Tropical Cyclone Intensification and fullness: The role of size configuration

Xi Guo[1,2], Zhe-Min Tan[2]

1. Jiangsu Meteorological Observatory, Nanjing, China
2. Nanjing University, Nanjing, China

1 Abstract

The relationships between the intensification rate (IR) and the size configuration of tropical cyclones (TCs) are investigated. Theoretically, the intensity, size configuration, and relative vorticity of TCs are intrinsically linked. TC fullness (TCF) is used to quantify the size configuration of TCs and can be expressed as the product of the critical fullness (TCF_0) and the ratio of fullness (*Rf*). TCF_0 represents the fundamental constraint on size configuration shared by TCs at a given intensity and is the lower limit of fullness, whereas Rf reveals a TC's unique wind structural feature. Intermediate TCF_0 (~0.55), moderate Rf (~1.4), and thus high TCF (~0.8) collectively facilitate the occurrence of a large IR of TC. Obtaining a stable and moderate Rf at low TCF_0 favors the subsequent intensification of a TC. The TCF-TCF_0 diagram is proposed to illustrate the co-evolution of TC size configuration and intensity, and to reveal how they modulate intensification.

2 Data and definitions

2.1 Tropical cyclone data

Global TC data from 2001 to 2021 is obtained from the International Best Track Archive for Climate Stewardship (IBTrACS). Only keep fixes with Vmax greater than $17ms^{-1}$. Remove storm fixes (6-hourly estimates) whose Vmax and/or TCF are missing. Only keep intensifying TC fixes.

2.2 Definition of tropical cyclone fullness (TCF)

$$TCF = 1 - \frac{RMW}{R17}. \quad (1)$$

2.3 Intensification rate

IR(t) = Vmax(t+12hr)-Vmax(t).
Moderate intensification (MI): 0<IR<10ms-1, account for 80%;
Rapid intensification (RI): 10≤IR<15ms-1, account for 14%;
Extremely rapid intensification (ERI): IR≥15ms-1, top 6% fixes;

3 Inherent connection between intensity and fullness

For simplification, take a two-dimensional integrated view to discuss the physical implication of fullness. The vertical component of relative vorticity in an axisymmetric storm is given as follows:

$$\boldsymbol{\zeta = \frac{\partial rv}{r\partial r} = \zeta_r} \quad (1)$$

where r is the radius; v is the tangential wind speed at **r**, and **ζr** is the relative vorticity at r. Integrating from RMW to R17 yields:

$$\boldsymbol{\gamma_i = \gamma_s + \frac{1}{2}\gamma_\zeta\left(\frac{1}{\gamma_s} - \gamma_s\right)} \quad (2)$$

where $\gamma_s = \frac{RMW}{R17}$, $\gamma_\zeta = \frac{\zeta_{r0}}{\zeta_{max}}$, $\gamma_i = \frac{V17}{Vmax}$. Equation (2) reveals a physical connection among the intensity, size, and relative vorticity of a TC. With (2) and (3), fullness can be expressed as

$$\boldsymbol{TCF = Rf\ TCF_0} \quad (3)$$

where $TCF_0 = 1 - \frac{V17}{Vmax} = TCF|_{\gamma_\zeta=0}$, is referred to as critical fullness, and *Rf* is an integrated structural parameter, which is referred to as ratio of fullness. TCF_0 is the intensity-related part of the fullness, and it has a one-to-one relationship with the storm intensity. It is noted, the TCF_0 describes the critical feature of size configuration shared by TCs at a given intensity, which falls still within the scope of fullness. On the other hand, *Rf* could vary dramatically among TCs with a similar storm intensity.

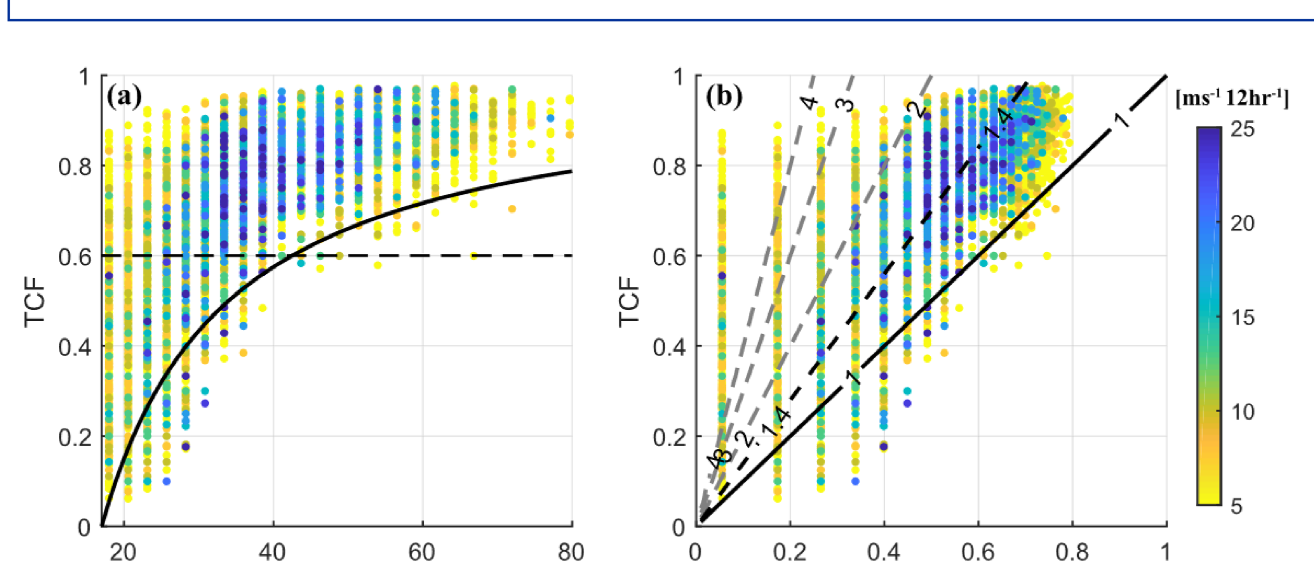

Figure 1 The distribution of TC fullness (TCF) against (a) intensity and (b) critical fullness (TCF_0), with the intensification rate shown by shading. The solid line in (a) show the TCF_0 under the given storm intensity; the contour in (b) provides the ratio of fullness, *Rf*.

4 TC Intensification Rate and Size Configuration

The majority of TCs (about 95%, Fig. 1) possess TCF greater than their TCF_0 (i.e., TCF>TCF_0 or *Rf*>1). On the contrary, a TC with fullness less than TCF_0 (i.e., TCF<TCF_0 or *Rf*<1) would have negative relative vorticity (ζ_{r0}<0) in the outer-core region, which may lead to an inertially unstable TC wind structure and can hardly support the intensification or even the maintain of TC. To this end, it is expected that TCF_0 (or *Rf* = 1) describes the basic size configuration for storm intensification, which can be approximately treated as the lower bound of the fullness given the intensity.

The modulation of size configuration on TC IR is explored through TC fullness, which could be explained collectively by the critical fullness, TCF_0, and the ratio of fullness, Rf. It is evident that the TCF_0, the *Rf* and then the fullness, can be collectively used to identify the favorable wind structure for storm intensification. In particular, the wind structure with TCF_0 of around 0.55, moderate *Rf* around 1.4, and thus fullness of about 0.8 (Figs. 1, 2) may be the most favorable for storm intensification. It is also noted, although more research is needed to interpret the detailed mechanisms, size configuration associated with a moderate ratio of fullness might be efficient in facilitating TC intensification.

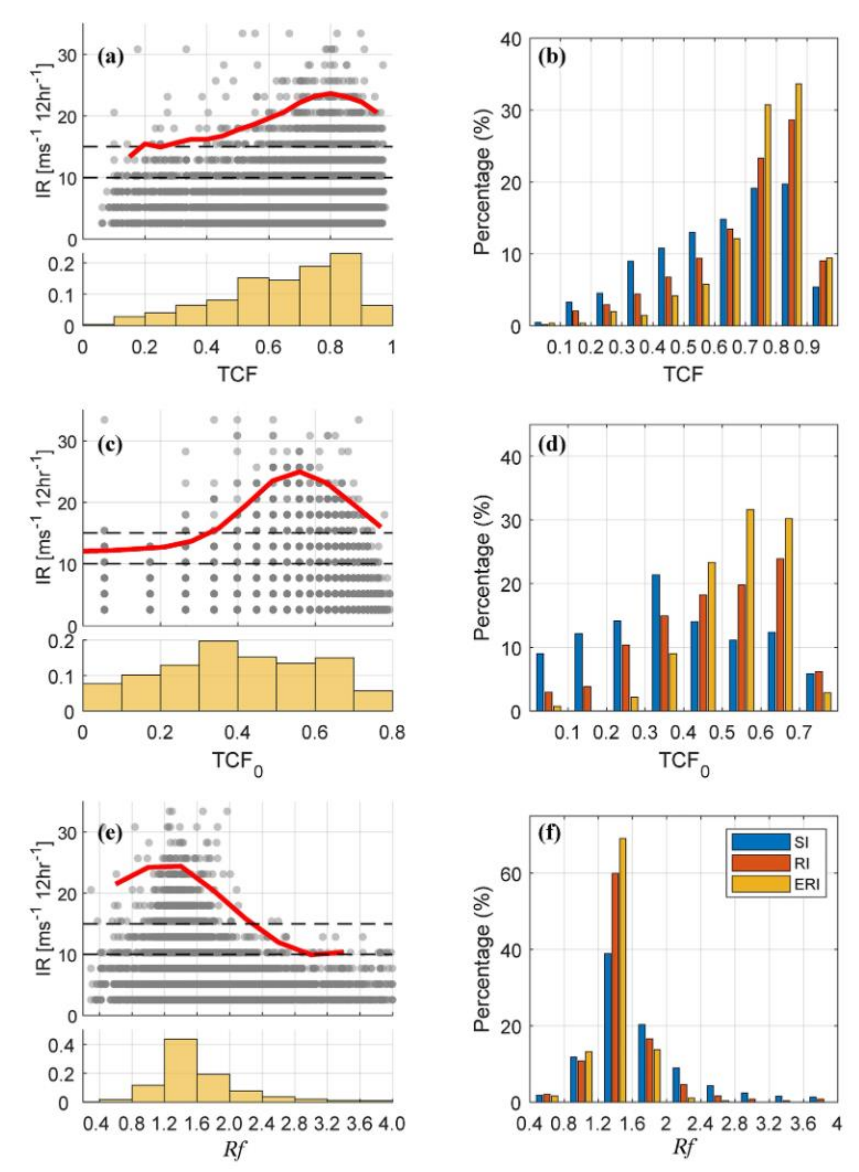

Figure 2 The scatter diagrams of the subsequent 12-hourly intensification rate (IR) against the (a) TC fullness (TCF), (c) critical fullness (TCF_0), and (e) ratio of fullness (*Rf*). The histogram at the bottom shows the probability distribution. The red curve provides the smoothed 99th percentiles of IR. The frequency distribution of the (b) TC fullness (TCF), (d) critical fullness (TCF_0), and (f) ratio of fullness (*Rf*) in the corresponding interval for TC events with slow (SI) rapid (RI) and extremely rapid (ERI) intensification rate.

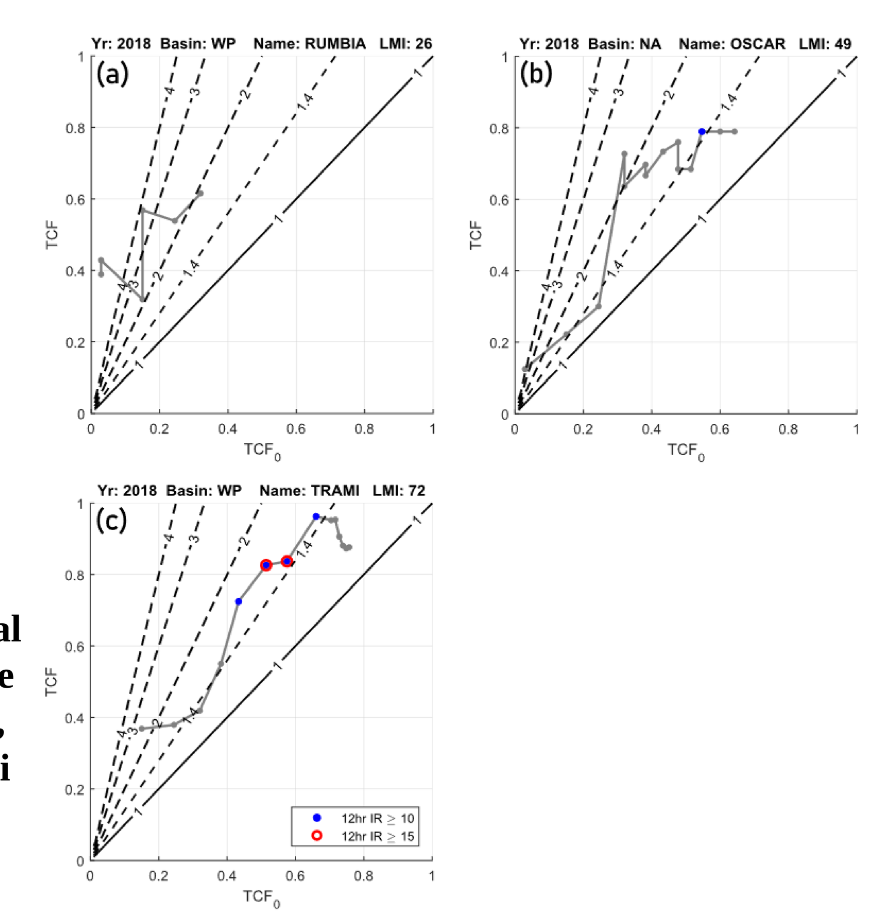

Figure 3 The evolution of TC fullness (TCF), critical fullness (TCF0) and ratio of fullness (Rf) during the intensification stage of (a) Typhoon Rumbia (2018), (b) Hurricane Oscar (2018), and (c) Typhoon Trami (2018). The gray lines show the evolution of Rf with time (6 hr interval). The contour provides the values of *Rf*, with *Rf* = 1 shown by bold lines.

5 Fullness-Intensity Co-evolution of Intensifying TCs

A TCF-TCF_0 diagram (T-T diagram) can be constructed to illustrate how TCF-related factors evolve in the intensification stage (the period before a TC reaches lifetime maximum intensity). The T-T diagram shows the covariation of TCF, TCF_0, and *Rf*, which reflects the collective evolution of TC intensity and size configuration. Comparing Typhoon Rumbia (2018), Trami (2018) and Hurricane Oscar (2018), it is found that the evolution of TCF_0 and Rf may affect the subsequent IR of TCs, and achieving a stable and moderate *Rf* at early stage when TCF_0 is low seems to favor the subsequent intensification.

6 Main conclusion

- The tropical cyclone (TC) intensity is inherently connected to its wind structure, relatively high TC fullness benefits TC intensification;
- Critical fullness measures the intensity-related part of TC fullness and reveals the basic size configuration given the intensity;
- The occurrence of a large intensification rate is often accompanied by a moderate ratio of fullness.