NOAA's Hurricane Intensity Forecasting Experiment (IFEX): A Progress Report

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Abstract

1. Introduction

The challenge of improving tropical cyclone (TC) intensity forecasts is well-documented (e.g., Rogers et al. 2006, hereafter R06; DeMaria et al. 2005), and significant research efforts have been directed to improving them. These efforts have included development of numerical models, such as operational models that are approaching cloud-permitting resolution (HWRF, GFDL refs….) and research models that are capable of resolving energy-containing eddies (AHW-LES refs….), new techniques for assimilating inner-core observations into these numerical models (F. Zhang refs, others?….), techniques for optimizing ensemble forecasts of TC intensity (refs….), and refinement of statistical/dynamical models for predicting TC intensity change and rapid intensification (RI; SHIPS and RII refs….). Progress remains elusive, however. For example, while the NHC official 48-h track forecast error has decreased about 50% between 2000 and 2010, the intensity forecast error over the same period has remained virtually unchanged (see, e.g., http://www.nhc.noaa.gov/verification/verify5.shtml). Clearly a great deal more work is needed.

In 2005 NOAA began a multi-year experiment called the Intensity Forecasting Experiment (IFEX; R06). As the name states, the ultimate aim of IFEX is to improve the prediction of TC intensity. There are three primary goals proposed by IFEX to improve TC intensity predictions, as spelled out in R06. They are as follows:

1. Collect observations that span the TC life cycle in a variety of environments for model initialization and evaluation;

2. Develop and refine measurement strategies and technologies that provide improved real-time monitoring of TC intensity, structure, and environment;

3. Improve the understanding of physical processes important in intensity change for a TC at all stages of its life cycle.

NOAA, through a partnership among various agencies such as the Hurricane Research Division, Aircraft Operations Center, National Hurricane Center, and Environmental Modeling Center, has flown IFEX aircraft missions every year since 2005. While improvement in intensity forecasts has been limited during that time, a significant amount of research and development deriving from IFEX activities is ongoing, and this holds the potential from producing improvements in intensity forecasting. The purpose of this paper is to provide a brief summary of significant IFEX missions that have occurred since 2005 and an overview of the research and development efforts that have arisen from these missions that aim to improve TC intensity forecasts.

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2. Summary of significant IFEX missions

Since TC intensity change is a multi-scale process (e.g., Marks and Shay 1998), the experiments flown during IFEX are designed to collect measurements of physical processes that span many of these spatial and temporal scales. An example of this multi-scale approach to data collection is shown in Fig. Rog1, which lists the experiments proposed for the 2011 IFEX Field Program[1] and shows where each experiment falls on the spectrum of spatial scales, from environmental to microscale scale. Figure Rog1 also shows which IFEX goals are covered by each experiment. Note that in several cases one experiment can address multiple spatial scales

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[1] For a complete description of IFEX experiments during 2011, see (URL????)

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and IFEX goals. The measurements taken in the various experiments are collected primarily using NOAA's heavy manned aircraft that are used in TC reconnaissance and surveillance: the two NOAA WP-3D and G-IV aircraft. However, as will be discussed later, some measurements have been collected using high-altitude and low-altitude unmanned aerial systems.

A similar distribution of experiments was proposed for previous years as a part of IFEX. Whether or not an experiment is flown in a given year is of course dependent on the availability of appropriate targets, proximity to bases, and other logistical considerations. However, with several years of IFEX flights, plus the addition of flights from years prior to the beginning of IFEX, a significant proportion of these experiments have been flown and are being analyzed. Table XX provides a summary of significant IFEX missions from 2006-2011. [……]

3. Addressing the IFEX Goals

The IFEX research efforts span all three goals listed above. While the primary IFEX activities focus on the collection and analysis of aircraft observations, they by necessity are closely linked with other research and development activities geared toward improving TC intensity forecasts. Since a significant component of intensity forecasting is dependent on numerical model guidance, much of the analysis of data collected during IFEX is used to improve numerical models by advancing data assimilation and model evaluation. An additional aspect of improving intensity forecasts is improving the real-time assessment of TC structure, intensity, and environment through enhanced observational capabilities and improved sampling strategies. Finally, an improved understanding of the physical processes important for TC intensity change is an essential component of any efforts for improving intensity forecasting, as they provide the context for assessing the performance of numerical models and for modifying

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the model representation of physical processes. An overview of the analyses and advancements resulting from some of these missions is provided below.

a) IFEX Goal 1: Collect observations that span the TC life cycle in a variety of environments for model initialization and evaluation

(1) Real-time Doppler radar analysis and transmission of data from aircraft (Gamache, Tallapragada)

(2) Data assimilation development (Aksoy, Vukicevic, Sellwood, Aberson)

HEDAS development and testing

(3) Numerical model development and evaluation

(a) HWRFv3.2 development

The HWRF system was developed at NOAA's National Weather Services (NWS)/ NCEP to address the Nation's next generation hurricane forecast problems and became an operational track and intensity guidance tool in 2007. A version of this evolving system is available at the Development Test bed Center (DTC), National Center for Atmospheric Research (NCAR), in Boulder, Colorado and the scientific documentation (Gopalakrishnan et al. 2010) is also available at:

http://www.dtcenter.org/HurrWRF/users/docs/scientific_documents/HWRFScientificDocumentation2011.pdf. An Experimental version of the HWRF system (dubbed as "HWRFX") was specifically adopted and developed at the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory (AOML) to study the intensity change problem at cloud-resolving scales (about 1-3 km). This modeling system is supported by NOAA's Hurricane

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Forecast Improvement Project (HFIP) and complements the operational HWRF system. The HWRFX can be run both in an idealized (Gopalakrishnan et al. 2011a and Bao et al., 2011) as well as real framework (Zhang et al. 2011, Yeh et al. 2011 and Pattanayak et al. 2011) and is also linked to the Hurricane Ensemble Kalman Filter Data Assimilation System (HEDAS). Until recently, we developed and tested new techniques with the HWRFX, and evaluated their potential to improve hurricane forecasts, before they are formally adopted for operation within the HWRF (e.g. Gopalakrishnan et al., 2011b and Laureano et al., 2011). As the research and operational communities work together under the auspices of HFIP to improve tropical storm intensity forecasts, we realized an urgent need to merge the two systems. The merger of the Experimental and operational system, HWRFV3.2 is currently used in NOAA for further advancements of the high resolution intensity forecasts.

One popular configuration, with a potential to transition to operations, is the triply nested version of the HWRFV3.2 system (X.Zhang et al., 2011). That system is configured with a coarse mesh of 27 km horizontal grid spacing covering about 75^0x 75^0 degrees and two, two-way telescopic moving nests at 9 km covering about 15^0x 15^0 degrees and 3 km covering about 5^0x 5^0, respectively. There are 42 hybrid levels with at least 10 levels below the 850-mb-level. The 3 km domain configuration is designed to provide adequate coverage of the inner core storm structure essential to improve intensity forecasts. Similar to the operational HWRF, storm relocation, vortex initialization and cycling is performed at 9 km resolution, with the 3 km domain being downscaled from the 9 km analysis domain. The atmosphere component is coupled to the Princeton Ocean Model (POM) for all three domains, which employs feature-based initialization of loop current, warm and cold core eddies and cold wake during the spin-up phase. This version of the model also includes surface and boundary layer physics appropriate for higher

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resolution (Gopalakrishnan et al., 2011c). As a part of the HFIP demonstration effort and also a basic need to transition research to operations, the model was run for the 2011 hurricane season. The track and intensity errors obtained from these runs at this time are provided in Fig Gop1. The higher resolution version provides improved intensity forecast skills compared with the operational (i.e., 9 km grid length) HWRF. Based on the 2011 seasonal statistics as well as several retrospective runs from the 2007-2010 seasons we estimate a 10-15% improvement in intensity forecast with the high resolution version of the HWRF system. However, the Global Forecasting System (GFS) provides better track skills (Fig. Gop1). It is not clear at this time if the lag in track forecast skill of mesoscale models, in general, is related to the size of the domain configuration.

We propose a practical solution to target not only the domain size issues but also 7-day hurricane forecasts in the Atlantic basin with a high resolution modeling system: the multiple moving nests within a basin-wide HWRF system. Our objective is to develop a forecast system which can follow multiple storms with each storm having multiple nest levels to meet the required high- resolution and domain coverage to resolve the evolution of large-scale systems, the hurricane related mesoscale convective features, and multi-scale interactions. While the earlier generations of NOAA's regional scale hurricane models were based on storm specific events that pose constraints on advancing the data assimilations techniques, we introduce here a tropical prediction system. The high resolution tropical prediction system is also expected to open up multi-scale forecasting of the tropical weather from easterly waves that may have a potential to cause significant rain events along the coastal United States to the genesis of tropical cyclones. The prototype configuration is provided in Fig. Gop2. This system (without the multiple moving nest, but with a fixed domain over Florida for the benefit of the Weather

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Forecast Office at Miami and Melbourne) was run for the 2010 hurricane season to track large scale features such as tropical waves and hurricanes. This configuration will be evaluated at the end of the 2011 season.

(b) Model evaluation (Vukicevic, Murillo, Annane, Powell)

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With the advent of operational numerical models capable of being run at comparatively high resolution, the ability to evaluate the inner-core structure of TC's produced by these models using observations collected from aircraft becomes possible. If performed in a systematic, multi-case mode, such an evaluation can identify biases in the model and highlight possible model deficiencies such as errors in physical parameterizations and inadequate resolution. Figure Rog2 shows an example of this type of evaluation. A comparison of the axisymmetric tangential wind from a composite of aircraft flights in mature TC's (Rogers et al. 2011) with a composite of multiple simulations of mature TC's using a 3-km version of the HWRF model (Fig. Rog2a-b) shows that the model-generated axisymmetric tangential wind is generally similar to that observed from the Doppler radar. However, a comparison of the axisymmetric lower-tropospheric radial wind from a composite of several hundred GPS dropsondes in mature TC's (Zhang et al. 2011) with a comparable composite from the 3-km HWRF model (Fig. Rog2c-d) shows that the model inflow layer is much deeper and weaker than observed for this model configuration. Modifications to the planetary boundary layer parameterization can be proposed and evaluated using this framework, and work is ongoing on this topic.

Satellite simulators from model output

H*Wind development and application to model evaluation

b) IFEX Goal 2: Develop and refine measurement strategies and technologies that provide improved real-time monitoring of TC intensity, structure, and environment

(1) Unmanned aerial systems

(a) Low-altitude systems (Cione)

(b) High-altitude dropsondes (M. Black)

(2) Surface wind measurements

Accurately measuring surface wind speeds in tropical cyclones is important for determining tropical cyclone intensities. The Stepped Frequency Microwave Radiometer (SFMR) is a tool on the NOAA WP-3D aircraft that provides estimates of the surface wind speed and rain rate within the storm environment (Uhlhorn and Black 2003; Uhlhorn et al 2007). As noted in R06, SFMR instruments were installed on both NOAA P-3 aircraft for use during the 2005 hurricane season, and numerous flights have occurred across the Atlantic and East Pacific basins since those additions. The SFMR performs fairly well compared to the GPS dropsonde surface-adjusted wind speed within the hurricane wind speed regime (R06), but noticeable high bias is present in the tropical depression and tropical storm wind regimes when rain rates are high. In order to address this issue, ongoing work is being conducted to analyze the performance of the SFMR in high rain rate/low wind speed conditions. The SFMR is believed to have this wind speed bias because at the lower wind speeds, the current geophysical model function (GMF) was tuned to GPS dropsonde surface winds obtained within areas with little or no heavy precipitation. Additionally, a biased rain absorption model was used to develop the current surface emissivity vs. wind speed GMF, leading to the erroneous wind speeds.

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Increased emphasis has recently been placed on gathering dropsonde data in these high rain environments to help separate the two signals accurately. A database of paired SFMR surface wind speeds and GPS dropsonde surface-adjusted wind speeds has been expanded to include NOAA P-3 data between 2005-2011. These pairs are formed based on work presented in Uhlhorn and Black (2003) and Uhlhorn et al. (2007), where the GPS dropsonde surface adjusted wind speed is calculated using a reduction factor of the average wind speed within the lowest 150 m (Franklin et al. 2003) and is then paired with the SFMR wind at the launch time of the dropsonde. Figure BK01(a) shows a histogram of weak wind speeds (< 33 m s^{-1}) for NOAA wind pairs between 2005-2009 and between 2005-2011 in order to show the difference in the number of pairs added during the 2010-2011 seasons. Numerous pairs were added at the lower to moderate rain rates (< 15 mm hr^{-1}), but at the higher rain rates, the number increased by over 50% during the two year span. In Fig. BK01(b), the hurricane force winds are presented similarly to (a), but the number of pairs collected over the past two seasons increases consistently across a majority of the rain rate bins compared to the 2005-2009 period. These results show that while it may be easier to capture heavy precipitation within the hurricane wind speed regime, there is still some difficulty to do so in the weak wind regime. However, the additional pairs at the lower wind speeds and higher rain rates will improve the assessment of the wind speed bias and allow for correction of the SFMR algorithm.

(3) Optimal flight pattern design

Improvement of TC intensity forecasts is highly dependent upon advancements made in data assimilation, which in turn relies on the optimization of data sampling methods and flight pattern design. In an effort to provide a better initialization of TC inner-core structure greater emphasis has been put on improving the acquisition of real-time observational data. To do so,

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one of the IFEX activities investigates the optimum manner to collect airborne observational data that will maximize the impact of the data on model initialization. The goal is to carry out this activity through Observing System Simulation Experiments (OSSEs), where NOAA P3 flight tracks are designed, data are simulated from a nature run and then assimilated using HRD HEDAS system and the impact of a particular flight track is then assessed. The first step of the activity was to develop an OSSE system capable of such airborne data simulation and results are presented in Aksoy et al. (2011, in review).

(4) G-IV Tail Doppler Radar (Gamache, Reasor)

c) IFEX Goal 3: Improve the understanding of physical processes important in intensity change for a TC at all stages of its life cycle

(1) Multiscale structure of mature hurricanes

While a primary goal of IFEX (R06) is to sample TC's at all stages of their lifecycle, a significant number of flights in the HRD database have occurred in TC's at the mature stage of their lifecycle. Such a large database provides the opportunity to study the properties of these TC's in a composite framework, providing statistical characteristics such as the mean and variance properties and enabling a subsampling of TC structure based on prescribed parameters such as TC size, intensity, motion, and future intensity change. A significant amount of ongoing work involves mining this database to construct composites spanning several spatial scales.

(a) Vortex-scale

Rogers et al. (2011) examined the axisymmetric structure of mature tropical cyclones using composites of tail Doppler radar measurements from 40 radial penetrations in TC's over a decade. Figure Rog3 shows the tangential and radial wind, reflectivity, and horizontal relative

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vorticity from this composite. Many structures seen in previous radar-based studies are seen in this composite, including the primary and secondary circulations, eyewall slope, decay of the tangential wind with height, low-level inflow layer and region of enhanced outflow, radial variation of convective and stratiform reflectivity, eyewall vorticity, and rainband signatures in the radial wind and vorticity fields (e.g., Marks and Houze 1987, Marks et al. 1992, Hence and Houze 2008, Stern and Nolan 2009).

***(add asymmetric discussion here) *** (Reasor)

(b) Convective-scale

Statistics of convective-scale fields (e.g., vertical velocity, reflectivity, vorticity) and how they vary as a function of proximity to the radius of maximum wind were also calculated in Rogers et al. (2011). An example of this is shown in Fig. Rog4, which shows the vertical profile of mean vertical velocity as well as the contoured frequency by altitude diagram (CFAD; Yuter and Houze 1995) for two regions: the inner eyewall edge, defined as between 0.75 and 1 x radius of maximum axisymmetric tangential wind (where the radius of maximum wind is defined as where the normalized radius, $r^*=1$) at 2 km altitude, and the outer radii, defined as $r^* > 1.5$. Not surprisingly, the mean vertical velocity along the inner eyewall is higher than in the outer radii. The CFAD for the inner eyewall (Fig. Rog4b) shows a broad spectrum of updrafts and downdrafts, with peak up- and downdraft values ranging between 10 and -7 m s^{-1}, indicating that significant downdrafts can exist along the inner edge of the eyewall. The bulk of the distribution (15-30%), though, is found between -1 and 3 m s^{-1}. Modal values are between 1 and 2 m s^{-1} and reach a peak around 6 km, similar to the mean profile. The CFAD of vertical velocity for the outer radii (Fig. Rog4c) shows a narrower distribution of vertical velocities than in the eyewall,

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with peak up- and downdrafts of 5 and -4 m s^{-1}, respectively, and the bulk of the distribution between -1 and 1 m s^{-1}. This distribution is consistent with vertical incidence measurements of vertical velocities for stratiform regions (e.g., Black et al. 1996), indicating that this radial region is primarily associated with stratiform processes.

(c) Boundary-layer scale

The hurricane boundary layer (HBL) has long been known to play an important role in the energy transport processes of a hurricane, regulating the radial and vertical distributions of momentum and enthalpy that are closely related to storm development and intensification (e.g., Ooyama 1969; Emanuel 1986; Wroe and Barnes 2003; Smith et al. 2008; Rotunno et al. 2009; Bryan and Rotunno 2009; Smith and Montgomery 2010). While recent studies using observational data from the CBLAST field campaign in 2003-2004 have improved the understanding of the mean and turbulence structure of the boundary layer in tropical cyclones (e.g., Black et al. 2007, Zhang et al. 2008, 2009, Bell and Montgomery 2008), these measurements were primarily taken in wind speeds that were below hurricane strength. Recent composite analyses of airborne Doppler radar data (Rogers et al. 2011) and GPS dropsonde data (Zhang et al. 2011) from multiple hurricanes at various stages of their lifecycle, including major hurricane strength, have allowed for a more comprehensive representation of the HBL.

Figure LorZha1 shows the composite boundary-layer radial flow from both datasets. Many of the features found in the dropsonde composites of Zhang et al. (2011) are also indicated in the airborne Doppler composite. When scaled by the radial flow at the eyewall (r*=1) and 150 m altitude, the Doppler radial flow shows that the inflow depth, defined in Zhang et al. (2011) as the height representing 10% of the scaled low-level inflow value, increases with increasing

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distance from the eyewall. The inflow depth increases from about 750 m at the eyewall to 1250 m at r*=3 in both the Doppler and dropsonde composites. Furthermore, the peak inflow in both composites, indicated by regions > 100% near the surface, are located near r*=1.1-1.2, just outside the normalized radius of maximum winds. Finally, both composites show the outflow feature above the inflow layer just inside r*=1. This feature is much narrower in the Doppler composite, likely due to the higher radial resolution in this dataset compared to the dropsonde dataset (1.5 km for Doppler vs. ~8 km for dropsonde). The fact that both composites, using completely independent data sources, calculation methods, and hurricanes comprising the composite, produce such similar features lends greater confidence that the boundary-layer radial flow structures described here are robust.

The dropsonde composite analysis by Zhang et al. (2011) also revealed that there is a clear separation of the HBL height defined thermodynamically and dynamically. Zhang et al. (2011) found that the thermodynamic boundary layer height increases with increasing distance from the storm center, similar to the dynamic boundary layer height, and the height of the maximum tangential wind and mixed layer depth occurs inside the HBL regardless of hurricane intensity. Given the extensive dataset (i.e., HRD's 20 year Doppler radar and dropsonde data from the research aircraft), statistical analyses of the various characteristics of the HBL structure (e.g., inflow layer depth, inflow/outflow magnitude, turbulent kinetic energy, equivalent potential temperature) are now possible and will enable the investigation of the potential relationships of these characteristics with TC strength, intensity change, vertical wind shear magnitude and location with respect to the shear direction.

(thermodynamic structure) (Cione, Uhlhorn, J. Zhang)

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(d) Turbulent-scale

Turbulent transport processes in the hurricane boundary layer play a significant role in the redistribution of momentum and enthalpy, and are therefore very important to hurricane maintenance and intensification (e.g., Emanuel 1995; Smith et al. 2008; Foster, 2009; Rotunno et al. 2009). However, there have been few direct measurements of turbulence in the boundary layer of hurricanes or tropical storms until now. The fast-response (40 Hz) flight-level data collected by NOAA's P3 aircraft in the hurricane boundary layer (60-400 m above the sea surface) during HRD's annual field program in the 2002-2004 hurricane seasons provide a unique opportunity for studying turbulence in the hurricane boundary layer. Through analyzing the above data set, Zhang et al. (2009) for the first time presented vertical structure of directly measured turbulent fluxes in the boundary layer of intense hurricanes. They conducted also the turbulent kinetic energy (TKE) budget and found that the major source, the shear production, is dissipated locally with the buoyancy and turbulent transport terms being relatively unimportant. Their TKE budget indicates also that the dissipation term is greater than the production terms by 50% in the surface layer extrapolated from above. Analyzing the turbulence data below 200 m above the sea surface, Zhang (2010) estimated the dissipative heating using two different methods, one by integrating the directly measured rate of dissipation in the lowest 200 m above the sea surface, and the other by multiplying the cube of the surface wind speed and the drag coefficient. The latter method has been used in theoretical and numerical hurricane models (e.g., Bister and Emanuel 1998, Zhang & Altshuler 1999; Wang 2001; Jin et al. 2009; Bryan & Rotunno 2009). Zhang (2010) found that this theoretical method significantly overestimates the magnitude of dissipative heating, suggesting that it is essential to understand the physical processes associated with dissipative heating while implementing it into hurricane models.

In numerical models, turbulent flux in the atmospheric boundary layer is generally parameterized through eddy diffusivity. Theoretical and numerical studies have shown that both vertical and horizontal eddy diffusivities are important for hurricane intensity and structure simulations (e.g., Foster 2009, Bryan and Rotunno 2009). However, observational estimates of the eddy diffusivity are scares, especially for high wind conditions (> 15 m s^{-1}). The NOAA P-3 data again provided a unique tool for estimation of the eddy diffusivity. Using the data from the periods of eyewall penetrations in the intense Hurricanes Hugo (1989) and Allen (1980), Zhang et al. (2011) made the first estimate of vertical momentum flux and the corresponding vertical eddy diffusivity in the inflow layer in intense hurricanes. These authors found that the vertical eddy diffusivity is on the order of 100 m^2 s^{-1} at ~ 500 m in the intense eyewall with flight-level mean wind speed up to 65 m s^{-1}. They found also that the vertical eddy diffusivity increases with increasing wind speed at the similar altitude. Zhang and Montgomery (2012) estimated the horizontal eddy diffusivity and mixing length by analyzing the data from Hurricane David (1979) in addition to the Allen and Hugo data. They found that the magnitude of horizontal momentum flux is comparable to that of the vertical momentum flux, indicating that horizontal mixing of turbulence becomes non-negligible in the hurricane boundary layer, especially in the eyewall region. The above results based on the data collected during HRD's field experiments would provide useful guidance of numerical models simulating hurricanes, and part of those have been implemented in the Hurricane Weather Research and Forecast model (HWRF) under development at HRD in collaboration with EMC.

In addition to turbulence properties derived from flight-level data described above, the tail Doppler radar has also been used to obtain information about the distribution of turbulent kinetic energy (TKE) in mature TC's (Lorsolo et al. 2010). The analysis is based on the fact that

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the Doppler measurement can be expressed as the sum of the mean radial velocity over a grid cell and a turbulent part. The turbulent part is represented by the variance of measurements of ~150 m spatial resolution about the mean Doppler radial velocity of a 10 km (across flight track) x 1.5 km (along flight track) x 0.15 km (vertical) grid cell centered on the flight track. To compute TKE the profile values of all three wind components are determined from all the 150-m range gates within a profile volume. The projection of this velocity is then subtracted from all the individual range-gate observations to determine a residual radar-radial velocity variance that represents the TKE. Although the method cannot capture the far (blue) end of the spectrum, the fine bin spacing allows the resolution of the energy associated with small scales of motion.

A composite of TKE using the same TC's as that shown in Figs. Rog3-4 was presented in Rogers et al. (2011). Two primary regions with relatively high TKE are apparent (Fig. Lor1) -- in the boundary layer outside of the RMW and within and just along the inner edge of the eyewall. The highest values are located at r*=0.75 below 2 km and could be related to the high gradient in radial wind occurring here. A secondary maximum in TKE is evident at r*=2-2.5 between the surface and 6 km altitude, reflecting other areas of stronger turbulence (e.g., rainbands and secondary eyewalls). The analysis suggests that TKE can be an effective diagnostic tool to assess the dynamical boundary depth as it can be challenging to estimate (e.g., Zhang et al. 2011a). The high values of TKE in the HBL and in the eyewall imply that turbulent energy is being injected into the eyewall region to supplement the already existing turbulent energy as mentioned by Smith and Montgomery (2010).

(2) Rapid intensification

While TC intensity prediction represents a challenge for the forecasting community, predicting rapid intensification (RI) is even more difficult, and it is potentially much more

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significant if an RI event occurs near landfall. Most research has focused on various spatial scales and their importance in RI, primarily ranging from the environmental (e.g., Bosart et al. 2000, Shay et al. 2000, Kaplan and DeMaria 2003, Dunion and Velden 2004) to the vortex (Kossin and Eastin 2001, Nolan et al. 2007, Sang et al. 2008, Reasor et al. 2009) to the convective scales (Kelley et al. 2004, Squires and Businger 2008, Guimond et al. 2010, Rogers 2010). IFEX is continuing this line of research by continuing to develop statistical-dynamical models for predicting RI based on environment, vortex, and convective structure and performing intensive multiscale analyses of cases of RI sampled by the NOAA aircraft.

(a) RI index (Kaplan)

(b) Earl preliminary analysis

One RI event that was particularly well-sampled by aircraft occurred in Hurricane Earl in 2010. Figure Rog5 shows the times samples by NOAA aircraft during one portion of Earl's lifecycle, from ~18 UTC August 28 to 00 UTC August 31. At the beginning of this time window Earl was a moderate tropical storm with peak winds of 50 kt (from the Best Track). Over the next 54 h, Earl underwent RI, increasing from a 55-kt tropical storm to a 115-kt major hurricane between 09 UTC August 29 and 21 UTC August 30. Five NOAA WP-3D flights occurred during this window, including before, during, and at the end of RI. Additionally, three NOAA G-IV flights occurred, providing excellent inner-core and environmental sampling during RI (while not shown, note that two NASA DC-8 flights and four Air Force C-130 flights also occurred during this time). The evolution of the axisymmetric tangential wind during RI is shown in Fig. Rog5b. This field is derived from the airborne Doppler radar onboard the WP-3D. Figure Rog6 shows the wind field at 2 km and 8 km during the WP-3D flight during the 12 h prior to the onset of RI and again during the subsequent WP-3D flight when RI began. The circulation center is indicated on each figure. Note that the circulation center at 8 km is significantly displaced to the east of the 2-km center prior to the onset of RI (Fig. Rog6a-b). By the time of RI onset (Fig. Rog6c-d), the 8-km center is nearly collocated with the 2-km center. This evolution highlights the potential importance of vortex alignment in RI, something which has been studied in previous case studies (e.g., Guillermo of 1997 in Reasor et al. 2009, Reasor and Eastin 2011, other obs or modeling studies??). Given the excellent inner-core and environmental coverage by the various aircraft sampling Earl, this case should provide new insight into the role of environmental, vortex, and convective structure in RI.

(3) Dry air impacts (Dunion)

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The American Meteorological Society's (AMS) Glossary of Meteorology (Glickman 2000) defines arc clouds as a line of cumuliform clouds that form as a result of local convergence along the boundary separating low-level convective storm outflow from the surrounding environment. Although arc clouds are common features in mid-latitude thunderstorms and MCSs, they have only occasionally been noted in TC environments (Knaff and Weaver 2000). Arc clouds denote the presence of a density current that forms when dry low to mid-level (~600-800 hPa) air has interacted with precipitation. The convectively-driven downdrafts that result can reach the surface/near-surface and spread out from a thunderstorm's convective core. We hypothesize that the mid-level moisture found in the *moist tropical* North Atlantic sounding described by Dunion (2011) is insufficiently dry to generate extensive arc clouds around African easterly waves (AEWs) or TCs. However, substantial arc clouds (100s of km in length and lasting for several hours) consistently form in the tropics in the periphery of these tropical disturbances. Dunion (2011) described two additional types of air masses that are

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frequently found in the tropical North Atlantic and Caribbean that could effectively initiate the formation of large arc clouds: the *Saharan Air Layer* and *mid-latitude dry air intrusions*. Both of these air masses were found to contain substantially dry air (50-60% less moisture than the *moist tropical* sounding) in the middle levels of the atmosphere and can affect the tropical North Atlantic and Caribbean throughout the summer months. We hypothesize that the processes leading to the formation of arc cloud events can significantly impact an AEW or TC (particularly smaller, less developed systems). Specifically:

1. Enhanced static stability: the cool, dry air associated with the convectively-driven downdrafts that for arc clouds can help stabilize the middle to lower troposphere and may even act to stabilize the boundary layer. Additionally, when arc clouds form in the forward quadrants of a storm, their associated higher stability air may be more effectively entrained into the TC circulation;

2. Enhanced low-level outflow: the arc clouds themselves may also act to disrupt the storm. As they race away (~20-50 kt) from the convective core region, they create low-level outflow in the quadrant or semicircle of the African easterly wave (AEW) or TC in which they form. This outflow pattern counters the typical low-level inflow that is vital for TC formation and maintenance;

Recent analyses using the Statistical Hurricane Intensity Prediction Scheme (SHIPS) Rapid Intensity Index (RII, Kaplan et al. 2010) suggests that the positioning of low to mid-level dry air up-shear (i.e. the 200-850 hPa vertical wind shear direction) of a TC may be an important predictor regarding the influence of dry air on TC intensity. Specifically, twenty-one Atlantic total precipitable water (TPW) predictors were tested and identified in the RII database (1999-

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2008) and the most statistically robust TPW predictor was the percentage of dry pixels (<45 mm, Dunion 2011) located 0-500 km from the storm center and within a 90 degree wedge centered around the shear vector (Fig. jpd1). Interestingly, arc clouds also appear to preferentially form in these areas where low to mid-level dry air is located up-shear from the storm. We hypothesize that enhanced vertical wind shear (~≥15 kt) makes the storm increasingly vulnerable to dry air intrusions near the periphery of the inner core convection. These dry air masses would normally have large radius of trajectories around the periphery of the storm and entrainment would ordinarily require significantly more time to evolve. This analysis technique of identifying low to mid-level dry air with satellite imagery and its position relative to the up-shear vertical wind shear vector was recently used to successfully target aircraft sampling (NOAA G-IV jet) of arc clouds using GPS dropwinsondes in the environment of 2011 Hurricane Katia.

Future IFEX plans will include gathering more detailed observations of these unique environments around AEWs and TCs, observing their thermodynamic and kinematic impacts on the local environment near the TC inner core, and examining their formation and evolution using numerical simulations.

3. Progress in intensity forecasting and future plans

a) Potential for improved forecasts using HWRFv3.2 (Gopal, Tallapragada, Aksoy, X. Zhang, Yeh, Aberson, Goldenberg)

Include statistics from retrospective runs

b) IFEX interactions with Hurricane Forecast Improvement Project (Marks)

References

Dunion, J.P., 2011: Re-Writing the Climatology of the Tropical North Atlantic and Caribbean Sea Atmosphere. *J. Climate*. **24 no. 3**, 893-908.

Glickman, T. S., Ed., 2000: *Glossary of Meteorology*. 2d ed. Amer. Meteor. Soc., 782 pp.

Kaplan, J., M. DeMaria, and J.A. Knaff, 2010: A revised Tropical Cyclone Rapid Intensification Index for the Atlantic and eastern North Pacific basins, *Wea. Forecasting*, **25 no. 1**, 220-241.

Knaff, J. A., and J.F. Weaver, 2000: A mesoscale low-level thunderstorm outflow boundary associated with Hurricane Luis, *Mon. Wea. Rev*., **128**, 3352-3355.

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IFEX 2011 Flight Experiments

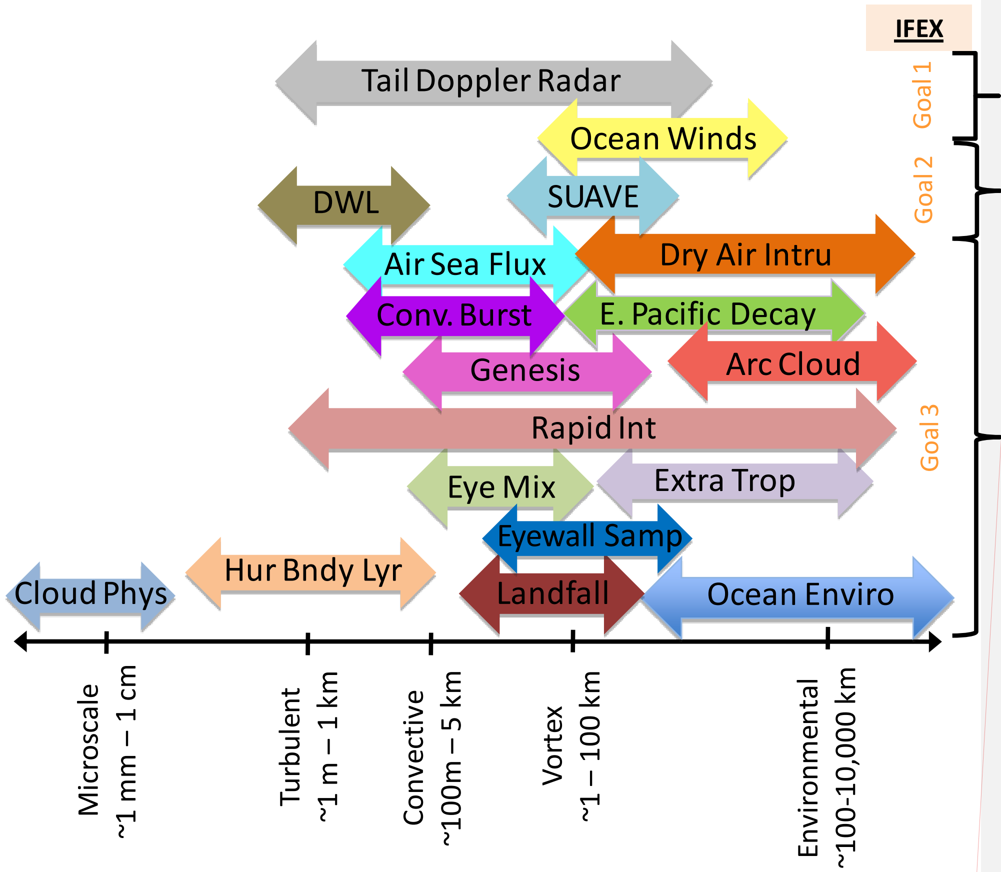

Figure Rog1: Airborne Doppler composite fields of axisymmetric (a) tangential wind (m s^{-1}); (b) radial wind (m s^{-1}); (c) reflectivity (dBZ); and (d) vertical relative vorticity (x 10^{-4} s^{-1}).

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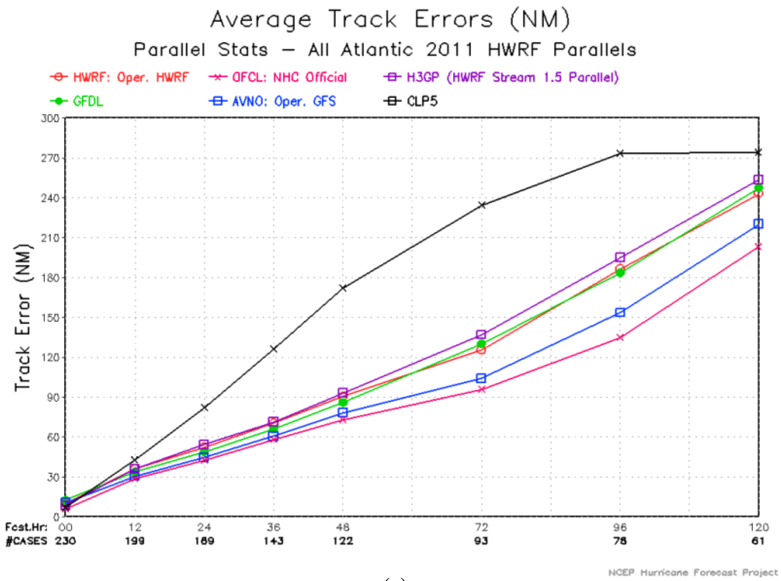
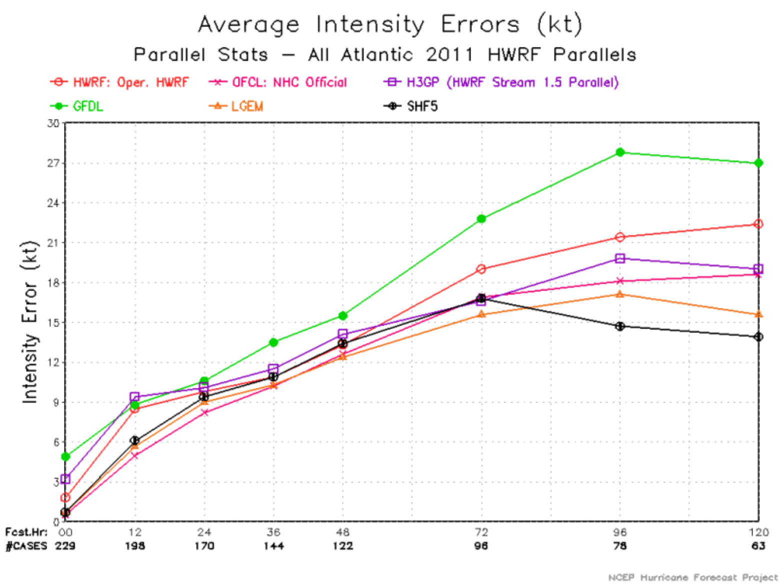


(a)



(b)

Figure Gop1: Average (a) track and (b) intensity errors for the 3 km HWRF system for the 2011 Atlantic Season (from tropical cyclone Arlene to Nate)

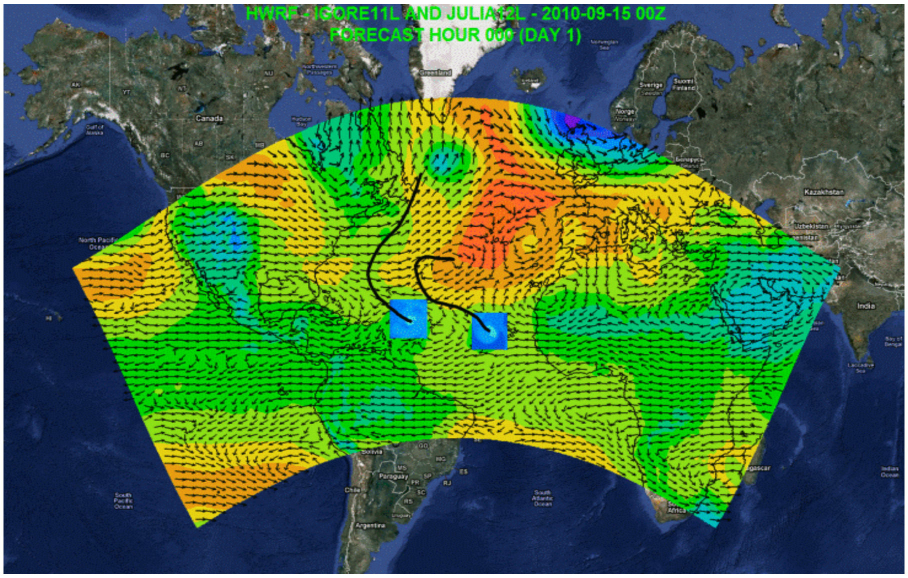


Figure Gop2: Basin Scale HWRF with multiple moving nested domain. The example shows tropical cyclones Igor and Julia with the tracks.

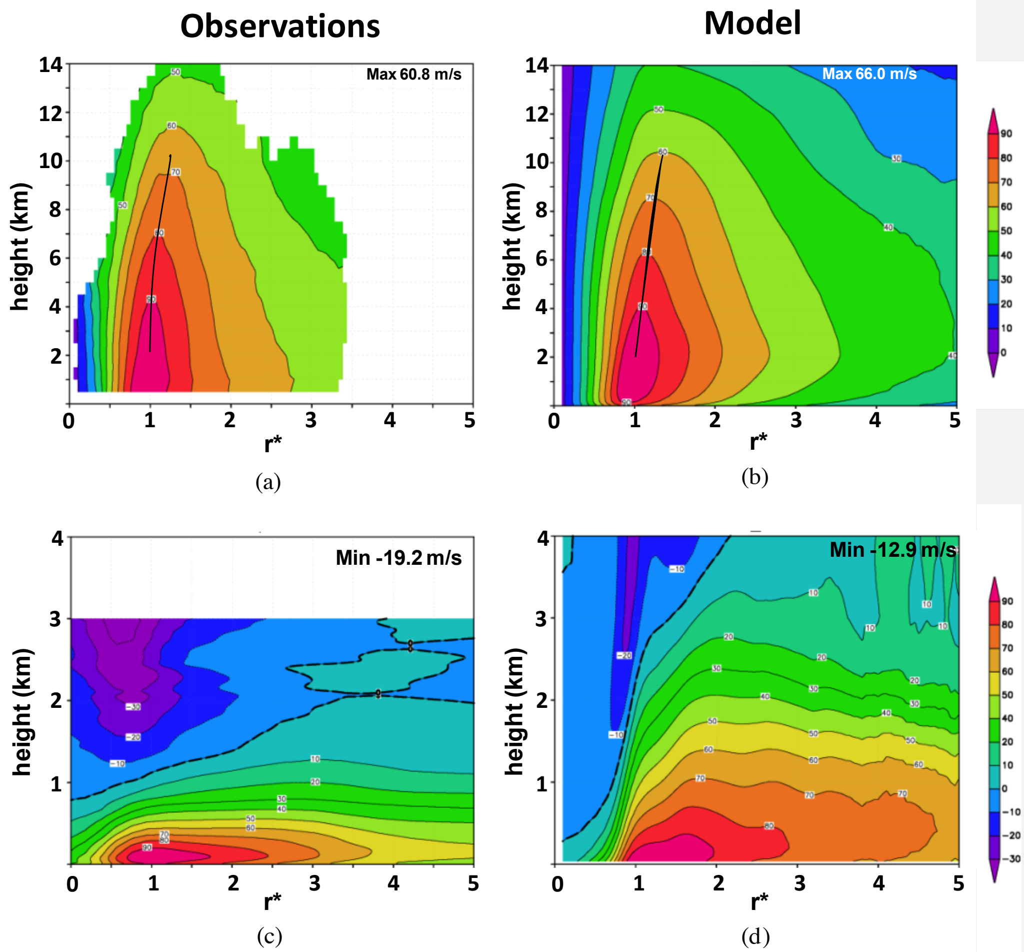


Figure Rog2: (a) Composite mean radius-height fields of axisymmetric tangential wind (shaded, %) from airborne Doppler dataset. Radial dimension plotted as normalized radius r*, where r* is the ratio of the actual radius and $RMATW_{2km}$. Field is plotted as a percentage of the maximum value, provided in figure; (b) As in (a), but for model composite; (c) Composite mean radius-height fields of axisymmetric radial wind (shaded, %) from GPS dropsonde dataset. Field is plotted as a percentage of the peak inflow, where positive (negative) percentages represent inflow (outflow); (d) As in (c), but for model composite. Solid lines in (a) and (b) denote axis of peak axisymmetric tangential wind; dashed line in (c) and (d) represent 0% contour, or transition from inflow to outflow.

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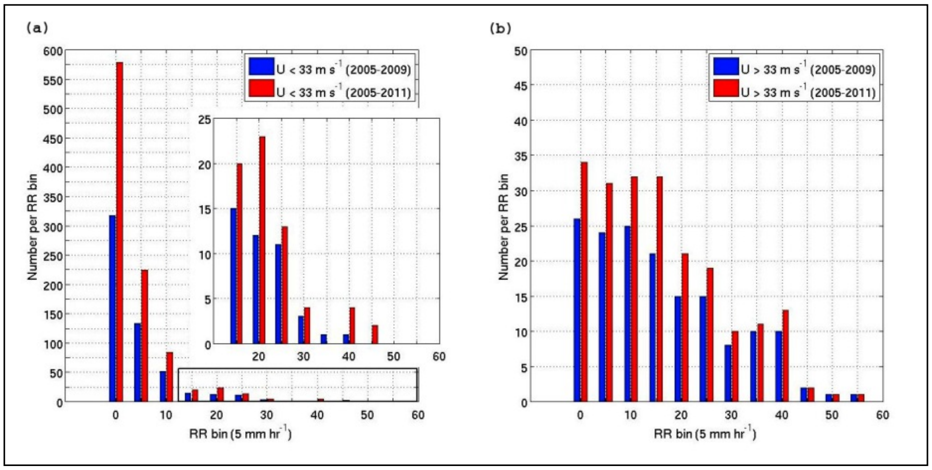

Figure BK01. (a) Histogram of SFMR wind speed (< 33 m s^{-1}) and GPS dropsonde surface-adjusted wind speed pairs for 2005-2009 and 2005-2011. The number per 5 mm hr^{-1} rain rate bin is shown with the 2005-2009 period represented by the blue bars. The insert in (a) is a zoomed in view of the area enclosed by the black rectangle, emphasizing the rain rate bins $\geq$ 15 mm hr^{-1}. (b) Histogram similar to (a) but showing wind speeds > 33 m s^{-1}.

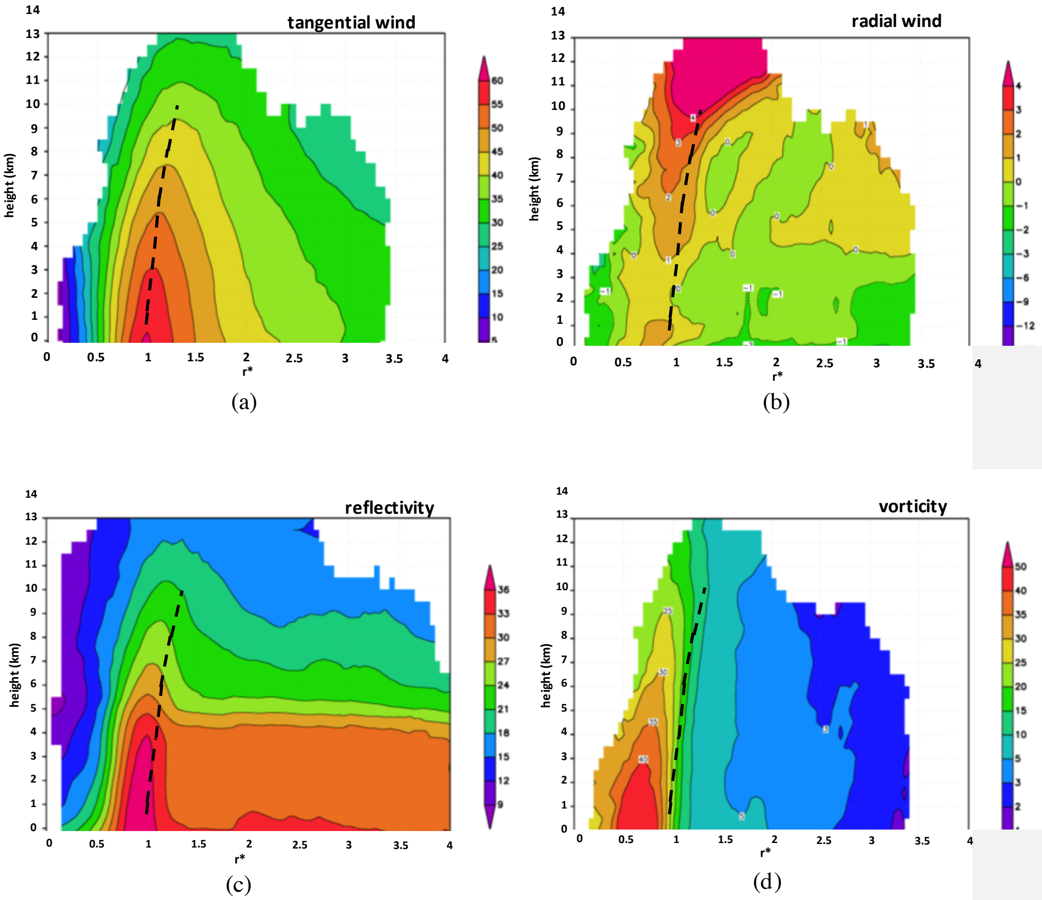

Figure Rog3: Airborne Doppler composite fields of axisymmetric (a) tangential wind (m s^{-1}); (b) radial wind (m s^{-1}); (c) reflectivity (dBZ); and (d) vertical relative vorticity (x 10^{-4} s^{-1}). Dashed lines in (a) œ(d) denote axis of peak axisymmetric tangential wind. From Rogers et al. (2011).

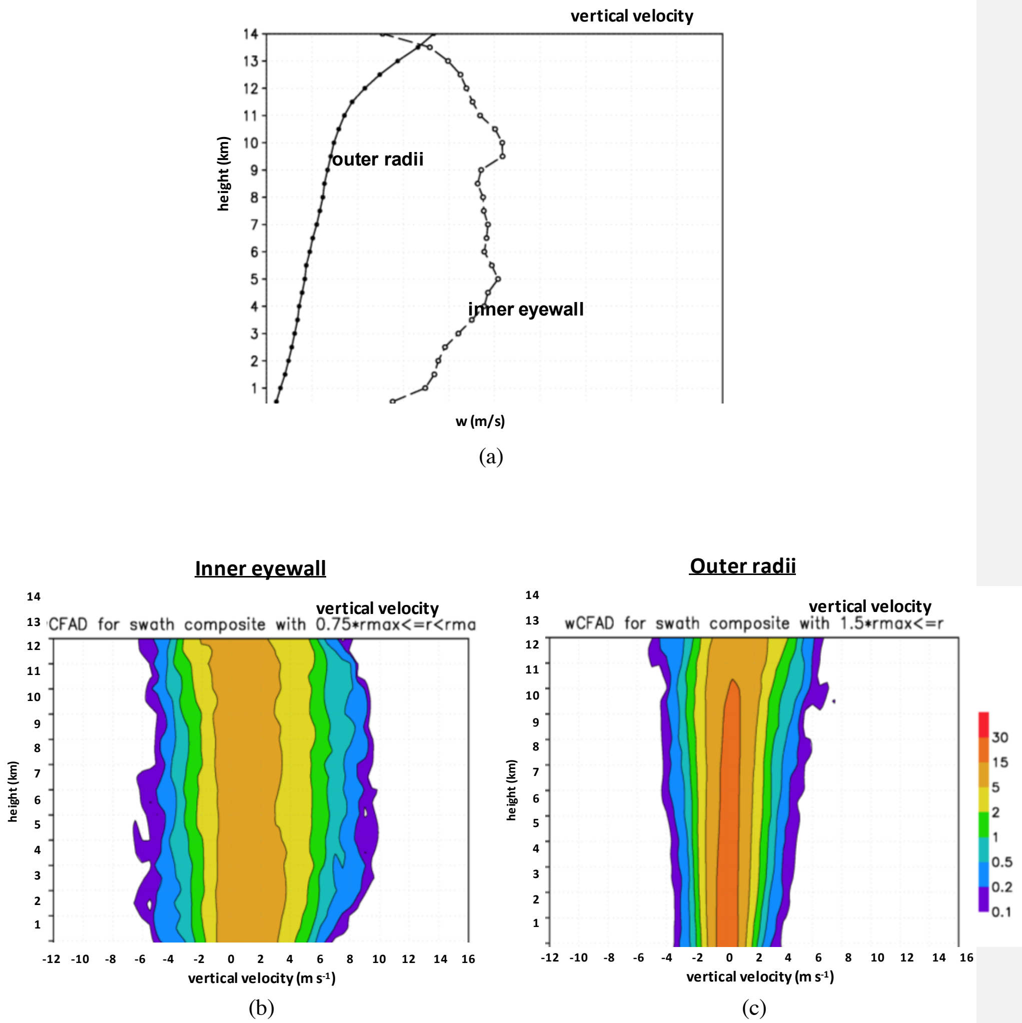

Figure Rog4. (a) Vertical profiles of swath-based composite mean of vertical velocity (m s^{-1}) for inner eyewall edge (dotted) and outer radii (solid); (b) CFAD of vertical velocity (shaded, %) for inner eyewall region; (b) as in (b), but for outer radii. From Rogers et al. (2011).

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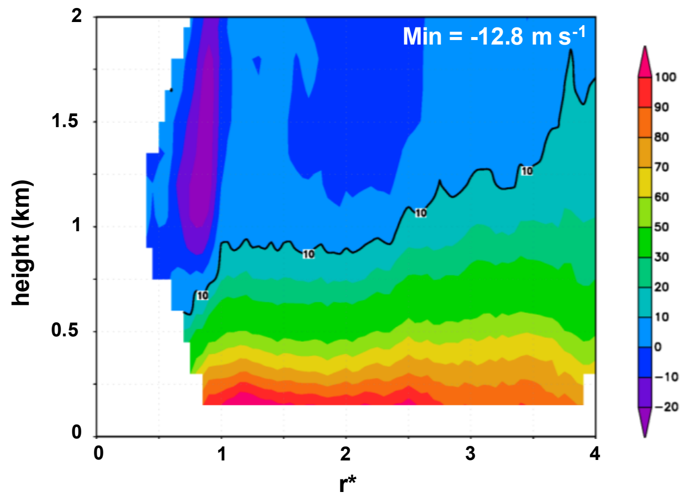

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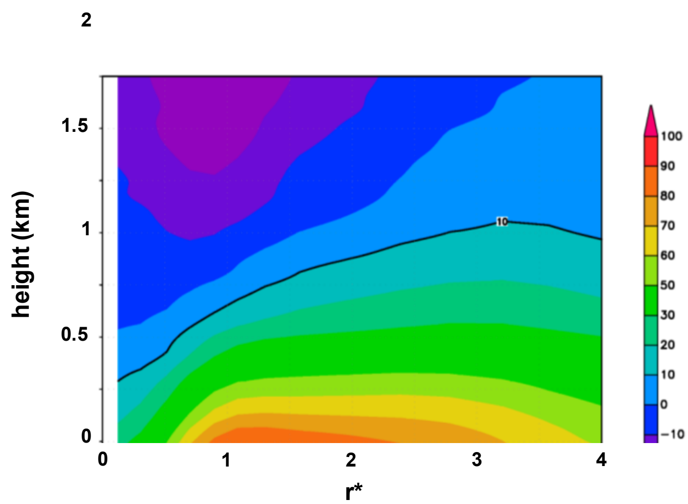
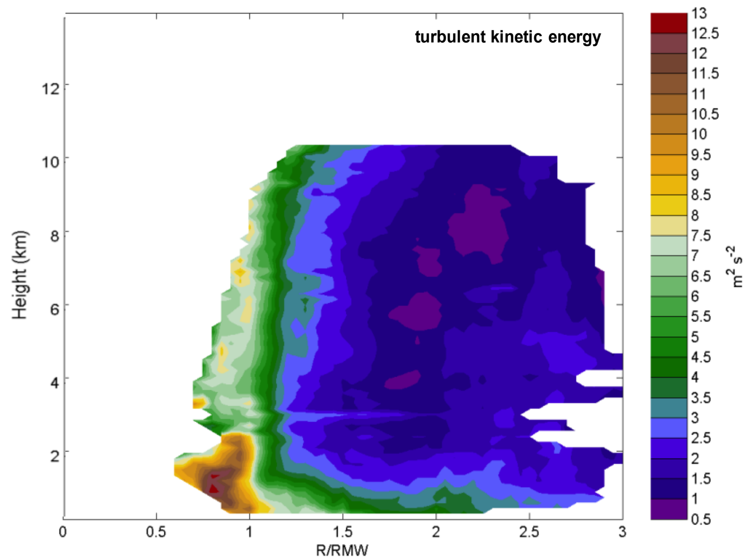


(b)

Figure LorZha1. (a) Radius-height plot of axisymmetric radial flow from airborne Doppler composite dataset used in Rogers et al. (2011). Fields are plotted as percentages, scaled by radial flow at eyewall (r*=1) and 150 m altitude (scaling value indicated). Positive (negative) values denote inflow (outflow). Dark line denotes contour representing 10% of scaling radial flow shown. (b) As in (a), but forGPS dropsondes using composite dataset in Zhang et al. (2011).



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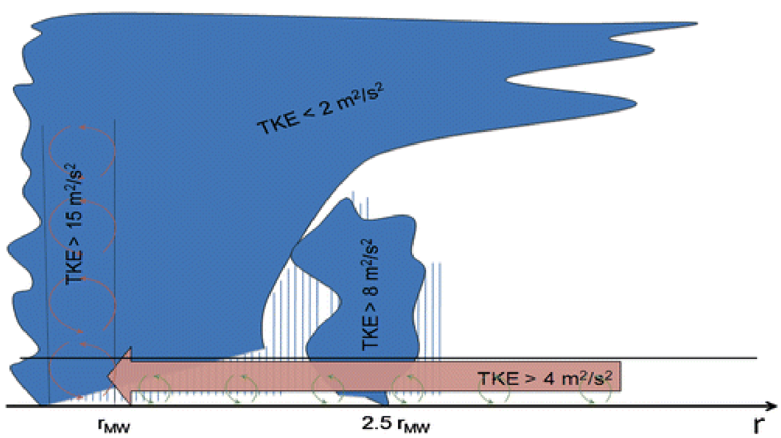
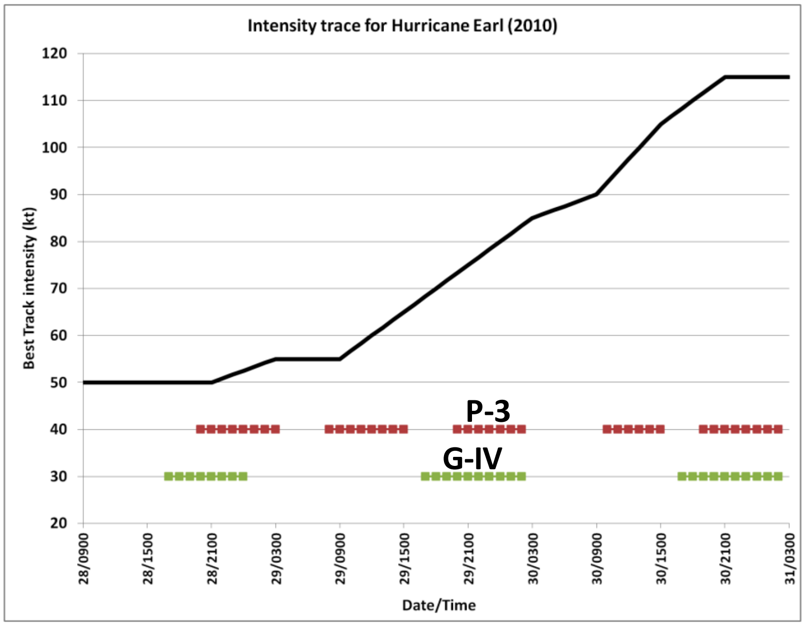


(b)

Figure Lor1. (a) Composite of turbulent kinetic energy (shaded, m2 s-2) calculated from radar profile data (from Rogers et al. 2011); (b) Simple conceptual model of TKE behavior in a hurricane with respect to radial location (from Lorsolo et al. 2010).



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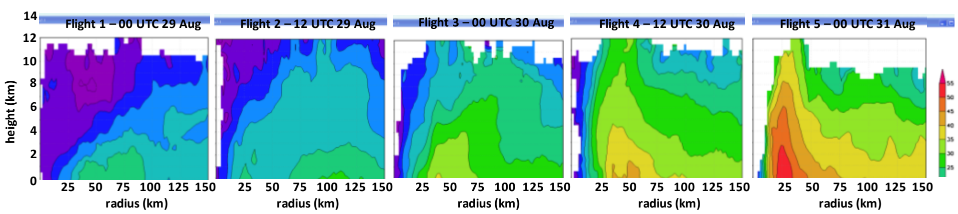

(b)

Figure Rog5. (a) Best Track intensity trace (black line) for Hurricane Earl (2010) and time that aircraft was in system (red blocks for WP-3D; green blocks for G-IV); (b) Radius-height plot of axisymmetric tangential wind (shaded, m s^{-1}) derived from tail Doppler radar on WP-3D during each of the five WP-3D flights into Earl.

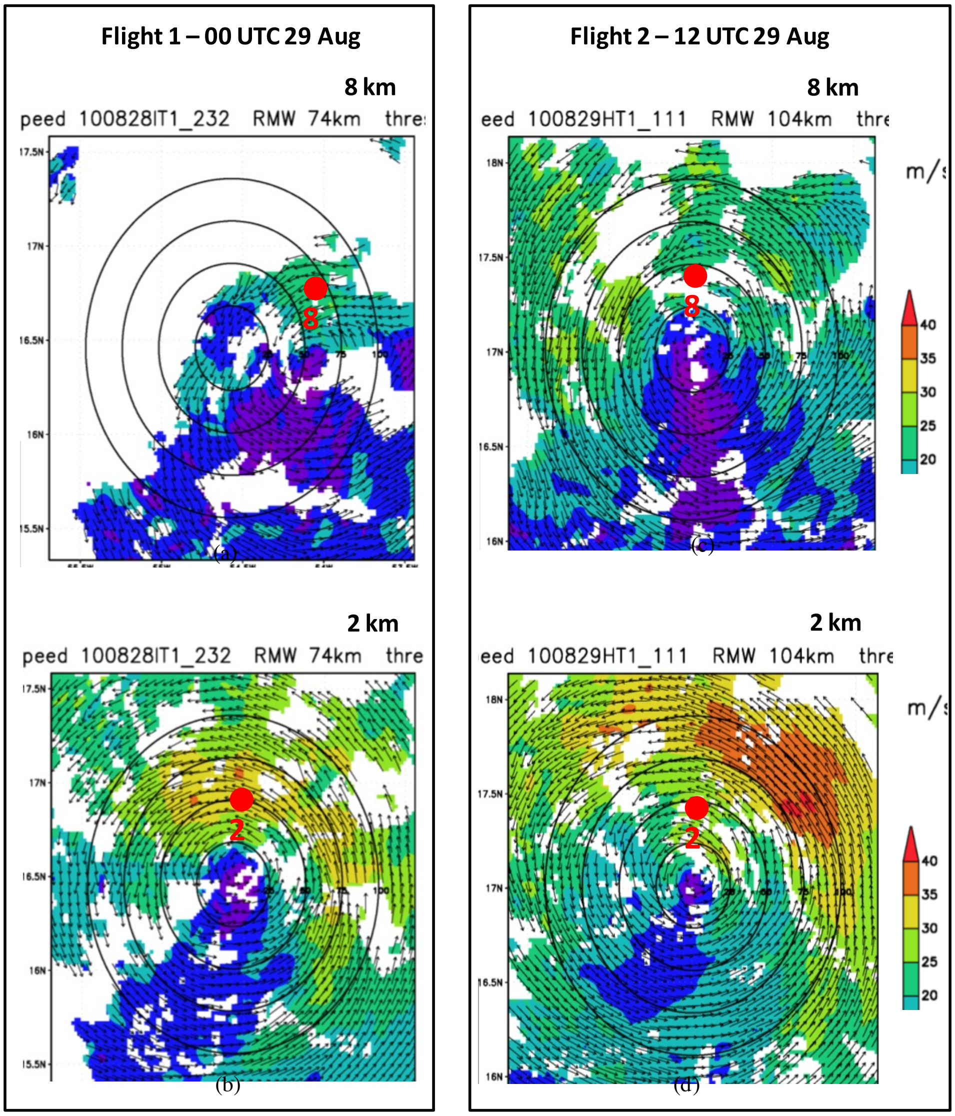

Figure Rog6. (a) Wind speed (shaded, m s^{-1}) and vectors (m s^{-1}) at 8 km in Earl during the first WP-3D flight, centered approximately at 00 UTC August 29; (b) As in (a), but at 2 km; (c) Wind speed and vectors at 8 km in Earl during the second WP-3D flight, centered approximately at 12 UTC August 29; (d) As in (c), but at 2 km. Red dots denote circulation center at each height. Range rings in all figures are in km.

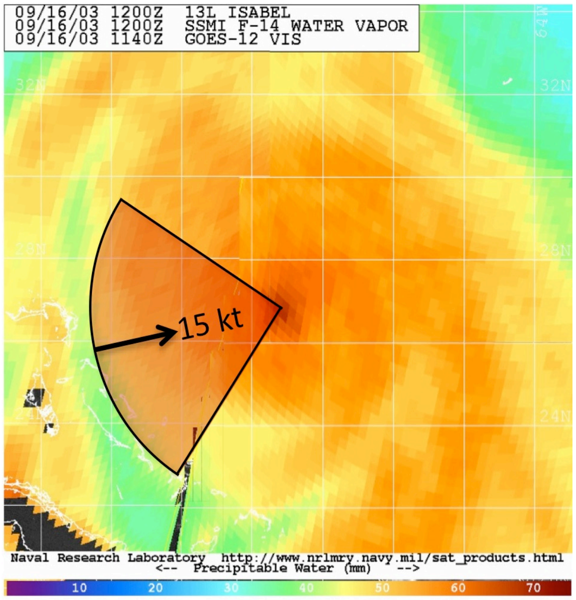

Fig. jpd1: SSM/I TPW imagery indicating areas of very dry low to mid-level air (green to blue shading; ≤45 mm) in the periphery of 2003 Hurricane Isabel on 16 Sep 1200 UTC. The red shaded wedge west of the center represents the region where dry air pixels were calculated in the RII and is centered around the SHIPS-analyzed vertical shear vector (258 deg at 15 kt).