Hurricane Intensity: Governing Factors and Forecasting Challenges

EAS 470 Final Paper

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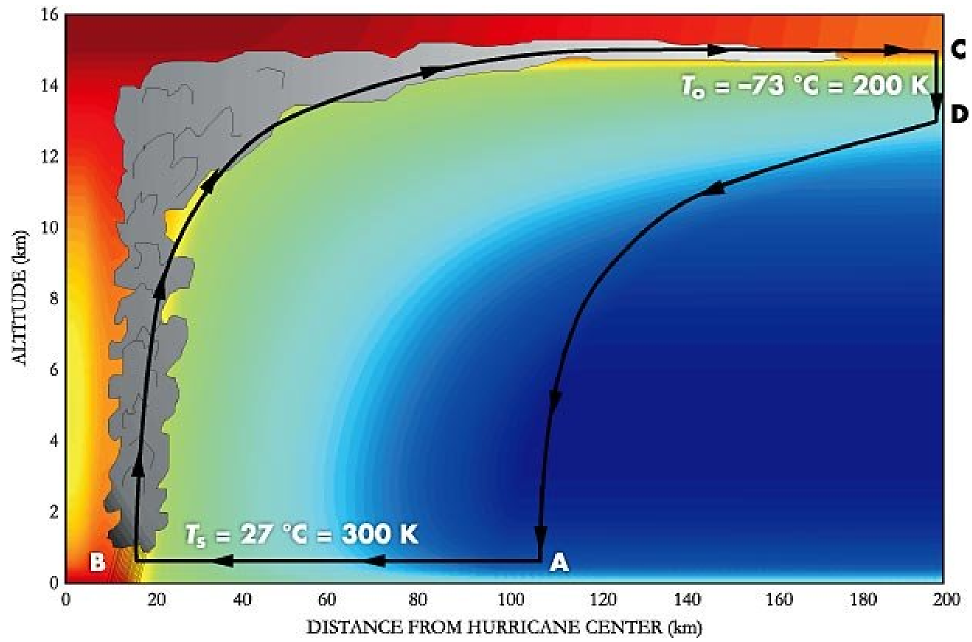
Tropical cyclones are undoubtedly among the mostly deadly and destructive natural phenomena found on Earth today. Over the past hundreds of years, hurricanes have altered our landscapes and changed political history. While hurricanes are capable of great destruction, they may also be important drivers of the global heat budget and have importance in maintaining the stability of the climate in the tropics. The fact that nature is capable of producing something so powerful and capable of such destruction has always astonished me and motivated me to study hurricanes. As more and more people move to the coastal areas in an era of uncertainty surrounding the possible effects of global climate change, accurate forecasting of hurricane tracks and intensity is even more important. In the past few decades, forecasts of hurricane tracks have improved substantially. Forecasts of hurricane intensity, however, have not followed this trend. This paper will examine the governing factors of hurricane intensity, challenges these give forecasters, and how we should go about improving our understanding and forecasting of hurricane intensity.

In understanding hurricane intensity, it is helpful to understand the factors that set an upper bound on their intensity. Emanuel (1986) argued that the intensification of tropical cyclones depend only on self-induced heat transfer (latent and sensible) from the ocean. This upper bound on intensity, is therefore determined by the maximum possible latent heat input from the ocean to the atmosphere and the thermodynamic efficiency. This thermodynamic efficiency is derived from modeling a tropical cyclone as a Carnot heat engine. This “maximum potential intensity” is based on the Carnot cycle, which is the most efficient heat engine possible. The Carnot cycle is characterized by four stages of expansion and compression in the following order: isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression. A mature tropical cyclone is a near textbook example of the Carnot heat engine. The following image depicts an idealized model of the Carnot cycle in a hurricane (*Emanuel* 2006):



In this image, the colors depict entropy distribution (blue-green indicates lower entropy; red-yellow indicates higher entropy). In hurricanes, the main process that drives the storm is latent heat release due to the evaporation of ocean water. Air flows inward towards the low pressure center of the storm (point A to B), and then rises nearly adiabatically up the eye wall of the storm to point C. One should note that in actual tropical cyclones, air flows outward at point C, and actually doesn't lose entropy (point C to D) until it radiates infrared radiation to space far from the storm's center. The potential intensity theory uses the thermodynamics of a hurricane as approximated by the Carnot cycle to derive the maximum theoretical intensity that the storm can obtain, using the Carnot efficiency (which is a ratio of outflow and inflow temperatures) and a quantification of the thermodynamic disequilibrium between the ocean and atmosphere. (*Emanuel* 1988) The equation is as follows:

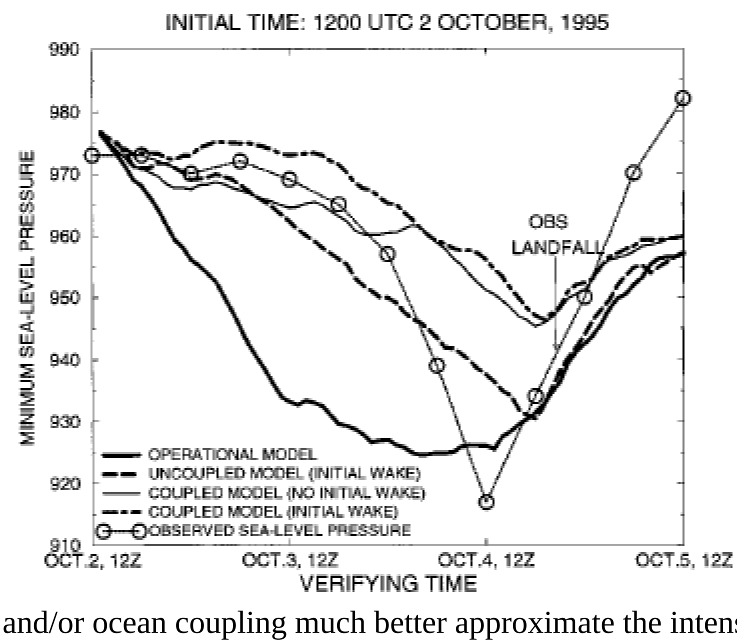
$$v^2 \cong \frac{C_k}{C_D}\left(\frac{T_s - T_o}{T_o}\right)T_s\left(\kappa_o{}^* - \kappa_a\right)$$

Therefore, it is clear that the theoretical upper bound on a hurricane's intensity is based on the sea surface temperatures, the outflow temperature in the lower stratosphere, and surface heat exchange coefficients. It is also interesting to note that the mechanical energy produced by the hurricane's heat engine shows up as the energy of the winds (hurricane intensity), but almost all of the frictional dissipation occurs in the inflow layer. This means that the power of the winds is converted back into heat which then flows back into the system; this recycling of waste heat makes hurricanes even more powerful than they would be otherwise. (*Emanuel* 2005)

As described above, the upper bound on hurricane intensity depends only on thermodynamics. However, most hurricanes never reach their 'maximum potential intensity.' The most basic reason is that hurricanes often make landfall or encounter adverse atmospheric and oceanic conditions before having time to reach their potential intensity. This brings us to the factors that truly govern the intensity that hurricanes actually reach; environmental factors. One such factor is vertical wind shear, which affects hurricanes in several ways. First, it causes the storm's circulation to lose its approximate circular symmetry, causing convection to be weak or even absent on the upshear side of the eye. Also, vertical wind shear causes ventilation of the hurricane's core with dryer, low energy air from the storm's environment. (*Emanuel et al.* 2004) This injection of dry air weakens the storm because some of the warm, moist air ascending in the eyewall mixes out of the core at middle levels, causing the effective cold reservoir temperature to be much warmer, decreasing the thermodynamic efficiency. Emanuel et al. (2004) used a forecast model, the Coupled Hurricane Intensity Prediction System (CHIPS) to assess whether or not including a shear parameterization in the model improves intensity hindcasts. They showed that including shear in the model clearly improves its prediction of intensity evolution by doing model hindcasts of several hurricanes. However, they noted that the addition of the shear parameterization into the model made the model more sensitive to initial conditions. This is especially important because it is difficult to observe and forecast winds and wind shear over the oceans, so the initial conditions put into forecast models are generally not at precise as they should be.

The other main environmental control on hurricane intensity is ocean interaction, which plays a role in several ways. First, Emanuel et al. (2004) found that bathymetry is important in areas of shallow water because this limits the downward increase of mixed layer depths by entrainment. This may happen where seafloors slope gradually towards coastlines or where storms approach the coast at an angle. They also found that the deintensification of storms after they make landfall is affected by the presence of standing water such as swamps or lakes. Ocean-hurricane interactions are important for hurricane intensity for several reasons. As a hurricane intensifies, the evaporation rate increases due to the higher wind speeds, which leads to an increase in the latent heat supply that drives the circulation. While this is a positive feedback, the strong winds cause turbulent mixing in the upper ocean, which causes localized cooling due to the entrainment of the cooler waters from the thermocline into the mixed layer. (*Bender and*

Ginis 2000) This introduces several uncertainties into intensity forecasting; the depth of the mixed layer must be known (because a shallower thermocline will allow more cold water to be mixed up from the increased wind stress), and the amount of cooling must be incorporated into the forecast models. Bender and Ginis (2000) performed a number of numerical simulations of hurricanes possible effected by this ocean feedback mechanism using the GFDL dynamical hurricane model coupled with a multilayer primitive equation ocean model. They found that the cooling of the SST induced by the tropical cyclone resulted in a significant decrease in storm intensity due to the reduction of total heat flux into the tropical cyclone circulation. They also found that the sea surface cooling was larger when the storms moved slower. An example of these results is the following graph from Bender and Ginis (2000), which depicts simulations of the minimum sea-level pressure of Hurricane Opal. It is clear that the models including the initial cold wake



and/or ocean coupling much better approximate the intensity evolution than the operational model which did not include these effects. The substantial improvements in the prediction of storm intensity by inclusion of the ocean coupling indicate that ocean feedbacks are an important mechanism that governs the intensity of tropical cyclones.

The above discussed thermodynamics and environmental factors that govern the intensity of hurricanes are incorporated into intensity forecasts via the use of computer models. The National Hurricane Center makes uses of a large number of forecast models when making their official track and intensity forecasts. For instance, one of their most skillful sources of intensity guidance has traditionally been the Statistical Hurricane Intensity Prediction Scheme (SHIPS), which is a statistical-dynamical model. (*Rhome* 2007) The most complex and computationally expensive models that they use are dynamical models that solve the physical equations that govern the atmosphere. Model initialization errors (inaccurate initial data) are one of the primary sources of uncertainty and forecast errors within these types of models. Their dynamical models include the ECMWF model, which is the most sophisticated and computationally expensive, the GFDL Hurricane model (which has up to now been the only purely dynamical model that can provide both skillful intensity and track forecasts, due to its high horizontal resolution that allows it to simulate some of the inner core tropical cyclone structure), and the Hurricane Weather Research and Forecasting model (HWRF, which is coupled to the Princeton Ocean Model and will eventually replace the GFDL model). (*Rhome* 2007).

As stated previously, whereas the official National Hurricane Center track forecast errors have been greatly decreased in the Atlantic, the official intensity forecast errors have been reduced little over the past 15 years. Elsberry et al. (2007) evaluated the performance of five statistical and dynamical tropical cyclone intensity guidance techniques. They found that during the formation stage, statistical-dynamical techniques such as SHIPS tended to intensify all tropical depressions and were prone to false alarms, but the dynamical models were late in forecasting the transition to a tropical storm. During the intensification stage, the statistical-dynamical models did not predict rapid intensification cases 48 hours in advance but the dynamical model does predict some rapid intensification, but its timing is off. All of the techniques significantly under forecast the peak intensity. Overall, Elsberry et al. (2007) found that National Hurricane Center Forecasters have deficient model guidance for the following: (which most likely contributes to their large intensity errors)

(i) transition from tropical depression to tropical storm over forecast intervals as short as 24 hours

(ii) rapid intensification (>30 kt per 24 hours) at 48 hours in advance

(iii) peak intensity at 48 and 72 hours in advance

(iv) decay and reintensification cycles involving changes of at least 10 kts

(v) rapid decay

Therefore, research must be done so the model guidance can be improved in these areas, thus improving intensity forecasts.

It is obviously apparent that forecasting hurricane intensity is somewhat of a challenge for forecaster. This is a result of many factors. First of all, our understanding of the environmental controls of hurricane intensity, such as vertical wind shear and ocean-hurricane interactions, are still incomplete. To further complicate this problem, it is difficult to get good data for vertical wind shear and ocean mixed layer depth/SST feedbacks with which to initialize models. Because small errors in initializations can cause huge forecast errors, especially at longer lead times, it is important to improve our data collection and assimilation techniques. (*Rogers et al.* 2006) There are also limitations in the numerical models themselves, such as insufficient computing resources to run them at high vertical and horizontal resolutions. To help address these concerns, NOAA has started a program, the Intensity Forecasting Experiment, which has the following goals:

(i) collect observations that span the tropical cyclone life cycle in a variety of environments

(ii) develop and refine measurement technologies that provide improved real-time monitoring of tropical cyclone intensity, structure, and environment

(iii) improve our understanding of the physical processes important in intensity changes for a tropical cyclone at all stages of its life cycle.

(*Rogers et al.* 2006)

These efforts and improvements because of them are ongoing. For example, there have already been substantial modifications to the SHIPS model. Major changes include the addition of a method to account for the storm decay over land, the extension of the forecasts from 3 to 5 days, and the replacement of a simple dry-adiabatic model with the NCEP operational global model for the evaluation of the atmospheric predictors. (*DeMaria et al.* 2005). These changes have provided some modest decrease in intensity errors in certain areas.

In summary, hurricane intensity has an upper bounded as defined by Carnot cycle thermodynamics. In reality though, environmental factors such as vertical wind shear and ocean interactions regulate hurricane intensity. Our forecasts of hurricane intensity are quite lacking in skill, despite substantial improvements over the years in track forecasting. In order to improve intensity forecasts, we must take more and better measurements of the atmosphere, improve the ways of using atmospheric measurements to initialize numerical forecast (better data assimilation), achieve better accuracy of numerical algorithms (higher resolution, more computing power), and improve the model physics by improving our understand of the physical process and our ability to parameterize them.

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