualization allows us to apply a residual-based method to infer how snowmelt is partitioned between contributing to runoff and remaining within the soil to supply evaporation.

We first calculated the amount of monthly-scale snowmelt (M_j) by working backwards from the monthly-scale SWE data:

$$M_j = \begin{cases} \text{SWE}_{j-1} + P_{sj} - \text{SWE}_j, & \text{SWE}_j < \text{SWE}_{j-1} \\ 0, & \text{SWE}_j \geq \text{SWE}_{j-1} \end{cases} \quad (25)$$

where SWE_j represents the amount of SWE in month j , P_{sj} represents the amount of snowfall in month j .

Assuming snowmelt mixes completely with rainfall as net water input and both follow the same infiltration pathways into the unsaturated zone, we introduced a coefficient (R_{M-P}) (Equation 26), representing the proportion of snowmelt in net water input, that is the sum of rainfall and snowmelt, to calculate the amount of snowmelt contributing to runoff (Q_{snow}) (Equation 27). By subtracting Q_{snow} , the amount of evaporation from snowmelt (E_{snow}) can be obtained by Equation 28:

$$R_{M-P,j} = \frac{M_j}{P_{\text{rain},j} + M_j} \quad (26)$$

$$Q_{\text{snow},j} = R_{M-P,j} Q_j \quad (27)$$

$$E_{\text{snow},j} = M_j - Q_{\text{snow},j} \quad (28)$$

where, $P_{\text{rain},j}$, M_j , and Q_j represent the rainfall, snowmelt, and total runoff in the month j . Then, f_{SR} and f_{SE} can be calculated using Equations 19 and 20.

2.4. Model Performance Metrics

To better evaluate the FLEX-Global performance in comparison with the observation data and two other independent methods, the following metrics were selected for analysis and evaluation: the Kling-Gupta efficiency (KGE) (Equation 29), and Absolute difference (AD) (Equation 30).

$$\text{KGE} = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_s}{\sigma_0} - 1\right)^2 + \left(\frac{\mu_s}{\mu_0} - 1\right)^2} \quad (29)$$

$$\text{AD} = F - I \quad (30)$$

where r is the correlation coefficient between the simulated values and the observed values. σ_s and σ_0 are the standard deviations of the simulated and observed values, respectively. μ_s and μ_0 are the means of the simulated and observed values, respectively. F represents simulations from FLEX-Global model, and I represents simulations from two other independent methods.

The KGE provides a comprehensive measure of model performance by simultaneously accounting for correlation, variability, and bias between simulated and observed values, with KGE closer to 1 indicating higher consistency. The AD measures the direct magnitude of deviation between FLEX-Global model and other two independent methods. Because it quantifies error, smaller AD values indicate better model performance.

3. Results

3.1. Model Performance

3.1.1. Runoff Validation

Measured monthly streamflow data were obtained from the Global Runoff Database (GRDC), of which twenty-two stations for large river basins were selected for verification. Figure 2 shows the time series of the simulation results with the FLEX-Global model compared to the measured monthly average flow of GRDC. The simulation results are in close agreement with the observation data. The average KGE coefficient of the twenty-two river basins is 0.57, which is comparable with other eight global hydrological models (Wang et al., 2021).

3.1.2. Snow water Equivalent Validation

SWE refers to the amount of water contained within the snowpack (i.e., if all the snow melts) (Bormann et al., 2018). In our model, the snow reservoir S_w represents the SWE. At present, directly monitoring SWE using remote sensing remains a significant challenge (Dozier et al., 2016; Kraaijenbrink et al., 2021; Smith & Bookhagen, 2018, 2020). To validate the reliability of our model in simulating snowmelt, we compared the simulated snow water reservoir S_w with in situ observational SWE from the SNOTEL network at corresponding grids (Figure S2 in Supporting Information S1). Considering that the model's spatial resolution is relatively coarse and the SNOTEL sites are located at high elevations, we used site-specific precipitation and temperature data to drive the FLEX-Global model for SWE validation. The average KGE coefficient of the 15 sites is 0.45 (Figure 3). Note that to reduce the influence of seasonal climatology caused by snow-free periods (from June to September) on model evaluation, KGE was calculated separately for each month of the year using all daily values within that month across the study period. The final performance metric was obtained by averaging the KGE values across 12 months (Detailed calculation results are presented in Table S2 of Supporting Information S1). The primary biases likely stem from colder and wetter climates at higher elevations, which tend to amplify the bias in observed

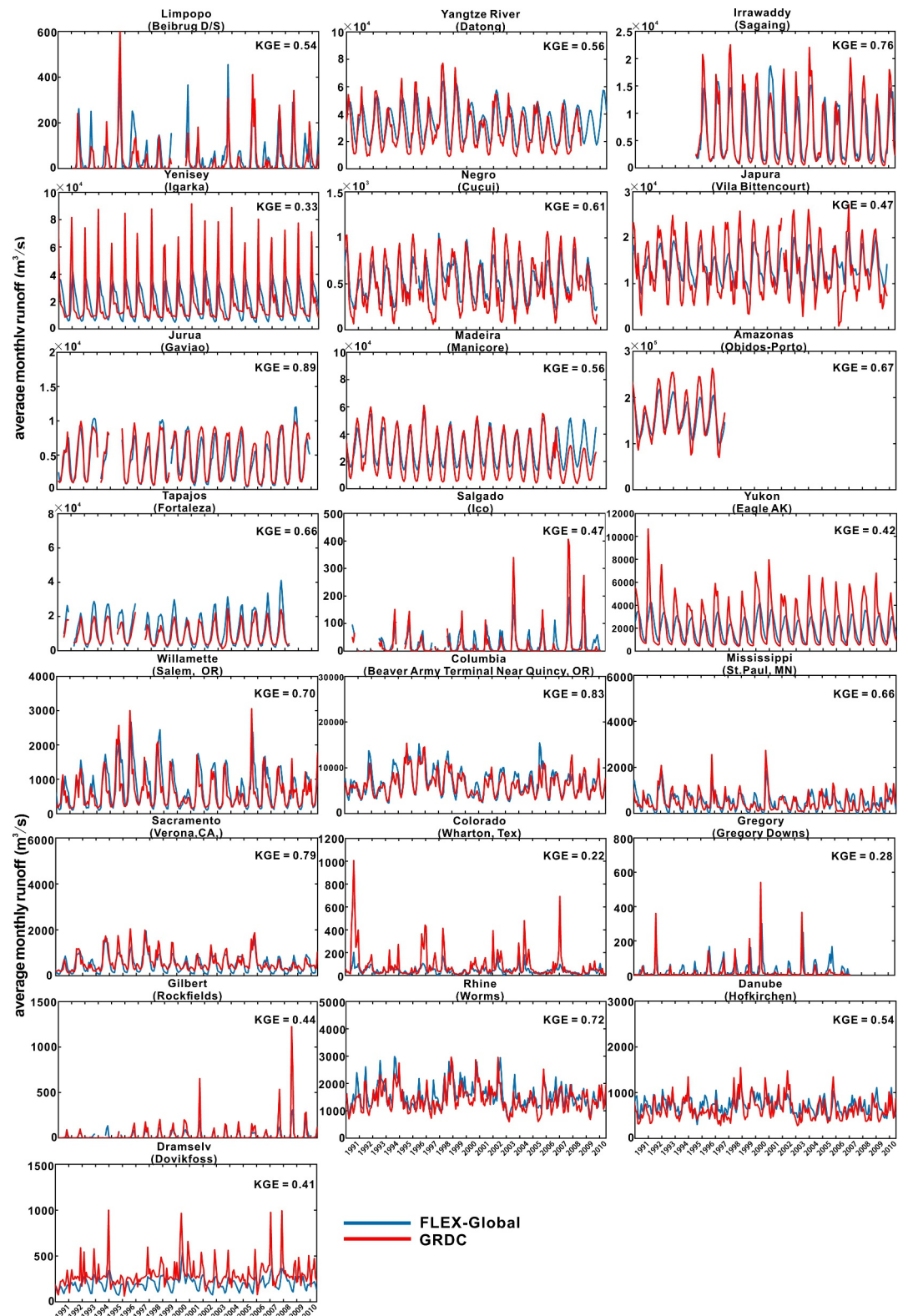


Figure 2. Daily time series of simulation results from the FLEX-Global model, compared with the measured monthly average streamflow from twenty-two GRDC observation stations.

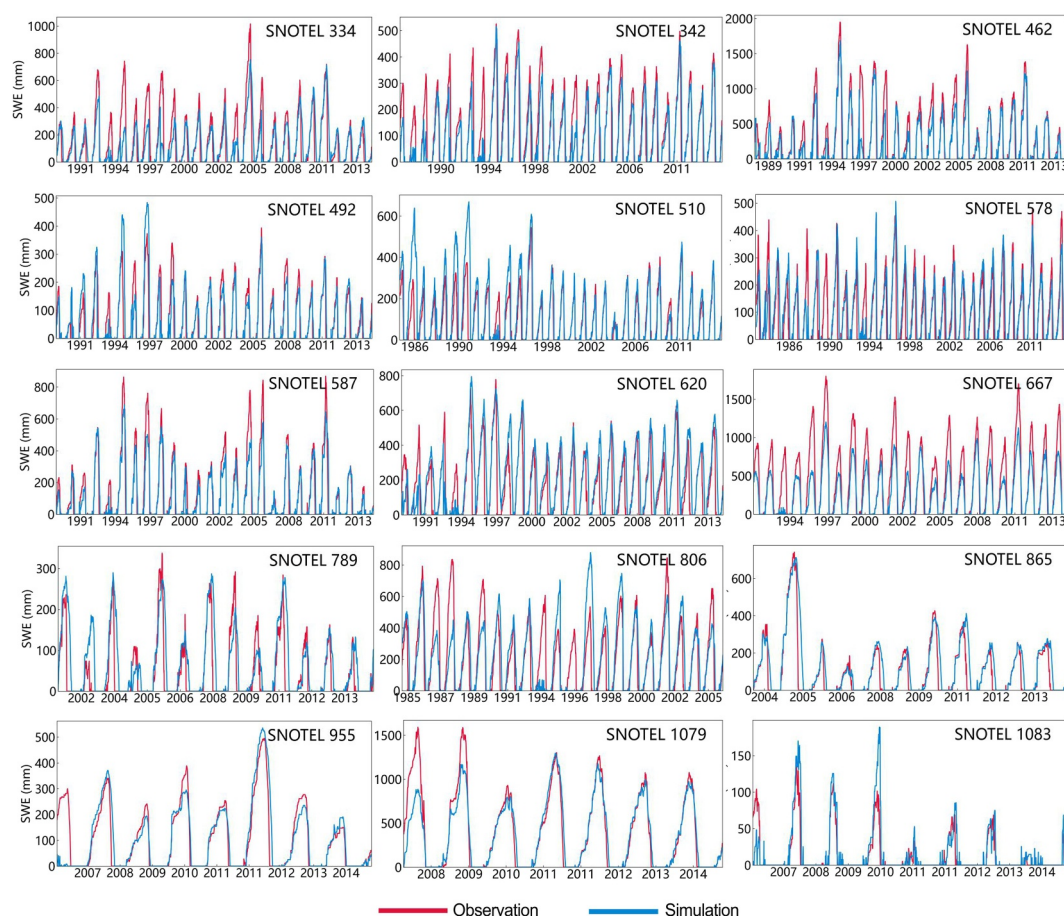


Figure 3. Daily time series of simulated Snow water equivalent (SWE) (based on the simulation of FLEX-Global model) and observed SWE of fifteen SNOTEL stations. The red line denotes observations and the blue line denotes model simulations. Note that the start dates differ across panels because the observation records begin at different times for each station.

SWE, leading to in situ data larger than modeled ones (Cho et al., 2022). Overall, the model successfully captured the variability of SWE, demonstrating its robustness and utility.

3.1.3. Validation of the Proportion of Evaporation Between FLEX-Global Model and Two Independent Methods

Since we employed an empirical equation and the inverse estimation method (outputs from H08, HydroPy, and WaterGAP2) to calculate f_{SE} , we calculated the absolute difference (AD) between the f_{SE} results obtained by the FLEX-Global model and the two other independent methods. The closer AD is to zero, the more consistent the simulation of the FLEX-Global model is with the value calculated by the other two methods. A positive difference indicates that the FLEX-Global model estimates a greater f_{SE} .

For the inverse estimation method, the absolute difference is generally within 0.4 (Figures 4a–4c). f_{SE} calculated by the inverse-estimation method is higher in regions such as the Middle East, central United States, and parts of Chile in South America. These areas are characterized by high aridity (Figure S3 in Supporting Information S1), which further highlights the significant contribution of snowmelt to ecosystems as green water. For the empirical equation, derived from specific regions and periods, may introduce some bias when applied globally, the overall results are deemed reliable (Figure 4d). We can observe that the difference of the empirical infiltration method and the FLEX-Global model is below 0.6.

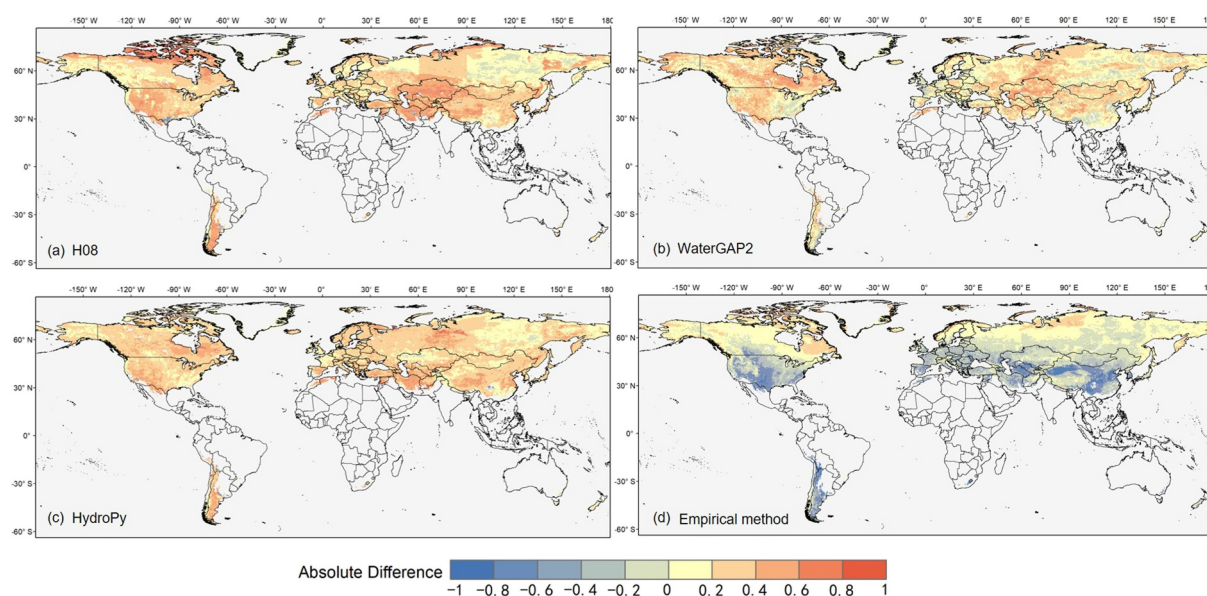


Figure 4. The global spatial pattern of absolute difference (AD) of the proportion of evaporation (f_{SR}) between simulation of FLEX-Global and other two independent methods (i.e., inverse estimation method and empirical infiltration method). A positive difference (red regions) indicates that the FLEX-Global model estimates a larger f_{SE} , whereas a negative value (blue regions) reflects a larger proportion in the inverse-estimation method or empirical method.

3.2. Global Spatial Pattern of Snowmelt Partitioning to Runoff and Evaporation

The long-term mean partitioning of snowmelt into runoff and evaporation during 1980–2014 is shown in Figure 5. Ensemble model results of 324 simulations from the FLEX-Global model reveal that f_{SR} reaches 62%–69% (Figure S4 in Supporting Information S1), with an average of 65% ($5,381 \text{ km}^3 \text{ yr}^{-1}$), while f_{SE} fluctuates between 31% and 38%, with an averaging of 35% ($2,847 \text{ km}^3 \text{ yr}^{-1}$), supporting vegetation evaporation.

For the empirical equation method, the snowmelt-derived runoff is estimated at $4,725\text{--}5,882 \text{ km}^3 \text{ yr}^{-1}$, corresponding to a $f_{SR} \sim 57\%\text{--}71\%$, while evaporation fluxes range from $2,346$ to $3,503 \text{ km}^3 \text{ yr}^{-1}$, corresponding to a $f_{SE} \sim 29\%\text{--}43\%$. With $\theta = 0.5$, the average evaporation flux is $2,927 \text{ km}^3 \text{ yr}^{-1}$, close to the FLEX-Global result ($2,847 \text{ km}^3 \text{ yr}^{-1}$). Furthermore, using the inverse approach, the estimated fraction of snowmelt runoff (f_{SR}) was 59%, 53%, and 62%, respectively, while the fraction of snowmelt evaporation (f_{SE}) was 41%, 47%, and 38%. These two independent methods, with full consideration of uncertainty, provide further robust validation of the FLEX-Global snowmelt partitioning results. Therefore, based on the results of the above three methods, we conclude that 29%–47% ($2,401\text{--}3,891 \text{ km}^3 \text{ yr}^{-1}$) of global snowmelt contributes to evaporation, while 53%–71% ($4,388\text{--}5,878 \text{ km}^3 \text{ yr}^{-1}$) contributes to runoff. Previous studies have shown that 60% of global terrestrial precipitation (rainfall and snowfall combined) returns to the atmosphere through evaporation, with only 40% generating runoff, including surface runoff, lateral groundwater flow, and baseflow (Gao et al., 2023; Oki & Kanae, 2006; Seneviratne et al., 2010). In contrast, snowmelt shows the opposite partitioning pattern—nearly two-thirds contributing to runoff—underscoring its crucial role in sustaining river discharge.

In spite of substantial local and regional heterogeneity, global snowmelt partitioning follows discernible patterns (Figure 5): In the Northern Hemisphere, f_{SR} generally increases with latitude, while f_{SE} declines. According to the Köppen climate classification (Beck et al., 2018) (Figure S5 in Supporting Information S1), we analyzed the pattern of spatial distribution of f_{SR} and f_{SE} . In high-latitude regions characterized by Df (continental humid), Ds (continental dry summer) and ET (polar tundra) climate zones, over 60% of snowmelt becomes runoff due to low solar energy input for evaporation and near-saturated soil conditions and thus limited additional water storage throughout much of the warm season (Greve & Seneviratne, 2015; Konapala et al., 2020; Stocker et al., 2023). However, certain Arctic regions (e.g., Alaska's North Slope, northwestern Siberia, and western Canada) exhibit the opposite pattern, with over 50% of snowmelt ending up as evaporation. This finding aligns with a previous study showing that increased Arctic vegetation over the past few decades has resulted in more than 50% of snowmelt being consumed by ecosystems (Hoek Van Dijke et al., 2022).

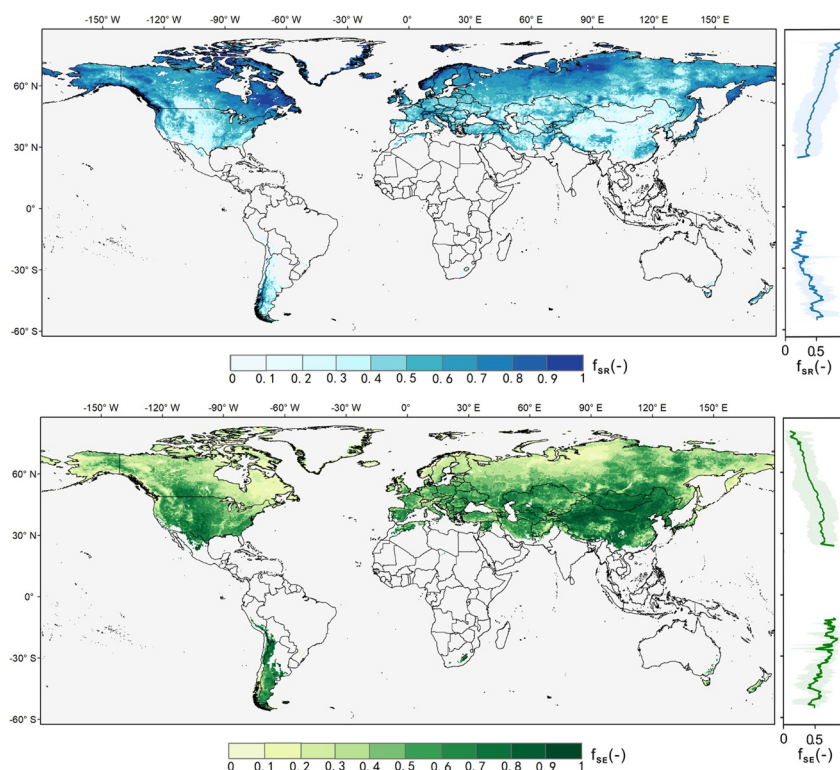


Figure 5. Geographical pattern of the proportion of snowmelt contributing to runoff (f_{SR} , top panel) and evaporation (f_{SE} , bottom panel) during 1980–2014 (based on the simulation of FLEX-Global model). The two right panels are the latitudinal mean of f_{SR} and f_{SE} .

The drier the region, the higher a fraction of snowmelt contributes to evaporation. In arid, mid-latitude regions with aridity index >1.5 the snowmelt contribution to evaporation f_{SE} reaches 63%–91%. Specifically, f_{SE} in Dw, BS, BW, and Cw climate zones reaches 58%–70%, 60%–91%, 66%–98%, and 60%–82%, respectively (Figure 6). BW and BS represent typically arid and semi-arid climates, such as in central Asia and the southwestern United States. However, in Cw and Dw climates, characterized by dry winters, such as in Northeast China, Southwest Asia, and Southeast Russia. The root zone soils in these regions are generally water deficient. Therefore, snowmelt primarily supplies water to support spring and early-summer vegetation growth. In contrast, the traditional definition (f_{SR_old}) assumes all snowfall to generate runoff (Barnett et al., 2005), exclusively focusing on the fraction of snowfall in total runoff. It neglects the fraction of snowmelt contributing to evaporation, largely overestimating the contribution of snowmelt to runoff, and underestimating or even ignoring its importance for terrestrial ecosystems.

Elevation also influences snowmelt partitioning. In high mountain regions such as the Rocky Mountains, Alps, Scandinavia, Himalayas, Verkhoyansk Mountains, and Patagonian Plateau, f_{SR} is with 62%–69% found to be substantially higher than in lower regions (<1500 m), where it ranges from 23% to 56%. Mountain regions are a major source of surface water and groundwater recharge in the world (Dettinger, 2014; Viroli et al., 2007). Rivers originating from Asia's high mountains, such as the Yangtze, Yellow, and Brahmaputra River, sustain about 567 million people downstream (Lutz et al., 2014; Schaner et al., 2012).

In the Southern Hemisphere, over 60% of snowmelt in the central–southern Andes and Patagonian Plateau ends up as evaporation. This is primarily linked to the arid or semi-arid climates of these regions, where spring and early-summer dry periods lead to substantial soil moisture deficits, causing snowmelt to be predominantly infiltrated into the soil, replenishing the root-zone storage rather than directly generating runoff. The stored soil moisture is subsequently consumed by vegetation, leading to a higher f_{SE} .

River basin analyses reveal that snowmelt contributes mostly to evaporation in the Yellow, Mississippi, and Colorado River basins (Figure 6c). The Yellow River is particularly striking, with FLEX-Global simulations

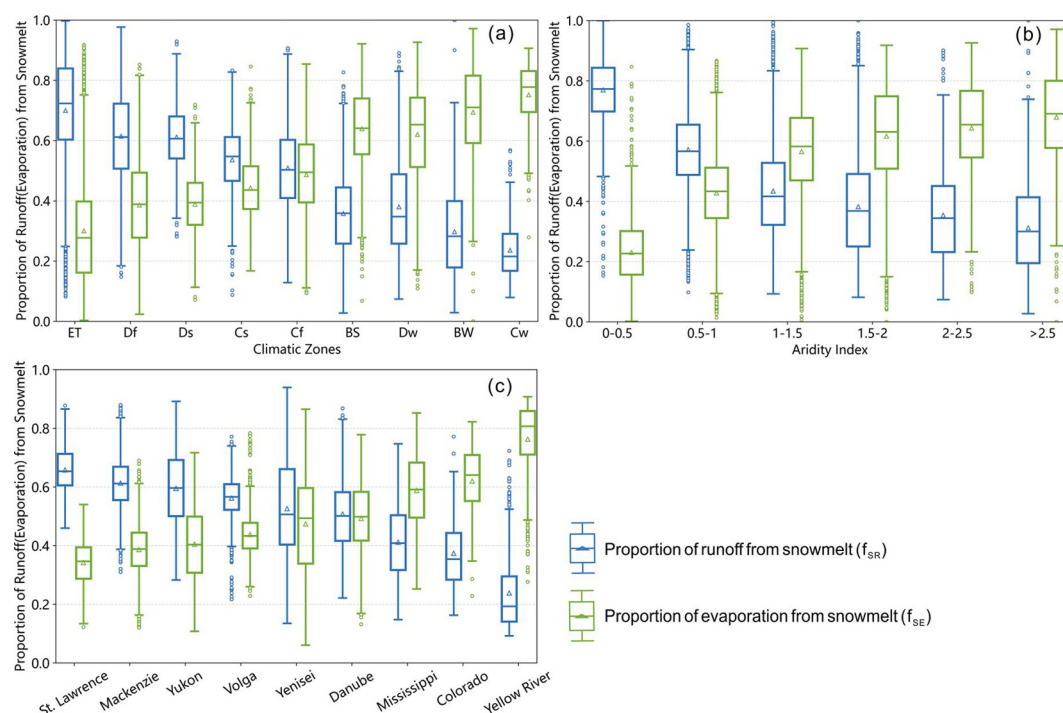


Figure 6. The proportion of snowmelt contributing to runoff (f_{SR}) and evaporation (f_{SE}) in different ranges of aridity index (a), in different climate zones (b) and in different basins (c) (based on the simulation of FLEX-Global model). BW: arid desert, BS: semi-arid steppe, Cs: Mediterranean, Cw: mild temperate dry winter, Cf: mild temperate humid, Ds: continental dry summer, Dw: continental dry winter, Df: continental humid, ET: polar tundra. In boxplots, the lower hinge represents the 25% quantile, the upper hinge the 75% quantile, and the center line is the median.

showing that 71%–85% of snowmelt becomes evaporation, reflecting its dry climate and high evaporation rates (Huang et al., 2024). This highlights that the ecosystem is currently under water stress. Especially, the implementation of afforestation in the water-limited areas of the Yellow River basin may result in conflicting water demands from both ecosystems and human consumption (Feng et al., 2016). In contrast, although the Mississippi and Yellow Rivers lie at similar latitudes, their snowmelt partitioning differs significantly. The Mississippi basin receives high winter snowfall (McCauley et al., 2022), and maintains relatively moist soil conditions. Moreover, its relatively low elevation allows for frequent winter warm spells, which promote intra-winter snowmelt events. These processes facilitate the rapid conversion of snowmelt into runoff rather than prolonged snow storage, resulting in a higher f_{SR} . Other basins, including the Yukon, Mackenzie, and St. Lawrence, show that ~60% of snowmelt becomes runoff, further highlighting the vital hydrological role of snowmelt in regional water resources (Figure 6c).

We also analyzed monthly variations of f_{SR} . Generally, before the onset of summer rainfall (January–May), snowmelt mainly contributes to evaporation in the central and western parts of the United States, the northeastern region of China, as well as the Yellow River Basin, the Ob River Basin, and the Yenisei River Basin, where vegetation growth largely depends on snowmelt (Figure S6 in Supporting Information S1). From May onward, as snow begins to melt in the Arctic Circle, f_{SR} is greater than 60%, particularly in the Yukon basin. By September, as temperatures fall and snowfall resumes in regions such as eastern Russia, northern Canada, and Alaska, snowmelt decreases, with only a small fraction (<50%) generating runoff. In the Yellow River basin, where summer rainfall accounts for 50%–70% of annual precipitation (Shi et al., 2024), snowmelt plays a limited role in replenishing soil moisture in summer, leading to higher f_{SR} . In the Colorado and Mississippi River basins, monthly f_{SR} peaks in spring and decline in summer. In the whole Danube basin, which is largely fed by the Alps, the f_{SR} peaks in August (Figure 7), when high-altitude snowmelt contributes a large proportion of total runoff (Hanus et al., 2021; Mauser & Prasch, 2016).

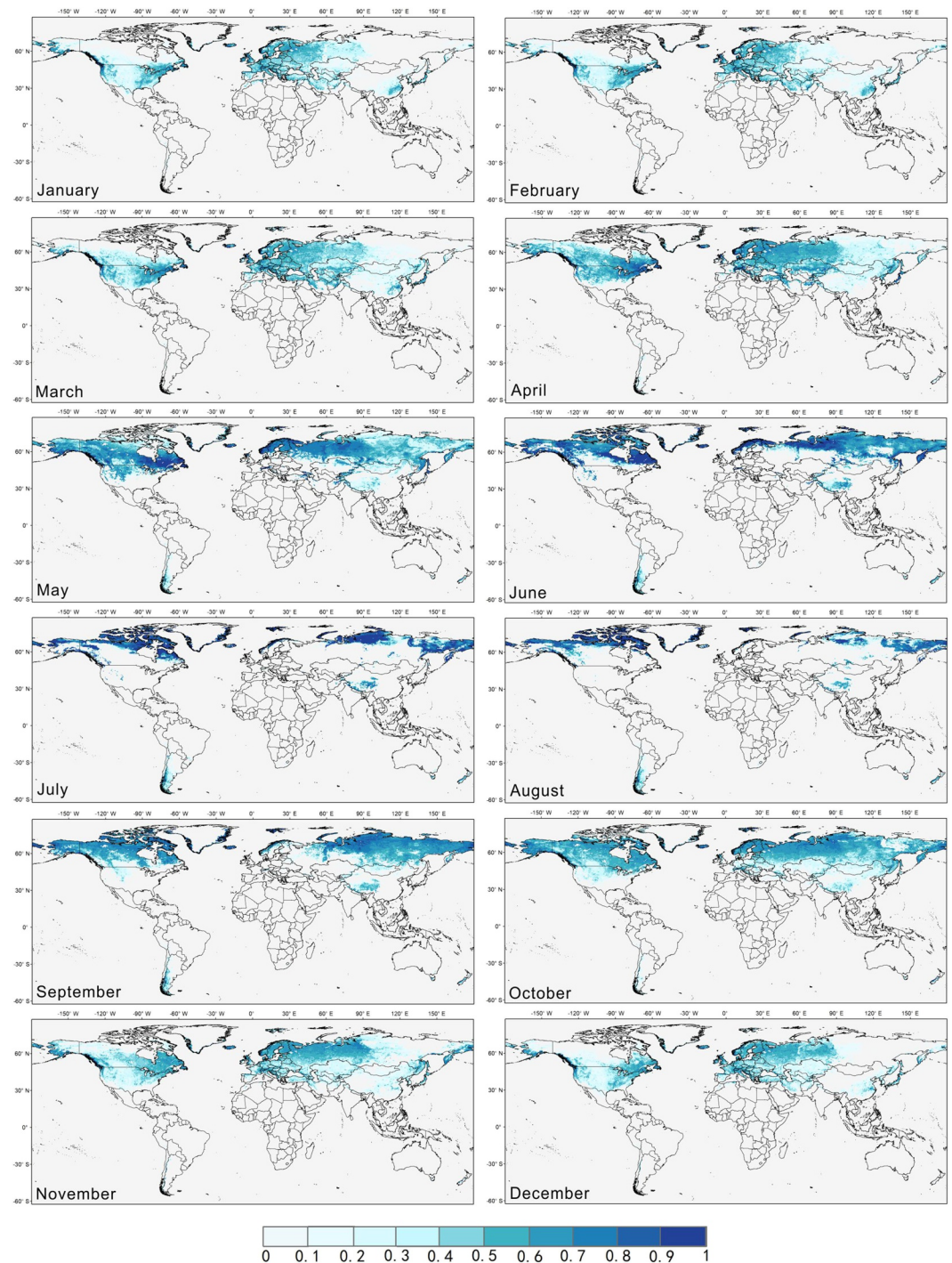


Figure 7. Geographical pattern of the proportion of snowmelt contributing to runoff (f_{SR}) during 1980–2014 (based on the simulation of FLEX-Global model), categorized by month.

3.3. Global Spatial Pattern of Fractions of Snowmelt-Derived Runoff and Evaporation

We further quantified the proportion of snowmelt-derived runoff in the composition of global total runoff ($f_{Q_{snow}}$) and the proportion of snowmelt-derived evaporation in the composition of global total evaporation ($f_{E_{snow}}$). Globally, $f_{Q_{snow}}$ reaches 11%–18% while $f_{E_{snow}}$ does not exceed 4%–8%. In the Northern Hemisphere, both $f_{Q_{snow}}$ and $f_{E_{snow}}$ increase with latitude (Figure 8). The results for $f_{Q_{snow}}$ are consistent with previous studies, which suggest

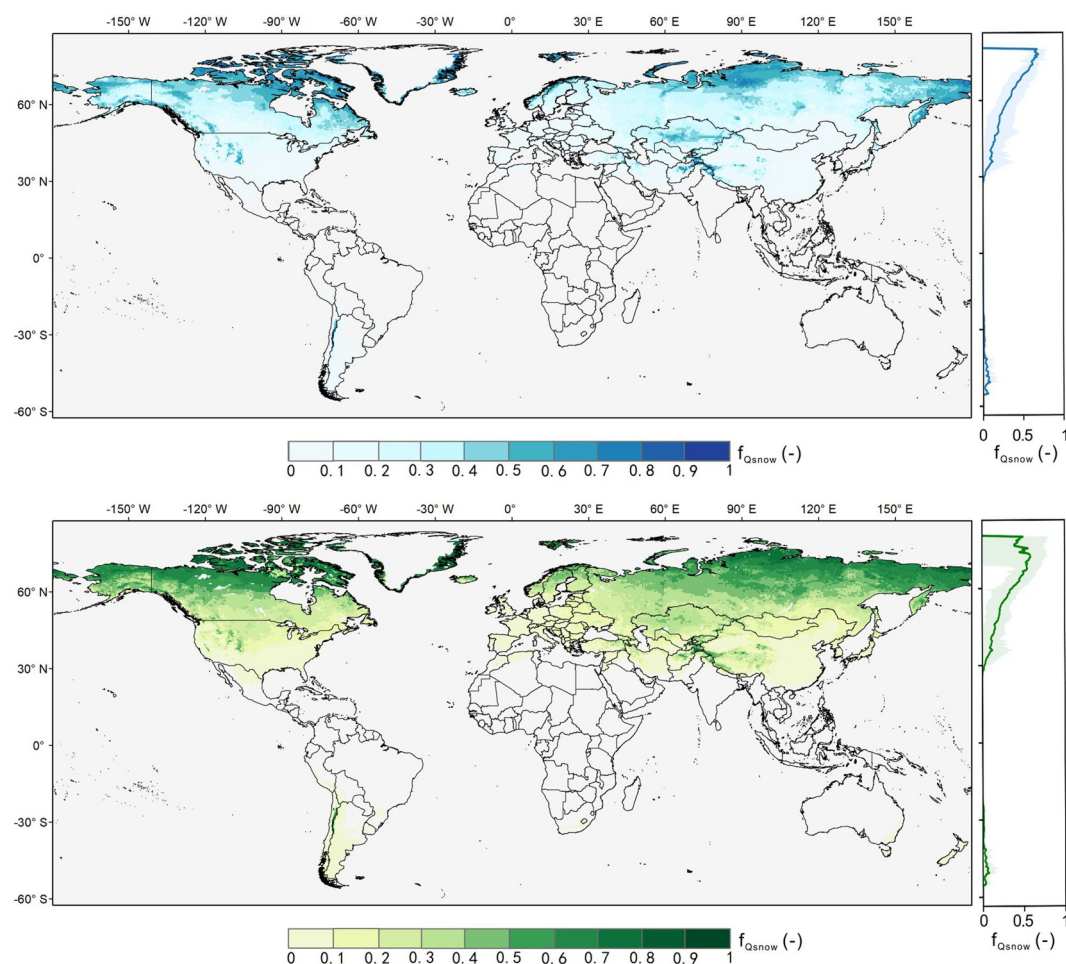


Figure 8. The proportion of runoff from snowmelt to total runoff ($f_{Q_{\text{snow}}}$, top panel) and the proportion of evaporation from snowmelt to total evaporation ($f_{E_{\text{snow}}}$, bottom panel) during 1980–2014 (based on the simulation of FLEX-Global model). The two right panels represent the latitudinal mean of $f_{Q_{\text{snow}}}$ and $f_{E_{\text{snow}}}$.

snowmelt forms a dominant component of streamflow across the boreal Arctic (Pan et al., 2021; Zheleznyakov et al., 1974). In mid-latitude mountain regions such as the southern Rocky Mountains, Himalayas and Pamir, snowmelt plays an even greater role in water supply. In these high-elevation regions, snowmelt constitutes 58%–74% of the total runoff and 51%–66% of the total evaporation, whereas in lower lying regions, it constitutes merely 22%–30% and 26%–35%, respectively. This contrast underscores both the ecological significance of snowmelt in mountain ecosystems and its hydrological importance for downstream regions. In high-latitude regions above 60°N, such as northwestern Siberia, northern Canada, and Alaska's North Slope, f_{SE} is relatively low (Figure 5). Nevertheless, $f_{E_{\text{snow}}}$ is greater than 60%, indicating that snowmelt plays a critical role in alleviating ecosystem water stress and mitigating soil moisture deficits in high-latitude environments.

3.4. Comparison Between New Definitions and Traditional One

Based on our previous analyses, we found that the simulation results under different parameter settings of the FLEX-Global model exhibit relatively small uncertainty. Therefore, we use the snowfall and runoff calculated with the baseline parameter set to derive the traditional snowmelt-runoff ratios ($f_{SR_{\text{old}}}$), as shown in Figure 9a.

From the perspective of the global area-weighted mean, the proportion of snowfall to total runoff ($f_{SR_{\text{old}}}$) is 38%, larger than $f_{Q_{\text{snow}}}$. This indicates that the traditional assumption that all snowfall contributes directly to runoff substantially overestimates the contribution of snow to runoff, ignoring a large fraction that actually supplies ecosystem (f_{SE}). The overestimation is particularly pronounced in semi-arid and arid regions, such as Central

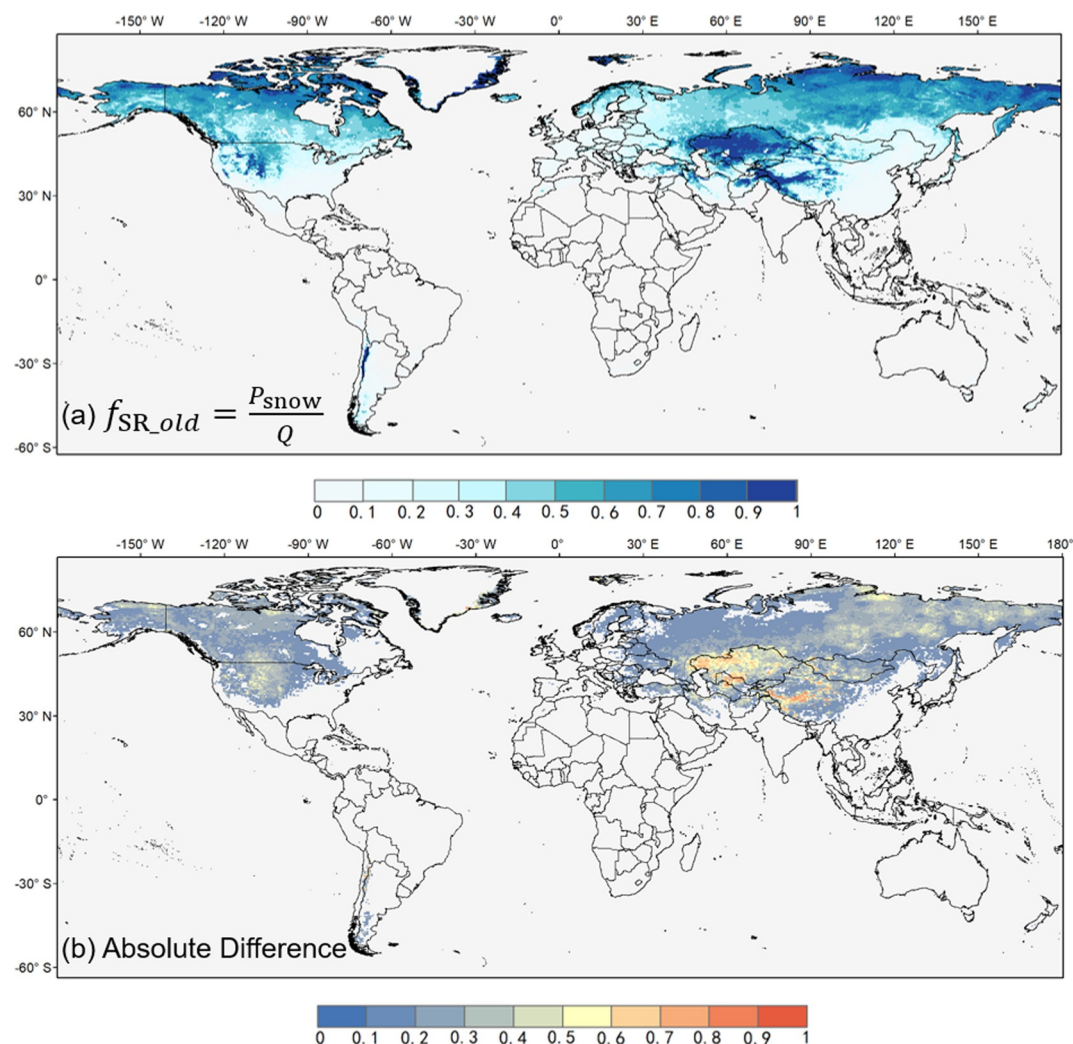


Figure 9. The top panel is global spatial pattern of the proportion of snowfall to total runoff (f_{SR_old}). The bottom panel is global spatial pattern of the absolute difference (AD) between the proportion of snowfall to total runoff (f_{SR_old}) and the proportion of runoff from snowmelt to total runoff (f_{Q_snow}) during 1980–2014 (based on the simulation of FLEX-Global model).

Asia, northwest China, and the southwestern United States (Figure 9b). In addition, some regions in eastern Russia are cold and dry, and the f_{SR_old} is also greatly overestimated compared to the f_{Q_snow} .

Indeed, modern process-based hydrological models generally and explicitly allow snowmelt to infiltrate into the soil and subsequently contribute to evaporation. However, what this article emphasizes is a distinct research perspective: while traditional studies take runoff as their starting point, this study centers on the fate of snowmelt.

4. Discussion

The traditional definition of snowmelt runoff (f_{SR_old}) primarily aims to quantify how much snowmelt is in the composition of runoff, based on the assumption that snowmelt directly generates surface runoff, which largely neglects the contribution of snowmelt to terrestrial evaporation. In contrast to previous studies, this study adopts a process-based model to partition snowmelt into runoff and evaporation. Specifically, snowmelt evaporation refers to the portion infiltrating the root zone to support vegetation growth and subsequently returning to the atmosphere through transpiration, while snowmelt runoff represents the fraction contributing to streamflow. This framework establishes an integrated perspective on snowmelt as a connector between hydrological and ecological processes, enabling its explicit representation in models and advancing beyond conventional precipitation-based formulations.

Our results align broadly with findings from previous catchment-scale studies. For instance, Kirchner and Allen (2020), employing isotopic and end-member methods, reported that snowmelt predominantly contributes to runoff in the Hubbard Brook Watershed, with an f_{SR} of 63%–100%. This is reasonably consistent with our simulated value of 60%–81% for the Hubbard Brook Watershed grid cell, considering the substantial differences in spatial scale and time series between the studies. Similarly, Liu et al. (2023) applied a distributed tracking model in a mesoscale basin on the Tibetan Plateau and found an $f_{Q_{snow}}$ of 10%–24%, which aligns closely with the value of 9%–34% in the corresponding grid cell of our FLEX-Global model. Furthermore, our finding that $f_{Q_{snow}}$ is generally higher in the Rocky Mountains than in coastal Pacific regions is spatially and quantitatively consistent with the pattern reported by Li et al. (2017).

The inevitable uncertainty in snowmelt simulations of FLEX-Global mainly arises from two sources: (a) input data uncertainty—precipitation is generally underestimated in cold regions, with the largest biases in mountainous regions, leading to snowmelt errors (Liu & Margulis, 2019; Yatagai et al., 2025); in addition, temperature data sets exhibit cold biases at high elevations, further affecting melt processes (Cho et al., 2022); (b) methodological limitations—most models, including this study, rely on the degree-day factor method, which often fails to account for snow sublimation due to limited radiation data. Although the FLEX-Global model used here does not explicitly simulate sublimation, previous studies have shown that accurate representation of this process remains challenging (Lundquist et al., 2024). Comparisons across six sublimation models revealed substantial differences among model estimates, indicating a lack of consistent agreement across all sites (Boelman, 2019; Yang & Bai, 2023). Theoretically, this simplification—particularly the omission of snow sublimation—would lead to overestimated SWE in model results. However, comparisons with observed SWE from 15 SNOTEL stations revealed no systematic overestimation in our simulations; instead, underestimation occurred in some cases (Figure 3). This suggests that neglecting sublimation may not substantially affect the simulation of snow accumulation and melting processes. Furthermore, as illustrated in Figure 1, neglecting sublimation and condensation implies an assumption that snowmelt (M) equals snowfall (P_{snow}). Whereas sublimation plays a non-negligible role, this assumption may lead to potential underestimation of E_{snow} and E , and overestimation of M , Q_{snow} , and Q . Based on the equations for f_{SR} and f_{SE} (Equations 2 and 3), this would result in a slight overestimation of f_{SR} and underestimation of f_{SE} . Similarly, from the equations for $f_{Q_{snow}}$ and $f_{E_{snow}}$ (Equation 4 and 5), a marginal overestimation of $f_{Q_{snow}}$ and underestimation of $f_{E_{snow}}$ would be expected. Overall, further investigation into sublimation and condensation processes is warranted to improve their parameterization in large-scale studies.

Furthermore, the choice of the degree-day method over the energy balance approach also deserves clarification. The degree-day method is widely used in large-scale hydrological modeling due to its robustness under data-limited conditions (Hock, 2003). While physically based energy-balance models explicitly resolve radiative and turbulent fluxes, they require numerous input variables that are often not directly observed and must be derived from reanalysis or remote sensing products, introducing substantial uncertainties, particularly in mountainous and high-latitude regions. In contrast, the degree-day approach implicitly integrates the net effect of these energy fluxes through temperature, which has been shown to provide reliable estimates of snowmelt dynamics at regional to global scales with regionalized values (Ismail et al., 2023; Yong et al., 2026). In the context of this study, which focuses on the partitioning of snowmelt rather than resolving detailed energy exchange processes, the degree-day method provides a parsimonious and sufficiently accurate representation of snowmelt processes, while avoiding the propagation of uncertainties associated with poorly constrained energy balance components. Moreover, the close agreement between simulated and observed SWE further supports the reliability of this approach.

Additionally, the FLEX-Global applies the same partitioning mechanism to both snowmelt and rainfall. Because snowmelt generally occurs more slowly than rainfall (Jia et al., 2023), a larger fraction may infiltrate into the root zone as compared to rainfall infiltration, potentially leading our approach to underestimate the proportion of snowmelt contributing to evaporation. On the other hand, frozen soil processes are not considered in this study. In permafrost regions, snowmelt infiltration is limited compared with non-frozen soils, implying that our analysis may overestimate evaporation fractions (Chang et al., 2024). These two simplifications act in opposite directions, introducing some uncertainty into the global estimates, but their combined influence is unlikely to change the key spatial and climatic patterns identified in this study.

Under future climate change, snowfall is projected to decline, with precipitation shifting from snowfall to rainfall (Huss et al., 2017). Since the runoff coefficient of snowmelt is generally higher than that of rainfall (Berghuijs

et al., 2014), such a transition is likely to reduce runoff and enhance evaporation in cold regions, posing potential challenges for regional water security. However, this effect may depend on the relative importance of surface and subsurface runoff processes. In particular, increased rainfall and rain-on-snow events under warming climates may enhance surface runoff generation in some snow-dominated regions, potentially offsetting the reduction in snowmelt-derived runoff (Hotovy et al., 2025; Maina & Kumar, 2025). The net effect of these competing processes on future runoff volume therefore remains uncertain and warrants further investigation.

5. Conclusions

This study presents a new perspective on the contribution of snowmelt to runoff and evaporation: snowmelt that flows into rivers is defined as blue water, while the portion infiltrating into soils and subsequently taken up by vegetation to support evaporation is defined as green water. To highlight the critical role of snow in meeting the water demands of both terrestrial ecosystems and human societies, we employed the process-based FLEX-Global model to simulate the global partitioning of snowmelt into runoff (f_{SR}) and evaporation (f_{SE}) for the 1980–2014 period. To enhance the robustness of our results, we further validated FLEX-Global simulations against observed streamflow, SWE, an empirical equation method, and inverse estimations from three ISIMIP global hydrological models.

Our results show that globally, 53%–71% of snowmelt (on average 65%, $5,381 \text{ km}^3 \text{ yr}^{-1}$) contributes to runoff (f_{SR}), while 29%–47% (on average 35%, $2,847 \text{ km}^3 \text{ yr}^{-1}$) contributes to evaporation (f_{SE}). The fraction of snowmelt contributing to runoff (f_{SR}) increases with latitude and elevation. In contrast the fraction of snowmelt contributing to evaporation (f_{SE}) reaches up to 63%–91% in arid regions, providing essential water resources for fragile ecosystems. Further analysis reveals that the proportion of snowmelt-derived runoff in the composition of global total runoff ($f_{Q_{snow}}$) is 11%–18% and the proportion of snowmelt-derived evaporation in the composition of global total evaporation ($f_{E_{snow}}$) is 4%–8%, and both are also increase with latitude. In high-elevation regions, $f_{Q_{snow}}$ reaches 58%–74%, $f_{E_{snow}}$ reaches 51%–66%, whereas the corresponding fractions in low-elevation areas are with 22%–30% and 26%–35%, respectively, significantly lower. These results underline the hydrological and ecological significance of snowmelt in high mountain regions. Additionally, the traditional definition of snowmelt runoff ($f_{SR_{old}}$) yields a value of 38%, which substantially overestimates snowmelt-derived runoff compared with $f_{Q_{snow}}$ after accounting for the portion of snowmelt allocated to ecosystem.

Overall, this study provides the first global-scale estimates of the partitioning of snowmelt into runoff and evaporation and their spatial patterns, offering a foundation for future research on the role of snowmelt in water resources and ecosystems. With the advancement of hydrological models and forcing data sets, future studies are expected to further deepen our understanding of ecohydrological processes and provide more robust scientific support for the management of snowmelt resources.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The forcing data and output data from hydrological model simulations (e.g., H08, WaterGAP2, and HydroPy) used in this study are publicly available from the Inter-Sectoral Impact Model Intercomparison Project Phase 3b (ISIMIP3b, <https://www.isimip.org/>). The SWE validation was conducted using in situ observational data from the SNOTEL network (<https://www.wcc.nrcs.usda.gov/snow/>) and the ESM-SnowMIP project (Menard & Essery, 2019).

Code availability: All the code files for data compilation and analysis used in this Article are available from Zhou (2026).

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