A Review of the Interactions between Tropical Cyclones and Environmental Vertical Wind Shear

Rosimar Rios-Berrios,[a] Peter M. Finocchio[b], Joshua J. Alland[c,d], Xiaomin Chen[e,f], Michael S. Fischer[g,f], Stephanie N. Stevenson[d], and Dandan Tao[h]

[a] *National Center for Atmospheric Research, Boulder, Colorado*

[b] *Naval Research Laboratory, Monterey, California*

[c] *University Corporation for Atmospheric Research, Boulder, Colorado*

[d] *NOAA National Hurricane Center, Miami, Florida*

[e] *Department of Atmospheric and Earth Science, University of Alabama in Huntsville, Huntsville, Alabama*

[f] *NOAA/OAR/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida*

[g] *Cooperative Institute For Marine And Atmospheric Studies, University of Miami, Miami, Florida*

[h] *Geophysical Institute, University of Bergen, Bergen, Norway*

Corresponding author: Rosimar Rios-Berrios, rberrios@ucar.edu

ABSTRACT: Tropical cyclone (TC) structure and intensity are strongly modulated by interactions with deep-layer vertical wind shear (VWS)—the vector difference between horizontal winds at 200 and 850 hPa. This paper presents a comprehensive review of more than a century of research on TC-VWS interactions. The literature broadly agrees that a TC vortex becomes vertically tilted, precipitation organizes into a wavenumber-one asymmetric pattern, and thermal and kinematic asymmetries emerge when a TC encounters an environmental sheared flow. However, these responses depend on other factors, including the magnitude and direction of horizontal winds at other vertical levels between 200 and 850 hPa, the amount and location of dry environmental air, and the underlying sea-surface temperature. While early studies investigated how VWS weakens TCs, an emerging line of research has focused on understanding how TCs intensify under moderate and strong VWS (i.e., shear magnitudes greater than 5 m s^{-1}). Modeling and observational studies have identified four pathways to intensification: vortex tilt reduction, vortex reformation, axisymmetrization of precipitation, and outflow blocking. These pathways may not be uniquely different because convection and vortex asymmetries are strongly coupled to each other. Besides discussing these topics, this review presents open questions and recommendations for future research on TC-VWS interactions.

1. Background

Meteorologists started to notice that the vertical profile of horizontal winds influences tropical cyclone (TC) formation and intensification even before the advent of weather satellites. Based on observations of different types of clouds, Weightman (1919) argued that deep easterlies through the troposphere were conducive for the formation of the 1919 West India TC. This argument was also supported by Riehl and Shafer (1944), who performed an analysis of balloon-based wind charts at the Institute of Tropical Meteorology in Puerto Rico. They found that deep easterlies to the north of tropical disturbances were most favorable for TC development, but that a vertical profile with easterlies at the surface and westerlies at 14,000 ft (approximately 4.3 km) “prevented development of strong rotating vortices” in the North Atlantic. Fifteen years later, Ramage (1959) analyzed balloon-based wind charts and found that large changes in the horizontal winds with height also prevented TC development over the South China Sea and the Bay of Bengal. These early studies using cloud motions and sparse sounding observations provided some of the first evidence that TCs are most likely to form where the horizontal winds have small variations with height.

As aircraft and satellite observations became available later in the 20th century, more detailed studies were conducted to explore the effects of the wind profile on TC development and intensification. Simpson and Riehl (1958) introduced the concept of “ventilation”, where dry air is imported from the environment into the TC inner core by the vertically sheared flow. López (1968) combined flight-level observations with satellite data to compare a disturbance that developed into Hurricane Carla (1961) with a disturbance that did not develop into a TC. This comparison showed that the disturbance that did not evolve into a TC was embedded in an environment with stronger vertical wind shear (VWS) than the disturbance that later became Hurricane Carla (López 1968). This result was later generalized with composites of satellite observations of upper- and lower-tropospheric winds for developing and non-developing disturbances around the world (Gray 1968). These composites showed that TC development occurred where the VWS was “a minimum or zero” —a finding that was later supported by the composites of McBride and Zehr (1981). The composite approach was also employed by Merrill (1988), except this study compared intensifying and non-intensifying TCs. Consistent with previous studies, intensifying TCs were characterized by weaker VWS than non-intensifying TCs.

Due to limited wind observations within the middle troposphere, Gray (1968) and others defined VWS as the wind vector difference between 200 and 850 hPa. The shear calculated between these two pressure levels is commonly referred to as the "deep-layer" VWS. In calculating the deep-layer VWS around a TC, early studies such as Gray (1968) considered the full vector difference—that is, including both the environment and the TC winds—between the observed winds at these two levels. Gray (1968) and others did not account for the VWS that is induced by the TC itself given that the strongest winds in TCs are located in the lower troposphere and that the winds turn from cyclonic to anticyclonic with height. Subsequent studies developed various methods to estimate the VWS primarily contributed by the environmental winds (e.g., Kurihara et al. 1993; DeMaria and Kaplan 1994; Galarneau and Davis 2013; Wang et al. 2015). These methods have been re-evaluated and challenged over the past decades due to limitations and uncertainties in their estimations of *environmental* VWS (Velden and Sears 2014; Ryglicki et al. 2020; Dai et al. 2021; Ryglicki et al. 2021).

The strong influence of deep-layer VWS magnitude on TC intensity motivated the inclusion of this variable in statistical models for intensity prediction. One of the first models to include VWS was the Statistical Hurricane Intensity Prediction Scheme (SHIPS) model (DeMaria and Kaplan 1994), in which deep-layer VWS magnitude was ranked as the second most important predictor of TC intensity (only behind the maximum potential intensity). The deep-layer VWS is a key predictor in more recent versions of the SHIPS model and other statistical models for intensity prediction (DeMaria and Kaplan 1999; Emanuel et al. 2004; DeMaria et al. 2005). New shear-related predictors quantifying shear in shallower layers have also been incorporated into these models. Deep-layer VWS is routinely estimated from real-time satellite products (see, for example, `https://tropic.ssec.wisc.edu/`), and it is one of the key variables routinely examined by hurricane forecasters.

The important relationship between 200–850 hPa VWS and TC intensity has inspired a plethora of studies since the 1990s aimed at understanding the effects of VWS on TC formation, intensity, and structure. Jones (1995) and DeMaria (1996) were amongst the first studies to show that a TC vortex is tilted in the presence of VWS. These studies, which relied on simple computer models of TC-like vortices, also found that the tilted vortex resulted in asymmetric patterns of upward and downward motions around the TC center. Several years later, observational studies confirmed these findings by documenting that TCs under VWS exhibited enhanced precipitation in their downshear quadrants, and suppressed precipitation in their upshear quadrants (Black et al. 2002; Corbosiero and Molinari 2002; Chen et al. 2006; Cecil 2007; Hence and Houze 2011; Reasor et al. 2013; DeHart et al. 2014). Detailed observations, including those taken during field campaigns, enabled detailed case studies (Molinari et al. 2006; Shelton and Molinari 2009; Molinari and Vollaro 2010; Stevenson et al. 2014; Bukunt and Barnes 2015; Rogers et al. 2015; Zawislak et al. 2016; Rogers et al. 2016; Nguyen et al. 2017; Ryglicki et al. 2021; Wadler et al. 2021b; Alvey et al. 2022) and multi-case composite analyses (Rogers et al. 2013; Reasor et al. 2013; DeHart et al. 2014; Wadler et al. 2018; Fischer et al. 2022) of TC-VWS interactions. The recent theoretical and modeling developments of the concept of "ventilation", which was originally coined by Simpson and Riehl (1958), has led to further advancement in our understanding of the thermodynamic impacts of VWS on TC structure and intensity (Tang and Emanuel 2010; Riemer et al. 2010). While much of the focus of early work on TC-VWS interactions centered around how TCs weakened under the influence of VWS, a new line of research has emerged focusing on how certain TCs can intensify while interacting with moderate-to-strong shear.

This review article provides a comprehensive summary of the scientific literature on TC-VWS[1] interactions and their effects on TC structure and intensity changes. While other review articles have broadly summarized the existing knowledge about TCs (Emanuel 2003; Wang and Wu 2004; Smith and Montgomery 2015; Montgomery and Smith 2017; Emanuel 2018), those articles only provide brief discussions about TC-VWS interactions owing to their broad scope. Their limited discussions together with a more than doubling of peer-reviewed manuscripts on the topic during the last decade motivated this synthesis solely focused on TC-VWS interactions. Recent advances in modeling and analysis techniques, including artificial intelligence/machine learning, and the proliferation of novel observing platforms offer several new avenues for research on sheared TCs. By summarizing the rapidly growing body of research and identifying key knowledge gaps, this review can serve as a starting point for future research utilizing new tools, techniques, and datasets to better understand and predict sheared TCs.

We begin our review by discussing how VWS, both by itself and in combination with other environmental factors, influences TC structure and intensity (Sections 2 and 3). This discussion sets the stage for a review of knowledge about how TCs can intensify—sometimes rapidly—under

[1]Hereafter, the acronym "VWS" will refer to deep-layer (200–850 hPa) *environmental* shear of the horizontal wind.

moderate-to-strong VWS (Section 4). The intricate multi-scale nature of processes associated with TC-VWS interactions challenge their prediction, and we summarize the work on this topic in Section 5. Lastly, we present our conclusions, open questions, and recommendations for future research in Section 6.

2. Effects of VWS on TC Structure and Intensity

A central focus of TC research is understanding how a storm responds to both external and internal factors (Emanuel 2018). The literature on TC-VWS interactions offers plenty of evidence that VWS is one of the most influential external factors of TC structure. This section will describe the main effects of VWS on TC structure and how those effects can modulate TC intensity changes under environmental sheared flow.

a. Vortex tilt

If a TC is represented by a column of potential vorticity, a vertically sheared flow will differentially advect the vortex column. This process results in a vertically tilted vortex as illustrated in Fig. 1. The earliest work on TC vortex tilt focused on dry dynamics. Jones (1995) was amongst the first to document in detail the dynamics of vortex tilt using dry, adiabatic, and nonhydrostatic models. Her seminal work showed that vortex tilt magnitude is largely dependent on VWS magnitude and on properties of the TC vortex (e.g., size, strength, etc.). The dynamics of vortex tilt evolution have been described by two different paradigms: (1) potential vorticity anomalies and (2) vortex Rossby waves.

The first paradigm relies on "potential vorticity" thinking to describe how the winds associated with the tilted vortex modulate both the direction and magnitude of vortex tilt (Jones 1995, 2000a,b). In this view, the winds associated with an upper-tropospheric vorticity anomaly due to the tilted vortex can advect the lower-tropospheric vorticity anomaly and vice versa (Jones 1995). Provided the environmental vertical wind shear is not strong enough to irreversibly shear apart the TC (e.g., Smith et al. 2000; Reasor et al. 2004), the upper and lower portions of a tilted vortex will begin to co-rotate, or precess, cyclonically about one another (Jones 1995; Wang and Holland 1996; Jones 2000a; Reasor and Montgomery 2001; Reasor et al. 2004). In a quiescent environment, the upper and lower portions of the tilted TC vortex may continue to orbit around one another multiple

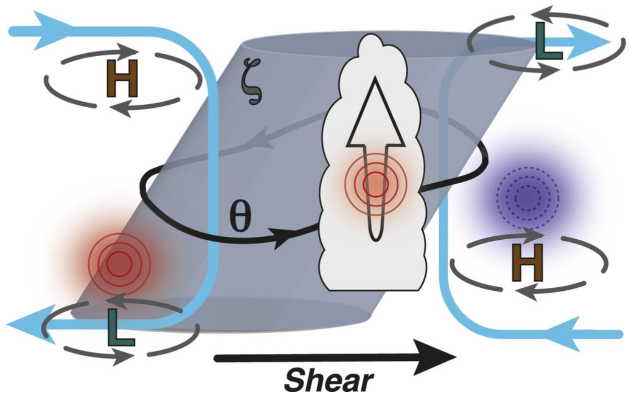

FIG. 1. Summary schematic of the kinematic and thermodynamic structure of Hurricane Rita (2005). The gray cylinder represents the vortex tower of the eyewall, which is tilted by the environmental wind shear (black vector). Green "L" symbols and vectors denote cyclonic low pressure anomalies, and brown "H" symbols denote anticyclonic high pressure anomalies. Thermal anomalies are denoted by blue (cold) and red (warm) circles and shading associated with slanted isentropic surfaces. Blue arrows show the modified secondary circulation. The thick black contour denotes a representative potential temperature surface, with arrows illustrating the cyclonic vortex flow around the eyewall. In the downshear-right quadrant, air parcels move cyclonically downstream and adiabatically upward along the potential temperature surface resulting in individual convective motions denoted by the cumulus cloud and upward arrow. A warm anomaly is shown in the convective cloud to denote the release of latent heat associated with the buoyant updraft. From Fig. 15 in Boehm and Bell (2021).

times; however, in the presence of a sheared background flow, dry idealized modeling studies have discovered a preferred tilt orientation along—and to the left of—the VWS vector (Jones 1995; Wang and Holland 1996; Reasor et al. 2004). When the vortex tilt is directed downshear-left, the projection of the cyclonic flow associated with the storm's lower-tropospheric circulation onto the displaced mid–upper-tropospheric circulation acts to oppose the environmental vertical wind shear, which can halt the cyclonic precession of the vortex. This process can also lead to vortex tilt reduction, which will be discussed in detail in Section 4a.

The second paradigm describes vortex tilt evolution as being governed by vortex Rossby waves (Reasor and Montgomery 2001; Schecter et al. 2002; Schecter and Montgomery 2003; Reasor et al. 2004; Reasor and Montgomery 2015). These waves, which are excited by a tilted vortex under VWS, are analogous to midlatitude Rossby waves except their restoring mechanism is the radial vorticity gradient of the TC vortex. By examining a tilted quasigeostrophic vortex in a dry model, Reasor and Montgomery (2001) found the evolution of vortex tilt was consistent with the projection of the tilted vortex onto a near-discrete VRW, or “quasi mode", which is similar to an edge wave propagating on a Rankine vortex. In this paradigm, the evolution of vortex tilt is largely described by the azimuthal propagation and, as will be discussed in more detail in Section 4a, inviscid damping of the discrete vortex Rossby waves that are excited by shear.

In a balanced framework, tilted TC vortices are associated with thermal and convective asymmetries (Jones 1995; DeMaria 1996; Jones 2000a; Xu and Wang 2013; Boehm and Bell 2021), as reflected by the schematic in Fig. 1. More specifically, a cold anomaly is found in the downtilt region of the storm, whereas a warm anomaly is located within the up-tilt portion (Jones 2000a). Observations of tilted, mature TCs corroborate this balanced thermal state (Reasor and Eastin 2012; Boehm and Bell 2021). The structure of a tilted TC vortex also varies vertically, as the direction of vortex tilt and the corresponding vorticity and temperature anomalies rotate anticyclonically with height (Jones 2000a; Reasor and Eastin 2012; Boehm and Bell 2021). These tilt-induced thermal asymmetries impact the TC convective structure, as will be discussed in more detail in the following subsection. As air travels cyclonically around the TC vortex, adiabatic ascent is promoted along upward-slanted isentropes located to the right-of-tilt direction; however, observations indicate convectively-driven diabatic heating maximizes in the downtilt portion of the inner core (Reasor and Eastin 2012; Reasor et al. 2013; Boehm and Bell 2021). The location of peak ascent may be influenced by other factors, such as diabatic lifting, microphysics processes, and frictional convergence (e.g., Frank and Ritchie 2001; Didlake and Kumjian 2018; Feng and Bell 2019; Laurencin et al. 2020; Schecter 2022). Additionally, the magnitude of the asymmetric ascent depends on the TC vortex strength, VWS magnitude, amongst other factors (Jones 2000a; Xu and Wang 2013; Finocchio and Rios-Berrios 2021).

If a TC is not strong enough to be characterized by a column of potential vorticity, the effects of VWS on the vortex structure differ from those discussed above. Consider, for example, a weak tropical storm. The vortex structure is most likely shallow in comparison to the vortex of a major hurricane (Fischer et al. 2022). The extent to which VWS can “tilt” such a shallow vortex is unclear from the existing literature. Instead, idealized numerical simulations and airborne radar observations suggest that tropical storms and other weak TCs under VWS exhibit displaced centers of circulations in the middle and lower troposphere (Nugent and Rios-Berrios 2018; Rios-Berrios et al. 2018; Ryglicki et al. 2018b; Rogers et al. 2020; Schecter and Menelaou 2020; Chen, X. et al. 2021; Schecter 2022; Fischer et al. 2022). Convective anomalies and their associated outflow co-evolve with the tilted vortex, as demonstrated in satellite observations (Ryglicki et al. 2018a, 2019) and idealized simulations (Rios-Berrios et al. 2018; Ryglicki et al. 2018b; Schecter 2022). The corresponding thermodynamic response includes both warm anomalies above the surface circulation and cool anomalies below the middle tropospheric circulation (Tao and Zhang 2019). Vertical motions respond more strongly to buoyant accelerations underneath the midtropospheric vortex (Ryglicki et al. 2018b) and to frictional convergence (Schecter 2020, 2022) than to the adiabatic ascent and descent induced by the temperature anomalies. Consequently, the evolution of vortex misalignment in weak vortices is largely governed by the influences of diabatic processes (Kwon and Frank 2008; Hogsett and Stewart 2013; Nguyen and Molinari 2015; Rios-Berrios et al. 2018; Ryglicki et al. 2018b; Tao and Zhang 2019; Rogers et al. 2020; Schecter and Menelaou 2020; Schecter 2022; Stone et al. 2023). However, the literature on vortex tilt of weak TCs is limited, and this is an area of much needed research.

b. Asymmetric precipitation

The asymmetric pattern of vertical motions that results from VWS tilting a mature TC vortex influences the distribution of precipitation around the storm center. Moderate-to-strong VWS (i.e., magnitudes exceeding 2.5 m s $^{-1}$) can produce a distinct wavenumber-one precipitation asymmetry, with most precipitation occurring downshear and the maximum precipitation in the inner core located downshear left (Fig. 2a). This relationship is consistent across many observational (e.g., Corbosiero and Molinari 2002; Chen et al. 2006; Wingo and Cecil 2010; Pei and Jiang 2018; Stevenson et al. 2016) and modeling (e.g., Rogers et al. 2003; Braun et al. 2006) studies using a variety of metrics for measuring convective intensity. The downshear-left quadrant corresponds to the previously-described preferential tilt orientation. Convective initiation is favored within the downshear-right quadrant (Fig. 2b), but the inner-core precipitation maximum occurs downwind in the downshear-left quadrant due to a combination of strong ascent and azimuthal advection of hydrometeors (Hence and Houze 2011; Reasor et al. 2013; DeHart et al. 2014). In the outer region of mature TCs known to contain the outer rainbands, convection is maximized downshear right due to the adiabatic ascent induced by the vortex tilt (Corbosiero and Molinari 2002; Stevenson

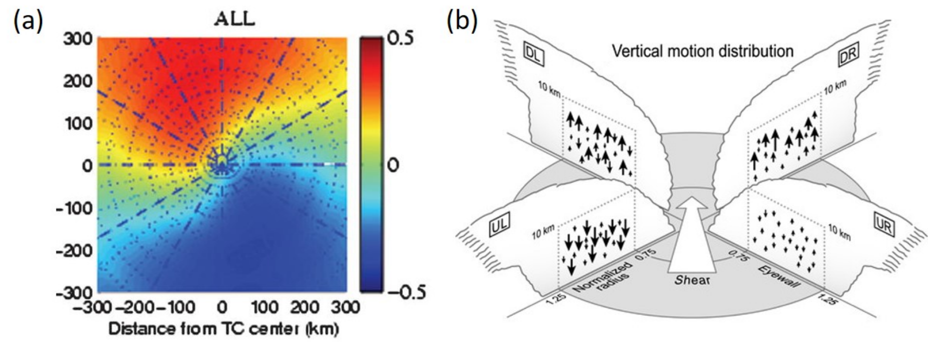

Fig. 2. (a) Fraction of the wavenumber-1 asymmetry of rainfall rates normalized by the azimuthal mean value (shading) relative to the 200–850-hPa environmental VWS, with the shear vector pointing to the top [adapted from Fig. 4a in Chen et al. (2006)]. (b) Schematic of the vertical motion distribution in a sheared environment. The environmental shear vector is denoted by the white arrow, and quadrants are labeled according to their direction relative to the shear vector (DR: downshear right, DL: downshear left, UL: upshear left, UR: upshear right) [adapted from Fig. 15a in DeHart et al. (2014)].

et al. 2016). This region exhibits a persistent and nearly stationary region of precipitation, known as the stationary band complex (Willoughby et al. 1984; Riemer 2016).

Asymmetric convection within the downshear-left quadrant of weak-to-moderately sheared TCs provides a focal point for the formation of concentric eyewalls that can lead to eyewall replacement cycles (Wang and Tan 2022). Using airborne Doppler radar observations in Hurricane Earl (2010), Didlake et al. (2018) showed that a descending air stream, originating in the asymmetric stratiform precipitation, enhanced the boundary-layer convergence outside the eyewall and eventually led to the formation of a secondary eyewall.

While shear is frequently the dominant factor in causing azimuthal precipitation asymmetries in TCs (Chen et al. 2006), Stevenson et al. (2016) found that rainfall asymmetries were more closely tied to the storm motion vector for fast-moving TCs. Those TCs exhibited an upshear lightning maximum, suggesting that shear alone could not explain their convective asymmetries. Other factors—including frictional convergence, orographic lifting, and the TC circulation—also contribute to TC rainfall production and organization (Lonfat et al. 2004, 2007; Lu et al. 2018). Additional research is needed to understand the relative importance of each factor.

c. Ventilation

VWS can also impact the thermodynamic and convective TC structure through ventilation—or simply, the transport of low-equivalent potential temperature (θ_e) air into the TC inner core. Ventilation occurs through either vertical fluxes of low-θ_e air in downdrafts, radial fluxes of low-θ_e air from the environment, or a combination of both mechanisms. The literature has traditionally labeled ventilation pathways based on their vertical position (i.e., low-level, mid-level, and upper-level ventilation). However, in this review, we adopt the terms downdraft and radial ventilation to establish a clear relationship to the physical mechanism responsible for transporting low-θ_e air into the inner TC circulation (Alland et al. 2021a,b). We recognize that these processes are not fully independent of each other and they can both co-exist at a given time (Riemer et al. 2010).

1) Downdraft ventilation

Downdraft ventilation refers to downward transport of low-θ_e air. Riemer et al. (2010) identified downdraft ventilation in low to mid levels as being associated with the shear-induced, wavenumber-one precipitation asymmetry and the stationary band complex described in Willoughby et al. (1984). As precipitation from convection downshear is transported cyclonically left-of-shear and upshear, it evaporates into the unsaturated air below to develop downdrafts. The evaporatively-cooled downdraft air within the subcloud layer is generally transported radially outward upshear, which can limit the areal extent of convection there, and radially inward right-of-shear (Riemer et al. 2010, 2013; Shu et al. 2014; Molinari et al. 2013; Alland et al. 2021a, see Fig. 4a). The magnitude of downdraft ventilation and the extent to which it limits TC development generally increases as the magnitude of VWS increases, as shown in Fig. 3.

The extent to which downdraft ventilation affects TC structure and intensity is sensitive to the ability of surface fluxes to recover the θ_e. The term recovery in this context refers to the process by which enthalpy fluxes from the sea surface fully increase the θ_e of evaporatively-cooled downdraft air in the subcloud layer. In many cases, air parcels are unable to fully recover from the effects of downdraft ventilation (e.g., Riemer et al. (2010)), which makes the boundary layer upshear dynamically (i.e., radial outflow) and thermodynamically (i.e., lower θ_e) less favorable for deep convection. As such, downdraft ventilation tends to suppress convection in the upshear quadrants – the same part of the TC where balanced downward motions (i.e., another form of downdraft

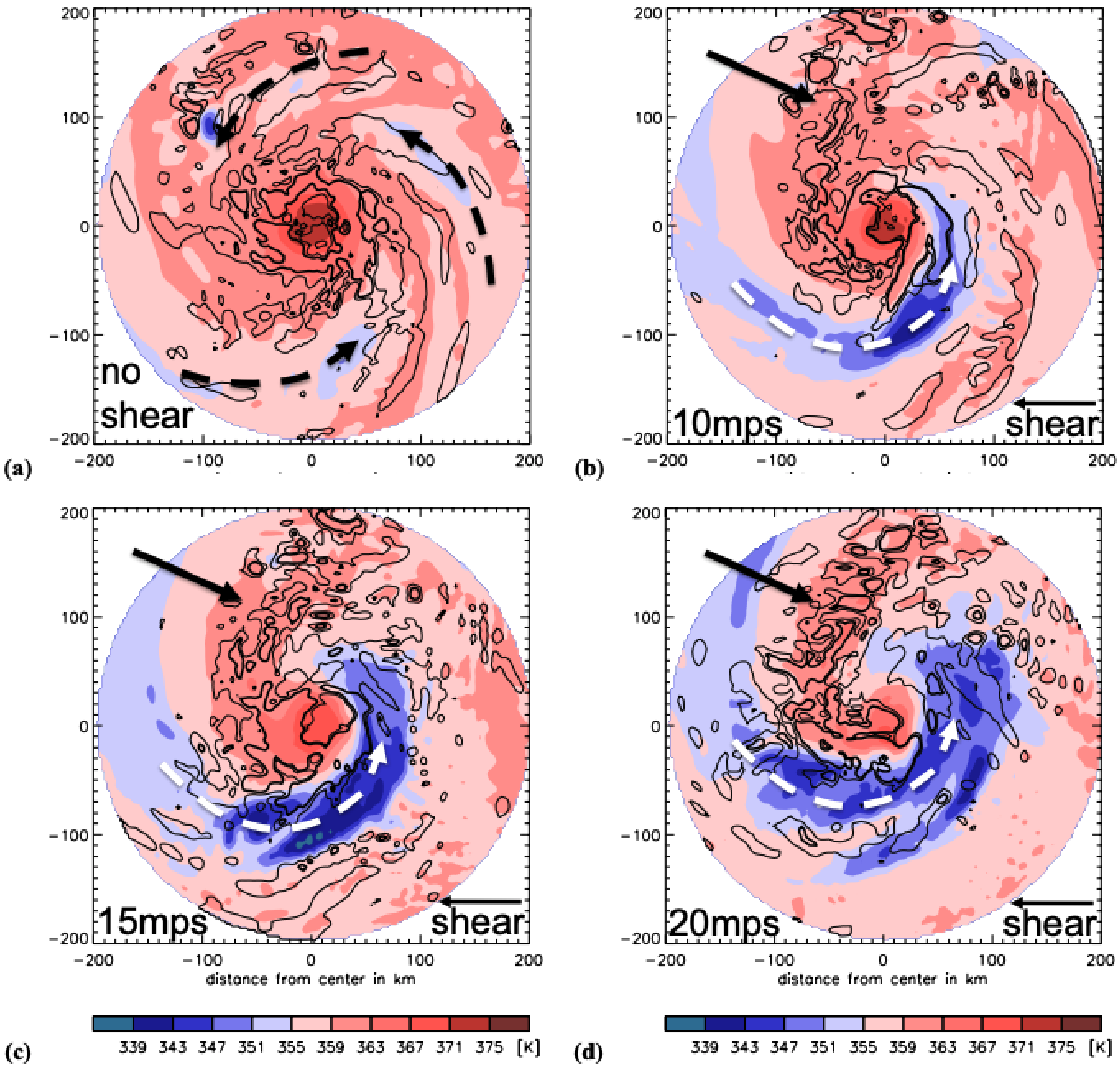

FIG. 3. Boundary layer θ_e (color, averaged over the lowest 1 km), and upward motion (thin contour: 0.2 ms^{-1}, thick contour: 1 ms^{-1}, averaged between 1.25 and 2 km height) at 5 h. The center of the TC averaged over the lowest 2 km is in the middle of the domain. The no_shear case is depicted in (a), the 10 ms^{-1}, 15 ms^{-1}, and 20 ms^{-1} case in (b), (c), and (d), respectively. The shear direction is indicated in the lower right corner of each plot. Solid arrows highlight the quasi-stationary convective asymmetry outside of the eyewall in the shear cases and dashed white arrows the quasi-stationary region of depressed BL θ_e air. The dashed black arrows indicate transient bands of less-reduced θ_e values in the no_shear case. The depicted times are representative for the early part of the experiments. [adapted from Fig. 7 in Riemer et al. (2010)].

ventilation) act to suppress convection in a tilted vortex (Jones 1995; DeMaria 1996; Zawislak et al. 2016). Entrainment of this relatively low-θ_e air into eyewall updrafts downshear can result in shallower convection, less latent heating, a hydrostatic pressure rise in the eye, and reduced TC intensity (Riemer et al. 2013; Riemer and Laliberté 2015; Zhang and Rogers 2019).

In contrast to a lack of recovery, several studies provide evidence of enhanced surface fluxes counteracting the debilitating effects of downdraft ventilation, allowing for a complete recovery of low-θ_e air upon entry into eyewall updrafts (Tang and Emanuel 2012a; Tao and Zhang 2014; Juračić and Raymond 2016; Gao et al. 2017; Nguyen et al. 2019; Chen, X. et al. 2021; Alland and Davis 2022). The likelihood of recovery increases for warmer SST environments (Chen, X. et al. 2021), air that is closer to the sea surface (Wadler et al. 2021a), and more intense TCs (Finocchio and Rios-Berrios 2021). For early-stage storms that have not yet formed an eyewall, downdraft-cooled parcels that recover can ascend in the left-of-shear quadrants, develop into deep convection at the leading edge (i.e., cyclonically downwind) of a tilt-related convective precipitation shield, and contribute to eyewall formation (Chen, X. et al. 2021).

2) Radial ventilation

Simpson and Riehl (1958) were the first, to the authors' knowledge, to document radial ventilation. Radial ventilation refers to the horizontal transport of low-θ_e air from the surrounding environment into the TC inner core by storm-relative radial inflow, horizontal eddy fluxes, or both (discussed further in the following two paragraphs). This can result in the reduced areal extent of convection in the inner core and acts as a constraint on the TC heat engine (Bender 1997; Shelton and Molinari 2009; Munsell et al. 2013; Shu et al. 2014; Nguyen et al. 2017; Alland et al. 2021a; Alland and Davis 2022).

Radial ventilation can occur in the mid and upper troposphere via storm-relative inflow associated with the superposition of a tilted TC circulation in a vertically-sheared background flow (Simpson and Riehl 1958; Willoughby et al. 1984; Marks et al. 1992; Bender 1997; Cram et al. 2007; Shelton and Molinari 2009; Davis and Ahijevych 2012; Nguyen et al. 2017; Alland et al. 2021b; Fischer et al. 2023a, see Fig. 4b). Radial inflow maximizes upshear and right-of-shear (Corbosiero and Molinari 2003; Reasor et al. 2013; DeHart et al. 2014), which can transport low-θ_e air into the TC inner core. If the radial ventilation occurs in upper levels where the TC warm anomaly is generally

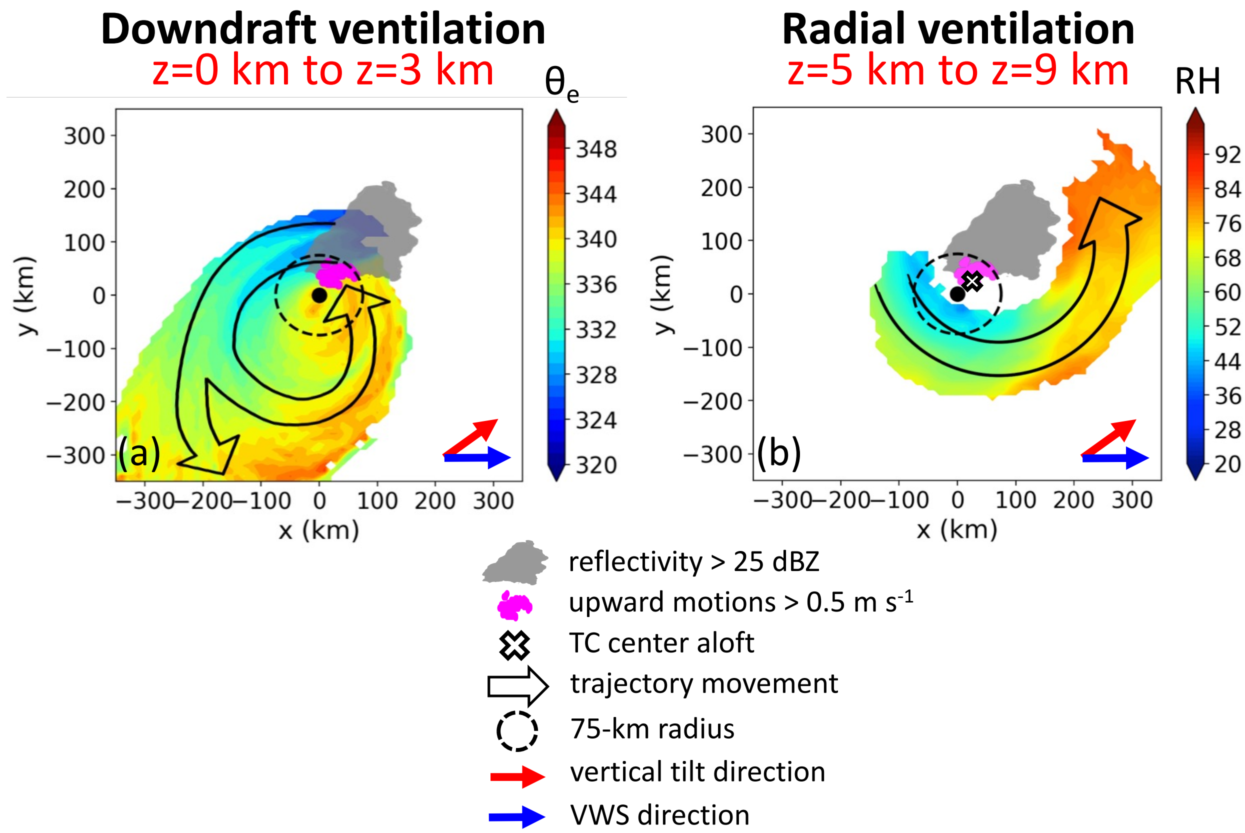

FIG. 4. Conceptual diagrams of ventilation pathways showing, in shading, the (a) average equivalent potential temperature (K) of trajectories initialized in downdraft ventilation regions between heights of 0 and 3 km, and (b) average RH (%) of trajectories initialized in radial ventilation regions between heights of 5 and 9 km. Other information includes reflectivity greater than 25 dBZ (gray shading), upward motions greater than 0.5 m s^{-1} (magenta dots), the TC center averaged between heights of 5 and 9 km (white x), parcel movement (black arrows), the inner 75 km (dashed circle), the vertical tilt direction from the surface to 6 km (red arrow), and the VWS direction (blue arrow). [Adapted from Fig. 17 of Alland et al. (2021a) and Fig. 13 of Alland et al. (2021b).]

most prominent, it has been hypothesized to result in a top-down weakening of the TC by inducing a hydrostatic increase in the surface pressure, a decrease in troposphere-mean diabatic heating, and a weakening of the mean secondary circulation (Gray 1968; Frank and Ritchie 2001; Kwon and Frank 2008; Fu et al. 2019).

Radial ventilation in midlevels can also be associated with shear-induced eddies that are excited in response to a TC's vertical tilt (e.g., Cram et al. 2007; Tang and Emanuel 2010, 2012a). This ventilation pathway, which is shown conceptually in Fig. 5 along with the downdraft ventilation pathway

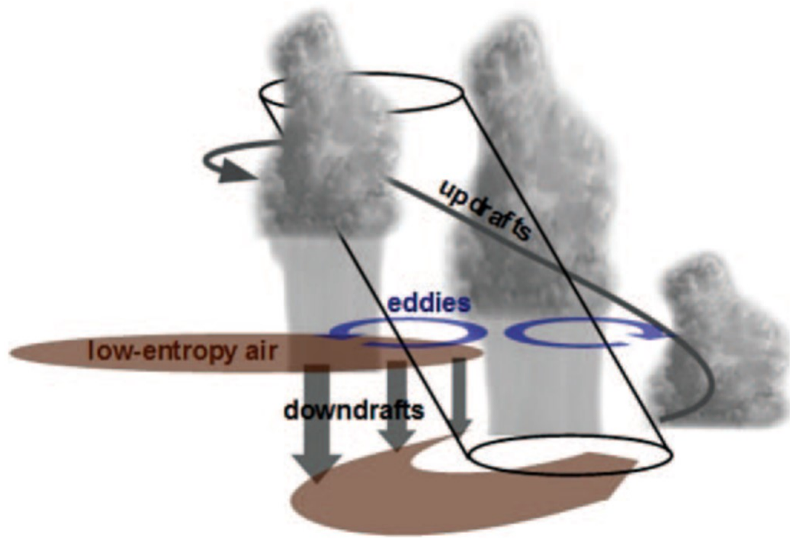

FIG. 5. A conceptual illustration of a TC undergoing two types of ventilation. Radial ventilation is depicted as horizontal eddies (blue arrows) that transport low-entropy air from the environment into eyewall convection of the tilted vortex. Downdraft ventilation is depicted by gray arrows labeled "downdrafts", which are the result of precipitation falling from the asymmetric convection in the tilted TC into subsaturated air below. Regions of low-entropy air in the mid-levels and in the subcloud layer are denoted by brown shading. [Figure adapted from Fig. 1 in Tang and Emanuel (2012a).

described above, locally decreases θ_e within the upward branch of the secondary circulation. In axisymmetric models of TCs with parameterized radial ventilation, this type of radial ventilation is capable of weakening TCs in environments that, by all other measures, favor intensification (Tang and Emanuel 2010, 2012b).

The extent to which radial and downdraft ventilation in the mid levels disrupts a TC depends not only on the magnitude of VWS, but also on the environmental humidity. A TC is more likely to resist ventilation if the air being transported from the surrounding environment into the inner core has higher θ_e (Tang and Emanuel 2010; Alland et al. 2021a,b). Tang and Emanuel (2012b) created a ventilation index that combines environmental VWS, the entropy deficit of the surrounding mid-level environment, the air-sea vapor pressure deficit, and the potential intensity. This index is able to distinguish environments that are favorable for developing versus non-developing TCs. Larger and more intense TCs are also more resilient to radial ventilation because the stronger and more expansive tangential wind field increases the inertial stability of the vortex and thereby prevents radial intrusions of air parcels from the surrounding environment with relatively lower θ_e into the inner-core (Riemer and Montgomery 2011; Finocchio and Rios-Berrios 2021).

Radial and downdraft ventilation can work together to affect TC structure and intensity. In the middle and upper troposphere, dry air from radial ventilation (Fischer et al. 2023a), as well as convergence of storm-relative inflow with the TC's upper-tropospheric outflow upshear (Dai et al. 2021), can result in troposphere-deep subsidence (i.e., downdraft ventilation). These combined ventilation pathways dry and stabilize the upshear TC inner core. In the lower and middle troposphere, descending radial inflow from rainband activity can flush lower-θ_e air into the subcloud layer, reduce the areal extent of convection in the inner core, and limit TC development (Barnes et al. 1983; Powell 1990; Hence and Houze 2008; Didlake and Houze 2009, 2013), (see Fig. 4a).

3) Relative importance of ventilation pathways

The relative importance of the downdraft and radial ventilation pathways in modulating a TC's convective structure and intensity remains an open question with contrasting views in the literature, and may be case-dependent. Alland et al. (2021a) showed in idealized simulations that downdraft and radial ventilation can operate at the same time, while Alland and Davis (2022) showed in simulations of Hurricane Michael (2018) that downdraft ventilation preceded radial ventilation in limiting TC development. Riemer et al. (2010) and Riemer and Laliberté (2015) suggested that downdraft ventilation at low levels may be more destructive to TC development than radial ventilation above the boundary layer because downdraft ventilation directly impacts the energy cycle of a TC in the subcloud layer where convection initiates. In addition, the inflowing air in the mid and upper troposphere associated with radial ventilation may be deflected by the TC's swirling winds, effectively limiting its destructive potential (Willoughby et al. 1984; Riemer and Montgomery 2011). For weaker TCs, though, this deflection may be less prominent, resulting in stronger interaction between the environment and the inner core (Alland et al. 2021b; Finocchio and Rios-Berrios 2021). Tang and Emanuel (2012a) suggested that radial ventilation is less effective at interfering with the development of a TC when it occurs primarily in the upper levels because radial gradients of θ_e are smaller in the upper troposphere than in the lower and middle troposphere. However, Fu et al. (2019) showed that radial ventilation aloft can be particularly effective at weakening already intense TCs due to the combination of a well-developed warm core and stronger storm-relative flows in the upper levels compared to in the mid and low levels.

The importance and timing of ventilation pathway(s), or the ability of a TC's resiliency to ventilation, are likely dependent on the storm conditions (e.g., the size and intensity), and environmental conditions (e.g., the vertical and radial locations of the dry air and VWS) (Finocchio and Rios-Berrios 2021). Despite our improved understanding of ventilation, more research is still needed to better understand why ventilation negatively affects some TCs and has only a limited effect on others.

d. Boundary layer asymmetries

Deep-layer VWS also introduces distinct thermodynamic and kinematic asymmetries within the TC boundary layer. As a consequence of the aforementioned effects of downdraft ventilation and subsequent boundary layer recovery, θ_e is generally lowest in the left-of-shear quadrant and highest in the downshear-right quadrant (e.g., Riemer et al. 2010; Zhang et al. 2013; Nguyen et al. 2017; Chen, X. et al. 2019; Alland et al. 2021a). The downdraft-modified boundary layer parcels enhance surface enthalpy fluxes left of shear, enabling a subsequent boundary layer recovery of these low-θ_e parcels. Thus, a wavenumber-one asymmetry in the azimuthal distribution of θ_e and surface enthalpy fluxes has been observed in sheared TCs (Zhang et al. 2013; Nguyen et al. 2019).

The amplitude of the wavenumber-one asymmetry in boundary-layer θ_e is related to factors other than just the magnitude of VWS (Riemer et al. 2010; Nguyen et al. 2019; Wadler et al. 2022). A composite analysis of dropsondes collected in relatively weak TCs showed that TCs with higher intensification rates have larger values of surface enthalpy fluxes in the upshear quadrants compared to the downshear quadrants (Nguyen et al. 2019). TCs in environments with a southerly component of VWS have also been found to have a larger wavenumber-one asymmetry in boundary-layer θ_e outside of the radius of maximum winds than TCs in environments with a northerly component of VWS (Wadler et al. 2022). This asymmetry likely results results from the superposition of large-scale advection of θ_e on the shear-induced θ_e asymmetries.

For the kinematic boundary layer structure, both observational and modeling studies (Zhang et al. 2013; Gu et al. 2016; Zhang et al. 2023) indicate that the boundary-layer height, either represented by inflow layer depth or the height of maximum tangential wind, tends to increase with radius in

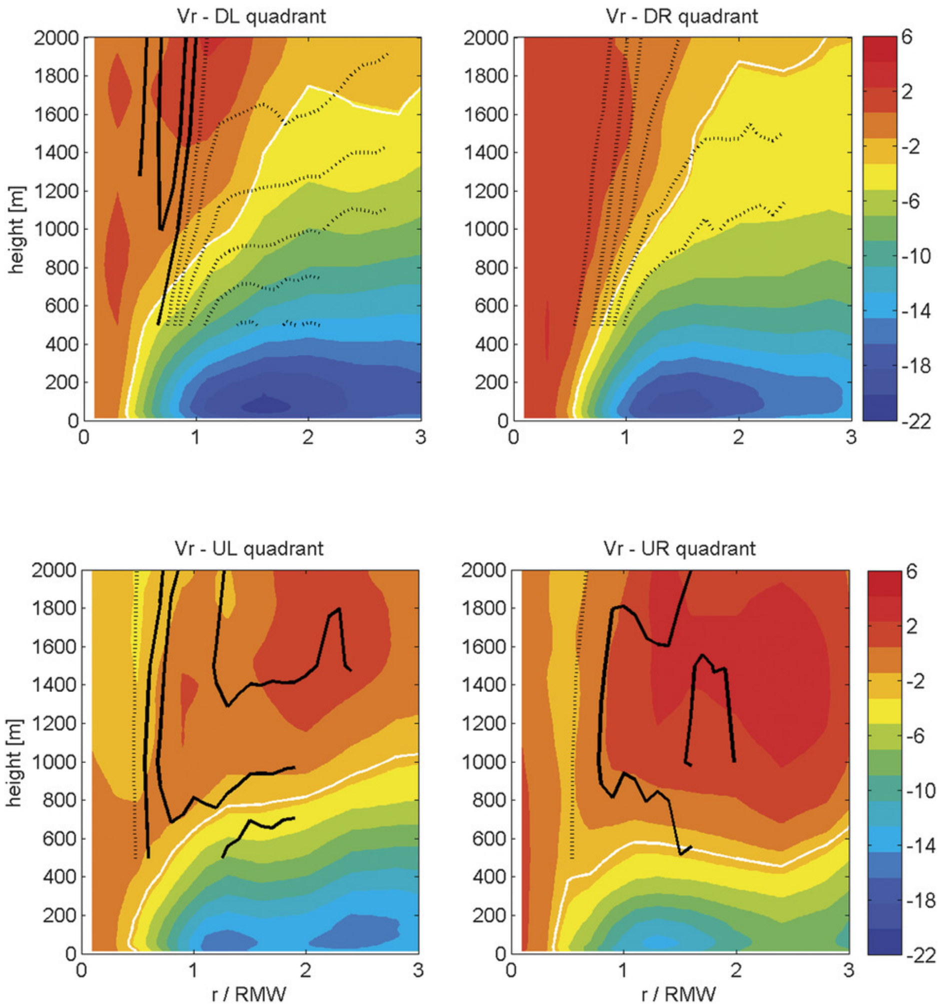

FIG. 6. Dropsonde composites of the relative radial wind velocity (shaded, every 2 m s^{-1}) as a function of altitude and the normalized radius to the storm center for the four quadrants relative to the shear direction. The white line in each panel represents the height of 10% peak inflow. Doppler radar composite results are shown in the black lines with solid lines representing outflow and dotted lines representing inflow with a contour interval of 0.5 m s^{-1}. Adapted from Fig. 4 of Zhang et al. (2013).

each shear-relative quadrant. The boundary-layer inflow is strongest and deepest in the downshear quadrants (Fig. 6), which is aligned with the location of the downshear convergence zone. However, the strongest tangential winds are located to the left of shear (Zhang et al. 2013; Rogers et al. 2015; Gu et al. 2016). Thermodynamically, the boundary-layer inflow is an ideal conduit to bring low-θ_e parcels into the inner-core convection (Section 2c and Ahern et al. (2021)). However, the inflow also can accelerate the tangential wind in the downshear-left quadrant through the inward advection of absolute angular momentum and immediately downwind through azimuthal advection, while the tangential winds in the right-of-shear quadrants steadily weaken. In fact, Gu et al. (2016) found that during the initial weakening stage of modeled TCs in VWS, the left-of-shear tangential winds can continue to intensify for a few hours while the tangential winds to the right of shear decay.

Given that the TC boundary layer is relatively under sampled with in-situ observations, more research is needed to understand the shear-induced asymmetries within that layer. The limited evidence discussed herein suggests that VWS induces both thermal and kinematic boundary-layer asymmetries. Those asymmetries can have important implications by, for example, determining the location of maximum near-surface winds. Their effects on turbulent aspects that affect mixing and updraft development should also be investigated.

3. Compound Effects of VWS and Other Factors on TC Structure and Intensity

While many studies have isolated the effects of VWS *magnitude* on TC structure and intensity, that metric alone cannot fully capture the myriad ways in which a TC responds to a given environment. Additional external factors —including details of the environmental wind profile, the relative direction of surface flow with respect to the shear direction, environmental moisture, and underlying SSTs—also influence vortex and precipitation asymmetries that emerge under VWS. This section discusses interactions between VWS magnitude and those factors with the goal of exposing the complex nature of TC-VWS interactions.

a. Details of the wind profile

The magnitude of the deep-layer VWS is often the only metric used to characterize how favorable an environmental wind profile is for TC intensification. Historically, this was due to a paucity of real-time satellite-derived atmospheric motion vectors in the middle troposphere, which hindered operational estimates of shear in layers other than 200-850 hPa (Velden and Sears 2014). However, details of the environmental wind profile beyond the deep-layer shear magnitude can have a strong influence on TC structure and intensity.

Studies primarily focused on TC genesis have explored whether the impacts of VWS on developing disturbances depend on the shear direction. Tuleya and Kurihara (1981) found that easterly shear was more favorable for genesis than westerly shear of the same magnitude, which they argued was due to easterly shear allowing for greater coupling between the upper and lower parts of westward-propagating disturbances within the deep tropics. The intrinsic northwesterly beta shear of the TC vortex partially offsets easterly environmental shear, which could also explain why easterly shear has been found to be less destructive to a TC than the same magnitude of westerly shear (Ritchie and Frank 2007). Statistical studies based on large samples of cyclogenesis and post-genesis TC cases are mostly consistent with the result that easterly shear is more favorable for genesis and intensification than westerly shear (Zeng et al. 2010; Nolan and McGauley 2012). However, in idealized simulations on the beta plane that isolate the impact of shear direction from factors such as maximum potential intensity, Nolan and McGauley (2012) found westerly shear was actually more favorable for genesis than easterly shear. This suggests that easterly shear only appears to be more favorable for TC genesis because it tends to occur in regions where other environmental factors such as SST are also favorable. The shear direction sensitivity may also differ for genesis cases compared to more developed TCs. Wei et al. (2018) found that, for post-genesis TCs in the Western North Pacific, westerly shear was more strongly correlated with short-term weakening than easterly shear after controlling for SST.

The vertical distribution of shear through the troposphere can also influence TC development. Elsberry and Jeffries (1996) described two hypothetical wind profiles with the same deep-layer shear: one with all of the shear concentrated in the upper troposphere (Fig. 7a), and the other with shear linearly distributed through the depth of the troposphere (Fig. 7b). They hypothesized that the upper-level shear profile is more favorable for TC development because the TC outflow can counteract upper-level shear, while more deeply distributed shear is more likely to tilt and ventilate the TC inner core. Ryglicki et al. (2018a) usefully pointed out that TC environments with deeply-distributed shear (as in Fig. 7a) tend to be associated with upper-level troughs, while environments with upper-level shear (as in Fig. 7b) tend to be associated with upper-level anticyclones.

A consensus has yet to emerge on whether upper or lower-level shear is more favorable for TC intensification. Finocchio et al. (2016) conducted idealized simulations exposing weak, symmetric vortices to environmental wind profiles with 10 m s^{-1} of westerly VWS maximized at different heights and extending through different depths of the troposphere. They found that shear concentrated lower in the troposphere was more destructive to a developing TC than upper-level shear because it tilted the vortices further downshear and caused stronger downward fluxes of low-θ_e air

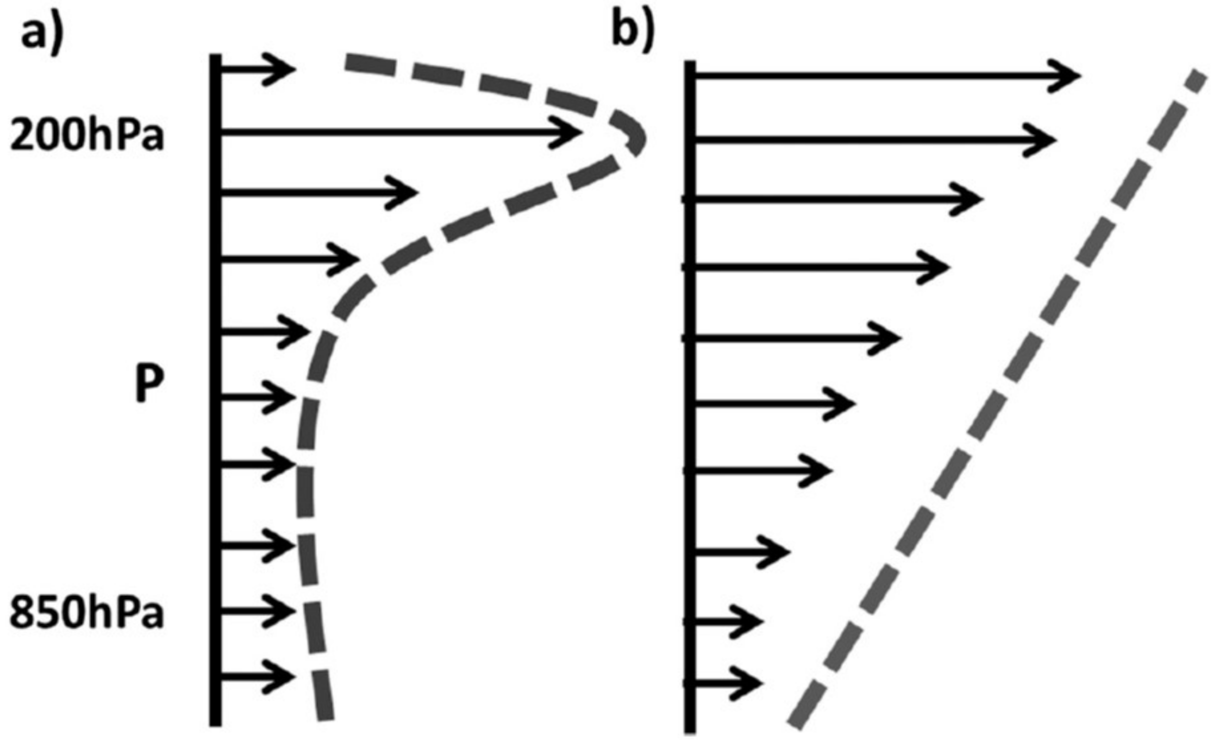

Fig. 7. Schematics of two vertical wind profiles typical of environmental flow regimes that impinge on TCs, but which provide identical 200–850 hPa wind shear values as traditionally calculated. These two profiles arise from a (a) low-latitude systems with the strongest upper-tropospheric winds concentrated in a shallow layer and (b) linearly distributed wind profile over a deep layer as might exist poleward of the deep tropics and associated with transient midlatitude troughs. Adapted from Fig. 1 in Velden and Sears (2014), and reproduced from Fig. 11 in Elsberry and Jeffries (1996).

into the TC boundary layer from convective downdrafts. These findings are consistent with earlier (Frank and Ritchie 1999) and subsequent (Ryglicki et al. 2018b) modeling studies that involved experiments exposing developing TCs to different vertical distributions of VWS.

In contrast to these studies, Xu and Wang (2013) and Fu et al. (2019) exposed mature hurricanes to different wind profiles with 10 m s^{-1} of easterly VWS and found that simulated TCs in upper-level shear weakened more and exhibited stronger inner-core asymmetries than the TCs in lower-level shear. Fu et al. (2019) attributed the greater weakening in upper-level shear to stronger upper-level ventilation of the warm core. They hypothesized that upper-level shear is less destructive to the weak TCs examined in previous modeling studies because the weaker storms are too shallow to be exposed to the strongest storm-relative flows aloft (e.g., Nam and Bell 2021). However, more research is needed to understand the different responses to upper- versus lower-level shear and how they might relate to shear direction and aspects of the TC vortex.

Statistical analyses of real sheared TCs have generally found that low-level shear is more commonly associated with weakening than upper-level shear (Zeng et al. 2010; Wang et al. 2015). However, Finocchio and Majumdar (2017b) did not find a clear relationship between TC intensity change and their metrics describing the vertical distribution of VWS. These contradictory findings could be due to differences in the metrics used to define the VWS height and/or the geographic focus areas among the different statistical studies. The vertical distribution of VWS may also have a larger and more consistent impact on the intensity of developing disturbances and weak TCs compared to the more developed storms considered in these studies. More detailed statistical and observational analysis of weak and developing storms is needed to better understand the apparent disagreements regarding the impacts of different VWS profiles on TC intensity change.

Different multi-directional shear flows can also have distinct impacts on TC intensity and structure. In the mid-latitudes, environments with winds that rotate clockwise with altitude (positive helicity) favor stronger and longer-lived convective updrafts (Davies-Jones et al. 1990). Positive TC-relative environmental helicity is also more favorable for TC intensification. Nolan (2011) and Onderlinde and Nolan (2014) used idealized simulations of TCs in horizontally uniform environments with a mean wind vector that rotates either clockwise (positive helicity) or counterclockwise (negative helicity) with increasing altitude. Both studies found the clockwise-rotating wind profile (positive helicity) resulted in more TC intensification, despite all experiments having the same deep-layer VWS magnitude.

Onderlinde and Nolan (2016) reasoned that positive helicity is more favorable for TCs than negative helicity because, in their simulations, air parcels ingested into downshear convective updrafts experienced more warming and moistening via surface enthalpy fluxes in positive helicity environments. However, Gu et al. (2018) demonstrated that balanced (dry) dynamics alone can explain why positive helicity is more favorable for TC development: a clockwise-rotating environmental wind profile advects the lower part of the vortex azimuthally downwind of the overall vortex tilt vector, resulting in a superposition of positive local helicity and balanced ascent associated with the tilted vortex. This configuration promotes the propagation of convection toward the upshear quadrants. In identical experiments but with active moist physics, diabatic heating in convection keeps the moist vortices more vertically coupled than in the corresponding dry simulations (Gu et al. 2019). Moreover, the favorable configuration of vortex tilt and convection established early in the experiments sets up a positive feedback with diabatic heating in convection that allows for the faster upshear precession of vortices in positive-helicity environments. In other words, favorable dry dynamics set the stage for subsequent convective feedbacks that hasten vortex alignment in multi-directional shear environments with positive helicity. Collectively, these model-based results suggest that, with all else being equal, TCs in negative helicity environments are more likely to remain misaligned than TCs in unidirectional shear or positive helicity environments.

b. Surface flow

The surface flow in the TC environment modulates the TC intensity and structural response to VWS by influencing the horizontal distribution of boundary layer convergence and surface enthalpy fluxes. The distribution of low-level convergence around a TC partly determines where the stationary rainband complex forms (Willoughby et al. 1984; Riemer 2016), while the surface enthalpy fluxes determine the extent of thermodynamic recovery of downdraft air parcels in the TC boundary layer (Powell 1990). Riemer and Montgomery (2011) also demonstrated how storm-relative surface flow distorts the circulation in the lower levels of a TC, determining the extent to which environmental air is able to reach the inner core.

Only recently have the combined effects of low-level flow and VWS on TC structure and intensity been explored systematically. Rappin and Nolan (2012) showed that surface flow counter-aligned with the shear vector is more favorable for TC genesis than surface flow aligned with the shear vector. In the counter-aligned scenario, the superposition of the vortex circulation and the surface wind results in a surface wind maximum to the left of the shear vector, which increases surface enthalpy fluxes ahead of the asymmetric convective complex. This favors the upshear propagation of asymmetric convection, leading to a more rapid reduction in vortex tilt.

Chen, B.-F. et al. (2018) examined a wide array of low-level flow orientations relative to the deep-layer shear vector using analysis and observational composites of post-genesis TC cases. They found low-level flow directed toward the right of shear favors expansion of the 34-kt wind radius, while low-level flow directed toward the left of shear favors intensification. They conducted idealized simulations to explore the reasons for this result and found that low-level flow pointing toward the upshear-right quadrant favors wind-field expansion because of enhanced rainband activity (Chen, B.-F. et al. (2019), Fig. 8b). The opposite orientation of the low-level flow relative to the shear vector increases the mean low-level inflow downshear and the humidity of air parcels ingested into inner-core convection. This promotes intensification through the earlier development of a symmetric eyewall (Fig. 8a). Similar to Rappin and Nolan (2012), upshear-oriented low-level flow generally favored intensification more than downshear low-level flow in the Chen, B.-F. et al. (2019) study, but only in their simulations over a warmer prescribed SST. However, comparisons between these two studies is complicated by the fact that Rappin and Nolan (2012) conducted their simulations in radiative-convective equilibrium environments, where warmer SST results in higher saturation deficits that must be overcome in order for genesis to occur. In a follow-up analysis of real TC cases, Chen, B.-F. et al. (2021) showed that TC intensification is favored in environments with low-level flow directed toward the downshear-left quadrant regardless of the background SST, deep-layer shear magnitude, or environmental humidity.

Lee et al. (2021) conducted similar simulations to Chen, B.-F. et al. (2019), except they imposed the shear and the different low-level flows on more mature TCs. They found that for these more intense storms, the low-level flow associated with the fastest intensification is directed upshear-left (c.f. downshear-left in Chen, B.-F. et al. (2019)). This low-level flow orientation results in surface fluxes maximized downshear, which invigorates upshear-left convection and promotes a more symmetric diabatic heating structure.

c. Environmental moisture

The tropics generally have a minimum in θ_e near 700 hPa (Jordan 1958; Ooyama 1969; Dunion 2011). As such, moistening of the lower and middle troposphere is necessary for the development and sustenance of deep convection within the TC vortex (Gray 1968; Emanuel 1989; Bister and Emanuel 1997; Nolan 2007; Raymond et al. 1998; Rappin et al. 2010; Komaromi 2013; Zawislak and Zipser 2014; Helms and Hart 2015; Rios-Berrios et al. 2016b). In idealized simulations of weak TCs in environments with no VWS, Braun et al. (2012) showed that a layer of dry air between 850 and 600 hPa could only limit TC intensification when it was initialized very close to the storm center. Dry air can only weaken a TC if it is able to penetrate into the inner core

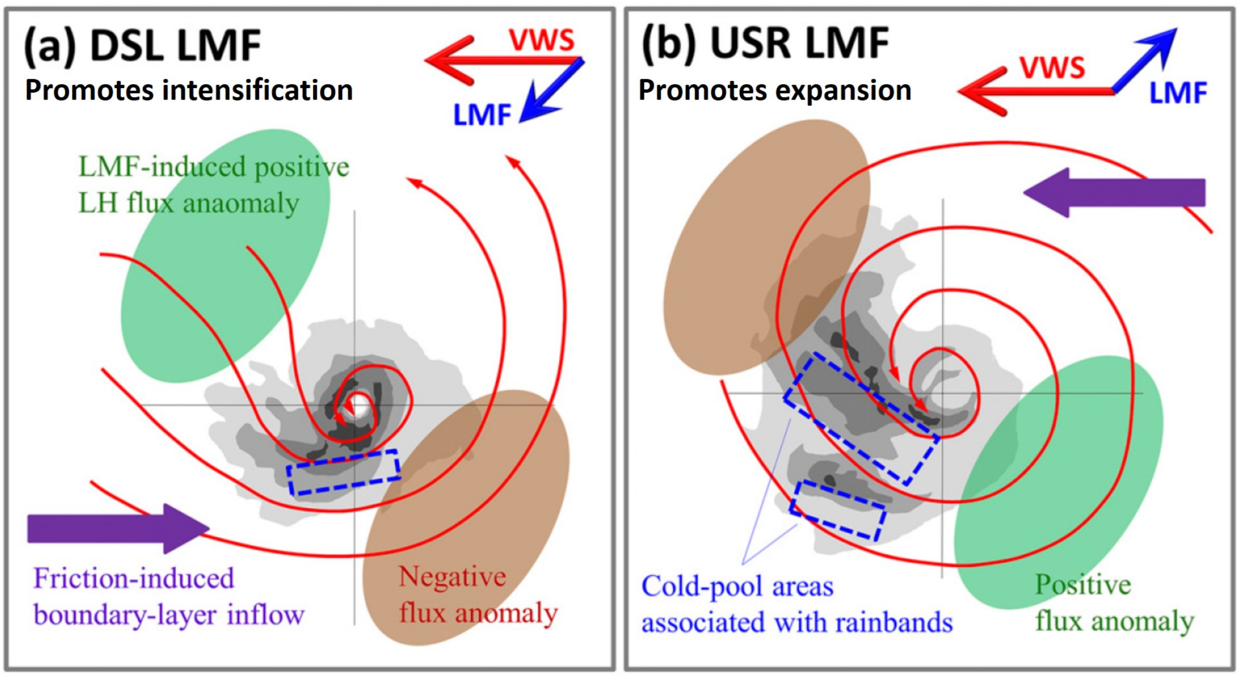

FIG. 8. Conceptual models showing the resposnes of a Northern Hemisphere TC to (a) downshear-left (DSL) low-level mean flow (LMF) and (b) upshear-right (USR) LMF. Gray shading indicates radar reflectivity. Red streamlines represent the boundary layer trajectories in a shear-relative coordinate system. Adapted from Fig. 1 of Chen, B.-F. et al. (2021).

to reduce the upward vertical mass flux and convergence of angular momentum in the subcloud layer (Montgomery and Smith 2014; Tang and Zhang 2016; Alland et al. 2017). If dry air does not penetrate into the inner core, it can still reduce convection outside the moist region (Tao and Zhang 2014), which can reduce the radial extent of the moist envelope and leave a TC more vulnerable to subsequent dry air intrusions (Kimball 2006; Hill and Lackmann 2009; Braun et al. 2012).

The combination of VWS and dry air around a vortex can be particularly effective at limiting TC intensification of weak TCs (Tang and Emanuel 2012a; Molinari et al. 2013; Tao and Zhang 2014; Rios-Berrios et al. 2016a,b; Rios-Berrios and Torn 2017; Nguyen et al. 2017, 2019; Alland et al. 2021a). For example, Molinari et al. (2013) analyzed observations of a tropical storm under strong VWS (11–15 m s^{-1}) and exceptionally dry air (15% relative humidity). The tropical storm remained fairly asymmetric and weak, which Molinari et al. (2013) hypothesized was a result of radial and downdraft ventilation through the combination of strong VWS and dry environmental air. Nguyen et al. (2017) also attributed the asymmetric convective structure of Tropical Storm Cristobal to the combination of dry air and strong VWS. In general, as environmental relative humidity decreases, the likelihood for radial and downdraft ventilation increases (Riemer et al. 2010, 2013; Alland et al. 2021a,b).

The location of dry air with respect to the VWS is also important. Ge et al. (2013) found in idealized simulations that mid-tropospheric dry air initially located to the right of the shear vector is advected by the TC's cyclonic flow toward the downshear quadrants, where it limits convection and thwarts the realignment of a tilted TC vortex. Consistent with this result, Rios-Berrios et al. (2016b) found in an ensemble simulation of a moderately sheared TC that members simulating a stronger storm had higher humidity in the lower troposphere to the right-of-shear. In composites of moderately sheared TCs, Rios-Berrios and Torn (2017) found that intensifying storms have higher mid-tropospheric relative humidity upshear compared to steady-state or weakening storms. Rios-Berrios and Torn (2017) suggest that the higher humidity upshear may reduce midlevel dry air intrusions and allow for a more symmetric distribution of convection. Source regions of dry air entering the TC inner core at a particular level are closely related to the environmental storm-relative flow. For example, the flow topology of a TC in westerly storm-relative flow favors environmental intrusions from the northwest quadrant (Riemer and Montgomery 2011). The inner cores of stronger TCs are also more insulated from intrusions of environmental air than weak TCs. However, more research is needed to better understand the dependence of TC structure and intensity change on different configurations of VWS and dry air, including the altitude and azimuthal location of dry air relative to the strongest storm-relative flows (i.e., ventilation).

d. Sea-surface temperature

The underlying ocean temperatures, commonly characterized by the sea-surface temperature (SST), also affect the outcome of TC-VWS interactions. Studies have identified two contrasting SST impacts on sheared TCs: a positive impact of higher SST on TC development through enhanced surface fluxes (Tao and Zhang 2014; Chen, X. et al. 2018a, 2021; Alland and Davis 2022; Schecter 2022), and a perhaps less-intuitive negative impact of higher SST mainly found under radiative convective equilibrium (RCE) conditions (Nolan and Rappin 2008; Rappin and Nolan 2012).

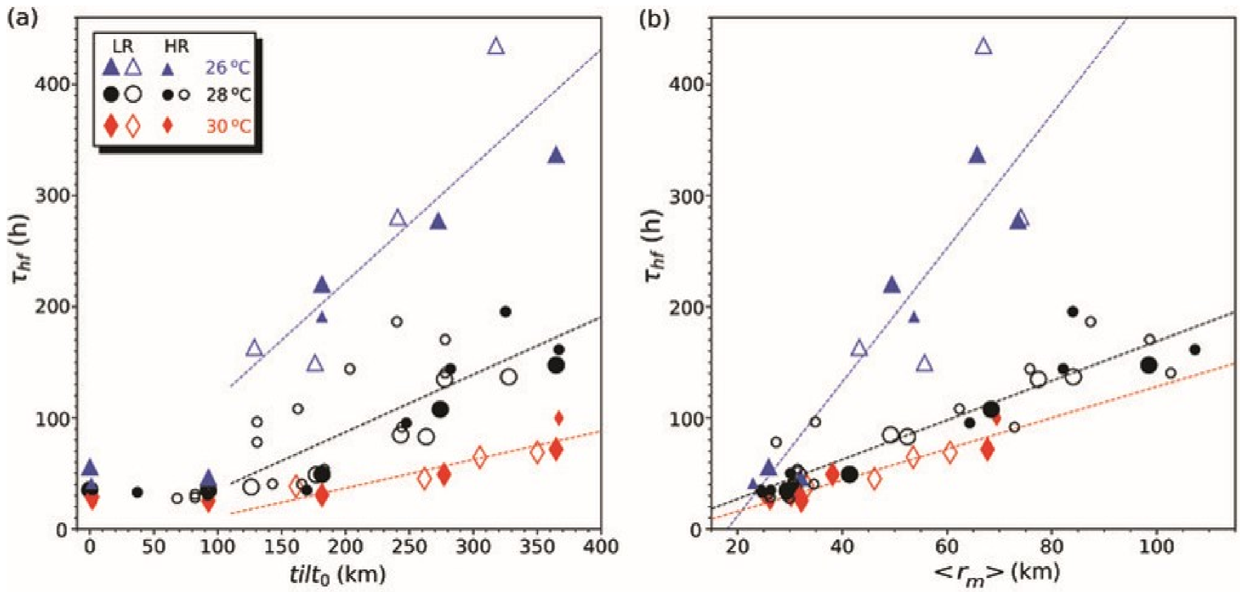

FIG. 9. (a) Length of the hurricane formation period (τ_{hf}) vs. the initial tilt magnitude ($tilt_0$). The color and shape of each symbol corresponds to the SST (legend). The dashed lines are linear regressions among all points in each SST group with $tilt_0$ > 100 km. (b) Relationship between τ_{hf} and the radius of maximum surface wind speed $< r_m >$ time averaged during the hurricane formation period. Dashed lines are linear regressions as in (a), but over all data points within the pertinent SST group. Figure adapted from Fig. 1 in Schecter (2022).

With higher SST, the low-θ_e air flushed into the boundary layer via shear-induced downdrafts (Section 2c.1) is refuelled by surface fluxes more rapidly before becoming entrained in inner-core convection. The enhanced surface fluxes thereby reduce the effect of downdraft ventilation and strengthen the connection between the midlevel and low-level vortices (Tao and Zhang 2014; Chen, X. et al. 2018a, 2021; Alland and Davis 2022). Meanwhile, higher SST excites more vigorous convective activity at larger radii, which broadens the vortex circulation and increases TC resistance to shear (Schecter 2022). The rate of tilt reduction is sensitive to SST such that the higher the SST, the faster reduction of tilt magnitude (Schecter 2022, and Fig. 9).

In contrast, Nolan and Rappin (2008) found in idealized simulations of sheared TCs in RCE environments that higher SST can actually make a TC less resilient to VWS. They found that the higher SST increases the height of the freezing level, which in turn increases the altitude of the developing mid-level vortex. For the wind profile used in their simulations, the higher altitude of the midlevel vortex meant it was exposed to stronger storm-relative flow and shear-induced ventilation. In addition, Rappin et al. (2010) found that increasing SST in RCE simulations results in a drier midlevel environment and, hence, stronger ventilation due to shear at the altitude of the midlevel vortex. Although RCE may be a valid approximation for the large-scale tropical environment on daily time scales and longer, the local environment around TCs can be far from RCE. Therefore, more research is needed on the validity of the RCE assumption as it relates to TC-VWS interactions.

4. Pathways to TC Development and Intensification in Shear

Despite the substantial body of research highlighting the predominantly negative impacts of VWS on TC structure and intensity discussed so far, VWS is not always destructive to a TC. An emerging line of research has sought to better understand the intensification of TCs in environments with VWS magnitudes that are neither too weak nor too strong (e.g., Molinari et al. 2004, 2006; Molinari and Vollaro 2010; Montgomery et al. 2010; Foerster et al. 2014; Stevenson et al. 2014; Rios-Berrios et al. 2016a,b; Zawislak et al. 2016; Nguyen et al. 2017; Ryglicki et al. 2018a; Chen, X. et al. 2018a; Rogers et al. 2020, and many others). This range of VWS magnitudes is commonly referred to as “moderate shear.” Four pathways to TC intensification under moderate shear have emerged from the literature: vortex tilt reduction, vortex reformation, axisymmetrization of precipitation, and outflow blocking. This section reviews each pathway separately even though they may not be mutually exclusive; for example, vortex tilt reduction may occur together with vortex reformation. These pathways most likely explain the intensification of weak, disorganized TCs (e.g., tropical depressions and tropical storms) into major hurricanes.

a. Vortex tilt reduction

Multiple studies have suggested that a nearly aligned vortex is often a precursor to TC intensification, including the onset of rapid intensification (Frank and Ritchie 2001; Reasor et al. 2004; Reasor and Eastin 2012; Rappin and Nolan 2012; Zhang and Tao 2013; Tao and Zhang 2014; Rogers et al. 2015; Nguyen and Molinari 2015; Rios-Berrios et al. 2016b, 2018; Chen, X. et al. 2019; Rogers et al. 2020; Rios-Berrios 2020; Alvey et al. 2020; Schecter and Menelaou 2020; Nam et al. 2023). While the literature often uses the terminology “vortex re-alignment” to describe how a TC vortex evolves from being tilted to being nearly aligned, recent work (discussed below) has uncovered different pathways that explain such evolution. Therefore, we adopt the concept of "tilt reduction" herein to acknowledge the multiple processes that explain the transition from a tilted to a nearly aligned TC vortex.

Idealized TC simulations have been extensively used to study the relationship between VWS, vortex tilt, and TC intensity (Jones 1995; DeMaria 1996; Frank and Ritchie 1999, 2001; Jones 2000a,b, 2004; Patra 2004; Wong and Chan 2004; Kwon and Frank 2005, 2008; Rappin and Nolan 2012; Riemer et al. 2013; Zhang and Tao 2013; Tao and Zhang 2014; Miyamoto and Nolan 2018; Rios-Berrios et al. 2018; Tao and Zhang 2019; Rios-Berrios 2020; Schecter and Menelaou 2020; Schecter 2022; Nam et al. 2023). These simulations use models of varying complexities ranging from dry, nonhydrostatic models (Jones 1995; DeMaria 1996; Jones 2000a,b; Patra 2004; Wong and Chan 2004; Kwon and Frank 2005) to models that include moist processes (Flatau et al. 1994; Wang and Holland 1996; Frank and Ritchie 1999; Wong and Chan 2004; Kwon and Frank 2008; Rappin and Nolan 2012; Riemer et al. 2013; Zhang and Tao 2013; Tao and Zhang 2014; Miyamoto and Nolan 2018; Rios-Berrios et al. 2018; Tao and Zhang 2019; Rios-Berrios 2020; Ryglicki et al. 2018b; Schecter and Menelaou 2020; Schecter 2022; Nam et al. 2023). A cloud-free, vertically aligned TC-like vortex is usually specified in the initial conditions along with environmental flow and a thermodynamic sounding characteristic of the tropical atmosphere. The vortex is initially tilted towards the downshear quadrant, followed by an azimuthal rotation of the tilt vector towards the downshear-left and upshear-left quadrant. If the vortex is not completely sheared apart, intensification typically follows after a substantial reduction in tilt magnitude that typically coincides with a left-of-shear tilt configuration. For example, Fig. 10 shows that the onset of rapid intensification in multiple idealized TC simulations is strongly correlated with the vortex tilt magnitude. This figure implies that for larger vortex tilt, the onset of rapid intensification occurs later or becomes less likely.

Limited observational evidence also supports that a small vortex tilt or tilt reduction precede intensification under moderate and strong VWS. Reasor and Eastin (2012) used the concept of "resiliency" to shear to describe TCs that maintain a small vortex tilt under moderate and strong VWS. Their observational analysis of Hurricane Guillermo (1997) showed that the persistent small vortex tilt explained (at least partly) how Guillermo was able to resist and intensify in strong VWS. Additional observational studies of individual TCs have also found a relatively small vortex

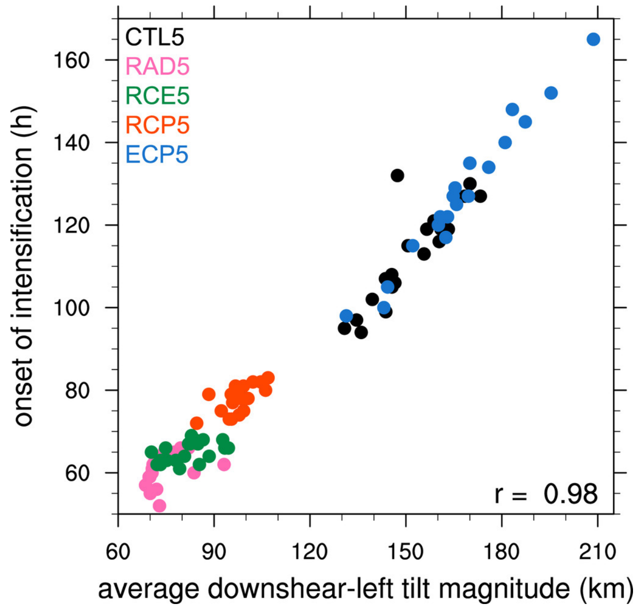

FIG. 10. Comparison between the onset of intensification and 400–900-hPa tilt magnitude averaged only during the time period when the tilt vector pointed downshear left (defined as a mathematical angle between 0° and 90°). Colors represent different 20-member ensembles with the same5 m s^{-1} shear magnitude: (black) a control configuration without radiation (CTL5), (pink) a configuration with radiation(RAD5), (green) a configuration in radiative-convective equilibrium(RCE5), (orange) a configuration with reduced cold pools (RCP5), and (blue) a configuration with enhanced cold pools (ECP5). Pearson's correlation coefficient appears at the lower-right corner. Adapted from Fig. 16 of Rios-Berrios (2020).

tilt coinciding with intensification under moderate and strong VWS (e.g., Molinari et al. 2006; Stevenson et al. 2014; Rogers et al. 2015, 2020; Alvey et al. 2022). More recently, an observational analysis of hundreds of airborne Doppler radar analyses demonstrated that early-stage TCs with small vortex tilt were associated with greater rates of intensification (Fischer et al. 2023b). Given that a tilted vortex is strongly coupled to convection (Section 2a), satellite imagery has also provided evidence that a small vortex tilt precedes TC intensification (Ryglicki et al. 2018a, 2021).

The importance of vortex tilt reduction for TC intensification has motivated many studies aimed at identifying the physical processes responsible for changes in vortex tilt. As discussed in Section 2a, early investigations focused on the role of dry dynamics. These studies found a preferred tilt orientation along—and to the left of—the VWS vector (Jones 1995; Wang and Holland 1996; Frank and Ritchie 2001; Reasor et al. 2004). Simulations with sheared barotropic vortices demonstrated that once the vortex tilts upshear, differential vorticity advection of the sheared flow acts to realign the vortex (Jones 1995). A different paradigm describes vortex tilt reduction through inviscid damping of vortex Rossby waves, which are excited by VWS (Reasor and Montgomery 2001; Schecter et al. 2002; Schecter and Montgomery 2003; Reasor et al. 2004; Reasor and Montgomery 2015). In this paradigm, the tilt evolution is described by a vortex Rossby wave asymmetry, often referred to as the "quasi-mode" on a background azimuthally-averaged flow. Moving outward from the TC center, a critical radius exists where the rotation rate of the background flow is equal to the precession frequency of the vortex tilt mode, where resonance between the two can occur. Stirring of the flow at this critical radius requires a damping of the vortex tilt at a rate proportional to the local vorticity gradient, provided the radial vorticity gradient is negative. While this mechanism invokes dry dynamics, additional studies (Schecter and Montgomery 2007; Reasor and Montgomery 2015) demonstrated that the location of the critical radius is dependent upon the static stability, or "cloudiness", of the TC core, with the critical radius shifting to smaller radii as static stability decreases. Thus, diabatic processes have been hypothesized to indirectly affect the vortex resilience by modifying the static stability and the TC's radial vorticity profile (Reasor et al. 2004).

More recent studies have emphasized the direct role of moist diabatic processes in vortex tilt reduction. Including moist processes in idealized simulations yield smaller vortex tilt magnitudes for otherwise similar but dry configurations, which led to the hypothesis that diabatic heating is important for vortex tilt reduction under VWS (Flatau et al. 1994; Wang and Holland 1996; Frank and Ritchie 1999). This hypothesis was challenged by Jones (2004), who demonstrated that TCs could experience a small vortex tilt in the absence of moist processes and that vortex tilt depends on the Rossby penetration depth and vortex strength. Yet, more recent studies that have relied on full-physics idealized TC simulations continue to emphasize the complex role of moisture and diabatic processes during vortex tilt reduction, especially in TCs below hurricane intensity. The main precipitating regions in these TCs is strongly coupled to the midtropospheric vortex, and their co-evolution can reduce or amplify the vortex tilt induced by VWS (Rios-Berrios et al. 2018; Ryglicki et al. 2018b; Chen, B.-F. et al. 2021). A substantial vortex tilt reduction happens through a relatively rapid re-structuring of the TC vortex (Miyamoto and Nolan 2018; Rios-Berrios et al. 2018; Rogers et al. 2020; Schecter and Menelaou 2020; Schecter 2022; Alvey and Hazelton 2022;

Alvey et al. 2022), instead of through the gradual alignment of distinct lower and midlevel vorticity anomalies. This process may take several iterations (Ryglicki et al. 2018b) especially in marginal environments of moderate VWS and dry air (Nam et al. 2023).

During the re-structuring process, convectively coupled vorticity anomalies aid the establishment of a nearly aligned and deep TC vortex (Miyamoto and Nolan 2018; Rios-Berrios et al. 2018). At the same time, precipitation transitions from being highly asymmetric to being more symmetric with an established eyewall. The established eyewall aids TC intensification through increased axisymmetric diabatic heating (Tao and Zhang 2014) while the nearly aligned vortex is more likely to intensify via surface heat fluxes (Molinari et al. 2004) and boundary-layer vortex stretching (Rios-Berrios et al. 2018). Divergent outflow from the shear-induced convection also counteracts the sheared environmental flow (Ryglicki et al. 2018b, 2019, 2021). Observations and model simulations of real-world TCs also support this re-structuring process (Molinari et al. 2004; Rogers et al. 2020; Ryglicki et al. 2021; Alvey and Hazelton 2022; Stone et al. 2023), although the precise pathway to vortex tilt reduction can include vortex precession and vortex reformation in some cases (Alvey and Hazelton 2022). Vortex reformation is described in greater detail in the next subsection.

While vortex tilt reduction increases the likelihood that a TC will intensify, there is no unanimous consensus about the relationship between vortex tilt and intensity changes. In an observational composite analysis of TCs of hurricane intensity, Rogers et al. (2013) found no significant difference in the magnitude of vortex tilt between the intensifying and steady-state hurricanes. Some studies have also proposed that the onset of rapid intensification precedes a complete vortex alignment (e.g., Chen and Gopalakrishnan 2015; Judt et al. 2016; Chen, X. et al. 2018a; Alvey et al. 2022). However, Fischer et al. (2023b) found that a vortex tilt is more important for intensity changes of TCs below hurricane intensity than for stronger TCs. These discrepancies could stem from differences in datasets (i.e., model simulations vs. observations), challenges of defining and identifying vortex tilt, the rapid evolution of convective processes, amongst other factors. Future work should seek to elucidate how external influences affect the relationship between TC intensity change and vortex tilt magnitude, and further explore cases that intensify prior to substantial tilt reduction.

b. Reformation

Observational and modeling studies have indicated that early-stage TCs (including tropical depressions, tropical storms, and category-1 hurricanes) are able to resist moderate-to-strong VWS by generating a new vorticity core or low-level circulation beneath or near the mid-level circulation in the downshear quadrant. This pathway has been termed downshear reformation (Molinari et al. 2004, 2006), and occurs most frequently for tropical storms (e.g., Davis et al. 2008; Molinari and Vollaro 2010; Nguyen and Molinari 2012; Chen, X. et al. 2018a; Rogers et al. 2020; Alvey and Hazelton 2022). In this pathway, a broad and relatively weak parent TC circulation and the resulting weak axisymmetrization allow the development of a reformed vorticity core in a region of sustained diabatic heating (Schecter 2020). Downshear reformation notably alters the vortex structure and the thermodynamic state within the core, as a more compact and vertically-aligned TC inner core forms in a more humid downshear environment. This sets up a more favorable configuration for TC intensification and, sometimes, rapid intensification. How fast a TC will intensify has been found to depend on the vortex tilt and the saturation fraction within the core after reformation (Chen, X. et al. 2019). As reformation and the related structural changes occur within a few hours, they remain extremely difficult to observe and predict. The reformation can also change the steering flow the TC feels due to the center relocation, which has a long-term impact on the track forecasts. Thus, it is not surprising to see large forecast errors for both track and intensity when downshear reformation occurs (e.g., Chen, X. et al. 2018a; Alvey et al. 2022).

The development of the reformed vorticity core relies crucially on the stretching, tilting, and upward advection of vorticity through convective processes (Nguyen and Molinari 2015; Chen, X. et al. 2018a; Rogers et al. 2020). The timing of reformation is thereby intrinsically dependent on the factors affecting the downshear convective activity, including TC intensity, VWS magnitude, and thermodynamic instability. The preference for reformation to occur at tropical-storm intensity suggests that the new vortex can become the dominant vortex when the pre-existing circulation is relatively weak. The presence of moderate-to-strong VWS also implies that sufficiently strong balanced lifting (cf. Jones 1995) and Ekman-like pumping (Schecter 2022) in the downshear region are important prerequisites, especially in the scenario where the surface enthalpy flux is nearly zero (Davis et al. 2008).

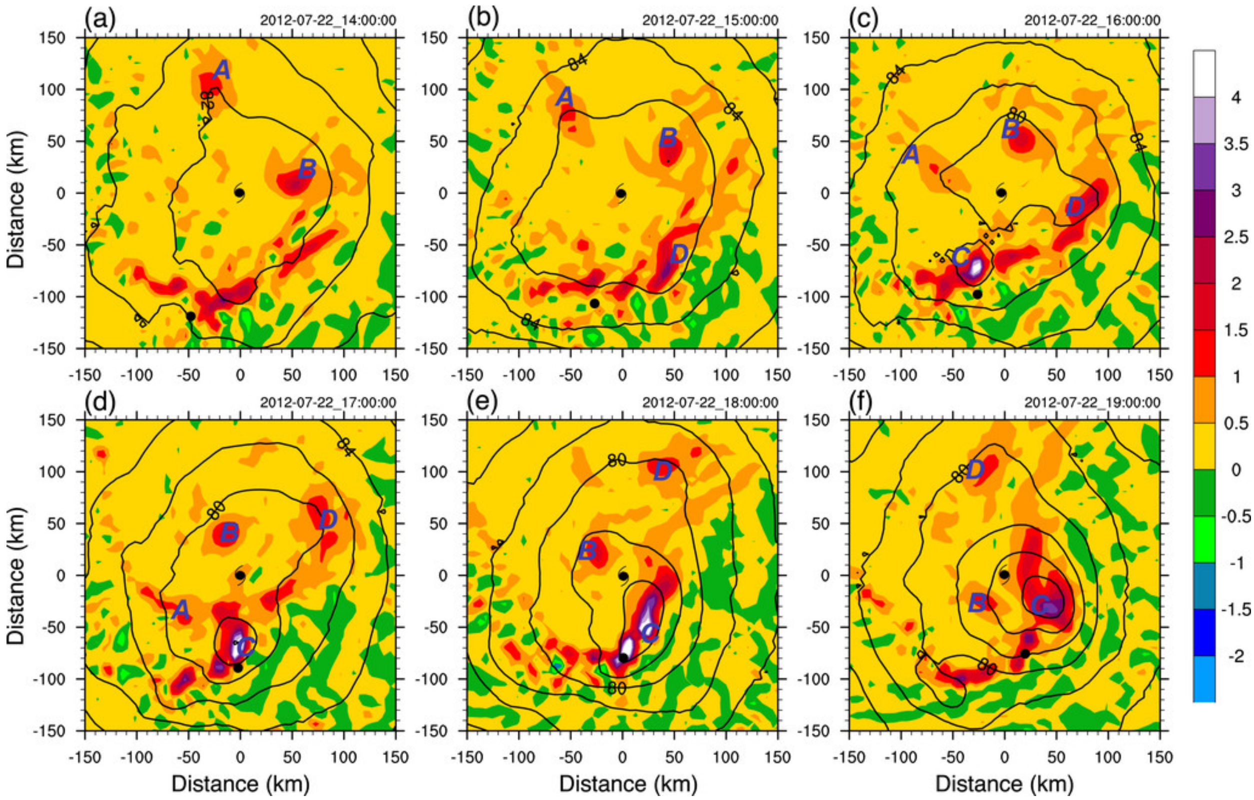

FIG. 11. Hourly evolution of 900-hPa relative vorticity (shading; 10^{-3} s^{-1}) and geopotential height (contoured every 2 x 10^2 m^{-2} s^{-2}) from (a) 1400 to (f) 1900 UTC 22 Jul. The black hurricane symbol (dot) in each panel denotes the surface (500 hPa) TC center. Labels A–D denote different mesovortices, and mesovortex C becomes the reformed inner vortex of simulated Typhoon Vicente (2012). The 200–850 hPa VWS is heading southwest. From Fig. 7 in Chen et al. (2018b).

Another favorable condition for reformation is the counter-aligned surface wind and deep-layer VWS, which positions the maximum surface wind left-of-shear such that the enhanced surface enthalpy fluxes can support stronger asymmetric convection (Chen, X. et al. 2018a). The timing of reformation is also related to a downshear environment characterized by weak instability (Raymond et al. 2011) and high column moisture. Such conditions favor bottom-heavy mass flux profiles and low-level vorticity stretching (Rios-Berrios et al. 2018; Rogers et al. 2020), which can be an outcome of several previous episodes of deep convection. These episodes of deep convection can induce the formation of multiple mesovortices that propagate downstream (Chen, X. et al. 2018a); however, only the mesovortex that successfully grows in size and strength with time becomes the reformed inner vortex (e.g., mesovortex C in Fig. 11) whereas the other mesovortices weaken after leaving the downshear convergence zone (Wang et al. 2022). In some cases, convective processes leading to reformation can benefit from diurnal, radiative influences (Alvey and Hazelton 2022), or interactions with island topography (Alvey et al. 2022). Despite these insightful findings, more research utilizing different observational platforms and high-resolution numerical simulations is needed to quantify the frequency and predictability of vortex reformation.

c. Precipitation Axisymmetrization

From a kinematic perspective, TC intensification requires the inward advection of angular momentum surfaces across the location of the radius of maximum wind within the boundary layer (e.g., Smith et al. 2009; Montgomery and Smith 2014; Smith and Montgomery 2015). This process is typically achieved due to sufficient diabatic heating within the TC inner core; however, as previously discussed, the pattern of diabatic heating in sheared TCs is asymmetric. Some studies have hypothesized TC intensification can be achieved through asymmetric processes, such as the injection of high-entropy air from the low-level TC eye into the eyewall region (Persing and Montgomery 2003; Cram et al. 2007; Reasor et al. 2009, e.g.,), the mixing of momentum between the TC eye and eyewall (Schubert et al. 1999; Kossin and Schubert 2001; Rozoff et al. 2009), or sufficiently intense asymmetric convection with robust warming via compensating subsidence (e.g., Heymsfield et al. 2001; Guimond et al. 2010; Nguyen and Molinari 2012; Guimond et al. 2016; Rogers et al. 2016; Hazelton et al. 2017; Wadler et al. 2018). Intense asymmetric regions of convection can also spin up the TC primary circulation via the axisymmetrization of local potential vorticity anomalies (e.g., Möller and Montgomery 2000; Hendricks et al. 2004; Montgomery and Smith 2014).

Nevertheless, through the use of dry, idealized simulations of hurricane-like vortices, Nolan et al. (2007) demonstrated TC intensification is significantly more responsive to the axisymmetric projection of heating than localized, asymmetric heating. Consistent with this idea, an increasing number of studies have begun to identify a relationship between the TC intensification rate and the degree of precipitation axisymmetry. For instance, multiple observational case studies of TCs in shear have linked TC intensification to increases in upshear precipitation and more axisymmetric convective structures (e.g., Stevenson et al. 2014; Rogers et al. 2015; Susca-Lopata et al. 2015;

Zawislak et al. 2016; Rogers et al. 2016; Munsell et al. 2021). Additional studies of multiple TC cases have corroborated these results, showing that TCs with more axisymmetric precipitation structures tend to intensify more rapidly (e.g., Harnos and Nesbitt 2011; Jiang and Ramirez 2013; Zagrodnik and Jiang 2014; Alvey III et al. 2015; Tao and Jiang 2015; Harnos and Nesbitt 2016; Tao et al. 2017; Fischer et al. 2018; Ryglicki et al. 2018a). Using a satellite-based precipitation partitioning scheme, Tao et al. (2017) indicated an increase in stratiform precipitation—especially in the upshear quadrants—was particularly important for the initiation of rapid intensification. Tao et al. (2017) hypothesized the increase in stratiform precipitation may be linked to a moistening of the inner core, promoting a local thermodynamic environment that favors more axisymmetric heating during rapid intensification. This hypothesis is consistent with a comparison of steady-state and intensifying TCs in the presence of moderate VWS by Rios-Berrios and Torn (2017), who found intensifying TCs have a more humid mid-troposphere and a greater coverage of upshear precipitation (Fig. 12). Composite analyses from other observational platforms, such as geostationary satellite imagery (Fischer et al. 2018; Shi and Chen 2021), airborne Doppler radar analyses (Rogers et al. 2013; Wadler et al. 2018), and global lightning detection networks (Stevenson et al. 2018), have also emphasized the importance of greater convective axisymmetry for increased rates of TC intensification.

Full-physics numerical simulations similarly point toward the significance of greater precipitation axisymmetry for increased rates of TC intensification in environments with VWS (e.g., Miyamoto and Takemi 2012; Rios-Berrios et al. 2016b; Onderlinde and Nolan 2016; Chen, X. et al. 2018a; Leighton et al. 2018; Miyamoto and Nolan 2018; Tao and Zhang 2019; Alvey et al. 2020; Hazelton et al. 2020; Alland et al. 2021b). Analyses of such simulations have inspired hypotheses to explain the increased precipitation axisymmetry of sheared TCs. Some studies have suggested the significance of vortex alignment in facilitating more axisymmetric precipitation structures (e.g., Tao and Zhang 2014; Chen, X. et al. 2018b; Rios-Berrios et al. 2018; Ryglicki et al. 2018b; Tao and Zhang 2019; Alvey et al. 2020; Hazelton et al. 2020; Rios-Berrios 2020; Alland et al. 2021b; Chen, X. et al. 2021). As discussed in the previous subsection, vortex tilt and asymmetric convection are strongly coupled to each other and, consequently, a nearly aligned vortex is also associated with a more axisymmetric distribution of precipitation. Other studies have emphasized the important role of the boundary layer in facilitating precipitation axisymmetry. In a comparison of two simulations

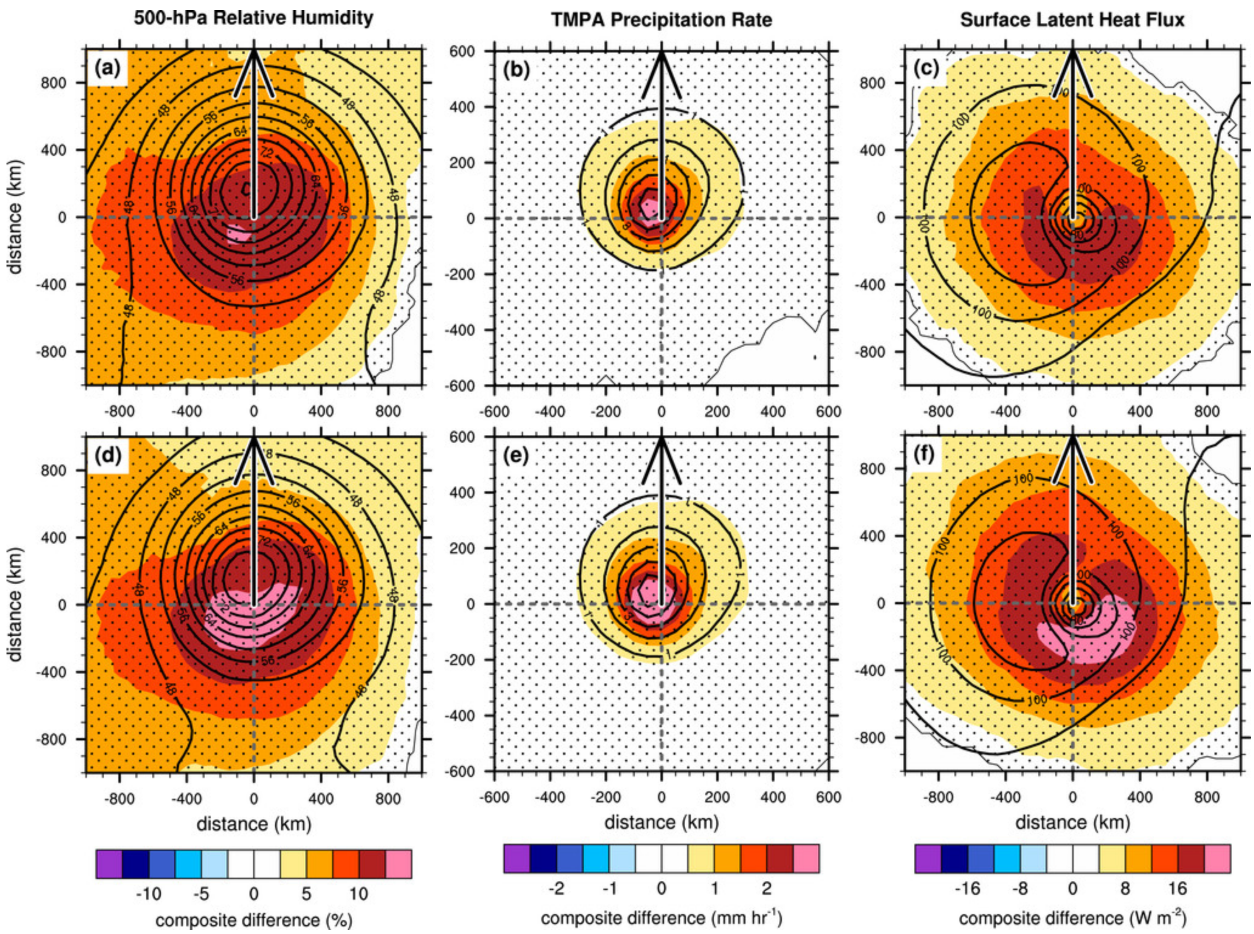

FIG. 12. Storm-centered, shear-relative analyses of (a),(d) 500-hPa RH (%); (b),(e) precipitation rate (mm h^{-1}); and (c),(f) surface LHF (W m^{-2}) at (top) 0 h and (bottom) averaged between 0 and 24 h. Black contours represent the mean of all intensifying and steady-state events, shading represents the composite difference between intensifying and steady-state events, and the stippling pattern represents statistically significant differences at the 99.9% confidence level. All fields were rotated with respect to the 200–850-hPa shear vector such that the shear vector (black and white arrow) points along the positive ordinate. From Fig. 11 in Rios-Berrios and Torn (2017).

of the same TC vortex over different SSTs, Chen, X. et al. (2021) demonstrated how enhanced surface enthalpy fluxes—in this case from warmer sea surface temperatures—promoted more vigorous inner-core convection that propagated farther upshear, leading to greater precipitation axisymmetry and increased TC intensification rates. Likewise, dropsonde observations (Nguyen et al. 2019), reanalysis output (Rios-Berrios and Torn 2017; Richardson et al. 2022), and other numerical simulations (Rappin and Nolan 2012) generally agree that larger upshear surface enthalpy fluxes favor increased precipitation axisymmetry and subsequent TC intensification.

d. Outflow blocking

The divergent upper-level outflow of a TC can in some cases counteract storm-relative flows due to VWS, enabling TCs to intensify in shear. Black and Anthes (1971) recognized the ability of the TC outflow to deflect the upper-tropospheric flow in which the TC is embedded, but more recent work has revealed the implications of this flow deflection for the intensification of sheared TCs. Ryglicki et al. (2018a) identified a class of storms that undergo rapid intensification in moderate to strong deep-layer VWS. A common feature of these storms is that they all exhibit bursts of convection that increase the component of outflow directed upshear, which tends to occur once the vortex tilts to the left of shear (Ryglicki et al. 2020).

Outflow blocking promotes the intensification of sheared TCs by re-routing the environmental flow away from the TC center (Ryglicki et al. 2019, 2021). This reduces the radial thermodynamic ventilation of the warm core in the upper troposphere (Finocchio and Rios-Berrios 2021) and locally reduces the effective wind shear over the TC inner core (Dai et al. 2021). In a climatological study of several TCs in the Northern Hemisphere, Shi and Chen (2021) found that, consistent with Ryglicki et al. (2020), rapid intensification in moderate to strong shear is preceded by an increase in the component of outflow directed upshear and a coincident reduction of the total shear near the TC inner core. Idealized simulations have identified an asymmetric divergent flow within the outflow layer of sheared TCs that is responsible for locally reducing the vertical wind shear over the inner core (Xu and Wang 2013; Ryglicki et al. 2019; Dai et al. 2021). Because the TC outflow is confined to the upper troposphere, the asymmetric divergent flow is more effective at counteracting VWS that is also concentrated in the upper troposphere (Elsberry and Jeffries 1996; Ryglicki et al. 2018b; Shi and Chen 2021). As discussed in Section 3a, upper-level anticyclones are usually responsible for these types of upper-level shear environments (Ryglicki et al. 2018a). Shi and Chen (2021) found that 76% of TCs that rapidly intensity in moderate to strong shear are sheared by an upper-level anticyclone, indicating a possible relationship between the large-scale shearing mechanism and the likelihood for the outflow to counteract VWS. From an operational forecasting perspective, such relationships between the large-scale flow and the likelihood for TC intensification in shear are particularly valuable in the moderate VWS environments that are frequently associated with lower TC predictability.

5. Effects of Shear on TC Predictability

The presence of VWS increases the complexity of interactions between the TC and its surrounding environment that can strongly limit skillful predictions of TC structure and intensity change. Bhatia and Nolan (2013) found that the short-range intensity forecast errors from both the National Hurricane Center and operational statistical and dynamical models at the time were largest for hurricane-strength storms in moderate magnitudes (5–10 m s^{-1}) of deep-layer VWS. This range of VWS magnitudes is near the threshold values that are traditionally used in operational settings to broadly distinguish favorable from unfavorable flow environments. Although operational intensity forecast skill has improved since Bhatia and Nolan (2013), TCs in moderate VWS environments are still widely considered to be less predictable than TCs in weak or strong shear.

Numerous studies over the last several decades have examined how VWS, and in particular moderate VWS, affects both the intrinsic and practical predictability of a TC. Intrinsic predictability refers to "the extent to which prediction is possible if an optimum procedure is used" (Lorenz 2006). Zhang and Tao (2013) studied the intrinsic predictability of weak TCs in shear using idealized ensemble simulations in which they added small, random moisture perturbations in the TC boundary layer of each ensemble member. They found that as the deep-layer VWS magnitude increased, the uncertainty in the timing of TC intensification increased until the shear became strong enough to prevent intensification in any of the ensemble members (Fig. 13). Tao and Zhang (2015) further explored this result and found that the large ensemble spread in RI onset times of the moderately sheared TCs was attributed to moist convection. The chaotic nature of moist convection introduces small-scale differences among the ensemble members which grow up to the vortex-scale as the TCs precess through the downshear-left quadrant, ultimately resulting in differences in vortex precession rates and the timing of RI onset.

VWS also reduces a TC's practical predictability, which is "the extent to which we ourselves are able to predict by the best-known procedures, either currently or in the foreseeable future" (Lorenz 2006). The presence of VWS heightens the sensitivity of the storm to environmental characteristics that are often poorly observed, such as mid-level humidity. Munsell et al. (2013) studied an ensem-

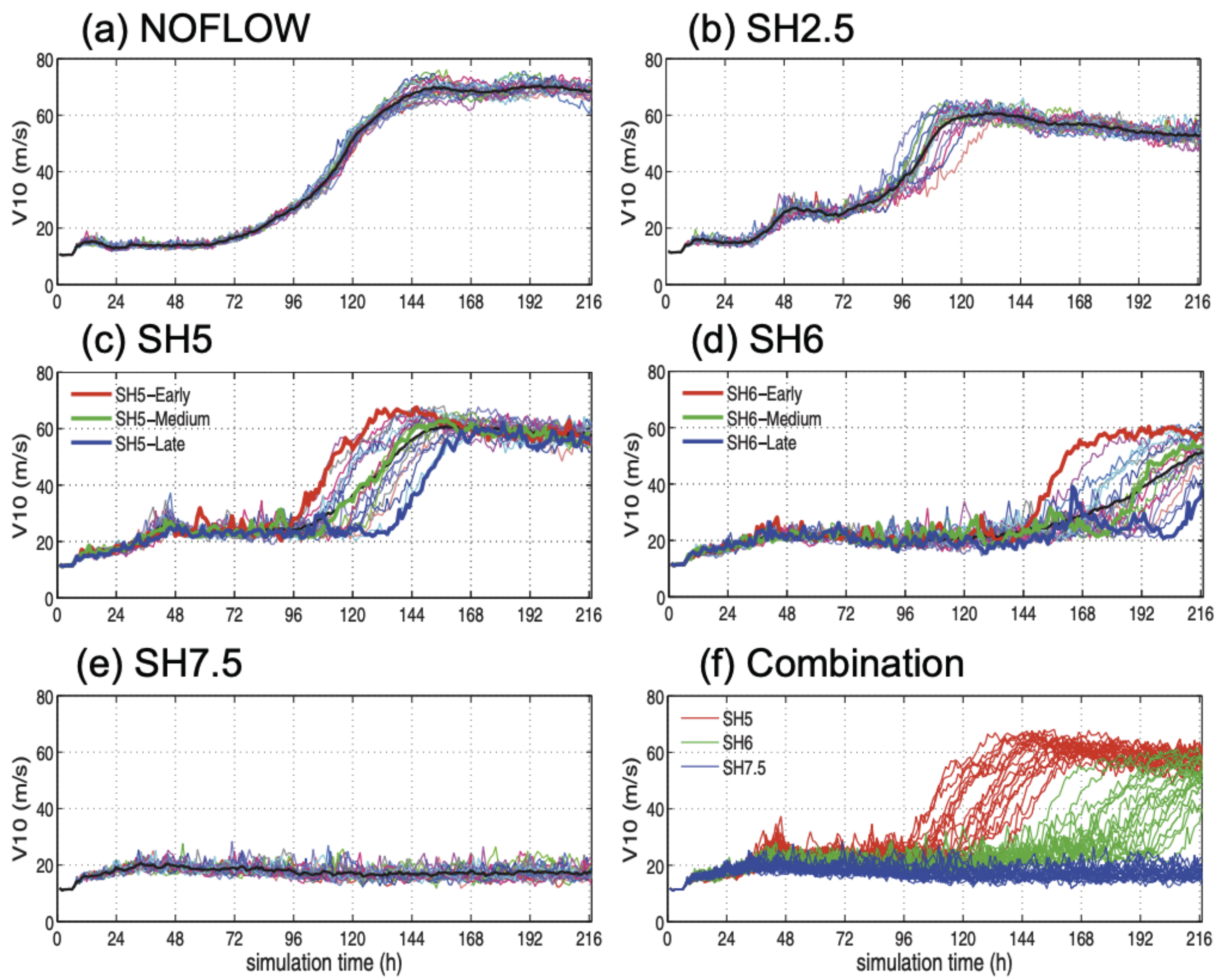

FIG. 13. Time evolution of tropical cyclone intensity in terms of the 10-m maximum wind speed for ensembles with (a) no shear ("NOFLOW"), (b) SH2.5, (c) SH5, (d) SH6, (e) SH7.5, and (f) combination of SH5, SH6, and SH7.5. The numbers after "SH" indicate the magnitude of westerly deep-layer VWS in each ensemble. All simulations have SST=27°C. Adapted from Fig. 2 in Tao and Zhang (2015).

ble of a sheared Tropical Storm Erika (2009) and showed how large variability in midlevel dry-air intrusions played a key role in increasing the ensemble forecast intensity spread. Rios-Berrios et al. (2016a,b) analyzed ensemble simulations of TC Katia (2011) and Hurricane Ophelia (2011) respectively, and found that the key differences between developing and non-developing members were the lower-tropospheric moisture in the right-of-shear quadrant for Katia and midtropospheric moisture in the downshear and left-of-shear quadrants for Ophelia. Uncertainty in the environmental VWS itself also introduces uncertainties into TC intensity forecasts (Emanuel et al. 2004).

Both idealized and real TC modeling studies have demonstrated how small variations in the wind profile can lead to bifurcating TC intensity responses that are related to differences in vortex tilt and convective bursts near the radius of maximum winds (Finocchio et al. 2016; Finocchio and Majumdar 2017a; Munsell et al. 2017).

Other factors related to numerical weather prediction techniques, such as radiation schemes, also influence how VWS affects the practical predictability of a TC. Rios-Berrios (2020) found that using a comprehensive radiation scheme in idealized simulations increases predictability of sheared TCs by stabilizing the lower troposphere, thereby reducing the variability of the non-linear feedbacks among lower-tropospheric ventilation, cold pools, convection, and vortex tilt. More research is needed on how cloud microphysical parameterizations influence the practical predictability of sheared TCs.

The presence of VWS also affects the structural predictability of a TC through its influence on the evolution of wind, cloud, and precipitation asymmetries. Judt et al. (2016) examined TC structural predictability by azimuthally decomposing the tangential wind field of Hurricane Earl (2010). The mean vortex and wavenumber-one asymmetry had the longest intrinsic predictability of at least seven days. Notably, they found that the predictability of the mean vortex and wavenumber-one asymmetry was strongly influenced by the predictability of the environmental deep-layer VWS, which itself remains predictable for longer than a week (Komaromi and Majumdar 2014, 2015). At the scales of individual convective cells (azimuthal wave numbers >20), however, errors grow more rapidly in both magnitude and scale, resulting in a much shorter predictability horizon of only 6–12 h (Judt et al. 2016). Similar to the tangential winds, the low-wavenumber asymmetries of the precipitation structure of a sheared TC remain predictable longer than the convective-scale asymmetries (Finocchio and Majumdar 2017a). Moderate shear environments are generally associated with lower intrinsic predictability of TC structure due to heightened sensitivity to the environmental wind profile (Finocchio and Majumdar 2017a), and a higher uncertainty in the vortex tilt evolution (Tao and Zhang 2015; Yu et al. 2023) and the occurrence of eyewall replacement cycles (Zhang et al. 2017).

6. Conclusions and Recommendations

Deep-layer VWS, broadly defined as the 200–850 hPa shear of the horizontal wind, has profound effects on TC structure and intensity. This review article summarizes the growing body of research into those effects in terms of their influence on the likelihood and timing of TC intensification. VWS tilts the TC vortex, organizes precipitation into a wavenumber-one asymmetric pattern, and causes thermal and kinematic asymmetries. While VWS is a useful metric for TC intensity forecasting, recent research demonstrates how shear alone often cannot fully capture the myriad ways in which a TC responds to a given environmental flow. A particularly challenging forecasting situation, which is the focus of several studies reviewed herein, involves an intermediate range of shear magnitudes commonly referred to as moderate shear. Within this range of shear magnitudes, the sensitivity of a TC to subtle aspects of both the storm and its environment are amplified, such that the response of the TC becomes exceedingly difficult to predict.

Several recent studies have identified underlying processes that limit the predictability of moderately sheared TCs. A focus of many of these studies has been on the surprising ability of some TCs to intensify in moderate-to-strong VWS. Figure 14 shows a summary of the key structural features that distinguish intensifying from non-intensifying TCs under moderate-to-strong VWS, based on the *existing* knowledge reviewed herein. This review article summarized four different pathways by which a TC can become resilient to such shear environments. Those pathways include the reduction of shear-induced vortex tilt, the formation of a new TC vortex within the shear-organized convection, the transition from a highly asymmetric to nearly symmetric precipitation structure, and the reduction of shear-induced ventilation by outflow blocking (Fig. 14). Several of these pathways operate simultaneously; for example, shear-organized asymmetric convection can lead to the formation of a new, nearly aligned vortex and the associated outflow can counteract the storm-relative inflow due to shear.

Despite the remarkable progress in understanding TC-VWS interactions, many open questions and opportunities for future research remain. There is no widely-accepted definition of VWS that can be generally applied in operational and research applications. Some methods estimate VWS by simply taking an area average of the 200 and 850 hPa winds over a large enough radii (e.g., 500 km or 200–800 km) to sample the environment, whereas other methods remove the contributions from the TC vortex before taking such area averages. The specific radii are largely based on

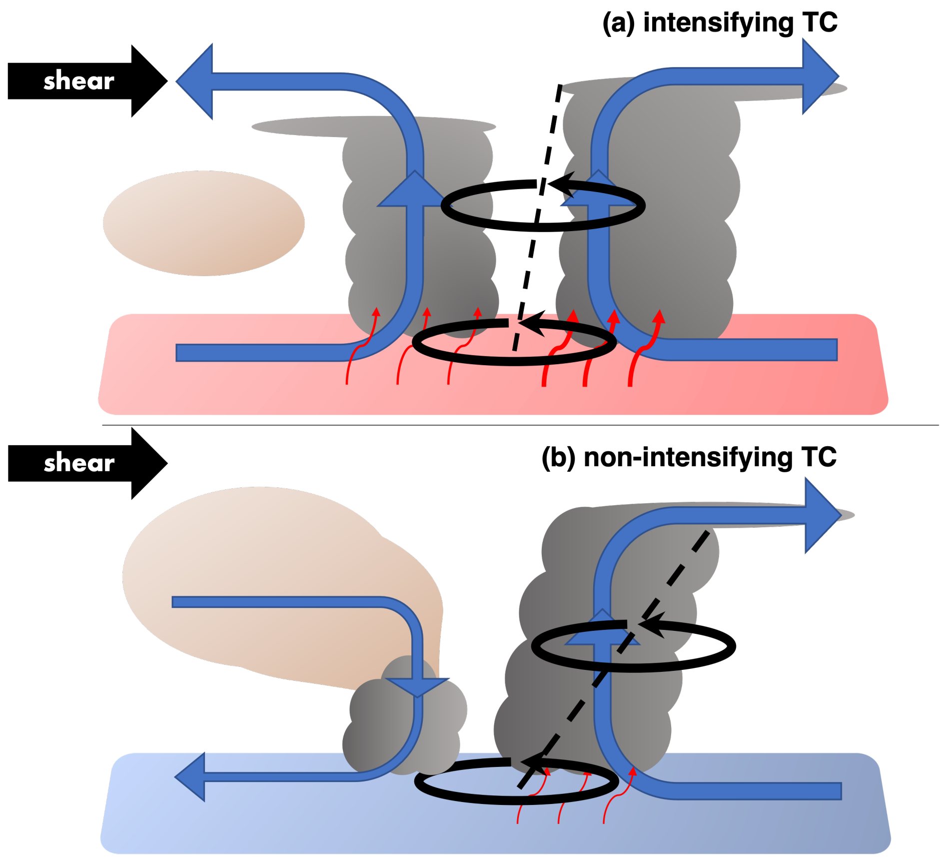

FIG. 14. Summary schematics of key structural properties of (a) intensifying and (b) non-intensifying TCs under moderate VWS. The intensifying TC is associated with nearly symmetric convection (represented by the clouds), a relatively small vortex tilt (represented by the circulations), and relatively strong surface fluxes (represented by the small red arrows) in all quadrants. Dry air (represented by the brown circle), if present, is not able to disrupt the TC secondary circulation. The non-intensifying TC is associated with asymmetric convection in the downshear half, a relatively large vortex tilt, and relatively strong surface fluxes in the downshear half. Dry air is able to disrupt the TC through either radial ventilation, downward ventilation, or a combination of both. The intensifying TC is over relatively warmer ocean temperatures than the non-intensifying TC. Inspired by schematics from Nguyen et al. (2017), Richardson et al. (2022), and others.

legacy from previous studies without physically based justifications. The precise VWS magnitude can vary substantially from one method to another as noted, for example, by Velden and Sears (2014), Ryglicki et al. (2019), and Ryglicki et al. (2021). More broadly, it is unclear how much the calculated shear and other environmental parameters truly affect a TC. For example, does the inner-core vortex of a TC experience the environmental shear that is calculated from a 200–800 km radial averaging around it? Although the answer to this question will depend on many factors (e.g., TC size, vortex depth, etc.), a broadly agreed upon and physically based definition is much needed.

Another area of much opportunity is better understanding the response of early-stage TCs (i.e., below major hurricane intensity) to VWS. Much of the theoretical work on TC intensity and structure is based on the assumption of an axisymmetric vortex; however, early-stage TCs challenge that assumption due to their disorganized and asymmetric nature. For example, how strongly coupled are the displaced circulations of a weak TC in comparison to a vertically tilted vortex of a mature hurricane? Which processes govern the azimuthal distribution and intensity of precipitation of weak TCs? The emerging work on TC intensification under moderate VWS has largely focused on early-stage TCs, but that work has heavily relied on model simulations. Recent advancements in observing platforms (e.g., GOES-R, small satellites, uncrewed aircraft) and increased research flights into early-stage TCs are potential avenues for expanding our knowledge and aiding theoretical developments applicable to weak and mature TCs alike.

Future studies should continue to interconnect the four pathways discussed here to explain TC intensification under moderate VWS. It is evident that the coupling between circulation and convection is important; however, there are some findings that need clarification. While a recent series of studies emphasizes the role of divergent outflow from shear-induced convection enabling vortex tilt reduction (Ryglicki et al. 2018a,b, 2019, 2020, 2021), other studies focus on boundary-layer processes that promote and sustain convection leading to vortex tilt reduction (Rios-Berrios et al. 2018; Rios-Berrios 2020; Chen, X. et al. 2021). These processes are not necessarily independent of each other. Hence, more studies are needed to unify these processes.

Many of the studies discussed herein used idealized TC simulations of different complexities, but their numerical configuration could be improved to advance our process-based understanding of TC-VWS interactions. These simulations usually apply spatially and temporally homogeneous VWS, but Rios-Berrios and Torn (2017) showed that such assumption is valid for less than 36 h in real-world TCs. New methods to account for the spatial and temporal variability of VWS (e.g., Onderlinde and Nolan 2017) should be used more often to mimic more closely the evolution of observed TCs. Moreover, details of the experimental configuration vary substantially amongst studies including: the specified profile of environmental winds, the choice to introduce shear in the initial conditions or abruptly at some point in the simulation, the inclusion of warm rain processes alone vs. also including ice processes, the inclusion of radiative processes, etc. This could potentially be alleviated by developing and adopting a generalized configuration. However, details of the simulations will inevitably depend on the underlying model and choices of model parameterizations. To date, all simulations have used convection-permitting or coarser resolution, but large-eddy simulations (LES) remain an area of future research. LES experiments could shed new light on the role of convective processes during TC-VWS interactions; for example, is ventilation a mesoscale process, turbulent process affecting cloudy updrafts, or both?

Lastly, there is a critical need for bridging the gap between operational and research efforts. Real-time observational strategies should be informed by the findings of process-based research by developing observational technologies and techniques that sample relevant regions and quantities (such as upshear moisture or boundary-layer wind asymmetries). Co-located observations of moisture and winds near ventilation regions could help characterize ventilation in real time. At the same time, future research and forecast product development should be informed by the needs of forecasters given the limited predictability of sheared TCs.

To sum up, we offer the following recommendations for future research on sheared TCs:

- Develop physically-based and general methods to diagnose VWS in both operational and research applications.
- Adapt observational strategies and exploit existing observations to better quantify TC-VWS interactions.
- Conduct more research to understand when VWS is detrimental versus beneficial for TC intensity, to further explore the dependency of VWS impacts on TC structure and intensity, and to better interconnect the pathways to intensification under moderate VWS.

Research and operational efforts on the topics above would be highly beneficial for advancing our understanding and improving the prediction of TC formation and intensification.

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