# A Simple Prediction Model of Hurricane Intensity

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A simple model to predict hurricane intensity based on energetics is described and tested. It is assumed that future hurricane intensity is solely determined by its large-scale environmental condition and the present condition of the hurricane including its previous tendency, implying that sub-scale processes, if important, are strongly conditioned by its environment. It is also assumed that hurricane track and its large-scale environmental condition that are used as inputs to the current intensity model can be reasonably predicted by comprehensive numerical models. In this study, the model is tested for Hurricane Humberto (September, 2001) for the period from 09/23/00Z to 09/27/12Z. A set of runs starting at different times are performed. The results by this model are fairly consistent with observations. The intensity sensitivity to various factors and parameters used in the model is also discussed.

# 1 Introduction

One of the most challenging issues in hurricane forecasting is the forecast of hurricane intensity. However, there is little skill for numerical models in predicting hurricane intensity. Fig. 1 shows a couple of examples of hurricane intensity prediction with the National Oceanic and Atmospheric Administration(NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model. Large deviation from observations is typical for all the current deterministic models. Much of the problem may lie with the inability of the physical processes and their parameterizations in the current numerical models to resolve some of the important features in hurricanes. It is quite common that with change of a major physical parameterization (i.e., on cumulus convection), a model hurricane that would otherwise quickly intensify may not develop at all or vice versa. Insufficiency in physics may also affect the roles of model resolution and use of observational data in improving hurricane intensity prediction. The fact that model hurricane intensity is very sensitive to the choices of physical paramters and process parameterizations implies that the current numerical models may not be able to sufficiently resolve some of the important processes to meet the need of intensity prediction. It has been argued that resolution and the way to treat the sub-scale processes in the current deterministic models are limiting their capabilities. However, including finer details with higher resolution may lead to the models being dependent on the sub-scale features which are little understood at the moment.

Unlike sophisticated numerical models with comprehensive physics schemes, empirical intensity models use simple parameters and schemes. An advantage of using simple empirical models in the hurricane intensity case is that one can control its bias by using statistical constraints at the level that current numerical models may not be able to reach. In fact, statistical models, such as the Statistical Hurricane Intensity Prediction System (SHIPS) (Demaria and Kaplan 1994; Demaria and Kaplan

1999), have shown more skills in predicting intensity than the comprehensive numerical models. It is probably for the same reasons that the Coupled Hurricane Intensity Prediction System (CHIPS), which is basically an axisymmetric model plus an empirically parametrized shear effect, can demonstrate better skills than 3-dimensional deterministic models (Emanuel et al 2004).

Shen (2004) proposed a model of hurricane energetics where the tendency of total kinetic energy in a hurricane is determined by its surface dissipation, surface entropy flux, environmental Convective Available Potential Energy (CAPE) and the hurricane circulation itself. In this energetics model, the major inputs are the radial profile of surface wind and its large scale environmental conditions. Details in the atmosphere are not explicitly used but their impacts are included via a simple parameterization of the thermodynamic efficiency which represents the effectiveness of the conversion of local surface entropy flux and atmospheric CAPE into kinetic energy in a hurricane. Compared to the CHIPS model, the current intensity model further simplifies the atmospheric processes by using an empirical parameterization of the thermodynamic efficiency. The energetics model will be briefly described in the next section. The main objective of this paper is to extend this model to a prediction model and test the skills of such a model for intensity prediction in a real hurricane case.

The energetics model is extended simply by linking the energy tendency to hurricane intensity change. The extension also includes a modification in the thermodynamic efficiency from the vertical shear of environmental wind (hereafter, vertical shear for short). This is because the large-scale environment is considered to be always favorable in the energetics model by Shen (2004) so that the air parcel underneath the eyewall can be adiabatically lifted to the tropopuse. This is not true in the presence of hostile environment. In this study of intensity prediction, we assume that vertical shear is the dominant hostile factor or behind all the major hostilities. In the current model, vertical shear simply causes a reduction of the thermodynamic efficiency in a hurricane. From Shen (2004), without such a reduction, hurricanes would not decrease with increasing latitude as was indicated by majority of the historical cases. The prediction model is tested for hurricane Humberto (September, 2001). By this study, we also intend to understand the roles of various conditions, such as hurricane initial conditions, SST, vertical shear, and atmospheric CAPE which are important in energy balance, in regulating hurricane intensity. The paper is organized as following: The prediction model is described and discussed in section 2. The results by applying this model in hurricane Humberto are presented in section 3 and summarized in section 4.

# 2 The model of intensity prediction

## 2.1 The energetics model

The energetics model by Shen (2004) can be written as

$$K_t = K_{sflx} + K_{CAPE} - K_{diss} \qquad (1)$$

where

$K_{sflx} = 2\pi\rho T_s\bar{\varepsilon}\int_0^{r_0} C_h V_s(S_s - S_a)rdr$,

$K_{diss} = 2\pi\rho\int_0^{r_0} C_d {V_s}^3 rdr$, and

$K_{CAPE} = \bar{\varepsilon}(2\pi\rho r_0 D_b V_n^*|_{r_0})CAPE$ with

$\bar{\varepsilon} = \frac{\int_0^{r_0}\varepsilon C_h V_s(S_s-S_a)rdr}{\int_0^{r_0} C_h V_s(S_s-S_a)rdr}$

are the entire kinetic energy changes due to surface entropy flux, dissipation and atmospheric CAPE and $\bar{\varepsilon}$ the overall thermodynamic efficiency. In the above, $\rho$ is the air density near surface, $T_s$ is the sea surface temperature (SST), $r_0$ is the radius of hurricane inner core defined as the inner area of large-scale (relative to convection and internal subscale processes) upward motion, which is roughly the area filled with organized convection/clouds for well-developed tropical storms, $C_h$ and $C_d$ are the surface heat and momentum exchange coefficients, $V_s$ is the near-surface wind, $S_s - S_a$ is the surface entropy disequilibrium, $D_b$ is the surface boundary layer depth (the first 100mb is used), $V_n^*|_{r_0}$ is the radial component of boundary layer velocity and is estimated based on the radial profile of surface wind, $\varepsilon$ is the thermodynamic efficiency corresponding to the local surface entropy flux and all the others have conventional meanings (see Shen 2004 for details). For simplicity, $K_{sflx}$ is the total sea surface entropy flux multiplied by an overall efficiency and $(2\pi\rho r_0 D_b V_n^*|_{r_0})$ in $K_{CAPE}$ is the total vertical mass flux in the inner core (within $r_0$). $r_0$ can be attained by $\frac{d(V_s r)}{dr}|_{r_0} = 0$.

This model assumes that the surface heat and moisture fluxes outside the hurricane inner core perfectly offset the loss due to the dry air intrusion into the surface boundary layer and the vertical diffusion at its top so that the entropy of converging air in the surface boundary layer is conserved. The nearly unchanged surface pressure, mixing ratio and temperature in the surface boundary layer in the outer core are in a good agreement with hurricane observations. It is also assumed that in the outer core of slow subsidence, the air is in thermodynamic equilibrium with its large scale environment so that the environmental sounding also applies to this area. From energetics point of view, it is equivalent to assume that the free atmosphere is convectively adjusted so that the downward-moving air does not gain excessive energy before entering the surface friction layer. This implicitly assumes that CAPE, if any, is solely due to the "excessive" energy in the surface boundary layer. Its contribution to the hurricane energetics is represented by the second term in (1). It is worthy noticing that in the outer core, the local conversion of the sea surface entropy flux into kinetic energy is considered to be ineffective and relatively insignificant. In practice, the dissipation in the outer core is also not counted for the present calculation because the dissipation is highly confined to the eyewall area. In the presence of major rainbands of deep convection in the outer core, the above approximation may bias the picture of total energy. However, even in this case, whether these "remote" rainbands can considerably affect the inner core structure under which the major surface pressure drop occurs is still questionable. Therefore, it is possible that the inner core energy budget may be better responsible for the instant hurricane intensity evolution than the total one.

## 2.2 Asymmetry in surface wind

The energetics model above assumes that hurricanes are axisymmetric or the effect of asymmetry is assumed to be small and ignored. In this study, it is not our intention to introduce the whole issue of hurricane asymmetry but we consider the effect of surface wind asymmetry, a common feature in hurricanes. Further more, we intend to only include the asymmetry in surface wind due to a uniform background flow.

For simplicity, the composite wind, $\mathbf{V}$, is assumed to take the form of $\bar{\mathbf{V}}_s + \mathbf{V}_s(r)$ where $\bar{\mathbf{V}}_s$ is the mean (background) flow and $\mathbf{V}_s(r)$ the axisymmetric component. We further assume that the surface wind asymmetry only affects the surface dissipation and entropy flux but not the other features in the model so that all the methods and parameters used in the axisymmetric system are still the same. Under these circumstances, we only need to change the surface dissipation and kinetic energy generation (due to surface entropy flux) to the following

$$K_{diss} = \rho \int_0^{r_a} [\int_0^{2\pi} C_d |\mathbf{V}|^3 d\theta] r dr \qquad (2)$$

and

$$K_{sflx} = \rho \int_0^{r_0} [\varepsilon T_s (S_s - S_a) \int_0^{2\pi} C_h |\mathbf{V}| d\theta] r dr \qquad (3).$$

Such a result for maximum potential intensity (with $K_t = 0$ in (1)) is shown in Fig. 2. In general, asymmetry caused by mean flow reduces hurricane intensity. The reduction increases with increasing mean wind, hurricane size (or decreasing B) and intensity. For weaker hurricanes of smaller sizes, the changes are negligible. Given the fairly high correlation between the lower tropospheric wind and the hurricane translation speed, the intensity decrease due to surface wind asymmetry implies that a faster moving hurricane tends to have a lower intensity.

## 2.3 Shear effect on thermodynamic efficiency

Besides the critical role of surface exchanges in hurricane energetics, hurricane-environment interaction can also considerably affect the energetics and thus intensity. In this study, only the effect of wind vertical shear as an adverse factor for hurricane intensity is considered. Theoretically, the shear effect should be realized via all the relevant terms in all the dynamic and thermodynamic equations. In practice, however, insufficiency in numerical models can seriously affect the role of vertical shear. Present numerical models are quite divided on the shear effect on hurricane intensity at least regarding its magnitude (i.g., Tuleya and Kurihara 1981; Wang and Holland 1996), while observations in general suggest that the effect of vertical shear is negative on intensity [1]. Since the atmospheric details are not explicitly treated in the energetics model, the shear in the current model simply acts to reduce the thermodynamic efficiency by a factor of $e^{-(\frac{sh}{sh_0})^{\alpha}}$ where $sh$ is the vertical shear defined as $|\mathbf{V_{200mb}} - \mathbf{V_{8500mb}}|$, $sh_0$ is the reference shear of 10m/s and $\alpha$ is taken to be 1 if $sh \leq$10 m/s and 5 if $sh >$10 m/s. Fig. 3 shows such an effect (by the solid curve). By this, we assume vertical shear plays a significant role only when it is large. The dashed curve in Fig. 3 will also be used for a comparison. We point out that the specific form of $e^{-(\frac{sh}{sh_0})^{\alpha}}$ is just an approximation. The parameters ($\alpha$ here but can be more than one with other pssoible forms) can be determined empirically (for example, using best fit with historical cases). But this is not pursued in the current study for a very first step exploration.

For the current model, the thermodynamic efficiency without shear is that by Shen (2004):

$$\varepsilon = \varepsilon_0 (\frac{r_m}{r})^{\Gamma} \qquad (4)$$

where $\varepsilon_0$ is the potential (near $\frac{1}{3}$), and $\Gamma = 1 + \eta(r_m - r_c)$ with $\eta = 0.012km^{-1}$ and $r_c = 30km$. Basically, the efficiency decreases with increasing radius outside eyewall. The current choice of $\Gamma$ assures a slight increase in potential intensity with a decrease in eye size ($r_m$) and an increase of storm size ($r_0$). In theory, given the form of (4) and $\Gamma$, $r_c$ and $\eta$ can be attained by using any two potential intensity values observed. Apparently, (4) is only a rough approximation and is improvable in future. Worthy of noticing is that in the presence of shear, $\varepsilon$ must be asymmetric and

[1] The tough question of which future advance may rely on our understanding is how the impact of vertical shear is modulated by other factors/conditions.

the $K_{CAPE}$-related derivation is also somewhat different. However, as was previously mentioned, current numerical models with the shear effects through all the relevant terms in the governing equations are apparently not very capable of catching the right asymmetries and hurricane-environment interactions particularly towards predicting intensity. Therefore, the current treatment of shear effect by reducing the thermodynamic efficiency without changing the ways to compute the others is equivalent to using an overall empirical constraint.

## 2.4 Model of prediction

The energetics model by (1) is only able to give the current kinetic energy tendency ($K_t$). For intensity prediction, we now link it to the change of intensity. To make such a link, we define an equivalent hurricane depth as following

$$D_e = \frac{K}{\pi \rho_b \int_0^{r_a} {V_g}^2 r dr} \qquad (5)$$

where $K$ is the total kinetic energy and $V_g = \mu V_s$ with $\mu$ =1.2 is the axisymmetric wind at the top of the surface friction layer, $\rho_b$ is the air density there and $r_a$ the outer radius of storm. Hence the maximum (axisymmetric) wind above the friction layer becomes

$$V_m^2 = \gamma K \qquad (6)$$

where

$$\gamma = \frac{1}{D_e \pi \rho_b \int_0^{r_a} (\frac{V_g}{V_m})^2 r dr}.$$

We now discuss the $\gamma$ in (6). Fig. 4 shows the radial distribution of $\frac{V_g}{V_m}$ with different intensities in the case of fixed storm size ($r_0$) and $r_m$. The distributions are nearly identical in these cases of different intensities. For a first order approximation, the following assumptions are made: 1. For a well-organized tropical storm of intensity above a certain magnitude, the size changes of hurricane inner core and its eye are small; 2. The total kinetic energy change is proportional to the total kinetic energy change in the surface boundary layer whose depth change is also very small, which implies that the change of equivalent depth ($D_e$) is small. Thus, the change of $\gamma$ is considered to be small enough to ignore[2]. Under this circumstance, eq. (6) can be written as

$$dV_m^2 = \gamma K_t dt \qquad (7).$$

Thus, $\gamma$ for the previous step can be directly calculated using (7) instead of using its original definition by (5), and used for the current time step for prediction. Using the gradient wind relationship for a wind profile following Holland (1980), we have

$$d(P_c - P_e) = -\gamma^* K_t dt \qquad (8)$$

where $P_c$ is the central pressure at surface, $P_e$ is the environmental surface pressure, $\gamma^* = \frac{\rho_b e}{B}\gamma$ and $e$ the natural base of logarithm. Using (1), (8) becomes a prediction model for minimum surface pressure:

$$dP_c = (K_{sflx} + K_{CAPE} - K_{diss})\gamma^* dt + dP_e \qquad (9)$$

Details regarding how the model works towards predicting hurricane intensity is described in Appendix A.

[2]Change in $\gamma$ may be related to various conditions and will be further discussed in the next section.

# 3 Real case application

## 3.1 Hurricane Humberto

The prediction model is applied to Hurricane Humberto (September, 2001). Humberto started with a tropical depression over the western Atlantic ocean near 64W,25N on the 21st and recurved near 68W, 31N to northeast. It developed into a hurricane around 12Z on the 23rd just before the recurvature and peaked twice with maximum surface wind of about 85 knots and 90 knots around 00Z on the 24th and 12Z on the 26th respectively.

In our experiment, the flight-level ($\sim$850mb) and Stepped Frequency Microwave Radiometer-derived wind across the storm core near 04Z on the 23rd was used to obtain the shape of the wind profile at 00Z (presumably at the top of the friction layer). Using the wind profile and other available data (such as environmental and central surface pressures, and the hurricane position at the initial time), the inner core radius of 93km is attained. As was mentioned previously, the inner core size is kept to be same for our integration up to 12Z on the 27th but the size effect in this case will be a little discussed later. Fig. 5 shows the satellite pictures of the storm evolution.

## 3.2 Application and Results

For the first set of experiments, the intensity model is run from 09/23/00Z to 09/27/12Z with the environmental conditions from the National Centers of Environmental Prediction (NCEP) AVN analysis and observed hurricane track from the Tropical Prediction Center (TPC) Best Track Reanalysis. The hurricane information at and before 09/23/00Z as well as its environmental conditions at this time are used to determine the parameter $\gamma$. The so-attained $\gamma$ is 9.4x$10^{-15}$ which is used in (7) for maximum surface wind prediction and in (9) for minimum surface pressure prediction in our first set of experiments.

The environmental conditions from the AVN analysis are at every 12 hrs. The environmental SST is used for the 10m air temperature in the outer core, while the lowest level relative humidity of the AVN analysis is used to approximate the 10m relative humidity. In the inner core, the air temperature is the average of the SST and that of an air parcel converging from the outer core through an adiabatic thermal expansion. The Best Track storm position data is also used. The AVN analysis data is linearly interpolated in order to get the data at every 2 hrs (one time step in the current integration).

Experiments were performed to examine the roles of the various conditions involved. The upper panel in Fig. 6 shows the simulated maximum surface winds. The wind shear and CAPE used in this case are also shown below. The result (thick solid) seems quite reasonable. In this case, the shear effect is important and hurricane Humberto would otherwise be much stronger (thin doted). It is the shear that makes the intensity considerably lower than its potential. For the whole day of the 26th, the shear effect is negligible. This is responsible for the second intensity peak in our simulation but it is still much below the potential intensity (roughly the no shear case at this time). This also implies that the previous storm condition including the initial state is important for the late situation.

It is interesting that the CAPE alone (thin dashed) can not maintain the initial magnitude but is important for the hurricane development during the first 24 hours and thus the intensity afterward. By surface entropy flux alone (thin solid) the storm could only maintain its initial intensity. The thick dashed line shows the case with a slight difference in the shear effect paramterization (by the dashed in Fig. 3). Due to the sensitivity of the mean flow to the area of calculation, half of the translation speed is used to approximate the surface mean wind. The wind asymmetry in this case only has a minor impact on the hurricane intensity and its change except for a little aysmmetry-related increase in maximum surface wind. The size of hurricane eye ($r_m$) in this case varies little (from 25km to 32km). Experiments with fixed eye size were also performed. The results (not shown) are quite close to those shown in Fig. 6. Fig. 7 shows the central pressure changes in these experiments. The central pressure is in general over-estimated.

For the second set of experiments, all the environment conditions and hurricane positions are from the 3-day AVN forecasts. In theory, the initial storm wind profile of each case should be from observations. However, due to the limited data available, the initial $r_m$ (or RMW) after 09/23/00Z is derived to fit in the Best Track maximum surface wind and surface pressure drop ($p_e - p_c$) by using the Holland wind profile with the same inner core size ($r_o$). The so-obtained RMW is shown in Table 1 which also shows the corresponding $K_t$ and $\gamma$. It is seen that the change rate of net kinetic energy ($K_t$) is quite consistent with the observed intensity tendency shown in Figs 6 and 7. Note that the above method for creating the initial surface wind profile with derived $r_m$ barely affects the qualitative picture of the tendency. An alternative method by keeping the same RMW but with the inner core size ($r_o$) derived leads to a quite similar result of kinetic energy change.

Table 1 also shows that $\gamma$ varies a lot. Apparently, its value should not be trusted when either $dV_m^2$ or $dK_t$ in (7) is near zero, which may lead to either a very small or a very large value of $\gamma$ due to the limited accuracy of the data and the very coarse time resolution (12hr) used in the current case[3]. In particular, $\gamma$ is calculated by using $dV_m^2$ of the previous 12 hrs while $dK_t$ is actualy at the current time. Thus, in practice, the nearest previous "stable" value should be used under these circumstances. We believe that the variability of $\gamma$ would be smaller than those shown in table 1 if higher resolution data were used. Nevertheles, in this study for a very first exploration, the $\gamma$ values except for the zeroes in Table 1 are used for the intensity prediction in each case. The results of the 3-day runs starting from 09/23/00Z, 09/23/12Z,

[3]The zero values of $\gamma$ can be immediately rejected from its definition.

09/24/00Z, 09/24/12Z, and 09/25/00Z are shown in Fig. 8. The intensity results are fairly reasonable. To better examine the effect of the magnitude change of $\gamma$ on the intensity results in the current cases, experiments with use of the $\gamma$ at 09/23/00Z (9.4x10$^{-}$15) for all the above cases were also performed. The results are shown in Fig. 9. Compared to those in Fig. 8, the intensity changes in Fig. 9 are smaller but the overall tendencies are quite similar.

Simply put, the energy tendency in a hurricane is determined by various factors such as vertical shear, surface conditions, environmental CAPE, hurricane structure and intensity. The high correlation found between the energy and intensity tendencies seems to suggest that eqs (7) or (8) may be a good approximation that can be used for predicting intensity. In the current cases, lack of observation, limited data accuracy and coarse resolution are limiting the accuracy of $\gamma$, which affects the quantitative magnitude of intensity change. However, the impacts are found not critical on the overall picture.

# 4 Summary

A simple prediction model for hurricane intensity is described. This model is based on the energetics model of Shen (2004), in which the major sink and source of energy in a hurricane occur over the sea surface. In the present prediction model, the effect of vertical shear of wind on hurricane intensity is included as an adverse factor on the conversion of surface flux into kinetic energy or the thermodynamic efficiency. The model predicts intensity by using the predicted large-scale environmental conditions and hurricane track as well as observed hurricane and environment conditions at the initial time.

The results by applying this model to hurricane Humberto (September, 2001) are fairly consistent with observations. The results indicate that both the environment, such as SST, wind shear and CAPE (depending on its value), and initial hurricane conditions are important for hurricane intensity and its change. Some of the important parameters used in this model are tested and their impacts on intensity are in general on the magnitude but not the qualitative picture. However, only one hurricane was tested in the present study although the results are quite encouraging. More case will be investigated and reported in furure.

The main purpose of this paper is to demonstrate the potential skill of a simple model in predicting hurricane intensity and how the initial hurricane condition and the environment can affect hurricane intensity in this simple model. In doing so, we assumed the size change of hurricane inner core is small enough to ignore for the time-scale of interest. Apparently, alternative conditions can be used. Also, ocean coupling that may be important in limiting over-intensification in some hurricanes is currently not included. The present treatment of thermodynamic efficiency and the involvement of vertical shear of environmental wind are very simple and the specific methods/forms for the treatment are somewhat arbitrary. All these are challenging issues and will be further addressed in future.

# Appendix A

## Numerical approach

In general, this prediction model requires the current and future conditions of a hurricane and its environmental conditions. The hurricane conditions include the radial profile of surface wind and the minimum surface pressure at the initial time, and its future track. The environmental conditions include SST under the hurricane ($r \leq 2r_0$ is used in the current study), mixing ratio near the surface, surface pressure, vertical shear of wind, and CAPE.

The surface wind profiles used in the model follow the rectangular hyperbolas of Holland (1980). In principle, to determine such profiles, three of the following four values are required: central pressure (more accurately $P_e - P_c$), radius of maximum wind ($r_m$), maximum surface wind and the profile shape parameter ($B$) or the inner core size ($r_0$). Best fit can be used if more than necessary information on the wind profile is provided. All the energy terms in (9) can be attained by using the wind profile and the other hurricane and environmental conditions mentioned above. $\gamma^*$ at the initial time can be attained by using (8) with the previous minimum surface pressure tendency and the net kinetic energy change which can be readily obtained with observations at the initial time. Therefore, in practice, the data requirement for the model should be extended back to a previous step.

We can then attain the minimum surface pressure at $\Delta t$ by (9). At $\Delta t$, however, only the minimum surface pressure is predicted. So, in order to continue to predict, one needs to know two of the three other factors: the maximum surface wind, the radius of maximum wind, and the profile shape parameter ($B$) or $r_0$ (in the current approach) to determine the surface wind profile at this time ($\Delta t$). In the current approach, we assume $dr_m$ and $d(P_c - P_e)$ have the following relationship:

$$dr_m = \begin{cases} max[(r_m - 10km), 5km]\frac{d(P_c-P_e)}{100mb - min[(P_e-P_c), 90mb]} & \text{if } r_m > 10\text{km OR} \\ & \text{if } r_m \le 10\text{km, } d(P_c - P_e) \ge 0 \\ & \quad \text{and } P_e - P_c > 90\text{mb} \\ 0 & \text{otherwise} \end{cases}$$

and that the change of hurricane inner core is small enough to ignore for a well-developed hurricane[4]. With these assumptions, iteration is used to reach the wind profile. $K_t$ of (1) at $\Delta t$ and thus $P_c$ at $2\Delta t$ by (9) can be obtained. In principle, $\gamma$ or $\gamma^*$ during the first $\Delta t$, which is used in (9) for predicting $P_c$ at $2\Delta t$, can be updated by using $(K_t|_{t=0} + K_t|_{t=\Delta t})/2)$ instead of $K_t|_{t=0}$ in (7) or (8). The rest is simply repeating the above steps.

It is worthy noticing that by the assumption on the $dr_m$-$d(P_c - P_e)$ relationship, we basically let the hurricane eye size increase (or decrease) with a decrease (or increase) of intensity. Since what determines the eye size is not clear and may be

[4]This implies that descrete change of storm such as during eyewall replacement (e.g.,Willoughby et al 1982) is beyound the current approach.

complicated, this assumption can be considered as a statistical control in the current model. Shen (2004) showed that the dependence of energy balance on the size of eye is generally minor for medium and weak hurricanes. So, its impact is actually small under the current workframe. The assumption about the inner core size may affect the accuracy of the model if large change in storm size occurs since energy balance and its net change somewhat depend on storm size (Shen 2004). However, little is known about what is behind the size change. For the current approach, we simply assume that for well-organized hurricanes, the inner core size will remain unchanged. In future, it may be possible that numerical models will be able to provide useful information of storm size that will help the intensity prediction of the current model.

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# Figure captions

Figure 1. The operational forecasts of central pressures by the GFDL hurricane model for two Atlantic hurricanes: Iris (1995) and Bertha (1996). The dashed lines are the observations from the Best Track Reanalysis.

Figure 2. Effects of mean flow on maximum potential intensity. The radial profiles of surface wind follow Holland (1980). $B$ is the profile shape parameter and increases with decreasing hurricane size. SST of 300K and $r_m$ of 30km are used.

Figure 3. Shear effects on thermodynamic efficiency used for experiments.

Figure 4. Radial distributions of $\frac{V_g}{V_m}$ in the case of different intensities with $r_m$=30km and $r_0$=120km. Wind profiles following Holland (1980) are used.

Figure 5. Satellite pictures of hurricane Humberto at 09/23/12Z, 09/24/12Z, 09/25/12Z and 09/26/12Z. The inner size marked is attained using the current model approach with observed wind profiles (see Shen 2004 for details).

Figure 6. Upper: Maximum surface wind evolutions for various experiments with environment conditions from ANV analysis and observed track. Triangle: observed; Thick solid: predicted; Thin dot: without shear effect; Thin solid: without CAPE effect; Thin dashed: with kinetic energy generation due to CAPE alone; Thick dashed: predicted with the shear effect via the dashed in Fig. 3. Middle: Vertical shear $|\mathbf{V_{200mb}} - \mathbf{V_{8500mb}}|$. Lower: Environmental CAPE (Parcel of $P_s$-50mb is used).

Figure 7. Same as the upper panel of Fig. 6 but for hurricane central pressure.

Figure 8. Maximum surface winds and minimum surface pressures with environment conditions and hurricane tracks from AVN forecasts.

Figure 9. Same as Fig. 8. but with the same $\gamma$ of 9.4x$10^{-15}$.