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Maximum potential intensity increases due to azimuthal variation in the eyewall's surface-wind speed

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Abstract: Maximum potential intensity (MPI) is usually calculated without factoring in the varying degree of asymmetry that different tropical cyclones have in their eyewall surface-wind. This study shows that MPI can increase 7% to 19% (4 to 9 m s^{-1}) when one considers how frictional loss and enthalpy gain is effected by boundary-layer azimuthal wind-speed variation at the radius of maximum wind. Azimuthal variation is incorporated in this study by integrating surface frictional loss and enthalpy gain around the radius of maximum wind. Climate studies and some operational intensity forecasts may wish to include this asymmetry factor, which increases MPI estimates.

Introduction:

One way to illustrate how MPI is commonly calculated is first to estimate a tropical cyclone's maximum-possible thermodynamic efficiency ε_{max} and then to increase intensity I until the efficiency required to sustain that intensity rises to ε_{max} (point A, Fig. 1a). In Fig. 1a, efficiency as a function purely of intensity is represented as the line $\varepsilon(I,0)$ because azimuthal variation Δv in eyewall surface-wind speed is assumed to be zero.

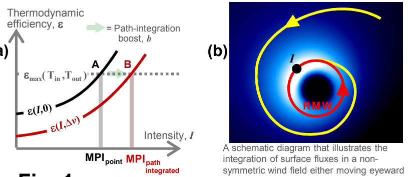

Fig. 1

A schematic diagram that illustrates the integration of surface fluxes in a non-symmetric wind field either moving eyeward from large radii (yellow spiral), or at the radius of maximum wind (red circle), or at only the maximum wind speed (black dot).

Emanuel (1997, Eq. 7) states that, strictly speaking, MPI should be calculated by integrating ocean-surface fluxes along the boundary-layer paths taken by all air parcels approaching eyewall updrafts (yellow spiral, Fig. 1b). It is computationally much simpler and sometimes asserted to be almost equivalent to approximate the path integrals with surface fluxes evaluated at only the maximum wind speed (Emanuel 1997, Eq. 8), even though the maximum wind speed occurs in a very small portion of the wind field, perhaps only at a single point at the radius of maximum wind (**black** dot, Fig. 1b). In contrast, Shen (2004) reports that if the path integrals were evaluated starting at large radii, then an unrealistically high MPI would result unless MPI theory were otherwise modified.

This study proposes a physically plausible and computationally tractable improvement over the two extremes of integrating starting from large radii or of evaluating fluxes at just the maximum wind speed. Specifically, this study integrates around the radius of maximum wind (**red** circle, Fig. 1b). Focusing on the radius of maximum wind (RMW) may be reasonable because the fast winds there give a boost to enthalpy that may help keep eyewall updrafts buoyant relative to air beyond the eyewall that does not experience these fast surface wind speeds. Furthermore, not starting the integration path at large radii may be reasonable because an incremental increase to enthalpy outside of the eyewall could either increase or decrease MPI. It could trigger convection outside the eyewall that could reduce the eyewall's supply of moist, warm, surface air or that could lead to an eyewall replacement cycle that eventually increases intensity.

Method:

When integrating thermodynamic efficiency over the range of wind speeds experienced by air parcels at the radius of maximum wind, the resulting "path-integrated" MPI (point B in Fig. 1a) is greater than the traditional MPI calculated at just the wind-field maximum, hereafter referred to as "point" MPI (point A in Fig. 1a). For a given horizontal surface-wind field, the efficiency calculated at the wind field's maximum (i.e., intensity I) can equal the path-integrated efficiency for that wind field plus a wind boost b (m s^{-1}). If the average wind speed along the path integrals that include b is comparable to the original intensity excluding b, then the thermodynamic efficiency remains unchanged. Boost b can be calculated by numerically solving Eq. 1 for b, which is the only unknown in the equation (See Appendix).

$$I^2 = \frac{\int \left\| \vec{v} + \hat{\theta} b \right\|^3 ds}{\int \left\| \vec{v} + \hat{\theta} b \right\| ds} \quad \textbf{Eq. 1}$$

Results:

First, we substitute into Eq. 1 an idealized wind field with wave-number 1 asymmetry: $\vec{v} = \hat{\theta} v_0 + \hat{x} v_f$ where the forward motion v_f of the storm center is added to a symmetric storm-relative wind v_0 (Fig. 2a). Around the radius of maximum wind (RMW), the speed varies from $v_0 - v_f$ to $v_0 + v_f$ relative to storm and from $I - \Delta v$ to I relative to the ground. The total spatial variation in wind speed Δv is twice the storm-center forward speed v_f. As shown in Table 1, integrating Eq. 1 azimuthally around the RMW results a 7% to 19% increase in intensity without requiring any increase to thermodynamic efficiency:

Table 1: The path-integration boost b to intensity making a complete circle around the eye at the RMW. Boost b is tabulated as a function of eyewall azimuthal surface wind-speed variation Δv and initial intensity I

	Eyewall wind-speed variation Δv		
Intensity, I	10 m s^{-1}	20 m s^{-1}	40 m s^{-1}
42 m s^{-1}	4 m s^{-1}	8 m s^{-1}	N/A
70 m s^{-1}	5 m s^{-1}	9 m s^{-1}	15 m s^{-1}

Second, we examine the 3D wind field from the Braun et al. (2006) simulation of Hurricane Bonnie (1998) (Fig. 2b). We find that 80% of air parcels starting at the ocean surface within 8 km of the RMW will circle the eyewall less than half-way around before entering an eyewall updraft within 4 km of the RMW at the top of the boundary layer. Making less than a complete revolution at the radius of maximum wind increases the path-integration boost beyond the values stated in Table 1 when the ≤180° arc traveled is on the far side of the eyewall from the wind-speed maximum.

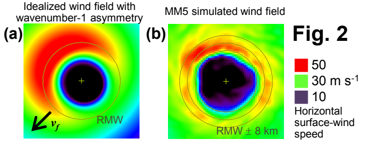

Fig. 2

Discussion:

There are trends in the SHIPS predictor file and the best track data that we speculate may be related to MPI's dependence of eyewall wind asymmetry. Fig. 3 plots the fraction of MPI realized, referred to subsequently as f, which is the best track intensity divided by MPI. For this figure, MPI is referred to as MPI_{94} because it is calculated from the sea surface temperature in the best track data using the formula of DeMaria and Kaplan (1994), without the path-integration boost proposed in this study and without Cione (2005)'s SST cooling correction.

Fig 3a clearly shows an increasing trend in the median f for each 1 m s^{-1} interval of forward motion (plotted with squares). Path-integration provides one possible explanation of this trend, as follows: Suppose that intensity is independent of forward speed and also that adding the path-integration boost b to MPI_{94} would increase the accuracy of MPI_{94}. Under these assumptions, the value of f plotted in Fig. 3a. should increase with v_f because f is calculated with the inaccurate MPI_{94}. To estimate how much the inaccurate f would increase, start with its plotted value of 0.55 for a symmetric storms (v_f=0) and multiply 0.55 by the ratio of MPI_{path} / MPI_{94} for each degree of asymmetry on the x-axis of Fig. 3a. This ratio equals (MPI_{94} + b) / MPI_{94} or more generally (1 + b / MPI). The quantity b / MPI is readily available by dividing the central columns of b values in Table 1 by the left-hand column representing MPI in Table 1. In this manner, the shaded region in Fig. 3a is generated.

Cione (2005) proposes an alternative explanation for the observed trend in the squares plotted in Fig. 3a: the sea surface temperature cools a few degrees less under rapidly moving tropical cyclones than under slow-moving tropical cyclones, so fast moving storms have higher MPI. The sea surface temperature explanation is less satisfactory because it requires that MPI be calculated from temperatures that only exist only after the tropical cyclone's passage. Cione (2005)'s cooling algorithm provides approximately the same magnitude of correction to MPI as the does the path-integration boost proposed in this study, but for a different physical reason.

In Fig. 3b, the fraction f of MPI realized is plotted against the spatial variation, Δv, in eyewall surface wind speed estimated from the structure information in best track data: I, RMW, and the 34 m s^{-1} wind radii in four quadrants. The shaded region shows how path-integration might explain the increasing trend in f in the same manner as in Fig. 3a. Specifically, the shaded region assumes that intensity is independent of the degree of eyewall asymmetry. In contrast, the numbers 1 to 5 in Fig. 3b show that intensity is correlated with spatial variation, Δv. Instead of relying on path-integration to explain the trend in Fig. 3b, the trend may instead be due to strong tropical cyclones, on average, realizing a larger fraction of their MPI and also having more eyewall wind asymmetry.

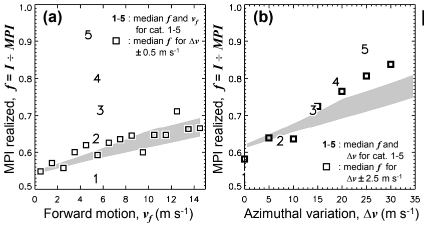

Fig. 3

Conclusion:

Maximum potential intensity (MPI) as it is traditionally calculate may underestimate true MPI by 7% to 19% because such calculations ignore the azimuthal variation in eyewall surface wind that can be 5–20 m s^{-1} at the radius of maximum wind (RMW). Realtime operational estimates are available of azimuthal surface wind speed variation at the RMW. This study proposes that increasing the MPI estimate for tropical cyclones with large wind asymmetry would make MPI more accurate. Accurate MPI is important for forecasting intensity because weak tropical cyclones tend to intensify toward their MPI and strong tropical cyclones tend to weaken when they move into a region where they exceed their MPI.

References:

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Appendix: Deriving Eq. 1

To derive Eq. 1, start with the equations for ocean-surface frictional flux (F_{out}), input enthalpy flux (F_{in}), and thermodynamic efficiency (ε), which is the ratio of these two fluxes (Emanuel 2003, Eq. 4, 5):

$$F_{out} = c_d \rho v^3 \qquad F_{in} = c_k \rho \Delta\eta\, v \qquad \varepsilon = \frac{F_{out}}{F_{in}}$$

In the equations above, c_d and c_k are the coefficients of friction and enthalpy flux, ρ is surface air density, $\Delta\eta$ is the enthalpy difference between the ocean surface and the boundary layer air, and v is the air's wind speed at the ocean surface. To calculate "point" MPI, evaluate the thermodynamic efficiency at the wind field maximum, i.e., at intensity I:

$$\varepsilon_{point}(\vec{v}) = c I^2 \qquad c \equiv \frac{c_d}{c_k \Delta\eta}$$

To calculate "path" MPI, integrate the thermodynamic efficiency over the wind speed along the path followed by boundary-layer air parcels approaching eyewall updrafts.

$$\varepsilon_{path}(\vec{v}) = c \frac{\int \left\| \vec{v} \right\|^3 ds}{\int \left\| \vec{v} \right\|^3 ds}$$

To find the boost to MPI due to path integration, add an azimuthal wind-speed boost b (m s^{-1}) to the wind field before integrating. The scalar quantity b is multiplied by the azimuthal unit vector so that the boost increases the azimuthal wind speed. In the equation below, choose constant b such that the path integrated efficiency ε_{path} after b is added equals the point efficiency ε_{point} without b:

$$\varepsilon_{point}(\vec{v}) = \varepsilon_{path}\left(\vec{v} + \hat{\theta} b\right)$$

This last equation becomes Eq. 1 in the Method section when the preceding formulas for ε_{point} and ε_{path} are substituted in.