Observed and Simulated Vertical Structure of Tropical Convective Storms: Implications for GCM Parameterization

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Introduction

General circulation model (GCM) simulations of equilibrium greenhouse gas-induced climate change suggest that the single largest contributor to uncertainty in cloud feedback is due to changes in the areal extent and cloud water contents (CWC) of mesoscale convective systems (Yao and Del Genio 1999). Among the physics difficult to parameterize is the vertical transport and detrainment of cumulus condensate, the physics controlling the area of the mesoscale anvil, and the partitioning between ice mass in small (cloud) and large (precipitating) particles. The bottom-up view from Atmospheric Radiation Measurement (ARM) instruments at Manus and Nauru can be combined with the top-down view from the National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) satellite to give us a comprehensive look at the vertical structure and radiative characteristics of tropical convective systems. While we await the advent of ARM millimeter cloud radar (MMCR) vertical profiles of liquid water and ice at the Tropical Western Pacific (TWP) sites, we are compiling statistics on hydrometeor profiles in tropical convective storms derived by matching TRMM Microwave Imager (TMI) radiances (10 GHz, 19 GHz, 21 GHz, 37 GHz, and 85 GHz) to a “database” of Goddard Cumulus Ensemble Model simulations for various tropical scenarios (Kummerow et al. 1996). Twenty-nine orbits of data (covering February 1 and 2, 1998) have been processed thus far, sampling the rain areas of 25,318 storms between 37°N and 37°S latitude.

Satellite pixels with nonzero surface rain and cloud above the 5-km level are assumed to be associated with deep convective systems. Since cumulus mass flux is the product of area and updraft strength, we stratify retrievals by storm size and strength. We use a clustering algorithm (Machado and Rossow 1993) to define a single “storm” as all contiguous raining pixels with cloud above 5 km. Individual cells within a mesoscale cluster separated by areas with no rain are thus counted as separate storms. However, visual inspection of TMI images indicates that the vast majority of storms defined in this way are isolated convective events. We use a 20 km equivalent radius (50 pixels given the TMI resolution and sampling) as an arbitrary threshold separating “big” from “small” storms. We also use TRMM Lightning Imaging Sensor (LIS) data as a proxy for updraft strength, separating storms according to the presence or absence of at least one lightning pixel within the rain area. Finally, we segregate storms by surface type.

The resulting composite properties correspond only to the precipitating part of the anvil and the convective cores. We estimate visible optical thicknesses using assumed particle sizes typical of those observed during field campaigns (Heymsfield and McFarquhar 1996). We are in the process of searching for examples of cluster passage or generation over Manus and Nauru at times of TRMM overflights to allow us to combine ARM surface downwelling radiation observations with satellite radiation budget estimates for the same storms. Finally, we have composited the hydrometeor profiles of 9,946 tropical convective storms simulated during a 1-day run of the Goddard Institute for Space Studies (GISS) GCM to get impressions of some of the strengths and weaknesses of the current cumulus and stratiform cloud parameterizations.

Small storms (mostly isolated cells) are much more common than mesoscale systems, a feature noted in previous satellite studies of the tropics but contrary to the popular impression from the sparse samples observed in field programs such as Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE). Ocean storms tend to be larger than land and coastal storms, and large ocean storms occur about twice as often as the 2:1 ratio of ocean and land areas would suggest. However, surface rain rates averaged over the storm area are significantly greater over land and even more so for coastal events. Lightning storms are a small fraction of the total for all sizes and surface types. On average, storms with lightning are bigger than storms without lightning. Although total lightning flash rates are much more numerous over land, the number of storms with lightning is comparable over land and ocean, so the frequency of occurrence of lightning storms over ocean is about half that over land. Rain rates increase with both storm size and updraft strength over ocean but are sensitive more to strength than size over land and coast.

Figure 1 shows the mean vertical profiles of the various hydrometeor types for several classes of storms. Big storms tend to have more hydrometeor mass of all kinds (cloud liquid, cloud ice, precipitating liquid, precipitating ice) than do small storms (not shown), except for continental lightning storms. Cloud ice is a small fraction of the total ice content for all storm types but tends to occur at higher altitude. Cloud ice is negligible in land storms. In general, cloud ice is somewhat more prevalent in lightning storms than non-lightning storms. The same is true for precipitating ice but only for the vertically integrated water path. The transition from liquid to ice in precipitation occurs near the freezing level (4 km to 5 km) for all storm types, but for cloud water it occurs at about -10°C (6 km to 8 km) in ocean storms and about -30°C or colder (~10 km) in continental storms. Ice in convective storms may be determined by the available moisture in the boundary layer or by the efficiency of conversion from cloud water to rain in the updraft. In the former case, we might expect ice amounts and rain rates to be positively correlated (with each other and by inference with planetary boundary layer [PBL] humidity). In the latter case we might expect ice amount and surface rain rate to be negatively correlated, i.e., ice is lofted and detrained into the upper troposphere at the expense of rain formation, as a function of updraft strength. The data suggest that for a given surface type the former effect may dominate. However, Table 1 indicates that lightning storms have greater ice water paths on average than do non-lightning storms in all size and surface type categories, so convection strength does appear to play a role as well.

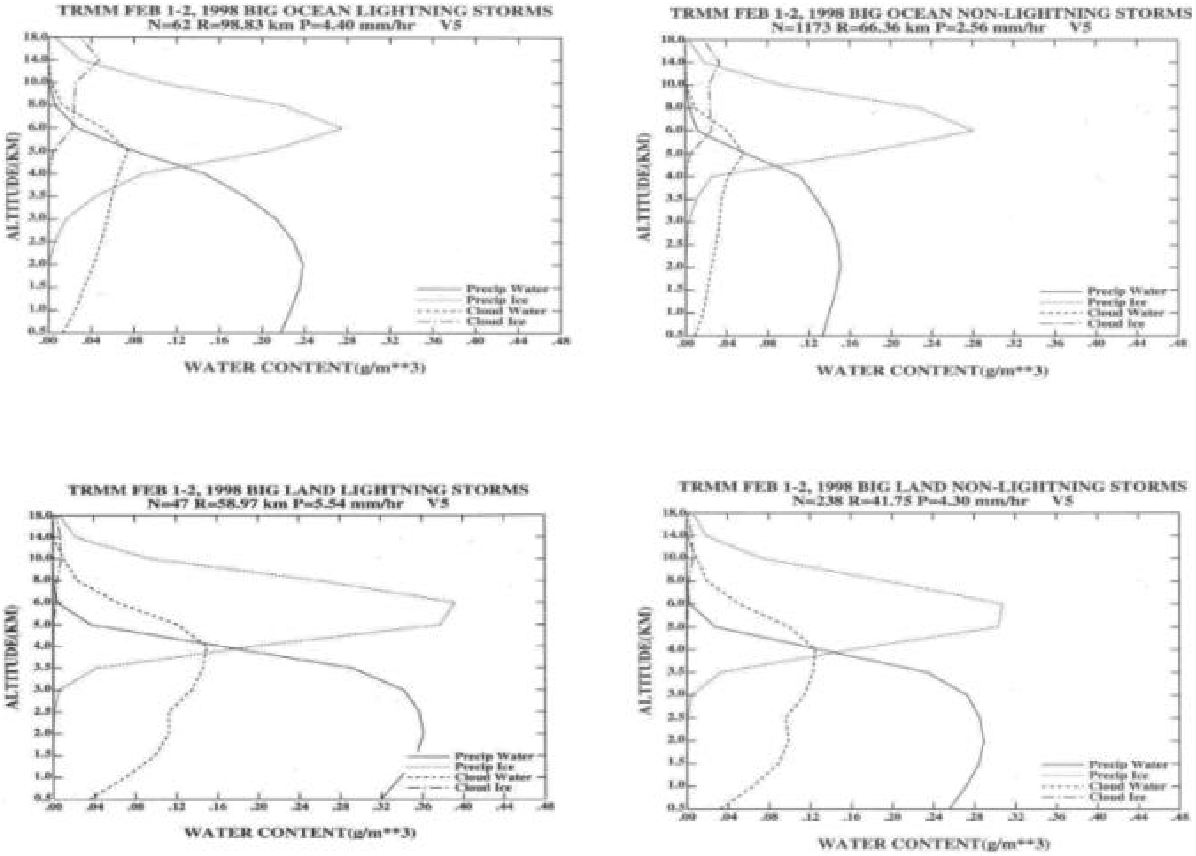

Figure 1. Mean vertical profiles of cloud ice (dash-dot), precipitating ice (dotted), cloud liquid (dashed), and precipitating liquid (solid) water content for four classes of large size tropical convective storms: strong ocean storms (upper left), weak ocean storms (upper right), strong land storms (lower left), weak land storms (lower right).

Table 1. Estimated microphysical and radiative properties of observed tropical convection.

	Total IWP (g/m^2)	**Cloud Ice Fraction of IWP**	**Cloud Ice**	**Optical Thickness Precipitation Ice**	**Total**
Ocean					
Big, Lightning	2017	.21	18 to35	21 to 32	39 to 66
Big, No Lightning	1765	.19	14 to 28	19 to 28	33 to 56
Small, Lightning	1600	.22	16 to 30	16 to 24	32 to 54
Small, No Lightning	1305	.17	10 to 18	14 to 21	24 to 40
Land					
Big, Lightning	2122	.035	3 to 6	27 to 40	30 to 46
Big, No Lightning	1655	.030	2 to 4	21 to 32	23 to 36
Small, Lightning	2230	.020	2 to 4	29 to 43	31 to 47
Small, No Lightning	1093	.017	1 to 2	14 to 21	15 to 23

To constrain the optical thicknesses of different storm types, we combine the derived ice water paths with assumed ranges of cloud particle effective radius (30 µm to 60 µm for cloud ice, 150 µm to 250 µm for precipitating ice). Table 1 suggests that small and large ice particles contribute roughly equally to the total optical thickness for ocean storms, but that precipitating ice dominates the radiative impact of systems over land and coast. This is an important conclusion for GCMs, many of which ignore the effect of precipitation-size particles on radiation. Because of the greater contribution from small particles, ocean storms are somewhat more reflective than land storms, a result that can be tested with available data sets (e.g., International Satellite Cloud Climatology Project [ISCCP]). Lightning storms tend to be optically thicker than non-lightning storms, suggesting that a parameterization of convective strength and not just mass flux must eventually be sought for climate GCMs.

The GISS GCM differs from the observed storm vertical structure in several ways: (1) it has more cloud ice than precipitating ice, (2) ocean-land differences in the relative contribution of cloud ice to total IWP are not simulated, (3) cloud water is excessive relative to rain water at low altitude, (4) an unrealistic peak in precipitation from boundary layer clouds is simulated. The deficit of precipitating ice is an underestimate of stratiform (anvil) large ice particles, while the excessive low-level rain is due to PBL stratus not directly associated with convection. The results suggest several avenues for parameterization development: Inclusion of a parameterized mesoscale updraft and downdraft (rather than the weaker grid-scale responses to condensation heating/cooling in the current model) might convert more cloud ice to precipitating ice and dry the lower troposphere enough to suppress low-level stratus. Vertical advection of cumulus condensate might be an additional precipitation source for the upper troposphere; however, simulation of land-ocean differences would necessitate a parameterization of convective updraft strength rather than just cumulus mass flux. A representation of vertically unresolved lowering of PBL height by subsidence and its effect on stratus formation is another possibility.

References

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