Unraveling the Discrepancies between Eulerian and Lagrangian Moisture Tracking Models in Monsoon- and Westerlies-dominated Basins of the Tibetan Plateau

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Abstract. Eulerian and Lagrangian numerical moisture tracking models, which are primarily used to quantify moisture contributions from global sources to specific regions, play a crucial role in hydrology and (paleo)climatology studies on the Tibetan Plateau (TP). Despite their widespread applications on the TP, potential discrepancies in their moisture tracking results and their underlying causes remain unexplored. In this study, we compare the most widely used Eulerian and Lagrangian moisture tracking models over the TP, i.e., WAM-2layers and FLEXPART-WaterSip, specifically focusing on an Indian Summer Monsoon (ISM)-dominated basin (Yarlung Zangbo River Basin, YB) and a westerlies-dominated basin (upper Tarim River Basin, UTB). Compared to the bias-corrected FLEXPART-WaterSip, WAM-2layers model generally estimates higher moisture contributions from westerlies-dominated and distant sources but lower contributions from local recycling and nearby sources downwind of the westerlies. These discrepancies can be mitigated by increasing the spatial-temporal resolutions of forcing data in WAM-2layers. A notable advantage of WAM-2layers over FLEXPART-WaterSip is its closer alignment of estimated moisture sources with actual evaporation, particularly in source regions with complex land–sea distributions. However, the evaporation biases in FLEXPART-WaterSip can be partly corrected through calibration with actual surface fluxes. For moisture tracking over the TP, we recommend using high-resolution forcing datasets with a focus on temporal resolution for WAM-2layers, while for FLEXPART-WaterSip, we suggest applying bias corrections to optimize the filter for precipitation particles and adjust evaporation estimates.

1 Introduction

Moisture tracking through numerical models play a pivotal role in advancing our quantitative understanding of the global and regional atmospheric water cycle, and is crucial for a variety of applications in meteorology, hydrology, and climate science (Gimeno et al., 2012; Gimeno et al., 2020). The Tibetan Plateau (TP) region, often referred to as the "Asia water tower", encompasses the world's highest plateau and has been experiencing a rapid retreat of glaciers and permafrost, accompanied by shifts in precipitation patterns and a pronounced warming trend in recent decades (Yao et al., 2018; Yao et al., 2022). Numerous research efforts based on meteorological analyses and climate proxy indicators (e.g., precipitation and ice-core isotopes) have comprehensively investigated the hydrologic cycle in this region (Yao et al., 2013; Yang et al., 2014; Liu et al., 2020b). Recent advancements in numerical moisture tracking models have further facilitated the quantitative diagnosis of moisture source–receptor relationships across the TP region (Chen et al., 2012; Zhang et al., 2017; Li et al., 2022a). In recent years, numerical moisture tracking has been widely used to analyze precipitation and water resource changes over the TP (Li et al., 2019; Ayantobo et al., 2022; Zhang et al., 2023b), interpret the characteristics of TP's climate proxy indicators (Shao et al., 2021; Li et al., 2022b; Wang et al., 2022), and investigate the impacts of TP's climatic conditions on downstream areas (Zhang et al., 2023a).

Table 1 summarizes the numerical moisture tracking studies over the TP for the past twenty years; the utilized models can be broadly classified into two categories: Eulerian and Lagrangian models. The Eulerian moisture tracking approach typically employs a fixed spatial grid system and primarily focuses on averaged physical quantities with predefined grid spacings, while Lagrangian models uses a particle tracking approach to infer the movement of moisture through diagnosing source–receptor relationships. Among these models, the Water Accounting Model-2layers (WAM-2layers) and the FLEXible PARTicle dispersion model (FLEXPART) coupled with the "WaterSip" moisture source diagnostic method (FLEXPART-WaterSip) are the most widely use Eulerian and Lagrangian moisture tracking models, respectively. As suggested in Table 1, existing studies mainly used either Eulerian or Lagrangian moisture tracking models driven by very diverse forcing datasets, meanwhile covering various study periods and regions across the TP. This diversity largely hinders the quantitative comparison of moisture tracking results from different models and the attribution of their discrepancies. Nevertheless, two general patterns can be observed through a quantitative comparison of the long-term moisture tracking results in these studies. First, moisture sources tracked by Eulerian models tend to cover a large part of the western Eurasian continent and can stretch southward to the southern Indian Ocean (Zhang et al., 2017; Li et al., 2019; Li et al., 2022a; Zhang et al., 2024). In contrast, moisture sources tracked by Lagrangian models predominantly extend southward (Chen et al., 2012; Sun and Wang, 2014; Chen et al., 2019; Yang et al., 2020), with broader westward extensions observed in the moisture tracking for the westernmost TP and Xinjiang region (Zhou et al., 2019; Liu et al., 2020a; Yao et al., 2020; Hu et al., 2021). Second, areas with higher evaporation rates, such as the ocean surface, in general contribute more moisture compared to surrounding land areas. While the moisture sources simulated by Eulerian models aligns well with the land–sea distribution (Zhang et al., 2017; Li et al., 2019; Li et al., 2022a;

Zhang et al., 2024), this alignment is less pronounced for Lagrangian models (Chen et al., 2012; Sun and Wang, 2014; Chen et al., 2019; Zhou et al., 2019; Liu et al., 2020a; Yang et al., 2020; Yao et al., 2020; Hu et al., 2021). In this context, we speculate that different moisture tracking methods (both Eulerian and Lagrangian ones) may involve certain unrecognized uncertainties or errors when applied to the TP region. This underscores the pressing need for further exploration to examine the discrepancies among these models to better characterize the complex hydrological processes of the TP.

Table 1: Overview of moisture tracking studies with Eulerian and Lagrangian models in the TP and its vicinity. Note that extensive studies on water isotopes in the TP with moisture tracking simulations are not included here. "E and P" means the model diagnoses evaporation and precipitation separately, while "E – P" means the model diagnoses contributions through water budget (i.e., evaporation minus precipitation).

	Model	Moisture source diagnosis	Study area	Forcing dataset	Study period	Reference
Eulerian	WAM-1layer	E and P	Central-western TP	ERA-I, NCEP-2	1979–2013	Zhang et al. (2017)
	WAM-2layers	E and P	Endorheic TP	ERA-I, MERRA-2, JRA-55	1979–2015	Li et al. (2019)
	WAM-2layers	E and P	Southern/northern TP	ERA-I	1979–2016	Zhang et al. (2019a)
	WAM-2layers	E and P	TP	ERA-I	1979–2015	Guo et al. (2019)
	WAM-2layers	E and P	TP	ERA-I	1998–2018	Zhang (2020)
	WAM-2layers	E and P	TP	ERA-I, MetUM	1982–2012	Guo et al. (2020)
	WAM-2layers	E and P	Major basins in TP	ERA-I, MERRA-2, JRA-55	1979–2015	Li et al. (2022a)
	WAM-2layers	E and P	TP (forward tracking oceanic evaporation)	ERA-I, MERRA-2, JRA-55	1979–2015	Li et al. (2022b)
	WAM-2layers	E and P	TP (forward tracking TP evaporation)	ERA5	2000–2020	Zhang et al. (2023a)
	WAM-2layers	E and P	Five typical cells in the TP	ERA5	2011–2020	Zhang et al. (2024)
	CAM5.1 with a tagging method	E and P	Southern/northern TP	MERRA	1982–2014	Pan et al. (2018)
Lagrangian	FLEXPART	E – P	TP	NCEP-GFS	2005–2009 (summer)	Chen et al. (2012)
	FLEXPART	Areal source–receptor attribution	Grassland on eastern TP	NCEP-CFSR	2000–2009	Sun and Wang (2014)
	FLEXPART	WaterSip	Four regions within TP	ERA-I	1979–2018 (May–August)	Chen et al. (2019)
	FLEXPART	Areal source–receptor attribution	Xinjiang	NCEP-FNL	2008–2015 (April–September)	Zhou et al. (2019)
	FLEXPART	WaterSip	Southeastern TP	ERA-I	1980–2016 (June–September)	Yang et al. (2020)
	FLEXPART	WaterSip	Xinjiang	NCEP-CFSR	1979–2018	Yao et al. (2020)
	FLEXPART	WaterSip	Northern/Southern Xinjiang	NCEP-CFSR	1979–2018	Hu et al. (2021)
	FLEXPART	Areal source–receptor attribution	Source region of Yellow River	NCEP-FNL	1979–2009	Liu et al. (2021)
	FLEXPART	WaterSip	Xinjiang	NCEP-CFSR	1979–2018 (April–September)	Yao et al. (2021)
	FLEXPART	E – P	Three-rivers headwater region	ERA-I	1980–2017 (boreal summer)	Zhao et al. (2021)
	FLEXPART	E – P	Three-rivers source region	NCEP-FNL	1989–2019	Liu et al. (2022)
	FLEXPART	WaterSip	Three-rivers headwater region	ERA-I	1980–2017	Zhao et al. (2023)

HYSPLIT	WaterSip	Three-rivers headwater region	NNR1	1960–2017 (June–September)	Zhang et al. (2019b)
HYSPLIT	E – P	Western TP	ERA-I	1979–2018 (winter)	Liu et al. (2020a)
HYSPLIT	Maximum specific humidity	Seven regions within TP	NCEP/NCAR	1961–2015 (summer extreme event)	Ma et al. (2020)
HYSPLIT	Contribution function and weighting	TP	NCEP-GDAS	1950–2015 (extreme precipitation events)	Ayantobo et al. (2022)
HYSPLIT	WaterSip	Southern Xinjiang	ERA5	2021(June 15–17)	Chen et al. (2022)
LAGRANTO	WaterSip	Southeastern TP	ERA-I	1979–2016 (winter extreme precipitation)	Huang et al. (2018)
LAGRANTO	WaterSip	Three regions within TP	ERA-I	1979–2016 (winter extreme precipitation)	Qiu et al. (2019)
LAGRANTO	WaterSip	Northern TP	ERA-I	2010–2018 (monsoon season)	Wang et al. (2023)
QIBT	E and P	Southeastern TP	ERA-I	1982–2011 (April–September)	Xu and Gao (2019)

It is noteworthy that several studies have employed both Eulerian and Lagrangian models to diagnose moisture sources and perform comparative analyses in other regions. For example, a comparison among RCM-tag (coupled with MM5), WAM, and 3D-T (a modification of QIBT) models in West Africa revealed that the number of vertical layers and the mixing assumption for evaporation significantly influence simulations, especially in regions with strong wind shear (van der Ent et al., 2013). Another comparison between Eulerian and Lagrangian approaches (implemented in the COSMO model) in Europe found that the linkage of moisture uptakes in the atmospheric boundary layer to evaporation in the Lagrangian approach is mostly consistent with the advanced Eulerian model (Winschall et al., 2014). Tuinenburg and Staal (2020) compared a set of moisture tracking models for 7 source locations globally and concluded that the three-dimensional Lagrangian models were most accurate and suitable for areas with relatively complex terrain, as they can better track moisture with strong vertical variability in horizontal transport. Using the Eulerian WRF-WVT model as a benchmark for moisture tracking over the Mediterranean region, Cloux et al. (2021) considered the Lagrangian FLEXPART-WRF model more appropriate for a qualitative description of moisture origin rather than a precise estimation of source contributions. These comparative studies emphasize that the most suitable moisture tracking model depends on the specific case, including but not limited to the research question, spatial extent, and computing resource available. Despite these existing efforts, it remains unclear whether their conclusions are applicable to moisture tracking over the TP, especially concerning the most widely used models in the region. Moreover, the studies on the generation mechanisms of model uncertainties through moisture tracking intercomparison is still lacking.

The overall objective of this study is to investigate potential errors/uncertainties in numerical moisture tracking models and the underlying mechanisms of their discrepancies over the TP. This is achieved through a comparison between the most commonly used Eulerian and Lagrangian models in the region, specifically WAM-2layers and FLEXPART-WaterSip. Given that the TP's climate is mainly influenced by the interactions between the Indian Summer Monsoon (ISM) and mid-latitude westerlies, we selected two representative basin for our comparative analysis: the ISM-dominated Yarlung Zangbo River Basin (YB) and the westerlies-dominated upper Tarim River Basin (UTB) (Fig. S1 in the Supplement). Section 2 describes the mechanisms, forcing data, and numerical settings for both moisture tracking models. Section 3 provides a comprehensive comparison of the moisture tracking results for both basins. Section 4 delves into the intermediate processes of moisture tracking in the two models: moisture fluxes in WAM-2layers and particle trajectories in FLEXPART. To further illustrate the differences between these two models, Section 5 examines the relationship between the simulated moisture contributions and actual evaporation from various source regions. Section 6 introduces a two-step bias correction method for FLEXPART-WaterSip simulations based on a comparison between actual and simulated surface fluxes. Section 7 further investigates the potential determinants of the observed discrepancies between the two approaches through a series of carefully designed numerical experiments.

2 Eulerian and Lagrangian approaches for moisture tracking: WAM-2layers and FLEXPART-WaterSip models

In this study, the WAM-2layers V3.0.0b5 is adopted for Eulerian moisture tracking. This two-layers version, designed to deal with wind shear in the upper air, is an update to the earlier single-layer version (van der Ent et al., 2010). As illustrated in the conceptual diagram (Fig. 1a), the underlying principle of WAM-2layers is the water balance equation (van der Ent et al., 2014), which in the lower layer is given by:

$$\frac{\partial S_{g,lower}}{\partial t} = -\frac{\partial (S_{g,lower}u)}{\partial x} - \frac{\partial (S_{g,lower}v)}{\partial y} + E_g - P_g \pm F_{v,g} \quad (1)$$

where subscript g denotes the tagged moisture; S is the moisture content in the atmosphere; t is time; u and v are the zonal (x) and meridional (y) wind fields, respectively; E is evaporation (which only occurs in the bottom layer); P is precipitation; and F_v is the vertical moisture transport between the two layers. The model prescribes a two-layer structure, typically dividing at approximately 810 hPa with a standard surface pressure. Modifications to F_v ($4F_v$ in the net flux direction and $3F_v$ in the opposite direction) are implemented to account for turbulent moisture exchange. Note that the division between two layers varies with topography, which decreases to ~520 hPa over the TP (~4000 m).

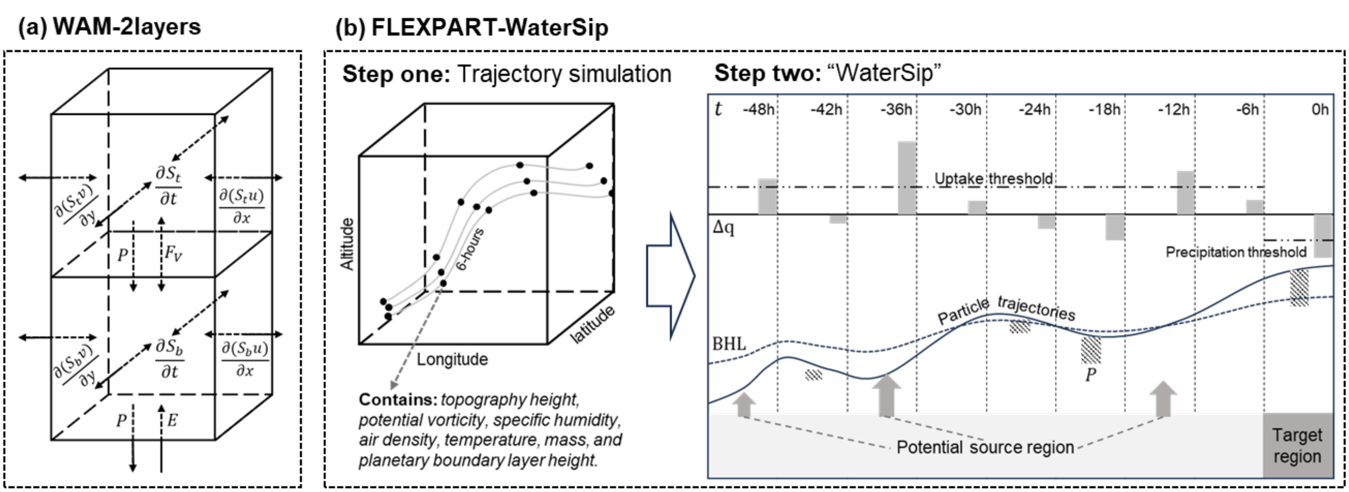

Figure 1: Mechanisms of (a) WAM-2layers and (b) FLEXPART-WaterSip models. "Step two" in (b) is adapted from Sodemann et al. (2008).

The Lagrangian particle trajectory simulation in this study is conducted using FLEXPART V10.4, a versatile model widely employed to simulate the transport and turbulent mixing of gases and aerosols in the atmosphere (Pisso et al., 2019). FLEXPART can operates in domain-filling mode to represent the entire atmosphere using uniformly distributed particles with equal mass. It is independent of a computational grid, which enables effective descriptions of atmospheric transport at a theoretically infinitesimal spatial resolution. For this study, five million particles were released at altitudes ranging from 100 m to 20,000 m across the entire target region. The outputs from FLEXPART include detailed three-dimensional position, topography height, potential vorticity, specific humidity, air density, temperature, mass, and planetary boundary layer height (BLH) of each particle/parcel at 6-hourly intervals (Fig. 1b). Similar to other Lagrangian models such as HYSPLIT (Stein et al., 2016) and Lagranto (Sprenger and Wernli, 2015), FLEXPART on its own does not identify potential moisture sources for precipitation in the target region nor quantify their contributions. To address this limitation, we adopted the "WaterSip" method proposed by Sodemann et al. (2008). This method identify moisture sources using humidity information along particle trajectories simulated by FLEXPART, which involves key processes such as filtering trajectories that lead to precipitation, calculating specific humidity changes and their attributed fractions, and determining potential moisture sources based on moisture uptake thresholds and BLH (Fig. 1b). A more detailed description of this method can be found in Sodemann et al. (2008). Default screening thresholds in this study are set at 0.2 g kg^{-1} for specific humidity change, 80% for relative humidity, and 1.5 times the BLH for particle height, although adjustments were made for sensitivity experiments detailed in Sections 6 and 7. In summary, the FLEXPART-WaterSip approach adopted here integrates the particle trajectory simulated by FLEXPART with the moisture source–receptor diagnostics of WaterSip.

Both WAM-2layers and FLEXPART-WaterSip operate as offline models that rely on meteorological fields as forcing inputs. Here we used the fifth-generation atmospheric reanalysis product from the European Centre for Medium-Range Weather Forecasts (ERA5) as the forcing dataset, which benefits from decades of advancements in data assimilation, core dynamics, and model physics (Hersbach et al., 2020). The moisture tracking simulations specifically target July 2022, a month significantly influenced by the ISM in the TP region (Yao et al., 2013; Curio and Scherer, 2016). The moisture tracking domain spans from 30°S to 80°N and from 40°W to 140°E, covering nearly all potential oceanic and terrestrial source regions of precipitation over TP (Chen et al., 2012; Li et al., 2022a). In the simulations, the two representative basins are represented with gridded boundaries as shown in Fig. S1 in the Supplement. Considering the number of particles released, data size, and computational resources needed, both models are driven by 1°×1° and 3-hourly ERA5 data, although some specific variables used in the two models are different due to their distinct physical mechanisms.

In WAM-2layers, tagged moisture is continuously released into Eulerian grids and tracked as it progressively accumulates and diffuses across grids over time. The tagged moisture was released throughout the entire July (from 31-July to 1-July in backward mode), with the backward tracking period extending back to 1 June. A previous study in the TP region demonstrated that a ~30-day tracking period can ensure that approximately 95% of the tagged moisture returns to the ground (Zhang et al., 2017), which is consistent with our numerical experiments in the YB and UTB (Fig. 2a). In comparison, FLEXPART-WaterSip model tracks atmospheric particles released at each step independently, thereby avoiding interference between particles released at different times. This differs from WAM-2layers, which ensures that in FLEXPART-WaterSip moisture released at various times does not converge into the same set of Eulerian grids. Typically, the average residence time of moisture in the atmosphere (~10 days) is used as the tracking period for a single particle release in FLEXPART-WaterSip. To align the tracking duration and maximize the tracking of tagged moisture in both models (Fig. 2), the backward tracking time in FLEXPART-WaterSip was extended to 30 days. For FLEXPART-WaterSip, although large deviations in actual air parcel movements may occur beyond the average 10-day residence time, the associated uncertainties in trajectories beyond this period are unlikely to substantially impact the results, as the majority of moisture uptake occurs within the first 10 days (Sodemann et al., 2008). Our numerical experiments, as illustrated in Fig. 2b, indicate that within the first 10 days (20 days), we traced 89% (99%) of the precipitation moisture in the YB and 97% (99%) in the UTB. Detailed configurations of WAM-2layers and FLEXPART models can be found in Part 2 of the Supplement. The WaterSip source code we developed in this study can be found in Part 3 of the Supplement.

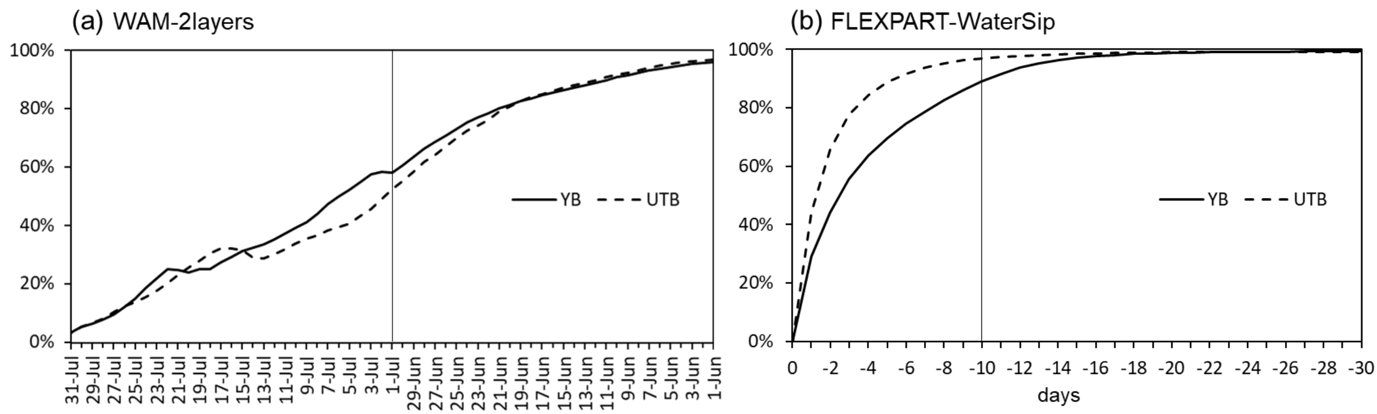

Figure 2. Backward moisture tracking periods and accumulated moisture uptake from all source regions in (a) WAM-2layers and (b) FLEXPART-WaterSip models. Solid lines represent the YB, and dotted lines represent the UTB.

3 Moisture tracking in two representative basins

Figure 3 shows the simulated moisture sources for precipitation in July 2022 over the YB and UTB based on WAM-2layers and FLEXPART-WaterSip models. Moisture contributions are quantified as equivalent water height (mm) over the source regions. For the YB, in addition to significant local recycling, the distribution of most moisture sources aligns with the path of the ISM, extending from the southern slopes of the Himalayas through the Bay of Bengal (BB) and the Indian subcontinent to the Arabian Sea (AS), and reaching as far as the Southern Indian Ocean (SIO) (Fig. 3a and c). Moisture sources for the UTB mainly stretch along the westerlies to the Central Asia region (Fig. 3b and d). Generally, WAM-2layers simulations suggest a broader range of distant moisture sources (including both the westerlies-dominated and ISM-dominated regions) when compared to those identified by FLEXPART-WaterSip.

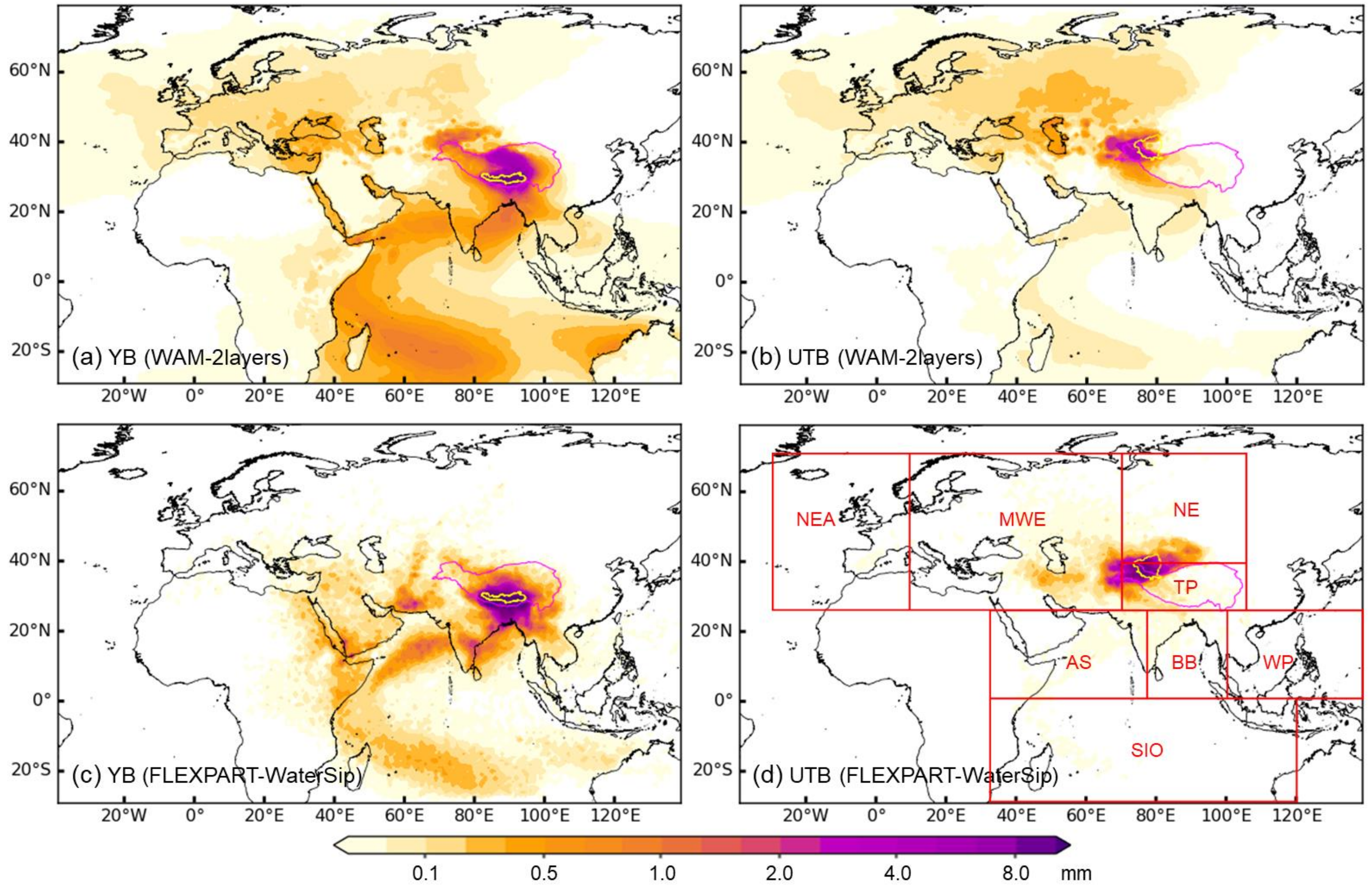

Figure 3: Spatial distributions of moisture contributions (equivalent water height over source regions; mm) to precipitation in July 2022 in the (a and c) YB and (b and d) UTB simulated by (a and b) WAM-2layers and (c and d) FLEXPART-WaterSip models. Purple lines represent the TP boundary and yellow lines represent the boundaries of the two representative basins. Red boxes in (d) delineate the eight source regions: Northeastern Atlantic (NEA), Midwestern Eurasia (MWE), Northern Eurasia (NE), TP, Arabian Sea (AS), Bay of Bengal (BB), Western Pacific (WP), and Southern Indian Ocean (SIO).

The differences between the moisture tracking results from the two models are shown in Figure 4 (WAM-2layers minus FLEXPART-WaterSip). Compared to FLEXPART-WaterSip, WAM-2layers model tends to estimate a higher moisture contribution from the westerlies-dominated northwestern source regions for both basins, spanning from nearby sources northwest of the YB and west of the UTB to distant sources across the entire northwestern Eurasian continent and northeastern Atlantic. Additionally, WAM-2layers model estimates greater moisture contributions from large parts of the Indian Ocean, particularly the distant Southern Indian Ocean in the YB simulation. In contrast, lower contributions estimated by WAM-2layers are mainly from local and nearby source regions downwind of the westerlies, specifically around the southern slopes of the Himalayas in the YB simulation and the entire Tarim Basin in the UTB simulation. Notably, over the Red Sea and Persian Gulf regions, WAM-2layers model indicates higher moisture contributions from the oceans but lower moisture contribution from the surrounding lands than FLEXPART-WaterSip, especially in the YB simulation (Fig. 4a). These discrepancies between the two moisture tracking models are consistent both in absolute and relative terms (Figs. 4 and S2).

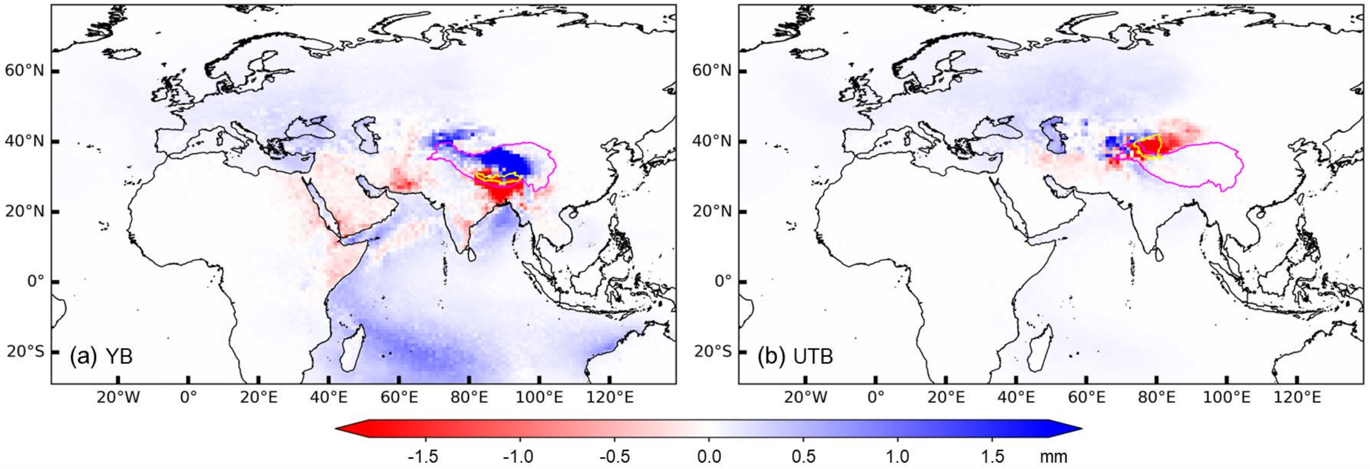

Figure 4: Absolute differences in moisture contributions between WAM-2layers and FLEXPART-WaterSip (WAM-2layers minus FLEXPART-WaterSip) for the (a) YB and (b) UTB simulations.

Considering the distribution of moisture sources, eight critical source regions (see the red boxes in Fig. 3d) are selected for further quantitative analysis. Figure 5 shows the relative contributions from the eight critical regions and remaining regions to precipitation in the YB and UTB. Both models indicate that the major moisture sources for the YB are local recycling and the ISM regions (TP, AS, BB, and SIO), whereas for the UTB, the primary sources are local recycling and westerlies-influenced regions (TP, NE, and MWE). Specifically, WAM-2layers model estimates that the TP contributes 32% of the moisture toward the YB, which is about two-thirds of the estimate by FLEXPART-WaterSip model (53%). An even greater discrepancy is observed for the contribution of the TP to the UTB, for which WAM-2layers model estimates 28% compared to FLEXPART-WaterSip's 72%. For distant sources, the SIO is the most representative one for the YB, with WAM-2layers estimating its contribution at 30%, compared to only 11% by FLEXPART-WaterSip. For the UTB, the MWE is a key distant source, with WAM-2layers estimating a 36% contribution, doubling that calculated by FLEXPART-WaterSip (15%). In summary, compared to FLEXPART-WaterSip, WAM-2layers model generally estimates higher moisture contributions from the westerlies-dominated sources as well as distant sources, but lower contributions from local recycling and nearby sources downwind of the westerlies.

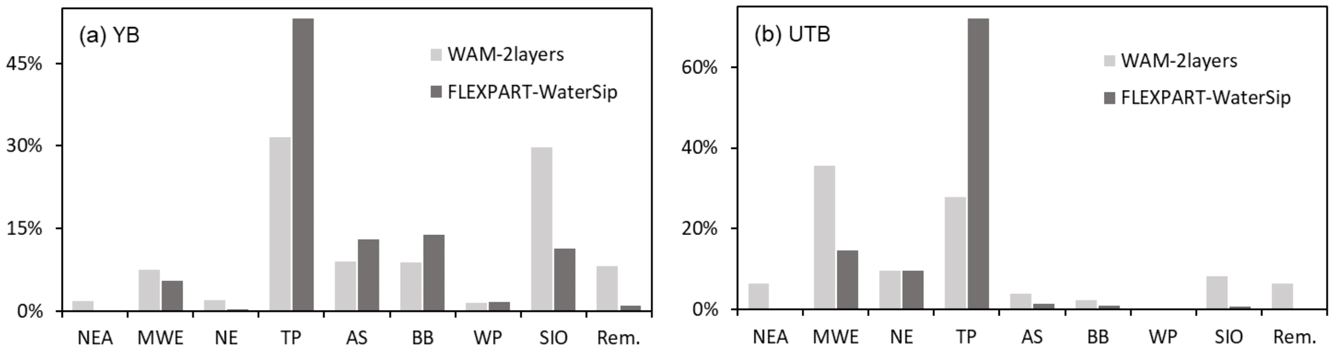

Figure 5: Relative moisture contributions (%) to precipitation over the (a) YB and (b) UTB from the eight selected source regions (NEA, MWE, NE, TP, AS, BB, WP, and SIO) and the remaining (Rem.) source regions simulated by WAM-2layers and FLEXPART-WaterSip models.

4 Moisture fluxes in WAM-2layers and particle trajectories in FLXPART-WaterSip simulations

When tracing moisture sources, WAM-2layers model primarily utilizes horizontal moisture fluxes in the upper and lower atmospheric layers to determine the water vapor transport from global sources to the target region in a backward mode. Figure 6 illustrates the average moisture transport fluxes in the two layers during the entire simulation period as estimated by WAM-2layers. The ISM-dominated moisture transport to the TP region primarily occurs in the lower layer, whereas the westerlies-dominated moisture transport to the region is mainly from the north in the lower layer and from the west in the upper layer, a phenomenon pronounced in the northwest vicinity of the UTB.

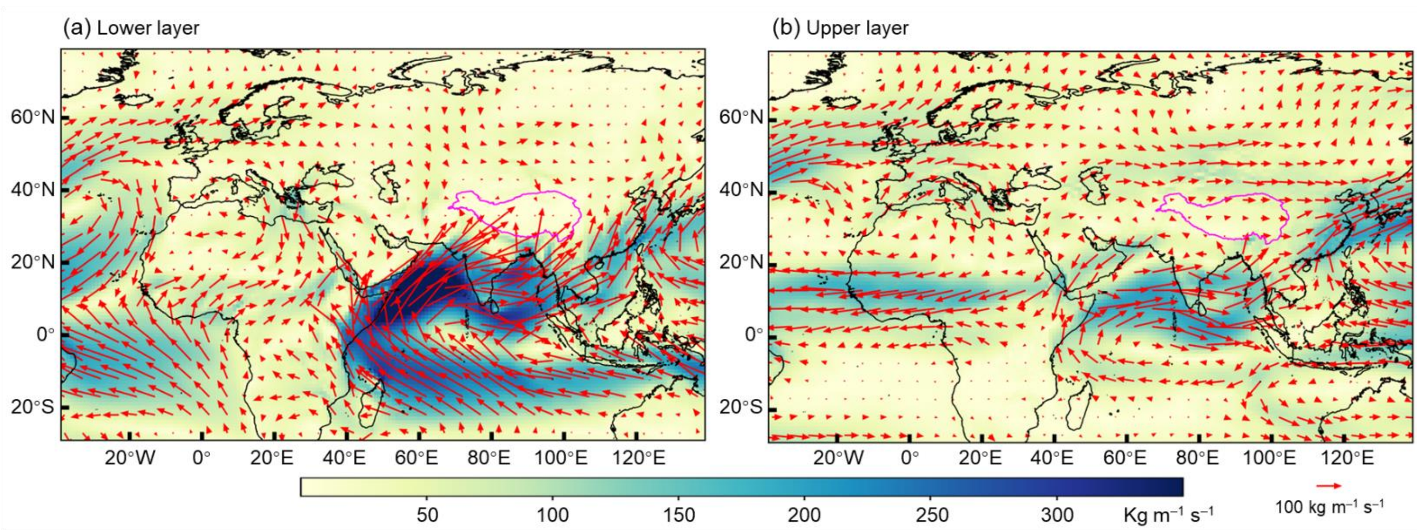

Figure 6: Average moisture transport fluxes (kg m^{-1} s^{-1}) in the (a) lower and (b) upper layers in WAM-2layers during the entire simulation period.

In comparison, FLEXPART outputs detailed information on air particles and trajectories critical to diagnosing moisture sources. Figure 7 shows the spatial distributions of particles and trajectories contributing to precipitation over the YB and UTB in the FLEXPART-WaterSip simulation. It should be noted that the particles and trajectories in Fig. 7 are clustered results using the K-means clustering method for clearer graphical representation, reducing the number of particles by a factor of 100 and the number of trajectories by a factor of 150. This treatment may have filtered out some chaotic and distant particles and trajectories. In Lagrangian backward simulations, particles released from the YB predominantly travel southwestward, while those from the UTB primarily spread westward (Fig. 7a and b). Within about 15 days, the traced particles can reach the farthest source regions. The results of backward tracking days suggest approximately three distinct, fastest moisture transport paths to the YB: the northwestern route from the MWE, the southwestern route from the AS, and the southeastern route from the WP. The most pronounced moisture transport path to the UTB is confined to western routes. Additionally, there is a notable rapid northeastward transport of tracked particles in the UTB over a short period after release (Fig. 7b and Fig. 3d), a phenomenon indiscernible in WAM-2layers simulations (Fig. 3b and d and Fig. 6). This phenomenon may be associated with the complex and variable convective activities as well as the simulation biases in the region, as indicated by the vertical wind patterns at different pressure levels across the study domain (Fig. S3 in the Supplement) and the overestimated local evaporation in FLEXPART-WaterSip (see Sections 5 and 6).

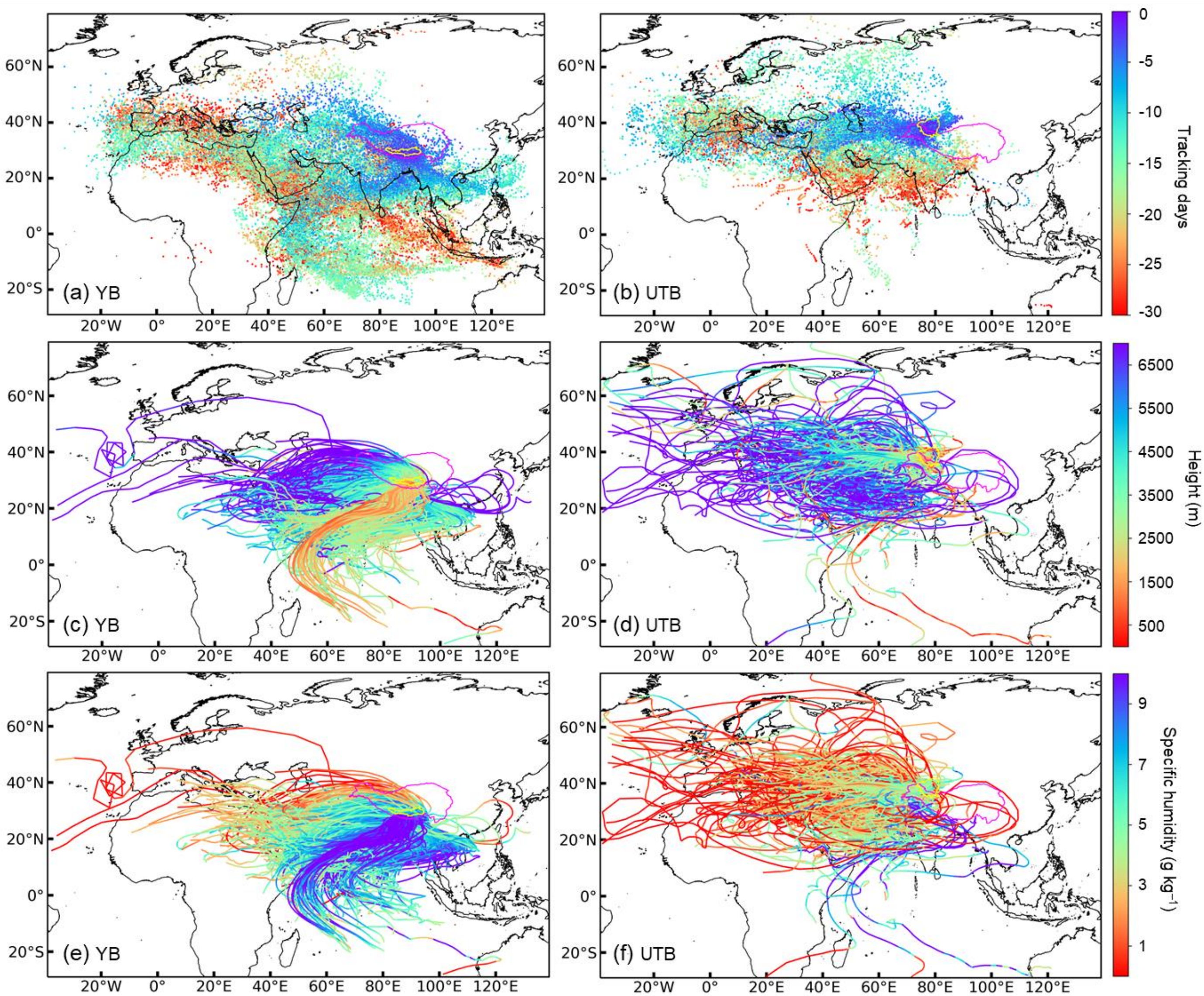

Figure 7: Spatial distributions of (a and b) particles and (c–h) trajectories that transport moisture to the (a, c, and e) YB and (b, d, and f) UTB as simulated in FLEXPART model: (a and b) particles color-coded by backward-tracking days (0–30 days), (c and d) trajectories color-coded by height (m, above ground) at each numerical step, and (e and f) trajectories color-coded by specific humidity (g kg^{-1}) at each numerical step.

As suggested in Fig. 7c–d, trajectories originating from the western sources are typically at higher altitudes, some even exceeding 6000 m, but they notably descend before reaching the target region, forming a strip-like lower atmospheric transport channel in the western part of the target region. This is in general consistent with WAM-2layers simulations, in which the upper-layer horizontal transport of moisture originating from the northwestern Eurasian is higher than that in the lower layer

(Fig. 6). In comparison, trajectories from the ISM-dominated sources are at relatively lower altitudes, with some originating from the SIO even descending below 1000 m. Generally, the moisture-carrying capacity of these trajectories correlates with both their altitude and the moisture conditions in their source regions. As shown in Fig. 6e–f, trajectories from the ISM-dominated regions and lower altitudes exhibit higher moisture content, whereas those from the westerlies-dominated regions and higher altitudes are characterized by lower moisture content.

A notable difference between WAM-2layers and FLEXPART-WaterSip simulations, as illustrated in Fig. 4, is that the spatial extent of source regions identified in FLEXPART-WaterSip is much smaller than in WAM-2layers, especially in distant regions such as northwestern Eurasia. Particle trajectories simulated by FLEXPART are only sparsely distributed across northwestern Eurasia, particularly for the YB (Fig. 7). This inconsistency is also evident when comparing previous studies using WAM-2layers (Zhang et al., 2017; Li et al., 2022a) and FLEXPART-WaterSip (Chen et al., 2019; Yao et al., 2020). This indicates that the underestimated moisture contributions from these distant sources in FLEXPART-WaterSip, as compared to WAM-2layers, are largely due to a lower proportion of particles originating from these source regions reaching the target region.

5 Relationship between "actual evaporation" and simulated moisture contributions

In general, for moisture source–receptor diagnostics within a specific source region, areas with higher evaporation rates generally contribute more moisture to the target region than areas with lower rates, especially where the contrast between oceanic and terrestrial evaporation is pronounced. To further investigate the relationship between evaporation and simulated moisture contributions from various source regions, we employ evaporation data from ERA5 as the benchmark ("actual evaporation"; Fig. 8a) for the entire tracking period (June–July 2022). As shown in Figs. 3 and 8a, the distribution of moisture sources simulated by WAM-2layers aligns more closely with global evaporation patterns from ERA5 (oceanic evaporation rates exceed those of surrounding terrestrial areas) compared to that by FLEXPART-WaterSip. This alignment is particularly evident in the Red Sea and Persian Gulf regions, where one of the most pronounced discrepancies between the two models is observed (Fig. 4a).

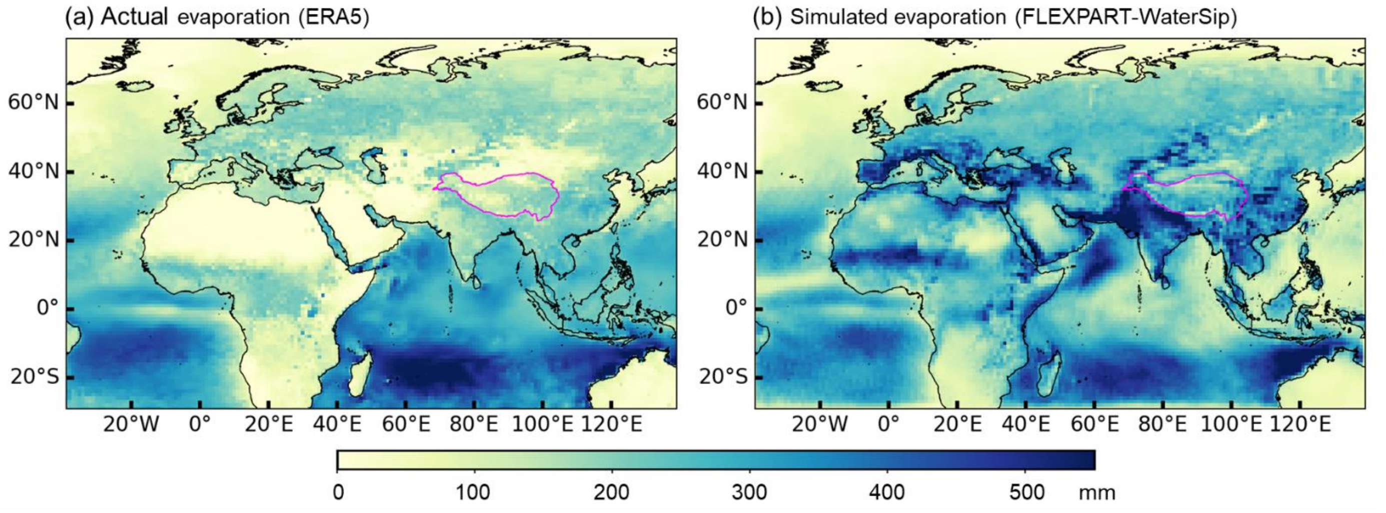

Figure 8: (a) Evaporation from ERA5 and (b) simulated evaporation from FLEXPART-WaterSip during June–July 2022.

We then examine the relationship between "actual evaporation" and simulated moisture contributions across all grid cells in the eight selected source regions (Fig. S4). It is clear that, for both basins, positive correlations between "actual evaporation" and moisture contributions mainly appears in WAM-2layers simulations, especially in the westerlies-dominated NEA and MWE as well as the ISM-dominated AS and SIO regions, where correlation coefficients all exceed 0.3. In contrast, FLEXPART-WaterSip simulations rarely show strong positive correlations between "actual evaporation" and moisture contributions. A striking example is the Red Sea and Persian Gulf regions where oceanic evaporation is notably higher than terrestrial evaporation (Fig. 8a). As mentioned above, FLEXPART-WaterSip model appears to inadequately capture the relatively high evaporation over the Red Sea, Persian Gulf, and eastern Mediterranean (see Fig. 3c), despite extensive tracking particles in these regions (see Fig. 7a). We speculate that the complex atmospheric activities in these regions, as partially evidenced by vertical velocities in Fig. S3, may contribute to these issues in moisture source diagnosis using the WaterSip method. To further illustrate the underlying mechanisms, we randomly selected two representative trajectories: one from the SIO to the YB, and the other from the NEA to the UTB (Fig. S5 in the Supplement). Comparisons between model outputs and ERA5 data, as shown in Fig. S6 in the Supplement, suggest that the modeled changes in specific humidity for particles may not fully reflect the actual processes of precipitation and evaporation during the moisture transport. Relying solely on specific humidity changes and particle height to assess evaporation, precipitation, and moisture transport can be quite challenging. Although the WaterSip method employs thresholds (e.g., 1.5 BLH and 0.2 g^{-1} kg^{-1} every 6 h for specific humidity changes) to exclude a large number of potential misdiagnoses over the source regions, further advancements in diagnostic and correction methods are still needed.

Similar to the moisture source-receptor diagnosis for precipitation particles in the target area, computing all released particles in the atmosphere would provide simulated evaporation over the entire tracking domain. Therefore, Fig. 8b displays the FLEXPART-WaterSip simulated evaporation over the tracking domain during the entire tracking period. In comparison with "actual evaporation", FLEXPART-WaterSip model generally captures the spatial pattern of evaporation across oceanic regions but largely overestimates terrestrial evaporation from mid- and low-latitudes (e.g., surrounding the Mediterranean, the Middle East, and the Indian subcontinent; all of which are critical source regions for the two basins in the TP). These findings are consistent with a previous long-term, global scale study by Keune et al. (2022). Although FLEXPART-WaterSip demonstrates potential in capturing complex local atmospheric activities, the bias in simulated evaporation can inevitably affect the quantification of moisture source–receptor dynamics.

6 Bias correction of FLEXPART-WaterSip simulations

Keune et al. (2022) introduced the Heat And MoiSture Tracking framEwoRk (HAMSTER), a unified framework designed to correct biases in moisture source–receptor diagnostics based on particle trajectories from Lagrangian models. This framework leverages the relationships between actual and simulated surface fluxes (evaporation and precipitation). The first step, in line with WaterSip, is to use specific thresholds for specific humidity changes, relative humidity, and particle height to quantify moisture source–receptor relationships for precipitation in the target region (a "random attribution" method was also introduced). Subsequently, a first round of corrections is conducted by comparing actual and simulated precipitation in the target region (i.e., bias correction of receptor variables). A second round of corrections then focuses on comparing actual and simulated evaporation across all source regions (i.e., bias correction of source variables). These processes aim to achieve reasonable, bias-corrected moisture source contributions. It is noteworthy that the HAMSTER method does not include calibration for the filtering thresholds of precipitation particles in the target region, potentially leading to certain deviations in the spatiotemporal distribution of tracked particle trajectories. If actual precipitation data in the target region were used to calibrate the filtering thresholds of precipitation particles, the step of "bias correction of receptor variables" in HAMSTER could be replaced. Inspired by the HAMSTER method, we develop a simplified two-step approach to correct moisture tracking results from FLEXPART-WaterSip:

Step 1: Optimize the filtering thresholds of precipitation particles in the target region. Using the default precipitation particle filtering thresholds for specific humidity change (0.2 g kg^{-1}) and relative humidity (80%), we conducted numerical experiments to examine how adjustments to these thresholds impact simulated precipitation. As shown in Fig. 9a and b, maintaining a constant relative humidity threshold at 80% while varying the specific humidity change threshold from 0.05 to 0.2 g kg^{-1} results in a minimal decrease in simulated precipitation (less than 1 mm for both basins). In contrast, fixing the specific humidity change threshold at 0.2 g kg^{-1} while changing the relative humidity threshold leads to substantial changes in simulated precipitation (Fig. 9c and d). Our experiments indicate that precipitation simulation is more sensitive to changes in the relative humidity threshold, with the optimal values of 63% for the YB and 74% for the UTB. This step ensures a more accurate selection of precipitation particles for subsequent moisture source diagnosis.

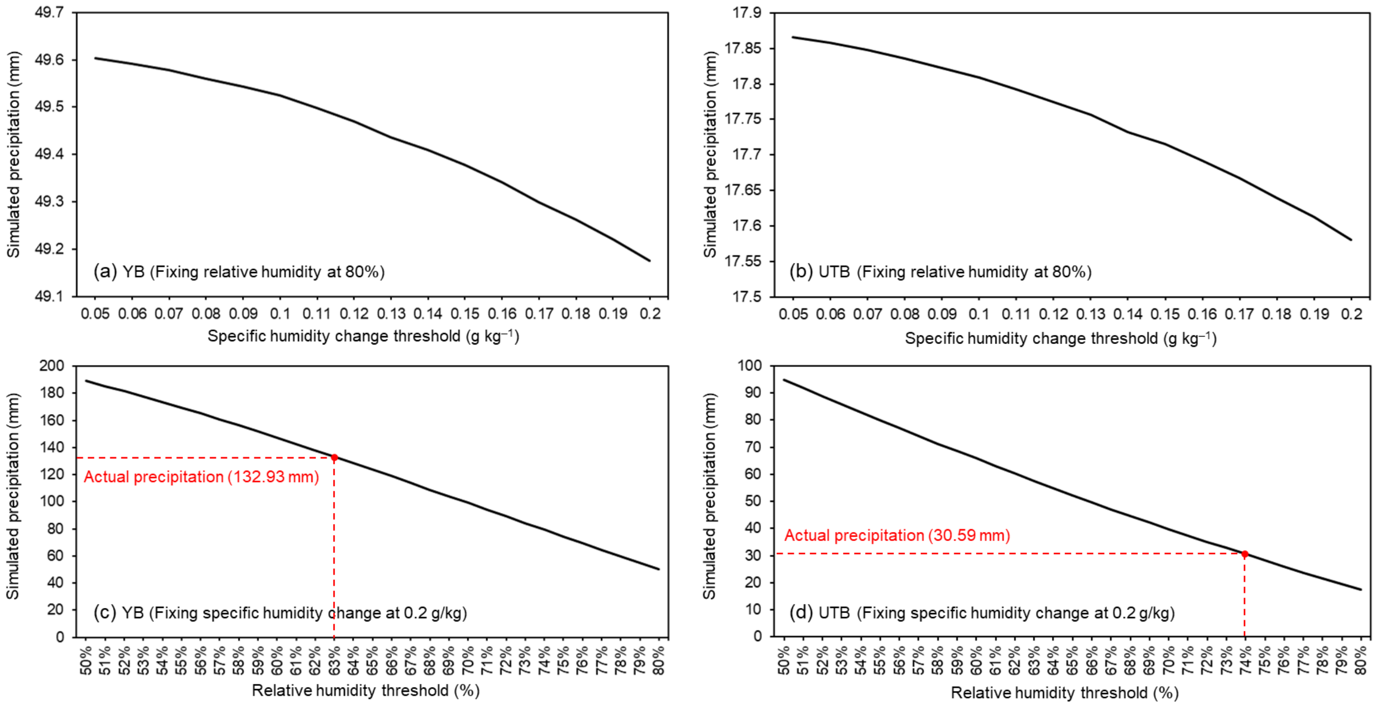

Figure 9: Sensitivity of the simulated precipitation in the (a and c) YB and (b and d) UTB to (a and b) the threshold of specific humidity change and (c and d) the threshold of relative humidity.

Step 2: Correct biases in simulated evaporation over the source regions. First, use the optimized thresholds from Step 1 to quantify moisture source contributions. Next, calculate grid-scale correction factors by dividing actual evaporation by simulated evaporation for each grid cell over the entire moisture tracking period (Fig. S7 in the Supplement). These correction factors are then applied to correct moisture source contributions. This step addresses the simulation biases in evaporation across the moisture tracking domain when using the WaterSip method. It is important to note that although these correction factors are likely to vary over time, this variability was not accounted for in this study due to the relatively short simulation period. For long-term moisture source diagnosis corrections, implementing time-varying correction factors would be more appropriate.

The bias-corrected FLEXPART-WaterSip simulations for the YB and UTB, based on the two-step bias correction approach, are shown in Fig. 10a and b. The bias correction align the FLEXPART-WaterSip simulation results more closely with the global pattern of terrestrial and oceanic evaporation, especially around the Red Sea and Persian Gulf regions. Additionally, it enhances the moisture contributions from the high-latitude Eurasian continent and the Indian Ocean, while reducing contributions from the western land areas in the mid- and low-latitude (Fig. S7 in the Supplement). We further compare these bias-corrected simulations with the original WAM-2layers and FLEXPART-WaterSip simulations, as shown in Fig. 10c–f. The differences depicted in Fig. 10c–d are generally consistent with those in Fig. 4, indicating that WAM-2layers model tends to estimate higher moisture contributions from the westerlies-dominated sources and distant sources, but lower contributions from local recycling and nearby sources downwind of the westerlies for both the YB and UTB. Compared to the bias-corrected results, the original (uncorrected) FLEXPART-WaterSip simulations for the YB estimate lower moisture contributions from areas surrounding the target region and oceanic source regions, but higher contributions from the western land areas (Fig. 10e). For the UTB, the uncorrected FLEXPART-WaterSip simulations mainly estimate higher moisture contributions from the target region and its surrounding areas (Fig. 10f), including the northeastward stretch of moisture sources observed in Fig. 3d. These comparisons demonstrate that through bias correction, the original discrepancies in reflecting actual evaporation between WAM-2layers and FLEXPART-WaterSip simulations can be significantly mitigated.

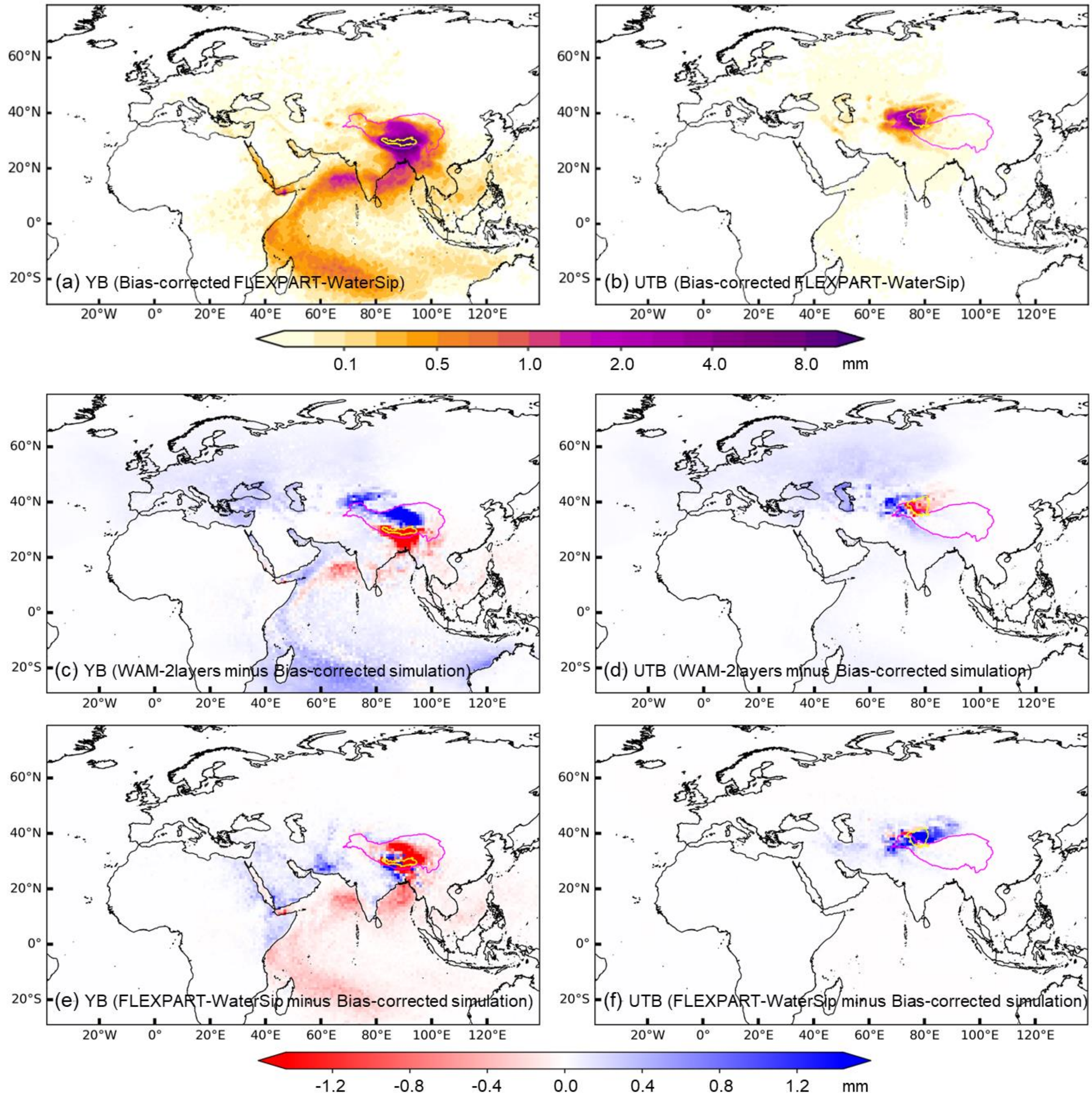

Figure 10: (a and b) Spatial distributions of bias-corrected moisture contributions (equivalent water height over source regions; mm) to precipitation in July 2022 in the (a) YB and (b) UTB simulated by FLEXPART-WaterSip model. (c–f) Absolute differences in

moisture contributions between original WAM-2layers/FLEXPART-WaterSip simulations and bias-corrected FLEXPART-WaterSip simulations for the (c and e) YB and (d and f) UTB.

7 Potential determinants of discrepancies in moisture tracking

We now turn to a more comprehensive examination of the discrepancies observed in the original WAM-2layers and FLEXPART-WaterSip simulations. Considering the underlying physics of the models, forcing datasets, parameter selections, and our computational resources, we designe four sets of numerical experiments to investigate potential factors contributing to the discrepancies in different simulations.

Experiment 1 – model resolution: Simulation of moisture sources using WAM-2layers is essentially a dynamic reproduction of moisture transport conditions based upon forcing datasets, which means that the accuracy heavily depends on the spatial and temporal resolutions of input data. In addition to the original settings (1°×1° at 3-hourly resolution), we introduce three additional configurations of ERA5 data to determine whether improved spatial and/or temporal resolutions in forcing data could provide more accurate moisture source attributions: 1°×1° at hourly resolution, 0.25°×0.25° at 3-hourly resolution, and 0.25°×0.25° at hourly resolution. The results from these additional simulations are summarized in Fig. S8 in the Supplement.

Experiment 2 – moisture source diagnosis thresholds: Quantifying moisture source–receptor relationships in FLEXPART-WaterSip hinges on the diagnosis of potential precipitation particles and evaporation sources, which in turn depends on a set of threshold settings. Previous studies have suggested that optimal configurations for these thresholds may vary globally (Sodemann et al., 2008; Fremme and Sodemann, 2019; Keune et al., 2022). In addition to the original setting (a relative humidity threshold of 80% and a specific humidity change threshold of 0.2 g kg^{-1}), we introduce one additional configuration for precipitation particles selection using the optimized relative humidity threshold for the YB and UTB (63% and 74%, respectively), and two additional configurations for evaporation source identification with specific humidity change threshold set at 0.1 and 0 g kg^{-1}. The results from these additional simulations are summarized in Fig. S9 in the Supplement.

Experiment 3 – number of particles: Using particle trajectories for source diagnostics inevitably limits the identified moisture sources to these trajectories. Consequently, a lower number of trajectories may result in potential inaccuracies, particularly when representing small to medium-scale atmospheric processes. This numerical experiment is designed to determine whether the relatively sparse particle trajectories over distant source regions could introduce substantial uncertainties when estimating moisture contributions in FLEXPART-WaterSip. In this experiment, we reduce the number of particles initially released in FLEXPART from five million to one million. The results of this experiment are summarized in Fig. S10 in the Supplement.

Experiment 4 – "areal source–receptor attribution" method: Different from the WaterSip method proposed by Sodemann et al. (2008), which attributes precipitation at a specific point within the target region to moisture uptake from multiple points along the trajectories, Sun and Wang (2014) introduced the "areal source–receptor attribution" method, focusing on a regional rather than a point scale. The "areal source–receptor attribution" method calculates the total moisture contribution from an examined source to precipitation across the entire target region instead of at specific points. It facilitates the differentiation of moisture contributions from within and outside the examined sources along the trajectories. The basic framework of the "areal source-receptor attribution" method is shown in Fig. S11 in the Supplement, and the detailed methodology can be found in Sun and Wang (2014). In this numerical experiment, we apply "areal source–receptor attribution" method to quantify moisture contributions from the eight source regions.

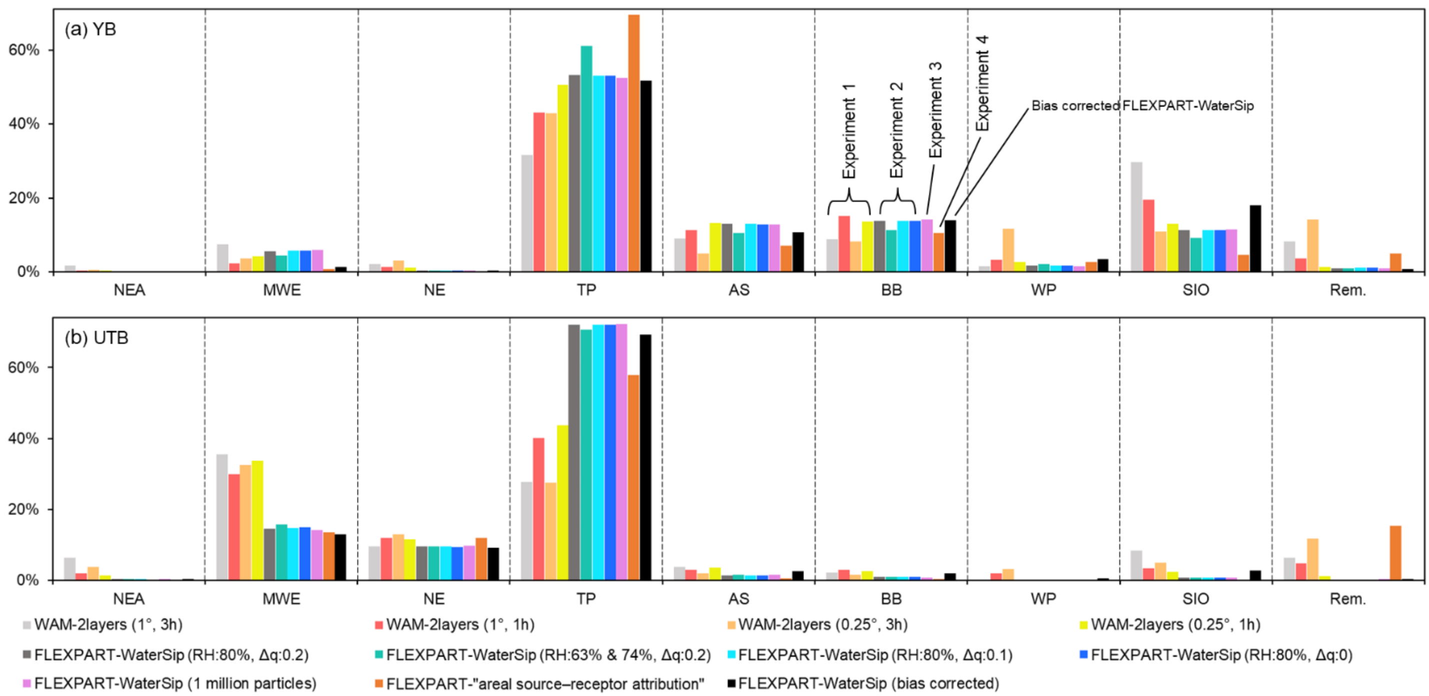

Figure 11: Relative moisture contributions (%) to precipitation over the (a) YB and (b) UTB from the eight selected source regions and the remaining (Rem.) source regions simulated by four sets of numerical experiments (including different configurations in WAM-2layers and FLEXPART-WaterSip and FLEXPART-"areal source–receptor attribution") as well as the bias-corrected FLEXPART-WaterSip simulations. Black histograms represent the bias-corrected FLEXPART-WaterSip simulations. RH and Δq represent relative humidity threshold and specific humidity change threshold (g kg^{-1}), respectively.

Figure 11 shows the relative moisture contributions from the eight selected source regions and the remaining source regions to the YB and UTB in the four set of numerical experiments and the bias-corrected FLEXPART-WaterSip simulations. The results for each source region includes 11 sets of simulations, including original simulations in Section 3 and the bias-corrected simulations in Section 6. In Experiment 1, increasing the spatial and temporal resolutions of the forcing dataset in general aligns WAM-2layers simulations more closely with the bias-corrected FLEXPART-WaterSip (e.g., see results with 0.25°×0.25° at hourly resolution in Fig. S8e and f in the Supplement), particularly for the YB. For nearby sources, moisture contributions from the TP to the YB (UTB) increases from 32% (28%) to 51% (44%). For distant sources, contributions from the SIO and MWE to the YB (UTB) decrease from 30% (8%) to 13% (2%) and from 7% (36%) to 5% (34%), respectively. Our sensitivity experiments for temporal and spatial resolutions reveal that increasing temporal resolution (from 3h to 1h) substantially enhances the reliability of moisture source simulations (Fig. S8a–b in the Supplement). In contrast, solely increasing spatial resolution (from 1° to 0.25°) may lead to a stronger eastward extension of moisture sources for both basins (Fig. S8c–d in the Supplement), which is inconsistent with WAM-2layers (0.25°, 1h) and bias-corrected FLEXPART-WaterSip results. Overall, Experiment 1 demonstrates that improving the spatiotemporal resolutions of forcing data in WAM-2layers can mitigate the underestimation of nearby sources and overestimation of distant sources for both basins, particularly for the YB.

In Experiment 2, adjusting the thresholds of relative humidity substantially enhances the overall moisture contributions from the source regions to both basins of the TP, yet it has minimal effect on the spatial patterns of moisture sources (Fig. S9a–b in the Supplement). Sensitivity experiments on specific humidity change threshold show only a slight impact on moisture source simulations for the two basins (Fig. S9c–f in the Supplement). Generally, modifying the thresholds of moisture source–receptor diagnostics does not seem to reduce the potential biases in the spatial distributions of moisture sources when compared to the bias-corrected FLEXPART-WaterSip. In Experiment 3, reducing the number of released particles somewhat limits our ability to discern finer details in the spatial distribution of moisture sources (Fig. S10 in the Supplement), although the quantified moisture contributions closely resemble those in the original FLEXPART-WaterSip simulations with 5 million particles. In Experiment 4, unlike the WaterSip method, the "areal source–receptor attribution" method utilizes all simulated trajectories for moisture source diagnosis, which may accumulate errors in trajectories that do not result in precipitation in the target region. Reapplying the "areal source–receptor attribution" method with trajectories filtered by the WaterSip method can produce moisture contributions that more closely align with the FLEXPART-WaterSip estimates (results not shown). Overall, these sensitivity experiments underscore that current approaches to diagnosing moisture sources for the TP using numerical moisture tracking models still hold substantial potential for improvement and refinement.

8 Discussion and conclusions

Over the past few decades, considerable efforts have been made to identify and quantify the contributions of moisture sources to precipitation over the TP. A synthesis of these studies indicates that the most commonly used Eulerian and Lagrangian moisture tracking models are WAM-2layers and FLEXPART-WaterSip, respectively. However, the suitability and reliability of these models for moisture tracking over the TP, especially the potential discrepancies in moisture tracking results, have not yet been thoroughly examined. This study addresses this gap by focusing on two representative basins of the TP: the YB (representing the ISM-dominated regions) and the UTB (representing the westerlies-dominated regions). Moisture source contributions to precipitation over these two basins were tracked using both WAM-2layers and FLEXPART-WaterSip models. We then investigated the discrepancies in moisture tracking results between these two models and their potential determinants through comparisons with actual evaporation, bias correction, and a set of sensitivity experiments.

The WAM-2layers model, designed for moisture tracking based on the water balance equation at a spatial-temporal resolution constrained by the forcing dataset, may face challenges in accurately capturing moisture transport to target regions through smaller-scale atmospheric processes. Compared with FLEXPART-WaterSip, the application of WAM-2layers over the TP is more computationally efficient. A persistent issue with WAM-2layers, relative to the bias-corrected FLEXPART-WaterSip, is its tendency to estimate higher moisture contributions from westerlies-dominated sources and distant sources but lower contributions from local recycling and nearby sources downwind of the westerlies. However, this can be mitigated by utilizing higher spatial and temporal resolutions for forcing dataset in WAM-2layers, with a priority on improving temporal resolution, particularly in the ISM-dominated YB region. In addition, WAM-2layers offers one notable advantage over FLEXPART-WaterSip: its simulated spatial distribution of moisture sources is more consistent with the pattern of actual evaporation, particularly around the Red Sea and Persian Gulf regions where the contrast between terrestrial and oceanic evaporation is strong.

The FLEXPART model, designed to track air particles in the atmosphere based on well-established physical mechanisms, is complemented by the WaterSip method to diagnose moisture source – receptor relationships with information from simulated trajectories. FLEXPART-WaterSip enables us to investigate the movement of air particles transporting moisture in a detailed three-dimensional space. We investigated the potential impact of different filtering thresholds in the WaterSip method and varying numbers of released particles on moisture source–receptor diagnostics. The simulation of precipitation in the two basins is more sensitive to changes in relative humidity thresholds, while adjusting specific humidity change threshold does not significantly alter the estimated moisture source contributions. Nevertheless, the WaterSip method facilitates calibration of simulation biases by comparing results with actual observations (such as precipitation and evaporation). Therefore, if possible, we recommend bias-correcting the simulations from FLEXPART-WaterSip (through e.g., the method proposed by Keune et al. (2022) or the simplified two-step approach proposed in this study). The corrected results substantially reduce the evaporation biases over the source regions, particularly addressing the discrepancies arising from land–sea contrast in evaporation.

This study serves as a valuable reference for future numerical simulations aimed at tracking moisture sources across the TP region, including several crucial aspects such as model selection, error and uncertainty analysis, and strategies for enhancing simulate accuracy. While recognizing that each model is best suited to specific scenarios, this study highlights the critical need to account for the distinct characteristics of different models and the potential uncertainties in diagnosing moisture sources.

Although this investigation is confined to short-term simulations using WAM-2layers and FLEXPART-WaterSip models in two typical basins over the TP, it is anticipated that future research will extend such intercomparisons to other regions and even continental or global scale. Furthermore, investigating the application of more sophisticated techniques for moisture source–receptor identification, particularly those that enhance the capability of Eulerian or Lagrangian models to capture small-scale atmospheric convection and turbulence, would be of significant benefit.

Code availability. The official website of WAM-2layers is https://wam2layers.readthedocs.io/en/latest/. The official website of FLEXPART is https://www.flexpart.eu/. The relevant code and installation tutorials can be obtained from these official websites. For the WaterSip method, the authoritative website is https://wiki.app.uib.no/gfi/index.php?title=WaterSip. The WaterSip source code we developed in this study can be found in Part 3 of the Supplement. All additional algorithms are available on request from the first/corresponding author.

Data availability. ERA5 data are publicly available at the Climate Data Store (CDS) (https://cds.climate.copernicus.eu/). The input data of WAM-2layers were downloaded according to the example code in https://github.com/WAM2layers/WAM2layers/tree/main/scripts. The forcing data of FLEXPART were downloaded and pre-processed using the flex_extract v7.1.2 (https://www.flexpart.eu/flex_extract/). All simulation results in this study are available on request from the first/corresponding author.

Author contributions. YL conceptualized the study, carried out numerical simulations, conducted formal analysis, prepared figures, and wrote the initial draft. CW contributed to the editing, discussion, and interpretation. QT, SY, and BS provided comments on the manuscript. HP and SX provided supervision during the simulations and writing.

Competing interests. The contact author has declared that neither they nor their co-authors have any competing interests.

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Response to Dr. Ruud van der Ent:

General comments:

Li and co-authors study the moisture sources of precipitation in 2 river basins for the (seemingly randomly chosen) 2022 July period with 2 moisture tracking algorithms WAM2layers and FLEXPARTWaterSip. They compare the methods and subsequently test sensitivities when changing certain parameters. The study is timely, relevant, generally easy-to-follow and substantiated with good figures and tables. However, I have two major comments:

1. The study is not at all reproducible as no detailed model settings are provided in relevant scripts. Moreover, people that use other moisture tracking models or settings would not be able to compare their results against that of the authors as no output data is provided. Only generic links to input scripts and data are available which are by far insufficient in this new era of FAIR and Open Science.

2. The authors make several strong statements and conclusions about the tracking models ability, which, in my opinion are mere hypotheses by lack of knowledge about an actual truth. These hypotheses should be substantiated by additional analysis and/or toned down.

Response: Thanks for your thorough review and valuable comments on our manuscript. We appreciate the time and effort you have dedicated to evaluating our work and are grateful for the constructive feedback provided. Please see below for our responses to your general comments and a summary of changes made in the revision:

Selection of river basins: We would like to clarify that the two river basins are not randomly selected. As suggested in previous studies, the Tibetan Plateau (TP) is influenced by the intricate interactions between the Indian monsoon and the westerlies (Yao et al., 2022). The selected two river basins exemplify the influences of these two systems. Specifically, the Yarlung Zangbo River Basin (YB) is mainly influenced by the monsoon, which travels across the Himalayas, while the upper Tarim River Basin (UTB) is mainly influenced by the westerlies after crossing the Pamirs. Analyzing these two representative basins will also facilitate a comprehensive study of the basin-scale water balance, including both atmospheric moisture dynamics and runoff.

Reproducibility of our study: We have provided all the relevant model settings and our customized algorithms/codes in the supplement. In addition, we will release our simulation results in an open-access data repository upon the publication of this work. We have further stated that all codes and data are available on request from the first/corresponding author.

Experimental designs, statements, and conclusions about the tracking models: We have: 1) conducted a detailed sentence-by-sentence revision to improve the descriptions in the research background and results sections; and 2) enhanced the manuscript by incorporating additional analyses, discussions, and sensitivity experiments to thoroughly substantiate all conclusions.

More specifically, we have made substantial changes to the manuscript. The revised structure becomes:

1. Introduction

2. Eulerian and Lagrangian approaches for moisture tracking: WAM-2layers and FLEXPART-WaterSip models

3. Moisture tracking in two representative basins

4. Comparison between moisture fluxes with WAM-2layers and particle trajectories with FLEXPART-WaterSip

5. Relationship between "actual evaporation" and simulated moisture contributions

6. Bias correction of FLEXPART-WaterSip simulations

7. Potential determinants of discrepancies in moisture tracking

8. Discussion and conclusions

In Section 1, we thoroughly revised the logic flow of the introduction section: 1) we narrowed down the scope of our current study to focus exclusively on moisture tracking over the TP; 2) we clearly pointed out potential simulation differences that may exist in previous research; 3) we emphasized that the aim of this study is to investigate potential errors/uncertainties in existing moisture tracking studies in the TP; 4) we cautioned readers against generalizing our comparison results in the TP to other regions.

In Section 2, we 1) provided detailed descriptions of the two selected models; 2) clearly specified all numerical settings for these two models and detailed their configurations in Part 2 of the supplement; 3) shared our customized code for WaterSip in Part 3 of the supplement.

In Sections 3 and 4, we 1) removed redundant content and inaccurate descriptions; 2) strengthened the logic of our analyses.

Sections 5 and 6 are newly added chapters. In section 5, we evaluated the relationship between evaporation data from ERA5 and the simulated moisture contributions to further clarify the strengths and weaknesses of the two models. Building on these comparison results, in Section 6, we presented the bias-corrected simulation results of FLEXPART-WaterSip, which substantially improved model's accuracy in simulating evaporation.

In Section 7, we included additional sensitivity experiments for WAM-2layers (including additional configurations with different spatial and temporal resolutions) and FLEXPART-WaterSip (including additional combinations of specific and relative humidity thresholds). These new analyses have strengthened the robustness of the conclusions drawn in this manuscript.

In Section 8, we removed or revised conclusions not fully substantiated by our analyses.

Specific comments:

1. L. 23: "the Eulerian or Lagrangian method"

There is no such thing as 'the XXX' method and there are many other factors (possibly more dominant factors) that contribute to differences in moisture source attribution.

Response: Thanks for pointing this out. We have carefully revised all these inaccurate statements in our revised manuscript. We changed "the Eulerian or Lagrangian method" to specific models (e.g. WAM-2layers). This is to acknowledge that the two models used in this study are examples of Eulerian and Lagrangian models/approaches (e.g., WAM-2layers is AN Eulerian model/approach for moisture tracking). For consistency, we also replaced "methods" with "approaches" or "models" in the revision.

2. L. 29-31: "The inherent ability in WAM-2layers to distinguish between evaporation and precipitation makes it more effectively in identifying varying moisture contributions arising from distinct surface evaporation sources."
Effectively by what measure?

Response: Thanks for the comments. The effectiveness is based on quantitative assessment of simulated evaporation. In this revision, we added a new Section 5 to compare the results of the two models with evaporation data from ERA5 over the entire source regions.

3. L. 31-33: "In contrast, in regions heavily influenced by smaller-scale convective systems with high spatial heterogeneity, such as the UTB when compared to the YB, simulations from FLEXPARTWaterSip tend to be more reliable."
Reliable by what measure?

4. L. 34: "However, FLEXPART-WaterSip is prone to introducing additional errors when using specific humidity information in particles to infer moisture uptake and loss, although it accurately depicts the three-dimensional movement of air particles."
Accurate by what measure?

Response: Sorry for the confusion. We have carefully checked and revised all statements/conclusion to ensure that they are sufficiently supported by our results. As a result, these speculative statements have been removed from the revised manuscript.

5. L. 44-49: "In comparison, the Lagrangian method employs a particle trajectory tracking approach, inferring the movement of moisture through individual three-dimensional particle trajectories solved with differential equations. While Lagrangian models typically involves more complete physical mechanisms in particle dispersion processes, they exhibit substantially less numerical diffusion than Eulerian models, making them more adept at capturing small-scale atmospheric phenomena such as turbulence, convection, and dispersion, particularly over complex terrains (Wang et al., 2018; Tuinenburg and Staal, 2020)."
But do most or all Lagrangian models include actual diffusion through turbulence, velocity differences, rainfall re-evaporation etc.? If not, then having no diffusion either numerically or explicitly modeled would also lead to errors.

Response: Thanks for pointing this out. Indeed, both Eulerian and Lagrangian models include diffusion. By "less numerical diffusion" here we meant "less numerical diffusion error". Eulerian models use a fixed grid system and track changes in each grid cell, which can potentially lead to less accurate results in tracking moisture movements when compared to particle (parcel)-based Lagrangian models. To avoid ambiguity, we have removed this part from our revised manuscript.

6. L. 53-55: "However, these studies have not extensively explored the limitations of different model types and the causes of discrepancies between moisture tracking results. Moreover, the studies on the generation mechanisms of model uncertainties through the moisture tracking intercomparison is severely lacking."

I think the authors' study is a good addition, but I do not think that objectively they do much more than these previous studies. So, they should tone down this comment and somewhere in the introduction explain the relevance of their own contribution. A missing moisture tracking model comparison study is also the one by Van der Ent et al. (2013).

Response: Thanks for the comment. The motivation of this study originates from the extensive literature on precipitation moisture tracking in the Tibetan Plateau (TP) (Table 1 only presents a subset of existing efforts). However, to the best of our knowledge, no effort has been made to address the discrepancies or uncertainties among these TP-focused studies. This situation has led us to develop this manuscript, aspiring to encourage future researchers to critically assess the reliability of their simulation outcomes. Toward this goal, we strive to identify potential factors contributing to discrepancies among models over the TP region. Based on your suggestions, we have thoroughly revised the Introduction section to emphasize the following two aspects:

1. We have narrowed down the scope of the present study to focus exclusively on moisture tracking over the TP. In this context, we have specifically highlighted that the most widely used numerical moisture tracking models are WAM-2layers and FLEXPART-WaterSip. The subsequent paragraphs in Introduction also focus solely on these two representative models.

2. The aim of this manuscript was to investigate potential errors/uncertainties in existing moisture tracking studies in the TP as well as to understand their underlying mechanisms/determinants. We have emphasized the significance of this study in the last paragraph of Introduction.

7. L. 64-65: "the Eulerian… the Lagrangian"

Same comment as above.

Response: Thanks. Please see our previous response to your specific comment #1 above.

8. Table 1: "Overview …"

- Please note that this overview table is non-exhaustive
- Particularly missing studies are those by Guo et al. (2019, 2020)
- Is CAM a tracking model?
- I'd say the moisture source diagnosis of WAM2layers is simply the E and P from the data (as in QIBT or UTrack)

Response: Thanks for your comments.

- In our revised manuscript, we emphasized that this overview table is non-exhaustive ("extensive studies on water isotopes in the TP with moisture tracking simulations are not include here"). In addition, we added several studies to Table 1 (including Guo et al. 2019; 2020).
- Sorry for the oversight. "CMA" here should be "CAM5.1 with a tagging method".

The authors developed a moisture tracer technology for the CAM5.1 model (Pan et al., 2017), enabling it to trace moisture source (Pan et al., 2018).

- Thanks, these blank cells were filled with "E and P" in the revised Table 1.

Please see the revised Table 1 below:

Table 1: *Overview of Eulerian and Lagrangian moisture tracking studies in the TP and its vicinity. Note that extensive studies on water isotopes in the TP with moisture tracking simulations are not included here. "E and P" means the model diagnoses evaporation and precipitation separately, while "E – P" means the model diagnoses contributions through water budget (i.e., evaporation minus precipitation).*

	Model	Moisture source diagnosis	Study area	Forcing dataset	Study period	Reference
Eulerian	WAM-1layer	E and P	Central-western TP	ERA-I, NCEP-2	1979–2013	Zhang et al. (2017)
	WAM-2layers	E and P	Endorheic TP	ERA-I, MERRA-2, JRA-55	1979–2015	Li et al. (2019)
	WAM-2layers	E and P	Southern/northern TP	ERA-I	1979–2016	Zhang et al. (2019a)
	WAM-2layers	E and P	TP	ERA-I	1979–2015	Guo et al. (2019)
	WAM-2layers	E and P	TP	ERA-I	1998–2018	Zhang (2020)
	WAM-2layers	E and P	TP	ERA-I, MetUM	1982–2012	Guo et al. (2020)
	WAM-2layers	E and P	Major basins in TP	ERA-I, MERRA-2, JRA-55	1979–2015	Li et al. (2022a)
	WAM-2layers	E and P	TP (forward tracking oceanic evaporation)	ERA-I, MERRA-2, JRA-55	1979–2015	Li et al. (2022b)
	WAM-2layers	E and P	TP (forward tracking TP evaporation)	ERA5	2000–2020	Zhang et al. (2023)
	WAM-2layers	E and P	Five typical cells in the TP	ERA5	2011–2020	Zhang et al. (2024)
	CAM5.1 with a tagging method	E and P	Southern/northern TP	MERRA	1982–2014	Pan et al. (2018)
Lagrangian	FLEXPART	E – P	TP	NCEP-GFS	2005–2009 (summer)	Chen et al. (2012)
	FLEXPART	Areal source–receptor attribution	Grassland on eastern TP	NCEP-CFSR	2000–2009	Sun and Wang (2014)
	FLEXPART	WaterSip	Four regions within TP	ERA-I	1979–2018 (May–August)	Chen et al. (2019)
	FLEXPART	Areal source–receptor attribution	Xinjiang	NCEP-FNL	2008–2015 (April–September)	Zhou et al. (2019)
	FLEXPART	WaterSip	Southeastern TP	ERA-I	1980–2016 (June–September)	Yang et al. (2020)
	FLEXPART	WaterSip	Xinjiang	NCEP-CFSR	1979–2018	Yao et al. (2020)
	FLEXPART	WaterSip	Northern/Southern Xinjiang	NCEP-CFSR	1979–2018	Hu et al. (2021)
	FLEXPART	Areal source–receptor attribution	Source region of Yellow River	NCEP-FNL	1979–2009	Liu et al. (2021)
	FLEXPART	WaterSip	Xinjiang	NCEP-CFSR	1979–2018 (April–September)	Yao et al. (2021)
	FLEXPART	E – P	Three-rivers headwater region	ERA-I	1980–2017 (boreal summer)	Zhao et al. (2021)
	FLEXPART	E – P	Three-rivers source region	NCEP-FNL	1989–2019	Liu et al. (2022)
	FLEXPART	WaterSip	Three-rivers headwater region	ERA-I	1980–2017	Zhao et al. (2023)
	HYSPLIT	WaterSip	Three-rivers headwater region	NNR1	1960–2017 (June–September)	Zhang et al. (2019b)
	HYSPLIT	E – P	Western TP	ERA-I	1979–2018 (winter)	Liu et al. (2020)
	HYSPLIT	Maximum specific humidity	Seven regions within TP	NCEP/NCAR	1961–2015 (summer extreme event)	Ma et al. (2020)
	HYSPLIT	Contribution function and weighting	TP	NCEP-GDAS	1950–2015 (extreme precipitation events)	Ayantobo et al. (2022)
	HYSPLIT	WaterSip	Southern Xinjiang	ERA5	2021(June 15–17)	Chen et al. (2022)
	LAGRANTO	WaterSip	Southeastern TP	ERA-I	1979–2016 (winter extreme precipitation)	Huang et al. (2018)
	LAGRANTO	WaterSip	Three regions within TP	ERA-I	1979–2016 (winter extreme precipitation)	Qiu et al. (2019)
	LAGRANTO	WaterSip	Northern TP	ERA-I	2010–2018 (monsoon season)	Wang et al. (2023)

QIBT	E and P	Southeastern TP	ERA-I	1982–2011 (April–September)	Xu and Gao (2019)

9. L. 92-93: "The model prescribes a two-layer division (~810 hPa with a standard surface pressure)"
Probably good to stress that the layer separation is very different over the Tibetan Plateau.

Response: Thanks. In the revised manuscript, we have mentioned that the division varies with topography, and include a sentence to explain the situation over the TP region: "~520 hPa over the TP (~4000 m)". See Lines 120–121 in our revised manuscript.

10. Figure 1: "method"
- In WAM2layers P also goes out the upper layer
- WaterSip is not necessarily 6 hours I suppose?

Response: Thanks.
- Indeed. We have added P in the upper layer in our revised Fig. 1a.
- Yes, the output intervals can be different in FLEXPART. We used 6-hours here because it represents the most commonly used (also the default) time interval in WaterSip. This is also consistent with our illustration in "step two" in Fig. 1b.
Please see below for the revised Fig. 1:

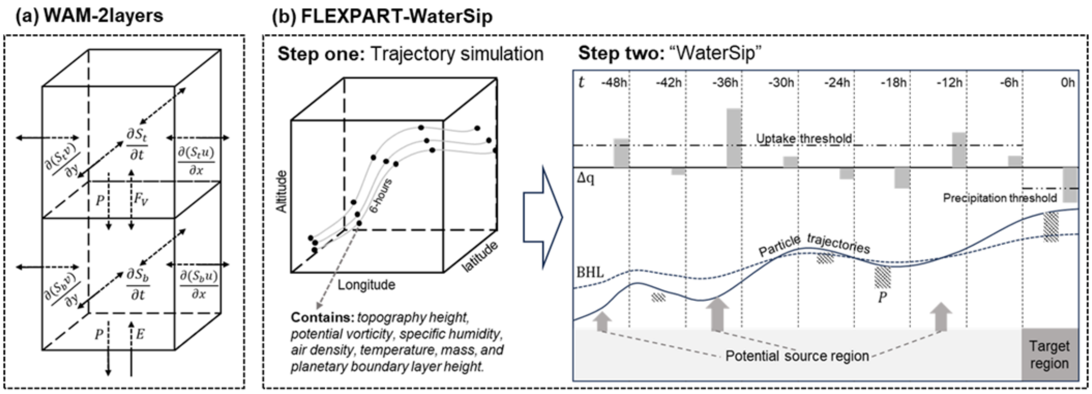


Figure 1: *Mechanisms of (a) WAM-2layers and (b) FLEXPART-WaterSip models. "Step two" in (b) is adapted from Sodemann et al. (2008).*

11. L. 145-146: "Our numerical experiments, as illustrated in Fig. S2b, indicate that within the first 10 days (20 days), we traced 89% (99%) of the precipitation moisture in the YB and 97% (99%) in the UTB."
The amount of attributed moisture seems very high to me. Do the authors think this realistic? How does the E simulated from WaterSip compare to actual E from ERA5?

Response: Thanks for the comments.

1. We found one previous study that used the same method (FLEXPART-WaterSip) for moisture tracking in Xingjiang (north of the TP) (Yao et al., 2020), which includes a figure illustrating the relationship between tacking days and cumulative contribution rates (see the Figure below). Within 10 days, ~95% of the precipitation moisture in the region was tracked, which is consistent with our results.

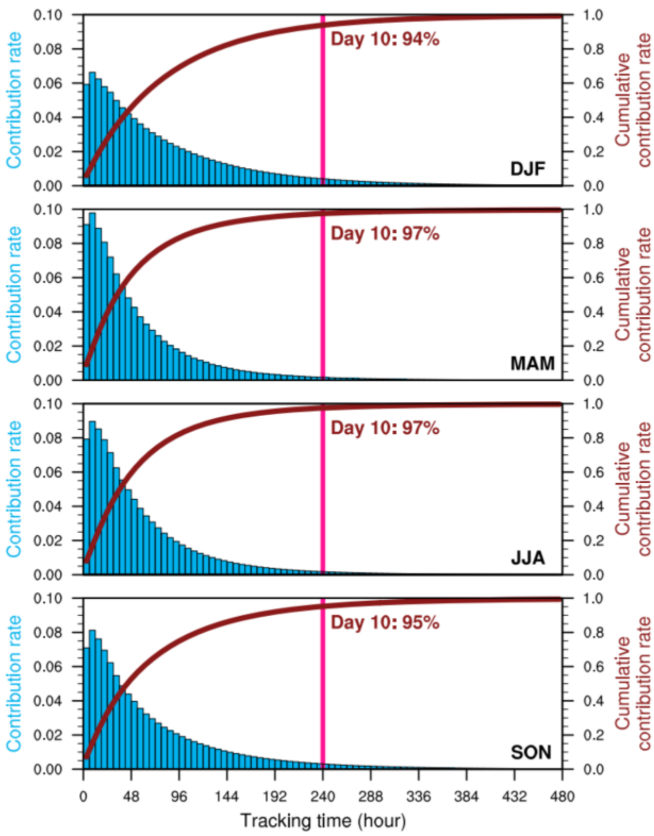


FIGURE 3 The contribution rates (bars) of moisture that can be traced by different backtracking times among seasons, together with their cumulative contribution rates (curves). The percentages are the cumulative proportions of moisture that can be traced back to 10 days

2. In the revision, we further evaluated the relationship between the simulated moisture contributions and actual evaporation from ERA5 over the entire tracking domain. Results are shown in the newly added Section 5. In general, results from WAM-2layers are more consistent with actual evaporation compared to those from FLEXPART-WaterSip.

12. L. 156-159: "Another noteworthy detail is the clear north-eastward extension of moisture sources for UTB precipitation resolved by FLEXPART-WaterSip, reaching almost to the easternmost Tianshan Mountains (Fig. 2d), a feature absent in the results of WAM-2layers (Fig. 2b)."

It is not clear exactly where the Tianshan Mountains are in Figure 2. Moreover, the word 'resolved' suggests that there is orthogonal evidence for those moistures to be the 'truth', but I fail to see where that is presented.

Response: Thanks for the comments.

1. We have labeled all the mountain ranges around the study areas in the revised Fig. S1 (see below).

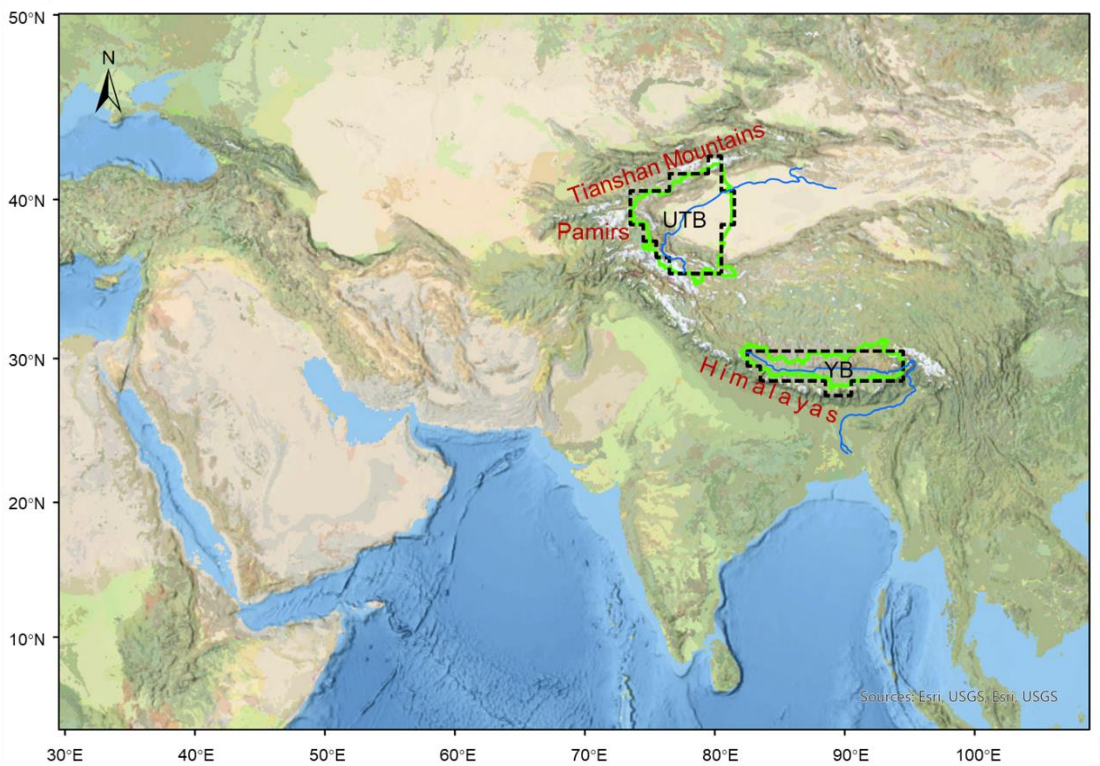


Figure S1. *Topography of the Yarlung Zangbo River Basin (YB) and the upper Tarim River Basin (UTB). Cyan solid lines represent the actual watershed boundaries. Dotted black lines depict the computational boundaries. Blue lines represent the rivers. Generally, the monsoon impacts the YB after traveling across the Himalayas, while the westerlies impact the UTB after crossing the Pamirs and Tianshan Mountains.*

2. Based on the newly added analyses in Section 5 and Section 6 in the revision, we found this "north-eastward extension of moisture sources for UTB precipitation" partially stems from simulation errors in FLEXPART-WaterSip model. We have pointed this out in the revision: "For the UTB, the uncorrected FLEXPART-WaterSip simulations mainly estimate higher moisture contributions from the target region and its surrounding areas (Fig. 10f), including the northeastward stretch of moisture sources observed in Fig. 3d." (Lines 364–365 in our revised manuscript). For further details, please see Sections 5 and 6 in our revised manuscript.

13. Figure 2: "Spatial distributions …"

- FLEXPART-WaterSip attributes vast areas of evaporative sources from as far away as the Arabian Desert and the Sahara in the same order of magnitude as evaporative contributions from the Red Sea, Gulf of Aden and Gulf of Oman. With actual evaporation being several orders of magnitudes lower in the desert, this feature is completely unrealistic and warrants more investigation by the authors. What does this tell in general about the trustworthiness of this method?

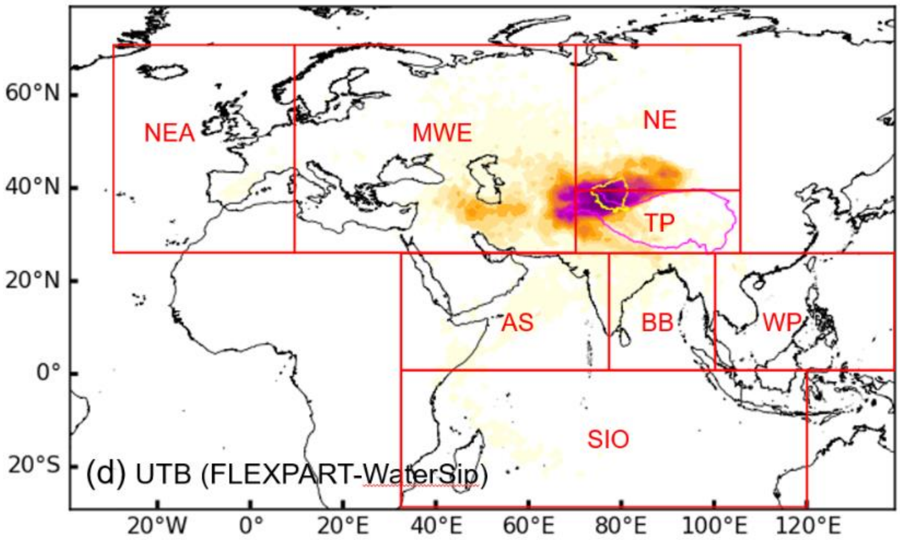
- The blank area between MWE and AS seems not a very logical way to separate regions.

Response: Thanks for the comments.

1. Indeed, this "unrealistic" phenomenon warrants further investigation. In our revised manuscript, we added a new Sections 5 to evaluate the relationship between

actual evaporation from ERA5 and the simulated moisture contributions, and a new Section 6 to bias-correct the results of FLEXPART-WaterSip. These two sections are designed to improve our understanding of the reliability of these two moisture tracking models. Based on our new analyses, we found that FLEXPART-WaterSip is somewhat biased in simulating evaporation. However, these biases can be partially corrected using actual surface fluxes. The bias correction also substantially reduces evaporative contributions from Arabian Desert and the Sahara. For more details, please see Sections 5 and 6 in our revised manuscript.

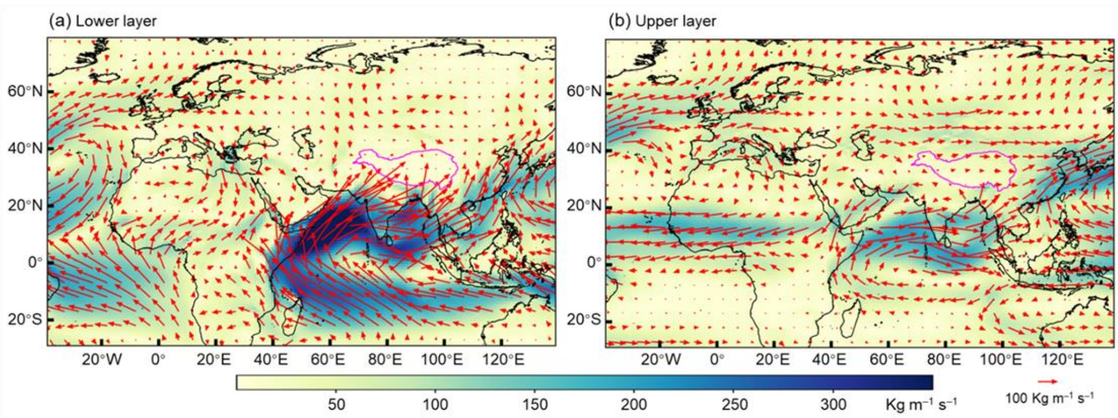
2. In the revision, we have modified the division of the eight major moisture sources to cove the blank area between MWE and AS (see figure below). All relevant figures and results have been updated accordingly.



14. Figure 5 and 6:

What is the exact meaning in a quantitative sense of the red arrows?

Response: Sorry for the confusion. In the revised manuscript, we have added a quantitative legend for the red arrows (see the revised figure below).



In original Fig. 6, the red arrows in (a) and (b) are somewhat redundant. To avoid confusion, we have removed these arrows. Note that the original Fig. 6 becomes Fig. 7 in the revised manuscript.

15. L. 242-244: "This further implies that the modelling capability of WAM-2layers for moisture sources of the UTB may be less robust than for the YB, consistent with the observation that the simulation disparities between the two models are more pronounced in the UTB than that in the YB (Fig. 4)."
As mentioned before, this hypothesis is not substantiated by any quantitative analysis. Alternatively, my hypothesis would be that while moisture goes to the northeast (back in time), there was very little evaporation in that area from the ERA5 data, so it wasn't identified as a source, whereas FLEXPART-WaterSip erroneously assigns an imbalance in its Lagrangian moisture budget as surface evaporation which may also have be caused by, for example, convergence. I do not have any evidence directly for my hypothesis either, but it is up to the authors to investigate the matter in more detail before jumping to conclusions.
Response: Thanks for your insightful comments. In our revised manuscript, we have included additional analyses and discussions to substantiate these hypotheses. This includes the comparison between actual evaporation from ERA5 and simulated moisture sources (Section 5) as well as the bias correction for FLEXPART-WaterSip results (Section 6). Please also see our responses to your specific comment #13 and general comments above.

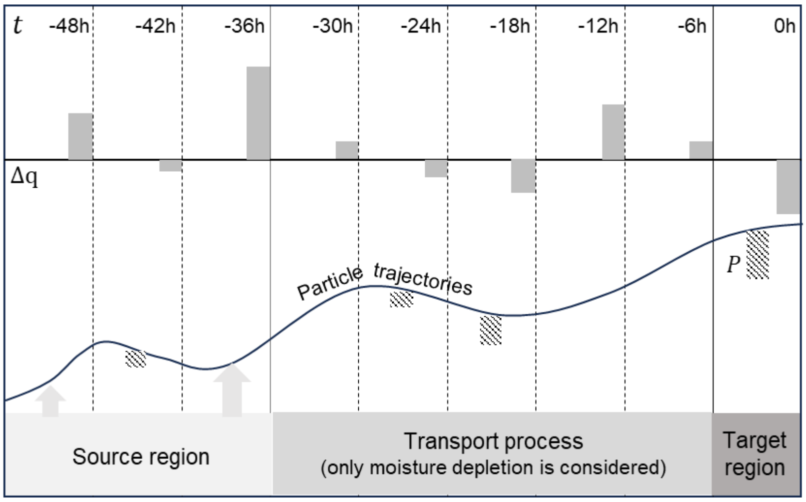
16. L. 268-270: "A notable difference between WAM-2layers and FLEXPART-WaterSip, as highlighted in Fig. 2, is that FLEXPART-WaterSip model fails to capture most moisture source regions across the entire northwestern Eurasia for both basins when compared to WAM-2layers."
The word fails suggests that we know that WAM2layers would be more correct, but we don't know, do we?
Response: Sorry for the inaccurate description. We have carefully checked and revised all statements/conclusion to ensure that they are sufficiently supported by our results. As a result, these speculative statements have been removed from the revised manuscript.

17. L. 281-287: "Experiment 1 …"
This is a nice sensitivity test, however, its results can only be interpreted in case we also know how the timestep was adjusted, which together with spatial resolution drives the numerical diffusion and hence the average travel distance.
Response: To better understand how the spatiotemporal resolutions of forcing dataset could influence moisture tracing results, in the revision, we conducted two additional sensitivity experiments for WAM-2layers model. The Experiment 1 in Section 7 now has four different configurations: 3h and 1°×1°, 1h and 1°×1°, 3h and 0.25°×0.25°, and 1h and 0.25°×0.25°. Through these tests, we found that increasing the spatial and temporal resolutions of forcing data for WAM-2layers can reduce the moisture tracking discrepancies between the two models. For further details please see Section 7 in our revised manuscript.

18. L. 297-304: "Experiment 3 …"

More details on the areal source-receptor attribution method are needed here as well.

Response: In the revision, we have added a new schematic diagram for the "areal source-receptor attribution method" to the Supplement (Figure S11; see below). Together with Fig. 1b, this clearly illustrates the differences between WaterSip and the "areal source-receptor attribution method".



19. Figure 8: "Relative moisture contributions …"

- What is the remaining percentage from other regions?
- What is the remaining percentage from outside the domain?
- What is the remaining percentage unaccounted for altogether?
- The labelling should be more precise for WAM2layers in terms of resolution for both exp 1 and the original run.

Response: Thanks for the questions. In the revision, we added an extra set of histograms to show the moisture contributions from areas outside the eight selected regions (shown as the "Remaining" regions in Figs. 5 and 11 in our revised manuscript). We have also renamed all the experiments to include resolutions, e.g., WAM-2layers (1h, 0.25°×0.25°) and WAM-2layers (3h, 1°×1°). The revised Fig. 8 (now Fig. 12 in our revised manuscript) is shown below:

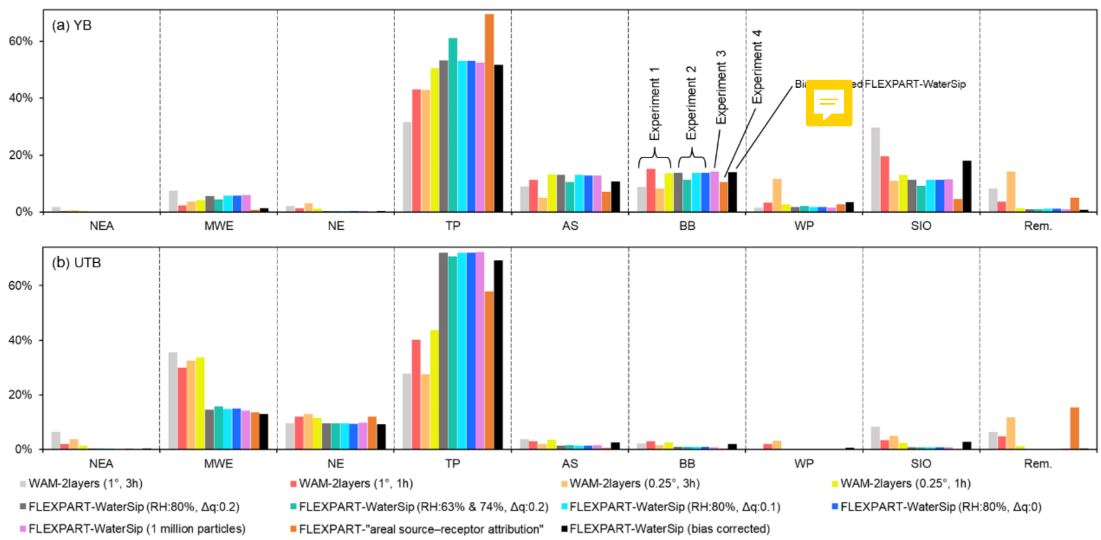


Figure 11: *Relative moisture contributions (%) to precipitation over the YB (a) and UTB (b) from the eight selected source regions and the remaining regions, simulated by four sets of numerical experiments (including different configurations in WAM-2layers and FLEXPART-WaterSip, FLEXPART-"areal source–receptor attribution", and bias-corrected FLEXPART-WaterSip). Black histograms represent the bias-corrected FLEXPART-WaterSip.*

20. L. 328: "original WAM-2layers"
I think both experiments are WAM-2layers with different settings, so the word 'original' is perhaps a bit misleading.
Response: Thanks for pointing out this. We have renamed all experiments to include resolutions. Please see Fig. 11 in our revised manuscript.

21. Fig. 10. "Time series …"
- Please improve the caption to make sure all details are explained.
- Is precipitation and evaporation the ERA5 data, or the inferred data from the WaterSip algorithm.
- If the latter, how does it compare to actual ERA5 data?
Response: Thanks.

1. We have revised the caption to: "Time series of particle heights, 1.5 BLH, specific humidity changes, vertical velocities at 700 hPa, precipitation, and evaporation at a 6-hourly interval in the selected trajectories: (a) a trajectory from SIO to YB between 12:00 21-July (arrival time) and 12:00 1-July; and (b) a trajectory from NEA to UTB between 12:00 14-July (arrival time) and 12:00 24-June. Note that particle heights, 1.5 BLH, specific humidity changes are from FLEXPART-WaterSip, while vertical velocities at 700 hPa, precipitation, and evaporation are from ERA5. The time series is in reverse order." Considering Dr. Sodemann's suggestion, we have moved this figure to supplement.
2. The particle heights, 1.5BLH, and changes of specific humidity are all from FLEXPART simulation, while the vertical velocities at 700 hPa, precipitation, and evaporation are from ERA5 data. The interpretation of this figure has been also moved to supplement.

22. L. 382-385: "Its effectiveness in regions with complex weather conditions is generally inferior to that of FLEXPART-WaterSip when operating with forcing datasets of the same resolution."
By lack of a clear benchmark 'truth', observational or orthogonal evidence, these conclusions are not substantiated. The authors should refrain from using words like 'inferior' and/or provide additional analysis to substantiate or revise such conclusions.
Response: Thanks for the suggestion. We have carefully checked and revised all statements/conclusion to ensure that they are sufficiently supported by our results. As a result, this speculative statement has been removed from the revised manuscript.

23. L. 402-405: "Nevertheless, compared to WAM-2layers, FLEXPART-WaterSip offers a precise depiction of the three-dimensional distribution of moisture sources, especially in capturing smaller-scale convective systems with high spatial heterogeneity."

In the lines before the authors discuss the shortcomings of WaterSip, but then they go on to conclude that FLEXPART-WaterSip offers a precise depiction … This reasoning does not seem logical to me.

Response: Thanks for pointing this out. We have carefully checked and revised all statements/conclusion to ensure that they are sufficiently supported by our results. As a result, this speculative statement has been removed from the revised manuscript.

24. L. 415-420: "Code availability … data availability …"

This is insufficient. The authors should revisit the policy of sharing data https://www.atmosphericchemistry-and-physics.net/policies/data_policy.html and make the actual code and data they used during their research publicly available to the community. If software is used, they should refer to exact versions with doi's and the scripts the authors used themselves to run the models, so not to generic websites that are subject to change. All data underlying the figures should also be deposited meaning numeric values for moisture sources, masks for the tagging region etc.

Response: In the revision, we have strictly adhered to ACP's policies and specified all used data and algorithms. Specifically, we revised our code availability and data availability sections (lines 494–504 in our revised manuscript). We also provided the detailed configurations of WAM-2layers and FLEXPART in Part 2 of the Supplement and customized algorithm for WaterSip in Part 3 of the Supplementary.

Technical corrections:

1. Equation (1): The equation as used by Findell et al. (2019) is more correct than the one in Van der Ent et al., (2014)

Response: Thanks. This Equation has been revised to " $\frac{\partial S_{g,lower}}{\partial t} = \frac{\partial (S_{g,lower} u)}{\partial x} + \frac{\partial (S_{g,lower} v)}{\partial y} + E_g - P_g \pm F_{v,g}$" to be consistent with Findell et al. (2019). Please see line 115 in our revised manuscript.

2. Figure 3: "Absolute differences ..."

The green outline with red underlying data is not color-blind friendly.

Response: Thank you for pointing this out. We have revised this color combination to ensure color-blind friendly. All other figures with similar color combination have also been revised.

3. L. 380: "WAM-2layers model"

The WAM2layers model

Response: We have added "the" in the revision.

Response to Dr. Harald Sodemann:

General comments:

The authors perform a sensitivity study of two methods to identify moisture origin for one selected summer month over two regions in the Tibetan plateau. From the comparison between the two methods, the authors see differences with regard to moisture contributions from Eurasia and over coastal regions, that are explored in a sensitivity study. The authors then draw conclusions about the consistency and validity of the two methods. The manuscript is overall written coherently and in a well-readable manner. However, I find the conclusions are too general given the episodic evidence presented in the manuscript itself. The authors could consider changing this paper to a shorter, research letter format. I also have some comments about the structure of the manuscript, the precision of the language, reference to code and use of literature, and the presentation and interpretation of the results. I hope my comments will help the authors to prepare an improved version of their manuscript.

Response: We are very grateful for your thorough review and comments, which provide excellent guidance on our revision and future research. Per your comments, we have thoroughly revised this manuscript in terms of language, content, and logic coherence. We hope that the revised manuscript aligns more closely with the requirements of a research article. The revised structure becomes:

1. Introduction
2. Eulerian and Lagrangian approaches for moisture tracking: WAM-2layers and FLEXPART-WaterSip models
3. Moisture tracking in two representative basins
4. Comparison between moisture fluxes with WAM-2layers and particle trajectories with FLEXPART-WaterSip
5. Relationship between “actual evaporation” and simulated moisture contributions
6. Bias correction of FLEXPART-WaterSip simulations
7. Potential determinants of discrepancies in moisture tracking
8. Discussion and conclusions

In Section 1, we thoroughly revised the logic flow of the introduction section: 1) we narrowed down the scope of our current study to focus exclusively on moisture tracking over the TP; 2) we clearly pointed out potential simulation differences that may exist in previous research; 3) we emphasized that the aim of this study is to investigate potential errors/uncertainties in existing moisture tracking studies in the TP; 4) we cautioned readers against generalizing our comparison results in the TP to other regions.

In Section 2, we 1) provided detailed descriptions of the two selected models; 2) clearly specified all numerical settings for these two models and detailed their configurations in Part 2 of the supplement; 3) shared our customized code for WaterSip in Part 3 of the supplement.

In Sections 3 and 4, w: 1) removed redundant content and inaccurate descriptions; 2) strengthened the logic of our analyses.

Sections 5 and 6 are newly added chapters. In section 5, we evaluated the relationship between evaporation data from ERA5 and the simulated moisture contributions to further clarify the strengths and weaknesses of the two models. Building on these comparison results, in Section 6, we presented the bias-corrected simulation results of FLEXPART-WaterSip, which substantially improved model's accuracy in simulating evaporation.

In Section 7, we included additional sensitivity experiments for WAM-2layers (including additional configurations with different spatial and temporal resolutions) and FLEXPART-WaterSip (including additional combinations of specific and relative humidity thresholds). These new analyses have strengthened the robustness of the conclusions drawn in this manuscript.

In Section 8, we removed or revised conclusions not fully substantiated by our analyses.

Main comments:

1. In their introduction, the authors set forth a basic distinction into Eulerian and Lagrangian methods for "moisture tracking". I find this distinction too coarse with regard to the results presented in this study. The two methods that are being compared are broadly seen part of the respective categories, but there are many (other) approaches within the Lagrangian category (see for example the discussions in Keune et al., 2022), and many other within the Eulerian category, that are not compared here. For example, moisture tagging in a regional model (Yoshimura et al., 2004), or the E-P Lagrangian approach of Stohl and James (2004), and so on. The authors claim that the two methods they compare are most widely used - I think this is debatable, plus they are focussing here on the Tibetan Plateau only.

Response: Thanks for the comment. The motivation of this study originates from the extensive literature on precipitation moisture tracking in the Tibetan Plateau (TP) (Table 1 only presents a subset of existing efforts). However, to the best of our knowledge, no effort has been made to address the discrepancies or uncertainties among these TP-focused studies. This situation has led us to develop this manuscript, aspiring to encourage future researchers to critically assess the reliability of their simulation outcomes. Toward this goal, we strive to identify potential factors contributing to discrepancies among models over the TP region.

As you mentioned in the comments, the descriptions of some concepts (e.g., those related to Eulerian and Lagrangian methods) in this manuscript are not accurate. In the revision, we have thoroughly revised the Introduction section to emphasize the following two aspects:

1. We have narrowed down the scope of the present study to focus exclusively on moisture tracking over the TP. In this context, we have specifically highlighted that the most widely used numerical moisture tracking models are WAM-2layers and FLEXPART-WaterSip. The subsequent paragraphs in Introduction also focus solely on these two representative models.

2. The aim of this manuscript was to investigate potential errors/uncertainties in existing moisture tracking research on the TP as well as to understand the underlying

mechanisms/determinants. We have emphasized the significance of this study in the last paragraph of Introduction.

2. The study now only compares one month (July 2022) and two specific catchment areas of the Tibetan Plateau. It remains thus unclear if the findings here can be generalised, or are rather coincidental. Therefore, it would be adviseable to tune down the quite authoritative/concluding language and formulate more modestly, such that it be in agreement with the somewhat anecdotal evidence that is actually investigated and presented here. This concerns both the Abstract, Introduction, and Conclusions.

Response: Thank you. Both you and Dr. Ruud van der Ent have expressed similar concerns on this. We have thoroughly revised our manuscript to address this issue:

1. We have made every effort to ensure that the manuscript maintains accuracy and logical coherence. Additionally, we have either tuned down or removed any authoritative/concluding statements that are not fully supported by our results.
2. We have strengthened the manuscript by incorporating additional analyses, discussions, and sensitivity experiments to ensure that all conclusions are well substantiated.

For more details, please also see our response to your General comments above.

3. The authors state that they use the FLEXPART-WaterSip method. I don't think this is correct, since the WaterSip code is a specific implementation of the Sodemann et al. (2008) moisture source diagnostic in C++ language which is currently not yet available publicly. The WaterSip code has first been used by Sodemann and Stohl (2009) and later my many other studies (Bonne et al., 2014; Läderach and Sodemann, 2016; Sodemann 2020 to name a few). The authors also state that all original codes are available from the official websites - this is not correct for the WaterSip method. A separate publication on this actual "WaterSip" code is in preparation by this reviewer. My impression is that the authors have written their own implementation of the algorithm of Sodemann et al. (2008), which they then use for this study. This must be stated clearly and correctly, and the authors' own code should be linked to in the Code availability section. In any case, the reference to the website at University of Bergen is no proper code reference to the WaterSip method.

Response: Sorry for the confusion. Yes, we developed our own Python implementation of the algorithm described by Sodemann et al. (2008). In the revised manuscript, we have provided the models' settings in Part 2 of the Supplement and our Python code for WaterSip in Part 3 of the Supplement. We have also updated "Code availability" and "Date availability" sections (see lines 494–504 in our revised manuscript).

4. The immense literature review presented in Table 1 is never properly described and hardly used in the manuscript. I also note that a similar table has been presented already in the supplement material of Li et al. (2022), a study by the same authors that is not cited in this manuscript. I do appreciate the effort put into this table. Currently, however, there are just two sentences in the introduction that make general remarks about this table. A more systematic discussion of what was found during the literature review would be needed to justify including this table in the main manuscript. In addition, it would be useful to tie the results from this study up agains the reviewed literature in a Discussion section in the end.

Response: Thanks for the comments. When compiling Table 1, our objective was not only to categorize different studies but also to derive insights by contrasting their methodologies, forcing datasets, and geographical focuses (i.e., different parts of the TP region). Initially, we did not find an effective method to comprehensively compare these diverse studies beyond what was presented in Table 1. However, after re-examining these studies, particularly their results of long-term average spatial distributions of moisture sources, we identified several contrasting findings among these studies. These have been added to the revised Introduction section: "First, moisture sources tracked by Eulerian models tend to cover a large part of the western Eurasian continent and can stretch southward to the southern Indian Ocean (Zhang et al., 2017; Li et al., 2019; Li et al., 2022a; Zhang et al., 2024). In contrast, moisture sources tracked by Lagrangian models predominantly extend southward (Chen et al., 2012; Sun and Wang, 2014; Chen et al., 2019; Yang et al., 2020), with broader westward extensions observed in the moisture tracking for the westernmost TP and Xinjiang region (Zhou et al., 2019; Liu et al., 2020; Yao et al., 2020; Hu et al., 2021). Second, areas with higher evaporation rates, such as the ocean surface, in general contribute more moisture compared to surrounding land areas. While the moisture sources simulated by Eulerian models aligns well with the land–sea distribution (Zhang et al., 2017; Li et al., 2019; Li et al., 2022a; Zhang et al., 2024), this alignment is less pronounced for Lagrangian models (Chen et al., 2012; Sun and Wang, 2014; Chen et al., 2019; Zhou et al., 2019; Liu et al., 2020; Yang et al., 2020; Yao et al., 2020; Hu et al., 2021). In this context, we speculate that different moisture tracking methods (both Eulerian and Lagrangian ones) may involve certain unrecognized uncertainties or errors when applied to the TP region. This underscores the pressing need for further exploration to examine the discrepancies among these models to better characterize the complex hydrological processes of the TP." (see lines 60–72 in our revised manuscript).

We did not include Li et al. (2022) in Table 1 because our summary primarily focuses on studies using backward moisture tracking over the TP, whereas Li et al. (2022) mainly focuses on forward tracking. The revised Table 1 now further includes forward tracking studies (including Li et al. 2022). In addition, Table 1 does not include moisture tracking studies in the TP focusing on water isotopes. We have pointed out this limitation in the table caption.

Please see below for the revised Table 1:

Table 1: *Overview of Eulerian and Lagrangian moisture tracking studies in the TP and its vicinity. Note that extensive studies on water isotopes in the TP with moisture tracking simulations are not included here. "E and P" means the model diagnoses evaporation and precipitation separately, while "E – P" means the model diagnoses contributions through water budget (i.e., evaporation minus precipitation).*

	Model	Moisture source diagnosis	Study area	Forcing dataset	Study period	Reference
Eulerian	WAM-1layer	E and P	Central-western TP	ERA-I, NCEP-2	1979–2013	Zhang et al. (2017)
	WAM-2layers	E and P	Endorheic TP	ERA-I, MERRA-2, JRA-55	1979–2015	Li et al. (2019)
	WAM-2layers	E and P	Southern/northern TP	ERA-I	1979–2016	Zhang et al. (2019a)

	WAM-2layers	E and P	TP	ERA-I	1979–2015	Guo et al. (2019)
	WAM-2layers	E and P	TP	ERA-I	1998–2018	Zhang (2020)
	WAM-2layers	E and P	TP	ERA-I, MetUM	1982–2012	Guo et al. (2020)
	WAM-2layers	E and P	Major basins in TP	ERA-I, MERRA-2, JRA-55	1979–2015	Li et al. (2022a)
	WAM-2layers	E and P	TP (forward tracking oceanic evaporation)	ERA-I, MERRA-2, JRA-55	1979–2015	Li et al. (2022b)
	WAM-2layers	E and P	TP (forward tracking TP evaporation)	ERA5	2000–2020	Zhang et al. (2023)
	WAM-2layers	E and P	Five typical cells in the TP	ERA5	2011–2020	Zhang et al. (2024)
	CAM5.1 with a tagging method	E and P	Southern/northern TP	MERRA	1982–2014	Pan et al. (2018)
Lagrangian	FLEXPART	E – P	TP	NCEP-GFS	2005–2009 (summer)	Chen et al. (2012)
	FLEXPART	Areal source–receptor attribution	Grassland on eastern TP	NCEP-CFSR	2000–2009	Sun and Wang (2014)
	FLEXPART	WaterSip	Four regions within TP	ERA-I	1979–2018 (May–August)	Chen et al. (2019)
	FLEXPART	Areal source–receptor attribution	Xinjiang	NCEP-FNL	2008–2015 (April–September)	Zhou et al. (2019)
	FLEXPART	WaterSip	Southeastern TP	ERA-I	1980–2016 (June–September)	Yang et al. (2020)
	FLEXPART	WaterSip	Xinjiang	NCEP-CFSR	1979–2018	Yao et al. (2020)
	FLEXPART	WaterSip	Northern/Southern Xinjiang	NCEP-CFSR	1979–2018	Hu et al. (2021)
	FLEXPART	Areal source–receptor attribution	Source region of Yellow River	NCEP-FNL	1979–2009	Liu et al. (2021)
	FLEXPART	WaterSip	Xinjiang	NCEP-CFSR	1979–2018 (April–September)	Yao et al. (2021)
	FLEXPART	E – P	Three-rivers headwater region	ERA-I	1980–2017 (boreal summer)	Zhao et al. (2021)
	FLEXPART	E – P	Three-rivers source region	NCEP-FNL	1989–2019	Liu et al. (2022)
	FLEXPART	WaterSip	Three-rivers headwater region	ERA-I	1980–2017	Zhao et al. (2023)
	HYSPLIT	WaterSip	Three-rivers headwater region	NNR1	1960–2017 (June–September)	Zhang et al. (2019b)
	HYSPLIT	E – P	Western TP	ERA-I	1979–2018 (winter)	Liu et al. (2020)
	HYSPLIT	Maximum specific humidity	Seven regions within TP	NCEP/NCAR	1961–2015 (summer extreme event)	Ma et al. (2020)
	HYSPLIT	Contribution function and weighting	TP	NCEP-GDAS	1950–2015 (extreme precipitation events)	Ayantobo et al. (2022)
	HYSPLIT	WaterSip	Southern Xinjiang	ERA5	2021(June 15–17)	Chen et al. (2022)
	LAGRANTO	WaterSip	Southeastern TP	ERA-I	1979–2016 (winter extreme precipitation)	Huang et al. (2018)
	LAGRANTO	WaterSip	Three regions within TP	ERA-I	1979–2016 (winter extreme precipitation)	Qiu et al. (2019)
	LAGRANTO	WaterSip	Northern TP	ERA-I	2010–2018 (monsoon season)	Wang et al. (2023)
	QIBT	E and P	Southeastern TP	ERA-I	1982–2011 (April–September)	Xu and Gao (2019)

5. Section 2 discusses the generalities of the two selected methods. I think the broad description of these two examples as Eulerian and Lagrangian methods in general does not fit the two specific methods that are applied here. Also, how these specific methods work are described sufficiently elsewhere in the literature. Instead, the authors would need to describe more clearly how exactly the respective simulations have been set up. Specifically regarding the FLEXPART-WaterSip like method, was a domain-filling setup selected in FLEXPART? Was the calculation run in forward mode? Has convection parameterisation been used? What domain has been used? All these details are important. Furthermore, the WaterSip code is currently not available publicly, and the website pointed out in the data section only provides a manual. What code has then been used to diagnose the moisture sources from the FLEXPART particle trajectories, and where is this code accessible? How were Lagrangian moisture sources gridded? What output interval and humidity thresholds were used? These aspects are all essential aspects for reproducibility of the work, and to understand the preconditions of this comparison.

Response: Thanks for all the questions. We recognize the importance of providing specific descriptions of the methods used in this manuscript. In our revised manuscript, we provided further details of the two moisture tracking models (see revised Section 2), and outlined specific numerical settings in Part 2 of the Supplement. We also released our WaterSip algorithm written in Python in Part 3 of the Supplement. We further revised the "Code availability" and "Date availability" sections (see lines 494–504 in our revised manuscript).

6. The difference in moisture source contribution from Eurasia between the two methods is quite interesting. We don't know what is the truth from the two approaches, but a gridded map of air parcel location density for trajectories arriving in the study domains could help indicate if FLEXPART (based on ERA5) does identify transport pathways from Europe. In this context, I find the sensitivity of the WAM2layer method to finer resolution quite striking. What is possibly going on that leads to such a strong senstivity to grid resolution in the results? Maybe be there is numerical diffusion at coarser resolution (see Sodemann 2020, Sec. 7)? Additional sensitivity experiments or analyses of different time snapshots could be useful.

Response: Thank you for the comments. To address these issues, we made three major improvements in our revised manuscript:

1. We added a new Section 5 to evaluate the relationship between actual evaporation from ERA5 and the simulated moisture contributions.
2. We added a new Section 6 to bias-correct simulations from FLEXPART-WaterSip.
3. In Section 7, we incorporated additional sensitivity experiments for WAM-2layers and FLEXPART-WaterSip. In particular, we found that increasing the spatial and temporal resolutions of WAM-2layers can partly reduce the moisture tracking discrepancies between the two models.

These modifications have strengthened the robustness of our conclusions.

7. The sensitivity study in Sec. 5 is quite interesting, but does not really include the most important sensitive parameters of this approach, as discussed widely in the literature. Instead of number of particles (Fremme et al., 2023), it would be more important to test the threshold of specific humidity (dqc in Sodemann et al., 2008) as well as the relative humidity at arrival (RHc in Fremme and Sodemann, 2019). The areal source-receptor attribution method comes a bit out of the blue here. It is an entirely different method of the Lagrangian category. The difference between this method and the others should be described in the methods.

Response: Thanks for the suggestions.

1. In the newly added Section 6, we tested the sensitivity of the simulated precipitation in YB and UTB to thresholds of changes in specific humidity and relative

humidity. Results are shown in Fig. 10 in our revised manuscript (see below):

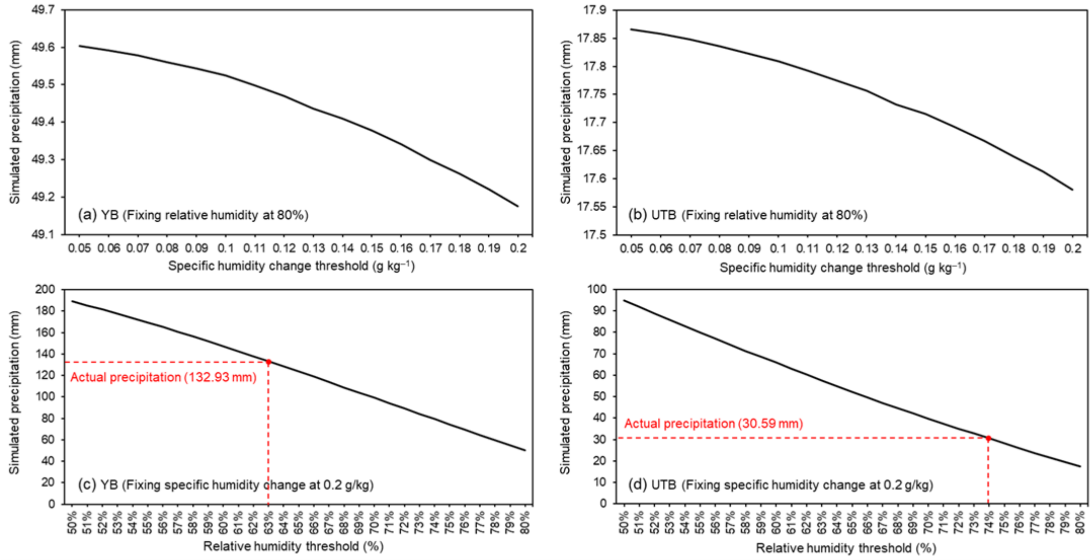


Figure 9: *Sensitivity of the simulated precipitation in the (a and c) YB and (b and d) UTB to (a and b) the threshold of specific humidity change and (c and d) the threshold of relative humidity.*

In revised Section 7, we included additional numerical experiments to examine the sensitivity of moisture source diagnosis to these two thresholds; see Experiment 2 in the figures below (Fig. 11 in our revised manuscript):

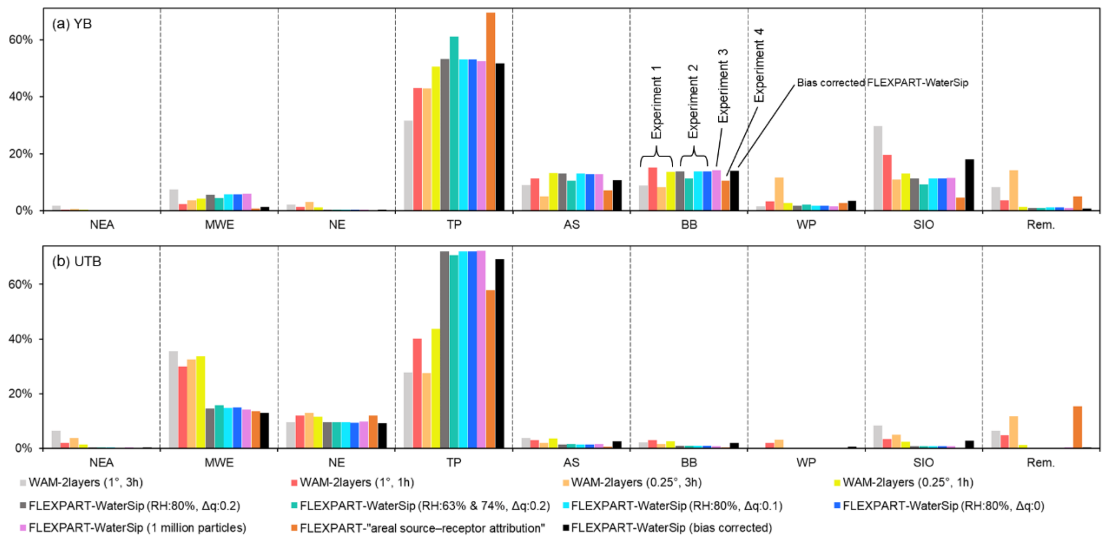
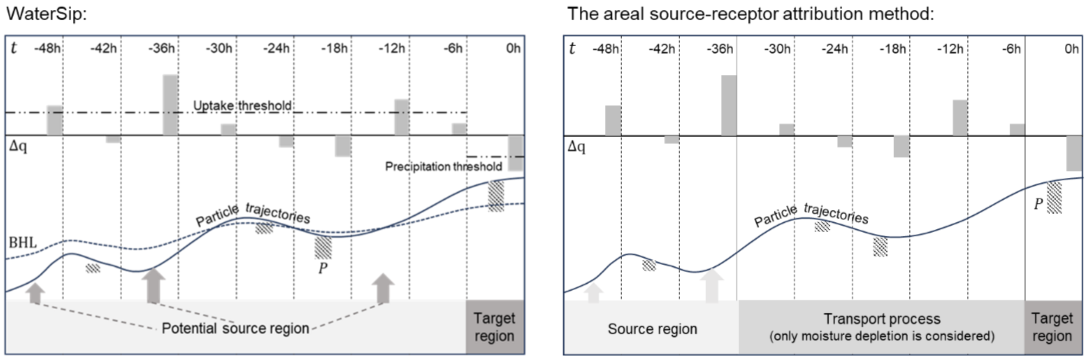


Figure 11: *Relative moisture contributions (%) to precipitation over the YB (a) and UTB (b) from the eight selected source regions and the remaining regions, simulated by four sets of numerical experiments (including different configurations in WAM-2layers and FLEXPART-WaterSip, FLEXPART-"areal source–receptor attribution", and bias-corrected FLEXPART-WaterSip). Black histograms represent the bias-corrected FLEXPART-WaterSip.*

In addition, we also added a Section to bias-correct the FLEXPART-WaterSip simulations. We hope these new revisions could meet your expectations. For details, please also see our response to your General comments above.

2. In the revision, we have added a new schematic diagram for the "areal source-receptor attribution method" to the Supplement (Figure S11; see the second subplot

below). Together with Fig. 1b (the first subplot below), this will help readers better understand the differences between WaterSip and the "areal source-receptor attribution method".



8. I am puzzled that the authors do not discuss nor cite their own study in NHESS about the spatial distribution of moisture sources for the Tibetan Plateau using the WAM2layer model (Li et al., 2022). In the supplementary material of that paper, they show a map with Eurasian moisture sources, just as discussed here from the two methods. What could possibly be the reason that you do not discuss this previous work done with the WAM2layers method? Is this not a golden opportunity to balance or rectify any conclusions drawn in Li et al. (2022) in the light of new evidence? I also note that Li et al. (2022) contains a table similar to Table 1 presented here. A discussion of the relation between this work and your own previous work is definitely required.

Response: Thanks for noticing our earlier work (Li et al., 2022) published in HESS. In the supplementary material of Li et al. (2022), we tracked long-term moisture sources of the entire TP using WAM-2layers driven by ERA-I, MERRA2, and JRA55. In comparison, this manuscript focuses short-term moisture tracking using two models driven by ERA5. The differences in the forcing datasets, study areas, and study periods have presented substantial challenges for directly comparing these results. Nevertheless, we have included Li et al. (2022) in the revised Table 1. Further discussion on the reviewed studies has also been added to Introduction (please also see our responses to your main comments #4 above). We would like to point out that Table 1 in Li et al. (2022)'s supplement focuses on oceanic contributions to precipitation over the TP, while Table 1 in the present study focuses on the comparison between Eulerian and Lagrangian moisture tracking models. In addition, Table 1 in the present study covers 32 studies, which substantially expands our previous summary in Li et al. (2022) (17 studies).

Detailed comments:

1. Figure 2: The gridding of the FLEXPART-WaterSip results in Fig. 2 looks more spotty than the WAM2layers - I would argue that either a larger grid spacing or larger gridding radius of the identified sources should be used, or the number of particles increased to mute these distracting artifacts. Maybe just show the same resolution as used in Fig. 3 where the same grid was used for both models?

Response: Thanks for noticing this. In the initial submission, we used an output resolution of 1°×1° in Figs. 2a and 2b (consistent with the resolution of the original forcing dataset used in WAM-2layers) but 0.25°×0.25° in Figs. 2c and 2d (FLEXPART-WaterSip). Unlike the gridded results from WAM-2layers, FLEXPART-WaterSip outputs particle-level data. Initially, we interpolated these particle-level data to a 0.25°×0.25° resolution for visualization, which may have caused confusion. Following your comments, we have standardized all outputs to a 1°×1° resolution in our revision (all relevant figures and analyses have been updated).

For example, here is the revised Fig. 2 (now Fig. 3 in our revised manuscript):

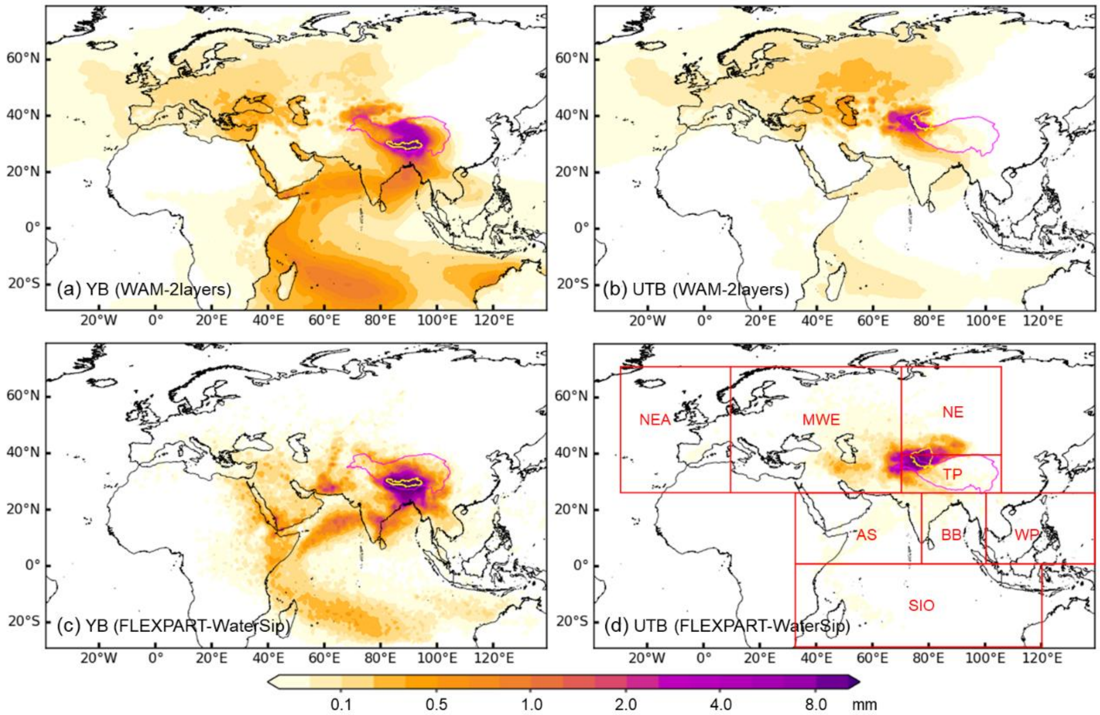


Figure 3: *Spatial distributions of moisture contribution (equivalent water height over source areas) to precipitation in July 2022 in (a and c) YB and (b and d) UTB, simulated by (a and b) WAM-2layers and (c and d) FLEXPART-WaterSip. Purple lines represent the TP boundary and yellow lines represent the boundaries of the two basins. Red boxes in (d) delineate the division of the eight source regions: North-eastern Atlantic (NEA), Midwestern Eurasia (MWE), Northern Eurasia (NE), TP, Arabian Sea (AS), Bay of Bengal (BB), Western Pacific (WP), and Southern Indian Ocean (SIO).*

2. Figure 6: I find panels a and b hard to interpret objectively, as there are subjective/conceptual arrows superimposed on the panels. Are these two panels adding new information compared to the trajectory examples shown in panels c-f?

Response: Thanks for pointing this out. Panels a and b were meant to show the spatial distribution of particles. However, we acknowledge that the conceptual red arrows do not contribute additional information beyond what is already explained in the paper. We have removed these arrows from our revised manuscript to avoid confusion.

Please see below for the revised Fig. 6 (now Fig. 7 in our revised manuscript):

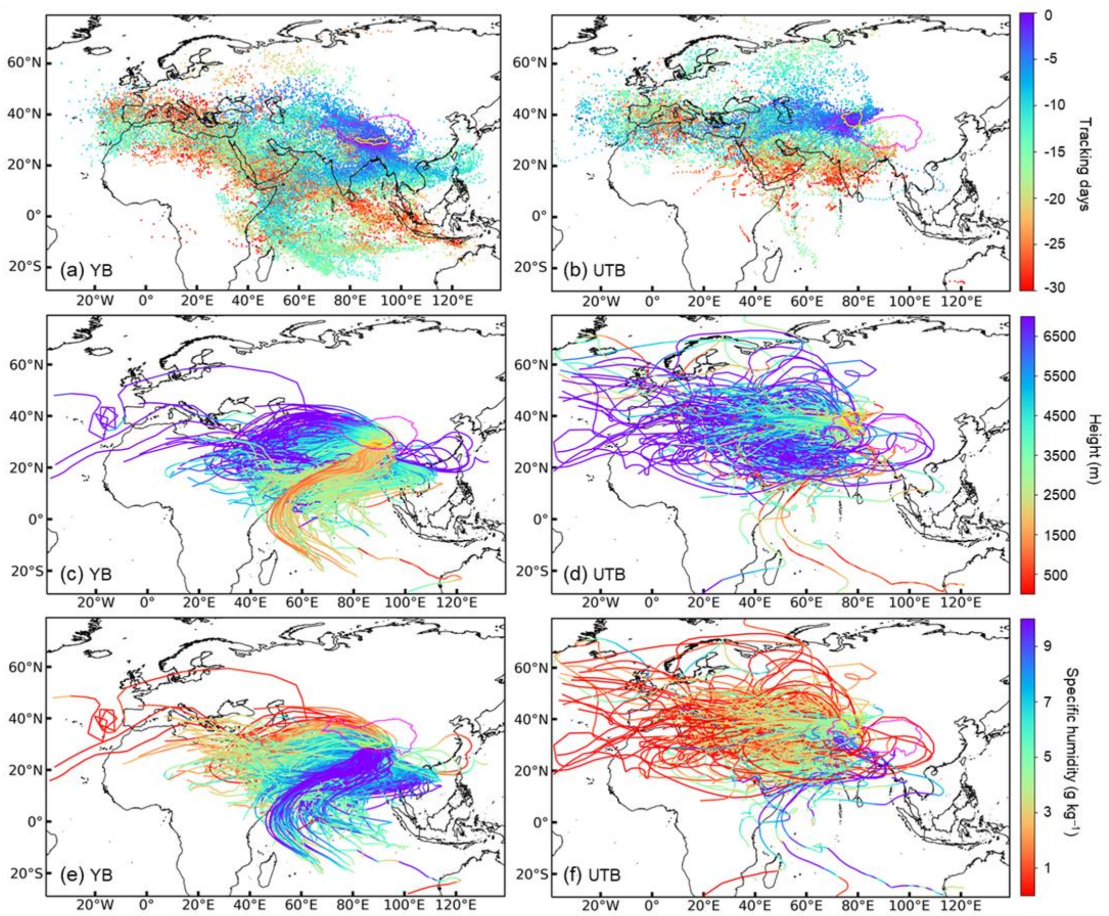


Figure 7: *Spatial distributions of (a and b) particles and (c–h) trajectories that bring moisture to precipitation over (a, c, and e) YB and (b, d, and f) UTB, as simulated by FLEXPART. (a and b) are particles color-coded by backward-tracking days (0–30 days). (c and d) are trajectories color-coded by height (m, above ground) at each numerical step. (e and f) are trajectories color-coded by specific humidity (g kg^{-1}) at each numerical step.*

3. Figure 7: Why do you show 300hPa vertical velocity in panel b? Maybe it would be more useful to add a figure that shows the average/median vertical air motion as a view of trajectory (pressure) altitude vs time arriving at the two selected regions. These vertical pathways seem to be quite different.

Response: Thanks for the comment. We chose ~300 hPa (~9000 m) as an illustration of the vertical air motion over the TP region (cf. ~700 hPa for the entire domain), which is indeed a bit arbitrary. To further illustrate the vertical air motion at different pressure levels, in the revision, we included two additionally levels: 500 hPa (~5500 m) and 850 hPa (~1500 m), corresponding to moisture transport for the westly region (and the TP) and the monsoon region, respectively.

The revised figure was moved to supplement as Fig. S3 (see below):

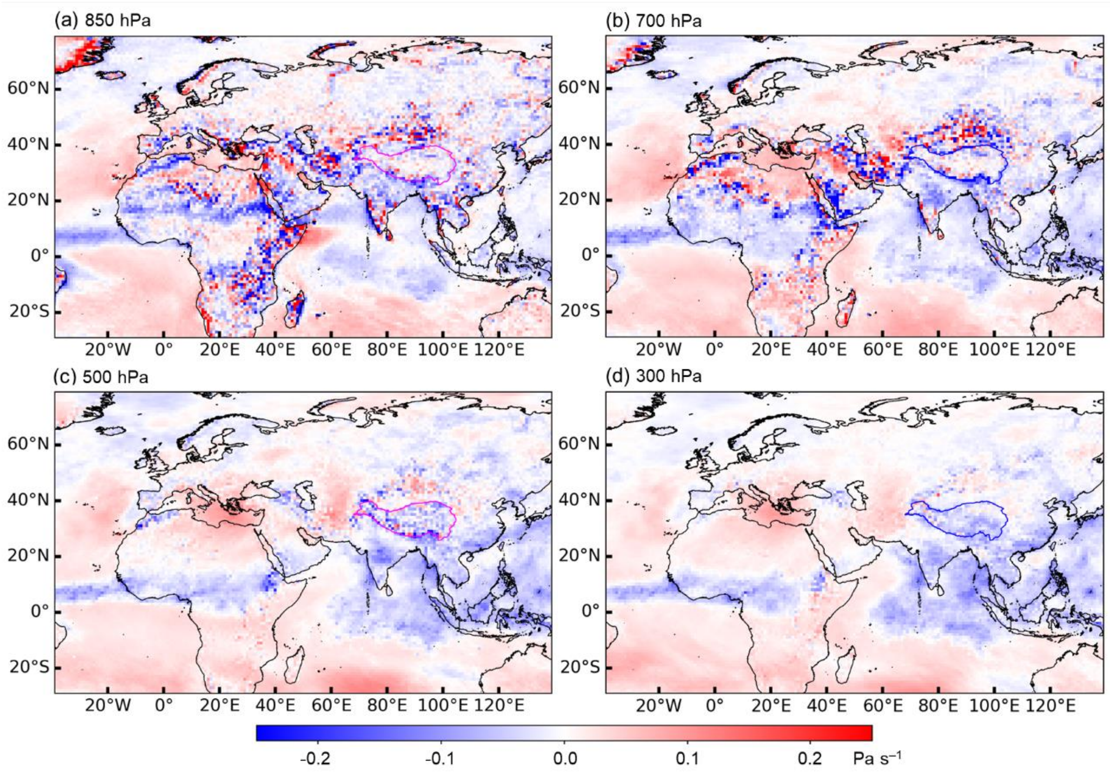


Figure S3. *Vertical velocities (Pa s^{-1}) at (a) 850 hPa and (b) 500 hPa across the entire study domain. Note the negative values indicate upward motion (ascent).*

4. Figure 10: These two examples from a set of 5 million trajectories can hardly be considered representative. What is really the value of discussing exactly these two examples? It does not become entirely clear to me what to take away from these examples, and I think i is not justified to draw as general conclusions about the weaknesses of the Lagrangian diagnostics (L. 399 onward) as the authors do on this basis alone. Also, I got confused by the time axis at first, it should be made clear where the arrival point is. Winschall et al. (2014) have discussed with similar examples before that (deep) convection can contribute to moistening at upper levels that is not captured by motion of individual trajectories. Is this the case here as well? Do you use a convection parameterisation in FLEXPART? Are these locations over land or ocean? It would also be helpful to indicate the specific humidity threshold adopted in this study, and maybe include specific humidity and relative humidity in addition.

Response: Thanks for your questions.

1. We did use a convection parameterization scheme in FLEXPART (the configuration settings of all the models are now included in Part 3 of the revised supplement). In the revision, we mentioned the arrival time and additional details in the figure caption and marked out the range of land/ocean in the figure. Given that the two trajectories shown here are only illustrative examples, we moved Fig. 10 to supplement as Fig. S6 (see below):

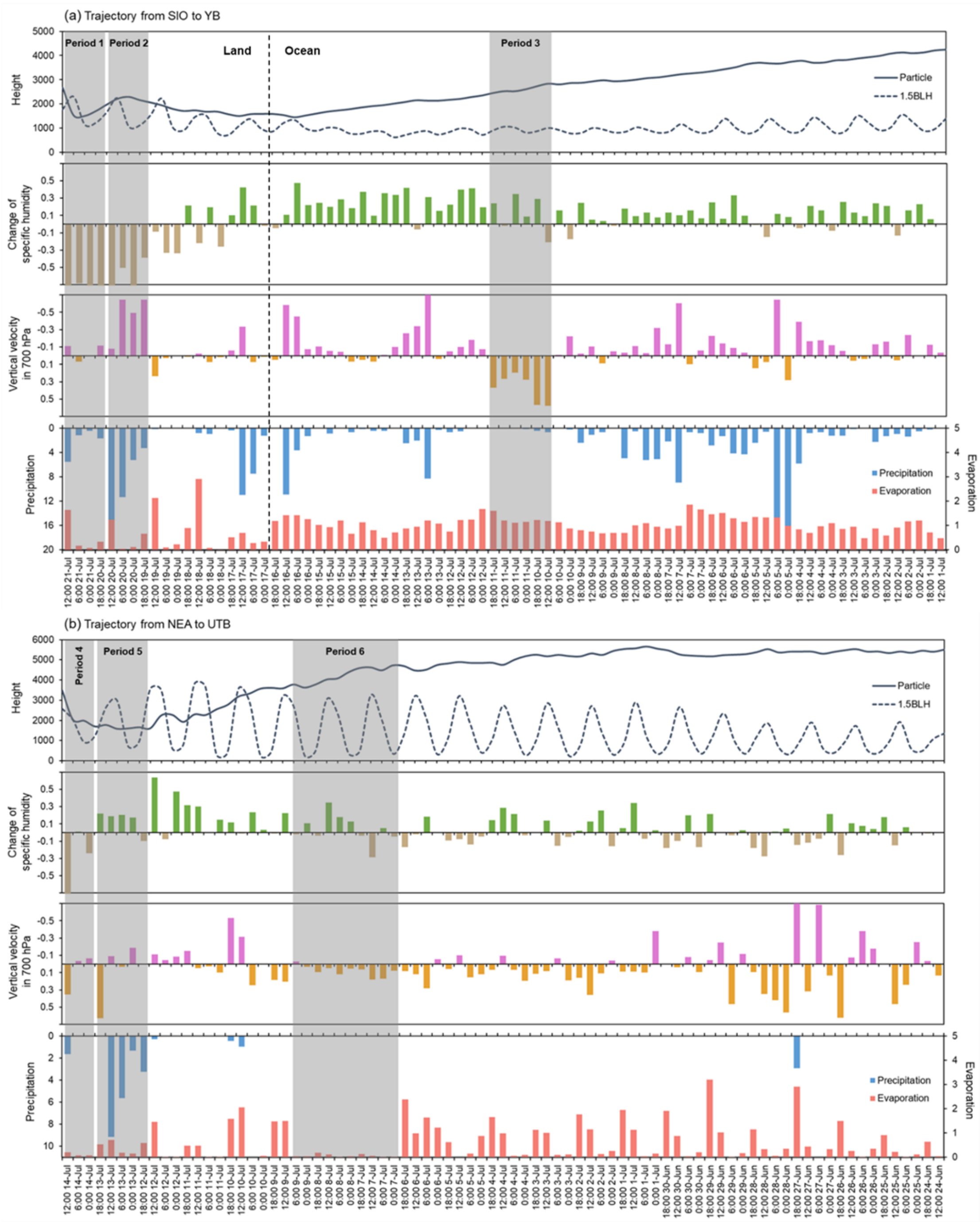


Figure S6. *Time series of particle heights, 1.5 BLH, specific humidity changes, vertical velocities at 700 hPa, precipitation, and evaporation at a 6-hourly interval in the selected trajectories: (a) a trajectory from SIO to YB between 12:00 21-July (arrival time) and 12:00 1-July; and (b) a trajectory from NEA to UTB between 12:00 14-July (arrival time) and 12:00 24-June. Note that particle heights, 1.5 BLH, specific humidity changes are from FLEXPART-WaterSip, while vertical velocities at 700 hPa, precipitation, and evaporation are from ERA5. The time series is in reverse order.*

2. To more thoroughly examine the characteristics and discrepancies between the two models, we added two new sections (Sections 5 and 6 in our revised manuscript) with additional sensitivity experiments for both models (e.g., Fig. 11 in our revised

manuscript). For details, please also see our response to your general comments above.

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