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Tropical cyclogenesis: Controlling factors and physical mechanisms

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Abstract

In this review, advances in the understanding of the controlling factors and physical mechanisms of tropical cyclogenesis (TCG) are summarized from recent (2018–2022) research on TCG, as presented in the Tenth International Workshop on Tropical Cyclones (IWTC-10). Observational, theoretical, and numerical modeling studies published in recent years have advanced our knowledge on the influence of large-scale environmental factors on TCG. Furthermore, studies have shown clearly that appropriate convective coupling with tropical equatorial waves enhances the development chances of TCG. More recently, illuminating research has been carried out on analyzing the mechanisms by which oscillations and teleconnections (El Niño Southern Oscillation (ENSO) in particular) modulate TCG globally, in association with changes in the sea surface temperature (SST). In addition to this, recent research has diligently addressed different aspects of TCG. Multiple studies have reported the applicability of unified theories and physical mechanisms of TCG in different ocean basins. Recently, research has been carried out on TCG under different flow pattern regimes, dry air intrusion, importance of marsupial pouch, genesis of Medicanes, wind shear, convection and vertical structure. Furthermore, studies have discussed the possibility of near equatorial TCG provided that there is enough supply of background vertical vorticity and relatively low vertical wind shear. Progress has been made to understand the role of climate change on global and regional TCG. However, there are still significant gaps which need to be addressed in order to better understand TCG prediction.

Keywords: Tropical cyclogenesis; AEW; ENSO; SST; Marsupial pouch; Dry air intrusion; Moderate shear; Convection; Near equatorial TCG; Climate change

1. Introduction

Tropical cyclones (TCs) are among the most disastrous weather phenomena over the global ocean basins. Tropical cyclogenesis (TCG) prediction remains as a challenging task due to the limited understanding of the mechanisms associated with it. There are multiple controlling factors that modulate the

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TCG, and a detailed understanding of these controlling factors is important to deduce the underlying physical mechanisms leading to TCG.

Convectively coupled tropical and equatorial waves are often the seedlings of TCs and can influence the environment in which a TC forms. TCG is modulated by regions where African easterly wave (AEW) activity dominates; to the north and south of African easterly jet (AEJ) (Reed et al. 1988a; Lau and Lau 1990). Over the North Atlantic (NA), AEWs are the main precursors of about 60% of TCs (Landsea 1993; Avila et al. 2000; Russell et al. 2017). Recent studies have shown that appropriate convective coupling with tropical equatorial waves enhances the chances of TCG (Fink and Reiner 2003; Hopsch et al. 2010; Semunegus et al. 2017; Núñez Ocasio et al. 2020b).This coupling between convection and AEWs is strongly modulated by moisture-convection interactions (Núñez Ocasio and Rios-Berrios 2023) that are more likely with favorable West African Monsoon conditions (Núñez Ocasio et al. 2021). With an AEW climatology of developing (those that do become TCs) and non-developing AEWs, Núñez Ocasio et al. (2020b) found that the convection coupled to developing AEWs over western Africa and eastern Atlantic is more intense, more in phase with the wave vortex, and with larger cloud cover areas than convection coupled to non-developing AEWs. These results agree with Hopsch et al. (2010) that found the developers had stronger low-level circulations over the eastern Atlantic related to more convective activity.

Furthermore, recent studies (Yamada et al. 2019; Song et al. 2020; Lu et al. 2022) have investigated the impacts of different states of El Niño–Southern Oscillation (ENSO) on variation in TCG frequency in the western North Pacific (WNP); which is the most active TCG region worldwide. An extremely active TCG over the WNP in summer 2018 was primarily caused by the central-Pacific El Niño (Gao et al. 2020). Li et al. (2022) have indicated that TCG frequency over the WNP are modulated by the Pacific Meridional Mode (PMM) (Amaya, 2019), Atlantic Multidecadal Oscillation (AMO), and global warming. The positive phase of the PMM in the tropical North Pacific remotely enhances TCG frequency over the WNP (Liu et al. 2019a), e.g., in summer 2018 (Takaya, 2019). A decrease in the moisture condition over South China Sea (SCS) and WNP associated with a long-lasting MJO has been discussed in Jin et al. (2022a). Over the North Indian Ocean (NIO), Rajasree et al. (2016a) have discussed the genesis sequence of TC Madi (2013). The authors have shown that the protective pouch associated with the westward moving parent disturbance provided a moistening environment for the pre-disturbance. A recent study by Núñez Ocasio and Rios-Berrios (2023) suggest that more moisture content in the atmosphere may not signify more favorable growth driven by moisture, more intense tropical waves nor more intense TCG. Many studies have focused on the impact of dry air (Fritz and Wang 2013; Komaromi 2013; Rajasree et al. 2021) on TCG. The pouch associated with the parent disturbance plays an important role in protecting the pre-disturbance from dry air intrusion (Rajasree et al. 2016b).

As far as knowledge of fundamental mechanisms controlling the response of TCG to climate is concerned, it remains elusive, and there is no extant theory for the global rate of TCG. TC frequency changes at global and regional scales remain one of the more challenging and uncertain aspects of the projected impacts of climate change on TCs (Knutson et al. 2020). Many studies suggest that the number of TCs will decline in a warmer world (Knutson et al. 2020), especially in the Southern Hemisphere (Roberts et al. 2020), but some dynamical and statistical-dynamical models predict increased TC frequency with warming (Bhatia et al. 2018; Emanuel 2021a; Lee et al. 2020). The Tenth International Workshop on Tropical Cyclones (IWTC-10) has discussed various aspects of TCs based on the recent research (2018–2022). This paper reviews the latest advances in research on TCG, with a special emphasis on controlling factors and physical mechanisms. Multi-scale controls of TCG are discussed in section 2, and thermodynamic conditions influencing TCG are discussed in section 3. Impacts of shear on TCG and near equatorial TCG are discussed in section 4 and section 5, respectively. Section 6 discusses the mesoscale controls and section 7 describes the impacts of climate change on TCG. Section 8 presents the summary and conclusions.

2. Multi-scale controls of tropical cyclogenesis

2.1. Tropical equatorial waves

The prominent wave types associated with TCG in different ocean basins include Mixed Rossby Gravity waves, tropical depression (TD) disturbances, Equatorial Rossby (ER) waves, Kelvin waves, and Madden-Julian Oscillation (MJO)

2.1.1. Western North Pacific and North Indian Ocean

Wu and Takahashi (2018) studied the relationship between different wave types and TCG in the WNP. They found that the synoptic low-level vorticity and convection associated with each type of wave contribute to TCG events. It is, however, in the region where both the cyclonic vorticity and active convection overlap where the majority (83.2%) of TCs form, and not in the region where there is only low-level vorticity or active convection. Wu and Takahashi (2018) found that two-thirds of TCG events are credited to one or two coexisting wave types and Kelvin waves account for the smallest percentage of tropical wave-related TCG.

Using empirical orthogonal function (EOF) analyses, Zhao et al. (2019a) showed that it is the combined role of the intra-seasonal MJO, quasi-biweekly oscillation (QBWO), ER waves and synoptic-scale waves that modulate the majority of TCG events in the WNP. Moreover, Lai et al. (2020) showed that 84% of TCG occurs within the active phase of convectively coupled equatorial waves similar to Wu and Takahashi (2018) findings. In the active phase of multiple tropical cyclone (MTC) events where consecutive TC events occur in a period of three days or less, ER waves provide the primary favorable moist and convective environmental conditions for subsequent TCG (Lai et al. 2020). During the inactive phase of MTC events when consecutive TCG events occur nine days or more from each other it is TD-type waves that are the largest contributor to TCG.

Similar to the WNP, over the Bay of Bengal (BoB), TCG is favored when more than one type of wave is present or active (Landu et al. 2020). The dynamically favorable conditions provided by ER waves (increase in relative vorticity) in combination with the favorable thermodynamic conditions provided by the MJO (increase in RH) are associated with a higher number of TCG events over the BoB. Landu et al. (2020) also showed that Kelvin waves contributed the least to cyclogenesis with relatively low cyclonic vorticity. An example of a TCG event from a wave, specifically a convectively coupled equatorial easterly wave, over the BoB was 'Ockhi' in November of 2017 (Sanap et al. 2020).

2.1.2. Atlantic Ocean and eastern Pacific Ocean

Núñez Ocasio et al. (2021) found that developing AEWs (DAEWs), and thus, those that undergo TCG, are more likely southern-track AEWs, where southern-track AEWs develop along the southern flank of the AEJ. These southern-track DAEWs are more prone to interact with mesoscale convective systems (MCSs) from the Inter Tropical Convergence Zone (ITCZ) and West African Monsoon (WAM), as shown in Núñez Ocasio et al. (2021) and in Núñez Ocasio et al. (2020a) (their Fig. 4) even with origins over eastern Africa, which eventually leads to subsequent TCG. Previous studies have noted that the merger of the northern and southern tracks can lead to TCG but recently, Duvel (2021) showed that the merger does not necessarily lead to TCG, and subsequent deepening of the vortices and favorable environmental conditions must be present.

Núñez Ocasio et al. (2021) investigated the origins of TC precursors (and thus, DAEWs) and found that AEWs that initiate over eastern Africa, in the vicinity of the Ethiopian Highlands, are more probable to undergo TCG than those that initiate over central or western Africa. Moreover, they found a relationship between the large-scale environment over east Africa and the likelihood of an AEW subsequently undergoing TCG. Núñez Ocasio et al. (2021) proposed the following key predictors of TCG over eastern Africa.

1. Stronger northerly and WAM flow;
2. More intense zonal Somali jet and stronger convergence over the Marrah Mountains (region of AEW forcing);
3. Larger WAM moisture and convective signature concentrated west of the Marrah Mountains.

Over western Africa, TC precursors include.

1. Stronger WAM;
2. More intense and extended AEJ off the west coast of Africa and offshore waters.

The interactions between AEWs and MCSs have been shown to be significant for TCG in the Atlantic. Núñez Ocasio et al. (2020b) evaluated the propagation of MCSs relative to the AEW they are associated with (i.e., wave-relative framework) and they found statistically significant differences between MCSs associated with DAEWs and non-developing AEWs (NDAEWs). Unlike the MCSs associated with NDAEWs which are likely to move south of the AEW trough and faster, MCSs of DAEWs tend to move with the DAEW, and thus, in phase with the AEW trough (Fig. 1, adapted from Núñez Ocasio et al. 2020b).These differences between DAEWs and NDAEWs become important for the intensification of the AEW vortex and subsequent TCG as this slower-moving convection, i.e. moving at the same speed of the AEW trough, supplies moisture and latent heat to the AEW vortex supporting its further growth. Núñez Ocasio et al. (2020b) also found that DAEWs have more squall line type of MCSs associated with them over western Africa than NDAEWs. In a similar wave-following framework, Lawton et al. (2022) found that convectively coupled Kelvin waves (CCKWs) can influence the life cycles of NDAEWs that have qualitatively similar characteristics to DAEWs. They found that convective coverage around AEWs changed in phase with CCKW crests, as also shown in Núñez Ocasio et al. (2020b). This is relevant to TCG as the strong convective area is a significant contributor to the latent heat rate associated with DAEWs.

In the Eastern Pacific, the initiation and evolution of easterly waves (EWs) can be influenced by anomalous low-level westerly MJO and Caribbean low-level jet (CLLJ) periods which together provide favorable conditions for TCG (Whitaker and Maloney, 2018). Whitaker and Maloney (2020) further showed that the EW that became Hurricane Carlotta (2012) originated from an intense MCS over the Panama Bight.

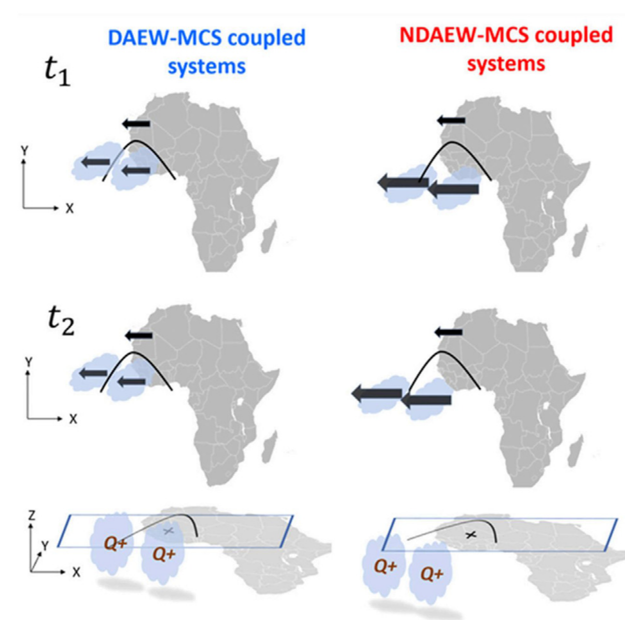

Fig. 1. Conceptual model describing how the chances of TCG increase with appropriate convective coupling. For DAEW–MCS systems, TCG is favored when convective cloud clusters (CCCs; denoted by the cloud) move at the same speed as the AEW trough (direction and magnitude of propagation are denoted by solid black arrows) and are latitudinally in phase with the trough. Maintaining the same speed insures the same phase relationship. Note that convection of NDAEWs is positioned south of the trough and propagates faster than the trough; thus, phase locking and further intensification are less likely. Adapted from Núñez Ocasio et al. (2020b).

The coupled MCS-EW system was strongly modulated by the Choco and Papagayo jets (that are an extension of the CLLJ).

2.2. Oscillations and teleconnections

It is of great importance to elucidate the mechanisms responsible for changes in TCG to improve accurate forecasts over the major TC development regions, such as the WNP, eastern North Pacific (ENP) and the tropical North Atlantic Ocean (TNA). TCG variation from the interdecadal to the intraseasonal time scales has been actively discussed in the literature during the last five years (2018–2022).

On the interdecadal time scale, Zhao et al. (2019b) found that the covariability of TCG latitude and longitude is increasing since 1998, which is found to be closely linked to shifting ENSO conditions and tropical Pacific climate regime shift. In addition, Wang et al. (2022) identified an anti-phase decadal variation in TCG between the WNP and TNA. The *trans*-basin TC connection results from a subtropical east-west "relay" teleconnection triggered by AMO, involving a chain atmosphere-ocean interaction in the North Pacific. Both studies (Liu and Chen, 2018; Cao et al. 2018a) have detected an intensified impact of the ENSO Modoki on TCG frequency over the WNP since early 1990s, but with different mechanisms.

On the interannual time scale, Chen et al. (2018a) found that TCG is closely related to the ENSO, which is a dominant signal of the atmosphere and ocean. Other than SST spatial pattern, Liang et al. (2022a) found that the onset time difference of El Niño events has various influences on TCG. The equatorial Pacific Ocean warming can be separated into spring (April–June; SP) and summer (July–October; SU) modes based on the onset time of El Niño events. In the SP type, the location of TCG over the WNP shifts significantly eastward and equatorward, whereas in the SU type, only an eastward shift occurs. In addition to the SST anomalies in the central-eastern Pacific, Pu et al. (2019) demonstrated that the spring Victoria mode, the second EOF (EOF2) of SST anomalies in the North Pacific north of 20°N, exhibits a positive correlation with the following summer TC frequency over the eastern WNP and negative correlation over the western WNP. A combination mode (C-mode), formed by nonlinear interactions between the western Pacific warm pool annual cycle and ENSO variability (Stuecker et al. 2013), has a significant negative relationship with WNP TCG frequency on a monthly timescale from 1970 to 2019 (Fig. 2, adapted from Song et al. 2021). The related atmospheric conditions are linked to an anomalous large-scale anticyclone over the WNP induced by the C-mode. Zhang et al. (2020) found a dominant role of the SST variation in the central Pacific in the TCG over the WNP compared to the simultaneous impact of the PMM. However, Wu et al. (2021) revisited the interannual impact of the PMM on TCG over the WNP and found the important effect of the PMM on WNP TC activity, especially during neutral ENSO years. Liu et al. (2019a) found that the statistical relationship between PMM and WNP TCG is dominated by their co-variability on the decadal time scales. Thus, the role of the PMM deserves to be further studied.

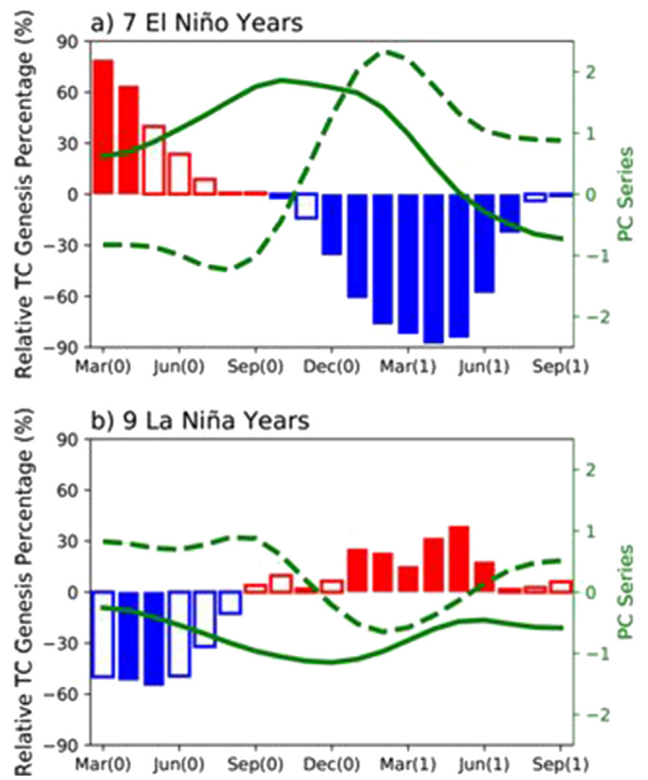

Fig. 2. Composite monthly evolution of the first PC (green solid line), the second PC (green dashed line), and the WNP TC frequency anomaly percentage relative to its corresponding climatological mean (bar) for(a) 7 El Niño and (b) 9 La Niña winters during 1970–2019. The abscissa indicates a 19-month period from March of year 0 to September of year 1. Filled bars indicate composited values significant at the 0.05 level based on a two-sample Student's t-test, compared to 36 neutral winters. Adapted from Song et al. (2021).

On the other hand, atmospheric variability also plays a role in the interannual variation of TCG over the WNP. Cao et al. (2021) found that TCG frequency has a significant positive correlation with the intensity of intraseasonal oscillation (ISO), but a weak correlation with the intensity of synoptic variation of environmental factors during the peak season over the WNP. Zhan et al. (2022) found a significant positive correlation between TCG frequency over the WNP and the jet intensity in the entrance region of the tropical easterly jet over the tropical western Pacific, which is associated with strong ageostrophic northerly winds in the entrance region.

On the intraseasonal scale, the 20-70-day oscillation mainly modulates the frequency of TCG, while the 10-20-day QBWO usually influences the genesis location over the WNP and SCS region (You et al. 2019). Through affecting the strength of monsoon trough and the location of the western Pacific subtropics high, the ISO combinations modulate the thermodynamic conditions and lead to changes in the frequency and location of TCG. A comparison research through observational analysis and numerical simulation indicated that RH associated with the MJO plays the most important role in modulating TCG over the WNP, the Gulf of Mexico and the western Caribbean Sea, while VWS has the most significant impact on TC activity over the eastern Atlantic (Zhao and Li 2019). In addition to the WNP and TNA, the study of Bhardwaj et al. (2019) specifically focused on the MJO's impacts on TCs in the BoB during the two peak TC periods, April–June and October–December. TC activity is significantly enhanced (suppressed) over the BoB when the convectively active MJO phase is positioned over the eastern Indian Ocean and the Maritime Continent (the western hemisphere and Africa). Chen et al. (2018a) synthetically examined the influence of intraseasonal-to-interannual oscillations on TCG by measuring the productivity of TCG from the developing and non-developing precursory tropical disturbances. They found that the percentage value of precursory tropical disturbances evolving into TCs increases (decreases) during the phases of positive-vorticity (negative-vorticity) ER wave, the active (inactive) MJO and El Niño (La Niña) years. Relative vorticity acts as the most important factor to modulate the percentage value of precursory tropical disturbances evolving into TC compared with VWS and mid-level RH. Previous studies are mostly concerned with the environmental conditions of the TCG on a large spatial scale averaged in a certain period. Cao et al. (2018b, 2019) examined the state at a locality of TCG to find out the relative contributions of different time scales (interannual, intraseasonal and synoptic variations) to the TCG over the WNP and TNA. They found that the synoptic variation is the most important component over the TNA, while the leading component is the intraseasonal variation over the WNP.

2.3. Marsupial paradigm

There have been significant advances in studies related to the Marsupial paradigm, particularly focusing on the evolution of the mid-level pouch circulation and its accompanied influence on TCG. Similar analyses were conducted for the case of Typhoon Nepartak (2016) in the WNP (Wu and Fang 2019) and Hurricane Karl (2010) in the NA (Bell and Montgomery 2019). From both case studies, alternative enhancement of low- and midlevel circulations (MLCs) is observed during each TCG event and both emphasized the thermodynamic role of MLC aiding low-level spin up. From the vorticity budget analysis, Wu and Fang (2019) revealed that the MLC is enhanced during deep convection due to vertical advection and tilting of vorticity from low-levels and is further intensified due to accompanying midlevel convergence during stratiform precipitation. According to Bell and Montgomery (2019), such midlevel convergence of vorticity may increase the depth of protective pouch and the cooling and moistening in the stratiform precipitation region may promote convective bursts and recur the enhancement of low-level vortex. However, one should be cautious that the dynamic impact of the stratiform divergence at low-levels would weaken the near-surface circulation and lead to eventual low-level spin-down. That is, stratiform precipitation and the midlevel vortex play a supporting role in the genesis process, whereas the deep convection is a primary element in the genesis. Among various components of convection, a key feature leading up to TCG is investigated by Wang (2018). By investigating more than 150 named Atlantic storms, the author confirmed that the convection contrasts between inner and outer pouch region (neither convection intensity nor the area) is the key feature.

The Marsupial paradigm has been examined in TCs in different ocean basins. Rajasree et al. (2021) examined a developing and a non-developing disturbance in the NIO based on the marsupial theory using an operational numerical model. The evidence of a synoptic scale parent disturbance, its protection of the vortex from hostile environmental factors and positive vorticity tendency at low-level are clearly observed, not only during the developing disturbance but also during the non-developing one. However, the eventual failure of development was due to the interaction of the vortex with strong deep layer (850-200 hPa) environmental wind shear and a strong ridge developed over the central Indian land mass and colder sea water. Yoshida and Fudeyasu (2020) examined the horizontal distribution of the genesis environment in different flow pattern regimes. In terms of geographical location, TCG most frequently occur over the eastern edge of the area presenting high genesis potential index, high RH and weak VWS. In terms of temporal evolution, such favorable conditions are found to gradually organize three days before genesis in the monsoon shear line and easterly wave regimes, while they organize 13 days before genesis in monsoon confluence regions. Raavi and Walsh (2020) conducted a basinwide statistical analysis of factors limiting tropical storm formation by adopting the Okubo-Weiss Zeta Parameter (OWZP) introduced by Tory et al. (2013) to trace developing and non-developing depressions. The contrast between developing and non-developing depressions is pronounced as strong positive (negative) OWZP was found in the core (surrounding) region for developing cases but a weaker shear sheath in the northwest/west side of the depression was found in non-developing cases.

3. Thermodynamic conditions influencing tropical cyclogenesis

3.1. Impacts of sea surface temperature

TCG is strongly forced by conditions in the atmosphere and ocean, which provide energy for storm development. Because large-scale atmospheric environments are modulated by SSTs, an understanding of the relationship between SST variability and TCG is important for predicting TCG frequency. TCG frequency on an interannual time scale is modulated by SSTs in association with climate mode such as the ENSO (Amaya, 2019).

A potential role of SST warming in PMM effects on TCG frequency was suggested by Ishiyama et al. (2022) in relation to the 2015 super-El Niño. Thus, remote effects such as SST anomalies outside of the WNP appear to affect TCG frequency. Recent studies (Wu et al. 2018; Wu et al. 2019; Wu et al. 2020; Gao et al. 2018; Zhang et al. 2018; Zhan et al. 2019) have identified various impacts of SST anomalies in NA Ocean and/or Indian Ocean (IO) on TCG locations and frequencies over the WNP, demonstrating the effects of large-scale environmental modulation. For example, Liu et al. (2019b) estimated the impacts of SST anomalies in the Indo-Pacific region on TCG frequency over the WNP. The combined impacts of the ENSO and Indian Ocean Dipole (IOD) enhanced an anomalous cyclonic circulation in the lower troposphere, leading to higher TCG frequency in the southeastern WNP, while an anomalous anticyclonic circulation led to lower TCG frequency in the northwestern WNP. A significant correlation was detected between the IOD and TCG frequency over the SCS (Wang et al. 2019a). According to Shi and Fang (2022), high SSTs in the TNA in June and July 2020 triggered cyclonic circulations over the tropical ENP, resulting in strong upward motion and subsidence in the tropical central-Pacific, which caused the western Pacific subtropical high to extend westward and strengthened easterly winds on its south side, in turn weakening the monsoon trough and producing unfavorable conditions for TCG and “the no-typhoon (no-TCG over the WNP)” phenomena in July 2020. Furthermore, the categorization of TCG environments over the WNP according to shear line, monsoon gyre, and Rossby wave energy dispersion from preexisting cyclones showed that TCG is associated with higher SSTs in the WNP (Fudeyasu et al. 2020). Jin et al. (2022b) has discussed the possible role of a local monsoon trough favoring weak TC formation over SCS and WNP.

Climate modes that influence TCG in the NA include the ENSO, AMO, the Atlantic meridional mode, and global warming, while in the ENP they include the ENSO and AMO (Li et al. 2022). The ENSO was found to be the main factor influencing TCG frequency in the ENP and southwest Pacific due to the effects of local SSTs. The PMM also exerts an influence on TCG frequency over the ENP, as demonstrated by the strongly positive SST component of the PMM, which led to favorable TCG conditions in 2018 (Wood et al. 2019). Magee and Verdon-Kidd (2018) found a relationship between SST variability in the IO and TCG over the southwest Pacific when the ENSO was in an inactive phase. Warmer (cooler) SSTs in the IO caused statistically significant northeastward (southwestward) migration of TCG over the southwest Pacific. Ensemble simulations have shown that due to interannual variability forced by observed SSTs, TCG over the NA is modulated primarily by potential intensity and VWS (Mei et al. 2019). The role of ocean heat content (OHC) including SSTs in TCG over the BoB, a semi-marginal sea in the NIO, was investigated in Albert and Bhaskaran (2020) that detected differences in positive (negative) OHC anomalies to the south during the pre- (post-) monsoon season, leading to the higher TCG over the BoB.

Recent studies (e.g., Takaya, 2019; Wang et al. 2019b; Wood et al. 2019; Gao et al. 2020) have investigated the extremely active TCG that occurred over the Northern Hemisphere in summer 2018. The active TCG in the North Pacific was found to have been caused primarily by warming in the subtropical Pacific and secondarily by warming in the tropical Pacific (Qian et al. 2019). The impact of midlatitude SST anomalies has been found to affect TCG at lower latitudes in the WNP due to large-scale atmospheric responses and intraseasonal oscillation (Nasuno et al. 2022). Enhanced TCG over the NA was caused by favorable large-scale environmental conditions forced by subtropical NA SST warming (Wang et al. 2019b). Future research should continue to investigate the influence of SST spatial patterns in different basins and different background flows on TCG over different scales. Moreover, investigating the influence of SST anomalies on TCG would lead to accurate predictions of TCG frequency.

3.2. Impacts of moist/dry air

Hypotheses explaining the physical mechanisms related to moisture entrainment and dry air intrusion have been tested in different ocean basins in the recent years. Most of these studies discuss the underlying physical mechanisms by which the intrusions of moist/dry air into the core of tropical disturbances lead to/inhibit TCG. A moisture pooling effect is discussed by Liang et al. (2022b) in WNP TCG case studies. Ramakrishna et al. (2019) show the presence of cyclonic circulation and moisture convergence six days ahead of the development of NIO TC Thane (2011) and the cyclone is strengthened by moisture advection from the SCS. In the genesis environment of Pacific Ocean tropical disturbance pre-Faxai (2019), the development of a Kelvin cat's eye is found to be one of the reasons for the persistence of vortices (Fudeyasu et al. 2022). Positive feedback between near surface wind and latent heat flux increases the boundary layer specific humidity and leads to TCG under favorable conditions (Gao et al. 2019). Teng et al. (2021) addressed the sensitivity to moisture patterns in the cases of TCG related to monsoon environment compared to that of easterly environment. The importance of mid-level moisture is higher in the case of WNP TCG associated with easterly environments and more sensitive to moisture patterns compared to that of monsoon environments. In the developing cases, TCG is favored by the generation of stronger potential vorticity produced by diabatic heating as a result of increased mid-level moisture. Moist Static Energy can be used as a proxy for understanding moistening processes in the lower to middle troposphere (Chen et al. 2019a; Wing et al. 2019; Yu et al. 2019; Fu et al. 2021; Carstens 2022). Significant advances have been reported in the case of Medicanes (Mediterranean tropical-like cyclones) in the last five years; particularly in understanding the role of moist and dry air advection on the genesis of Medicanes. The increase in humidity induces an early onset of genesis in Medicanes by producing stronger and longer persisting vortices (Miglietta et al. 2021).

Dry air intrusion reduces both the thickness of the moist absolutely unstable layer and maximum intensity of convective updrafts (Saito et al. 2022) and longer residence time of dry air causes the disruption of convection (Alland et al. 2021b). A dry lower troposphere may limit diffusive exchange (Sun et al. 2022), however, smallness in size of the core as well as weak VWS can offset the adverse effects of dry air and ocean cooling (Shimada, 2022). Once the convection is generated then the instability index is more important than saturation fraction (SF, Column RH) in the inner ring of the core whereas in the outer ring, the SF is more important than instability indices (Raymond and Kilroy, 2019). In a study carried out by Akter (2022), on TCG connected to dryline over BoB, the author showed that large values of convective inhibition, due to hot and dry air, support the stable environment over the northern and Northwestern BoB. As shown in Helms and Bosart (2021), the core of persistent convection collapses when an Atlantic Ocean tropical disturbance, pre-Gabrielle (2013) interacts with mid-level dry air flow layer. The authors suggested that the pre- Gabrielle disturbance might have benefited if a protective pouch was present in the genesis environment. Similar case studies of dry air intrusion have been reported from different ocean basins in the last five years. In a comparative study of developing and non-developing TCs, Rajasree et al. (2021) found that the non-developing system weakened because of the intrusion of dry air from the north of the core and the trajectories were traced back to the northwestern part of India as a possible source as shown in Fig. 3, adapted from Rajasree et al. (2021). Future research should continue research on understanding how different aerosol types interact with the TCG, using available chemical models.

4. Impacts of shear on tropical cyclogenesis

Strong VWS often delays or completely thwarts TCG due to vortex tilt, precipitation asymmetry, and dry air ventilation. These dynamic and thermodynamic processes constitute a positive feedback cycle. TCG follows the vertical alignment of the vortex tower, and strong VWS advects the vortex in different vertical layers to opposite directions, in other words, tilts the vortex tower (e.g., Rios-Berrios et al. 2018). Then a tilted vortex tower is more susceptible to dry air ventilation as shown by Alland et al. (2021a, b) who investigated the combined effect of dry air and VWS on TC intensification. VWS also moves the convection down-shear side, and convection farther from the vorticity center is not efficient in amplifying the vortex (e.g., Schecter and Melanou 2020). Well-established TCs may withstand moderate to even the strong intensity of VWS, but pre-genesis TCs are rather vulnerable to the negative impacts of strong VWS (Finocchio and Rios-Berrios 2021; Fischer et al. 2022).

The focus of recent research in this field has been on moderate VWS, because the uncertainty of TCG forecasts in moderate shear is the largest (Nam and Bell 2021; Rios-Berrios et al. 2018; Rogers et al. 2020). Weak VWS provides a conducive environment and strong VWS is generally unfavorable for TCG, but under moderate shear, genesis scenarios can swing a lot depending on environmental and internal factors. TCs that successfully underwent genesis in moderate shear share the characteristics of continuous and strong convection (Rogers et al. 2020; Nam and Bell 2021). Deep convection near the vorticity center is a necessary factor for vortex reformation and eventually successful TCG despite shear (e.g., Rios-Berrios et al. 2018). Schecter and Melanou (2020) showed that the vortex advection and misalignment can be simulated with an adiabatic dry model, but vortex realignment and intensification in a sheared environment can be only modeled with moist convection included. In addition to deep convection, recent studies have highlighted the roles of different kinds of convection in vortex reformation and precession – the role of convective congestus in tilting horizontal vorticity to vertical vorticity (Nam and Bell, 2021), stratiform precipitation in intensifying the mid-level vortex and preventing dry air ventilation (Bell and Montgomery 2019), and coldpools with radiative effects (Rios-Berrios 2020).

Various large or synoptic scale weather systems such as upper-level troughs serve as sources of VWS (Fig. 4 adapted from Nam and Bell 2021; Yoshida and Fudeyasu 2020). Then the impact of shear reduces to convective meso scales, and convection in turn affects the tropical disturbance's resilience against VWS through vorticity generation of vortex stretching and tilting (Fig. 4b, d). The idealized modeling studies have made progress on bridging the gap between the model world and the complex real atmosphere – adding radiative effects (Rios-Berrios 2020), diversifying the timing of shear introduction (Finocchio and Rios-Berrios 2021), and simulating the combined effects of shear and dry air (Alland et al. 2021a, b). Nevertheless, more modeling research is needed to analyze the multi-dimensional variable space of internal and environmental

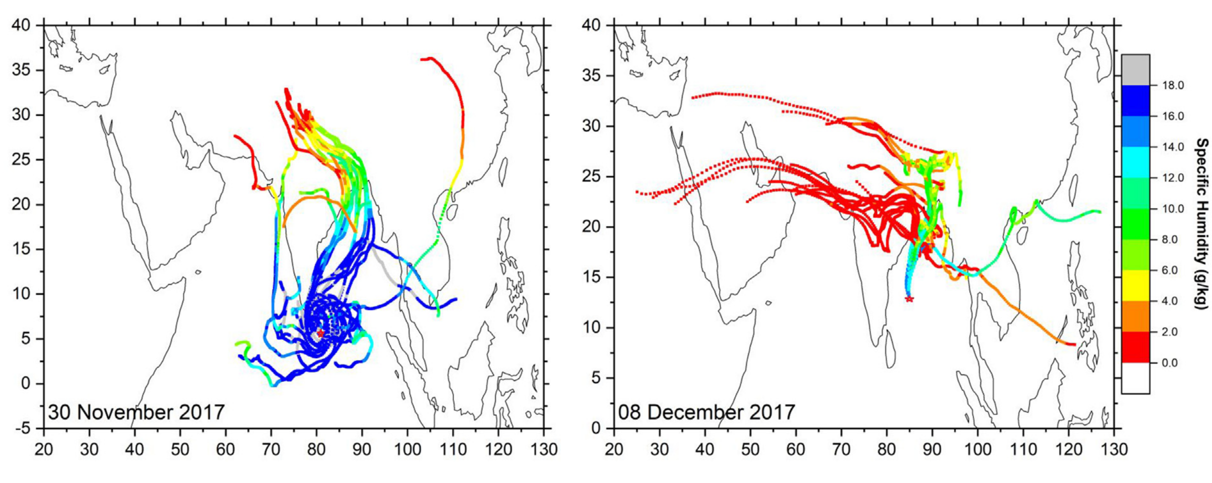

Fig. 3. Backward trajectories of specific humidity (g kg^{-1}) obtained from HYSPLIT model at deep depression (DD) stages of (a) TC Ockhi and (b) depression valid at 00 UTC of 30 November and 08 December 2017. Red * mark represents the center of the storms. Adapted from Rajasree et al. (2021).

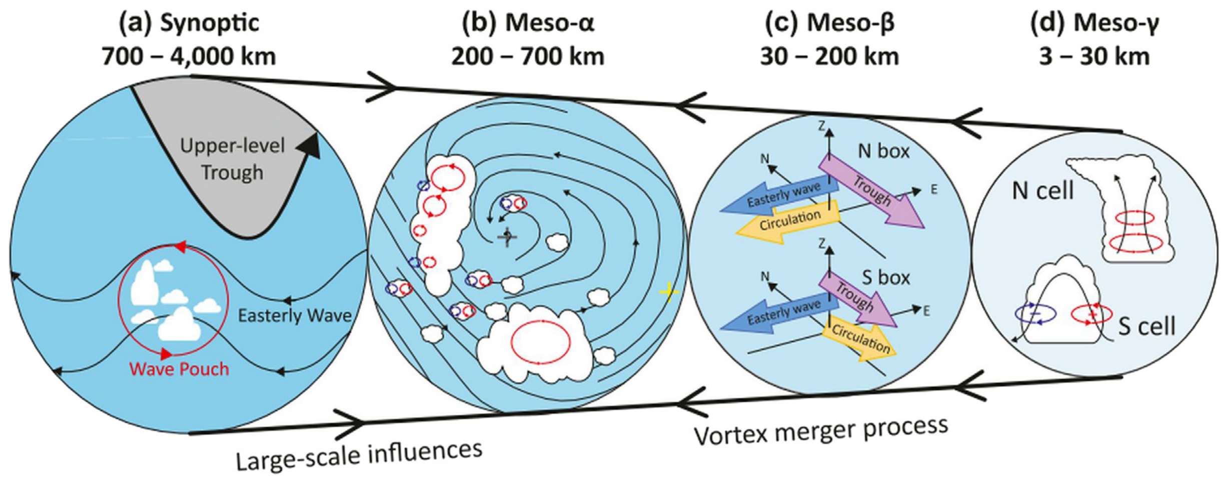

Fig. 4. Schematic of the multiscale interactions in Hagupit (2008)'s cyclogenesis in a shear environment: (a) Synoptic-scale active features are the upper-level trough and easterly wave that carries the marsupial wave pouch, denoted as red circulation. (b) In the meso-α-scale wave pouch, the low-level cyclonic streamlines are shown with the circulation center marked with a black cross and the midlevel center marked with a yellow cross. Overlaid on the clouds to the southwest of the low-level center is vorticity (positive: red, negative: blue), illustrating vorticity dipoles from tilting, enhanced vorticity from stretching, and a midlevel MCV over the stratiform area. (c) In the meso-β scale, the local wind shear profile that influences the convective organization comprises winds from cyclonic circulation inside the pouch, easterly wave propagation, and the trough. (d) Meso-γ-scale convective cells produce vorticity that serves as building blocks for the wave-pouch intensification through tilting of horizontal vorticity associated with low-level wind shear (S cell) and stretching of the local vertical vorticity (N cell). Adapted from Nam and Bell (2021).

factors for TCG in sheared environments. For observational analyses, one of the challenges is that high-resolution observational data of developing disturbances under moderate to strong shear are scarce. High-resolution data are essential to show the upscale cascade of energy from the convective scale to larger scales in the vortex realignment process (Nam and Bell 2021; Rogers et al. 2020), and to verify the findings from idealized modeling studies. We recommend that future research should focus on understanding the complicated multi-scale interactions in TCG under moderate vertical wind shear which would enable better understanding of vortex resilience, precession, or reformation in sheared environments.

5. Near equatorial tropical cyclogenesis

It is typically stated in classical meteorological textbooks that TCs do not form within 5° of the equator, due to the diminishing effects of the Coriolis force closer to the equator. In other words, according to these textbooks, the formation of TCs depends on there being adequate background planetary rotation present. A series of papers in the recent years have shown that, while relatively rare, TCs can occur close to the equator provided that there is a large enough supply of background relative vertical vorticity.

A study by Steenkamp et al. (2019) investigated several real cases of near equatorial TCs using European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses, with an emphasis on understanding the origins of these regions of enhanced vertical vorticity. For Typhoon Vamei (2001), the initial enhanced background rotation was provided by the Borneo vortex, while for Super Typhoon Dolphin (2015) the rotation was associated with unstable roll-up of vorticity in a shear line marking an ITCZ. For Hurricane Pali (2016) there was a monsoon-like shear line close to the equator. In all cases, TC development occurs when deep convection consistently flares close to the center of these large-scale circulations. The authors conclude that cyclone development near the equator appears to be dynamically the same as in other higher latitude storms.

Another study by Li et al. (2019), using best track data from the Joint Typhoon Warning Center and ECMWF interim reanalysis, showed that TCs form close to the equator in the WNP in boreal winter as the large-scale flow changes, when the north-easterly trade winds turn anticlockwise near the equator. This turning leads to the occurrence of an increased region of low-level absolute vorticity within 5° of the Equator. Other changes in the large-scale environment, such as RH, SST or mean atmospheric temperature fields did not seem to be undergoing drastic seasonal changes, and were deemed unimportant (Deng and Li, 2020).

Lu et al. (2021) further analyzed the controlling parameters in the formation of TCs near the equator (in the WNP and NA basins). They found that no cases of near-equatorial development occurred in the NA. As in the studies by Li et al. (2019) and Deng and Li (2020), it is found that low-level relative vertical vorticity is likely a dominant factor. They also showed that VWS is more favorable in the WNP compared to the NA.

In an analysis of Advanced Research Weather Research and Forecasting (WRF-ARW) model output, Deng and Li (2020) highlighted the importance of small-scale vortical hot towers (VHTs) in converging the large-scale background vorticity into vortex-scale monopole. This convergence of vorticity is not different from that which occurs at higher latitudes. Using a highly-idealized numerical model setup, Kilroy et al. (2020) showed that TCs occurring at the equator can also undergo rapid intensification (RI), however, they decay rather rapidly also. After a few days of development, the storms deplete their initial cyclonic vorticity source and begin to ingest the negative vertical vorticity in the surrounding environment as air parcels large distances from the center are drawn inward. The ingesting of negative vertical vorticity leads to the development of regions that are inertially unstable close to the cyclone center, which consequently leads to a rapid vortex breakdown. At higher latitudes, away from the equator, planetary vorticity would play an important role at this stage of development.

6. Meso-scale controls

6.1. Role of convection/heating

Generally, the location of TCG is related to environmental vorticity and moisture, while the probability and timing of TCG mainly depend on convective characteristics (Narenpitak et al. 2020). Convection is a precursor, trigger, and energy source of TCG at the initial stage. It provides heating, vertical ascent, and moisture around the disturbance center and leads to mid-level vortex development and vertical mass transport during the TCG process. It is also highly stochastic in nature, leading to uncertainty in model forecasts. Therefore, understanding the role of convection and heating in the TCG environment is important to interpret the physical mechanisms that differentiate the developing systems from non-developing systems. Cumulus congestus and deep convection respectively moisten the lower to middle troposphere and upper troposphere (Wang, 2014), convergence enhances around the center through ice microphysical processes and diabatic forcing, and then strengthens the mid-level circulation/vortex due to conservation of angular momentum (Nicholls et al. 2018; Bell and Montgomery 2019; Wang et al. 2019c; Carstens and Wing 2020).

The mid-level circulation/vortex protects the disturbance from the dry air intrusion and further enhances the convection and vertical mass transport, favoring low-level spin up and TCG.

Because convection-related characteristics affect the TCG process, they may become important indicators for TCG. The total rain area, rain volume, and coverage area of deep convection near the circulation center have notable differences between developing and non-developing disturbances. They are useful predictors for TCG in observations (Zawislak 2020). Moreover, in the inner core, the structure of vortical convection substantially changes before the initial disturbance intensifies rapidly into a TC, i.e., an increase in cyclonic vertical vorticity. This is a potential indicator to characterize the period of TCG (Kilroy 2021). Conversely, boundary layer physics of the large scale vortex, producing an Ekman pumping, is a key mechanism for convection maintenance and intensification. Convection-induced convergence in the boundary layer and mass flux governed by thermodynamic conditions highly impact inner-core vortex expansion and the subsequent TCG process (Raymond and Kilroy 2019; Smith et al. 2021). These characteristics can be further applied to improve convective parameterizations for models and TC formation forecasts.

Many studies have investigated the pathways of TCG. Smith and Nicholls (2019), described different mechanisms through which low-level convectively induced vorticity anomalies (LCVA) initiate TCG. At the edges of cold pools, vorticity is concentrated by convection and LCVA forms above the regions of increased vorticity. LCVA has maximum vorticity near the surface, outlives the convection itself and occasionally get strengthened by subsequent convection. These mechanisms stretch the ambient vorticity into a coherent vortex. LCVA reaching the center of the parent disturbance becomes the low-level core of the TC, forming a small vortex that generates in the center of the parent disturbance. LCVA undergoes merger similar to VHTs (Hendricks et al. 2004). Future research should continue to explore the convection physics, and diabatic heating to improve the forecast skill of TCG prediction. Furthermore, research should continue to understand the top-down and bottom-up mechanisms of TCG in detail, and further quantify the stochastic processes of convective development and TCG using ensemble probabilistic forecast. Further research should focus on understanding the roles of water vapor and convection and how these interact at different scales in influencing TCG prediction.

6.2. Vertical structure

Pre-genesis and weak TCs often develop a top-heavy potential vorticity structure (Raymond and Session 2007; Murthy and Boos 2019) via stratiform precipitation. Although stratiform precipitation commonly cools the lower troposphere, its latent heating maximizes in the middle troposphere and provides a key component for the initial spin-up and maintenance of a mid-level circulation. The persistence of convection, on the other hand, is also critical to achieve early stage of TC development, as it provides a more bottom-heavy mass flux to spin up vorticity in the lower troposphere. A recent study from Levina (2018) hypothesized that a criterion summarizing the combined effects of favorable helicity and instability (e.g., convective available potential energy) may be beneficial towards identifying sufficient convective development in TCs that results in TCG. Persistent vortical convection can generate vertical vorticity by tilting of horizontal vortex filaments within updrafts that are also amplified by stretching, which can help spin up the low-level vortex.

VWS of the horizontal wind can detrimentally cause misalignment between developing low-level and mid-level vortices, particularly in undeveloped or weak TCs, wherein they have increased susceptibility to environmental influences (Jones 1995; Frank and Ritchie 2001). Previous studies have highlighted the importance of achieving a vertically aligned configuration of the vortex (e.g., Zhang and Tao 2013; Rios-Berrios et al. 2016; Munsell et al. 2017; Schecter, 2022) to favorably promote a more symmetric precipitation structure, which is favorable for RI and may also increase resiliency from surrounding environmental dry air and VWS (Tang and Emanuel 2010, 2012; Davis and Ahijevych 2012; Alland et al. 2021a, b; Chen et al. 2019b; Alvey et al. 2020). Multiple pathways towards achieving an aligned vortex have been identified in the literature: precession (Jones 1995; Reasor et al. 2004), downshear reformation (Nguyen and Molinari 2015;

Chen et al. 2018b; Rogers et al. 2020; Schecter 2020; Alvey et al. 2022), and (diabatically induced) and advection (Schecter and Menelaou 2020). More common in weaker, disorganized storms, a new low-level circulation can reform either beneath or near the MLC via persistent convection. A recent study by Zhang et al. (2022) have indicated that distribution of deep convection is mainly affected by wind shear. Furthermore, sensitivities to the environment like increasing or decreasing the SST and changes in the VWS (Finocchio and Rios-Berrios 2021) can affect the distribution/intensity of convection, which can alter the relationship between vortex tilt magnitude and subsequent TC intensity change.

7. Role of climate change

There has been no discernible trend in the annual global number of TCs over the last four decades (Schreck et al. 2014; Ramsay 2017; Klotzbach et al. 2022), however some global reanalysis datasets suggest a long-term decline in global TC frequency since about 1900 (Chand et al. 2022). Fig. 5 shows the hypothesized link between anthropogenic-induced global warming and associated reduction in annual TC numbers, adapted from Chand et al. (2022). Declining trends in the normalized composite index derived from the environmental vertical wind shear, upward mass flux and saturation deficit suggest a similar declining trend in TC numbers for all the TC basins around the globe. The authors have attributed the decreasing upward mass flux and increasing saturation deficit and environmental vertical wind shear to the warming of the climate over the twentieth century. Further, the reduction in the upward mass flux has been linked to the weakening of the Walker and Hadley circulations during twentieth century compared to the pre-industrial period, which is further increasing the likelihood of dry air entrainment and thereby reducing chances of TCG.

Although the annual global number of TCs has remained steady since the early 1980s, there have been notable regional

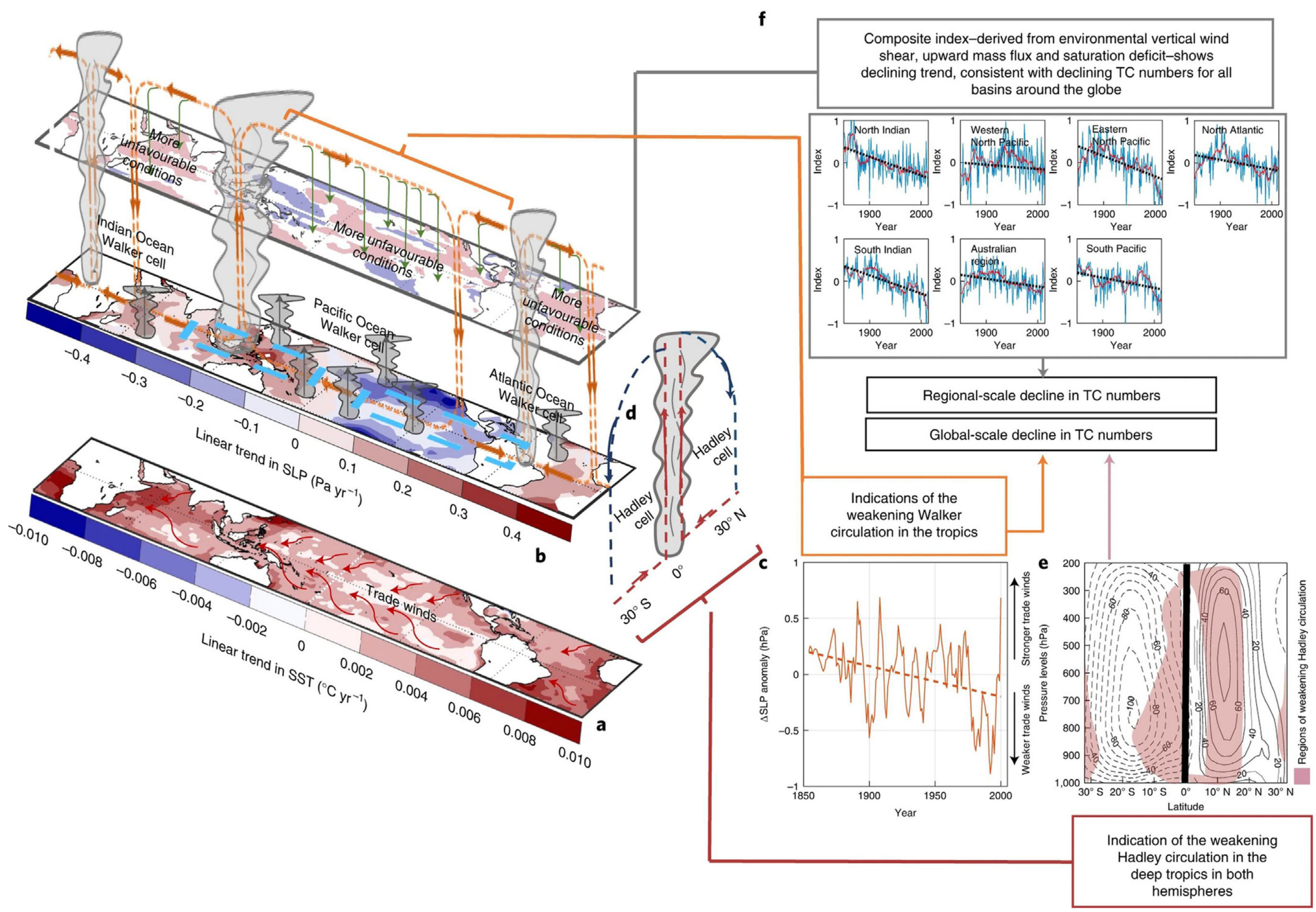

Fig. 5. Schematic showing the hypothesized link between anthropogenic-induced global warming and associated reduction in annual TC numbers. a, Linear trends in SSTs since the mid-nineteenth century, overlaid with the mean trade wind directions (red arrows). b, Linear trends in sea-level pressure (SLP) (dashed blue rectangles are used to define the Indo–Pacific SLP gradient, ΔSLP, which serves as a proxy of changes in mean intensity of the Pacific Walker circulation. The three Walker cells are represented in orange. Sinking dry air is represented by green arrows and moist rising air is represented by grey arrows). c, Changes in the Indo–Pacific SLP gradient since the mid-nineteenth century. d, An illustration of the Hadley circulation. e, Observed Hadley circulation pattern, represented by mass stream function of the zonal-mean meridional winds during the period 1900–2012 (red shadings indicate regions where the summertime mean intensity of the circulation has weakened significantly relative to the pre-industrial counterpart). f, Environmental conditions represented as the normalized composite index. Adapted from Chand et al. (2022).

trends in annual TC frequency (Murakami et al. 2020), including a sharp increase in the NA basin and decreases in the Australian region (Chand et al. 2019) and in the WNP basin (Liu and Chan 2013; Zhang et al. 2018). The significant upward trend in the NA is associated with a regional TC drought during the 1970s and 1980s (Vecchi et al. 2021), when thermodynamic conditions over the main development region were unfavorable (Emanuel 2021b) due to both enhanced anthropogenic aerosols and an increase in Saharan dust (Rousseau-Rizzi and Emanuel 2022). The warming of the TNA has resulted in several notable active hurricane seasons: Murakami et al. (2018) attributed the active major hurricane season of 2017 to the relative warming of the NA (i.e., warming relative to the tropical mean SST), rather than La Niña conditions, and the extremely active hurricane seasons of 2005 and 2020 have been also attributed to rising regional SSTs (Pfleiderer et al. 2022).

TC frequency trends in basins outside the NA have received less attention and are arguably not as well understood. An observed poleward shift in the latitude of TCG during the period 1980–2014 has been linked to an expansion of the tropics as reflected by changes in regional Hadley circulations (Sharmila and Walsh 2018). Murakami et al. (2020) showed that decreasing TC numbers in the South Indian, Coral Sea and WNP basins since 1980 are generally consistent with a forced response from monotonically increasing greenhouse gases. Similarly, Chu et al. (2020), using a high-resolution coupled general circulation model forced with increasing CO2, found decreasing TC numbers in all TC basins except for the NA. The forced TCG response in their experiments was linked to a weakening of the summer Hadley cells, consistent with the observational results of Sharmila and Walsh (2018). The decline in TC numbers over the WNP basin since about 1998 has also been linked to multidecadal variability – specifically the negative phase of the Interdecadal Pacific Oscillation and associated La Niña like state have likely acted to suppress TCG in parts of the WNP (Zhao et al. 2018; Zhao et al. 2020; Chan and Liu 2022). In the NIO basin, the number of intense TCs (Lifetime maximum intensity≥90 kts) has increased over the period 1970–2020 together with increasing potential intensity and OHC (Swapna et al. 2022).

Idealized models have served as a valuable testbed for understanding climatic controls on TCG (Merlis and Held 2019), allowing for a more systematic exploration of the parameter space. Federov et al. (2019) investigated the effect of a reduced equator-to-pole temperature gradient on TCG using a cloud-system resolving model and found an increase in both the total number of TCs and the number of category 4-5 storms for sufficiently reduced SST gradients. In a series of aquaplanet experiments with uniform thermal forcing, Chavas and Reed (2019) showed that TCG rate increased almost linearly with Coriolis parameter f up to a critical value, and also that the minimum genesis distance from the equator scaled with the equatorial Rhines scale.

Using a similar approach, Walsh et al. (2020) found that increased static stability associated with surface warming was strongly related to a reduction in TCG. The global number of TCs has also been shown to be sensitive to the latitude of the ITCZ in aquaplanets, with increasing TC frequency associated with a poleward migration of the ITCZ up to ~25°N (Burnett et al. 2021), consistent with previous work. Using a tropical channel aquaplanet model, Vu et al. (2021) showed that the global number of TCs reached a similar upper bound despite differences in the frequency of synoptic-scale precursors. In addition, midlevel moisture and 850 hPa absolute vorticity were shown to be key factors associated with episodic global TCG.

At cloud-permitting resolutions (~3 km), TCs can form spontaneously (i.e., without an imposed pre-existing disturbance) over uniform SST on an f-plane (Bretherton et al. 2005). This approach has been used to explore the sensitivity of TCG to a range of climates and feedback processes, including radiative feedbacks (Wing et al. 2016; Muller and Romps 2018), surface warming (Ramsay et al. 2020), surface moisture (Cronin and Chavas 2019), and planetary vorticity (Carstens and Wing 2020). The absence of convective parameterization as well as the ability to resolve important dynamical features of TCs (e.g., eyes) and their precursors (e.g., mid-level vortices) has allowed for a more detailed, process-based understanding of TCG in response to different climate parameters. A drawback of this approach is that typically only a single TC is simulated (at least for Earth-like f) due to domain size constraints, which makes it difficult to test the dependence of TC frequency on climate with fidelity.

Finally, there is ongoing debate about the role of TC precursor disturbances ("seeds") in determining the rate of TCG in both observations and climate model projections. Specifically, there is debate as to whether precursor disturbances themselves are sensitive to climate change or should be regarded as background weather noise that is largely independent from TC climatology.

Vecchi et al. (2019) argued that TC frequency response to global warming can be thought of as the product of the change in seed frequency and the change in likelihood that a seed amplifies to a TC. The probability of seeds and the seed-to-TC transition have been linked to different environmental constraints (Hsieh et al. 2020). This framework has also been applied successfully to explain the annual cycle of TCs in various basins (Yang et al. 2021). Sugi et al. (2020) and Yamada et al. (2021) showed that changes in TC seed frequency played an important role in determining the overall TC frequency response to warming in climate change simulations, including inter-model differences. On the other hand, several studies have shown that global and regional TC climatologies are largely insensitive to the frequency of low-amplitude synoptic disturbances (Patricola et al. 2018; Vu et al. 2021; Emanuel 2022). There are a number of avenues for future research that are likely to advance our understanding of TCG and climate change. These include regional climate change and TCG, including the influence of ENSO and other natural modes of variability, additional idealized simulations, including aquaplanet experiments, aimed at exploring and testing the parameter space in relation to TCG. In parallel, future research should address the role of seed disturbances in determining climatological aspects of TCG in recent historical observations and in future climate projections.

8. Summary and conclusions

The results of the recent studies demonstrate the importance of understanding the potential effects of regional- to hemispheric-scale variation in TCG. During the last five years, multi scale influences on TCG have been investigated in different environments and background flows with TC representations from global ocean basins. Also, alternative pathways of TCG have been proposed. The development of TCs near the equator is possible, provided that there is a reasonably large enough source of background vertical vorticity, and relatively weak vertical shear. Conditions are often more favorable for near equatorial TCG over the WNP in boreal winter, while development over the NA basin has not been well documented. Storms that occur close to the equator should not survive for more than a few days if they do not track poleward, as ingestion of negative relative vorticity must occur once the initial cyclonic supply is depleted. Recent studies have focused on convection, vortex alignment, developing and non-developing systems. However, some of these studies require validation with real case studies. A few of the studies represent important validations and continuation of earlier studies. Understanding convective processes and improving model forecasts of TCG would lead to the ability to make better decisions at the operational level. Our understanding of the impact of climate change on TCG has been remarkably improved.

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Acronyms

AEW African Easterly Wave
AMO Atlantic Multidecadal Oscillation
BoB Bay of Bengal
CCCs Convective Cloud Clusters
CCKWs Convectively Coupled Kelvin Waves
CLLJ Caribbean low-level jet
C-mode Combination mode
DAEWs Developing AEWs
DD Deep Depression
ECMWF European Centre for Medium-Range Weather Forecasts
ENP Eastern North Pacific
ENSO El Niño–Southern Oscillation
EOF Empirical orthogonal function
EOF2 Second EOF
ER Equatorial Rossby
EWs Easterly waves
HYSPLIT Hybrid Single-Particle Lagrangian Integrated Trajectory
IO Indian Ocean
IOD Indian Ocean Dipole
ISO Intraseasonal oscillation
ITCZ Inter Tropical Convergence Zone
LCVA Low level convectively induced vorticity anomalies
MCSs Meso-scale Convective Systems
MCV Meso-scale Convective Vortex
MJO Madden-Julian Oscillation
MLC Midlevel circulation
MTC Multiple tropical cyclone
NA North Atlantic
NDAEWs Non-developing AEWs
NIO North Indian Ocean
OHC Ocean Heat Content
OWZP Okubo-Weiss Zeta parameter
PMM Pacific Meridional Mode
QBWO Quasi-Biweekly Oscillation
RH Relative Humidity
RI Rapid Intensification
SCS South China Sea
SF Saturation Fraction
SP Spring (April–June)
SST Sea Surface Temperature
SU Summer (July–October)
TC Tropical Cyclone
TCG Tropical Cyclogenesis
TD Tropical Depression
TNA Tropical North Atlantic Ocean
VHTs Vortical Hot Towers
VWS Vertical Wind Shear
WAM West African Monsoon
WNP Western North Pacific
WRF-ARW Advanced Research Weather Research and Forecasting

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