本文主要就是介绍了一个新的概念fullness, 它能够较好的反应气旋强度, 并且通过将使用的气旋进行分组, major 和 no major , 再将每组分为 rapid 和 slow ,进行了进一步的验证. fullness能够较好的反应intensity

最后作者还考虑了在warmer climate 的背景下的情况.

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Geophysical Research Letters

RESEARCH LETTER

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Tropical cyclone fullness: A new concept for interpreting storm intensity

在阅读的时候, 进行验证的部分(快速/慢速) 没有仔细看.

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Key Points:
- A large TC may not be intense, and a small TC is not necessarily weak
- TC fullness is strongly correlated with TC intensity, and a higher TC fullness is necessary for intense TC to occur
- Rapidly increasing fullness favors TC intensification at early stages

Supporting Information:
- Supporting Information S1

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Abstract Intensity and size are two crucial factors in determining the destructiveness of a tropical cyclone (TC), but little is known about the relationship between them because of a lack of observations. TC fullness, a new concept, is proposed to quantitatively measure the storm wind structure, which is defined as the ratio of the extent of the outer-core wind skirt to the outer-core size of the TC. TC intensity is more strongly correlated with fullness than with other measures comprising just a single size parameter. A scale is introduced to classify TCs into four categories based on TC fullness (FS1 to FS4). Regardless of the specific inner-core and outer-core size, the FS4 fullness structure is necessary for an intense TC's development, while category FS1 and FS2 TCs are generally weak. Most major TCs achieve FS4 fullness structure earlier and more frequently than nonmajor TCs. Rapidly increasing fullness favors the intensification of TC.

Plain Language Summary Tropical cyclone (TC) disasters caused tremendous property loss and casualties all over the world every year, while the knowledge on what essentially determines TC intensity is far beyond enough. Should a large TC ought to be intense and disastrous? And is a small TC doomed to be weak? It confused us when some dapper small TCs struck us with their fierce wind and torrential rain, while other large TCs that finally turned out to be a false alarm tricked us with their puffiness body. The underlying factor that truly controls TC intensity has been grasped here. We unveil the mysteries between TC intensity and size by raising a new concept: TC fullness. Either small or large TC can be intense, it depends on the fullness. TCs should possess FS4 fullness structure (high fullness) as long as they are intense; on the other hand, TCs with low fullness are weak in majority. In addition, rapidly increasing fullness is beneficial for the intensification of TC. The concept of TC fullness may provide a new path in the exploration of TC intensity and intensity change and may also be helpful for the forecast of TC intensity even its future change.

1. Introduction

Concern about how climate change will affect tropical cyclone (TC) activity and threats has gained attention worldwide [*Emanuel*, 2005; *Knutson et al.*, 2010; *Mendelsohn et al.*, 2012; *Lin and Emanuel*, 2015]. TC intensity, which is a measure of the near-center peak wind speed, has long been assumed to be the dominant factor in determining TC destructiveness (measured as the potential dissipation index and accumulated cyclone energy) [*Camargo and Sobel*, 2005; *Emanuel*, 2005]. Observations have shown an upward trend in TC intensity and occurrence frequency of intense TCs in recent decades. Thus, the destructiveness of TCs is projected to increase [*Knutson and Tuleya*, 2004; *Emanuel*, 2005; *Elsner et al.*, 2008; *Bender et al.*, 2010; *Knutson et al.*, 2010; *Mendelsohn et al.*, 2012; *Mei and Xie*, 2016]. However, for a given intensity, TC size can vary significantly. Model simulations have revealed that TC effects (e.g., rainfall and storm surge level) increase in tandem with increasing TC size [*Lin et al.*, 2012, 2015]. An important question to consider is this: in a warming climate, how will TC size change in response to increasing intensity? The answer may be of critical importance for projecting TC-related risks in the future.

台风的两个重要参数:
1. 最大风半径RMW (核心区的风)
2. 大风半径R17 (外围风)

TC size can refer to several different measurements of the TC wind field. The radius of maximum wind (RMW) and the radius of gale-force wind (R17) are widely used size parameters; the former describes the radius of the near-center extreme wind (inner-core region), and the latter describes the extent of TC outer circulation (outer-core region). In general, TCs are considered to be intense when they have a small inner-core and/or large outer-core size and weak when they have a large inner-core and/or small outer-core size [*Wu et al.*, 2015; *Knaff et al.*, 2016]. Moreover, there is an upper bound of TC size in radiative convective equilibrium, which increases with increasing TC potential intensity [*Emanuel*, 1986; *Emanuel and Rotunno*, 2011; *Chavas and Emanuel*, 2014; *Chavas et al.*, 2015]. However, in reality, TC intensity and size are not closely related to a single size parameter, such as RMW or R17 (Figure S1 in the supporting information).

强台风: 小的内核 or/and 大的外围尺度
若提风: 大的内核 or/and 小的外围尺度

能量来源:
1. 角动量辐合
2. 非绝热加热

The energy input from the underlying ocean [*Wang and Xu*, 2010; *Xu and Wang*, 2010], the angular momentum convergence from the outer region [*Chan and Chan*, 2013, 2015], and the distribution of diabatic heating [*Smith et al.*, 2015; *Kilroy et al.*, 2016] are significant contributors to the maintenance and intensification of a TC. Model simulations suggest that an entropy flux of up to 2–2.5 RMW is crucial for TCs to balance the high dissipation near the inner-core region and is essential for intensification [*Wang and Xu*, 2010]. Moreover, the angular momentum outside R17 can be transported inward, strengthening the wind field and leading to an increase in size of the inner and outer cores and hence intensification of the TC [*Chan and Chan*, 2015]. All these processes are closely related to the size of the inner and outer cores of the TC. Therefore, the integrated effect of TC inner- and outer-core size on intensity may be a key factor in understanding the relationship between intensity and size.

The purpose of this study is to explore the relationship between TC size and both intensity and intensity change. Section 2 describes the data used in this study. A new concept (TC fullness) is proposed in section 3. The relationship between fullness and intensity is examined in section 4. Section 5 investigates the characteristics of the evolution of TC fullness and intensity during the intensification stage. Finally, the main findings are summarized and discussed in section 6.

2. Data

数据介绍:
1. 数据类型: EBT
2. 时间: 1988-2015
3. 地点 : Atlantic
4. 时间间隔: 6 h

The extended best-track (EBT) data set [*Demuth et al.*, 2006] was used to obtain the TC wind field parameters (i.e., V_{max}, RMW, and R17) of Atlantic TCs during 1988–2015. The EBT data set is a supplement to the second-generation Atlantic hurricane database for Atlantic TCs since 1988. It contains 6-hourly TC locations (latitude and longitude); maximum 1 min mean sustained surface wind (V_{max}); radius of the maximum wind; and the 17, 25.7, and 33 ms^{-1} wind radii in four quadrants for each TC.

经过一些条件筛选后的数据:
5428 Vmax sample
4830 RMW sample
4839 R 17 sample

Strict data selection was conducted to minimize noise and uncertainty and thereby ensure high-quality wind field data. The criteria were as follows: (1) remove records that are centered within 50 km of land; (2) for each time record, if the 17 ms^{-1} wind radius (R17) is unavailable for more than two quadrants, then the R17 of this record is considered missing (otherwise, R17 is recorded as the average 17 ms^{-1} wind radius of each quadrant); (3) for each TC, retain the records between the first time V_{max} reached 20 ms^{-1} and the last time V_{max} exceeded 20 ms^{-1}; (4) remove TCs whose total number of valid records (RMW and R17) is less than four during the intensification stage; and (5) remove TCs whose valid records account for less than 50% of the total during the intensification stage. Based on the criteria above, a total of 5428 V_{max} samples, 4830 RMW samples, and 4839 R17 samples from 194 TCs were available for analysis.

3. Concept of TC Fullness

In general, the ring region between the RMW and R17, which includes strong wind, vigorous convection, and rainbands, is a key region affecting the evolution of TC intensity and structure. Here the difference between the outer- and inner-core sizes is defined as the extent of the outer-core wind skirt (i.e., DR = R17 − RMW). Based on DR, TC fullness (hereafter, TCF), a new concept, is defined as follows:

$$\mathrm{TCF} = \frac{\mathrm{DR}}{\mathrm{R17}} = 1 - \frac{\mathrm{RMW}}{\mathrm{R17}}, \qquad (1)$$

Clearly, the fullness can vary among TCs and between different periods during the evolution of a given TC (Figure S1 and Text S1 in the supporting information). Unlike a single size parameter, TC fullness is an integrated characteristic of TC wind structure. The fullness increases as the outer-core size increases and/or the inner-core size decreases. There is an upper limit to fullness: it approaches 1.0 when R17 is much larger than RMW.

Based on the fullness of all TC samples, a fullness scale is introduced to separate TCs into four categories, FS1 through FS4, as follows: FS1 ($\mathrm{TCF} \le 0.4$), FS2 ($0.4 < \mathrm{TCF} \le 0.6$), FS3 ($0.6 < \mathrm{TCF} \le 0.8$), and FS4 ($\mathrm{TCF} > 0.8$). Here the wind structure with fullness of category FS4 is regarded as the "FS4 fullness structure," which means that the TC achieves a high fullness larger than 0.8 (FS4 fullness).

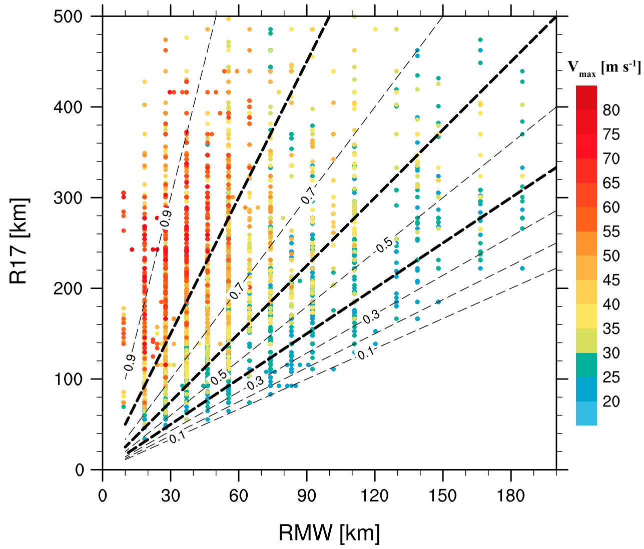

Figure 1. Dependence of TC intensity V_{max} (color dots) on the corresponding TC size parameters, i.e., the radius of maximum wind (RMW) and the radius of gale-force wind (R17) in different fullness regions (dashed lines). The fullness scale is divided into four categories: FS1 (TCF ≤ 0.4), FS2 (0.4 < TCF ≤ 0.6), FS3 (0.6 < TCF ≤ 0.8), and FS4 (TCF > 0.8). The bold dashed lines denote fullness values of 0.4, 0.6, and 0.8.

4. Relationship Between TC Fullness and Intensity and Size

Figure 1 shows the dependence of TC intensity (V_{max}) on TC size parameters (i.e., RMW and R17) for different fullness-scale regions. In general, a TC is intense ($V_{max} > 50$ ms^{-1}) when its RMW is less than 60 km and its R17 is between 150 and 350 km. However, the relationships between intensity and size parameters are weak: the correlation coefficient between V_{max} and RMW is −0.38 and that between V_{max} and R17 is 0.29 (all the correlation coefficients mentioned in this study have confidence levels exceeding 99%), consistent with the results of previous studies [*Merrill*, 1984; *Kimball and Mulekar*, 2004; *Chavas and Emanuel*, 2010]. This indicates that a small inner-core size or large outer-core size does not always imply an intense TC. Instead, a TC can be intense with a large inner-core size or small outer-core size. However, as shown in Figure 1, TC intensity is significantly correlated with TC fullness. The Pearson's correlation coefficient is about 0.64, and the Spearman's correlation coefficient is 0.71, far exceeding the correlations obtained for individual parameters related to TC size (i.e., RMW and R17).

这是基础知识问题吗?相关性的确是增加了,但是为什么为啥能想到和绝对角动量有关呢?

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 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.

Figure 2 presents a scatter diagram relating TC fullness to intensity V_{max}. It should be noted that the intensity scale (TS, CAT1 to CAT5) [*Saffir*, 1973; *Simpson*, 1974] and the fullness scale (FS1 to FS4) in this study are related to stages during the evolution of a TC, not its lifetime characteristics. As shown in Figure 2, the intensities of FS1 and FS2 TCs are always below CAT1; those of category FS3 TCs are generally within TS to CAT2, with a few extending to CAT3 and CAT4, while for FS4 TCs their intensities range from TS to CAT5. This reveals that as fullness increases, TCs are more likely to achieve a greater intensity. Moreover, the majority of intense TCs possess a FS4 fullness structure, especially for CAT4 and CAT5 TCs (Figures 2 and S2), indicating that only high fullness can promote extremely intense TCs. Thus, the FS4 fullness structure is necessary for catastrophic TCs to occur.

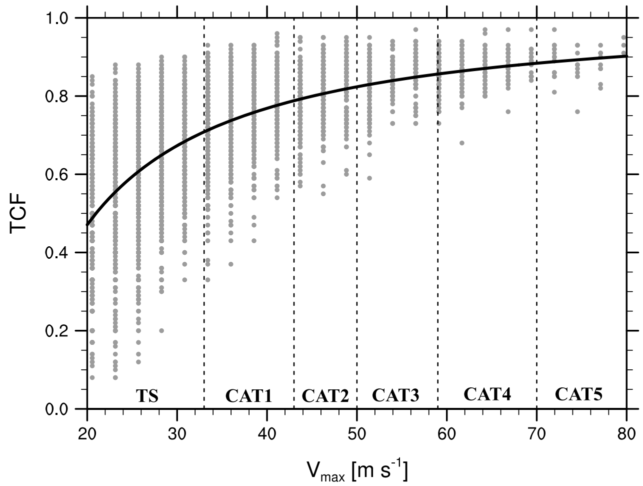

Figure 2. Scatter diagram of TC fullness (TCF) versus intensity V_{max}. The solid line shows the fitting curve for the relationship between fullness and intensity; the root-mean-square error is 0.12. The vertical dashed lines show the tropical cyclone intensity ranges for tropical storms and categories 1 to 5 according to the Saffir-Simpson hurricane scale.

右边的公式是咋想出来的啊?
自己拟合的???

The relationship between TC fullness and intensity can be fitted with a power function as follows:

$$\mathrm{TFC} = 1.0 - 0.65\left(\frac{V_{max}}{V_{17}}\right)^{-1.16}, \quad (2)$$

where V_{max} is the maximum sustained near-surface wind in ms^{-1} and V17 is the wind speed at R17 (V17 = 17 ms^{-1}). In this study, V_{max} is always larger than V17.

The best fit curve of TC fullness in Figure 2 shows that TC fullness generally increases with increasing intensity V_{max}. The relationship between fullness and intensity can be divided into two distinct regions. Fullness increases rapidly as intensity increases when V_{max} <50 ms^{-1} and more slowly when V_{max} >50 ms^{-1}. When TCs develop gradually into FS4 fullness structures, the wind structure tends to be stable and the fullness slowly approaches a larger saturated value.

5. Evolution of Fullness and Intensity

The relationship between fullness and intensity, as well as the interactions between these factors, during the intensification stage of a TC (the period before and during the first time a TC reaches its lifetime maximum intensity, LMI) is investigated with regard to TC evolution.

As discussed above, TCs require a higher fullness to achieve greater intensity. All of the major TCs (LMI of CAT3 and higher) studied are intense at the end of the intensification stage, while none of the nonmajor TCs (LMI of CAT2 and below) attain intensities greater than 50 ms^{-1} throughout their lifetimes. It can thus be speculated that the evolution of wind structure differs between nonmajor and major TCs. As a result, we first separate TCs into nonmajor and major TC groups and investigate them separately. The FS4 fullness structure probability (defined as the percentage of TCs that attain FS4 fullness at least once during their intensification stage, relative to all TCs in the corresponding group) of a major TC is as high as 83.8% (Table 1), consistent with the finding that the FS4 fullness structure is important for the occurrence of intense TCs. Moreover, among TCs that reach FS4 fullness during intensification, the average FS4 fullness structure occurrence ratio (the percentage of records with FS4 fullness structure, relative to the total records in the intensification stage) for major TCs is 40.2%, which is much higher than that of nonmajor TCs, indicating that once reaching FS4 fullness, major TCs tend to attain a FS4 fullness structure more frequently. Furthermore, it

Table 1. Fullness Characteristics of TCs That Achieve an FS4 Fullness Structure During Intensification in Each TC Group[a]

	Nonmajor TC (120)	Major TC (74)
FS4 fullness structure probability	25.8%	83.8%
FS4 fullness structure timing (hour)	65	55
FS4 fullness structure occurrence ratio	24.7%	40.2%

[a]The number of TCs in the corresponding intensity group is given in parentheses next to the group name. FS4 fullness structure probability is the percentage of TCs that attain FS4 fullness at least once during their intensification stage, relative to all the TCs in the corresponding group. FS4 fullness structure timing is the time when the TC first reaches FS4 fullness. The FS4 fullness structure occurrence ratio is the percentage of records with an FS4 fullness, relative to the total records in the intensification stage.

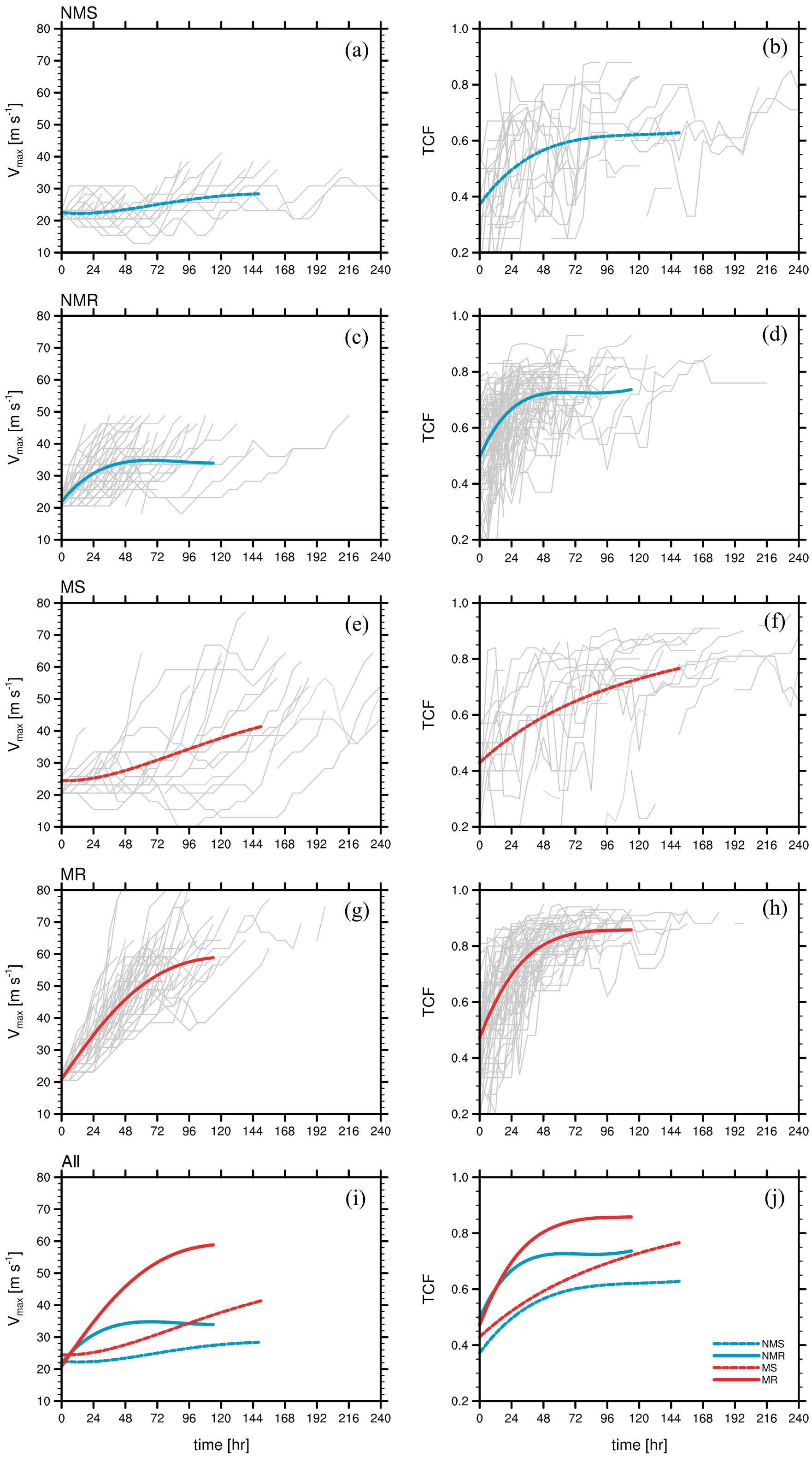

Figure 3. Evolution of (left column) TC intensity V_{max} and (right column) TC fullness TCF with time for each class during the intensification stage. (a and b) NMS; (c and d) NMR; (e and f) MS; (g and h) MR. Regression curves of (i) intensity and (j) fullness for each class indicate the critical features of TC evolution of in the corresponding class. The gray lines show the evolution of individual TCs. The regressed evolution curves of nonmajor and major groups are plotted with blue and red lines, respectively. The regressed evolution curves of "slow" and "rapid" classes are plotted with dashed and solid lines, respectively.

takes an average of 55 h for major TCs and 65 h for nonmajor TCs to achieve an FS4 fullness, indicating that the fullness of major TCs increases faster than those of nonmajor TCs. In addition, we find that among major TCs, 64% can reach FS4 fullness for the first time when they are at the TS, CAT1, and CAT2 stages, after which they continue to intensify while their fullness tends to saturate. This also explains the occurrence of FS4 fullness in TS, CAT1, and CAT2 TCs (Figures 2 and S2).

Although TCs in the same group share some similar characteristics in fullness and intensity, the detailed interactions between intensity and fullness during intensification remain unknown. To this end, based on the evolution of both fullness and intensity, a clustering analysis technique [*Gaffney et al.*, 2007; *Camargo et al.*, 2007; *Daloz et al.*, 2015; *Jang and Chun*, 2015] was used to categorize TCs of nonmajor and major groups separately (Text S2). Finally, nonmajor TCs are categorized into nonmajor slow (NMS) and nonmajor rapid (NMR) classes, which account for 25% and 75% of nonmajor TCs, respectively. Major TCs are categorized into major slow (MS) and major rapid (MR) classes, accounting for 22% and 78% of major TCs, respectively.

As shown in Figure 3, for nonmajor and major TCs there exist classes (NMR and MR) with more rapidly increasing fullness and intensity during the early stage and higher fullness and greater intensity at the end than their counterparts (NMS and MS). Therefore, we regard classes NMR and MR as "rapid" classes and NMS and MS as "slow" classes.

For TCs in MR (Figures 3g and 3h), most develop quickly into FS4 fullness structure, with their intensity increasing rapidly as fullness increases. After achieving FS4 fullness structure at ~50 h, the fullness of MR TCs increases gradually toward saturation and their intensities continue to increase. Such kind of fullness evolution favors the occurrence of intense TCs; therefore, the MR is the most intense and contains the majority of CAT5 TCs (not shown). In contrast, TC fullness in the MS (Figures 3e and 3f) grows slowly during the early stage, and intensity gradually increases until FS4 fullness is reached, after which the intensity starts to increase rapidly and the TC finally becomes intense. This suggests that achieving FS4 fullness structure at an early stage and attaining it repeatedly favors the formation of intense TCs. For nonmajor TCs, those in the NMR (Figures 3c and 3d) possess higher growth rates for fullness and intensity at the beginning and achieve higher fullness and greater intensity at the end than TCs in the NMS (Figures 3a and 3b). However, the majority of TCs in the NMS and NMR never achieve the FS4 fullness structure in their lifetimes (not shown), and their intensities are weak at the end.

To summarize, rapidly increasing fullness at early stages favors the intensification of TCs. In addition, the repeated occurrence of a high fullness is crucial for developing intense TCs. Achieving FS4 fullness structure at an early stage and possessing it frequently thereafter is favorable for the formation of the most intense TCs.

6. Discussion and Summary

The intensity and size of a TC play a significant role in determining the potential destructiveness of the storm. However, the relationship between these two aspects of the TC wind field is poorly understood. The weak correlation between intensity and size indicates that an intense TC does not always have a small RMW and/or large R17 and a weak TC does not always have a large RMW and/or small R17. Such inherent uncertainties must be reduced for accurate predictions of TC activity. In this study, the concept of TC fullness is introduced, which comprehensively considers the overall characteristics of the TC wind field and overcomes the limitation of a single size parameter when investigating the relationship between TC intensity and wind field structure. A strong positive correlation exists between intensity and fullness: TCs with greater intensity always demonstrate higher fullness, regardless of their inner- and outer-core sizes. Moreover, an FS4 fullness structure (the TC fullness is larger than 0.8) is necessary for the development of an intense TC, especially for CAT4 and CAT5 catastrophic TCs, while category FS1 and FS2 TCs are usually weak.

全文看到的是fullness和intensity的关系 和尺度有啥关系?

Changes in TC intensity are closely tied to storm structure, which can be affected by a variety of internal and external processes. Fullness provides a new path to understand the relationship between the intensity or intensity change and the size of a TC. Compared with changes in RMW or R17, increases in TC fullness are more closely related to increases in intensity. Rapidly increasing fullness favors the intensification of a TC, especially during the early stages. Moreover, achieving the FS4 fullness structure early and often is favorable for the formation of an intense TC. This is evident in the case of major TCs, as they usually have a large FS4 fullness structure probability and high occurrence ratio of FS4 fullness structure.

Of course, in addition to internal dynamics, TC intensity also depends on environmental conditions such as maximum potential intensity. The detailed impact of TC fullness on intensity in different external environments is still unclear. In addition, it should be noted that although our present study was conducted mainly over the Atlantic basin, the relationships between fullness and intensity over other basins were briefly examined, also showing strong positive correlations and can be fitted by power functions (not shown).

Although much remains unknown about how TC activity, especially with respect to frequency and size, will vary in a changing climate, TC intensity is projected to increase under conditions of global warming. In theory, the overall size of a TC (defined as the storm's outer radius of vanishing wind) expands linearly with increasing maximum potential intensity [*Emanuel and Rotunno*, 2011; *Lin et al.*, 2012; *Chavas and Emanuel*, 2014; *Chavas et al.*, 2015], which implies that a warmer climate may induce a broadening of the overall size of TCs. Given the findings of this study, for intense TCs the variation of fullness with intensity is small (Figure 2); therefore, the outer radius expansion may induce an increase in the inner-core size in a warmer climate. In such cases, the damage caused by the near inner-core extreme wind and that brought about by the outer-core wind will be enhanced, leading to even tougher challenges in disaster management.

The relationship between TC intensity and wind structure described here may help achieve the challenging task of projecting changes in wind structure, as well as possible changes in TC destructiveness in a warmer climate. As a concept focused on TC wind structure, fullness could be considered in a statistical intensity forecasting model to help understand the characteristics of TC wind structure, thereby offering a new approach to investigations of TC destructiveness under climate change.

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