Modulation of Terrestrial Convection by Tropospheric Humidity, and Implications for Other Planets

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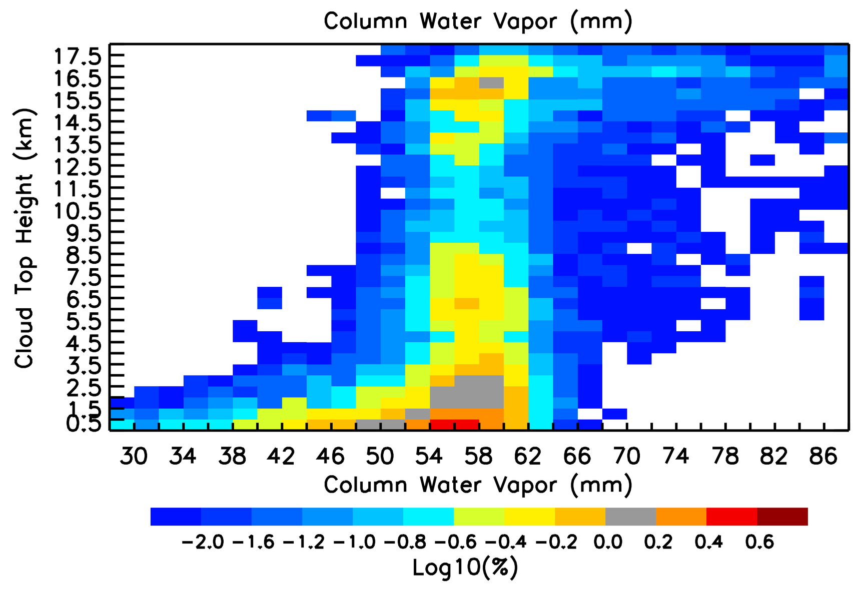
Introduction

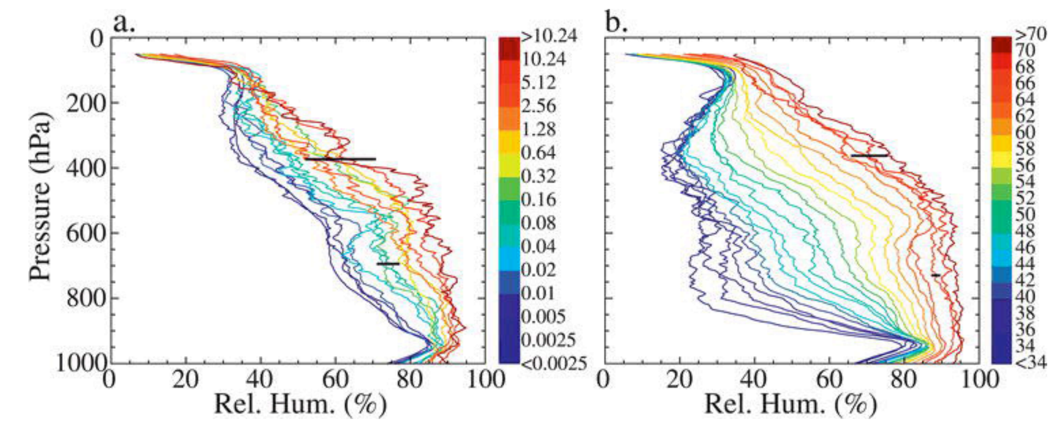
For decades, deep cumulus convection was viewed as consisting partly of undilute plumes that do not interact with their surrounding environment in order to explain their observed tendency to reach or penetrate the tropical tropopause. This behavior was built into all cumulus parameterizations used in terrestrial global climate and numerical weather prediction models, and it still persists in some models today. In the past decade, though, some embarrassing failures of global models have come to light, notably their tendency to rain over land near noon rather than in late afternoon or evening as observed, and the absence in the models of the Madden-Julian Oscillation (MJO), the major source of intraseasonal (30-90 day) precipitation variability in the Indian Ocean, West Pacific, and surrounding continental regions. In the past decade it has become clear that an important missing component of parameterizations is strong turbulent entrainment of drier environmental air into cumulus updrafts, which reduces the buoyancy of the updrafts and thus limits their vertical development. Tropospheric humidity thus serves as a throttle on convective penetration to high altitudes and delays the convective response to large-scale destabilizing influences in the environment.

Observed dependence of convection depth on water vapor



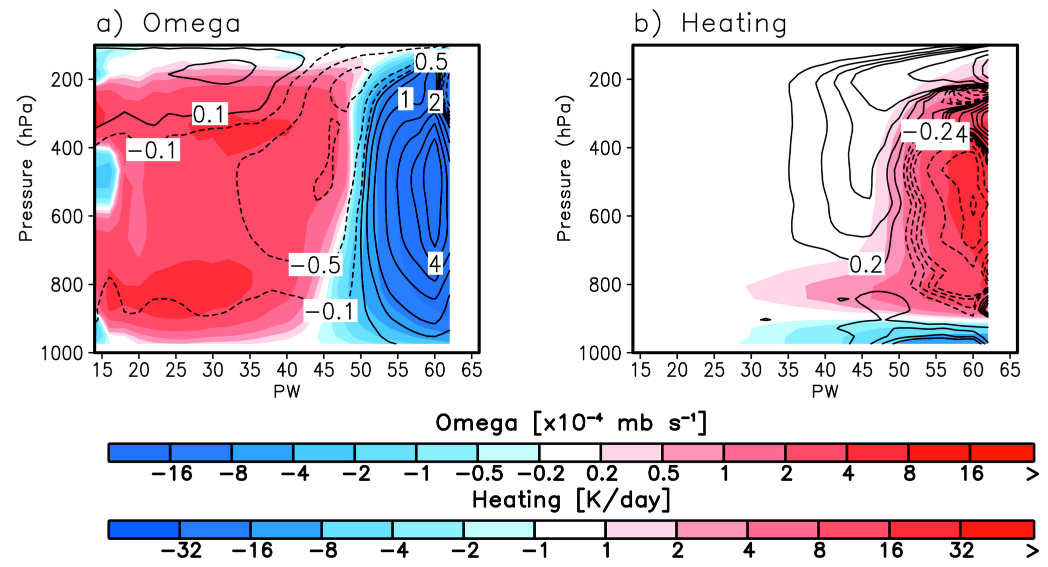
We used CloudSat/CALIPSO satellite radar/lidar products to detect convective clouds over the tropical ocean warm pool during the developing stage of 10 MJO events during July 2006 – May 2010 (Del Genio et al. 2012, J. Clim.). For pixels with a convective cloud, the figure above shows the histogram of convective cloud top height as a function of column integrated water vapor as measured by the AMSR-E passive microwave instrument on the Aqua satellite. Convection depth is a very nonlinear function of column water vapor: The transition from shallow to deep convection occurs rather suddenly at CWV ~ 48 mm, with a mix of convection depths for CWV = 48-64 mm and primarily deep convection only when CWV > 64 mm. Does deep convection not occur when CWV < 48 mm because boundary layer air is not sufficiently humid to be lifted to its level of free convection, or is something else going on?

Relative humidity profiles sorted by precipitation, CWV



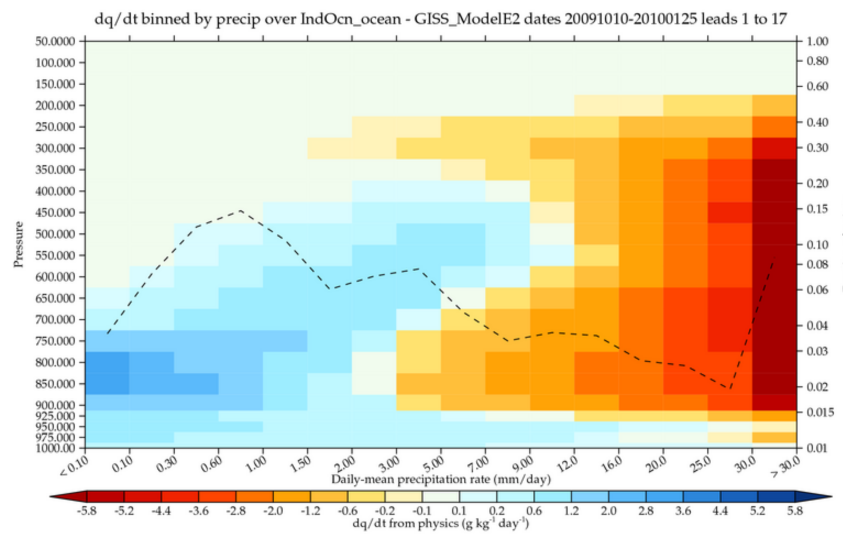
Composite soundings of relative humidity at Nauru Island in the equatorial Pacific sorted by precipitation (left panel) and by column integrated water vapor (right panel) show that weakly vs. strongly precipitating environments are differentiated more by variations in the humidity of the free troposphere than by variations in the humidity of the boundary layer where rising parcels originate (Holloway and Neelin, 2009, JAS). Likewise, the variations in column water vapor seen from satellites are controlled mostly by variations in the humidity of the middle and lower free troposphere, rather than by boundary layer variability. Quasi-equilibrium parameterizations of convection underestimate this sensitivity to humidity above the boundary layer and tend to deeply convect as soon as convective available potential energy exists and a moist parcel of air can be lifted to its level of free convection. Only with sufficiently strong entrainment of dry air in the free troposphere can convection depth be limited in an otherwise unstable column.

Effect of entrainment on convective heating and organization



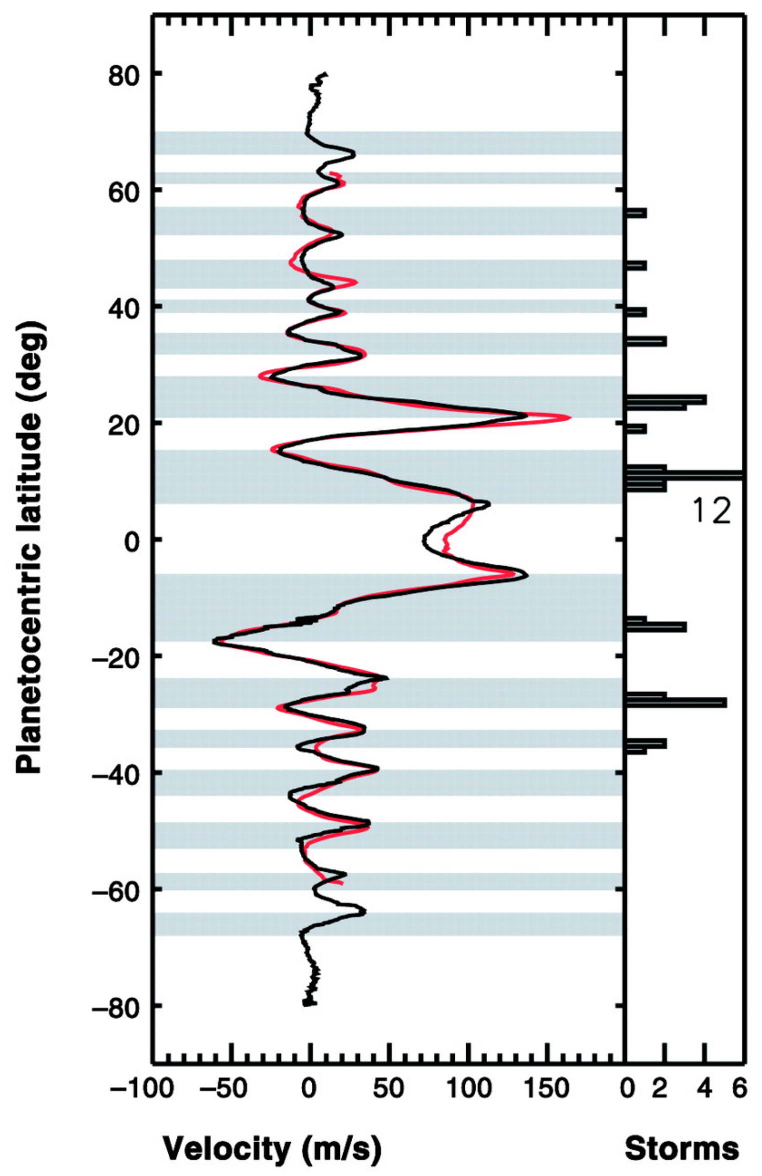
The GISS GCM does not produce an MJO when entrainment is too weak, but it does when entrainment is stronger. To understand why, Kim et al. (2012, J. Clim.) used the strong entrainment version of the GCM as an initial condition for running a series of hindcasts with the weak entrainment version of the GCM. The figure above shows the 500 mb pressure vertical velocity (ω) and convective heating profiles as a function of column water vapor (here called precipitable water, PW). The colors show the mean field from the "good MJO" model, the solid and dashed contours the difference between the "bad MJO" and "good MJO" models after one day of hindcast. The "bad MJO" model has weaker upwelling and downwelling, indicating that its atmosphere is less organized into strongly convective and suppressed regions. The "bad MJO" model initiates convection at intermediate humidity, while the "good MJO" model waits until the column is more moist before deep convection breaks out.

Convective moistening vs. drying



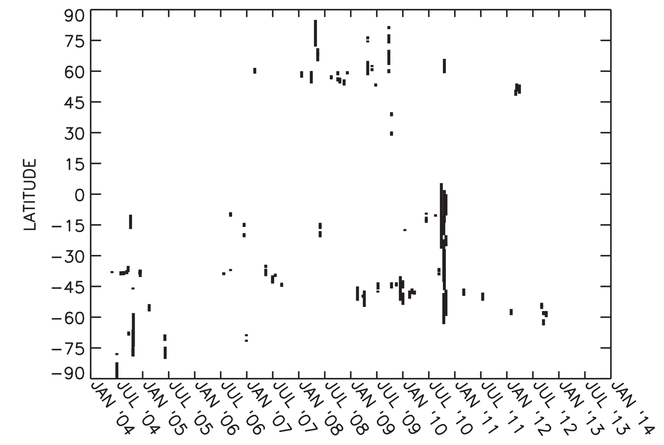
Via entrainment, humidity affects convection. However, the interaction is 2-way. By detraining saturated air into the environment and evaporating falling rain, convection moistens the environment, while by compensating subsidence, it dries the environment. The figure above shows the GCM's vertical profile of convective moistening (dq/dt > 0) and drying (dq/dt < 0) as a function of precipitation during two MJO events. The model was run through a set of 20-day hindcasts, initialized each day with an ECMWF analysis. This GCM version with strong entrainment and rain evaporation is fairly successful at producing the observed MJO events. When convection is shallow or midlevel in depth, moistening dominates. Only in strongly precipitating conditions does convection dry the troposphere.

Why should you care? Part 1: Jovian planets



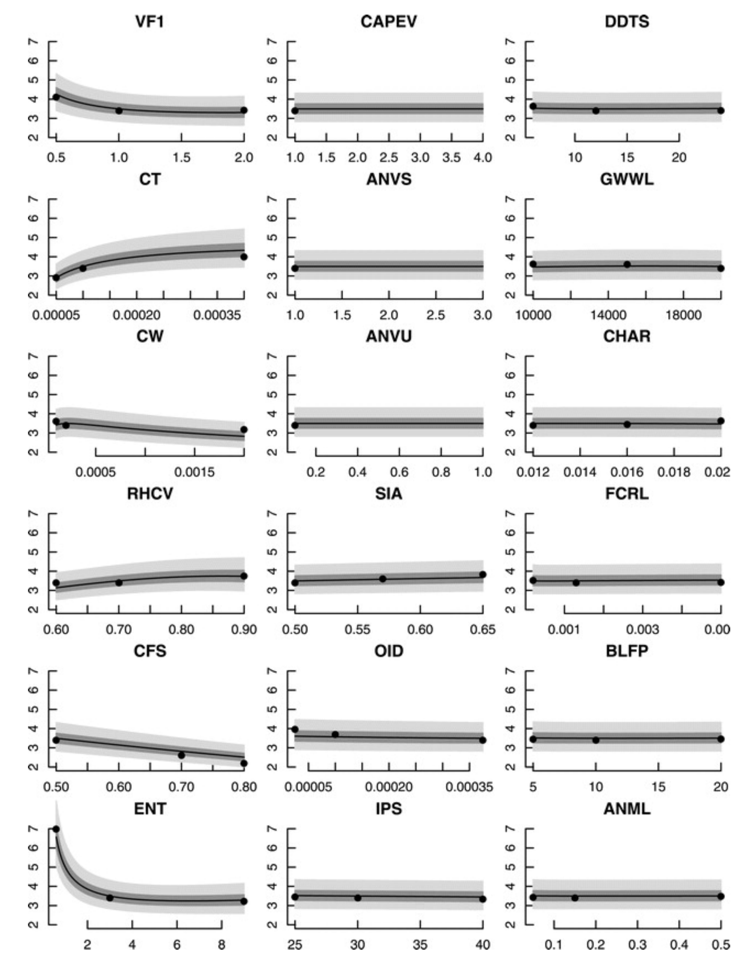
On Jupiter (Porco et al. 2003, Science), the zonal wind profile (black = Cassini, red = Voyager 2) correlates with bright zones (anti-cyclonic, white) and darker belts (cyclonic, shaded). It had been thought that zones/belts were regions of up/downwelling. However, convective features (bright in continuum and methane band filters) occur preferentially in the belts, implying that the mean meridional circulation is indirect, with mean rising motion in the belts. This can only be reconciled with the overall lower cloud tops and drier conditions in the belts if convection is organized into a few small, very humid regions, with gentle subsidence and drier conditions elsewhere. This in turn requires convection to be sensitive to tropospheric humidity.

Why should you care? Part 2: Titan



We use Cassini near-IR images to detect tropospheric methane clouds due to rising motion and moist convection and thus to map the seasonal progression of Titan's circulation. Since Cassini's arrival during Titan late southern summer, clouds have occurred often in southern midlatitudes, the predicted location of the rising branch of the Hadley cell, as seen above (an update of Turtle et al. 2011, GRL). After vernal equinox in 2009, extensive tropical convection broke out in Fall 2010, signaling a likely shift to an equinoctial Hadley cell with rising branch at the equator. Titan GCMs predict that a further shift to a northern summer configuration dominated by northern midlatitude clouds should have happened by now, but the data show no evidence of this. Is convergence and moistening only occurring right now at low levels in the north, with a still-dry free troposphere above, and would a cumulus parameterization with strong entrainment successfully predict the delay in the seasonal transition?

Why should you care? Part 3: Habitable Zone



Perturbed physics simulations that systematically vary free parameters in GCMs can reveal the aspects of the physics that have the greatest effect on climate sensitivity to a doubling of CO_2 concentration. One such experiment with the Hadley Centre GCM showed that varying the parameter ENT that controls the convective entrainment rate (lower left panel above) had the greatest impact on sensitivity of all parameters tested (Rougier et al. 2009, J. Clim.). As entrainment weakens, convection deepens, eventually transporting large amounts of water vapor into the stratosphere, which (unrealistically) produces the high sensitivity (Joshi et al. 2010, ACP). Given the "water loss" view of the inner edge of the exoplanet habitable zone that occurs when the tropopause erodes and water vapor builds at high levels where it can be lost to space via UV dissociation, might the underestimated entrainment of today's cumulus parameterizations make models too quick to get to the water loss limit?

Conclusions

✧Tropospheric humidity controls the onset of deep convection; strong entrainment of drier air into convective updrafts explains this behavior.

✧Deep convection on Jupiter occurs in belts rather than zones, even though belts are drier; this can be explained if convection is restricted to a few very humid regions with subsidence drying elsewhere in the belts.

✧The seasonal progression of Titan's mean circulation is delayed relative to the predictions of GCMs; is the timing affected by the impact of dry air above the boundary layer on the outbreak of methane deep convection?

✧ Weak entrainment increases stratospheric water vapor and causes high climate sensitivity; are existing models adequate to predict convection's effect on water loss and the inner edge of the exoplanet habitable zone?

✧Thanks to Jingbo Wu for assistance with this poster.