Investigating the role of CAPE for the energy conversion during tropical cyclone intensification

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Introduction

Tropical cyclones (TCs) are viewed to result from the transfer of heat and moisture from the underlying sea to the atmosphere. During the intensification of a TC, ocean heat energy is converted into convective available potential energy (CAPE), then into total potential energy and finally into kinetic energy of the storm (Fig. 1). Therefore, the ocean provides the source of energy for driving the cyclone circulation. Theories on intensification differ in their view on the role of CAPE. Emanuel's widely accepted theory which has gained immense popularity suggests that while a TC is intensifying the atmosphere always remains neutral to convection (Emanuel 1986). This theory was dubbed Wind Induced Surface Heat Exchange (WISHE). In recent times many are questioning if this may be so. Frisius and Schönemann (2012) conducted analysis using Emanuel's axisymmetric model with a few modifications to allow slantwise CAPE (SCAPE) to be a part of the model set up. However, since their focus was on the mature stage of the cyclone it really does not address the value CAPE may have when the storm is transitioning from an initial vortex to a full blown Hurricane. Here we show that CAPE raises the intensification rate of TCs.

OIE → CAPE → PE → KE

Figure 1. The energy pathway during TC-intensification. OIE denotes ocean internal energy, PE atmospheric potential energy and KE atmospheric kinetic energy.

Model and Experiment Setup

The cloud resolving nonhydrostatic model CM1 (Bryan and Fritsch 2002) provided the model framework where a 2 km grid spacing with 600 grid points in the horizontal and 500 m grid spacing with 40 grid points in the vertical were used. Two sets of sensitivity tests were conducted: adjustment of initial sounding and different values for the surface transfer coefficient for enthalpy (C_E). In the first group the atmosphere cooled (High lapse rate) and warmed (Low lapse rate) at 1K/km in the vertical direction. In the second group C_E was quadrupled ($4xC_E$) and quartered ($0.25xC_E$). Results were taken at the time when the rate of intensification was the highest.

In addition, similar experiments were conducted with the Ooyama-model (Ooyama 1969) which is more simple and more comprehensible in view of energetics. The model is axisymmetric and comprises two layers of constant density coupled to a slab-boundary layer model. We use a modified model in which the balance assumption is not made (see Schecter and Dunkerton 2009).

Results

From Fig. 2a we see that an increase of heat energy transported from the ocean via C_E increases the rate of intensification. Fig. 2b shows that a TC with higher strength develops when the atmosphere is cooled but having too warm an atmosphere will hinder tropical cyclogenesis. Fig. 3 displays the fields of CAPE and wind speed at the time of maximum intensification rate for the various CM1-experiments. The Control experiment (Fig. 3, middle panel) reveals that CAPE is zero in and near the centre but there are two strong bands where one is just outside the eyewall and the other far away from it. In the areas where the wind speeds are very intense there is low CAPE but as one moves away from the eyewall the wind speeds decrease and CAPE increases. It is notable that in the experiment with low lapse rate there is no CAPE. From the other experiments we can deduce a rise of CAPE with increasing intensification rate.

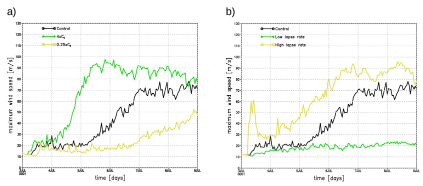

Figure 2. Time evolution of maximum wind speed for a) the C_E experiments and b) the initial lapse rate experiments.

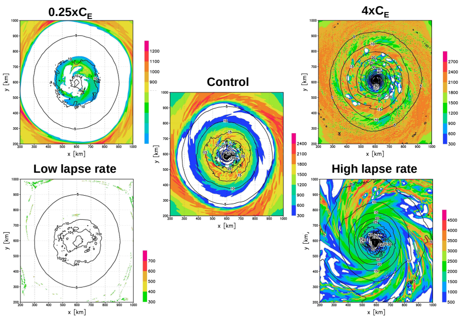

Figure 3. CAPE (J/kg) (shadings) and wind speed [m/s] at the lowermost level for $0.25xC_E$ (upper left), $4xC_E$ (upper right), Control (center), Low lapse rate (lower left) and High lapse rate (lower right).

The Ooyama model reveals qualitatively similar responses to changes in C_E and lapse rate (Fig. 4). The larger sensitivities likely result from the axisymmetry and the simpler model formulation.

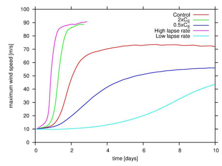

Figure 4. Time evolution of maximum wind speed for the experiments in the Ooyama model. In two cases the integration stops after about three days because the lower layer dissolves at the center of the vortex.

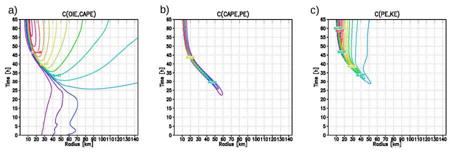

Figure 5. Local energy conversions [W/m] as a function of radius and time for the Control experiment in the Ooyama model: a) OIE→CAPE, b) CAPE → PE, c) PE → KE.

Fig. 5 shows the energy conversions for the Control experiment in the Ooyama model. One can clearly see that CAPE is generated by evaporation over a large area of the vortex while the conversion of CAPE to potential energy takes place in a very narrow ring representing the eyewall. Conversion to kinetic energy results from cross-isobaric flow and is also distributed over a larger area.

Conclusion

The experiments suggest a relationship between the amount of CAPE and wind speed intensification. Too warm an atmosphere will not support cyclogenesis and C_E is vital in the development of a TC. The changes in the C_E value affect the amount of CAPE that is generated. We noticed that the radial gradient of CAPE is related to the intensification rate of TCs.

We explain the role of CAPE as follows: Evaporation from the sea surface generates CAPE while air flows into the cyclone. The generated CAPE by this process is not released before the air reaches the eyewall where air rises. There, CAPE is converted into potential energy and finally into kinetic energy. The delayed release of CAPE close to the center near the radius of maximum wind is a requisite for intensification according to the Sawyer Eliassen equation. Further analysis and experiments will be conducted to better understand how CAPE is impacting on TC-intensification.

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