# TOPIC 2.5 INTENSITY CHANGE: EXTERNAL INFLUENCES

Marie-Dominique Leroux

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Rapporteur: Marie-Dominique LEROUX
LACy, Meteo-France
50 Boulevard du Chaudron
97491 Sainte Clotilde Cedex
LA REUNION
Email: marie-dominique.leroux@meteo.fr
Phone: +262 262921185

*Working group: S. A. Braun (NASA Goddard Space Flight Center), J. Courtney (BoM), M. E. Kucas (JTWC), C. M. Nguyen-Hankinson (Meteorological Service Singapore), P. D. Reasor (NOAA, HRD), Y. Wang (University of Hawaï), K. M. Wood (University of Arizona), Z. Yu (CMA), F. Zhang (The Pennsylvania State University), D. Tao (The Pennsylvania State University).*

**Abstract:** This report focuses on new advances regarding tropical cyclone (TC) intensity change induced by external influences. It briefly recalls the framework and main areas of progress identified during the last IWTC. It then highlights the major operational improvements in TC intensity forecasting since then and describes the research studies conducted to augment our understanding of the processes governing TC intensity changes under external forcing. Important shortcomings that remain are pointed out and suggestions are given to initiate discussion at the workshop on how to further progress on these matters.

### 2.5.0 Introduction

The refinement of our knowledge regarding environmental control on TC intensity was highlighted during the IWTC-VII. Several advances were reported on the four dominant synoptic-scale factors influencing TC intensity: (i) vertical wind shear (VWS), (ii) relative humidity (RH), (iii) sea surface temperature (SST) and ocean heat content (OHC), as well as (iv) outflow-layer interactions with the environment. A spectrum of shear values and TC intensities that permit continued intensification was identified from observational and modeling studies. Tang and Emanuel (2010) underlined two mechanisms for inner-core ventilation, defined as the entrainment of low-entropy air from the environment (Simpson and Riehl 1958) under vertical shear: inward eddy fluxes (e.g., through vortex Rossby waves) and downward fluxes through convective downdrafts. Riemer et al. (2010) demonstrated how asymmetries resulting from the relative shear flow help import low entropy environmental air towards the TC core at mid levels where it excites downdrafts (by ice melting and evaporative cooling) that flush the inflow layer with low-entropy air, which is then taken into downstream updrafts; these processes reduce the eyewall buoyancy and convection and thus the storm intensity (Figure 1). There was disagreement on the role of the Saharan Air Layer in the Atlantic basin on TC intensity change. A composite study indicated that the rate of TC intensification was only weakly dependent on environmental conditions, suggesting that rapid intensification (RI; maximum wind speed increasing by at least 30 kt in 24 h) would be more influenced by internal dynamical processes, provided that a preexisting favorable environment exists (Hendricks et al. 2010).

Despite some additional guidance and considering that intensity change forecasts were still challenging, IWTC-VII encouraged continued research towards improving the understanding of the impact of various environmental parameters on TC structure and intensity. These encompassed (i)-to-(iv), as well as water vapor advection, dust, topography, and boundary-layer fluxes. IWTC-VII also recommended research into predictability limits for intensity forecasting.

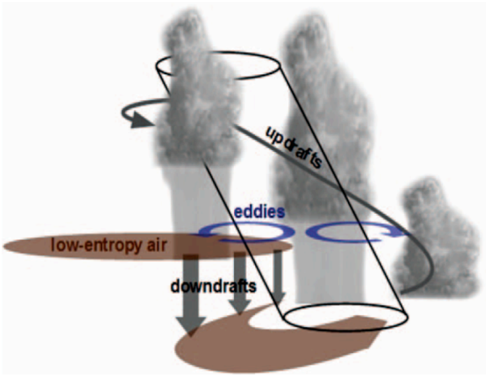


**Figure 1. An illustration of a TC undergoing ventilation. The vertically sheared environmental flow tilts the vortex inner core and causes convective asymmetries, which both excite mesoscale eddies. These eddies transport low-entropy air, found at mid levels of the environment, into the TC. The low-entropy air then mixes into the inner core and undercuts helical updrafts, where evaporation of rain produces downdrafts that flush the inflow layer with low-entropy air. These processes counteract the generation of available potential energy by surface fluxes and weaken the TC. From Tang and Emanuel (2012a)**

Since 2010, a number of studies have further investigated the impact of the thermodynamic and dynamic factors (i) to (iv) on TC intensity change and its predictability. Approaches include climatological analyses, satellite and other remotely sensed data, and numerical simulations. New studies have examined the role of aerosols on TC development and intensification and shed light on the role of potential vorticity (PV) injection from coherent structures evolving within the near-TC environment. Rapid intensification remains extensively studied, although an increasing interest exists for dissipated or rapidly weakening cases (e.g., Hurricane Felicia (2009), Bukunt 2014) as well as heavy rainfall events associated with environmental interactions.

### 2.5.1 Forecasting TC intensity change

Continued study of external influences on TC intensity change is merited, as improvements in 24-48 h intensity forecasts persist in lagging behind their counterpart track forecasts (DeMaria et al. 2014). Over the western North Pacific (WNP), verification of the operational forecasts from the JMA, the JTWC, and the CMA exhibits no obvious improvement in intensity forecasts during the last 4 years (Figure 2, Yu, pers. comm. 2014).

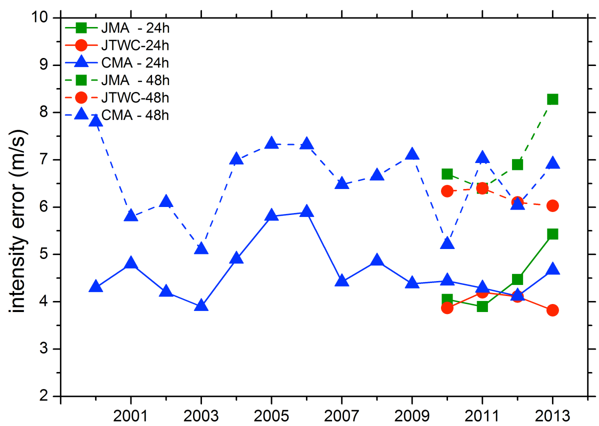


**Figure 2. Mean intensity errors in official operational forecast from 3 centers: the Japan Meteorological Administration (JMA), the Joint Tropical cyclone Warning Center (JTWC), and the China Meteorological Administration (CMA)**

### a) Improvements in operational procedures for intensity forecasting

In most operational centers, subjective assessments of large-scale features prevail as a cornerstone of the intensity forecast process. These include atmospheric and surface conditions such as low-level inflow, mid- and low-level humidity variations, vertical wind shear, upper-level divergence, evolution of upper-level circulations such as the Tropical Upper Tropospheric Trough (TUTT), jet streams, upper-level ridge axes, land impacts, and SST/OHC variations. However, applying these dominant external factors to intensity changes in the operational setting remains a key challenge in the forecast process (Courtney, Kucas, pers. comm. 2014).

The forecaster's subjective analysis of current conditions at JTWC largely rely on animated loops of geostationary satellite imagery enhanced to highlight water vapor, as well as hand-analyzed streamline flow charts for both the gradient level and upper troposphere (Figure 3, Kucas, pers. comm. 2014). Broad-scale upper-level flow patterns and consequent storm-centric outflow are diagnosed primarily through inspection of in-situ observations from sondes and aircraft, CIMSS satellite-derived upper-level wind and VWS imagery, model analysis fields, and MJO monitoring data from the Australian Bureau of Meteorology and US Climate Prediction Center. Forecasters also inspect skew-T data plots, total precipitable water data (provided by CIMSS), and microwave-band satellite imagery from FNMOC and NRL in order to identify potential intrusion of dry air from external features into the cyclone center. A "Low-Medium-High worksheet" has recently been developed to help monitor and classify 24-hour TC formation potential (Kucas and Darlow 2012).

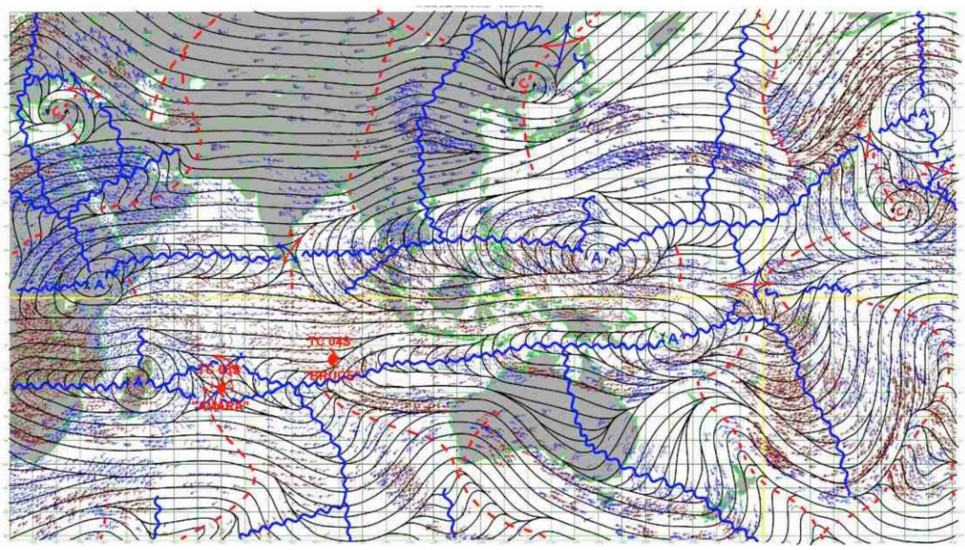

**Figure 3. Example 400-200 mb layer streamline flow chart prepared by the JTWC Satellite Analyst**

Forecasters anticipate that external influences will dominate as the primary driver of intensity change during formation or demise. However, once a certain level of organization is achieved in the system, particularly at tropical storm intensities (34-64 knots), intensity estimates due to external factors are nowadays adjusted based on the forecaster's analysis of internal dynamics that may induce rapid intensity changes. For instance, identifying eyewall changes such as secondary eyewall formation and eyewall replacement cycles can affect intensity forecasts (Kucas, Courtney, pers. comm. 2014). The Kieper and Jiang (2012) method can be helpful to anticipate RI periods using the 37 GHz ring pattern identified from passive microwave measurements. Statistics over the WNP also showed that deep-layer shear less than 7-9 m $s^{-1}$ or low-level shear less than 3.5 m $s^{-1}$ promotes TC intensification with the highest probability of RI (Wang et al. 2014).

A combination of synoptic assessment and persistence is usually weighted most heavily for the short term (to +24 h at the BoM; to +24 or +36h at JTWC). In the majority of centers, forecasters express the overall influence of external factors on TC intensity change in terms of the Dvorak T-number change over 24 hours (D+/D/D-/S/W-/W/W+) and relate that to the maximum wind intensity before considering objective guidance. Afterwards, increasing weight is given to objective guidance combined with subjective interpretation of changes in dynamical models depiction of these external factors (Courtney, Kucas, pers. comm. 2014). The Statistical Typhoon Intensity Prediction System (STIPS, Knaff et al 2005) still provides valuable standard output of environmental predictors such as VWS, SST, RH, etc., that are convenient to compare in a standardized approach. A suite of objective operational intensity forecasting tools now supplement this single most skillful objective intensity prediction aid in years prior at JTWC. For instance, the Statistical Hurricane Intensity Prediction System (SHIPS, DeMaria et al 2005) and the Logistic Growth Equation Model (LGEM, DeMaria 2009) were added in 2013 and 2014 for all forecast basins. Note that since **the low-level shear** was demonstrated to provide a better representation of the VWS effect on TC intensity change **over the WNP** (Shu et al. 2013, Wang et al. 2014), its **use in statistical intensity prediction schemes may improve the intensity forecast skill for this basin**.

Finally, the development of software for displaying fields of external factors in the Australian region has improved the forecasters' ability to conceptualize changes and compare between models. For example, transparent overlays of vorticity at 850, 700, and 500 hPa along with vertical wind shear allow forecasters to depict any vortex tilting response to the environment; and being able to quickly vary the VWS depth makes it easier to understand the vertical shear profile. The software also integrates satellite and radar imagery along with observations, making it easier to verify NWP analysis fields.

**b) Capability of model guidance**

Resolution upgrades, improved parameterizations and particularly assimilation of a range of data types have undoubtedly improved the performance of global numerical model large-scale patterns in the medium to extended forecast period, i.e. beyond 36 hours (Courtney, pers. comm. 2014). Access to mesoscale dynamical model forecasts has also increased. The Geophysical Fluid Dynamics Model, Navy version (GFDN) continues to provide skillful operational intensity forecasts for JTWC. In 2013, data from the Coupled Ocean-Atmosphere Mesoscale Prediction System for TCs (COAMPS TC) and the Hurricane Weather Research and Forecasting (HWRF) model were added to the forecasting suite at JTWC. With a number of skillful statistical-dynamical and mesoscale model intensity forecasts at hand, JTWC, in coordination with the NRL, has expanded testing and operational application of multi-model consensuses for intensity forecasting. Finally, new techniques to forecast the range of potential intensity values, such as GPCE (Goerss and Sampson 2014) and WANI (Elsberry and Tsai 2014) are under evaluation.

Two of six models evaluated in the WNP over the 2010-2011 period show significant skill over a statistical baseline in predicting Vmax at some lead times; that is, 60 and 72 h for ECMWF-GSM, and 24–72 h for GFDN (Yu et al. 2013). GFDN is the only model that demonstrates significant skill in its Pmin forecasts at some lead times (36, 60, and 72 h). The poor performance of all the models at short lead times, especially in 24 h, together with the significant correlation between the initial and forecast errors, implies that the models have serious problems in representing the initial vortex whether or not a bogus scheme is being applied. This deficiency can be compensated by using a multimodel consensus with a statistical calibration scheme that is more effective for Pmin than Vmax (Yu et al. 2013).

### c) Shortcomings and ongoing issues

Despite the advances discussed above, and although forecasters are more aware of the combination of wind shear and dry air, the potential effects of large-scale atmospheric flow/TC interaction can be difficult to accurately quantify (Courtney, Kucas, pers. comm. 2014). While there is confidence in interpreting the broad scale conditions, it is not clear how they may change the intensity because of the differing responses models can have with similar representations of external factors such as the wind shear. For example, models may treat the approach of a deep mid-latitude trough consistently and intensify a circulation - that lies in an area of anomalous upper-level divergence - but the timing of the peak intensity and the change to weakening under increased wind shear - as the TC circulation moves under the jet stream - can vary. Shieh et al. (2013) insisted on the importance of correctly capturing the structure of an upper-tropospheric trough and the associated diffluence/divergence magnitude, especially as the interaction alters both the trough and TC structures and intensities. Shortcomings in model forecasts of such structures contributed to large errors in predicting the explosive deepening of Typhoon Vicente (2012). The authors are developing an objective TUTT cells tracker that will help quantify the nature of TC-trough interactions.

Interpreting environmental wind shear remains a key forecasting challenge. It is not always clear what the effective shear on the circulation actually is because it is difficult to discern the environment from the circulation, or because the circulation is affecting the environmental flow which varies considerably at the periphery of the circulation (Courtney, pers. comm. 2014). The 'environment' of small circulations is especially difficult to quantify and contributes to intensity forecast challenges.

Forecasters widely feel unequipped to deal with situations when some factors may favor development (or intensification) and others may oppose them. In particular, **it is not known how quickly a TC may intensify or weaken as it interacts with TUTTs of various magnitudes and storm-relative positions (Kucas, pers. comm. 2014)**. Forecasters also wish they could verify the Dvorak approach to determine how good it really is compared to objective intensity aids which are more easily verified. **Combining** one’s **subjective initial estimate of intensity with objective guidance** - **if one knew the best way to do so** - would also probably benefit future intensity forecasts (Courtney, pers. comm. 2014).

### 2.5.2 Surface impacts on TC intensity

Following conventional wisdom, weakening TCs in the WNP exhibit lower SSTs than strengthening cases (Shu et al. 2014). A major breakthrough since the last IWTC meeting is that changes in the SST field near the TC can be as important as the absolute value of SST. It has indeed been shown that upper-ocean stratification can modulate surface cooling induced by vertical mixing underneath TCs by up to one order of magnitude (Vincent et al. 2012). In the Bay of Bengal for example, surface cooling induced by TCs is about three times larger during the pre-monsoon than during the post-monsoon season due to seasonal changes in oceanic stratification rather than to differences in TC wind energy input (Neetu et al. 2012). Greater cooling rates increase the likelihood of TC decay while higher values of OHC lead to less TC-induced cooling and thus greater frequency of intensification (Lloyd and Vecchi 2011).

The potential impact of SST on internal storm structure is also sometimes considered at the JTWC, most notably for intense cyclones that could transition to an annular structure as external influences – SST and easterly flow aloft – favor the transition (Kucas, pers. comm. 2014).

When cyclones pass over particularly warm and moist land surfaces, most notably areas across northern Australia, the intensity forecast now typically reflects a much slower or no weakening trend (Kucas, Courtney, pers. comm. 2014) following the work of Emanuel et al. (2008) highlighted at the last IWTC meeting. By providing increased frictional inflow into the circulation, land proximity may have assisted the development of a weak circulation into an unnamed TC in March 2014 as it straddled the coastline off northern Australia.

### 2.5.3 Shear impacts on TC intensity

The generally negative control of ventilation on intensification has been statistically confirmed for hurricanes over the North Atlantic and WNP during the 1981–2008 period (Zeng et al. 2010; Wang et al. 2014), while new studies of TC intensity change in vertically-sheared environmental flow have further explored the mean dynamics of sheared TCs.

Dynamical effects imposed by the VWS on TC structure and intensity were further examined from idealized numerical experiments (Xu and Wang 2013). Results show that unbalanced processes play important roles in the initial development of asymmetric vertical motion and horizontal relative flow for a vertically-sheared TC. The shear-induced vertical motion depends not only on the shear magnitude but also on storm intensity and is confined in the eyewall, which acts as a material wall or the outside of a vessel (Willoughby 1998), leading to the development of convergence/divergence and downdraft/updraft along the outer edge of the eyewall upshear/downshear. Results further demonstrate that the asymmetric divergent winds produce a vertical shear in the inner core region in the opposite direction, but of similar magnitude, to the imposed environmental vertical shear, which helps reduce the vertical tilt of the storm axis. The divergent wind outside the eyewall, however, generally increases the environmental vertical shear. Also, asymmetric eddy angular momentum transport is shown to be responsible for the top-down weakening of the simulated storm in vertical shear.

With respect to the thermodynamic effects of VWS, the robustness of the low-level ventilation framework proposed by Riemer et al. (2010) was verified using more realistic numerical simulations (Riemer et al. 2013). The basic structural and intensity responses of the TC in shear are reproduced, including the relationship between convective downdrafts and the depression of moist entropy outside the eyewall, and the correlation between the moist entropy depression underneath the eyewall and the subsequent weakening of the TC. Riemer and Montgomery (2011) also pointed out that the parcel trajectories of steady flow may permit environmental air to entrain into the inner core in the limit of strong shear and weak vortex intensity. Conversely, the inner core of mature TCs in an average-shear environment is generally protected from intrusions of environmental air; in such cases, low-entropy air intrusion requires time-dependent and/or vertical motions.

Gu et al. (2014) suggested a **new path for VWS effect on TC intensity: upward flux of high-entropy air,** associated with shear-induced updraft from the boundary layer outside the eyewall into mid levels, can weaken the radial gradient of moist entropy across the eyewall, and thus weaken the storm.

The sensitivity of intensity change to the vertical location of ventilation was also underlined in the context of an axisymmetric numerical model with parameterized ventilation (Tang and Emanuel, 2012b). The greatest impact on intensity occurs when the ventilation is placed at middle to lower levels; ventilation at upper levels has little impact on intensity. Low-level shear computed between 850 hPa and 10 m was indeed found to have more impact on TC intensification than the commonly analyzed 200-850-hPa shear over the WNP in the 2000-2006 period (Shu et al. 2013). In the same basin but over the 1981-2010 period, Wang et al. (2014) found that the shear between 700 hPa (or 850 hPa) and 1000 hPa averaged in the annulus between 5-9 degree latitudes from the TC center has the highest correlation with the 24-h lagged TC intensity change. Surprisingly, the low-level shear is no longer important when a similar analysis is conducted over the North Atlantic, suggesting that the VWS effect is basin-dependent**, a result of differences in other environmental conditions which need to be investigated in future studies** (Wang, pers. comm. 2014). Over the North Atlantic, the statistical analysis of Zeng et al. (2010) indicates that VWS in a deep layer affects the strong, slow moving, and low latitude (south of 35$^{o}$N) hurricanes while the weak, fast moving, and high latitude (north of 35$^{o}$N) hurricanes are rather impacted by VWS in the mid-lower troposphere. The consistency of these results is not surprising since the depth of the layer in which VWS affects TC intensity is likely to be dependent on the storm vertical extension (as for the depth of the steering flow layer impacting the storm track).

Studies have started to examine the methodology used to compute VWS because the traditional two-level approach seems oversimplified when the effect of VWS on TC intensity change is concerned (Velden et al. 2014, Zeng et al. 2010, Wang et al. 2014). Velden et al. (2014) advocates to derive the deep-tropospheric wind shear from two mass-weighted layer-mean wind fields; one upper-tropospheric and one lower-tropospheric, as routinely produced by the CIMSS. While this new method seems more physically based, the linear negative correlation coefficients of lagged TC intensity change with shear still only explain a small portion of the variance (about 30%) for North Atlantic TCs, as in Zeng et al. (2010). This implies a possible need for a VWS diagnostic that would take into account the total vertical profile of the ambient wind in order to include both the dynamical and thermodynamic effects of shear on TC intensity change. Upper tropospheric shear is indeed expected to play a more important role than low-level shear on the ventilation of the warm core while it might have a relatively weaker effect on mid-level ventilation (Wang, pers. comm. 2014).

The direction of shear was found to play a role in TC intensity change as well. Overall easterly shear, especially in the mid-lower troposphere, has considerably weaker effects than westerly shear because part of the easterly shear could be offset by the beta-induced northwesterly shear (Zeng et al. 2010). Furthermore, westerly vertical shear appears to promote the intrusion of dry environmental air in weakening TCs over the WNP (Shu et al. 2014). NCEP reanalysis data from 41 Atlantic storms also exhibited significantly stronger VWS associated with stronger westerly winds above weakening storms (Braun 2010).

Finally, the timing and rate of TC intensification can be significantly affected by the environmental shear. The latter influences the spatial distribution of convection and subsequently changes the positive feedback between diabatic heating and the TC vortex primary circulation. This result was demonstrated with a series of convection-permitting ensemble simulations (Tao and Zhang 2014a, b). Except for the initial spin-up periods, the larger the vertical wind shear, the farther and weaker the convection from the TC center, which leads to a weakening TC vortex circulation and more time for the onset of RI.

Nevertheless, intensification cases under shear forcing continue to be reported. Molinari and Vollaro (2010) noted that the RI of Tropical Storm Gabrielle (2001) likely occurred because of the vertical wind shear rather than in spite of it. The role of shear was to promote downshear redevelopment of a new circulation; it was the vertical shearing of this new circulation that led to conditions favorable for the growth of an inner-core deep convective cell that preceded RI. Nguyen and Molinari (2012) also observed a shear- and motion-induced convective asymmetry that preceded the rapid intensification of Hurricane Irene (1999). As in the Gabrielle case, convection focused radially inside the maximum winds, a location where heating most effectively intensifies the vortex (Nolan et al. 2007; Vigh and Schubert 2009; Rogers et al. 2013b). **What governs the radial distribution of convection in sheared storms remains an area of active research**. They furthermore speculated that the negative impacts of convective downdrafts following Riemer et al.

(2010, 2013) might have been offset by enhanced enthalpy fluxes from the ocean. In a study of Tropical Storm Edouard (2002), Molinari et al. (2013) again highlighted this competition between the weakening influence of ventilation through downward transport of low-entropy air into the boundary layer by convective downdrafts and the intensifying role of surface heat and moisture fluxes.

It is well recognized that the shear-induced intensity change hypotheses still have not been adequately tested with observations (Reasor, pers. comm. 2014). A plan for thorough testing of these hypotheses has been developed at the Hurricane Research Division of NOAA's Atlantic Oceanographic and Meteorological Laboratory as part of the overarching Intensity Forecasting EXperiment (IFEX; Rogers et al. 2013a). The purpose of the TC in shear Experiment (http://www.aoml.noaa.gov/hrd/HFP2014/HFP_2014.pdf) is to sample the TC during distinct phases of its interaction with vertical wind shear, and to measure kinematic and thermodynamic fields with the azimuthal and radial coverage necessary to test the hypotheses. The experiment utilizes in-storm measurements that are focused on dense observations of vortex-scale thermodynamic structure outside the eyewall combined with simultaneous near-storm (environmental) measurements.

### 2.5.4 Relative humidity / aerosols impacts on TC intensity

The potential negative influences of dry air at low and mid levels on TC development and intensification is another active area of research. Dry air sensitivity experiments confirm that the reduction in environmental moisture content eventually leads to weakened convection and delayed or failed precession in the latter stages if the TC forms at all (Tao and Zhang 2014a, b). They also reveal that a tilted TC is more vulnerable to impacts from a drier environment than a less tilted vortex. In the presence of moderate shear, the dry air is able to penetrate the TC core and wrap around the center, therefore preventing further development (Zhang, Tao, pers. comm. 2014). This process contributed to the failure of TC intensification in some ensemble members of Tropical Storm Erika (2009) (Munsellet al., 2013) penetrated by deep-layer shear-induced dry air (Figure 4). In low-sheared environments, idealized simulations with no mean flow (Braun et al. 2012) suggested that dry air may slow intensification only when it is located very close to the vortex core at early times. The dry air suppresses convective development where it is entrained into the storm circulation, leading to increasingly asymmetric convection, azimuthally averaged heating at a larger radius, and slower storm development following Nolan et al. (2007) and Vigh and Schubert (2009). The relative location of dry air to the right of the VWS direction (in the northern hemisphere) appears especially detrimental to TC development because this dry air is subsequently advected by the vortex primary circulation to the downshear side and taken into the forced updrafts (idealized experiments of Ge et al. 2013). Overall, **whether dry air can be taken into the updrafts seems the most important process for the dry air intrusion mechanism** (Zhang, Tao, pers. comm. 2014). Braun et al. (2012) further highlighted that the presence of a moist envelope in the inner-core (from the vortex center to a radius of 150 or 75 km) eliminates the deleterious impact of surrounding dry air on storm intensity.

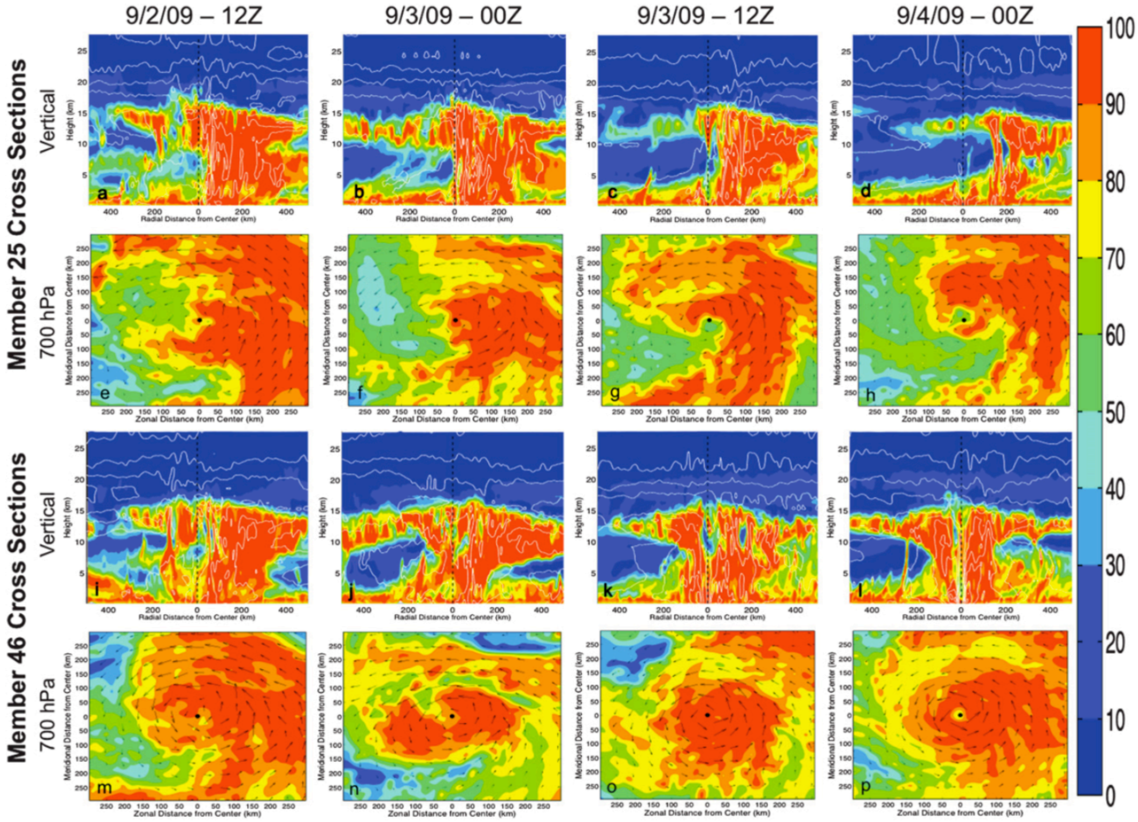


**Figure 4. (First row) Radius–height cross sections of relative humidity (%, shaded) and winds (white lines contoured every 15 kt) in the downshear direction for member 25 every 12 hours from basetime 1200 UTC 2 Sep 2009. Cross sections span a 500-km radius from the surface center. (Second row) Relative humidity (%, shaded) and winds (vectors) at 700hPa for member 25 at the same times around the surface center (black dot). 3rd and 4th row: as in the first two rows but for member 46. Adapted from Figure 13 of Munsell et al. (2013)**

Earlier studies following Dunion and Velden (2004) agreed on the general suppressing influence of the Saharan Air Layer (SAL) in the North Atlantic. Braun (2010) argues that the SAL may indeed slow intensification during the pre-depression to depression stages, but it is not a primary determinant of storm intensity following formation. This hypothesis is verified in three cases with different methodology. Braun et al. (2013a) examines the SAL surrounding Hurricane Helene (2006) using satellite and airborne data as well as global meteorological analyses. Dry air observed to wrap around the periphery of Helene is diagnosed as primarily non-Saharan in origin (the result of subsidence) and appears to have limited impact on storm intensity due to the weak vertical wind shear. The most obvious SAL-related factor to statistically affect intensity in mesoscale ensemble forecasts of Tropical Storm Debby (2006) is dry air above 2 km, which delayed organization of the low-level vortex (Sippel et al. 2011); Warm temperatures within the SAL and shear associated with the African easterly jet exhibit a weak, secondary relationship with forecast intensity variability. An important result is that sensitivity to the dry environmental air depended considerably on cyclone strength, and it became insignificant once a tropical storm formed. A nice illustration is the RI phase of Hurricane Earl (2010) during which the strong cyclonic circulation likely prevented intrusion of the surrounding Saharan dust and dry air into the inner core (Figure 7 of Braun et al. 2013b). With dust remaining in its environment, Earl maintained Category 3-4 intensity for several days, including an eyewall replacement cycle, suggesting a very limited impact of the SAL compared to the hypothesized inhibiting effect of Dunion and Velden (2004).

More and more studies start to examine the separate role of dust, or the indirect effects of aerosols, on TC development and intensification (Carrio et al. 2011, Rosenfeld et al. 2011, Rosenfeld et al. 2012, Cotton et al. 2012, Herbener et al. 2014). The modification of cloud properties via aerosols injected into idealized TCs is hypothesized to initiate interactions between cloud microphysics and storm dynamics that ultimately lead to appreciable changes in the large-scale features of the storm (Herbener et al. 2014): Aerosols introduced at the periphery of a TC with increasing concentration ranging from 100 to 2000 $cm^{-3}$ can impact both storm intensity (up to 17% general increase) and size (up to 16% general decrease).

### 2.5.5 Role of outflow-layer interactions

A primary pathway through which a TC communicates with its surrounding environment is known to be the outflow layer, a region of weak environmental inertial stability (Rappin et al. 2011). Its 3-dimensional structure and dynamics was recently analyzed through observations (Molinari et al. 2014). Results suggest that the central dense overcast (CDO) creates its own distinctive stability profile that strongly influences the distribution of turbulence and the transition to outflow in tropical cyclones. Turbulent layers (with Richardson number less than 0.25) fall into three broad groups: They are located beneath cirrus base (due to the sublimation of precipitation); above cirrus base (related to cloud-top cooling); and at the base of the outflow layer well outside the CDO (in association with large vertical wind shear).

Rossby wave breaking events force storms to interact with their environment and spawn PV coherent structures that can be advected into TCs by the imposed asymmetric radial circulation. These cases have raised interest from the scientific community because of the large forecast errors they cause. Recent studies interestingly highlight that the interaction does not necessarily occur in the outflow layer. PV injection in the mid-upper TC circulation has been demonstrated to be a potential contributor to TC intensification (Leroux et al. 2013, Nguyen-Hankinson, pers. comm. 2014). TC Oswald (2013) is a recent example of a system that made landfall over northeast Australia as a minimal storm and strengthened as it moved southward over land. It is proposed that the interaction between the ex-Oswald circulation and an amplifying Rossby wave, which propagated northeastward from high latitudes, resulted in the extreme 7-day rain event observed (Davidson et al. 2014). As the wave amplified, a potential vorticity anomaly descended to mid levels, moved equatorward, and merged with or axisymmetrized the ex-Oswald circulation through mid levels. Innovative backward trajectories from locations scattered within ex-Oswald's mid-level circulation quantify the injection of high cyclonic PV air from the evolving Rossby wave and illustrate that the ex-Oswald circulation transitioned from an isolated vortex into a circulation which was interacting strongly with its environment for at least 5 days (Figure 5). It is suggested that this not only acted to directly spin up at least the mid-level circulation, but it also provided very favorable conditions for enhanced ascent, convection and rainfall within the circulation, as the heavy rain coincided with the commencement and maintenance of the PV injection (Nguyen-Hankinson, pers. comm. 2014).

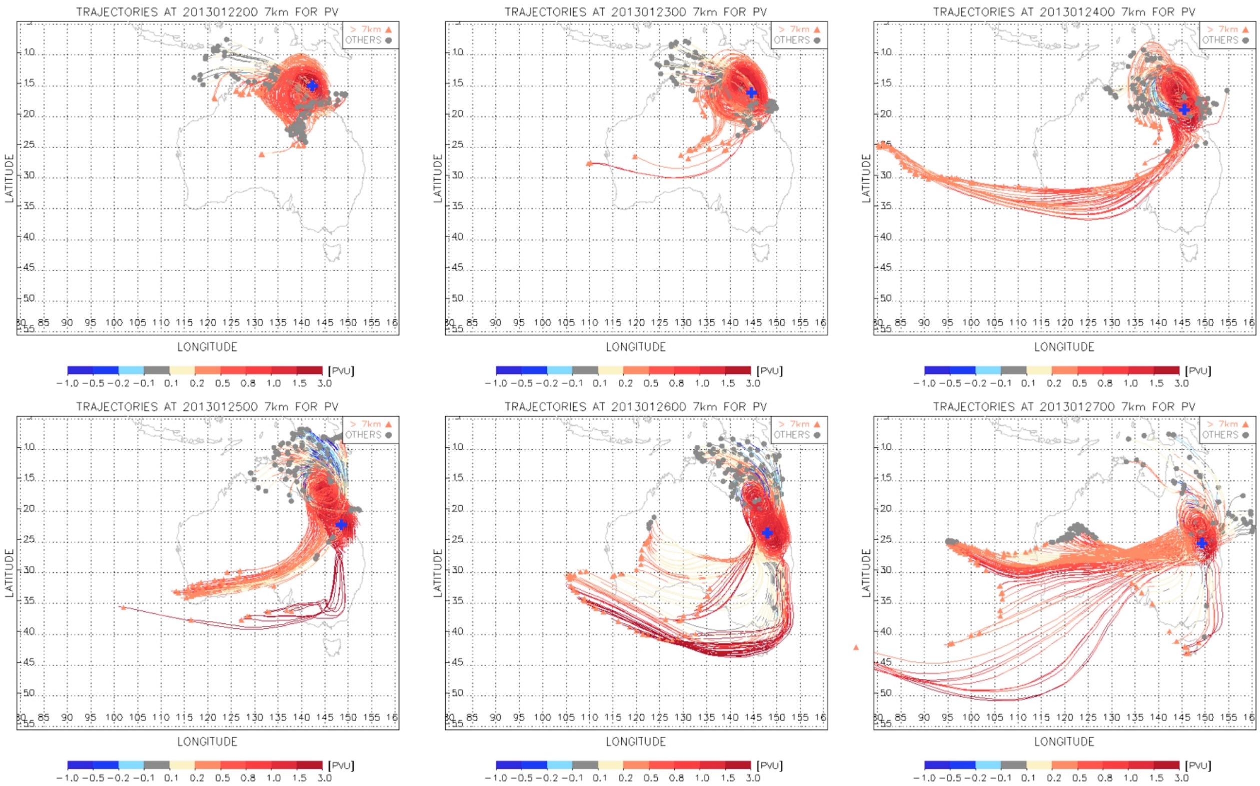


**Figure 5. 3-day back trajectories from ERA-Interim analyses from points scattered through the mid levels of the Oswald circulation. The panels show trajectories from times 24 hours apart and for 6 days starting just prior to and during the heavy rain event (0000 UTC on 21 to 26 January 2013)**

Another case of PV injection that led to the rapid intensification of TC Dora (2007) in the southwest Indian ocean was investigated with a numerical model able to reproduce the main features of the eyewall replacement cycle observed for TC Dora (Leroux et al. 2013). The main mechanisms identified for vortex intensification were PV superposition (associated with angular momentum convergence) in a thick 200-500-hPa layer (Figure 6), followed by secondary eyewall formation induced by eddy angular momentum convergence, eddy PV (or absolute vorticity) fluxes, and dynamically forced upward motion from the trough which contributed to mean and eddy vertical advection of the tangential wind in the outer eyewall. While explaining how an upper-level trough can induce cyclonic spinup over the whole troposphere at outer radii, this study also highlights the role of forced ascents. Finally, it clearly demonstrates that external forcing may excite internal processes within 200 km of the hurricane core, an idea originally speculated by Molinari and Vollaro (1989) and supported by Nong and Emanuel (2003) using an axisymmetric model forced by idealized external eddy angular momentum fluxes. If and how quickly the TC may intensify depending on its initial strength and trough-relative position is the subject of an ongoing study using sensitivity experiments to answer the forecasters' need (Leroux et al. 2014).

So far, no consensus has been reached toward a unified theory or conceptual model for TC–trough interaction, which could provide the forecasters with specific criteria to use or suitable signatures to follow in the various fields produced by a numerical weather prediction system. **More studies are therefore needed to clarify the dynamics behind TC-trough interactions and systematically quantify the potential effects (baroclinicity among others) of large-scale atmospheric flow on TC intensity during such interactions.** Major efforts have already been undertaken in the WNP to develop a first conceptual model regarding TC-TUTT cell interaction but it is designed for operational track guidance only (Patla et al. 2009).

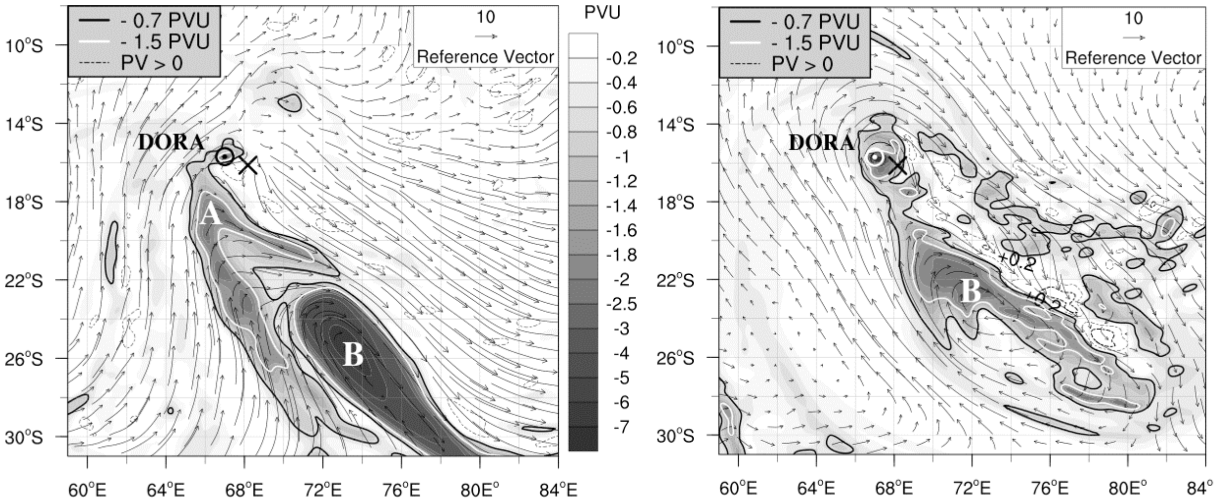


**Figure 6. Wind vectors (arrows) and PV field (negative, shaded with -0.7 and -1.5 PVU contours; positive, 0.2 and 1 PVU dotted contours) at (left) 200 and (right) 400 hPa after 36 h of model integration. Crosses and encircled dots indicate Dora's best-track and predicted centers, respectively. Labels A and B indicate main PV advection from the coherent structure toward TC Dora, illustrating the high equatorward tilt of the trough.**
**Adapted from Figure 7 of Leroux et al. (2013)**

### 2.5.6 Rapid intensification / rapid weakening

Research studies have continued to explore the relevant environmental factors affecting RI. A 9-year composite analysis of Atmospheric Infrared Sounder (AIRS) humidity data in the North Atlantic (Wu et al. 2012) report that free tropospheric environmental relative humidity (ERH) values are more than 10% larger (relative to the averaged ERH for all TCs) in RI events than in weakening TCs; however, the differences between rapidly intensifying and intensifying cases are not statistically significant, consistent with Hendricks et al. (2010). More interestingly, greater intensification rates are associated with stronger radial gradients of RH at upper levels (between 300 and 400 hPa) in the front-right quadrant relative to TC motion. Dynamical work on specific cases of RI (ex: Typhoon Vicente 2012, TC Dora 2007) was also pursued in the context of TC-trough interaction (section 5). Cloud-permitting predictions of Hurricane Wilma (2005) down to 1-km resolution indicated that both the upper-level inertial stability increases and static stability decreases sharply 2–3 h prior to RI, and that the formation of an upper-level warm core, from the subsidence of stratospheric air associated with the detrainment of convective bursts, coincides with the onset of RI (Chen and Zhang 2013).

Conditions conducive to rapid weakening (RW; maximum wind speed decreasing by at least 30 kt in 24 h) were explored over the eastern North Pacific (ENP). RW is much more common in the ENP than in the North Atlantic (33% as opposed to 11%; Figure 7) in part due to the lower areal extent of SSTs at or greater than 26°C (Wood and Ritchie 2014). RW frequency in the ENP is positively correlated with SST anomalies associated with the El Niño-Southern Oscillation (ENSO), likely as a result of stronger (weaker) TCs in El Niño (La Niña) seasons. The strongest contributor to accelerated TC decay appeared to be from decreasing 400-700-hPa relative humidity in the southern part of 33% of all TCs from 1979-2012. In addition, the strongest ENP TCs exhibit the greatest frequency of RW events, implying that ENP TCs cannot maintain high intensities once they leave the conducive genesis environment (Wood and Ritchie 2014).

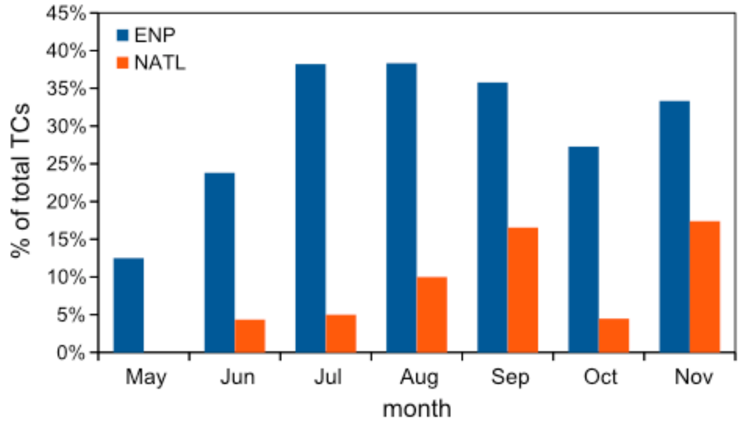

**Figure 7. Percent of all TCs with at least one RW period by month in the ENP (blue) and North Atlantic (orange)**

Over the WNP, TCs drifting between 3 m $s^{-1}$ and 8 m $s^{-1}$ have a relatively higher probability than those with translational speed less than 3 m $s^{-1}$ to intensify rapidly under low shear (e.g. $VWS_{300\text{-}850}$ <11 $ms^{-1}$ and $VWS_{700\text{-}1000}$ <5 m $s^{-1}$), primarily due to weaker negative ocean feedback (Wang et al. 2014). Also, TCs have the highest probability to intensify rapidly and little chance to weaken rapidly when SST is above 29°C, low probability to intensify rapidly when SST is lower than 28°C, and very low probability to intensify when SST is below 27°C (Wang et al. 2014).

### 2.5.7 Predictability of RI

A recent study on the practical predictability of TC intensity using 5-yr forecasts in the Atlantic basin demonstrated that SST and VWS have a greater impact on intensity forecast errors than other thermodynamic environmental parameters such as moisture and instability (Zhang et al. 2014), although in the case of rapidly-intensifying Hurricane Humberto (2007) the variations in mid-level moisture and low-level convective instability were responsible for the storm strength spread in the intensity forecast (Sippel and Zhang 2010). The larger the shear magnitude, the less predictable the onset time of RI and the larger the uncertainty in the intensity forecast (Zhang and Tao, 2013) until the shear magnitude is large enough to prevent TC formation (Figure 8, Tao and Zhang, 2014b). This uncertainty in RI onset is suggested to result from the inherent randomness in moist convection which accumulates at later times and eventually leads to deviations in vortex development. Note that Emanuel et al. (2004), who first argued that environmental wind shear reduces the inherent predictability of storm intensity, cautioned against considering the various environmental influences on storm intensity as operating independently from each other since, for example, in suppressing storm intensity, shear also suppresses ocean feedback.

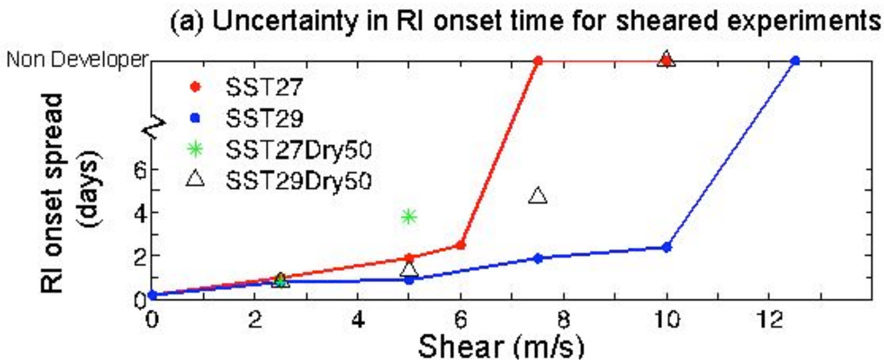

**Figure 8. Uncertainty in RI onset time for all sheared experiments. Adapted from Figure 16 of Tao and Zhang (2014b)**

Predictability is in fact largely dependent on the environment hostility to TC development and on the vortex vulnerability. Under moderate to large vertical wind shear, environmental dry air may have a negative impact on TC predictability (Figure 8, Tao and Zhang, 2014a, b). Besides its influence on cyclogenesis and intensity change, SST also affects the vortex predictability (Tao and Zhang 2014a, b; McGauley and Nolan 2011). Higher SSTs shorten the onset time of RI and increase the VWS magnitude threshold for vortex development (Figure 8). Given the positive feedback between the diabatic heating and the vortex mean circulation, much stronger heat forcing will shorten the precession process, reduce the impact that high-frequency transients such as moist convection have on the RI onset time, and subsequently increases the predictability of RI onset under higher SSTs (Tao and Zhang 2014b).

### 2.5.8 Summary

Though some focus is shifting to the relationships between inner core processes and TC intensity in the research community, the work presented here indicates that continued study of external influences on TC intensity change is merited to better forecast both the timing and magnitude of TC intensification/weakening.

Recent studies demonstrated that the hostility of the environment control both the development and predictability of TCs. The relationship of large-scale environmental conditions with hurricane intensity, particularly RI and RW, was refined or revealed in the western North Pacific, North Atlantic and eastern North Pacific basins. A ventilation index (Tang and Emanuel 2012a) was derived based on the major three environmental factors impacting TC intensity (SST, RH and VWS). Relying on gridded data, this tool may be of potential utility to the research and operational TC communities to assess intensity changes. The radial ERH gradient at upper levels in the front-right quadrant - relative to TC motion - might also be a useful predictor for the statistical forecast of TC intensification in the North Atlantic, as much as the use of a low-level wind shear predictor in the WNP. Continuous work is warranted to improve the methodology used to represent the vertical profile of ambient winds in order to find a universal diagnostic that would best reflect the total effect of VWS on TC intensity change.

Progress has also been made regarding ocean control on TC intensity. The thermal stratification of the near-surface ocean at large scales was pointed out as an important factor for TC intensity that merits further consideration. An improved representation of upper-ocean salinity and temperature effects in statistical and dynamical TC forecasts is advised since it could lead to significant improvements of TC intensity prediction skill (Neetu 2012).

The impact of dry and dusty SAL air on TC development and intensity was suggested to be limited to the earliest stages of development. Research in this area is progressively focusing on the indirect effects of aerosols or cloud microphysics, using increasing numerical model resolution and better parameterizations.

While the injection of cyclonic environmental PV into the mid-level circulation of a TC was highlighted as a potential contributor to vortex intensification, the study case of TC Dora (2007) also demonstrated that external forcing from upper-level troughs or cutoff lows may excite internal processes within 200 km of the hurricane core. Studies generally agreed that external factors (e.g., VWS and SST) impact the development of TCs through influencing the organization of inner core moist convection, which is part of the internal factors. Further addressing these scale interactions should shed light on the complex set of linear and nonlinear interactions between a TC and its environment and lead to refined or extra tools for TC intensity prediction.

The comprehensive map illustrated in Figure 9 summarizes the contents of the report and the state-of-the-art knowledge on the problem of TC intensity change under external influences. Highlighted in red are issues, or knowledge gaps, as well as suitable future research routes to improve the prediction of TC intensity change.

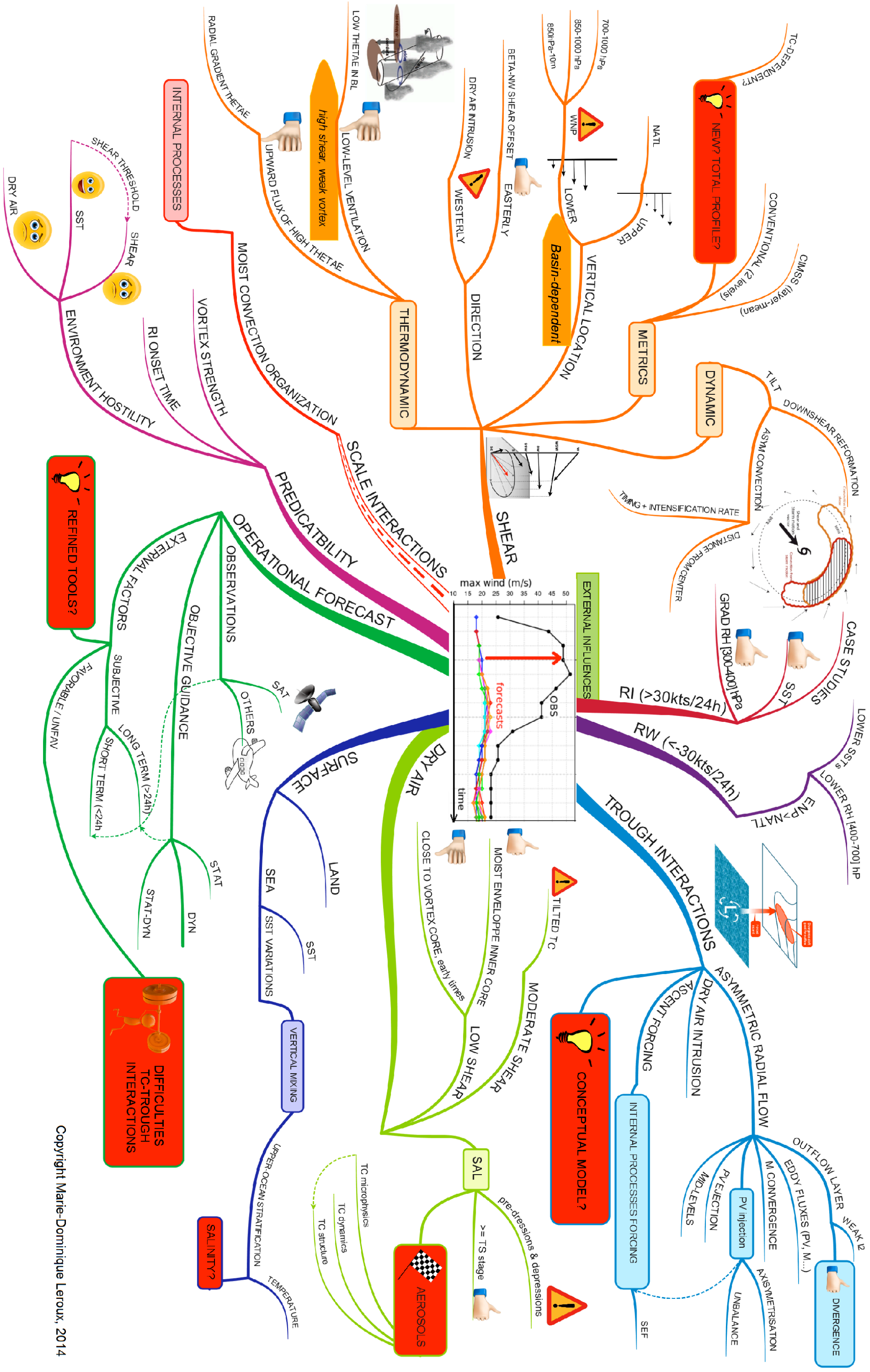


**Figure 9. Comprehensive map on the problem of TC intensity change under external influences (Leroux, pers. contribution)**

**Acronyms used in the report**

| | |
|---|---|
| AIRS | Atmospheric Infrared Sounder |
| BoM | Bureau of Meteorology |
| CDO | Central Dense Overcast |
| CIMSS | Cooperative Institute for Meteorological Satellite Studies (University of Wisconsin-Madison) |
| CMA | China Meteorological Administration |
| COAMPS | Coupled Ocean-Atmosphere Mesoscale Prediction System |
| ECMWF | European Center for Medium range Weather Forecasting |
| ENP | Eastern North Pacific |
| ERH | Environmental Relative Humidity |
| FNMOC | Fleet Numerical Meteorology and Oceanography Center |
| GFDN | Geophysical Fluid Dynamics Model, Navy version |
| GPCE | Goerss Predicted Consensus Error |
| GSM | Global Spectral Model |
| HRD | Hurricane Research Division |
| HWRF | Hurricane Weather Research and Forecasting |
| IFEX | Intensity Forecasting EXperiment |
| IWTC | International Workshop on Tropical Cyclones |
| JMA | Japan Meteorological Agency |
| JTWC | Joint Typhoon Warning Center |
| LGEM | Logistic Growth Equation Model |
| NASA | National Aeronautics and Space Administration |
| NCEP | National Centers for Environmental Prediction |
| NOAA | National Oceanic and Atmospheric Administration |
| NRL | Naval Research Laboratory |
| NWP | Numerical Weather Prediction |
| OHC | Ocean Heat Content |
| PV | Potential Vorticity |
| PVU | Potential Vorticity Unit |
| RH | Relative Humidity |
| RI | Rapid Intensification |
| RW | Rapid Weakening |
| SAL | Saharan Air Layer |
| SHIPS | Statistical Hurricane Intensity Prediction Scheme |
| STIPS | Statistical Typhoon Intensity Prediction System |
| SST | Sea Surface Temperature |
| TC | Tropical Cyclone |
| TUTT | Tropical Upper Tropospheric Trough |
| VWS | Vertical Wind Shear |
| WANI | Weighted Analog Intensity |
| WNP | Western North Pacific |

## References


Braun, S. A., 2010: Re-evaluating the role of the Saharan Air Layer in Atlantic tropical cyclogenesis and evolution. *Mon. Wea. Rev.*, **138**, 2007-2037.

Braun, S. A., J. A. Sippel, and David S. Nolan, 2012: The impact of dry mid-level air on hurricane intensity in idealized simulations with no mean flow. *J. Atmos. Sci.*, **69**, 236-257.

Braun, S. A., J. A. Sippel, C.-L. Shie, and R. A. Boller, 2013a: The evolution and role of the Saharan Air Layer during Hurricane Helene (2006). *Mon. Wea. Rev.*, 141, 4269-4295.

Braun, S. A., and 15 coauthors, 2013b: NASA's Genesis and Rapid Intensification Processes (GRIP) Field Experiment. *Bull. Amer. Meteor. Soc.*, **94**, 345-363.

Bukunt, B., 2014: The Rapid Collapse of Hurricane Felicia (2009) near Hawaii, *31st Conf. on Hurricanes and Tropical Meteorology*, San Diego, CA, Amer. Meteor. Soc.

Carrio, G. G., and W. R. Cotton, 2011: Investigations of aerosol impacts on hurricanes: Virtual seeding flights. Atmos. *Chem.Phys*., **11**, 2557–2567.

Chen, H., and D.-L. Zhang, 2013: On the rapid intensification of Hurricane Wilma (2005). Part II: Convective bursts and the upper-level warm core. *J. Atmos. Sci.*, **70**, 146-162.

Cotton, W. R., G.M. Krall, and G. G. Carrio, 2012: Potential indirect effects of aerosol on tropical cyclone intensity: Convective fluxes and cold-pool activity. *Trop. Cyclone Res. Rev.*, **1**, 293–306.

Davidson, N. E., C. M. Nguyen-Hankinson, M. Reeder, and M.-D. Leroux, 2014. Influence of Amplifying Rossby Waves on Tropical Cyclone Intensity, Structure Change and Rainfall. Preprints, *31st Conf. on Hurricanes and Tropical Meteorology*, San Diego, CA, Amer. Meteor. Soc.

DeMaria, M., 2009: A simplified dynamical system for tropical cyclone intensity prediction. *Mon. Wea. Rev.*, **137**, 68–82.

DeMaria, M., M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531–543.

DeMaria, M., C. R. Sampson, J. A. Knaff, and K. D. Musgrave, 2014: Is Tropical Cyclone Intensity Guidance Improving?. *Bull. Amer. Meteor. Soc.*, **95**, 387–398.

Dunion, J.P. and C.S. Velden, 2004: The impact of the Saharan air layer on Atlantic tropical cyclone activity, *Bull. Amer. Meteor. Soc.*, **85**, 353-365.

Elsberry, R., and H.-C. Tsai, 2014: Situation-dependent intensity skill metric and intensity spread guidance for western North Pacific tropical cyclones. *Asia-Pacific Journal Atmos. Sci.* , **50**, 297-306.

Emanuel, K., C. DesAutels, C. Holloway, and R. Korty, 2004: Environmental control of tropical cyclone intensity. *J. Atmos. Sci.*, **61**, 843–858.

Emanuel, K., J. Callaghan, and P. Otto, 2008: A hypothesis for the redevelopment of warm-core cyclones over Northern Australia. *Mon. Wea. Rev.*, **136**, 3863–3872.

Ge, X., T. Li, M. Peng, 2013: Effects of Vertical Shears and Midlevel Dry Air on Tropical Cyclone Developments. *J. Atmos. Sci*., **70**, 3859–3875.

Goerss, J. S. and C. R. Sampson, 2014: Prediction of consensus tropical cyclone intensity forecast error. *Wea. Forecasting*, **29**, 750–762.

Gu, J. F., Z.-M. Tan, X. Qiu, 2014: Effects of vertical wind shear on inner-core thermodynamics of an idealized simulated tropical cyclone. *J. Atmos. Sci.*, (in press).

Hendricks, E. A., M. S. Peng, B. Fu, and T. Li, 2010: Quantifying environmental control on tropical cyclone intensity change. *Mon. Wea. Rev.*, **138**, 3243-3271.

Herbener, S. R., S. C. van den Heever, G. G. Carrio, S. M. Saleeby, and W. R. Cotton, 2014: Aerosol indirect effects on idealized tropical cyclone dynamics. *J. Atmos. Sci.*, **71**, 2040-2055.

Kieper, M., and H. Jiang, 2012: Predicting tropical cyclone rapid intensification using the 37 GHz ring pattern identified from passive microwave measurements. *Geophys. Res. Lett.,* **39**, L13804.

Knaff, J. A., C. R. Sampson, and M. DeMaria, 2005: An operational Statistical Typhoon Intensity Prediction Scheme for the western North Pacific. *Wea. Forecasting*, **20**, 688–699.

Kucas, M.E. and J.W.E. Darlow, 2012: A subjective method for assessing tropical cyclogenesis at the Joint Typhoon Warning Center. *Tropical Cyclone Research and Review*, **1**, 325-330.

Leroux, M.-D., M. Plu, D. Barbary, F. Roux, and P. Arbogast, 2013: Dynamical and physical processes leading to tropical cyclone intensification under upper-level trough forcing, *J. Atmos. Sci.*, **70**, 2547-2565.

Leroux, M.-D., M. Plu, F. Roux, 2014: On the sensitivity of TC intensification under upper-level trough forcing. Preprints, *31st Conf. on Hurricanes and Tropical Meteorology*, San Diego, CA, Amer. Meteor. Soc.

Lloyd, I. D., and G. A. Vecchi, 2011: Observational Evidence for Oceanic Controls on Hurricane Intensity. *J. Climate*, **24**, 1138–1153.

McGauley, M. G., and D. S. Nolan, 2011: Measuring environmental favorability for tropical cyclogenesis by statistical analysis of threshold parameters. *J. Climate*, **24**, 5968–5997.

Molinari, J., and D. Vollaro, 1989: External influences on hurricane intensity. Part I: Outflow layer eddy momentum fluxes. *J. Atmos. Sci.*, **46**, 1093–1105.

Molinari, J., and D. Vollaro, 2010: Rapid Intensification of a Sheared Tropical Storm. *Mon. Wea. Rev.*, **138**, 3869–3885.

Molinari, J., J. Frank, and D. Vollaro, 2013: Convective Bursts, Downdraft Cooling, and Boundary Layer Recovery in a Sheared Tropical Storm. *Mon. Wea. Rev.*, **141**, 1048–1060.

Munsell, E. B., F. Zhang, and D. P. Stern, 2013: Predictability and dynamics of a non-intensifying tropical storm: Erika (2009). *J. Atmos. Sci.*, **70**, 2505-2524.

Neetu, S., M. Lengaigne, E. M. Vincent, J. Vialard, G. Madec, G. Samson, M. R. Ramesh Kumar, and F. Durand (2012), Influence of upper-ocean stratification on tropical cyclone-induced surface cooling in the Bay of Bengal, *J. Geophys. Res.*, **117**, C12020, doi:10.1029/2012JC008433.

Nguyen, L. T. and J. Molinari, 2012: Rapid Intensification of a Sheared, Fast-Moving Hurricane over the Gulf Stream. *Mon. Wea. Rev.*, **140**, 3361–3378.

Nolan, D. S., Y. Moon, and D. P. Stern, 2007: Tropical Cyclone Intensification from Asymmetric Convection: Energetics and Efficiency. *J. Atmos. Sci.*, **64**, 3377–3405.

Nong, S., and K. Emanuel, 2003: A numerical study of the genesis of concentric eyewalls in hurricanes. *Quart. J. Roy. Meteor. Soc.*, **129**, 3323–3338.

Patla, J. E., D. Stevens, and G. M. Barnes, 2009: A Conceptual Model for the Influence of TUTT Cells on Tropical Cyclone Motion in the Northwest Pacific Ocean. *Wea. Forecasting*, **24**, 1215–1235.

Rappin, E. D., M. C. Morgan, and G. J. Tripoli, 2011: The impact of outflow environment on tropical cyclone intensification and structure. *J. Atmos. Sci.*, **68**, 177–194.

Riemer, M. and M. T. Montgomery, 2011: Simple kinematic models for the environmental interaction of tropical cyclones in vertical wind shear. *Atmos. Chem. Phys.*, **11**, 9395-9414.

Riemer, M., M. T. Montgomery, and M. E. Nicholls, 2010: A new paradigm for intensity modification of tropical cyclones: Thermodynamic impact of vertical wind shear on the inflow layer. *Atmos. Chem. Phys.*, **10**, 3163-3188.

Riemer, M., M. T. Montgomery, and M. E. Nicholls, 2013: Further examination of the thermodynamic modification of the inflow layer of tropical cyclones by vertical wind shear. *Atmos. Chem. Phys.*, **13**, 327-346.

Rogers, R., and Coauthors, 2013a: NOAA's Hurricane Intensity Forecasting Experiment (IFEX):A progress report. *Bull. Amer. Meteor. Soc.*, 94, 859–882.

Rogers, R., P. Reasor, and S. Lorsolo, 2013b: Airborne Doppler Observations of the Inner-Core Structural Differences between Intensifying and Steady-State Tropical Cyclones. *Mon. Wea. Rev.*, **141**, 2970–2991.

Rosenfeld, D., M. Clavner, and R. Nirel, 2011: Pollution and dust aerosols modulating tropical cyclone intensities. *J. Atmos. Res.*, **102**,66–76.

Rosenfeld, D., W. L. Woodley, A. Khain, W. R. Cotton, G. G. Carrio, I. Ginnis, and J. H. Golden, 2012: Aerosol effects on microstructure and intensity of tropical cyclones. *Bull. Amer. Meteor. Soc.*, **93**, 987–1001.

Shieh, O. H., M. Fiorino, M. E. Kucas, and B. Wang, 2013: Extreme rapid intensification of Typhoon Vicente (2012) in the South China Sea. *Wea. Forecasting*, **28**, 1578–1587.

Shu, S., Y. Wang, and L. Bai, 2013: Insight into the role of lower-layer vertical wind shear in tropical cyclone intensification over the western North Pacific. *Acta Meteor. Sinica*, **27**, 356-363.

Shu, S., F. Zhang, J. Ming, and Y. Wang, 2014: Environmental Influences on the Intensity Changes of Tropical Cyclones over the Western North Pacific. *Atmos. Chem. Phys*, **14**, 6329–6342.

Simpson, R. H., and H. Riehl, 1958: Mid-tropospheric ventilation as a constraint on hurricane

development and maintenance. Technical Conf. on Hurricanes, Amer. Meteor. Soc., D4-10.

Sippel, J. A., and F. Zhang, 2010: Factors affecting the predictability of hurricane Humberto (2007). *J. Atmos. Sci.*, **67**, 1759-1778.

Sippel, J. A., S. A. Braun, and C.-L. Shie, 2011: An ensemble analysis of environmental influences on the strength of Tropical Storm Debby (2006). *J. Atmos. Sci.*, **68**, 2557-2581.

Tang, B., and K. Emanuel, 2010: Midlevel Ventilation's Constraint on Tropical Cyclone Intensity. *J. Atmos. Sci.*, **67**, 1817–1830.

Tang, B., and K. Emanuel, 2012a: A Ventilation Index for Tropical Cyclones. *Bull. Amer. Meteor. Soc.*, **93**, 1901–1912.

Tang, B., and K. Emanuel, 2012b: Sensitivity of Tropical Cyclone Intensity to Ventilation in an Axisymmetric Model. *J. Atmos. Sci.*, **69**, 2394–2413.

Tao, D., and F. Zhang, 2014a, Effect of environmental shear, sea-surface temperature, and ambient moisture on the formation and predictability of tropical cyclones: An ensemble-mean perspective. *J. Adv. Model. Earth Syst.*, **6**, 384–404

Tao, D., and F. Zhang, 2014b: Effect of environmental shear, sea-surface temperature and ambient moisture on the formation and predictability of tropical cyclones: ensemble sensitivity and intrinsic error growth dynamics. *Quart. J. Roy. Meteor. Soc.*, submitted.

Velden, C. S., and J. Sears, 2014: Computing deep-tropospheric vertical wind shear analyses for tropical cyclone applications: Does the methodology matter? *Wea. Forecasting*, (in press).

Vigh, J. L. and W. H. Schubert, 2009 : Rapid Development of the Tropical Cyclone Warm Core. *J. Atmos. Sci.*, **66**, 3335–3350.

Vincent, E. M., M. Lengaigne, G. Madec, J. Vialard, G. Samson, N. C. Jourdain, C. E. Menkes, and S. Jullien (2012), Processes setting the characteristics of sea surface cooling induced by tropical cyclones, *J. Geophys. Res.*, **117**, C02020, doi:10.1029/2011JC007396.

Wang, Y., Y. Rao, and Z.-M. Tan, 2014: A statistical analysis of vertical wind shear effect on tropical cyclone intensity change over the western North Pacific. *Mon. Wea. Rev.*, (submitted).

Wood, K. M. and E. A. Ritchie, 2014: Large-scale moisture and thermodynamic properties associated with rapid weakening in the eastern North Pacific. Preprints, *31st Conf. on Hurricanes and Tropical Meteorology*, San Diego, CA, Amer. Meteor. Soc.

Wu, L., H. Su, R. G. Fovell, B. Wang, J. T. Shen, B. H. Kahn, S. M. Hristova-Veleva, B. H. Lambrigtsen, E. J. Fetzer, and J. H. Jiang, 2012: Relationship of environmental relative humidity with North Atlantic tropical cyclone intensity and intensification rate. *Geophys. Res. Lett.*, **39**, L20809.

Xu, Y.-M., and Y. Wang, 2013: On the initial development of asymmetric vertical motion and horizontal relative flow in a mature tropical cyclone embedded in environmental vertical shear. *J. Atmos. Sci.*, **70**, 3471–3491.

Yu, Hui, Peiyan Chen, Qingqing Li, and Bi Tang, 2013: Current Capability of Operational Numerical Models in Predicting Tropical Cyclone Intensity in the Western North Pacific. *Wea. Forecasting*, **28**, 353–367.

Zeng, Z.-H., Y. Wang, and L. Chen, 2010: A statistical analysis of vertical shear effect on tropical cyclone intensity change in the North Atlantic, *Geophys. Res. Lett.*, **37**, L02802.

Zhang, F., and D. Tao, 2013: Effects of vertical wind shear on the predictability of tropical cyclones. *J. Atmos. Sci*, **70**, 975-983.

Zhang, Y. J., Z. Meng, Y. Weng, and F. Zhang, 2014: Predictability of Tropical Cyclone Intensity Evaluated through 5-year Forecasts with a Convection-permitting Regional-scale Model in the Atlantic Basin. *Wea. Forecasting*, accepted.