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SIXTH INTERNATIONAL WORKSHOP ON TROPICAL CYCLONES

Topic 1.1 : **Environmental Effects on Tropical Cyclone Structure and Structure Change**

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Abstract:

Recent research to increase understanding, and techniques to improve forecasts, of the structure and structural changes of a tropical cyclone due to interaction with the environment are summarized. The atmospheric environment is considered here, and the oceanic, and air-sea interface environments are summarized in Topic 1.3. Progress in understanding how a tropical cyclone interacts with its environment, and in developing techniques to forecast tropical cyclone intensity- and structure-change events, has been made over the past few years. Whereas any increase in skillful forecasts due to these research and techniques may take some years to develop, it is felt that improvement in tropical cyclone intensity forecasts is likely, due in part to the work described here.

1.1.1 Introduction

The impacts of the environment on tropical cyclone structure and structure change have been studied for many years. Here, an update on progress in research and forecast techniques since the fifth IWTC is provided. It is well known that favorable environmental conditions (including minimum vertical wind shear) are required for tropical cyclone formation. Emanuel (1988) and Holland (1997) have developed separate relationships between the maximum potential intensity (MPI) and the sea-surface temperature (SST) and the environmental conditions, which include the static stability, upper-tropospheric conditions, and relative humidity. The wind structure (intensity) changes of a tropical cyclone from formation to maximum intensity to decay depend on a balance between favorable and inhibiting environmental conditions. Whereas, mostly atmospheric factors will be considered here, in a later topic (1.3) the sea-surface and oceanic forcing will be summarized. Environmental conditions summarized in the following sections include:

1) Low- or No-flow environments – the wind field is near zero throughout the troposphere;
2) Uniform flow environments – the wind field is near constant throughout the troposphere;

3) Vertical wind shear environments –the mean wind changes with height. The most common measure of vertical wind shear is the mean wind at 850 hPa subtracted from the mean wind at 200 hPa although different definitions do exist. The resulting value has both a magnitude and a direction. Furthermore, a shallow shear is sometimes defined as the mean wind at 500 hPa minus the mean wind at 850 or 925 hPa. The mean wind is usually calculated as an average over an area extending

radially from the center of the tropical cyclone. Mean winds have been calculated over a circular area extending up to 600 km from the tropical cyclone center, or in annular areas extending, for example, from 200 km radius to 600 km radius, or 200 km to 800 km radius from the center of the tropical cyclone. Whereas vertical wind shear is strictly a measure of velocity gradient with units of either s^{-1} or m s^{-1} $(hPa)^{-1}$, it is more commonly reported as m s^{-1} with the depth over which the shear is calculated implied as 200 – 850 hPa or stated. There is no standardized measure of shear as a function height. i.e., a simple subtraction of the winds at two levels does not represent the vertical structure of the shear. It is possible to have the same shear calculated between 200 and 850 hPa when in one case, the shear is all located in the upper atmosphere, and in another, in the lower atmosphere. It is expected that the tropical cyclone would respond differently to these two types of mean vertical wind structure;

4) Upper-level trough interactions;

5) Environmental moisture and the Saharan air layer.

1.1.2 Low- or no-flow environments

A study by Knaff et al. (2003a) highlights a small subset of tropical cyclones in the North Atlantic and eastern North Pacific basin that briefly developed unusual structural and intensity characteristics in low easterly vertical wind shear environments over constant or decreasing SSTs. As observed in infrared imagery, these tropical cyclones tended to have larger than average eye sizes, symmetrically distributed cold brightness temperatures in the eyewall, and little or no rainband features. In addition, these “annular” tropical cyclones were significantly stronger, maintained their peak intensities longer, and filled more slowly, than the average tropical cyclone in these basins. Furthermore, average official forecast intensity errors for these types of tropical cyclones were 10 – 30 % larger than the 5-y mean official errors during the same period. A simulation of a tropical cyclone in environmental conditions similar to those found by Knaff et al. (2003a) to be conducive to annular-hurricane formation was more intense than its beta-plane counterpart, and had a more axisymmetrically distributed inner-core precipitation pattern similar to that inferred from infrared imagery for the annular hurricanes, and more power in the wave-number-0 (symmetric) component of the potential vorticity field (Ritchie 2004). As a personal observation, it has been interesting to note the use of the term “annular” in TC-community discussions of existing tropical cyclones. It seems that this research into one class of “outliers” has begun to pay off.

An idealized modeling study by Ritchie and Frank (2006a) found that a tropical cyclone on a *f*-plane (i.e., no large-scale asymmetries) could develop vertical wind shear within at least 300 km of its center due to its own unstable outflow (Wong and Chan 2004). This weak vertical wind shear (maximum of 4.5 m s^{-1} averaged over the inner 300-km radius) was strong enough to generate small-scale asymmetries in convective and precipitation structure. It was found that if shear of magnitude greater than 2.3 m s^{-1} persisted for more than about 3 hours, then persistent, shear-forced asymmetries in the convection and precipitation fields would develop. Note that these asymmetries in the structure of the TC did not appear to impact the rate of intensification of the tropical cyclone to any degree.

1.1.3 Uniform (non-zero) Flow

It would be unusual for the near-tropical cyclone environment (within 1000 km radius) to consist of a uniform flow because of the vertical wind shear associated with the beta gyres. However, it is educational to consider how a mean flow on a *f* plane and a beta plane affect tropical cyclone structure and intensity. A previous study (Frank and Ritchie 2001) found that a weak uniform (3.5 m s^{-1}) background flow that intensified slightly more rapidly, and reached a slightly higher intensity, than the comparable control no-flow case. In this case, the asymmetry in convection produced by frictional convergence in the front quadrant of the tropical cyclone (Shapiro 1983) produced an enhancement in the average precipitation of 2-5 cm (3 h)$^{-1}$ in the inner 50 km of the tropical cyclone when compared to the no-flow case (Frank and Ritchie 2001).

A more recent study by Kwok and Chan (2005) found that a strong uniform flow (6-8 m s^{-1}on a *f* plane) resulted in a weakening of the tropical cyclone. Their principle finding was that the interaction between the uniform flow and the tropical cyclone circulation resulted in a wave number one asymmetry in vertical motion, which, along with a rotation of the upper-level anticyclone, produced an effective vertical wind shear over the tropical cyclone. In weak flow cases (0-4 m s^{-1}), the vertical motion asymmetry was not induced, and no reduction in intensity was observed, a result consistent with the earlier finding of Frank and Ritchie (2001).

The direction of environmental uniform flow has also been found to be a factor in modeling studies when the beta effect is included. Peng et al. (1999) found that uniform westerly flow was more favorable for tropical cyclone intensification than uniform easterly flow. They concluded that westerly (easterly) uniform flow partially cancelled (enhanced) the northwesterly tropical cyclone motion induced by the beta gyres and thus reduced (increased) any motion asymmetry resulting in more symmetrically (asymmetrically) organized convection. Kwok and Chan (2005) support this finding. They find that on a variable-*f* geometry, westerly uniform flow partially cancels the beta-induced vertical wind shear, while easterly uniform flow enhances it. This result is also consistent with Ritchie (2004) and Ritchie and Frank (2006b).

1.1.4 **Environmental vertical wind shear**

The effects of vertical wind shear on the intensity and to a lesser extent the structure, of a tropical cyclone is qualitatively well known. Strong vertical wind shear has an inhibiting, and even weakening, effect on tropical cyclone intensification. In strong shear, the low-level center of the tropical cyclone will often become exposed, with the convection and cloud shield shifted downshear of the exposed center and the tropical cyclone will typically weaken. This result was incorporated into the original Dvorak technique to infer intensity trends from infrared and visible satellite imagery. However, the relationship between weak to moderate shear and tropical cyclone structure and intensity change is less clear. More recent studies have begun to elucidate more details regarding the effects of different strength, and structure, of vertical wind shear and how this affects the intensity and structure of tropical cyclones of different intensities.

a) Theoretical Studies – dry vortices

Recent theoretical calculations show that dry vortices exhibit resiliency to the presence of vertical wind shear (Reasor et al. 2004; Jones 2004). Mechanisms discussed include rotation of a tilted vortex such that when the vortex is tilted “upshear” the vertical shear effectively constrains and reduces the tilt, and when it is “downshear” the environment will enhance the tilt (Jones 2004). The resiliency of the vortex to the environmental shear is dependent on the value of the Rossby penetration depth, i.e., the larger the depth, the greater the resiliency of the vortex to the shear. Reasor et al. (2004) present a different, but complimentary view on the resiliency of dry vortices to vertical shear forcing. They argue that when the vortex tilts, the asymmetries are projected onto vortex Rossby waves and damped out thus reducing the tilt of the vortex. One major difference between the two papers still seems to be the location of the forced vertical motion. Jones (2004) finds it to be left of the vortex tilt (consistent with previous work) and finds that the tilt rotates with time whereas Reasor et al. (2004) find that the tilt is steady at downshear-left (contrary to other authors) where presumably the forced positive vertical motion is located. As Jones (2004) points, perhaps the definition of vortex center used to define “tilt” is critical in determining which mechanism might be working.

Another recent paper by Patra (2004) supports the earlier finding by Frank and Ritchie (1999) that latent heat release in neutral ascent in the inner-core of a tropical cyclone results in a shift of the ascent pattern to downshear left. One particularly interesting result is that if the region of saturated ascent is confined to one side of the vortex, the tropical cyclone can still intensify suggesting that tropical depressions and sheared tropical storms may still be able to intensify under vertical wind shear.

b) Intensification and weakening trends in tropical cyclones

Previous observational and modeling studies have shown a relationship between the strength of the environmental vertical wind shear and the amount of weakening or intensification that occurs in a tropical cyclone (Gallina and Velden 2002; Frank and Ritchie 2001). In particular, Gallina and Velden (2002) found that for Atlantic tropical cyclones, the critical shear value where the tendency changes from intensifying to weakening tropical cyclones occurs at about 7-8 m s^{-1} (200 – 850 hPa) of vertical wind shear. For the western North Pacific basin this critical shear value is 9-10 m s^{-1} (200 – 850 hPa). More recently, Wong and Chan (2004) support these findings with a series of numerical simulations. They found that whereas tropical cyclones in weak (0-4 m s^{-1}) shear intensified during the simulation, increasing the shear to 6-8 m s^{-1} resulted in a relatively weaker tropical cyclone that maintained its intensity (but did not strengthen). Furthermore, at shear values of 10 m s^{-1}, the tropical cyclone weakened significantly. These values are very similar to those empirically deduced by Gallina and Velden (2002). In support of this, Zeng et al. (2006) find that very few tropical cyclones in the western North Pacific intensify when the environmental vertical wind shear is greater than 20 m s^{-1}, a result that is certainly not contradictory to anything previously found.

The impact of the vertical wind shear is also sensitive to the size of the tropical cyclone (Wong and Chan 2004). A smaller tropical cyclone weakened in only 4 m s^{-1} of vertical wind shear, and in 6 m s^{-1} of vertical wind shear, dissipated by 48-h of simulation. This is also similar to the observational result of Gallina and Velden that under the same vertical shear environment, more intense tropical cyclones were impacted more slowly than weaker tropical cyclones.

Zehr (2003) used a case study of Hurricane Bertha to demonstrate that the asymmetry in infrared cloud structures can be related to the model-derived vertical wind shear. This process may prove to have utility in assessing actual environmental vertical wind shear from the infrared cloud asymmetries.

An extremely interesting result is from Emanuel et al. (2004) who report adding a crude parameterization of vertical wind shear into their “CHIPS” model, which is an axisymmetric atmospheric model coupled to an ocean model for intensity forecasting. Whereas the original model did not perform well when the tropical cyclone was embedded in relatively high shear, the addition of a parameterization for vertical wind shear dramatically improved their results in these situations. The new configuration outperformed GFDL for the 2002 Atlantic hurricane season, and performed almost as well as SHIPS out to 48 h.

c) Secondary circulation, convective asymmetries, and precipitation patterns

A study by Zhang and Kieu (2005) isolates the forced secondary circulation by the vertical shear of horizontal winds from the latent heating and friction circulations associated with a simulated hurricane vortex. They find that when an environmental westerly shear is superposed with an axisymmetric balanced vortex, an anticlockwise forced secondary circulation appears across the inner-core region with the rising motion downshear and easterly sheared horizontal flows in the vertical. The resulting horizontal flows act to reduce the influence of the vertical shear inside the storm by as much as 30–40%, opposing the destructive role of the vertical shear.

Recently, model simulations that include diabatic effects (Frank and Ritchie 1999, 2001; Kimball and Evans 2002) and several observational studies (Reasor et al. 2000; Corbosiero and Molinari 2002a, 2002b; Black et al. 2002; Zehr 2003) have established and verified the existence of persistent patterns of asymmetric convection and rainfall that develop in the downshear-left quadrant of the storm. The model study of Frank and Ritchie (2001) found that the asymmetries developed due to the storm’s response to imbalances caused by the shear, but differ from the prior adiabatic simulations because saturation in the eyewall leads to a different lifting mechanism. Interestingly, an observational study (Corbosiero and Molinari 2002a) that used lightning flash density in 35 tropical cyclones found that in the inner core region (< 100 km radius) the flashes occurred preferentially in the downshear left quadrant, which is consistent with the predictions of Frank and Ritchie (2001). In the outer rainbands (100–300 km of the center) the preference for the lightning was for downshear right, similar to the adiabatic model studies of Jones (2000) and Frank and Ritchie (1999). These lightning distributions were valid both over land and water, and for depression, storm and hurricane stages.

A more recent modelling study by Rogers et al. (2003) has shown that while the magnitude of the convective asymmetries and instantaneous rainrate are directly related to the magnitude of the environmental vertical wind shear, the distribution of accumulated rainfall was related also to the direction of the vertical wind shear and the storm motion. The accumulated rainfall had a more symmetric distribution across the track of the storm if the shear vector was strong and across track, but showed a distinct maximum on the left side of the storm track when the shear was weak and along track.

d) Tropical cyclone thermal structure

Probably the principle reason why a tropical cyclone eventually will weaken under the influence of strong environmental vertical wind shear is because the tropical cyclone upper-level warm core cannot be maintained at a level that will continue to support the surface low pressure. Model studies (e.g., Frank and Ritchie 2001; Ritchie and Elsberry 2001) indicate that environmental vertical wind shear would impact the tropical cyclone at the upper-levels initially, which is where the inertial stability associated with the tropical cyclone primary circulation would be a minimum. Ritchie and Elsberry (2001) simulated an initial advection downstream of the upper-level warm core of the tropical cyclone, and thus a reduction in the magnitude of the warm core aloft. This resulted in a reduction in the height of the maximum warm core, an enhancement of the warm core at lower levels (due to subsidence into the core forced by convergence between the environmental winds and the cyclonic flow of the tropical cyclone), an associated rise in the sea-level pressure, and a reduction in the cyclonic flow aloft, which further reduced the inertial stability aloft. Consequently the vortex became more susceptible to the vertical wind shear and thus more of the warm core was advected downstream. Although this negative feedback could lead to continued erosion of the deep convection and upper-tropospheric warm core, and thus finally a dissipation of the tropical cyclone, Ritchie and Elsberry (2001) found that an eventual balance between the environment and (weaker, shallower) tropical cyclone was established.

The introduction of the Advanced Microwave Sounding Unit (AMSU) has allowed the routine examination of tropical cyclone thermal structure. While the AMSU soundings lack the horizontal resolution to resolve the warm core of the tropical cyclone eye, the broader-scale warm core envelope can be measured. The strength of this broad-scale warm signature has been related to intensity (Brueske and Velden 2003) and the horizontal extent of the warm core along with an estimate of maximum intensity can be related to surface wind structure (DeMuth et al. 2003). A study using the advanced microwave sounding unit (AMSU) (Knaff et al. 2004) that analyzed the temperature anomaly in tropical cyclones in vertical wind shear found that typically as vertical wind shear increased, the warm-core vortex became shallower. These observations are consistent with the modeling results.

1.1.5. **Upper-level trough interactions**

It is difficult to find any reported research in the past four years since IWTC-V that investigates the interactions between upper-level troughs and tropical cyclones *except as part of extratropical transition*, which is not covered here. The purview of this section is to report how upper-level troughs impact tropical cyclone structure and intensity *while they remain tropical in structure*. Previous research, which is reported in existing IWTC reports, will support the thesis that the precise manner and degree to which upper-level troughs weaken or intensify a tropical cyclone's circulation is not yet well understood. Although an upper-level trough in close proximity increases the vertical wind shear over the tropical cyclone, studies have demonstrated that complicated dynamic processes occur during the interaction between an upper-level trough and a tropical cyclone that then affect the core dynamics of the tropical cyclone in ways that are only just beginning to be investigated. A trough interaction has been defined by Hanley et al. (2001) to occur when the eddy momentum flux convergence calculated over a 300-600 km radial range is greater than 10 m s^{-1} d^{-1}.

A favorable factor for intensification of a tropical cyclone has been characterized as a “good trough” interaction and two types of “good troughs” have been identified and described using composite analysis (Hanley 1999; Hanley et al. 2001). In this scenario, an upper troposphere trough becomes juxtaposed with the warm outflow from the tropical cyclone to cause: (*i)* a positive eddy momentum flux convergence that contributes to a cyclonic spinup of the inner vortex; and/or (*ii)* an enhancement of the jet streak that contributes to a larger outflow from the tropical cyclone, and consequently a spinup of the vortex (Hanley et al. 2001; Hanley 1999). Kimball and Evans (2002) note that a merger between a simulated shallow upper-level trough and tropical cyclone leads to reduced vertical wind shear from the trough over the tropical cyclone. Rapid intensification of the tropical cyclone followed in conjunction with contraction of the radius of maximum winds.

In the contrasting “bad trough” scenario, the strong winds on the leading side of an approaching upper-level trough produce a strong vertical wind shear that is concentrated in the upper portions of the troposphere over the tropical cyclone. This scenario has been observed to occur when the upper-level trough either remained relatively far from the tropical cyclone so that the effective impact on the tropical cyclone was a debilitating one associated with the vertical wind shear Hanley et al. 2001). In addition, Kimball and Evans (2002) note that in their model simulations, the deformed trough inhibited outflow on the east side of the tropical cyclone, which hampered future intensification.

Although composite and model studies of an upper-level trough and its associated vertical shear interaction have provided insight into the mechanisms of trough interaction, it has proved particularly difficult to apply these insights to individual cases. In recent years, Hurricane Opal of 1995 has become one of the most intensely studied hurricanes ever. However, the cause of the hurricane's rapid intensification over the Gulf of Mexico is still a matter of controversy. Several insightful studies (e.g., Bosart et al. 2000; Persing et al. 2002; Möller and Shapiro 2002; Shapiro and Möller 2002) used a range of techniques to elucidate the role of the upper-level trough in the intensification of Hurricane Opal. However, there was no general consensus out of these studies. Furthermore, additional studies (e.g., Hong et al. 2000 and Shay et al. 2000) suggest that the oceanic warm core ring that Opal passed over during the period of rapid intensification had significant impact on the hurricane’s heat budget and thus also impacted its intensification.

Hanley (2002) has used water vapor imagery with some success to identify a tropical cyclone-trough interaction, which gives some hope that continued investment in remote sensing technology may help with this forecast challenge.

1.1.6 Effects of environmental moisture (or lack thereof)

Environmental moisture has been shown to be positively correlated to future tropical cyclone intensity trends (Emanuel 1988; Holland 1997; DeMaria and Kaplan 1999; Knaff et al. 2003b) although their affects are secondary to the effects of SST, ocean heat content and vertical wind shear. The advection of Saharan dust over the tropical Atlantic is symptomatic of an increased low-level (~700 hPa) easterly jet that propagates westward from the northwest African continent. This low-level dry-air surge can cause a marked increase in vertical wind shear and dry air entrainment that can act to influence tropical cyclones that encounter it (Dunion and Velden 2002a). Recently developed multispectral Geostationary Operational Environmental Satellite (GOES) infrared imagery detects the SAL's entrained dust and dry air as it moves westward over the tropical Atlantic (Dunion and Velden 2004). This imagery reveals that as the air masses overtake a tropical cyclone the convective intensity and organization can be reduced resulting in a general weakening and that as the tropical cyclones emerge from the air mass intensification can subsequently occur (Dunion and Velden 2002b).

The effects of dry air intrusion on simulated landfalling hurricanes are investigated by Kimball (2006). Primary results are that storms with a small radial extent of moisture develop minimal rainbands and weaken as dry air from the 800–850-hPa layer wraps cyclonically and inward around the storm core. Storms with a large radial extent of moisture develop into storms with large rainbands, having smaller intensification rates initially, but then continue to intensify for a longer period of time. For these cases, the rainbands act as a barrier between the moist core and the dry environment, preventing dry air from penetrating the storm core. In the absence of land, a hurricane can sustain itself in a dry environment, provided its moist envelope is large enough.

1.1.7 **Summary, forecast challenges, and recommendations for future directions**

Clearly significant challenges exist in forecasting tropical cyclone structure and intensity change during interaction with dynamic environments. A tropical cyclone moving into an exceptionally low shear environment may cause increased intensity forecast errors. A weakening of the tropical cyclone in response to an unexpected encounter with an enhanced vertical wind shear environment can cause over-forecasts of intensity increase. In addition, an encounter between a tropical cyclone and a midlatitude trough presents many different challenges: is it a "good trough" or a "bad trough," and does the "good" part of a "good trough" interaction depend on the difference between the tropical cyclone's current intensity and its MPI? It is also difficult, at times, to diagnose the current intensity and wind structure associated with tropical cyclones. In addition, current intensity forecast models are seldom able to outperform forecasts derived from climatology and persistence (Gross 1999; JTWC 2002), and only recently has a systematic way to forecast and verify wind radii information been developed (McAdie 2002).

Studies involving model simulations show promise in fundamental understanding of the physical processes occurring during intensity and structural changes of tropical cyclones that occur due to environmental forcing. However, much work clearly still is needed in order to translate this understanding to useful guidance for forecasters.

Studies using satellite remote sensing products to enhance general understanding of the effects of the environment on future tropical cyclone intensity and structure change also show much promise and may prove to be a fruitful way to bridge the gap between theoretical knowledge and practical guidance for forecasters. Currently there are several efforts underway to develop useful techniques for forecasting tropical cyclone intensity. Examples of these efforts include but are not limited to: Multimodel superensemble approaches to forecasting tropical cyclone intensity (Kumar et al. 2003), probabilistic forecasts of tropical cyclone intensity (Weber 2005), the addition of microwave satellite information to the SHIPS model (Jones et al. 2006), and the addition of low-level cloud-drift winds from GOES into the H-wind algorithm (Dunion et al. 2002). Techniques that have been transitioned in the last 4-5 years include but are not limited to: the operational use of AMSU-derived intensities and wind radii estimates; the implementation of STIPS to the western North Pacific (Knaff et al. 2005); the addition of ocean heat content and Geostationary IR satellite information to the SHIPS model (DeMaria et al. 2005); the H-wind algorithm (Powell, 2002); and a rapid intensification probability index for the Atlantic Basin (Kaplan and DeMaria 2002).

1.1.8 **References**

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