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Theories for Past and Future Monsoon Rainfall Changes

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Abstract

Purpose of Review Long-standing biases in simulations of past and present climate states and climate model disagreement even in sign of future monsoon rainfall changes evince limitations in our theoretical understanding.

Recent Findings The dominant theoretical paradigms for understanding monsoon rainfall—convective-quasi equilibrium (CQE), the moist static energy (MSE) budget, and monsoons as local Intertropical Convergence Zone (ITCZ) shifts—all jettison the traditional "land-sea breeze" paradigm. Summer monsoon precipitation falls when the assumptions of CQE are most satisfied but those of the ITCZ shift framework are least satisfied. Zonal asymmetries, changes in ITCZ width and strength, hydrology-vegetation-CO_2 coupling, and timescale-dependent responses complicate inferences of monsoon rainfall from paleoclimate proxy records. The MSE budget framework applied to deliberately designed simulations can illuminate key mechanisms underlying monsoon responses to external forcings, presenting a path toward falsifying model projections.

Summary Sustained, rapid progress in monsoon rainfall theory is urgently needed by society and is plausible based on recent advances.

Keywords Monsoons · Convective quasi-equilibrium · Moist static energy · Intertropical convergence zone · Paleoclimate · Climate change

Introduction

Earth's monsoons generate rainfall relied upon by billions of people and countless ecosystems. This makes the societal and ecological implications of any changes in the monsoon potentially enormous; the Indian finance minister once deemed the Indian monsoon the country's "real finance minister" [1]. Yet, general circulation models (GCMs) exhibit pronounced biases in monsoon rainfall compared to modern observations in simulations of present day [2] and compared to proxy records in simulations of past paleoclimate states [3, 4]. And projections of future rainfall change in monsoon regions differ starkly across GCMs, as model- and region-dependent circulation changes [5] amplify or counteract simple thermodynamic scaling-paced changes driving the zonal-mean tropical precipitation response [6]. At a time when society demands actionable information to guide climate adaptation efforts, we remain unable to constrain even the sign of future precipitation change in any of Earth's monsoon regions, at least from GCM simulations alone.

Computing power that makes global, convection-resolving simulations routine—and thus problematic cumulus parameterizations obsolete—may one day greatly reduce model biases and future uncertainty [7•], but such an era remains years to decades away [8]. Some means of falsifying model projections is needed in the interim. Past warm states in Earth's history may provide useful lessons, but, at current levels of understanding, the paleoclimate record's ability to provide quantitative constraints is limited for reasons discussed further below. As such, I argue that improved theoretical understanding of monsoon rainfall responses to external forcings is vital. Only with such knowledge can we improve GCMs' representations of monsoons through better-informed model development and, given the models' current state, use physically based arguments such as emergent observational constraints [9] to narrow probability distributions for the future beyond

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whatever emerges from the CMIP (Coupled Model Intercomparison Project) archive.

Fortunately, our theoretical understanding of region-mean monsoon precipitation has improved markedly in recent decades. Three primary frameworks have emerged: convective quasi-equilibrium (CQE) [10–12], the moist static energy (MSE) budget [13–16], and monsoons as local manifestations of energetically forced shifts in the Intertropical Convergence Zone (ITCZ) [17•]. The ITCZ shift framework has become particularly popular, both for the zonal mean and increasingly as a basis for understanding zonally confined monsoons [17•]. Successfully adapting from the ITCZ to individual monsoons would be a tremendous accomplishment in terms of importance but also, I will argue, difficulty. Meanwhile, recent progress within the CQE and MSE frameworks has been no less brisk.

Here, I review recent advances in our theoretical understanding of forced monsoon rainfall changes based on these three frameworks. For brevity, I largely restrict attention to the region- and wet-season-mean scales—considering transients only insofar as they contribute to the mean state—at the expense of promising recent work on the theory of synoptic-scale monsoon phenomena [18, 19]. For each of the CQE, MSE, and ITCZ frameworks, I present their foundational ideas, recent success stories, and key limitations, and, for each limitation, encouraging results from recent studies or ideas for future work that could help resolve it. The MSE budget discussion includes an example of the MSE budget being used toward developing an emergent observational constraint on future rainfall change in the West African Monsoon. I then discuss the implications of recent studies on inferring past monsoon rainfall changes from paleoclimate proxy records and the constraints that they can place on future anthropogenically driven changes. Finally, a parting discussion reflects on how to make the theoretical community's work more societally useful.

Two prefatory points remain. First, none of the theories are consistent with the traditional view of monsoons as giant land-sea breezes fundamentally driven by land-sea contrasts in heat capacity and thus seasonal surface temperature evolution [20]. Monsoon-like overturning circulations can emerge in aquaplanet simulations with (sufficiently small) uniform surface heat capacity [21]. Surface thermal gradients usefully predict monsoon rainfall insofar as they are correlated with near-surface MSE (or, nearly equivalently, moist entropy or equivalent potential temperature). When relative humidity gradients are large, the dry and moist thermodynamic tracers decouple, and monsoon rainfall continues to track the moist tracer [12, 22]. Interannually, mean continental precipitation and surface temperature in each of Earth's major monsoon regions are *anti-correlated*: moisture delivered to the soil by rainfall promotes evapotranspiration at the expense of sensible heat flux, cooling the surface [23]. Over oceans, SST gradients are known to generate boundary layer convergence that drives convection [24–26], but the relevance of these circulations to continental monsoon rainfall is not obvious.

Second, our understanding of the dynamics (rather than thermodynamics or energetics) of monsoons has also improved markedly in the past decades [21, 27, 28]. While the classical angular momentum conserving model of the Hadley cells [29–31] and zonally confined monsoons [11, 32] usefully characterizes the core of the cross-equatorial, solstícial, zonal-mean overturning cells, otherwise the cells are strongly influenced by eddy stresses and do not homogenize angular momentum [28, 33–36]. During monsoon onset, the monsoonal cell rapidly transitions from the eddy-driven toward the classical regime, mediated by feedbacks from the mean flow and the rapid cessation of eddy stresses in the cell core [21, 27, 37–39]. Outstanding challenges for this framework include that cells regularly fall in an intermediate regime, neither purely angular momentum conserving nor purely eddy-dominated [34], and that zonally oriented circulations can alter the leading-order balances within zonally confined monsoons [40]. As regards monsoon rainfall, in what follows, I show several useful ways that these free tropospheric zonal momentum considerations have been combined with the other, more thermodynamically focused frameworks.

CQE: Convection-Driven Control of the Column by the Subcloud Layer

CQE is the state in which moist convection is sufficiently frequent and vigorous as to generate nearly moist adiabatic stratification, thereby prohibiting large time-mean values of convectively available potential energy. To a good approximation, a column's thermodynamic structure is then set entirely by its near-surface MSE (strictly speaking, its subcloud moist entropy, an unimportant distinction in the present context) [10], a vertical truncation that has become fundamental to our understanding of myriad phenomena of the tropical atmosphere [41] and of the idealized numerical models used to generate much of that understanding [42]. Most notably for monsoons, it requires that, provided vertical shear is weak, the summer edge of a cross-equatorial monsoonal cell be co-located with a local maximum in near-surface MSE [43], placing the monsoon rainbelt at or just equatorward thereof. Observational and reanalysis data confirm that the core summer monsoon rainbelts coincide with local maxima in boundary layer equivalent potential temperature and upper tropospheric temperature [12]. In a dry form, CQE also accounts for the shallow, dry circulations embedded (and acting to inhibit rainfall) within the deep, moist circulations in several monsoon regions, most notably the West African Monsoon [12, 44, 45].

Combining this general CQE assumption with the angular momentum conserving theory discussed above [10, 11] leads to the existence of a "critical" near-surface MSE field, i.e., that in gradient wind balance with an angular momentum conserving circulation (subject to the caveat that the coupling between the local boundary layer and free troposphere can be severed within a monsoon's descending branch if subsidence is sufficiently strong). In reality, angular momentum is never fully homogenized throughout a monsoonal or cross-equatorial Hadley cell, but it is often nearly so along the cell's individual streamlines within the free troposphere. Combined with the core CQE assumption, this requires that moist isentropes, angular momentum contours, and overturning cell streamlines all be parallel in the free troposphere [46]. Recently, Singh [47•] has used this state of "slantwise convective neutrality" to derive a scaling for the latitude of the cross-equatorial, solsticial Hadley cell's edge in the summer hemisphere. It generalizes the aforementioned diagnostic of Privé and Plumb [43] to cases with appreciable shear and is quantitatively accurate applied to simulations in an idealized aquaplanet GCM across which the planetary rotation rate is varied. How accurately the scaling characterizes Earth's Hadley cells and individual monsoons is an important outstanding question.

The scaling's major limitation is that it is diagnostic, requiring knowledge of the dynamically equilibrated temperature and near-surface MSE fields throughout the cell. A tempting means of generating a fully prognostic scaling (i.e., one requiring knowledge only of the hypothetical RCE state in the absence of any large-scale circulation) would be to replace the diagnosed near-surface MSE field with the critical analytical solution from CQE theory. But the critical MSE field is itself diagnostic, varying with the very cell edge latitude being sought. A potentially useful approach could be to apply the slantwise convective neutrality scaling to analytically [48] or empirically derived near-surface MSE profiles that reflect typical monsoon angular momentum distributions while remaining prognostic. Arguably, the simplest prognostic scaling comes from the well-known Hide's theorem, which requires neither slantwise neutrality nor exact angular momentum conservation, but strictly speaking it provides only a lower bound on the cell edge and is generally only qualitatively accurate as an actual predictor [29, 47•].

The MSE Budget: Leading-Order Balances to Identify Key Processes Limiting Monsoon Rainfall

The Framework, Its Successes, and Its Limitations

The thermodynamic equation of an atmospheric column can be usefully approximated as the column-integrated budget of MSE, $c_pT + gz + Lq$, the sum of sensible heat, gravitational potential energy, and latent heat. Conceptually, the budget states that the time tendency of column-integrated internal energy depends on the balance between net energetic input via top-of-atmosphere radiative fluxes, surface radiative fluxes, and surface latent and sensible heat fluxes on the one hand, and the column-integrated flux divergence of MSE by the atmospheric circulation on the other. Though not in itself a coherent theory for any particular circulation (it is an expression of physical laws that must be satisfied whether or not a monsoon is present), its value stems from how the relative magnitudes of its terms succinctly characterize the nature of local circulations. For example, it has been used to identify key mechanisms underpinning the response of tropical precipitation to El Niño [49], global warming [49, 50], and anthropogenic aerosols [51].

For monsoons, it has been used to identify key mechanisms limiting the poleward extent of monsoon rainfall [14–16]. Specifically, monsoon extent can be limited by high surface albedo that prevents large net energetic input into the column needed to drive deep moist convection (as for the bright Sahara Desert and the West African Monsoon), or promoted by orography that shields the monsoon from "ventilation"—the horizontal advection of low-MSE air into the monsoon region (as for the Tibetan Plateau and the Indian monsoon) [52]. In response to warming, monsoon rains are influenced by the famous "rich-get-richer" mechanism but also by the "upped-ante" mechanism, wherein prevailing moisture and MSE gradients are enhanced by the mean warming, which combined with prevailing inflow into convective regions directed up these gradients suppresses precipitation at convective zone margins [50].

A key limitation of the MSE budget framework is a technical one: diagnosing the various budget terms from model output or reanalysis data post hoc typically results in residuals larger than many of the actual budget terms, precluding meaningful quantitative (and sometimes even qualitative) analyses. Existing adjustment methods that empirically correct for these residuals can be difficult to implement and require onerous amounts of data [7•, 53, 54]. As has been known for years [55], this could be largely solved by models diagnosing the budget terms as they run, with column-integrated terms outputted as standard. Fortunately, some recent model development [56] and intercomparison [57] efforts have taken this to heart, hopefully spurring others to do likewise.

It is important to distinguish this framework from the energetic framework for ITCZ shifts to be discussed next. The MSE budget characterizes energetics locally and is typically expressed in terms of MSE flux divergences. The ITCZ shifts framework considers planetary-scale energy flows and integrates the column MSE budget zonally and meridionally in order to examine meridional MSE fluxes. Similarly, though the previous section described the CQE framework primarily in terms of near-surface MSE, the CQE assumptions are not made in MSE budget diagnoses generally, and CQE was originally derived and is most properly expressed in terms of moist entropy.

Case Study: Rainfall Change in the Sahel Driven by Mean SST Warming

This subsection details a recent success story of the MSE budget, wherein the framework is applied to targeted SST perturbation simulations in an atmospheric GCM (AGCM) in order to better understand anthropogenically forced rainfall changes in the Sahel, the northernmost region that receives appreciable rainfall from the West African Monsoon [7•, 58•].

Though coupled atmosphere-ocean GCMs forced with all of the likely changes to radiative forcing agents and other boundary conditions remain our best tool for projecting the climate's future, inferring mechanisms of any regional changes in such simulations is hindered by the myriad, confounding processes triggered by those forcings. Prescribed SST simulations can disentangle those factors by imposing only one at a time—although at the expense of breaking the coupling between the atmosphere and ocean, the importance of which for future tropical precipitation change remains debated [59]. The key forcings include those due to the coupled model's present-day SST biases [60, 61], the direct influence of altered radiative forcing [62], changes in the global-mean SST value [6], and changes in the spatial pattern of SSTs [63–66]. This procedure can be extended even further to isolate, e.g., the effect of plant physiological responses to CO_2 [67].

By diagnosing the MSE budget balances in uniform SST warming simulations, Hill et al. [7•] demonstrate that mean SST warming triggers the upped-ante mechanism for the Sahel by enhancing the meridional MSE gradient spanning from the Sahara Desert to the Gulf of Guinea; acted upon by prevailing northerlies, this inhibits Sahelian precipitation. This mechanism also acts in reverse for global-mean cooling, yielding increased Sahel rainfall. But in either case, the magnitude of the anomalous dry air advection and its downstream impacts on Sahel precipitation are sensitive to the convective parameterization, and as such vary in strength across AGCMs [58•].

Copious industrial sulfate aerosol emissions in the Northern Hemisphere during the twentieth century acted to cool the globe overall and the Northern Hemisphere relative to the Southern Hemisphere. A previous study [68] computed SST anomalies driven by this historical aerosol anthropogenic aerosol forcing as simulated by the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) AGCM AM2.1 [69, 70] coupled with a slab ocean [71], and then re-ran the AGCM with those SST anomalies added to an observational climatological SST field (preventing contamination from model-generated climatological SST biases) in three different ways: without modification, with their tropical mean value (− 1.1 K) applied at every ocean gridpoint, or with the tropical mean value subtracted from the full anomalies at each gridpoint (leaving the spatial pattern intact but with little mean change). Here, I analyze the precipitation response in July–August–September over northern Africa in the original experiments and repeated in two additional GFDL AGCMs, AM3 [72], and HiRAM [73]; see Fig. 1 of Hill et al. [68] for maps indicating the annual mean of the imposed SST perturbations in each case.

Figure 1 shows the precipitation responses in each simulation. In all three models, the spatial pattern component of relative Northern Hemisphere cooling and Southern Hemisphere warming acts to draw the Atlantic ITCZ and West African monsoon rainfall southward, resulting in widespread drying over the Sahel, consistent with expectations from the ITCZ shifts framework to be discussed in the next section [74]. Mean SST cooling, meanwhile, triggers the (reversed) upped-ante mechanism, but its differing strength across the models results in widely varying precipitation responses, from strong Sahel wettening in AM2.1 to little coherent response in HiRAM [58•, 75]. As such, in response to the full aerosol SST anomalies, only in AM2.1 does the mean-driven wettening win out over the pattern-driven drying, so that Sahel precipitation actually increases appreciably, adjacent to strong drying in the Atlantic ITCZ.

In short, with knowledge of the Sahara-driven mechanism for Sahel wettening with mean cooling (which is ill-suited for interpretation via the CQE or ITCZ shifts frameworks), its differing magnitude across models, and the SST spatial pattern's drying influence (which, conversely, does naturally adhere to the ITCZ shifts framework), the disparate model responses to the full aerosol SST pattern are readily understood.

But which, if any, of these three differing model responses should we believe? The upped-ante mechanism of Sahel drying with mean SST warming has the potential to generate an emergent observational constraint, as follows. If the enhancement of dry Saharan air advection scales with the climatological convective depth in the Sahel (on the grounds that deeper convection will more effectively moisten and warm the region in the column integral relative to the Sahara than would shallow convection), then we should discount those models with convective depths much shallower or much deeper than the observational value. Indeed, AM2.1 has a very top-heavy ascent profile in the Sahel compared to observations and most other AGCMs [58•]. Although various complications precluded developing a definitive formal emergent constraint in this case [9, 58•], this seems like a useful methodological template for future work toward developing emergent constraints for other regions and/or based on other physical mechanisms.

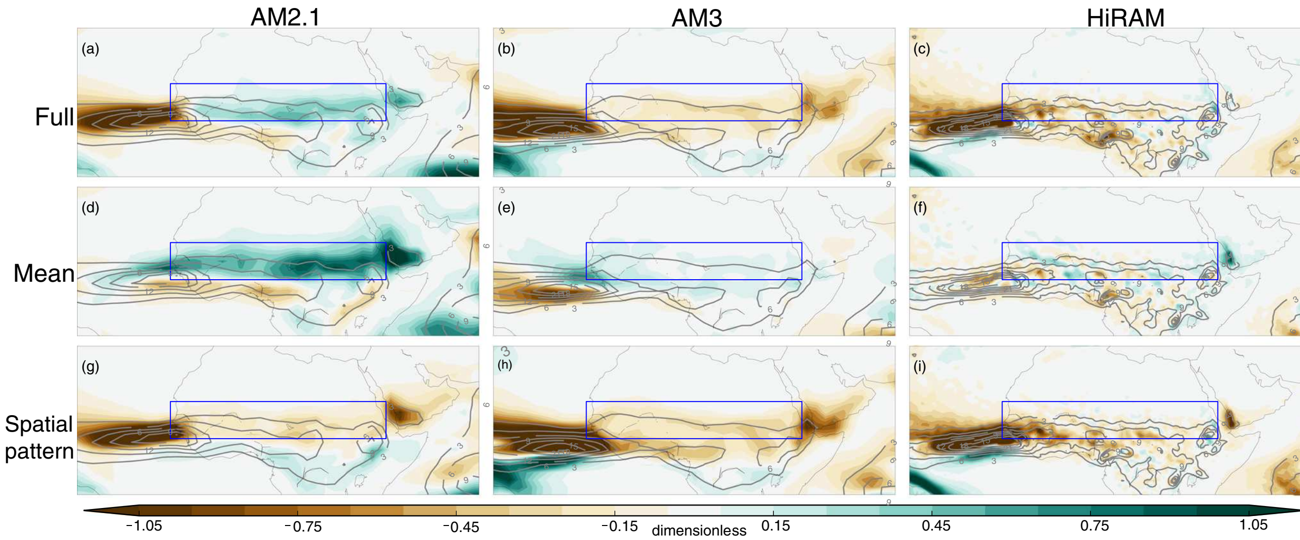

Fig. 1 July–August–September precipitation response in (left) AM2.1, (center) AM3, and (right) HiRAM to the (top row) full, (middle row) mean, and (bottom row) spatial pattern components of the SST anomalies due to historical anthropogenic aerosol emissions. Precipitation is normalized by the control simulation Sahel region-mean JAS value in each model, with the region boundaries shown as the blue box. Overlaid gray contours show the control simulation precipitation, with 3 mm/day contour spacing

ITCZ Shifts: Monsoons as Regional Manifestation of Energetically Driven Rainbelt Migrations

The precipitation in the zonal-mean ITCZ is the hydrological imprint of the ascending branch of the zonal-mean Hadley cells. In the simplest picture, the ITCZ is co-located with the zero crossing of the total atmospheric energy transport as well as the shared inner edge of the two Hadley cells. That ascending branch, and with it ITCZ rainfall, can migrate north and south in response to hemispherically asymmetric forcings, such as when the ITCZ "follows the sun" over the annual cycle. In the annual mean, forcings with appreciable meridional structure can also move the ITCZ, as has been posited for historical anthropogenic aerosol emissions and the growth and retreat of high-latitude ice sheets [76–80].

More recently, Bischoff and Schneider have developed a formalism yielding a quantitative prediction for ITCZ shifts and double ITCZ states based on anomalous cross-equatorial energy transport and the net energy input at the equator [81–84]. Other studies have documented the often leading-order role played by processes the framework initially neglected, including Ekman-driven coupling with shallow ocean heat transports [85–87], interactions with the deep ocean meridional overturning circulation [88], radiative feedbacks from clouds [89] and water vapor [90] that attend ITCZ shifts, and the propensity for changes in ITCZ width and strength in addition to position [91•]. Recent work has even implicated the ITCZ's position [92] and width [93] as influencing the poleward extent of the Hadley cells' *descending* branch based on the notion that the cells nearly conserve angular momentum until they are truncated by the onset of baroclinic instability [94, 95]. Finally, the framework has recently been used to identify several otherwise-unintuitive predictors of the infamous "double ITCZ" bias [2], include biases in land surface albedo [96] and temperature [97], biases in cloud cover over the Southern Ocean [98], and values of tropical surface energy fluxes in prescribed SST AMIP simulations [99].

These ITCZ arguments bear on individual monsoons insofar as the local precipitation closely follows that of the zonal-mean, but this is not always the case. Pairs of GCM simulations exhibiting identical changes in cross-equatorial energy transport or in the position of the ITCZ can exhibit drastically different precipitation responses within different monsoon sectors [66]. And the Atlantic ITCZ and adjacent West African Monsoon precipitation can respond with opposite sign to precessional orbital forcing [100, 101]. As such, the energetic shifts framework must incorporate zonally asymmetric processes. This has led to recent work incorporating zonally confined meridional MSE transports and precipitation shifts [84] and zonally oriented transports and precipitation shifts [102] into the framework.

As is often true of the original, zonal-mean version, results from these initial studies largely indicate qualitative, but not quantitative, utility of the theory. Accordingly, the remainder of this section considers several possible refinements. To be of value for monsoon rainfall, those couched in terms of the zonal-mean framework will ultimately need to be investigated as applied to zonally confined monsoons as well.

Seasonality Mismatch Between ITCZ Energetic Framework Accuracy and Monsoon Rainfall

The ITCZ, energy flux equator, and the Hadley cells' shared inner edge are all nearly co-located under equinoctial and annual-mean conditions, but they separate during solsticial seasons, with the core ITCZ precipitation moving equatorward of both the energy flux equator and the boundary between the cross-equatorial winter cell and the weak summer cell [103]. Meanwhile, monsoon rain falls predominantly during local summer—i.e., precisely when the assumptions underlying the ITCZ shifts framework are least satisfied! A pressing need, therefore, is to determine how useful the shifts framework is in a perturbative sense (which only requires that the various metrics be well correlated, rather than coincident) despite its relative inadequacy for the unperturbed solsticial state. For starters, linearizations of the ITCZ position need be performed about the unperturbed energy flux equator, not the geographic equator [104].

To address this, one could start by applying hemispherically asymmetric extratropical forcing as standard [105] in simulations with insolation set to either its annual mean, perpetual solstice, or the full annual cycle. In perpetual solstice simulations, though insolation and (at least on aquaplanets) MSE both maximize at the summer pole, dynamical constraints prevent the tropical rainbelts from extending much beyond their maximal extent with a real seasonal cycle [29, 47•, 106].

The ITCZ energetic framework is agnostic regarding the Hadley cells' dynamical regime: whether the cells are angular momentum conserving or eddy-dominated is immaterial so long as the ITCZ, energy flux equator, and cell edge are well correlated. At the same time, the aforementioned slantwise neutrality metric and other recent work invoking angular momentum-related arguments place limits on the poleward edge of the Hadley cells in the summer hemisphere [29, 47•, 106]. Any such constraint on the cell's overall poleward edge in turn places an upper bound on the poleward extent of the ITCZ: provided the summer Hadley cell is negligible relative to the cross-equatorial cell (as often occurs under solsticial forcing), the ITCZ cannot sit poleward of where the cross-equatorial cell terminates. For example, relative warming of the summer hemisphere may shift the ITCZ less far poleward than identical but opposite signed forcing shifts the ITCZ equatorward. This could also be informed by recent work on the boundary layer momentum dynamics of ITCZ excursions [106–108].

On the Context Dependence and Relationship to Seasonality of the ITCZ-Cross Equatorial Energy Flux Slope

The regression of the zonal-mean ITCZ position on cross-equatorial atmospheric energy fluxes has been diagnosed in several contexts including the seasonal cycle to be approximately 3° PW^{-1} [77], leading to two claims that increasingly appear problematic. The first is that this 3° PW^{-1} slope is effectively invariant across climate states [103]. However, large [i.e., O [1]] differences between the slope during the seasonal cycle and in the annual mean response to external forcings emerge in some GCMs [109•]. Moreover, the aforementioned Bischoff and Schneider formalism—arguably the closest we have to a closed theory for the ITCZ position—suggests that this slope varies inversely with the equatorial net energetic input [81], which is known to vary on various timescales, e.g., interannually between El Niño and La Niña years [83].

The second claim is that the slope is fundamentally determined by the seasonal cycle: because the annual mean ITCZ position reflects the residual of large seasonal swings into either hemisphere, annual mean shifts also must follow this slope [103]. However, as just noted, the annual cycle and annual mean slopes can in fact differ appreciably in GCMs. And ITCZ shifts in simulations perturbed with asymmetric forcings but lacking a seasonal cycle—which arguably constitutes the bulk of theoretical studies on the topic to date—do not obviously differ from those with seasonal cycles.

Nevertheless, a related claim—that future annual-mean ITCZ shifts are bound to be weak (i.e., $< 1°$)—is indeed plausible [103]. Barring some forcing or radiative feedback process that is far more hemispherically asymmetric than anticipated or is not currently represented, anomalous low-latitude energy fluxes will likely be much less than 1 PW in the coming century. Meanwhile, although the 3° PW^{-1} value can vary, there is no argument or simulation suggesting that it will increase in magnitude by several multiples. This may not usefully constrain shifts of any individual monsoon rainbelt; however, as the solsticial, zonally confined circulation may have a different slope than the annual- and zonal-mean.

Role of Hadley Cell Gross Moist Stability and Eddy MSE Fluxes in the ITCZ Shifts Framework

The coupling of movements in the ITCZ location, energy flux equator, and Hadley cell edge hinges on anomalous energy fluxes by the Hadley cells dominating over anomalous eddy energy fluxes (or at least the two being well correlated), as well as on the anomalous Hadley cell energy fluxes in the vicinity of the ITCZ being effected predominantly by changes in the mass overturning strength rather than in the efficiency of energy transport per unit mass overturning, i.e., the Hadley cell gross moist stability (GMS) [68, 110, 111]. Otherwise, the ITCZ and energy flux equator can separate, as can occur during monsoon retreat with the two features sitting in opposite hemispheres [112]. And simulations of the mid-Holocene and other states exist in which, even absent the complications of ocean dynamical coupling, the zonal-mean ITCZ responds to asymmetric forcing counter to expectations due either to changes in GMS [100, 111] or eddy MSE fluxes [113].

Though GMS is often usefully approximated as the difference between upper- and lower-level MSE values (under the assumption that flow is concentrated into one narrow layer with each branch, each with a single representative MSE value), the actual GMS value can be sensitive to the vertical profile of the cell's meridional flow, for example decreasing the more the upper-branch flow is spread toward the mid-troposphere where MSE in the tropics is generally smallest [112]. As such, a potentially useful approach could be a three-layer conceptual model in which the upper branch flow is partitioned between upper- and mid-troposphere layers according to, e.g., the meridional Laplacian of SSTs, motivated by the propensity for sharp SST gradients to generate shallow circulations embedded within the larger cell [24, 25, 112, 114].

The roles of GMS and eddies are, in fact, related, with all else equal the eddy energy fluxes increasing in magnitude the smaller GMS is. Annual-mean GMS decreases in the deep tropics in an idealized aquaplanet GCM when the convective parameterization is made less active [115]; it becomes negative when the parameterization is turned off entirely, meaning that the Hadley cells *converge* energy into the equatorial region, to be transported away be eddies. This modulation of GMS through the convection scheme could be exploited via experiments imposing the canonical asymmetric extratropical forcings [105] to mean states with GMS values from strongly positive to negative, to see how strongly the ITCZ response is affected.

Perhaps the simplest approach to incorporating transient eddy MSE fluxes into the energetic framework would be through a simple down-gradient diffusive approximation as is standard in other contexts and appears to be reasonably accurate in reanalysis data for various monsoon regions [44]. Separately, one could apply the well-known phase speed-wavenumber spectral decomposition of equatorial variability [116] to meridional energy transports; knowing, e.g., the relative contributions of equatorial Rossby waves vs. the MJO to energy export out of the deep tropics (especially during solsticial seasons) could advance our mechanistic understanding of the mean state, differences across models [consider that the widely used Frierson idealized GCM's equatorial wave spectra is, unlike observations, dominated by Kelvin waves [117]], and the response to forcing, the latter perhaps akin to how changes in the phase-speed spectra of extratropical waves have been linked to Hadley cell expansion with warming [118]. For the monsoons, this could also be informed by the recent theoretical studies of monsoon intraseasonal variability mentioned in the Introduction [18, 19].

On Past Monsoon Rainfall Behavior and Interpretations of Paleoclimate Proxy Records

This section considers challenges in inferring monsoon rainfall changes from paleoclimate proxy records and, in turn, using those inferences to constrain future changes. Some stem directly from the monsoon theoretical frameworks. Others are more general, but their relevance to monsoons, I contend, bears discussion.

Distinguishing among Local Monsoon Behavior and Zonal-Mean Change Modes

On the one hand, aforementioned results [100, 109•] imply that the rainfall signal recorded by any individual point proxy record in a monsoon region need not reflect the zonal-mean ITCZ behavior. And, even if no zonal asymmetries existed, the propensity for the ITCZ to vary in width and strength in addition to position [91•] complicates interpretations of proxy records. Simultaneous changes in ITCZ position, width, and intensity could largely cancel one another—or, conversely, could all contribute with the same sign—in terms of the local precipitation change recorded at a single point proxy record, in either case leading to an incorrect inference if interpreted purely as a shift. Separately, ITCZ shifts are often computed as changes in the centroid or some other median-like quantity of the zonal-mean precipitation distribution. This requires knowledge of precipitation over the entire tropics, a tall order for past paleoclimate states [109•].

On the other hand, a recent simple model of zonal-mean tropical precipitation responses to orbital variations based on the ITCZ shifts framework is remarkably accurate at the obliquity and precessional timescales in reproducing rainfall proxy records at selected individual tropical sites at different latitudes [119•]. It would be useful to compare this model to proxies for sites at the same latitude but different longitudes, with mutually shared signals likely reflecting zonally symmetric influences and discrepancies reflecting zonally asymmetric processes. Similarly, it could be compared to precipitation at different sites in long-running simulations in intermediate complexity GCMs, removing the uncertainties stemming from the proxy records themselves (at the expense of cruder and potentially errant simulated physics). Finally, the model could be readily modified in order to account for seasonal ITCZ width variations (which it currently neglects) and the ITCZ's tendency (at least in Earth's recent history) to be north of the equator because of northward ocean heat transport [88].

Interpreting Abrupt Shifts in Point Records Given Sharp Spatial Rainfall Gradients

Many published interpretations of paleoclimate monsoon rainfall records conclude that past rainfall changes have been abrupt, often with the implication that future changes will be as well. However, as has been pointed out, a locally abrupt change in precipitation could result from gradual changes in a monsoon rainbelt, given the latter's often sharp spatial gradients [120]. And a recent study demonstrates that "tipping points" and other nonlinear responses of monsoon rainfall inferred from simple theoretical models are based on questionable assumptions and do not emerge in GCM simulations subject to a range of forcings well beyond any likely in recent or coming centuries [121•].

A potentially useful approach would be to construct a toy model of paleoclimate proxy records, starting with, e.g., a single point measurement that perfectly records annual mean precipitation subject to a local rainbelt of fixed shape and sinusoidal seasonal migrations. The complicating factors of noise, a spatially aggregated signal, sampling bias, multiple records, more complex annual cycles of the rainbelt position, and secular changes representing, e.g., orbital forcing or zonal migrations could be progressively introduced, and the ability to detect the rapidity of changes in monsoon rainfall could be assessed. This could also assist with the aforementioned need to disentangle changes in width, strength, and position.

Coupling Among Hydrology, CO_2, Vegetation, Temperature, and Albedo on Land

For the oceans, the saturated surface makes standard bulk aerodynamic formulas adequate for computing evaporation and the sensible heat flux; for land, a complex interplay exists among the supply of moisture by precipitation, the soil's ability to absorb that water, the partitioning of the resulting soil moisture into direct evaporation and into transpiration by plants, the vertical distribution of water within the soil, and the surface energy balance. Moreover, stomatal closure by plants (which acts to decrease transpiration) with increasing CO_2 can lead to divergent responses of soil moisture and vegetation growth under CO_2-driven climate change [122•]. As summarized by a recent series of literature reviews [123–125], this can lead to offline diagnostics such as the aridity index, Palmer Drought Severity Index, and the Penman-Monteith computation of potential evapotranspiration falsely indicating drought when in fact photosynthesis and runoff are enhanced. Fortunately, simple time-mean precipitation tends to be a useful predictor of the more directly impacts-related fields of runoff and photosynthesis [122•]. Nevertheless, the monsoon community should recognize this potential for hydroclimatic indicators to diverge, particularly under large CO_2 changes such as glacial-interglacial variations and future anthropogenic warming.

A further complication comes from the coupling of vegetation cover with surface albedo. Plants tend to be darker than the soil they grow over, such that the more insolation is absorbed, the more plants grow. This is thought to have figured centrally in the Green Sahara paleoclimate state of the Holocene, wherein the West African Monsoon rainfall expanded far north into what is now the Sahara desert. In this view, orbital precession enhanced boreal summer insolation, pushing the monsoon rains slightly farther northward, bringing with them enhanced vegetation growth, increasing the column absorbed shortwave radiation, and thus further enhancing the monsoon (along with other, non-albedo-mediated positive feedbacks from soil hydrology) [3]. However, GCMs with dynamic vegetation models typically strongly underestimate the northward expansion of vegetation cover and of West African Monsoon rainfall into the Sahara. As such, one potential means of progress would be to introduce simple vegetation-dependent surface albedo formulations in simpler models [126], including idealized GCMs and diffusive moist energy balance models that include simple parameterizations of moisture fluxes by meridional overturning cells [127].

Interpretation of Paleoclimate Analogs Given Long Equilibration Times of Deep Ocean

Past warm states in Earth's history such as the Pliocene have become increasingly of interest as potential "analogs" to future warming. However, some proxy records arguably reflect near-equilibrium conditions [128], which reflects the deep ocean's response that takes millennia and need not even be temporally monotonic: surface warming initially slows the Atlantic Meridional Overturning Circulation (AMOC), but after multiple millennia the AMOC can ultimately be enhanced [128] or weakened [129] and/or a Pacific Meridional Overturning Circulation (PMOC) generated [129]. PMOC or no, the concurrent slow release of heat from the deep ocean increases polar amplification of the initial warming signal. Both the AMOC [130] and polar amplified warming [131] have been argued to influence West African Monsoon rainfall, and other monsoons may well be impacted also. Therefore, past climate states as recorded in proxies may have only limited relevance as analogs for monsoon behavior in coming decades and maybe even centuries [132].

Conclusions

Recent work at the nexus of social science and climate science suggests that the standard probabilistic framework to future uncertainty may not provide much actionable information for stakeholders; this could be ameliorated via a "storylines" approach in which a discrete number plausible outcomes are analyzed in detail [133]. By no means should all theorists be compelled to engage directly with the public in this way. But being more reflective about our motivations—and about the research tools and frameworks that most effectively address those motivations—stands to accelerate the community's already rapid progress. This review has attempted to promote that progress by highlighting important outstanding theoretical challenges in forced monsoon precipitation and their potential solutions.

A theorist espousing the societal value of theory may arouse skepticism, but already the advances in understanding described above are being used to improve CMIP-class GCMs: aforementioned predictors of the double ITCZ bias based on the ITCZ shifts framework have informed model development and tuning of the newest NOAA GFDL atmospheric GCM, AM4, leading to substantial reductions in the double ITCZ bias and Southern Ocean cloud albedo biases in AMIP simulations [134]. Results such as these should bolster our commitment to improving our theoretical understanding of monsoon rainfall and its responses to climate changes past and future.

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Compliance with Ethical Standards

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