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Assessing changes in atmospheric circulation due to ecohydrological restoration: how can global climate models help?

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In a steady-state hydrological cycle, terrestrial precipitation is divided into evapotranspiration-a measure of biological productivity-and liquid water runoff. Both processes are crucial to local communities, and ecohydrological restoration should enhance both. Here, based on the law of mass conservation, we show that a necessary condition for runoff to increase alongside evapotranspiration is an increase in precipitation coupled to a change in air circulation. Precipitation is governed by atmospheric dynamics, particularly how quickly moist air rises. Unless these dynamics also intensify, an increase in evapotranspiration, while boosting biological productivity, will simultaneously cause an undesirable decrease in runoff, reducing water availability for people and livestock. Therefore, it is essential to assess how ecohydrological restoration influences atmospheric circulation. Based on theoretical considerations and observations, previous studies have suggested that atmospheric moistening through evapotranspiration can enhance atmospheric moisture convergence, thereby increasing runoff. However, global climate models commonly used for climate guidance may artificially suppress certain positive feedbacks between precipitation and air motion due to the constraints of convective parameterization. A key question is whether such feedbacks exist in the real atmosphere at large scales, even if their amplitudes are weaker than those simulated by current models with convective parameterization turned off. Here, we briefly review the challenges in representing precipitation-air motion feedbacks and outline a research perspective to assess the ability of global climate models to capture these processes and clarify their underlying physics. This could inform large-scale ecohydrological initiatives that are ongoing or planned worldwide and underscore the importance of preserving ecohydrologically resilient ecosystems.

KEYWORDS

precipitation, transpiration, moisture convergence, forests, ecological restoration, streamflow (runoff), air circulation, condensation

1 Introduction

The vegetation-water nexus has been at the core of the human predicament since the distant past. In the *Epic of Gilgamesh*, perhaps the oldest account of ecohydrological collapse dating to around 2000 BCE, the hero deliberately destroys an ancient *Forest of Cedar* in Mesopotamia and witnesses a terrible drought and a sharp decline in the level of the Euphrates river as a result of deforestation (Balogh, 2022). Several thousand years later, but still long before the dawn of climate modeling, Friedrich Engels pointed out in 1876 that *"the people who, in Mesopotamia, Greece, Asia Minor and elsewhere, destroyed the forests to obtain cultivable land, never dreamed that by removing along with the forests the collecting centres and reservoirs of moisture they were laying the basis for the present forlorn state of those countries"* (Engels, 2010). Archaeological research confirms the important role of vegetation disturbances in the extreme climate conditions that led to the collapse of ancient societies (Beresford-Jones et al., 2009; Oglesby et al., 2010). Nowadays, we are witnessing the water levels in the Amazon River basin, which has been subject to massive deforestation in recent decades, at record lows (Maciel et al., 2024; Espinoza et al., 2024).

Reduction in runoff means reductions in the availability of freshwater, hydropower, irrigation, and navigation. When implementing large-scale ecorestoration projects, it is essential to understand potential changes in runoff. If vegetation degradation reduces runoff, then the restoration of functional vegetation should increase it. However, the literature contains considerable controversy, with opposing views on whether adding or removing vegetation increases or decreases runoff (e.g., Ellison et al., 2012; Sheil et al., 2019; Makarieva et al., 2023a; Ma et al., 2024, and references therein).

Here, we highlight a point that often escapes emphasis. In a steady state (i.e., when local moisture stores remain unchanged), liquid water runoff—the net amount of water leaving the region per unit time—is equal to the net amount of water vapor supplied to the region laterally via the atmosphere per unit time, i.e., to the

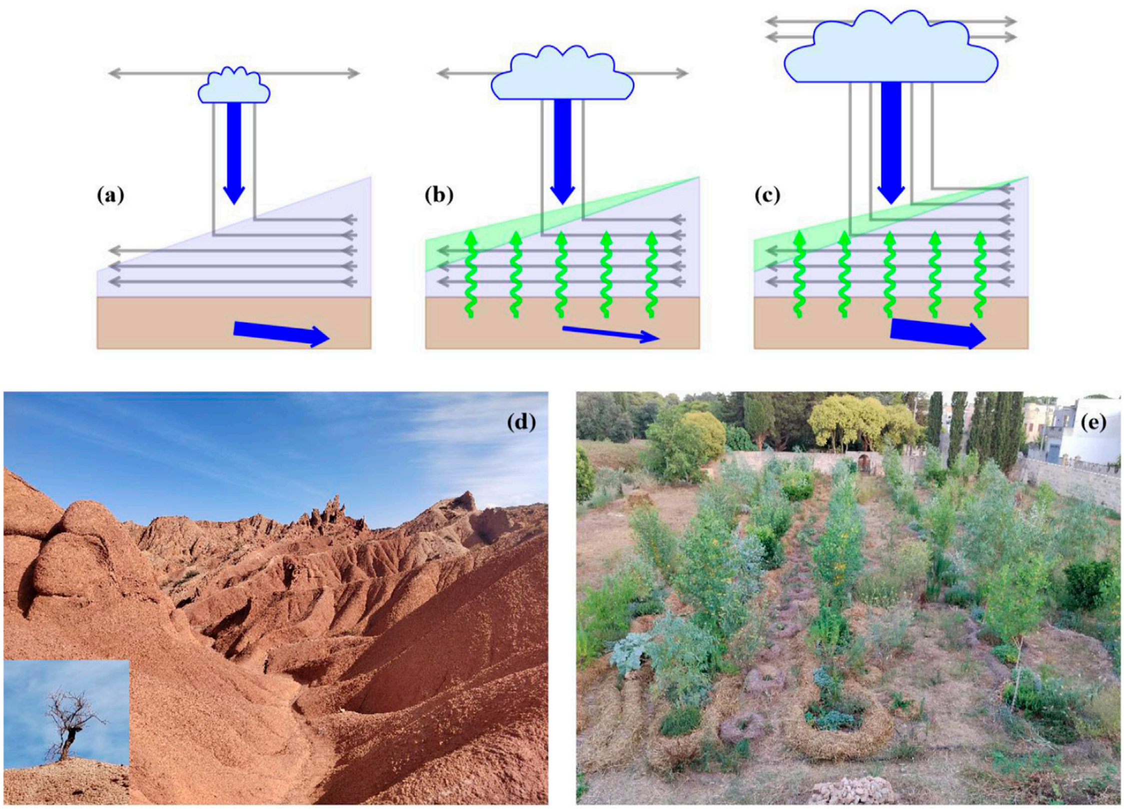

FIGURE 1
Interplay between air circulation, evapotranspiration, and runoff **(a–c)** and examples of **(d)** land degraded by overgrazing (Southern Issyk-Kul, Kyrgyzstan) and **(e)** the early stages of ecohydrological restoration (Depressa, Italy, restoration plot managed by Felipe Passini and Dayana Andrade). In **(a)**, evapotranspiration is zero, and all rainfall (downward blue arrow) goes to runoff (slanted blue arrow). Gray arrows indicate air streamlines, while the blue triangle represents atmospheric water vapor concentration, which declines along the streamline due to precipitation. In **(b)**, the air circulation remains the same as in **(a)**, but evapotranspiration is introduced (represented by wavy green arrows). This adds water vapor to the atmosphere (the added vapor is represented by the green triangle) and slows the decline of water vapor concentration along the streamline. As a result, the outgoing air carries away more moisture than in **(a)**, and even as the rainfall increases compared to **(a)** due to the added water vapor (recycling), the runoff decreases compared to **(a)**. In **(c)**, the air circulation has intensified compared to **(a)** and **(b)**. Even though there is more export of water vapor with the outflow, the inflow has increased even more, such that runoff has also increased compared to both **(a)** and **(b)**. Degraded land **(d)** is an example of case **(a)**. During syntropic restoration **(e)** efforts are made to retain as much moisture as possible by protecting soil (Andrade et al., 2020). If the air circulation does not change, this reduces runoff as in **(b)**. Increased runoff is only possible if the air circulation intensifies and precipitation rises more than evapotranspiration as in **(c)** (Makarieva et al., 2023a). (Ironically, due to its Martian-like appearance, the degraded land in **(d)** became a local tourist attraction under the name Fairy Tale Canyon).

atmospheric moisture convergence (see Supplementary Equation A13). It follows unambiguously from the law of matter conservation that if evapotranspiration increases while air circulation remains unchanged, runoff will decline. A necessary condition for runoff to increase alongside evapotranspiration is a change in local air circulation, i.e., in the air velocity field, that is associated with increased precipitation. In Supplementary Appendix SA, we provide a detailed derivation of this statement, while here, we discuss it in simpler terms and illustrate it schematically (Figure 1).

The primary source of liquid moisture for an ecosystem is precipitation. As moist air moves inland and ascends, water vapor condenses and precipitates. Along the air path, water vapor concentration (represented by a large blue triangle in Figure 1a) decreases as precipitation removes moisture from the air column. There is more water vapor flowing in than flowing out, with the difference equal to runoff. In degraded drylands, where evapotranspiration is negligible, all precipitated moisture is lost as runoff (Figure 1a).

Following vegetation restoration, evapotranspiration intensifies, returning a portion of the precipitated moisture to the atmosphere. This additional moisture, represented by a green triangle in Figure 1b, affects two key processes. First, it increases the local atmospheric water vapor content, leading to enhanced precipitation. Since precipitation is proportional to both vertical velocity and local water vapor concentration (e.g., Savenije, 1995), an increase in the latter can drive higher precipitation rates even in the absence of changes in air velocity. Second, the additional moisture from evapotranspiration reduces the gradient of water vapor density along the airflow trajectory. If atmospheric circulation remains unchanged, a greater volume of water vapor is exported from the region compared to conditions without evapotranspiration. As a result, despite increased precipitation due to moisture recycling, runoff decreases.

For runoff to increase alongside rising evapotranspiration, air circulation must change (Figure 1c; Supplementary Appendix SA). Moist air in the lower atmosphere, where most water vapor is concentrated, must flow in more rapidly and/or flow out more slowly. The latter can occur through more intense upward air motion, where air enters the region at lower atmospheric levels and exits at higher levels, depleted of water vapor.

Such changes in air circulation can arise from a positive feedback between precipitation and both horizontal and vertical air motion, where increased precipitation due to moisture recycling enhances the horizontal advection of moisture, which in turn fuels further precipitation. In this Perspective, we examine the evidence supporting this feedback and discuss how it can be assessed in models and observations.

Other important aspects of ecorestoration can also influence atmospheric dynamics, including changes in albedo and surface roughness associated with different vegetation types (e.g., Yang and Dominguez, 2019; Eiras-Barca et al., 2020; Ruv Lemes et al., 2023), though we do not address them here. Additionally, when the hydrological cycle is not in a steady state, extra terms appear in the ecosystem water budget, including infiltration and changes in soil moisture and groundwater storage. This more general case is explored in Supplementary Appendix SA. In a steady state, infiltration (moisture input to the soil) is balanced by plant transpiration, meaning it does not factor into the partitioning of precipitation between evapotranspiration and runoff.

2 Positive feedback between precipitation and air motion in observations and models

To our knowledge, Fu et al. (1999) were the first to ask whether local evaporation, condensation and precipitation over forests could drive large-scale moisture convergence. Working with observational data for the Amazon forest, Fu et al. (1999) found that prior to the wet season, the lower atmosphere experiences moistening that appears to be *"the cause, rather than the result, of the wet season"*. However, they concluded that this moistening results *"from the increase of low-level moisture convergence rather than the increase of moisture and sensible heat fluxes at land surface"* arguing that moisture transport in the Amazon is controlled by the land-ocean temperature gradient. This conclusion was revised by Fu and Li (2004), who argued that the temperature gradient over Amazonia is too weak and instead proposed that large-scale moisture convergence over Southern Amazonia is driven by an increase in surface latent heat flux (i.e., ultimately evapotranspiration). Isotope analysis of precipitation confirmed the local origin of the low atmosphere moistening (Wright et al., 2017).

A parallel line of thought was pursued by Levermann et al. (2009): *"The release of latent heat from precipitation over land adds to the temperature difference between land and ocean, thus driving stronger winds from ocean to land and increasing in this way landward advection of moisture, which leads to enhanced precipitation and associated release of latent heat."* Levermann et al. (2009) proposed that this positive feedback, with more latent heat released per unit time causing a larger temperature difference between land and ocean, may be responsible for the abrupt changes in monsoon regimes observed in the past, apparently unrelated to any similarly abrupt external forcing.

In numerical atmospheric circulation models, a feedback between precipitation and air motion has long been known and posed a serious problem known as numerical point storms (Lilly, 1960; Rosenthal, 1979; Molinari and Dudek, 1986; Giorgi, 1991; Baldwin et al., 2002). These manifest themselves as explosively growing small-scale disturbances. Giorgi (1991) explained that the mechanism responsible for the numerical point storms is *"a feedback between local circulations and release of latent heat of condensation"*. The release of latent heat *"warms the air locally"*, which leads to air *"convergence and vertical motions"*, which in turn *"accelerate condensation and latent heat release, and with it convergence"*. Provided the surrounding atmosphere contains enough moisture, this may result in an explosive process yielding precipitation rates of up to 1 m per day (Giorgi et al., 2023), comparable to what is observed in major hurricanes.

One conceptual problem is that the common explanation of the feedback—that more latent heat means more warming—does not appear to be physically sound. To illustrate the degree of controversy, in the same year that Giorgi (1991) explained how the release of latent heat warms the air, leading to air convergence, Emanuel (1991) argued that the statement *"hurricanes are driven by* *the condensation of water vapor"* is analogous to an engineer claiming that *"elevators are driven upward by the downward acceleration of counterweights"*. Emanuel et al. (1994) further explained that a faster release of latent heat does not lead to an increase in temperature, as it is offset by the equally rapid cooling of adiabatically rising air. Indeed, the temperature profile of the tropical atmosphere is largely determined by the moist adiabate, which is independent of vertical velocity—a key variable controlling the rate of latent heat release. Boos and Storelvmo (2016a), Boos and Storelvmo (2016b) used this argument in their critique of the mechanism proposed by Levermann et al. (2009) to explain abrupt shifts in past monsoons (see also Levermann et al., 2016). Accepting this criticism as valid means that those changes remain unexplained.

3 Convective parameterization

Early in climate modeling, convective parameterizations were introduced to suppress numerical point storms (Lin et al., 2022). Convective parameterization schemes assess how unstable a given grid point is to convection at a given time. Convective instability occurs when air temperature decreases too rapidly with altitude—specifically, when the vertical lapse rate of air temperature exceeds the moist adiabatic lapse rate. In this case, a rising moist air parcel, ascending adiabatically, remains warmer than the surrounding air, allowing it to continue and accelerate its vertical motion. If a grid point is found to be unstable, convection of a predefined magnitude is artificially initiated to adjust the temperature profile toward the moist adiabate.

Convective parameterizations were designed to address two related but distinct problems. First, they helped dampen numerical instabilities, allowing climate models to generate stable solutions (Manabe et al., 1965). Second, they reduced unrealistically high local precipitation, bringing modeled precipitation closer to observations (Lilly, 1960). As climate models became more sophisticated and their spatial resolution improved, convective parameterization ceased to play a major role in numerical stability. A project designed to investigate the impact of convective parameterization on global climate model outputs—SPOOKIE (the Selected Process On/Off Klima Intercomparison Experiment)—found that disabling convective parameterization in models with a $2.5^\circ \times 2.5^\circ$ resolution did not cause numerical instability (Webb et al., 2015). While numerical point storms still occur in certain modern models, they do not lead to overall instability (Giorgi et al., 2023).

What remains the role of convective parameterizations? The SPOOKIE project found that turning convective parameterization off does not considerably alter the global mean precipitation, but significantly modifies its spatial distribution and, consequently, the atmospheric moisture transport. Precipitation over land, especially in the Amazon rainforest, is markedly reduced (Maher et al., 2018). The inability of global climate models to capture high-intensity precipitation events, which pose the greatest danger in the tropics, is also interpreted as a deficiency related to convective parameterizations (Rios-Berrios et al., 2022). Similarly, in regional climate modeling, a more effective suppression of numerical point storms is associated with an underestimation of the most intense precipitation events (Giorgi et al., 2023).

With the development of convection-permitting global climate models, which operate at kilometer-scale resolution and can explicitly resolve convection, the role of convective parameterizations in simulating realistic precipitation and air circulation has become especially evident. In models with convective parameterization, a portion of precipitation is generated within the grid cell by parameterization schemes, while the rest results from resolved larger-scale air motions. To address scale dependency, a scale-aware convective parameterization was developed, reducing the contribution of parameterized precipitation as grid cell size decreased. This enabled a comparison of convective parameterization impacts across different spatial resolutions. Contrary to expectations, at the finest kilometer-scale resolutions, where parameterized precipitation is already relatively small, completely disabling parameterization of deep convection led to an abrupt departure of the model output from realism (Freitas et al., 2020; Vidale, 2022). In the numerical experiment of Freitas et al. (2020), precipitation intensity ceased to correlate with the column water vapor and even the direction of zonal circulation in the Arctic was reversed.

Another major effect of disabling convective parameterization in convection-permitting models is a significant strengthening of tropical moisture convergence, with precipitation over the Intertropical Convergence Zone (ITCZ) potentially tripling compared to observations (Vidale, 2022). A similar increase in ITCZ rainfall when convective parameterization is turned off has also been observed in lower-resolution models (Maher et al., 2018). In an aquaplanet numerical experiment, Rios-Berrios et al. (2022) found that without convective parameterization, their kilometer-scale model generated a tropical precipitation peak 1.7 times more intense than when convective parameterization was enabled. This led the researchers to conclude that current models with parameterized convection may be missing a crucial feedback loop between convective organization and moisture transport processes.

This brings us back to some of the fundamental challenges that were identified early on and remain unresolved. Lilly (1960) pointed out that a major weakness of convective parameterizations is their inherently arbitrary nature. A key issue is the larger-scale impact of artificially relaxing local instabilities through convective parameterizations. When local convection is artificially initiated, its influence on broader atmospheric circulation—i.e., the motions explicitly resolved by the model—is also pre-determined. Small errors in this local specification can lead to the unintended suppression or enhancement of larger-scale circulations that might otherwise emerge naturally from local disturbances. Lilly (1960) further noted that, under certain conditions, condensation-related motions can develop on scales larger than the more commonly observed mesoscale and cloud-scale convection. How much of this feedback is real but lost due to convective parameterizations?

4 Research perspective: condensation-induced atmospheric dynamics

An alternative explanation for the positive feedback between precipitation and air motion has been proposed within the framework of condensation-induced atmospheric dynamics (for

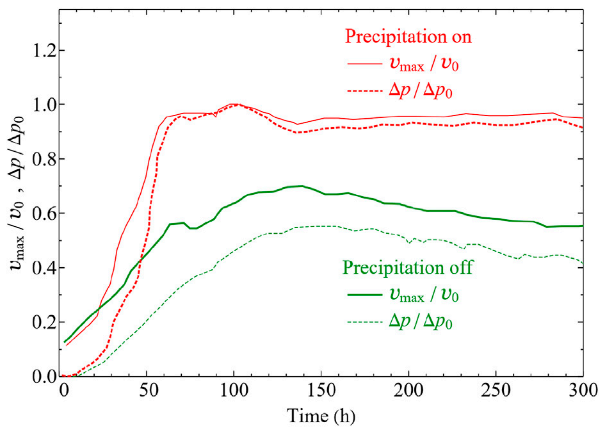

FIGURE 2
Time evolution of maximum velocity v_{max}/v_0 (solid curves) and central pressure deficit $\Delta p/\Delta p_0$ (dashed curves) in modeled storms with precipitation off (condensate fallout disabled, reversible storm) and on (condensate fallout enabled, control storm), in relative units. Normalization quantities are v_0 = 106 m s^{-1} and Δp_0 = 127 hPa. Data from Figure 2 of Wang and Lin (2020), see also Figure 6 of Makarieva and Nefiodov (2024).

details, see Makarieva and Gorshkov, 2007; Gorshkov et al., 2012; Makarieva and Nefiodov, 2024). In the Earth's atmosphere, water vapor—the condensable gas—has a non-equilibrium vertical distribution, with an exponential scale height (~2 km) much smaller than that of the approximately hydrostatic air (~9 km). As water vapor condenses in ascending air and precipitates out, it generates non-equilibrium vertical pressure gradients, which relax toward hydrostatic equilibrium through the redistribution of air masses. One consequence of these dynamics is a reduction in surface pressure due to precipitation removing mass from the air column. The higher the precipitation rate, the more rapidly surface pressure decreases, which in turn enhances the horizontal advection of moisture, further sustaining precipitation.

In an ecosystem context, this means that plant transpiration—by enhancing moisture recycling and increasing precipitation—is not a waste of soil moisture but can be seen as an "investment". By moistening the atmosphere, evapotranspiration facilitates even greater moisture import. This aligns with the interpretation of the prominent Soviet hydrologist M. I. L'vovich, who described transpiration as "*one of the highest forms of use of water resources*" (L'vovich, 1979).

To evaluate the impact of the precipitation mass sink on atmospheric dynamics and distinguish it from latent and sensible heat effects in model simulations, atmospheric models can be run in the so-called reversible mode. In this mode, condensate remains suspended as cloud water rather than falling as precipitation. The term "reversible" refers to the thermodynamic process in which condensed water can fully re-evaporate within the same air parcel. While latent heat is released in both conventional and reversible simulations, the precipitation mass sink is present only in the former.

Numerical experiments with tropical storm models show that disabling condensate fallout strongly suppresses storm dynamics. Storms either fail to develop or form much more slowly, with significantly lower maximum wind speeds and weaker central pressure deficits. In the example shown in Figure 2, the maximum velocity of the reversible storm is about 30% lower, while its central pressure deficit is reduced by a factor of two compared to the control storm with precipitation enabled.

In tropical storm research, it was recognized early on that "*the experienced numerical experimenter can pick and choose closures [i.e., specific convective parameterization schemes—our clarification] that will provide almost any desired result*" (Rosenthal, 1979). Accordingly, unlike global climate models, many commonly used models of tropical cyclones do not include convective parameterization. In such models, agreement with observations is instead achieved by tuning turbulence parameters, which may lack independent constraints (e.g., Bryan and Rotunno, 2009a). To a large extent, the statement by Rosenthal (1979) regarding convective parameterization remains applicable to turbulence parameterization as well. For instance, by adjusting turbulence parameters, it is possible to enhance so-called dry storms—driven solely by heat—allowing them to accelerate at a rate comparable to precipitating storms (e.g., Rousseau-Rizzi et al., 2021).

The situation is further complicated by the role of convective parameterization in representing turbulence. Even at high resolutions—where its direct contribution to precipitation becomes minimal—convective parameterization continues to influence atmospheric dynamics through its implicit effect on turbulent diffusion. This explains the unrealistic behavior observed in high-resolution models when convective precipitation is disabled (Freitas et al., 2020). In essence, convective parameterization introduces an additional degree of freedom in turbulence representation by linking it to convective motions. If such a connection exists in the real atmosphere, retaining certain aspects of convective parameterization may be crucial for realistically modeling turbulence.

Certain model setups—emerging from specific combinations of grid size, time steps, and parameterizations—may suppress condensation-induced dynamics while amplifying heat-driven dynamics, or vice versa. As a result, these setups could produce differing predictions for atmospheric processes involving condensation. For instance, preliminary findings suggest that some storm-resolving models without convective parameterization predict a weaker decline in Amazon rainfall following deforestation due to enhanced air convergence over the warmer, deforested land (Yoon and Hohenegger, 2025). This could reflect an artificially strengthened heat-driven circulation. Supporting this interpretation, the model struggles to reproduce the diurnal precipitation cycle, overestimating rainfall over land and exhibiting a spurious midday precipitation peak, coinciding with maximum solar heating (cf. Segura et al., 2022, their Figure 1). Moreover, recent studies suggest that global climate models may systematically overestimate heat-driven moisture transport to drier land regions (Simpson et al., 2023).

Turbulence and convection can be parameterized in multiple ways, each capable of producing a satisfactory—albeit imperfect—agreement with observations. Some high-resolution models are tuned to observations without relying on convective parameterization, whereas others are calibrated using both convective and turbulent parameterizations. If different parameterizations yield distinct scenarios for how changes in vegetation cover influence ocean-to-land moisture transport, independent constraints are needed to assess the realism of these scenarios. Establishing such constraints would also help distinguish which model-observation mismatches are critical for reliable predictions and which are less consequential.

In this context, we would like to highlight condensation-induced atmospheric dynamics as a promising avenue. The framework of condensation-induced dynamics imposes a constraint on atmospheric power: the steady-state kinetic energy generation (K) is proportional to precipitation (P). As a long-term climatological mean, this theoretical relationship is supported by observations on a global scale (Makarieva et al., 2013a), at a regional level in the Amazon River basin (Makarieva et al., 2014), and within mesoscale circulation systems such as tropical storms (Makarieva and Nefiodov, 2025). Since kinetic energy generation equals dissipation in a steady state, this K-P relationship serves as a global constraint on turbulence parameterization. One can expect that model configurations with a more consistent K-P relationship will better simulate ocean-to-land atmospheric moisture transport.

Furthermore, we propose that artificially suppressing precipitation by preventing condensate fallout can help quantify the relative roles of differential heating and condensation in driving ocean-to-land moisture transport within a given model setting. We suggest disabling precipitation (i.e., preventing the conversion of cloud water to rainwater) in global climate models to determine whether they exhibit a similar suppression of dynamics as tropical storm models. Tropical cyclones are of particular interest, as their representation in global climate models remains a long-standing challenge (Baker et al., 2024). While the reversible mode—where storm models exclude condensation fallout—has provided insights into storm physics (e.g., Bryan and Rotunno, 2009b; Wang et al., 2014; Wang and Lin, 2020; Makarieva and Nefiodov, 2024), a similar analysis has not yet been conducted in global climate models.

For each model configuration, one can define a measure, D, to quantify differences in atmospheric dynamics between simulations with and without condensation fallout. For instance, D can be expressed as the relative difference in moisture convergence over the Amazon between simulations where precipitation fallout is enabled versus disabled. Our hypothesis is that sensitivity to vegetation cover changes may correlate with D, such that model configurations with a higher D—indicating a stronger role of condensation—should exhibit greater sensitivity. If confirmed, D could serve as a proxy for a given model setting's capacity to reproduce the dynamics of ocean-to-land moisture transport. Such a proxy could potentially reduce computational costs, which is particularly relevant for high-resolution simulations.

Heat-driven ocean-to-land moisture transport—a distinct mechanism from condensation-induced dynamics—depends on the temperature contrast between land and ocean. Since land is warming faster than the ocean on average, this transport is expected to intensify with global warming, particularly in high-precipitation regions (the "wetter-get-wetter" scenario). In contrast, condensation-driven moisture transport may halt when the land-ocean temperature difference becomes critically high (Makarieva et al., 2022).

Notably, maximum moisture convergence and the most intense convection occur in the eyewalls of tropical storms, where evaporation rates peak and surface air temperatures reach their lowest values (Makarieva et al., 2017; Makarieva and Nefiodov, 2025). Storm simulations driven solely by sensible heat produce weaker storms (Wang and Lin, 2020). Qualitatively, this suggests that reduced evapotranspiration and the associated surface warming may weaken rather than enhance moisture convergence. Quantitatively, model projections will depend on how these processes are parameterized. We suggest focusing on quantifying models' ability to reproduce ocean-to-land moisture transport as a function of temperature contrasts, particularly during significant anomalies.

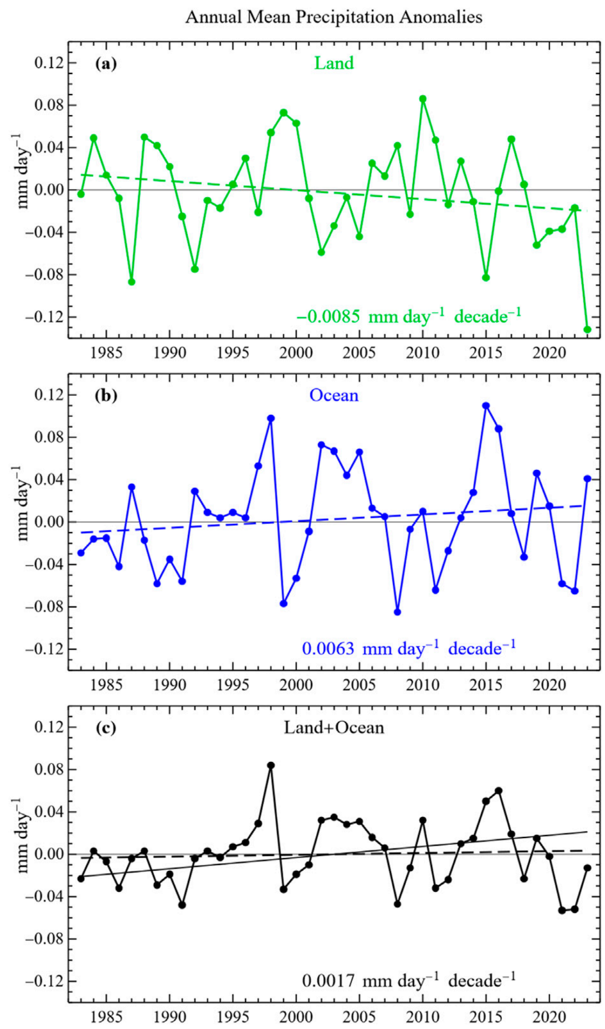

FIGURE 3
Global total precipitation anomaly from 1983 to 2023, deduced from GPCP v. 3.2 (Huffman et al., 2023). The climatological global mean precipitation is 2.21, 3.07, and 2.81 mm day^{-1} for land **(a)**, ocean **(b)**, and global **(c)**, respectively. Dashed lines represent ordinary least squares regressions (with slopes shown at the bottom of the graphs), none of which are statistically significant. The solid line in **(c)** represents the theoretical slope of 0.01 mm day^{-1} decade^{-1}, corresponding to 1.5% K^{-1}, assuming a temperature increase of approximately 1 K from 1983 to 2023 (see text and Supplementary Appendix SB for details).

Global climate models predict that land precipitation should increase with warming at approximately 1.5% per degree Kelvin (Adler and Gu, 2024). However, observations do not support this. Over the past 40 years, the mean global surface temperature has risen by about 1 K (Hansen et al., 2025), implying an expected increase in global mean precipitation of 0.04 mm day^{-1}. Yet, the observed trend, 0.0017 mm $day^{-1}decade^{-1}$, is statistically insignificant and several times smaller than predicted (Figure 3).

One of the warmest years on record, 2023, saw a significant negative precipitation anomaly over land (Figure 3), particularly in the Amazon (Adler and Gu, 2024; Espinoza et al., 2024). If models do not capture changes in ocean-to-land moisture transport in response to large temperature anomalies, their reliability in simulating smaller-scale effects—such as the local impacts of deforestation on precipitation via local heating (e.g., Qin et al., 2025)—also comes into question.

In summary, we suggest three research directions for consideration, as we believe they hold promise for improving our understanding of ocean-to-land moisture transport. These directions are currently being explored using the Brazilian Earth System Model (BESM, Nobre et al., 2009; Capistrano et al., 2020), with a focus on the Amazon River basin. First, examining historical climate data and different model configurations to assess whether the correlation between precipitation and kinetic energy generation is linked to a model's ability to accurately simulate ocean-to-land moisture transport. Second, investigating the role of condensation-induced atmospheric dynamics in shaping moisture transport by analyzing model simulations with and without precipitation fallout, which may offer insights into the significance of these processes for large-scale atmospheric circulation. Third, exploring how temperature anomalies influence ocean-to-land moisture transport, distinguishing between heat-driven and condensation-driven mechanisms, particularly in light of observed discrepancies between climate model projections and real-world precipitation trends.

5 Discussion

The United Nations has designated 2021-2030 as the Decade of Ecological Restoration, emphasizing the urgent need to rehabilitate ecosystems degraded by overexploitation (Fischer et al., 2021; Cooke et al., 2022). At the same time, humanity faces an escalating freshwater crisis, including the depletion of groundwater resources (Mekonnen and Hoekstra, 2016; Kuang et al., 2024; Uchôa et al., 2024). There is increasing awareness that these challenges can be addressed simultaneously through regionally tailored ecorestoration strategies that rehabilitate natural vegetation and stabilize the water cycle (e.g., Liu et al., 2025).

Here, we have discussed that for river runoff to increase alongside rising evapotranspiration, a change in atmospheric circulation is necessary. Without such a shift, increased evapotranspiration from ecological restoration may instead reduce runoff and potentially deplete soil water and groundwater reserves (Supplementary Appendix SA). Consequently, optimizing ecological restoration strategies—particularly on a large scale—requires interdisciplinary assessments that account for potential changes in atmospheric dynamics.

An increased evapotranspiration leads to higher precipitation through moisture recycling. A critical question, therefore, is: how will atmospheric dynamics respond to this increase in precipitation? The current scientific understanding is marked by conflicting concepts, as summarized in Table 1. In global climate models with convective parameterization disabled, a strong feedback between precipitation and air motion is observed. However, the exact nature of this feedback remains uncertain, and it cannot be solely attributed to latent heat warming. In the absence of further investigation into the underlying mechanisms, this feedback is suppressed in these models by convective parameterizations.

These parameterizations play a crucial role in shaping how current models represent ocean-to-land moisture transport (Maher et al., 2018). Additionally, the modeled responses of regional land-ocean moisture transport to warming and/or deforestation vary significantly across models, with some even differing in the direction of the response (e.g., Luo et al., 2022; Heidemann et al., 2023; Ruv Lemes et al., 2023; Yoon and Hohenegger, 2025). Given this variability, while there is an urgent need for accurate predictions, the capacity of current models to provide reliable guidance for large-scale efforts to restore both ecosystems and the water cycle remains limited.

Investigating the positive feedback between atmospheric moistening, precipitation, and moisture convergence is essential not only for guiding ecohydrological restoration but also in the context of the unprecedentedly rapid changes our planet is currently undergoing. These changes include at least two major aspects of climate change: the increase in global surface temperature and the accumulation of atmospheric carbon dioxide. In 2023, both rates reached record values that were unpredicted by global climate models.

The biotic carbon sink, which has been removing about one-third of anthropogenic carbon emissions, ceased to function, presumably due to drought in the Amazon and fires in the Canadian forests (Ke et al., 2024). Additionally, the global mean surface temperature increased by about 0.2 degrees Kelvin in just one year—a tenfold acceleration compared to the average warming trend of 1°–2° per century.

The causes of this extraordinary warming remain unclear, but it is likely related to long-distance correlations in atmospheric and oceanic circulation (Schmidt, 2024). While this paper was under review, a new study found that the warming anomaly observed in 2023 can be attributed to an abrupt decrease in planetary albedo due to a reduction in low-level clouds (Goessling et al., 2024), with pronounced cloud reduction hotspots over the Amazon and Congo rainforests (Makarieva et al., 2025). This reduction was accompanied by a significant negative anomaly in annual precipitation over land (Adler and Gu, 2024) (Figure 3).

If the anomalous warming is indeed caused by changes in oceanic and atmospheric circulation, and there is a positive feedback between evapotranspiration and atmospheric moisture convergence, the globally significant ecological dysfunction manifested as the collapse of the biotic carbon sink could contribute to the anomalous warming via its feedbacks on atmospheric circulation. Long-range effects on oceanic circulation from changes in vegetation cover have been previously identified (e.g., Nobre et al., 2009; Bauer et al., 2025).

Expanding on this perspective, a larger proportion of global warming than currently assumed may have been driven by large-scale disruptions in atmospheric circulation linked to the widespread degradation of primary vegetation by human activity during the industrial era. The observed ~ 1% relative reduction in the intensity of the global water cycle, compared to model predictions (Figure 3c), may have contributed to significant additional warming (Makarieva et al., 2023b).

TABLE 1 Rationale for the proposed numerical experiments.

Statements	References
1. Empirical evidence suggests a positive feedback between precipitation and air motion	Fu and Li (2004), Makarieva and Gorshkov (2007), Levermann et al. (2009), Chikoore and Jury (2010)
2. Theoretical arguments indicate that latent heat release cannot cause such a feedback	Emanuel (1991), Emanuel et al. (1994)
3. Theoretical arguments indicate that such a feedback can be caused by pressure changes associated with condensation and precipitation	Makarieva and Gorshkov (2007), Gorshkov et al. (2012), Makarieva et al. (2013b)
4. Global climate models feature a positive feedback between precipitation and air motion on local and global scales; this feedback is (partially) suppressed by convective parameterization	Lilly (1960); Giorgi (1991); Rios-Berrios et al. (2022)
5. In models of tropical storms without convective parameterization, storm dynamics are strongly suppressed when the condensate fallout is disabled	Bryan and Rotunno (2009a), Wang and Lin (2020), Wang and Lin (2021), Makarieva and Nefiodov (2024)
6. Statement No. 5 supports Statement No. 3; additional evidence in favor of No. 3 includes the approximate equality between observed intensification rates and precipitation in tropical storms	Makarieva and Nefiodov (2024)
7. It is proposed to turn off the fallout of condensate in global climate models to investigate their capacity to capture the condensation sink dynamics	This study

There is an urgent need to elucidate the nature of the positive feedback between precipitation and air motion, starting at the conceptual level and subsequently addressing its integration into numerical models. There is growing recognition among climate scientists, particularly those focused on land processes, that theoretical understanding has not kept pace with the advancement of both numerical models and empirical datasets (Byrne et al., 2024). The framework of condensation-induced atmospheric dynamics, with its verifiable analytical formulations, represents a promising direction for advancing this topic.

Climate change mitigation and hydrological restoration are inherently multidisciplinary challenges. As a team composed of theoreticians, modelers, and ecorestorationists working on the ground, we present these proposed analyses to the broader scientific community for discussion and possible cooperation. We believe that such investigations could ultimately contribute to the development of effective strategies for re-stabilizing the terrestrial biosphere and its water cycle.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AM: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. AVN: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. LC: Investigation, Writing – original draft, Writing – review and editing. ADN: Investigation, Writing – original draft, Writing – review and editing. FP: Investigation, Writing – original draft, Writing – review and editing. DA: Investigation, Writing – original draft, Writing – review and editing. PN: Investigation, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1516747/full#supplementary-material

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