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Short Communication

Greater role of atmospheric circulation than evapotranspiration in reshaping terrestrial moisture recycling

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As a promising nature-based solution to mitigate anthropogenic climate change, reforestation and afforestation initiatives have been carried on persistently for decades worldwide. In addition to the carbon sink benefits via directly sequestering atmospheric CO_2, afforestation also influences climate from local to global scales by altering land–atmosphere exchanges of water and heat [1]. A key biophysical modification of forested land is the enhanced evapotranspiration (ET) as forests can access deep-layer soil moisture and facilitate turbulent moisture transfer between the land surface and the atmosphere [1]. Remote sensing evidence indicates that forest expansion and greening—due to climate change, CO_2 fertilization, or large-scale ecological restoration practices—has been a major contributor to enhanced terrestrial ET over the past two decades [2]. In a warming world with rapidly growing water demand by forests, the ET enhancement has emerged as the most prominent driver of the accelerated hydrologic cycle.

An open scientific question persists regarding how Earth greening and large-scale afforestation affect regional to global freshwater availability, given freshwater's vital role in sustaining biodiversity, food security, and human livelihood. There is an increasing recognition that the hydrological outcomes of forest expansion rely on the balance between increased evaporative water loss and potentially enhanced precipitation [3,4]. From a terrestrial moisture recycling perspective, this is a dynamic tradeoff between moisture sources (ET) and sinks (precipitation). Recent advances in atmospheric moisture-tracking techniques have provided a powerful approach to disentangle terrestrial versus oceanic moisture sources of precipitation [5,6] and track remote connections between moisture sources and sinks [3,7].

In addition to thermodynamic processes such as enhanced ET and atmospheric moisture, dynamic processes (i.e., large-scale atmospheric circulation patterns) profoundly affect land moisture recycling by determining the trajectory and capacity of moisture transport. In the real world, the atmospheric moisture sources and sinks vary greatly from seasonal to annual and multi-decadal scales due to internal climate variability and external climate change. For example, circulation changes are critical for the translation of evaporation anomalies into subsequent precipitation, and thus precipitation recycling, during droughts [8]. Under climate change, the global land mean precipitation recycling ratio is projected to decrease by 1.5%–3% per degree of global warming, with some locations exceeding 20% by the end of this century [9]. However, despite the well-recognised dynamic nature of water vapor transport and its role in moisture redistribution, this role is underappreciated in the context of anthropogenic land cover changes. Some studies implemented a dynamic ET but static moisture trajectories (climatological means of circulation patterns) [10,11] to understand the hydrological consequences of vegetation-enhanced ET and terrestrial moisture recycling from regional [12], national [13,14], to global scales [4]. While such studies illustrate the effects of enhanced ET via directly supplying extra moisture to the atmosphere, they overlook the role of a dynamic circulation in reorganising the location of moisture sources and sinks, particularly for regions where the prevailing circulation is progressively shifting. Up to date, the extent to which a dynamic circulation affects moisture recycling and how this effect compares to that of direct ET changes remains unquantified. This knowledge gap limits our

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understanding of changes in land moisture recycling and the hydrological implications for afforestation.

Here we employ a numerical moisture-tracking model, the Water Accounting Model-2layers version 3 (WAM2layers v3) [5], prescribed by ERA5 climatic forcings, to evaluate the dominant driving force of observed changes in land precipitation recycling from 1980 to 2020. Specifically, we conducted a pair of factorial simulations that set either atmospheric circulation patterns (wind and air humidity fields) or ET to be invariant using its seasonally varying climatological values. These simulations, combined with a baseline simulation for which atmospheric circulation and ET are both temporally varying, allow for isolating changes in precipitation recycling resulting from atmospheric circulation or evapotranspiration changes (Supplementary Methods). In addition, we also explored the fluctuations of precipitation recycling in El Niño and La Niña years that exhibit contrasting oceanic-atmospheric circulation configurations. Our results are robust compared to a three-dimensional Lagrangian model that allows for vertical motion of multi-layer moistures [15] (Fig. S1 online), and when assessed using relative changes of precipitation recycling (Fig. S2 online).

Our analysis reveals that circulation changes play a comparable or even greater role than ET changes in determining the trend of land recycled precipitation across the globe in the past four decades (Fig. 1; also see the baseline of annual mean recycled precipitation in Fig. S3 online). Globally, atmospheric circulation dominates over ET in driving the trend in recycled precipitation in 55% of the global land surface (Fig. 1c, d). The impacts of circulation changes on moisture recycling are most prominent in the tropics and Southern Hemisphere extra-tropics, and less prominent in Northern Hemisphere extra-tropics (Fig. 1c, d). Specifically, more than 2/3 (68%) of tropical land and about 1/2 (48%) of extra-tropical land show a dominant role of circulation changes (Fig. 1d). Although the circulation-dominated regions partly overlap with the areas of high oceanic moisture contribution [15], the role of circulation changes here refers to spatial redistribution of terrestrial ET and associated recycled precipitation, and does not involve driving any additional oceanic moisture input to land.

Spatially, ET shows latitudinally divergent, but relatively homogeneous, impacts on the trend in recycled precipitation (Fig. 1a), with negative values prevailing in the tropics and positive values in the extra-tropics (except western North America). ET causes a notable and widespread increase in recycled precipitation in the East Asia, South Asia, and Europe, likely related to the extensive greening and warming in these regions. In contrast, circulation exhibits a more heterogenous pattern of effects due to the complexity of atmospheric dynamics. We identified a regionally strong circulation-induced reduction of recycled precipitation in Central Africa, eastern South America many extra-tropical regions, in line with previous studies [16,17]. These hotspots also overlap with those caused by ET changes, suggesting that precipitation declines in these regions result synergically from reduced land-sourced moisture and altered circulation patterns.

The impact of atmospheric circulation on land recycled precipitation shows strong year-to-year fluctuations (Fig. 2), as expected, associated closely with the El Niño-Southern Oscillation (ENSO)-driven climatic variability. We observe a statistically significant negative correlation (r = −0.42, P < 0.01) between

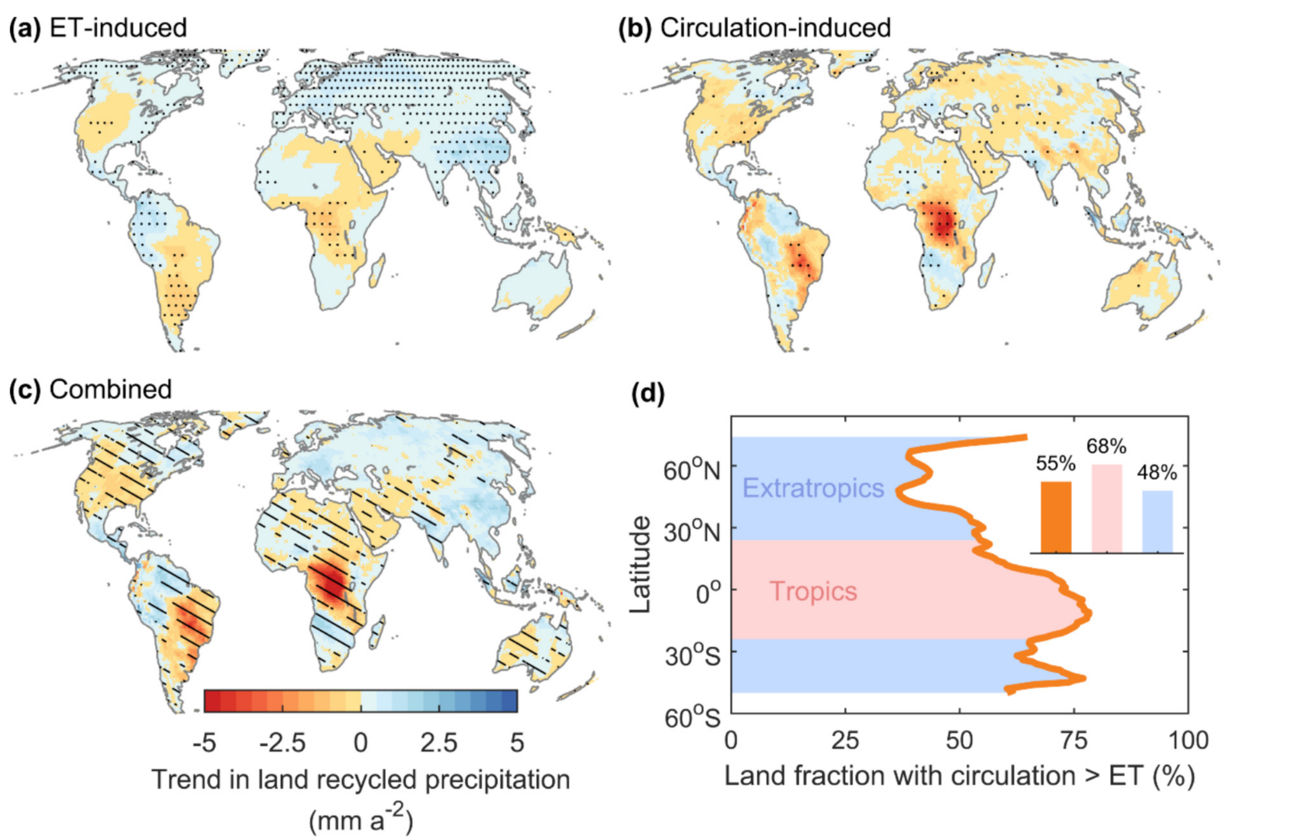

Fig. 1. Comparison of trends in land recycled precipitation attributed to evapotranspiration (ET) and atmospheric circulation changes. (a–c) Trends in land recycled precipitation associated with ET changes (a), atmospheric circulation changes (b), and their combined effect (c) during 1980–2020. Stippling in a and b indicates regions with statistically significant (P < 0.05) trends. Hatching in (c) indicates areas where circulation-induced trend in land recycled precipitation is larger than the ET-induced trend. (d) Zonal proportion of land with greater impacts of circulation than ET on the trend in land recycled precipitation (orange line). The light red and blue shaded areas mark the latitudinal range of tropics and extra-tropics. The upper-right inset bars represent the land percentage averaged over the global land (orange), tropics (light red), and extra-tropics (light blue) with dominant impact of circulation on the trend in land recycled precipitation.

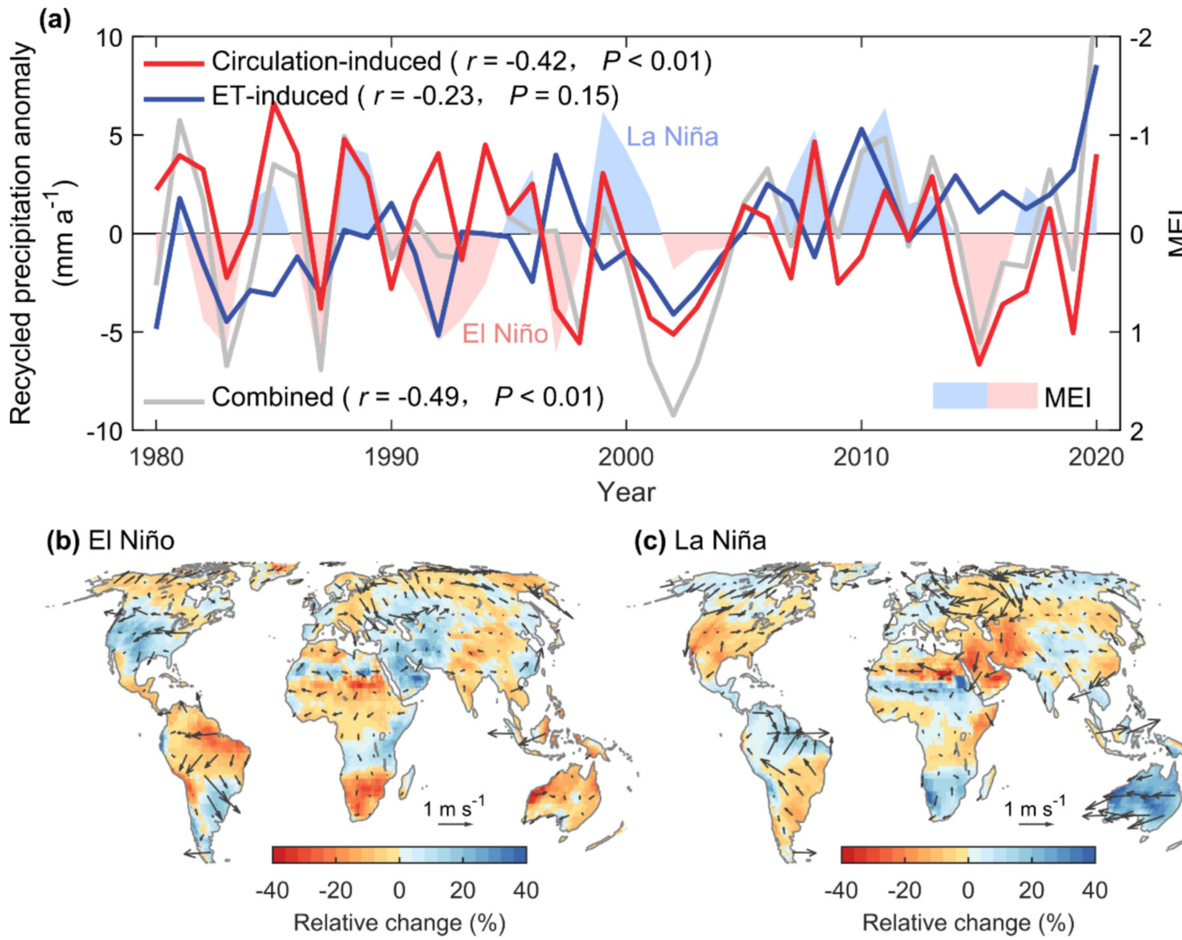

Fig. 2. Interannual variability of land recycled precipitation and its relation to the El Niño-Southern Oscillation (ENSO). (a) Lines show anomalies of global land-average (Antarctica excluded) recycled precipitation caused by circulation (red) and ET (blue) changes, and their combined effect (gray). Shading shows the multivariate ENSO index (MEI) as an indicator of ENSO intensities. Positive MEI values (> 0.5) indicate El Niño and negative values La Niña (< –0.5). Labels in the upper left indicate the Pearson correlation coefficients between recycled precipitation anomaly and MEI, and the corresponding *P* values based on a two-sided Student's *t* test. (b, c) Spatial patterns of recycled precipitation change anomaly composited for El Niño (b) and La Niña years (c). The arrows represent the near-surface wind field anomaly.

circulation-induced recycled precipitation anomaly and multivariate ENSO index (MEI, which defines ENSO phases and intensities), suggesting a tendency of more (less) land-sourced precipitation in La Niña (El Niño) years. This teleconnection is shaped by a dipole pattern of atmospheric circulation anomalies for the two ENSO phases, which drive different continental moisture transport pathways. In El Niño years, recycled precipitation decreases over 58% of global land, because the associated circulation anomalies typically lead to a divergence of moisture from key continental regions such as the South America, central and southern Africa, and Australia (> 40% precipitation decline) (Fig. 2b). In contrast, the opposing circulation patterns during La Niña years favor the convergence and increased precipitation of terrestrially sourced moisture over the same regions (Fig. 2c). Furthermore, we find that ET-induced recycled precipitation anomaly is insignificantly correlated to MEI (r = –0.23, P = 0.15), suggesting that land-based moisture alone cannot capture interannual, and interdecadal, variabilities of precipitation recycling.

Our simulations demonstrate that how much, and where, evapotranspiration from a certain area returns as rainfall is strongly affected by atmospheric circulation dynamics. The background circulation determines the large-scale pattern of moisture sources and sinks by controlling the pathway and flux of moisture transport. The use of a climatological mean or a fixed circulation pattern, as in previous studies [4,12–14], only accounts for the effects of accelerated ET, but fails to capture the highly dynamic water vapor transport in the real world. This may lead to biased or even wrong quantification of hydrological teleconnections over land and interpretation of its temporal evolution, as fixed circulation patterns could artificially redistribute land-sourced moisture to unrealistic locations. This systematic bias holds global significance, given the comparable global roles of altered ET and circulation in the land precipitation recycling (Fig. 1c, d). We thus recommend using dynamic circulation patterns for assessing changes of land moisture recycling, particularly for tropical regions where circulation is the dominant force that reshapes moisture recycling patterns.

It is worth noting that circulation changes not only result from internal climate variability or climate change, but also relate to vegetation-induced alterations in atmospheric thermodynamics. For example, large-scale afforestation can reshape regional land-surface energy balance via altering surface albedo and partitioning of sensible and latent fluxes, changing thermal gradients that modulate circulation patterns and moisture transport [1]. In addition to ET and circulation, precipitation efficiency, which depicts the tendency of atmospheric water vapor to rain out, is another player in modulating precipitation pattern. The atmospheric moisture tracking framework used here is deficient in disentangling these two effects above [5], and understanding their isolated roles may require the use of fully coupled land–atmosphere models. Our experimental design of factorial simulations may disturb the water balance within the model due to the forced modification of input data (i.e., static ET or circulation). Using water loss as an indicator of model water imbalance, we find that although these factorial simulations do not substantially (1%–4%) alter the water balance at the global scale, some hotspots of water imbalance emerge regionally (Fig. S4 online), which may affect the accuracy of isolating ET- and circulation-induced changes in recycled precipitation in these regions.

Given the major contribution of Earth greening to enhanced terrestrial ET [2], the dependence of moisture recycling on the background circulation patterns is highly relevant to the planning of afforestation policies. Circulation changes are a critical factor disrupting the balance between evaporative water loss and precipitation compensation from moisture recycling, and thus determining whether vegetation greening increases or reduces regional water resources. Furthermore, the hydrological impacts of forests might change with circulation patterns under future warming. For instance, projections of climate models suggest a shift of mean climate toward more El Niño-like conditions, which could heighten the risk of freshwater deficits in certain regions such as South America, central and southern Africa, Australia, India, and particularly North China (Fig. 2b), where there have already been intense afforestation activities. We highlight the necessity of incorporating atmospheric circulation dynamics into formalisation of afforestation strategies to ensure sustainable water management and avoid unintended hydrological consequences under climate change.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Jiangpeng Cui and Xu Lian conceived the idea and designed the study. Jiangpeng Cui ran the model and performed data processing and analyses. Ruud J. van der Ent provided helpful suggestion on the model simulation. All authors contributed to the interpretation of the results and the text.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.11.060.

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