**Direct observations of the *dynamics* of tropical convection**

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# Key Earth system science question

Deep tropical convection is a vital process in the hydrological and energy cycles, and is responsible for the vertical transport of heat, moisture and momentum from low levels of the atmosphere into the upper troposphere. Moist convection is a basic building block of the major storm systems of the planet, producing much of Earth’s precipitation, clouds, and extreme weather. Until recently, progress in representing moist convection in global numerical models has been elusive. But recent computational advances using limited-domain high-resolution “cloud-resolving” models have provided consistent options to represent convection in global models (de Rooy et al., 2013). The critical question is: which model options best represent reality for given environmental conditions? Answering this question is difficult because, despite the fundamental importance of deep convection, global model improvements are still mostly based on the use of other, higher resolution models. Existing observations of precipitation and cloud vertical structure, while useful as constraints, fail to discern the transport processes upon which convective closures are based. The moment is ripe for making new observations that will allow ***time-resolved* monitoring of convective processes to improve their representation in numerical weather models** – from the small-scale cloud-resolving models to the global scale climate prediction models.

## The vertical transport of mass and its impact on the interactions between tropical and extra-tropical circulations

Deep tropical convection can be viewed as an entropy exchange process between the boundary layer and the tropical upper troposphere (TUT). The energy inserted into the TUT by tropical convection is in the form of increased mass associated with the updraft entropy of the convective plume, equivalent to an increase in potential energy at specific height levels, resulting from an increase in air density at that height. When compared to atmospheric layers at the same height in the extratropics, the air in the TUT is therefore of higher density, and so higher potential energy. Relative to the extratropical atmosphere, the excess tropical potential energy is “available” to be converted to kinetic energy (Lorenz, 1955). Given a permitted process, the energy conversion typically results in the formation of a subtropical jet structure (Krishnamurti, 1961). Because the upper troposphere is dynamically isolated from the surface-based frictional sources of angular momentum, air in this available potential energy (APE) “bubble” is essentially “trapped” by the inertial stability of Earth’s rotation. Deep tropical convection is therefore the vehicle that adds mass to the TUT, and only interaction with – or transport to – the extratropics can complete the energy cycle, which occurs in small-scale “surges” of the TUT into the extratropics (Mecikalski and Tripoli, 1998). It is still unclear what factors lead to the eruption of such tropical plumes from the tropical APE bubble. Yet these surges transcend the diurnal cycle and so are most likely to spawn severe weather in the extratropics. Today’s models are still not able to accurately represent howthe potential energy is built up by deep convection, or how it gets intermittently transferred from the TUT to the extratropical wave-train in localized bursts, influencing weather far downstream.

## The vertical transport of moisture and its impact on climate and hydrological sensitivities

### Furthermore, convective transports influence the sensitivity of Earth’s climate system to forced change. Predicted increases in global mean surface temperature range between 2 and 4.6 K for a doubling of CO2 (Forster et al, 2013) and global precipitation increases of about 2–3% for each degree of warming. These are referred to as the climate and hydrological sensitivities, respectively, and the need to develop an understanding of the factors that determine them, and their regional consequences, underscores the grand science challenges posed by the World Climate Research Programme (WCRP, Asrar et al, 2015). Inferences from observational records place the climate sensitivity near the lower end of the model range (Otto et al., 2013; Masters 2014; Lewis and Curry, 2015), and a hydrological sensitivity that is significantly larger than that predicted by state-of-the-art models (Zhang et al., 2007; Lambert et al., 2008; Durack et al., 2012). Reasons for these disparities based on unaccounted-for details of aerosol forcing have been proposed (Shindell, 2014), though missing negative feedbacks involving tropical high clouds produced by deep convection could also play a role (Mauritsen and Stevens, 2015).

### One of the reasons climate is so sensitive to convective transport is because of its influence on water transports. Water in the atmosphere, both in vapor and condensed states, is such a strong absorber of infrared radiation, that the movement of water away from the warmer temperatures of the lower atmosphere to the colder temperatures of the upper troposphere dramatically enhances the Earth’s greenhouse effect. Global models of the Earth System have to make inadequately constrained assumptions about how much mass and water are deposited in the upper troposphere and then what fraction of this is spread out into high clouds through the process of detrainment. Climate and hydrological sensitivities are acutely sensitive to the assumptions relating to this pumping of water by deep convection. Improving the representation of the vertical structure of water in global climate models is absolutely critical if we are to accurately predict such climate and hydrological sensitivities.

# Why is it the right time to observe the dynamics of convection

Regarding moist convective processes, regional and global models that predict our weather and project how storms are likely to change with future warming are fast evolving. Climate model resolutions are changing from order 100km for climate models of the IPCC AR54 to 25km today. Weather forecast models are evolving even more rapidly. Global operational forecasts are now performed at or near 10km (IFS, GFS) and the resolutions of global forecast systems are expected to soon be on the order of 5km. Because these models do not yet resolve the main convective transports directly, they have to resort to statistical approximations via a convective parameterization scheme. These schemes are guided mostly by cloud-resolving models. These models have emerged as important research tools in studying storms, and their outputs are now the basis for the statistical methods developed for coarser climate models. There has been a concerted effort over the recent years to produce global versions of these models in the form of slightly coarser “cloud resolving” models (CRMs) and today these latter models enable global simulations at resolutions of about 1-5km (e.g. NICAM). Yet these higher-resolution models still possess serious biases associated with the representation of convection and convective processes, including:

* Transports of moisture, momentum, heat, trace gases and aerosols from the boundary layer to the upper troposphere that are too widespread and too weak (Lane and Moncrieff, 2010; van den Heever et al., 2011).
* Precipitation that is typically far too frequent and too light in all models, with heavy precipitation far too infrequent (Chakraborty, 2010)
* Errors in the mean locations of convective precipitation are well documented, such as the persistence of an unrealistic double ITCZ.
* Incorrect diurnal timing of the development, propagation and precipitation of severe convective storms leading to serious forecasting errors (Chakraborty, 2010; Mapes and Neale, 2011).
* An overestimation of vertical updraft velocities in those numerical models that resolved vertical motion (Varble et al., 2014)

In a nutshell, the numerical models are now ready for – and, indeed, need guidance from – systematic observations of the dynamics of convection.

# Why are space observations critically needed

The need to sample the dynamical properties of convection under the existing variety of environmental conditions of surface temperature, column specific humidity, lower-atmosphere moisture convergence and convective available potential energy requires a space-based observation strategy. Analyses of data from the Tropical Rainfall Measuring Mission have shown the extent to which the characteristics of convection vary around the globe and as a function of mesoscale systems (Houze et al, 2015). Indeed, the main water source necessary for deep convection is the low-level moisture convergence and the two main sinks of water are precipitation and the detrainment of air and condensate at the tops of tropical storms. Convective mass flux of air *Qair*is a measure of how much mass is lifted or sinks in convective plumes and is thus a principal diagnostic of the convective transport, a measure of convective strength and is the variable upon which convection parameterization closures are based (Yanai and Johnson, 1993). *Despite its fundamental importance, no wide-scale information about Qair exists* to guide parametrization development or to verify the credibility of predictions from finer-scale forecast systems. Nor indeed, are any global observations of the vertical motions through deep convective storms available.

Similarly, the vertical flux of condensed water *Qcw* is a measure of the moistening of the upper troposphere, and together with the rate of change (dCW/dt) of the condensed water mass CW, they quantify the efficiency with which TUT clouds are created (instead of CW precipitating out to the surface). Neither *Qair* nor *Qcw* nor dCW/dt are currently observed systematically. Furthermore, observations of the vertical velocities within deep convective storms, a primary component of *Qair* and *Qcw* are not even routinely available. Not only are systematic observations necessary, they need to be sampled over the existing variety of environmental conditions (surface temperature, column specific humidity, lower-atmosphere moisture convergence, and convective available potential energy) within the wide range of deep convective storm types (from isolated convective towers through to the more dynamically organized mesoscale convective systems and hurricanes) in order to confirm (and quantify) the relations between convective development and the larger-scale conditions. Spatially or temporally limited observation strategies (such as fixed ground-based concepts or airborne campaigns) would fall far short of producing a sufficiently representative data set, both in terms of storm type and environmental conditions, to allow for robust inferences about existing parameterizations to be drawn, let alone for the development of more realistic parameterizations. However, from space, *Qair*, *Qcw* and dCW/dt can be observed given the emerging capability to build and formation-fly small satellites, to observe the temporal evolution as well as the spatial distribution of convective cores.

In summary, it is important and timely to start making systematic observations of the *dynamics* of tropical convection, including vertical air mass flux, flux of condensed water, updraft vertical velocities, and the time rate of change of condensed water mass, if we are to make significant strides forward in now-casting, sub-seasonal to seasonal forecasting, data assimilation techniques, and to improve climate-scale modeling.

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