

On the definition and tracking of tropical cyclone seeds from a climate perspective

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On the Definition and Tracking of Tropical Cyclone Seeds from a Climate Perspective

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1. Introduction

Future projections of tropical cyclone (TC) frequency in a changing climate remain uncertain despite substantial advances in climate models (e.g., Knutson et al. 2020). While most climate models project a decrease in global TC frequency through the twenty-first century, several models project an increase in global TC frequency or no significant change (Bhatia et al. 2018; Vecchi et al. 2019). Furthermore, the sign of TC frequency changes in some statistical–dynamical downscaling projections depends on the design of the statistical model, particularly on the choice of humidity variables and the formulation of humidity within the statistical framework (e.g., Lee et al. 2018, 2020), although other models do not show such sensitivity (e.g., Emanuel et al. 2008; Emanuel 2013). As part of a framework to understand the controls of TC frequency in present and future climates, the concept of “TC seeds” has received increasing attention in recent years in the climate community (Vecchi et al. 2019; Hsieh et al. 2020, 2022; Emanuel 2022). TC seeds is a broadly used term to describe the disturbances that precede tropical cyclogenesis. However, the lack of a standardized physics-based definition of TC seeds hinders research into understanding whether TC frequency is mainly controlled by large-scale environmental conditions alone or by both large-scale environmental conditions and the statistics of TC seeds (e.g., Sobel et al. 2021; Emanuel 2022). In this short note, we propose a physics-based definition of TC seeds to inform the development of TC seed tracking methodologies and facilitate research on TC frequency.

2. Physics-based definition

In the present climate, one of the necessary conditions for TC genesis is a preexisting lower-tropospheric cyclonic disturbance (e.g., Gray 1968), and TC formation may be considered a problem of finite-amplitude instability (Emanuel 1989). In the weather community, such disturbances are often referred to as “precursors,” with the understanding that a precursor may

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or may not develop into a TC.¹ Although the specific origin of the term “seed” in the context of TCs is unclear,² its usage was popularized by Emanuel et al. (2008), who introduced a downscaling technique whereby “random seeds are planted everywhere and at all times.” Ironically, this framework is predicated on the hypothesis that seeds themselves are unimportant for modulating TC frequency, with the development (or lack thereof) of TCs being determined by large-scale environmental conditions. More recently, the term has been increasingly used in reference to dynamical or convective precursors in global climate models (GCMs) (Vecchi et al. 2019; Hsieh et al. 2022). Here, we focus on the term seeds and the applicability of the concept to climate science, with the understanding that a TC seed is equivalent to a preexisting disturbance that may or may not develop into a TC.

Generally, there are two conceptual models for the development of a real-world TC from a preexisting disturbance:

- (i) a synoptic-scale cyclonic disturbance → a convectively active synoptic-scale cyclonic disturbance → a TC;
- (ii) a cloud cluster or mesoscale convective system → a strongly rotating, organized cloud cluster → a TC.

A typical example of the first type is TCs originating from tropical easterly waves. These waves may originate in North Africa (i.e., African easterly waves; Burpee 1972; Thorncroft et al. 2008; Rajasree et al. 2023) or Central America (Torres et al. 2021), or they may result from

¹ In operational forecasting, other distinct (but related) terms are often used. For example, the U.S. NOAA National Hurricane Center (NHC) uses “invest” to refer to a weather system “for which a tropical cyclone forecast center (NHC, CPHC, or JTWC) is interested in collecting specialized data sets (e.g., microwave imagery) and/or running model guidance,” but “the designation of a system as an invest does not correspond to any particular likelihood of development of the system into a tropical cyclone” (<https://www.nhc.noaa.gov/aboutgloss.shtml>).

² The earliest known study is Lander (1994), who referred to “seed disturbances” in the context of TCs that developed within a monsoon gyre (see footnote 3).

the intertropical convergence zone (ITCZ) breakdown (e.g., Guinn and Schubert 1993; Wang and Magnusdottir 2005). A tropical easterly wave may persist for more than a week and propagate from the eastern North Atlantic to the eastern North Pacific, spawning a TC in these basins (Thorncroft and Hodges 2001; Dunkerton et al. 2009). In addition, these waves are also present over the western North Pacific and can lead to TC formation there (McBride 1981; Ritchie and Holland 1999; Feng et al. 2023). Other types of synoptic-scale precursors include tropical depression disturbances (Lau and Lau 1990; Takayabu and Nitta 1993) and monsoon depressions. The former are often observed in the western North Pacific, and the latter are common in the western North Pacific (e.g., Ritchie and Holland 1999; Briegel and Frank 1997), the north Indian Ocean (e.g., Cohen and Boos 2016), and the Australian region (McBride and Keenan 1982).

Many previous studies have distinguished between developing and nondeveloping tropical easterly waves (e.g., McBride and Zehr 1981; Hopsch et al. 2010). It is generally accepted that tropical cyclogenesis becomes possible only after an easterly wave becomes convectively active (Wang 2018; Núñez Ocasio et al. 2020, 2021). For example, African easterly waves, generated mainly at the African easterly jet level (~ 700 hPa), are more cyclogenetic after extending downward and developing a vertically aligned structure associated with convection (e.g., Raymond and López Carrillo 2011; Wang et al. 2012).

The second type of TC genesis has been observed over the western North Pacific, associated with mesoscale convective systems embedded in a monsoon gyre³ or a convergence zone (Lander 1994; Ritchie and Holland 1999). One theory suggests that the development of midtropospheric cyclonic vortices within mesoscale convective systems can lead to a local reduction of the Rossby radius of deformation, the intensification and downward extension of a cyclonic circulation, and the initiation of the surface–heat flux feedback, leading to the development of a TC (Simpson et al. 1997; Harr et al. 1996).

³ Unlike a monsoon depression, a monsoon gyre is a large-scale, nearly circular low-level cyclonic circulation with an outermost closed isobar diameter of approximately 2500 km, occurring roughly once per year over the western North Pacific (Lander 1994; see also the AMS Glossary).

Both conceptual models emphasize two essential aspects of preexisting disturbances: rotation and organization of convection. Based on these conceptual models, we propose a generalized definition of TC seed as

a lower-tropospheric cyclonic moist disturbance that may or may not develop into a tropical cyclone.

This definition emphasizes the presence of a lower-tropospheric cyclonic circulation but does not preclude disturbances originating from the mid- or upper troposphere (i.e., tropical transition; Davis and Bosart 2004). The moist nature of a disturbance indicates its potential to become convectively active, promoting further growth. In addition, a TC seed may or may not develop into a TC, depending on large-scale environmental conditions and, possibly, the intensity and structure of the TC seed itself.

It is worth mentioning that we intentionally avoid including specific vorticity or humidity thresholds in the TC seed definition. Previous studies suggest that a humidity threshold likely exists as an indicator for the impending tropical cyclogenesis (e.g., Nolan 2007; Wang 2012) and that a low-level vorticity or wind threshold probably exists for a TC-*proto* vortex to become a self-sustaining entity (Emanuel 1986). However, the development of such “mature” seeds already involves a significant contribution from the large-scale environmental conditions, and the boundary between these seeds and tropical depressions becomes rather blurred. One can naturally expect a strong relationship between TC frequency and the frequency of such mature seeds. Therefore, it is more interesting and physically insightful to focus on

disturbances in the early stage of potential TC formation. In the very early stage of TC formation, thresholds for humidity and vorticity may not be physically meaningful, as implied by idealized numerical simulations of spontaneous tropical cyclogenesis. In these simulations, TCs can develop from random convection if large-scale conditions remain favorable for a sufficiently long period, and a distinct regime shift does not occur until shortly before genesis (e.g., Nolan et al. 2007).

3. Considerations for TC seed identification and tracking

Next, we discuss the key factors for TC seed identification and tracking. While satellite data (imagery) may be used to identify and track a convective system, our focus here is on tracking in gridded (re)analysis data or dynamical model output, with the emphasis placed on providing recommendations to the modeling community. Furthermore, rather than prescribing specific tracking criteria, we outline the key factors (or ingredients) to consider when developing a tracker. This outline will enable flexibility in tracking based on data properties and availability, while improving consistency between tracking algorithms and fostering consensus among studies.

To assess the two aspects of a TC seed emphasized in our definition, two categories of subdaily variables would be required: one representing lower-tropospheric rotation and one representing convection or convective potential. In TC seed tracking, while lower-tropospheric (e.g., 850 hPa) vorticity is often used for the former category, other related variables have been used as well, such as sea level pressure, lower-tropospheric geopotential height, or streamfunction (e.g., Duvel 2015; Vishnu et al. 2020; Moon et al. 2025). Pressure, geopotential height, or streamfunction minima correspond to vorticity maxima for balanced flow. For convective activity, key fields include precipitation and outgoing longwave radiation, the latter serving as a proxy for tropical convection. Additionally, convection is closely related to column water vapor (or column relative humidity) (e.g., Raymond 2000; Bretherton et al. 2004). Column water vapor or relative humidity can thus be used to estimate convective potential and exclude “dry seeds” or apparent nondevelopers, which are unlikely to develop into TCs within a reasonable time window.

Subjective thresholds are commonly used in tracking algorithms to identify features of interest. The specific value of a threshold depends on the variable(s) used, the spatial resolution of the dataset, and the specific objectives of the study. Such thresholds introduce undesirable uncertainty and subjectiveness. In particular, the partitioning of TC frequency variability between seed statistics and environmental conditions—within the framework where TC frequency is expressed as the product of seed frequency and transition probability (Hsieh et al. 2020, 2022)—is sensitive to the thresholds used in a tracker (Emanuel 2022). A chosen threshold should be weak enough to classify many more disturbances as TC seeds than those that become TCs, while simultaneously being stringent enough so that the seed statistics are well separated from the background state. For example, while the TC seed frequency should be related to the background (or long-term mean) vorticity in vorticity-based tracking, irrelevant vorticity features should be excluded so that the TC seed climatology is distinct from the vorticity climatology. Additionally, it may be advantageous to smooth or filter high-resolution data to exclude small-scale features, especially for vorticity-based trackers (Hodges et al. 2017).

A disturbance needs to be sufficiently persistent to spawn a TC, and therefore, a seed-duration threshold could be considered (e.g., Vidale et al. 2021). However, the duration threshold may not be independent of the intensity threshold used in a tracker (a stronger seed is often more persistent), which would strongly affect the frequency and spatial distribution of identified seeds. Similar to the intensity threshold, the duration threshold should not be overly stringent to ensure that seeds are distinguishable from TCs.

4. Some complicating factors

Tropical cyclogenesis is a complex, multiscale process. Different types of precursor disturbances and tropical cyclogenesis pathways may dominate in different basins (e.g., McTaggart-Cowan et al. 2013), and the relationship between TC seeds and TC frequency, if it exists, may vary across different basins and time scales. Accordingly, an all-inclusive TC seed definition may be too cumbersome and uninformative for tracker development. However, several complicating factors require highlighting.

a. Regional and seasonal dependence. Dominant types of precursor disturbances vary with basin or region (e.g., Ritchie and Holland 1999). Although our definition of TC seeds is broad enough to include different types of precursors, developing an effective tracker for all possible types of precursors is challenging. Additionally, past studies have suggested that the local dynamic and thermodynamic factors that differentiate developers from nondevelopers may differ across basins (McBride and Zehr 1981; Peng et al. 2012; Fu et al. 2012). This finding suggests that, even if large-scale environmental conditions and TC seed statistics both control TC frequency, their relative importance may vary across basins and time scales.

b. Different tropical cyclogenesis pathways. There are different pathways for tropical cyclogenesis (McTaggart-Cowan et al. 2008, 2013). In particular, a nonnegligible fraction of TCs (up to 40% over the North Atlantic) develop under extratropical influence, such as subtropical fronts and cyclones, termed “tropical transition” (Davis and Bosart 2004). Although our definition of TC seeds is general enough to include various types of precursor disturbances, the performance of a tracker and the relationship between TC seed frequency and TC frequency may vary for different genesis pathways.

c. TC seed characteristics. In addition to frequency, the intensity, structure, and propagation speed of a TC seed may also affect its transition probability into a TC (McBride and Zehr 1981; Wang et al. 2012; Núñez Ocasio et al. 2020; Lu et al. 2025). In tracking, while thresholds of rotation and convection could represent intensity, other TC seed characteristics are more challenging to consider, especially if the data used have poor temporal or spatial resolution.

d. Sensitivity to the model numerics and parameterized physics. Another complicating factor is the uncertainty in numerical models. The simulated TC frequency, TC seed frequency, and large-scale climate conditions are all sensitive to the numerics (such as grid resolution) and parameterized physics of a numerical model. For example, Zhao et al. (2012) showed that the simulated global TC frequency, large-scale climate, and small-scale atmospheric noise are sensitive to the horizontal convective mixing rate and divergence damping rate in the model. The relationship between TC frequency and TC seeds, if it exists, may vary across models, making it difficult to assess the relative contributions of TC seeds and large-scale climate conditions to changes in TC frequency. Observational analysis and global cloud-resolving models (Satoh et al. 2019) may provide an approach to constraining model uncertainty and better understanding the physical processes involved.

5. Concluding remarks

In this note, we proposed a standardized, physics-based definition for TC seeds and discussed the key factors to consider in TC seed identification and tracking. We expect that our definition will inform future studies and improve consistency between TC seed trackers. Ultimately, having a unified definition is a key step toward fostering a better understanding of TC frequency and its dependence on climate.

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