# Bulletin of the American Meteorological Society


## Revisiting the 26.5∘C Sea Surface Temperature Threshold for Tropical Cyclone Development

--Manuscript Draft--

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| **Manuscript Number:** | BAMS-D-13-00254 |
| **Full Title:** | Revisiting the 26.5∘C Sea Surface Temperature Threshold for Tropical Cyclone Development |
| **Article Type:** | Article |
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| **Manuscript Classifications:** | 2.272: Hurricanes; 3.192: Hurricanes/typhoons; 3.336: Sea surface temperature; 3.444: Tropical cyclones; 4.276: Hurricanes/typhoons |
| **Abstract:** | A high sea surface temperature is generally accepted to be one of the necessary ingredients for tropical cyclone development, indicative of the potential for surface heat and moisture fluxes capable of fueling a self-sustaining circulation. Although the minimum 26.5°C threshold for tropical cyclogenesis has become a mainstay in research and education, the fact that a non-negligible fraction of storm formation events (about 5%) occur over cooler waters casts some doubt on the robustness of this estimate. Tropical cyclogenesis over sub-threshold sea surface temperatures is associated with low tropopause heights, indicative of the presence of a cold trough aloft. To focus on this type of development environment, the applicability of the 26.5°C threshold is investigated for tropical transitions from baroclinic precursor disturbances in all basins between 1989 and 2013. Although the threshold performs well in the majority of cases without appreciable environmental baroclinicity, the potential for development is underestimated by up to 27% for systems undergoing tropical transition. An alternative criterion of a maximum 22.5°C difference between the tropopause-level and 850-hPa equivalent potential temperatures (defined as the coupling index) is proposed for this class of development. When combined with the standard 26.5°C sea surface temperature threshold for precursor-free environments, error rates are reduced to 3-6% for all development types. The addition of this physically relevant representation of the deep-tropospheric state to the ingredients-based conceptual model for tropical cyclogenesis improves the representation of the important tropical transition-based subset of development events. |
| **Author Comments:** | In response to reviewer comments, we have created an electronic supplement that we wish to be published, as well. |
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# Revisiting the 26.5°C Sea Surface Temperature Threshold for Tropical Cyclone Development

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*Capsule Statement:* A measure of tropospheric depth and bulk convective stability replaces the traditional sea surface temperature-based threshold as a necessary ingredient for tropical cyclogenesis from baroclinic precursors.

ABSTRACT

A high sea surface temperature is generally accepted to be one of the necessary ingredients for tropical cyclone development, indicative of the potential for surface heat and moisture fluxes capable of fueling a self-sustaining circulation. Although the minimum 26.5°C threshold for tropical cyclogenesis has become a mainstay in research and education, the fact that a non-negligible fraction of storm formation events (about 5%) occur over cooler waters casts some doubt on the robustness of this estimate. Tropical cyclogenesis over subthreshold sea surface temperatures is associated with low tropopause heights, indicative of the presence of a cold trough aloft. To focus on this type of development environment, the applicability of the 26.5°C threshold is investigated for tropical transitions from baroclinic precursor disturbances in all basins between 1989 and 2013. Although the threshold performs well in the majority of cases without appreciable environmental baroclinicity, the potential for development is underestimated by up to 27% for systems undergoing tropical transition. An alternative criterion of a maximum 22.5°C difference between the tropopause-level and 850-hPa equivalent potential temperatures (defined as the coupling index) is proposed for this class of development. When combined with the standard 26.5°C sea surface temperature threshold for precursor-free environments, error rates are reduced to 3–6% for all development types. The addition of this physically relevant representation of the deep-tropospheric state to the ingredients-based conceptual model for tropical cyclogenesis improves the representation of the important tropical transition-based subset of development events.

The development of a tropical cyclone is the net result of numerous processes that promote the growth of a weak perturbation into an intense self-sustaining circulation. A list of five necessary ingredients is typically used to assess the favorability of an environment for tropical cyclogenesis: high sea-surface temperature (SST), a steep vertical temperature gradient (reduced stability), high lower-tropospheric relative humidity, low wind shear, and a non-zero Coriolis force (Palmén 1948; Riehl 1954; Miller 1958; Gray 1968; Lee et al. 1989; DeMaria et al. 2001). We focus here on the SST element of this list.

Since the statement by Palmén (1948) that "hurricanes can be formed only in the oceanic regions outside the vicinity of the Equator where the surface water has a temperature above 26–27°C," a 26.5°C threshold for tropical cyclogenesis has become so well established that it appears in many current textbooks (Wallace and Hobbs 2006; Williams 2009; Ahrens 2009; Laing and Evans 2011; Ackerman and Knox 2015) and review articles [Galvin (2008), rounding up to 27°C]. However, the precise value of the SST threshold has been a matter of debate since its inception.

The value of 26.5°C is conveniently the closest half-degree Celsius to 80°F, a fact thought to have contributed to its selection (Sadler (1964, p. 352), based on Palmén (1956)). This threshold was found to be globally applicable by Gray (1968) despite being developed based on experience in the Gulf of Mexico, western North Atlantic and western North Pacific basins; however, alternative values based on early observational studies include 26.1°C (Fisher 1958) and 26.8°C (Wendland 1977). More recently, Dare and McBride (2011) present a global climatology of SSTs associated with tropical cyclogenesis, finding that almost 7% of formations occur over waters whose temperature at the time of formation lies below the 26.5°C threshold. They propose an adjustment of this value to 25.5°C, such that only 1.4% of developments occur over sub-threshold SSTs. However, Dare and McBride (2011) also find that 26.5°C is a reasonable threshold when the SST is averaged over the two-day period leading up to storm formation.

Tropical cyclone development over the relatively cold waters of the northeastern North Atlantic Ocean is found by Mauk and Hobgood (2012) to be associated with the presence of baroclinicity in the storm environment, consistent with the increasing recognition of the potential importance of baroclinic processes in tropical cyclogenesis (Bosart and Bartlo 1991; Bosart and Lackmann 1995; Davis and Bosart 2004; McTaggart-Cowan et al. 2008, 2013; Evans and Guishard 2009; Guishard et al. 2009). The majority of low-SST formations documented by Mauk and Hobgood (2012) are classified as strong tropical transitions, a development pathway characterized by the presence of a well-defined extratropical precursor that evolves into a warm-core system through the vertical redistribution of mass and momentum by sustained convection (Davis and Bosart 2003, 2004). Considering both the weak and strong forms of tropical transition (TT), McTaggart-Cowan et al. (2013) find that 16% of all tropical cyclones develop from baroclinic precursors.

In this study, we investigate the significant differences that exist between environments associated with tropical cyclogenesis over waters on either side of the 26.5°C threshold. The presence of upper-level baroclinic disturbances during low-SST formation events motivates a development pathway-specific analysis of the relevance of an SST-based threshold for cyclogenesis. For pathways involving the TT of a precursor baroclinic disturbance, a 22.5°C maximum threshold of the coupling index (computed as the difference between upper- and lower-level equivalent potential temperatures) is preferable to the SST threshold in terms of both effectiveness and physical relevance to the problem at hand. The addition of such an element to the list of ingredients required for tropical cyclogenesis will help to refine our understanding of, and improve our ability to predict, this important class of development events.

## 1. Data and Methods

This study employs four global datasets that cover a common 25-year period from 1989 to 2013: tropical cyclone best tracks, high resolution SST, atmospheric analyses and cyclone development pathway classifications. A total of 1757 tropical cyclones are included across all basins, thus allowing for the development of robust statistics even for relatively rare events. As a result, the term "significant" will be used hereafter in the strict statistical sense to indicate the rejection of the null hypothesis at the 99% confidence level.

All tropical cyclone tracking information used in this study is derived from the International Best Track Archive for Climate Stewardship, version 4, revision 5 (Knapp et al. 2010). The subset of best track data from the World Meteorological Organization's Regional Specialized Meteorological Centers is used to determine storm location and estimated intensity. The tropical storm wind speed threshold for the North Atlantic basin (35 kt) is used to determine the development time of the cyclone[1]. This definition focuses on the point at which the precursor vortex becomes a self-sustaining circulation (Laing and Evans 2011) and is consistent with the definition adopted by Dare and McBride (2011). The study thereby concentrates on the early intensification stage of developing storms rather than on precursor tropical depressions that may or may not intensify. Of the 2125 tropical cyclones in the 1989-2013 dataset, 2026 reach the 35 kt threshold after a median of 30 h of precursor tracking. An analogous investigation performed using a development time definition of the first IBTrACS entry shows limited sensitivity as described in section 2 of the electronic supplement. Additionally, any storm with an initial intensity estimate greater than or equal to 35 kt in the best track record is rejected from further analysis because the early intensification stage is deemed to have been missed. This criterion eliminates a further 269 storms, leaving a remaining total of 1757 for this study (83% of the original dataset). In section 3 of the

[1]In the western North Pacific basin, the Koba et al. (1991) pressure–wind relationship is used to estimate the initial intensity because wind speeds below 35 kt are not reported in the Japanese Meteorological Agency best track (Knapp et al. 2013).

electronic supplement, this condition is shown to be effective at eliminating invalid ITBrACS entries without noticeably affecting results. Dare and McBride (2011) consider only formations that occur equatorward of 35°, a condition that is not applied here in recognition of the fact that TT can occur at a relatively high latitude. However, consistent with Dare and McBride (2011), storms classified as either "subtropical" or "extratropical" in the best track archive are not considered in this investigation in order to eliminate non-tropical systems from the dataset.

The Reynolds et al. (2007) SST dataset, available daily with a 0.25° grid spacing, is employed throughout this study. The analyzed state is interpolated linearly for each storm to the formation time derived from the best track record. A pair of definitions of development SST are evaluated by Dare and McBride (2011): the point-SST at formation time at the storm center, and the maximum SST over the previous 48-h along the precursor track. In this study, we instead adopt a storm-centered area averaging approach over a 2° radius in order to obtain a representative SST on the storm scale without introducing a potential bias from storms with short pre-formation tracks. A comparison of the different development SST definitions (Fig. 1) shows that the choice of technique has predictable impacts on the development SST distribution: the Dare and McBride (2011) back-tracking increases the SST value by definition, while the use of area averaging reduces the sensitivity of the estimate.

Throughout this study, the atmospheric state is represented by the European Centre for Medium-Range Weather Forecasts Interim Reanalysis (Dee and Coauthors 2011), archived at 6-hourly intervals on a 1.5° grid. These analyses are used to compute quantities on the dynamic tropopause, here defined as the 2 PVU surface [1 Potential Vorticity Unit (PVU) = $10^{-6}\,\mathrm{K\,m^2\,kg^{-1}\,s^{-1}}$], in order to assess the structure of the upper boundary of the troposphere (Morgan and Nielsen-Gammon 1998). Low values of dynamic tropopause pressure are indicative of the elevated tropopause typical of the tropical environment, higher values are consistent with cold upper-level troughs, and sharp gradients between these extremes represent the upper-level fronts along which lie the subtropical and midlatitude jets.

The tropical cyclone development pathway climatology developed by McTaggart-Cowan et al. (2013) is used to determine the formation characteristics of storms in this study. McTaggart-Cowan et al. (2013) use a linear discriminant analysis (Friedman 1989) to assign each tropical cyclone to one of five categories depending on a pair of metrics: lower-level thickness asymmetry ($Th$) and upper-level quasigeostrophic forcing for ascent ($Q$). For the purposes of the current study, the TT categories (*weak TT* and *strong TT*) are considered independently, whereas the remaining pathways (*nonbaroclinic*, *low-level baroclinic* and *trough induced*) are combined into a *non-TT* group (Table 1)[2]. The study thereby remains focused on the TT pathways in which the ingredients required for low-SST tropical cyclogenesis are found to reside. The metric-based divisions between the development pathways are shown in Fig. 2, from which it is evident that the bulk of events fall into the *non-TT* category (Table 1). An important distinction between the investigation of McTaggart-Cowan et al. (2013) and the current study is that the former did not evaluate the likelihood of tropical cyclogenesis. It focused instead on the development pathway that would be followed if development were to occur. In the current study, these pathway classifications underpin the conditional application of a modified thermodynamic limit for tropical cyclogenesis, precisely to assess the probability of tropical cyclone development.

## 2. Tropical Cyclone Formation Environments

Given the large amount of energy required to create and sustain a tropical cyclone, high SSTs are expected to dominate the development distribution as shown in Fig. 1. Without a warm sea surface and oceanic mixed layer, most nascent tropical disturbances are unable to extract the sur-

[2] Development pathway category names are typeset in italics to avoid confusion with similar phrases in the text that do not refer specifically to the classification scheme.

face enthalpy fluxes required to support active convection and to promote the development of a self-sustaining circulation (Emanuel 1986, 1989; Black and Coauthors 2007; Zhang et al. 2008). However, the long left tail of the development SST distribution leads to a slow ramp-up (sustained shallow slope) in the cumulative distribution function, and indicates that in a minority of cases a tropical cyclone is able to develop without the benefit of such a plentiful source of energy.

A total of 70 tropical cyclones form in regions with 2° area-averaged SSTs below the 26.5°C threshold: roughly 4% of the 1757 storms considered in this study. These will be called "cold events" to distinguish them from the "warm events" that occur over waters with SSTs greater than 26.5°C. Dare and McBride (2011) characterize 5–7% of formations as cold events for a similar definition of cyclogenesis. The discrepancy between these percentage estimates is primarily a result of the differing definitions of SST as evidenced by the comparison of the cumulative distributions functions in Fig. 1. Adopting the point SST definition of Dare and McBride (2011) yields an estimate of 6%; however, the area-mean definition will be used in this study because of its relevance to the storm-scale circulation and its reduced sensitivity to small-scale spatial SST variability.

Although the global average of about three cold formation events per year (70 such developments occur in this 25-year climatology) represents a small component of the overall tropical cyclogenesis rate of 80–90 per year (Emanuel 1991), this subset of events is of particular interest because it appears to challenge the conventional description of the physics of tropical cyclone development. Moreover, the fact that these storms tend to form at relatively high latitudes, combined with their prevalence in the northern North Atlantic basin (Fig. 3), makes them a particular threat to populations and infrastructure not accustomed to, or designed for, the impacts of tropical cyclones.

Investigations of individual low-SST formation events such as the 2004 South Atlantic tropical cyclone Catarina (Pezza and Simmonds 2005; McTaggart-Cowan et al. 2006), generally emphasize the role of upper-level baroclinic features in the development process. In their small-sample climatology for the northeastern North Atlantic basin, Mauk and Hobgood (2012) show that the environments in which these storms develop are generally characterized by large vertical wind shears and low equilibrium levels (the altitude at which a parcel ascending from lower levels becomes neutrally buoyant). These results suggest that important differences should exist between the environments of warm- and cold-SST formation events.

The distribution of mean dynamic tropopause pressure in the environment surrounding the developing tropical cyclone is significantly different between warm and cold tropical cyclone formation events (Fig. 4). The mean tropopause pressure for cold events is 140 hPa, 25 hPa greater than the average for tropical cyclones developing over warmer waters (median values are 128 hPa and 115 hPa, respectively). The shape of the distributions is also noticeably different, with a secondary maximum at 175 hPa in the cold-SST distribution indicative of the existence of a distinct class of formations that occur preferentially in association with reduced tropopause heights.

The physical implications of tropical cyclone formation in an environment with a lowered tropopause stem from the fact that such a background is associated with the presence of a cold upper-level trough. This feature may be of midlatitude origin (Davis and Bosart 2003), or it may have formed at lower latitudes within the tropical upper-tropospheric troughs (Sadler 1975). The presence of cold air aloft reduces bulk tropospheric stability, putting more convective available potential energy at the disposal of the developing disturbance. The reduced static stability also leads to an increased Rossby penetration depth, which promotes vertical connections between the upper- and lower-level perturbations (DeMaria 1996), and leads to enhancement of both the developing secondary circulation and the vertical motions resulting from quasigeostrophic forcing for ascent downshear of the upper-level trough (Kelley and Mock 1982).

In light of the apparent relationship between tropopause pressure and development-time SST, and the implications of such an environment for cyclogenesis, a physically based framework is needed for further analysis of these events. Of particular relevance to this study will be the ability of the scheme to identify TT events (Davis and Bosart 2003, 2004), because this development paradigm depends strongly on the presence of a cold trough aloft. Once classifications have been made, the resulting development pathway-specific climatologies can be evaluated to determine whether 26.5°C is a universally applicable threshold, or whether a different quantity yields a more relevant necessary condition for tropical cyclogenesis from baroclinic precursors.

## 3. Pathway Dependence of the SST Threshold

The TT of an initially baroclinic vortex into a developing tropical cyclone is a distinct form of tropical cyclogenesis (Davis and Bosart 2003, 2004) that accounts for approximately 16% of formations around the globe (McTaggart-Cowan et al. 2013). These events are divided into two groups depending on the strength of the initial lower-level circulation. Developments involving weak extratropical cyclones [the WEC events of Davis and Bosart (2004)] are here referred to as *weak TT* events. In these cases, near-surface winds around the precursor are not strong enough to enhance surface fluxes sufficiently to sustain the vortex [less than 10–15 $\mathrm{m\,s^{-1}}$ (Emanuel 1995; Fairall et al. 2003)]. Conversely, the winds associated with an initial disturbance involved in strong extratropical cyclone TT [defined as SEC by Davis and Bosart (2004) and *strong TT* here] are capable of triggering wind-induced surface heat exchange to promote the growth of a self-sustaining circulation driven primarily by surface enthalpy fluxes (Emanuel 1986). Despite their differing lower-level intensities, the *weak TT* and *strong TT* development pathways both rely on the cyclogenetic influence of an upper-level trough at the early stages of transition. This dependence suggests that the TT pathways may be particularly well suited to overcoming the detrimental impacts of low SSTs during storm formation.

The *weak TT* and *strong TT* development pathway classifications of McTaggart-Cowan et al. (2013) are used here to identify this form of development. All other formation events are classified as *non-TT*, a general category in which the baroclinicity of either the upper- or lower-level disturbances is too weak for the storm to follow a TT development pathway (Table 1). The majority of tropical cyclogenesis events in this study follow the *non-TT* pathway (83%), whereas 14% and 3% follow the *weak TT* and *strong TT* pathways, respectively.

The frequency of occurrence of cold events depends on the pathway to tropical cyclogenesis (Fig. 5). Although 84% of warm events follow the *non-TT* pathway, only 55% of cold events resemble this dominant development archetype. Instead, large increases in the relative frequency of *weak TT* and *strong TT* formations are evident. The relative frequency of cold events is highest for the *strong TT* category, in which 27% of events (14/51) occur over waters with area-averaged SST below the 26.5°C threshold.

The relative dominance of the *strong TT* pathway in tropical cyclogenesis over colder waters is also apparent in the cumulative distribution functions (Fig. 6). The slow ramp-up of the *strong TT* pathway over low SSTs, indicative of a left-skewed distribution containing an appreciable number of cold events, provides further evidence that the 26.5°C threshold is not highly applicable to this class of development[3]. The utility of the threshold for storms following the *weak TT* pathway is also questionable since its curve lies above the dominant *non-TT* class for lower SSTs.

The specification of any SST threshold as a necessary (but not sufficient) condition for tropical cyclone development needs to be based on an "acceptable" level of sensitivity. In the formulation

[3]An ideal threshold model would arise from a cumulative distribution function that abruptly transitions from a near-zero sub-threshold slope to a steep slope once the threshold is reached.

used here, sensitivity refers to the fraction of tropical cyclone formation events that occur over SSTs above the specified threshold. Conversely, the Type-II error rate is defined as the complement of sensitivity (1-sensitivity) to represent the fraction of events that take place on the "wrong" side of the threshold (development over cold SSTs in this case). Because the traditional threshold was defined without any development pathway partitioning, we can deduce the acceptable Type-II error rate to be about 4% based on the cumulative distribution functions for the full dataset at 26.5°C (black line in Fig. 6). We round this value to 5% for consistency with standard confidence intervals and the Dare and McBride (2011) range of 5–7%. This corresponds to 95% sensitivity for the threshold model, a value that practical use has shown to be acceptable to the community.

The existence of the pathway-dependent sensitivity apparent in Fig. 6 is problematic from the perspective of threshold application. Water temperatures of 26.5°C serve as an effective thermodynamic boundary for *non-TT* formations, yet appear to have relatively little impact on *strong TT* events. Ideally, the threshold would have a consistent meaning for the different development types, expressed as uniform, non-zero[4] Type-II error rates. Modifications to the SST threshold for TT developments may be made to achieve the same level of sensitivity (Fig. 6). However, the traditional value would need to be adjusted downwards by over 2°C (to 24.3°C) for *strong TT* developments. Such revisions may be considered a first step towards accounting for the impact of environmental baroclinicity on tropical cyclogenesis, but could also be interpreted as an indication that an important element is missing from the description of the thermodynamic factors limiting development.

[4]A threshold with a null Type-II error rate (perfect sensitivity) is entirely achievable, but is likely useless in practice. Consider redefining the SST threshold as 0°C: no tropical cyclone will form below this threshold (0% Type-II error rate), but neither will any realistic potential development be excluded by this value.

## 4. A Threshold for Tropical Transition

Given the significant differences in tropopause pressure (Fig. 4) and frequency of TT (Fig. 5) between warm and cold events, a pathway-dependent investigation of the upper-tropospheric state is expected to yield additional insight into the factors acting to facilitate tropical cyclogenesis under low-SST conditions. The pathway-dependent relationships between the pressure of the dynamic tropopause and SST shown in Fig. 7 demonstrate that the environment plays an important role in modulating the sensitivity of the development process to the energy available from the underlying surface. The *weak TT* and *strong TT* pathways both possess significant relationships between tropopause pressure and SST, with cold development events tending to occur in association with stronger troughs aloft.

Distinguishing between the *non-TT* and TT-based pathways also affords an explanation for the bimodal distribution of dynamic tropopause pressure for cold events, centered at 150 hPa in Fig. 4. This value appears to divide cold, near-threshold *non-TT* events occurring under elevated tropopauses (light grey backgrounds in Fig. 7b), from those undergoing *weak TT* and *strong TT* over much lower SSTs in the presence of a trough aloft (dark grey backgrounds in Fig. 4c and d). There appears to be an important physical distinction between these subsets of cold development events that is not fully described by SST.

The thermodynamic interpretation of the relationship between tropopause pressure and SST is that the depressed tropopause is potentially colder, and thus creates an environment in which the bulk column stability is similar to that of the deep tropics despite a lower surface temperature (Emanuel 1986). The deep moist stability is characterized by Mauk and Hobgood (2012) using the equilibrium level and by Emanuel (1986) using a surface–300-hPa lifted index, but here we use the coupling index (Bosart and Lackmann 1995) because of its direct relevance to the baroclinic dynamics that characterize the TT-based development pathways (McTaggart-Cowan et al. 2006, 2010). This quantity is defined as the difference between the dynamic tropopause potential temperature and the 850-hPa equivalent potential temperature. It approximates bulk stability (larger values represent more stable conditions than smaller values), which modulates the degree of interaction between perturbations on the upper and lower boundaries of the free troposphere via the Rossby penetration depth. Because such boundary thermal perturbations can be regarded as potential vorticity anomalies (Bretherton 1966), interactions between these edge waves can promote baroclinic growth in the Eady model (Davies and Bishop 1994), a process highly relevant to TT events. The use of the 850-hPa level rather than the surface in the coupling index formulation is consistent both with the lower free-tropospheric boundary for edge potential temperature perturbations (Hoskins et al. 1985), and with recent modifications to the original undiluted form of the Emanuel (1986) Carnot cycle model. The latter are designed to account for both mid-level entrainment and downdraft-induced moist entropy reductions (Cram et al. 2007; Riemer et al. 2010; Tang and Emanuel 2012).

Recasting the cumulative distribution function in terms of the coupling index instead of SST demonstrates that this quantity is effective at reducing the slow ramp-up of the *strong TT* category by steepening the distribution's slope (cf. Figs. 6 and 8). The sharper onset of development for decreasing coupling index values suggests that a threshold based on this quantity will represent an improvement over the SST condition. Moreover, both TT pathways display similar coupling index distributions as evidenced by their similarity across a broad range of values in Fig. 8, suggesting that a single threshold value should be applicable to TT events in general.

Based on the cumulative distribution functions shown in Fig. 8, a coupling index threshold of 22.5°C is identified as the upper limit for TT. This value is chosen as the point at which the 5$^{\text{th}}$ percentile crosses the cumulative distributions, such that the Type-II error rate approaches the acceptable 5% value determined from the 26.5°C SST threshold. Errors implied by the use of the 22.5°C coupling index threshold are compared to their SST-based equivalents in Table 2, from which it appears that the former is effective for TT-based developments. The consistency of the Type-II error rate across the *weak TT* and *strong TT* pathways, a direct result of their proximity in Fig. 8, is particularly important because it suggests that the threshold is equally applicable across this subrange of formation types. Use of the 22.5°C coupling index maximum for TT-based developments, and the 26.5°C SST minimum for all other events, yields a combined threshold performance that is superior to either of these criteria in isolation in terms of both error rate consistency and overall sensitivity (final column of Table 2).

The increase in Type-II error rate when the coupling index threshold is applied to *non-TT* events (second column of Table 2) can be understood through an analysis of the coupling index itself. A low coupling index value requires three ingredients: high 850-hPa equivalent potential temperature, a steep tropospheric lapse rate, and a low tropopause (the latter two ingredients imply a low dynamic tropopause potential temperature). Large values of the first two ingredients are unambiguously favorable for all forms of tropical cyclogenesis because they favor the release of latent heat in active convection. The third ingredient, a low tropopause height indicative of an upper-level trough, is a requirement during the initial stages of TT. The trough provides quasigeostrophic forcing for ascent, which enhances the circulation by stretching and brings the mid-levels towards saturation, thereby creating a synoptic-scale region favorable for sustained deep moist convection and development of the tropical cyclone vortex. The favorable dynamics and thermodynamics for TT are therefore well described by a low coupling index. However, an elevated tropopause is beneficial to *non-TT* developments because it implies a lower temperature in the outflow layer, a factor that enhances the thermodynamic efficiency of the Carnot cycle that represents the storm energy cycle (Emanuel 1986). With this ingredient favoring a higher coupling index for *non-TT* formations, it is not surprising that these events do not adhere to the same coupling index threshold that applies to *weak TT* and *strong TT* developments. The completion of the TT process is characterized by the replacement of the upper-level trough with an outflow anticyclone, a change that renders the system energetically and morphologically indistinguishable from one that has undergone a *non-TT* form of development. This implies that a direct relationship between the coupling index and TT formation processes exists primarily before and during transformation, the baroclinically influenced portion of the storm life cycle that is incompletely described by SST alone.

The utility of the coupling index is further demonstrated by the relationship between its spatial distribution and the locations of TT events (Fig. 9). Because low values depend on both a cool upper-troposphere and a relatively warm boundary layer, a "Goldilocks zone" emerges in the subtropics. It is in this band that midlatitude troughs penetrate sufficiently equatorward to play a role TT-based development over SSTs that are warm enough to sustain deep convection (Schumacher et al. 2009). For example, the western South Atlantic basin, an area long thought to be devoid of tropical cyclones (Gray 1968), has recently given rise to two possible cold events via TT in an area of reduced coupling index values (Pezza and Simmonds 2005; Evans and Braun 2012; Pinto et al. 2013). Discussion continues about whether such systems constitute tropical or subtropical storms given their high latitude of formation, relatively low underlying SSTs and initially asymmetric structures; however, even subtropical storms rely largely on surface enthalpy fluxes and reduced tropospheric stability to sustain their circulations (Guishard et al. 2009). Cyclonic features with these characteristics can be found in all oceanic regions from the deep tropics (tropical cyclones) to the high latitudes [the cold-low class of polar lows (Businger and Reed 1989)]. Because these systems rely on similar energetics for their formation and maintenance, they possess similar storm morphologies: radial symmetry, a clear eye, spiral bands and outflow anticyclone indicative of a warm core (Rasmussen 1979; Ernst and Matson 1983; Rasmussen and Zick 1987; Emanuel and Rotunno 1989; Yanase and Niino 2007).

As a result of these similarities, the area covered by the climatological coupling index threshold (Fig. 9) extends well beyond the tropics, into regions where the cold analogs of tropical cyclones form: the Mediterranean Sea (Reale and Atlas 2001; Emanuel 2005; Tous and Romero 2013), the Australian east coast (Qi et al. 2006; Garde et al. 2010; Pezza et al. 2013), the eastern North Atlantic (Shapiro et al. 1987; Føre et al. 2012), and the northern West Pacific (Watanabe and Niino 2014). This expansion is consistent with physical relevance of the coupling index, but may be problematic for estimates of tropical cyclone development potential that rely largely on the SST threshold to constrain large values to near-equatorial regions. Following Schumacher et al. (2009), the 21°C SST isotherm is included in Fig. 9 as a potential secondary condition that could be used to limit the poleward extent of the region expected to support the TT-based pathways to tropical cyclogenesis. The application of this condition may be acceptable because it has no effect on the results presented in this study; however, it is arbitrary and error-prone because there is no clear physical distinction between these events and their higher-latitude counterparts.

## 5. Implications

The pathway-dependent utility of the 26.5°C SST threshold as a thermodynamic limit for tropical cyclogenesis has direct implications for forecasting, because its uniform application may lead to an underestimation of the likelihood of tropical cyclogenesis via TT. This problem is particularly relevant for developments occurring in the subtropics because, although they tend to be less intense than their lower-latitude counterparts, they tend to affect regions not accustomed to the effects of tropical cyclones. Although baroclinic precursors that are candidates for TT are readily identified in satellite imagery (Davis and Bosart 2004), their thermodynamic feasibility is impossible to assess from SST alone. The 22.5°C coupling index threshold provides guidance concerning the possibility of the transition of such systems into tropical cyclones in a manner analogous to the 26.5°C threshold for *non-TT* events.

The applicability of the 22.5°C coupling index threshold extends beyond the TT-based pathways for which it was designed, to include the subtropical and hybrid storms in the best track record that meet the selection criteria for this study. Cold events dominate in this development class, with 65% (13/20) of events occurring over waters below 26.5°C . Given the reliance of subtropical storms on sustained convection to trigger moist baroclinic instability (Davis 2010), it is expected that the coupling index will provide an improved estimate of the thermodynamic limits on development. Indeed, the Type-II error rate falls to 10% using the 22.5°C coupling index threshold, with all tracked subtropical cyclogenesis events falling within the climatological range of this value (formation locations marked with crosses in Fig. 9). This result is consistent with the expected robustness of the coupling index for the full spectrum of diabatically enhanced cyclones that occur across the global basins.

The use of SST and SST anomalies as predictors in statistical models for seasonal forecasts of tropical cyclone activity is widespread [review provided by Camargo et al. (2007)], a consequence of the direct relevance of underlying water temperature to the majority of tropical cyclogenesis events. The addition of a coupling index predictor should enhance the sensitivity of the seasonal guidance to baroclinically influenced systems, thus improving their ability to predict the frequency of occurrence of TT on seasonal time scales. This preliminary introduction of a pathway-dependent predictor in statistical models of tropical cyclogenesis potential represents a first step towards an index that is conditional on the development pathway supported by the storm environment.

On climate time scales, the sensitivity of the coupling index to tropospheric stability makes it well suited to adapt to the non-uniform vertical profiles of temperature trends that affect the validity of SST-based thresholds for convection (Yoshimura et al. 2006; Knutson et al. 2008; Johnson and Xie 2010). Although upper-level warming is expected to offset SST increases in the tropics (Vecchi and Soden 2007; Fu et al. 2011; Vecchi et al. 2013), this constancy in tropospheric stability may not extend into the subtropics (Thorne et al. 2010). The relationship between TT and the coupling index suggests that the climatological prevalence of such events may therefore change as the difference in upper and lower boundary temperatures evolves. Particularly given the apparent poleward expansion of tropical cyclone activity (Kossin et al. 2014), the coupling index may be increasingly useful as an estimator of the impacts of a changing atmospheric state on the thermodynamic limits for tropical cyclone formation in the subtropics.

The traditional 26.5°C SST threshold is of practical use for the majority of tropical cyclogenesis events; however, the presence of a baroclinic precursor can alter the formation process sufficiently to promote development over cooler waters. During such events, a 22.5°C coupling index threshold appears to be a more sensitive and reliable measure of the thermodynamic limits on development. Added to the list of ingredients required for tropical cyclogenesis, this threshold introduces a conceptually distinct element of direct physical relevance to the important TT subset of storm formation events.

*Acknowledgments.* This article arose from the second author's third-year undergraduate dissertation at the University of Manchester. Partial funding for Schultz was provided by the UK Natural Environment Research Council (NERC) to the Diabatic Influences on Mesoscale Structures in Extratropical Cyclones (DIAMET) project at the University of Manchester (grant NE/I005234/1), and partial funding for Fairman was provided by NERC to the PREcipitation STructures over

Orography (PRESTO) project at the University of Manchester (grant NE/1024984/1). Partial funding for Galarneau was provided by NOAA/HFIP Grant NA12NWS4680005. The National Center for Atmospheric Research is sponsored by the National Science Foundation. Early versions of the study benefitted significantly from comments supplied by Drs. John Gyakum, James McTaggart-Cowan and Ayrton Zadra. The constructive comments of three anonymous reviewers during the peer review process greatly helped to improve the final study.

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# LIST OF TABLES

| Pathway Name | Sub-pathway<br><br>(% contribution) | Description | Occurrence (%) |
|---|---|---|---|
| *Non-TT* | | No superposition of upper- and lower-level baroclinic disturbances | 83 |
| | *Nonbaroclinic* (85%) | No appreciable baroclinic influences | |
| | *Low-level baroclinic* (6%) | Strong lower-level thremal gradients without an upper-level disturbance | |
| | *Trough induced* (9%) | Upper-level disturbance without appreciable lower-level thermal gradients | |
| *Weak TT* | | Upper-level disturbance with moderate lower-level thermal gradients | 14 |
| *Strong TT* | | Upper-level disturbance with strong lower-level thermal gradients | 3 |

TABLE 1: Summary description of the tropical cyclogenesis development pathways identified used in this study, based on the classifications of McTaggart-Cowan et al. (2013). The original *nonbaroclinic*, *low-level baroclinic* and *trough induced* categories are listed individually as sub-pathways of the combined *non-TT* group, with their percentage contribution to *non-TT* developments identified in parentheses in the second column.

| Pathway | Type-II Error Rate (%) | | |
|---|---|---|---|
| | 26.5°C SST | 22.5°C Coupling Index | Combined Thresholds |
| *Non-TT* | **2.5** | 14.7 | 2.5 |
| *Weak TT* | 6.0 | **5.6** | 5.6 |
| *Strong TT* | 27.5 | **5.9** | 5.9 |
| All | 3.7 | 13.2 | 3.0 |

TABLE 2: Pathway-specific Type-II error rates (storm formation on the cold side of the threshold) for the traditional 26.5°C SST threshold (first column) and a 22.5°C coupling index threshold (second column). The combined threshold in the third column uses the criteria corresponding to the values in bold typesetting in the previous two columns to enhance the performance of the ingredients-based tropical cyclogenesis model across the full range of development environments.

# LIST OF FIGURES

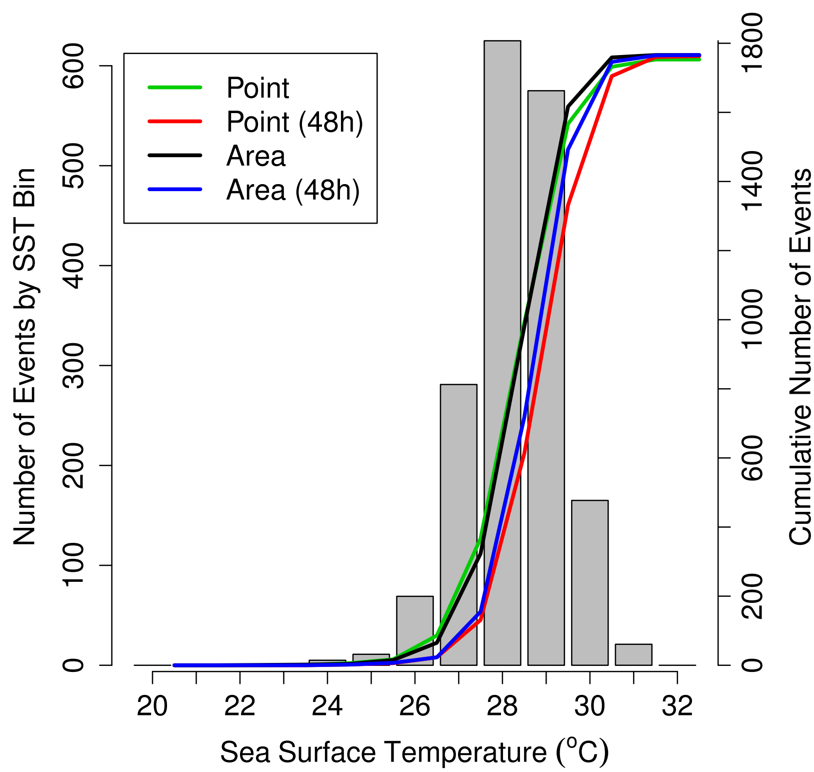


FIG. 1: Distribution of storm-centered 2° area average SST at tropical cyclone development time (grey bars plotted against the left-hand axis, corresponding to the "Area" entry in the legend). The cumulative distribution functions for four different representations of SST are plotted against the right-hand axis, with line colors as indicated in the legend. The "Point" and "Point (48h)" definitions follow "SST" and "SST48" of Dare and McBride (2011), respectively. The "Area" and "Area (48h)" represent analogous descriptions that incorporate 2° area averaging, with the results of the study qualitatively insensitive to reasonable changes in the averaging radius. The "Area" cumulative distribution function corresponds to the histogram plotted in grey bars. Binning is performed at 1°C intervals centered on integer SST values between the 20°C and 34°C extrema of the dataset: the 26°C bin therefore contains all events that occur over waters between 25.5°C and 26.5°C.

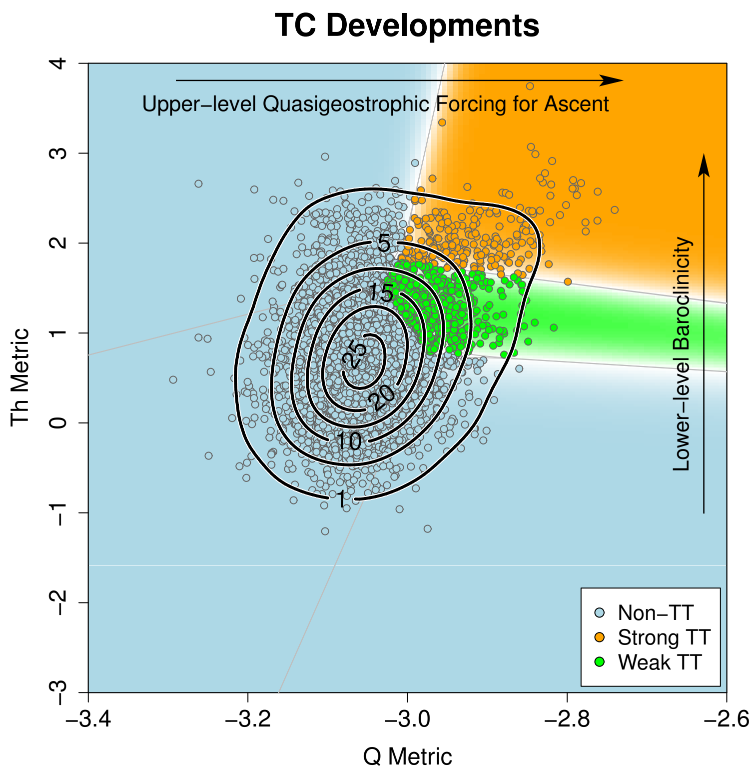


FIG. 2: Classification schematic for the development pathway climatology described by McTaggart-Cowan et al. (2013) and synthesized here into three categories from the original five as described in section 1. The axes of the classification space are the $Q$ and $Th$ metrics that relate to environmental upper-level quasigeostrophic forcing for ascent and lower-level baroclinicity, respectively [section 2a of McTaggart-Cowan et al. (2013)]. Background colors follow the legend and represent the classification for each position on the plane. Annotations are used to ease interpretation of the dimensions. Development events for the 1948-2010 period are plotted and classified for reference (points), along with the corresponding kernel density estimate [contours; a continuous function that represents the underlying distribution of TC developments across metric space (Duong 2007)].

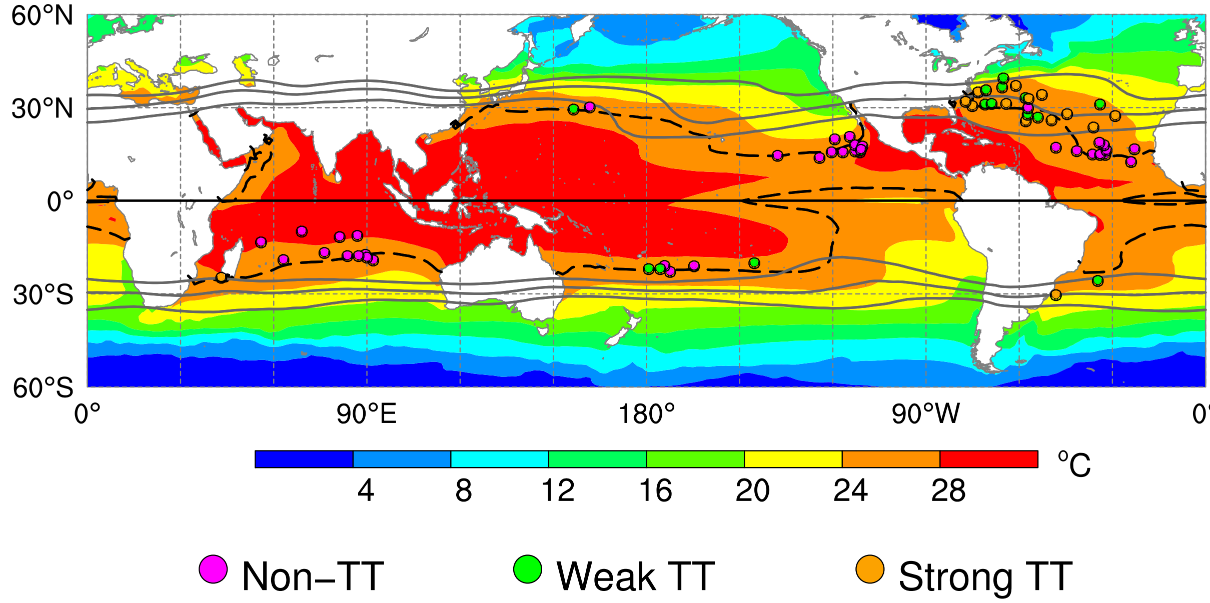


FIG. 3: Formation locations of cold events between 1989 and 2013. The seasonal-mean SST is plotted in the background using colors as indicated on the color bar, with the 26.5°C isotherm highlighted with a thin dashed line for reference. The "season" is defined as the summer and fall for each hemisphere, corresponding to June–November in the Northern Hemisphere and December–May in the Southern Hemisphere. A black line at the Equator divides the separate climatologies. The seasonal-mean position of the 150 hPa, 175 hPa and 200 hPa isobars on the dynamic tropopause are shown by grey lines, with the lower-pressure isopleths positioned equatorward of their higher pressure counterparts. The symbol for each tropical cyclone formation location is plotted according to the storm development pathway as indicated in the plot legend (Table 1).

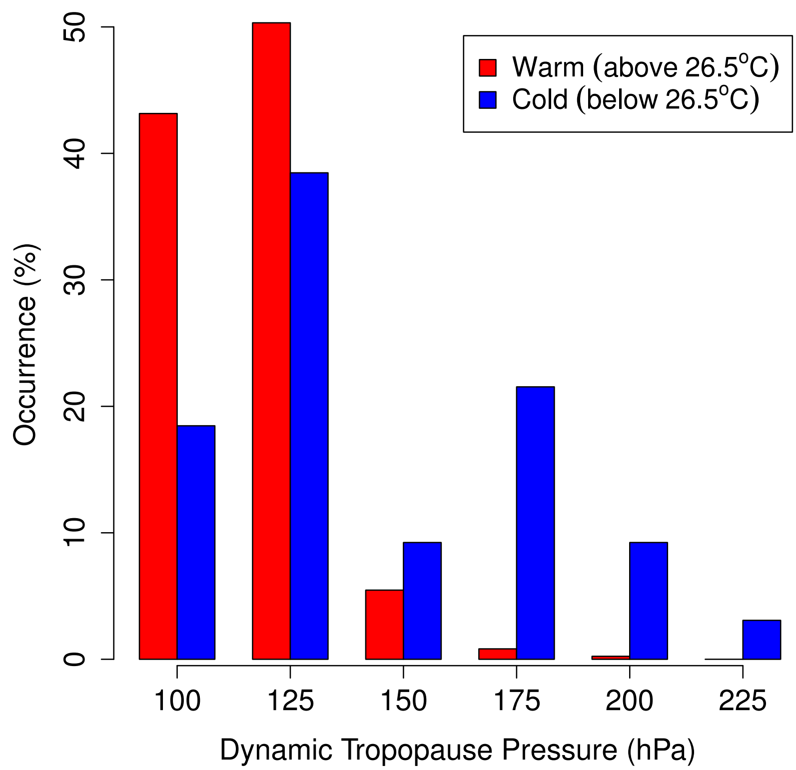


FIG. 4: Probability distribution of the mean dynamic tropopause pressure within 10° of the formation location of the tropical cyclone. Storms are classified as "warm" or "cold" depending on their formation-time SST value and plotted with red and blue bars, respectively. Binning is performed at 25-hPa intervals centered on the values shown along the abscissa. The 10° radius is used to represent the near-storm environment for consistency with previous studies, and the results of this work are not highly sensitive to reasonable values of this averaging radius.

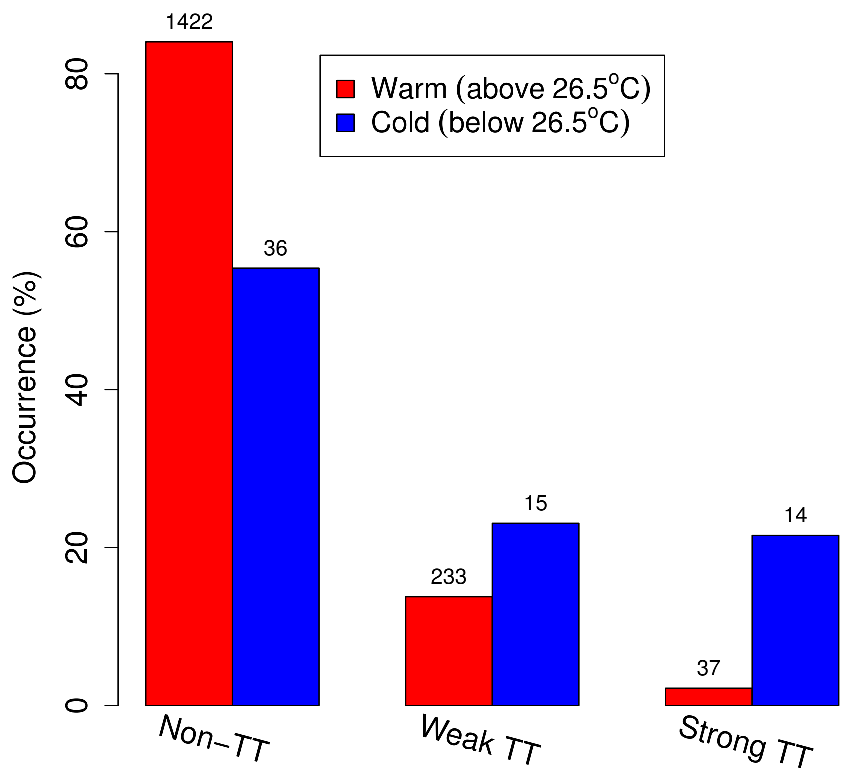


FIG. 5: Frequency of occurrence of warm-SST (red) and cold-SST (blue) tropical cyclogenesis events by development pathway. The number of events in each group is annotated at the top of the bar. A description of the development pathways can be found in Table 1.

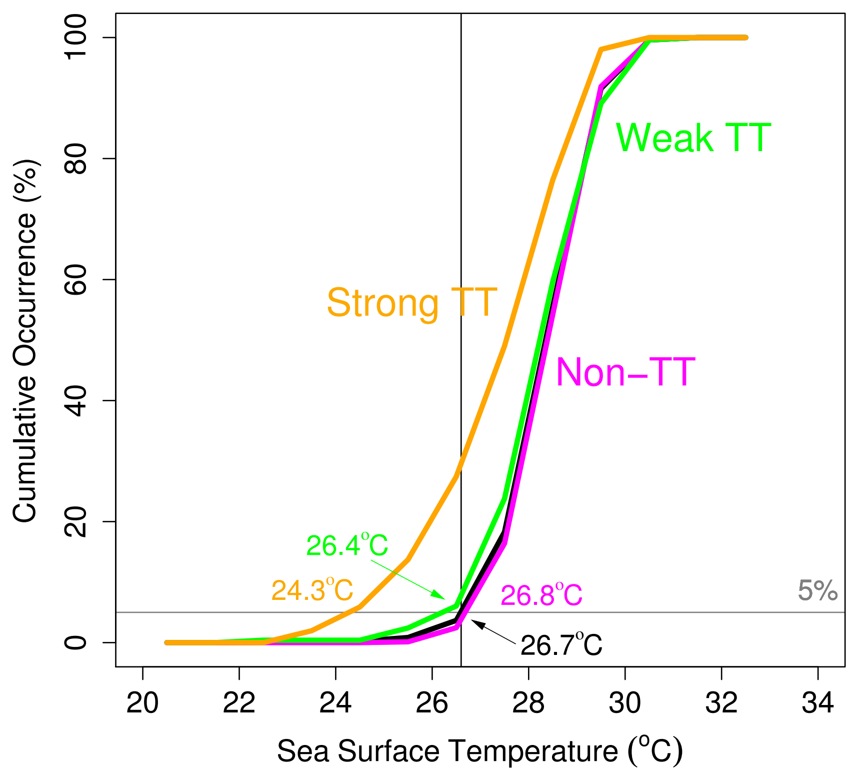


FIG. 6: Pathway-dependent cumulative distribution functions of development SST. Binning is performed at 1°C intervals as described for Fig. 1, and plotted using different line colors for individual pathways as labeled (black for the cumulative distribution of all events). The 5th percentile line is plotted in grey, with the values of its intersection point with the cumulative distribution functions annotated in the appropriate color for the pathway. The 26.5°C threshold is identified with a thin vertical line.

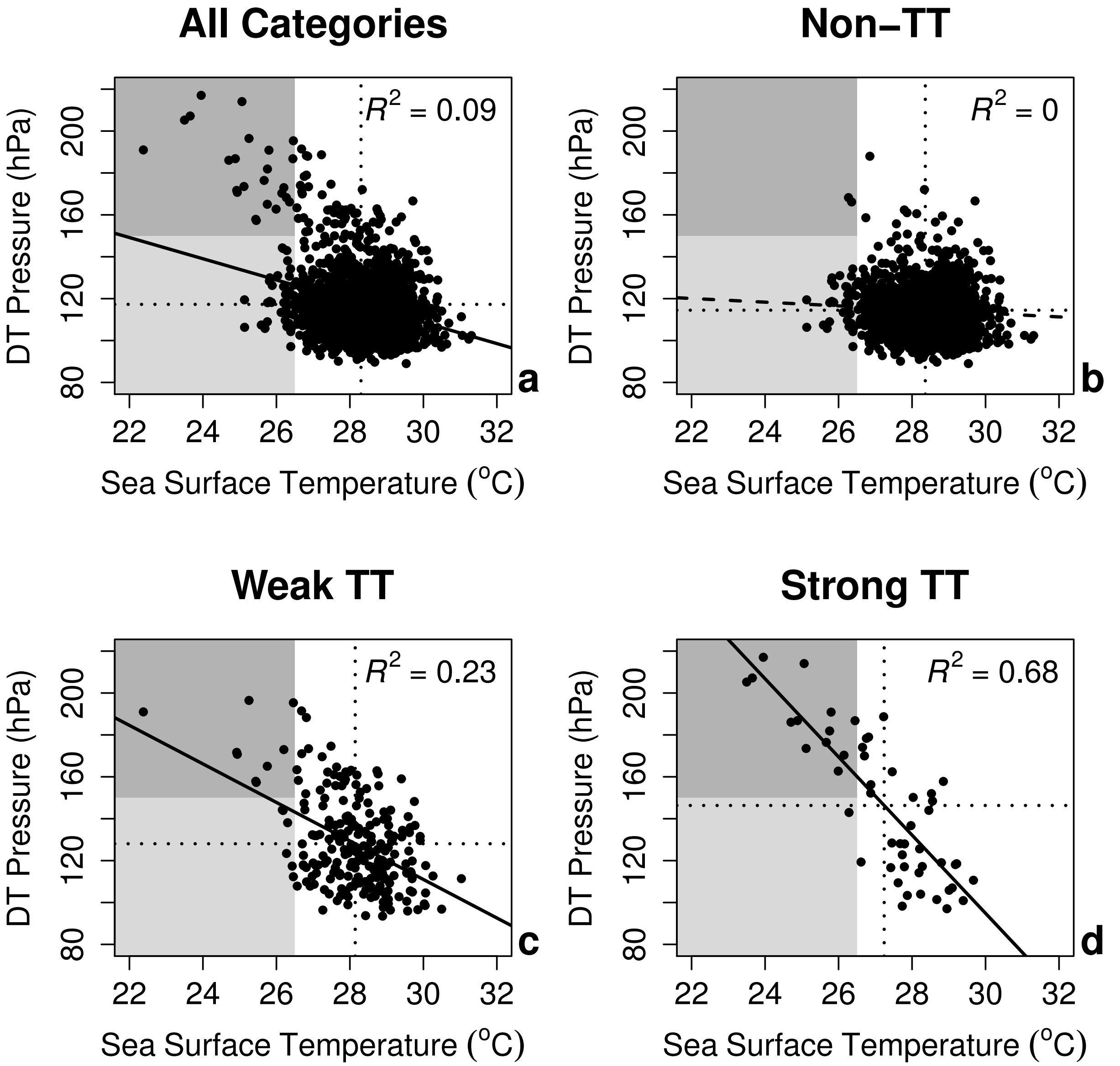


FIG. 7: Pathway-dependent dynamic tropopause pressure, as defined for Fig. 4. Individual panels present development-time SST and tropopause pressure (black dots) for the formation pathway indicated in the plot title. Grey shading appears as a background for SST values below 26.5°C , with light grey for dynamic tropopause pressures above 150 hPa and dark grey for lower tropopauses. The 150 hPa distinction is used because it represents the local minimum in the Fig. 4 distribution for cold events. Horizontal and vertical dotted lines represent the category-mean pressure and SST, respectively. The linear model that best describes the relationship between these quantities is plotted with a solid line if the relationship is significant, and in a dashed line for reference if it is not. The square of the correlation coefficient ($R^2$) is provided in the upper-right corner of each panel.

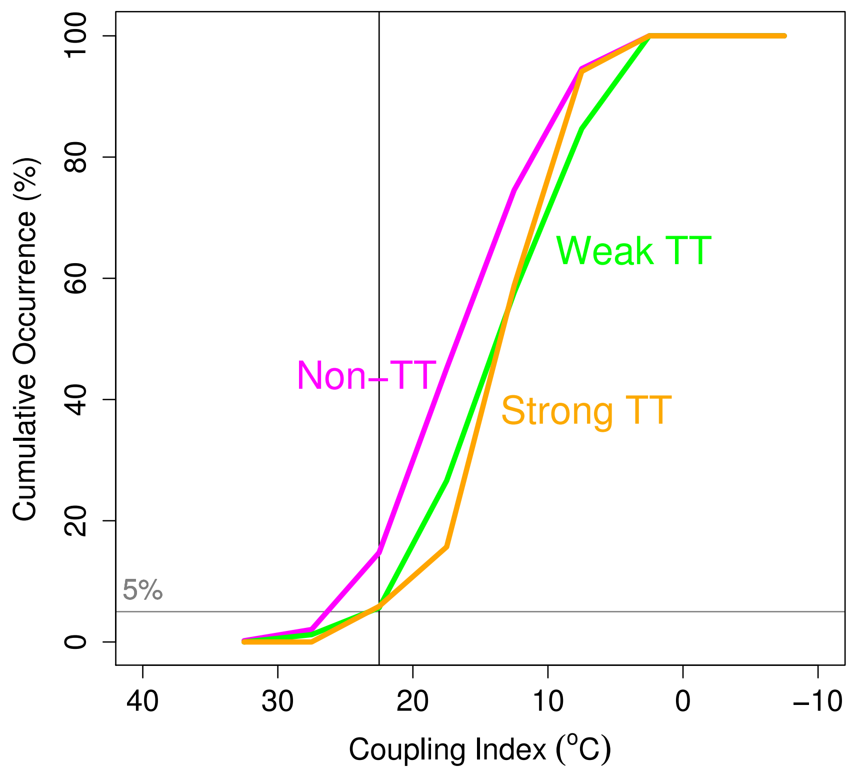


FIG. 8: Pathway-dependent cumulative distribution functions of development-time coupling index in the environment, plotted as in Fig. 6, except for coupling index binning performed at 5°C intervals from -10°C to 40°C. The 22.5°C threshold is identified with a thin vertical line.

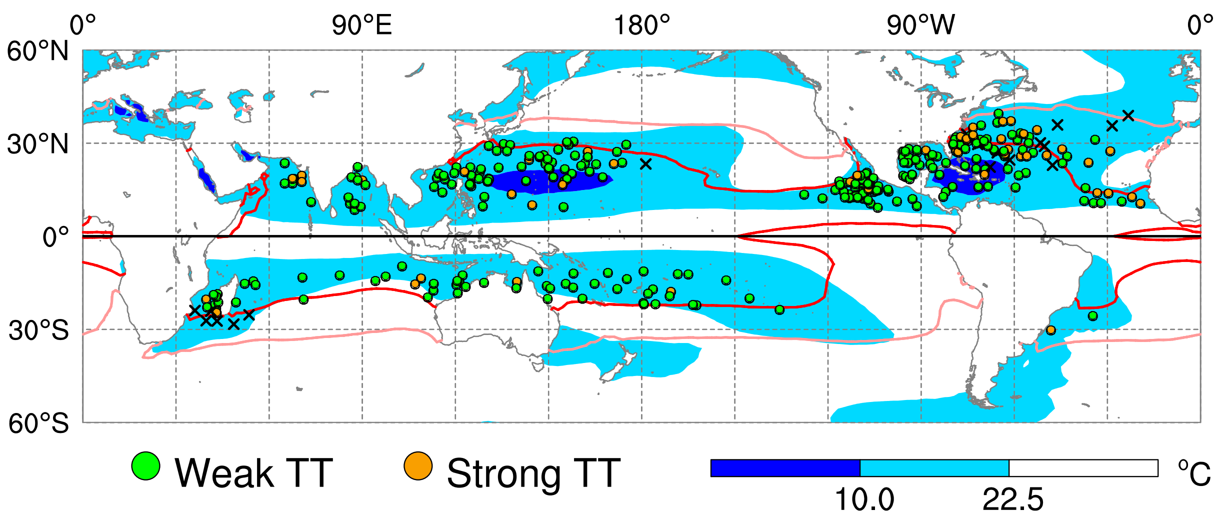


FIG. 9: Climatology of mean coupling index values (plotted according to the color bar) for the summer-fall period in each hemisphere, as for Fig. 3. Also plotted is the formation location of each TT event (dots, color-coded by pathway as shown in the legend) and each subtropical storm (black crosses) in the best track dataset over the 1989-2013. The seasonal-mean 26.5°C and 21°C SST isotherms are plotted with red and salmon lines, respectively.

Supplemental Material
Click here to download Supplemental Material: fg_ci_climo_annot.eps

Supplemental Material

Click here to download Supplemental Material: fg_dpavg_hist.eps

Supplemental Material

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Supplemental Material

Click here to download Supplemental Material: fg_sst_climo_annot.eps

Reviewer comments are in black, and our responses in red.

Reviewer A

General Comments:

This is an interesting study that investigates tropical cyclones that form with sea surface temperatures below the "traditional" 26.5 deg C threshold. The development of a new thermodynamic parameter that includes atmospheric stability and tropopause information provides a better measure for identifying genesis events for a certain class of cyclones, and has potential application to short term forecasting and climate studies. My primary issue with this manuscript is the way the tropical cyclone cases where selected and the definition of formation. This requires further discussion, so my recommendation is for publication after major revisions. Further details are provided below.

Thank you for the careful comments and constructive suggestions. We have investigated the sensitivity of the results to the definition of "genesis" and the initial intensity threshold as described in more detail below, and had added the results of these tests as electronic supplements so that they are available for interested readers. At the same time, we have added justification for using the TS-threshold and have clarified the fact that the focus is on "development" of the TC rather than its initial genesis (this includes a change to the title of the study). The result is a more robust and transparent analysis.

Major Issue:

In this study, TC formation is defined as the first appearance of 35 kt winds. This is confusing choice, since it makes it difficult to relate this work to other studies (other than the Dare and McBride (2011) paper that they followed) and is not consistent with the operational definition of TC genesis. This condition screens out all unnamed depressions as well (tropical cyclones that never reached 35 kt). Also, it appears that cases where the initial intensity is greater than 35 kt are eliminated. This also seems like a poor choice because some of the higher latitude formations start with the larger intensities. The description of how subtropical and extratropical classificaitons were handled was also not clear. Were these screened out or not?

As a simple example, I looked at the 14 tropical cyclones from the 2013 Atlantic hurricane season (through Melissa). Of those 14 cyclones, 3 to 5 may have been screened by the procedures used in this study, either because the first record had an intensity that was too high, or because the max wind never reached 35 kt. Also, in one case, there was a 30 h time lag between the first tropical cyclone position and when the cyclone reached 35 kt. A much simpler definition of genesis would be to use the first position in the best track when a system was classified a tropical cyclone.

Because of the above issues, this paper is not about tropical cyclogenesis as the title indicates, but is really about early stage intensification. I considered recommending rejection of the manuscript, but there are many good results in this paper that are worthy of publication. As a compromise, the authors need to include more discussion of their assumptions and why they consider this to be a paper about tropical cyclone genesis. This discussion should include an analysis of how many cases are missed because of the requirement for a storm history before 35 kt is reached, and the elimination of all unnamed depressions. The discussion should also include an analysis of the time lag between the first position in the best track as a tropical cyclone and the time it took to get to 35 kt.

This is a very perceptive set of comments that we hope we have thoroughly addressed both in the revised study and through the new electronic supplement. The reviewer is correct that following the technique of Dare and McBride (2011) was one of the motivations for this definition of “genesis” (i.e. the first 35-kt intensity estimate). However, we also set this threshold to ensure that we focus on systems that reach an intensity sufficient to allow them to becomes self-sustaining circulations [e.g. Chapter 8.3 of Laing and Evans (2011)]. We have added a direct statement to this effect in section 2 of the revised study, “This definition focuses on the point at which the precursor vortex becomes a self-sustaining circulation (Laing and Evans 2011) and is consistent with the definition adopted by Dare and McBride (2011). The study thereby concentrates on the early intensification stage of developing storms rather than on precursor tropical depressions that may or may not intensify.” We have also changed the title to de-emphasize “tropical cyclogenesis” in favour of “tropical cyclone development”, because it is developing systems that we investigate as noted by the reviewer. The reviewer's concerns about the potential impact of this choice are perfectly valid, and have led to the addition of an electronic supplement to the manuscript in which the sensitivity to the “development time” definition is evaluated (section 2 of the supplement). This is also referenced and described briefly in the second paragraph of section 1 of the main study.

With regards to the rejection of storms whose first entry wind estimates are greater than 35 kt, McTaggart-Cowan et al. (2008) note at the end of section 2a that, “to eliminate cases in which the cyclogenesis stage of the TC life cycle is missing from the archive—and in keeping with Elsner et al. (1996)—only storms with estimated winds in the first best-track report less than tropical storm strength (17 m $s^{-1}$) are retained (95 of the 591 storms in the 1948–2004 best-track record are rejected by this condition, leaving 496 TCs in this study)." Although the <= 35-kt condition does not affect the majority of storms in the dataset, the reviewer makes a good point that it may disproportionately influence the counting of higher latitude systems. A climatology in which this threshold is dropped has been performed, with the results qualitatively identical to those of originally presented[1]. This climatology is now presented and discussed in section 3 of the electronic supplement and a discussion of the impact has been added to the second paragraph of section 2 of the revised study.

In light of the second paragraph of this comment, we double-checked the threshold application in our climatology to ensure that of the 14 tracked North Atlantic tropical cyclones, 12 would have been included in this study (v03r05 of IBTrACS does not include the 2013 North Atlantic season). Tropical Depression Eight would not be included because it did not reach Tropical Storm strength and is thus not considered to have "developed" as a tropical cyclone. Tropical Storm Karen would not be included because its initial intensity estimate is 45 kt in the best track. Given that Dvorak-based analyses from TAFB had been tracking and intensifying the system from 25 kt over the previous 24 h, it seems defensible to say that the initial intensification stage of the storm is not covered by the best track (see Fig. 2 of the storm report prepared by Todd Kimberlain).

Storms classified "extratropical" or "subtropical" were screened out as noted by the reviewer. The statement to this effect on lines 378-381 of the original submission was unclear and has been revised to read, "Dare and McBride (2011) consider only formations that occur equatorward of 35$^{o}$, a condition that is not applied here in recognition of the fact that TT can occur at a relatively high latitude. However, consistent with Dare and McBride (2011), storms classified as either "subtropical" or "extratropical" in the best track archive are not considered in this investigation in order to eliminate non-tropical systems from the dataset."

Minor Comments:

Lines 61-71: In the 2009 Weather and Forecasting paper by Schumacher et al (Objective Estimation of the 24-h Probability of Tropical Cyclone Formation), they use an SST threshold of 21 deg C as the lower limit for tropical cyclone formation. That is fairly consistent with the current study and should probably be

1 The creation of this dataset required a rerunning of the full McTaggart-Cowan et al. (2013) development pathway climatology with a similar restriction relaxed.

mentioned somewhere in the paper.

Thank you for pointing out this relevant publication. For consistency with Schumacher et al. (2009), the 22$^{o}$C isotherm has been replaced by 21$^{o}$C in Fig. 8 and this reference has been added in the final paragraph of section 4.

Pages 5-6: Is this section part of the abstract or is it the introduction?

Introduction. BAMS articles do not have a separate section labelled "Introduction", which is why the two appear to merge together. The page break indicates the distinction.

Line 354: Suggest changing "into subtropics" to "into the subtropics".

Fixed.

Line 437: "using" is misspelled as "usnig".

Fixed.

Line 531: "Pacific" is misspelled as "Pacifc"

Fixed.

Figure 4 caption: "black" should be "blue"

Fixed. Thank you.

Reviewer B

Review of "Revisiting the 26.5°C Sea Surface Temperature Threshold for Tropical Cyclogenesis (BAMS-D-13-00254) " by Ron McTaggart-Cowan, Emily Davies, Jonathan Fairman Jr., Thomas Galarneau, and David Schultz.

This manuscript discusses a proposed new method for determining the potential for tropical cyclone development. Although I found the manuscript to be both interesting and generally well written (save for some issues discussed in Major point 2) I also feel that some additional supporting material and more detailed explanations regarding certain aspects of the manuscript are required before it is suitable for publication. Thus, I am recommending that this manuscript be accepted once the major and minor points discussed below are adequately addressed.

Thank you for stressing the importance of links to the underlying climatologies, and improved descriptions thereof. In order to clarify the development pathway classification technique, we have expanded the related discussion and included a supporting figure that displays the classification strategy (Fig. 2 of the revised manuscript). We have also merged the “Data” section and the sidebar into the body of the manuscript to integrate further the methodological description.

Major Points:

1. P.14. The authors state that their new coupling index can be used to develop a combined threshold for assessing the potential for tropical cyclone development that is superior to using either the traditional 26.5° C SST threshold or their newly developed coupling index alone. While this may be true, I feel that it would be helpful if the authors provided some objective criteria for determining when an event should be classified as a non-TT, weak TT, and strong TT event (perhaps this could be included in a short table). For instance, was or if not couldn't the tropopause height or coupling index themselves be used to help objectively classify which of the three development groups an event fell into? I understand that the McTaggart-Cowan (2013) classification scheme was used to a certain degree for this study. However, I think that other criteria (such as those cited above) that were obtained based upon the results of this study could and perhaps should have been used as well. Otherwise, it will likely be difficult for climate and statistical seasonal forecast modelers and other potential users of the author's new development prediction scheme to successfully employ their technique as was suggested in section 5 of the current manuscript.

This study does indeed depend strongly on McTaggart-Cowan et al. (2013) for its development pathway classifications, so we have strengthened the ties to that work. A new figure (Fig. 2) has been added to show the classification strategy employed by McTaggart-Cowan et al. (2013) as it applies to the three categories used here. The paragraph explaining the development pathway climatology has been expanded and moved to the body of the manuscript (now the final paragraph of the "data and methods" section). Included in this expansion is a discussion of the differing goals of the McTaggart-Cowan et al. (2013) and current studies that explains why the current work makes use of the pathway climatology but does not impact the classifications themselves:

"An important distinction between the investigation of McTaggart-Cowan et al. (2013) and the current study is that the former did not evaluate the likelihood of tropical cyclogenesis. It focused instead on the development pathway that would be followed if development were to occur. In the current study, McTaggart-Cowan et al. (2013) pathway classifications underpin the conditional application of a modified thermodynamic limit for tropical cyclogenesis, precisely to assess the probability of tropical cyclone development."

2. P. 18-P. 20. Line 367-409. I believe that the manuscript would be significantly improved if the authors incorporated the material contained in the Sidebar 1-Methods section into the appropriate sections of the main portion of the text rather than having it remain as a separate section at the end of manuscript. Specifically, I believe most readers (myself included) would benefit from knowing how such things as the determination of storm intensity and location, SST, dynamic tropopause height, and pathways for classification of storm development type were determined while reading the main portion of the manuscript rather than after the Implication section of the manuscript as the aforementioned material describes important aspects of this study that are likely to impact a reader's evaluation of the study's results.

Sorry about this. We were trying to follow the BAMS suggestion to set detailed "data and methods" material apart from the main body of the study in a sidebar (http://www2.ametsoc.org/ams/index.cfm/publications/authors/journal-and-bams-authors/bams-authors/less-is-more-some-writing-tips/). In print the sidebar would (hopefully) have appeared beside the "Datasets" section rather than at the end of the study; however, we agree than in the current draft manuscript form the layout is more confusing than anything else. We have thus eliminated the sidebar and incorporated all of the material into section 1 (now called "Data and Methods"), including a brief discussion of the sensitivity tests now described in detail in the electronic supplement in response to the suggestion of Reviewer #1.

Minor Points:

1. P.10. Lines 177-179. The authors note that all other formation events are classified as non-TT events even though some were characterized by upper and/or lower level baroclinicity. Further, on P. 20 lines 406-408 the authors mention that there were five classification categories used. Thus, it may be useful to at least cite the % of cases from each of the three non-TT pathways (non-baroclinic, low level baroclinic, and trough induced) that were ultimately included in the singular non-TT classification group that was utilized in this study.

Original versions of this study indeed used the full spectrum of development pathways; however, the results were synthesized in this submission for simplicity after it was found that the conditional application of the coupling index-based threshold was useful primarily for the TT-based categories. We have added the fraction of cases following each of the original pathways in Table 1 of the revised manuscript.

2. P. 11 Lines 189-191. The authors state that there is a slow ramp up of the strong TT pathway, whereas it appears to me that there is actually a faster ramp up for storms in that pathway relative to those in the weak and non-TT groups given that there is a higher cumulative occurrence of such events for the lower SSTs. To illustrate, Fig. 5 appears to indicate that almost 30% of strong TT events occurred for SSTs from ~20-26.5°C with only a few percent of non-TT and weak TT events occurring over that same range of SSTs. Could the author's please provide additional clarification that will aid in the interpretation of the above statement?

A distribution with a long left tail has a sustained shallow slope (large ramp-up) at the low end of the cumulative distribution function as for the strong TT group in Fig. 5. This definition of "ramp-up" has been added in the first paragraph of section 2: "... the long left tail of the development SST distribution leads to a slow ramp-up (sustained shallow slope) of the cumulative distribution function ...". A perfect (and useful) threshold would have a very sharp transition from a zero slope (no sub-threshold formations) to a very steep slope (lots of formations just above the threshold). This is why the sustained low slope or "ramp-up" for the strong TT group is an indication of both the large fraction of cold events and, related, the poor performance of the SST threshold. This is now emphasized in fourth paragraph of section 3 in reference to Fig. 5: "The slow ramp-up of the strong TT pathway over low SSTs, indicative of a left-skewed distribution containing an appreciable number of cold events, provides further evidence that the 26.5$^{o}$C threshold is not applicable to this class of development [footnote: An ideal threshold would result in a cumulative distribution function that abruptly transitions from a near-zero sub-threshold slope to a steep slope once the threshold is reached.]."

3. P. 13 Lines 248. Again as discussed in Minor point 2 above, the slow ramp up cited by the authors appears to be a fast ramp up from my vantage point.

The text has been modified to clarify that it is the onset of a steep slope that is the desired behaviour of a well-defined threshold: "Recasting the cumulative distribution function in terms of the coupling index instead of SST demonstrates that this quantity is effective at reducing the slow ramp-up of the strong TT category by steepening the distribution's slope ...".

Reviewer C

This is a very well written and informative paper and I accept it with some minor revisions listed below. I have divided the revisions into essential and non-essential.

Thank you for the kind words on our manuscript. In response to your suggestions, we have enhanced our description of the underlying development pathway climatology and have provided further justification for our use of the coupling index in this study.

Essential:
1) What objective criteria did you use to classify a storm as a Tropical Transition (TT)? Is it the 20 degree latitude mentioned in Davis and Bosart 2003?

The use of the McTaggart-Cowan et al. (2013) development pathway climatology to define the pathway to tropical cyclogenesis (non-TT, weak TT or strong TT) has been emphasized in the revised study, with the relevant discussion (now the final paragraph of the "Data and Methods" section) incorporated into the body of the manuscript. In response to this comment and a similar question raised by Reviewer B, a figure (Fig. 2) has been added to the revised manuscript that displays the classification strategy. No geographical information is used in the determination of development pathway.

2) You used the "coupling index" as your proxy for deep moist stability yet you mentioned several others (ie. equilibrium level, etc.) Did you actually test the others to see if the coupling index was indeed a better performer?

We chose to use the coupling index for several reasons, and have not applied the techniques developed in this study to the equilibrium level. The points provided below are summarized in an expanded version of the third paragraph of section 4 in the revised study to provide readers with a better understanding of the rationale behind the selection of this predictor.

1. The coupling index is directly related to the relevant dynamics of the baroclinic environments in which the majority of cold development events occur. Because the coupling index is defined using the potential temperature of the dynamic tropopause and the lower-level equivalent potential temperature, it provides a direct evaluation of the link between upper- and lower-level disturbances [e.g. Roebber and Gyakum (2003)]. This is consistent with the Eady model of baroclinic growth, where boundary temperature perturbations act as surrogates for potential vorticity anomalies as Eady "edge waves" (Davies and Bishop 1994). With

"boundaries" defined as the top of the boundary layer [~850 hPa, a boundary condition proposed by Hoskins et al. (1985)] and the dynamic tropopause, the superposition of edge waves is directly represented by the coupling index.

2. The coupling index has proven useful in describing the evolution of hybrid and tropical cyclone-like developments, where it clearly identifies the preferred region for interaction between upper- and lower-level PV features (Bosart and Lackmann 1995; McTaggart-Cowan et al. 2003, 2006, 2010).
3. The coupling index is generally related to the classification metrics used by McTaggart-Cowan et al. (2013) to develop the pathway climatology, and is therefore well-suited to be a pathway-specific predictor. The upper-level Q-vector forcing typically represents the presence of a progressive trough (lowered potential temperatures on the dynamic tropopause and therefore a lower coupling index), while lower-level baroclinicity results in a portion of the near-storm environment with reduced lower level temperatures (again lower the coupling index). This is not a coincidence, but the result of the application of an Eady-type growth model for baroclinically influenced tropical cyclone development (see item 1 above).
4. The coupling index is easy to compute and interpret. This makes it methodologically preferable to the equilibrium level that requires a multi-page explanation of the computational technique (Mauk and Hobgood 2012b). (Note that one of the attractive features of the SST-based threshold is its simplicity.) This is important for follow-up studies that aim to reproduce and extend the current work, and also for the physical justifications for the threshold provided in the study.
5. Technical aspects of the equilibrium level calculation notwithstanding, the coupling index provides a more direct link to the relevant baroclinic dynamics than the primarily thermodynamically based equilibrium level. The coupling index incorporates a strong background of baroclinic dynamics via both its link to edge waves and the Rossby penetration depth, while the equilibrium level focuses primarily on the characteristics of the convective profile. Given the direct relevance of baroclinic processes to TT, we believe that the coupling index provides a better representation of the underlying mechanisms involved in tropical cyclogenesis following these pathways and therefore serves as a more physically justified predictor.

Non-essential (I will leave this up to you to decide on implementation). 1) Page 5, you mention that the 26.5C SST threshold has been a matter of debate. Maybe include a few references?

The subsequent paragraph provides some examples of the debate, showing that 26.5$^{o}$C is not universally accepted.

2) You included a 'sidebar' to include the datasets, why not put it in the section 'datasets?' I rarely see sidebars used.

Sorry about this. We were trying to follow the BAMS suggestion to set detailed "data and methods" material apart from the main body of the study in a sidebar (http://www2.ametsoc.org/ams/index.cfm/publications/authors/journal-and-bams-authors/bams-authors/less-is-more-some-writing-tips/). However, we agree than in the current draft manuscript form the layout is more confusing than anything else. We have thus eliminated the sidebar and incorporated all of the material into section 1 (now called "Data and Methods").

3) Bottom of Page 7. "The discrepancy between these estimates..." would sound better if you put "The discrepancy between these percentage estimates..."

Thank you. Done.

4) Page 15 you labeled the area in Figure 8 as the "Goldilocks Zone." A Goldilocks zone usually refers to a region where if one parameter were too high or too low it wouldn't be ideal. The parameter you are actually referring to is baroclinity. Yet at higher latitudes you have more baroclinicity, however it's the lower SST that limits TC events. But if you'd like to keep the name, that's perfectly fine with me.

That's a fair point. It's really the ingredients of the coupling index that we're referring to rather than baroclinicity itself. At low latitudes, upper tropospheric temperatures are too high (little baroclinicity); at high latitudes, SSTs are too cold (little deep convection). We have clarified this in the text as, "Because low values depend on both a cool upper-troposphere and a relatively warm boundary layer, a ``Goldilocks zone'' emerges in the subtropics. It is in this band that midlatitude troughs penetrate sufficiently equatorward to play a role TT-based development over SSTs that are warm enough to sustain deep convection (Schumacher et al. 2009)."

**References**

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