LATENT HEAT RELEASE ESTIMATES IN HURRICANES USING A PR-TMI COMBINED ALGORITHM

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1 Introduction

This paper presents some of the results obtained on latent heat release estimates from space-borne passive and active instruments. Using the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) supported by a rain profile database built from TRMM Precipitation Radar (PR), we were able to retrieve an estimate of the latent heat release in 3 hurricanes observed during the year 2000. These hurricanes were observed by the TRMM sensor package more than once during their life cycle which allowed us to relate the obtained results to the systems evolution.

Section 2 presents the basic principles that allowed us to infer the latent heat release from the retrieved variables, namely the content of the different species of water: cloud, liquid precipitation and ice precipitation. Section 3 tries to demonstrate the good correlation that exist between the obtained Q_H estimates and the hurricane evolution with three examples: Bret (1999), Alberto (2000) and Debby (2000).

2 Methodology

The thermodynamic equation relates the temporal evolution, the vertical and horizontal advection and the turbulent fluxes of potential temperature (θ) and the source/sink term of latent heating S_θ. The latter represents the sources and sinks due to the water phase changes in the atmosphere, mainly: condensation, evaporation and melting. The retrieved water contents q_c (cloud) and q_p (liquid and ice precipitation) can be used in two mass-conservation equations for the water species similarly to Hauser and Amayenc 1986 or Roux and Sun 1997). It is then possible to define the precipitation production function $F(q_p)$ as:

$$F(q_p) = w\frac{\partial q_p}{\partial z} + \frac{1}{\rho}\frac{\partial(\rho V_p q_p)}{\partial z} = Konv - Evap \quad (1)$$

where w is the vertical velocity, ρ is the air density, V_p is the terminal fall speed of the drops/particle and z is the altitude.
$Konv$ represents the gain of precipitation due to the cloud auto-conversion/collection processes while $Evap$ represents the loss in precipitation due to evaporation processes. $F(q_p)$ is then > 0 when the air is saturated and ≤ 0 when unsaturated

Similarly, it is possible to define the cloud production function $F(q_c)$ as:

$$F(q_c) = w\frac{\partial q_c}{\partial z} = Cond - Konv \quad (2)$$

where $Cond$ represents the production of cloud through condensation and $Konv$ the losses through auto-conversion/collection into precipitation. Neglecting horizontal transport and turbulence, it is possible to write that:

$$S_\theta(z) = \Pi_0 Q_H(z) \quad (3)$$

where Π_0 is the reduced pressure at sea level. Then Q_H becomes:

$$Q_H(z) = \frac{L_v}{c_p}\left[(1-\delta)F(q_p) + \delta F(q_c)\right] - Q_{Hmelting} \quad (4)$$

where $\delta = 1$ when $F(q_p) > 0$ and $\delta = 0$ when $F(q_p) \leq 0$. The melting term is calculated using an approach similar to Leary and Houze 1979.

The q_p and q_c are retrieved from TMI measurements using a so-called Bayesian algorithm similar in principle to those described in Olson et al. 1996 and Kummerow et al. 2001 among others. The main originality of the BRAIN algorithm developed at CETP comes from the database made of PR profiles completed by meso-scale cloud model simulations (Burlaud 2003). This database made of co-located TMI and PR data is large enough to be able to infer precisely BRAIN performances and test the database representativeness.
Table 1 shows the quality of the retrieved q_p for hurricane Bret (1999) when compared with PR estimates. Since PR was our reference for building the database, this table is not a validation. It simply shows that BRAIN is capable to retrieve a tri-dimensional field of q_p which is very consistent with the more "direct" PR data over a case that is not initially in the database. This point is not trivial since the problem is very ill-posed from the beginning when retrieving about 70 variables from only 9 brightness temperatures. The bias is sligtly

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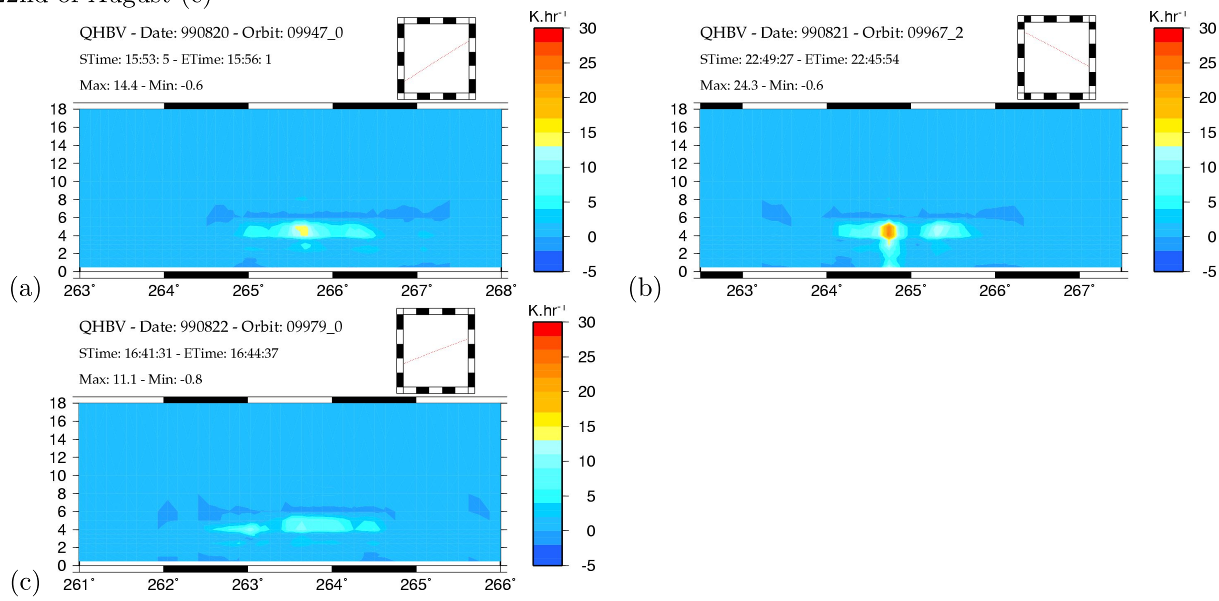
Table 1: Comparison of BRAIN-retrieved q_p vs. PR (reference) estimated q_p (all altitudes mixed from 0 to 5 km). All units are g.m^{-3} except # of pixels.

q_p Range	# Pixels	Bias	Mean Retrieved q_p	Mean Reference q_p	Std. Dev.
4.0- 3.0	6	-1.631	1.787	3.417	0.338
3.0- 2.0	34	-0.847	1.586	2.432	0.342
2.0- 1.0	114	-0.118	1.310	1.428	0.363
1.0- 0.5	527	0.078	0.727	0.649	0.222
0.5- 0.1	1679	0.073	0.331	0.259	0.139
0.1- 0.0	2750	0.019	0.041	0.023	0.049

Figure 1: Vertical cross-section of Retrieved Q_H for hurricane Bret (1999) on the 20th (a), 21st (b) and 22nd of August (c)



dependent of the water content itself with an underestimation at the high end of the water contents range. If plotted in terms of content and altitude, the relative error on the retrieved q_p is minimal around 1.2 g.m^{-3} for altitudes between 0 and 5 km, while the error is minimal around 0.5 g.m^{-3} for altitudes above 5 km. For almost all altitude ranges, the shape of the error curve is similar with overestimation for small contents and underestimation for the highest contents.

Once q_p and q_c are retrieved, it is necessary to infer w which cannot be retrieved directly. We followed Yang and Smith 1999 assuming that there is a relationship between the profile of precipitation intensity and the profile of vertical velocity. A linear regression between the different water content and w is established from cloud-model simulation of hurricane Bret (Nuissier 2003). Two distinct sets of coefficients are established, one for convective regimes and one for stratiform rain. BRAIN provides as an output a convective/stratiform index (CS index) that varies continuously from 1 (stratiform) to 2 (convective). This index is used to decide which set of coefficient to use for a given pixel with a weighting proportional to the CS index.

Determination of w is obviously a critical issue that has a strong impact on the results quality. We tested various sets of coefficients and made a series of comparisons with NOAA-P3s airborne radar data to validate the retrieved fields of w. The results are good, even if the retrieved field is smoother than those obtained from the averaged airborne data. The order of magnitudes are consistent and subsidenses can be retrieved in the stratiform regions. The set of coefficients is only valid for hurricanes for the moment.

3 Results

All the results presented here were obtained using a stratification of the atmosphere in 14 layers, similar to the Gprof algorithm (Kummerow et al. 2001) for historical reasons. These layers are not evenly distributed and the vertical resolution is 0.5 km near the surface but is as loose as 4.0km for the uppermost ones. This is not very good since the calculation of Q_H requires the computation of first derivative with respect to z. This means that the results above the melting layer have to be considered keeping this possible artifact in mind.

3.1 Q_H structure of Bret (1999) and evolution

Bret is a small and intense hurricane which lasted a few days (August 18th to 25th) and experienced a extremely fast growing process between the 19th and the 22nd when it reached its maximum intensity. Three TRMM orbit sampled the system: the first one (#9947) during the early stage of intensification, the second one (#9967) at the end of intensification and the last one (#9979) right at the maximum intensity at the early landfall stage.

Fig. 1 shows the temporal evolution of the vertical Q_H structure in the cyclone during three different phases. On the 20th, the circulation is still not very strong (max estimated horizontal wind 50 knots) with probably weak ascending motions leading to a rather low Q_H, essentially concentrated near the freezing level. Water vapor content might be far from saturation in the lower lecvels, but the satellite retrieval does not give any information on that particular point for the moment. On the 21st, the system is deepening rapidly (max wind around 100 knots) probably in a favorable environnements. The air is close to saturation in the lower levels and Q_H liberation begins near the surface inside the eye-wall where sustained ascending motions are most probably present (confirmed by airborne Doppler data, not shown here). The Q_H liberation is probably important enough to balance the circulation and the excess of energy is used for the deepening. On the 22nd, the hurricane is at its peak intensity (maximum wind around 120 knots) but the presence of land on its west prevents the water vapor advection. In this last stage, even with a fully developed circulation, the hurricane will start to decay within the next few hours because the Q_H relaxation cannot support the primary circulation anymore.

This short study on Bret showed the consistency between the retrieved Q_H and the hurricane evolution. Unfortunately, TRMM overflew Bret only three time while over the ocean which do not make the case so conclusive. The main interest of the Bret Study is the availability of both airborne data and an excellent cloud-model simulation of the hurricane landfall phase (Nuissier 2003).

3.2 Evolution and structure of Alberto (2000) and Debby (2000)

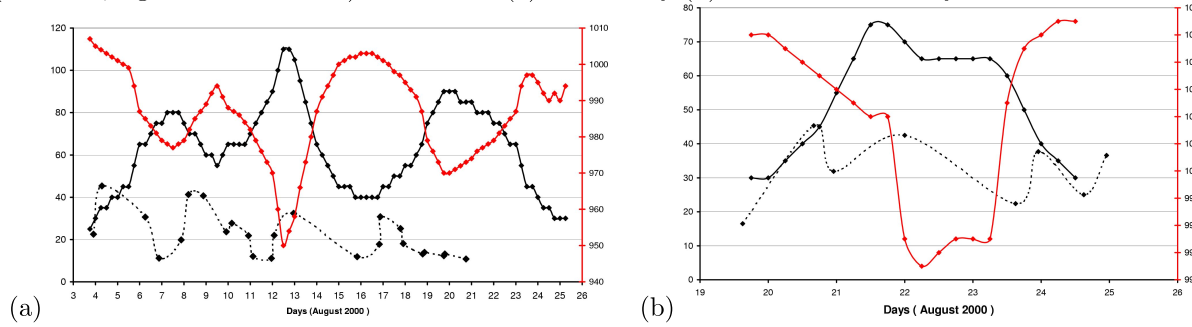
Fig. 2 shows the respective evolution of Alberto (a) and Debby (b). Even if the two storms are very different in characteristics, the temporal evolution of their retrieved mean total Q_H seem to exhibit some very similar features, correlated with the phase of evolution of the wind and pressure curves. Both storms remained long enough over ocean to be sampled by TMI over a long period of time and at very critical stages of their evolution. Alberto started on the 3rd of August 2000 and finished on the 23rd becoming the second longest lasting storm observed in the Atlantic basin. It experienced a series of weakening and re-intensification cycles with 3 maxima (7th, 12th and 20th of August with maximum estimated wind about 80, 110 and 90 knots respectively.

Debby occured between the 19th and the 24th of August 2000 and was behaving very unexpectedly. Its intensification was slow and occured within a very poorly organized system. Its weakening was fast, while the storm was expected to be a threat to South Florida. The maximum wind were estimated on the 22nd around 75 knots.

Both systems seem to have a similar trend in Q_H evolution: a sharp increase is associated with the beginning of intensification; a very sharp decrease is correlated with the middle of the intensification phase; a maximum of Q_H seem to happen right after the maximum of wind intensity and close to the minimum pressure; then a slow decrease of Q_H production goes along with the weakening of the system. This cycle is observed almost twice for Alberto and once for Debby.

The initial sharp increase goes along with the circulation intensification and pressure deepening, probably when most of the released latent heating is used as a source of motion (e.g. Willoughby 1990), the very sharp decrease might be associated with the fact that momentum overtakes the energy production in the system. Then when reaching its peak intensity, the heat source grows again when the balance is reached again between the circulation and the available energy. The slow decrease of Q_H that follows is just the decrease of the intensity of circulation that weakens the water vapor transport and condensation.

Figure 2: Evolution of Q_H (black dashed) along with wind intensity (black solid) and central pressure (red solid, right-hand-side axis) for Alberto (a) and Debby (b) as a function of days of the month.



4 Conclusion

This study was aimed to verify if TRMM TMI observation were a useful set of information to follow the temporal evolution of a tropical cyclone. The methodology is tested on Bret (1999) were three over-pass are available and airborne/in-situ measurements and cloud model simulation are available. Then it is applied to Alberto and Debby (2000) were multiple over-passes are available.

An interesting correlation is found between the hurricane evolution and the Q_H intensity and structure. A three step process seems to take place where the latent heat source/sink term can be related to some of the conceptual models of hurricane balance interms of Momentum and heat sources and sinks. This is a preliminary study that would require more work to be consolidated. Particularly, the use of auxilary data such as sea surface temperature or integrated water vapor will help interpreting the obeserved results.

In the near future, a simple model relating the estimated maximum wind speed and the central pressure will allow us to estimate the horizontal tranports and thus a more complete Q_H estimate.

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