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Article

The Interaction between Moist Convection and the Atmospheric Circulation in the Tropics

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ABSTRACT: Theories of the interaction between moist convection and the atmospheric circulation in the tropics are reviewed. Two main schools of thought are highlighted: (i) one that emphasizes the lower-level control of convection through moisture convergence and variations in convective inhibition, and (ii) one that sees convection as an adjustment process in reaction to larger-scale instabilities, referred to as convective quasi-equilibrium theory. Conceptually the two views consider moist convection to have fundamentally different roles in the tropical circulation. In one case the presence of low-level inhibition and the conditional nature of the atmospheric instability allows for convective vertical motion and latent heating to drive and reinforce synoptic-scale disturbances and overturning circulations; in the other case, because low-level inhibition is not acknowledged to be a widespread controlling barrier, convection is believed to balance and dampen vertical instabilities at the rate they are created by larger-scale processes over the vertical extent of the atmosphere. More recently, investigations of the moisture dynamics surrounding organized convective structures have led to an emerging consensus on the theory of convection–circulation coupling in the tropics that acknowledges the important role of lower- to midtropospheric moisture variations, and the significance of moist convection and convective clouds for initiating and establishing circulations. However, the implementation of these new insights in numerical models lags behind. This is exemplified by the apparent inadequacy of climate models to correctly represent decadal variability in the tropical Pacific, a fact that potentially has implications for the confidence in climate change projections based on such models.

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Convection–circulation interaction sets the tone in the tropics

The interaction between moist convection and the atmospheric circulation in the tropics takes place on a large range of scales, from the mesoscale dynamics of organized convective systems (Houze 1977; Houze and Betts 1981; Hartmann et al. 1984; Houze 1989, 2004), to synoptic-scale tropical disturbances like convectively coupled waves (Riehl 1945; Reed and Recker 1971; Lau and Lau 1990), and large-scale overturning cells such as the Hadley and Walker circulations (Bjerknes 1969; Held and Hou 1980). Conceptually the problem of the interaction between moist convection and the atmospheric circulation can be broken down into two questions: how and to what extent does the atmospheric circulation govern convective development, and vice versa, in what way does moist convection impact and feed back onto the circulation. A complete theory about tropical convection–circulation coupling comprises both of these aspects.

A certain view on the interaction between moist convection and the circulation is still widespread in textbooks and tacitly underlies many studies, the idea that latent heat release and vertical motion from convection reinforces and energizes phenomena such as tropical cyclones and waves, and drives larger-scale circulations in the absence of baroclinic instability in the tropics. This theory is usually associated with the concept that convection is mainly controlled by low-level atmospheric circulation regimes through moisture convergence and related changes to convective inhibition.

However, maybe somewhat surprisingly, the prevailing paradigm for tropical convection–circulation coupling in the research community over the last 25 years or so has been quite different: in the so-called convective quasi-equilibrium theory,[1] convection is considered to be an adjustment process that removes instability created by larger scales over relatively short time periods and thus dampens circulations. In this conceptual framework, convection is typically considered to be governed by a vertically integrated measure of atmospheric instability. This instability is supposed to be generated by larger-scale processes and approximately balanced by moist convection, since lower-level inhibition is not considered to be an obstacle to this process in most parts of the globe.

In both views, low-level moist static energy anomalies play an important role, and so in the present article the exact distinction between the two theories will be clarified. Not all scientific studies related to convection–circulation coupling can be categorized as falling either under one or the other of the two aforementioned ways of thinking, and the present article includes aspects of the problem that cannot be unequivocally attributed to either of two perspectives. Nevertheless, the two contrasting views serve as a common thread that helps to put other elements and approaches into context.

To better understand the background of the two schools of thought, the topic is first presented according to the historical course of the debate. Then a few basic features of the tropical atmosphere are discussed in more detail such as the climatological precipitation distribution. In a separate section the conceptualization of the tropical atmosphere as a radiative–convective equilibrium state, and the underlying view of the role of convection, are discussed. Finally, decadal variability in the tropical Pacific, and the difficulty of current global climate models to represent the observed decadal trends, are reconsidered. The importance of convection–circulation coupling for climate variability and climate change is highlighted from a conceptual perspective in this example. A discussion that contains an outlook toward an emerging consensus on the interaction between moist convection and the atmospheric circulation in the tropics, which emphasizes the role of lower- to midtropospheric moisture dynamics, concludes the article.

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[1] A more detailed discussion of the term *quasi equilibrium* can be found in Plant and Yano (2016). Here the concept is used as described in the text and is not supposed to imply any other meaning.

A historical perspective

The subject of convection–circulation interaction in the tropics is first reviewed following the historical development of the main theories. This allows for better understanding about the meteorological situations and observational data on which the concepts were based, and for appreciating the context of the debate.

The dawn of tropical meteorology and the debate. Hadley (1735) recognized the pivotal role of convection for the tropical circulation in his theory of what is now known as the Hadley circulation. According to Hadley, the circulation is driven by solar heating near the surface, which is strongest near the equator. As a consequence, the warm air becomes less dense and rises. Due to mass and angular momentum conservation the air subsides again farther away from the equator.

Tropical cyclones are such an impressive phenomenon that they were some of the earliest subjects of studies in tropical meteorology (e.g., Shaw 1922; Haurwitz 1935; Durst and Sutcliffe 2007). These early works recognized vertical instability and motion, that is, convection, as part of the structure of the revolving storms.

Although African easterly waves were first discovered by German meteorologists (Regula 1936; Piersig 1944), it became clear that they are related to tropical cyclones in the Atlantic (Hubert 1939), a circumstance that soon sparked the interest of American meteorologists (Dunn 1940).

Herbert Riehl studied easterly waves, based on Dunn's groundwork, when researching at the Institute of Tropical Meteorology at Rio Piedras in Costa Rica. Riehl recognized that areas of convergence and divergence as well as diabatic heating and evaporative cooling are central features of the waves (Riehl 1945). Riehl's influential book on tropical meteorology (Riehl 1954) summarized his insights into the interaction between moist convection and the atmospheric circulation in the tropics at that time. Although Riehl did not develop a comprehensive theory of the interaction between moist convection and the circulation in the tropics, in the longest chapter of the book, the chapter on tropical storms, he adopts the view that latent heat release from condensation drives the dynamics of the storm. The tropical storm is compared to a heat engine in which the energy input from convective latent heating is converted into the kinetic energy of winds.

Thus, the coupling of moist convection and the circulation is an intrinsic part of some of the most fundamental phenomena in tropical meteorology such as large-scale overturning circulations (Hadley and Walker circulation), tropical cyclones, and easterly waves, and the debate about convection–circulation interaction took its course starting from detailed studies of these features.

CISK and the role of moisture convergence. In Charney (1963) Riehl's book is cited, and tropical depressions like those resulting from easterly waves were considered to be a model for the tropical circulation as a whole. Charney and Eliassen (1964) proposed a theory of the interaction between moist convection and the circulation in tropical depressions and termed the mechanism "convective instability of the second kind" (CISK), also independently put forward by Ooyama (1964). CISK emphasizes the role of low-level moisture convergence in triggering and governing convection by suggesting that the rate of latent heat release in deep convective clouds is proportional to the convergence of moisture in the boundary layer. The crucial role of moisture convergence in CISK is related to the assumption that moist convection develops in an atmosphere characterized by conditional instability. The low-level moisture dynamics allows for convection to break through a lower-tropospheric level of convective inhibition, either because of changes in the thermodynamic structure of the lower troposphere or by mechanical uplift. Emanuel et al. (1994) give an excellent and concise summary of the

CISK perspective: “By preventing the spontaneous release of APE [available potential energy], it [convective inhibition] permits the latter to accumulate under certain conditions. When this happens, the problem of predicting convection and of relating it to large-scale flows is largely one of predicting when and where the convective inhibition will disappear, or when some turbulent or mechanical process will provide enough energy to conditionally unstable parcels to overcome the potential barrier to convection. Once triggered, the convection can reach great intensity and, potentially, can act as an energy source for large scales of motion.”

Indeed, a key aspect of the theory is the idea that deep convection reinforces disturbances such as hurricanes and tropical waves in that the buoyancy force and temperature anomalies due to latent heat release associated with moist convection cause the vorticity of the disturbance to intensify, which in turn increases low-level moisture convergence (mainly through Ekman pumping and enhanced moisture transport from moisture-abundant regions) and convection (Smith 1997). Charney and Eliassen (1964) write: “The cumulus- and cyclone-scale are thus to be regarded as cooperating rather than competing—the clouds supplying latent heat energy to the cyclone, and the cyclone supplying the fuel, in the form of moisture, to the clouds.”

Under the influence of CISK a number of convection parameterizations in numerical models were based on the assumption that moist convection in the tropics is mainly governed by low-level moisture convergence (Kuo 1965, 1974; Lindzen 1988; Tiedtke 1989). These authors cited studies such as Riehl (1950), Riehl and Malkus (1958), and Riehl and Malkus (1961), or work on easterly waves like Reed and Recker (1971) as evidence.

Convective adjustment and convective quasi equilibrium. Emanuel et al. (1994) vividly criticized Charney and Eliassen’s conceptual view and called it an “influential and lengthy dead-end road in atmospheric science.” They argued that moist convection requires instability and should be regarded as a process of adjustment in which “the production of available energy for convection by large-scale processes approximately balances its dissipation by convection,” essentially assuming that convective adjustment occurs on time scales shorter than the time scales of the larger-scale processes, as suggested earlier by Arakawa and Schubert (1974). Emanuel et al. (1994) refer to the observation that in tropical cyclones, convection acts to rapidly adjust the atmospheric state toward a moist adiabatic profile. The fast removal of atmospheric instability by convection assumes that there is no low-level barrier to this process. Emanuel et al. (1994) argue that “the unambiguous existence of conditionally unstable soundings has only been rigorously established in a few continental areas, especially in North America where much of the research on severe convective storms has originated.” They conclude that mean ascent in the tropical atmosphere mainly occurs within small-scale convective clouds, and that away from convection, vertical motion is governed by clear-sky radiative cooling and atmospheric stability, both of which are assumed not to be substantially affected by moist convection, an important assumption discussed in more detail below. Consequently, because convection does not drive circulations in this view, there is considered to be limited feedback of convection onto the sub-cloud-layer entropy (except through the secondary effect of convective downdrafts) and subsequent convective development via the atmospheric circulation.

The fundamental importance of the quasi-equilibrium view as formulated by Emanuel et al. (1994) lies in the fact that it basically implies, at least from a conceptual point of view, that convective latent heating does not reinforce, but dampens larger-scale atmospheric circulations. In the abstract of Emanuel et al. (1994) it reads: “We argue that the direct effect of convection on large-scale circulations is to reduce by roughly an order of magnitude the effective static stability felt by such circulations, and to damp all of them.” They also suggested that convection has a damping effect on tropical waves. The overall damping effect of moist convection on atmospheric circulations is termed “moist convective damping.”

In 1994 the European Centre for Medium-Range Weather Forecasts (ECMWF) changed the closure assumption in their convection parameterization from a moisture convergence (Tiedtke 1989) to a convective available potential energy (CAPE) closure (Nordeng 1994). Most weather and climate models to date employ convection parameterizations that are notionally based on a quasi-equilibrium view and implicitly consider convection as an adjustment process that consumes CAPE in reaction to larger-scale instabilities. In the fifth phase of the Coupled Model Intercomparison Project (CMIP5) the following models, and variants thereof, were based on a CAPE, or similar convective adjustment, closure: HadGEM, MPI-ESM, CCSM, CESM, LMDZ5A, CanCM, ACCESS, CMCC-CM, NorESM, GISS, EC-EARTH, BCC_CSM.

Emanuel et al. (1994) were not the first to consider moist convection as an adjustment process, but their discussion of the subject is the most comprehensive exploration of the implications of this view for convection–circulation coupling. The idea goes back to Manabe et al. (1965), and was used as a guiding principle in convection parameterizations for instance by Arakawa and Schubert (1974) and Betts (1986).

Beyond convective quasi equilibrium. CISK does not suggest that convection occurs without instability being present (Smith 1997). The central difference between CISK and the quasi-equilibrium view is that in CISK convection is controlled by lower-level instability and inhibition, whereas in the quasi-equilibrium view moist convection is governed by a vertically integrated measure of instability and is considered to adjust the entire atmospheric profile in response to larger-scale processes (Mapes 1997). Because in the convective quasi-equilibrium view, conditional instability (and the implied low-level convective inhibition) is considered to be overall less important, the build-up and release of available potential energy, controlled by lower-level tropospheric processes, is not acknowledged to be a control and driver of atmospheric circulations. Instead, vertically integrated convectively available potential energy generated by large-scale forcing is assumed to be consumed by moist convection subject to an adjustment time scale, thus damping circulations fueled by vertical static instabilities.

Stevens et al. (1997) noted that “the view of convection as a source of kinetic energy for large-scale disturbances has an observational basis.” Stevens et al. (1997) refer to observational evidence that latent heating from moist convection is positively correlated with temperature anomalies in the tropical Pacific, implying that convection does not simply adjust in response to instabilities, but can instead create available potential energy and drive circulations.

Implicit in the quasi-equilibrium theory is the assumption that convective adjustment occurs on time scales that are short compared to the time scales involved in larger-scale circulations that the adjustment feeds back on. This supposition is not necessarily true in the case when convection exhibits organization and therefore involves longer time scales (Jones and Randall 2011). Moreover, the quasi-equilibrium theory basically presumes that deep convection induces the lower-tropospheric convergence required to maintain a sufficient moisture supply for further convection, a presumption that is particularly problematic over land and had been questioned in previous studies (Schneider and Lindzen 1977; Schneider 1977; Stevens et al. 1977; Stevens and Lindzen 1978).

More recently, the quasi-equilibrium paradigm has come under scrutiny in additional ways. One starting point is the observation that precipitation in the tropics is relatively closely tied to vertically integrated column water vapor (Bretherton et al. 2004; Neelin et al. 2009). This per se does not contradict a quasi-equilibrium assumption, but closer investigations suggested that the connection between the boundary layer and the free troposphere is imperfect, and that free-tropospheric moisture is important to buoyancy (Derbyshire et al. 2004; Neelin et al. 2009; Raymond and Herman 2011).

Detailed analysis of mesoscale convective systems in African easterly waves have clearly demonstrated that moist convection sustains and intensifies the disturbances (Berry and Thorncroft 2005, 2012; Tomassini et al. 2017), contrary to the idea of "moist convective damping" suggested by Emanuel et al. (1994). In low-level cold-core easterly waves over the Sahel, lower-tropospheric moisture is the main factor that creates the instability necessary for convection to develop and organize at and ahead of the wave trough, and feed back into the dynamics of the wave (Tomassini et al. 2017; Tomassini 2018).

In conjunction with the renewed interest in the theory of convection–circulation coupling, over recent years efforts have been stepped up in the development of new convective parameterizations in numerical models (e.g., Arakawa 2004; Holloway et al. 2014). New closure assumptions have been proposed, some of which go back to emphasizing the lower-tropospheric control of moist convection such as closures based on boundary layer convective inhibition (Fletcher and Bretherton 2010) or the mesoscale organized flow within the planetary boundary layer (Rio et al. 2009; Park 2014). This is built on the idea that low-level convective inhibition is not only controlled by larger-scale moisture convergence, but by local dynamical and thermodynamical boundary layer processes, such as cold pools, as well (Mapes 1997).

The difference in the role that low-level moist static energy anomalies play in CISK versus the convective quasi-equilibrium theory is somewhat subtle. In both frameworks the dynamics of low-level moist static energy anomalies is crucial for moist convective development and precipitation, but because the controls of convection and the feedback of convection on the circulation are different, they imply different tropical precipitation distributions. In the CISK perspective tropical convection is governed by lower-level moisture *convergence*, whereas in the convective quasi-equilibrium view precipitation patterns are related to a vertically integrated measure of atmospheric instability, and thus closely tied to lower-level moist static energy anomalies. Since rainfall in the tropics predominantly stems from convection, it is therefore natural to ask whether one can learn about convection–circulation coupling by studying the climatological pattern of precipitation in the tropics and its relation to the atmospheric circulation.

Tropical precipitation patterns and the role of the subcloud layer

Assume that the tropical sea surface temperatures (SSTs) are given. In reality, SSTs are also a result of convection and the atmospheric circulation, but from a conceptual point of view it is useful to first examine how the atmosphere responds to the observed SST pattern. In a CISK perspective, due to the assumed widespread presence of a certain amount of convective inhibition, convection is governed mainly by low-level moisture convergence that overcomes this low-level barrier by lowering the lifting condensation level and providing mechanical uplift. The SST pattern will induce a moisture convergence field. The difficulty is that in CISK moist convection is considered to feed back on the circulation via vertical motion and latent heat release [for a more detailed discussion of this issue see Sobel (2007)]. Nevertheless, rainfall would still be expected to be closely related to moisture convergence, although the moisture convergence is not considered to be defined solely by the SSTs, but also by ensuing convective activity.

What about the convective quasi-equilibrium theory? In the convective quasi-equilibrium view low-level moist static energy anomalies are an important control of convection because they dominate the vertically integrated atmospheric instability due to the small temperature gradients in the free troposphere in the tropics and the concentration of the bulk of the moisture at lower levels. One might think that the areas of low-level moisture convergence are actually identical to the areas of positive low-level moist static energy anomalies. In that case CISK and the convective quasi-equilibrium view would predict essentially the same tropical rainfall patterns. But the patterns of low-level moisture convergence and moist static energy anomalies are not identical, and low-level moist static energy anomalies follow much more closely the SST patterns than moisture convergence (Fig. 1).

Nevertheless, it is important to appreciate that sub-cloud-layer moist static energy anomalies do not need to be identical to SST anomalies. Boundary layer processes and the atmospheric circulation impact the sub-cloud-layer structure. An important aspect of the quasi-equilibrium view as formulated in Emanuel et al. (1994) however is that moist convection does not feed back strongly onto the sub-cloud-layer entropy (see "Convective adjustment and convective quasi equilibrium" section); and the latter is suggested to be the main control of convective development.

Back and Bretherton (2009a) investigate some of these issues and try to understand the main controls of the climatological rainfall distribution in the tropics using a simple, conceptual model. Their starting point is the observation, as shown in Fig. 1, that over the tropical oceans the precipitation pattern follows the pattern of low-level wind convergence quite closely, and that climatologies of rainfall and winds suggest that surface convergence is closely related to vertical motion near the top of the trade inversion. Therefore, the question about the controls of the low-level convergence pattern arises, assuming the observed SST distribution is given. Can the low-level wind and moisture convergence really be considered to govern moist convection, or is it a result of convection? A previous, similar study (Lindzen and Nigam 1987)

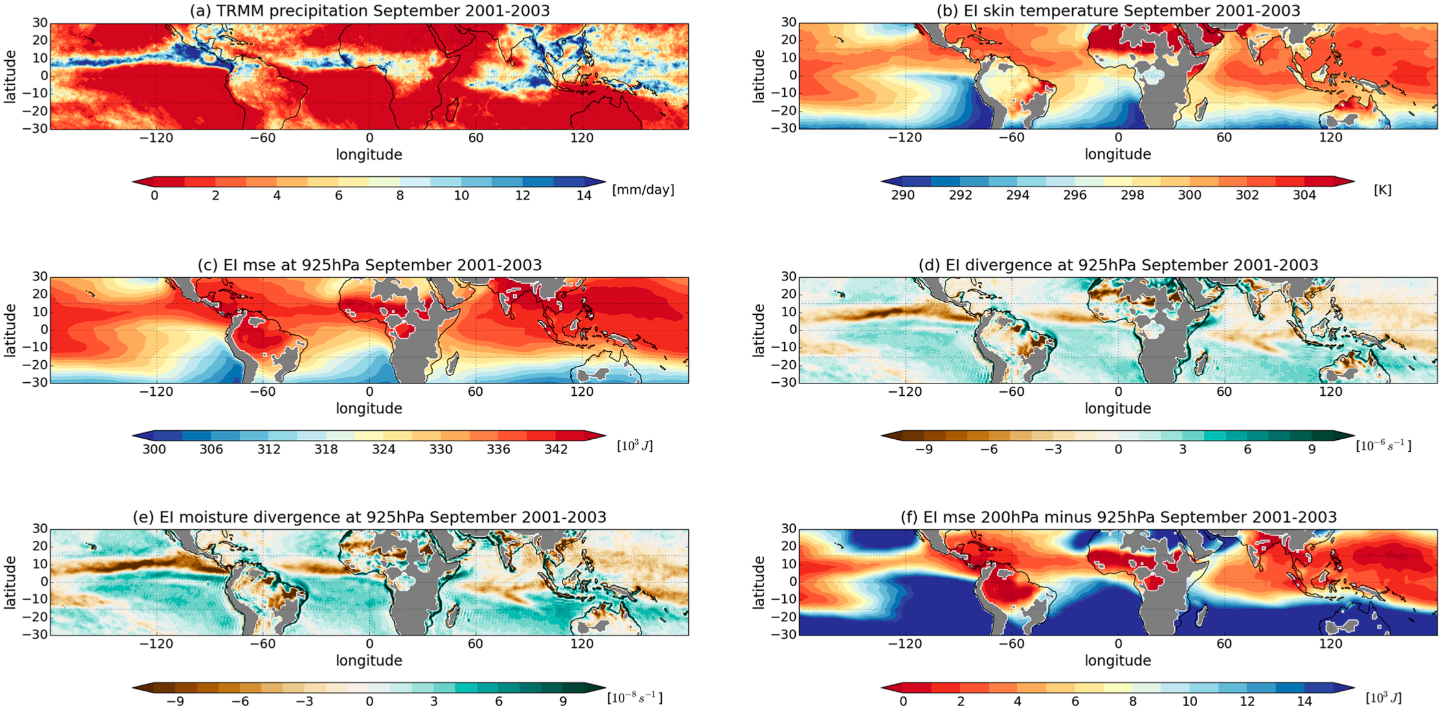


Fig. 1. (a) Mean precipitation distribution for the month of September of the years 2001 to 2003 based on the Tropical Rainfall Measuring Mission (TRMM) 3B42 V7 observational product; (b) ERA-Interim reanalysis mean skin temperature for the month of September of the years 2001 to 2003. Here and in the subsequent panels areas with orography higher than 500 m are grayed out; (c) ERA-Interim reanalysis mean moist static energy at 925 hPa for the month of September of the years 2001 to 2003; (d) ERA-Interim reanalysis mean wind divergence at 925 hPa for the month of September of the years 2001 to 2003; (e) ERA-Interim reanalysis mean moisture divergence at 925 hPa for the month of September of the years 2001 to 2003; (f) ERA-Interim reanalysis mean difference between moist static energy at 200 and 925 hPa for the month of September of the years 2001 to 2003. The moisture divergence pattern follows most closely the precipitation distribution, but most of the spatial variability is explained already by the wind divergence pattern. Low-level moist static energy does not explain some of the features of tropical precipitation. The pattern of the difference between moist static energy at 200 and 925 hPa, an indicator of vertically integrated stability, largely follows the low-level moist static energy because temperatures are relatively uniform at upper levels of the atmosphere.

argued that surface convergence causes deep convection and can in large parts be explained by SST *gradients*.

Back and Bretherton (2009a) separate atmospheric boundary layer processes and deep-tropospheric processes by using a semiempirical simple boundary layer model (Stevens et al. 2002) in the analysis. They argue that it is possible for deep-tropospheric processes to be the result of deep convection. In contrast, the component of the SST distribution that leads to near-surface convergence is unlikely to be a consequence of deep convection. The horizontal wind at 850 hPa, that is, above the subcloud layer, is prescribed based on reanalysis data. The conceptual model of Back and Bretherton (2009a) explains the pattern of low-level wind convergence well. They conclude that (i) boundary layer temperature gradients are responsible for most of the observed near-surface convergence and 850-hPa vertical motion distribution, and (ii) that boundary layer temperature gradients and convergence needed for deep convection near the equator is primarily induced by SST gradients. The results of Back and Bretherton (2009a) are thus in broad agreement with Lindzen and Nigam (1987).

Back and Bretherton (2009a) however note that the climatological ratio of surface convergence to rainfall varies geographically, and that in order to quantitatively model surface convergence it is important to include the effect of free-tropospheric heating on surface convergence. In a companion paper they therefore go one step further and attempt to better understand how exactly the free troposphere responds to the surface convergence distribution (Back and Bretherton 2009b). Their hypothesis is that “variations in the amount of rainfall per unit surface convergence are due to differences in instability in these regions.” One might consider this as a mixture of a CISK perspective and a convective quasi-equilibrium view, and a recognition that in different regions of the globe different mechanisms can be of varying importance: while low-level convergence mainly determines the rainfall pattern, the actual amount of rainfall is impacted by the vertically integrated atmospheric stability, an idea confirmed by observational evidence (Fu et al. 1994).

Again, the conceptual model of Back and Bretherton (2009b) shows considerable success in explaining quantitatively the tropical rainfall distribution. Two vertical modes are used to represent variations in the relationship between boundary layer convergence and rainfall: a “shallow mode” that impacts low-level convergence between the surface and 850 hPa, and a “deep mode.” The deep mode is supposed to be proportional to a measure of vertically integrated atmospheric stability similar to CAPE and does not project strongly on surface convergence. Back and Bretherton (2009b) note that the two modes are not independent.

Although it is instructive to try to understand the climatological rainfall distribution in the tropics, more detailed investigations of the mesoscale dynamics around organized convective systems, so-called mesoscale convective systems (MCSs), reveal the intricate nature of the interaction between convection and the circulation on shorter time scales. MCSs can maintain themselves over several days and nights, and the mesoscale circulations created by the systems are essential in this process (Tomassini 2018). The convergence and strong vertical motions in the MCSs can affect the lower troposphere, including the subcloud layer, directly and transport moisture to regions where it is available for further convective development and organization.

Considering the important role of moisture convergence in governing the position of the tropical rainbands, it is not surprising that landmasses, and related temperature and humidity gradients, have a substantial impact on their structure and migration, as manifested in the dynamics of the monsoons (Voigt et al. 2016, and references therein). Moreover, ascent associated with the rain belt over Africa often commences higher up in the atmosphere, consistent with the picture that the rain belt is composed of mesoscale convective systems, which, in many cases, are initiated above the boundary layer and exhibit a nighttime rainfall maximum (Nicholson 2018). In agreement with this view, a detailed analysis of the West African monsoon shows that regional circulations and associated moisture dynamics are crucial for the position of the rainbands (Thorncroft et al. 2011). So moisture convergence in the boundary layer alone does not determine the exact position of the location of the rainfall maximum; circulations that impact midtropospheric moisture availability have an important influence as well (Thorncroft et al. 2011). Therefore, the view that sub-cloud-layer moisture convergence governs convection is somewhat too narrow; elevated convection is quite widespread over tropical land regions, and there is a feedback of midtropospheric moisture on to convective development as well in many situations (Möbis and Stevens 2012).

The radiative–convective equilibrium puzzle

In the context of the World Climate Research Programme (WCRP) Grand Challenge on Clouds, Circulation, and Climate Sensitivity, Bony et al. (2015) suggested that progress in understanding fundamental problems such as convection–circulation coupling can be achieved through conceptual studies and simplified model experiments. This is one of the reasons why in recent years a renewed and pronounced interest in the study of radiative–convective equilibrium (RCE) has been seen in the research community (e.g., Wing et al. 2018). RCE refers to a simulation setup in which the incoming solar radiation is constant (usually equal to the time-mean, tropical-mean incoming solar radiation), there is no Earth rotation, and the SST is fixed to a spatially uniform value. This numerical experiment is often used to understand the interaction between moist convection and the atmospheric circulation, motivated by the legitimate attempt to simplify the problem of understanding convection–circulation coupling in the tropics. In Emanuel (2005, p. 45), it is stated: “The tropical climate can be thought of as a radiative-convective equilibrium state with a Hadley Circulation superimposed” (see also Emanuel 2007). It should be noted that in the real tropical atmosphere, the balance between convective latent heating and radiative cooling only holds on large scales of several thousand kilometers, not locally. Broader regions of subsidence and radiative cooling are separated from narrower areas of intense deep convection and latent heating (Jakob et al. 2019).

Given that SST gradients and related low-level convergence are crucial to understanding the rainfall distribution in the tropics (see “Tropical precipitation patterns and the role of the subcloud layer” section), it is important to keep in mind the limitations of considering RCE as a model for the tropical atmosphere as a whole. Due to the lack of strong low-level temperature and pressure gradients, and the neglect of the Coriolis effect, RCE understates dynamical aspects of the problem. Instead, it emphasizes the role of radiative processes. Particularly in a convective quasi-equilibrium view, moist convection is often regarded to be “spatially small” (Emanuel et al. 1994; Mapes 1997), and the prevailing balance in the tropics is considered to be encapsulated in the equation

$$w_e \frac{\partial \theta}{\partial z} \approx \frac{\theta}{T} \frac{Q_{\text{rad}}}{c_p},$$

where w_e is the vertical velocity in the nonconvective region (i.e., in most parts of the tropics), θ potential temperature, T temperature, c_p the specific heat capacity of air at constant pressure, and Q_{rad} the radiative cooling rate. In this equation, convective latent heating and the vertical ascent related to convection do not appear explicitly, and often, as in (Emanuel et al. 1994), it is concluded that the subsidence in clear air is not affected by convective ascent. In this picture it seems that moist convection, and the tropical circulation, are actually mainly governed by radiative cooling in areas of subsidence. This view does not acknowledge the important and active role of moist convection in affecting the vertical stability of the atmosphere in nonconvecting areas through gravity waves (Mapes 1997), and the effect of moisture dynamics, driven partly by convection, on radiative cooling rates in areas of subsidence. Thus, to view RCE as a model of the tropical atmosphere is related to the convective quasi-equilibrium perspective in the sense that the role of moist convection is mainly seen as being slaved to the larger scales and adjusting the atmosphere back to an equilibrium state in response to the destabilizing effect by radiative processes.

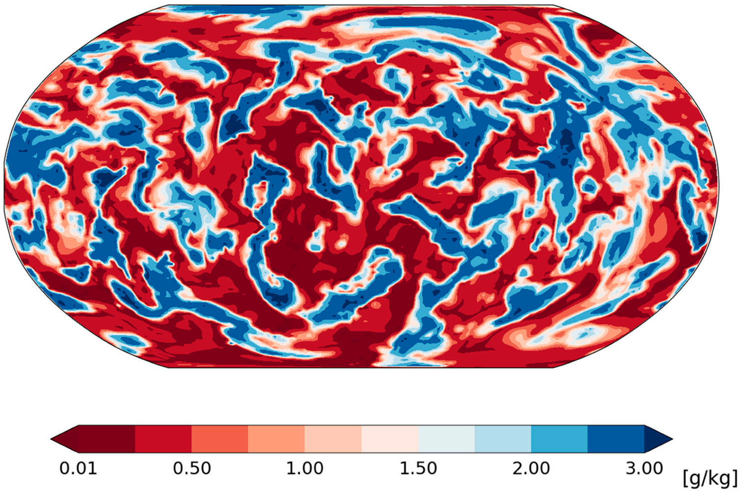
However, a paradox emerges when simulating RCE. If RCE was the basic paradigm for the interaction between moist convection and its larger-scale environment in the tropics, it would be expected to be a stable state of the atmosphere. However, it turns out that, unless explicitly suppressed in one way or another, RCE proves to be unstable in many numerical simulations, particularly in high-resolution runs in which convection is coupled to circulation in a realistic way (e.g., Bretherton et al. 2005). As already pointed out in early studies, RCE is unstable to convective self-aggregation; that is, moist convection localizes in a relatively small area of the domain as one single, organized blob (Held et al. 1993; Tompkins and Craig 1998a,b; Bretherton et al. 2005; Beucler and Cronin 2016). This is true not only at high surface temperatures (Beucler and Cronin 2016). Held et al. (1993) attributes the cause of this behavior to the memory effect of water vapor, together with the low-level convergence that is eventually generated in the convecting regions. Convection moistens the lower levels of the atmosphere, and this moisture remains to encourage the convection to reform at the same location.

In several studies, the exact mechanism that governs convective self-aggregation in RCE has been mainly attributed to the dynamical response to radiative feedbacks from water vapor and low clouds (Muller and Held 2012; Wing and Emanuel 2014; Wing et al. 2017), as well as surface flux and wind interactions (Tompkins and Craig 1998a). Nevertheless, the fact that in RCE simulations the behavior of moist convection and its organization seems to be largely owed to radiative effects and surface flux feedbacks might be due to the specific experimental setup that emphasizes these two aspects. It can be argued that ultimately responsibility for the instability of RCE lies in the dynamics of moisture (Fig. 2; Craig and Mack 2013; Tompkins and Semie 2017). Moisture dynamics couples the convective regions with areas of subsidence through radiative effects and through the impact on atmospheric stability and low-level moist static energy variations (Becker et al. 2017). Moreover, mesoscale circulations can intensify the self-aggregation by fluxing moist static energy from dry to moist regions (Bretherton et al. 2005). The instability of the RCE state, and the prominent role of convection–moisture coupling in this instability, points to a paradigm for the tropical atmosphere that acknowledges the important role of convection–circulation interaction through moisture dynamics.

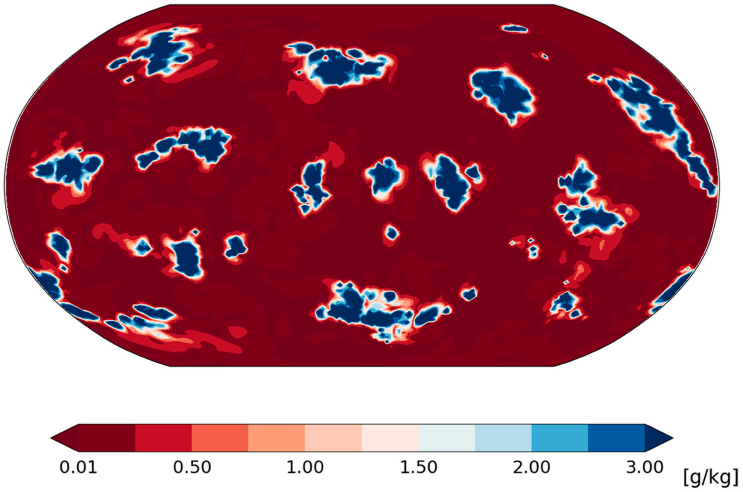
The tropical Pacific as a testbed

Climate variability and climate change is impacted by tropical convection–circulation coupling on a global scale. This can best be seen when turning the attention to the tropical Pacific and, in particular, to decadal trends in the Pacific Walker circulation. Emanuel et al. (1994) explicitly discuss the role of moist convection in large-scale overturning circulations such as the Walker cell, one of the most fundamental features of the tropical atmosphere and the global climate system as a whole. According to their view, large-scale overturning circulations are mainly driven by differences in sea surface temperatures and resulting pressure gradients. In this framework, moist convection counteracts any unstable lapse rate created by larger-scale processes and adjusts the vertical profile of the atmosphere to the moist adiabat defined by the boundary layer moist static energy pattern, which is largely determined by the SSTs (Emanuel 1995). This mechanism is an expression of moist convective damping: moist convection (assumed to be spatially small) removes instability on time scales much shorter than the time scales of the larger-scale processes and thus mutes atmospheric circulations. In contrast, in a CISK perspective, latent heat release from convection is considered a driver of the Walker circulation, and moist convection, in turn, is viewed to be controlled predominantly by low-level moisture convergence. Recent decadal variability in global mean surface temperature has been

(a) RCE specific humidity at 5000m: reference



(b) RCE specific humidity at 5000m: convection scheme off



(c) RCE specific humidity at 5000m: low entrainment

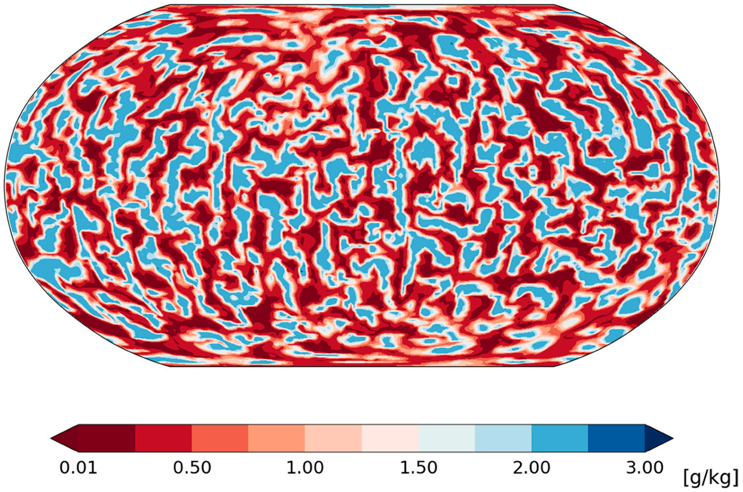


Fig. 2. Snapshots after three years of radiative–convective equilibrium (RCE) simulations with the global configuration of the Met Office Unified Model GA7 at 135 km resolution. The prescribed sea surface temperature (SST) is 295 K, about 5° cooler than the present-day mean tropical SST. (a) Specific humidity at 5,000 m height in the reference simulation; (b) specific humidity at 5,000 m height with the convection parameterization switched off; (c) specific humidity at 5,000 m height when using low lateral entrainment rates in the deep and midlevel convection schemes. In agreement with results by Becker et al. (2017), the simulation with convection parameterization switched off shows strong convective organization, whereas the simulation with low lateral entrainment rates in the convection scheme exhibits small convective aggregation. The convection–moisture feedback (Craig and Mack 2013; Tompkins and Semie 2017) plays an important role in this context: low lateral entrainment rates reduce the convection–moisture feedback, and therefore the convective organization. By comparison, in the simulation with explicit convection the saturation deficit between the convecting regions and the environment is substantially larger, a condition fostering convective aggregation (Craig and Mack 2013; Becker et al. 2017).

dominated by tropical Pacific variability (Trenberth 2015). Thus, decadal trends in the Pacific Walker circulation could become an important test bed for theories of the interaction between moist convection and the atmospheric circulation.

Over the last two decades or so, the Walker circulation and the low-level east–west temperature gradient over the tropical Pacific have been strengthening (L'Heureux et al. 2013; Fyfe and Gillett 2014; McGregor et al. 2014; England et al. 2014). Climate models have struggled to reproduce this trend. It has been suggested that climate variability, in particular the interdecadal Pacific oscillation (IPO), has been responsible for the trend. However, CMIP5 models are not able to reproduce any 20-yr periods with wind intensification and SST gradient change that matches the observed increase over the 1992–2011 period (England et al. 2014; Coats and Karnauskas 2017; Seager et al. 2019).

To first order it is evident that many atmosphere models are too sensitive to warm SSTs, and generally not sensitive enough to moisture and circulation regimes (Lin 2007; Hirota et al. 2011; Oueslati and Bellon 2015), not only over the Pacific, but also over the Atlantic (Biasutti et al. 2006, and Fig. 3).

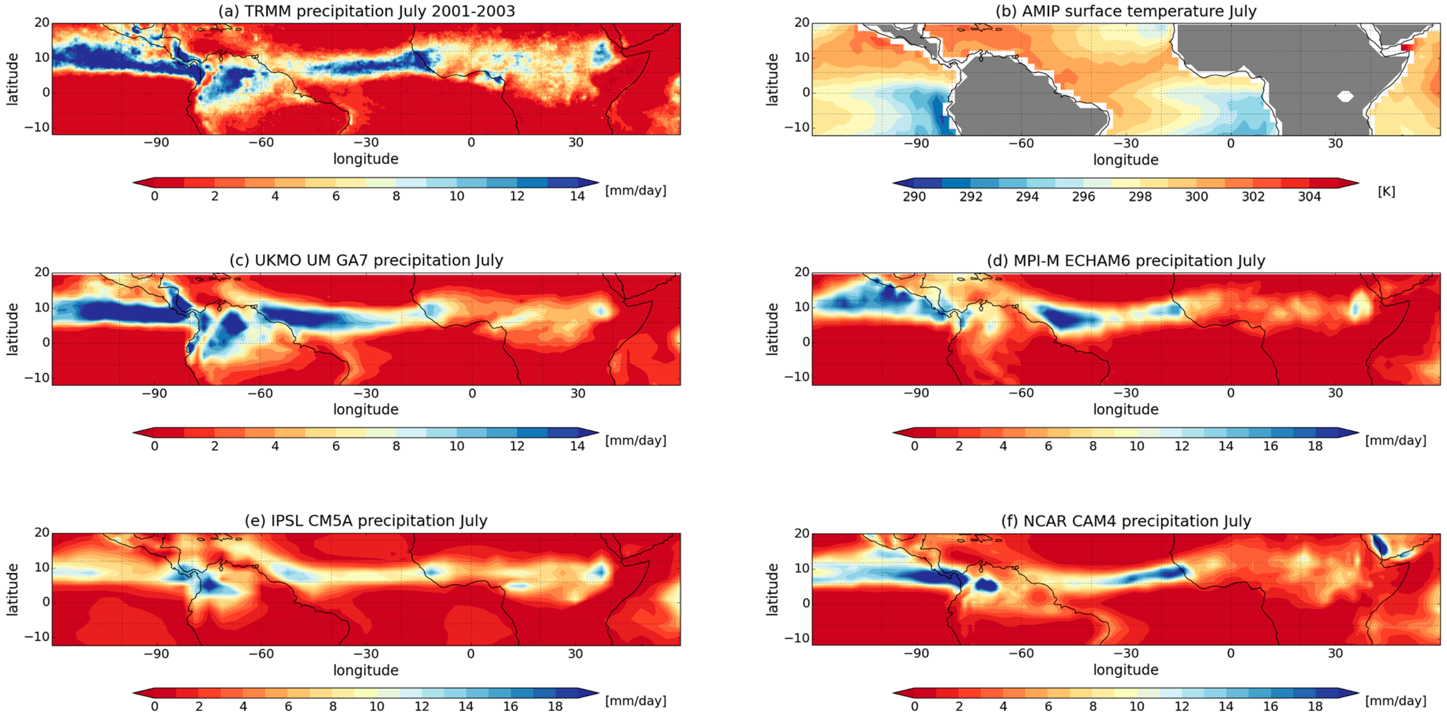


Fig. 3. (a) Structure of the mean precipitation pattern over the tropical Atlantic and eastern Pacific for the TRMM observational product for July of the years 2001 to 2003; (b) mean sea surface temperatures over the same period based on the AMIP protocol, which is used to force the three atmospheric general circulation models below; mean precipitation over the same period as simulated by (c) the Met Office Unified Model GA7, (d) MPI-M ECHAM6, (e) IPSL CM5A, and (f) NCAR CAM4. The Unified Model and ECHAM6 show a rainfall maximum in the western tropical Atlantic corresponding to the SST maximum, whereas the observations indicate a maximum in the eastern and central part of the Atlantic. CM5A generally exhibits a dry bias, and also simulates a maximum over the western Atlantic, apart from rainfall peaks associated with orography: the Guinea Highlands over West Africa and the Andes over Colombia. CAM4 shows the most realistic rainfall pattern over the tropical Atlantic, after a careful revision of the convective parameterization that includes a dilute plume calculation of CAPE and the introduction of convective momentum transport (Neale et al. 2013).

Maher et al. (2018) demonstrate that variability in the tropical Pacific can be understood without referring to influences external to the tropical Pacific region, not only on interannual, but also on decadal time scales (Fig. 4). They show that the Bjerknes feedback, by which increased easterly wind reinforces upwelling of cold subsurface water and cools the SST over the eastern tropical Pacific, is a very robust mechanism, on various temporal scales. Assuming this feedback is correct, the main ambiguity resides in the SST–wind feedback, which is primarily mediated by convection–circulation coupling and the associated Walker circulation.

Let us assume there is a perturbation in the low-level temperature gradient and a related reinforced east–west surface pressure differential. In a CISK-type theory this would lead by definition to enhanced convection due to increased moisture convergence, and as a consequence to an enhancement of the Walker circulation and low-level easterlies. In other words, convection–circulation coupling would act as a positive feedback onto the initial perturbation. In the context of a convective quasi-equilibrium view the situation is less straightforward as the moist convective damping mechanism could come into play and take on the role of a negative feedback. A warm anomaly in the western tropical Pacific would simply cause the adjustment of the entire atmospheric profile to a different moist adiabat and would not necessarily imply an enhancement of the Walker circulation.

To what degree the Walker circulation is enhanced or impeded by moist convection is therefore a matter of balance between the sensitivity of convection to low- to midtropospheric moisture convergence (CISK) and the effect of latent heating on the circulation, versus the

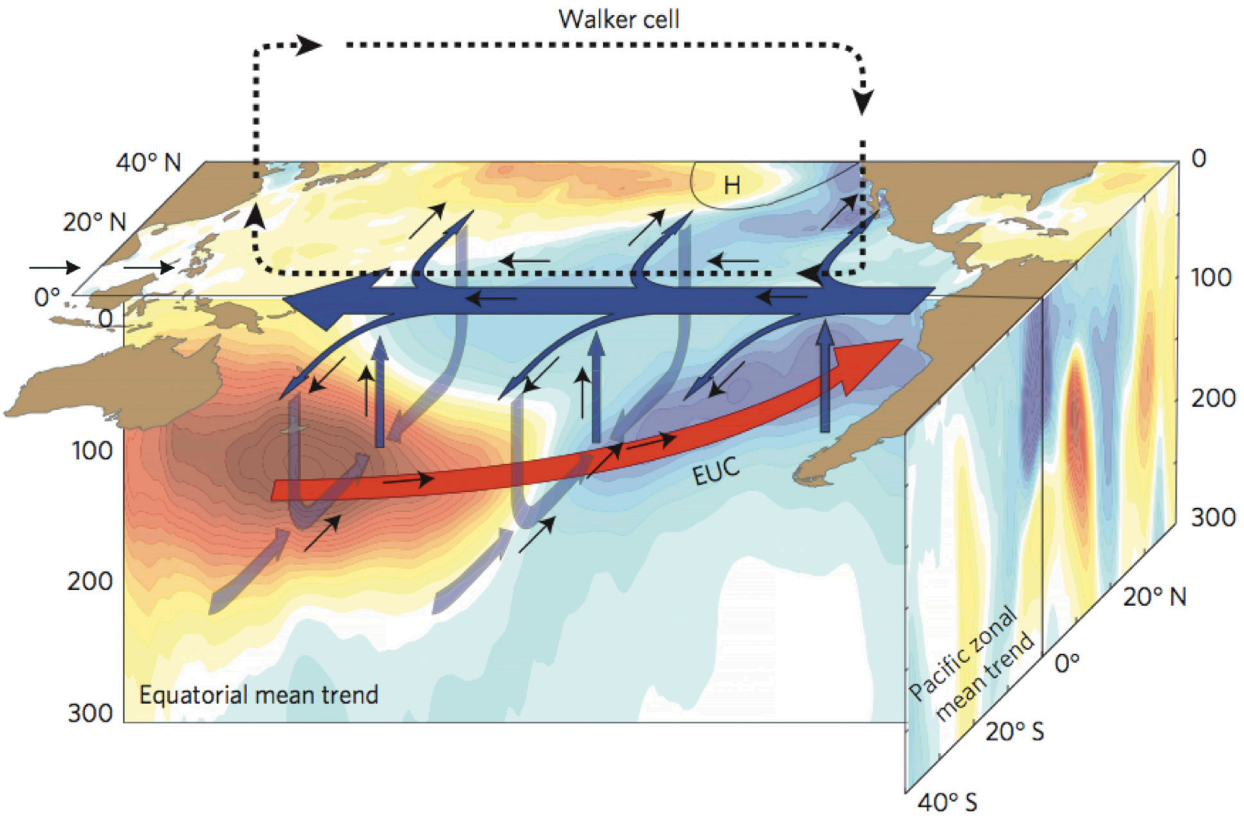


Fig. 4. Features of the climate system over the tropical Pacific, with color shading indicating observed ocean temperature trends for the period 1992–2011. If moist convection scales with low-level moisture convergence, then increased moisture convergence over the western Pacific will lead to enhanced convection, implying a positive feedback to perturbations in the east–west temperature and pressure gradient from convection–circulation coupling. In the convective quasi-equilibrium view, moist convective damping might lead to a negative feedback of moist convection onto a strengthening of the Walker circulation. Figure adapted from England et al. (2014).

sensitivity of convection to vertically integrated stability and related moist convective damping (convective quasi equilibrium). If the low-level moisture convergence mechanism is dominant, then the feedback will inevitably be positive, such as for instance in the simple Zebiak–Cane model (Cane and Zebiak 1985; Zebiak 1986; Ramesh et al. 2017; Seager et al. 2019). If the quasi-equilibrium mechanism prevails, a negative feedback on the circulation from the overall stabilizing effect of convection and related changes in clear-sky radiative cooling rates is possible.

Sherwood (1999) concluded based on observations that low- to midtropospheric moisture can be identified as the prevailing factor regulating convective outbreaks in the tropical western Pacific area. Fu et al. (1994) suggested, again based on observations, that seasonal variations in deep convection over the tropical Pacific respond immediately to surface solar radiation increase and its effect on the planetary boundary layer through surface wind convergence and resulting changes in lower-tropospheric lapse rate and humidity, instead of waiting for the rise of SST and related CAPE (see the discussion in the “Tropical precipitation patterns and the role of the subcloud layer” section).

It should be noted that the particular behavior of a global model with parameterized convection cannot easily be predicted based on the nominal closure assumption in the convection parameterization alone, other aspects such as lateral entrainment rates will affect the sensitivity of the scheme to moisture as well. This is exemplified in Möbis and Stevens (2012), where the characteristics of two convection schemes with different closures are compared. The particular implementation has a big impact on the performance of the parameterization.

It is shown how in practice a scheme with a moisture-convergence closure can actually be less sensitive to moisture than a parameterization with a CAPE closure. Nevertheless, the key aspect of the different behaviors of the parameterizations examined in Möbis and Stevens (2012) is shown to be related to the varying sensitivity to lower- and midtropospheric moisture.

Toward a consensus

In the convective quasi-equilibrium theory of moist convection the time scale of adjustment, the vertical extent of the adjustment, and the amount of entrainment of environmental air into moist convective updrafts are important. This is evident in the example of the tropical Pacific. A long adjustment time scale in the quasi-equilibrium theory will, in practice, lead to large departures from quasi equilibrium. CISK on the other hand also acknowledges that vertical instability needs to be present and is a prerequisite for convection to occur. The main differences between the two theories are (i) to what degree moisture dynamics and related lower-tropospheric instability are important versus vertically integrated instability, and (ii) to what degree moist convection simply leads to an adjustment and stabilization of the entire atmospheric column, or drives circulations. These two aspects are key for the way moist convection interacts with the atmospheric circulation and atmospheric moisture. However, a convection parameterization with a quasi-equilibrium closure, but long adjustment time scale, may in practice behave in a similar fashion to a CISK-based scheme if in addition it is sensitive to environmental moisture via, for instance, high lateral entrainment rates (Möbis and Stevens 2012; Bechtold 2016).

Nevertheless, the notional debate is of practical relevance and has significant, measurable implications. Questions such as how sensitive convection parameterizations are to lower- and midtropospheric moisture and moisture convergence, whether models are able to adequately simulate tropical disturbances such as easterly waves (Skinner and Diffenbaugh 2013), whether models are too sensitive to warm SSTs, and whether convection parameterizations tend to adjust the atmosphere too quickly and widely in response to larger-scale instabilities, are of crucial importance to the simulation of both climate variability and climate change (Sherwood et al. 2014; Tomassini et al. 2015).

Conceptually a consensus is emerging that could be called “lower-tropospheric quasi equilibrium,” a term introduced in Raymond and Herman (2011) and Raymond et al. (2015). It would acknowledge that

- moist convection drives circulations in many situations;
- moisture convergence is an important control of moist convection in the tropics;
- there is a “quasi equilibrium” in the lower troposphere in the sense that the state of the lower troposphere allows for predicting the bulk effect of moist convection in principle;
- moist convection is not only governed by boundary layer processes in the strict sense, MCSs, for example, are often initiated above the boundary layer; and
- also midtropospheric moisture variability, which is affected by circulations, impacts convective development.

Recent studies have explored some of those issues (e.g., Sobel 2007; Neelin et al. 2008; Muller et al. 2009; Sherwood et al. 2010; Stevens et al. 2017; Schulz and Stevens 2018). Satellite images reveal how close the relationship between convection and moisture dynamics is in the tropics, and that the rainbands do not consist of uniform areas of precipitation, but are composed of a multitude of organized cloud clusters (Fig. 5) and synoptic-scale disturbances (Lau and Lau 1990). When carefully reflecting on Fig. 5, it becomes clear that it is not only that moisture fosters and activates convective rainfall, but the spatial distribution of moisture is closely related to convective motions like those arising from mesoscale convective systems, convectively coupled tropical waves or tropical depressions. The intimate, two-way interaction between convective motions and the moisture distribution means that convective rainfall is not just a consequence of moisture dynamics, but convection actively impacts moisture dynamics and the moisture pattern in the tropics.

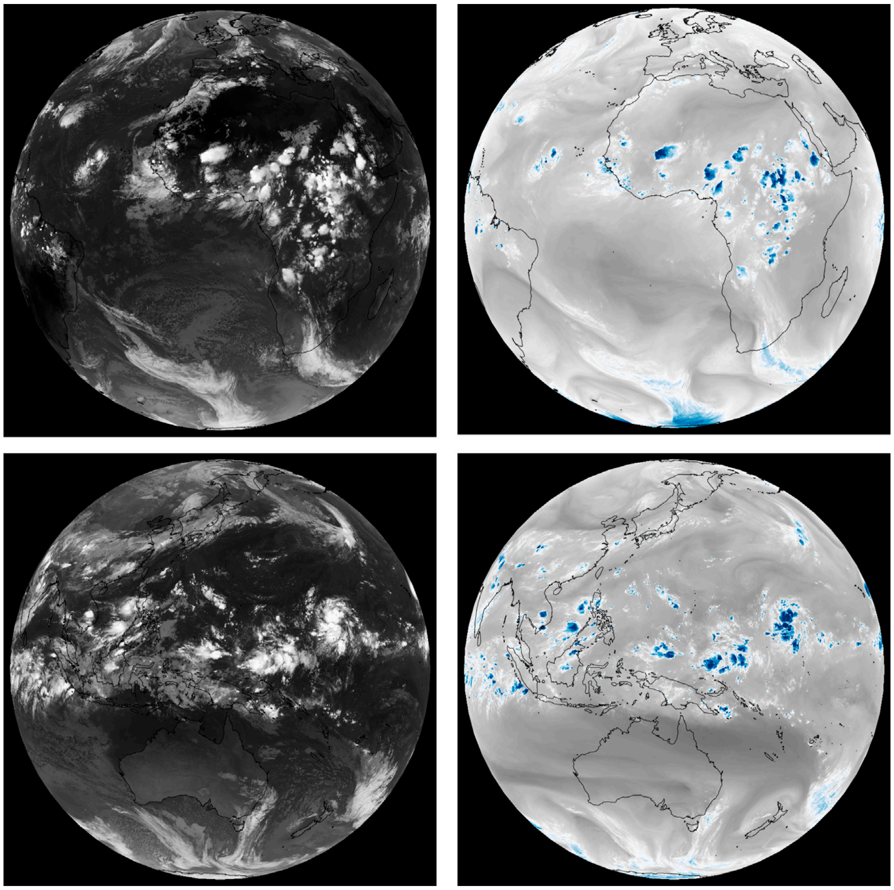


Fig. 5. Brightness temperatures derived from the (top) Meteosat Second Generation (MSG) satellite over Africa and the tropical Atlantic and (bottom) *Himawari-8* over the tropical Pacific for 1800 UTC 6 Sep 2018. (left) Brightness temperatures at 10.8 μm, highlighting high clouds, and (right) brightness temperatures corresponding to water vapor channels, 6.2 μm for MSG and 6.9 μm for *Himawari-8*. The tropical rainbands consist of large organized convective structures and cloud clusters. The images suggest that there truly is a two-way interaction between moist convection and moisture dynamics. Moist convective rainfall is not simply slaved to the moisture pattern, but circulations related to moist convection influence and feed back on the moisture distribution.

However, it is also important to acknowledge that meteorological conditions can greatly vary under different circumstances and in different parts of the world (Back and Bretherton 2009b; Raymond et al. 2015). Over the Sahel, for example, a unique place with some of the largest and most vigorous mesoscale convective systems, the thermodynamic structure of the free troposphere is generally not very closely coupled to the boundary layer. Whereas over the western tropical Pacific, for instance, oceanic deep convection, since moisture is abundant, tends to keep the atmosphere relatively close to a moist adiabatic profile. This means that the factors that control convective activity are not always the same, or have different levels of importance under different circumstances. Nevertheless, variations in moisture sensitivity of convective parameterizations can have a big impact on the resulting atmosphere even in idealized aquaplanet simulations, where moisture is unlimited in principle (Möbis and Stevens 2012). Moisture variability and related convection–circulation coupling can also play an important role in organizing shallow-convective structures in subsidence regions over the ocean (Bretherton and Blossey 2017; Bony and Stevens 2019).

It is evident that the term “interaction” between moist convection and the atmospheric circulation always means “two-way interaction,” which makes it difficult conceptually to separate convection from the “larger scales” (Mapes 1997; Tompkins and Craig 1998a). Moreover, it is an open problem whether the nature of the interaction between convection and the atmospheric circulation depends on the considered scales (e.g., Beucler and Cronin 2019). Nevertheless, the question of how circulations govern and sustain moist convection, and whether moist convection drives circulations or merely removes instability created by other processes, is of central importance when it comes to understanding climate variability and climate change. New multiscale modeling frameworks, including convection-permitting and convection-resolving simulations, are now able to, at least partly, resolve convection–circulation coupling across scales and on large domains without, as is likely to be a key aspect, assuming any sort of scale separation. Together with ever more detailed Earth observations and dedicated field campaigns (e.g., Bony et al. 2017) they can enable the research community to make major progress in understanding convection–circulation coupling in the tropics in the coming years.

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