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On tropical cyclone fullness

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Abstract:
A series of recent papers have explored the usefulness of a new "fullness" metric characterizing the ratio of the inner and outer core size of tropical cyclones and suggesting that this metric is better correlated with tropical cyclone intensity, and even intensification rate, than single size metrics. Given the potential importance of the fullness metric, we examine its dynamical significance in terms of the rotating-convection paradigm, a new conceptual framework for understanding tropical cyclone behaviour. We conclude that the silence of the fullness metric in characterizing the forcing of the overturning circulation by the aggregate effects of deep cumulus convection raises questions about its value as a possible predictor of storm intensity.

KEY WORDS Tropical cyclones, typhoons, hurricanes, size metrics, fullness

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1 Introduction

Nearly a decade ago, Guo and Tan (2017) introduced a new concept for interpreting storm intensity to which they gave a rather strange name "tropical cyclone fullness", a metric that was assigned the acronym TCF. They defined this metric by the equation

$$TCF = \frac{R17 - RMW}{R17}, \tag{1}$$

where R17 is the radius of gales and RMW is the radius of maximum wind speed. Although not stated explicitly, these two radii relate to wind speeds at the standard 10 m altitude. The presumption is because they show a scatter plot of observed values of these quantities from the best track data for Atlantic tropical cyclones during the period 1988–2015 (their Fig. 1). In essence, the fullness is a measure of the size of the outer region of the storm, the region beyond the RMW out to the radius of gales, to the radius of gales, itself. It follows that values of fullness cannot exceed unity and that storms where the wind speed decays rapidly with radius beyond the RMW, e.g., midget storms, have relatively small values of fullness.

The foregoing observations presented in their Fig. 1 confirm the long known fact that there is only weak correlation between storm intensity, as measured by the maximun near surface wind speed and either the RMW or R17 (reference to Chapter 1 in book). However, Guo and Tan went on to show that there is appreciably better correlation between intensity and fullness. The physical interpretation provided is encapsulated in the following paragraph on page 4386 of their article:

> To understand the significant increase in correlation described above, the radial advection of the absolute angular momentum (AAM) is considered. The radial transport of AAM depends on the product of the magnitude of the low-level radial inflow and the AAM at a certain radius of TC. A large AAM import (i.e., relatively strong inflow and/or AAM) is beneficial for the intensification and expansion of the inner- and outer-core TC wind. In general, a strong low-level inflow is always accompanied by a small RMW, and a large outer-core AAM often corresponds to a large R17. For TCs with small RMW and large R17 (i.e., high fullness), the low-level radial inflow, outer-core wind, and AAM outside the RMW are large, indicating large AAM import and favoring the formation of an intense TC. In contrast, a TC with large RMW and small R17 (i.e., low fullness) exhibits weak radial inflow, relatively weak outer-core wind, and small AAM outside the RMW. Thus, the AAM import is small and does not favor strong intensity. However, for TCs with small R17, the AAM import can be large if the radial inflow is sufficiently strong, which corresponds to a smaller RMW. In contrast, a TC with large RMW can also possess substantial AAM import if the outer-core AAM is large, indicating a large R17. As a result, regardless of the specific RMW and R17, high fullness generally guarantees

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> a large AAM import and is essential for a TC to attain strong intensity and a relative broad wind field distribution. Therefore, TC intensity is strongly correlated with TC fullness, in contrast to the case for individual size parameters.

The fullness metric has been invoked in several subsequent papers (e.g., Chen and Li 2021; Guo and Tan 2022; Tao et al. 2022; Hong and Wu 2023; Casas et al. 2023; Ming et al. 2025) and it would seem useful to examine its physical significance more deeply than has been the case hitherto. This examination is especially called for in the light of the new rotating-convection paradigm for tropical cyclone behaviour that has been developed by the current authors. Such an examination is the purpose of the present article.

2 The rotating-convection paradigm: vorticity aspects

The rotating-convection paradigm is an outgrowth of the classical axisymmetric theory for tropical cyclone intensification, discussed in Chapter 8 of Smith and Montgomery (2023), but applies to fully three-dimensional flows. Important additions to the classical theory are detailed in Chapter 11 of the foregoing book. In essence, it is a collection of physical principles that are generally applicable to understanding the complete life cycle of tropical cyclones. The relationship to a prominent alternative axisymmetric theory for tropical cyclone intensification is discussed by Smith and Montgomery (2025) and a further extension to translating vortices is presented by Persing et al. (2025).

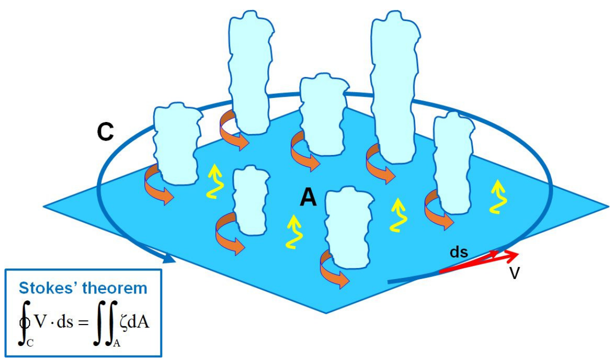

Figure 1. Schematic of a region of deep rotating updrafts, with a hypothetical horizontal circuit indicated by a circle. By Stokes' theorem, the relative circulation about the circuit is equal to the areal integral of the relative vorticity enclosed by the circuit. The yellow squiggly arrows indicate moisture fluxes from the ocean. To avoid clutter, the local and system-scale overturning circulations associated with the updraughts and downdraughts are not shown. See text for further discussion. Adapted from Smith and Montgomery (2016).

For non-axisymmetric flows, absolute angular momentum, as used in Guo and Tan (2017)'s discussion quoted above, is not materially conserved as it can be generated or removed by favourable or adverse azimuthal pressure-gradient forces as well as by non-zero torques, such as those associated with friction. A more general framework is based on the azimuthal-mean tangential momentum equation, or equivalently by the vertical vorticity equation in conjunction with Stokes' theorem.

Stokes' theorem equates the circulation, Γ, about any fixed closed loop C to the area integral of the vorticity within that loop. Taking A to be the area enclosed by loop C and the area to be in a horizontal plane, Stokes' theorem may be written in the form

$$\oint_C \mathbf{V} \cdot d\mathbf{s} = \int \int_A \zeta dA, \qquad (2)$$

where $\mathbf{V}$ is the velocity vector, $d\mathbf{s}$ is a vector increment along the curve C, dA is an area element of A, and ζ is the vertical component of relative vorticity. If C is taken to be a circle of any fixed radius, R_C, at any given height, the azimuthal mean tangential velocity at this radius and height is simply $\Gamma/(2\pi R_C)$.

It follows from a theorem by Haynes and McIntyre (1987) that for the circulation about the circuit C to increase, implying that the mean tangential wind about this circuit increases, vertical vorticity must increase within the region bounded by the fixed loop C. In general, this increase can occur only by horizontal advective and non-advective vorticity fluxes (see, e.g., Sections 2.15 and 11.1 of Smith and Montgomery 2023, especially Fig. 11.2). In the former case, cyclonic vorticity may be brought horizontally into the region across the boundary of C. In the latter case, horizontal vortex lines may be tilted into the vertical within C in such a way that the positive part of the vorticity dipole becomes manifest as a horizontal influx of cyclonic vorticity across the loop C. Conversely, horizontal vortex lines may be tilted into the vertical within C in such a way that the negative part of the vorticity dipole becomes manifest as a horizontal outflux of cyclonic vorticity across the loop C, which is what happens as a result of friction effects (see e.g. Panel (c) of Fig. 11.2 in Smith and Montgomery 2023).

The subtlety that arises from the Haynes and McIntyre theorem is the fact that, in general, the horizontal flux of vertical vorticity across C is not equal to just the radial advection of vertical vorticity across C. The statement that *for the circulation about the circuit C to increase, vertical vorticity must increase within the region bounded by the fixed loop C* is the three-dimensional analogue of the idea that for spin up to occur in an axisymmetric flow, there has to be a component of flow across the absolute angular momentum (or M-) surfaces in the direction of lower values of M.

A corollary to Haynes and McIntyre's theorem is that the *local* enhancement of vertical vorticity by vortex-line stretching in convective updraughts totally inside C does not increase the circulation about C. It turns out that the amplification of vorticity is exactly compensated by the reduced area of the enhanced vorticity. In this case, the entire vertical vorticity dipole produced by the tilting of horizontal vorticity by the updraught is contained entirely within C so that the associated non-advective flux does not enhance the circulation around C.

In a tropical cyclone, the horizontal import of vertical vorticity into the circuit C is brought about, in part, through advection by the low-level inward branch of the mean overturning circulation produced by the convection within this circuit. However, the import of cyclonic vorticity by horizontal advection occurs in combination with the generation of cyclonic vorticity (or a destruction of anti-cyclonic vorticity) associated with the horizontal non-advective flux within the circuit. Typically, the non-advective vertical vorticity flux is associated with convection or by frictional forces. Thus, in application to tropical cyclones, it is important to distinguish between the dynamical processes at play in the frictional boundary layer and the free atmosphere above. It follows that the arguments offered in the quote from Guo and Tan in Section 1 are at best incomplete as there is no explicit mention of frictional effects or of deep convective forcing (see section 4). We examine these arguments in the next section and in the section that follows it, we indicate what elements are required to build a more complete picture of the dynamical processes involved.

3 Interpretations of fullness

We seek now to unpick the arguments provided by Guo and Tan (2017) for why their fullness metric is important, focussing on the quote reproduced in Section 1. For ease of reading, we itemize the main points in the order that they appear.

- First, we note that the radial transport of AAM depends on the product of the magnitude of the low-level radial inflow and *the radial gradient of AAM* at a certain radius of a TC, *not on the AAM itself*.
- In this context, we note further that sole consideration of the radial advection of absolute angular momentum would not apply unless axial symmetry is assumed, which is unlikely to be justifiable out to the radius of gales (R17) and then only if the effects of vertical advection are ignored also. Moreover, near the surface, where Guo and Tan obtain values for the RMW and R17 from observations, frictional torques must be considered.
- The statement that “A large AAM import ... is beneficial for the intensification and expansion of the inner- and outer-core TC wind” is simply equivalent, but less general, to saying that the vertical vorticity within any circuit C must increase, but it says nothing about the dynamics of how this increase comes about. Needless to say, the fullness metric is silent about dynamics.
- The statement that “In general, a strong low-level inflow is always accompanied by a small RMW, and a large outer-core AAM often corresponds to a large R17. For TCs with small RMW and large R17 (i.e., high fullness), the low-level radial inflow, outer-core wind, and AAM outside the RMW are large, indicating large AAM import and favoring the formation of an intense TC” is simply a kinematic statement which says nothing about the processes of intensification or, indeed, about the supposed causal role of *fullness* in the intensification process.
- The statement that “As a result, regardless of the specific RMW and R17, high fullness generally *guarantees* (our emphasis) a large AAM import and is essential for a TC to attain strong intensity and a relative broad wind field distribution” again tells us nothing about the supposed causal role of *fullness* in the intensification process.
- Accordingly, the statement “*Therefore* (our emphasis), TC intensity is strongly correlated with TC fullness, in contrast to the case for individual size parameters” is *non sequitur*. Moreover, the reader will be well aware that “correlation does not imply causality”.

While we applaud the efforts of Guo and Tan in trying to devise a more robust metric to anticipate the formation of an intense tropical cyclone, the neglect of all dynamical processes involved in storm intensification raises what we believe to be important questions about the insight provided by their fullness metric.

4 The rotating-convection paradigm: dynamical aspects

The discussion of the rotating-convection paradigm in section 2 is focussed largely on the vorticity aspects of tropical cyclone intensification in a relatively quiescent environment. However, the vertical vorticity equation is derived from the horizontal momentum equation and is just one of several equations that are required for a complete theoretical understanding of intensification. As pointed out by Smith and Montgomery (2015), it is not possible to build a robust theory of tropical cyclone evolution without incorporating the physics represented by all of the governing equations.

In a recent paper (Smith and Montgomery 2025), we pointed out that, in general, there are two fundamental requirements for vortex amplification in any flow: a source of rotation and some forcing mechanism to concentrate the rotation. We showed also that many aspects of tropical cyclone behaviour in an axisymmetric framework may be illustrated by two simple laboratory experiments, and that *an essential element of such a framework* *should be the assumption that absolute angular momentum, M, is materially conserved in the absence of frictional forces*.

In the case of a tropical cyclone, *the material conservation of M calls for radial inflow in a layer above the frictional boundary layer*, a requirement that is generalized in the non-axisymmetric case by invoking Stokes' theorem as outlined in section 2[1]. Conversely, in regions where the radial flow is outwards, the tangential flow will spin down.

The next question is: what causes the radial inflow? The answer lies in the collective effects of deep cumulus convection, which lead to a mean overturning circulation with inflow towards the convective region in the lower troposphere and outflow from the region in the upper troposphere. Nevertheless, in a vortical flow embedded in a stably stratified atmosphere without deep convection present, the frictional boundary layer leads also to an overturning circulation with radial inflow in the boundary layer, itself, and outflow in a shallow layer above it. When these effects are combined, it is clear that the inflow produced by deep convection above the boundary layer must be strong enough and persistent enough to oppose the perpetual tendency of friction to produce outflow there in order for the tangential circulation of the vortex to intensify.

Put another way, an amplification of the low-level tangential circulation above the boundary layer requires that the aggregate of deep convection be more than able to ventilate[2] the air converging in the boundary layer, itself, and carry this air to the upper troposphere. In this case, mass continuity ensures that there has to be inflow at low levels above the boundary layer. If the aggregate convection is too weak to accomplish such ventilation, the fraction of unventilated boundary layer air will flow outwards above the boundary layer and the tangential flow there will spin down.

5 Discussion and conclusion

In their paper introducing the fullness concept, Guo and Tan (2017) state that little is known about the relationship between the intensity and size of tropical cyclones because of a lack of observations. We suggest that this lack of knowledge is because size is not the single factor in determining intensity, so that, on theoretical grounds, one would not expect such a relationship to exist. The reason is, of course, that deep convective forcing is not simply related only to storm size.

Since that time, the concept of fullness has been pursued or invoked in many recent studies, which are cited in the Introduction. However, to the best of our knowledge, none of these studies appear to offer a satisfactory conceptual framework to suggest that why the fullness metric should be important, or why correlations of intensity with this metric have any causal implications.

For example, Chen and Li (2021) used aircraft reconnaissance data for tropical cyclones in the North Atlantic and Eastern Pacific during the period 1997-2015 to re-examine fullness applied to flight-level characteristics. They found a strong positive correlation between the flight-level fullness and intensity, but did not explore the causal implications of this correlation in any conceptual framework.

Hong and Wu (2023) proposed that fullness

> ... can characterize the spatial distribution of deep convection in storms and serve as a representation of the growth of TC outer region size.

claiming that

> These results have implications for understanding the mechanisms behind TC outer size growth.

However, again, they do not elaborate on the dynamics underpinning this understanding. The question remains as to how the higher coverage of deep convection affects the ventilation metric that characterizes the forcing role of deep convection?

Based on the ventilation and other considerations in the previous section, it is clear that tropical cyclone intensification *cannot depend simply on metrics associated only with the wind profile near the surface*, such as the RMW and R17, without consideration given to the forcing by the overturning associated with aggregate deep convection. Thus, *any apparent correlation between fullness and intensification, or indeed intensification rate, must be viewed with utmost caution and would seem to us to have no physical basis*.

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[1]The further generalization to a translating vortex is discussed by Persing et al. (2025).

[2]A ventilation index was first introduced by Smith et al. (2021) to help quantify the ventilation concept in idealized numerical life cycle simulations. This concept has undergone further development by Torgerson et al. (2023), Persing et al. (2025) and Vinour and Montgomery (2025) for more complex environments.

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