

Divergent impacts of Tibetan Plateau lakes on local and downstream water availability

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Abstract

The Tibetan Plateau (TP), a key amplifier of global climate change, has undergone widespread lake expansion, altering regional hydrology through intensified lake–atmosphere interactions. This effect is particularly pronounced during the autumn (October–November) after the monsoon; however, its mechanisms and downstream impacts remain underexplored. This study integrates high-resolution Weather Research and Forecasting (WRF) model and reanalysis data (1980–2019) to quantify how TP lake clusters regulate moisture transport and water availability via two competing mechanisms: retention (local moisture recycling) and compensation (downwind moisture export). In strong lake-effect (LE) years, intensified thermal convection and weak westerlies increase precipitation over lakes (retention), reducing moisture transport to the Salween, Mekong, Yangtze and Yellow River source regions, thereby decreasing downstream LE precipitation and water availability. In contrast, weak LE years, characterised by stronger westerlies, promote efficient LE moisture export (compensation), increasing LE precipitation and water availability in the downstream basins. A long-term decline in LE water availability over the lake region (−0.18 Gt per decade, $p < 0.05$) is correlated with an increase in river basins (+0.04 Gt per decade, $p < 0.1$), driven by enhanced lake evaporation and subsequent downwind precipitation. Extreme years (e.g. 1997 vs 1999) demonstrate the basin-scale impacts of these mechanisms, with the Yellow River source facing a 0.45 Gt deficit in retention-dominated years but a 0.73 Gt surplus during compensation phases. These findings redefine TP lakes as critical retainers and redistributors of water resources, directly affecting dry-season water security across river basins under climate change.

Keywords: Tibetan Plateau; Lake-effect; Moisture transport; River basin; Water availability

1. Introduction

The Tibetan Plateau (TP), known as the Third Pole because of its vast high-elevation ice and snow cover, significantly influences regional and global atmospheric circulation and hydrology (Huang et al., 2023). Its unique topography and location are pivotal in shaping the Asian

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monsoon system, which affects weather patterns across the globe (Wu et al., 2007).

In recent decades, the TP has experienced substantial lake expansion, primarily driven by climate warming, glacier melt and altered precipitation patterns (Zhang et al., 2014; Song et al., 2013). These lakes act as crucial moisture sources, modulating atmospheric circulation via evaporation and heat exchange, a phenomenon known as the lake-effect (LE) (Krinner, 2003; Rouse et al., 2008). The Great Lakes region in North America is a well-known example, where increased evaporation enhances winter precipitation in surrounding areas, underscoring the role of lakes as regional moisture regulators (Notaro et al., 2015).

A growing body of research shows that expanding lakes on the TP alter local convection, precipitation patterns and temperature dynamics (Su et al., 2020; Dai et al., 2020; Qiu et al., 2023; Xu et al., 2024). Lake evaporation on the TP often peaks in October and November rather than in summer, exerting a strong influence on regional atmospheric moisture during autumn (Wang et al., 2020). This peak coincides precisely with the retreat of the Asian monsoon, which sharply reduces external moisture input. Consequently, autumn becomes a pivotal transition phase in the hydrological cycle of TP, where intense evaporation ascends to become a critical local moisture source for the regional atmosphere.

During this critical window, the redistribution of substantial water vapour from lake evaporation directly determines subsequent dry-season water reserves for both the interior TP and downstream river basins across Asia. Research on the Great Lakes region demonstrates how lake-evaporated moisture contributes to remote precipitation through multi-stage atmospheric processes. Upstream lakes provide additional moisture and heat that significantly enhance the persistence and inland extent of the primary LE snowband downwind of Lake Ontario, allowing it to reach approximately 200 km or farther inland (Villani et al., 2017). Orographic uplift over the Tug Hill Plateau inland from Lake Ontario further amplifies LE snowfall (Veals and Steenburgh, 2015), while a pronounced lee shadowing effect occurs over the Black River valley, with some precipitation extending downstream into the western Adirondacks (Veals et al., 2018). Previous studies have identified near-lake effects on precipitation within ~80 km downwind of major TP lakes and lake clusters, including Nam Co (Dai et al., 2020; Zhao et al., 2022), Selin Co (Qiu et al., 2023), Qinghai Lake (Su et al., 2020) and grouped lakes (Dai et al., 2024). However, the remote hydrological impacts of TP lakes remain poorly understood. Cui and Li (2015) reported that evaporation from Qinghai Lake contributed approximately 23.4% to local precipitation. Similarly, Xu et al., 2011 found that lake-derived vapour accounted for approximately 28.4% of the precipitation around Nam Co. Under the westerly wind regime, moisture evaporated from TP lakes is incorporated into large-scale atmospheric moisture transport pathways (Dacre et al., 2015), indicating that clustered lake groups

may synergistically amplify remote moisture transport through intensive recycling, potentially reconfiguring water allocation across major river basins in Asia.

However, the following questions are raised: Do autumn lake-derived water vapours on the TP precipitate locally via the retention mechanism (potentially increasing internal water storage on the TP but reducing outflow) or are they effectively transported downstream via the compensation mechanism to form precipitation over the source regions of major rivers (Yangtze, Yellow, Mekong and Salween), replenishing dry-season runoff? What are the relative strengths of these competing mechanisms, their dominant controlling factors (e.g. westerly circulation, topography), and how do they exhibit significant interannual variability, particularly during extreme high/low LE years? Understanding these dynamics is essential for assessing the balance between internal water consumption and external supply on the TP and for predicting dry-season water security, which is critical for hundreds of millions of people downstream. This represents a significant knowledge gap.

This study addresses this critical gap during the pivotal autumn transition period (October–November). By integrating reanalysis data and high-resolution regional climate model (the Weather Research and Forecasting (WRF) model) simulations, we systematically quantified how the LE, particularly from lake clusters, regulates atmospheric moisture transport across the TP. The separation and quantitative assessment of the retention and compensation mechanisms, which are the primary physical processes governing the spatial allocation of dry-season water resources, are key innovations. Through trend analysis (1980–2019) and detailed examination of extreme years, we demonstrate how retention and compensation mechanisms dynamically dominate water vapour under varying meteorological conditions and topographic constraints. These mechanisms differentially influence: 1) enhanced local autumn precipitation in TP lake basins (retention effect) and 2) critical precipitation in downstream major river source regions, supporting dry-season runoff recharge (compensation effect). Ultimately, this study provides new insights into the regulatory role of lakes in the hydrological cycle of TP and offers a scientific foundation for improving water resource management in a changing climate.

2. Data and methods

2.1. Study area

Over 70% of the TP lakes are concentrated within the Inner TP, where they significantly impact atmospheric conditions (Zhang et al., 2014). This study focuses on lake clusters within the 31°–32°N belt in the southern TP (30.5°–32°N, 82.5°–92.5°E, Fig. 1a), which hosts the vast majority of the plateau's largest lakes and experiences a later freeze-up onset (typically December) compared with northern lakes (Cai et al., 2019). The warming rate of lakes

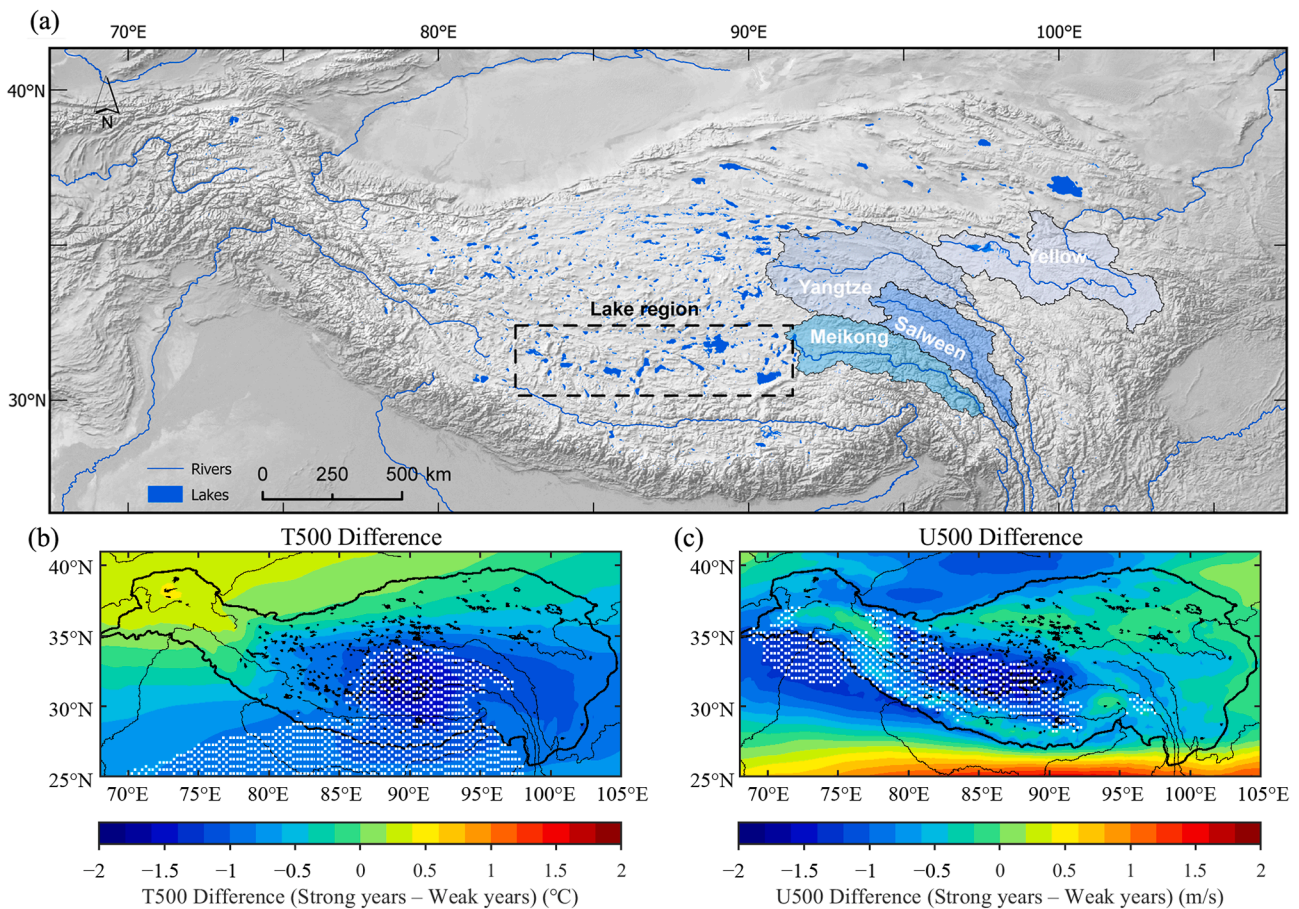


Fig. 1. Study area (a), differences in 500-hPa air temperature (b), and zonal wind (c) between strong and weak lake-effect (LE) years (The dots denote statistically significant grid points at the 90% confidence level).

in the southern TP is twice that of the northern TP, which suppresses evaporation in the north relative to the south (Zhu et al., 2025). Consequently, southern TP lakes exhibit considerable LE, making them a priority for investigation because of their climatic significance (Dai et al., 2024).

In addition, this study focuses on the headwaters of four eastern river basins, the Yangtze, Yellow, Mekong and Salween (Fig. 1a), which lie directly downwind of this lake region during prevailing autumn winds. This positioning makes them highly susceptible to LE influences, underscoring the need to understand these dynamics for water availability and regional climate, given their role in sustaining millions of people and a diverse ecosystem downstream.

2.2. Data

The study focused on the period from October to November 1980–2019. ECMWF Reanalysis v5 (ERA5) reanalysis data, with a spatial resolution of $0.25^\circ \times 0.25^\circ$, were obtained from the Copernicus Climate Change Service (C3S) Climate Data Store at <https://cds.climate.copernicus.eu/>. Lake surface temperature data were

obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Surface Temperature product (MOD11A1 V006), available from NASA EOS-DIS Land Processes DAAC at DOI: 10.5067/MODIS/MOD11A1.006 (Wan, 2014). Lake boundary data for the TP were obtained from the HydroLAKES database (v1.0), developed by the World Wildlife Fund and McGill University, available at <https://www.hydrosheds.org/products/hydrolakes> (Messager et al., 2016). TP river basin boundaries were sourced from Fan et al. (2024), available at <https://doi.org/10.5281/zenodo.10060590>. The Third Pole High-Resolution Meteorological Forcing Dataset (TPMFD) (Jiang et al., 2023), provided by the National Tibetan Plateau Data Centre (<http://data.tpdc.ac.cn>), offers high-resolution ($0.1^\circ \times 0.1^\circ$) near-surface meteorological data tailored for the Third Pole region (TP and surrounding areas). This dataset integrates multi-source observations and reanalysis data using advanced techniques to generate refined gridded meteorological data suitable for complex terrain studies, including high-resolution monthly precipitation data (Jiang et al., 2023).

2.3. Methods

2.3.1. WRF model

The WRF model (version 3.8) coupled with a one-dimensional (1D) lake model (Gu et al., 2015) was used to study the climatic effects of lakes on the TP, focusing on LE precipitation and regional climate variations. Previous studies, such as those at Lake Nam Co, have used the coupled WRF-lake model to simulate lake–atmosphere interactions (Dai et al., 2018; Zhao et al., 2022), demonstrating the significant influence of lakes on local and regional climates (Dai et al., 2020, 2024).

Two nested domains with two-way feedback were configured with grid resolutions of 25 and 5 km for the outer and inner domains, respectively. The outermost domain, centred at 35.65°N, 87.08°E, comprises 160 meridionals by 120 zonal grids, while the inner domain comprises 451 meridionals by 211 zonal grids. The model uses 30 eta levels up to 50 hPa vertically.

The Eta Ferrier microphysics scheme, which is effective for detailed cold cloud processes (Rogers et al., 2001), combined with the Betts-Miller-Janjic convection scheme, which effectively simulates strong convection (Janjić, 1994), is well-suited for modelling LE precipitation over TP lakes (Dai et al., 2018). To capture the thermodynamic and hydrological contrasts between water and land, the Noah Land Surface Model was selected for its accurate simulation of energy, water and momentum exchanges at the land surface (Tewari and Chen, 2004). The Yonsei University scheme, which enhances mixing in thermally driven convection while limiting excessive mixing under strong winds (Hong et al., 2006), was employed. For computational efficiency and reasonable physical representation, the Dudhia scheme for shortwave radiation (Dudhia, 1989) and the Rapid Radiative Transfer Model for longwave radiation (Mlawer et al., 1997) were chosen for radiation parameterisation.

Two experiments were conducted to assess LEs, using land use data and the HydroLAKES database (<https://www.hydrosheds.org/products/hydrolakes>). 1) No LE experiment: the lakes were represented by filling them with surrounding land cover types, which is referred to as WRF-nolake. 2) LE experiment: incorporated LE by coupling WRF with the 1D lake model by Gu et al. (2015), which is referred to as WRF-lake. To enhance the representation of the thermal and morphological characteristics of the lake, two key enhancements were made. First, the long-term monthly mean land surface temperatures derived from the MODIS observations were used as the dynamic lake surface temperature. Second, a key refinement improved the accuracy of the lake depth data in the WRF static fields. This was achieved by implementing a masking and replacement procedure, directly incorporating the comprehensive lake polygon dataset from HydroLAKES (including all attributes) in shapefile format. This approach ensured precise lake depth representation in the WRF

model, thereby improving the geographical and bathymetric accuracy of the coupled system.

The ERA5 dataset was used to derive the initial and 3-h updated boundary conditions at $0.25^\circ \times 0.25^\circ$ spatial resolution. The study period encompassed October and November 1980–2019, capturing peak lake-induced evaporation and moisture transport in December before most TP lakes freeze. Annual simulations were conducted from 00:00 UTC on August 1 to 21:00 UTC on November 30 to ensure coverage of the critical period when westerly winds shift southward, enhancing lake evaporation and atmospheric moisture transport (Haginoya et al., 2009; Li et al., 2015; Wang et al., 2017). This configuration enables a comprehensive analysis of the impact of lakes on the regional climate during their active phase.

The model results were validated using station-based observations and remote sensing data (Dai et al., 2018, 2020). These validations indicate that the model performed well in simulating the magnitude and spatial distribution of precipitation. Building upon this, this study rigorously validates the magnitude and spatial distribution of WRF-simulated precipitation for extreme hydroclimatic years (1997 vs. 1999) during October–November using the TPMFD for near-surface meteorological inputs (Jiang et al., 2023). The results demonstrate good agreement between the WRF-lake simulations and TPMFD data in terms of precipitation amount and spatial pattern over the lake area and downwind river source regions (Fig. A1).

2.3.2. Definition of LE intensity and selection of extreme years

The LE, which represents the lake's contribution to changes in a chosen variable, is defined as the difference between the lake control experiment and the sensitivity experiment (WRF-nolake). The mean difference in the lake cluster area (30.5°–32°N, 82.5°–92.5°E) represents the LE in the lake region, whereas the LE in each headwater is calculated separately.

LE precipitation (LEP) is defined as precipitation influenced by LE and is used to assess its impact on regional precipitation. Similarly, LE evaporation (LEE) refers to evaporation driven by the LE, while LE water availability (LEW) is determined as the difference between LEP and LEE, representing the net water contribution of the LE.

An increase in wind shear typically indicates a stronger LE because it enhances atmospheric convection and precipitation formation. The LE intensity in the lake region (30.5°–32°N, 82.5°–92.5°E) was quantified by combining the wind shear and LEP magnitude. Wind shear is calculated as the vertical difference between the 500 hPa and 10-m surface wind speeds. The LE intensity is then derived by a weighted average of wind shear and LEP magnitude, with each factor equally weighted (0.5).

Based on LE intensity in the lake region, the years 1980, 1982, 1986, 1997, 2002, 2004, 2006, 2013, 2016 and

2017 are classified as strong LE (magnitude greater than 0.5), whereas 1981, 1983, 1984, 1985, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1998, 1999, 2000, 2001, 2003, 2005, 2007, 2008, 2009, 2010, 2011, 2012, 2014, 2015, 2018, and 2019 are classified as weak LE years. This study examines two key mechanisms—the retention mechanism, where lakes intercept and precipitate moisture locally, and the compensation mechanism, where moisture bypasses the lake region and enhances downwind precipitation.

Temporal variations in LEW from 1980 to 2019 were analysed, with extreme years (1997 and 1999) selected to investigate how the LE redistributes moisture between the lake region and river basins under contrasting conditions. The selection of these years highlights the dynamic interplay between retention and compensation effects, providing key insights into the influence of LE on downstream moisture distribution.

2.3.3. Moisture flux

The moisture flux was calculated following the methodology of Xie et al. (2023). The nearest isobaric layers at 500 and 300 hPa were selected as the bottom and top levels for each grid, respectively. This approach ensures the

accurate capture of vertical moisture transport over the TP within the troposphere.

3. Results and discussion

3.1. Thermodynamic-dynamic controls on moisture redistribution

Strong LE years are characterised by lower 500-hPa temperatures and weaker 500-hPa westerlies (Fig. 1b and c), with the lake region experiencing approximately 1 °C lower average temperatures and a reduction in average wind speed of approximately 1.5 m/s. Cold air masses passing over warmer lake surfaces can trigger intense thermal instability, driving vigorous convection. Concurrently, weaker westerlies suppress horizontal advection, concentrating energy locally. Conversely, weak LE years exhibited higher temperatures and stronger upper-level westerlies. Elevated temperatures limit convection, whereas intense westerlies enhance downstream air mass advection, thereby diluting thermal processes via dynamic transport.

In strong LE years, strong thermal convection generates vigorous vertical motions over lakes, resulting in a modest increase in lake-surface vertical wind shear (Fig. 2a). As

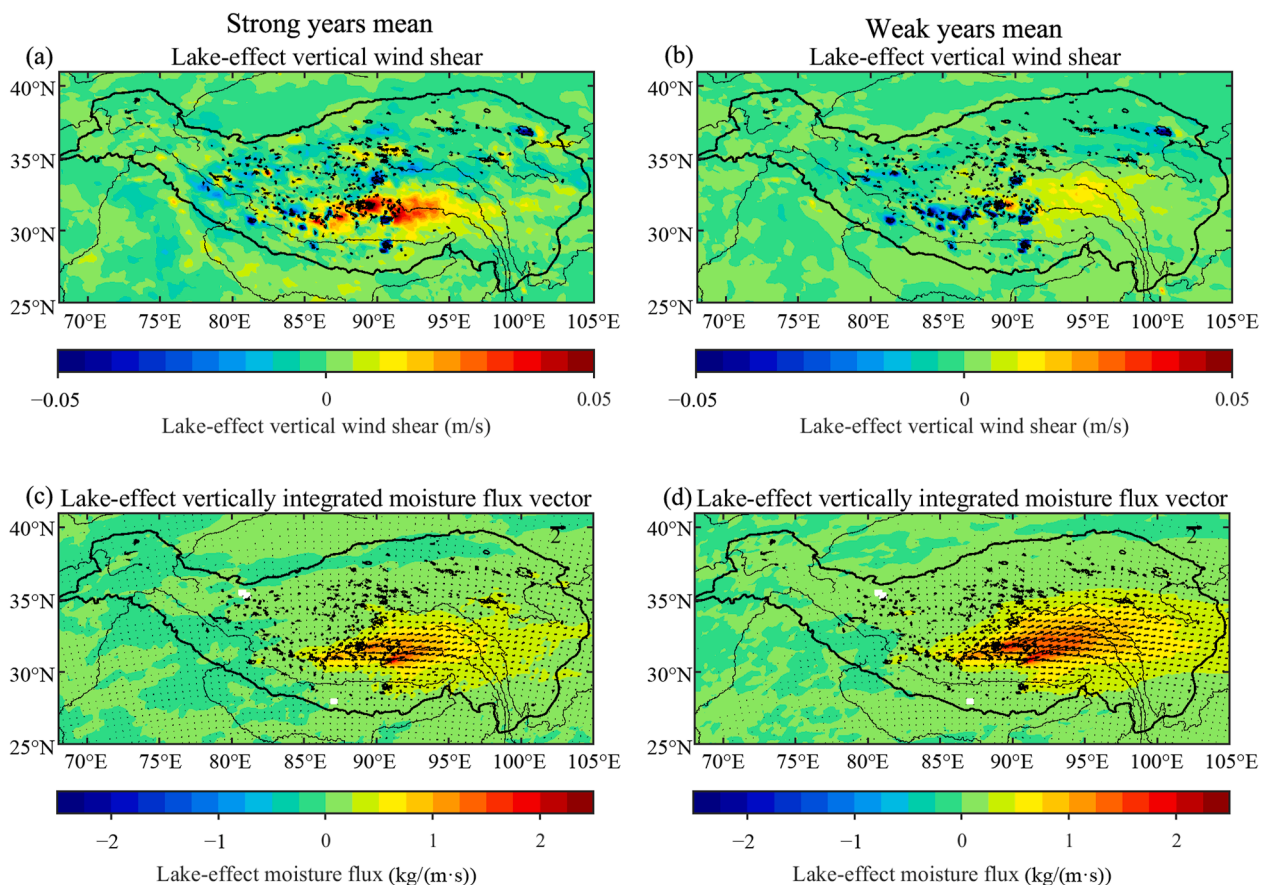


Fig. 2. Distribution of LE vertical wind shear in strong (a) and weak LE years (b), and LE vertically integrated water vapour transport vectors in strong (c) and weak LE years (d).

lake-warmed air advects onto colder land, surface cooling creates a stable layer that slows near-surface winds. Terrain friction and orographic lift near shorelines further enhance vertical wind shear. Conversely, weak LE years exhibit weaker convection, allowing turbulent mixing to dominate and reducing the lake-surface wind shear (Fig. 2b). Strong westerlies transport air masses far downstream, and the gradual cooling of deep layers increases wind shear at distant locations.

Fig. 2c and d shows how LE intensity governs the transport of moisture evaporated from the lake. In strong LE years (Fig. 2c), persistent vertical recycling traps most lake-evaporated vapour over the lake region, dramatically suppressing downstream export to river source areas. In contrast, weak LE years (Fig. 2d) exhibit efficient westerly

advection, delivering lake-originated moisture downstream and substantially enhancing its contribution to headwater basins. This contrast highlights a lake-centric compensatory mechanism: suppressed LE activity mobilises the moisture reservoir of the lake towards downstream regions, directly offsetting deficits of LE vapour during intense LE periods. Consequently, LE intensity regulates basin-scale precipitation by controlling the spatial redistribution of lake-contributed moisture.

3.2. LE on precipitation and water availability

Fig. 3a and c shows the spatial differences in precipitation between strong and weak LE years. In strong LE years, large lake clusters induce pronounced localised

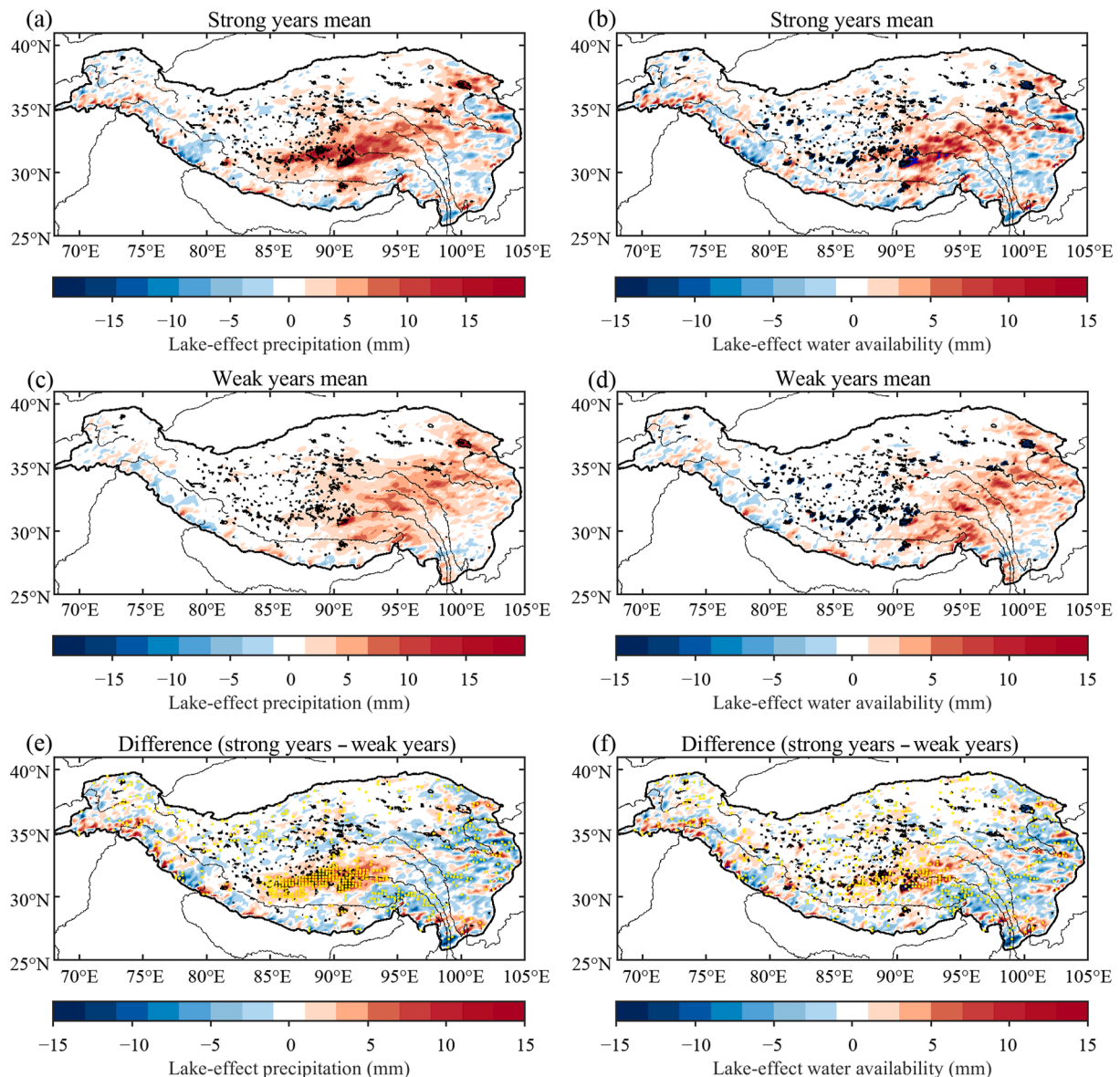


Fig. 3. Distribution of LE precipitation in strong (a) and weak (c) LE years, and the composite difference between strong and weak LE years (e), distribution of LE water availability in strong (b) and weak LE years (d), and the composite difference between strong and weak LE years (f) (The dots in panels (e) and (f) denote statistically significant grid points at the 90% confidence level).

precipitation enhancement, averaging approximately 15 mm in the lake region throughout autumn (October–November; Fig. 3a). This suggests that strong LE years promote local condensation and precipitation of lake-derived moisture, thereby limiting downstream transport. In contrast, the LE is less pronounced in weak LE years, resulting in a more dispersed precipitation pattern. More moisture is transported downstream, increasing precipitation by approximately 5 mm in river basins (Fig. 3c). This indicates that weak LE years enhance moisture transport, facilitating precipitation recharge in river basins.

Fig. 3e compares precipitation patterns between strong and weak LE years. The red areas indicate regions with increased precipitation during strong LE years, whereas the blue areas indicate regions with decreased precipitation. The data confirm that strong LE years increase precipitation in the lake region but decrease it in the downstream river basins. This finding supports the retention effect, where moisture remains within the lake region, limiting precipitation in downstream areas.

The distribution pattern of LEW availability during strong and weak LE years closely follows that of LEP. In both strong and weak LE years, LEW exhibits its largest negative anomaly over the lakes, approximately -50 mm, indicating net water loss from the lakes. In strong LE years, the positive water budget is concentrated around the lake shores, reaching values near 10 mm (Fig. 3b), functioning as an interception mechanism. In contrast, LEW is transported to river source areas in weak LE years, reaching approximately 5 mm (Fig. 3d), supplementing downstream water resources. These patterns highlight the dynamic effect of the lake in regulating regional moisture and precipitation distribution, significantly influencing water availability in river basins.

3.3. LE retention vs. compensation mechanisms

In strong LE years, weak westerlies limit moisture dispersion, trapping evaporated lake moisture via shore-based wind shear-driven low-level convergence. This creates a ‘moisture ascent feedback’, concentrating high-intensity convective precipitation over lakes and narrow coastal zones. In contrast, during weak LE years, strong westerlies advect moisture far downstream, where diffused moisture flux interacts with enhanced wind shear uplift, generating widespread but weaker precipitation across river headwaters.

This demonstrates that the interannual LE intensity and spatial patterns emerge from the interaction between the thermal modification efficiency of cold air and atmospheric advective capacity. In strong years, thermally dominated processes drive extreme localised precipitation. In weak years, dynamic advection disperses moderate precipitation over diffuse areas. Analysis of strong and weak LE years revealed two distinct mechanisms. Under the retention mechanism, cooler air temperatures and localised updrafts enhance LE evaporation, moisture

condensation and precipitation over the lakes, thereby reducing downstream transport (Fig. 4). Under the compensation mechanism, moisture that does not precipitate over the lakes is transported by large scale circulation patterns to river basins, where it ultimately forms precipitation (Fig. 4). These mechanisms underscore the crucial role of LE in controlling moisture distribution and precipitation patterns, with direct implications for water availability in river basins.

3.4. Significant impact of LE on water resources in river source regions

Although precipitation is a key factor in water availability, evaporation significantly influences the final amount of useable water. To assess the long-term impact of the LE, we analysed 40-year variations in LEW (LEP minus LEE) across the lake region and river basins. The results reveal significant temporal and spatial differences in LEW between these regions.

Over the past four decades, the lake region has exhibited a statistically significant decline in LEW ($p < 0.05$), indicating reduced water availability. In contrast, the river basins exhibited a statistically significant increase in LEW ($p < 0.1$, Fig. 5c). This pattern suggests a gradual redistribution of water, driven by the evolving moisture transport dynamics. During October–November, when lake surface evaporation peaks, increased evaporation elevates atmospheric moisture levels ($p < 0.05$, Fig. 5b). This moisture is transported downstream, increasing precipitation ($p < 0.05$, Fig. 5a) and water availability in river basins ($p < 0.1$, Fig. 5c).

These findings reveal a long-term shift in water availability from the lake region to river basins under the influence of LE. This underscores the role of lakes as both sources of moisture and regulators that spatially redistribute water resources.

We further investigated LEW availability for two extreme LE years (1997 as the strong LE year and 1999 as the weak LE year) alongside the 40-year mean to illustrate the variability and regulatory capacity (Fig. 6). In 1997, LEP reached peak levels in the lake region, whereas both LEP and available water in river source areas were relatively low. This effect was particularly pronounced in the Yellow River basin, where LEW recorded a negative value (-0.33 Gt), marking a reduction of 0.45 Gt compared to the multi-year average. These findings indicate that strong LE retention concentrates LEW in the lake region, reducing downstream water resources, particularly in the Yellow River basin.

In contrast, an increase in LEW availability across all basins was experienced in 1999. In the Yangtze and Yellow River basins, LEW reached 0.75 and 0.73 Gt, respectively, contributing to a total increase of approximately 2.2 Gt in available water—1.1 Gt above the multi-year average. These two basins alone accounted for over 1.4 Gt, highlighting a strong water supply effect from the LE in 1999.

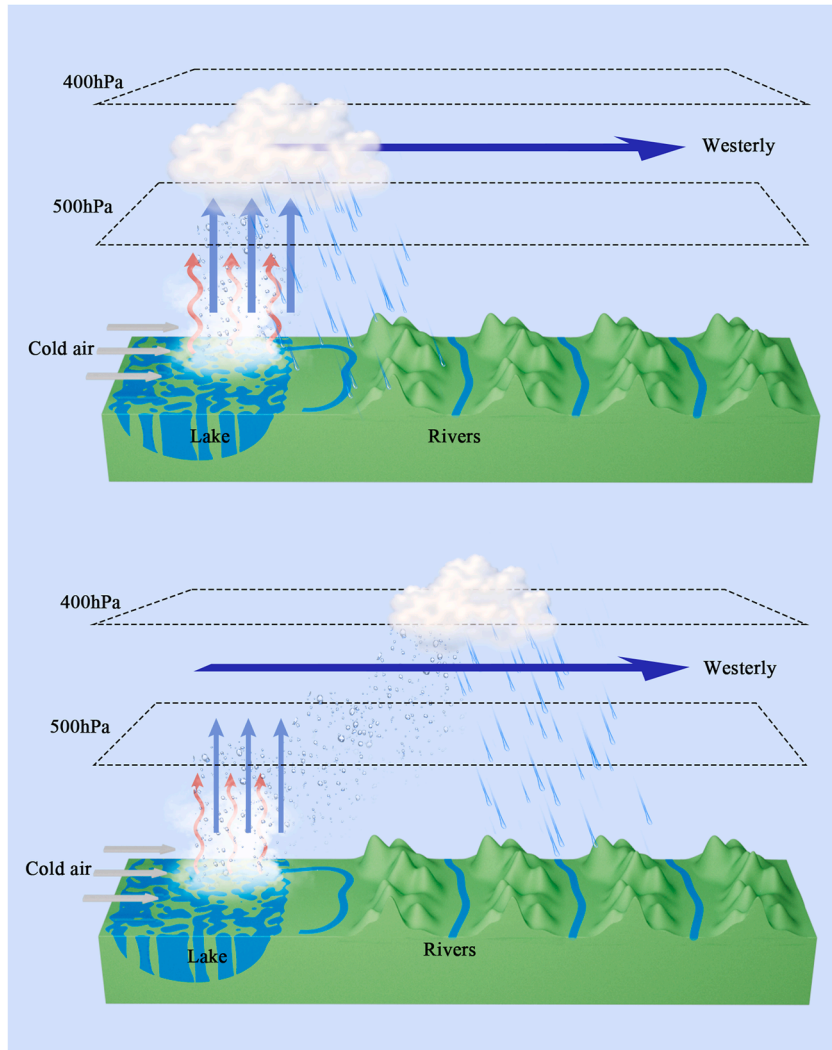


Fig. 4. Schematic of the mechanisms of strong (top) and weak LE (bottom) on the TP in October–November.

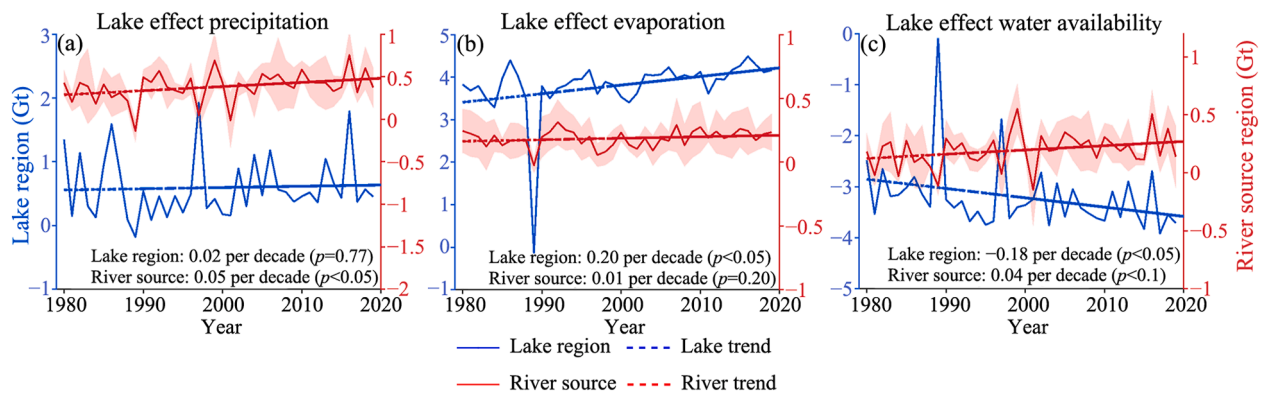


Fig. 5. Temporal variation in (a) LE precipitation, (b) LE evaporation, and (c) LE water available for the lake region and downstream river basins from 1980 to 2019.

These findings indicate that in weak LE years, LEW is concentrated in downstream river basins, significantly increasing water resources, particularly in the Yangtze and Yellow River basins.

3.5. Discussion

This study advances conventional unidirectional moisture transport models by revealing a

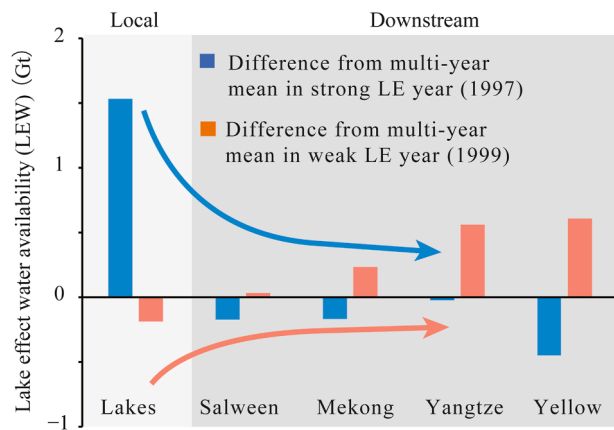


Fig. 6. LEW availability difference from multi-year mean in strong LE year (1997) and weak LE year (1999) from the local lake region to the downstream four major river basins (the headwaters of Salween, Mekong, Yangtze and Yellow Rivers).

retention–compensation binary dynamic mechanism through which TP lake clusters regulate regional hydrology. Unlike traditional LE studies that focus on localised, downwind precipitation enhancement (Veals et al., 2018; Zhao et al., 2022), our findings establish TP lakes as active climate-responsive hydraulic pivots that drive competitive water redistribution across synoptic to decadal scales.

The retention–compensation mechanism acts as a climatic switch: in strong LE years, thermally driven retention enhances local precipitation but suppresses downwind moisture transport, intensifying the orographic rain-shadow effect and causing significant water deficits (e.g. 0.45 Gt) in leeward basins such as the Yellow River headwaters. In contrast, in weak LE years, compensation through westerlies-driven vapour export mitigates this deficit, increasing downwind precipitation and yielding surpluses (e.g. 0.73 Gt). This dynamic explains the sustained decrease in LE water availability (−0.18 Gt per decade) in the lake region alongside increased supply to downstream river sources (+0.04 Gt per decade), reconciling previously paradoxical trends in TP hydrology.

However, several uncertainties and limitations in our study should be acknowledged. First, the precise quantification of terrain-phase change coupling, such as vapour modulation across the Tanggula Mountains, remains challenging. Although our mechanism accounts for observed moisture redistribution, the exact contribution of topographic forcing versus lake-induced thermodynamics is not fully resolved, potentially affecting the mechanistic completeness. Second, although the Yellow River headwaters are identified as highly vulnerable, the underlying drivers for their distinct sensitivity compared to other basins remain unclear, limiting our ability to predict basin-specific responses under changing climate conditions. Finally, the applicability of the proposed mechanism to other high-altitude regions requires further evaluation. The unique interplay of monsoon retreat and peak lake evap-

oration during autumn on the TP may not directly translate elsewhere, indicating that regional factors play a larger role than our current framework captures.

Despite these limitations, our findings redefine TP lakes as dual-function moisture regulators with important implications for water resource forecasting. The extreme cases of 1997 and 1999 demonstrate the critical role of LE in water reallocation, affecting nearly one billion people.

To address these uncertainties, future work should prioritise coupled WRF-isotope modelling to separate topographic from lacustrine influences, conduct gradient-based comparative studies across basins to clarify differential sensitivity mechanisms, and perform global comparisons of plateau lake systems to assess the universality of the retention–compensation dynamics.

4. Conclusions

The influence of LE on regional moisture transport, precipitation distribution and water resource availability varies interannually. In strong LE years, moisture is primarily retained within the lake region, limiting downstream transport and reducing water availability in river basins. In contrast, efficient moisture transport to downstream regions enhances water availability in river basins in weak LE years.

Over the past four decades (1980–2019), LEW availability has undergone a significant shift, with a decline in the lake region and an increase in river source areas ($p < 0.1$). This redistribution coincides with enhanced LEE during October–November, which increases the amount of atmospheric moisture transported to downstream river basins. Extreme years highlight this variability and the regulatory role of the LE. In 1997, a strong LEP caused substantial moisture retention over the lakes, reducing LEW in the Yellow River basin. In contrast, in 1999, LEW significantly increased across all basins, particularly in the Yangtze and Yellow River basins, demonstrating a strong compensatory effect during weak LE years.

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Yu-Feng Dai: Writing — original draft, Funding acquisition, Data curation. **Deliang Chen:** Writing — review & editing. **Lei Wang:** Writing — review & editing, Supervision, Methodology. **Tinghai Ou:** Writing — review & editing, Methodology, Data curation. **Hong-Bin Chen:** Writing — review & editing, Visualization. **Xiao-Wen Zhang:** Writing — review & editing, Methodology. **Yang Gao:** Visualization. **Tan-Dong Yao:** Writing — review & editing, Supervision, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.accres.2025.09.013>.

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