P1F.15 EVALUATING THE INTENSIFICATION OF TROPICAL CYCLONES WITH THE GFS MODEL

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1 INTRODUCTION

The ability of models to correctly simulate tropical cyclones (TC) has increased over time as a result of an increment in computational resources, improved data assimilation techniques and observational platforms and a better representation of the physical processes. However, TC intensity forecast still show large errors (DeMaria et al. 2005; Rogers et al. 2006). Many factors contribute to the difficulty of an accurate TC intensity forecast. Among them, is the incomplete understanding of the physical processes that favor the TC development.

This study evaluates how the Global Forecast System (GFS) model reproduces the intensification of TCs. It is of great interest to study this model since it is used by the National Hurricane Center (NHC) as one of the global dynamical models to predict TC tracks and intensities. The dynamical and thermodynamical mechanisms that determine whether a tropical cyclone will develop into a hurricane or not are investigated, following the ideas of Raymond et al. (1998) and Bister and Emanuel (1997).

2 DATA AND METHODOLOGY

GFS is the global numerical weather prediction model run by NCEP (National Centers for Environmental Prediction) four times per day that produces forecasts up to 16 days in advance. It consists of a forecasting model and the Global Data Assimilation System (GDAS), which provides the initial meteorological state. Forecast outputs from the GFS model were obtained for the period June-July 2005. Only the first 24 h forecasts were gathered for each day. They include traditional fields in 37 vertical pressure levels from 1000 to 100 hPa and at the surface with a horizontal resolution of 1° x 1°. A tropical storm (TS) that developed in the East Pacific and a hurricane (Hu) that developed in the Atlantic basin were chosen for this study. They were analyzed in a 4° x 4° square box centered at their visually observed centers (chosen from the surface wind fields) on model outputs and only the period of TCs intensification was chosen.

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2.1 Theoretical considerations

2.1.1 Dynamical aspects

The vorticity equation in pressure coordinates was formulated in flux form by Haines and McIntyre (1987):

$$\frac{\partial \zeta_a}{\partial t} + \frac{\partial Z_x}{\partial x} + \frac{\partial Z_y}{\partial y} = 0 \quad (1)$$

where Z_x and Z_y have the following form:

$$Z_x = u\zeta_a + \omega\frac{\partial v}{\partial p} - F_y \quad (2)$$

$$Z_y = v\zeta_a + \omega\frac{\partial u}{\partial p} + F_x \quad (3)$$

ω is the pressure vertical velocity, p is pressure, ζ_a is the absolute vorticity, u and v are the horizontal wind components and F_x and F_y represent the horizontal components of the force due to eddy momentum fluxes $\mathbf{F} = (F_x, F_y, 0)$. The equation (1) can be integrated over an area A^* that encompasses the TC area at all levels (Fig. 1) and the relation (4) is used.

$$\frac{d\Gamma_a^*}{dt} = \frac{d}{dt}(\int_A \zeta_a dA) \quad (4)$$

Thus, with further manipulation of the equations, the following relation is obtained:

$$\frac{d\Gamma_a^*}{dt} = -\oint_{\delta A^*} \zeta_a u_{out} ds - \oint_{\delta A^*} \omega\frac{\partial \mathbf{V}}{\partial p}\cdot\mathbf{t}ds + \oint_{\delta A^*} \mathbf{F}\cdot\mathbf{t}ds \quad (5)$$

where Γ_a^* is the absolute circulation, $\mathrm{u_{tan}} = \mathbf{V}\cdot\mathbf{t}$ and $\mathrm{u_{out}} = \mathbf{V}\cdot\mathbf{n}$ are the tangential and normal components of the wind ($\mathbf{V}$) to the area element δA^* over the study area A^*, and $\mathbf{t}$ and $\mathbf{n}$ are unit vectors (Fig. 1). Equation

5 shows that the spinup of a TC (absolute circulation tendency) depends on the convergence of the absolute vorticity (CAV) into the system at all levels and the circulations of vertical advection of momentum (VAM) and friction around A^*.

The absolute circulation, the detrained mass flux ($\triangle^*$) and the vertical mass flux (M^*) are calculated from the following expressions:

$$\Gamma_a^* = \oint_{\delta A^*} \mathrm{u}_{\mathrm{tan}} ds + A^* f = \int_{A^*} (\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}) dA + A^* f \quad (6)$$

$$\triangle^* = \oint_{\delta A^*} \mathrm{u}_{\mathrm{out}} ds = \int_{A^*} (\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}) dA \quad (7)$$

$$M^*(z) = -\int_0^z \rho \triangle^* dz \quad (8)$$

where f is the Coriolis parameter and ρ is the air density.

The friction term in (5) is obtained from two different ways. First, $\mathbf{F}$ is assumed to represent the vertically averaged drag force per unit mass due to surface friction and thus it is calculated with the bulk formula: $\mathbf{F} = -C_D u_s \mathbf{u_s}/d$. The bulk transfer coefficient (C_D) was obtained graphically from figure 2, d is the boundary layer depth and $\mathbf{u_s}$ is the wind speed at the surface. The depth over which friction is concentrated in the model is not known and there is no way to find it out. Therefore, the bulk friction represents only a rough test, assuming a 1 km boundary layer depth (approximately the 1000-900 hPa layer). A second friction term is calculated as a residual from the rest of the other terms in (5) and it is compared with the bulk friction term to analyze how it represents the friction effects in the balance.

2.1.2 Thermodynamic aspects

The specific moist entropy s (calculated from Emanuel 1994) obeys the governing equation in pressure coordinates:

$$\frac{\partial s}{\partial t} + \nabla \cdot (\mathbf{u} s) + \frac{\partial (\omega s)}{\partial p} = S_t \quad (9)$$

where $\mathbf{u}$ is the horizontal velocity relative to the possibly moving target of the budget analysis (such as a tropical cyclone), ω is the pressure vertical velocity, and S_t is the entropy source term, containing the effects of surface fluxes, radiation flux divergence, and irreversible generation. Mass continuity is given by:

$$\nabla \cdot (\mathbf{u}) + \frac{\partial \omega}{\partial p} = 0 \quad (10)$$

If (9) is integrated over the area A^* shown in figure 1 and it is divided by A^* (indicating this operation by angle brackets $\langle\rangle$), then (9) becomes

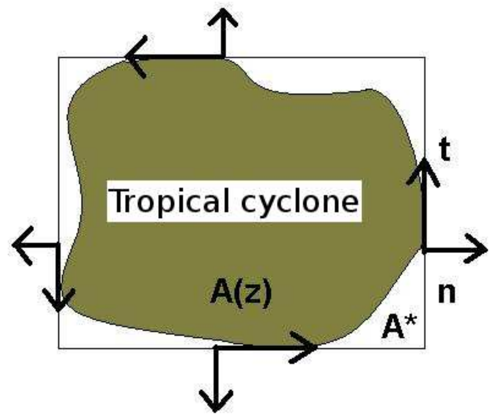

Figure 1: Schematic representation of the tropical cyclone area and the area A^* where calculations are made at each pressure level. Vectors $\mathbf{n}$ and $\mathbf{t}$ are normal and tangential vectors to the periphery of A^*.

$$\frac{\partial \langle s \rangle}{\partial t} + \frac{1}{A^*} \oint \mathbf{s u} \cdot \mathbf{n} dl + \frac{\partial \langle \omega s \rangle}{\partial p} = \langle S_t \rangle \quad (11)$$

where the divergence theorem has been used. s is now divided into two parts: $s = \overline{s} + s'$ where $\overline{s}$ is the average of s around the loop at each pressure level and s' is the deviation from this average. Substituting s into the integral of (11), using (10) and doing some mathematical manipulation, the following expression is obtained:

$$\left[\frac{\partial \langle s \rangle}{\partial t}\right] = [\langle S_t \rangle] + \left[-\langle w \rangle \frac{\partial \overline{s}}{\partial p}\right] + [-V_s] \quad (12)$$

where square brackets [] indicates an average over the depth of the troposphere. V_s is defined as the entropy ventilation: $V_s = \frac{1}{A^*} \oint \mathbf{s'u} \cdot \mathbf{n} dl$.

The first term in (12) is the mean moist entropy tendency inside the box defined by the line integral, the surface and the tropopause. The third term is the entropy tendency due to vertical advection of entropy (VAE). The fourth term is the contribution to the entropy tendency by ventilation through the sides of the box. Positive ventilation corresponds to the replacement of high entropy air inside the box by air with lower entropy, decreasing the entropy tendency inside the box.

The surface entropy flux was calculated in this study with the following bulk formula:

$$F_{es} = [\rho C_D U_{BL}(s_{ss} - s_{BL})] g/\Delta p \quad (13)$$

where ρ is the air density, C_D is the exchange coefficient, U_{BL} and s_{BL} are the wind speed and the specific entropy, respectively, averaged over the first two model

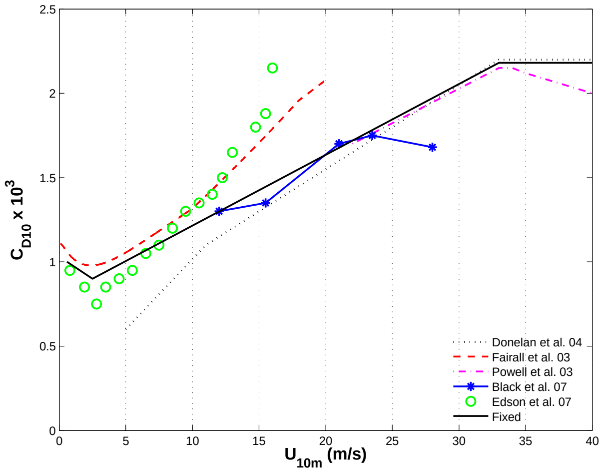

Figure 2: Drag coefficient estimates as a function of the 10 m neutral wind from several recent studies shown in the legend. The solid line labeled "Fixed" shows the C_D obtained from them for this study.

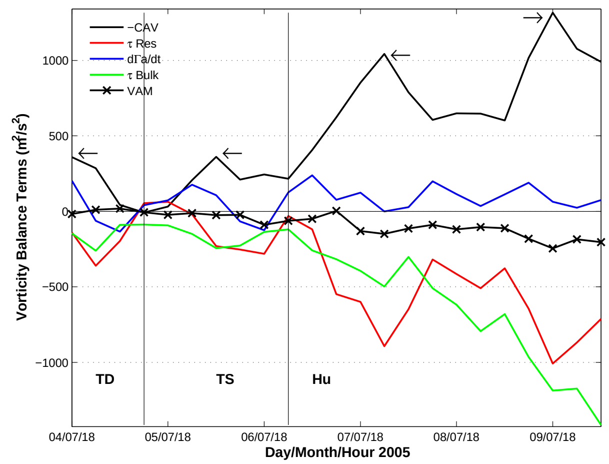

Figure 3: Terms in the balance of (5) averaged over the layer 1000-900 hPa for hurricane Dennis. Vertical solid lines represent the times when it reaches different stages (letters at the bottom). The legend shows what the different lines represent.

levels (1000 and 975 hPa) and S_{ss} is the saturated specific entropy at the sea surface temperature (SST) and mean sea level pressure (MSLP). The entropy flux was divided by $\Delta p/g$ to obtain its influence over the depth of the troposphere as expressed in (12), where Δp is 900 hPa and g is the acceleration of gravity. The effects of radiation flux divergence and irreversible generation of entropy contained in the $[\langle S_t \rangle]$ term of (12) are not considered here.

3 RESULTS

3.1 Vorticity balance

The different terms in (5) were analyzed for both TC cases, averaged over the 1000-900 hPa layer. Figure 3 shows this analysis for hurricane Dennis. The CAV causes the TCs to intensify, while friction and VAM tend to decrease their intensity. Therefore, a positive Γ_a tendency is observed at the times that the CAV is larger than those two terms, while a negative one is shown when friction and VAM predominate. The intensification of TCs is accompanied by a marked increase in the CAV, which is mainly due to an increase in the horizontal mass convergence into the systems (Fig. 4). The horizontal mass inflow largely controls the CAV over the absolute vorticity at the TC's boundary. However, variations in the latter seem to largely influence those on the CAV at the times that it shows large values (Hu stage). In general, the bulk friction term does not reproduce the residual friction behavior and the largest differences are observed when TCs show a large intensification.

Figure 5a shows the vertical profiles of CAV at four times in Dennis (indicated by the horizontal arrows in figure 3). The intensification from the TD to the Hu stage is characterized by a large increase in the CAV at low levels. This is the result of an increase in the horizontal mass inflow (Fig. 6) and the absolute vorticity at the TC's boundary at these levels (Fig. 5b). The mass inflow advects these positive values of absolute vorticity into the TC and also causes a strong vertical mass flux (M) inside it (Fig. 6). Vertical profiles of CAV and horizontal mass inflow concentrate in a shallower layer as Dennis intensifies, causing the maximum value in the M profile (level of non-divergence) to concentrate in a lower height (Fig. 6).

3.2 The entropy balance

Hurricane Dennis

The SST, averaged over the 4° x 4° domain, decreases during the TD stage in Dennis (Fig. 7d) and causes a decrease in F_{es} (Fig. 7c). At the same time, a decrease in the entropy of Dennis averaged over the domain (solid line with filled circle) and over the depth of the troposphere (1000-100 hPa), as well as a decrease of the entropy at its center averaged over the depth of the troposphere (solid line with open circle) were also observed (Fig. 7b). However, SST values are larger than 27.5°C, which is favorable for the TC development and ventilation and VAE terms in figure 7c (averaged over the 1000-100 hPa layer) reduce their negative influence on the entropy tendency during this stage. All these result in a small decrease in intensity (Fig. 7a), but the relative large values

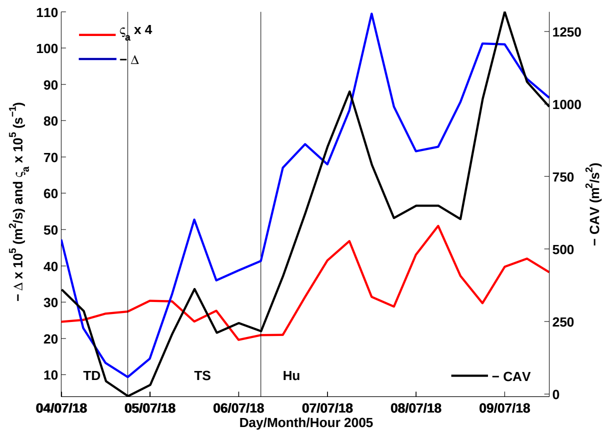

Figure 4: Hu Dennis. Time evolution of the -CAV (black line), $-\triangle$ (blue line), and the absolute vorticity at its boundary (ς_a) (red line) averaged over the 1000-900 hPa. ς_a was multiplied by 4 for a better comparison with the other variables.

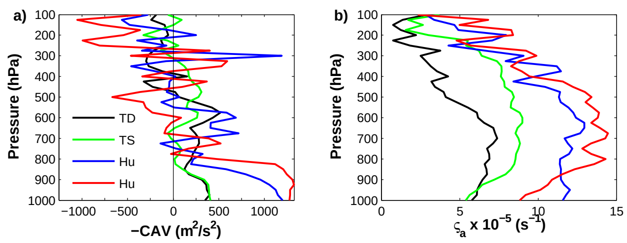

Figure 5: Vertical profiles of -CAV and ζ_a at the boundary for hurricane Dennis at four times during its life cycle (see legend).

of Γ_a still present allow Dennis to maintain its intensity.

At the TS stage, Dennis shows an increase in magnitude in the horizontal mass inflow (Fig. 4) and SST values larger than 28°C, favorable for intensification. This results in larger values of F_{es} that favors an increase in entropy. The ventilation term shows positive or very small negative values over this period, which influences positively the entropy tendency and the VAE term shows a negative influence on entropy. As a result, the positive influences of SST, F_{es} and ventilation increase the entropy, and together with a favorable mass inflow produce the intensification of Dennis (Fig. 7a). During the Hu stage, the TC moves over warmer waters and together with an increase in the mass inflow, larger values of F_{es} are observed. Its influence on the system is strong enough to overcome the negative influences of ventilation and VAE with the overall result of an increase in the domain averaged entropy over this period and the intensification.

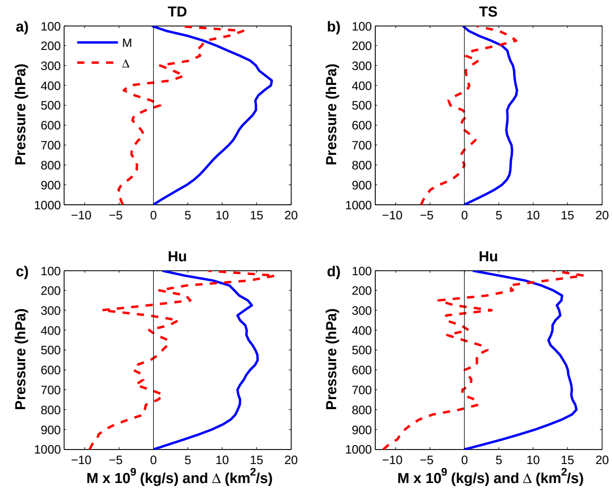

Figure 6: Vertical profiles of horizontal (Δ, red dashed line) and vertical (M, blue solid line) mass fluxes for hurricane Dennis at a) the TD time, b) the TS time, c) the first Hu time and d) the second Hu time analyzed.

Tropical Storm Eugene

TS Eugene shows a small increase in the mass inflow (not shown), together with quite large SST values (Fig. 8d) during the TD stage. This favors relative large values of F_{es}, that overcome the negative influence of VAE on the entropy tendency (Fig. 8c). Ventilation shows very small values during this stage. The overall effect over this period is an increase in entropy and the subsequent intensification into the TS stage (Figs. 8a,b).

The TS stage is characterized by the movement of the TC over colder waters in the Pacific Northwest. During the first 18 hours, the F_{es} can counteract the negative effects of ventilation and VAE with the resulting increase in entropy. This, together with mass inflow causes the TC to intensify over this period. After that, a dramatic decrease in SST and mass inflow result in a reduction of F_{es} to near zero values. The VAE changes to positive values favoring the increase of entropy but they are as small as those from F_{es}. On the other hand, the negative influence of ventilation on entropy increases and a time before Eugene reaches the TD stage, very large values of ventilation are observed over the whole atmospheric column. This is the result of air inflow with very low entropy values from the northwest into the TC at the lowest levels (not shown). All this causes the reduction of entropy with the subsequent decrease in intensity back to TD.

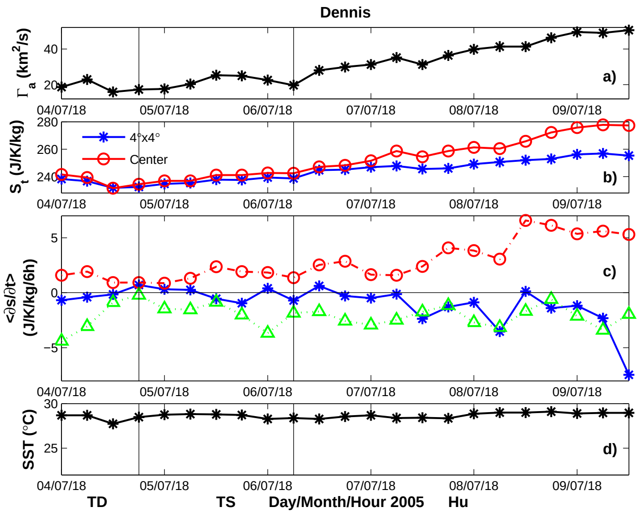

Figure 7: Hu Dennis. Temporal distribution of a) Γ_a averaged over the layer 1000-900 hPa, b) Averaged entropy over the 4° x 4° domain (blue star) and the entropy at its center (red circle) averaged over the depth of the troposphere (1000-100 hPa), c) Ventilation (blue star) and VAE (green triangle) averaged over the 1000-100 hPa layer and the bulk entropy flux (red circle) averaged over the inner points of the 4° x 4° domain, and d) SST averaged over the 4° x 4° domain.

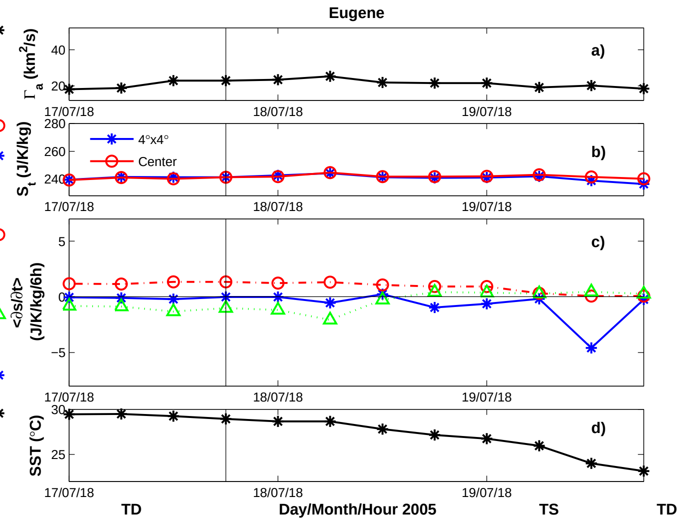

Figure 8: Same as figure 7 but for TS Eugene.

4 CONCLUSIONS

Forecast outputs from the GFS model were used in this study to investigate the different atmospheric mechanisms that favor the intensification of TC into hurricanes and those responsible for the TC demise, based on the vorticity and entropy balance equations. The analysis of two TC cases corroborates the strong influence of the air-sea transfer processes and the interaction with the environment on the intensification or decay of tropical cyclones.

The intensification of a tropical cyclone is accompanied by a large increase in CAV that overcome the negative influences of friction and VAM. This is the result of a strong mass inflow, carrying large positive vorticity values from the system's boundary inwards. The intensification process is also characterized by the increase of CAV and the horizontal mass inflow at the surface and their vertical profiles being concentrated in a shallower layer. It thus produces an increase in the vertical mass flux, whose maximum locates at a lower height than in previous, less intense stages. The absolute circulation of the storm also shows larger values at all heights and an appreciable increase at higher levels is observed when the TC goes to a more intense stage. The weakening of a tropical cyclone is the result of a larger influence of friction and VAM over the CAV and a decrease in the latter.

The thermodynamical analysis shows that the intensification of a TC into a hurricane is characterized by the influence of several factors working together, and summarized as follows:

- Warm waters above 27°C.
- Large surface entropy fluxes that can counteract the negative influences of ventilation and VAE.
- The ventilation and VAE terms show low negative values or even positive values.
- An increase of the TC's entropy at its center and the overall increase of the entropy averaged over the TC area.

On the other hand, the TS case, which did not intensify into Hu was characterized by:

- Its movement over SST colder than 27°C.
- A subsequent decrease in the surface entropy flux that cannot provide the necessary favorable conditions to counteract the negative influences of ventilation and VAE.
- A large increase in ventilation and VAE during the TS period.
- A decrease in entropy over the area of the TC and even at its center.

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