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COULD HURRICANES FORM FROM RANDOM CONVECTION IN A WARMER WORLD?

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1. INTRODUCTION

The notable increase in hurricane activity in the Atlantic basin over the last decade, and the extreme activity of the 2004 and 2005 seasons, have brought greatly increased attention to the relationships between tropical cyclones (TCs), climate, and climate change. How tropical cyclone frequency and intensity might be changing, or will change, with climate remains essentially unknown. The modeling study of Knutson and Tuleya (2004) indicated that mean cyclone intensity could increase by about 5% over the next century. While recent studies have identified large increases in TC activity in recent decades (Emanuel 2005a,b; Webster et al. 2005), others have argued that the present data set is insufficient to establish such trends (Pielke et al. 2005; Landsea 2005).

Here, we focus on a different question, which is the degree to which the *frequency* of tropical cyclogenesis depends on regional and global climate. In particular, we hope to *isolate* the way in which the likelihood of tropical cyclogenesis varies with such parameters as environmental vorticity and the locally esimated maximum potential intensity (MPI), which subsumes local variations of both sea surface temperature (SST) and the overlying atmospheric temperature profile.

2. A NEW GENESIS INDEX

Gray (1975) introduced the concept of a genesis index indicating the likelihood of tropical cyclogenesis in a particular region, based on such parameters as SST, mean low-level vorticity, and mean vertical wind shear. Recently, Emanuel and Nolan (2004) presented a new genesis index which depends on MPI rather than SST itself, i.e.,

$$I = \left|10^5\eta\right|^{\frac{3}{2}}\left(\frac{H}{50}\right)^3\left(\frac{V_{pot}}{70}\right)^3(1+0.1V_{shear})^{-2} \qquad (1)$$

where the parameters are local mean values of absolute vorticity at 850 mb (η), relative humidity at 600 mb (H), the MPI wind speed (V_{pot}) based on the theory of Emanuel (1995), and the 250 to 850 mb wind shear (V_{shear}), and I is the number of storms per decade per 2.5 deg square of latitude and longitude. An example of spatially varying I is shown in Fig. 1, along with the incidents of genesis for the same time period.

Tropical cyclogenesis is generally viewed as a "finite amplitude instability," that is, a pre-existing disturbance of sufficient amplitude is necessary for the genesis to occur. The increase in I with each of the first three parameters could be interpreted as a lowering of the threshold amplitude for a disturbance to transition to a tropical cyclone.

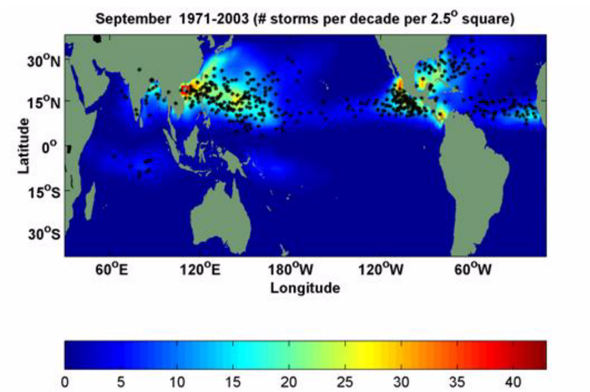

Figure 1: Genesis index I based on reanalysis data for September, 1971-2003, along with genesis events for the same period.

3. HYPOTHESIS

Our current goal is to assess and hopefully quantify the relationship between local values of MPI, Coriolis parameter f, and the likelihood of tropical cyclogenesis. We propose that the effects of varying MPI and f are summarized by the phase space diagram shown in Fig. 2. During their respective hurricane seasons, the Earth's development regions sit near the center of the diagram, requiring some non-trivial initial disturbance for genesis to occur. For sufficiently high values of MPI and f, we expect that cyclones could form spontaneously, and for low enough values of either parameter, all cyclones decay. This phase diagram will be explored with cloud-resolving simulations of radiative-convective equilibrium (RCE) over fixed SSTs.

4. MODEL AND PARAMETERIZATIONS

The atmospheric model used for this study is version 2.1.1 of the Weather Research and Forecast Model (WRF). WRF is a "next-generation," regional, fully-compressible model of the atmosphere (Michalakes et al. 2001). WRF uses high-order advection schemes on an Arakawa-C grid, with $\eta = p_h / p_{hs}$ as a terrain-following vertical coordinate (although there is no terrain in the simulations presented here), where p_h and p_{hs} are the hydrostatic pressure and the hydrostatic surface pres-

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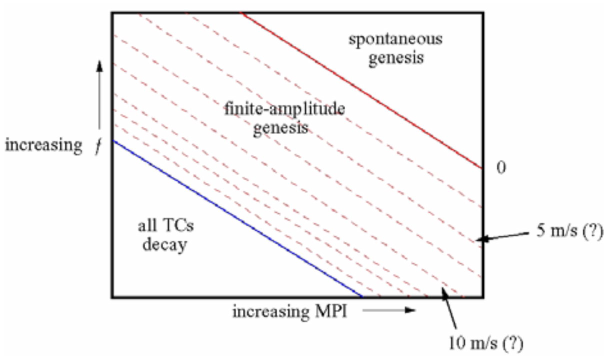

Figure 2: A hypothetical phase-space diagram for the likelihood of tropical cyclogenesis. The red contours are hypothetical wind speeds of weak initial vortices necessary to initiate tropical cyclogenesis.

sures, respectively (Laprise 1992). The time integration uses 3rd order Runge-Kutta time stepping (Wicker and Skamarock, 2003).

The domain for all simulations is a square with doubly periodic boundary conditions. The grid spacing is 4 km in the north and south directions, with 40 vertical levels; these levels are equally spaced in η coordinates, and thus are stretched in height, with 10 levels in the lowest 2km. The model top is defined by pressure but sits at approximately 20 km altitude.

Parameterizations for unresolved physical processes that are available with WRF 2.1 were used, all of which are closely related to commonly used schemes for research and numerical weather prediction. Convection is resolved explicitly and there is no cumulus parameterization. For microphysics, the WRF Single-Moment (WSM) 6-class scheme (with graupel) is used (Hong et al. 2004). For the boundary layer, we use the Yonsei State University (YSU) scheme (Noh et al. 2003), which is an improvement of the MRF scheme. The sophisticated Rapid Radiative Transfer Model (RRTM) scheme is used for long-wave radiation (Mlawer et al. 1997).

There is no parameterization for shortwave radiation. Rather, the effects of upper-tropospheric heating and the generation of the tropopause is mimicked by the use of a relaxation scheme on the upper-level temperatures. Above z = 15 km, the atmosphere is relaxed to an isothermal profile with a relaxation time scale of 5 days. At each column in the model, the relaxation temperature is determined every 15 minutes from the mean temperature in the levels above 15 km. This allows the model to freely determine the tropopause temperature, based on the intensity of the simulated convection which is pushing into the upper troposphere. Despite the arbitrary choice of the altitude above which the relaxation is enforced, it also gives some freedom to the height of the tropopause.

In a doubly periodic domain with rotation, it is not physically reasonable to include either a mean surface wind or a mean wind shear which is constant throughout the domain. However, as will be shown below, radiative-

Table 1 MPI and I for $f = 0.75 \times 10^{-4}$ s^{-1} (small domains only)

	SST= 25	30	35
u_m = 0.0	83 11	113 112	128 238
3.0	80 78	93 153	101 277
8.5	53 34	61 66	68 85

red = MPI; blue = genesis index

convective equilibrium without a mean surface wind produces a thermodynamic atmosphere which is excessively unstable to tropical cyclones and is associated with extremely high values of MPI. To adjust for this, we modify the wind speed used in the calculation of the surface evaporation rate as follows:

$$|V^*| = |\vec{\mathbf{v}} + u_m \hat{i}| \tag{2}$$

where u_m is the speed of the mean surface wind.

5. SIMULATION DESIGN

To save computing time, simulations are first performed on smaller, 200km x 200km domains, which also are too small to allow cyclogenesis during the transition to RCE. When the domain-averaged profiles of temperature and RH reach a steady state, these profiles are then used as initial conditions for larger domains. These large domain simulations are used to capture one of three processes:

1) Spontaneous TC genesis (or failure). These are initiated with random convection on a domain 800km x 800 km in size. These domains are too small to adequately simulate the evolution of a mature hurricane, but they are sufficient to capture the genesis process.
2) Genesis (or failure) from an incipient vortex. These are initiated with a weak, balanced, warm-core vortex on a 1200 x 1200 km domain, and are used to evaluate the finite-amplitude instability threshhold.
3) TC decline over cooler temperatures. These will first use method (2) to generate a cyclone, and then the SST will be lowered until the storm cannot sustain itself.

Results from simulations of type (1) and (2) are discussed below; simulations of type (3) remain for future work.

6. RESULTS

Small-domain simulations were integrated out to 30 days or more for a variety of values for SST, f, and u_m. RCE was typically achieved betwen 30 and 50 days, when the mean vertical profiles of temperature and RH were found to become approximately constant with time.

Table 2 Summary for $u_m = 8.5$ m/s

	SST= 25	30	35
f= 1.0x10^{-4}	54	61	66
	53	101	131
	11	12	11
0.75x10^{-4}	54	61	66
	34	66	85
	17	16	18
0.5x10^{-4}	54	62	66
	18	36	45
	*	*	*

MPI
Genesis Index
Days to Genesis

Before performing large-domain simulations, the mean profiles from the small domain simulations were evaluated for their MPI and their genesis index I. Some results are shown in Table 1. As mentioned above, MPI decreases as u_m increases. However, we have the interesting result that I is larger for small u_m (3.0 ms^{-1}) before decreasing for larger values. This is due to greatly enhanced values of mid-level RH (H in equation 1) when the surface wind is present (not shown).

To date, large-domain simulations of type (1) above have been completed for SST values of 25, 30, and 35 C, and values of f of 0.5, 0.75, and 1.0 x 10^{-4} s^{-1}. The value of u_m = 8.5 ms^{-1} was used for these initial large-domain simulations since it was found to hold the Jordan Mean Hurricane Season Sounding (Jordan 1958) in RCE over a SST of 28.5 C. The results of these 9 simulations are shown in Table 2. Spontaneous genesis occured for all 3 values of SST, when f was equal to or greater than 0.75 x 10^{-4} s^{-1}.

An example of this genesis is illustrated in Fig. 3, which shows vertical motion at 5 km for days 11, 15, and 17 of the simulation with f = 1.0 x 10^{-4}s^{-1} and SST = 30 C. The orgainzation of vorticity (not shown) from a seemingly random field to an incipient weak vortex occurs relatively quickly, between days 11 and 13, while the vertical motion organizes more slowly. At the very least, these simulations show that “spontaneous” TC formation could be possible if tropical or even subtropical SSTs were to expand far enough toward the poles. These results are consistent with those of Bretherton et al. (2005), who also found spontaneous TC genesis from RCE, using a different model, different parameterizations, and a smaller domain.

The apparent lack of sensitivity to SST for the spontaneous genesis cases may be due to our choice of u_m. After these simulations were completed, we noted that the atmospheric RH profiles produced for RCE with u_m = 8.5 ms^{-1} were excessively moist, with values of RH > 75% throughout the middle troposphere, even for SST = 25 C. This may also explain the seemingly contradicotry

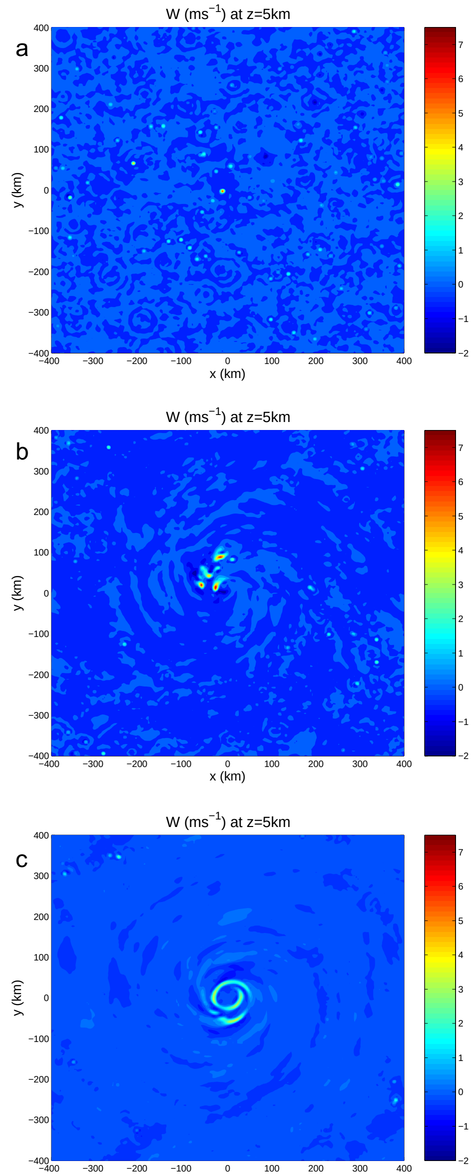

Figure 3: Vertical winds at z = 5 km for a simulation of spontaneous cyclogenesis: a) at t = 11 days; b) t = 15 days; c) t = 17 days.

results of our initial simulations of type (2). As shown in Fig 4., the intensification for weak vortex with initial cyclonic surface winds of 3.0 ms^{-1} begins *sooner* for SST = 25 C than for 30 C and 35 C (although the rate of intensification is clearly slower, and increases with SST).

In Table 1, the genesis index shows a much larger sensitivity to SST for lower values of u_m, and similar values will be used in current and future simulations. Setting u_m = 0, while a seemingly useful starting point, may be problematic: in this case, our small-domain simulations of RCE make a sudden transition around 50 days from random convection to an “aggregated” state, with an isolated area of intense convection surrounded by much drier conditions. This phenomenon of self-aggre-

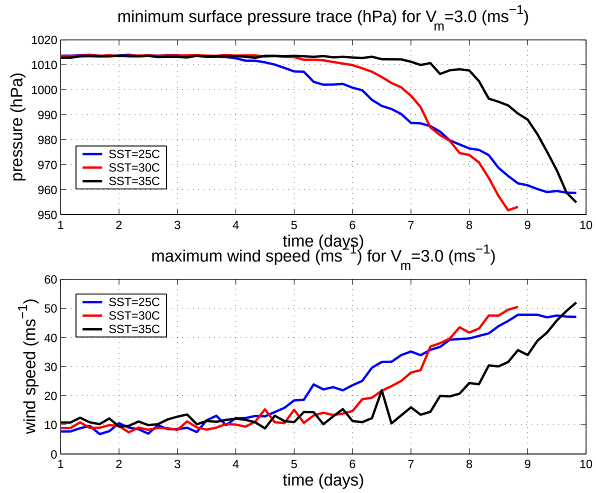

Figure 4: Maximum surface winds and minimum pressures for simulations over various SSTs initialized with a weak surface vortex with maximum cyclonic wind of 3.0 ms^{-1}.

gation in 3D simulations of RCE has been documented and discussed by Bretherton et al. (2005). Domain-averaged profiles of temperature and RH change drastically after the aggregation occurs, leaving open the question of whether it is appropriate to represent RCE with profiles from before or after aggregation.

Fortunately, even small values of u_m such as 3.0 ms^{-1} seem to overcome this problem, as these simulations have been integrated out to 90 days with no sign of self-aggregation. Whether spontaneous genesis occurs for these cases, and if the mechanism is similar or fundamentally different to the mechanism of self-aggregation, are intriguing questions which remain for our ongoing work.

7. CONCLUSIONS

Motivated by the observed relationship between MPI and the frequency of tropical cyclogenesis, we have undertaken a carefully designed modeling study to asess the effect of MPI on the likelihood of tropical cyclogenesis. Initial results have shown that even in radiative-convective equilibrium, the expected MPI and genesis index I both increase significantly with SST. We have also found that the speed of the mean surface wind over the ocean has a large impact on these values and on the process of cyclogenesis.

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