

#### **Tropical Cyclone Rapid Intensification (TCRI)** A New FY20 Departmental Research Initiative

#### Ron Ferek and Josh Cossuth ONR Marine Meteorology Program, 322MM

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## **BLUF**

 ~2 decades of *basic* research investment has led to historic improvement in TC intensity prediction, mainly due to the development of <u>skillful mesoscale models</u>

- Despite steady progress, mesoscale models <u>perform worst</u> in cases of Rapid Intensification (RI); accounts for the largest source of the total intensity errors

- RI can be triggered with the ideal combination of favorable *environmental conditions*, *ocean forcing, internal dynamics* and *scale interactions* 

- RI is the right problem to address now (highest JTWC and NHC priority), and can be addressed by building on CBLAST results through basic research focused on *internal dynamics* and *scale interactions*, and applied research focused on modeling



### Navy Relevance: Requirements Documents

- Multiple long term requirements across the DoD/US Gov support the work this project provides to benefit operational missions:
  - USPACOM Ins. 5216 Ser: J33/#002, 23 Aug 09:
    - 15-20 yr operational objective: "Reduce uncertainty, provide projections past the current five day forecast... in a rolling, storm-following dynamic and probabilistic sense"
  - OPNAV N2N6E FY19 RDT&E Priorities, 19 Mar 18:
    - High priority processing objective P-1c, "Develop improved deterministic and *probabilistic* TC prediction tools with a focus on *decreasing the error*.... in intensification"
  - NOAA-OAR-OWAQ-2019-2005820 for JHT, list of priorities for improved tropical cyclone analysis and prediction at JTWC, NHC, and CPHC:
    - #3: "Improved tropical cyclone intensity guidance including the onset, duration, and magnitude of *rapid intensification* events..."

	СОММАНДЕК, U.S. PACIFIC COMMAND (дерисом) САМР Н.М. 5МТН, НАИХИ 50851-4028 5216 56г. 133 игоод 23 Анал 09	b. Intercent the lowcast of utern effects to entitive operational physical productors response and force protection. Suggested specific component matrice of this objective include: (1) Forecast the intervaly providence within 2015 through
From: Deputy Direr	ctor for Operations, U.S. Pacific Command	168 hours. (2) Forecast the cyclone associated storm surge (within 10% of maximum height) to include conset time within alk hours, areal coverage within 25%, and duration of
Subj: GOALS FOR	R TROPICAL CYCLONE FORECASTING	inundation within six hours for a 72 hour forecast period. (3) Forecast the overland rainfall amount at military installations, population
<ol> <li>Tropical cyclons in the U.S. Pacific C severe weather cha in the theater.</li> <li>The Meteophone</li> </ol>	s are a continuing threat to operations and a challenge to planners commard (USPACOM) area of espensibility. These storms present illenges that are a clear danger to naval, air and ground operations	certeins, and mudside risk areas within 25% for amounts over six inches per 24 hours. <ol> <li>I request that you enclose the MGRACOM tropical forecasting goals and forward them to the Chief of Naval Operations and AF proce Chief O Start METOC collenses in order to channel the efforts of METOC DoD researchers and operational forecasters in the USPACOM theater.</li> </ol>
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esearch and operat Department of Defe he following operat	Ional Meteorology and Oceanography (METOC) communities of the nse (DoD) coordinate and concentrate their efforts toward meeting ional objectives over the next 15-20 years:	William Office JR.
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(1) Reduce the hour forecast period	center position error to less than 75 nautical miles (nm) for a 72 , 150 nm for a 120 hour forecast period and 200 nm for 168 hour	
(2) Predict the through 168 hours.	radius of 35 knot and 50 knot winds within 20% (by quadrant)	
(3) Develop an rolling, storm-followi historical averages).	d/or improve forecasting products that convey uncertainty in a ing dynamic and probabilistic sense (as opposed to straight	
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To: Comm Chief	nander, Naval Information Fouces (Čode N8) uf Naval Research (Code 322)	<ol> <li>Improve the Navy's ability to deliver accurate PTA, in support of assured command and control per Department of Defense requirements;</li> </ol>
Soly: TESCAL YEAR 2019 NAVAL OCEANOGRAPHY RESEARCH, DEVELOPMENT, TEST AND EVALUATION PRIORITIES		<ul> <li>e. Improve the Nary's ability to employ unmanned systems (US3) through the collection of environmental data firms equatic sensors, exploitation of environmental observations and predictions to support US3 autonomy and decision tools, and acceleration of US3 development.</li> </ul>
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(f) Ni (g) M	aval Oceanography Umaanod Systems Sirategy (Jul 2015) Ig Standing Advisory/Coenditation Team of 13 Dec 17	<ol> <li>My point of contact is CDR Ben Jones, CIPNAV N2NHET, who can be trached at commercial: (703) 614-1768, or by email at: <u>herjitnin.ajores@navy.mil.</u></li> </ol>
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<ul> <li>larger conditions in prediction ca</li> </ul>	we the Navy's ability to accurately measure, analyze and predict accuracy rephic support of undersea warfare with an exeptanis on onboard data assimilation and pabilities for fleet platforms and the effect on acoustic systems;	2
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where JHT projects Pacific Hurricane Co by the United States projects, science pris www.nhc.nosa.gov/j	could be tested and evaluated include the WRC, the NOAA Central network (CPRC), and the Joint Typhone Warning Center (TWC) operated Novy and Air Terce. For additional deviation biotrul TT, part finded critics, business practices, and messures of success, go to http:// htt.	techniques or specific programme informations true, harmany, size, and vanit queed probability forecases, indimes for two point performance and the hardware effective of the specific programme and the specific programme and the hardware and a low right and the maintenerange (44-120) heaving but enhibits and hardware and a low right and the specific programme and the specific programme and dispusses and predict the formation of trupical cyclams via humanism of non-channel dispusses and predict the formation of trupical cyclams via humanism of non-channel dispusses and predict the formation of trupical cyclams via humanism of non-channel dispusses and predict the formation of trupical cyclams via human predict the formation dispusses and predict the formation of trupical cyclams via human predict the dispusses and predict the formation of trupical cyclams via human predict the dispusses and predict the formation of trupical cyclams via human predict the dispusses and predict the formation of trupical cyclams via human predict the dispusses and predict the formation of trupical cyclams via human predict the dispusses and predict the formation of trupical cyclams via human predict the dispusses and predict the formation of trupical cyclams via human predict the disputse and the disputses and trupical cyclams via human predict the disputses and disputses of the disputses and trupical cyclams via human predict the disputses and disputses and disputses an
<ul> <li>B. Program Prioritie</li> <li>The program pri Applicants should el</li> </ul>	rs orifies are listed in detail below for each of the three competitions. any indicate in the proposal the competition for which they are	BIT-5: Greenest tools) Guidance for topical system tack including the identification, these reduction of the occuments of patheme and efficial tools output pathemesters bare productions (e.g., exclusioning measureman indications) and particular pathemesters in the observation of the observation of the observation of the observation templanest trajection systems, track interacts near town land-spectrally deviated branch, entrative landmain systems and an estimation by some training and pathemester have an estimation of the observation of the statistical by some training and the observation of
applying and address 1) Joint Humicone 3	s one or more of the associated priorities described below. Festbed	contá include multi-model consensus approaches provided in probabilistic and other form JHT-6: (Impacts of storm surge, winds, waves) Advanced constal immátrion modeling
The program prioriti	ies for the JHT competition are:	and/or applications, visualization, or dissemination technology that enhances operational storm surge forecast accuracy or delivery.
JHT-1: (Observation environment to supp techniques to improvi intensity and location	nsimplyses) Improved capability to observe the tropical cyclone and its out forecaster analysis and model initialization. This would include we the utility of microwave satellite and radar data for tropical cyclone an analysis (e.g. develop a "Devench-like" technapse ming microwave	JHT-7: (Impacts of storm surge, winds, surves) Operational analysis of the surface wind field in tropical cyclones, including the analysis of the maximum statistical winds, and wi affecting elevated termin and high-rise buildings: as well as griduance for changes in tropic cyclone size/wind structure and related parameters, including combuted sus heights.
imagery), to modern subtropical cyclones estimating the intens	ize the satellite-based classification system used for monitoring (e.g., the Herbert-Potest Technique), and to improve techniques for ity of tropical cyclones passing over and north of sea-surface	HIT-8: (Inpacts of storm surge, winds, waves) Development of probabilistic wave height forecasts in trepical cyclones for a possible new public product geneed toward the marine community.

JHT-9: (Applications) Develop tropical cyclone climatology software that provide on closest point of approach to a station, bearing and distance to a station, cyclone statistics for a noise or location stream neriod statistics, stre.



## Past History of ONR's TC DRIs

- CBLAST
  - Improved understanding of drag at surface led to first realistic pressure/wind relationship in mesoscale models
  - Applied research developed and transitioned COAMPS-TC; first skillful operational mesoscale TC model
- TCS-08
  - Focused on storm scale processes
  - Increasingly reliable *intensity* and surface wind radii predictions (*structure*)
- ITOP
  - Improved ocean coupling (improves forecast *in some cases*)
- TCI-15
  - Improved upper level physics and demonstrated value of in-situ observations for better model initialization and DA
  - Improved the ensemble through initial condition sensitivity



**JTWC Official forecasts are improving** 

# Yearly improvement gains by the operational COAMPS-TC

#### **JTWC Forecast Improvement**



Upgrades are transitioned once annually through the AMOP process

(Courtesy of Jim Doyle)



## **"Rapid" Intensification**

#### Definition: winds increasing by 30 knots or more in a 24-hour period

- Patricia (2015) +105 kts in 24 h (all-time record)
- Michael (2018) + 65 kts in the 48 hours before landfall (70 to 135 kts)
- NHC successfully predicted RI in only 5 of 36 cases in 2018
- 20-year summary of RI events:
  - 66% of Atlantic hurricanes underwent RI
  - 75% of WestPac typhoons underwent RI
- For TCs reaching at least **Cat 3** (100kts):
  - 91% underwent RI in the Atlantic
  - 96% underwent RI in the WestPac
- For TCs reaching **Cat 5** (140kts):
  - 100% underwent RI in both basins (61 total)
- 50% of Cat 5 TCs went through a "super-RI" of at least 60 kt in 24 h!



(Courtesy of Jon Moskitas)

Accurate prediction of RI is essential to provide adequate warning for impacts associated with Cat 3-5 TCs



**RI vs. non-RI cases** errors are fundamentally different



Intensity mean absolute error (solid) and mean error (dashed) for 2017 real-time cases with RI observed during the 0-24 h lead time window (left panel) and with no RI observed during the 0-24 h (right panel).

Intensity forecasts have much faster error growth and much larger biases for RI cases relative to non-RI cases.

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## **RI: Approaching the Problem**



RI occurs when a TC crosses the threshold of internal conditions (thermodynamic and dynamic state) supported by favorable atmospheric and oceanic conditions

• In priority order: Scale Interactions, Internal Dynamics, Ocean Forcing, Environmental Influences

## **Environmental Influences**



- Hurricane Joaquin underwent rapid intensification (and RW)
  - Upper-level winds and wind profiles (shear) were well predicted, but the storm response was not
- Mesoscale model failed to capture storm response to change in winds and shear profile
- Need to better represent details of *internal dynamics* on the mesoscale and their response to the background environment

**UNDERSTOOD:** GLOBAL MODEL ADEQUATELY PREDICTS THE ENVIRONMENT

## **Ocean Forcing**

- Lessons learned from CBLAST (2003) still being applied
- Air-sea enthalpy fluxes (left) and drag coefficients (right) need some additional refinement, testing/V&V to push into operational model



## **Internal Dynamics**

- Need radial penetrations that sample core storm cells
- Repeated sampling of developing cells to understand evolution of convective bursts
- Changes in fluxes and microphysics affect structure and intensity tendencies



Onboard radar will direct A/C to developing features of interest:







#### **OBJECTIVES:**

- RI is diagnosed by increased liquid and ice hydrometeors, latent heating by stratiform and shallow convection, and increasing symmetry of precipitation about center and upshear
- Need to understand conditions that foster symmetric storm development and differentiate from null events that do not RI

#### **DRI FOCUS: OBSERVE PROCESSES WITH FIELD CAMPAIGN**

### **Scale Interactions**

Wind Speed (m/s)



- As resolution of LES increases, modeling enables:
  - More detailed and realistic structures to be resolved
  - Updrafts tend to get stronger
  - The inner core tends to get smaller
  - The eyewall decreases in width and the area of strong winds decreases
- Conclusion: system scale energetic organization is dominated by upscale cascade of smaller internal convective/turbulent processes
  - (Fierro et al. 2009, Gentry and Lackmann 2010, Stern et al. 2018)
- Use LES alongside COAMPS-TC and field campaign observations to understand features important to eyewall boundary layer evolution and improve sub-grid parameterization

#### **DRI FOCUS: UNDERSTAND ENERGY SCALES VIA MODELING**



- Research Aircraft: NOAA P-3 and G-IV
  - AVAPS (and HDSS?) dropsondes
  - Tail Doppler Radar (TDR)
  - Stepped Frequency Microwave Radiometer (SFMR) for surface winds
  - Others (TBD):
    - Doppler Wind LIDAR (DWL)
    - Compact rotational Raman LIDAR (CRL, below) for water vapor, temp, aerosols
    - Full suite of cloud microphysics probes
  - Ideal platforms for flight through and around TCs to obtain obs. of temperature, water vapor, cloud properties, etc.
  - Obtain measurements for (1) data assimilation/ model testing, and (2) to help improve turbulence and microphysical parameterizations in numerical models

#### Field Experiment

- <u>Multiple</u> opportunities w/ NOAA in 2020-2022
- Possibly NASA WB-57 in year 3
  - HDSS dropsondes and HIRAD



# **Summary**

- TCRI will build on key findings from previous ONR field campaigns at the air-sea interface (CBLAST), at the tropopause (TCI-15), and through the atmospheric column (TCS-08, ITOP)
- Addressees the missing pieces of the RI puzzle: to understand processes and model structures that create RI
  - ✓ Small scale internal processes that tie together air-sea flux to outflow
  - Focus on boundary layer, convection and microphysics processes
- Unprecedented opportunities during 2020-2022 to obtain the necessary in-situ observations at sufficient detail
  - ✓ Partnership with NOAA for aircraft observations
  - ✓ Fly every interesting Atlantic case in Years 1-3
  - Deploy NASA WB-57 in year 3 if needed
- Past experience (and steady improvement in Operations) has shown that this methodology is robust
  - ✓ Understand processes (theory and field expts)
  - Represent new understanding in models (State-of-the-art DA and quantitative RS)
  - Transition innovations into prediction systems

### TCRI DRI Awards (as of 2/20)

PIs	Institution	Title
Jason Dunion, Rob	NOAA/OAML	Investigating interactions between the TC inner core and near
Rogers, Jon Zawislak,	CIMAS/UM	environment and their impacts on intensity change
Joe Cione		
Jim Doyle	NRL	Dynamics and Predictability of Tropical Cyclone Rapid Intensification
Michael Bell	CSU	Heating, Cooling, and Rapid Intensity Change in TCs
Brian Tang,	U Albany	Boundary-Layer Processes Associated with Rapid Intensification in TCs
George Bryan,	NCAR	
Jun Zhang	CIMAS/UM	
Anthony Wimmers	University of	A Deep Learning Approach to Examining and Predicting Tropical Cyclone
Chris Velden	Wisconsin	Rapid Intensification
David Richter	Notre Dame	Boundary layer structure and large eddy simulation of intensifying TCs
Sharanya Majumdar	RSMAS/UM	Multi-scale interactions and predictability of TC intensification
David Nolan		
Chun-Chieh Wu	National Taiwan	Rapid Intensification in TCs: Dynamics, Thermodynamics and
	University	Predictability
David Raymond	New Mexico Tech	Convection in TC Intensification
Zeljka Fuchs		
Chanh Kieu	Indiana University	On the Dynamics and Predictability of Tropical Cyclone Rapid
Louis Fan		Intensification
Ralph Foster	U Washington	High-Resolution Hurricane Boundary Layer Structure From Satellite
		Synthetic Aperture Radar and Aircraft Observations