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A RECALCULATION OF MPI USING UPPER-OCEAN DEPTH AVERAGED TEMPERATURES: CLIMATOLOGY AND CASE STUDIES

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1. INTRODUCTION

Several theories have been developed over the past fifty years which attempt to arrive at an upper bound or Maximum Potential Intensity (MPI) of tropical cyclones. Emanuel (1988, 1995), in particular, uses the sea-surface temperature (SST) and atmospheric sounding to arrive at a maximum intensity (EMPI) for the hurricane using a Carnot Engine cycle approach to the energetics of the storm (Emanuel 1986; Rotunno and Emanuel 1987).

While this approach has captured the upper bound or greatest intensity of hurricanes reasonably well, the use of SST alone for EMPI calculations may be overestimating the maximum intensity. Hurricanes draw their energy from a significant depth of the upper ocean, the average temperature of which is almost always less than the SST. Consequently, there may be more cases of tropical cyclones approaching or exceeding their EMPI than an SST-based EMPI would dictate alone. Presumably, a purely SST-based EMPI calculation would only be valid for intense storms if the entire layer affected by hurricane mixing was isothermal. Furthermore, the Carnot approach is based on an axisymmetric tropical cyclone thus ignoring potential asymmetric influences on a tropical cyclone's strength—whether internal (vortex Rossby waves, eyewall replacement cycles) or external (trough interaction).

A recalculation of the MPI climatology acknowledging this oceanic variability (NMPI) is performed here in an attempt to better isolate those storms that have approached or exceeded a more realistic MPI. Further, a comparison of the most intense NMPI climatology to the observed TC intensity climatology will reveal the impact of some of the assumptions of TC structure at extreme intensities. A case study on Hurricane Isabel (2003) indicates the upper oceanic cooling may have significantly contributed to the rapid weakening of the storm.

Finally, it has been unclear on how to use EMPI within the storm itself since EMPI assumes atmospheric moisture and temperature profiles from the unperturbed environment. A calculation of EMPI using climatological SST's is performed twenty days prior to a storms arrival at each location along the storm's track. The maximum EMPI and the day (lag) of occurrence are recorded. The results yield insight into the stabilizing effects of tropical cyclones on the ambient environment, and cyclical nature of tropical energetics.

2. METHODOLOGY AND DATA

North Atlantic Hurricane track and intensity data is provided by the NHC/TPC best track dataset (Neumann et al. 1993; Jarvinen et al. 1984) over a period extending from 1982-2003. Specific humidity profile data, mean sea level pressure data and air temperature data for EMPI come from the NCEP/DOE Reanalysis2 data set (Kanamitsu et al. 2002b). This data has a spatial resolution of 2.5° x 2.5° and a temporal resolution of every six hours beginning on 1st January 1979.

The SST data used for the climatological EMPI are the NODC (Levitus) 1994 World Ocean Atlas 1° x 1° climatological long term monthly mean SST. The data used to produce the depth averaged SST for the NMPI are the NODC (Levitus) 1994 World Ocean Atlas 1° x 1° layer mean temperatures which contains long term monthly mean oceanic temperatures at nineteen different levels. Both data sets are linearly interpolated in time centered on the 15th of each month producing a daily ocean temperature over the globe.

The hypothetical equation to calculate heat content (HC) for input into NMPI is as shown:

$$HC = \frac{\left(5SST + 4T_{10m} + 3T_{20m} + 2T_{30m} + T_{50m}\right)}{15} \quad (1)$$

This depth of averaging (50m) is supported by a previous study of the upper ocean mixing observed with the passage of Hurricane Felix (1995) over a moored testbed buoy near Bermuda (Dickey et al. 1998). Is it also supported by a climatology of all category five storms as compared to the depth-mean surface-50m September ocean temperature (Figure 2.1).

The actual coefficients of weighting above were arbitrarily chosen to imply linearly decreasing mixing with depth. A more detailed modeling study that determines these coefficients as a function of both ocean depth and storm intensity is necessary.

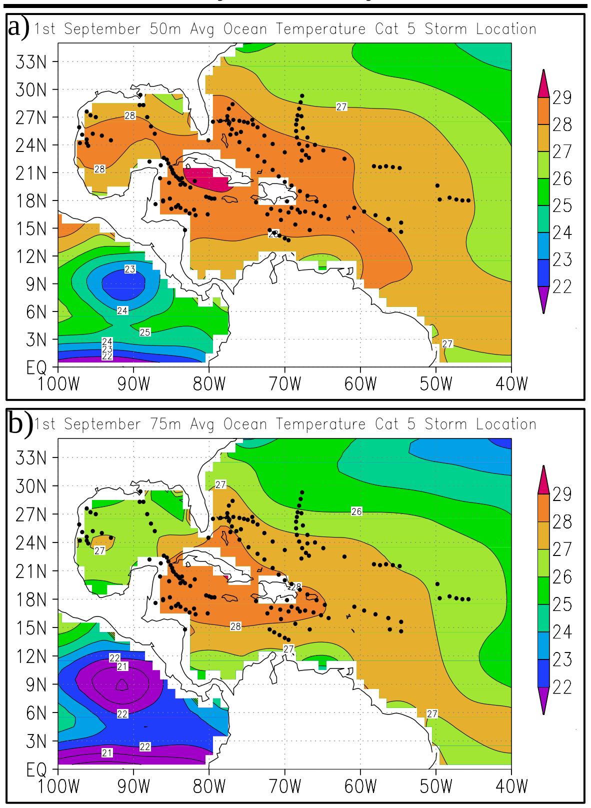
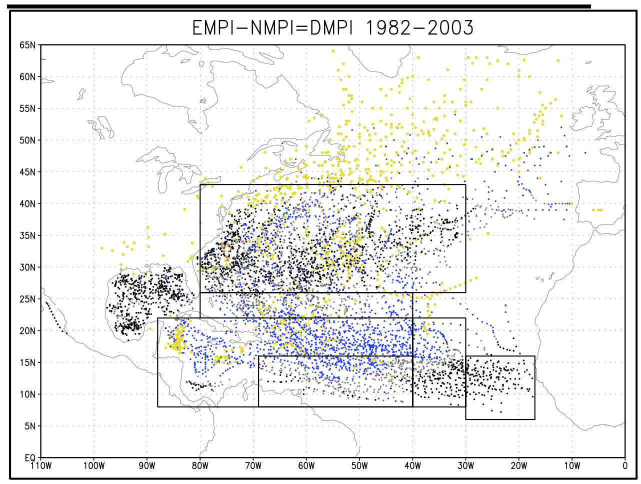


Figure 2.1: Position of all category five storm occurrence from 1886-2005 compared to the 1 September mean ocean temperature over a depth of a) 50m and b) 75m. Note that the 27°C mean temperature encompasses well the Category 5 occurrence in a) but not b), suggesting the maximum mixing depth on average of an intense hurricane is no more than 50-75m.

3. RESULTS

For every 6-hr best-track position of every storm from 1982 through 2003, the traditional EMPI (using SST as energetics source) was calculated. Thereafter, the same process was performed except using a 50-m weighted mean ocean temperature profile (1), to arrive at a new MPI calculation (NMPI). The impact of using this more realistic energy source in the MPI calculation is discussed below.

The largest differences in MPI (Figure 3.1) occur over regions with shallow pools of warm water. Conversely the smallest differences occur over regions with very deep pools of warm water. Figure 3.2 shows the mean 1st September 50m temperature across the basin, to illustrate the relative depth of the warm water. Notice the relative agreement in patterns between Figures 3.1 and 3.2



Black- $DMPI \le -10$ hPa
Grey - $DMPI > -10 \le -5$ hPa
Blue - $DMPI > -5 < -1$ hPa
Yellow- $DMPI \ge -1 \le 1$ hPa
Orange- $DMPI > 1 \le 5$ hPa
Red- $DMPI > 5$ hPa

Figure 3.1: The impact of using depth-mean ocean temperature rather than SST for MPI calculation (DMPI=EMPI-NMPI) across the Basin 1982-2003. Cool colors indicate that EMPI was overestimating and warm colors indicate that EMPI was underestimating the maximum potential intensity. The orange dots are primarily a result of erroneous interpolation across the strong ocean temperature gradient that varies in intensity with depth in those regions.

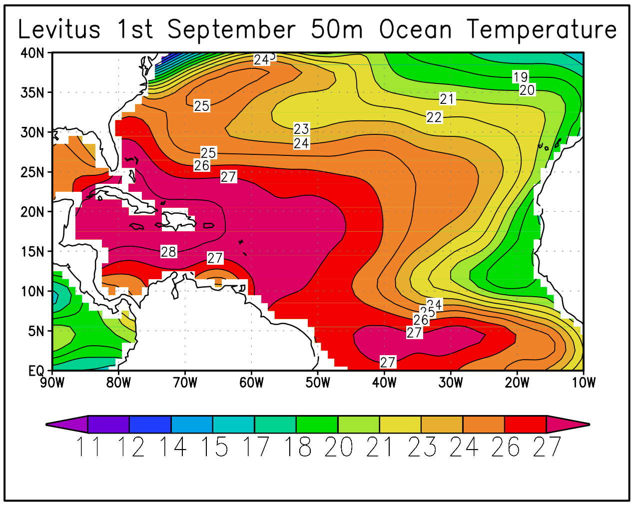


Figure 3.2: 1st September average ocean temperature (°C) at a depth of 50 meters.

	Obs.-EMPI Average Difference	**Obs.-NMPI** Average Difference
Top 70 Intensities	45.3 hPa	26.7 hPa
MSLP < 1000hPa	38.7 hPa	25.0 hPa

Table 3.1: Average Observation-EMPI and Observation-NMPI difference. Note that the large dependence on intensity for EMPI (45.3hPa vs. 38.7hPa) nearly vanishes for NMPI (26.7hPa vs. 25.0hPa).

Table 3.1 shows the average difference between observations and EMPI and the average difference between observations and NMPI. This is done for the strongest storms over the period and then for all intensities of depression strength or larger. The difference between observations and EMPI varies with storm strength, while the same difference using NMPI does not vary with storm strength. This indicates that the hypothetical calculation acts to successfully normalize the MPI to storm intensity and is a fairly good estimation of the upper ocean heat content that is available for use by the TC.

While NMPI provides on average a 40% reduction in the excess of MPI (45.3hPa to 26.7hPa), there still exists an overestimation of the overall potential intensity. The most intense hurricane observed during the period of study was Gilbert (1988) at 888hPa. Yet, the most intense NMPI during this period was approximately 840hPa. Such a difference between historical observed vs. theoretical MPI values argues that in ideal thermodynamic oceanic conditions and dynamic atmospheric conditions, the Carnot cycle approximation to extreme TC structure given by Emanuel (1986,1988) is too basic.

One of the most noteworthy limitations of the theory is that the role of the eye itself is not captured. As the TC becomes increasingly intense, the eye decreases in size. Observed pressures of 840hPa would require eye diameters of less than 5nm, which have never been observed. Such a small eye would severely restrict the amount of mass sinking within the eye as part of the indirect circulation that accentuates the warmth of the eye itself, helping to lower the pressure hydrostatically.

It is suggested that the inability of the Carnot cycle approximation to capture the limit the decreasing eye size presents on hurricane intensification is one reason why the MPI theory overestimates the intensity bounds by 40hPa. However, this speculation requires further study.

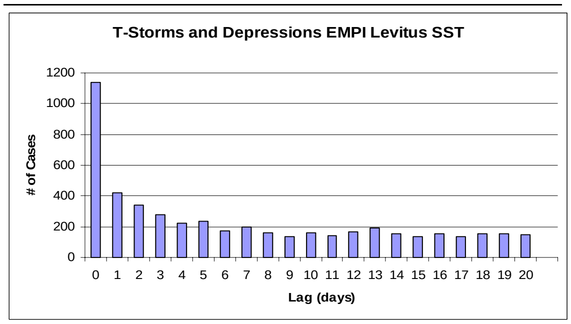


Figure 3.3: Lag (day) of most intense MPI for tropical depressions and storms 1982-2003. A lag of 10 would indicate that the maximum MPI was calculated for a storm at a given location by looking at the sounding at that location 10 days before the storm arrived. In this case, the maximum frequency for maximum MPI is a lag of zero, indicating that the most energetic conditions for TC intensification occur at the actual storm time. Such a result is consistent given the storm is newly formed.

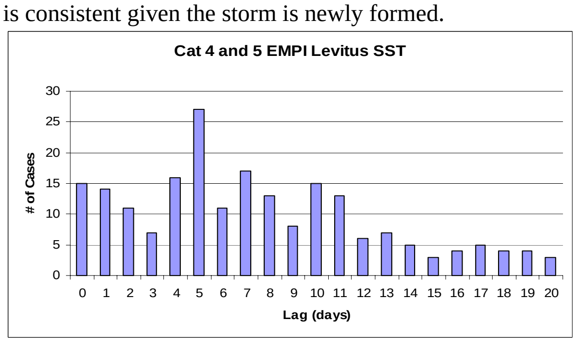


Figure 3.4: Same as Figure 3.3, except for category 4 and five hurricanes. The peak lag frequency at 5 days indicates that the intense hurricane stabilizes the atmosphere leading up to its arrival for at least 5 days.

Further results indicate the effects on the ambient environment as a function of storm strength. Figure 3.3 shows the day (lagged from the current time) in which the most intense EMPI is calculated for the weakest storms. The peak frequency at a lag of 0 days suggests that weak storms do not readily affect the ambient environment and that the EMPI within the storm is valid. Indeed, the peak in available energy for TC development (lag of zero days) is likely part of the reason why the TC has formed in the first place.

Figure 3.4 indicates the impact that the strongest systems have on the ambient environment. For the most intense storms, the peak frequency of most intense MPI is around 5-10 days. This further suggests that the strongest storms affect the ambient environment such that stabilization of the atmosphere begins five or more days prior to the cyclone's arrival. The best determination then of the MPI for these storms is, on average, determined by the energetics of the ambient environment five days prior to storm arrival.

4. CONCLUSION

The results indicate that EMPI may be an overestimate on storm maximum potential intensity. The largest differences between EMPI and NMPI occur over regions of the basin containing shallow warm pools; the smallest differences occur over regions with the deepest warm pools. Use of the upper ocean heat content reduces the average difference between observations and MPI by approximately 40%. Further, observation-EMPI average difference varies with storm strength while observation-NMPI remains constant regardless of storm strength. This may suggest that the hypothetical equation to capture the heat content normalizes the difference and may be a good approximation in capturing the heat content. However, rigorous studies modeling the upper ocean response to storms of various strengths will help produce a more accurate measure of the available heat content.

Even when the profile of oceanic temperature is accounted for, the MPI calculation still produces maximum intensities that are 40hPa too deep compared to long-term observed maximum intensities. This suggests that aspects of TC structure not accounted for by the MPI theory are a limiting factor on storm intensity. One such proposed factor is the role the eye plays in limiting intensification as it shrinks to extremely smaller diameters.

Results further suggest that storms begin to stabilize the ambient environment as a function of storm strength. The weakest storms do not significantly affect the ambient environment and the energetics within the storm environment are sufficient for storm growth. On average, the strongest storms begin to affect the ambient environment five days prior to arrival. These storms begin to stabilize the ambient environment such that the energetics nearby these strong systems does not produce the most intense MPI.

5. REFERENCES

Dickey, T., D. Frye, J. McNeil, D. Manov, N.Nelson, D. Sigurdson, H. Jannasch, D. Siegel, A. Michaels, and R. Johnson,1998: Upper ocean temperature response to Hurricane Felix as measured by the Bermuda Testbed Mooring. *Mon. Wea. Rev.*, **126**, 1195-1201.

Emanuel, K. A., 1986: An air–sea interaction theory for tropical cyclones. Part 1: Steady-state maintenance. *J. Atm. Sci.,* **43,** 585–604.

_______, 1988: The maximum intensity of hurricanes. *J. Atmos. Sci.,* **45,** 1143–1155.

Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.*,**52**, 3969-3976.

Holland, G. J., 1997: The maximum potential intensity of tropical cyclones. *J. Atmos. Sci.,* **54,** 2519-2541.

Jarvinen, B. R., C. J. Neumann, and M. A. S. Davis, 1984: A tropical cyclone data tape for the North Atlantic basin, 1886-1983: Contents, limitations, and uses. NOAA Tech. Memo. NWS NHC 22, NOAA/National Hurricane Center, Miami, FL, 21 pp.

Kanamitsu, M., W. Ebisuzaki, J. Woolen, J. Potter and M. Fiorino, 2002b: NCEP/DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Met. Soc.,* **83**, 1631-1643.

Miller, B. I., 1958: On the maximum intensity of hurricanes. *J. Meteor.,* **15,** 184–195.

Neumann, C. J., B. R. Jarvinen, C. J. McAdie, and J. D. Elms, 1993: Tropical cyclones of the North Atlantic Ocean, 1871-1992. National Climatic Data Center in cooperation with the National Hurricane Center, Coral Gables, FL, 193 pp.

NODC (Levitus) World Ocean Atlas 1994 data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/.

Rotunno, R., and K. A. Emanuel, 1987: An air–sea interaction theory for tropical cyclones, II. *J. Atmos. Sci.,* **44,** 542–561