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Origins of Precipitation in the World's Water Towers

Bomei Zhang¹ , Hongkai Gao¹ , Lan Wang-Erlandsson^{2,3,4,5} , and Yan Li^{6,7}

Key Points:

- About 50% of precipitation in water tower units (WTUs) originates from terrestrial evaporation, with inland WTUs more reliant than coastal ones
- Short vegetation transpiration dominates terrestrial moisture contributions globally, while forests and bare soil contribute regionally
- Oceanic moisture drives snowfall, whereas terrestrial transpiration sustains rainfall—except in parts of the southern Tibetan Plateau

Supporting Information:

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

Correspondence to:

H. Gao,
hkgao@geo.ecnu.edu.cn

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Author Contributions:

Conceptualization: Bomei Zhang, Hongkai Gao, Lan Wang-Erlandsson
Formal analysis: Bomei Zhang
Funding acquisition: Hongkai Gao
Project administration: Hongkai Gao
Resources: Hongkai Gao
Supervision: Hongkai Gao
Visualization: Bomei Zhang, Lan Wang-Erlandsson, Yan Li
Writing – original draft: Bomei Zhang
Writing – review & editing: Bomei Zhang, Hongkai Gao, Lan Wang-Erlandsson, Yan Li

¹State Key Laboratory of Estuarine and Coastal Research, Key Laboratory of Geographic Information Science (Ministry of Education), School of Geographic Sciences, East China Normal University, Shanghai, China, ²Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden, ³Anthropocene Laboratory, The Royal Swedish Academy of Sciences, Stockholm, Sweden, ⁴Potsdam Institute for Climate Impact Research, Potsdam, Germany, ⁵Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden, ⁶State Key Laboratory of Earth Surface Processes and Hazards Risk Governance (ESPHR), Beijing Normal University, Beijing, China, ⁷Institute of Land Surface System and Sustainable Development, Faculty of Geographical Science, Beijing Normal University, Beijing, China

Abstract High-mountain systems act as the planet's vital water towers, sustaining freshwater supplies for billions of people. Climate change is exacerbating hydrological imbalances in these regions, yet the moisture sources maintaining their precipitation—the primary water input—remain poorly quantified. Here, we combine two atmospheric moisture tracking methods to analyze 73 water tower units (WTUs), revealing that terrestrial evaporation contributes approximately half of total precipitation (52% UTrack, 50% WAM-2layers) over these regions, with inland WTUs relying more on land-sourced moisture than coastal systems. Transpiration from short vegetation dominates terrestrial contributions globally, while forest transpiration (e.g., Amazon) and bare-soil evaporation (e.g., interior Tibetan Plateau) are regionally significant. Importantly, oceanic moisture drives snowfall, whereas terrestrial transpiration sustains rainfall—except in the southern Tibetan Plateau. These findings refine the atmospheric water cycle's role in high-mountain hydrology, offering a mechanistic basis to project water tower resilience under global change.

Plain Language Summary High mountain regions, known as world's water towers, supply essential freshwater resources to billions of people. While precipitation is their primary water source, it has been unclear exactly where this moisture originates. In this study, we tracked atmospheric moisture sources for 73 water tower units (WTUs) and found that roughly half of the precipitation comes from terrestrial evaporation, predominantly through transpiration from short vegetation. Inland WTUs depend more heavily on terrestrial moisture sources compared to coastal WTUs. Regionally, forest transpiration is notably important in some WTUs located in the Central Andes, while bare-soil evaporation plays a key role in the interior Tibetan Plateau. Additionally, ocean-derived moisture primarily contributes to snowfall, whereas terrestrial moisture, especially vegetation transpiration, largely sustains rainfall—except in the southern Tibetan Plateau. These results provide crucial insights into how changes in climate and land use, even in distant regions, may affect water supplies in these critical regions.

1. Introduction

High mountains serve as the world's water towers due to their water supply and storage functions (Immerzeel et al., 2020). As headwaters of many major rivers, they supply water to both local and downstream regions (Viviroli et al., 2007). Additionally, the lower temperatures at high altitudes allow water to be stored as snow and ice, ensuring a consistent supply during hot and dry periods (Pritchard, 2019). The water tower functions in the world's high mountains provide a foundation for implementing critical ecosystem services (Grêt-Regamey & Weibel, 2020; Ren et al., 2022) and meeting the water requirements of billions of people (Viviroli et al., 2020). However, global warming is accelerating glacier retreat and snowmelt (Dussaillant et al., 2020; Huss & Hock, 2018). The permanent water stored in high mountains is shrinking fast, making precipitation increasingly important for maintaining sustainable water resources in these regions (Fan et al., 2022; Yao et al., 2022; Zhang, Shen, et al., 2023). Yet, the sources of high-mountain precipitation remain poorly quantified, limiting our capacity to assess water security.

Precipitation can fall as solid, liquid, or mixed phases, each of which has distinct impacts on the water cycle (Li et al., 2020; Song & Liu, 2021). Rainfall typically infiltrates into soils, replenishes root zone soil moisture deficits, and drains into aquifers and rivers (Gao et al., 2024). Snowfall, by contrast, often accumulates as surface

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snowpack and later melts, contributing to runoff and groundwater recharge as temperatures rise above a critical threshold. Moreover, snowfall is a crucial component in maintaining glacial mass balance (Kumar et al., 2019), and it also increases surface albedo and lowers land surface temperature, thereby influencing meteorological and climatic patterns (Senan et al., 2016; Yuan et al., 2019). In snowy seasons, much of the precipitation is stored temporarily and released during subsequent seasons (Kirchner & Allen, 2020). Since the hydrological impacts of rainfall and snowfall differ markedly, identifying their respective moisture sources is crucial for sustaining high-mountain water tower functions.

Atmospheric water cycle describes the process from evaporation and moisture transport to the formation of precipitation. Globally, over 40% of continental precipitation originates from evaporation from land (Tuinenburg et al., 2020a; van der Ent et al., 2010). Under the influence of topography and atmospheric circulation, the role of terrestrial moisture sources in precipitation varies across different regions (Dirmeyer et al., 2014; Gimeno et al., 2012). High mountains, in particular, are a key terrain feature influencing the terrestrial moisture recycling process. Additionally, considering land surface biophysical conditions, such as vegetation regulation (Keys et al., 2016), different types of land evaporation play different roles in terrestrial moisture recycling (Te Wierik et al., 2022; van der Ent et al., 2014). For instance, while bare soil evaporation depends only on soil moisture and solar radiation, forest transpiration, due to complex canopy structures and deep roots, provides greater and more stable evaporation compared to other short vegetation (O'Connor et al., 2021; Mu et al., 2021; Staal et al., 2024). At the same time, climate-driven increases in oceanic evaporation indicate a growing contribution of oceanic sources to continental precipitation (Findell et al., 2019), highlighting the need to quantify the relative roles of terrestrial and oceanic moisture sources.

Here, we integrate two independent atmospheric moisture tracking methods to quantify the relative contributions of terrestrial and oceanic sources to precipitation across 73 global water tower units (WTUs), with explicit consideration of land-surface biophysical properties. By partitioning rainfall and snowfall, we uncover distinct source patterns. These findings offer a globally consistent diagnosis of high-mountain precipitation origins, with implications for water security and hydroclimate resilience under climate change.

2. Materials and Methods

2.1. Study Area

This study focuses on high-mountain regions classified as WTUs, following the definition of Immerzeel et al. (2020). WTUs represent the intersections of major global river basins with mountainous areas that contain either glacier volumes exceeding 0.1 km³ or average annual snow cover persistence greater than 10%. These regions not only generate substantial orographic precipitation that feeds downstream runoff but also store water in snowpack and glacier ice, buffering seasonal and interannual variability. Due to limitations in the atmospheric moisture connection data set and uncertainties in evaporation data related to condensation processes (Link et al., 2020; Tuinenburg et al., 2020a), we excluded five high-latitude WTUs to ensure the reliability of atmospheric moisture tracking. A total of 73 WTUs were selected for analysis (Table S1 in Supporting Information S1).

2.2. Quantifying Moisture Source Contributions

Atmospheric moisture connection data sets were used to track the moisture sources for each WTU. We primarily employed the UTrack atmospheric moisture connection data set (Tuinenburg et al., 2020b), a Lagrangian moisture tracking product generated by the UTrack model and driven by ERA5 reanalysis (Hersbach et al., 2023). This data set provides a global 10-year (2008–2017) monthly climatology at 0.5° spatial resolution and reports fractions of evaporation allocated to downwind precipitation from the source grid. To ensure water balance, we combined the UTrack data set with ERA5 evaporation data to quantify the moisture contribution value to each WTU as follows:

$$E_{i \rightarrow \text{WTU}} = \sum_{j \in \text{WTU}} E_i \times f_{i \rightarrow j}$$

where $E_{i \rightarrow \text{WTU}}$ represents the moisture contribution value from source grid cell i to the target WTU. Here, i denotes the source grid cell, and j denotes the sink grid cell located in the WTU. $f_{i \rightarrow \text{WTU}}$ is the fraction of evaporation allocated to grid cell j from the source grid cell i . E_i represents the total evaporation from grid cell i .

Furthermore, based on the moisture contribution value for the WTU, we can calculate the moisture contribution ratio for the target WTU as follows:

$$F_{i \rightarrow \text{WTU}} = \frac{E_{i \rightarrow \text{WTU}}}{\sum_{i \in \text{global}} E_{i \rightarrow \text{WTU}}}$$

$F_{i \rightarrow \text{WTU}}$ is the moisture contribution ratio from source grid cell i to the target WTU.

Through the above equation, we can calculate the moisture contribution from any grid cell i worldwide to the target WTU. Subsequently, for a specific moisture source region, for example, if we want to evaluate the importance of terrestrial contribution, just need to sum the value of $E_{i \rightarrow \text{WTU}}$ for all grid cell i located on land ($\sum_{i \in \text{land}} E_{i \rightarrow \text{WTU}}$) in the numerator, and then proceed with the subsequent calculations.

Additionally, we used the WAM-2layers atmospheric moisture tracking data set (Link et al., 2019) to verify the terrestrial evaporation contribution. This data set is generated by the Eulerian moisture tracking model, WAM-2layers (Water Accounting Model–2 layers; van der Ent et al., 2013, 2014), and driven by ERA-Interim reanalysis data, and it provides the evaporation destinations for most land grid cells between 79.5°N and 79.5°S, excluding Greenland and Antarctica, at a spatial resolution of 1.5° and monthly temporal resolution. It directly provides the moisture contribution value from source grid cell i to the sink grid cell j ($E_i \times f_{i \rightarrow j}$). Since the source grid cells encompass most terrestrial regions, the data set enables an independent verification of land-derived contributions to WTU precipitation. These two moisture tracking products are widely used to quantify moisture source-sink relationships (Nyasulu et al., 2024; Posada-Marín et al., 2024; Theeuwens et al., 2023; Zan et al., 2024). Results based on UTrack are presented in the main text, while those from WAM-2layers are shown in the Supporting Information S1 for validation purposes.

2.3. Attributing Moisture Contributions by Evaporation Type

To attribute terrestrial contributions by evaporation type, we used GLEAM v3.8a evaporation data (Martens et al., 2017) and MCD12C1 land cover data (Friedl & Sulla-Menashe, 2022) from 2008 to 2017. The GLEAM ET data set provides monthly estimates of terrestrial evaporation components, including transpiration (E_t), bare soil evaporation (E_b), interception loss (E_i), snow sublimation (E_s), and open-water evaporation (E_w), at a spatial resolution of 0.25°. The land cover type data used is MCD12C1, generated by the MODIS-derived LAI/FPAR scheme, with a spatial resolution of 0.05°. To better reflect the impact of terrestrial vegetation, we reclassified the MCD12C1 land cover types into four categories: forests, short vegetation, bare lands, and land water bodies (Table S2 in Supporting Information S1). Both data sets were aggregated to match the resolution of UTrack (0.5°) and WAM-2layers (1.5°). Assuming evaporation types within the same grid cell are well mixed and share common moisture trajectories, the moisture contribution from different land evaporation types is as follows:

$$f_{\text{etype, land} \rightarrow \text{WTU}} = \frac{\sum_{i \in \text{land}} E_{f_{\text{etype}, i}} \times E_{i \rightarrow \text{WTU}}}{\sum_{i \in \text{global}} E_{i \rightarrow \text{WTU}}}$$

where $f_{\text{etype, land} \rightarrow \text{WTU}}$ represents the moisture contribution ratio from different land evaporation types to the target WTU region, $E_{f_{\text{etype}, i}}$ represents the proportion of specific evaporation components (e.g., transpiration) accounts for the total evaporation in grid cell i (through GLEAM) or the areal proportion of specific land cover types (e.g., forest) in grid cell i (through MCD12C1).

2.4. Partitioning Moisture Contributions by Precipitation Phase

Considering that different precipitation phases exert distinct influences on hydrological and climatic processes, as well as on the water tower functions of WTUs, we classified precipitation into two simplified categories: snowfall and rainfall. We utilized monthly ERA5 precipitation and snowfall data from 2008 to 2017 at a spatial resolution

of 0.5°. The ERA5 precipitation data include all forms of precipitation, while the snowfall data set includes only snowfall. Similar definitions have been used in other reanalysis-based studies, where rainfall is obtained by subtracting snowfall from total precipitation (Sun et al., 2023; Wang et al., 2022). This allows derivation of snowfall and rainfall proportions relative to total monthly precipitation for each WTU. The equation used to calculate the moisture contributions for different precipitation phases is as follows:

$$f_{i \rightarrow \text{WTU_ptype}} = \frac{E_{i \rightarrow \text{WTU}} \times Pf_{\text{ptype,WTU}}}{\sum_{i \in \text{global}} E_{i \rightarrow \text{WTU}} \times Pf_{\text{ptype,WTU}}}$$

where $f_{i \rightarrow \text{WTU_ptype}}$ represents the ratio of moisture contributions from grid cell i to a specific precipitation phase (snowfall or rainfall) of the target WTU, $Pf_{\text{ptype,WTU}}$ denotes the proportion of snowfall or rainfall that accounts for the total precipitation in target WTU. Both the numerator and denominator are first calculated on a monthly basis and then aggregated to obtain annual-scale values, thereby capturing intra-annual variability in precipitation phases and source contributions. Furthermore, by considering the spatial extent of grid cells i or different evaporation types in grid cell i , we can further discuss the role of specific moisture source regions or evaporation types.

3. Results

3.1. The Moisture Sources of Precipitation Over WTUs

To facilitate regional comparison of moisture source characteristics, 73 WTUs were grouped into 11 subregions based on major mountain systems and atmospheric circulation patterns (Table S1 in Supporting Information S1). Using the precipitationshed framework, core moisture source regions were defined as those contributing cumulatively to the first 40% of precipitation in each WTU (Keys et al., 2012; Zhang, Gao, & Wei, 2023). The results clearly indicate that WTUs within the same subregion exhibit similar core moisture source patterns (Figure 1). In the North American Rockies, moisture sources are primarily influenced by prevailing westerly winds from the Pacific Ocean. For WTUs in Northeastern America, a substantial amount of moisture is contributed by the nearby North Atlantic Ocean, with additional input transported from the North American continent by westerly winds. In the North Andes, easterly trade winds carry some moisture from the Atlantic Ocean. In the Central Andes, low-level jets over South America exert a dominant influence. In the South Andes, prevailing westerly winds from the South Pacific Ocean are the primary contributors. The moisture of the Scandinavian WTUs mainly originates from the North Atlantic Ocean. In the Alps, the moisture sources of the WTUs are concentrated in the Mediterranean Sea and its surrounding areas, while moisture transported by westerly winds from the North Atlantic also contributes to precipitation. In Northern Eurasia, the moisture sources of the WTUs are mainly affected by westerlies transporting moisture from the Eurasian continent. In the Middle East and Central Asia, major moisture sources include the Arabian Sea and several enclosed or semi-enclosed seas, such as the Red Sea, the Mediterranean Sea, the Caspian Sea, the Black Sea, as well as the surrounding land areas near the WTUs. For the WTUs in the Tibetan Plateau, moisture sources originating within the plateau itself contribute significantly. In New Zealand, the moisture source of the WTU is mainly affected by prevailing westerly winds from the Tasman Sea.

However, due to the impact of topography and atmospheric circulation, some adjacent WTUs exhibit notable differences in their moisture sources. For instance, Sodemann and Zuber (2010) noted that the Alps serve as a barrier to meridional moisture transport. Actually, the WTUs in the southern Alps receive more precipitation from the Mediterranean Sea than those in the northern Alps (Figure S4 in Supporting Information S1). The WTUs in the Tibetan Plateau are similarly affected by orography (Zhang, C. et al., 2019) and moisture sources in the northern and southern regions are notably different (Figure S7 in Supporting Information S1). In the northern Tibetan Plateau, moisture sources are primarily influenced by local moisture recycling and prevailing westerly winds, with most sources located within the plateau. In the southern Tibetan Plateau, the Indian monsoon plays an important role, with some moisture sources transported from the south region of the plateau and the Indian Ocean. In the South American Andes, prevailing winds create a sharp contrast in the moisture sources of the northern and southern Andes. Furthermore, due to the blocking effect of the mountains, the Pacific Ocean contributes moisture to the western slope of the Central Andes, whereas the eastern slope receives less (Figure S9 in Supporting Information S1).

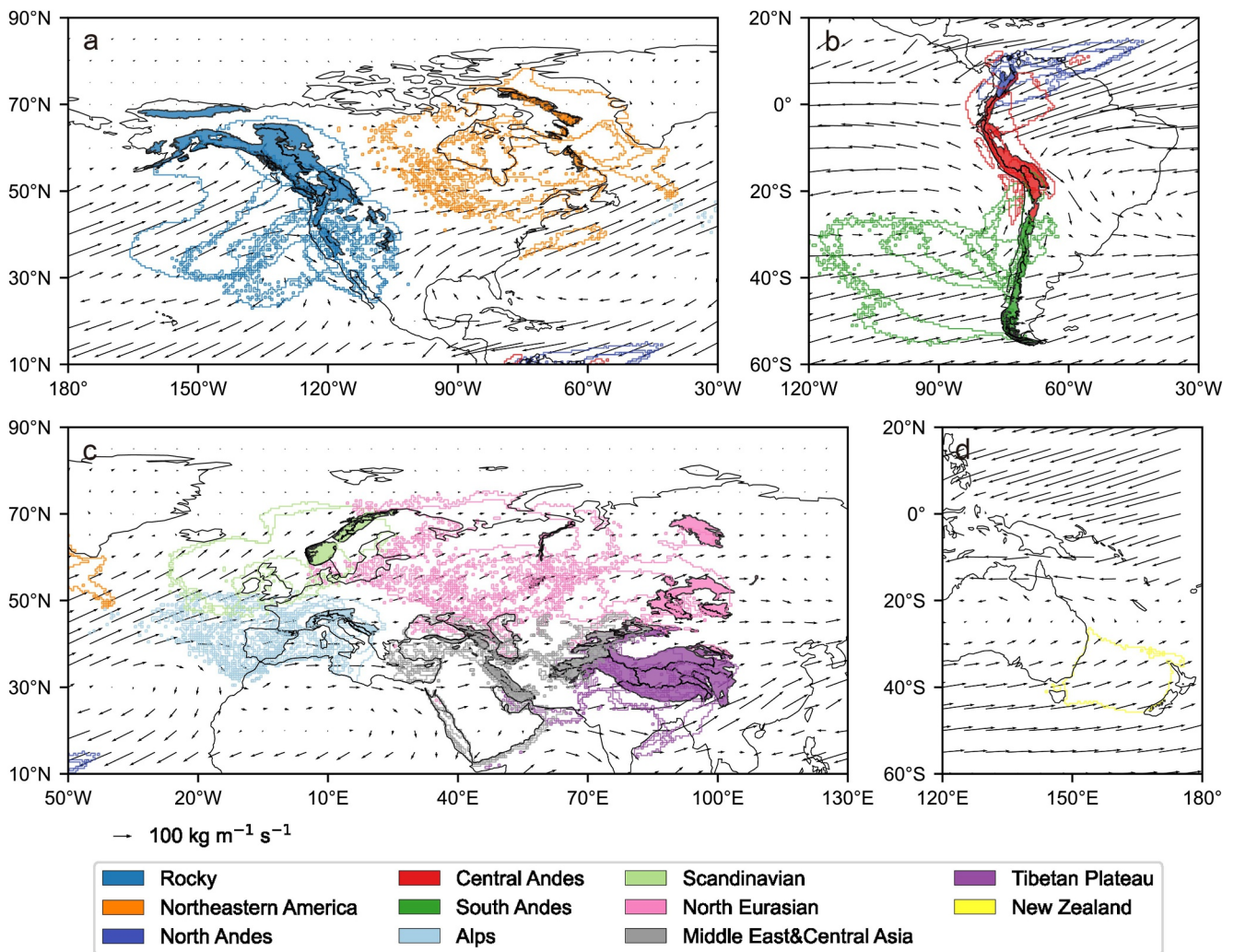


Figure 1. Spatial distribution of the core moisture sources for the 73 global water tower units (WTUs) during 2008–2017. (a)–(d) Show WTUs and their corresponding core source regions over (a) North America, (b) South America, (c) Eurasia, and (d) Oceania. The 73 WTUs are grouped into 11 subregions, each represented by a unique color (see legend at bottom). Colored areas represent the WTUs, while solid contours of the same color delineate their respective core moisture source regions. Black arrows indicate the climatological horizontal (vertically integrated) moisture flux. Detailed moisture source information for each WTU is provided in Figures S1–S11 in Supporting Information S1.

3.2. Terrestrial Moisture Contributions to Precipitation Over WTUs

For the 73 WTUs worldwide, terrestrial evaporation contributes about half of the total precipitation (Figures 2a–2d and Figures S12a–d in Supporting Information S1). The average terrestrial contribution ratio to precipitation over WTUs is approximately 52% in the UTrack model and 50% in the WAM-2layers model. Regarding individual WTUs, the UTrack model identifies 38 WTUs where over 50% of precipitation originates from terrestrial moisture recycling, while the WAM-2layers model shows this for 36 WTUs. Both models consistently show that WTUs with higher terrestrial contribution ratios are mainly located in the northern Tibetan Plateau, such as the Huang He (the Yellow river) and the Tarim Interior. Additionally, the spatial distribution of the terrestrial contribution ratio for each WTU shows that WTUs located inland have a higher terrestrial contribution ratio than those near the ocean. In North America, WTUs in the western Rocky Mountains, closer to the Pacific Ocean, exhibit lower terrestrial moisture contributions than WTUs in the eastern Rockies. Similarly, in South America, the Andes Mountains follow the same pattern. In Eurasia, WTUs in the Alps, situated closer to the ocean, show lower terrestrial contributions than those in the Tibetan Plateau, which is located in the continental interior. Meanwhile, WTUs in the northern Tibetan Plateau have higher terrestrial contributions compared to those in the southern Tibetan Plateau, which is nearer to the Indian Ocean.

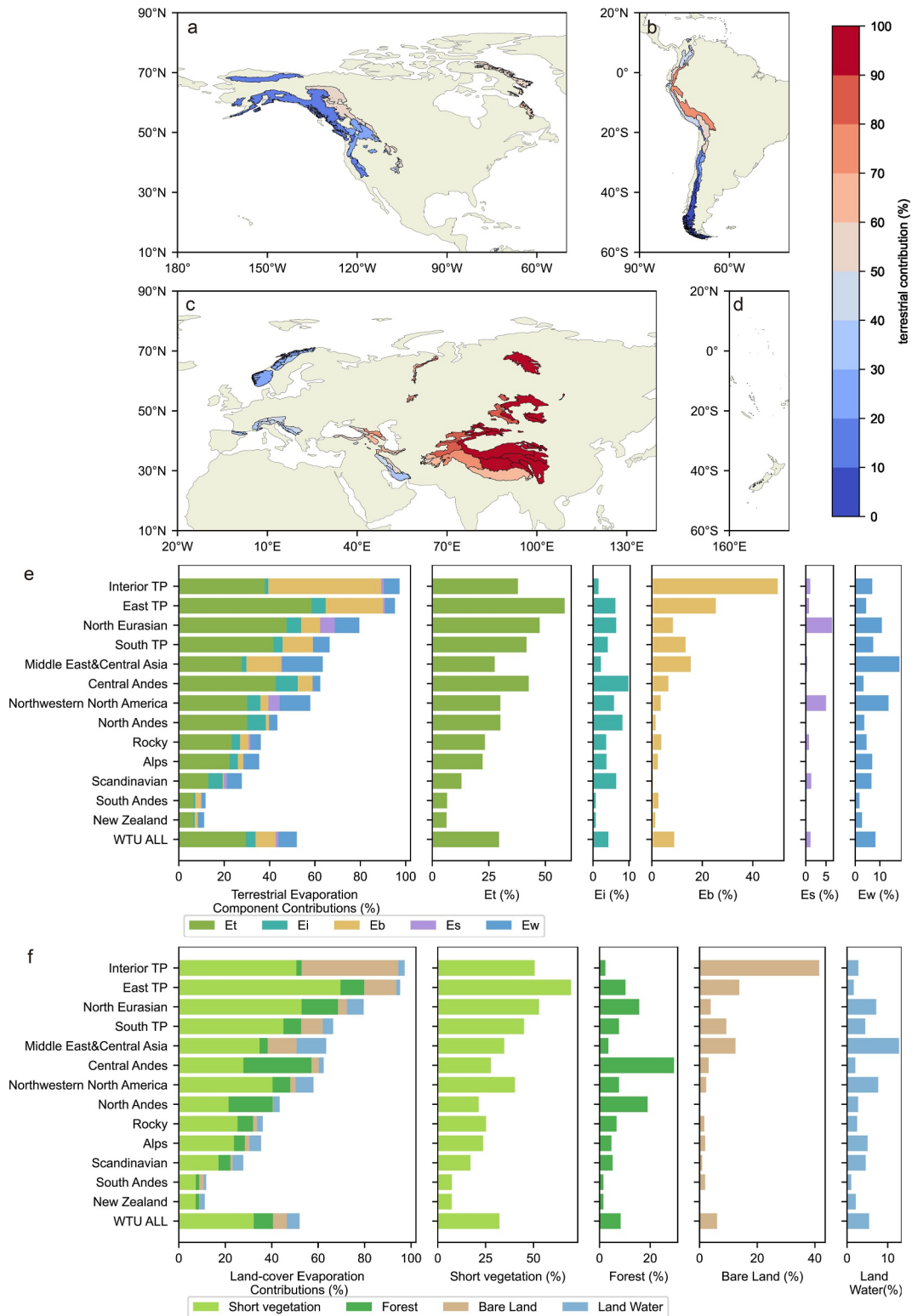


Figure 2.

According to the moisture contribution from different land evaporation types, both models revealed similar spatial patterns (Figures S13 and S14 in Supporting Information S1). Among the various land evaporation components, transpiration (E_t) and bare soil evaporation (E_b) play a significant role in certain WTUs. Spatially, WTUs located downwind of the Amazon rainforest, such as La Plata, and those situated in the Eurasian interior, such as Huang He, receive over 50% of their precipitation from terrestrial transpiration. In the interior of the Tibetan Plateau, WTUs like the Tarim Interior and Plateau of Tibet Interior benefit significantly from bare soil evaporation as a terrestrial moisture source. Meanwhile, contributions from interception loss (E_i), snow sublimation (E_s), and open water evaporation (E_w) are generally lower but show distinct spatial patterns. WTUs with higher interception contributions are often accompanied by higher transpiration contributions, particularly from forests, as observed in the Amazon. Enhanced land water evaporation contributions are primarily observed in WTUs located downwind of large inland water bodies, such as the Caspian Sea and Aral Sea. Moreover, WTUs at high latitudes exhibit relatively greater contributions from snow sublimation.

For most WTUs, a significant portion of terrestrial moisture originates from transpiration, particularly from short vegetation (Figures 2e–f and Figure S12e–f in Supporting Information S1). On average, terrestrial vegetation transpiration accounts for approximately 29.5% of precipitation based on the UTrack model and 26.4% according to the WAM-2layers model, making it the dominant terrestrial moisture source in nearly all WTUs (Figures S15–S18 in Supporting Information S1). To better capture regional variability, WTUs on the Tibetan Plateau were subdivided into South, Interior, and East subregions, based on their distinct patterns of terrestrial evaporation contributions (Figures S13 and S14 in Supporting Information S1). Among all subregions, the three subregions with the highest transpiration contributions are East TP (58.5%), North Eurasia (47.5%), and Central Andes (42.6%), according to UTrack. In East TP and North Eurasia, transpiration is predominantly from short vegetation such as grasslands, accounting for 69.6% and 52.9% of precipitation, respectively. In contrast, forest transpiration is more influential in the Central Andes (29.4%), accompanied by relatively high interception loss (9.8%). Bare soil evaporation remains a key contributor in the interior Tibetan Plateau, providing 49.9% of precipitation in UTrack and 31.0% in WAM-2Layers. Additionally, WTUs in the Middle East and Central Asia show relatively elevated contributions from inland water evaporation.

3.3. Moisture Source Characteristics for Different Precipitation Phases

Different precipitation phases exert distinct influences on hydrological and climatic processes. For the comparison of moisture sources between snowfall and rainfall, WTUs in the North Andes were excluded from the analysis due to negligible snowfall (Figure S21 in Supporting Information S1). For most remaining WTUs, ocean evaporation contributes more to snowfall (56.4%) than to rainfall (43.0%), while terrestrial plant transpiration shows the opposite pattern, contributing 33.9% to rainfall and 20.8% to snowfall (Figure 3). This difference may be attributed to vegetation growth, which naturally ceases during the cold season, leading to reduced transpiration. However, in parts of the southern Tibetan Plateau, terrestrial transpiration contributes more to snowfall than ocean evaporation, possibly due to monsoon influence and relatively warm winter conditions. Additionally, WTUs such as those on the Tibetan Plateau, where snowfall occurs year-round, exhibit minimal differences in moisture source contributions across precipitation phases. In contrast, snowfall is extremely rare throughout the year in low-latitude WTUs such as the Central Andes. Snow sublimation also plays an important role in snowfall events, particularly in high-latitude regions.

Among all precipitation phases, snowfall is particularly important for the storage function of WTUs due to its high accumulation potential. To characterize seasonal snowfall patterns, we defined the snowy season as December to February in the Northern Hemisphere and June to August in the Southern Hemisphere based on the snow-to-precipitation ratios of WTUs (Figures S19–S21 in Supporting Information S1). During these periods, moisture source regions tend to contract spatially, especially for terrestrial contributions (Figures S22–S31 in Supporting Information S1). In the North American Rockies, oceanic sources from the Pacific dominate, while continental inputs decline. Similar patterns are observed in the South Andes, Northwestern America, Scandinavia, and the

Figure 2. Terrestrial moisture contributions to precipitation across the 73 global water tower units (WTUs). (a)–(d) Spatial distribution of the terrestrial contribution to precipitation for WTUs over (a) North America, (b) South America, (c) Eurasia, and (d) Oceania. (e)–(f) Relative contributions of (e) terrestrial evaporation components and (f) land-cover types to precipitation in each subregion and the global average (WTU ALL). Terrestrial evaporation components include transpiration (E_t), interception loss (E_i), bare soil evaporation (E_b), snow sublimation (E_s), and open-water evaporation (E_w). Land-cover types are categorized as short vegetation, forest, bare land, and land water. Subregions are ordered from top to bottom by decreasing terrestrial contribution.

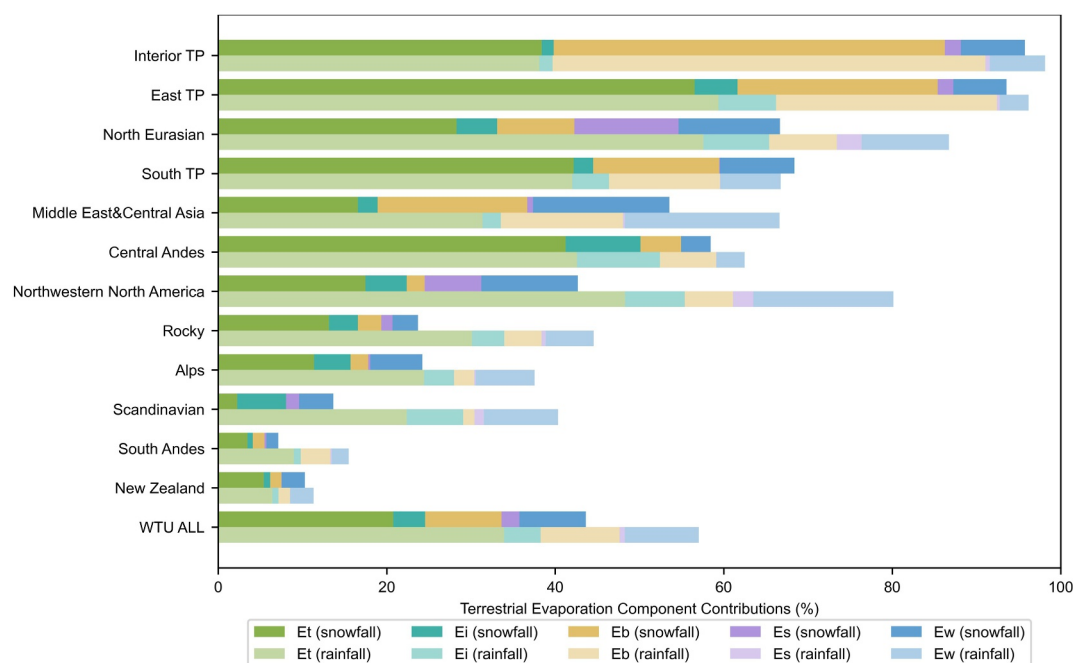


Figure 3. Contributions of terrestrial evaporation components to snowfall and rainfall. The bars show the average contributions of five terrestrial evaporation components to snowfall (upper, darker colors) and rainfall (lower, lighter colors) across water tower units (WTUs) within each subregion and the global average (WTU ALL).

Alps, where continental sources diminish and oceanic contributions dominate. In Northern Eurasia, oceanic and inland water sources, such as the Caspian Sea, become increasingly important, while continental Eurasian inputs decrease (Figure S26 in Supporting Information S1). In the Tibetan Plateau, western source regions such as the Red Sea and Persian Gulf are key contributors, while WTUs in the southern plateau (e.g., Irrawaddy, Ganges-Brahmaputra) continue to receive substantial input from the continent, likely influenced by monsoonal influence (Figure S28 in Supporting Information S1). These seasonal patterns are consistent with findings by Cheng and Lu. (2023), who reported similar trends across global monsoon and mid-to-high latitude regions.

4. Discussions

Global warming threatens the water balance of the world's water towers, increasing reliance on precipitation to sustain their water availability. Our analysis of 73 WTUs highlights the critical role of terrestrial moisture recycling in continental precipitation, with high mountains acting as key terrain features that shape the fate of terrestrial evaporation. For WTUs located farther inland, such as the northern Tibetan Plateau and Central-eastern Andes, precipitation is more dependent on terrestrial evaporation, increasing their vulnerability to land cover changes. For example, Amazon deforestation reduces local evaporation, disproportionately decreasing downwind precipitation (Zemp et al., 2017). Ecological restoration projects on the Tibetan Plateau have been shown to enhance downwind precipitation (Li et al., 2023). Moreover, although WTUs are upstream in their watersheds, their main moisture sources often originate from distant upwind regions (Keune & Miralles, 2019; Wang-Erlandsson et al., 2018), revealing a spatial disconnect that challenges traditional watershed-based management (Gebrehiwot et al., 2019; Sang et al., 2025). In some WTUs, such as those in the Central-eastern Andes and Central Asia, primary moisture sources are located in their downstream areas, highlighting the importance of considering co-dependence within the same watershed in future integrated water resource management strategies. In the Tibetan Plateau, strong regional moisture recycling confines core moisture source areas largely to the plateau itself, creating a “double water tower” effect with major implications for regional water governance. Considering potential land cover changes (Fahrländer et al., 2024; Weng et al., 2018), integrating atmospheric water cycle processes into water resource management strategies (Berger et al., 2014; Keys et al., 2017) is essential for future hydrological assessments and for promoting water sustainability.

Although our analysis offers a climatological perspective on moisture sources for WTUs, it is based on a 10-year (2008–2017) average climatological condition. As such, it does not resolve decadal variability or longer-term trends, and the results should be interpreted as a baseline climatology rather than a full description of ongoing changes. In recent decades, both evaporation patterns and atmospheric circulation have been substantially altered by warming and human activity (Findell et al., 2019). Global evaporation has been increasing, while land cover variations, such as vegetation greening, have shifted the proportions of different types of evaporation (Yang et al., 2023; Zhuang et al., 2024). Productive (e.g., transpiration) and non-productive (e.g., interception loss, soil evaporation) evaporation play distinct roles in the atmospheric water cycle, with the latter recycling more rapidly in the atmosphere (van der Ent et al., 2014). Seasonal vegetation dynamics and warming further shift evaporation composition. For example, while warming raises the likelihood of snowfall melting before reaching the surface, intensified evaporation from retreating Arctic sea ice has paradoxically contributed to increased high-latitude precipitation, particularly in the form of extreme snowfall events (Bailey et al., 2021; Liu et al., 2024). In addition, global atmospheric circulation patterns are shifting, including the expansion of the Hadley circulation (Shaw, 2019). Ocean–atmosphere interactions, such as El Niño and La Niña events, are also expected to modify the atmospheric water cycle (Posada-Marín et al., 2023). Land-use feedbacks can also alter atmospheric circulation. For example, large-scale irrigation in India has been associated with a weakening of the monsoon system (Douglas et al., 2009). In future research, it is crucial to examine both historical and projected variations in moisture source characteristics, along with their key drivers. Such investigations are essential for assessing the vulnerability of WTUs and informing integrated strategies for managing these critical water towers under a changing climate.

This study integrates two moisture tracking methods to assess the moisture source characteristics of the world's water towers. However, several unavoidable limitations persist, including data accuracy, model assumptions, and coarse spatial resolution. Limitations in moisture connectivity and evaporation data related to condensation processes increase uncertainty in high-latitude areas (Link et al., 2020; Tuinenburg et al., 2020a). Although some high-latitude WTUs were excluded, other regions may still be affected. Furthermore, both moisture-tracking models exhibit limitations in mountainous regions. In WAM-2Layers, the simplified two-layer structure cannot fully capture atmospheric processes over complex mountainous topography (Kalverla et al., 2025; Link et al., 2020). Likewise, UTrack shows larger deviations from ERA5 in mountainous regions than in lowlands, reflecting similar terrain-related uncertainties (Tuinenburg et al., 2020a). When estimating the proportions of different evaporation types, the GLEAM data set may overestimate plant transpiration (Chen et al., 2022; Wei et al., 2017). Additionally, forests generally exhibit higher evaporation than grasslands of equal area (Breil et al., 2021), further influencing the estimated contributions from different land types. This study also assumes that all forms of evaporation are well mixed in the atmosphere. In reality, different evaporation sources rise to different altitudes, complicating the attribution of moisture to specific evaporation types (Gimeno et al., 2012). Regarding precipitation phase, because mixed-phase precipitation (e.g., sleet) is relatively rare and difficult to classify accurately (Dai, 2008; Jennings et al., 2025), we classified precipitation into two categories in this study: rainfall and snowfall. Consequently, moisture-source characteristics associated with mixed-phase precipitation are not examined. Spatial resolution presents another constraint because the input data exceed the spatial extent of some WTUs, such as La Plata, leading to coarse estimates of moisture sources. Terrestrial moisture source estimates face similar issues. Some coastal areas are classified as land, which may lead to an overestimation by misattributing open-water contributions. Despite these limitations, the results obtained from these two moisture tracking products remain consistent, especially in the estimated terrestrial moisture contributions, suggesting that our findings are robust. Moreover, regarding the forcing, ERA5 is the successor to ERA-Interim, and the two reanalyses exhibit broadly similar climatological characteristics for most regions (Link et al., 2020). Incorporating additional observational or reanalysis data sets, ideally with region-specific input data, would strengthen future studies.

Our study offers new insights into the sustainability of the water-supply and storage functions of WTUs from the perspective of the atmospheric water cycle. Nevertheless, to further explore the sustainability of water resources in the world's water towers, it is necessary to use more granular, region-specific input data, incorporate future land-use scenarios, and apply multiple moisture-tracking methods.

Conflict of Interest

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

Data Availability Statement

The ERA5 reanalysis data are available from <https://doi.org/10.24381/cds.f17050d7>. The UTrack atmospheric moisture connection data set is provided by Tuinenburg et al. (2020b) and available from PANGAEA at <https://doi.org/10.1594/PANGAEA.912710>. The WAM-2layers data set is provided by Link et al. (2019) and available from PANGAEA at <https://doi.org/10.1594/PANGAEA.908705>. The GLEAM evaporation data are available from <https://www.gleam.eu/>. The MODIS MCD12C1 land cover data are available from <https://doi.org/10.5067/MODIS/MCD12C1.061>. MATLAB and Python codes of this study are available at Zenodo (<https://doi.org/10.5281/zenodo.18051217>).

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