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Temporal Evolution of vertical structure of precipitation

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What:

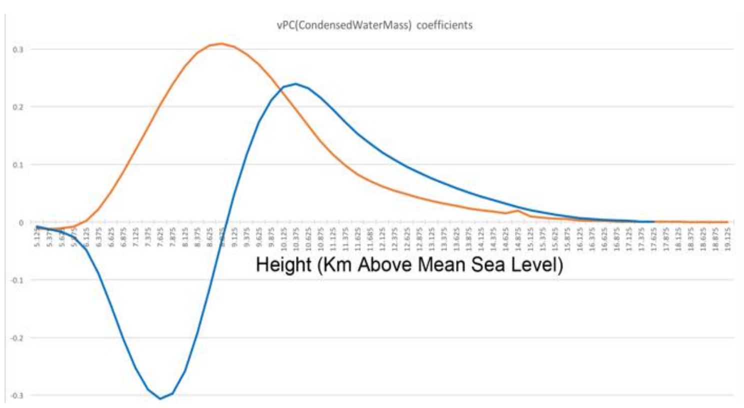
Today's constellation of passive microwave radiometers in low-Earth orbit includes two broad categories of instruments: the "opaque-channel" sounders with channels near different gas absorption lines (making them particularly useful to estimate quantities associated with these gases, namely temperature and relative humidity) and the "window-channel" imagers with channels away from the absorption lines (so that their sensitivity to the amount of condensed water can be more easily quantified). The millimeter-wavelength channels of today's radiometers are mostly near the oxygen absorption line at 118.75 GHz or the water vapor absorption line at 183.31 GHz. While this suggests that the absorption would limit their utility over clouds, the reverse is actually true. The figure to the right illustrates this ability, with measurements at different frequencies obtained by the millimeter-wave SAPHIR sounder and the window-channel MADRAS imager. The central question is: to what extent can the high-frequency radiances be used to estimate the vertical structure, however coarsely, over the convective clouds; and conversely can one predict the mm-wavelength radiances from simulated clouds.

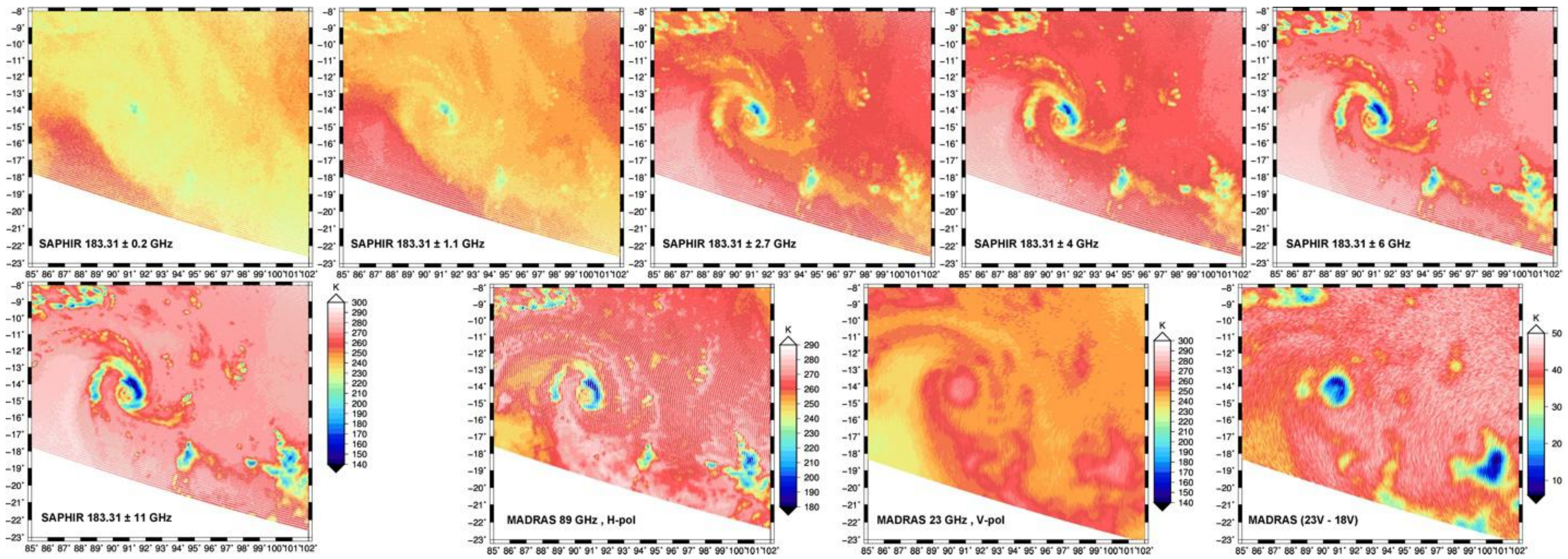
Analyses over the past year have laid the foundation for the production of such vertical cloud structure information from the radiometers in the Global Precipitation Measurement (GPM) mission constellation including the GPM Microwave Imager (GMI)'s 6 higher-frequency channels (GMI-HF). Indeed,

1) the high-frequency channels are actually at least as sensitive to the condensed mass in the upper levels as to precipitation at the surface (witness the cold temperatures measured over the deepest portions of the clouds in the figure to the right);

2) the analyses demonstrate the ability to estimate cloud-top heights (or rather condensed-water heights) for different condensed-mass thresholds, e.g. three thresholds which would produce three heights cwH1, cwH2 and cwH3, as well as the first two vertical principal components vPC1 and vPC2 of condensed mass, and the total Condensed Water Path (CWP);

3) while these variables are mutually correlated, it takes at least 3 PCs of brightness temperature to capture 99% of the variability for any given radiometer, so there are at least three independent pieces of information in the radiances from any one beam – these different pieces of information are useful for different interpretations of the condensed water within the column sensed by the beam.





How:

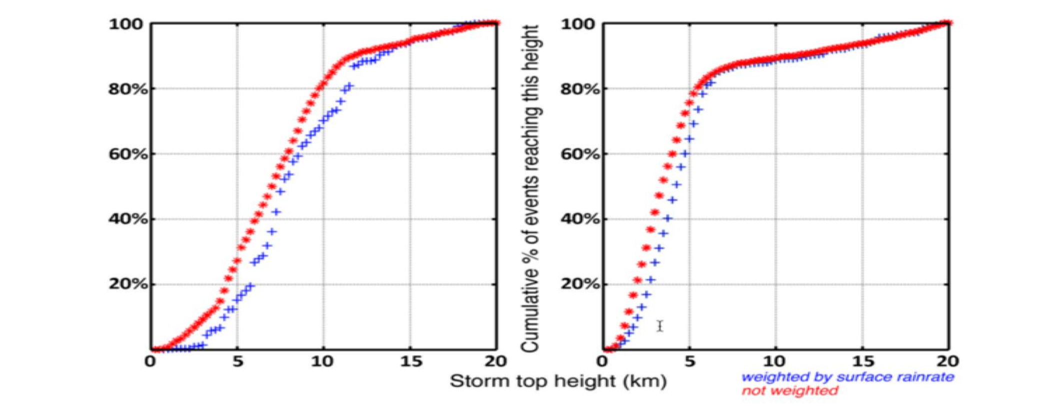
The basic approach to interpret the MMW observations in terms of the underlying convection, is semi-empirical and proceeds in two steps. First, a reference dataset is compiled, consisting of nearly-simultaneous (within 3 minutes) nearly-coincident (allowing for different instrument geometry) observations by a space-borne radar (TRMM PR or GPM DPR) and the sounder in question. The radar is used to separate the observed columns into two categories: "clear" and "not clear". Different criteria can be used to define this detection. Parametric criteria that were tested (using half of the reference dataset for "training", and the other half to evaluate the detector and, later, to quantify the uncertainty in the estimates) rely on the radar-derived condensed water mass (CWM) at the different 250m-thick height bins resolved by the radar within an atmospheric column. The criteria (using two parameters p1 and p2) were of the form: "not clear" = "CWM > p1 g/m3 in at least one bin above p2 km above mean sea level". Different values of p1 ranging from 0.05 g/m3 (chosen because it essentially matches the radar detection threshold) up to 0.2 g/m3, and p2 ranging from 0 up to 8 km, were tested. In each case, two categories are obtained, and the corresponding linear discriminant is derived empirically from the training dataset. A second, non-linear discriminant is also derived in each case, by first augmenting the observed brightness temperatures with channel-to-channel normalized differences (to try to reduce the surface effects) and then deriving the linear discriminant in this higher-dimensional space. The results are illustrated in the figure to the right, which quantifies the performance of each instrument and each detector. This curve is obtained after the expression for the discriminant has been derived, by applying the discriminant to the "evaluation" half of the dataset, and calculating the proportion of correct "not clear" detections (vertical axis) versus the proportion of false "not clear" classifications (horizontal axis), for different values of the detection threshold – varying the detection threshold produces the curve (from high threshold values which seldom detect falsely but miss many correct detections, to low threshold values which detect most of the time, the good and the bad).

In the figure to the right, the performance of the detectors obtained with p2 = 0 km is shown in the left panel, and that for p2 = 5 km is shown in the right panel. Half the curves correspond to the discriminants that were derived after including the "augmented" observations (the normalized brightness-temperature differences). The fact that the curves in the right panel show consistently better performance than the curves in the left panel confirms that the radiometer measurements are more specifically sensitive to the upper levels of taller clouds.

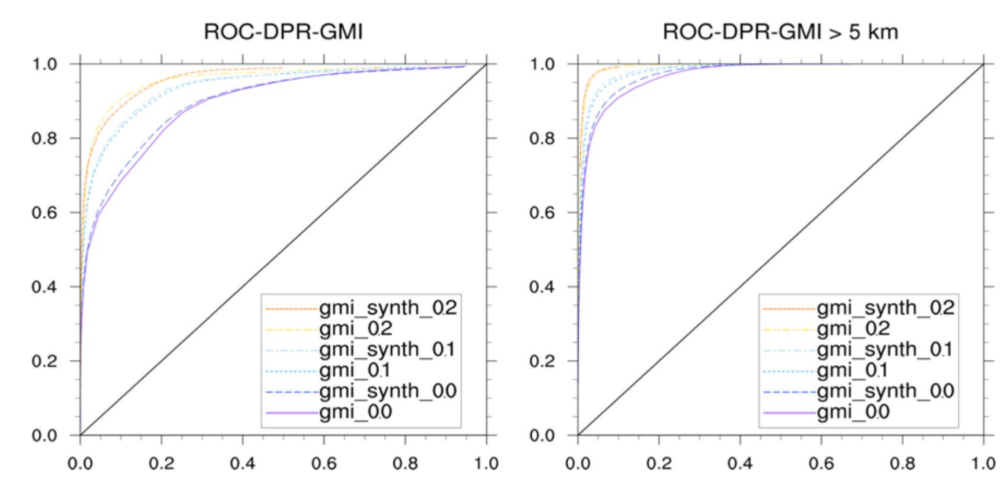
Once a column has been detected as "not clear", the training dataset can be used to estimate the conditional mean of any radar-derived quantity for the observed brightness temperatures for that column. As demonstrated in [1], the approach is to use as inputs to the estimation the principal components of the brightness temperatures that are orthogonal to the first principal component in clear air, to minimize the effect of the clear-sky background ([1]). The Bayesian approach can be used to estimate the maximum height of condensed-water-content above p3 g/m3 (for different values of the parameter p3), as well as the first and second vertical principal components, vPC1(CWM) and vPC2(CWM), of the radar-derived condensed-water-content profile (described in detail in Haddad et al, 2017, for the case of the MHS sounder). The coefficients of vPC1(CWM) and vPC2(CWM) are shown in figure 3, and roughly correspond respectively to the weighted average of all condensed water above 5km (vPC1(CWM)), and the difference between the average condensed water between 5km and 9km minus the condensed water content above 9km (vPC2(CWM)).

Why:

The main reason that all this information is important, however relatively coarse its level of detail, is that it provides systematic estimates of the spatial structure of the cloud and, when tracked in time, its evolution. Such cloud-structure information is crucial to understand tropical storms and their evolution. At the moment, the only systematic sources for such contextual data are the geostationary-IR cloud-tracking algorithms, which suffer from two shortcomings: they do not agree among one another in the segmentation or the tracking (with coarser segmentation producing inconsistent lifecycle statistics though it is a more consistent indicator of storm organization and intensification); and they are not sensitive to the water below the very top of the cloud. The main significance of retrieving cwH1, cwH2, cwH3, vPC1, vPC2 and CWP from all the GPM radiometers with millimeter-wavelength channels is that it will provide a systematic data set that identifies precipitation type and storm vertical properties at reasonable horizontal resolution, using sensors that are considerably better able to observe the structure within clouds than the infrared (IR) analyses, and with much better temporal sampling than any satellite radars.



To illustrate the climate scale significance, the figure above displays the cumulative distributions of storm-tops calculated over two different 5°x5° domains, obtained by aggregating the observations of the TRMM radar from 1998 until 2013. The red curves correspond to the number of times a given PR storm-top height was observed; the blue ones are weighted by the value of surface rain. The cumulative distributions show a striking difference between the tropical regime (left panel), and the transition regime (right panel). In the tropical case, the storm top has to reach 10-km before one can account for 80% of the cases counted by event (in red), and further up to 11-km to account for 80% of the cases counted by surface precipitation (in blue). In contrast, in the transition case, 80% of all cases have storm tops below 5km. These distributions illustrate the differences in the occurrence of deep convection as one moves from the tropics to the mid-latitudes. While the histograms shown in the figure required a very long period of data aggregation (because of the poor sampling frequency of the space-borne radar), the result of this proposal will generate sufficiently high sampling frequency to enable the estimation of seasonal storm histograms at high spatial resolution (nominally 0.25° in longitude and latitude), thus enabling the evaluation of interannual change and trends that would correspond to the climate-scale changes in the Hadley circulation.



Expected results:

The approach demonstrates a method to estimate the coarse vertical characteristics of convective clouds from millimeter-wavelength radiometer measurements for every one of today's constellation of orbiting mm-wave instruments. Reference databases of coincident observations by the radiometers and the GPM radar have been compiled, and the corresponding detection and Bayesian retrieval algorithms have been developed. Below 85 GHz, the retrieval is complicated by the competing effects of absorption/emission by the hydrometeors and out-of-beam scattering – and below about 25 GHz, where out-of-beam scattering is negligible, the spatial resolution becomes too coarse. The reference databases of nearly-simultaneous nearly-coincident radar and radiometer observations need to be augmented periodically to ensure that the reference is as representative as possible of real clouds. To that end, the coordinates and times of all possible 3-minute coincidences between the radiometer and the radar in question need to be identified using orbital propagation routines with daily two-line element (TLE) ephemeris data. After matching the corresponding observations from intersecting satellites, the reference dataset needs to be divided into the "training" half and the "validation" half, the training portion being used to derive the detector and the estimator, and the validation portion to quantify the uncertainty in the retrievals. Because Bayesian methods aim to minimize variance, they tend to produce estimates of extremes that are biased towards the overall mean. To mitigate this issue, an alternate percentile-matching method has been tested in the cases of GMI-HF and SAPHIR. The alternate approach starts by dividing each reference database into ~ 1000 sub-databases using discretized ranges for the first three principal components of the inputs (~5 for PC3, ~10 for PC2, ~20 for PC1). About 100 of the resulting sub-databases turn out to have the property that the probability distribution of the measurements is dominated by the first principal component (i.e. PC1 captures over 80% of the variability within the sub-database) – these are the cases with the more substantial rain. This implies that the retrieval problem within each of these sub-databases is essentially 1-dimensional. That is why it is possible to consider using a straightforward 1-dimensional percentile matching, instead of a Bayesian method, for each of our 6 structure variables. In the initial test on the 0.05 g/m3 height, pdf-matching reduced the bias by about 30% at the expense of an 8% increase in additive noise.