CHAPTER 14. TROPICAL CYCLONE INTENSIFICATION: PREDICTION AND MECHANISMS

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Abstract

Presentations related to tropical cyclones at the World Weather Open Science Conference (WWOSC-2014), Montreal, Canada, 16-21 August 2014 focused on the problems of tropical cyclone intensity prediction, including the prediction of tropical cyclone formation. Observational studies presented revealed the importance of the spatial distribution of convection more than its intensity in determining genesis and intensification. Both environmental and convective-scale perspectives on the importance of vertical shear, surface entropy flux and convection organization revealed the complexity of intensity change process and why probabilistic intensity prediction is essential. Finally, the forefront of intraseasonal (and longer) prediction of tropical cyclone was shown to contain windows of opportunity, but advancement is still impeded by model error.

14.1 INTRODUCTION

In this chapter, we explore the subject of tropical cyclone (TC) intensity change based on the recent work presented at the WWOSC-2014 (http://wwosc2014.org/).Tropical cyclone intensity generally refers to the maximum sustained (one minute or ten minute) wind at 10 m elevation. This parameter is notoriously difficult to predict, especially in cases of rapid intensification, defined as an increase in the maximum winds of 30 knots or greater in 24 hours. The hazard posed by a TC undergoing rapid intensification before landfall is exemplified by the case of Super-typhoon Haiyan in 2013. Many of the factors affecting TC intensity have been identified, but some conditions may still be unknown, especially those responsible for rapid intensity change. Similarly, while environmental conditions favouring TC formation and intensification are generally recognized, the mesoscale details, including the essential behaviour of convection, are still not clear. The work presented at the conference, collectively suggests that, in addition to high ocean heat content and weak vertical wind shear, the coverage and radial location of convection are more important than the intensity of convection for determining rapid intensification. The coverage of deep convection is closely related to enhanced tropospheric relative humidity. Furthermore, predictive skill for tropical waves and intraseasonal oscillations appears to have increased, as have the advances in convective scale models. However, the intensification of weak disturbances in moderate vertical shear appears inherently unpredictable.

14.2 MECHANISMS OF TC FORMATION AND INTENSIFICATION DEDUCED FROM OBSERVATIONS

14.2.1 Large-scale aspects

While we typically think of large-scale conditions as determining whether or not a cyclone will occur or where it will track, rather than details about its intensity, there is an important link between intensity and the large-scale. It is widely believed that TCs will reach extreme intensity, at least to their maximum potential intensity (MPI) (Emanuel 2003), or greater (Bell and Montgomery 2008), unless impeded somehow by the environmental conditions in the atmosphere and ocean. Thus, given that both formation and maximum intensity are strongly constrained by environmental parameters, it should not be surprising that environmental parameters also influence hurricane intensity change.

It is well established that equatorial waves generate environments favourable for tropical cyclogenesis. Roundy (WWOSC-2014) used an extended dataset and performed a similar analysis to that of Frank and Roundy (2006). In Figure 1 are shown composites for the Western Pacific several days before genesis. These represent the well-known patterns associated with tropical waves (Kiladis et al. (2009), the Madden-Julian Oscillation (MJO, Figure 1a), and equatorial

Rossby waves (Figure 1b) (mixed Rossby-gravity waves not shown), foremost in the outgoing longwave radiation (OLR) but also in the shear and the surface wind anomalies. As day zero approaches, the negative OLR anomalies become coincident with the TC genesis location (TS symbol). Evidence was shown for the importance of Kelvin waves (Figure 1c). Kelvin-wave modulation of genesis in the Atlantic basin was also found, where it has traditionally been assumed that Kelvin waves had little effect on TC formation.

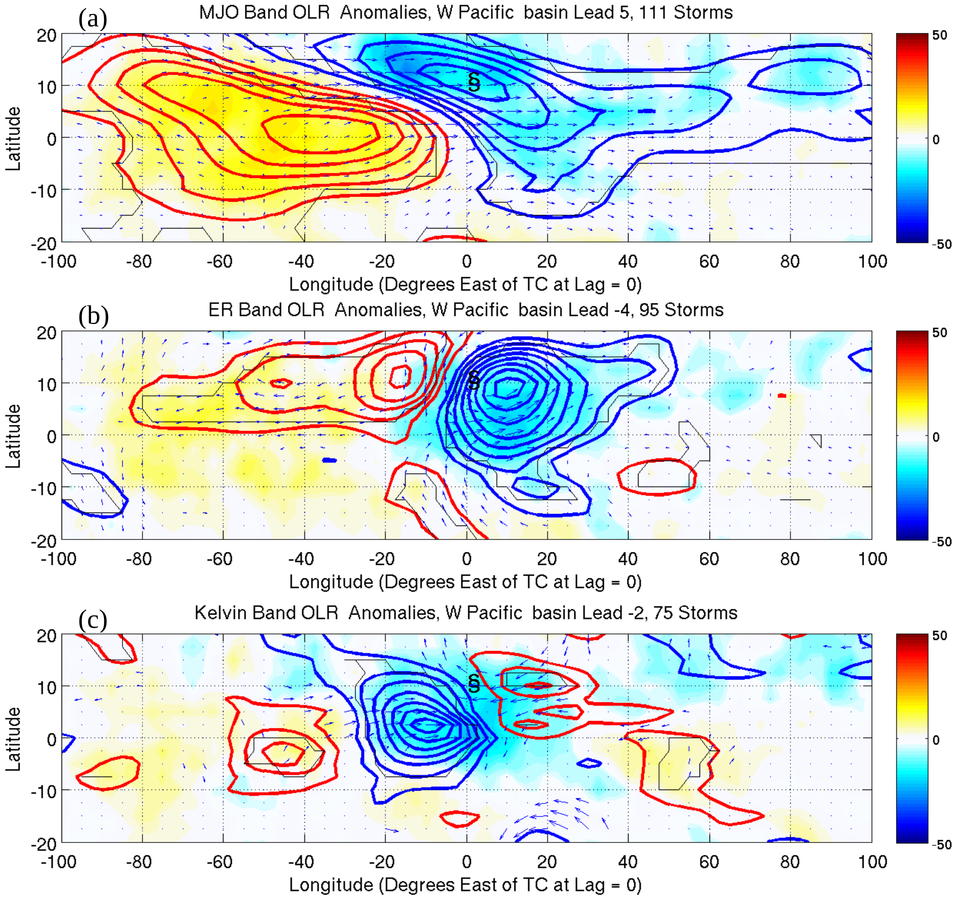

Figure 1. Time lagged composites of unfiltered OLR anomalies (shading, Wm^{-2}) and filtered OLR anomalies (Contours, plotted every 2.5 Wm^{-2} with negative in blue and positive in red, with the zero contour omitted). Composite wind anomalies are plotted at 850 hPa. Composites are based on averaging fields of data shifted to centre on the longitude of the tropical cyclogenesis event located at hurricane symbol. The latitude of the symbol is the mean latitude of genesis over the set of included events. The time lag noted in the title is the number of days since the genesis event.

Source: Adapted from figure provided by Paul Roundy

The Atlantic and Eastern Pacific also feature westward-moving easterly waves that are known to initiate tropical cyclones, albeit with a modest 20% efficiency in the Atlantic (Frank 1970, Dunkerton et al. 2009). It has recently been shown that named storms in the Atlantic and eastern Pacific basins are almost all associated with a cyclonic Kelvin cat’s eye of a tropical easterly wave critical layer, located equatorward of the easterly jet axis (Dunkerton et al. 2009). Based on spatially and temporally filtered fields from the ECMWF ERA-Interim 6 hourly reanalyses for the 1998-2001 hurricane seasons, and idealized barotropic simulations, Asaadi et al. (WWOSC-2014) showed that the nonlinear evolution of instabilities associated with critical layers play a significant role in generating coherent cyclonic vortices with spatio-temporal structures consistent with tropical cyclogenesis analysis.

However, most waves, especially in the Atlantic, feature some vertical wind shear. While it is generally accepted that low shear is more favourable for genesis, it has recently been suggested (Nolan and McGauley 2012) that TC genesis occurs more often in easterly shear whereas, given a favourable thermodynamic environment and easterly surface winds, their numerical simulations indicated that westerly shear is more favourable than easterly shear. Galarneau and Davis (WWOSC-2014) used the ERA Interim reanalysis and the Hodges tracking algorithm (Hodges 1995, 1999) to identify developing and non-developing disturbances in the four basins of the Northern Hemisphere. Tracking was applied to the 800–5000 km band-pass filtered 700-hPa relative vorticity field. Maxima in filtered vorticity were tracked above a threshold of 2.0×10^{-5} s^{-1}. Galarneau and Davis stratified the sample to remove dry disturbances that occur frequently in westerly shear by requiring the total precipitable water to exceed 50 mm during the 2 days leading up to genesis (or maximum intensity in the case of non-developers). Figure 2 shows the efficiency of genesis in different flow configurations in different basins. Of note is that counter-aligned shear is generally not more favourable than other configurations. But westerly surface winds and easterly shear are quite favourable in the Pacific, and very unfavourable in the Atlantic. At higher latitudes and over the western Atlantic, westerly shear and easterly surface winds are particularly favourable and it appears that the left-of-shear- maximum in surface latent heat fluxes contributes substantially to developing cases.

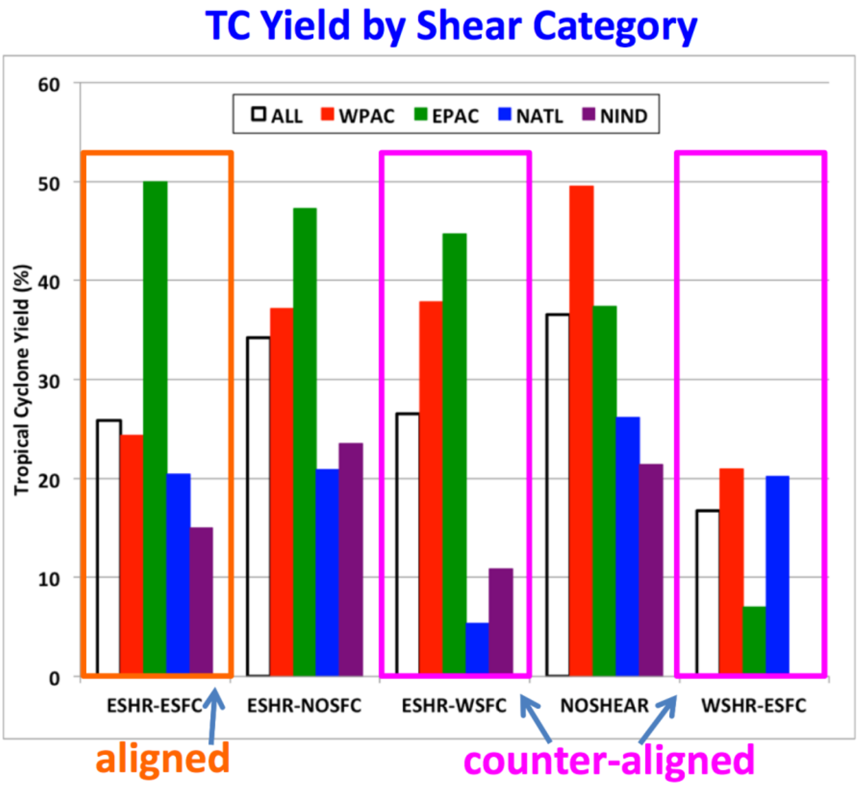

Figure 2. Histograms of the yield of tropical cyclones in each basin, defined as the number of tropical cyclones divided by the total number of tracked disturbances. White bars: total for each flow configuration; red for Western Pacific; green for Eastern Pacific; blue for Atlantic; and purple for Northern Indian Ocean. ESHR=easterly shear (850-200 hPa) greater than 2.5 m s^{-1}; WSHR=westerly shear; ESFC=easterly surface greater than 1.0 m s^{-1}; NOSFC=surface winds weaker than 1.0 m s^{-1}; NOSHEAR=shear less than 2.5 m s^{-1}. Environmental flows are computed after removal of the vortex.

Source: Adapted from figure provided by Tom Galarneau

Oceanic cyclones exhibiting properties of both tropical and extratropical systems have been categorized as subtropical cyclones (STCs) since the early 1950s. The synoptic-scale characteristics of STCs were examined by Bentley et al. (WWOSC-2014) and found to agree with earlier results (Evans and Guishard 2009; Guishard et al. 2009) concerning the seasonal occurrence and synoptic-scale environment. Of note was that anticyclonic wave breaking, accompanied by a PV streamer plunging as far south as the tropics, was a key for STC formation.

For South Atlantic STCs, in addition to the "PV streamer" genesis, there is also a second region of development downstream of the Andes in years when the Brazil Current extends further southward (Evans and Braun, 2012).

14.2.2 Storm-scale and inner-core aspects

Herein we summarize results concerning aspects of intensity change that involve processes within the storm. As stated by Zipser et al. (WWOSC-2014), “There has been a long-standing debate about the requirements for tropical cyclogenesis, and for rapid intensification of tropical cyclones, once formed. One school of thought, stimulated by the original “hot tower” hypothesis from the Riehl-Malkus era, can be framed as “the more intense the convection, the better”.” Both Zipser et al. (WWOSC-2014) and Davis and Ahijevych (WWOSC-2014) challenged the idea that more intense convection was better for tropical cyclone formation. The former examined 12000 overpasses of tropical cyclones from 16 years of data from the Tropical Rain Measuring Mission (TRMM) satellite. Zipser et al. concluded, “While there is no doubt that intense convection in the eyewall or in rainbands can contribute to deepening, the more important requirement seems to be a greater degree of symmetry in the convection, and in latent heat release in the inner core of the storm.”

Davis and Ahijevych (WWOSC-2014) inferred a similar result from the thermodynamic structure of pre-genesis disturbances in which a mid-tropospheric vortex is accompanied by only marginal convective instability owing to the warm anomaly above the vortex and cool anomaly below. Their conclusion, based on the study of Karl prior to genesis, was that having parcel buoyancy limited in depth would contribute to a “bottom heavy” mass flux profile (Raymond et al. 2011), and would be consistent with a mix of cumulus congestus and deep convection (Wang 2012). There was also evidence of a precession of a weaker surface vortex around the mid-tropospheric vortex that ultimately favoured vertical alignment of a coherent vortex.

For an existing storm, a leading question is what causes rapid intensification (RI) in some cases. While the influence of the synoptic-scale environment is well established, processes operating on scales smaller than the environmental scale also contribute to intensity change (Hendricks et al. 2010). Convection and its role in RI have focused primarily on the role of convective bursts (CBs). The exact role that CBs play has been tied to warming from upper-level subsidence around the periphery of the bursts and to the stretching and subsequent axisymmetrization of low-level vorticity collocated with the updraft in vortical hot towers.

Using composites of airborne Doppler measurements, Rogers et al. (2013) compared the vortex- and convective-scale structure of hurricanes that intensify with those that remain steady-state. On the convective scale, the primary difference was a higher concentration of CBs inside the low-level radius of maximum wind (RMW) for intensifying hurricanes, consistent with the theoretical efficiency with which diabatic heating released within the storm core, where inertial stability is high, is converted into an increase in the kinetic energy of the storm (Vigh and Schubert 2009). Rogers (WWOSC-2014) showed a contrast of two cases: Earl (2010) and Gustav (2008) (Figure 3). Earl was rapidly intensifying at this time, 12 UTC 30 August, whereas Gustav was near a steady intensity at 00 UTC 1 September 2008 (Rogers et al. 2013). It is apparent that CBs in Earl occurred at or within the RMW, whereas many CBs occurred beyond the RMW in Gustav. Furthermore, CBs in Earl were found azimuthally closer to the upshear side of the storm, that is, the intense convection wrapped farther around the vortex. The difference in the radial distribution of CBs is further illustrated in Figure 3c, which shows a peak in CB distribution between 0.75 and 1 x RMW for Earl, and between 1 and 1.25 x RMW for Gustav.

Research on RI has focused on two modes of radial inflow: a deep, relatively weak inflow that converges absolute angular momentum above the boundary layer, where it is conserved; and strong inflow in the lowest 1 km that also converges angular momentum and creates super-gradient flow as the inflowing air converges absolute angular momentum at a rate that exceeds its dissipation to the ocean surface via friction (Montgomery and Smith 2014). The importance of super-gradient flow is that it results in outward acceleration of the radial wind, creating a region of low-level convergence that can potentially lead to primary and secondary eye wall formation

(Huang et al. 2012). An analysis of the structure and forcing of eye wall convection observed during the rapid intensification of Hurricane Rita (2005) from the RAINEX/IFEX field campaign was able to approximately quantify the structure and magnitude of the a-gradient wind (Bell et al. WWOSC-2014). However, the presentation also showed how difficult it is to obtain reliable estimates of the pressure gradient in the boundary layer from aircraft at the usual penetration altitude of 2.5-3 km. This implies that deducing the mechanism of secondary eye wall formation will rely partially on numerical simulations (Section 14.2) provided that such models use boundary layer schemes that are not too diffusive (Montgomery and Smith 2014).

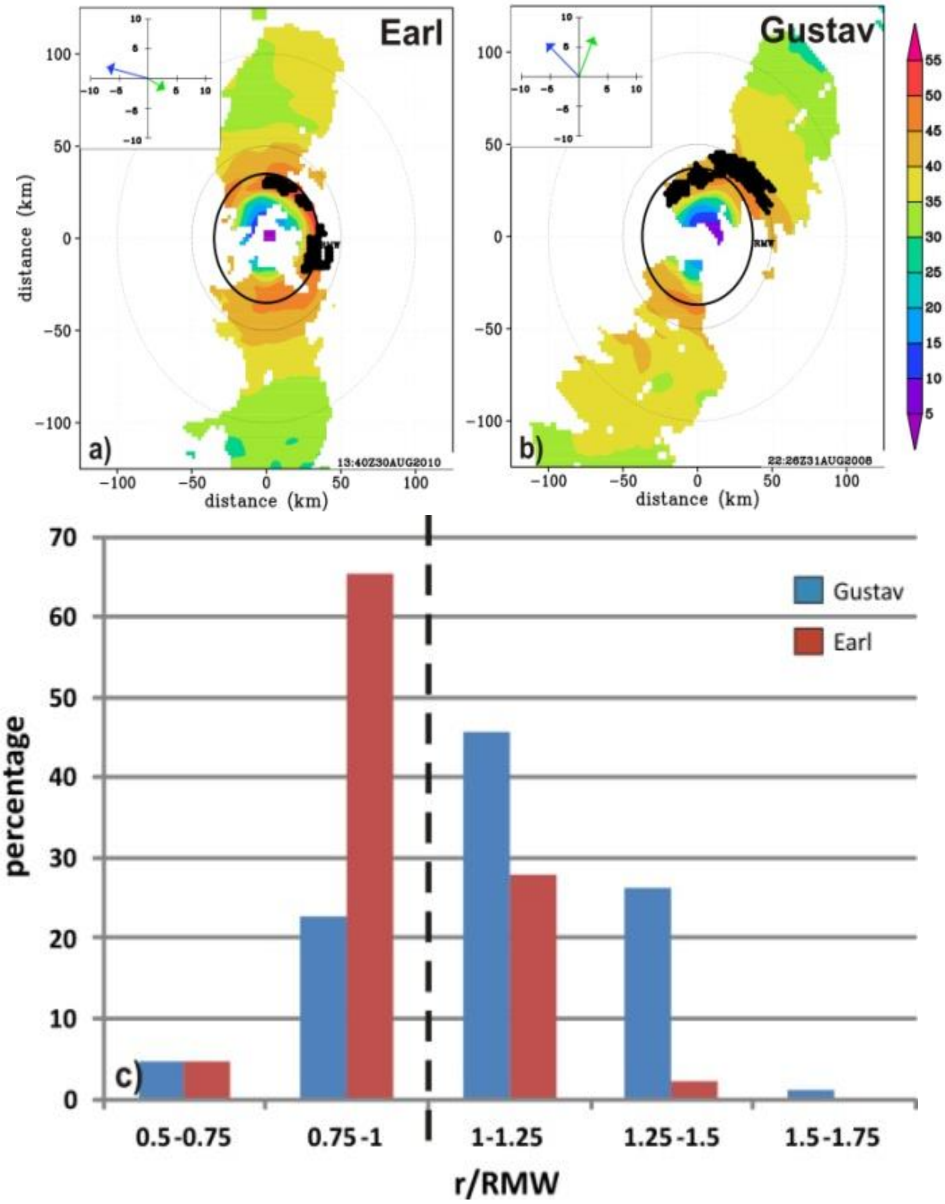

Figure 3. (a) Storm-relative wind speed (shaded, m s^{-1}) at 2 km altitude for pass centred at 1340 UTC from mission 100830H1 in Hurricane Earl; (b) As in (a), but for pass centred at 2226 UTC from mission 100831H1 in Hurricane Gustav; (c) Normalized radial distribution of convective bursts for all passes from the missions in Earl and Gustav from (a) and (b). Dashed line in (c) denotes location of RMW. Insets on (a) and (b) show the Statistical Hurricane Intensity Prediction System (SHIPS)-derived shear vector (green arrow, m s^{-1}) and storm motion vector (blue arrow, m s^{-1}) for the 6 hour time nearest to the mission.

Source: Adapted from figure provided by Robert Rogers

Simultaneously a product of the “environment” and the storm itself is the interaction of the upper ocean to the passage of a tropical cyclone. Over the past two decades, upper ocean impacts on intensity have received considerable attention including the cold wake structure and the negative feedback over quiescent oceans. Persistent western-boundary currents represent deeper mixed layers (higher oceanic heat content) that respond much less to the passage of a TC. During the hurricane Earl case, Jaimes et al. (2015) showed elevated enthalpy fluxes, deduced from more than 500 GPS dropsondes, were aligned with these deeper pools of high OHC just prior to rapid intensification. Shay (WWOSC-2014) and Lin (WWOSC-2014) noted that this trend in the vicinity of the western boundary currents, perhaps coupled with its more rapid translation, was a factor that allowed Haiyan to achieve its remarkable intensity (Lin et al. 2014). With intensity peaked at 170 kts, supertyphoon Haiyan devastated the Philippines in November 2013. In addition to the western boundary-current limit on mixing, Pun et al. (2013) discovered that the region where Haiyan developed has undergone significant subsurface warming. As compared to the early 1990s, upper ocean heat content has increased by 15%. Lin et al. (2013) and Lin (WWOSC-2014) showed that a new ocean coupling potential intensity (OCPI) index accounts for the subsurface ocean condition and can possibly identify the potential for exceptionally intense storms. The new index replaces SST by a pre-cyclone ocean temperature averaged from the surface to the expected depth of the TC-induced mixing. With little interference from unfavourable environmental conditions, including the state of the upper ocean, Haiyan was able to achieve intensity unmatched for a landfalling storm.

In summary, the observational studies presented at the WWOSC-2014 generally described necessary conditions for TC formation and intensification. The examination of environmental factors benefits from having more cases but causality is still difficult to establish. Storm-scale studies benefit from detailed reconnaissance data and an abundance of microwave data, but generally lack the time continuity to resolve the relevant processes. Large uncertainty remains in documenting convective processes, including the spatial distribution of heating (horizontally and vertically) relative to the structure of the vortex, which theory tells us should strongly affect intensity change. As a result, numerical models provide an important framework within which theoretical ideas are evaluated.

14.3 MODELLING OF TC INTENSIFICATION

Intensity changes of tropical cyclones (TCs) remain a significant forecast challenge. One roadblock to improved forecasts is our incomplete understanding of the governing processes. An important environmental contribution to intensity change is vertical shear of the environmental winds. Various shear-related mechanisms have been proposed to explain the deleterious effects of wind shear on storm intensity. These include filamentation of the upper-tropospheric piece of the PV monolith (Frank and Ritchie (2001), ventilation of the mid-troposphere (Gray 1968; Tang and Emanuel 2013), subsidence induced over the low-level centre of a tilted vortex (DeMaria 1996) and ventilation of the boundary layer inflow (Riemer et al. 2010).

Riemer et al. (WWOSC-2014) summarized a conceptual model for the interaction with vertical wind shear based on idealized numerical experiments (Riemer et al. 2010, 2013; Riemer and Montgomery, 2011). In this model, vertical shear is prone to excite a persistent downdraft pattern tied to the tilt of the TC vortex in shear. The persistent downdrafts flush the inflow layer with low-entropy air. It is hypothesized that surface fluxes do not compensate for this entropy decrease completely and air within the inner-core updrafts rises with reduced entropy values. Air masses from above the boundary layer but at low levels (approx. 1.5-3 km height) are brought into the frictional inflow layer of the TC, thus diluting the TC’s heat engine and providing the thermodynamic reason for intensity decrease. Figure 4 illustrates schematically the three-dimensional interaction between the rotational flow and the thermodynamic influence of dry air. The helical primary precipitation band initiates mainly downshear from the centre and ascends as it rotates around the centre. Beneath this rather strong updraft are downdrafts enhanced by the import of dry air as storm-relative trajectories of environmental origin in the lower troposphere make their closest approach to the eye wall.

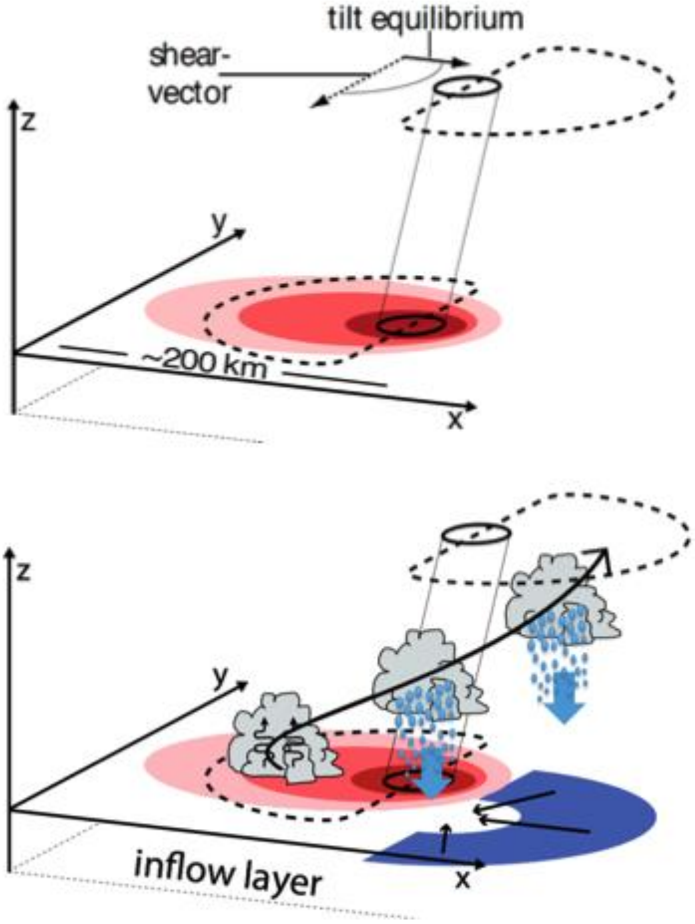

Figure 4. Schema of a tilted vortex in vertical shear, with the tilt to the left of the shear vector. Due to the shear interaction, the distribution of high-entropy "vortex" air at lower is highly asymmetric (red colours, top). Bottom panel shows the consequences for the distribution of convection, precipitation, and downdrafts. Convection is forced in the high-vorticity, high-entropy region to the right of the shear vector and ascend on a helical path within the primary rain band (long black arrow). Precipitation falls into unsaturated air below and ensuing downdrafts (blue arrows) bring low-entropy air into the frictional inflow layer (blue shading).

Source: Adapted from figure provided by Michael Riemer

Further work on the importance of environmental moisture in the lower troposphere in shear was presented by Rios-Berrios and Torn (WWOSC-2014) who used a five-day, 96 member ensemble forecast for Hurricane Katia (2011) produced by the Advanced Hurricane Weather Research and Forecasting (AHW) model. Hurricane Katia posed great challenges for operational prediction and consistent with this difficulty, the ensemble showed an anomalously large spread of intensity after 4 days. All members were initialized with a moderately strong environmental vertical wind shear, but the weakest members had a drier environment than the strongest members. A water vapour budget confirmed that the strongest members had more water-vapour flux convergence at low levels and less water-vapour divergence at the mid levels. The result was greater water vapour through a deep layer in the strongest members. Consequently, the strongest members had more area-averaged deep convection and condensational heating, indicative of more active convection. It is hypothesized that a feedback between low-level water vapour, low-level convergence, and deep moist convection aided in vortex stretching that helped to spin up the strongest members. It is also possible that the additional water vapour at low levels offset the dilution of boundary-layer moist entropy discussed by Riemer et al. (WWOSC-2014).

While vertical shear can suppress intensification through the induced thermodynamic response mentioned above, it can also invigorate convective updrafts. Nguyen and Molinari (WWOSC-2014) examined the asymmetric rapid intensification of Tropical Storm Gabrielle (2001) using the

Weather Research and Forecasting (WRF) model with 1 km grid spacing. As the simulated tropical cyclone intensified, intense convective cells with associated cyclonic vorticity anomalies developed preferentially downshear. One particularly strong mesovortex developed initially downshear-right, revolved cyclonically around the TC centre for several hours, and subsequently aligned with the vortex in the mid-troposphere. This case provides an example of transient development in shear. Presumably, if the shear is maintained past a period of initial intensification, the storm will subsequently struggle to become an intense tropical cyclone owing to the otherwise negative effects of shear on intensity.

The asymmetric vorticity dynamics, often related to vertical shear, were examined in a highly idealized context by Menelaou and Yau (2014) who used a “dry” thermally forced model to conduct numerical experiments starting with a weak vortex forced by a localized thermal anomaly. They found that the response of the vortex was dominated by the radiation of a damped sheared vortex Rossby wave (VRW) that accelerated the symmetric flow through the transport of angular momentum. An increase of the kinetic energy of the symmetric flow by the VRW was shown also from the eddy kinetic energy budget.

A limiting case of outer convection bands is the formation of a secondary eye wall, a process that often drastically modulates storm intensity. The exact mechanism of secondary eye wall formation remains a matter of controversy. Wu et al. (WWOSC-2014) outlined several possible mechanisms, including vortex Rossby waves (Menelaou et al. 2014); β-skirt axisymmetrization formation hypothesis (Terwey and Montgomery 2008), unbalanced dynamics near the top of the boundary layer (Huang et al. 2012; Wang et al. 2013; Abarca and Montgomery 2013, Bell et al. WWOSC-2014), the balanced response to diabatic heating within an elevated inertial stability region (Rozoff et al. 2012), and friction-induced updraft via an Ekman-like process over a region with radial vorticity gradient. The super-gradient mechanism was explored by Wu et al. (WWOSC-2014) through an extension of simulations of Typhoon Sinlaku (2008) by Huang et al. (2012). Based on momentum budget analyses, it was shown that the tangential wind field broadens prior to the formation of a secondary wind maximum and the forcing of positive radial wind (Figure 5) moves outward as well, establishing a region of convergence near 75 km radius. It is also true that the expanded vortex has greater inertial stability at a larger radius, so that the heating from the convection that develops in response to this outer convergence more efficiently generates vorticity at a larger radius than prior to the expansion.

As is well known, the approach to land generally causes a weakening of the tropical cyclone. Furthermore, proximity to land can induce asymmetries that change the motion of the storm, as explored by Chan et al. (WWOSC-2014). It was found that differential friction results in a tropical cyclone drifting towards the rougher surface through the development of (a) a pair of counter-rotating gyres generated by changes in the relative vorticity budget and (b) asymmetric diabatic heating. In the presence of topography, the induced upslope and downslope flows also lead to the development of a set of counter-rotating gyres that tend to cause the tropical cyclone to move towards the location of onshore flow. Topography at a large distance away from the tropical cyclone could also have an effect of its track as well through a similar mechanism. While it is intuitive that more precipitation will occur on the upslope side in the presence of topography, whether stronger convection occurs on the onshore or offshore side depends on moisture availability as well as the vertical wind shear, generally occurring downshear-left with respect to the shear averaged within 400 km of the vortex (Li et al. 2015). Ultimately, hydrological considerations also determine the local flooding potential associated with landfalling TCs near complex terrain.

It is clear from the modelling studies discussed above that the influence of vertical shear varies from case to case. The proliferation of idealized simulations in the last several years has allowed progress into the basic dynamical response of deep convection to vertical shear within a strong vortex. The recent studies have focused on the combined influences of shear on the vorticity and on the moisture transport relative to the vortex thereby providing information on the thermodynamic consequences of vertical shear as well as the dynamical strain on vortex coherence.

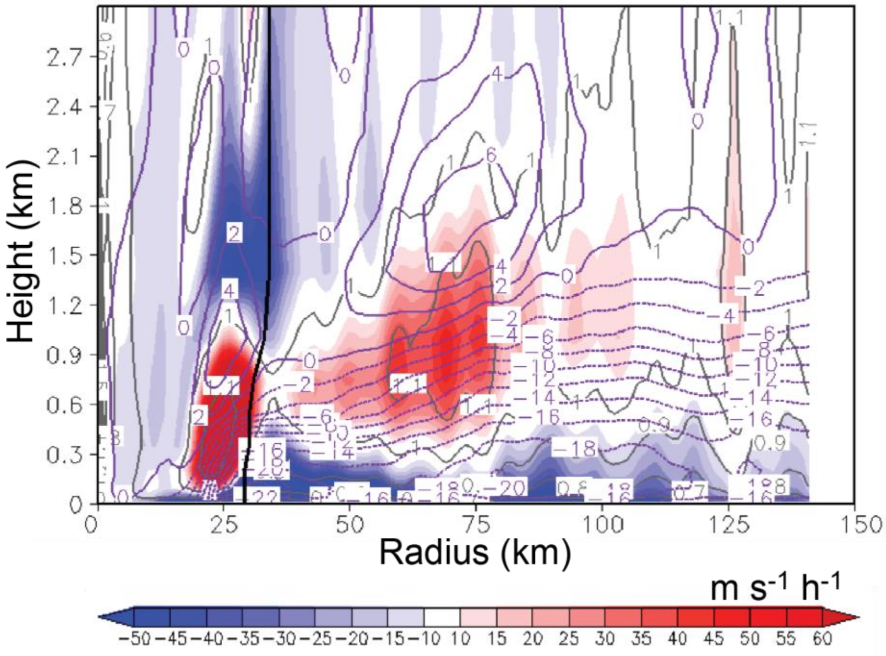

Figure 5. Radius (km) vs. Height (km) plot of azimuthal mean radial wind (contours) and a-gradient forcing (shaded) for the period 1-3 hours prior to secondary eye wall formation. Heavy black line denotes the location of the radius of maximum wind.

Source: Adapted from figure provided by Chun-Chieh Wu

14.4 PREDICTION AND PREDICTABILITY

Despite rapid advances in numerical weather prediction (NWP) models and ever-increasing computational capability, our ability to accurately predict various severe weather phenomena including tropical cyclones in the short-to-medium range remains limited. In particular, Zhang (WWOSC-2014) summarized the recent studies of Zhang and Tao (2013) and Tao and Zhang (2014) who used a series of convection-resolving ensemble experiments with varying magnitudes of vertical wind shear, each initialized with an idealized weak TC-like vortex, to examine predictability limitations. It was found that predictability is most limited for storms with environmental shear within the range of 5 to 7.5 m s^{-1} under moderately warm sea surface temperature (SST) of 27°C (Figure 6). With the imposition of random noise, the error growth from differences in moist convection first alters the tilt amplitude and angle of the incipient tropical storms, which leads to significant differences in the timing of precession and vortex alignment. The tropical cyclone intensifies immediately after the tilt and the effective local shear reach their minima. In some instances, small-scale, small-amplitude random noise may also limit the intensity predictability through altering the timing and strength of the eye-wall replacement cycle, which is to a certain extent similar to the upscale error growth processes that limit the intrinsic predictability of winter snowstorms and moist baroclinic waves discussed in Zhang et al. (2003, 2007). Further increasing SST to 29°C will lead to the largest intensity uncertainty for shear magnitude around 10-12.5 m s-1 since warmer SST will allow the storms to resist stronger shear (Tao and Zhang 2014). Limited predictability for moderately sheared storms may at least partially contribute to relatively larger operational forecast error under suboptimum conditions (Y. Zhang et al. 2014).

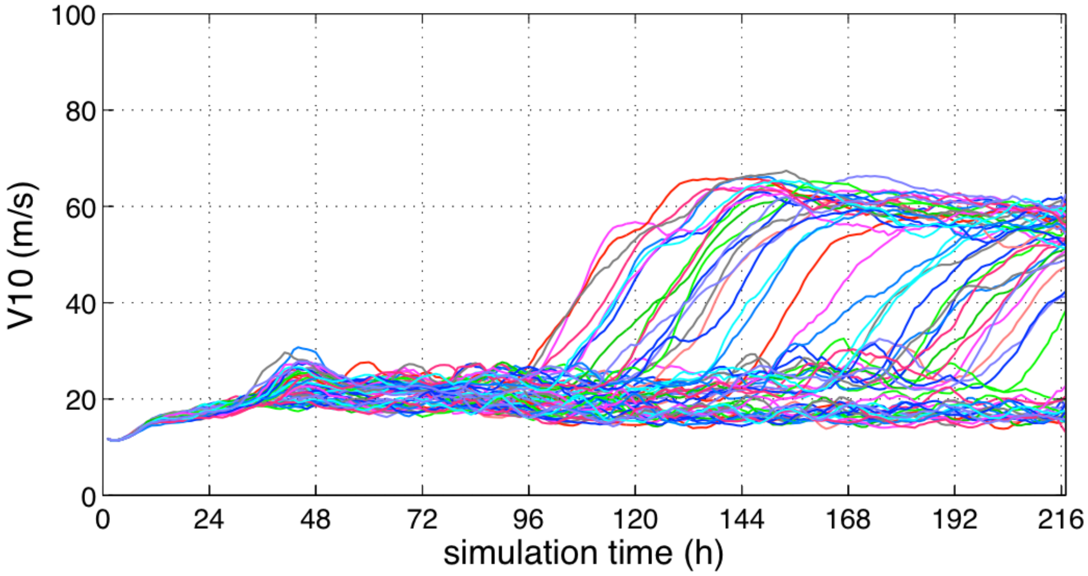

Figure 6. Maximum wind at 10 m for idealized simulations with 5, 6 and 7.5 m s^{-1} shear. All simulations are initialized with the same vortex and same environment (apart from the shear) with the addition of small random noise.

Source: Adapted from figure provided by Fuqing Zhang

Although tropical cyclone (TC) intensity change is fairly well understood under idealized scenarios, the predictability of TC intensity and structure under more realistic conditions is not as well known. In particular, it is unclear how the combination of errors associated with the vortex structure, near-storm environment and lower boundary condition (i.e., sea surface) limit intensity predictability. Torn (WWOSC-2014) determined the relative importance of different error sources using multiple sets of Advanced Hurricane WRF (AHW) ensemble forecasts of 20 Atlantic TCs over 35 initialization times during 2008-2011. Each set of ensemble forecasts was characterized by a different source of uncertainty, which included the atmosphere, ocean, and physical processes (i.e., surface layer physics, microphysics). The results from these experiments suggest that the uncertainty from the atmosphere has the greatest impact on intensity, with small TCs showing greater probability of large error growth compared to large TCs. By contrast, errors from the ocean or physical processes have lower error growth and more consistent error growth from one case to another.

Another source of systematic error is improper treatment of the upper ocean response to the TC. Ito et al. (WWOSC-2014, 2015) performed 281 3-day forecasts with the Japan Meteorological Agency (JMA) non-hydrostatic atmospheric model and the atmospheric model coupled to a simple upper ocean model. They found a 29% improvement in the minimum sea-level pressure forecasts using the coupled model. Most of this improvement was the removal of bias by the inclusion of the wind-driven mixing and upper-ocean cooling beneath the storm.

Given the variations in predictability from case to case that results from atmospheric flow dependent error growth, more useful forecasts might be obtained if one could predict whether a particular model forecast will be more or less skillful than average. Bhatia and Nolan (2013) studied the relationship between synoptic parameters, TC attributes and forecast errors, and found that certain storm environments are inherently more or less difficult for individual models to forecast. Bhatia and Nolan (WWOSC-2014) extended this work by using storm-specific characteristics as well as parameters representing initial condition error and atmospheric stability to predict both the absolute error (AE) and the actual error (bias). Error predictions were applied to 12-120 hour intensity forecasts for the Logistic Growth Equation Model (LGEM), Decay Statistical Hurricane Intensity Prediction Scheme (DSHP), Hurricane Weather Research and Forecasting Interpolated Model (HWFI), and Geophysical Fluid Dynamics Laboratory Interpolated Hurricane Model (GHMI). The methodology for the development of the error prediction models was very similar to that used for SHIPS (DeMaria and Kaplan 1994). The standard “cross-validation” approach was used, whereby all but one of the years from 2007-2013 were used as the training data, and then the excluded year was used for validation; this was repeated for all years. An example of very good correlation of predicted AE versus true AE is shown in Figure 7. The general trend is for better predictions of forecast errors for the longer intervals (96h, 120h).

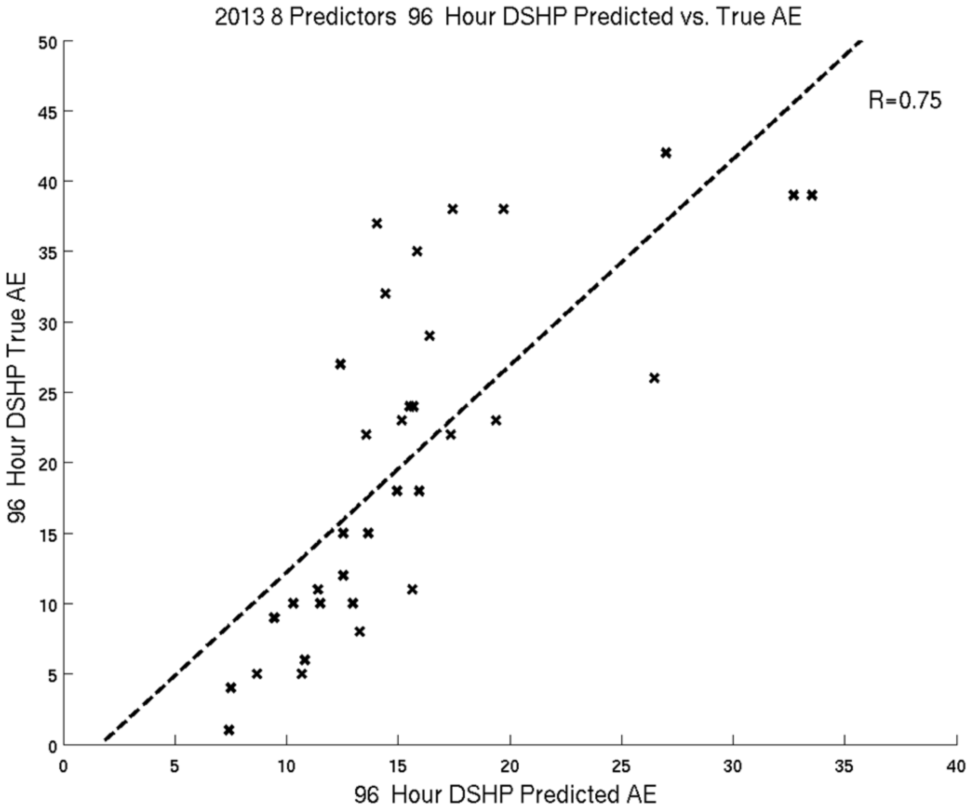

Figure 7. Predicted absolute error (AE) versus actual error for 96 hour forecasts for the Decay-SHIPS (DSHP model during the 2008 hurricane season).

Source: Adapted from figure provided by Kieran Bhatia

Although ensemble forecasting is gaining popularity for TC structure and intensity, the full information content of ensemble forecasts is not yet realized. The practical use of ensembles for prediction was explored by Evans and Kowaleski (WWOSC-2014) in the case of hurricane Sandy. They were able to derive track-based clusters in the ensemble that each represented not only a different track group, but also different structures of the storm for different tracks. Deriving scenarios from the ensemble in this way retains physical characteristics of the storm that are often lost through simple ensemble averaging. For example, it was shown that leftward-turning tracks, similar to the track of the observed storm, featured a realistic warm-core seclusion.

There is increasing emphasis on extended range predictability of tropical cyclones, even as far out as 1 month. Clearly on these time scales, it is essential to predict intraseasonal variability that constrains tropical cyclone formation. Nakano et al. (WWOSC-2014) conducted 31 extended-range (30-day) forecasts initialized on each day of August 2004 using 14 km-mesh Nonhydrostatic ICosahedral Atmospheric Model (NICAM). The formation of Megi, Chaba, Aere, and Songda were found to be predictable up to two weeks before their geneses.

There are also signals in observations of even longer-term relationships between atmosphere-ocean modes of variability and tropical cyclone formation. Camargo et al. (WWOSC-2014) examined successively longer-time-scale connections between TCs and large-scale variability. Beyond tropical waves and the MJO, which have pronounced influences on TC formation (see subtheme 1), there is the El Niño/Southern Oscillation (ENSO). The improved ability of coupled models to predict ENSO has led to improvements in numerical seasonal prediction (Vecchi and Villarini 2014). Beyond that, there are decadal oscillations that also modulate TC activity. The phase of the Atlantic Meridional Mode has a profound influence on the number of storms and the recurvature characteristics of these storms (Kossin et al. 2010). The ability of models to correctly simulate this mode of variability has clear implications for long-term investments in infrastructure along the eastern U. S. coast.

Although the potential influence of climate change on TCs has been the subject of number of recent studies, it is still difficult to confidently assess the magnitude of future changes in storm intensity. Although the resolution of climate models is increasing to the point where they are starting to resolve tropical cyclones, intensity prediction in climate models is not yet reliable. However, Lee et al. (WWOSC-2014) presented a new statistical-dynamical downscaling system to study the influence of climate on TCs. Using a multiple-linear regression model they found that monthly data from global models with only the most essential predictor, the difference between storm intensity and potential intensity, might be sufficient for us to understand the response of hurricane intensity to a changing climate from a statistical perspective.

It is apparent from the collection of studies presented at WWOSC that ensembles are indispensable for understanding the processes that affect hurricane intensity and quantifying the predictability of the results of those processes. It is clear that uncoupled models have significant biases that render their application in ensemble studies somewhat questionable. Furthermore, there still remain some important questions about the errors inherent in convection-permitting simulations. To better understand the response of convection to vertical shear, it may now be necessary to proceed to ultra-high, turbulence resolving simulations of hurricanes in shear.

14.5 CONCLUSIONS

The dominant theme among all the papers on tropical cyclones at the WWOSC-2014 was the subject of TC intensity and intensity change, with an emphasis on both mechanisms and prediction. It should be apparent from the foregoing discussion that intensity prediction has a large stochastic element. Observations are involuntarily subject to this stochasticity through the case-to-case variability that dilutes the signal in composites of genesis and intensification. This also means that deterministic forecasts of intensity are not fully justified. This may explain why purely statistical models do about as well as dynamical models concerning genesis and rapid intensification of TCs. Nonetheless, errors in models remain obstacles to modelling the correct probability distribution of tropical cyclone intensity change. Because there may be long lead times (months) for certain large-scale patterns, it is important that models are improved so that reasonable probabilities are derived as these states change. This underpins all efforts to capture the long-term climate change signal in tropical cyclones. Detailed observations have been used in recent years to make numerous improvements in hurricane models, but there is a long way to go in terms of faithful modelling of convective-scale atmospheric-ocean coupled system.

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