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Phase transitions between tropical, subtropical, and extratropical cyclones: A review from IWTC-10

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Abstract

This review, which was adapted from a Tenth International Workshop on Tropical Cyclones (IWTC-10) report, discusses research findings and operational practices relevant to cyclone types and phase transitions (extratropical, subtropical, and tropical). The cyclone phase space (CPS) method is widely used in both historical investigations and real-time evaluation of cyclone type and transition; however, CPS parameter values depend on input data resolution, and universal thresholds do not currently exist to delineate when a cyclone transitions from one type to another. Assessments of phase transitions in a changing climate highlight potential latitude shifts in extratropical transition and increased potential for tropical transition, but realistic projections of future trends likely require high-resolution simulations that can capture the cyclone warm core.

Operational meteorological centers apply varied approaches to cyclone classification via CPS parameters and other criteria, some of which depend on the tropical basin, yet these approaches cannot fully address challenges in operational classification and subsequently in communicating risks associated with these phase transitions. We recommend a multivariate historical assessment of tropical and subtropical cyclones across all basins in which they occur, including the South Atlantic Ocean and the Mediterranean Sea, to identify the potential for a more universal cyclone classification approach that meets operational needs.

Keywords: Tropical cyclone; Subtropical cyclone; Extratropical transition; Tropical transition

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1. Introduction

A tropical cyclone (TC) is a synoptic-scale warm-core cyclone driven by heat fluxes from the ocean surface, and the energy from those fluxes is diabatically released via organized deep convection. An extratropical cyclone (EC) is a synoptic-scale cold-core cyclone driven by the conversion of available potential energy from strong horizontal temperature gradients (baroclinic instability) into kinetic energy that strengthens winds and decreases surface pressure. Though their dynamics differ, both a TC and an EC are capable of bringing significant hazards such as strong winds, heavy rain, and storm surge to populated areas.

Extensive research has explored the nature, dynamics, and climatologies of these two cyclone types. A growing body of literature focuses on a third type of cyclone that does not fit into either category in part because its maintenance relies on both energy sources to some degree (e.g., Guishard et al., 2009; Gozzo et al., 2014; Bentley et al., 2016). The term generally applied to this hybrid cyclone type is *subtropical cyclone* (SC), though such storms may receive other names depending on location: examples include *Kona lows* in the central and eastern North Pacific, *east-coast lows* near Australia, and *medicanes* in the Mediterranean Sea (da Rocha et al., 2019). Note that local terms are not necessarily applied based on the cyclone's thermal structure: the term *east-coast low* may refer to any cyclone that develops near the east coast of Australia, and the term *medicane* is applied to cyclones with a range of characteristics.

According to the WMO Global Guide to Tropical Cyclone Forecasting (WMO, 2019), a TC is operationally defined as "*a warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center*." An EC is defined as "*a synoptic-scale low pressure system which derives its energy primarily from available potential energy in a pre-existing horizontal temperature gradient*."

The definition of an SC is comparatively detailed (WMO, 2019; ICAMS, 2023):

"*A non-frontal low-pressure system that has characteristics of both tropical and extratropical cyclones. Like tropical cyclones, they are non-frontal, synoptic-scale cyclones that originate over tropical or subtropical waters, and have a closed surface wind circulation about a well-defined center. In addition, they have organized moderate to deep convection, but lack a central dense overcast. Unlike tropical cyclones, subtropical cyclones derive a significant proportion of their energy from baroclinic sources, and are generally cold-core in the upper troposphere, often being associated with an upper-level low or trough. In comparison to tropical cyclones, these systems generally have a radius of maximum winds occurring relatively far from the center (usually greater than* 60 nm*), and generally have a less symmetric wind field and distribution of convection*."

However, key characteristics such as how much energy is derived from baroclinic sources or the level of asymmetry in the wind field and convection are not readily quantifiable.

It is known that a cyclone can evolve from one type to another, a process referred to as a *phase transition*. For example, a TC becoming an EC is known as extratropical transition (ET; Evans et al., 2017), an evolutionary pathway that can occur as a TC gains latitude and enters a baroclinic environment characterized by horizontal temperature and moisture gradients. It is also possible for an EC or SC to undergo tropical cyclogenesis in the presence of an upper-level disturbance when convection helps develop a deep warm core over a sufficiently warm ocean, known as tropical transition (TT; Davis and Bosart, 2004; WMO, 2019). Finally, an individual TC or EC can evolve into an SC when baroclinic influences increase (TC to SC) or when deep convection supports warm core development (EC to SC); both trajectories are known as subtropical transition (ST). Since the nature of hazards such as strong winds, heavy rainfall, and storm surge are related to cyclone type and structure, it is critical to identify these cyclone types and phase transitions (Table 1), to predict the likelihood for a given phase transition before it occurs, and to subsequently communicate the evolving cyclone's potential impacts in an actionable manner.

Various tools exist to support cyclone type and phase transition identification. Infrared (IR) satellite imagery enables evaluation of a cyclone's cloud pattern (e.g., Klein et al., 2000) and has been in operational use for decades, but IR images are limited to cloud-top or surface temperature estimates and thus cannot capture the thermodynamic environmental conditions that affect cyclone type and evolution. In response to this need, the cyclone phase space (CPS; Hart, 2003) was developed to depict three-dimensional thermal structure of a cyclone via three parameters computed from numerical weather prediction (NWP) or reanalysis fields (Fig. 1). The first parameter is the difference in 600–900-hPa geopotential thickness between the left and right semicircles of the cyclone relative to its motion vector (a measure of thermal symmetry, B) to infer the strength of the frontal nature of the cyclone. The second and third parameters are thermal wind values computed over two layers, 600–900 hPa ($-V_T^L$) and 300–600 hPa ($-V_T^U$). In the original method, all parameters are calculated within 500 km of the cyclone center.

In a thermally-asymmetric EC, the presence of fronts would produce a greater difference in 600–900-hPa thickness between the cyclone's left and right semicircles and thus a higher B value (>10 m), whereas the absence of fronts in a thermally-symmetric TC would produce a B value that is near 0. An EC has a cold core relative to its environment and thus increasing winds with height according to thermal wind balance, and a TC has a warm core and thus decreasing winds with height; a deep warm core is characterized by $-V_T^L > 0$ and $-V_T^U > 0$, and a deep cold core is characterized by $-V_T^L < 0$ and $-V_T^U < 0$. As a hybrid between these two cyclone types, an SC tends to exhibit a low-level warm core ($-V_T^L > 0$) and an upper-level cold core ($-V_T^U < 0$) alongside a range of B values.

However, observed cyclones do not always follow these thresholds: SCs have been documented with values that imply a lower-level cold core ($-V_T^L < 0$; Guishard et al., 2009), and occluded ECs can exhibit CPS values that resemble a

Table 1
Definitions of cyclone type and phase transitions. References for CPS threshold values listed in the third column are noted in the second column.

Phenomenon	Definition	CPS thresholds
Extratropical Cyclone (EC)	A synoptic-scale low pressure system driven by horizontal temperature gradients (baroclinicity) that persists for at least 24 h. Strongest winds are in the upper levels.	$B \gg 0$ $-V_T^L < 0$ $-V_T^U < 0$
Tropical Cyclone (TC)	A meso-to-synoptic scale low pressure system driven by latent heat release from surface enthalpy fluxes that persists for at least 24 h. Strongest winds are in the lower levels near the cyclone center.	$B < 10$ $-V_T^L > 0$ $-V_T^U > 0$
Subtropical Cyclone (SC)	A synoptic-scale low pressure system with a low-level warm core and, at times, an upper-level cold core. Strongest winds are in the lower levels but often far from the center. An SC should not have been tracked as either a purely cold- or warm-cored structure for more than 24 h prior to attaining hybrid structure, has cyclolysis as an SC, and the system needs to persist in its hybrid form for at least 36 h (i.e., more than one diurnal cycle). (Guishard et al., 2009; Gozzo et al., 2014).	*North Atlantic:* $-V_T^L > -10$ $-V_T^U < -10$ *South Atlantic:* $B < 25$ $-V_T^L > -50$ $-V_T^U < -10$
Extratropical transition (ET)	The process by which a TC evolves into an EC with an intermediate subtropical phase or by which an SC evolves into an EC. This report focuses on the former that generally occurs when a TC encounters a baroclinic environment and reduced SST at higher latitudes (Evans et al., 2017).	*North Atlantic:* Start: $B > 10$ End: $V_T^L < 0$ *South Atlantic:* Start: $B > 25$ End: $V_T^L < -50$
Tropical transition (TT)	The process by which an EC evolves into a TC with an intermediate subtropical phase or by which an SC evolves to a TC (McTaggart-Cowan et al., 2015; Bentley et al., 2016; Chang et al., 2019).	*CPS thresholds are not defined*
Subtropical transition (ST)	The process by which an EC or a TC evolves into an SC and has its cyclolysis in this phase (Quitán-Hernández et al., 2020; Kouroutzoglou et al., 2021; Reboita et al., 2022; Calvo-Sancho et al., 2022).	*CPS thresholds vary*

subtropical phase possibly related to a warm anomaly in the low levels (Hart 2003; Reboita et al., 2017). In addition, CPS thresholds applied to SCs vary by basin: $V_T^L > -10$ and $-V_T^U < -10$ in the North Atlantic (Guishard et al., 2009) and $B < 25$, $-V_T^L > -50$, and $-V_T^U < -10$ in the South Atlantic (Gozzo et al., 2014). Finally, the 500-km radius for calculations may need to be adjusted for cyclone size, such as small 'tropical-like cyclones' in the Mediterranean Sea (Miglietta et al., 2013). Also, the CPS values themselves depend on the resolution of input fields from either NWP or reanalysis data. Such caveats pose challenges to defining global thresholds for these cyclone types and the phase transitions between them.

Despite limitations in the method, CPS has been used to explore cyclones across the globe, including subtropical cyclones and medicanes. Guishard et al. (2009) crafted a North Atlantic SC climatology via CPS. Evans and Braun (2012) used CPS parameters to help identify SCs in the South Atlantic and subsequently evaluate their characteristics and climatology. Gozzo et al. (2014) also evaluated South Atlantic SCs via CPS but expanded their assessment to include shallow and/or weak hybrid systems that can develop near the southeastern coast of South America. Beyond the Atlantic, CPS has been used to identify medicanes for further analysis (González-Alemán et al., 2019), and de la Vara et al. (2021) explored the viability of using less data with CPS to characterize medicanes for climate change analysis.

For phase transitions, CPS has been applied to ET in individual basins, such as Hart et al. (2006) and Zarzycki et al. (2017) in the North Atlantic, Kitabatake (2011) in the western North Pacific, and Wood and Ritchie (2014) in the eastern North Pacific. Recent work capitalized on these efforts to produce the first global ET climatology (Bieli et al. 2019a; 2019b). Corroborating basin-specific results, they found that most TCs follow the "traditional" ET pathway by first becoming asymmetric before developing a cold core (Fig. 1), but some eastern North Pacific and North Atlantic TCs develop a cold core prior to becoming asymmetric. It is likely that environmental conditions and the nature of the TC track affect evolution during ET, such as higher SSTs helping to maintain deep convection and thus the warm core while the TC becomes increasingly asymmetric. Also, the manner in which a TC formed may affect its later cyclone phase evolution: by combining the Bieli et al. (2019a,b) ET classification with the McTaggart-Cowan et al. (2013) TC genesis pathway classification, Datt et al. (2022) found a statistically significant relationship between the genesis pathway and ET. Specifically, the "strong tropical transition" and "trough induced" pathways exhibited a significantly greater ET fraction compared with all other pathways, and these relationships remained statistically significant when accounting for genesis latitude. As a result, there may be a lasting effect from the genesis pathway on the probability of an eventual ET, a potential consideration for forecasters when assessing ET likelihood.

Conversely, less work has applied CPS parameters to quantifying tropical transition (TT) and subtropical transition (ST). Bentley et al. (2016) explored a potential vorticity-based technique to capture baroclinic and diabatic processes to identify SCs and subsequently evaluate their TT pathways, citing limitations in CPS as one motivator. Case studies have employed CPS to explore the tropical transition of Anita (2010)

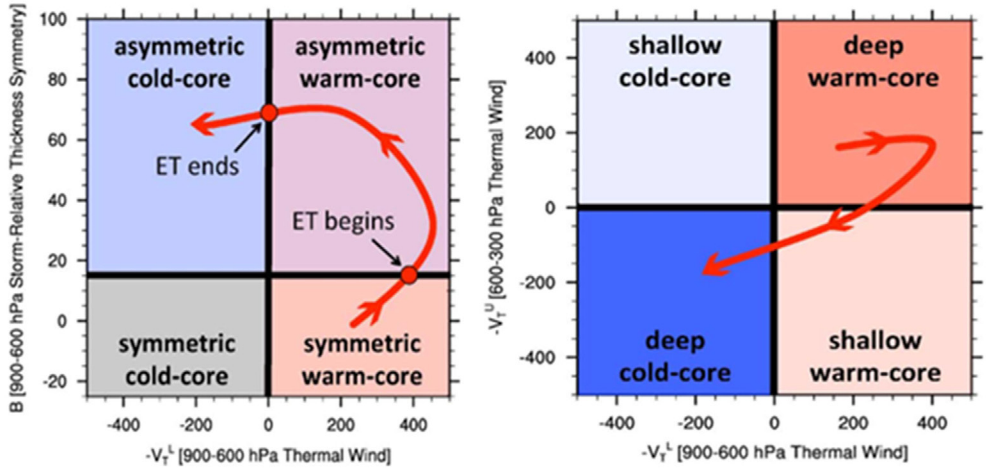

Fig. 1. CPS diagrams showing the phase space evolution of ET according to (left) *B* and -V_T^L and (right) -V_T^L and -V_T^U. Adapted from Zarzycki et al. (2017).

in the South Atlantic alongside satellite imagery analysis and assessment of eddy kinetic energy (Dias Pinto et al., 2013) and of Chris (2012) in the North Atlantic to assess ensemble forecasts of the transition process (Maier-Gerber et al., 2019). Evaluation of ST is less common, with one case study documenting the formation of Raoni (2021) from an EC via CPS, observations, and numerical simulations (Reboita et al., 2022) and another evaluating model representation of a ST event and the resulting SC via CPS parameters (Quitián-Hernández et al., 2018).

A common thread in the use of CPS in these studies is its relatively simple application to commonly-available reanalysis or NWP output fields, which also makes it comparatively straightforward to implement in operational practice. Regional Specialized Meteorological Centers (RSMCs) as well as the Joint Typhoon Warning Center (JTWC) and the Brazilian Navy incorporate CPS evaluation into their operational forecast process (e.g., Wang et al., 2023) and in post-storm analysis (e.g., Landsea 2023); see Appendix A for a detailed list of approaches by each forecast agency. However, none of these approaches solely rely on CPS, and no universal CPS parameter thresholds exist for cyclone type as noted earlier (Table 1).

Operational forecasting approaches regularly evolve to improve accuracy, develop or enhance products, and improve communication with users. These changes can be prompted by individual high-impact events (e.g., Dorian in 2019 bringing widespread hazards to eastern Canada) and by specific concerns (e.g., heavy rainfall in Japan caused by predecessor rain events or by a cyclone strengthening during and after ET). In addition, capturing media attention can be challenging for TCs that lose tropical characteristics and are declared “post-tropical,” such as Ida (2021), because they were not expected to bring headline-prompting hazards such as high winds, waves, and storm surge. Yet Ida's heavy rainfall while extratropical (with rain rates at times exceeding 75 mm per hour) produced widespread flooding impacts in the northeastern U.S. (Beven et al., 2022), providing yet another example of the importance of quantifying and predicting cyclone phase transition.

The review presented in this manuscript builds from the report (Wood et al., 2022) presented at the Tenth International Workshop on Tropical Cyclones (IWTC-10) in Bali, Indonesia, in December 2022, regarding recent progress in understanding and predicting phase transitions across the tropical-subtropical-extratropical cyclone spectrum, a deviation from past IWTC reports which largely focused on ET. Ironically, advances in understanding of cyclone type and transitions have improved interpretation of complex phenomena in the real atmosphere, yet these advances have also exposed challenges in consistently *defining* cyclone type and transition. Section 2 covers impacts of and variability in cyclone phase transitions, section 3 discusses updated approaches to identifying and predicting cyclone phase transitions, section 4 presents advances in operational forecasting and remaining challenges, and section 5 summarizes key points and suggests future recommendations.

2. Impacts of and variability in phase transitions

2.1. Extratropical transition (ET)

Our understanding of ET has further progressed in recent years concerning both local structural changes during ET and the remote downstream impact of transitioning cyclones. A TC undergoing ET exhibits changes in surface winds that differ from a typical TC, such as wind field expansion that subsequently affects hazards caused by these cyclones. The outer wind field of Sandy (2012) expanded at ET onset due to inward transport of absolute angular momentum (AAM; Shin, 2019), specifically AAM at lower levels associated with frontal convection. Note that inward AAM transport also accelerated and helped expand the wind field during the ET of Bonnie (1998; Evans and Hart 2008). In Sandy, the inner core maintained deep convection resembling that of an eyewall, and the lifting of the core's warm, moist air by the cooler, drier air of the approaching baroclinic zone enhanced that deep convection and supported Sandy's reintensification (Shin 2019).

In addition to altering the cyclone wind field, the ET process can produce heavy precipitation in a different manner from a

TC. Beyond warm frontogenesis, the interaction between the TC and the jet stream can induce asymmetric precipitation. In the Northern Hemisphere, a westerly jet can enhance not only northward outflow in the upper troposphere via weak inertial stability but also convection on the north side of a TC (Dai et al., 2019). Yanase et al. (2022) proposed that the westerly jet stream reduces both inertial stability in the upper troposphere and conditional symmetric stability in the lower and mid troposphere, enhancing slantwise convection north of the TC. Powell and Bell (2019) also noted that conditional symmetric instability may exacerbate heavy rainfall. Numerical simulations of Hagibis (2019) in the western North Pacific, which caused more than 100 fatalities in Japan, showed that the asymmetric distribution of precipitation during ET was caused by multiple processes including warm frontogenesis and reduced inertial and symmetric stability under the influence of a jet stream (Iizuka et al., 2021; Ito and Ichikawa 2021; Yanase et al., 2022).

It is important to identify and forecast both ET onset and ET completion due to the evolving nature of the cyclone and thus its evolving hazards. The synoptic-scale structure and dynamics of extratropically-transitioning TCs partly resemble those of ordinary ECs, including conveyor belts, frontal dynamics, and quasi-geostrophic forcing (e.g., Evans et al., 2017). However, these features are influenced by smaller-scale processes and ongoing diabatic heating due to the cyclone's tropical origin. A numerical simulation of Tropical Storm Karl (2016) showed that large inertial stability confined high equivalent potential temperature (θ_e) air within the inner core, potentially supporting the maintenance of deep convection during ET (Euler et al., 2019). These trajectories also showed that the warm conveyor belt originated from not only the warm sector but also other source regions, which is different from the warm conveyor belt of an ordinary EC.

Since results from a case study can be difficult to generalize, research has explored the interactions between a TC and the mid-latitude flow in a given basin due to the impacts of such interactions on both ET outcomes and downstream hazards. For example, North Atlantic cyclones that undergo warm seclusion tend to move into a region of strong low-level confluent flow that facilitates frontogenesis along the warm front in contrast to the cyclones that develop cold-core structures (Sarro and Evans 2022). Whether the post-ET cyclone intensifies does not appear to depend on the negative tilt of the upstream trough as this structure appears to be an outcome of the ET process, a finding corroborated by Ritchie and Elsberry (2003, 2007). Unlike earlier studies, however, Sarro and Evans (2022) found that the environment of reintensifying cyclones was not necessarily characterized by warm and moist lower-tropospheric air. This result was also noted in reintensifying TCs after ET in the western North Pacific, which occurred at relatively high latitudes with low θ_e (Yanase et al., 2020). They attributed this outcome to high potential vorticity (PV) in the upper troposphere at higher latitudes, a setup more favorable for downstream ridge building.

Downstream ridge building is one potential impact of ET on the downstream flow, but it is not the only possible outcome (Keller et al., 2019). The magnitude of the downstream response is proportional to the latitude and the speed of the upper-level jet stream interacting with the TC (Finocchio and Doyle 2019). TCs recurving in the western North Pacific which effectively phase lock with the upstream trough can promote strong amplification of downstream Rossby wave packets and increase the potential for atmospheric blocking at the exit of the North Pacific storm track (Riboldi et al., 2019). Flow amplification downstream of ET has been connected to hazardous weather such as European extreme precipitation events (Pohorsky et al., 2019) and fire weather over North America (Stuivenvolt-Allen et al., 2021) and may even influence the evolution of other TCs in the same basin (Prince and Evans 2020).

Brannan and Chagnon (2020) also identify the relative displacement between a recurving TC and the Rossby wave pattern as an important predictor of downstream flow amplification in the North Atlantic. Interestingly, they find that phasing can lead to a temporary *de*-amplification of the flow over the basin, attributing this outcome to barotropic instability and possibly to the North Atlantic jet waveguide generally having a reduced meridional extent compared with its Pacific counterpart. Their finding aligns with the absence of significantly amplified Rossby wave packets downstream of North Atlantic recurving TCs highlighted by Quinting and Jones (2016). Although the remnant track-based assessment undertaken by Aiyyer and Wade (2021) appears to favor the Riboldi et al. (2019) view of downstream response, more work is required to fully reconcile these recent results given the implications for impacts to the European region.

The influence of ET in the eastern North Atlantic has gained attention in the wake of high-impact cyclones that underwent ET [e.g., Debby 1982 (Laurila et al., 2020), Katia 2011 (Anfuso et al., 2020), and Ophelia 2017 (Rantanen et al., 2020)]. The likelihood of post-tropical storm landfall in Europe is highly correlated with the number of TCs in the basin (Sainsbury et al., 2022). This modulation is particularly important for high-impact weather because these systems tend to be stronger than their mid-latitude counterparts during the hurricane season (Sainsbury et al., 2020, Fig. 2). Sainsbury et al. (2022) relate the late-season peak in frequency of these events to the combination of increasing baroclinic instability and energy produced by latent heating during the warm seclusion process. This link to warm seclusion (Sarro and Evans 2022) corroborates Dekker et al. (2018), who show that post-tropical storms reach their peak intensity as they strike Europe. As a result, we encourage future research efforts to further investigate this late phase of the storm life cycle.

2.2. Tropical transition (TT)

As noted above, the ET process affects both storm evolution and the downstream flow with associated myriad impacts, with our knowledge advancing on both aspects in recent years. By contrast, effects of the TT process tend to be more confined to the storm itself. Tropical cyclogenesis processes associated with subtropical or extratropical precursors received

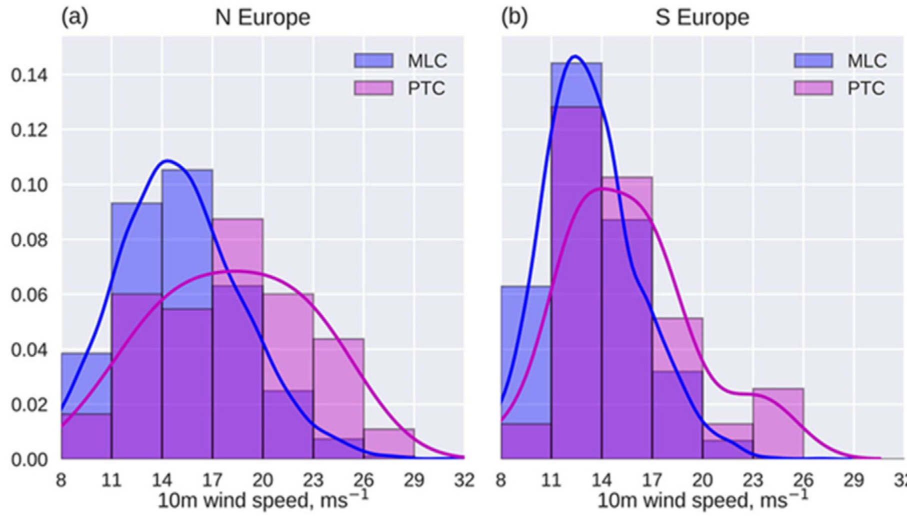

Fig. 2. Maximum intensity distributions for post-tropical cyclone (PTCs) and mid-latitude cyclones (MLCs) affecting (a) northern (N) Europe and (b) southern (S) Europe during the North Atlantic hurricane season (June to November). The latitude separating the two regions is 48°N. Adapted from Sainsbury et al. (2020).

considerable attention after the term “tropical transition” was introduced by Davis and Bosart (2004). Most early TT research focused on the western North Atlantic basin where baroclinic conditions influence a large fraction of TCs, but recent work has expanded assessment of TT to other regions. Over a 34-year period, Hamaguchi and Takayabu (2021) found that up to 30 % of western North Pacific tropical depression (TD)-like disturbances are associated with upper-level troughs, a feature of SCs (Section 1), and those troughs support moistening and destabilization of the atmospheric column through quasi-geostrophic forcing for ascent. Though such TCs tend to remain weaker than their tropically-initiated counterparts, their enhanced poleward motion increases the risk of hazards for the islands of Japan (Fudeyasu and Yoshida 2019; Takemura and Mukougawa 2021). Across basins, many SCs develop in an environment of blocking and cutoff lows where reduced vertical wind shear supports convective organization and eventual TT (da Rocha et al., 2019). There is evidence that TT behavior can vary within a given tropical basin as well: in the North Atlantic, eastern TT events occur more frequently in environments hostile to TC formation than central TT events (Calvo-Sancho et al., 2022).

Medicanes, the tropical-like cyclones observed in the Mediterranean Sea, often form via TT. By investigating a well-documented December 2005 medicane with a convection-permitting model, Fita and Flaounas (2018) proposed a three-stage life cycle for these cyclones: 1) increasing convection in a cold-core cyclone due to a potential vorticity streamer prompting the development of a warm core, 2) maturing of a deep warm core and an axisymmetric convective structure, and 3) eventual decay. Their investigation characterized medicanes as SCs in which the warm core forms by seclusion rather than diabatic heating alone. Miglietta and Rotunno (2019) described three categories of mature medicanes: one dominated by wind-induced surface heat exchange (WISHE), one in which baroclinic instability is of equal importance to WISHE, and one in which upper-level forcing is induced by a nearby large-scale EC, a categorization similar to Dafis et al. (2020). Of the three, the December 2005 case best aligns with the second category. A subsequent comprehensive review of medicanes by Flaounas et al. (2022) proposed a three-group classification scheme and highlighted the need for the research community to pursue process-level understanding of storm development and its relationship to TT.

2.3. Subtropical transition (ST)

Phase transition of ECs to SCs can follow the Shapiro-Keyser (1990) model in which a warm seclusion supports warm core development near the surface, which then supports deep convection and warm core development (Mazza et al., 2017; Fita and Flaounas 2018; Quitián-Hernández et al., 2020; Flaounas et al., 2021; Reboita et al., 2022). Typical extratropical dynamics are responsible for initial cyclogenesis, and subsequent transition results from a warm seclusion process (Mazza et al., 2017; Reboita et al., 2022). In the South Atlantic basin, conditions are typically hostile to TC development but more favorable for SC formation (da Rocha et al., 2019) in part due to the relative importance of both baroclinic and diabatic processes similar to that noted for TT in the Mediterranean Sea. The Shapiro-Keyser EC precursor of Raoni (2021) formed via forcing from a mid-upper-level trough that crossed the Andes Mountains, presenting a warm seclusion less than 24 h later (Reboita et al., 2022). Strong surface heat fluxes, deep-layer moisture, and the alignment of the warm seclusion with an upper-level cutoff pattern supported organized convection and eventual ST at 0600 UTC 28 June. For Raoni, CPS parameters depict an EC evolving to an SC (Fig. 3). In medicanes, latent heat release acts as the main PV source in the lower-to-middle troposphere (maintaining and/or strengthening cyclones) partly balanced by PV sinks of temperature diffusion and radiative cooling (weakening cyclones).

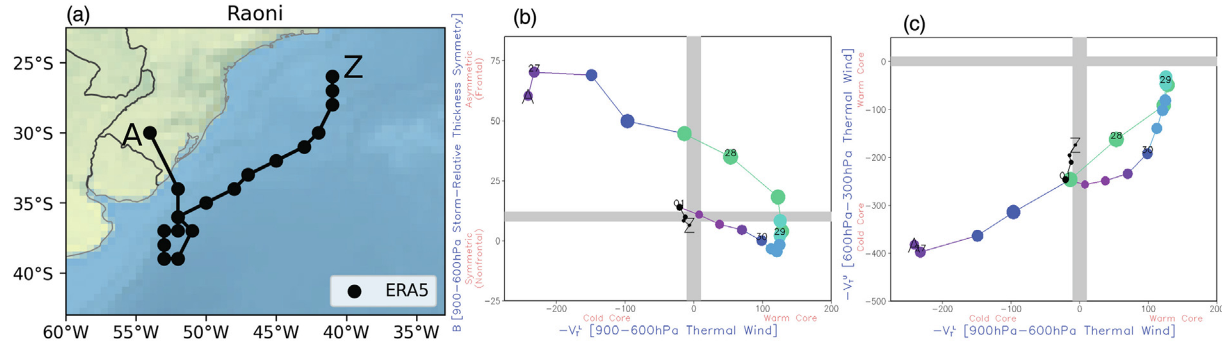

Fig. 3. An example of EC to SC transition for Raoni (2021) in the South Atlantic. The cyclone begins at A and ends at Z in all panels. (a) Depicts the ERA5 cyclone track, (b) shows B and -V_T^L, and (c) shows -V_T^L and -V_T^U. Adapted from Reboita et al. (2022).

As implied earlier (Section 2b), the synergy between baroclinic instability and convection may intensify tropical-like Mediterranean cyclones (Flaounas et al., 2021). Given the similarities between Mediterranean cyclones and those in other basins, there is a need for a more universal definition of ST and quantification of how ST differs from TT.

An assessment of the South Atlantic Ocean's first instance of pure tropical cyclogenesis found that TC Iba later evolved into an SC (Reboita et al., 2021). A deep-layer warm anomaly was present during the tropical portion of Iba's lifecycle, which became shallow and confined to lower levels as the cyclone transitioned to its subtropical phase. The initial genesis of Iba was associated with an anomalous wave pattern at 500 hPa that produced weak vertical wind shear and thus favored subsequent convective organization.

In the Australian region, the transition of a TC to an SC resembles the first stage of ET in Jones et al. (2003) with a further distinction between “cradled” and “captured” situations (Foley and Hanstrum 1994). The “captured” setup occurs when the cyclone interacts with a mid-latitude trough, a type of interaction that has been the focus of many studies. A “cradled” setup occurs when the subtropical ridge is the dominant synoptic influence, resulting in a more gradual transition to becoming an SC (Table 2). For cradled cases, CPS parameters can present a TC-like structure—thermal symmetry and a strong warm core—when systems are located well into the subtropics, challenging delineation between TCs and SCs.

3. Updated approaches to identifying and predicting cyclone phase transitions

A set of CPS criteria has been proposed for ET onset and completion: $B > 10$ m for onset and -$V_T^L < 0$ for completion assuming a TC initially had $B < 10$ m and -$V_T^L > 0$ (Evans and Hart 2003). However, these thresholds are often used as the *de facto* standard despite being derived from coarse datasets with horizontal resolutions of at least 100 km. To assess the validity of these thresholds with higher-resolution fields, Sarro and Evans (2022) examined 78 North Atlantic ET events using the 0.25° fifth-generation European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5; Hersbach et al., 2020). Results for 52 cases resembled those found using 1° resolution data (Hart et al., 2006), but only ET onset could be determined via ERA5 CPS for the remaining 26 cases. In these events, the warm core had not completely disappeared before the cyclone transformed into the warm-seclusion EC of Shapiro and Keyser (1990), events termed “instant warm seclusion.” For this type of transition, ET completion time cannot be determined by the criteria of Evans and Hart (2003), posing a classification challenge for operational applications and historical analyses. It is possible that instant warm seclusion events are more readily identifiable in higher-resolution fields because they depict smaller-scale warm core structures,

Table 2
Summary of features and synoptic differences between captured and cradled events in the Australian region.

	Captured	Cradled
Synoptic	Approach mid-latitude trough	Ridge to south; easterly flow poleward
Winds	Asymmetric: expansion east of center	Asymmetric: expansion poleward of center
Satellite appearance	Rapid change with increasing shear	Gradual change; warming cloud tops as SSTs decrease
Intensity change	Weakening due to increased wind shear; re-intensification possible with baroclinic forcing	Gradual weakening because shear can remain low to moderate
Motion	Acceleration toward the southeast, which can cause gale-force winds to persist as forward motion increases	Slow/steady, generally southward. Weaker (shallower) circulations may be steered more westward.
CPS	Asymmetric, shallow warm core	Retains warm core for longer
Examples	Indian Ocean: Alby (1978) Pacific: Gretel (2020)	Indian Ocean: Bianca (2011) Pacific: Oma (2019); Uesi (2020)

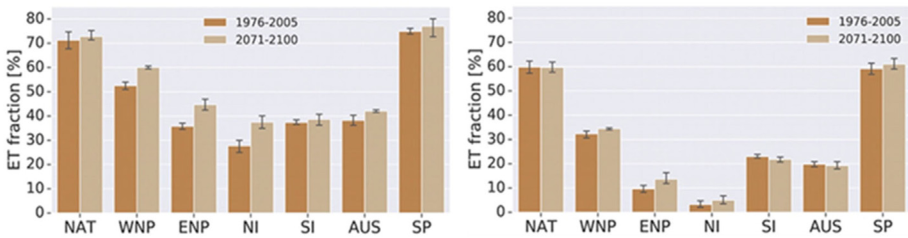

Fig. 4. Historical (1976–2005) and simulated future (2071–2100) ET fractions. (left) ET defined via CPS parameters. (right) ET defined via CPS modifications using the 95th percentile (p95) and smoothing (sm). Adapted from Bieli et al. (2020b).

but this result highlights potential limitations in CPS-dependent ET determination for increasingly high-resolution NWP output.

Other work on ET has found similarly challenging scenarios in the western North Pacific (Kitabatake 2008). The Japan Meteorological Agency (JMA) assumes that a TC becomes an EC once a front has developed near the center (Appendix A), prompting Kitabatake (2008) to focus on frontal structure during ET. Though the *B* parameter from CPS infers frontal characteristics, it does not explicitly identify fronts, thus JMA practice implies that frontal analysis could complement the CPS for defining ET in situations such as instant warm seclusion. However, frontal analysis is also insufficient for ET classification, as one ET pattern is accompanied by no surface front (JMA 1990; Fig. A1 of Kitabatake 2008), a scenario that occurs over a relatively cool sea surface which resembles an ET pattern noted in the eastern North Pacific by Wood and Ritchie (2014). These findings indicate more work is needed to assess the usefulness of and limitations in frontal analysis for ET determination, particularly from an operational perspective.

Since it is important to accurately forecast ET to support preparation efforts ahead of the arrival of hazards, Bieli et al. (2020a) developed a logistic regression model in the North Atlantic and western North Pacific to predict ET at lead times up to two days. They successfully identified 80 % of North Atlantic TCs undergoing ET and 92 % of western North Pacific TCs undergoing ET using latitude and SST as predictors. This model also produced errors regarding transition timing of less than 24 h in 90 % of cases. If this model is used as an instantaneous diagnostic of ET, it performs as well as the CPS in the western North Pacific and better than the CPS in the North Atlantic, predicting the timing of the transition better than CPS in both basins, indicating potential for operational applications.

The aforementioned studies examined past ET events, but other research has investigated potential impacts of climate change on ET. Using a climate model to compare 1976–2005 events with 2071–2100 events, Bieli et al. (2020b) noted multiple changes in ET characteristics between the two time periods. However, only a few changes were statistically significant, including an increase in the ET fraction (Fig. 4) and a decrease in the mean latitude at which ET occurs in the western North Pacific. Note that their method applied a modified version of CPS: they used the 95th percentile instead of the maximum value and applied smoothing to correct for biases from spurious diagnoses of cold cores in the climate model.

Note that the Bieli et al. (2020b) conclusions are drawn from climate model analyses; historical records in the North Atlantic have exhibited decreasing rates of acceleration and TC translation speed for TCs that interact with extratropical Rossby waves (Aiyyer and Wade 2021), implying a poleward shift in and weakening of these waves which would require TCs to gain latitude before reaching the baroclinic zone that would facilitate ET. A separate climate modeling study found that the North Atlantic may become up to 40 % more favorable to high-latitude TC development and eventual ET, but results are not consistent regarding the latitudes at which ET-related tropical-extratropical interactions occur (Michaelis and Lackmann 2019), further highlighting a continued need to study the mid-latitude waveguide to assess future ET trends. Finally, semi-idealized modeling results suggest that the impact of individual ET events could also be enhanced by climate change because the cyclone intensifies throughout the transition process (Jung and Lackmann 2021). Moreover, basin-scale impacts of ET may increase in the future as enhanced energy dispersion increases the likelihood of high-amplitude downstream development.

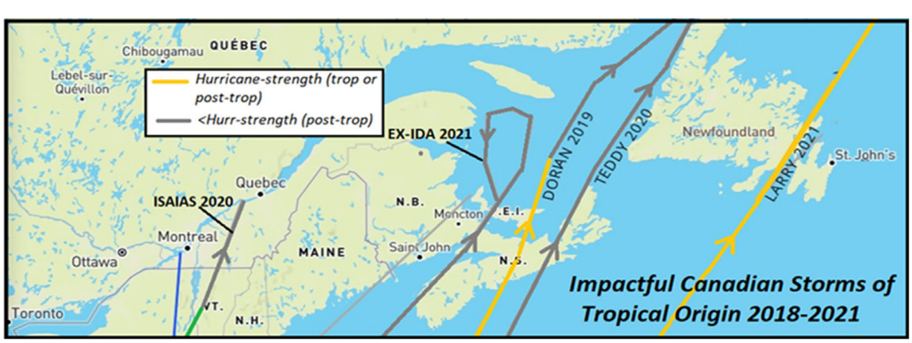

Fig. 5. Tracks of impactful Canadian storms of tropical origin during 2018–2021.

It is important to note that inferred relationships between ET and future climate change depend on each study's experimental design and assessment strategies. Haarsma (2021) proposed that high-resolution simulations are required to quantify the increase in risk from European wind storms associated with post-tropical cyclones. However, it remains unclear whether computing resources are best invested in such simulations or instead in large ensembles (e.g., Zhang et al., 2020) to study climate change-induced alterations to earlier stages of the TC life cycle. Consistent with Haarsma (2021), Baker et al. (2022) concluded that spatial resolutions capable of depicting realistic warm core intensities are likely required for accurate predictions of future trends.

Compared with changes to ET in a warming climate, less work has investigated possible changes to mid-latitude influences on the early stages of the TC life cycle. One regional exception occurs in the form of studies related to medicanes, which typically develop via TT as earlier discussed. Medicane frequency was found to decrease under expected climate change conditions, likely due to reduced baroclinicity and increased deep-tropospheric stability (González-Alemán et al., 2019). The importance of the latter is also emphasized by Koseki et al. (2021), who showed that temperature profile changes suppress medicane development.

Some modeling studies have begun evaluating TT and ST trends in the western South Pacific and the South Atlantic. For cyclones east of Australia, local ocean temperature offsets expected reductions in baroclinicity and thus increases the fraction of SCs (Cavicchia et al., 2020). Similarly in the South Atlantic, Reboita et al. (2019) used a range of SST forcings to find that 2 °C of sea surface warming would have been sufficient to promote the transition of subtropical cyclone Anita (2010) to a full-fledged tropical cyclone. If such approaches are applied to other basins, it may be possible to establish a more complete picture of possible future changes in baroclinically-influenced tropical cyclogenesis.

4. Advances in operational forecasting

Because the ET process can bring hazardous weather to latitudes less frequently impacted by TCs, operational forecasting centers must be able to identify when there is potential for such transitions and predict the regions at risk for associated hazards. One such hazard is heavy rainfall which can be directly caused by a post-transition cyclone (e.g., Ida, 2021) or indirectly result from moist air being advected by the cyclone toward a front in the form of predecessor rain events (e.g., Galarneau et al., 2010; Kodama and Satoh 2022). In such events, it is critical for local, regional, and national offices to coordinate efforts in messaging the rainfall risks for the potentially affected region. For example, JMA will hold press conferences for imminent threats and call on the public to be vigilant, offering context with distribution maps and time-sequence diagrams of heavy rain threats as well as other high-risk hazards such as gale-force winds, high waves, and storm surge.

Changes and advancements at the Canadian Hurricane Center (CHC) are often shaped by individual events in Eastern Canada (Fig. 5). In 2019, Dorian was a large post-TC that affected a sizable portion of the Meteorological Service of Canada's area of responsibility, highlighting the importance of large-scale, multi-departmental coordination. Communication gaps between the CHC and RSMC Miami (the National Hurricane Center or NHC) led to media confusion that compromised the effectiveness of the messaging. In the post-season, the two agencies collaborated to update internal communications and establish coordination protocols for significant events which led to improvements during Larry (2021) with consistent messaging between the agencies. Mid-latitude aircraft reconnaissance and recently upgraded Doppler radar provided forecasters with the confidence to issue predictions for this far-north hurricane. Their predictions were communicated to an emergency management organization in eastern Newfoundland, leading to the proactive cancellation of a major outdoor concert scheduled to take place at a venue that ended up destroyed by the storm. However, the track of a transitioning or transitioned TC can pose challenges for hazard messaging, such as Teddy (2020) which obliquely approached the Nova Scotia coastline resulting in its strongest winds remaining parallel to the coastline rather than moving ashore. Such examples highlight the need for versatile, trustworthy products from forecast centers as well as consistent collaboration between centers with adjoining areas of responsibility.

Operational centers apply varied methods for classifying cyclones and determining phase transitions (Appendix A) which may reflect regional differences in transition processes including CPS, cloud pattern assessment, front identification, and evaluation of environmental fields. The JTWC evaluates SCs and potential TT or ST using a worksheet with 13 observable criteria including low-level symmetry (Fig. 6), baroclinicity, and upper lows, but manually completing the worksheet is time-intensive and subjective. A UW-CIMSS automated worksheet was recently developed by Mr. Tim Olander to complement JTWC's manual process by providing independent, objective, and reliably available products. UW-CIMSS runs the automated version on near real-time data once every 3 h for all JTWC invest areas and all TCs in warning status. JTWC forecasters complete the worksheets manually once every 12 h and regularly review the UW-CIMSS automated worksheet output. Since JTWC monitors multiple tropical basins, these approaches should be investigated for cross-basin applicability and insights into common features between identified SCs.

It is also important to verify the accuracy of cyclone forecasts to assess skill and identify avenues for future improvement. Since 2009, the NHC has made public their probabilistic forecasts of TC and SC genesis in the North Atlantic basin, forecasts that include TT events. Overall, these genesis forecasts have a high level of reliability (https://www.nhc.noaa.gov/verification/verify3.shtml), but NHC forecaster experience suggested the possibility that forecasts for certain ST or TT cases were less accurate. To test this theory, genesis forecast verification was performed on 55 cases involving ST or TT

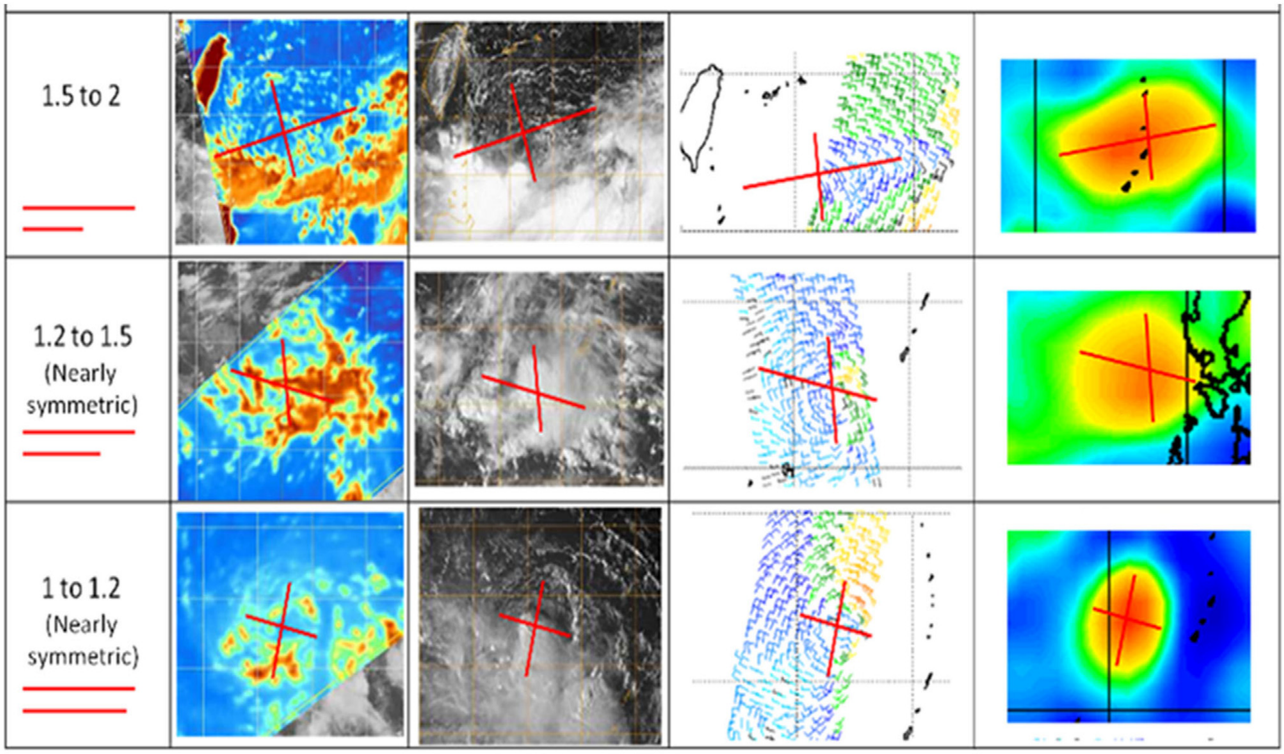

Fig. 6. Example imagery accompanying JTWC's cyclone phase classification worksheet to assess low-level symmetry. The ratio of long to short axis lengths (red lines) is evaluated using multiple products (e.g., microwave and visible satellite imagery, scatterometer observations, and 850-hPa vorticity).

between 2012 and 2021: 54 cases where an SC or TC formed and 1 case where advisories were initiated on a potential TC (a possible transition case) that never completed transition. Case selection included every event during these seasons for which the NHC TC report indicated that baroclinic interaction or ST/TT processes were important during genesis. Forecast verification for the ST/TT cases (red line in Fig. 7) shows a low bias, indicating that the potential for genesis was significantly underforecast: when the forecast genesis probabilities were 20–30 %, genesis occurred over 60 % of the time.

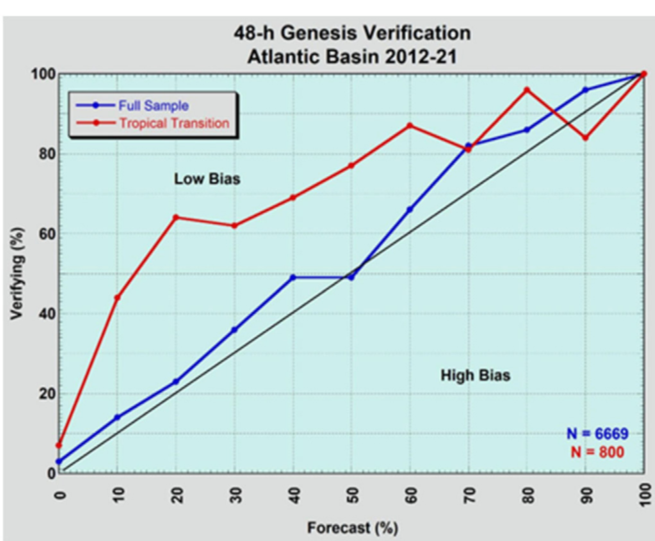

Fig. 7. Reliability diagram for all NHC 48-h probabilistic genesis forecasts (the blue line) and forecasts for selected ST/TT cases (the red line). Forecast genesis probabilities are on the horizontal axis and the verifying genesis percentage is on the vertical axis. The thin slanted black line represents ideal reliability. The total number of samples is listed in the lower right corner (6669 for all cases, 800 for the ST/TT cases).

These results support NHC forecasters' belief that genesis forecasts for the observed ST/TT cases were less reliable than the baseline for non ST/TT cases. One potential explanation for this reliability gap is uncertainty regarding the ability of ST/TT systems to develop and maintain organized convection in marginal thermodynamic environments, indicating a need for research to address this uncertainty. Also, the selected cases included in this analysis are skewed in favor of systems that developed; statistics for a complete set of NHC forecasts in transition situations that include non-developing systems may have a different reliability distribution.

5. Conclusions

This review expands from the IWTC-9 report that focused on extratropical transition to include tropical and subtropical transitions. Discussing all three cyclone phase transition types together helps highlight overlaps in research methodology and operational analysis of these processes as well as showcase the continuum of cyclone evolution. It also demonstrates advantages and caveats in the varied classification methods currently applied.

Cyclone phase space (CPS; Hart, 2003) has been the *de facto* objective classification method for a range of cyclone types and supported a global climatology of ET. However, as noted here and previously, the CPS was not developed for use with high-resolution fields that can more accurately depict the inner cores of transitioning cyclones, and some improvements to the original CPS have been proposed such as a variable radius dependent on cyclone size. Yet CPS remains an important component of operational cyclone analysis and prediction at many forecast centers in addition to satellite imagery analysis and environmental characteristics. Given that recent literature has showcased the variability in phase transitions depending on ocean basin with respect to structure and evolution, classification methods often depend on the region in which they are applied, and these methods should be compared across basins to identify similarities and potentially enable a broader classification approach in the future.

Much work has investigated the ET process (Evans et al., 2017; Keller et al., 2019), but it is not yet fully understood how mesoscale processes and diabatic heating induce structures and dynamics peculiar to ET. High-resolution simulations have provided new perspectives on these processes, but such efforts tend to focus on individual cases, thus the generality of their findings remains unclear. However, such efforts remain important due to varied basin-scale impacts resulting from ET, including hazards local to the cyclone and downstream hazardous weather. A transitioned EC can be stronger than typical mid-latitude cyclones for that time of year, leading to forecast and messaging challenges. Also, downstream Rossby wave responses to ET seem to differ between the western North Pacific and the North Atlantic, possibly because the different background atmospheric conditions can have a large influence on the downstream impact of ET. These transitioning TCs pose challenges to operational forecasting due to the evolving nature of the storm and its impacts as well as how to message these changes. Unfortunately, their predictability differs from that of TCs which remain fully tropical, and these storms often impact high-latitude regions where their hazards are less common. It is thus important that warning agencies collaborate and share experiences to ensure consistent, objective, and versatile products and services.

A global climatology of ET identified regional variability in the transition process likely related to environmental differences such as sea surface temperature. Recent work also showed some relationships between TT and ET during the TC lifecycle, demonstrating the usefulness of cross-sectional study on phase transitions. Future changes in ET frequency and latitude depend on the region being studied and on the experimental design. Regarding the latter, resolutions capable of depicting realistic warm core intensities are likely required for realistic predictions of future trends. Semi-idealized experiments indicate that the cyclone's strength and the basin-scale impacts of ET may increase in warmer climate scenarios.

Recent studies have expanded evaluation of tropical transition (TT) from the North Atlantic to other regions such as the western North Pacific and the formation of tropical-like cyclones (medicanes) in the Mediterranean Sea. The assessment of tropical transition is incomplete without considering subtropical cyclones (SCs), and the potential for SCs to more frequently become TCs in a warming climate further indicates the need for comprehensive study of varied cyclone types. However, a clear and present challenge in identifying SCs and diagnosing their role in cyclone phase transitions is the need for a holistic definition of what constitutes this type of cyclone. Indeed, SCs have received varied names across ocean basins, which exacerbates difficulties in characterizing these storms. SCs also pose challenges to forecasters since they comprise a range of baroclinic and convective structures: some exhibit features and evolutionary pathways similar to ECs while others more resemble TCs. Though the WMO definition (Section 1) captures the essence of what constitutes an SC, it lacks the dynamical, thermodynamical, and convective rigor critical to consistent classification of these systems.

i. The term "non-frontal" is somewhat non-intuitive, since if baroclinic energy conversion is sufficiently large to contribute energy to the cyclone, a baroclinic zone likely exists somewhere in the system;
ii. Even with tools such as CPS parameters, remotely-sensed temperature data, and scatterometer observations, it can be difficult to analyze frontal structures in these systems; and
iii. The importance of organized convection is noted but not the amount of convection necessary to provide the diabatic energy to distinguish SCs from typical ECs.

Many recent studies have investigated SCs, but there remains a need to apply and expand these findings to capture the differences between SCs and other cyclone types. A holistic definition would support operational practice in deciding when a cyclone becomes distinct from typical ECs and other types of hybrid cyclones to justify treating them operationally and climatologically like TCs. An NHC team is working on a revised definition and seeks additional tools to reduce subjectivity in operational decisions. Since SCs occur in ocean basins across the globe, partnerships are necessary across the forecasting and research communities to ensure a future SC definition is broadly representative.

Such a definition may require further understanding of the pathways that lead to SC development and later tropical or extratropical transition, such as the multiple categories of medicanes whose behavior depend on the relative role of baroclinic and diabatic processes. From a scientific perspective, it should be clarified whether SCs are a dynamically separate state that stands alone in the spectrum from TCs and ECs or an intermediate state between TCs and ECs. It is thus necessary to investigate how factors such as vertical wind shear, baroclinicity, convection, surface heat fluxes, and upper-level disturbances vary in their influence on different cyclone types. One potential forum for such efforts is the ongoing "MedCyclones COST Action" (Hatzaki et al., 2023) which aims to help coordinate research on and discussion of Mediterranean cyclones.

We recognize that each ocean basin has its own characteristics that can challenge the development of a universal definition for SCs and cyclone phase transitions. However, coordinated efforts within the operational and research communities would support the advancement of potential definitions for and thus our understanding of these phenomena.

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Appendix A. Operational classification of cyclones

Table A.1
Operational centers and their classification methods.

Center	Classification
BoM	Analysis/Forecast of ST of a TC Subjective evaluation of ST based on the following characteristics: ● The satellite signature losing tropical characteristics: a defined dry slot wrapping towards the center (around W-NW in SH); decrease in convection near the center; and a 'delta' rain shield forming poleward (SE of center in SH). ● The Dvorak technique no longer can be used to represent the intensity. ● The surface wind structure becomes highly asymmetric and the radius of maximum winds increases to be away from the center. ● The method to evaluate these changes include conventional visible, infra-red and water vapor; microwave (37 and 85–91 GHz); and scatterometry and radiometers for surface wind analysis. ● NWP guidance is also used for wind structure and via the CPS for thermal structure. Once subtropical, the service transfers from TC warnings to 'severe weather warnings,' but future scope to address the shortcomings of this approach
Brazilian Navy	Analysis of an SC In NORMAM-19/DHN, SCs are not associated with a frontal system and present characteristics of both TC and EC. Compared to TCs, they generally have maximum winds relatively farther from the center of the system, at distances greater than 60 nautical miles, and less symmetrical wind field and convective distribution. SCs are classified by the average maximum sustained wind near-surface, within 1 min: I. Subtropical Depression - less than 34 knots, 63 km/h, 39 mph or Force 7 on the Beaufort Scale; and II. Subtropical Storm - equal to or greater than 34 and less than 64 knots, 63–118 km/h, 39 to 74 mph or Force 8 to 11 on the Beaufort Scale. When an SC is confirmed, it receives a special name following the available list in NORMAM-19/DHN (anex C https://www.marinha.mil.br/dhn/sites/www.marinha.mil.br.dhn/files/normam/NORMAN-19-REV-1–Ed2018-CHM.pdf [in Portuguese]). Currently, the Brazilian Navy is adapting its guide and additional criteria are being considered, which are the analysis of the CPS in global and regional models and absence of upper level jet. SST is not used as a criterion.
CHC	Analysis of ET of a TC Analysis of cyclone phase is primarily based on satellite imagery Forecast of ET of a TC The CPS prognostics available at http://moe.met.fsu.edu/cyclonephase/are often consulted to get an idea of how the models are handling the transition. Consistency is sought, akin to track and intensity forecasting.
JMA	Analysis of ET of a TC Comprehensive consideration of three main methods. ● Weather map analysisET is recognized when a front reaches the TC center. ● Score addition method using satellite imagery, SSTs and other data ET is recognized when points are added if each of the following six items is satisfied and the points total exceeds the threshold: 1 Transition to SHEAR pattern: suggesting that vertical wind shear is increasing and ET is progressing. 2 Absence of dense cloud areas within 1.5° of the center: suggesting that convective cloud development is suppressed near the center and ET is progressing. 3 Absence of south-convex Ci or dense cloud bands southeast/southwest of the center: suggesting that upper and lower circulation is out of alignment based on increased vertical wind shear. 4 Brightness temperature of −31 °C or higher in the center in water vapor imagery: suggesting that there is no wetness resulting from upper-layer divergence near the center, and that convective activity near the center is suppressed with darkening. 5 Movement to sea areas with SSTs of 24 °C or lower 6 Movement to sea areas with SSTs of 26 °C or lower ● Method using 250-hPa geopotential height near the TC centerIf a TC center is present in the vicinity of: Up to 10,720 gpm: ET must be complete 10,720 gpm - 10,930 gpm: ET occurs 10,930 gpm - 11,000 gpm: TS becomes TD, but ET may also occur 11,000 gpm upward: TS becomes TD

(*continued on next page*)

Table A.1 (*continued*)

Center	Classification
	Forecast of ET of a TC Comprehensive consideration of four main methods: ● *Objectively analyzed front from NWP output*: ET is recognized when an objective front based on Thermal Front Parameters [TFPs; Renard and Clarke (1965)] reaches the TC center; JMA uses 925-hPa θ_e as the thermodynamic variable of TFP ● *CPS*: ET is recognized when the CPS indicates "asymmetric" and "cold core" ● *SST near the TC center*: ET should occur with SSTs of 24–26 °C or lower, but a TS should become a TD at temperatures above 26 °C ● 250-hPa geopotential height near the TC center from NWP: Based on the same criteria as the analysis of ET References ● Real time information: https://www.jma.go.jp/bosai/map.html#contents=typhoon&lang=en
JTWC	Analysis of an SC A cyclone phase classification worksheet based on 13 observable criteria is used to discriminate SCs from TCs: 1. Designation of value bin scores for each of the 13 criteria (the scores for the minimum and maximum cases are given in the parentheses): 1 Magnitude and pattern of total precipitable water (TPW): frontal (−3) – symmetric moist (+3) 2 Low level circulation: asymmetric (−1) – symmetric (+2) 3 Radius of maximum winds: larger (−1) – smaller (+2) 4 850 mb vorticity signature: asymmetry (−1) – symmetry (+2) 5 850 mb maximum vorticity: smaller (−1) – greater (+2) 6 Deep convection structure: asymmetric (−2) – symmetric (+2) 7 Size of convective envelope: diffuse (−1) – compact (+2) 8 Vertical wind shear: higher (−2) – lower (+2) 9 Sea surface temperature: lower (−1) – higher (+2) 10 Baroclinicity (1000–500 hPa thickness gradient): strong (−2) – no (+1) 11 Core temperature anomaly: cold (−1) – warm (+2) 12 Low level circulation center (LLCC) position relative to the 500 mb subtropical ridge axis: poleward (−1) – equatorward (+2) 13 LLCC position relative to upper low: under upper low (−1) – not under upper low (+2) 2. A total raw score is calculated by adding the value bin scores, and then normalized by potential minimum (negative) and maximum (positive) scores to determine a weighted ratio ranging from −1 to 1. The cyclones are classified as: Extratropical: 1 to −0.389 Borderline extratropical/subtropical: 0.389 to −0.278 Subtropical: 0.278 to 0.192 Borderline subtropical/tropical: 0.192 to 0.269 Tropical: 0.269 to 1 Analysis/forecast of ET of an TC The operational process for analyzing and predicting ET does not require referencing the cyclone phase classification worksheets because assessing ET is often a more straightforward process than diagnosing SCs. JTWC's final warning criterion for ET states that a TC must be becoming extratropical at the current forecast time and predicted to be fully extratropical within 12 h - otherwise warnings must continue until that is the case. So the forecasters sometimes use the worksheets to make sure that ET has started before sending out a final warning. References ● Overview of JTWC cyclone phase classification worksheet https://ams.confex.com/ams/31Hurr/webprogram/Manuscript/Paper245159/STC_JTWC.pdf ● Real-time information https://pzal.metoc.navy.mil/php/rds/login.php?

Acronyms used in this manuscript

AAM	Absolute Angular Momentum
AMS	American Meteorological Society
BoM	Australian Bureau of Meteorology
CHC	Canadian Hurricane Center
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CPS	Cyclone Phase Space
EC	Extratropical Cyclone
ET	Extratropical Transition
IWTC	International Workshop on Tropical Cyclones
JMA	Japan Meteorological Agency
JTWC	U. S. Joint Typhoon Warning Center
NHC	U. S. National Hurricane Center
NWP	Numerical Weather Prediction
PV	Potential Vorticity
RSMC	Regional Specialized Meteorological Center
SC	Subtropical Cyclone
SST	Sea Surface Temperature
ST	Subtropical Transition
TC	Tropical Cyclone
TD	Tropical Depression
TFP	Thermal Frontal Parameter
TS	Tropical Storm
TT	Tropical Transition
WMO	World Meteorological Organization

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