Review

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Review

How Forests May Reduce the Incidence of Destructive Tropical Cyclones, Hurricanes and Typhoons

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Abstract

Tropical cyclones cause thousands of deaths and immense damage annually. While ocean temperatures and atmospheric conditions dominate cyclone formation and behaviour, forests' potential influence has received little systematic attention. In this review I explore and evaluate how forests may affect tropical cyclone incidence, behaviour, and impacts. Evidence strength varies by mechanism and cyclone stage. Post-landfall effects show strongest support: forests demonstrably slow storm decay through surface roughness, reducing wind damage by 20–40% compared to cleared land, while forest soils buffer flooding through enhanced infiltration. Forests also influence storm tracks, though magnitudes remain uncertain. Evidence for pre-landfall effects is more limited but plausible. Forests release massive moisture through evapotranspiration, substantially modifying offshore humidity. Temperature and aerosol effects offer additional pathways. The Biotic Pump theory proposes that large forest areas generate pressure gradients drawing moisture inland, potentially limiting moisture available for ocean storms. Forest influences on cyclone formation and growth should be most evident near the thresholds where small changes matter. This context-dependency reconciles divergent findings and provides a framework for integrating forests into climate risk assessment. Forest conservation offers clear benefits for coastal disaster mitigation through post-landfall protection. Potential effects on cyclone genesis, while uncertain, strengthen the case for forest protection and identify critical research priorities.

Keywords: tropical cyclones; deforestation; ecosystem services; Biotic Pump; land-atmosphere coupling; climate adaptation; disaster risk reduction; atmospheric moisture; evapotranspiration

1. Introduction

In late 2025, Tropical Cyclone Senyar formed near the Strait of Malacca between Peninsular Malaysia and Sumatra, Indonesia. Senyar made landfall over several areas, killed over 1,500 people and caused US$19.8 billion in damages. Tropical cyclones affect an estimated 20.4 million people yearly, with 1.4 trillion USD in damages plus 779,000 deaths since 1970 (Krichene et al. 2023; WMO https://wmo.int/topics/tropical-cyclone). Long-term consequences include slowed economic growth (Young & Hsiang, 2024). Comparable patterns unfold worldwide, often hitting low- and middle-income areas hardest (Hallegatte et al. 2020). Even minor factors in cyclone risk thus hold profound significance.

Senyar attracted attention not only for its severe impacts but also because tropical cyclones rarely form in near-equatorial zones where favourable conditions seldom align (Gray, 1968; Emanuel, 2003, 2020; Li and Toumi 2025). The affected region has endured extensive forest loss. This raises a question as to whether land cover changes may influence such storms. Forests are seldom considered in this context. We know that vegetation shapes land–atmosphere processes that influence climate (Bonan, 2016; IPCC, 2021), including conditions linked to tropical cyclone formation and behaviour (Hansen et al., 2013; IPCC Chapter 8, 2021). The answer to such questions has implications extending far beyond Senyar. Tropical cyclones in marginal and atypical contexts is a theme examined later in this review.

Evidence suggests that tropical cyclones are becoming stronger (Emanuel, 2021), travelling further (Kossin et al., 2020; Wang & Toumi, 2021, 2022), and affecting larger regions (Li & Chakraborty, 2020). Increasing numbers of people face exposure. Landfalling storms travel farther inland and decay slower, amplifying destruction (Li & Chakraborty, 2020). Warmer oceans intensify storms and rainfall while rising atmospheric stability and circulation changes may also curb formation frequency in some regions (Knutson et al., 2020; Chand et al., 2022; Zhao et al., 2024). Meanwhile, the fiercest storms continue to strengthen and migrate further (Kossin et al., 2020; Bhatia et al., 2022; Li et al., 2023).

Concurrent with these tropical cyclone trends, rapid forest loss and degradation continues, particularly in the tropics. From 2001 to 2024, Global Forest Watch (2025) estimates that 230 Mha (13%) of global forest cover was lost, with 310 Mha severely disturbed or degraded and 130 Mha gained or regrown. These widespread land cover changes raise questions about potential feedbacks between deforestation and tropical cyclone dynamics. Regarding Senyar, the affected region—Peninsular Malaysia, Sumatra, and surrounding areas—were once covered in dense tropical forest but are now largely deforested, with remaining forests often fragmented and degraded. Much of this was recent, Malaysia having lost approximately 7.5 Mha and Sumatra 8 Mha since 2001 (Global Forest Watch, 2025). This raises questions about whether land cover changes may favour such storms.

Ecologists have long studied how tropical cyclones shape forest structure, composition, and dynamics (e.g., Sheil & Burslem, 2003; Lin et al., 2020). The converse—how forests influence tropical cyclones—has received far less attention. While forest-tropical cyclone interactions have received some attention in media and online discussions (Sheil 2017,Gies 2024), systematic peer-reviewed analysis remains limited.

My goal is to fill this gap. While my review focuses on tropical cyclones, similar processes and implications will likely apply to similar systems, such as the extratropical storms that occur in the Mediterranean (see Cavicchia et al., 2014, Flaounas et al., 2022).

Due to the significant threat they pose there has long been considerable interest and research on tropical cyclones (Emanuel 2005, 2018, Lin et al. 2022).

Forests deliver known benefits for biodiversity conservation, climate mitigation, hydrological regulation, and coastal protection (Ellison et al. 2017, 2024, Mo et al., 2023; Jia et al., 2019; Sheil 2018; Smith et al. 2023), alongside other goods and services (Ghazoul and Sheil 2010; Katila et al. 2019; Nambiar 2019; Taye et al. 2021). Some contribute to mitigating tropical cyclone impacts; mangroves, for instance, shield coastal communities from harm (Das and Vincent 2009; Hochard et al. 2019). Access to forest also aids recovery (Liswanti et al. 2011; Wunder et al. 2014). But the question I will consider here is narrower—if forest cover plausibly reduces cyclone incidence or impacts this further strengthens the case for conservation and restoration.

In this review I examine the possible influence of forests on tropical cyclones from genesis to landfall, weighing mechanisms, uncertainties, and scales to consider forests in risk strategies. Section 2 outlines potential pathways and evidence, summarized in Table 1. Sections 3–7 assess remote effects on cyclone genesis and development, while Section 8 covers local impacts at and after landfall. Sections 9–11 synthesize the evidence, including regional variations, and conclude with implications for risk management and research.

This review is targeted at readers unfamiliar with atmospheric sciences. A primer on tropical cyclones is provided in Box 1 and a glossary of key terms is provided at the end.

Box 1. A Primer on Tropical Cyclones.

This overview is aimed at interdisciplinary readers. See the *Glossary* at the end of the article for terms. Tropical cyclones—regionally hurricanes or typhoons—are rotating, warm-core storms forming over tropical and subtropical oceans, typically 5°–30° latitude (Figure 1). These storms feature a low-pressure core, organized deep convection, spiral rainbands, and winds exceeding 250 km/h in extreme cases (Emanuel, 2003, 2005, 2021; Trenberth 2007).

Tropical cyclones function as “heat engines”, converting temperature gradients into mechanical work. They harness energy from warm seas via evaporation; rising water vapour condenses, releasing latent heat that drives pressure gradients and circulation (Emanuel, 1986). Winds increase surface evaporation creating a positive feedback. Many details, processes and interactions have been proposed and examined. Some articles distinguish 'bottom-up' views, which stress surface processes like convection and fluxes (Montgomery & Smith, 2014), from 'top-down' emphases on large-scale circulation and thermodynamics (Emanuel, 1986; Wang and Kieu 2019). These perspectives complement each other and agree on the key processes.

Formation and growth require: (1) sea surface temperatures above ~26.5–27°C; (2) 70–80% relative humidity at 3–6 km (Chand et al., 2022; Vecchi et al., 2023); (3) low vertical wind shear to avoid disruption (Rios-Berrios et al. 2024); (4) sufficient Coriolis force (Li and Toumi 2025); (5) an initial atmospheric disturbance or area of low pressure to trigger development (Emanuel, 2003; Chand et al., 2022; Vecchi et al., 2023). Later sections expand on various details.

Near land, cyclones behaviour changes: friction and loss of consistent oceanic heat prompt weakening, often within days, though rainfall lasts longer (Chen & Chavas, 2020; Hlywiak & Nolan, 2021).

Tropical cyclones inflict most damage at landfall. Powerful winds destroy buildings, uproot trees, and turn debris into projectiles; storm surges (high sea levels) flood and erode coastlines; while heavy rains cause floods and trigger landslides. Severity hinges on landfall site (population, infrastructure, preparedness, topography), track, speed (slower prolongs exposure), and intensity (Young & Hsiang, 2024; Weinkle et al., 2012; Rappaport, 2014).

Figure 1 here

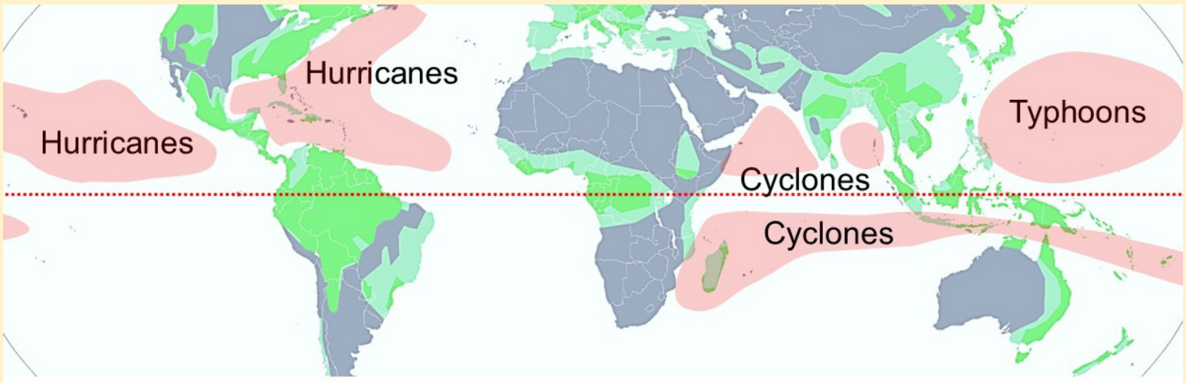

Figure 1. Approximate distribution of tropical cyclones, typhoons and hurricanes, and past and present forest cover. White: oceans; green: current forest, pale green; previous forest (lost or fragmented due to human activity), grey mainly non-forest. Pink: main areas where tropical cyclones occur. Compiled/drawn from multiple sources including https://commons.wikimedia.org/wiki/File:World_forest_cover_then_and_now.png#file https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/hurricanes/location & https://earthobservatory.nasa.gov/images/7079/historic-tropical-cyclone-tracks.

2. Potential Pathways and Evidence Framework

Forests may alter cyclone probabilities through many interconnected pathways. These span varied scales, processes, and outcomes and have various support (or not) from theory and evidence. Pathways group by tropical cyclone stage (genesis/development vs. landfall/decay) and evidence strength. I prioritize observational evidence, though tropical cyclone research generally relies on predictive models, statistical patterns, physical mechanisms, and theory (e.g., Schenkel et al. 2023, Takaya, et al. 2023, Montgomery & Smith 2017)—topics where expert views often differ—making the nature and interpretation of “evidence” somewhat subjective. Three confidence levels apply: high (consistent observations/models), medium (plausible with moderate support), low (theoretical/debated). These categories reflect both the strength of empirical support and the degree of scientific consensus. Table 1 summarizes these pathways; Sections 3-8 examine each in detail.

Table 1. Distinct forest-related processes influencing tropical cyclones, including spatial/temporal scales, potential implications of forest loss, evidence certainty, and key sources. *Evidence certainty: High = consistent observations/models; Medium = plausible with moderate support; Low = theoretical/debated indirect support. **Effects most plausible in marginal atmospheric conditions (e.g., near thresholds for storm genesis and growth).

Process/Effect	**Scale**	**Potential Implications of Forest Loss**	**Evidence Certainty***	**Key Sources**
Surface cooling via albedo, evapotranspiration, and roughness **	Local to regional (tens to hundreds of km); hours to seasons	Warmer land surfaces, weakening land-sea temperature contrasts and shifting convergence seaward, potentially increasing offshore storm activity in marginal areas	Low	(Bonan, 2016; Alkama & Cescatti, 2016; Li et al., 2015; Lawrence & Vandecar, 2015; Portmann et al., 2022; Fahrenbach et al., 2025)
Moisture recycling and evapotranspiration influencing atmospheric humidity **	Regional to continental (hundreds to thousands of km); seasonal to interannual	Reduced atmospheric moisture availability; effects on cyclone development depend on whether forests act as net moisture source or sink to oceanic areas, and on local circulation patterns	Medium	(Gentine et al., 2019; Zemp et al., 2017; Keys et al., 2012; Duque-Gardeazabal et al., 2025; Artaxo 2023; Trenberth et al., 2007a,b; Schneider et al., 2017; van der Ent, 2010; Boers et al., 2017)
Condensation-driven pressure gradients and circulation (Biotic Pump theory) **	Regional to continental (hundreds to thousands of km); seasonal	Diminished low pressure drawing moisture inland, potentially elevating oceanic moisture availability and cyclone likelihood	Low	(Makarieva et al., 2017; Baudena et al., 2021; Makarieva et al., 2023; Boers et al., 201; Findell et al., 2024;)
Aerosols (biogenic CCN/INP) influencing cloud microphysics and precipitation **	Local to regional (tens to hundreds of km); hours to days	Altered CCN/INP levels may suppress or invigorate convection with uncertain cyclone impacts, including possible suppression of early-stage intensification	Low	(Spracklen et al., 2011; Carslaw et al., 2013; Rosenfeld et al., 2014; Fan et al., 2018; Rosenfeld et al., 2007; Akinyoola et al., 2024; Tran et al., 2025)
Surface roughness accelerating energy loss at landfall	Local (tens to hundreds of km); hours to days	Faster storm decay over forest; cleared land extends storm life, increasing inland wind damage by 20-40%	High	(Wu et al., 2022; Chen & Chavas, 2020)
Hydrological buffering influencing flooding post-landfall	Local (tens to hundreds of km); hours to days	Increased runoff and flood risk due to reduced infiltration, though context-dependent (e.g., soil saturation limits; effects vary with storm speed and antecedent conditions)	Medium to high	(Jia et al., 2019; Hlywiak & Nolan, 2021; Wang & Matyas, 2022; Blöschl, 2022)

Forest influences on storm tracks (via friction, moisture, temperature, and pressure gradients)	Local to regional (tens to hundreds of km); hours to days	Altered landward drift, speed, and rainfall distribution, potentially increasing exposure frequency or duration in coastal areas	Low to medium	(Kossin, 2018; Szeto & Chan, 2010; Huang et al., 2011; Jian & Wu, 2008; Wu et al., 2015; Romdhani et al., 2024)

Many mechanisms in this review, particularly pre-landfall ones, are uncertain and rely on theoretical or indirect evidence. The precautionary principle holds that where serious harm is plausible, uncertainty should not postpone preventive action (United-Nations 1992; Kriebel et al., 2001). Thus, plausibility remains a key consideration until clearer evidence emerges.

3. Temperature-Mediated Effects

Forests regulate near-surface temperatures via albedo, evapotranspiration, and roughness. Intact forests sustain cooler surfaces than croplands or degraded areas, especially in humid tropics where evaporative cooling dominates (Bonan, 2016; Alkama & Cescatti, 2016). Satellite data show deforestation raises tropical temperatures by 1–3°C, peaking in dry seasons (Li et al., 2015). Temperature changes can extend to coastal zones with prevailing winds, potentially influencing cyclone genesis near land. For example, coastal temperature gradients may reshape pressure fields and convergence, displacing convection seaward (Findell et al., 2017).

Modelling indicates that deforestation-driven warming can weaken low-level convergence over forested continents while enhancing convergence over adjacent oceans, potentially shifting convective activity seaward (Portmann et al. 2022; Fahrenbach et al. 2025). Confirmation of these predictions appears absent from the literature. Despite these uncertainties, the modelled patterns offer a plausible pathway under suitable conditions.

4. Moisture and Circulation Effects

Moisture-related mechanisms offer plausible pathways for forest influence on cyclones, though debate surrounds the scales and mechanisms of land-moisture-rainfall feedbacks. While coarse models underpin much current understanding, recent findings question their ability to capture fine-scale processes (Lee and Hohenegger 2024). I note increased attention to the role of atmospheric moisture in cyclone research (Pérez-Alarcón et al. 2023; Gorja et al. 2024).

Methods are now available to show that while much of the moisture that generates and sustains tropical cyclones derives from the seas over which they develop, significant amounts can also derive from other sources including land (Pérez-Alarcón et al. 2022). For example, observations show that West Africa, and the Sahel contributed more moisture than expected by proximity alone to tropical cyclones forming in the eastern Atlantic north of the equator (Pazos and Gimeno 2017). These flows remain poorly characterised but likely reflect interactions with the monsoons as well as other processes (Drumond et al., 2011, Lélé et al. 2015).

Tropical forests release substantial moisture through evapotranspiration, fuelling precipitation. An estimated 39% of rainfall over the global land surface derives directly from ocean evaporation, the other 61% (71,800 km^3) recycles via vegetation following previous precipitation over land (Schneider et al. 2017; Sheil 2018). Forests, and tree cover more generally, play a major role in this recycling (van der Ent, 2010; Spracklen et al., 2012; Jasechko, et al. 2013; Schlesinger and Jasechko 2014, Sheil 2014); deforestation generally reduces regional rainfall (Boers et al. 2017; Andrich & Imberger 2013; McAlpine 2018) and this pattern has been seen across the tropics (Smith et al., 2023). Effects span hundreds to thousands of kilometers.

Recent Amazon data link over 2 cm dry-season rainfall decline to forest loss, with ~74% attribution (Franco et al. 2025). Declines in rainfall in deforested areas often appear to surpass estimates based on direct evapotranspiration losses alone (Li et al., 2026; Qin et al., 2025), implying that other processes amplify these changes.

Conventional theory attributes atmospheric circulation primarily to temperature gradients: warm air ascends, cool air descends, transporting moisture. Forests shape winds through heat, moisture, and momentum exchanges—collectively termed 'land–atmosphere coupling'—in the boundary layer (1–2 km). Land cover influences on atmospheric pressure and the resulting circulation are recognised (IPCC 2023).

Conventional theory attributes atmospheric circulation primarily to temperature gradients. While forests shape winds through heat, moisture, and momentum exchanges (termed 'land-atmosphere coupling') in the boundary layer, some more recent ideas propose that forest-dependent pressure gradients play a role too (I examine this in the following section below).

While sea-to-land transport prevails, reverse flows occur. Winds carry moisture downwind, including over seas (Keys et al., 2012). Intact forests are a major potential source of such humidity and, compared to other land cover, are often effective in maintaining such humidity during periods of drought (Sheil 2018). Degradation past thresholds slashes evapotranspiration, especially in dry periods, intensifying drying (Artaxo 2023; Franco et al. 2025). Dynamics depend on wind directions and geographical contexts.

Studies estimate extensive deforestation cuts offshore humidity in the lower atmosphere by 10–20%, varying by region, season, and method; uncertainties persist (Duque-Gardeazabal et al., 2025). The idea that downwind oceanic moisture that derives from forest contributes to cyclones is plausible but unstudied, though as noted above such moisture sourcing has revealed terrestrial sources (Pazos and Gimeno 2017, Pérez-Alarcón et al. 2022, 2023). The general assumption is that, for most of the time, the inverse effects dominate, with landward moisture flows from oceans far exceeding seaward flows from land (Trenberth et al., 2007a; Schneider et al., 2017)

The estimates of deforestation-related changes in humidity are small when compared with seasonal and interannual variability,—yet could be influential in borderline contexts. Beyond local moisture effects, the question remains whether forests influence circulation and pressure patterns in ways that affect tropical cyclone dynamics.

For completeness, I note published suggestions that forests could generate warm moist air supporting cyclone formation (Andersen and Shepherd 2017). However, frictional forces and diurnal temperature variations over forested landscapes (forest canopies tend to be cool, especially at night) prevent cyclone development, and no such processes have been observed.

5. Condensation-Driven Dynamics: The Biotic Pump

The Biotic Pump theory proposes that condensation drives circulation in addition to conventional temperature-driven mechanisms (Makarieva & Gorshkov 2007, 2010). Condensation removes vapour molecules from the air, altering vertical pressure profiles. This creates pressure gradients between regions that draw in surrounding air at low altitudes and return it aloft, establishing a self-sustaining circulation converging over areas of high condensation. Forests maintain high evapotranspiration and condensation, stabilizing low pressure and inflows over these areas (Makarieva & Gorshkov 2007; Sheil & Murdiyarso 2009).

The concepts underlying the Biotic Pump have been published in peer-reviewed physics and atmospheric science journals. While debated, recent reviews note increased theoretical support, though the mechanisms remain absent from operational models (Baudena et al., 2021; Makarieva et al., 2023). The theory is an additional mechanism rather than a replacement. The question is not whether condensation affects pressure—it does—but how much this shapes large-scale circulation and other relevant processes. There are some specific observations, such as the abruptness of the monsoon rains, that have proved hard to capture in models, but can perhaps be explained by this theory—though notably, there are distinct explanations, and mechanisms that may be seen as alternatives or additional mechanisms that may also generate the necessary feedbacks from forest derived moisture (Boers et al., 2017, Wright et al., 2017, Versieux and Costa 2024).

Similar physical insights as developed in the Biotic Pump have been applied to cyclones. Conventional views prioritize oceanic heat but the alternative view, echoing prior modelling work (Lackmann & Yablonsky, 2004), elevates the additional role of condensation as a major driver of tropical cyclone energetics and structure (Makarieva & Gorshkov, 2009; Makarieva et al., 2015). The theory also predicts that tropical cyclone power scales with rainfall, matching observations (Figure 2).

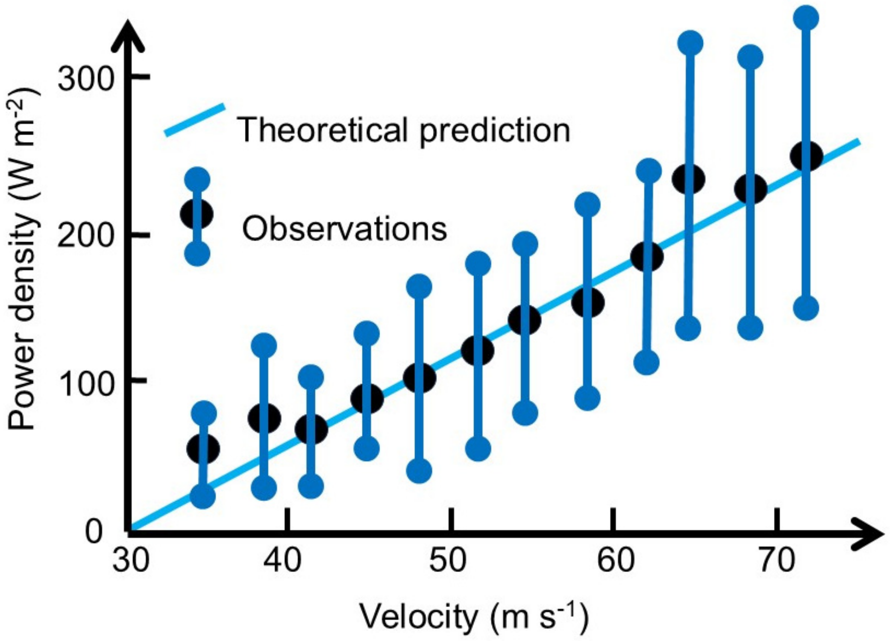

Figure 2. Predicted and observed power in the cyclone eyewall with respect to cyclone velocity. Empirical data (blue bars with two standard deviations) and predicted values, redrawn from data and analyses presented in [Sabuwala et al 2015; Makarieva, et al. 2015]. See these publications for more details on how the observations and calculations are made.

Data based observations show that tropical cyclones need to draw in moist air from over large regions and use it to fuel their dynamics—more moisture means a more powerful storm (Makarieva 2017). An estimate, using this theory, suggests that energy from water vapour contributes five times more than direct heat in powering tropical cyclones (Makarieva et al., 2017). A consequence of this theory being valid is that any process that reduces the availability of atmospheric moisture will reduce what is available to maintain and energise any such storms. This is how the presence or absence of forest could shape tropical cyclone's behaviour. The idea is that the low pressure over forests draws in significant winds and moisture from the ocean and it is unavailable for energizing storms. These ideas are elaborated to show the range of possible contexts and consequences in Figure 3.

The South Atlantic's warm seas meet tropical cyclone thresholds, yet unlike the neighbouring Caribbean, storms are scarce. Prevailing explanations stress strong wind shear, unfavourable circulation, and low humidity (Gray, 1968; Emanuel, 2003). Hurricane Catarina in March 2004 marked the satellite era's first South Atlantic tropical cyclone, landing in southern Brazil amid low shear and high moisture—a rare alignment (McTaggart-Cowan et al., 2006; Pezza & Simmonds, 2005).

South Atlantic cyclone rarity, despite warm seas, may reflect condensation-driven moisture drawdown by the Amazon and Atlantic forests (Makarieva et al., 2013b). Forest loss might contribute to changing this pattern if forests indeed are not simply a source of moisture but also draw moisture inland. Such interactions would peak in marginal cyclone zones.

Cyclones generally track with the ambient air flows that they are embedded in (Kossin, 2018) thus any impact of forest circulation could influence storm paths and risks. Even if strong effects occur, the summary risk assessment is uncertain. Forests might draw each storm's track to landfall; this may increase landfalls but also reduce the time available for intensification. Which effect dominates in terms of risk is uncertain—it will likely be context dependent.

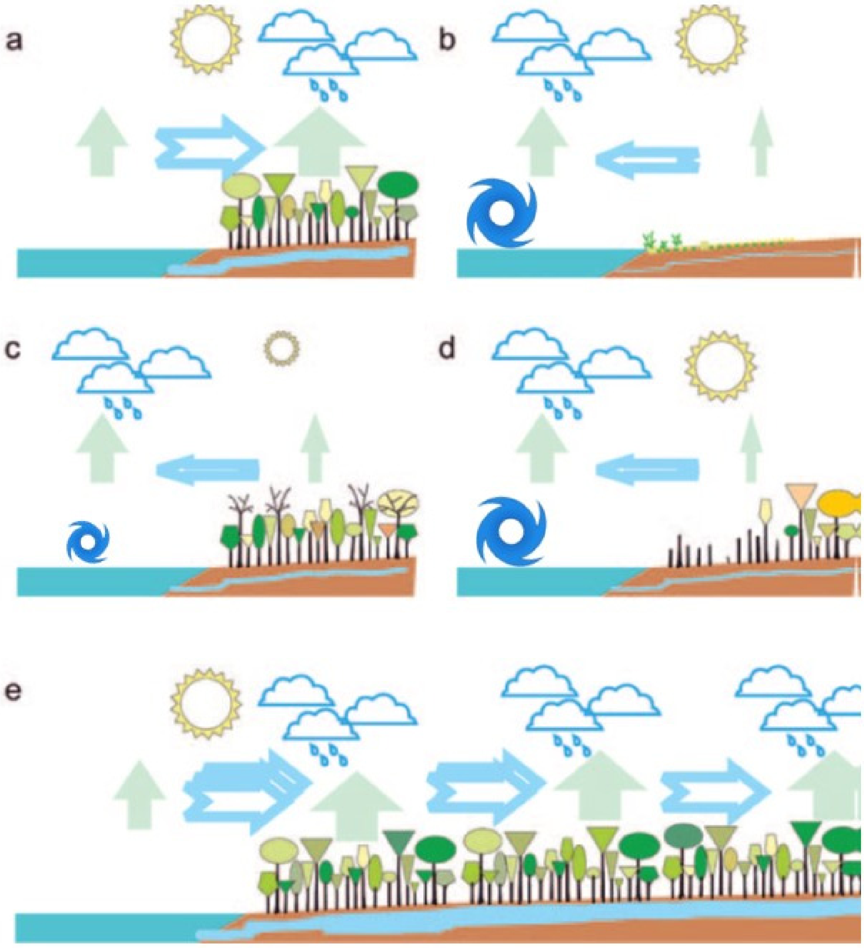

Figure 3. Schematic illustration of moisture dynamics and the biotic pump concept in relation to atmospheric conditions for cyclone formation. Vertical solid arrows represent evaporation intensity (arrow width indicates relative flux magnitude). The resulting low atmospheric pressure over regions with higher evaporation rates draws in moist air from areas with lower evaporation (horizontal open arrows), creating net moisture transfer toward high-evaporation regions. The dark blue spiral symbol indicates potential cyclone formation. (a) Under full sunshine, tropical forests maintain higher evaporation rates than oceans, drawing moist ocean air inland and reducing moisture available for cyclone formation over oceans. (b) In deserts with low evaporation, air flows toward oceans where moisture accumulates, potentially favouring cyclone formation. (c) In seasonal climates, forest evaporation may fall below oceanic rates during dry winter seasons when solar energy is insufficient; oceans then draw air from land and moisture may accumulate, though lower temperatures reduce cyclone likelihood. In summer, high forest evaporation is reestablished (as in panel a), creating seasonal monsoon circulation. (d) Following deforestation, reduced land evaporation cannot counterbalance oceanic evaporation; air flows seaward, land becomes arid, and moisture accumulates over oceans, potentially increasing cyclone formation. (e) Continuous forest cover maintaining high evaporation draws large volumes of moist air inland from coasts. Conditions most favourable for cyclone formation (sustained high oceanic moisture) occur primarily in scenarios b, c (warm season), and d; the smaller symbol in c reflects lower water vapour at cooler temperatures. Note: Dry air returns at higher altitudes from wetter to drier regions to complete the circulation cycle. Internal recycling of rain contributes significantly to continental-scale rainfall patterns but is not shown. Modified from Sheil and Murdiyarso (2009).

6. Aerosols

Forests emit biogenic aerosols—including cloud condensation nuclei (CCN) and ice nucleating particles (INP). These CCN and INP influence moisture condensation and freezing (Fan et al. 2007, Rosenfeld et al. 2007, Stier et al. 2024) and thus the location of energy release and the form and patterns of water transport (Thompson & Eidhammer, 2014; Yu et al., 2025). Effects are nonlinear; particle size, composition, and concentration matter (Carslaw et al. 2010; Kreidenweis et al. 2019; Tao et al. 2012). Theory suggests these can amplify or dampen cyclone formation depending on context the specific aerosols involved (Rosenfeld et al., 2014). Studies suggest anthropogenic aerosols delay and weaken cyclones over SE Asia but bolster peripheral rain (Wang et al. 2014; Seo et al. 2025).

Vegetation, including forests, supplies many aerosols (Sheil 2018). Forests release numerous biological particles (Pöschl 2010) and volatile organic compounds forming secondary aerosols as CCN/INP (Spracklen et al., 2011; Carslaw et al., 2013). These affect cloud formation, precipitation and convection (Artaxo et al. 2022; Després et al. 2012).

The potential of aerosols to influence tropical cyclones appears accepted. Simulations show cyclone sensitivity to aerosols, with context-specific, sometimes conflicting results (Akinyoola et al. 2024; Yu et al. 2025). Aerosols may curb early intensification by favouring condensation at lower levels of humidity reducing energy per air volume (Rosenfeld et al. 2007). Models suggest high loading may invigorate convection by delaying rain and elevating heat release, or may also suppresses it (Fan et al., 2018). One review notes aerosols interact with clouds, potentially altering cyclone development and intensity—an active research area (Akinyoola et al. 2024).

While the effects of biogenic aerosols on clouds and precipitation are well-established, their direct influence on cyclone-scale dynamics remains more speculative. The credibility of the concept appears supported by ongoing research into artificial aerosol interventions, such as cloud seeding, to modify cyclones (Willoughby et al., 1985; Tran et al., 2025), though forest-derived aerosols are not yet specifically studied.

Aerosol pathways appear potentially significant but remain highly uncertain. If moisture or condensation prove key (Sections 4, 5), aerosols may sometimes control them.

7. Landfall and Track Modification

Forests exert direct, well-supported influence at landfall. Studies show tropical cyclones weaken faster nearing forests than deforested or urban lands (Wu et al., 2022). Tree height, density, and profiles mean that forests are effective in slowing winds (Saha and Wasimi 2015; Lettau 1969). Typical cover slows powerful winds 20-40% quicker than occurs over open terrain. For average landfall, this hastens loss of powerful winds by hours, and shortens storm tracks. Simulations of tropical cyclones making landfall show that the presence of a coastal strip of mangroves rather than more open coastal wetlands results in a 10-20% reduction in peak wind speeds and area flooded (for details see Tiwari et al 2024).

The rain rate of tropical cyclones typically increases for two to three days before landfall. This is thought to reflect friction and reduced humidity over land that enhance convergence (Zhong et al. 2026b). Given forests' high surface roughness, they likely accentuate this effect, though formal examination appears absent from the literature.

Occasionally, tropical cyclones intensify as they near land—typically small storms under clear skies heating shallow seas (Lok et al., 2021). Simulations indicate that roughness and reduced evaporation cut latent heat flux, but sufficient available moisture may sometimes sustain intensification (Wang and Matyas, 2022). Observations show this occurs only where tree cover is sparse and moist heat is available---conditions absent in forested landscapes (e.g., a wet desert; Emanuel et al., 2008). Additional tree cover would presumably weaken, or reverse, such intensification

Forests also influence rainfall and flooding (Wang and Matyas 2022). Forest soils typically possess higher infiltration and storage than non-forest soils, curbing runoff. But after prolonged rain—common in slow storms—any soil saturates reducing the potential for buffering against floods (Blöschl 2022). Forest loss tends to accentuate landslide risk in steep terrain, while intact forests stabilize slopes, but such effects are context-dependent (Jia et al., 2019).

What do we know about storm tracks? Tropical cyclones exhibit beta drift—a shift poleward/westward at 1–3 m/s, faster in intense storms—from the interplay between the storm and the Coriolis force. There are also internal processes that can interact with variation in regional winds that cause significant drift (Zhong, et al. 2026a) .Warming slows and shifts mid-latitude circulation and thus also storm tracks (Kossin 2018). Near land, roughness, topography, and moisture induce wind/convection asymmetries, prompting landward drifts (Szeto & Chan 2010; Wong & Chan 2006). Key factors—roughness, moisture, shear—shape tracks and rain near landfall, varying by conditions (Huang et al. 2011; Jian & Wu 2008; Wu et al. 2015; Romdhani et al. 2024). Forests influence tracks via friction, moisture, temperature, and pressure, though magnitudes remain uncertain.

In summary, while many specific details and magnitudes are uncertain, post-landfall, forests moderate impacts and the severity of damage.

8. Context

Forest–tropical cyclone interactions depend on context. Boreal and temperate forests lie outside tropical cyclone formation zones, though landfall effects discussed here remain relevant to those regions.

The likelihood of observing an influence is highest under conditions that are just below the thresholds for storm development and growth. In favourable environments—warm oceans, low vertical wind shear, abundant moisture—effects from land cover are unlikely to be detectable. Conversely, where physical constraints strongly prevent formation or development, adding or removing forest is unlikely to change that. The sweet spot is thus the borderline conditions where storms prove rare but not impossible. In tropical cyclone hotspots like the western North Pacific or Caribbean, forest effects—if any—blend into noise.

From a research perspective, marginal zones, with rare alignments, offer easier detection potential. One option is to focus on regions near seasonal forests, where coupling fluctuates (Artaxo 2023) and tropical cyclone potential is seasonally limited. We would monitor storm formation and growth and link these to variations in conditions with estimates of the contribution of forest in determining these.

9. Synthesis: Weighing the Evidence

I assess the evidence by mechanism (Table 1).

High confidence: *Post-landfall effects*—roughness hastening energy loss, hydrological buffering against floods—align with observations and models (Section 8).

Medium confidence: *Moisture pathways*—evapotranspiration, recycling, condensation dynamics—garner moderate backing; recycling well-documented (Sections 4, 6).

Low confidence: *Temperature, circulation, aerosol* and *Biotic Pump* related pathways draw weaker support, lacking direct tropical cyclone ties (Sections 3, 5, 7). Aerosols appear speculative, though continued interest in seeding shows continued belief in their potential potency. Connecting forest-derived aerosols to cyclone-scale impacts remains speculative despite the theoretical plausibility. Biotic Pump mechanisms, while theoretically compelling, are similarly placed in this category due to the limited direct observational validation of cyclone-scale impacts.

Oceanic heat content, large-scale circulation, and vertical wind shear are seen as the dominant controls on tropical cyclone formation and growth (IPCC, 2021, Chapter 11). Forests may tweak these, shifting odds in specific marginal settings.

The Biotic Pump offers a specific mechanism for moisture effects that may—this is not agreed—operate at relevant scales and magnitudes. While debated it warrants continued scrutiny.

Most effects likely curb storm development, but this is not inevitable in every case and context. Forests might sometimes boost oceanic moisture, trigger otherwise absent processes via aerosols, or shift landfall patterns to strike settlements. As with many speculative effects discussed here, these possibilities too require acknowledgment.

Taken together, forests are most likely to matter where (i) atmospheric conditions are marginal for tropical cyclone development, (ii) forest cover is extensive and contiguous, and (iii) mechanisms reinforce one another. Where conditions are strongly favourable or unfavourable, forest effects are likely negligible. This context sensitivity reconciles divergent results and provides a practical framework for integrating forests into climate risk assessments.

10. Conclusion and Implications

Overall, theory and evidence indicate that tropical forests reduce storm-track damage and may limit the genesis, growth, and persistence of tropical cyclones (see Figure 4). Forests' post-landfall benefits are clear and well-supported: they slow decay, buffer flooding, and curb inland impacts. Evidence justifies integrating conservation and restoration into disaster strategies for at-risk zones.

Pre-landfall effects are less certain. In marginal cyclone zones, forest loss could elevate formation by disrupting moisture flows. Multiple mechanisms noted here warrant systematic appraisal; while speculative, we lack evidence to dismiss them. Given these uncertainties, the precautionary principle supports prioritizing forest conservation: we cannot rule out plausible cyclone risks from deforestation. Research to clarify these links is essential. Meanwhile, natural forests merit protection for their established roles in biodiversity, water security, climate stabilization, and coastal defence—if they also mitigate cyclones, that's an added benefit.

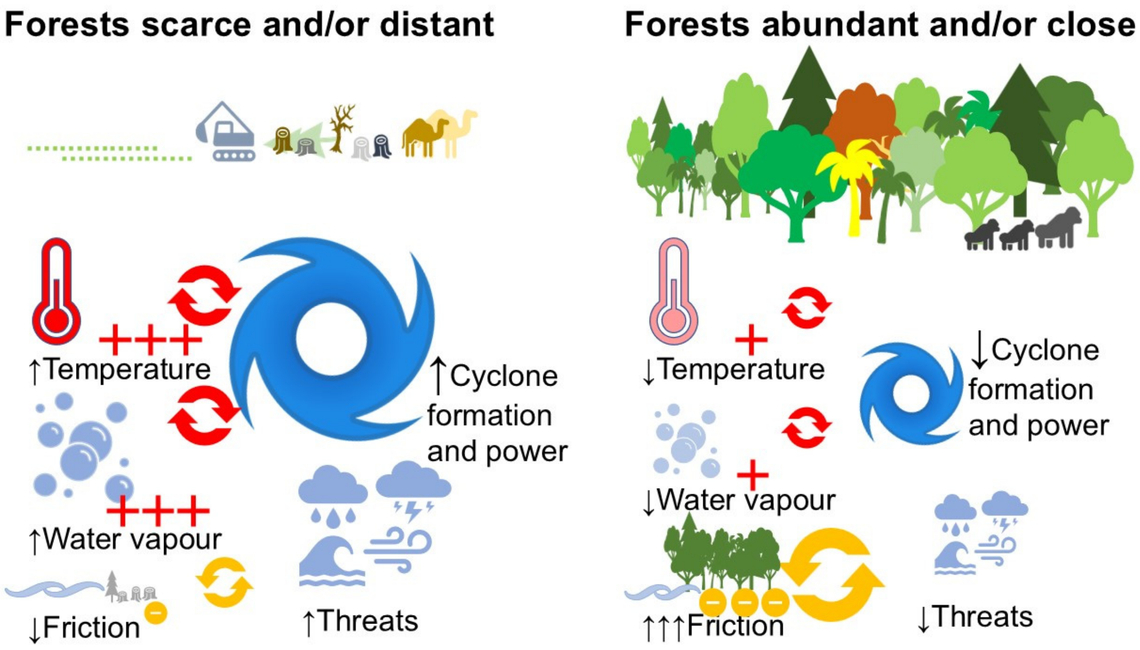

Figure 4. Schematic representation of the formation and power gain of tropical cyclones in a context without extensive forest and with (and near to) extensive forests. Red + signs show sources of energy (heat and vapour) that available to cyclones while yellow – show losses of energy (friction). We omit aerosols as though they likely play a role their contribution is uncertain. The magnitude of the relationships remains speculative though we are confident about the sign (plus or minus) : i.e., while friction plays a negative role in cyclone development, heat and moisture play positive roles.

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Graphical Abstract: See Figure 4.

Glossary

Aerodynamic roughness: A measure of how much a surface slows down and creates turbulence in air flowing over it. Forests have high aerodynamic roughness compared to smooth surfaces like water or grassland, which causes faster dissipation of wind energy.

Aerosols: Tiny solid or liquid particles suspended in the atmosphere, such as dust, sea salt, pollen, or compounds formed from plant emissions. These particles serve as surfaces on which water vapour can condense to form clouds, and thus influence cloud formation, precipitation, and atmospheric dynamics.

Albedo: The fraction of incoming solar radiation that a surface reflects back to space rather than absorbing. Forests typically have low albedo (they absorb more sunlight) compared to lighter surfaces like snow or bare soil, which affects how much solar energy heats the surface and lower atmosphere.

Atmospheric boundary layer (or boundary layer): The lowest 1–2 kilometres of the atmosphere where conditions are directly influenced by contact with the Earth's surface. This is the layer where daily temperature changes, surface winds, and turbulence from surface friction are strongest. Its behaviour differs significantly over forests versus cleared land.

Beta drift: The natural tendency of tropical cyclones to move poleward and westward (typically 1–3 m/s) due to interactions between the storm's rotation and Earth's varying Coriolis force, independent of larger-scale winds.

Biogenic aerosols: Aerosols produced by living organisms, such as particles or compounds emitted by forests, which can influence cloud formation and precipitation; distinct from human-made or mineral aerosols.

Biotic Pump: A theory, built from basic physical principles, that proposing that condensation of atmospheric water vapour over extensive forested regions generates low pressure that draws moist air from surrounding areas. This mechanism is proposed to sustain high rainfall deep inland.

Cloud condensation nuclei (CCN): Microscopic particles (typically 0.1–1 micrometre in size) that provide surfaces on which atmospheric water vapour can condense to form cloud droplets. Without these particles, the air would need to become far more saturated before clouds could form. Forests emit compounds that contribute to CCN formation.

Condensation-induced pressure gradients: Pressure differences created when water vapour condenses and removes gas molecules from the air, driving horizontal air flows; proposed as a key driver in mechanisms like the Biotic Pump.

Convection: The upward movement of air that occurs when warm, buoyant air rises and cooler air sinks to replace it. In tropical regions, strong convection creates towering thunderstorm clouds as moisture-laden air rises rapidly, cools, and releases latent heat through condensation, which further drives upward motion.

Convergence (or atmospheric convergence): The process where winds flow together from different directions, forcing air to accumulate and rise. This rising motion can trigger cloud formation and precipitation. Low-pressure areas naturally create convergence as air flows inward toward the centre, which is why they are associated with storms.

Coriolis force: The apparent deflection of moving air (or any moving object) caused by Earth's rotation. Air flowing toward a low-pressure centre gets deflected sideways—to the right in the Northern Hemisphere, left in the Southern—causing it to spiral rather than flow straight inward. This deflection creates cyclone rotation and weakens to zero at the equator.

Cyclogenesis (or genesis): The birth and initial development of a tropical cyclone from a pre-existing weather disturbance. This process requires specific atmospheric and oceanic conditions to be met simultaneously, and most disturbances fail to complete the transition to tropical cyclone status.

Deep convection: Particularly vigorous upward air motion that extends through the full depth of the troposphere (typically 10–15 km altitude in the tropics), often producing intense thunderstorms with heavy rain and sometimes hail. This is the fundamental building block of tropical cyclones and is fuelled by latent heat release from condensing water vapour.

Diurnal temperature variations: Daily cycles in temperature, typically warmer during the day and cooler at night, influenced by solar heating and surface properties such as forest canopies.

Evapotranspiration: The combined process of water evaporation from soil and water surfaces and transpiration (water release) from vegetation. Note that transpiration and evaporation are distinct processes leading some experts to prefer avoiding the combined term (Savenije 2004)—though in climate science it is useful shorthand for the total moisture coming from the land. In tropical forests, these combined processes typically return 3–6 mm of water per day to the atmosphere (higher in wet seasons), often comparable to or exceeding direct rainfall inputs in continental interiors.

Eyewall: The ring of intense thunderstorms surrounding a tropical cyclone’s calm central eye, where the strongest winds and heaviest rainfall occur.

Heat engine: A thermodynamic system that converts temperature differences into mechanical work. Tropical cyclones act as heat engines by extracting energy from the large temperature contrast between the warm ocean surface and the cold upper atmosphere, converting it into the storm’s rotational winds and circulation through evaporation, ascent, condensation, and latent heat release.

Hydrological buffering: The capacity of forests to moderate water flows by storing rainfall in soils and vegetation, reducing flood risks during storms, though limited by soil saturation.

Ice nucleating particles (INP): Microscopic particles that enable water droplets to freeze into ice crystals at temperatures where they would otherwise remain liquid (typically between 0°C and –38°C). Ice formation in tropical thunderstorms releases additional latent heat and affects storm dynamics, making INP potentially important for deep convection and cyclone development.

Land-atmosphere coupling: The two-way interaction between land surface properties (temperature, moisture, vegetation) and atmospheric conditions above. Surface characteristics affect air temperature, humidity, and wind, which in turn influence precipitation, radiation, and other processes that feed back to alter the surface. This coupling is particularly strong over forests due to high evapotranspiration rates.

Latent heat: Energy that is absorbed or released when water changes phase (between vapour, liquid, and ice) without changing temperature. When water evaporates from the ocean or forest, it absorbs energy; when that vapour later condenses in the atmosphere, it releases this energy.

Mid-level humidity (or mid-troposphere humidity): The amount of water vapour in the atmosphere at altitudes of roughly 3–6 kilometres. Developing tropical cyclones are particularly sensitive to humidity at these levels—relative humidity of 70–80% is typically needed—because dry air at these altitudes can penetrate the storm and suppress the convection necessary for organisation and intensification.

Moisture recycling: The process by which water evaporated from land surfaces (particularly through evapotranspiration) returns as precipitation over the same region or downwind areas, rather than being lost to distant locations. In large forest basins like the Amazon, 40–60% of rainfall comes from recycled continental moisture rather than directly from the ocean.

Monsoon: A seasonal wind system that reverses direction, typically causing an abrupt transition between dry (low rainfall) and wet (high rainfall) seasons.

Oceanic heat content: The total thermal energy stored in the upper ocean layers, beyond just surface temperature, which provides sustained fuel for tropical cyclone intensification.

Positive feedback: A self-amplifying process in which an initial change triggers effects that further increase the change, such as stronger cyclone winds enhancing evaporation to fuel even stronger winds.

Sea surface temperature (SST): The temperature of the ocean's surface layer (typically the top few metres), which is critical for tropical cyclone formation and intensification. SSTs generally need to exceed about 26.5–27°C to provide sufficient energy for cyclone development, though this threshold can vary slightly depending on other atmospheric conditions.

Storm surge: An abnormal rise in sea level above normal tidal levels, caused by a storm's low pressure and strong winds pushing water onshore.

Surface fluxes: The continuous exchanges of energy, water vapour, and momentum between the Earth's surface and the atmosphere. These include heat transfer (both sensible and latent), moisture release through evapotranspiration, and momentum exchange due to wind friction. Forests alter all three types of fluxes when compared to other land cover.

Tropical cyclone: A rotating, organised system of thunderstorms and strong winds that forms over tropical or subtropical waters, characterised by a warm core, low central pressure, and spiral structure. These storms are called hurricanes in the Atlantic and eastern Pacific, typhoons in the western Pacific, and simply cyclones in the Indian Ocean and South Pacific.

Troposphere: The lowest layer of Earth's atmosphere (typically 10–15 km altitude in the tropics), where most weather, clouds and convection occurs.

Vertical wind shear: The change in wind speed or direction with altitude. Strong vertical wind shear—where winds at the surface blow differently than winds at 10–15 km altitude—can tilt and disrupt a developing cyclone's vertical structure, preventing organisation. Low shear (winds moving in the same direction at all levels) allows storms to maintain the vertical alignment necessary for intensification.

Volatile organic compounds (VOCs): Gaseous chemicals that can react in the atmosphere to form secondary aerosols, or coat other particles, influencing cloud microphysics and potentially cyclone development. Forests and vegetation produce many such compounds.

References (Switch to Numbered in Final)

Akinyoola, J. A.; Afolabi, O. O.; Ogunbanjo, O. A.; Akinola, O. E. A review of atmospheric aerosol impacts on regional extreme weather and climate events. *Aerosol Sci. Eng.* **2024**, *8*, 249–274. https://doi.org/10.1007/s41810-024-00223-x.

Alkama, R.; Cescatti, A. Biophysical climate impacts of recent changes in global forest cover. *Science* **2016**, *351*, 600–604. https://doi.org/10.1126/science.aac8083.

Andersen, T.; Shepherd, M. Inland tropical cyclones and the 'brown ocean' concept. In *Hurricane Risk*; Springer: Cham, Switzerland, **2017**; pp 117–134. https://doi.org/10.1007/978-3-319-63614-6_7.

Andrich, M. A.; Imberger, J. The effect of land clearing on rainfall and fresh water resources in Western Australia: A multi-functional sustainability analysis. *Int. J. Sustain. Dev. World Ecol.* **2013**, *20*, 549–563. https://doi.org/10.1080/13504509.2013.850752.

Artaxo, P. Amazon deforestation implications in local/regional climate change. *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2317456120. https://doi.org/10.1073/pnas.2317456120.

Artaxo, P.; Pöhlker, C.; Pöhlker, M. L.; Saturno, J.; Machado, L. A. T.; Andreae, M. O.; Pöschl, U. Tropical and boreal forest–atmosphere interactions: a review. *Tellus B* **2022**, *74*, 24–163. https://doi.org/10.1080/16000889.2022.2020903.

Austin, K. G.; González-Roglich, M.; Schaffer-Smith, D.; Schwantes, A. M.; Swenson, J. J. Trends in size of tropical deforestation events signal increasing dominance of industrial-scale drivers. *Environ. Res. Lett.* **2017**, *12*, 054009. https://doi.org/10.1088/1748-9326/aa6d21.

Baudena, M.; Tuinenburg, O. A.; Ferdinand, J. P.; van Ek, R.; Staal, A. Effects of land-use change in the Amazon on precipitation are likely underestimated. *Glob. Change Biol.* **2021**, *27*, 5580–5587. https://doi.org/10.1111/gcb.15810.

Bhatia, K.; Baker, A.; Yang, W.; Vecchi, G.; Knutson, T.; Murakami, H.; Kossin, J.; Hodges, K.; Dixon, K.; Bronselaer, B.; Whitmore, C. A potential explanation for the global increase in tropical cyclone rapid intensification. *Nat. Commun.* **2022**, *13*, 6626. https://doi.org/10.1038/s41467-022-34321-6.

Blöschl, G. Three hypotheses on changing river flood hazards. *Hydrol. Earth Syst. Sci.* **2022**, *26*, 5015–5033. https://doi.org/10.5194/hess-26-5015-2022.

Boers, N.; Marwan, N.; Barbosa, H. M. J.; Kurths, J. A deforestation-induced tipping point for the South American monsoon system. *Sci. Rep.* **2017**, *7*, 41489. https://doi.org/10.1038/srep41489.

Bonan, G. *Ecological Climatology: Concepts and Applications*, 3rd ed.; Cambridge University Press: Cambridge, UK, **2016**. ISBN 9781107043770.

Carslaw, K. S.; Boucher, O.; Spracklen, D. V.; Mann, G. W.; Rae, J. G. L.; Woodward, S.; Kulmala, M. Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature* **2013**, *503*, 67–71. https://doi.org/10.1038/nature12674.

Carslaw, K.; Boucher, O.; Spracklen, D.; Mann, G.; Rae, J.; Woodward, S.; Kulmala, M. A review of natural aerosol interactions and feedbacks within the Earth system. *Atmos. Chem. Phys.* **2010**, *10*, 1701–1737. https://doi.org/10.5194/acp-10-1701-2010.

Cavicchia, L.; von Storch, H.; Gualdi, S. Mediterranean tropical-like cyclones in present and future climate. *J. Clim.* **2014**, *27*, 7493–7501. https://doi.org/10.1175/JCLI-D-13-00623.1.

Chand, S. S.; Walsh, K. J. E.; Camargo, S. J.; Kossin, J. P.; Tory, K. J.; Wehner, M. F.; Chan, J. C. L.; Klotzbach, P. J.; Dowdy, A. J.; Bell, S. S.; Ramsay, H. A.; Murakami, H. Declining tropical cyclone frequency under global warming. *Nat. Clim. Change* **2022**, *12*, 655–661. https://doi.org/10.1038/s41558-022-01388-4.

Chen, J.; Chavas, D. R. The transient responses of an axisymmetric tropical cyclone to instantaneous surface roughening and drying. *J. Atmos. Sci.* **2020**, *77*, 2807–2834. https://doi.org/10.1175/JAS-D-19-0320.1.

Das, S.; Vincent, J. R. Mangroves protected villages and reduced death toll during Indian super cyclone. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 7357–7360. https://doi.org/10.1073/pnas.0810440106.

Després, V. R.; Huffman, J. A.; Burrows, S. M.; Hoose, C.; Safatov, A. S.; Buryak, G.; Fröhlich-Nowoisky, J.; Elbert, W.; Andreae, M. O.; Pöschl, U.; Jaenicke, R. Primary biological aerosol particles in the atmosphere: a review. *Tellus B* **2012**, *64*, 15598. https://doi.org/10.3402/tellusb.v64i0.15598.

Drumond, A.; Nieto, R.; Gimeno, L. On the contribution of the Tropical Western Hemisphere Warm Pool source of moisture to the Northern Hemisphere precipitation through a Lagrangian approach. *J. Geophys. Res.* **2011**, *116*, D00Q04. https://doi.org/10.1029/2010JD015397.

Duque-Gardeazabal, N.; Friedman, A. R.; Brönnimann, S. An Atlantic influence on evapotranspiration in the Orinoco and Amazon basins. *Hydrol. Earth Syst. Sci.* **2025**, *29*, 3277–3295. https://doi.org/10.5194/hess-29-3277-2025.

Ellison, D.; Morris, C. E.; Locatelli, B.; Sheil, D.; Cohen, J.; Murdiyarso, D.; Gutierrez, V.; van Noordwijk, M.; Creed, I. F.; Pokorny, J.; Gaveau, D.; Spracklen, D. V.; Tobella, A. B.; Ilstedt, U.; Teuling, A. J.; Gebrehiwot, S. G.; Sands, D. C.; Muys, B.; Verbist, B.; Springgay, E.; Sugandi, Y.; Sullivan, C. A. Trees, forests and water: cool insights for a hot world. *Glob. Environ. Change* **2017**, *43*, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002.

Ellison, D.; Pokorný, J.; Wild, M. Even cooler insights: on the power of forests to (water the Earth and) cool the planet. *Glob. Change Biol.* **2024**, *30*, e17195. https://doi.org/10.1111/gcb.17195.

Emanuel, K. 100 years of progress in tropical cyclone research. *Meteorol. Monogr.* **2018**, *59*, 15.1–15.68. https://doi.org/10.1175/AMSMONOGRAPHS-D-18-0016.1.

Emanuel, K. An air-sea interaction theory for tropical cyclones. Part I: steady-state maintenance. *J. Atmos. Sci.* **1986**, *43*, 585–605. https://doi.org/10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2.

Emanuel, K. *Divine Wind: The History and Science of Hurricanes*; Oxford University Press: New York, NY, USA, **2005**. ISBN 9780195149418.

Emanuel, K. Evidence that hurricanes are getting stronger. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 13194–13195. https://doi.org/10.1073/pnas.2008073117.

doi:10.20944/preprints202410.2087.v2

Emanuel, K. Tropical cyclones. *Annu. Rev. Earth Planet. Sci.* **2003**, *31*, 75–104. https://doi.org/10.1146/annurev.earth.31.100901.141259.

Emanuel, K.; Callaghan, J.; Otto, P. A hypothesis for the redevelopment of warm-core cyclones over northern Australia. *Mon. Weather Rev.* **2008**, *136*, 3863–3872. https://doi.org/10.1175/2008MWR2535.1.

Emanuel, K.; Camargo, S. J.; Sobel, A. H. Response of global tropical cyclone activity to increasing CO_2: results from downscaling CMIP6 models. *J. Clim.* **2021**, *34*, 57–70. https://doi.org/10.1175/JCLI-D-20-0367.1.

Fahrenbach, N. L. S.; Wills, R. C. J.; De Hertog, S. J. Mechanistic insights into tropical circulation and hydroclimate responses to future forest cover change. *Weather Clim. Dyn.* **2025**, *6*, 1461–1477. https://doi.org/10.5194/wcd-6-1461-2025.

Fan, J.; Rosenfeld, D.; Zhang, Y.; Giangrande, S. E.; Li, Z.; Machado, L. A. T.; Martin, S. T.; Yang, Y.; Wang, J.; Artaxo, P.; Barbosa, H. M. J.; Braga, R. C.; Comstock, J. M.; Feng, Z.; Gao, W.; Gomes, H. B.; Mei, F.; Pöhlker, C.; Pöhlker, M. L.; Pöschl, U.; de Souza, R. A. F. Substantial convection and precipitation enhancements by ultrafine aerosol particles. *Science* **2018**, *359*, 411–418. https://doi.org/10.1126/science.aan8461.

Fan, J.; Zhang, R.; Li, G.; Tao, W.-K. Effects of aerosols and relative humidity on cumulus clouds. *J. Geophys. Res.: Atmos.* **2007**, *112*, D14204. https://doi.org/10.1029/2006JD008136.

Findell, K. L.; Yin, Z.; Seo, E.; Dirmeyer, P. A.; Arnold, N. P.; Chaney, N.; Fowler, M. D.; Huang, M.; Lawrence, D. M.; Ma, P.-L.; Santanello Jr., J. A. Accurate assessment of land–atmosphere coupling in climate models requires high-frequency data output. *Geosci. Model Dev.* **2024**, *17*, 1869–1883. https://doi.org/10.5194/gmd-17-1869-2024.

Flaounas, E.; Davolio, S.; Raveh-Rubin, S.; Pantillon, F.; Miglietta, M. M.; Gaertner, M. A.; Hatzaki, M.; Homar, V.; Khodayar, S.; Korres, G.; Kotroni, V. Mediterranean cyclones: Current knowledge and open questions on dynamics, prediction, climatology and impacts. *Weather Clim. Dyn.* **2022**, *3*, 173–208. https://doi.org/10.5194/wcd-3-173-2022.

Franco, M. A.; Rizzo, L. V.; Teixeira, M. J.; Artaxo, P.; Azevedo, T.; Lelieveld, J.; Nobre, C. A.; Pöhlker, C.; Pöschl, U.; Shimbo, J.; Xu, X.; Machado, L. A. T. How climate change and deforestation interact in the transformation of the Amazon rainforest. *Nat. Commun.* **2025**, *16*, Article number: 7944. https://doi.org/10.1038/s41467-025-63156-0.

Gentine, P.; Massmann, A.; Lintner, B. R.; Alemohammad, S. H.; Fu, R.; Green, J. K.; Kennedy, D.; Vilà-Guerau de Arellano, J. Land–atmosphere interactions in the tropics – a review. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 4171–4197. https://doi.org/10.5194/hess-23-4171-2019.

Ghazoul, J.; Sheil, D. *Tropical Rain Forest Ecology, Diversity, and Conservation*; Oxford University Press: Oxford, UK, **2010**. ISBN 9780199285884.

Gies, E. Is deforestation supercharging cyclones? *Hakai Magazine*, 21 October 2024. Available online: https://hakaimagazine.com/news/is-deforestation-supercharging-cyclones/ (accessed on 21 January 2026)

Global Forest Watch. Global Deforestation Rates & Statistics by Country. Available online: https://www.globalforestwatch.org/dashboards/global/ (accessed on 21 January 2026).

Gorja, M. M. K.; Vissa, N. K.; Viswanadhapalli, Y. Moisture sources for the genesis of tropical cyclones over the Bay of Bengal using the Lagrangian FLEXPART model. *Clim. Dyn.* **2024**, *62*, 7127–7147. https://doi.org/10.1007/s00382-024-07269-0.

Gray, W. M. Global view of the origin of tropical disturbances and storms. *Mon. Weather Rev.* **1968**, *96*, 669–700. https://doi.org/10.1175/1520-0493(1968)096<0669:GVOTOO>2.0.CO;2.

Hallegatte, S.; Vogt-Schilb, A.; Rozenberg, J.; Bangalore, M.; Beaudet, C. From poverty to disaster and back: a review of the literature. *Econ. Disasters Clim. Change* **2020**, *4*, 223–247. https://doi.org/10.1007/s41885-020-00060-5.

Hansen, M. C.; Potapov, P. V.; Moore, R.; Hancher, M.; Turubanova, S. A.; Tyukavina, A.; Thau, D.; Stehman, S. V.; Goetz, S. J.; Loveland, T. R.; Kommareddy, A.; Egorov, A.; Chini, L.; Justice, C. O.; Townshend, J. R. G. High-resolution global maps of 21st-century forest cover change. *Science* **2013**, *342*, 850–853. https://doi.org/10.1126/science.1244693.

Hlywiak, J.; Nolan, D. S. The response of the near-surface tropical cyclone wind field to inland surface roughness length and soil moisture content during and after landfall. *J. Atmos. Sci.* **2021**, *78*, 983–1000. https://doi.org/10.1175/JAS-D-20-0211.1.

Hochard, J. P.; Hamilton, S. E.; Barbier, E. B. Mangroves shelter coastal economic activity from cyclones. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 12232–12237. https://doi.org/10.1073/pnas.1820067116.

Huang, C.-Y.; Lin, L.-Y.; Huang, S.-Y.; Liu, S.-C. The influence of island topography on typhoon track deflection. *Mon. Weather Rev.* **2011**, *139*, 1708–1727. https://doi.org/10.1175/2011MWR3625.1.

IPCC. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, **2023**; 184 pp. https://doi.org/10.59327/IPCC/AR6-9789291691647.

IPCC. Water Cycle Changes. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, **2021**; Chapter 8. https://doi.org/10.1017/9781009157896.010.

IPCC. Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, **2021**; Chapter 11. https://doi.org/10.1017/9781009157896.013.

Jasechko, S.; Sharp, Z. D.; Gibson, J. J.; Birks, S. J.; Yi, Y.; Fawcett, P. J. Terrestrial water fluxes dominated by transpiration. *Nature* **2013**, *496*, 347–350. https://doi.org/10.1038/nature11983.

Jia, G.; Shevliakova, E.; Artaxo, P.; De Noblet-Ducoudré, N.; Houghton, R.; House, J.; Kitayama, K.; Popp, A.; Sirin, A.; Sukumar, R.; Verchot, L. Land–climate interactions. In *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Cambridge University Press: Cambridge, UK, **2019**; pp 133–206. https://doi.org/10.1017/9781009157988.004.

Jian, G.-J.; Wu, C.-C. A numerical study of the track deflection of Supertyphoon Haitang (2005) prior to its landfall in Taiwan. *Mon. Weather Rev.* **2008**, *136*, 598–615. https://doi.org/10.1175/2007MWR2309.1.

Katila, P.; de Jong, W.; Galloway, G.; Pacheco, P.; Mery, G., Eds. *Sustainable Development Goals: Their Impacts on Forests and People*; Cambridge University Press: Cambridge, UK, **2019**. https://doi.org/10.1017/9781108765015.

Keys, P. W.; van der Ent, R. J.; Gordon, L. J.; Hoff, H.; Nikoli, R.; Savenije, H. H. G. Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences* **2012**, *9*, 733–746. https://doi.org/10.5194/bg-9-733-2012.

Knutson, T.; Camargo, S. J.; Chan, J. C. L.; Emanuel, K.; Ho, C.-H.; Kossin, J.; Mohapatra, M.; Satoh, M.; Sugi, M.; Walsh, K.; Wu, L. Tropical cyclones and climate change assessment: Part II. *Bull. Am. Meteorol. Soc.* **2020**, *101*, E303–E322. https://doi.org/10.1175/BAMS-D-18-0194.1.

Kossin, J. P. A global slowdown of tropical-cyclone translation speed. *Nature* **2018**, *558*, 104–107. https://doi.org/10.1038/s41586-018-0158-3.

Kossin, J. P.; Knapp, K. R.; Olander, T. L.; Velden, C. S. Global increase in major tropical cyclone exceedance probability over the past four decades. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 11975–11980. https://doi.org/10.1073/pnas.1920849117.

Kreidenweis, S. M.; Petters, M.; Lohmann, U. 100 years of progress in cloud physics, aerosols, and aerosol chemistry research. *Meteorol. Monogr.* **2019**, *59*, 11.1–11.72. https://doi.org/10.1175/AMSMONOGRAPHS-D-18-0024.1.

Krichene, H.; Vogt, T.; Piontek, F. The social costs of tropical cyclones. *Nat. Commun.* **2023**, *14*, 7294. https://doi.org/10.1038/s41467-023-43114-4.

Kriebel, D.; Tickner, J.; Epstein, P.; Lemons, J., Levins, R., Loechler, E.L., Quinn, M., Rudel, R., Schettler, T. and Stoto, M.,The precautionary principle in environmental science. *Environmental Health Perspectives*, **2001**, 109(9), 871–876. doi: 10.1289/ehp.01109871

Lackmann, G. M.; Yablonsky, R. M. The importance of the precipitation mass sink in tropical cyclones and other heavily precipitating systems. *J. Atmos. Sci.* **2004**, *61*, 1674–1692. https://doi.org/10.1175/1520-0469(2004)061<1674:TIOTPM>2.0.CO;2.

Lawrence, D.; Vandecar, K. Effects of tropical deforestation on climate and agriculture. *Nat. Clim. Change* **2015**, *5*, 27–36. https://doi.org/10.1038/nclimate2430.

Lee, J.; Hohenegger, C. Weaker land–atmosphere coupling in global storm-resolving simulation. *Proc. Natl. Acad. Sci. USA* **2024**, *121*, e2314265121. https://doi.org/10.1073/pnas.2314265121.

Lélé, M. I.; Leslie, L. M.; Lamb, P. J. Analysis of low-level atmospheric moisture transport associated with the West African monsoon. *J. Clim.* **2015**, *28*, 4414–4430. https://doi.org/10.1175/JCLI-D-14-00746.1.

Lettau, H. Note on aerodynamic roughness-parameter estimation on the basis of roughness-element description. *J. Appl. Meteorol.* **1969**, *8*, 828–832. https://doi.org/10.1175/1520-0450(1969)008<0828:NOARPE>2.0.CO;2.

Li, L.; Chakraborty, P. Slower decay of landfalling hurricanes in a warming world. *Nature* **2020**, *587*, 230–234. https://doi.org/10.1038/s41586-020-2867-7.

Li, M.; Toumi, R. Can tropical cyclones exist near the Equator? *Q. J. R. Meteorol. Soc.* **2025**, e70014. https://doi.org/10.1002/qj.70014.

Li, X.; Wu, T.; Xia, K.; Tang, H.; Wang, X.; Wang, S.; Lyne, V.; Zu, Y. Forest loss intensifies meteorological drought in more than half of Earth's climate zones. *Sci. Adv.* **2026**, *12*, eadv7998. https://doi.org/10.1126/sciadv.adv7998.

Li, Y.; Wang, S.; Zhang, Y.; Song, J.; Wang, F. Recent increases in tropical cyclone rapid intensification events in global offshore regions. *Nat. Commun.* **2023**, *14*, 5466. https://doi.org/10.1038/s41467-023-40605-2.

Li, Y.; Zhao, M.; Manganello, J. V.; Xie, S.-P.; Deng, Z.; Stevens, B. Local cooling and warming effects of forests based on satellite observations. *Nat. Commun.* **2015**, *6*, 6603. https://doi.org/10.1038/ncomms7603.

Lin, J.; Qian, T.; Klotzbach, P. Tropical Cyclones. *Atmos.-Ocean* **2022**, *60*, 360–398. https://doi.org/10.1080/07055900.2022.2086849.

Lin, T.-C.; Hogan, G. D.; Ma, X.; Chang, C.-T. Tropical cyclone ecology: a scale-link perspective. *Trends Ecol. Evol.* **2020**, *35*, 594–604. https://doi.org/10.1016/j.tree.2020.02.012.

Liswanti, N.; Sheil, D.; Basuki, I.; Padmanaba, M.; Mulcahy, G. Falling back on forests: how forest-dwelling people cope with catastrophe in a changing landscape. *Int. For. Rev.* **2011**, *13*, 442–455. https://doi.org/10.1505/146554811798811326.

Lok, C. C. F.; Chan, J. C. L.; Wang, Y. Tropical cyclones near landfall can induce their own intensification through feedbacks on radiative forcing. *Commun. Earth Environ.* **2021**, *2*, 184. https://doi.org/10.1038/s43247-021-00259-8.

Makarieva, A. M.; Gorshkov, V. G. Biotic pump of atmospheric moisture as driver of the hydrological cycle on land. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1013–1033. https://doi.org/10.5194/hess-11-1013-2007.

Makarieva, A. M.; Gorshkov, V. G. Condensation-induced dynamic gas fluxes in a mixture of condensable and non-condensable gases. *Phys. Rev. E* **2009**, *80*, 046315. https://doi.org/10.1103/PhysRevE.80.046315.

Makarieva, A. M.; Gorshkov, V. G. The biotic pump: condensation, atmospheric dynamics and climate. *Int. J. Water* **2010**, *5*, 365–385. https://doi.org/10.1504/IJW.2010.038729.

Makarieva, A. M.; Gorshkov, V. G.; Li, B.-L. Revisiting forest impact on atmospheric water vapor transport and precipitation. *Theor. Appl. Climatol.* **2013b**, *111*, 79–96. https://doi.org/10.1007/s00704-012-0643-9.

Makarieva, A. M.; Gorshkov, V. G.; Nefiodov, A. V.; Chikunov, A. V.; Sheil, D.; Nobre, A. D.; Bunyard, P.; Li, B.-L. Empirical evidence for the condensational theory of hurricanes. *Phys. Lett. A* **2015**, *379*, 2396–2398. https://doi.org/10.1016/j.physleta.2015.07.042.

Makarieva, A. M.; Gorshkov, V. G.; Nefiodov, A. V.; Chikunov, A. V.; Sheil, D.; Nobre, A. D.; Bunyard, P.; Li, B.-L. Fuel for cyclones: the water vapor budget of a hurricane as dependent on its movement. *Atmos. Res.* **2017**, *193*, 216–230. https://doi.org/10.1016/j.atmosres.2017.04.006.

Makarieva, A. M.; Gorshkov, V. G.; Sheil, D.; Nobre, A. D.; Li, B.-L. Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics. *Atmos. Chem. Phys.* **2013a**, *13*, 1039–1056. https://doi.org/10.5194/acp-13-1039-2013.

Makarieva, A. M.; Nefiodov, A. V.; Vozbrannaya, A. E.; Chikunov, A. V.; Gorshkov, V. G.; Sheil, D.; Nobre, A. D.; Bunyard, P. The role of ecosystem transpiration in creating alternate moisture regimes by influencing atmospheric moisture convergence. *Glob. Change Biol.* **2023**, *29*, 2536–2556. https://doi.org/10.1111/gcb.16644.

McAlpine, C. A.; Johnson, A.; Salazar, A.; Syktus, J.; Wilson, K.; Meijaard, E.; Seabrook, L.; Dargusch, P.; Nordin, H.; Sheil, D. Forest loss and Borneo's climate. *Environ. Res. Lett.* **2018**, *13*, 044009. https://doi.org/10.1088/1748-9326/aaa4ff.

McTaggart-Cowan, R.; Bosart, L. F.; Davis, C. A.; Atallah, E. H.; Gyakum, J. R.; Emanuel, K. A. Analysis of Hurricane Catarina (2004). *Mon. Weather Rev.* **2006**, *134*, 3029–3053. https://doi.org/10.1175/MWR3235.1.

Mo, L.; Zohner, C. M.; Reich, P. B.; Liang, J.; de Miguel, S.; Nabuurs, G.-J.; Renner, S. S.; van den Hoogen, J.; Araza, A.; Herold, M.; Mirzagholi, L.; Ma, H.; Averill, C.; Phillips, O. L.; Gamarra, J. G. P.; Hordijk, I.; Routh, D.; Abegg, M.; Adou Yao, Y. C.; Alberti, G.; Almeyda Zambrano, A. M.; Alvarado, B. V.; Alvarez-Dávila, E.; Alvarez-Loayza, P.; Alves, L. F.; Amaral, I.; Ammer, C.; Antón-Fernández, C.; Araujo-Murakami, A.; Arroyo, L.; Avitabile, V.; Aymard, G. A.; Baker, T. R.; Bałazy, R.; Banki, O.; Barroso, J. G.; Bastian, M. L.; Bastin, J.-F.; Birigazzi, L.; Birnbaum, P.; Bitariho, R.; Boeckx, P.; Bongers, F.; Bouriaud, O.; Brancalion, P. H. S.; Brandl, S.; Brearley, F. Q.; Brienen, R.; Broadbent, E. N.; Bruelheide, H.; Bussotti, F.; Cazzolla Gatti, R.; César, R. G.; Cesljar, G.; Chazdon, R.; Chen, H. Y. H.; Chisholm, C.; Cho, H.; Cienciala, E.; Clark, C.; Clark, D.; Colletta, G. D.; Coomes, D. A.; Cornejo Valverde, F.; Corral-Rivas, J. J.; Crim, P. M.; Cumming, J. R.; de Gasper, A. L.; de-Miguel, S.; Decuyper, M.; Derroire, G.; DeVries, B.; Djordjevic, I.; Dolezal, J.; Dourdain, A.; Obiang, N. L. E.; Enquist, B. J.; Eyre, T. J.; Fandohan, A. B.; Fayle, T. M.; Feldpausch, T. R.; Ferreira, L. V.; Finér, L.; Fischer, M.; Fletcher, C.; Frizzera, L.; Gianelle, D.; Glick, H. B.; Harris, D. J.; Hector, A.; Hemp, A.; Hengeveld, G.; Hérault, B.; Herbohn, J. L.; Hillers, A.; Honorio Coronado, E. N.; Hui, C.; Ibanez, T.; Imai, N.; Jagodziński, A. M.; Jaroszewicz, B.; Johannsen, V. K.; Joly, C. A.; Jucker, T.; Jung, I.; Karminov, V.; Kartawinata, K.; Kearsley, E.; Kenfack, D.; Kennard, D. K.; Kepfer-Rojas, S.; Keppel, G.; Khan, M. L.; Killeen, T. J.; Kim, H. S.; Kitayama, K.; Köhl, M.; Korjus, H.; Kraxner, F.; Kucher, D.; Laarmann, D.; Lang, M.; Lu, H.; Lukina, N. V.; Maitner, B. S.; Malhi, Y.; Marcon, E.; Marimon, B. S.; Marimon-Junior, B. H.; Marshall, A. R.; Martin, E. H.; Meave, J. A.; Melo-Cruz, O.; Mendoza, C.; Mendoza-Polo, I.; Miscicki, S.; Merow, C.; Mendoza, A. M.; Moreno, V. S.; Mukul, S. A.; Mundhenk, P.; Nava-Miranda, M. G.; Neill, D.; Neldner, V. J.; Nevenic, R. V.; Ngugi, M. R.; Niklaus, P. A.; Oleksyn, J.; Ontikov, P.; Ortiz-Malavasi, E.; Pan, Y.; Paquette, A.; Parada-Gutierrez, A.; Parfenova, E. I.; Park, M.; Parren, M.; Parthasarathy, N.; Peri, P. L.; Picard, N.; Piedade, M. T. F.; Piotto, D.; Pitman, N. C. A.; Poulsen, A. D.; Poulsen, J. R.; Pretzsch, H.; Ramirez Arevalo, F.; Restrepo-Correa, Z.; Rodeghiero, M.; Rolim, S. G.; Roopsind, A.; Rovero, F.; Rutishauser, E.; Saikia, P.; Salas-Eljatib, C.; Saner, P.; Schall, P.; Schelhaas, M.-J.; Schepaschenko, D.; Scherer-Lorenzen, M.; Schmid, B.; Schöngart, J.; Searle, E. B.; Seben, V.; Serra-Diaz, J. M.; Sheil, D.; Shvidenko, A. Z.; Silva-Espejo, J. E.; Silveira, M.; Singh, J.; Sist, P.; Sonké, B.; Souza, A. F.; Stereńczak, K. J.; Svenning, J.-C.; Svoboda, M.; Swanepoel, B.; Targhetta, N.; Tchebakova, N.; ter Steege, H.; Thomas, R.; Tikhonova, E.; Umunay, P. M.; Usoltsev, V. A.; Valencia, R.; Valladares, F.; van der Plas, F.; Van Do, T.; van Nuland, M. E.; Vasquez, R. M.; Verbeeck, H.; Viana, H.; Vibrans, A. C.; Vieira, S.; von Gadow, K.; Wang, H.-F.; Watson, J. V.; Werner, G. D. A.; Wiser, S. K.; Wittmann, F.; Woell, H.; Wortel, V.; Zagt, R.; Zawiła-Niedźwiecki, T.; Zhang, C.; Zhao, X.; Zhou, M.; Zhu, Z.-X.; Zo-Bi, I. C.; Gann, G. D.; Crowther, T. W. Integrated global assessment of the natural forest carbon potential. *Nature* **2023**, *624*, 92–101. https://doi.org/10.1038/s41586-023-06723-z.

Montgomery, M. T.; Smith, R. K. Paradigms for tropical-cyclone intensification. *Q. J. R. Meteorol. Soc.* **2014**, *140*, 1233–1247. https://doi.org/10.1002/qj.2320.

Montgomery, M. T.; Smith, R. K. Recent developments in the fluid dynamics of tropical cyclones. *Annu. Rev. Fluid Mech.* **2017**, *49*, 541–574. https://doi.org/10.1146/annurev-fluid-010816-060022.

Nambiar, E. S. Tamm review: re-imagining forestry and wood business: pathways to rural development, poverty alleviation and climate change mitigation in the tropics. *For. Ecol. Manage.* **2019**, *448*, 160–173. https://doi.org/10.1016/j.foreco.2019.06.014.

NASA Global Precipitation Measurement (GPM) Mission. NASA Global Precipitation Measurement (GPM) Mission IMERG precipitation estimates for Cyclone Senyar, November 25-26, 2025. Available online: https://gpm.nasa.gov (accessed on 21 January 2026).

Pérez-Alarcón, A.; Fernández-Alvarez, J. C.; Sorí, R.; Nieto, R.; Gimeno, L. Moisture source identification for precipitation associated with tropical cyclone development over the Indian Ocean: a Lagrangian approach. *Clim. Dyn.* **2023**, *60*, 2735–2758. https://doi.org/10.1007/s00382-022-06429-4.

Pérez-Alarcón, A.; Sorí, R.; Fernández-Alvarez, J. C.; Nieto, R.; Gimeno, L. Where does the moisture for North Atlantic tropical cyclones come from? *J. Hydrometeorol.* **2022**, *23*, 457–472. https://doi.org/10.1175/JHM-D-21-0195.1.

Pezza, A. B.; Simmonds, I. The first South Atlantic hurricane: Unprecedented blocking, low shear and climate change. *Geophys. Res. Lett.* **2005**, *32*, L15712. https://doi.org/10.1029/2005GL023356.

Portmann, R.; Beyerle, U.; Davin, E.; Fischer, E. M.; De Hertog, S.; Schemm, S. Global forestation and deforestation affect remote climate via adjusted atmosphere and ocean circulation. *Nat. Commun.* **2022**, *13*, 5569. https://doi.org/10.1038/s41467-022-33279-9.

Pöschl, U.; Martin, S. T.; Sinha, B.; Chen, Q.; Gunthe, S. S.; Huffman, J. A.; Borrmann, S.; Farmer, D. K.; Garland, R. M.; Helas, G.; Jimenez, J. L.; King, S. M.; Manzi, A.; Mikhailov, E.; Pauliquevis, T.; Petters, M. D.; Prenni, A. J.; Roldin, P.; Rose, D.; Schneider, J.; Su, H.; Zorn, S. R.; Artaxo, P.; Andreae, M. O. Rainforest aerosols as biogenic nuclei of clouds and precipitation in the Amazon. *Science* **2010**, *329*, 1513–1516. https://doi.org/10.1126/science.1191056.

Qin, Y.; Xiao, Y.; Swenson, J. J.; Lawrence, D.; Zeng, Y.; Tuinenburg, O. A.; Fang, Y.; Wang, Y.; Zhang, X. Impact of Amazonian deforestation on precipitation reverses between seasons. *Nature* **2025**, *639*, 102–108. https://doi.org/10.1038/s41586-024-08570-y.

Rappaport, E. N. Fatalities in the United States from Atlantic tropical cyclones: New data and interpretation. *Bull. Am. Meteorol. Soc.* **2014**, *95*, 341–346. https://doi.org/10.1175/BAMS-D-12-00074.1.

Rios-Berrios, R.; Finocchio, P. M.; Alland, J. J.; Chen, X.; Fischer, M. S.; Stevenson, S. N.; Tao, D. A review of the interactions between tropical cyclones and environmental vertical wind shear. *J. Atmos. Sci.* **2024**, *81*, 713–741. https://doi.org/10.1175/JAS-D-23-0115.1.

Romdhani, O.; Zarzycki, C. M.; Chavas, D. R.; Davis, C. A. Hurricane track trends and environmental flow patterns under surface temperature changes and roughness length variations. *Geophys. Res. Lett.* **2024**, *51*, e2024GL109133. https://doi.org/10.1029/2024GL109133.

Rosenfeld, D.; Bellouin, N.; Field, P.; Forster, P.; Quaas, J.; Myhre, G.; Lohmann, U.; Samset, B. H. Global observations of aerosol-cloud-precipitation-climate interactions. *Rev. Geophys.* **2014**, *52*, 750–808. https://doi.org/10.1002/2013RG000441.

Rosenfeld, D.; Lohmann, U.; Raga, G. B.; O'Dowd, C. D.; Kulmala, M.; Fuzzi, S.; Reissell, A.; Andreae, M. O. Simulation of hurricane response to suppression of warm rain by sub-micron aerosols. *Atmos. Chem. Phys.* **2007**, *7*, 3411–3424. https://doi.org/10.5194/acp-7-3411-2007.

Sabuwala, T.; Gioia, G.; Chakraborty, S. Effect of rainpower on hurricane intensity. *Geophys. Res. Lett.* **2015**, *42*, 3024–3029. https://doi.org/10.1002/2015GL063785.

Saha, K. K.; Wasimi, S. A. Statistical modelling of tropical cyclones' longevity after landfall in Australia. *Aust. Meteorol. Oceanogr. J.* **2015**, *65*, 376–386. https://web.archive.org/web/20180602060216id_/http://www.bom.gov.au/jshess/docs/2015/saha.pdf.

Savenije, H. H. G. The importance of interception and why we should delete the term evapotranspiration from our vocabulary. *Hydrol. Process.* **2004**, *18*, 1507–1511. https://doi.org/10.1002/hyp.5563.

Schenkel, B. A.; Noble, C.; Chavas, D.; Chan, K. T.; Barlow, S. J.; Singh, A.; Musgrave, K. Recent progress in research and forecasting of tropical cyclone outer size. *Trop. Cyclone Res. Rev.* **2023**, *12*, 151–164. https://doi.org/10.1016/j.tcrr.2023.09.002.

Schlesinger, W. H.; Jasechko, S. Transpiration in the global water cycle. *Agric. For. Meteorol.* **2014**, *189*, 115–117. https://doi.org/10.1016/j.agrformet.2014.01.011.

Seo, K. H.; Choi, J.; Lee, S. S.; Lau, W. K. M.; Miyakawa, T.; Jin, H.-G. Aerosol effects on Maritime Continent precipitation: Oceanic intensification and land diurnal cycle delay. *npj Clim. Atmos. Sci.* **2025**, *8*, 326. https://doi.org/10.1038/s41612-025-01215-5.

Sheil, D. Forests, atmospheric water and an uncertain future: the new biology of the global water cycle. *For. Ecosys.* **2018**, *5*, 19. https://doi.org/10.1186/s40663-018-0138-y.

Sheil, D. How plants water our planet: advances and imperatives. *Trends Plant Sci.* **2014**, *19*, 209–211. https://doi.org/10.1016/j.tplants.2014.01.002.

Sheil, D.; Burslem, D. F. R. P. Disturbing hypotheses in tropical forests. *Trends Ecol. Evol.* **2003**, *18*, 18–26. https://doi.org/10.1016/S0169-5347(02)00005-8.

Sheil, D.; Murdiyarso, D. How forests attract rain: an examination of a new hypothesis. *BioScience* **2009**, *59*, 341–347. https://doi.org/10.1525/bio.2009.59.4.12.

Sheil, D. Forests versus hurricanes. *Forests News*, 18 Sep 2017. Available online: https://www.forestsnews.org/51566/forests-versus-hurricanes?fnl=en (accessed on 21 January 2026).

Smith, C.; Baker, J. C. A.; Spracklen, D. V. Tropical deforestation causes large reductions in observed precipitation. *Nature* **2023**, *615*, 270–275. https://doi.org/10.1038/s41586-022-05690-1.

Spracklen, D. V.; Arnold, S. R.; Taylor, C. M. Observations of increased tropical rainfall preceded by air passage over forests. *Nature* **2012**, *489*, 282–286. https://doi.org/10.1038/nature11390.

Spracklen, D. V.; Bonn, B.; Carslaw, K. S.; Kulmala, M.; Kerminen, V.-M.; Sihto, S.-L.; Riipinen, I.; Merikanto, J.; Mann, G. W.; Chipperfield, M. P.; Wiedensohler, A.; Birmili, W.; Lihavainen, H. Contribution of particle formation to global cloud condensation nuclei concentrations. *Geophys. Res. Lett.* **2008**, *35*, L06808. https://doi.org/10.1029/2007GL033038.

Spracklen, D. V.; Jimenez, J. L.; Carslaw, K. S.; Worsnop, D. R.; Evans, M. J.; Mann, G. W.; Zhang, Q.; Canagaratna, M. R.; Allan, J.; Coe, H.; McFiggans, G.; Rap, A.; Forster, P. Aerosol mass spectrometer constraint on the global secondary organic aerosol budget. *Atmos. Chem. Phys.* **2011**, *11*, 12109–12136. https://doi.org/10.5194/acp-11-12109-2011.

Stier, P.; van den Heever, S. C.; Christensen, M. W.; Gryspeerdt, E.; Dagan, G.; Saleeby, S. M.; Bollasina, M.; Donner, L.; Emanuel, K.; Ekman, A. M. L.; Feingold, G.; Field, P.; Forster, P.; Haywood, J.; Kahn, R.; Koren, I.; Kummerow, C.; L'Ecuyer, T.; Lohmann, U.; Ming, Y.; Myhre, G.; Quaas, J.; Rosenfeld, D.; Samset, B. H.; Schulz, M.; Stevens, B.; Stubenrauch, C. J.; Tao, W.-K. Multifaceted aerosol effects on precipitation. *Nat. Geosci.* **2024**, *17*, 719–732. https://doi.org/10.1038/s41561-024-01482-6.

Szeto, K.; Chan, J. Structural Changes of a Simulated Tropical Cyclone Approaching Land: Effects of Land–Sea Contrast. *Mon. Weather Rev.* **2010**, *138*, 4340–4360. https://doi.org/10.1175/2010MWR3339.1.

Takaya, Y.; Caron, L. P.; Blake, E.; Bonnardot, F.; Bruneau, N.; Camp, J.; Chan, J.; Gregory, P.; Jones, J. J.; Kang, N.; Klotzbach, P. J. Recent advances in seasonal and multi-annual tropical cyclone forecasting. *Trop. Cyclone Res. Rev.* **2023**, *12*, 182–199. https://doi.org/10.1016/j.tcrr.2023.09.003.

Tao, W.-K.; Chen, J.-P.; Li, Z.; Wang, C.; Zhang, C. Impact of aerosols on convective clouds and precipitation. *Rev. Geophys.* **2012**, *50*, RG2001. https://doi.org/10.1029/2011RG000369.

Taye, F. A.; Folkersen, M. V.; Fleming, C. M.; Buckwell, A.; Luckey, B.; Diwakar, K. C.; Le, D.; Hasan, S.; Saint Ange, C. The economic values of global forest ecosystem services: A meta-analysis. *Ecol. Econ.* **2021**, *189*, 107145. https://doi.org/10.1016/j.ecolecon.2021.107145.

Thompson, G.; Eidhammer, T. A study of aerosol impacts on clouds and precipitation development in a large winter cyclone. *J. Atmos. Sci.* **2014**, *71*, 3636–3658. https://doi.org/10.1175/JAS-D-13-0305.1.

Tiwari, P.; Rao, A. D.; Pandey, S.; Pant, V. Assessing the influence of land use and land cover data on cyclonic winds and coastal inundation due to tropical cyclones: a case study for the east coast of India. *Nat. Hazards* **2024**, *120*, 10219–10240. https://doi.org/10.1007/s11069-024-06603-3.

Tran, T. L.; Prinsley, R.; Rosenfeld, D.; Cleugh, H.; Fan, J. Can we mitigate tropical cyclone formation using aerosols? A review of cyclogenesis and aerosol effects as a theoretical basis. *Atmos. Res.* **2025**, *314*, 107779. https://doi.org/10.1016/j.atmosres.2024.107779.

Trenberth, K. E. Atmospheric moisture recycling: role of advection and local evaporation. *J. Clim.* **1999**, *12*, 1368–1381. https://doi.org/10.1175/1520-0442(1999)012<1368:AMRROA>2.0.CO;2.

Trenberth, K. E. Warmer oceans, stronger hurricanes. *Sci. Am.* **2007**, *297*, 44–51. https://doi.org/10.1038/scientificamerican0707-44.

Trenberth, K. E.; Smith, L.; Qian, T.; Dai, A.; Fasullo, J. Estimates of the Global Water Budget and Its Annual Cycle Using Observational and Model Data. *J. Hydrometeorol.* **2007**, *8*, 758–769. https://doi.org/10.1175/JHM600.1.

Trenberth, K. E.; Smith, L.; Qian, T.; Dai, A.; Fasullo, J. Water and energy budgets of hurricanes: case studies of Ivan and Katrina. *J. Geophys. Res.: Atmos.* **2007**, *112*, D23106. https://doi.org/10.1029/2006JD008303.

United-Nations. Rio Declaration on Environment and Development. Principle 15. United Nations Conference on Environment and Development, Rio de Janeiro, Brazil, 3–14 June 1992. United Nations. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_CONF.151_26_Vol.I_Declaration.pdf

van der Ent, R. J.; Savenije, H. H. G.; Schaefli, B.; Steele-Dunne, S. C. Origin and fate of atmospheric moisture over continents. *Water Resour. Res.* **2010**, *46*, W09525. https://doi.org/10.1029/2010WR009127.

Versieux, V.; Costa, M. H. Local Evapotranspiration Is the Only Relevant Source of Moisture at the Onset of the Rainy Season in South America. *Atmosphere* **2024**, *15*, 932. https://doi.org/10.3390/atmos15080932.

Wang, Q.; Kieu, C.; Vu, T.-A. Large-scale dynamics of tropical cyclone formation associated with ITCZ breakdown. *Atmos. Chem. Phys.* **2019**, *19*, 8383–8397. https://doi.org/10.5194/acp-19-8383-2019.

Wang, S.; Toumi, R. More tropical cyclones are striking coasts with major intensities at landfall. *Sci. Rep.* **2022**, *12*, 5236. https://doi.org/10.1038/s41598-022-09211-4.

Wang, S.; Toumi, R. Recent migration of tropical cyclones toward coasts. *Science* **2021**, *371*, 514–517. https://doi.org/10.1126/science.abb9038.

Wang, Y.; Lee, K. H.; Lin, Y.; Levy, M.; Zhang, R. Distinct effects of anthropogenic aerosols on tropical cyclones. *Nat. Clim. Change* **2014**, *4*, 368–373. https://doi.org/10.1038/nclimate2470.

Wang, Y.; Matyas, C. J. Simulating the Effects of Land Surface Characteristics on Planetary Boundary Layer Parameters for a Modeled Landfalling Tropical Cyclone. *Atmosphere* **2022**, *13*, 138. https://doi.org/10.3390/atmos13010138.

Weinkle, J.; Maue, R.; Pielke Jr., R. Historical global tropical cyclone landfalls. *J. Clim.* **2012**, *25*, 4729–4735. https://doi.org/10.1175/JCLI-D-11-00719.1.

Willoughby, H. E.; Jorgensen, D. P.; Black, R. A.; Rosenthal, S. L. Project STORMFURY: A Scientific Chronicle 1962–1983. *Bull. Am. Meteorol. Soc.* **1985**, *66*, 505–514. https://doi.org/10.1175/1520-0477(1985)066<0505:PSASC>2.0.CO;2.

Wong, M. L. M.; Chan, J. C. L. Tropical cyclone motion in response to land surface friction. *J. Atmos. Sci.* **2006**, *63*, 1324–1337. https://doi.org/10.1175/JAS3872.1.

World Weather Attribution. World Weather Attribution Report on Cyclone Senyar. Available online: https://worldweatherattribution.org (accessed on 21 January 2026).

Wright, J. S.; Fu, R.; Worden, J. R.; Chakraborty, S.; Clinton, N. E.; Risi, C.; Sun, Y.; Yin, L. Rainforest-initiated wet season onset over the southern Amazon. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 8481–8486. https://doi.org/10.1073/pnas.1621516114.

Wu, C.-C.; Li, T.-H.; Huang, Y.-H. Influence of Mesoscale Topography on Tropical Cyclone Tracks: Further Examination of the Channeling Effect. *J. Atmos. Sci.* **2015**, *72*, 3032–3050. https://doi.org/10.1175/JAS-D-14-0310.1.

Wunder, S.; Börner, J.; Shively, G.; Wyman, M. Safety nets, gap filling and forests: a global-comparative perspective. *World Dev.* **2014**, *64*, S29–S42. https://doi.org/10.1016/j.worlddev.2014.03.005.

Young, R.; Hsiang, S. Mortality caused by tropical cyclones in the United States. *Nature* **2024**, *633*, 580–586. https://doi.org/10.1038/s41586-024-07945-5.

Yu, X.; Lei, Y.; Wang, Z.; Zhao, D.; Li, Y.; Liu, L.; Wu, B.; Che, H.; Zhang, X. Inhomogeneous aerosol forcing increasing tropical cyclone intensity in western North Pacific by weakening vertical wind shear. *Environ. Res. Lett.* **2025**, *20*, 034042. https://doi.org/10.1088/1748-9326/adb766.

Zemp, D. C.; Schleussner, C.-F.; Barbosa, H. M. J.; Hirota, M.; Montade, V.; Sampaio, G.; Staal, A.; Wang-Erlandsson, L.; Rammig, A. Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nat. Commun.* **2017**, *8*, 14681. https://doi.org/10.1038/ncomms14681.

Zhao, H.; Klotzbach, P. J.; Chand, S. S.; Camargo, S. J.; Cao, J.; Wu, L. Decreasing global tropical cyclone frequency in CMIP6 historical simulations. *Sci. Adv.* **2024**, *10*, eadl2142. https://doi.org/10.1126/sciadv.adl2142.

Zhao, H.; Klotzbach, P. J.; Chand, S. S.; Camargo, S. J.; Chan, J. C. L.; Wu, L. Decreasing global tropical cyclone frequency in CMIP6 historical simulations. *Sci. Adv.* **2024**, *10*, eadl2142. https://doi.org/10.1126/sciadv.adl2142.

Zhong, Q. a; Gan, J.; Shi, D.; Tu, S.; Chan, J. C. L. Do Tropical Cyclones Have a Steady Translation Under a Uniform Steering Flow? *Geophys. Res. Lett.* **2026**, *53*, e2025GL119479. https://doi.org/10.1029/2025GL119479.

Zhong, Q. b; Gan, J.; Tu, S.; Toumi, R.; Chan, J. C. L. Global increase in rain rate of tropical cyclones prior to landfall. *Nat. Commun.* **2026**, *17*, 68070. https://doi.org/10.1038/s41467-025-68070-z.