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Ongoing breakthroughs in convective parameterization

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Abstract Purpose of review: While the increase of computer power mobilizes a part of the atmospheric modelling community towards models with explicit convection or based on machine learning, we review the part of the literature dedicated to convective parameterization development for large-scale forecast and climate models.

Recent findings: Many developments are underway to overcome endemic limitations of traditional convective parameterizations, either in unified or multi-object frameworks : scale-aware and stochastic approaches, new prognostic equations or representations of new components such as cold pools. Understanding their impact on the emergent properties of a model remains challenging, due to subsequent tuning of parameters and the limited understanding given by traditional metrics.

Summary: Further effort still needs to be dedicated to the representation of the life cycle of convective systems, in particular their mesoscale organization and associated cloud cover. The development of more process-oriented metrics based on new observations is also needed to help quantify model improvement and better understand the mechanisms of climate change.

Keywords convective parameterizations for large-scale models · stochastic approaches · convective memory · mesoscale circulation · cold pools · process-oriented metrics

1 Introduction

Atmospheric moist convection results from the radiative cooling of the atmosphere, surface fluxes, forcing by large-scale motions, and the buoyancy associated with water phase changes. It happens at various spatial and temporal scales, from shallow convective cells to individual deep convective cells of a few kilometers lasting a few hours, to mesoscale convective systems of hundreds of kilometers lasting a few days, up to synoptic clusters and

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convection organized at the planetary scale such as the Madden-Julian Oscillation (MJO) or the Intertropical Convergence Zone (ITCZ), and is associated with the formation of liquid and ice hydrometeors. This makes convection particularly challenging to be represented in global models with a horizontal resolution ranging from a dozen to a few hundreds of kilometers, in which convection and its associated clouds are entirely or partly sub-grid scale. The collective effect of sub-grid cumulus clouds on the resolved large-scale variables has to be taken into account via a set of equations called a convective parameterization. Arakawa (2004) defines it as "an attempt to formulate the statistical effects of cumulus convection without predicting each individual cloud". It is supposed to be valid over the various conditions encountered all over the globe but also to respond appropriately to large-scale modifications of the state of the atmosphere (Raymond, 1994). The convective parameterization is key in weather and climate simulations as it provides source terms for the dynamic equations of heat, humidity and momentum as well as macro- and microphysical properties of clouds for radiation. It determines the spatio-temporal distribution of precipitation and extreme weather events such as tropical cyclones, lightning or severe thunderstorms. It may also provide vertical profiles of mass flux and vertical velocity, as well as aerosol activation, chemical reactions and wet removal processes within clouds for the transport and evolution of hydrometeors, tracers, aerosols and chemical species.

The majority of the parameterizations currently at work in operational weather and climate models are updated versions of schemes built in the 1980s and 1990s (Arakawa and Schubert, 1974; Tiedtke, 1989; Gregory and Rowntree, 1990; Kain and Fritsch, 1990; Emanuel, 1991; Del Genio and Yao, 1993; Donner, 1993; Grell, 1993; Zhang and McFarlane, 1995). They are based on the mass-flux approach, which aims to explicitly represent the underlying convective physical processes, by decomposing the atmospheric column into different components (updrafts, downdrafts, subsiding environment). In recent years, however, the validity of traditional hypotheses has been questioned and there has been a resurgence of new original approaches to parameterization, with the use of stochastic components, revisiting of the mass-flux framework, or the introduction of new processes (cold pools, mesoscale circulations). Part of those developments have been motivated by the emerging question of scale-adaptability when model resolution enters the "gray zone" (5 to 25 km) and convective transport needs to be partitioned into parameterized and resolved components. It is noteworthy that some of these new developments have already been implemented in models, indicating a speeding of the model development process.

In the meantime, even if convective parameterizations are improved at the process scale, major model large-scale biases still remain in relation with clouds and precipitation, both in the mean state (e.g., the double ITCZ artifact, warm biases of mid-latitude continents and the eastern tropical oceans), and in variability from the diurnal to inter-annual time-scales (monsoon, MJO, ENSO, ...). Furthermore, much less attention has been paid to the clouds that accompany moist convection, even though shallow cumulus clouds represent the largest source of uncertainty in cloud feedback in the current generation of global climate models (Klein et al, 2017) and the anvils associated with deep convective cloud systems are a largely unconstrained contributor to climate change besides their well-documented increase in height with warming (Zelinka and Hartmann, 2011). The persistence of endemic model biases, combined with the inevitable trend toward higher model resolution, has led part of the community to abandon traditional convective parameterization development in favor of new approaches made possible by the increase of computing power, based on models resolving convection and clouds at the kilometer scale (cloud resolving models; CRMs). The super-parameterization or multi-scale modeling framework (Randall et al, 2003; Tao and Moncrieff, 2009) is a hybrid approach that replaces a conventional convective parameterization by a 2D CRM, or even a 3D large-eddy simulation (LES) model (Grabowski, 2016) in each atmospheric column. Ultimately, the goal of scale-aware parameterization efforts is to eventually give way to global cloud resolving models that operate on scales that do not require any cumulus parameterization at all (Miyamoto et al, 2013). More recently, first attempts to develop a novel class of convective parameterizations based on machine learning, using a deep neural network trained by explicit simulations, have been tried with some skill to reproduce convective tendencies and clouds (Schneider et al, 2017; Gentine et al, 2018; O'Gorman and Dwyer, 2018). The question thus arises: Is it beneficial to continue to develop conventional cumulus parameterizations? In this paper based on the recent literature, we argue that long-term community effort should still be dedicated to traditional convective parameterization development for large-scale models for several reasons. First, overcoming the difficulties of traditional parameterizations has led to original and exciting developments in the last few years, demonstrating that various limitations of convective parameterizations can be overcome. Second, parameterizations summarize our understanding of physical processes and their interactions with the large-scale flow. For climate models in particular, this distillation of knowledge must be central to any strategy to understand climate change. Third, parameterizations potentially permit us to disentangle the role different physical processes play in weather and climate. In addition to this, there will still be decades before routine climate simulations can be run at convection permitting resolution.

It is often stated that a good climate model should be a good weather model, and indeed, short term error growth on weather time scales can reveal important parameterization deficiencies that lead to mean state biases (e.g. Van Weverberg et al, 2018). It has not been demonstrated, though, that a good weather model is sufficient to produce a reliable climate change projection. The goal of parameterization development is not just to improve model performance and get models to agree with each other, but also to understand why models predict the climate changes that they predict, estimate what confidence we can have in them, and articulate the reasons for that confidence (or lack thereof). To achieve this, we need to understand better how convection interacts with other processes to modulate the weather or climate and to quantify better the impact of related tuning parameters. It is also important to precisely define what a climate and weather forecast model should be able to simulate and find new ways to confront large-scale models with observations and high-resolution simulations that reveal the fidelity with which general circulation models (GCMs) represent the convective scale processes that they seek to parameterize.

In the following, we address three major challenges the convective parameterization development community is facing: 1/improve the representation of convective cloud ensembles 2/improve the representation of convective memory and organization, 3/improve the representation of convection to large-scale interactions.

2 Improve the representation of convective cloud ensembles

2.1 Unified versus multi-object frameworks

Atmospheric convection organizes at various vertical scales, going from boundary-layer depth to the full troposphere depth for deep moist convection as sketched in Fig 1. Boundary-layer convection is active all year long over the tropical oceans, where it produces cumulus and strato-cumulus clouds and is a key of the representation of the diurnal cycle over continents. The importance of the continuity between dry and cloudy boundary-layer convection has been recognized for decades (LeMone and Pennell, 1976), as well as the need to account for the non-local asymmetrical vertical transport between buoyant plumes and compensatory environment to allow the systematic up-gradient transport of potential temperature. Cumulus clouds are thus associated with the positive wing of a positively skewed distribution of sub-grid water vapor. Two kinds of approaches developed in the last decades which fulfill those constraints have started to be used in weather forecast and climate models: Combination of eddy diffusion with mass-flux schemes (often called EDMF) (Hourdin et al, 2002; Köhler et al, 2011; Hourdin et al, 2013; Riette and Lac, 2016; Bhattacharya et al, 2018) and third order turbulent schemes (Guo et al, 2014, 2015).

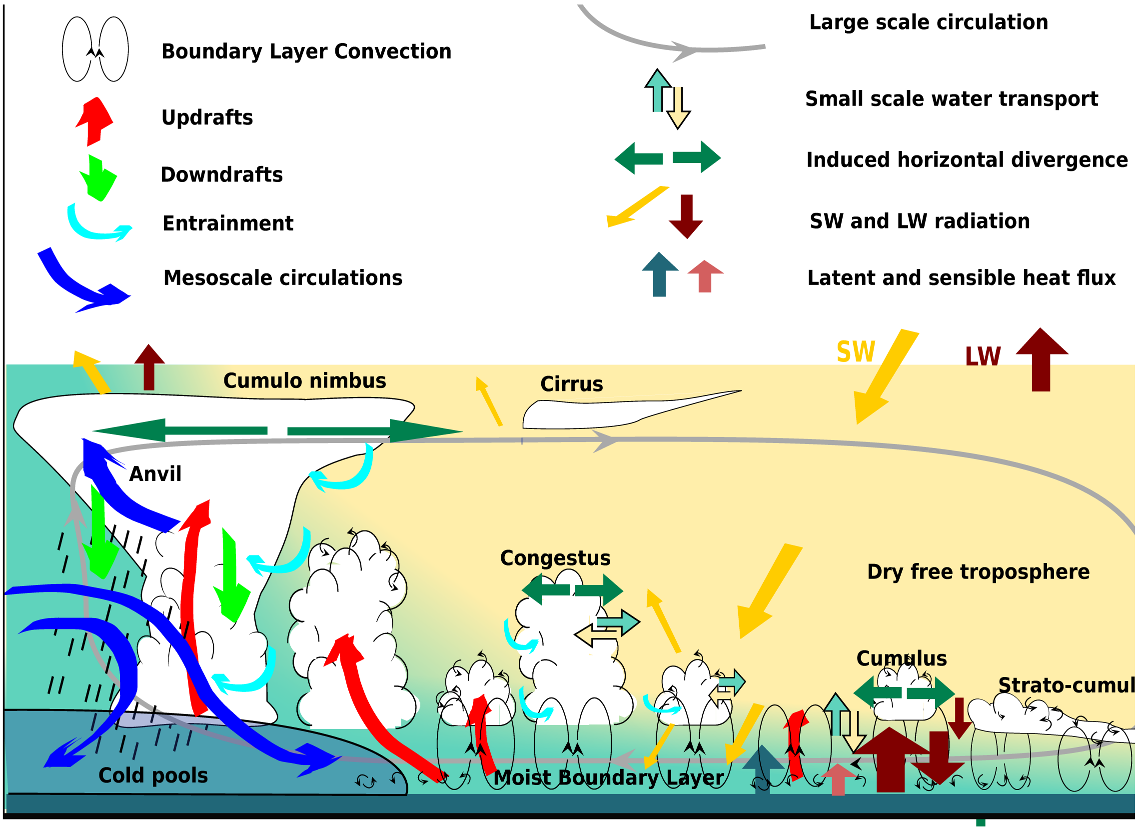

Fig. 1 Sketch of the various aspects of atmospheric convection and its interaction with radiation, humidity, surface fluxes and large-scale circulation which are targeted by parameterization developments, noticing that most of the aspects can co-exist within the same horizontal grid cell for a global climate model.

In regions where deep convection is active, observations show a trimodal distribution of clouds corresponding to (shallow) cumulus, (deep) cumulonimbus and the intermediate scale of congestus clouds (Johnson et al, 1999).

The various modes interplay in the Tropics. While shallow convection generally moistens and cools the free troposphere by detrainment of water vapor and cloud water that evaporates (Nitta and Esbensen, 1974), deep convection warms and dries the free troposphere by compensating subsidence and precipitation (Yanai et al, 1973). These three modes sketched in Fig 1 often coexist within domains that correspond to a model grid cell. Most models use mass-flux parameterizations for deep convective regimes, but with a variety of approaches and underlying conceptual models. Some modelers promote unified parameterizations for convection arguing that the physics of the convection is unique, and that a well-designed unified scheme should help represent the co-existence of various regimes (Guérémy, 2011; Park, 2014a,b; D'Andrea et al, 2014) and work at grid resolutions where cumulus convection is permitted but not fully resolved (Arakawa and Wu, 2013; Wu and Arakawa, 2014; Kwon and Hong, 2017; Ong et al, 2017; Zhao et al, 2018). Others underline the contrasting nature of shallow and deep convection, in terms of organization and main drivers (surface fluxes for boundary-layer convection and condensation, rain evaporation, and sometimes wind shear for deep convection) and advocate for the coexistence of different mass-flux schemes, considering the coupling between those two objects as a parameterization itself (Rio et al, 2013). Representing cold pools as entities distinct from the deep convection scheme permits the introduction of a sub-grid partitioning of the otherwise homogeneous environment: the exterior of cold pools in which convective cells initiate, and the cold pool area in which convective rain falls and evaporates (Grandpeix and Lafore, 2010).

Note that there are also tentative works to extend parameterizations derived more directly from perturbation development of the basic equations (Guo et al, 2015; Storer et al, 2015). Whether they are called unified or not, it seems important that physics packages clearly target the various aspects and scales of convection, either by coupling different parameterizations, or including in a unique model the ingredients needed to represent the various conditions properly, including the coexistence of different regimes within the same grid box.

2.2 Size distribution of convective clouds

In practice, most schemes used in large-scale models rely on two updraft classes, one for shallow and one for deep convection, although several fully spectral ensemble approaches exist (Arakawa and Schubert, 1974; Donner et al, 2011). A triggering criterion, usually based on instability, moisture convergence or boundary-layer vertical velocity, is used to decide what parts of the scheme should be activated or not. Then closure relationships are used to relate convection intensity to large-scale variables. In recent years, several studies have targeted the representation of the co-existence of more numerous cloud types within a model grid cell with scale-adaptativity.

One approach consists in using a Markov chain to derive fractional areas covered by 3 cloud types (congestus, deep, stratiform) given probabilities of transition dependent on chosen large-scale variables (for example CAPE and mid-tropospheric dryness) as proposed by Khouider et al (2010). These fractions can be combined with vertical profiles of heating and moistening inferred from observations to compute convective tendencies (Deng et al, 2015; Goswami et al, 2017a,b). Others consider more numerous cloud types with transitions conditioned on mid-tropospheric vertical velocity and relative humidity (Peters et al, 2013) or on the vertical velocity averaged over the lower part of the troposphere (Dorrestijn et al, 2013). Both approaches are tested in GCMs by using the deep convective area fraction to compute the closure of distinct versions of the Tiedtke (1989) mass flux scheme assuming a cloud-base vertical velocity of 1m s^{-1} (Dorrestijn et al, 2016; Peters et al, 2017).

Rather than considering a finite number of cloud types, another approach derives a stochastic closure from an exponential PDF of mass-flux per cloud (Plant and Craig, 2008). The inferred probability of initiating a plume of a given radius is tested against random numbers, the ensemble-mean mass-flux being derived using a CAPE closure computed from large-scale variables with space-time averaging. The stochastic scheme has been coupled to the Kain-Fritsch (Keane and Plant, 2012; Keane et al, 2016) and the Zhang-McFarlane (Wang and Zhang, 2016) schemes. A similar approach has been derived for shallow convection and coupled to an EDMF scheme by Sakradzija et al (2016). Those approaches consider that clouds are randomly distributed over the domain, with no convective aggregation. This aspect has been taken into account by Hagos et al (2018) via another stochastic framework, not implemented in a GCM yet, which aims to predict the evolution of the size distribution of convective cells from a probability of growth, a probability of decay and an imposed relationship between the cloud base mass-flux and the convective area fraction.

Similar approaches are also used to modify the triggering of deep convection. A positive deep convective fraction provided by the multicloud model can be used as a triggering criteria (Peters et al, 2017). Rochetin et al (2014a) compute a distribution of sizes and velocities of thermal plumes from a mean updraft issued from an EDMF scheme. Deep convection is triggered if the strongest thermal has a sufficient vertical velocity to overcome the convective inhibition and if one thermal within the grid cell is larger than a given threshold. Deep convection is initiated randomly according to the specified distribution of thermals. The stochastic components used in those frameworks in principle allow for scale-adaptability (Keane et al, 2014; Sakradzija et al, 2016).

2.3 Vertical structure of the updraft

Whatever the approach used for triggering and closure and the number of cloud types, there is still the need to compute the vertical profile of cloud properties. Using directly observed profiles of heating and moistening as in Goswami et al (2017b) may improve the coupling of convection with the large-scale dynamics but it has some limitations for deriving mass-fluxes for vertical transport of chemical species and aerosols or for simulating the evolution of the vertical profiles of convective tendencies under climate change. In the other approaches cited above, classical formulations of entrainment and detrainment are applied to each cloud type. This is convenient as in practice it remains challenging to find an exact same formulation of entrainment that is valid for both shallow and deep convection (Del Genio and Wu, 2010; Zhang et al, 2016). Direct computation of entrainment in LES models suggests that determining entrainment rates using the bulk approximation underestimates effective entrainment by a factor of 2 (Romps, 2010). The presence of shells around convective clouds (Heus and Jonker, 2008; Glenn and Krueger, 2014) implies that the air entrained at the edges of cumulus clouds does not have the properties of the mean environmental air as commonly assumed in parameterizations, but rather is a mixture of cloudy and environmental air (Zhang et al, 2016). However lower entrainment rates used in bulk-plume schemes might be an efficient way to simplify the more complex mixing occurring at cloud edges, the important aspect being to take into account properly the dilution of the updrafts by entrainment (Hannah, 2017). For example, Becker et al (2018), using a CRM, find that when convection aggregates, the entrainment rate actually increases in the lower troposphere due to the enhancement of turbulence, but that the dilution of cloud air decreases because the updrafts entrain the more humid air that surrounds aggregated updrafts.

While some use deterministic entrainment applied to several plumes with different cloud-base mass-flux, other studies have shown that models considering entrainment as a stochastic process capture more accurately the variability of cloud properties seen in LES (Romps and Kuang, 2010; Böing et al, 2014) than models using multiple updrafts with deterministic entrainment rates. This may be achieved by traditional episodic mixing and buoyancy sorting schemes (Raymond and Blyth, 1986; Emanuel, 1991; Grandpeix et al, 2004), provided the vertical profile of mixture distributions and the properties of updraft and environmental air that mix can be constrained from CRM or LES. Alternatively, Romps (2016) proposes a new approach tested in a single column model (SCM) based on an updraft initialized with a single set of properties at the first model level and made of convective parcels entraining stochastically as a Poisson process. An attempt to couple an earlier version of this scheme (Romps and Kuang, 2010) in an EDMF scheme has been made in a 1D framework (Sušelj et al, 2013).

Another issue concerns the vertical profile of vertical velocity, which is required for coupling with microphysics and eventually incorporating chemistry and aerosol effects on convection (Lee et al, 2009; Donner et al, 2016). While some schemes do not solve any equation for the vertical velocity, most of the ones doing so rely on slightly different implementations of the formulation proposed by Simpson and Wiggert (1969). However this equation does not take into account properly the effect of pressure perturbations, that influence maximum velocity and cloud top height, an issue addressed recently theoretically by Peters (2016); Morrison (2016a,b). Also, the role of buoyant and inertial acceleration in the triggering of convective mass-flux by cold pools has been addressed by Jeevanjee and Romps (2015).

The various cloud types that co-exist within a model grid cell are also involved in the life cycle of convective systems, an additional issue in that case being to represent the self-sustaining behavior of convection.

3 Improve the representation of convective memory and organization

3.1 Departure from quasi-equilibrium and memory

Even though several observational or CRM studies have shown the limitations of the quasi-equilibrium assumption between convection and the large-scale forcing introduced by Arakawa and Schubert (1974) (Zhang, 2002, 2003; Donner and Phillips, 2003), most climate model convective parameterizations still rely on it. However quasi-equilibrium breaks down for domains smaller than 250 km and when the forcing period becomes less than 30h for organized convection (Jones and Randall, 2011) and 12h for more scattered convection (Davies et al, 2013). In addition, even if quasi-equilibrium is observed over large domains or periods of time, it might best be used as an emergent behavior to evaluate a closure assumption rather than being a closure itself (Del Genio and Yao, 1993; Arakawa, 2004). The quasi-equilibrium hypothesis also does not account for convective memory effect (Davies et al, 2009). A way to include this effect is to introduce prognostic variables in the convection scheme. Pan and Randall (1998) propose a prognostic cumulus kinetic energy used to compute the cloud-base mass-flux. Some approaches introduce prognostic variables whose evolution depends on rain evaporation to modify the entrainment or closure formulations (Piriou et al, 2007; Hohenegger and Bretherton, 2011; Mapes and Neale, 2011; Chen and Mapes, 2018), without representing explicitly the physical processes responsible for these feedbacks (downdrafts, cold pools). Recently, Colin et al (2018) show using idealized CRM experiments that convective memory is mostly carried out by low-level thermodynamic structures and is enhanced when convection is organized at the mesoscale.

In recent years, attempts have been made to represent more explicitly the complex physics of processes involved in the self-sustaining behavior of convection. Grandpeix and Lafore (2010) introduce a full parameterization of an ensemble of cold pools whose thermodynamic properties and fractional coverage are prognostic and driven by unsaturated downdrafts of the Emanuel (1991) deep convection scheme. In turn, the cold pool parameterization provides a lifting energy and power used for the triggering and closure computations of the deep convection scheme. The number of cold pools per unit area is shown to be a key parameter of the parameterization (Grandpeix et al, 2010) which is different over land and ocean. Via a parameterization of intermediate complexity, Del Genio et al (2015) regulate the occurrence of weakly entraining convection by cold pools whose evolution is computed via the introduction of two prognostic variables (the cold pool area and pressure depth) and by relaxing their thermodynamic properties to those of the undisturbed boundary-layer on different time scales over land and ocean. In a unified framework, Park (2014a) introduces memory via a prognostic treatment of the sub-grid cold pool and mesoscale organized flow and their feedback on convective updrafts.

Without taking into account cold pools, some of the stochastic schemes presented in section 2.2 also introduce some memory effect via the use of Markov chains or a master equation (Peters et al, 2013; Hagos et al, 2018). An extended version of an EDMF scheme with a prognostic treatment of plume area fractions has also been proposed and tested in a 1D model by Tan et al (2018).

3.2 Towards mesoscale organization

Despite their importance for sustaining convection, only one operational GCM has represented any aspect of mesoscale convective systems (MCSs) (Donner et al, 2011), although several ideas for parameterizing various MCS effects have been proposed (Alexander and Cotton, 1998; Mapes and Neale, 2011; Khouider and Moncrieff, 2015; Yano and Moncrieff, 2016, 2018; Moncrieff et al, 2017). Doing so requires identifying which process controls the organization of deep convective cells: Wind shear, a moist free troposphere, and a long-lived moist boundary layer seem to promote “sustainability” of convection that precedes organization (Yuter and Houze, 1998; Houze, 2004; Schumacher and Houze, 2006). Traditionally, wind shear has received the most emphasis (Rotunno et al, 1988; Moncrieff and Liu, 1999), but convection can organize in weak shear as well (Houston and Wilhelmson, 2011). Cold pools generated by convective downdrafts are often a first step in deepening and sustaining convection (Khairoutdinov and Randall, 2006; Böing et al, 2012; Del Genio et al, 2012; Schlemmer and Hohenegger, 2014) and create memory as well. However, they do not explain organization in all cases; in the presence of a very moist boundary layer and low convective inhibition, gravity waves are probably the relevant organizing/propagation mechanism (Huang, 1990; Lane and Moncrieff, 2015; Grant et al, 2018). This has not been accounted for yet in any GCM.

Cold pools or gravity waves can be a precursor but actual organization implies subsequent development of a mesoscale circulation in the stratiform rain region (Houze, 2004). Sustaining convection to produce the thick anvil that generates the stratiform rain region places a premium on simulating the interaction between convective dynamics and the microphysics of convective ice, which determines detrainment and can affect climate sensitivity (Zhao et al, 2016). Radiative heating in the resulting anvil initiates a mesoscale updraft that nucleates more ice and ultimately drives a mesoscale downdraft via melting and evaporation of rain below (Houze, 2004). Cloud-resolving model simulations suggest that the magnitude of the updraft and downdraft can be constrained by the diabatic heating they produce (Del Genio et al, 2012).

Climate GCMs still operate at horizontal resolutions (50-200 km) at which MCSs are primarily deterministic and there is no horizontal propagation of convective systems, unless the resolved flow creates it. NWP models however run routinely at fine resolutions at which stochastic behavior is important. One suggestion for incorporating organization into a stochastic framework in such models is via cellular automata (Bengtsson et al, 2013).

3.3 Associated clouds and precipitation

Precipitation and clouds are involved in both the spatial organization and the time evolution of convective systems. Most microphysics schemes used in convection schemes are based on simple formulations that compute rain rates from liquid and ice thresholds and precipitation efficiency depending on pressure or updraft temperature involving tuning parameters (Zhang and McFarlane, 1995; Emanuel and Zivkovic-Rothman, 1999; Mauritsen and Stevens, 2015). Recently a two-moment diagnostic parameterization that calculates mass mixing ratio and number concentration of four hydrometeors (cloud liquid water, cloud ice, rain, snow) based on Morrison and Gettelman (2008) has been coupled to convection schemes (Song et al, 2012; Storer et al, 2015; Storer et al, 2015). Schemes including an equation for the vertical velocity can implicitly include the effects of microphysics in updrafts by specifying particle size distributions (PSDs) and size-fall speed relationships to partition precipitation and detrainment (e.g. Del Genio et al, 2005). When applied with PSDs and fall speeds derived from recent field experiments (Mitchell et al, 2011; Heymsfield et al, 2013), this approach can produce tropical anvil ice water paths in good agreement with satellite observations (Elsaesser et al, 2017). Realistic vertical velocities are also needed to adequately control aerosol activation of both liquid droplets and ice crystals (Feingold, 2003; McFiggans et al, 2006; Kay and Wood, 2008).

Regarding the computation of cloud cover, even if some early diagnostic cloud schemes have let deep convective clouds interact with radiation (Slingo, 1987), the lack of a proper coupling between convective suspended and falling hydrometeors and radiation is still responsible for important radiative biases of climate models (Li et al, 2016). Recently, several attempts have been made to improve convective cloud radiative effects based on LES analysis that have shown that the double-gaussian PDF is the most accurate to represent the subgrid scale cloud structure for both shallow and deep convection (Bogenschutz et al, 2010; Perraud et al, 2011) if the required input moments can be predicted or diagnosed accurately. Gaussian (Qin et al, 2018) and bigaussian (Jam et al, 2013; Hourdin et al, 2013) PDFs have been implemented in some models to represent shallow convective clouds with the PDF variances diagnosed from the turbulent and shallow convective processes. Double-Gaussian PDF are also used by Storer et al (2015) to extend the assumed probability density function method to deep convection. There is not yet a satisfactory way to treat the cloud cover associated with the anvil clouds formed by detrainment, even though prognostic stratiform cloud schemes that account for it exist (Tiedtke, 1993; Del Genio et al, 1996; Tompkins, 2002).

The most controversial aspect of convective clouds is their sensitivity to changes in aerosol concentration. In polluted environments, updrafts should nucleate more and thus yield smaller droplets, which would suppress rain by reducing fall speeds and increasing rain evaporation. However if the cloud deepens and the smaller droplets are more easily lifted into the mixed-phase region, they may increase ice formation and precipitation and invigorate convection instead (Rosenfeld et al, 2008). Fan et al (2018) suggest that in cleaner environments, condensation onto ultrafine aerosols and the resulting latent heat release is the invigoration mechanism. Khain (2009) summarizes possible aerosol and environmental influences on convective clouds, classifying them into regimes based on how condensate generation by aerosols competes with precipitation loss, to explain seemingly conflicting previous conclusions about aerosol suppression vs. invigoration. Unfortunately, it has been difficult to determine whether aerosol effects on convection are important, because in models, uncertainties in parameterized cloud microphysics greatly exceed the aerosol effect (White et al, 2017), while in real world case studies, meteorological and thermodynamic effects overwhelm any aerosol signal (Varble, 2018).

Disentangling the respective role of convective processes in the emergence of large-scale features proves to be difficult. Both radiative effects of convective clouds and convective transport play a role in the interactions between convection and the large-scale flow. In the last section, we discuss how the successive phases of the convective life-cycle interact with the large-scale and relevant observations to evaluate models at the process level.

4 Improve the representation of convection to large-scale interactions

4.1 Shallow convection

Shallow convective clouds are the saturated part of thermals initiated at the surface (LeMone and Pennell, 1976). Combining a mass-flux approach with a diffusion scheme within the boundary-layer produces a more efficient vertical transport in dry and shallow convective regimes. The associated enhanced export of the evaporated surface water to the dry troposphere and enhanced compensating subsidence enhances surface drying, in better agreement with observations over land (Cheruy et al, 2013; Diallo et al, 2017). Over ocean, this leads to an enhancement of the drying of the boundary-layer in subsiding regions. This increases the surface evaporative cooling, the underestimation of which was shown to explain part of the East Tropical Ocean (ETO) warm biases in CMIP simulations (Hourdin et al, 2015b). Shallow convection is also important for the injection to the free troposphere of trace species emitted at the surface (Locatelli et al, 2015), which are then further transported by deep convection (Folkins et al, 2006; Donner et al, 2007), as well as for coupling with chemistry (Nie et al, 2016). The mass-flux transport of horizontal momentum improves the representation of the diurnal cycle of near-surface winds, from desert areas, with a strong effect on dust lifting (Hourdin et al, 2015a), up to the Antarctic Plateau (Vignon et al, 2018).

The meridional distribution of the (shallow or deep) cloud radiative forcing has been shown from analysis of CMIP (Xiang et al, 2017) and idealized aquaplanet experiments (Dixit et al, 2018; Talib et al, 2018) to control the latitudinal distribution of tropical rainfall. This may be key to explain the systematic tendency of global models to overestimate convective rainfall south of the equator over the Atlantic and Pacific oceans (the so-called double ITCZ issue), as shown for example by Qin and Lin (2018). The underestimation of shadowing by strato-cumulus also in part explains systematic warm biases over ETO in CMIP models (Hourdin et al, 2015b).

Shallow convective clouds moreover explain a significant fraction of the range of cloud feedback estimates which dominate the spread in Equilibrium Climate Sensitivity (ECS) to greenhouse gases (Bony and Dufresne, 2005; Zelinka et al, 2016; Geoffroy et al, 2017; Vial et al, 2018). Aside from, or coupled with radiative effects, the literature increasingly emphasizes the role of vertical water vapor transport by convection (Sherwood et al, 2014; Klein et al, 2017; Cesana et al, 2018) or the condensate transport that determines detrainment of ice (Zhao et al, 2016) in the control of the ECS. The feedback from these clouds appears to be positive, due to drying of the subsiding regions in which these clouds occur. Observed inter-annual variations support such a conclusion (Klein et al, 2017). LES models subjected to an imposed climate change, though, find the feedback to be only weakly positive (Zhang et al, 2013).

4.2 Transition from shallow to deep convection

The transition from shallow to deep convection has received considerable attention, especially in connection with the representation of the diurnal cycle of precipitation (Couvreux et al, 2015) and medium-range predictability associated with the MJO (Klingaman et al, 2015). Various approaches have led to postpone diurnal deep convection initiation over land rather by modifying the convective entrainment formulation (Stratton and Stirling, 2012), modifying the CAPE closure (Bechtold et al, 2014) or introducing a separate EDMF scheme used to trigger deep convection (Rio et al, 2009; Rio et al, 2013). While models are known to rain too frequently (Dai, 2006) and to overestimate the autocorrelation with previous day precipitation over land (Roehrig et al, 2013), stochastic triggering is able to increase the day-to-day variability of precipitation over land (Rochetin et al, 2014b). The triggering criterion also strongly influences the MJO (Peters et al, 2017). An aspect that deserves more attention is the representation of the effect of sea breeze in deep convection initiation over islands, a key mechanism for the representation of precipitation over the maritime continent (Birch et al, 2015).

Once deep convection is initiated, a key issue is to be able to represent the correct partitioning between the various convective regimes and their respective effects. The often neglected congestus phase can influence the representation of spatio-temporal precipitation variations (Hirota et al, 2014). Numerous data analyses document the transition from shallow to deep convection and its association with the sensitivity of convection to free tropospheric humidity via entrainment (Morita et al, 2006; Benedict and Randall, 2007; Holloway and Neelin, 2009; Riley et al, 2011; Del Genio et al, 2012; Kuo et al, 2018). Still unresolved, though, is the tendency for models with strong intraseasonal variability caused by this sensitivity to also have strong positive tropical rain biases (Kim et al, 2011), suggesting that GCMs do not yet strike the right balance between suppressed and vigorous deep convection. Also, several studies point for the consequences of the misrepresentation of convective transport or microphysics on model biases: impact of momentum transport on large-scale fields (Zhang and Cho, 1991; Wu et al, 2007; Lane and Moncrieff, 2010; Orr et al, 2010; Woelfle et al, 2018), of convection induced gustiness on the structure of the ITCZ (Harrop et al, 2018), of convective entrainment on the double ITCZ syndrome (Oueslati and Bellon, 2015), of the assumed temperature at which convective updraft supercooled liquid water glaciates on the Southern Ocean shortwave radiation bias (Kay et al, 2016).

While recent developments have been directly based on in-situ data (Dorrestijn et al, 2013; Peters et al, 2013), surprisingly little effort has been made to validate the properties of either the spectrum of convective cells produced by parameterizations, or the "bulk plume" that represents their collective effects. Information about convective vertical velocities and/or mass fluxes now exists (Collis et al, 2013; Giangrande et al, 2013; Kumar et al, 2015; Giangrande et al, 2016; Masunaga and Luo, 2016; Labbouz et al, 2018). Combined with particle size distributions in convective outflow from field experiments and ice water path from satellites, detrainment can be evaluated (Elsaesser et al, 2017). Satellite observations now constrain the areal coverage and spatial distribution of convective cells (Fu et al, 1990; Schumacher and Houze, 2003; Sassen and Wang, 2008), and top height distribution (Takahashi et al, 2017), which might provide useful indirect constraints on entrainment.

4.3 Transition from deep to organized convection

Mesoscale convective systems (MCSs) are responsible for many important weather and climate phenomena: (1) Top-heavy heating that influences the tropical general circulation (Schumacher et al, 2004); (2) The maintenance and propagation of convection, which controls its diurnal peak (Nesbitt and Zipser, 2003); (3) Extreme precipitation events (Doswell et al, 1996; Houze and Churchill, 1987; Mathon et al, 2002; Moseley et al, 2016); (4) Coupling with large-scale tropical wave phenomena such as the Madden-Julian Oscillation (Xu and Rutledge, 2015) and possibly African easterly waves (Ventrice and Thorncroft, 2013); (5) The sign of convective momentum transport (Moncrieff et al, 2017); (6) Tropical cloudiness and energy balance (Kiehl, 1994; Rossow et al, 2005; Hartmann et al, 2018); (7) The cloud height feedback on climate (Hartmann and Larson, 2002).

The physical mechanisms responsible for the interaction of convection with these phenomena vary. In some situations, cold pools and their associated gust fronts may determine the organization and propagation speed of MCSs (e.g. Rotunno et al, 1988). In others, the system moves at a speed different from that of the cold pools (Lane and Moncrieff, 2015). Planetary-scale propagating disturbances usually have MCSs embedded in their disturbed phase. For some, such as the MJO, the MCSs are considered integral to the existence of the larger-scale phenomenon, since the mesoscale updrafts of the MCSs produce an extensive anvil cloud shield whose longwave heating is thought to be the ultimate source of moist static energy for the MJO (e.g. Andersen and Kuang, 2012; Kim et al, 2015). The mesoscale updraft-downdraft combination in the stratiform rain regions of many MCSs produces a dipole heating anomaly that shifts the overall heating profile of the system upwards, intensifying the upper-level large scale tropical circulation (Schumacher et al, 2004). GCMs currently represent all these interactions via their cellular convection or grid-scale condensation schemes since they do not represent MCSs.

The question for any convective organization scheme is the extent to which it reproduces the real-world behavior of MCSs: the extent to which their existence and behavior is deterministic vs. stochastic; the convective-stratiform partitioning of rain; the shape of the heating profile; and the clouds they produce. Validation of cold pool parameterizations has relied mostly on anecdotal information (Rozbicki et al, 1999), but statistics of observed (Zuidema et al, 2017; Schiro and Neelin, 2018) and simulated (Feng et al, 2015) downdrafts and cold pools now exist. Databases of satellite-derived MCS lifecycles and tracks also exist (Fiolleau and Roca, 2013) as do estimates of their macrophysical and microphysical properties (Bouniol et al, 2016), and of the convective-stratiform partitioning and heating profiles (Lang and Tao, 2018; Shige, 2009). These have not been widely utilized by the parameterization community. To the extent that such products have been used in model intercomparisons (e.g. Dai, 2006), model-data agreement must be interpreted as the result of compensations for missing physics in other parts of the parameterization since most models do not represent the mesoscale processes that actually determine convective-stratiform partitioning and the shape of the heating profile.

5 Discussion and conclusions

While a part of the community doubts parameterization will ever work for convection, recent developments of new concepts and approaches synthesized here rather draw the picture of ongoing breakthroughs in convective parameterizations in recent years. Consequently, while the computationally intensive approaches will continue to progress toward the ultimate goal of reducing the problem to parameterizations of microphysics, turbulence, and radiation, we anticipate vigorous parallel development of traditional parameterizations to include all the processes that need to be represented to understand the mechanisms of climate change. Indeed, several shortcomings of traditional parameterizations are being tackled by ongoing developments in different groups: the underestimation of vertical transport by shallow cumulus clouds by the development of unified approaches for boundary-layer dry and moist convection; the hypothesis that cumulus clouds cover a small fraction of a grid cell by scale-aware approaches; the mean bulk hypothesis by the consideration of a spectrum of cloud types of different sizes or stochastic entrainment; the quasi-equilibrium hypothesis by the introduction of new prognostic variables to allow both quasi-equilibrium and departures from it, depending on the situation; the too-short lived convective systems by the development of approaches to represent cold pools or, even still few, mesoscale circulations. The improvement of the representation of clouds associated with convection, including more fundamental approaches to precipitation efficiency and microphysics, certainly deserves to be reinforced, since it is as much involved in the interaction between convection and the large-scale as convective transport and is essential for any attempt to simulate aerosol-convection interactions. The role a convection scheme has to play at gray-zone resolutions also needs to be clarified, as some studies highlight that models without any cumulus parameterization perform better than models with parameterized convection at those resolutions, despite the fact that gray zone models do not explicitly resolve convective cells. This is verified for example when comparing models run at horizontal resolutions from 4 to 40 km with either parameterized or explicit convection over West

Africa (Birch et al, 2014) and over the Indian ocean (Holloway et al, 2012, 2013, 2015). A fundamental issue to be addressed is how cumulus parameterizations deteriorate feedbacks relevant for large-scale features such as the West-African monsoon or the Madden Julian Oscillation and what key behaviors cumulus (and other) parameterizations need to have in order to add value at these resolutions.

It will certainly still take time until developments concerning all those aspects of convection are developed and implemented in every operational model. Indeed, side by side with this enthusiastic picture, there is still the feeling that progress is slow in climate models. Several issues may deserve more attention. Only a few recent studies explore in a systematic way the sensitivity of convective parameterizations to the value of the very uncertain free parameters (Bernstein and Neelin, 2016). The use of “meta-models” or “emulators”, developed in the community of Uncertainty Quantification (Sacks et al, 1989; Williamson et al, 2015) may help explore more efficiently the parameter space and address an issue which is often informally discussed among climate modeling groups: the fact that significant changes in the rainfall distribution after changes of convective parameterization are often overruled by the subsequent re-tuning of the clouds’ radiative effect (Hourdin et al, 2017). This is a fundamental result of the fact that in steady state, atmospheric latent heating must balance radiative cooling, an unavoidable consequence of global coupled modeling (Schmidt et al, 2017). One relevant example is the apparent importance of radiative forcing for the presence or absence of features such as the double ITCZ bias. One consequence of this coupling between latent heating and radiative cooling is that if non-convective processes are not realistically represented, convection will have to be tuned in unrealistic directions to compensate. This may partly explain why potential improvements to cumulus parameterizations identified in studies that look only at some aspect of the convection itself often do not find their way into operational models. To make progress, a more integrated view of convection within the larger scope of other processes that affect the hydrologic cycle and energy cycle is required. For example, Webb et al (2015) show that removing the cumulus parameterization from a sample of GCMs significantly changes the cloud feedback in some of them, but not the overall spread in cloud feedback, and that the changes in feedback are greatly reduced when the models clouds’ are rescaled to the observed cloud radiative effect in the current climate.

The weight given to parameterization development vs. intercomparison exercises deserves serious discussion by the community as well. CMIP exercises have become central in climate modeling, and they are indeed the only way to properly measure the progress in fully integrated climate models and evaluate the component of uncertainties in climate modeling that comes from model “structural errors”. Many studies, some of them discussed in Section 4, have made full use of CMIP simulations (and in particular of pairs of atmosphere-only and coupled simulations (Xiang et al, 2017; Hourdin et al, 2015b) which constitute the essence of the CMIP6 “DECK”) to identify important processes which should be better parameterized. Comparatively, studies that try alternative solutions (such as those proposed in Sections 2 and 3) in real climate models are fewer. When such studies test changes in convection, taking into account a proper retuning of the model (Zhao et al, 2016), they underline the difficulty in disentangling the coupling between the various aspects of the physics parameterizations (convective transport, cloud micro- and macro-physics, convective moisture transport). The use of a hierarchy of model configurations is probably a promising path to follow: SCM configurations for detailed comparison with LES, 3D nudged simulations to get synoptic observations in phase with in situ observations, Transpose-

AMIP approaches to look at the fast response of model errors and finally atmosphere-alone and coupled models. Analysis of the recent literature suggests that those approaches are more efficient when used simultaneously in a single model to disentangle processes, than across models as a basis for new intercomparison exercises, the human cost of which is probably underestimated.

Another issue is to get rid of the tyranny of traditional metrics in favor of process-oriented metrics (Jakob, 2010). Large-scale phenomena such as the ITCZ, MJO, etc., as well as mean state biases, are often used to validate cumulus parameterizations, but emergent behavior of this kind can only be considered a necessary, rather than sufficient, condition for having confidence in any cumulus parameterization. The use of traditional metrics has not led to narrowing the range of model predictions of climate change, suggesting that these metrics do not target behaviors of the models that matter for their intended use. Even worse, reliance on such metrics discourages experimentation with novel approaches, which when implemented in models often make the models worse before they are fully understood. Likewise, "emergent constraints," though intended to bypass the problems of traditional mean state bias metrics, often have their own problems. Caldwell et al (2018) find that most proposed constraints on equilibrium climate sensitivity do not pass one or more tests for plausibility. Before large-scale emergent behavior is evaluated, cumulus parameterization performance needs to be measured against observational constraints closer to the process level. As discussed in section 4, the convective life cycle, which can be described as a progression from shallow to deep to organized mesoscale convection (Mapes et al, 2006), provides a useful framework for thinking about cumulus parameterization at the process level and for connecting parameterization development to explicit models and observations.

The last issue is the scheme complexity. The recent developments described above often result in an increasing complexity of the schemes with some counterparts: a difficulty to fully describe one particular scheme in the literature, making difficult the discussion of concepts and comparison of approaches, the increased probability of conceptual errors and bugs in codes that nobody else other than the developer can identify, and finally the difficulty to make new approaches work in real weather prediction or climate models (due to cost, numerical instability, difficulty in correcting undesirable behaviors when coupled to the dynamics). Reaching real progress in the representation of convection in climate models is probably not only a question of new brilliant ideas or concepts, but also a multi-dimensional issue that concerns physics understanding of convective systems, observations, tuning, methodological aspects, numerical issues and coding as well as human organization of modeling teams and priorities of research programs. Nonetheless, the progress that has occurred in recent years, despite these roadblocks, suggests that the field of cumulus parameterization development is more dynamic and promising than it seemed to be some decades ago.

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References

Alexander GD, Cotton WR (1998) The use of cloud-resolving simulations of mesoscale convective systems to build a mesoscale parameterization scheme. Journal of the atmospheric sciences 55(12):2137–2161

Andersen JA, Kuang Z (2012) Moist static energy budget of mjo-like disturbances in the atmosphere of a zonally symmetric aquaplanet. Journal of Climate 25(8):2782–2804

Arakawa A (2004) The cumulus parameterization problem: Past, present, and future. Journal of Climate 17(13):2493–2525, DOI 10.1175/1520-0442(2004)017¡2493:RATCPP¿2.0.CO;2

Arakawa A, Wu CM (2013) A unified representation of deep moist convection in numerical modeling of the atmosphere. part i. Journal of the Atmospheric Sciences 70(7):1977–1992, DOI 10.1175/JAS-D-12-0330.1

Arakawa RA, Schubert WH (1974) Interaction of a cumulus cloud ensemble with the large scale environment. part I. J Atmos Sci 31:674–701

Bechtold P, Semane N, Lopez P, Chaboureau JP, Beljaars A, Bormann N (2014) Representing equilibrium and nonequilibrium convection in large-scale models. Journal of the Atmospheric Sciences 71(2):734–753

Becker T, Bretherton CS, Hohenegger C, Stevens B (2018) Estimating bulk entrainment with unaggregated and aggregated convection. Geophysical Research Letters 45(1):455–462

Benedict JJ, Randall DA (2007) Observed characteristics of the mjo relative to maximum rainfall. Journal of the atmospheric sciences 64(7):2332–2354

Bengtsson L, Steinheimer M, Bechtold P, Geleyn JF (2013) A stochastic parametrization for deep convection using cellular automata. Quarterly Journal of the Royal Meteorological Society 139(675):1533–1543

Bernstein DN, Neelin JD (2016) Identifying sensitive ranges in global warming precipitation change dependence on convective parameters. Geophys Res Lett 43:5841–5850, DOI 10.1002/2016GL069022

Bhattacharya R, Bordoni S, Suselj K, Teixeira J (2018) Parameterization Interactions in Global Aquaplanet Simulations. J of Adv in Modeling Earth Systems 10:403–420, DOI 10.1002/2017MS000991

Birch CE, Parker DJ, Marsham JH, Copsey D, Garcia-Carreras L (2014) A seamless assessment of the role of convection in the water cycle of the west african monsoon. Journal of Geophysical Research: Atmospheres 119(6):2890–2912, DOI 10.1002/2013JD020887

Birch CE, Roberts MJ, Garcia-Carreras L, Ackerley D, Reeder MJ, Lock AP, Schiemann R (2015) Sea-breeze dynamics and convection initiation: The influence of convective parameterization in weather and climate model biases. Journal of Climate 28(20):8093–8108

Bogenschutz PA, Krueger SK, Khairoutdinov M (2010) Assumed probability density functions for shallow and deep convection. Journal of Advances in Modeling Earth Systems 2(4)

Böing SJ, Jonker HJ, Siebesma AP, Grabowski WW (2012) Influence of the subcloud layer on the development of a deep convective ensemble. Journal of the Atmospheric Sciences 69(9):2682–2698

Böing SJ, Jonker HJ, Nawara WA, Siebesma AP (2014) On the deceiving aspects of mixing diagrams of deep cumulus convection. Journal of the Atmospheric Sciences 71(1):56–68

Bony S, Dufresne JL (2005) Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. Geophysical Research Letters 32(20)

Bouniol D, Roca R, Fiolleau T, Poan DE (2016) Macrophysical, microphysical, and radiative properties of tropical mesoscale convective systems over their life cycle. Journal of Climate 29(9):3353–3371

Caldwell PM, Zelinka MD, Klein SA (2018) Evaluating emergent constraints on equilibrium climate sensitivity. Journal of Climate 31(10):3921–3942

Cesana G, Del Genio AD, Ackerman AS, Kelley M, Elsaesser G, Fridlind AM, Cheng Y, Yao MS (2018) Evaluating models' response of tropical low clouds to sst forcings using calipso observations. Atmos Chem Phys, submitted

Chen B, Mapes BE (2018) Effects of a simple convective organization scheme in a two-plume gcm. Journal of Advances in Modeling Earth Systems 10(3):867–880

Cheruy F, Campoy A, Dupont JC, Ducharne A, Hourdin F, Haeffelin M, Chiriaco M, Idelkadi A (2013) Combined influence of atmospheric physics and soil hydrology on the simulated meteorology at the SIRTA atmospheric observatory. Clim Dyn 40:2251–2269, DOI 10.1007/s00382-012-1469-y

Colin M, Sherwood S, Geoffroy O, Bony S, Fuchs D (2018) Identifying the sources of convective memory in cloud-resolving simulations. Journal of the Atmospheric Sciences 0(0):null, DOI 10.1175/JAS-D-18-0036.1

Collis S, Protat A, May PT, Williams C (2013) Statistics of storm updraft velocities from twp-ice including verification with profiling measurements. Journal of Applied Meteorology and Climatology 52(8):1909–1922

Couvreux F, Roehrig R, Rio C, Lefebvre MP, Caian M, Komori T, Derbyshire S, Guichard F, Favot F, D'Andrea F, et al (2015) Representation of daytime moist convection over the semi-arid tropics by parametrizations used in climate and meteorological models. Quarterly Journal of the Royal Meteorological Society 141(691):2220–2236

Dai A (2006) Precipitation characteristics in eighteen coupled climate models. Journal of Climate 19(18):4605–4630

D'Andrea F, Gentine P, Betts AK, Lintner BR (2014) Triggering Deep Convection with a Probabilistic Plume Model. J Atmos Sci 71:3881–3901, DOI 10.1175/JAS-D-13-0340.1

Davies L, Plant RS, Derbyshire SH (2009) A simple model of convection with memory. Journal of Geophysical Research: Atmospheres 114(D17)

Davies L, Plant R, Derbyshire S (2013) Departures from convective equilibrium with a rapidly varying surface forcing. Quarterly Journal of the Royal Meteorological Society 139(676):1731–1746

Del Genio A, Yao M (1993) Efficient Cumulus Parameterization for Long-Term Climate Studies: The GISS Scheme, pp 181–184

Del Genio AD, Wu J (2010) The role of entrainment in the diurnal cycle of continental convection. Journal of Climate 23(10):2722–2738

Del Genio AD, Yao MS, Kovari W, Lo KK (1996) A prognostic cloud water parameterization for global climate models. Journal of Climate 9(2):270–304

Del Genio AD, Kovari W, Yao MS, Jonas J (2005) Cumulus microphysics and climate sensitivity. Journal of climate 18(13):2376–2387

Del Genio AD, Chen Y, Kim D, Yao MS (2012) The mjo transition from shallow to deep convection in cloudsat/calipso data and giss gcm simulations. Journal of Climate 25(11):3755–3770

Del Genio AD, Wu J, Wolf AB, Chen Y, Yao MS, Kim D (2015) Constraints on cumulus parameterization from simulations of observed mjo events. Journal of Climate 28(16):6419–6442

Deng Q, Khouider B, Majda AJ (2015) The mjo in a coarse-resolution gcm with a stochastic multicloud parameterization. Journal of the Atmospheric Sciences 72(1):55–74

Diallo FB, Hourdin F, Rio C, Traore AK, Mellul L, Guichard F, Kergoat L (2017) The surface energy budget computed at the grid-scale of a climate model challenged by station data in west africa. J of Adv in Modeling Earth Systems 9(7):2710–2738, DOI 10.1002/2017MS001081, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017MS001081

Dixit V, Geoffroy O, Sherwood SC (2018) Control of ITCZ Width by Low-Level Radiative Heating From Upper-Level Clouds in Aquaplanet Simulations. Geophys Res Lett 45:5788–5797, DOI 10.1029/2018GL078292

Donner LJ (1993) A cumulus parameterization including mass fluxes, vertical momentum dynamics, and mesoscale effects. Journal of the Atmospheric Sciences 50(6):889–906, DOI 10.1175/1520-0469(1993)050¡0889:ACPIMF¿2.0.CO;2

Donner LJ, Phillips VT (2003) Boundary layer control on convective available potential energy: Implications for cumulus parameterization. Journal of Geophysical Research: Atmospheres 108(D22), DOI 10.1029/2003JD003773

Donner LJ, Horowitz LW, Fiore AM, Seman CJ, Blake DR, Blake NJ (2007) Transport of radon-222 and methyl iodide by deep convection in the gfdl global atmospheric model am2. Journal of Geophysical Research: Atmospheres 112(D17), DOI 10.1029/2006JD007548

Donner LJ, Wyman BL, Hemler RS, Horowitz LW, Ming Y, Zhao M, Golaz JC, Ginoux P, Lin SJ, Schwarzkopf MD, et al (2011) The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component am3 of the gfdl global coupled model cm3. Journal of Climate 24(13):3484–3519

Donner LJ, O'Brien TA, Rieger D, Vogel B, Cooke WF (2016) Are atmospheric updrafts a key to unlocking climate forcing and sensitivity? Atmospheric Chemistry and Physics 16(20):12,983–12,992

Dorrestijn J, Crommelin DT, Siebesma AP, Jonker HJ (2013) Stochastic parameterization of shallow cumulus convection estimated from high-resolution model data. Theoretical and Computational Fluid Dynamics 27(1-2):133–148

Dorrestijn J, Crommelin DT, Siebesma AP, Jonker HJ, Selten F (2016) Stochastic convection parameterization with markov chains in an intermediate-complexity gcm. Journal of the Atmospheric Sciences 73(3):1367–1382

Doswell I, Charles A, Brooks HE, Maddox RA (1996) Flash flood forecasting: An ingredients-based methodology. Weather and Forecasting 11(4):560–581

Elsaesser GS, Del Genio AD, Jiang JH, van Lier-Walqui M (2017) An improved convective ice parameterization for the nasa giss global climate model and impacts on cloud ice simulation. Journal of Climate 30(1):317–336

Emanuel KA (1991) A scheme for representing cumulus convection in large-scale models. J Atmos Sci 48:2313–2335

Emanuel KA, Zivkovic-Rothman M (1999) Development and Evaluation of a Convection Scheme for Use in Climate Models. J Atmos Sci 56:1766–1782, DOI 10.1175/1520-0469(1999)056¡1766:DAEOAC¿2.0.CO;2

Fan J, Rosenfeld D, Zhang Y, Giangrande SE, Li Z, Machado LA, Martin ST, Yang Y, Wang J, Artaxo P, et al (2018) Substantial convection and precipitation enhancements by ultrafine aerosol particles. Science 359(6374):411–418

Feingold G (2003) Modeling of the first indirect effect: Analysis of measurement requirements. Geophysical Research Letters 30(19), DOI 10.1029/2003GL017967

Feng Z, Hagos S, Rowe AK, Burleyson CD, Martini MN, de Szoeke SP (2015) Mechanisms of convective cloud organization by cold pools over tropical warm ocean during the amie/dynamo field campaign. Journal of Advances in Modeling Earth Systems 7(2):357–381

Fiolleau T, Roca R (2013) An algorithm for the detection and tracking of tropical mesoscale convective systems using infrared images from geostationary satellite. IEEE transactions on Geoscience and Remote Sensing 51(7):4302–4315

Folkins I, Bernath P, Boone C, Donner LJ, Eldering A, Lesins G, Martin RV, Sinnhuber BM, Walker K (2006) Testing convective parameterizations with tropical measurements of hno3, co, h2o, and o3: Implications for the water vapor budget. Journal of Geophysical Research: Atmospheres 111(D23), DOI 10.1029/2006JD007325

Fu R, Del Genio AD, Rossow WB (1990) Behavior of deep convective clouds in the tropical pacific deduced from isccp radiances. Journal of climate 3(10):1129–1152

Gentine P, Pritchard M, Rasp S, Reinaudi G, Yacalis G (2018) Could machine learning break the convection parameterization deadlock? Geophysical Research Letters 45(11):5742–5751, DOI 10.1029/2018GL078202

Geoffroy O, Sherwood SC, Fuchs D (2017) On the role of the stratiform cloud scheme in the inter-model spread of cloud feedback. J of Adv in Modeling Earth Systems 9:423–437, DOI 10.1002/2016MS000846

Giangrande SE, Collis S, Straka J, Protat A, Williams C, Krueger S (2013) A summary of convective-core vertical velocity properties using arm uhf wind profilers in oklahoma. Journal of Applied Meteorology and Climatology 52(10):2278–2295

Giangrande SE, Toto T, Jensen MP, Bartholomew MJ, Feng Z, Protat A, Williams CR, Schumacher C, Machado L (2016) Convective cloud vertical velocity and mass-flux characteristics from radar wind profiler observations during goamazon2014/5. Journal of Geophysical Research: Atmospheres 121(21)

Glenn IB, Krueger SK (2014) Downdrafts in the near cloud environment of deep convective updrafts. Journal of Advances in Modeling Earth Systems 6(1):1–8

Goswami B, Khouider B, Phani R, Mukhopadhyay P, Majda A (2017a) Implementation and calibration of a stochastic multicloud convective parameterization in the ncep c limate f orecast s ystem (cfsv2). Journal of Advances in Modeling Earth Systems 9(3):1721–1739

Goswami B, Khouider B, Phani R, Mukhopadhyay P, Majda A (2017b) Improving synoptic and intraseasonal variability in cfsv2 via stochastic representation of organized convection. Geophysical Research Letters 44(2):1104–1113

Grabowski WW (2016) Towards global large eddy simulation: Super-parameterization revisited. J Met Soc Japan 94(4):327–344, DOI 10.2151/jmsj.2016-017

Grandpeix J, Lafore J (2010) A Density Current Parameterization Coupled with Emanuel's Convection Scheme. Part I: The Models. Journal of Atmospheric Sciences 67:881–897, DOI 10.1175/2009JAS3044.1

Grandpeix J, Lafore J, Cheruy F (2010) A Density Current Parameterization Coupled with Emanuel's Convection Scheme. Part II: 1D Simulations. Journal of Atmospheric Sciences 67:898–922, DOI 10.1175/2009JAS3045.1

Grandpeix JY, Phillips V, Tailleux R (2004) Improved mixing representation in Emanuel's convection scheme. Q J R Meteorol Soc 130:3207–3222

Grant LD, Lane TP, van den Heever SC (2018) The role of cold pools in tropical oceanic convective systems. Journal of the Atmospheric Sciences (2018)

Gregory D, Rowntree PR (1990) A mass flux convection scheme with representation of cloud ensemble characteristics and stability-dependent closure. Monthly Weather Review 118(7):1483–1506, DOI 10.1175/1520-0493(1990)118¡1483:AMFCSW¿2.0.CO;2

Grell GA (1993) Prognostic evaluation of assumptions used by cumulus parameterizations. Monthly Weather Review 121(3):764–787, DOI 10.1175/1520-0493(1993)121¡0764:PEOAUB¿2.0.CO;2

Guo H, Golaz JC, Donner LJ, Ginoux P, Hemler RS (2014) Multivariate Probability Density Functions with Dynamics in the GFDL Atmospheric General Circulation Model: Global Tests. J Climate 27:2087–2108, DOI 10.1175/JCLI-D-13-00347.1

Guo H, Golaz JC, Donner LJ, Wyman B, Zhao M, Ginoux P (2015) CLUBB as a unified cloud parameterization: Opportunities and challenges. Geophys Res Lett 42:4540–4547, DOI 10.1002/2015GL063672

Guérémy JF (2011) A continuous buoyancy based convection scheme: one- and three-dimensional validation. Tellus A 63(4):687–706, DOI 10.1111/j.1600-0870.2011.00521.x

Hagos S, Feng Z, Plant RS, Houze JRA, Xiao H (2018) A stochastic framework for modeling the population dynamics of convective clouds. Journal of Advances in Modeling Earth Systems 10(2):448–465

Hannah WM (2017) Entrainment versus dilution in tropical deep convection. Journal of the Atmospheric Sciences 74(11):3725–3747

Harrop BE, Ma PL, Rasch PJ, Neale RB, Hannay C (2018) The Role of Convective Gustiness in Reducing Seasonal Precipitation Biases in the Tropical West Pacific. J of Adv in Modeling Earth Systems 10:961–970, DOI 10.1002/2017MS001157

Hartmann DL, Larson K (2002) An important constraint on tropical cloud-climate feedback. Geophysical Research Letters 29(20):12–1

Hartmann DL, Gasparini B, Berry SE, Blossey PN (2018) The life cycle and net radiative effect of tropical anvil clouds. Journal of Advances in Modeling Earth Systems 10(12):3012–3029

Heus T, Jonker HJ (2008) Subsiding shells around shallow cumulus clouds. Journal of the Atmospheric Sciences 65(3):1003–1018

Heymsfield AJ, Schmitt C, Bansemer A (2013) Ice cloud particle size distributions and pressure-dependent terminal velocities from in situ observations at temperatures from 0 to- 86 c. Journal of the Atmospheric Sciences 70(12):4123–4154

Hirota N, Takayabu YN, Watanabe M, Kimoto M, Chikira M (2014) Role of convective entrainment in spatial distributions of and temporal variations in precipitation over tropical oceans. Journal of Climate 27(23):8707–8723

Hohenegger C, Bretherton CS (2011) Simulating deep convection with a shallow convection scheme. Atmospheric Chemistry and Physics 11(20):10,389–10,406

Holloway C, Woolnough S, Lister G (2012) Precipitation distributions for explicit versus parametrized convection in a large-domain high-resolution tropical case study. Quarterly Journal of the Royal Meteorological Society 138(668):1692–1708

Holloway CE, Neelin JD (2009) Moisture vertical structure, column water vapor, and tropical deep convection. Journal of the atmospheric sciences 66(6):1665–1683

Holloway CE, Woolnough SJ, Lister GM (2013) The effects of explicit versus parameterized convection on the mjo in a large-domain high-resolution tropical case study. part i: Characterization of large-scale organization and propagation. Journal of the Atmospheric Sciences 70(5):1342–1369

Holloway CE, Woolnough SJ, Lister GM (2015) The effects of explicit versus parameterized convection on the mjo in a large-domain high-resolution tropical case study. part ii: Processes leading to differences in mjo development. Journal of the Atmospheric Sciences 72(7):2719–2743

Hourdin F, Couvreux F, Menut L (2002) Parameterisation of the dry convective boundary layer based on a mass flux representation of thermals. J Atmos Sci 59:1105–1123

Hourdin F, Grandpeix JY, Rio C, Bony S, Jam A, Cheruy F, Rochetin N, Fairhead L, Idelkadi A, Musat I, Dufresne JL, Lahellec A, Lefebvre MP, Roehrig R (2013) LMDZ5B: the atmospheric component of the IPSL climate model with revisited parameterizations for clouds and convection. Clim Dyn 40:2193–2222, DOI 10.1007/s00382-012-1343-y

Hourdin F, Gueye M, Diallo B, Dufresne JL, Escribano J, Menut L, Marticoréna B, Siour G, Guichard F (2015a) Parameterization of convective transport in the boundary layer and its impact on the representation of the diurnal cycle of wind and dust emissions. Atmosph Chemist and Physics 15:6775–6788, DOI 10.5194/acp-15-6775-2015

Hourdin F, Găinusă-Bogdan A, Braconnot P, Dufresne JL, Traore AK, Rio C (2015b) Air moisture control on ocean surface temperature, hidden key to the warm bias enigma. Geophys Res Lett 42:10, DOI 10.1002/2015GL066764

Hourdin F, Mauritsen T, Gettelman A, Golaz JC, Balaji V, Duan Q, Folini D, Ji D, Klocke D, Qian Y, Rauser F, Rio C, Tomassini L, Watanabe M, Williamson D (2017) The Art and Science of Climate Model Tuning. Bull Am Meteorol Soc 98:589–602, DOI 10.1175/BAMS-D-15-00135.1

Houston AL, Wilhelmson RB (2011) The dependence of storm longevity on the pattern of deep convection initiation in a low-shear environment. Monthly Weather Review 139(10):3125–3138

Houze JRA (2004) Mesoscale convective systems. Reviews of Geophysics 42(4)

Houze RA, Churchill DD (1987) Mesoscale organization and cloud microphysics in a bay of bengal depression. Journal of the atmospheric sciences 44(14):1845–1868

Huang XY (1990) The organization of moist convection by internal gravity waves. Tellus A: Dynamic Meteorology and Oceanography 42(2):270–285

Jakob C (2010) Accelerating progress in global atmospheric model development through improved parameterizations. Bulletin of the American Meteorological Society 91(7):869–876, DOI 10.1175/2009BAMS2898.1

Jam A, Hourdin F, Rio C, Couvreux F (2013) Resolved versus parametrized boundary-layer plumes. part iii: Derivation of a statistical scheme for cumulus clouds. Boundary-layer meteorology 147(3):421–441

Jeevanjee N, Romps DM (2015) Effective buoyancy, inertial pressure, and the mechanical generation of boundary layer mass flux by cold pools. Journal of the Atmospheric Sciences 72(8):3199–3213, DOI 10.1175/JAS-D-14-0349.1

Johnson RH, Rickenbach TM, Rutledge SA, Ciesielski PE, Schubert WH (1999) Trimodal characteristics of tropical convection. Journal of Climate 12(8):2397–2418, DOI 10.1175/1520-0442(1999)012¡2397:TCOTC¿2.0.CO;2

Jones TR, Randall DA (2011) Quantifying the limits of convective parameterizations. Journal of Geophysical Research: Atmospheres 116(D8)

Kain JS, Fritsch JM (1990) A one-dimensional entraining/detraining plume model and its application in convective parameterization. Journal of the Atmospheric Sciences 47(23):2784–2802, DOI 10.1175/1520-0469(1990)047¡2784:AODEPM¿2.0.CO;2

Kay J, Wood R (2008) Timescale analysis of aerosol sensitivity during homogeneous freezing and implications for upper tropospheric water vapor budgets. Geophysical Research Letters 35, DOI 10.1029/2007GL032628

Kay JE, Wall C, Yettella V, Medeiros B, Hannay C, Caldwell P, Bitz C (2016) Global climate impacts of fixing the southern ocean shortwave radiation bias in the community earth system model (cesm). Journal of Climate 29(12):4617–4636

Keane R, Plant R (2012) Large-scale length and time-scales for use with stochastic convective parametrization. Quarterly Journal of the Royal Meteorological Society 138(666):1150–1164

Keane RJ, Craig GC, Keil C, Zängl G (2014) The plant–craig stochastic convection scheme in icon and its scale adaptivity. Journal of the Atmospheric Sciences 71(9):3404–3415

Keane RJ, Plant RS, Tennant WJ (2016) Evaluation of the plant–craig stochastic convection scheme (v2. 0) in the ensemble forecasting system mogreps-r (24 km) based on the unified model (v7. 3). Geoscientific Model Development 9(5):1921–1935

Khain A (2009) Notes on state-of-the-art investigations of aerosol effects on precipitation: a critical review. Environmental Research Letters 4(1):015,004

Khairoutdinov M, Randall D (2006) High-resolution simulation of shallow-to-deep convection transition over land. Journal of the atmospheric sciences 63(12):3421–3436

Khouider B, Moncrieff MW (2015) Organized convection parameterization for the itcz. Journal of the Atmospheric Sciences 72(8):3073–3096

Khouider B, Biello J, Majda AJ, et al (2010) A stochastic multicloud model for tropical convection. Communications in Mathematical Sciences 8(1):187–216

Kiehl J (1994) On the observed near cancellation between longwave and shortwave cloud forcing in tropical regions. Journal of Climate 7(4):559–565

Kim D, Sobel AH, Maloney ED, Frierson DM, Kang IS (2011) A systematic relationship between intraseasonal variability and mean state bias in agcm simulations. Journal of Climate 24(21):5506–5520

Kim D, Ahn MS, Kang IS, Del Genio AD (2015) Role of longwave cloud–radiation feedback in the simulation of the madden–julian oscillation. Journal of Climate 28(17):6979–6994

Klein S, Hall A, Norris J, Pincus R (2017) Low-Cloud Feedbacks from Cloud-Controlling Factors: A Review, vol 65

Klingaman NP, Jiang X, Xavier PK, Petch J, Waliser D, Woolnough SJ (2015) Vertical structure and physical processes of the madden-julian oscillation: Synthesis and summary. Journal of Geophysical Research: Atmospheres 120(10):4671–4689

Köhler M, Ahlgrimm M, Beljaars A (2011) Unified treatment of dry convective and stratocumulus-topped boundary layers in the ECMWF model. Q J R Meteorol Soc 137:43–57, DOI 10.1002/qj.713

Kumar VV, Jakob C, Protat A, Williams CR, May PT (2015) Mass-flux characteristics of tropical cumulus clouds from wind profiler observations at darwin, australia. Journal of the Atmospheric Sciences 72(5):1837–1855

Kuo YH, Schiro KA, Neelin JD (2018) Convective transition statistics over tropical oceans for climate model diagnostics: Observational baseline. Journal of the Atmospheric Sciences 75(5):1553–1570

Kwon YC, Hong SY (2017) A mass-flux cumulus parameterization scheme across gray-zone resolutions. Monthly Weather Review 145(2):583–598, DOI 10.1175/MWR-D-16-0034.1

Labbouz L, Kipling Z, Stier P, Protat A (2018) How well can we represent the spectrum of convective clouds in a climate model? comparisons between internal parameterization variables and radar observations. Journal of the Atmospheric Sciences 75(5):1509–1524

Lane TP, Moncrieff MW (2010) Characterization of momentum transport associated with organized moist convection and gravity waves. Journal of the Atmospheric Sciences 67(10):3208–3225

Lane TP, Moncrieff MW (2015) Long-lived mesoscale systems in a low–convective inhibition environment. part i: Upshear propagation. Journal of the Atmospheric Sciences 72(11):4297–4318

Lang S, Tao WK (2018) The next-generation goddard convective-stratiform heating algorithm: New tropical and warm season retrievals for gpm. J Clim 31:5997–6026

Lee SS, Donner LJ, Phillips VT (2009) Impacts of aerosol chemical composition on microphysics and precipitation in deep convection. Atmospheric Research 94(2):220 – 237, DOI https://doi.org/10.1016/j.atmosres.2009.05.015, URL http://www.sciencedirect.com/science/article/pii/S016980950900163X

LeMone MA, Pennell WT (1976) The relationship of trade wind cumulus distribution to subcloud layer fluxes and structure. Monthly Weather Review 104(5):524–539, DOI 10.1175/1520-0493(1976)104¡0524:TROTWC¿2.0.CO;2

Li JL, Waliser D, Stephens G, Lee S (2016) Characterizing and understanding cloud ice and radiation budget biases in global climate models and reanalysis. Meteorological Monographs 56:13–1

Locatelli R, Bousquet P, Hourdin F, Saunois M, Cozic A, Couvreux F, Grandpeix JY, Lefebvre MP, Rio C, Bergamaschi P, Chambers SD, Karstens U, Kazan V, van der Laan S, Meijer HAJ, Moncrieff J, Ramonet M, Scheeren HA, Schlosser C, Schmidt M, Vermeulen A, Williams AG (2015) Atmospheric transport and chemistry of trace gases in LMDz5B: evaluation and implications for inverse modelling. Geosc Model Dev 8:129–150, DOI 10.5194/gmd-8-129-2015

Mapes B, Neale R (2011) Parameterizing convective organization to escape the entrainment dilemma. Journal of Advances in Modeling Earth Systems 3(2)

Mapes B, Tulich S, Lin J, Zuidema P (2006) The mesoscale convection life cycle: Building block or prototype for large-scale tropical waves? Dynamics of atmospheres and oceans 42(1-4):3–29

Masunaga H, Luo ZJ (2016) Convective and large-scale mass flux profiles over tropical oceans determined from synergistic analysis of a suite of satellite observations. Journal of Geophysical Research: Atmospheres 121(13):7958–7974

Mathon V, Laurent H, Lebel T (2002) Mesoscale convective system rainfall in the sahel. Journal of applied meteorology 41(11):1081–1092

Mauritsen T, Stevens B (2015) Missing iris effect as a possible cause of muted hydrological change and high climate sensitivity in models. Nature Geoscience 8(5):346

McFiggans G, Artaxo P, Baltensperger U, Coe H, Facchini MC, Feingold G, Fuzzi S, Gysel M, Laaksonen A, Lohmann U, Mentel TF, Murphy DM, O'Dowd CD, Snider JR, Weingartner E (2006) The effect of physical and chemical aerosol properties on warm cloud droplet activation. Atmospheric Chemistry and Physics 6(9):2593–2649, DOI 10.5194/acp-6-2593-2006, URL https://www.atmos-chem-phys.net/6/2593/2006/

Mitchell D, Mishra S, Lawson R (2011) Representing the ice fall speed in climate models: Results from tropical composition, cloud and climate coupling (tc4) and the indirect and semi-direct aerosol campaign (isdac). Journal of Geophysical Research: Atmospheres 116(D1)

Miyamoto Y, Kajikawa Y, Yoshida R, Yamaura T, Yashiro H, Tomita H (2013) Deep moist atmospheric convection in a subkilometer global simulation. Geophysical Research Letters 40(18):4922–4926, DOI 10.1002/grl.50944

Moncrieff MW, Liu C (1999) Convection initiation by density currents: Role of convergence, shear, and dynamical organization. Monthly Weather Review 127(10):2455–2464

Moncrieff MW, Liu C, Bogenschutz P (2017) Simulation, modeling, and dynamically based parameterization of organized tropical convection for global climate models. Journal of the Atmospheric Sciences 74(5):1363–1380

Morita J, Takayabu YN, Shige S, Kodama Y (2006) Analysis of rainfall characteristics of the madden–julian oscillation using trmm satellite data. Dynamics of atmospheres and oceans 42(1-4):107–126

Morrison H (2016a) Impacts of updraft size and dimensionality on the perturbation pressure and vertical velocity in cumulus convection. part i: Simple, generalized analytic solutions. Journal of the Atmospheric Sciences 73(4):1441–1454

Morrison H (2016b) Impacts of updraft size and dimensionality on the perturbation pressure and vertical velocity in cumulus convection. part ii: Comparison of theoretical and numerical solutions and fully dynamical simulations. Journal of the Atmospheric Sciences 73(4):1455–1480

Morrison H, Gettelman A (2008) A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (cam3). part i: Description and numerical tests. Journal of Climate 21(15):3642–3659

Moseley C, Hohenegger C, Berg P, Haerter JO (2016) Intensification of convective extremes driven by cloud–cloud interaction. Nature Geoscience 9(10):748

Nesbitt SW, Zipser EJ (2003) The diurnal cycle of rainfall and convective intensity according to three years of trmm measurements. Journal of Climate 16(10):1456–1475

Nie J, Kuang Z, Jacob DJ, Guo J (2016) Representing effects of aqueous phase reactions in shallow cumuli in global models. J Geophys Res 121:5769–5787, DOI 10.1002/2015JD024208

Nitta T, Esbensen S (1974) Heat and moisture budget analyses using bomex data. Monthly Weather Review 102(1):17–28, DOI 10.1175/1520-0493(1974)102¡0017:HAMBAU¿2.0.CO;2

O'Gorman PA, Dwyer JG (2018) Using machine learning to parameterize moist convection: Potential for modeling of climate, climate change, and extreme events. Journal of Advances in Modeling Earth Systems 0(0), DOI 10.1029/2018MS001351

Ong H, Wu CM, Kuo HC (2017) Effects of artificial local compensation of convective mass flux in the cumulus parameterization. Journal of Advances in Modeling Earth Systems 9(4):1811–1827, DOI 10.1002/2017MS000926

Orr A, Bechtold P, Scinocca J, Ern M, Janiskova M (2010) Improved middle atmosphere climate and forecasts in the ecmwf model through a nonorographic gravity wave drag parameterization. Journal of Climate 23(22):5905–5926

Oueslati B, Bellon G (2015) The double itcz bias in cmip5 models: interaction between sst, large-scale circulation and precipitation. Climate Dynamics 44:585–607, DOI 10.1007/s00382-015-2468-6

Pan DM, Randall DD (1998) A cumulus parameterization with a prognostic closure. Quarterly Journal of the Royal Meteorological Society 124(547):949–981

Park S (2014a) A Unified Convection Scheme (UNICON). Part I: Formulation. J Atmos Sci 71:3902–3930, DOI 10.1175/JAS-D-13-0233.1

Park S (2014b) A Unified Convection Scheme (UNICON). Part II: Simulation. J Atmos Sci 71:3931–3973, DOI 10.1175/JAS-D-13-0234.1

Perraud E, Couvreux F, Malardel S, Lac C, Masson V, Thouron O (2011) Evaluation of statistical distributions for the parametrization of subgrid boundary-layer clouds. Boundary-layer meteorology 140(2):263–294

Peters JM (2016) The impact of effective buoyancy and dynamic pressure forcing on vertical velocities within two-dimensional updrafts. Journal of the Atmospheric Sciences 73(11):4531–4551, DOI 10.1175/JAS-D-16-0016.1

Peters K, Jakob C, Davies L, Khouider B, Majda AJ (2013) Stochastic behavior of tropical convection in observations and a multicloud model. Journal of the Atmospheric Sciences 70(11):3556–3575

Peters K, Crueger T, Jakob C, Möbis B (2017) Improved mjo-simulation in echam 6.3 by coupling a stochastic multicloud model to the convection scheme. Journal of Advances in Modeling Earth Systems 9(1):193–219

Piriou JM, Redelsperger JL, Geleyn JF, Lafore JP, Guichard F (2007) An approach for convective parameterization with memory: Separating microphysics and transport in grid-scale equations. Journal of the Atmospheric Sciences 64(11):4127–4139

Plant R, Craig GC (2008) A stochastic parameterization for deep convection based on equilibrium statistics. Journal of the Atmospheric Sciences 65(1):87–105

Qin Y, Lin Y (2018) Alleviated double itcz problem in the ncar cesm1: A new cloud scheme and the working mechanisms. Journal of Advances in Modeling Earth Systems 10(9):2318–2332

Qin Y, Lin Y, Xu S, Ma HY, Xie S (2018) A diagnostic pdf cloud scheme to improve subtropical low clouds in ncar community atmosphere model (cam 5). Journal of Advances in Modeling Earth Systems 10(2):320–341

Randall D, Khairoutdinov M, Arakawa A, Grabowski W (2003) Breaking the cloud parameterization deadlock. Bulletin of the American Meteorological Society 84(11):1547–1564, DOI 10.1175/BAMS-84-11-1547

Raymond DJ (1994) Convective processes and tropical atmospheric circulations. Quarterly Journal of the Royal Meteorological Society 120(520):1431–1455

Raymond DJ, Blyth AM (1986) A stochastic model for non precipitating cumulus clouds. J Atmos Sci 43:2708–2718

Riette S, Lac C (2016) A New Framework to Compare Mass-Flux Schemes Within the AROME Numerical Weather Prediction Model. Boundary-layer Meteorol 160:269–297, DOI 10.1007/s10546-016-0146-9

Riley EM, Mapes BE, Tulich SN (2011) Clouds associated with the madden–julian oscillation: A new perspective from cloudsat. Journal of the Atmospheric Sciences 68(12):3032–3051

Rio C, Hourdin F, Grandpeix JY, Lafore JP (2009) Shifting the diurnal cycle of parameterized deep convection over land. Geophysical Research Letters 36(7)

Rio C, Grandpeix JY, Hourdin F, Guichard F, Couvreux F, Lafore JP, Fridlind A, Mrowiec A, Roehrig R, Rochetin N, Lefebvre MP, Idelkadi A (2013) Control of deep convection by sub-cloud lifting processes: the ALP closure in the LMDZ5B general circulation model. Clim Dyn 40:2271–2292, DOI 10.1007/s00382-012-1506-x

Rochetin N, Couvreux F, Grandpeix JY, Rio C (2014a) Deep Convection Triggering by Boundary Layer Thermals. Part I: LES Analysis and Stochastic Triggering Formulation. J Atmos Sci 71:496–514, DOI 10.1175/JAS-D-12-0336.1

Rochetin N, Grandpeix JY, Rio C, Couvreux F (2014b) Deep Convection Triggering by Boundary Layer Thermals. Part II: Stochastic Triggering Parameterization for the LMDZ GCM. J Atmos Sci 71:515–538, DOI 10.1175/JAS-D-12-0337.1

Roehrig R, Bouniol D, Guichard F, Hourdin F, Redelsperger JL (2013) The present and future of the west african monsoon: A process-oriented assessment of cmip5 simulations along the amma transect. Journal of Climate 26(17):6471–6505

Romps DM (2010) A direct measure of entrainment. Journal of the Atmospheric Sciences 67(6):1908–1927

Romps DM (2016) The stochastic parcel model: A deterministic parameterization of stochastically entraining convection. Journal of Advances in Modeling Earth Systems 8(1):319–344

Romps DM, Kuang Z (2010) Nature versus nurture in shallow convection. Journal of the Atmospheric Sciences 67(5):1655–1666

Rosenfeld D, Lohmann U, Raga GB, O'dowd CD, Kulmala M, Fuzzi S, Reissell A, Andreae MO (2008) Flood or drought: How do aerosols affect precipitation? science 321(5894):1309–1313

Rossow WB, Tselioudis G, Polak A, Jakob C (2005) Tropical climate described as a distribution of weather states indicated by distinct mesoscale cloud property mixtures. Geophysical research letters 32(21)

Rotunno R, Klemp JB, Weisman ML (1988) A theory for strong, long-lived squall lines. Journal of the Atmospheric Sciences 45(3):463–485

Rozbicki JJ, Young GS, Qian L (1999) Test of a convective wake parameterization in the single-column version of ccm3. Monthly weather review 127(6):1347–1361

Sacks J, Welch WJ, Mitchell TJ, Wynn HP (1989) Design and analysis of computer experiments. Statist Sci 4(4):409–423, DOI 10.1214/ss/1177012413, URL https://doi.org/10.1214/ss/1177012413

Sakradzija M, Seifert A, Dipankar A (2016) A stochastic scale-aware parameterization of shallow cumulus convection across the convective gray zone. Journal of Advances in Modeling Earth Systems 8(2):786–812

Sassen K, Wang Z (2008) Classifying clouds around the globe with the cloudsat radar: 1-year of results. Geophysical Research Letters 35(4)

Schiro KA, Neelin JD (2018) Tropical continental downdraft characteristics: mesoscale systems versus unorganized convection. Atmos Chem Phys 18:1997–2010

Schlemmer L, Hohenegger C (2014) The formation of wider and deeper clouds as a result of cold-pool dynamics. Journal of the Atmospheric Sciences 71(8):2842–2858

Schmidt GA, Bader D, Donner LJ, Elsaesser GS, Golaz JC, Hannay C, Molod A, Neale RB, Saha S (2017) Practice and philosophy of climate model tuning across six US modeling centers. Geoscientific Model Development 10:3207–3223, DOI 10.5194/gmd-10-3207-2017

Schneider T, Lan S, Stuart A, Teixeira J (2017) Earth system modeling 2.0: A blueprint for models that learn from observations and targeted high-resolution simulations. Geophysical Research Letters 44(24):12,396–12,417, DOI 10.1002/2017GL076101

Schumacher C, Houze JRA (2003) Stratiform rain in the tropics as seen by the trmm precipitation radar. Journal of Climate 16(11):1739–1756

Schumacher C, Houze JRA (2006) Stratiform precipitation production over sub-saharan africa and the tropical east atlantic as observed by trmm. Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography 132(620):2235–2255

Schumacher C, Houze JRA, Kraucunas I (2004) The tropical dynamical response to latent heating estimates derived from the trmm precipitation radar. Journal of the Atmospheric Sciences 61(12):1341–1358

Sherwood SC, Bony S, Dufresne JL (2014) Spread in model climate sensitivity traced to atmospheric convective mixing 505:37–42, DOI 10.1038/nature12829

Shige ea S (2009) Spectral retrieval of latent heating profiles from trmm pr data. part iv: Comparisons of lookup tables from two- and three-dimensional simulations. J Clim 22:5577–5594

Simpson J, Wiggert V (1969) Models of precipitating cumulus towers. Mon Wea Rev 97(7):471–489

Slingo JM (1987) The development and verification of a cloud prediction scheme for the ecmwf model. Quarterly Journal of the Royal Meteorological Society 113(477):899–927, DOI 10.1002/qj.49711347710

Song X, Zhang GJ, Li JL (2012) Evaluation of microphysics parameterization for convective clouds in the ncar community atmosphere model cam5. Journal of Climate 25(24):8568–8590

Storer RL, Griffin BM, Höft J, Weber JK, Raut E, Larson VE, Wang M, Rasch PJ (2015) Parameterizing deep convection using the assumed probability density function method. Geosc Model Dev 8:1–19, DOI 10.5194/gmd-8-1-2015

Storer RL, Zhang GJ, Song X (2015) Effects of convective microphysics parameterization on large-scale cloud hydrological cycle and radiative budget in tropical and midlatitude convective regions. Journal of Climate 28(23):9277–9297

Stratton R, Stirling A (2012) Improving the diurnal cycle of convection in gcms. Quarterly Journal of the Royal Meteorological Society 138(666):1121–1134

Sušelj K, Teixeira J, Chung D (2013) A unified model for moist convective boundary layers based on a stochastic eddy-diffusivity/mass-flux parameterization. Journal of the Atmospheric Sciences 70(7):1929–1953

Takahashi H, Luo ZJ, Stephens GL (2017) Level of neutral buoyancy, deep convective outflow, and convective core: New perspectives based on 5 years of cloudsat data. Journal of Geophysical Research: Atmospheres 122(5):2958–2969

Talib J, Woolnough SJ, Klingaman NP, Holloway CE (2018) The Role of the Cloud Radiative Effect in the Sensitivity of the Intertropical Convergence Zone to Convective Mixing. J Climate 31:6821–6838, DOI 10.1175/JCLI-D-17-0794.1

Tan Z, Kaul CM, Pressel KG, Cohen Y, Schneider T, Teixeira J (2018) An extended eddy-diffusivity mass-flux scheme for unified representation of subgrid-scale turbulence and convection. Journal of advances in modeling earth systems 10(3):770–800

Tao WK, Moncrieff MW (2009) Multiscale cloud system modeling. Reviews of Geophysics 47(4), DOI 10.1029/2008RG000276

Tiedtke M (1989) A comprehensive mass flux scheme for cumulus parameterization in large-scale models. Mon Wea Rev 117:1179–1800

Tiedtke M (1993) Representation of clouds in large-scale models. Monthly Weather Review 121(11):3040–3061

Tompkins AM (2002) A prognostic parameterization for the subgrid-scale variability of water vapor and clouds in large-scale models and its use to diagnose cloud cover. Journal of the atmospheric sciences 59(12):1917–1942

Van Weverberg K, Morcrette CJ, Petch J, Klein SA, Ma HY, Zhang C, Xie S, Tang Q, Gustafson WI, Qian Y, Berg LK, Liu Y, Huang M, Ahlgrimm M, Forbes R, Bazile E, Roehrig R, Cole J, Merryfield W, Lee WS, Cheruy F, Mellul L, Wang YC, Johnson K, Thieman MM (2018) Causes: Attribution of surface radiation biases in nwp and climate models near the u.s. southern great plains. Journal of Geophysical Research: Atmospheres 123(7):3612–3644, DOI 10.1002/2017JD027188

Varble A (2018) Erroneous attribution of deep convective invigoration to aerosol concentration. Journal of the Atmospheric Sciences 75(4):1351–1368

Ventrice MJ, Thorncroft CD (2013) The role of convectively coupled atmospheric kelvin waves on african easterly wave activity. Monthly Weather Review 141(6):1910–1924

Vial J, Bony S, Stevens B, Vogel R (2018) Mechanisms and Model Diversity of Trade-Wind Shallow Cumulus Cloud Feedbacks: A Review, p 159. DOI 10.1007/978-3-319-77273-8_8

Vignon E, Hourdin F, Genthon C, Van de Wiel BJH, Gallée H, Madeleine JB, Beaumet J (2018) Modeling the Dynamics of the Atmospheric Boundary Layer Over the Antarctic Plateau With a General Circulation Model. J of Adv in Modeling Earth Systems 10:98–125, DOI 10.1002/2017MS001184

Wang Y, Zhang GJ (2016) Global climate impacts of stochastic deep convection parameterization in the ncar cam5. Journal of Advances in Modeling Earth Systems 8(4):1641–1656

Webb MJ, Lock AP, Bretherton CS, Bony S, Cole JNS, Idelkadi A, Kang SM, Koshiro T, Kawai H, Ogura T, Roehrig R, Shin Y, Mauritsen T, Sherwood SC, Vial J, Watanabe M, Woelfle MD, Zhao M (2015) The impact of parametrized convection on cloud feedback. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 373(2054):20140,414, DOI 10.1098/rsta.2014.0414

White B, Gryspeerdt EG, Stier P, Morrison H, Thompson G, Z K (2017) Uncertainty from the choice of microphysics scheme in convection-permitting models significantly exceeds aerosol effects. Atmos Chem Phys 17(1):12,145–12,175

Williamson D, Blaker AT, Hampton C, Salter J (2015) Identifying and removing structural biases in climate models with history matching. Clim Dyn 45:1299–1324, DOI 10.1007/s00382-014-2378-z

Woelfle MD, Yu S, Bretherton CS, Pritchard MS (2018) Sensitivity of Coupled Tropical Pacific Model Biases to Convective Parameterization in CESM1. J of Adv in Modeling Earth Systems 10:126–144, DOI 10.1002/2017MS001176

Wu CM, Arakawa A (2014) A unified representation of deep moist convection in numerical modeling of the atmosphere. part ii. Journal of the Atmospheric Sciences 71(6):2089–2103, DOI 10.1175/JAS-D-13-0382.1

Wu X, Deng L, Song X, Zhang GJ (2007) Coupling of convective momentum transport with convective heating in global climate simulations. Journal of the Atmospheric Sciences 64(4):1334–1349, DOI 10.1175/JAS3894.1

Xiang B, Zhao M, Held IM, Golaz JC (2017) Predicting the severity of spurious “double ITCZ” problem in CMIP5 coupled models from AMIP simulations. Geophys Res Lett 44:1520–1527, DOI 10.1002/2016GL071992

Xu W, Rutledge SA (2015) Morphology, intensity, and rainfall production of mjo convection: Observations from dynamo shipborne radar and trmm. Journal of the Atmospheric Sciences 72(2):623–640

Yanai M, Esbensen S, Chu JH (1973) Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. Journal of the Atmospheric Sciences 30(4):611–627, DOI 10.1175/1520-0469(1973)030¡0611:DOBPOT¿2.0.CO;2

Yano JI, Moncrieff MW (2016) Numerical archetypal parameterization for mesoscale convective systems. Journal of the Atmospheric Sciences 73(7):2585–2602

Yano JI, Moncrieff MW (2018) Convective organization in evolving large-scale forcing represented by a highly truncated numerical archetype. Journal of the Atmospheric Sciences 75(8):2827–2847

Yuter SE, Houze JRA (1998) The natural variability of precipitating clouds over the western pacific warm pool. Quarterly Journal of the Royal Meteorological Society 124(545):53–99

Zelinka MD, Hartmann DL (2011) The observed sensitivity of high clouds to mean surface temperature anomalies in the tropics. Journal of Geophysical Research: Atmospheres 116(D23), DOI 10.1029/2011JD016459

Zelinka MD, Zhou C, Klein SA (2016) Insights from a refined decomposition of cloud feedbacks. Geophysical Research Letters 43(17):9259–9269

Zhang G, McFarlane NA (1995) Sensitivity of climate simulations to the parameterization of cumulus convection in the canadian climate centre general circulation model. Atmosphere-Ocean 33(3):407–446, DOI 10.1080/07055900.1995.9649539

Zhang GJ (2002) Convective quasi-equilibrium in midlatitude continental environment and its effect on convective parameterization. Journal of Geophysical Research: Atmospheres 107(D14):ACL 12–1–ACL 12–16, DOI 10.1029/2001JD001005

Zhang GJ (2003) Convective quasi-equilibrium in the tropical western pacific: Comparison with midlatitude continental environment. Journal of Geophysical Research: Atmospheres 108(D19), DOI 10.1029/2003JD003520

Zhang GJ, Cho HR (1991) Parameterization of the vertical transport of momentum by cumulus clouds. part ii: Application. Journal of the Atmospheric Sciences 48(22):2448–2457, DOI 10.1175/1520-0469(1991)048¡2448:POTVTO¿2.0.CO;2

Zhang GJ, Wu X, Zeng X, Mitovski T (2016) Estimation of convective entrainment properties from a cloud-resolving model simulation during twp-ice. Climate dynamics 47(7-8):2177–2192

Zhang M, Bretherton CS, Blossey PN, Austin PH, Bacmeister JT, Bony S, Brient F, Cheedela SK, Cheng A, Del Genio AD, et al (2013) Cgils: Results from the first phase of an international project to understand the physical mechanisms of low cloud feedbacks in single column models. Journal of Advances in Modeling Earth Systems 5(4):826–842

Zhao M, Golaz JC, Held I, Ramaswamy V, Lin SJ, Ming Y, Ginoux P, Wyman B, Donner L, Paynter D, et al (2016) Uncertainty in model climate sensitivity traced to representations of cumulus precipitation microphysics. Journal of Climate 29(2):543–560

Zhao M, Golaz JC, Held IM, Guo H, Balaji V, Benson R, Chen JH, Chen X, Donner LJ, Dunne JP, Dunne K, Durachta J, Fan SM, Freidenreich SM, Garner ST, Ginoux P, Harris LM, Horowitz LW, Krasting JP, Langenhorst AR, Liang Z, Lin P, Lin SJ, Malyshev SL, Mason E, Milly PCD, Ming Y, Naik V, Paulot F, Paynter D, Phillipps P, Radhakrishnan A, Ramaswamy V, Robinson T, Schwarzkopf D, Seman CJ, Shevliakova E, Shen Z, Shin H, Silvers LG, Wilson JR, Winton M, Wittenberg AT, Wyman B, Xiang B (2018) The gfdl global atmosphere and land model am4.0/lm4.0: 2. model description, sensitivity studies, and tuning strategies. Journal of Advances in Modeling Earth Systems 10(3):735–769, DOI 10.1002/2017MS001209

Zuidema P, Torri G, Muller C, Chandra A (2017) A survey of precipitation-induced atmospheric cold pools over oceans and their interactions with the larger-scale environment. Surveys in Geophysics 38(6):1283–1305