The Hurricane Forecast Problem: From R2O and O2S

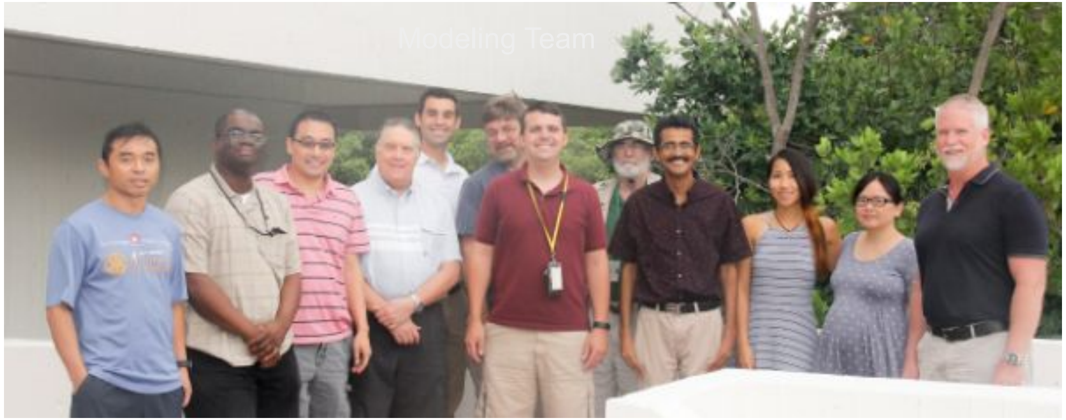
Sundararaman Gopalakrishnan (Gopal)

Modeling Team Leader and HFIP Developmental Manager

Hurricane Research Division, AOML, Miami

Presented at Joint HFIP-AOML Seminar, Feb 15, 2022

My HRD Collaborators



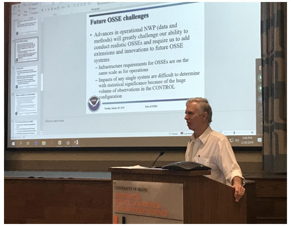
We fly into hurricanes, study the hurricanes, create next generation numerical models and data assimilation techniques...

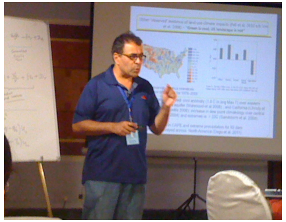
https://www.aoml.noaa.gov/hurricane-modeling-prediction/

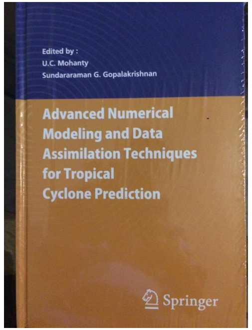
My Collaborators

Advanced Indo-US workshop on Modeling and Data Assimilation for Tropical Cyclone Predictions, 9-14 July, 2012

The Global Initiative for Academic Networks (GIAN), India, 2018

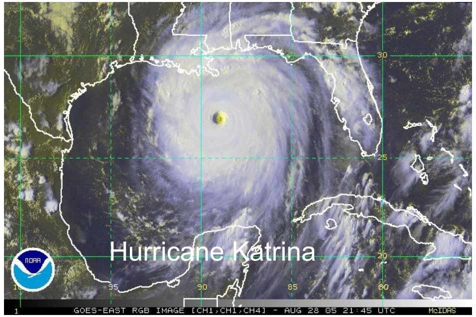






History: The 2005 Hurricane Season

The 2005 season was the most destructive for United States landfalling storms, largely due to Hurricane Katrina. Damage estimates for the 2005 season are over $100 billion dollars. Hurricane Rita was the strongest hurricane in AL



HFIP: Making Hurricane Forecasts Better

Goals

Improve Forecast Accuracy

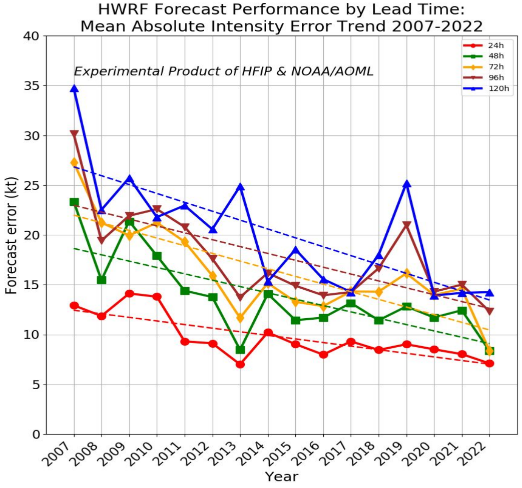
- Hurricane impact areas (track) – 50% in 10 years
- Severity (intensity) – 50% in 10 years
- Rapid intensity change detection

Extend forecast reliability out to 7 days

Quantify, bound and reduce forecast uncertainty to enable risk management decisions

Response

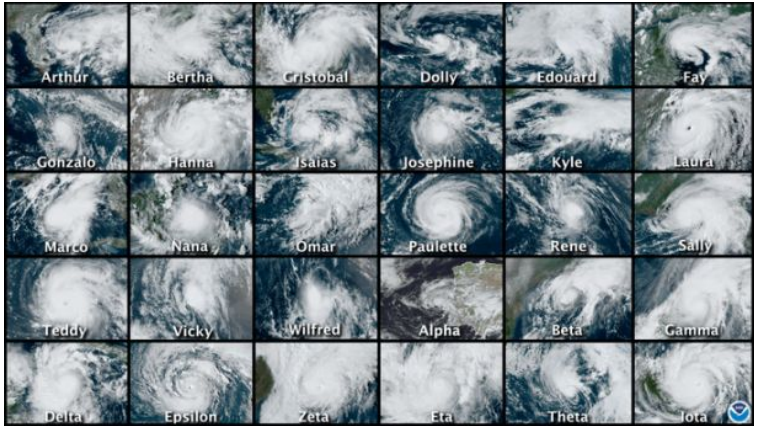
Improving coupled models, observation, DA techniques as well as invest on improved understanding of Hurricanes, especially those that undergo RI. Created HWRF system

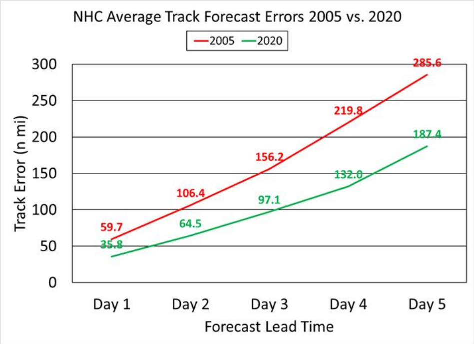


Credits: Gus Alaka

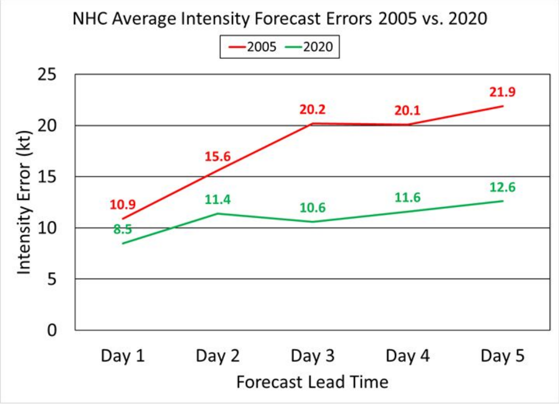
State-of-the-art in TC forecasting

The 2020 Atlantic hurricane season was the busiest year since 2005 and second busiest since 1990. There were 30 named storms, of which 14 developed into hurricanes (cover page image), with 7 major hurricanes.



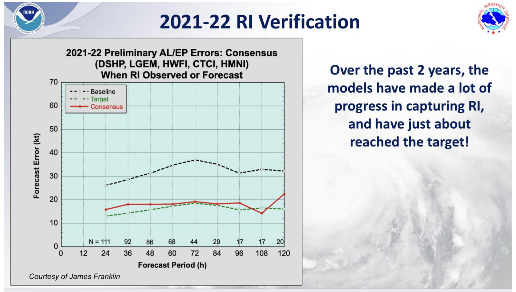


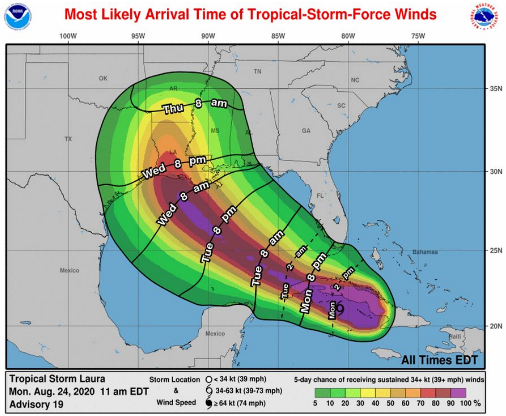
Credits: Mike Brennan NHC



Improved Global and Cloud-Permitting Regional models, observation, DA techniques as well as our investments on improved understanding of Hurricanes have all let to significant to TC forecast improvements

HFIP: State-of-the-Art



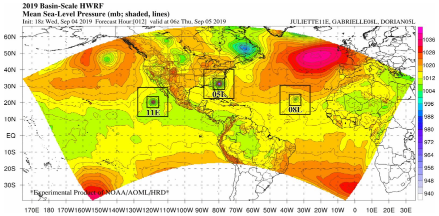


Credits: NHC

NOAA Capacity for Advancing Hurricane Prediction

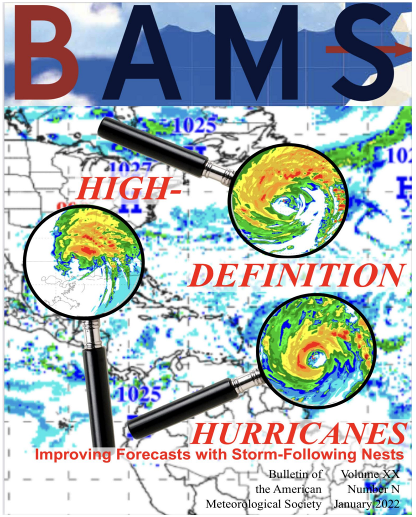
Basin-Scale HWRF: A Bridge to Next-Generation

BASIN-HWRF: For Improved Land-storm Storm-storm Interactions



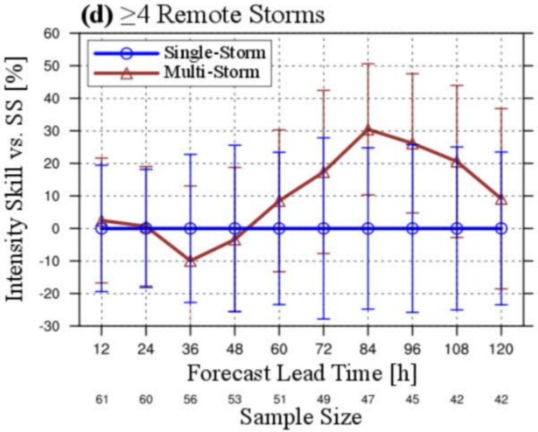
Tropical Cyclones 1000's of miles apart could influence each other via outflow region. Storm following nests offers a reliable NWP solution for capturing these interactions

X.Zhang et al. Representing multiple scales in the HWRF modeling system: Design of multiple sets of movable multi-level nesting and the basin-scale HWRF forecast verification. WAF, 2016

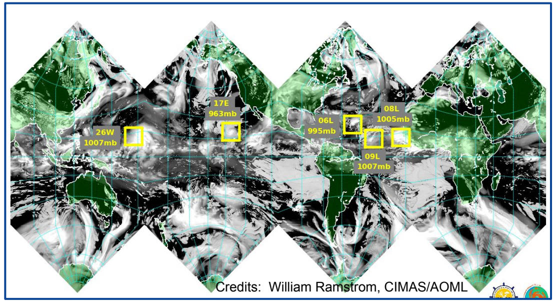


G Alaka, X.Zhang and Gopal," High Defination Hurricanes: Improving Forecasts with Storm-Following Nests", BAMS, 2022

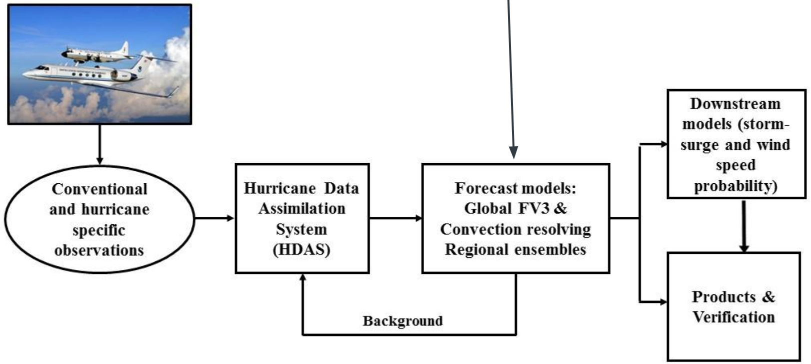
Intensity skills -vs- operational HWRF improves with number of moving nests in the domain. As much as 30% for 4 or more storms in the basin scale domain



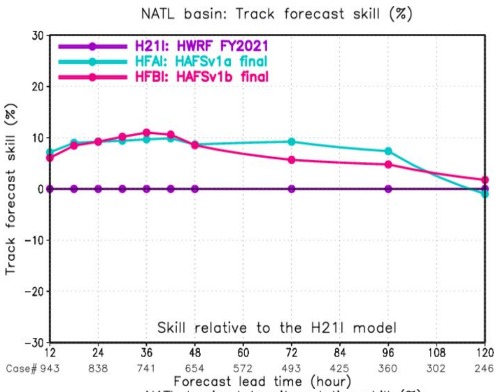
Next-Generation Developments: UFS-HAFS developments

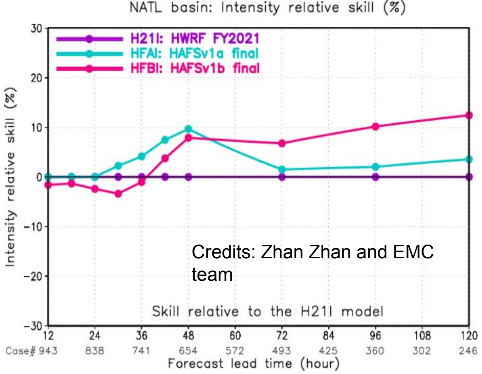


Initial Operational Capacity (IOC, 2023) : Regional domain, storm-centric, one moving-nest configuration of HAFS; Two configurations of HAFS based on physics diversity is expected to replace HWRF and HMON



The Hurricane Analysis and Forecast System (HAFS)





Credits: Zhan Zhan and EMC team

* One of the strategic plans of 2017 weather act

Both IOC versions of HAFS shows about 10% improvements in track forecasts and about 5-10% improvements in intensity forecasts compared to HWRF

O2S: Improving Understanding of Hurricanes

AMERICAN METEOROLOGICAL SOCIETY

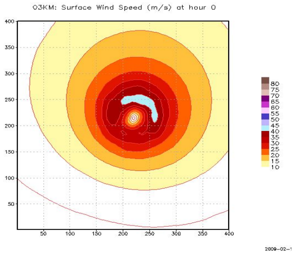
Monthly Weather Review

June 2011

The Experimental HWRF System: A Study on the Influence of Horizontal Resolution on the Structure and Intensity Changes in Tropical Cyclones Using an Idealized Framework

S.Gopalakrishnan, Frank Marks, Xuejin Zhang, J-W.Bao, K-S.Yeh and R.Atlas

In the current work, we use the HWRFX system to provide new and additional insights into the idealized vortex intensification problem. Specifically, we seek to answer the following questions: (i) Does the new forecasting system produce the fundamental features of vortex spinup consistent with some of the observations and theoretical works mentioned above? (ii) What is the role of convective asymmetries on the initial intensification of the storm? (iii) What is the impact of model grid resolution on the evolution of the TCs? To the best of our knowledge, this is the first extensive effort that objectively investigates the effects of model grid resolution on the rapid intensity change in TCs and the subsequent evolution of the matured storm. We also believe that the third aspect of this problem may be useful to the fore-



Idealized HWRF framework has been used for conducting control experiments and for understanding modeled intensification process [Gopal et al, 2011 (MWR), Bao et al., 2012 (MWR), Gopal et al, 2013 (MWR), Kieu et al, 2014 (GRL), Halliwell et al, 2014 (MWR), D.-L. Zhang et al. ,2014 (MWR), Zhu et al, 2015 (GRL)]

Axisymmetric Models: Cooperative Intensification Theory

February 1982 Journal of the Meteorological Society of Japan 369

Conceptual Evolution of the Theory and Modeling of the Tropical Cyclone

By Katsuyuki V. Ooyama

National Hurricane Research Laboratory, NOAA
Coral Gables, Fla. 33146, U.S.A.

(Manuscript received 7 October 1981, in revised form November 1981)

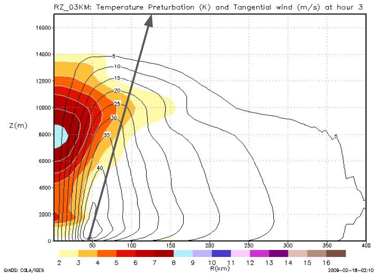
Cooperative intensification theory

The cooperative intensification theory assumes that the broad-scale aspects of a tropical cyclone may be represented by an axisymmetric, balanced vortex in a stably stratified, moist atmosphere. The basic mechanism was explained by Ooyama (1969, p18) as follows. 'If a weak cyclonic vortex is initially given, there will be organized convective activity in the region where the frictionally-induced inflow converges. The differential heating due to the organized convection introduces changes in the pressure field, which generate a slow transverse circulation in the free atmosphere in order to re-establish the balance between the pressure and motion fields. If the equivalent potential temperature of the boundary layer is sufficiently high for the moist convection to be unstable, the transverse circulation in the lower layer will bring in more absolute angular momentum than is lost to the sea by surface friction. Then the resulting increase of cyclonic circulation in the lower layer and the corresponding reduction of the central pressure will cause the boundary- layer inflow to increase; thus, more intense convective activity will follow.'

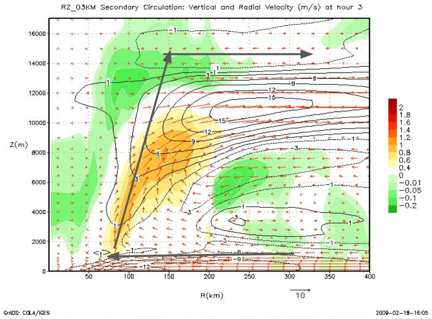
Intensification Pathway:
Heating ⟶ Pressure Adjustments ⟶ Secondary Circulation ⟶ increased Convergence of angular momentum ⟶ strengthening

HWRF idealized simulation

Azimuthally averaged Primary Circulation



Azimuthally averaged Secondary Circulation



(1) Ooyama, K.V. 1969. Numerical simulation of the life cycle of tropical cyclones. J. Atmos. Sci., 26, 3–40.
(2) Montgomery, M. T. and R. K. Smith, 2014: Paradigms for tropical-cyclone intensification. Aust. Meteorol. Ocean., 64, 37-66
(3) Kurihara, Bender and Tuleya - GFDL publications.

Role of Vertical Mixing in the Hurricane Intensification Problem

AMERICAN METEOROLOGICAL SOCIETY

Journal of the Atmospheric Sciences

Feb 2013

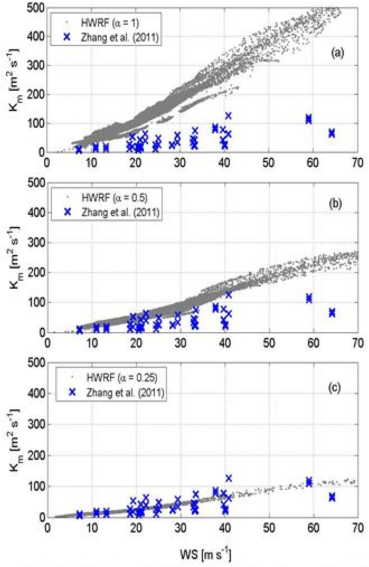
A Study of the Impacts of Vertical Diffusion on the Structure and Intensity of the Tropical Cyclones Using the High-Resolution HWRF System. J. Atmos. Sci., 70, 524–541

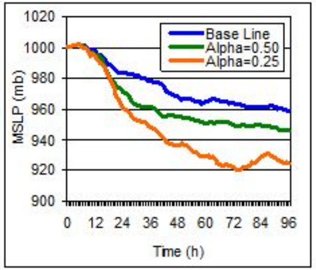
Sundararaman G. Gopalakrishnan, Frank Marks Jr., Jun A. Zhang, Xuejin Zhang, Jian-Wen Bao, and Vijay Tallapragada

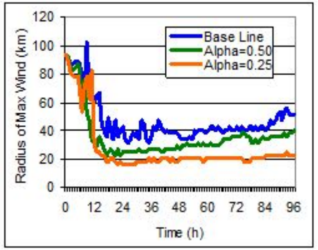
Abstract

The Hurricane Weather Research and Forecasting (HWRF) system was used in an idealized framework to gain a fundamental understanding of the variability in tropical cyclone (TC) structure and intensity prediction that may arise due to vertical diffusion. The modeling system uses the Medium-Range Forecast parameterization scheme. Flight-level data collected by a NOAA WP-3D research aircraft during the eyewall penetration of category 5 Hurricane Hugo (1989) at an altitude of about 450–500 m and Hurricane Allen (1980) were used as the basis to best match the modeled eddy diffusivities with wind speed. While reduction of the eddy diffusivity to a quarter of its original value produced the best match with the observations, such a reduction revealed a significant decrease in the height of the inflow layer as well which, in turn, drastically affected the size and intensity changes in the modeled TC. The cross-isobaric flow (inflow) was observed to be stronger with the decrease in the inflow depth. Stronger inflow not only increased the spin of the storm, enhancing the generalized Coriolis term in the equations of motion for tangential velocity, but also resulted in enhanced equivalent potential tempeature in the boundary layer, a stronger and warmer core, and, subsequently, a stronger storm. More importantly, rapid acceleration of the inflow not only produced a stronger outflow at the top of the inflow layer, more consistent with observations, but also a smaller inner core that was less than half the size of the original.

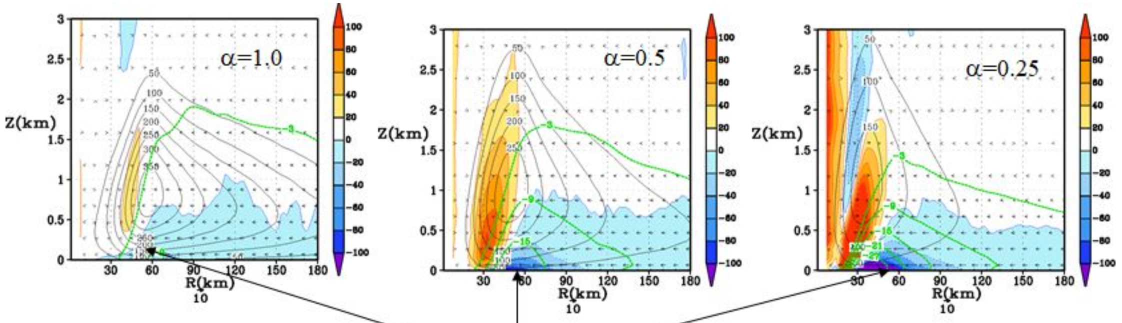
$$K_m = k(U_*/\Phi_m)Z[\alpha(1 - Z/h)^2]$$







Influence of Vertical Eddy Diffusivities on Structure and Intensity Predictions



Radial Flow (green)
Acceleration/Deceleration of Radial Flow (shaded)

$$\frac{dv_\lambda}{dt} = -\frac{1}{\rho r}\frac{\partial p}{\partial \lambda} \boxed{-\frac{u_r v_\lambda}{r} - f u_r} + D_{v\lambda}$$

Generalized Coriolis

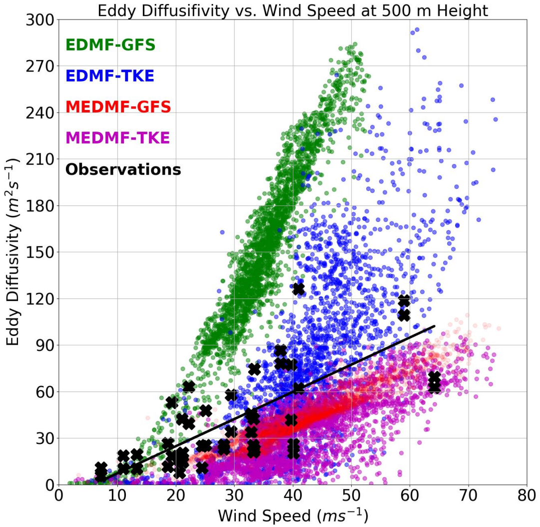
$$\frac{du_r}{dt} = \boxed{-\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{v_\lambda v_\lambda}{r} + f v_\lambda} + D_{ur}$$

Gradient wind imbalance

Vertical diffusion negates gradients. Stronger the diffusion, weaker are the gradients and the subsequent radial frictional forces. Weaker the diffusion, stronger the acceleration

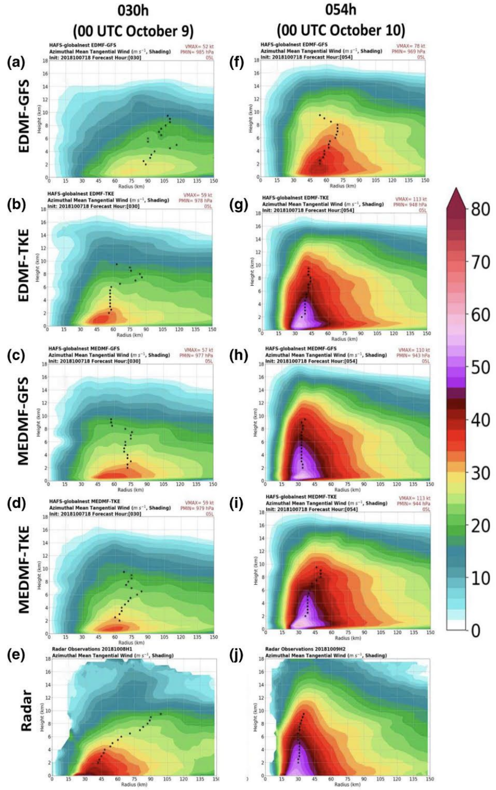
Agradient forces cannot be ignored for improved hurricane forecasting

Use of P3 Observations for Improving HAFS Physics



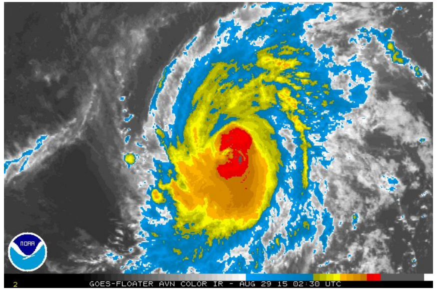
HAFS default PBL Physics too diffusive

Hurricane Michael 2018



- Gopalakrishnan, S., A. Hazelton, and J.A. Zhang. Improving hurricane boundary layer parameterization scheme based on observations, 2021. AGU- Earth and Space Science
- Hazelton, A., J.A. Zhang, and S.G. Gopalakrishnan. Comparison of the performance of the observation-based hybrid EDMF and EDMF-TKE PBL schemes in 2020 tropical cyclone forecasts from the Global-nested Hurricane Analysis and Forecast System, 2022. Weather and Forecasting,

Forecaster’s Challenge Shear & Convection

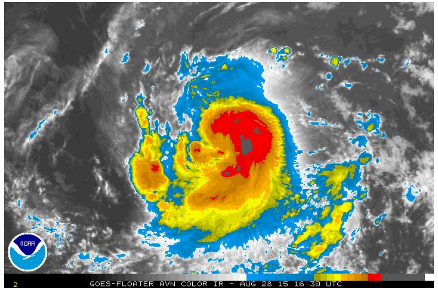


Weak shear/ near-symmetric intensification[1]

Intensification Pathway 1: Heating → Pressure Adjustments → Secondary Circulation → Convergence

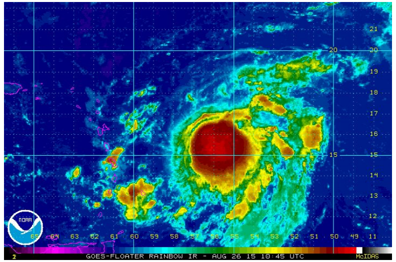
Intensification Pathway 2: Symmetric vertical plumes → Warm Core → Pressure drop -→ Secondary circulation

Gopal et al, 2011 (MWR), Bao et al., 2012 (MWR), Gopal et al, 2013 (MWR), Kieu et al, 2014 (GRL), Halliwell et al, 2014 (MWR), D.-L. Zhang et al. ,2014 (MWR), Zhu et al, 2015 (GRL)



Strong shear/ Asymmetric Intensification

Chen and Gopal, 2015 (JAS), Leighton et al, 2018 (JAS), Gopal et al, 2019, (Mausam) and Green et al, 2021 (Atmosphere), Hazelton et al., 2020 (MWR)



Large shear/ Dissipation

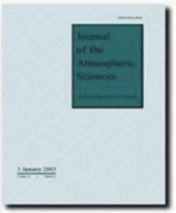
Balachandran et al, 2019 (Nature Scientific Report)

Intensification of sheared TCs

AMERICAN METEOROLOGICAL SOCIETY

Journal of the Atmospheric Sciences

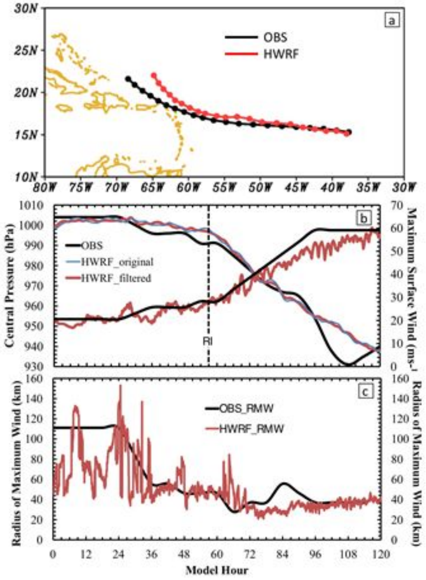
Feb 2015



A Study on the Asymmetric Rapid Intensification of Hurricane Earl (2010) using the HWRF System

Hua Chen and Sundararaman G. Gopalakrishnan

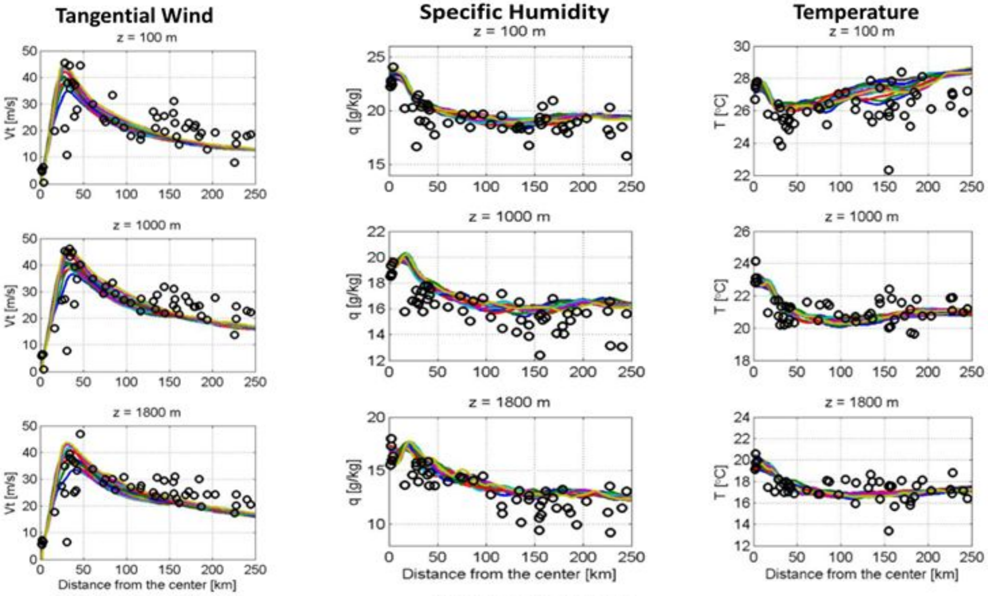
For the first time NOAA's HWRF hurricane track and intensity forecast model was used to help understand the complex processes of asymmetric Rapid Intensification (RI) in tropical cyclones. An important key to understanding the RI process was the availability of detailed aircraft observations in the inner core of the hurricane with which to compare the model results. The model was able to reproduce the evolution of the hurricane structure that caused the RI process similar to what was seen in the actual detailed observations. During the times and in the regions of the hurricane where detailed aircraft observations were not available, the model was able to used as a proxy to gain even more understanding of the four-dimensional intensification process.



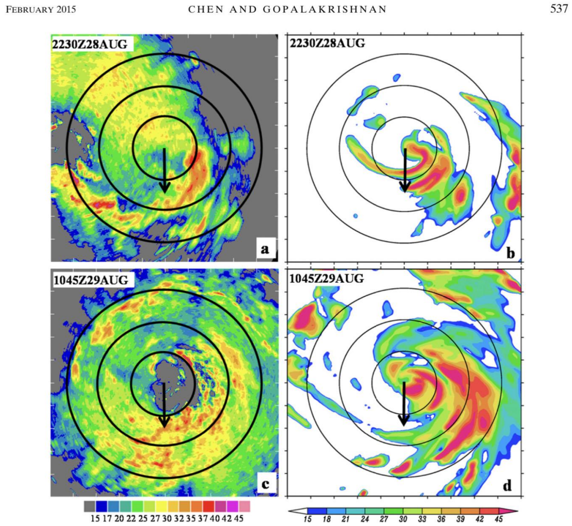
Aug 26, 2010, 18 Z forecast

Hurricane Earl (2010): How close is the forecast with reality?

Aug 26, 18 Z forecast



Credits: Jun Zhang



Persistent convection down shear left, pre-RI; Down shear left & up shear left during RI. Convection was asymmetric during RI

Hurricane Earl (2010): Convection & Eddy Vorticity Fluxes

MAUSAM, **70**, 4 (October 2019), 667-690

551.515.2

An inner-core analysis of the axisymmetric and asymmetric intensification of tropical cyclones: Influence of shear

SUNDARARAMAN G. GOPALAKRISHNAN, KRISHNA K. OSURI*,
FRANK D. MARKS and U. C. MOHANTY**
Hurricane Research Division, AOML, NOAA Miami, Florida, 33149, USA
**Department of Earth* and *Atmospheric Sciences, NIT Rourkela, Odisha, 769 008, India*
***School of Earth Ocean* and *Climate Sciences, IIT Bhubaneswar, Odisha, 752 050, India*
e mail : sundararaman.g.gopalakrishnan@noaa.gov

$$\frac{\partial\langle v\rangle}{\partial t} = -\langle u\rangle\langle f+\zeta\rangle - \langle w\rangle\frac{\partial\langle v\rangle}{\partial z} - \langle u'\zeta'\rangle - \langle w'\frac{\partial v'}{\partial z}\rangle + \langle D_V\rangle + \langle D_H\rangle$$

Earl Tilted Phase: Eddy Radial Vorticity Fluxes at 10 km

Red: Spin-up
Blue: Spin-down

Persistent Convective bursts especially within Ro produced positive eddy vorticity fluxes leading to spin-up

Hurricane Edouard (2014): Importance of the Azimuthal location of convection

AMERICAN METEOROLOGICAL SOCIETY

Journal of the Atmospheric Sciences

Jan 2018

Azimuthal distribution of deep convection, environmental factors and tropical cyclone rapid intensification: A perspective from HWRF ensemble forecasts of Hurricane Edouard (2014)

Hua Chen, Sundararaman Gopalakrishnan, Jun A. Zhang, Robert F. Rogers, Zhan Zhang and Vijay Tallapragada

In this study, forecasts from the operational Hurricane Weather Research and Forecasting (HWRF) based ensemble prediction system for Hurricane Edouard (2014) are analyzed to study the differences in both the tropical cyclone inner-core structure and large-scale environment between rapidly intensifying (RI) and non-intensifying (NI) ensemble members.

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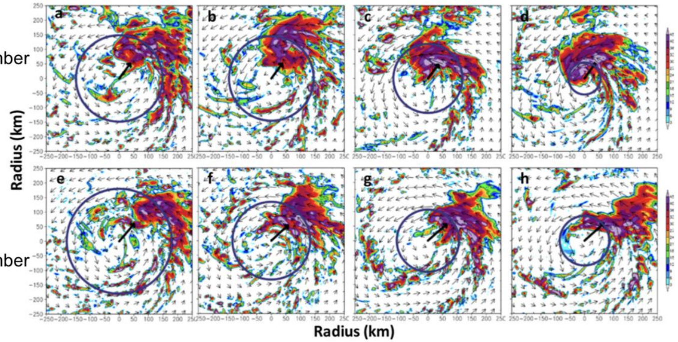


RI: Wrap around of convection from down-shear left to up-shear left

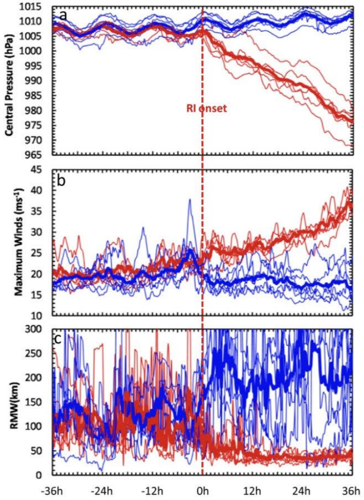


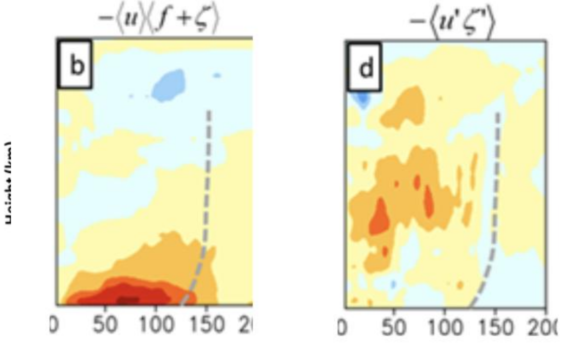
FIG. 2. Time series of (a) central pressure, (b) maximum winds, and (c) the RMW for six RI (red line) and six NI (blue line) members. Thick lines represent the mean value of each group, and thin lines represent individual members.

18 UTC Sept 11, 2014
40 member-ensembles

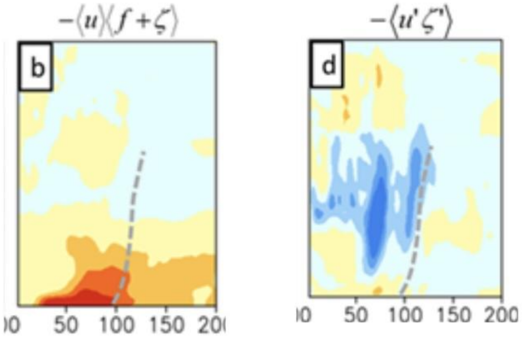
Hurricane Edouard (2014): Role of Eddy Fluxes

$$\frac{\partial \langle v \rangle}{\partial t} = -\langle u \rangle \langle f + \zeta \rangle - \langle w \rangle \frac{\partial \langle v \rangle}{\partial z} - \langle u' \zeta' \rangle - \langle w' \frac{\partial v'}{\partial z} \rangle + \langle D_V \rangle + \langle D_H \rangle$$

RI member



NI member



- Significant mean-spin up within the PBL in both cases
- Radial Eddy Vorticity fluxes contributes to spin-up in RI and spin-down in NI members
- Location of the convective bursts matters!

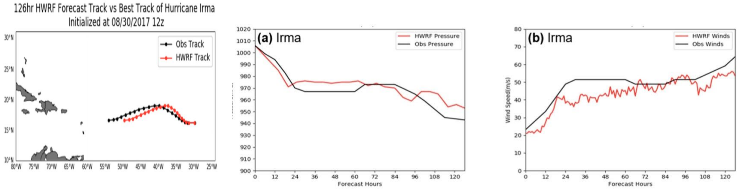
Leighton et al., 2018

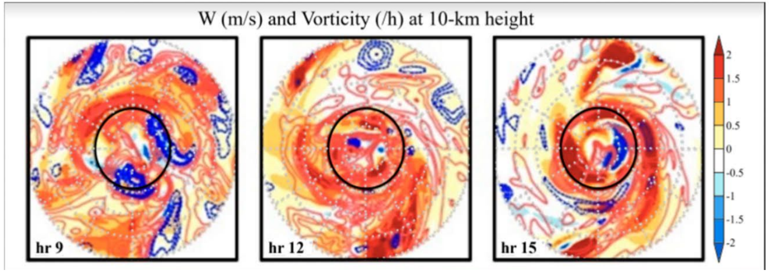
Understanding the Role of Mean and Eddy Momentum Transport in Rapid Intensification of Hurricane Irma (2017) and Hurricane Michael (2018)

atmosphere

Green et al., 2021

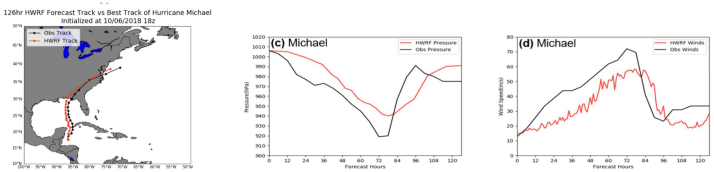
Hurricane Irmal, 2017

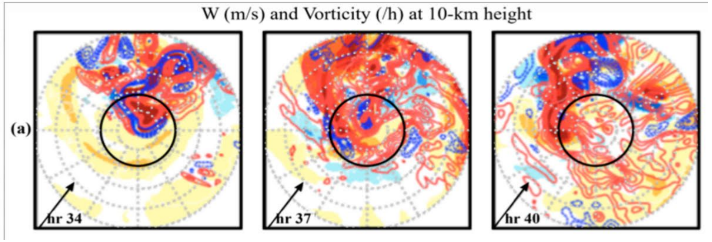




Green et al., 2021

Hurricane Michael, 2018





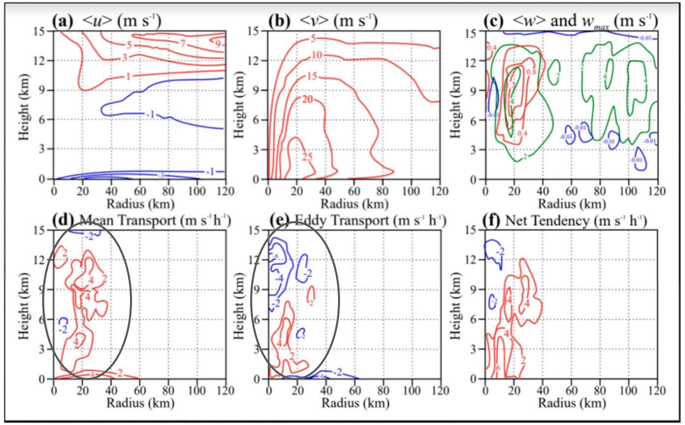
Supported by NERTO program

Spin-Up: Boundary Layer -vs- Eddy

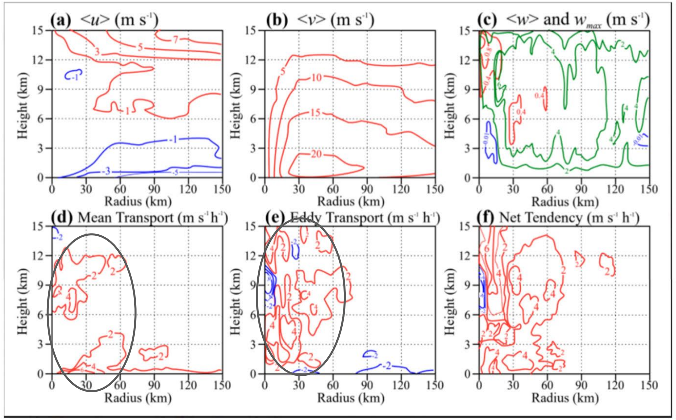
atmosphere

$$\frac{\partial \langle v \rangle}{\partial t} = -\langle u \rangle \langle f + \zeta \rangle - \langle w \rangle \frac{\partial \langle v \rangle}{\partial z} - \langle u'\zeta' \rangle - \langle w' \frac{\partial v'}{\partial z} \rangle + \langle D_V \rangle + \langle D_H \rangle$$

Hurricane Irmal, 2017



Hurricane Michael, 2018



Red: Spin-up
Blue: Spin-down

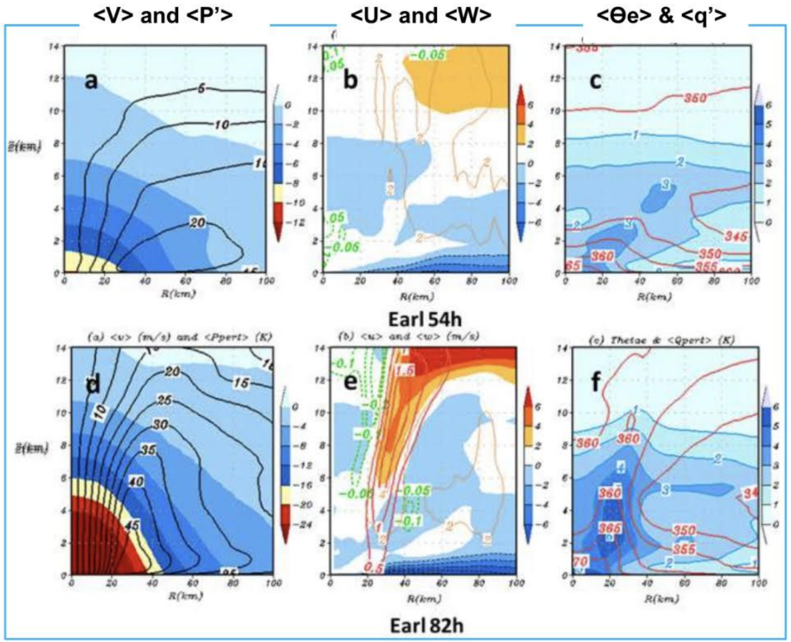
- Mean advection of absolute vorticity is a significant forcing term in either cases
- Radial Eddy Vorticity fluxes contributes significantly to spin-up in RI of Hurricane Michael

Green et al., 2021

The devil is in the details!

Ri

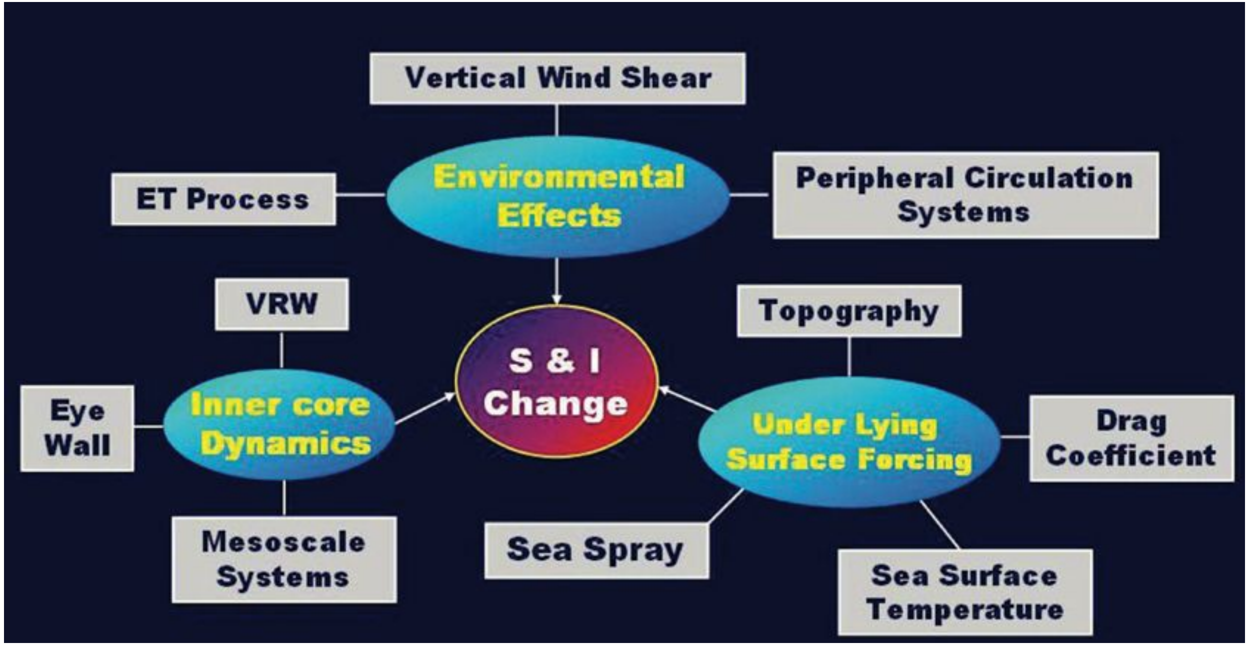
SS



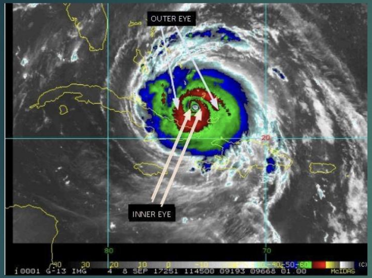
Intensification Pathway:
Heating → Pressure Adjustments →
Secondary Circulation →
increased Convergence of angular momentum
→ strengthening

Although a fully three-dimensional model is required to understand the real TC intensification problem, when viewed from an axially-averaged framework, the basic axisymmetric theory of intensification is still valid for all cases

Multi-Scale Interactions



Challenges in Structure Predictions: Size and ERCs



<u>Are ERC's predictable ?</u>
Evolution of W, secondary circulation and diabetic heating in HWRF for same microphysics parametrization but different fall velocity descriptions (Zhu et al., 2015)

AGU Geophysical Research Letters 10.1002/2015GL066436

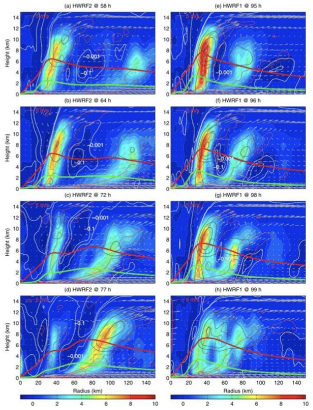
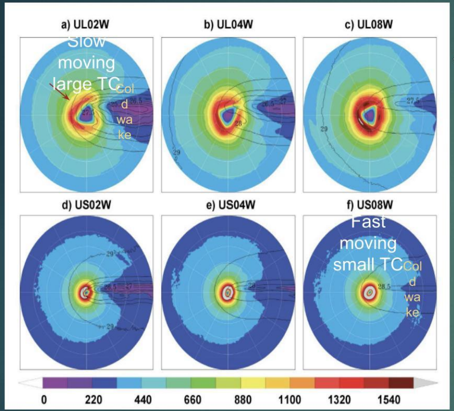


Figure 2. (a–d) Time evolution of azimuthal mean radius-height structure of diabatic heating (color shades, X1000 K s^{-1}), downdraft (white contours, −0.001, −0.1 m s^{-1}), transverse circulations (arrows), convergence of radial flow (red contours, −0.1e−3, −0.5e−3 s^{-1}), and total hydrometeor mixing ratio (black contours, 2, 3, 4, and 5 g kg^{-1}) during the course of ERC in HWRF2. Thick red curve is the azimuthal mean tangential wind (m s^{-1}) at 1 km altitude. Thick green curve is the azimuthal mean surface buoyancy fluxes (W m^{-2}). For an easy display using the same scale to the left (height scale), tangential wind and buoyancy flux has been divided by a factor of 10 and 100, respectively. (e–h) The same as Figures 2a–2d but for a representative convection episode during the TC vortex evolution in HWRF1.

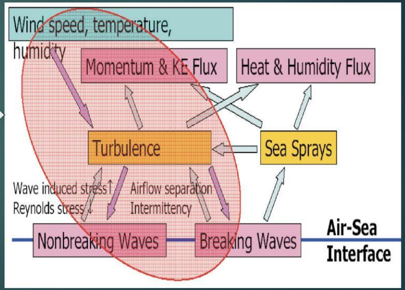
Air Sea Interaction: Impacts of Ocean and Waves



Total enthalpy flux at hour 60 with SST contours overlaid for six uniform-ocean forecasts initialized with warm ocean conditions. The top row is for large storms with translation speeds of (a) 2 m/s, (b) 4 m/s, and (c) 8 m/s. The bottom row is for small storms with translation speeds of (d) 2 m/s, (e) 4 m/s , and (f) 8 m /s. In all panels, SST is contoured at 0.5ºC intervals.

What we understand:
Bigger and slower storms feel the ocean much more than smaller and faster moving storms (from Halliwell et al., 2015, MWR)

What we don't:
Wave breaking and sea-spray (Isaac Ginis, URI, personal communication)



Ensembles and probabilistic predictions

Summary & Conclusions

- An overview of NOAA's Hurricane Forecast Improvement Program (HFIP), especially, related to modeling activities is provided
- Improved models, DA techniques, observations and, above all, improved understanding of the TCs from models and observations have all led to better intensity predictions.
- The state-of-the art HWRF and later HAFS model was used to explore processes that have been shown to be important to TC intensification
- A brief review of existing axisymmetric theory for the intensification of TCs is also provided
- Importance of unbalanced forces in the PBL for improved structure and intensity prediction is illustrated.
- We investigated how TCs intensify in sheared environment
- That is still the "tip of the iceberg". There are more unknowns than knowns!

The Hurricane Forecast Problem: From R2O and O2S

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Abstract

Predicting intensity changes, in particular, rapid intensity changes, in tropical cyclones (TCs) is a complex and challenging multiscale problem. To improve intensity forecasts, NOAA created the Hurricane Forecast Improvement Program (HFIP) in 2009. Supported by HFIP, significant progress has been made in the prediction of TC intensity changes by upgrading numerical models, advancing data assimilation techniques, expanding the observations assimilated into numerical models and, above all, investing in basic research to better understand TC intensification. In this presentation, we will discuss how the Hurricane Weather Research and Forecasting (HWRF) and, more recently, the Hurricane Analysis and Forecast System (HAFS) models have been used to understand the TC intensification problem. A brief review of the axisymmetric theory for the intensification of TCs is also provided. However, TCs are rarely axisymmetric. The asymmetric structure in the inner core of a TC may be generated by both internal dynamics and external forcing due to environmental factors such as wind shear and moisture. We used retrospective forecasts produced by HWRF and HAFS to investigate the role of shear-induced asymmetries in the rapid intensification of TCs. We seek to address the following questions: How do TCs rapidly intensify in a sheared environment? What is the role of eddy fluxes in TC intensification? Is the well-accepted theoretical framework of TC intensification still valid for sheared storms undergoing rapid intensification? We will also provide a brief overview of other studies in which we have used HWRF to advance our understanding of the forecast problem and discuss the challenges and unknowns.