Goddard Institute for Space Studies

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Convection Sensitivity to Atmospheric State During the Developing Stage of the MJO

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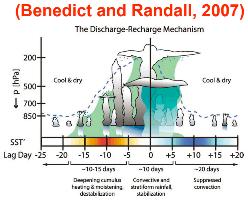
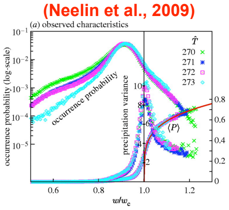
Introduction

The relationship between convection depth and tropospheric humidity is central to the development of the MJO, according to the recharge-discharge theory (see figure below from Benedict and Randall, 2007). Shallow cumulus clouds in the dry suppressed stage moisten the lower troposphere, allowing subsequent convection to penetrate deeper and moisten higher levels, until the column is sufficiently humid to trigger deep precipitating convection. Historically GCMs have had a difficult time simulating the MJO, though recent studies have suggested that by making convection more sensitive to humidity via stronger entrainment and humidity more sensitive to convection via stronger rain evaporation, it is possible to simulate a gradual progression from shallow convection to congestus to deep convection, leading to simulated MJO-like variability. TRMM TMI observations of the precipitation-humidity relationship show interesting behavior: a sharp increase in rainfall at an intermediate "critical" value of column water vapor (CWV), and large variance in rain rate near the critical value (see figure below from Neelin et al., 2009). This presents an interesting challenge to cumulus parameterizations.

(Benedict and Randall, 2007)

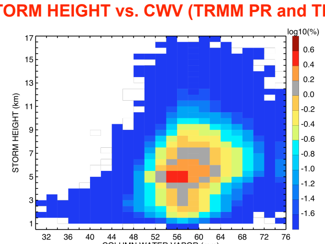


(Neelin et al., 2009)



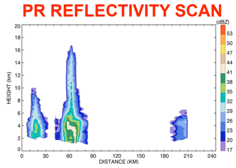
We use TRMM PR and TMI data together with CloudSat/CALIPSO and AMSR-E data to constrain the dependence of convection depth and vigor on atmospheric water vapor during the developing stage of the MJO and to test the ability of the GISS Model E2 GCM to simulate the observed variability. The peaks of 10 boreal non-summer MJO events from Sept. 2006 – May 2010 in the equatorial Indian Ocean, Maritime Continent, and West Pacific are located using the Wheeler-Hendon and NOAA CPC MJO indices. The developing stage is defined as 10-14 days before the peak. For these times and locations we gather TRMM PR storm heights and coincident TMI CWV, and analogous CloudSat/CALIPSO GEOPROF-LIDAR convective cloud top heights and AMSR-E CWV.

STORM HEIGHT vs. CWV (TRMM PR and TMI)

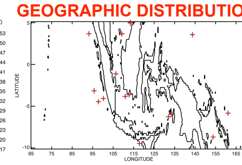


The pdf of PR storm height and TMI CWV for the MJO developing stage is shown above. Storm heights are screened using the rain quality and reliability flags and by requiring a maximum Z > 20 dBZ. We also exclude bins with only 1 point and all bins with storm height > 17 km, which were found by inspection to be noise. For CWV < 40 mm, convection detected by PR is exclusively shallow. Between 40-50 mm, there is a sharp transition in which congestus and deep convective clouds appear, consistent with the sharp increase in TMI precipitation seen in the Neelin et al. data. However, for CWV ~50-66 mm, there is considerable variability in storm height, with shallow, congestus, and deep clouds all possible. This indicates that the large precipitation variance at intermediate CWV shown by Neelin et al. is due largely to convection depth variability rather than variations in rain intensity for clouds of similar depths. For CWV > 66 mm, most storm heights penetrate above the freezing level. However, the deepest storms (storm heights up to 17 km) surprisingly do not occur at the highest CWV values, but rather at intermediate CWV values. Are these real storms? Why are they so deep while those in wet environments are not?

PR REFLECTIVITY SCAN



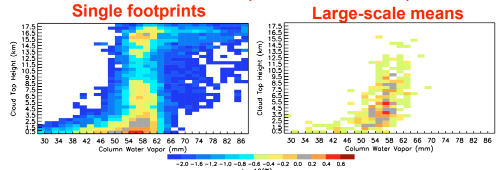
GEOGRAPHIC DISTRIBUTION



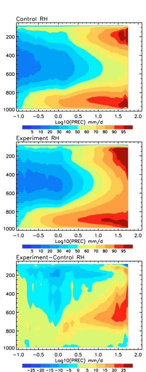
We visually inspected 27 PR reflectivity profiles with storm heights of 16-17 km. 19 are real storms that penetrate to this height; the others are storms of lesser depth with noise above that exceeds 17 dBZ. An example vertical cross-section of reflectivity along the PR scan for one very deep storm is shown at the left above. The geographic distribution of all such storms is shown at the right above. While it may seem surprising that ocean storms can penetrate to these heights with high reflectivity, the figure shows that all of them occur in the Maritime Continent, i.e., over very warm water and close to coastlines, which may suggest that some originated over land and maintain some continental character. Morita et al. (2006) in fact noted the presence of intense oceanic convection with TRMM LIS-detected lightning that occurred during the developing phase of the MJO.

CCTH vs. CWV (CloudSat/CALIPSO)

Single footprints / Large-scale means



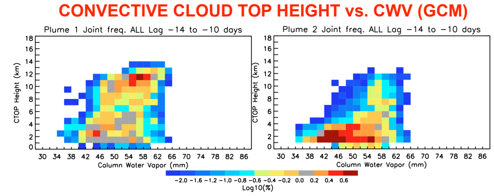
TRMM PR does not actually detect the top of the storm, only the altitude to which large particles penetrate. To locate actual convective cloud tops, we utilize the CloudSat/CALIPSO GEOPROF-LIDAR combined cloud radar-lidar product. For each cloud base between 0.5-2.0 km we define the altitude of the first echo top above as the convective cloud top height (CCTH). The pdf of CCTH vs. AMSR-E CWV is shown above, for single footprints at the left and for large-scale (~15°) along-track averages at the right (for later comparison to a GCM). CloudSat/CALIPSO observes a similar shallow-congestus-deep transition at 40-50 mm CWV, suggesting that for shallower clouds, PR often finds the actual cloud top (if it detects the cloud at all). Likewise, for CWV ~50-66 mm, CloudSat/CALIPSO sees large variability in CCTH for a given CWV, but with more of the deepest clouds (up to 18 km) than PR sees. At these CWV values, the trimodal distribution of cloud tops (Johnson et al., 1999) is obvious. CloudSat/CALIPSO also detects primarily deep convection when CWV > 66 mm, but unlike the PR data, these storms are just as deep as those at CWV ~ 50-66 mm. The combined impression from TRMM and CloudSat/CALIPSO is that very deep convection is possible for any CWV > 50 mm, but at the low end of this range storms are more vigorous (perhaps destabilized by previous shallow heating; see Rapp et al., 2011), while at the high end they exist in more neutrally stable environments.



RH vs. precipitation (GCM)

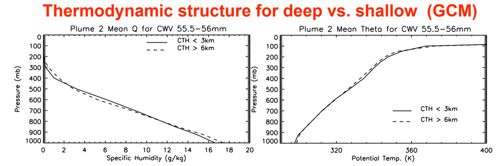
Although the CMIP5 GISS Model E2 GCM ("Control" in the figure at the left) does not simulate an MJO, an experimental version with stronger convective entrainment and rain evaporation does produce MJO-like variability (Kim et al., 2011; Del Genio et al., 2011). Strong entrainment produces shallow convection and a drier middle/upper troposphere at weak rain rates, while strong rain evaporation creates a more humid middle troposphere at high rain rates. Similar behavior has been noted in other GCMs (Kim et al., 2009; Thayer-Calder and Randall, 2009; Hannah and Maloney, 2011); it suggests that the sharp transition from weak to strong precipitation is controlled by midlevel humidity, as was concluded by Holloway and Neelin (2009).

CONVECTIVE CLOUD TOP HEIGHT vs. CWV (GCM)



GISS Model E2 partitions the cumulus mass flux into two plumes with different entrainment rates. The simulated pdf of convective cloud top height vs. CWV during the developing phase of a model MJO event for the more weakly entraining (plume 1) and more strongly entraining (plume 2) components of the mass flux are shown in the figures above. Plume 1 simulates the transition to deep convection at lower CWV (~42 mm) than is observed by TRMM and CloudSat/CALIPSO, while plume 2 exhibits a more gradual transition of peak convective depth between CWV = 40-50 mm, similar to that observed. However, plume 1 produces higher (and more realistic) tops for the deepest clouds than plume 2. The mass flux of plume 1 is determined by grid-scale low level convergence; apparently this is not a good indicator of when weakly entraining convection should occur. A better approach might be to relate weaker entrainment to parameterized mesoscale convergence when downdraft cold pools are present. Interestingly, the GCM manages to produce the full range of CCTH variability for intermediate CWV values, even though the cumulus parameterization contains no stochastic elements.

Thermodynamic structure for deep vs. shallow (GCM)



To understand how the GCM can produce shallow and deep convection for the same CWV, we created shallow (CCTH < 3 km) and deep (CCTH > 6 km) subsets of simulated convective events within a narrow range of CWV (55.5-56 mm). Mean profiles of grid-scale (2°x2.5°) specific humidity and potential temperature for the two subsets are shown above. Deep convection is preferred when the boundary layer is slightly wetter and the middle troposphere slightly drier, a conclusion also reached by Muller et al. (2009). However, the deep convective subset also has a slightly warmer PBL and more unstable upper troposphere than the shallow subset. Thus, although midlevel humidity appears to regulate the gross features of convection in dry vs. wet environments, boundary layer perturbations of both T and q may be needed to explain precipitation variance in threshold environments. This is consistent with recent analyses of of perturbations applied to CRM-simulated convection (Kuang, 2010; Tulich and Mapes, 2010).

Conclusions

✧ TRMM and CloudSat/CALIPSO active remote sensing together allow for a definitive assessment of variations in convective cloud depth and convective strength as a function of environmental state.

✧ During the developing stage of the MJO, there is not a systematic progression from shallow to congestus to deep convection as column water vapor increases. Rather, for a given environmental state a mix of clouds of different depths occurs, but with the probability of clouds of greater depth increasing as the column moistens.

✧ Midlevel humidity appears to control the sharp transition from weak to strong convection. The fact that many GCMs that simulate a large increase in midlevel humidity between weak and heavy precipitation situations also produce a fairly realistic MJO suggests that entrainment and rain evaporation should be a focus for parameterization development.

✧ Although stochastic behavior should be added to cumulus parameterizations, it is not required to produce the observed large variance in convection depth in intermediate CWV environments. Other factors such as subtropical dry intrusions and pre-conditioning by shallow clouds may be sufficient to produce significant variability in a deterministic model.