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SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 1 : **Tropical Cyclone Structure and Structure Change**

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Abstract:

Tropical-cyclone (TC) structure and structure change, including intensification and weakening, is at the frontier of forecasting science. Knowledge and techniques within each sub-topic here have seen significant advancement during the last decade, much of it during the four years since IWTC-5.

A more detailed understanding of the inhibitory role of shear of the prevailing wind around TC has emerged, and it has become evident that not shear alone, but shear in combination with environmental middle-level humidity and the strength of the oceanic enthalpy source dominates the process. Significant advances have occurred in understanding aspects of TC internal dynamics, including classical (and not-so-classical) “hot towers,” spiral bands, concentric eyewalls and eyewall replacements, vortex Rossby waves, boundary-layer dynamics, and the eye as a source of high θ_E air. Increasingly powerful computers have opened the possibility of numerical simulation with non-hydrostatic numerical models at resolutions of 1-2 km to represent these features realistically for individual TCs. Observations from spaceborne radar altimeters combined with those from air deployable probes clearly define strength of the oceanic moist enthalpy source in relation to deep oceanic mixed layers and strong local currents. Representation of these effects using a new generation of high-resolution, coupled models is beginning to improve intensity forecasts.

In the Atlantic Basin, piloted heavy aircraft provide incomparable data for model initialization and ground truth for remote sensor development. Autonomous aircraft promise a similar, though less elaborate, capability in other basins. Nonetheless most forecasters, most of the time, will continue to rely upon spaceborne remote sensing. Although the Dvorak technique has matured and is now universally applied, recent advances in TC structure and intensity observation focus on spaceborne active and passive microwave sensors, generally deployed on satellites in steeply inclined orbits. Sensitivity of meteorological motions to initial conditions means that predictions from future sophisticated numerical models will be communicated in probabilistic terms. Portraying uncertainty to everyone from sophisticated decision makers to the general public will be a continuing challenge, as will validation of probabilistic forecasts.

1.0.0 **Introduction**

TCs are relatively small (horizontal scale ~1000 km), discrete vortices that require a few days to a month to complete their life cycles. Historically, their meso spatial scales and synoptic time scales have meant that forecasts were framed in terms of TC parameters. By “parameters” one means quantities like latitude and longitude of the center, minimum pressure, maximum wind, radius of maximum wind, and so forth. Currently, advisories are cast in terms of TC parameters to the extent that warning centers have access to observations or models that can evaluate them. Additionally, in applications that assess underwriting risk or extent of storm-surge flooding, impacts are generally evaluated using "parametric" models that convert climatological parameters into geographic distributions of weather elements.

Before the late 1990s, a key obstacle to forecasting detailed impacts in real time was inability to simulate realistic structure and intensity--even if the track were correct. For example, size of simulated vortices was controlled by model resolution rather than by physical processes. Although the minimum pressure might be representative, coarse resolution caused too-weak maximum winds. Lack of coupling between the TC winds and ocean response exaggerated the oceanic heat source. Since the introduction of the GFDL model in the mid-1990s, operational models have become increasingly realistic. Demonstration experiments with high-resolution research models are extremely promising. The reality, however, is that while operational intensity forecast produced by some of these models are now skillful, the forecast of vortex wind structure is not; suggesting further improvement in vortex initialization, model resolution, and physical parameterizations are needed. Fortunately, both the well-established MM5 and new WRF models can potentially simulate hurricane structure and intensity in great detail. The forecasting community seems to be approaching a regime where uncertainty about the initial condition will predominate over model shortcomings as a limitation on forecast accuracy. Even as computational power and model sophistication have advanced, so too has understanding of TCs' essential physics.

1.0.1 **External Atmospheric Forcing**

Shear of the surrounding, synoptic-scale wind is the dominant atmospheric forcing agent for TC structure. If it is imposed suddenly in a model, it causes the vortex to precess cylonically and then assume a down-shear tilt. In both models and observations, convective cells trigger on the downshear side of the vortex, advect cyclonically around the left-of-shear side (northern hemisphere), and appear to dissipate on the upshear side. In actuality, buoyant bubbles generally rise above the 0^oC isotherm by the time they reach the upshear side. When the suspended hydrometeors freeze or fall out, the reflectivity decreases, but the updrafts continue to rise toward the tropopause as they are carried the rest of the way around the center to the downshear side.

Forecasters recognize shear-induced asymmetry easily in satellite and radar images. Since shear's negative influence in intensity is well known, diagnosis of shear patterns is a key element of satellite intensity estimates.

Shear does not act independently of other environmental influences. The earliest hypothetical mechanism for shear interaction was "ventilation," advection of cooler environmental air into the warm core of the TC vortex. Although it is possible to envision interactions involving eddy exports of angular momentum, for example, something very much like ventilation actually seems to occur, but it is in the lower troposphere, where the diabatic inflow takes place rather than in the upper troposphere where the temperature anomaly responsible for the low hydrostatic pressures lies. Entry of environmental air at 700 hPa, near the θ_E minimum, supplies low-moist-enthalpy air that promotes cold downdrafts leading to lower buoyancy at the base of convection. Thus, shear combines with a dry environment to inhibit intensification. Observations of Atlantic TCs interacting with the Saharan Air Layer (SAL) confirm this connection.

Other differential properties of the flow around TCs can also force interactions. Environmental deformation excites wavenumber-two asymmetries, and environmental vorticity gradients can interact to force wavenumber-one gyres similar to those forced by the poleward increase of planetary vorticity.

1.0.2 Inner-Core Dynamics

The thermodynamics of TC intensification resemble a classical Carnot heat engine in which the Maximum Potential Intensity (MPI) is determined by the temperatures of a warm heat reservoir at the Sea-Surface Temperature (SST, T_s, ~300K) and a cold reservoir at the tropopause temperature (T_c,~200K). MPI is proportional to the thermodynamic efficiency $(T_s - T_c)/T_s$. Inclusion of the heat generated by frictional heating at the ocean surface leads to enhanced efficiency in which T_c replaces T_s in the denominator. Most TCs fail to attain MPI.

In somewhat more detail, the Sawyer-Eliassen process (SEP) describes the kinematics of TC intensification. Latent heat release in the convective updrafts around the eye lofts air from the top of the frictional boundary layer to the tropopause. The updrafts entrain middle-level air as they rise. Thus, frictionally controlled inflow supplies moist enthalpy to sustain the updrafts and the diabatically induced middle level inflow supplies angular momentum needed to spin up the vortex. Intensification through this process is manifested primarily as an increase of the maximum wind and contraction of the radius of maximum wind. A reasonable, but as yet unproven, conjecture is that rapid intensification occurs when the SEP is unfettered by shear, dry-air ventilation, or storm-induced oceanic cooling. Nearly all major ($v_{\max} > 50$ m s^{-1}) TCs form through rapid intensification.

The SEP is quasi-steady in the sense that characteristic times (i.e. period of sinusoidal forcing) are longer than the local inertia period, $2\pi[\,(r^{-1}\partial(rv)/\partial r + f)\,(2v/r + f)\,]^{-1}$. The primary effect of time varying or asymmetric heating is to induce the same change as a quasi-steady symmetric injection of the same amount of *net* heat.

Since the early 1980s, it has been recognized that TCs, particularly intense ones, may exhibit multiple concentric eyewalls. Often the outer most eyewall, which intercepts the high θ_E inflow, will contract and supplant the inner eyewall, leading to a temporary weakening of the TC as a whole. Experience indicates that if conditions (low-shear, warm SST) remain favorable, the TC will generally re-intensify. If not, the eyewall replacement often marks the beginning of TCs' final weakening. Sometimes the eyewall replacement results in formation of an "annular hurricane" composed of an isolated eyewall without spiral band or outer rings of convection. These cyclones do not undergo further eyewall replacements. They generally have intensities about 85% of MPI and seem to be more resistant to shear. Prediction of the timing and intensity modulation due to eyewall replacements remains problematic, although recent results from high-resolution numerical simulations are encouraging.

Although the foregoing description seems to deprecate the roles of non-symmetric, non-steady processes, a well formulated theory of vortex asymmetries has emerged. It encompasses both inertia-buoyancy and vortex Rossby waves (VRWs). In common with their synoptic-scale analogs, VRWs transport wave energy, momentum, and enthalpy. For example, observations show that the air in contact with the sea in the lowest ~kilometer of the eye can attain the highest values of θ_E anywhere in the TC. In rapidly intensifying TCs, the wind profile inside the eye becomes U-shaped in response to the SEP. Thus, the axially symmetric relative vorticity has a maximum between the eyewall and the center of rotation. It then meets the necessary criterion for barotropic instability. Consequently, counter-rotating trains of growing VRWs form, straddling the vorticity maximum. These waves also mix high θ_E air into the eyewall updrafts to "supercharge" the SEP. VRWs may play other significant roles in TC intensification and motion.

Dropsonde observations of the TC boundary layer show a wind maximum at ~500 m altitude in the vortex core and somewhat higher, ~ 1 km, farther from the center. The profile-maximum wind in this jet tends to be 10-30% stronger than the wind at 2-3 km altitude where reconnaissance airplanes fly. The surface wind is somewhat weaker, 80-95% of flight-level wind. Beneath the eyewalls of intense TCs, or on the left of the motion (right in the Southern Hemisphere) it may be 100% of flight-level winds. The strength of the jet at 300-800 m increases toward the TC center. Deceleration of the inflow followed by outward acceleration as air rises above the frictional boundary layer is the primary cause of the jet.

Models and observations show that the greatest inflow occurs near the front of the storm, with the strongest jet about 90 degrees of azimuth downstream on the left side of the motion vector(right in the Southern Hemisphere).

1.0.3 **Air-Sea Interface and Oceanic Influences**

The sea surface provides the warm reservoir for MPI and other thermodynamic calculations, but pre-existent SST is not a good measure of the actual thermodynamic boundary condition at $z = 0$. As they pass, TCs induce mixing at 1 to 3 times the radius of maximum winds and upwelling in the ocean along the track. Shallow mixed layers and slow TC motion increase this effect; deep mixed layers and moderate to fast moving TCs decrease it. Because water has a specific heat twice a great as dry air and is 800 times denser, a few meters of water have the same heat capacity as the entire tropospheric column. Thus, most of the cooling due to TC passage results from entrainment of cold water across the thermocline with only a small contribution from the energy extracted by the storm. As shown above, SST that remains in the range 27-28^{o}C is essential to maintaining the most intense TCs.

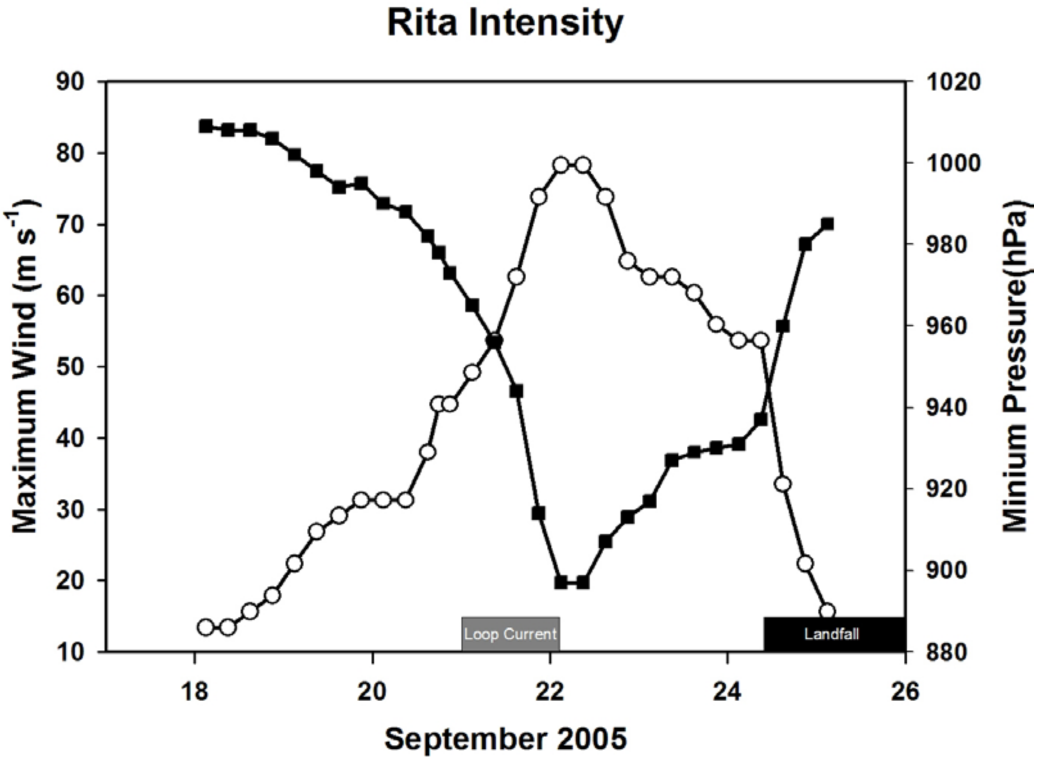

Fig. 1.0.1 Maximum wind (open circles)and minimum pressure (filled squares) histories of Hurricane Rita as it traversed the Gulf of Mexico, illustrating the role of the Loop Current in Rita's rapid intensification.

During the 2005 Atlantic Hurricane Season, four devastating hurricanes, Dennis, Katrina, Rita, and Wilma intensified over the Gulf of Mexico. The first three reached greatest intensity as they passed over the Gulf of Mexico Loop Current (Fig. 1.0.1). They weakened subsequently over the shallower mixed layers in the Gulf Common Water between the Loop Current and landfall. Wilma was a late-season hurricane that reached greatest intensity over the very high ocean heat content water of the western Caribbean, weakened over the Yucatan, and then reintensified as it moved northeastward while in substantial environmental wind shear across the Loop Current to landfall in Florida as a Category 3 hurricane. These events, and the increasing ability of fully coupled models to simulate them, emphasize the need for models that can be initialized to represent both warm and cold mesoscale oceanic features usually associated with strong currents.

Another aspect of the modeling is to capture the extent of the upper ocean cooling induced by shear-induced mixing at the base of the ocean mixed layer. Internal-wave driven shear (primarily at the inertial frequency) lowers the Richardson number below criticality and forces the ocean mixed layer to deepen and cool. However, the extent of the cooling is a function of the strength of stratification, initial layer depth and background currents. Thus, in a broader context, the levels of low-frequency internal wave shear in the upper ocean are analogous to the levels of shear in the atmosphere in affecting TC intensity.

A second frontier of investigation is turbulent transport across the ocean surface. Dropsonde wind profile measurements near the surface show that the wind profile is logarithmic up to 200 m altitude. Surface roughness and drag coefficients deduced from these profile decrease for winds > 33 m s^{-1} so that the drag itself increases very slowly with increasing wind. Laboratory experimentation as well as oceanic response studies find a similar leveling off the surface drag coefficient between 28 to 33 m s^{-1}. It remains unclear whether the surface drag coefficient decreases after this threshold value. Similarly, the enthalpy coefficient, which combines sensible and latent heat exchange effects, appears to level off beyond this wind speed threshold. Observations also support sea-state dependence of these surface exchange coefficients, however wind-wave effects only modulate intensity fluctuations rather than being a direct cause of large intensity and structure changes, as suggested by recent coupled modeling experiments. Nonetheless, these relationships point to a need for three-way coupling between atmospheric, ocean thermal structure and currents, and sea state in the next generation of TC models.

1.0.4 **Operational Techniques for Defining Structure**

Characterization of TC structure and intensity has always been challenging because observations over the sea are so sparse. Starting in the middle 1940s, aircraft observations began to address this problem in the Atlantic and northwestern Pacific. They provided position, maximum estimated surface wind, and extrapolated central pressure. Initially great faith was placed in pressure-wind relations. Airborne and land-based radar provided fairly reliable estimates of radius of maximum wind. The only other measures of structure were manually recorded estimates of outer winds from reconnaissance aircraft and sparse ship, coastal, or island reports.

The advent of polar orbiting provided more position fixes. In the mid-1970s, geostationary satellites supported intensity estimates based upon the Dvorak technique. At approximately the same time, aircraft Inertia Navigation Equipment (INE) allowed accurate measurement of flight-level winds. Aircraft observations could be transmitted to warning centers on low-bandwidth Aircraft-Satellite Data Link (ASDL). In the early 1980s, airborne active C-Band Scatterometers and passive Stepped-Frequency Radiometers promised remotely sensed surface winds, although calibration issues were problematic at first. By the middle 1980s, routine aircraft reconnaissance was confined to the Atlantic with occasional deployments to the northeastern and central Pacific. Thus, the modern climatology of detailed TC structure and intensity is derived from those basins.

Starting in the mid-1950s analytical approximations to the wind as a function of radius began to appear. The earliest version had a single spatial scale, defined by the radius of maximum wind, and a single velocity scale defined by the radius of maximum wind. If the structure of real TCs were actually defined so simply, a one-to-one relationship between minimum pressure and maximum wind would exist, apart from a small latitude-dependant correction proportional to the inverse Rossby-number at the radius of maximum wind.

At the turn of the 21st century, spaceborne sensors--principally scatterometers, passive microwave radiometers, and active radars--seem to offer means to determine TC structure globally by remote sensing. Scattermometers (i.e. QuikSCAT) can sense outer wind structure, although rain contamination and large footprint problems preclude observation of the vortex core. Passive radiometers (i.e. AMSU) can retrieve soundings in the TC environment and estimate surface pressures, at least in geometrically large TCs. Radiometers operating in the 85 GHz band produce images that mimic surface PPI radars. They, along with the TRMM spaceborne radar, can define TC convective structure and rain rate. Although development of algorithms to retrieve intensity by deconvolution of coarse-resolution sounding data given accurate estimates of TC structure have not been forthcoming, this approach seems feasible.

1.0.5 **Operational Guidance and Skill**

As track forecasts have improved, users have come to expect more information on structure and intensity. The concept of “intensity,” as measured by minimum sea-level pressure or maximum wind, is to a great extent artificial. It presents a decision maker with a worst-case estimate of the strongest wind if the storm were to pass directly over a given station. Despite significant advances in numerical weather prediction, the best intensity forecasting guidance comes from statistical models, such as the extrapolation built into the Dvorak technique or the SHIPS statistical technique, and specialized hurricane models, such as GFDL and GFDN. In recent years however, these guidance methods are driving very slow operational intensity forecasting improvements.

Short-term improvements of operational intensity forecasts will likely be realized by using consensus and ensemble methods formed from skillful and independent intensity guidance methods. In the long-term however, intensity forecast improvements will likely come from advanced operational numerical forecast systems. These models will be coupled with the ocean, including wave influences, will incorporate advanced data assimilation techniques which make use of all remotely sensed data, and explicitly resolve convection.

Decision makers require information on the onset and extent of gale-force, 50-kt, or hurricane-force winds. Current guidance based upon imperfect observations and statistical models is, at best, marginally skillful and forecasts provided by current operational numerical prediction models are not skillful. In many circumstances, the geographical extent of overcast or of radar reflectivity serves as a proxy for quantitative forecasts of weather elements. If ensemble forecasting with realistically intitialized high resolution numerical models proves to be feasible, it may be possible to forecast geographical distributions exceedance probabilities for crucial TC impacts. Although these forecasts will prove difficult to verify, they will also support rational decision making with well-defined cost-benefit ratios for preparations.

1.0.6 **Summary**

Accurate forecasts of TC structure and intensity lie on the scientific frontier. Essential prerequisites include: high-resolution (< 2 km) numerical models, ability to initialize them (for most of the world using remotely-sensed data); accurate coupling with ocean thermal structure, current and sea state; and improved representation of physical processes, such as microphyics and turbulent mixing. Because mesoscale motions are inherently sensitive to initial conditions, usable forecasts will probably require ensembles of these models. The benefit of this capability will be accurate and precise forecasts of geographically distributed weather elements, albeit cast in stochastic terms.