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 nonzero 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, p. 31) 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, and the 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 subthreshold SSTs. However, Dare and McBride (2011) also find that 26.5°C is a reasonable threshold when the SST is averaged over the 2-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.

**DATA AND METHODS.** This study employs four global datasets that cover a common 25-yr period from 1989 to 2013: tropical cyclone best tracks, high-resolution SST, atmospheric analyses, and cyclone development pathway classifications. A total of 1,757 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 (IBTrACS), 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 (18 m s⁻¹)] 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 2,125 tropical cyclones in the 1989–2013 dataset, 2,026 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 the “Sensitivity to development-time definition” section of the 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 total of 1,757 storms for this study (83% of the original dataset). In the "Sensitivity

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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 Japan Meteorological Agency best track (Knapp et al. 2013).
to initial intensity restriction” section of the supplement, this condition is shown to be effective at eliminating invalid IBTrACS 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 nontropical 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 is 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 preformation 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) backtracking 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 et al. 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} 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). 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

![Fig. 1. Distribution of storm-centered 2° area-average SST at tropical cyclone development time (gray 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 gray bars. Binning is performed at 1°C intervals centered on integer SST values between the 20° and 34°C extrema of the dataset: the 26°C bin therefore contains all events that occur over waters between 25.5° and 26.5°C.](image-url)
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.

**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 surface enthalpy fluxes required to support active convection and to promote the development of a self-sustaining circulation (Emanuel 1986, 1989; Black et al. 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 $2^\circ$ area-averaged SSTs below the $26.5^\circ$C threshold: roughly 4% of the 1,757 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 $26.5^\circ$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 distribution 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-yr 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.

![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 the “Data and methods” section. 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)].](image-url)
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 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 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

Table 1. Summary description of the tropical cyclogenesis development pathways 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 subpathways of the combined non-TT group, with their percentage contribution to non-TT developments identified in parentheses in the second column.

<table>
<thead>
<tr>
<th>Pathway name</th>
<th>Subpathway (%)</th>
<th>Description</th>
<th>Occurrence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-TT</td>
<td>Nonbaroclinic (85%)</td>
<td>No appreciable baroclinic influences</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>Low-level baroclinic (6%)</td>
<td>Strong lower-level thermal gradients without an upper-level disturbance</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Trough induced (9%)</td>
<td>Upper-level disturbance without appreciable lower-level thermal gradients</td>
<td>3</td>
</tr>
<tr>
<td>Weak TT</td>
<td>Upper-level disturbance with moderate lower-level thermal gradients</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Strong TT</td>
<td>Upper-level disturbance with strong lower-level thermal gradients</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

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.

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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 pro-
motes 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 (Kelly and Mock 1982).

In light of the apparent relationship between tro-
popause 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.

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 forma-
tions 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
(WEC) events (Davis and Bosart 2004) are here re-
ferred to as weak TT events. In these cases, near-sur-
faced winds around the precursor are not strong enough
to enhance surface fluxes sufficiently to sustain the
vortex [less than 10–15 m s\(^{-1}\) (Emanuel 1995; Fairall
et al. 2003)]. Conversely, the winds associated with
an initial disturbance involved in strong extratropical
cyclone (SEC) 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

Fig. 4. Probability distribution of the mean dynamic
tropopause pressure within 10° of the formation loca-
tion of the tropical cyclone. Storms are classified as
“warm” or “cold” depending on their formation-time
SST value and are 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 environ-
ment for consistency with previous studies, and the
results of this work are not highly sensitive to reason-
able 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.
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. 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 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, nonzero 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 downward by over 2°C (to 24.3°C) for strong TT developments. Such revisions may be considered a first step toward accounting for the

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

4 A threshold with a null type-II error rate (perfect sensitivity) is entirely achievable, but it 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.
impact of environmental baroclinicity on tropical cyclogenesis, but they could also be interpreted as an indication that an important element is missing from the description of the thermodynamic factors limiting development.

**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 gray backgrounds in Fig. 7b), from those undergoing weak TT and strong TT over much lower SSTs in the presence of a trough aloft (dark gray backgrounds in Figs. 4c and 4d). 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 it 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 midlevel 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 5th 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

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 (third column) uses the criteria corresponding to the values in boldface in the previous two columns to enhance the performance of the ingredients-based tropical cyclogenesis model across the full range of development environments.

<table>
<thead>
<tr>
<th>Pathway</th>
<th>26.5°C SST</th>
<th>22.5°C coupling index</th>
<th>Combined thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-TT</td>
<td>2.5</td>
<td>14.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Weak TT</td>
<td>6.0</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Strong TT</td>
<td>27.5</td>
<td>5.9</td>
<td>5.9</td>
</tr>
<tr>
<td>All</td>
<td>3.7</td>
<td>13.2</td>
<td>3.0</td>
</tr>
</tbody>
</table>
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 midlevels toward 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 of 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; Dias 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. 2014), 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 the physical relevance of the coupling index, but it 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.

**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 timescales. This preliminary introduction of a pathway-dependent predictor in statistical models of tropical cyclogenesis potential represents a first step toward an index that is conditional on the development pathway supported by the storm environment.

On climate timescales, the sensitivity of the coupling index to tropospheric stability makes it well suited to adapt to the nonuniform 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. 2011). 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 U.K. Natural Environment Research Council (NERC) to the Diabatic Influences on Mesoscale Structures in Extratropical Cyclones (DIAMET) project at the University of Manchester (Grant NE/1024984/1), and partial funding for Fairman was provided by NERC to the Precipitation Structures over Orography (PRESTO) project at the University of Manchester (Grant NE/I005234/1). Partial funding for Galarneau was provided by NOAA/ HFIP Grant NA12NWS4680005. Early versions of the study benefited significantly from comments supplied by Drs. John Gyakum, James McTaggart-Cowan, and Ayrton Zdra. The constructive comments of three anonymous reviewers during the peer review process greatly helped to improve the final study.

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