A Preliminary Exploration of the Upper Bound of Tropical Cyclone Intensification

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Roosevelt Skerrit - https://www.flickr.com/photos/rooseveltskerrit/albums/72157686922251424

Maria was forecast to intensify from 75 kt to 100 kt in the 24 h just prior to its approach to Dominica, however the track was still uncertain and islanders were expecting Category 1 or 2 conditions. Instead they got a Category 5.

Hurricane Maria's affects on Dominica:
31 deaths, 34 missing
$1.37 billion in damage
226% of the island's GDP

Photo credit: Roosevelt Skerrit - https://www.flickr.com/photos/rooseveltskerrit/albums/72157686922251424

http://dominicanewsonline.com/news/homepage/news/general/police-release-names-of-31-dead-34-missing-due-to-hurricane-maria/

Motivation

- The expectation of an upper bound on the intensification *rate* is motivated by observations of past storms
- On several occasions TCs have intensified on the order of 100-105 kt over a 24-h period
- However, this magnitude of intensification has never been observed to occur over time periods much shorter than a day

Motivation, cont'd

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- **What is the upper bound on tropical cyclone (TC) intensification, given an initial vortex structure and expected environmental conditions?**
- Dynamically, one expects that the upper limit on the intensification rate is largely determined by the efficiency at which the vortex converts thermodynamic to kinetic energy.
- Thus, environmental wind shear, humidity, and the thermal structure of the upper ocean are all key.

Definitions

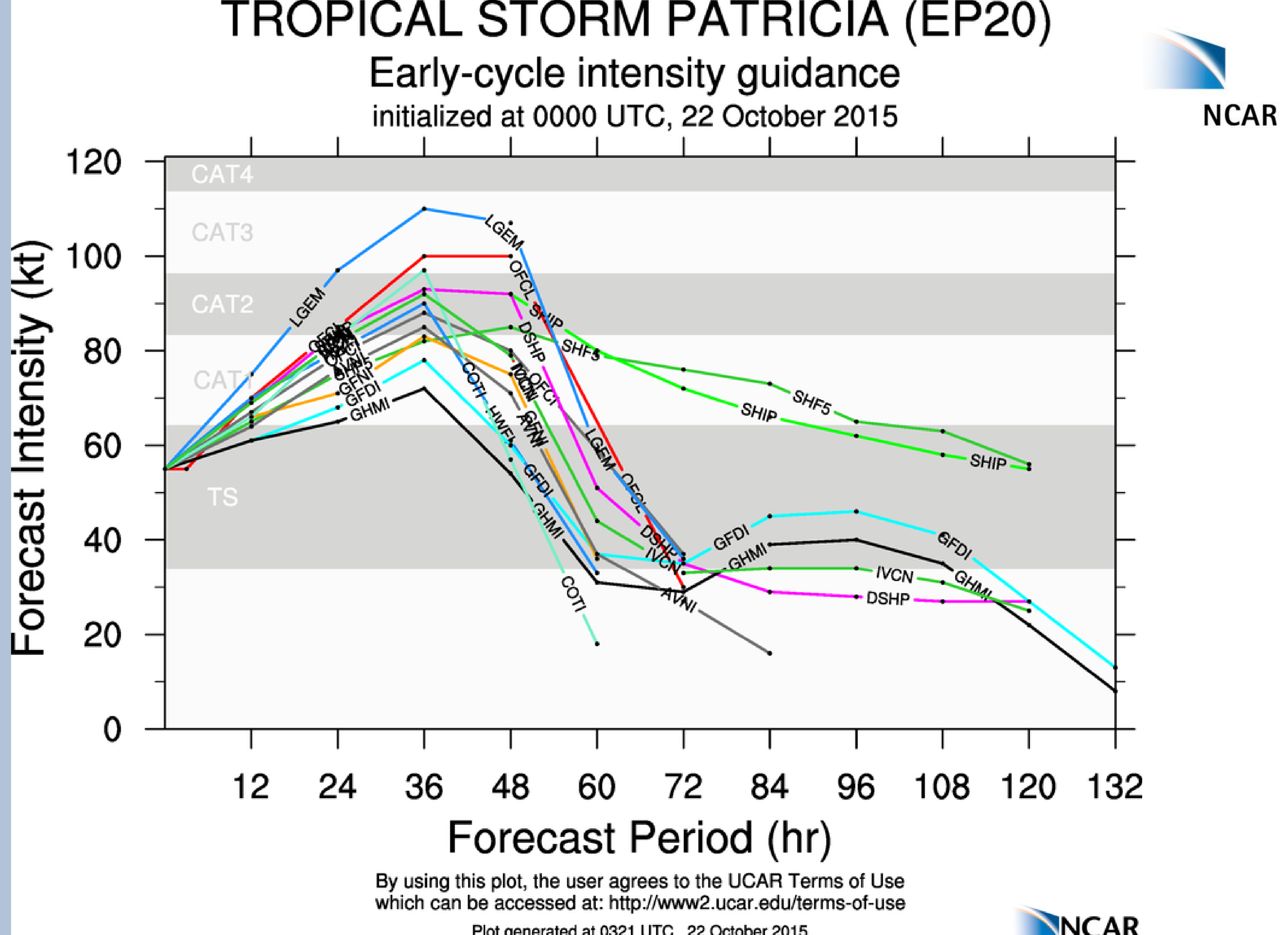
- ***Rapid Intensification (RI)***
  - 30 kt intensity increase in 24 h

- ***Very Rapid Intensification* (VRI)**
  - 30 kt intensity increase in 12 h
  - 45 kt intensity increase in 24 h

- ***Extreme Rapid Intensification* (ERI)**
  - 40 kt intensity increase in 12 h
  - 60 kt intensity increase in 24 h

Are there any models that can predict VRI and ERI?

- **Patricia (EP20)**
  - 00 UTC 22 Oct 2015
  - 60 kt -> 150 kt
  - 90 kt increase in 24 hours
- **Meranti (WP16)**
  - 06 UTC 10 Sep 2016
  - 35 kt -> 155 kt
  - 120 kt increase in 60 hours
- **Maria (AL15)**
  - 00 UTC 18 Sep 2017
  - 75 kt -> 145 kt
  - 70 kt increase in 24 h


TROPICAL STORM PATRICIA (EP20)
Early-cycle intensity guidance
initialized at 0000 UTC, 22 October 2015
NCAR
Forecast Intensity (kt)
Forecast Period (hr)
CAT4
CAT3
CAT2
CAT1
TS
0
20
40
60
80
100
120
12
24
36
48
60
72
84
96
108
120
132
LGEM
OFCL
SHIP
SHF5
DSHP
IVCN
GFDI
GHMI
AVNI
COTI
HWFI
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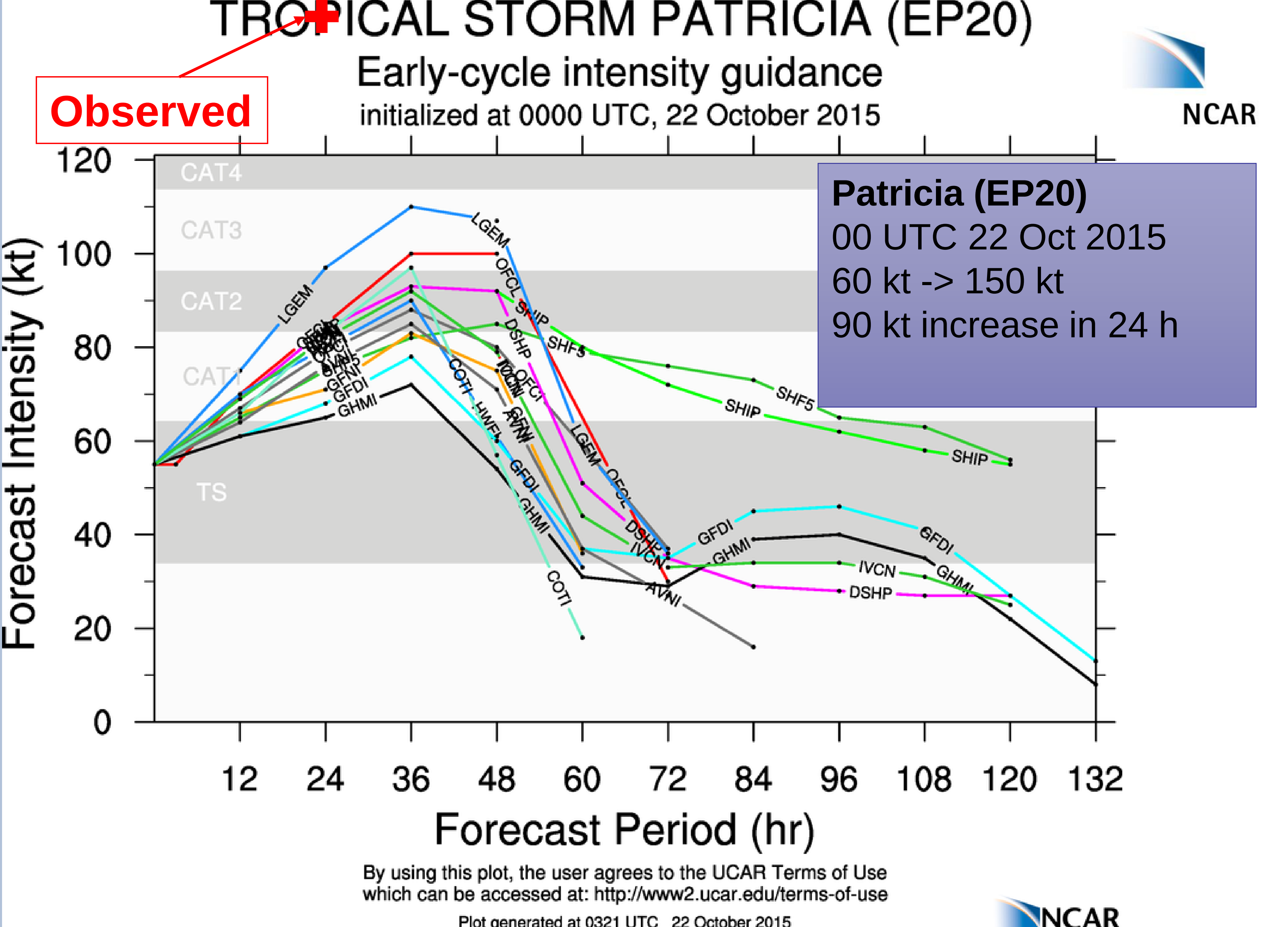
which can be accessed at: http://www2.ucar.edu/terms-of-use
Plot generated at 0321 UTC 22 October 2015
NCAR



Patricia (EP20)

00 UTC 22 Oct 2015

60 kt -> 150 kt

90 kt increase in 24 h

TROPICAL STORM PATRICIA (EP20)

Experimental late-cycle intensity guidance

initialized at 0000 UTC, 22 October 2015

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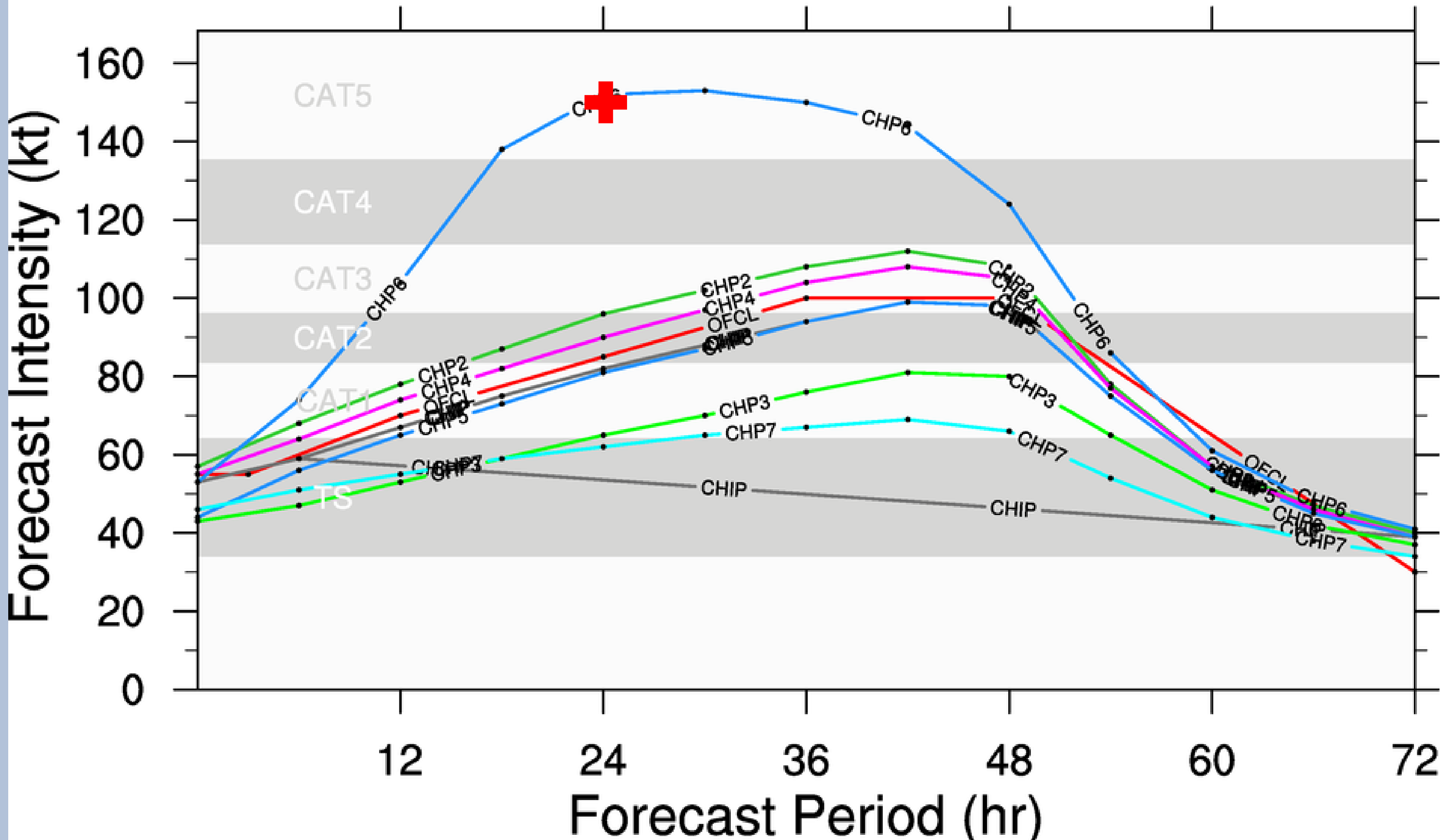

This plot displays experimental forecast aids from the HFIP stream 1.5 and other sources.
THESE MODELS MAY NOT BE SKILLFUL!

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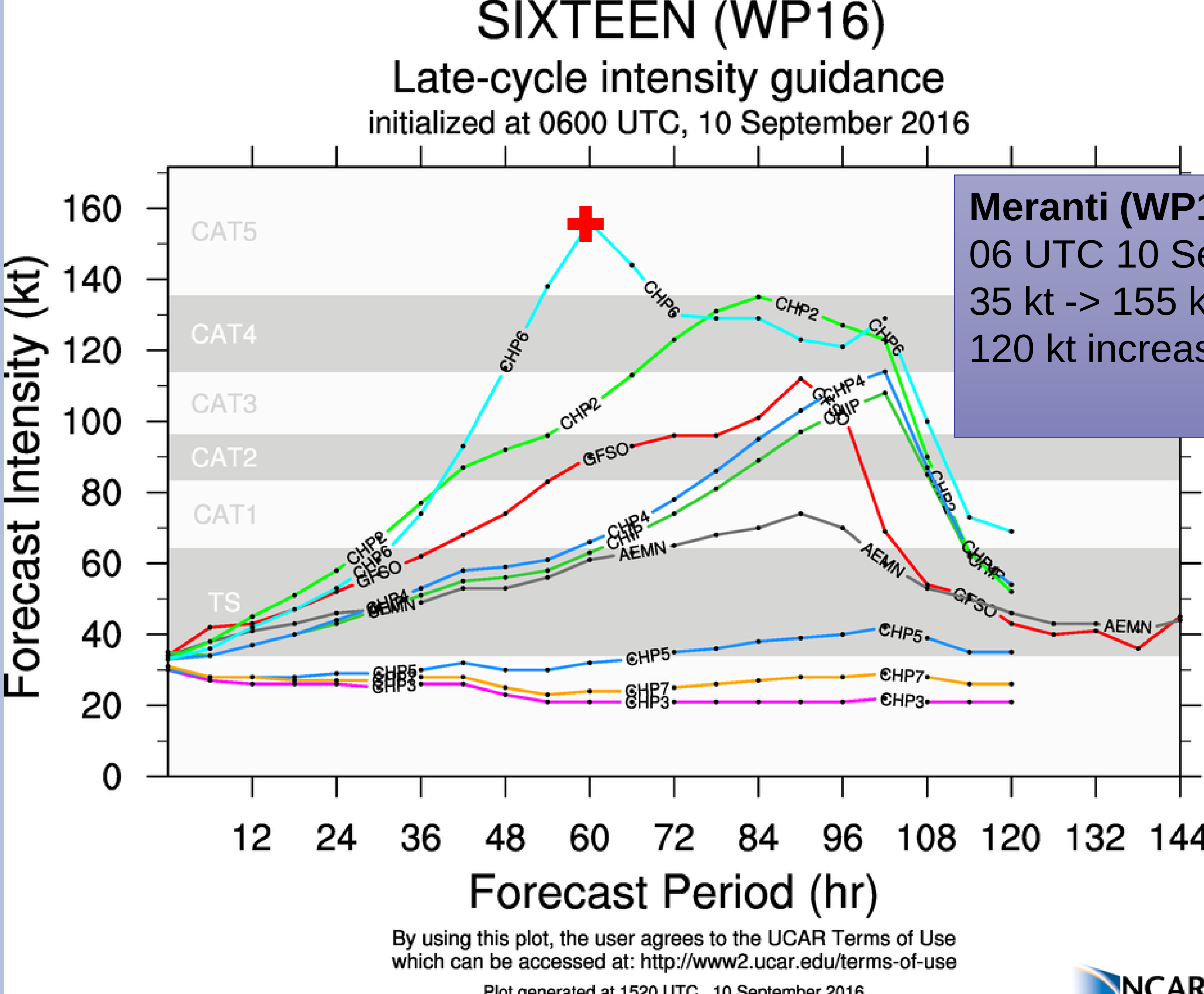
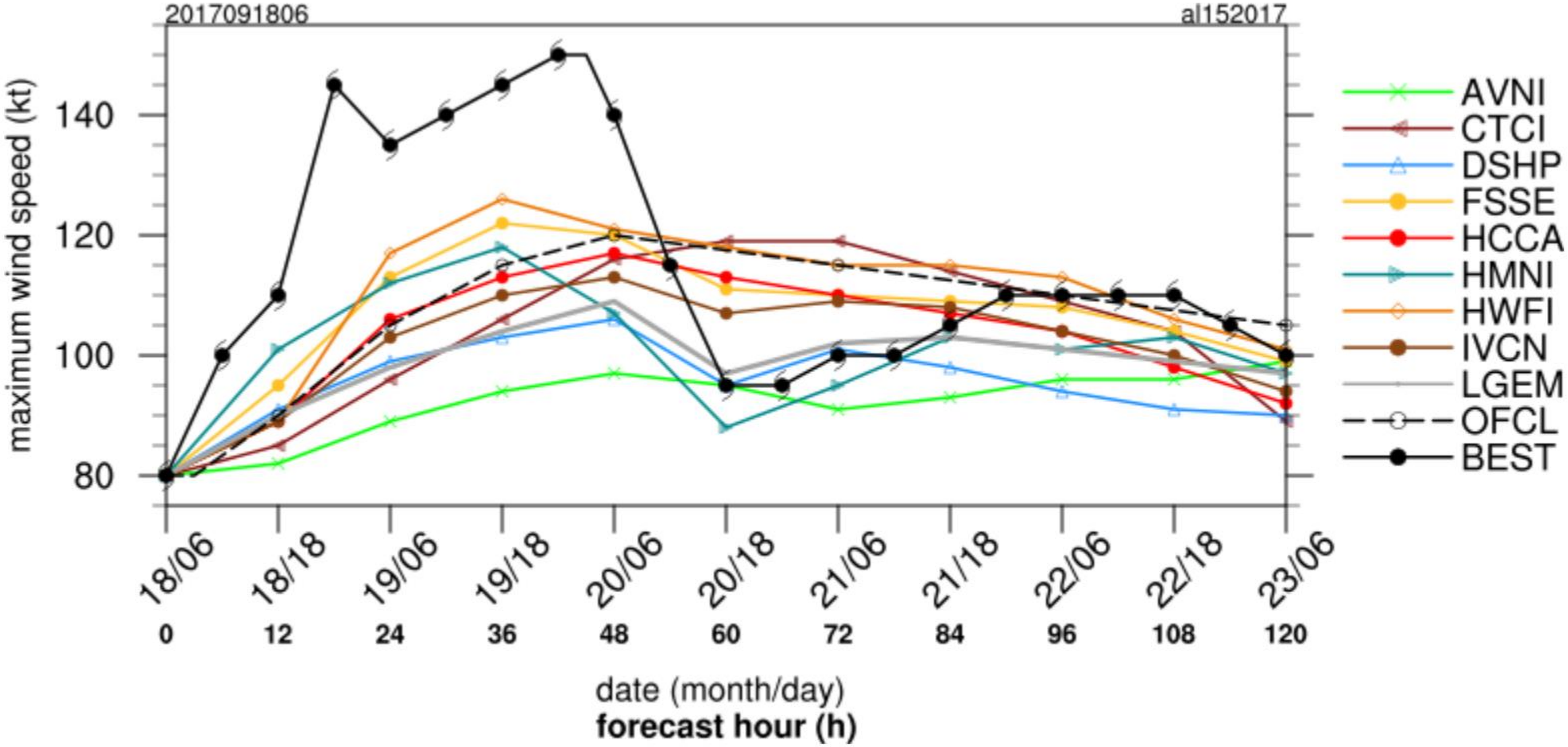
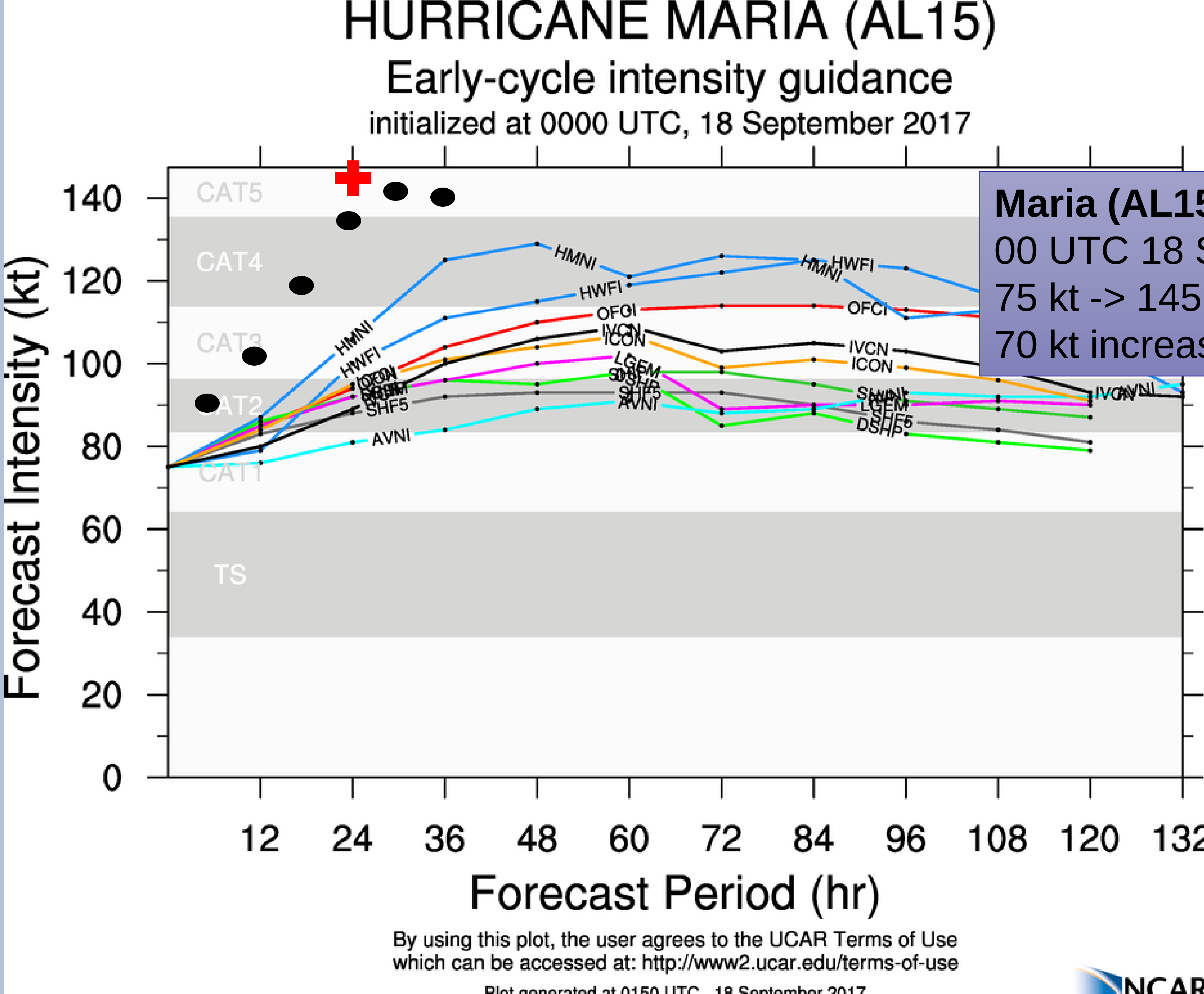
Plot generated at 0920 UTC 22 October 2015



Meranti (WP16)
06 UTC 10 Sep 2016
35 kt -> 155 kt
120 kt increase in 60 h



From NHC Tropical Cyclone Report for Maria



Maria (AL15)
00 UTC 18 Sep 2017
75 kt -> 145 kt
70 kt increase in 24 h

Coupled Hurricane Intensity Prediction System

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- CHIPS is a relatively simple two-dimensional (radius-height plane) dynamical model (Emanuel et al 2004).
- Uses a potential radius coordinate, providing very high resolution in the eyewall region, with lower resolution in the outer part of the model domain.
- Convection is parameterized as a quasi-equilibrium balance between the increase of entropy due to surface fluxes, radial transport, and the downward transport of low entropy air from mid-levels.
- Both the initial and outer boundary value of the mid-level moist entropy is provided from NCEP operational analyses.
- Effect of vertical shear is parameterized via the model's convective fluxes (more shear produces more ventilation of the storm, causing weakening).
- The model is coupled to 1D ocean models that are strung out along the storm's predicted path.

CHIPS, cont'd

- **Boundary conditions**
- GFS fields; GFS analyzed SST; mixed layer depth and sub-mixed layer thermal stratification from Levitus monthly climatology
- **Initialization**
  - The model is started from the beginning of the storm history, with the mid-level entropy being adjusted to keep the intensity as close as possible to the observed value up until the beginning of the forecast.
  - The potential intensity is computed from the Global Forecast System (GFS) model's full vertical column profiles of temperature and humidity, but lagged by 5 days so as to remove any influence of the storm

CHIPS Ensemble

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- Member 1 - CHIP: control (same as deterministic run)
- Member 2 - CHP2: initial intensity enhanced by 3 m/s in previous 24-hr period (ramped up)
- Member 3 - CHP3: initial intensity decreased by 3 m/s in previous 24-hr period (ramped down)
- Member 4 - CHP4: initial intensity same as control, but the intensity 12 hours previous is enhanced by 1.5 m/s to produce a negative intensification anomaly at the initialization time
- Member 5 - CHP5: initial intensity same as control, but the intensity 12 hours previous is decreased by 1.5 m/s to produce a positive intensification anomaly at the initialization time
- Member 6 - CHP6: initial intensity enhanced by 3 m/s in previous 24-hr period (ramped up) with vertical wind shear set to zero at all times -- meant to provide a plausible upper bound for the intensity forecast
- Member 7 - CHP7: initial intensity decreased by 3 m/s in previous 24-hr period (ramped down) with vertical wind shear enhanced by 5 m/s -- meant to provide a plausible lower bound for the intensity forecast

Verification Protocol

- All global basins
- 2013-2017
- Post-season best tracks from NHC/JTWC for 2013-2016
- Real-time best tracks for 2017
- Over water (land cases excluded)
- Models included: CHP6, HWRF, COTC, CTCX, OFCL/JTWC
- **Used the Model Evaluation Toolkit for Tropical Cyclones(MET-TC) v6.1**

30 kt / 24 h

CHP6			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	573	1637	2210
No	830	15924	16754
Total Obs	1402	17561	**19028**

HWRF			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	273	498	771
No	1194	17063	18257
Total Obs	1467	17561	**19028**

30 kt / 24 h

Hits

False Alarms

Misses

Correct Nulls

CHP6

RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	573	1637	2210
No	830	15924	16754
Total Obs	1402	17561	**19028**

HWRF

RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	273	498	771
No	1194	17063	18257
Total Obs	1467	17561	**19028**

RI: 30 kt / 24 h

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CLIMO = 7.7%

CHP6			
RI Forecast	**RI Observed**		
	Yes	**No**	**Total Forecasts**
Yes	**573**	**1637**	2210
No	**830**	**15924**	16754
Total Obs	1402	17561	**19028**

FMEAN = 11.9%
FBIAS = 1.55
POD = **0.434**
POFD = 0.093
FAR = 0.729
CSI = **0.205**
GSS = **0.157**

HWRF			
RI Forecast	**RI Observed**		
	Yes	**No**	**Total Forecasts**
Yes	**273**	**498**	771
No	**1194**	**17063**	18257
Total Obs	1467	17561	**19028**

FMEAN = 3.7%
FBIAS = 0.52
POD = 0.186
POFD = **0.028**
FAR = **0.646**
CSI = 0.139
GSS = 0.112

VRI: 30 kt / 12 h

NCAR

CLIMO = 2.3%

CHP6

RI Forecast	RI Observed		
	Yes	**No**	**Total Forecasts**
Yes	123	953	
No	284	16511	
Total Obs			17871

FMEAN = 6.0%
FBIAS = 2.64
POD = **0.302**
POFD = 0.055
FAR = **0.885**
CSI = **0.090**
GSS = **0.074**

HWRF

RI Forecast	RI Observed		
	Yes	**No**	**Total Forecasts**
Yes	17	139	
No	390	17325	
Total Obs			17871

FMEAN = 0.9%
FBIAS = 0.38
POD = 0.042
POFD = **0.008**
FAR = 0.891
CSI = 0.031
GSS = 0.025

ERI: 40 kt / 12 h

NCAR

CLIMO = 0.71%

CHP6			
RI Forecast	**RI Observed**		
	Yes	**No**	**Total Forecasts**
Yes	**24**	**471**	
No	**103**	**17273**	
Total Obs			**17871**

FMEAN = 2.8%
FBIAS = 3.89
POD = **0.189**
POFD = 0.027
FAR = 0.951
CSI = **0.040**
GSS = **0.034**

HWRF			
RI Forecast	**RI Observed**		
	Yes	**No**	**Total Forecasts**
Yes	**3**	**21**	
No	**124**	**17723**	
Total Obs			**17871**

FMEAN = 0.13%
FBIAS = 0.19
POD = 0.023
POFD = **0.001**
FAR = **0.875**
CSI = 0.020
GSS = 0.019

VRI: 45 kt / 24 h

NCAR

CLIMO = 2.7%

CHP6			
RI Forecast	**RI Observed**		
	Yes	**No**	**Total Forecasts**
Yes	**180**	**1016**	
No	**331**	**17501**	
Total Obs			**19028**

FMEAN = 6.3%
FBIAS = 2.34
POD = **0.352**
POFD = 0.055
FAR = 0.850
CSI = **0.118**
GSS = **0.099**

HWRF			
RI Forecast	**RI Observed**		
	Yes	**No**	**Total Forecasts**
Yes	**19**	**83**	
No	**492**	**18434**	
Total Obs			**19028**

FMEAN = 0.6%
FBIAS = 0.20
POD = 0.037
POFD = **0.004**
FAR = **0.814**
CSI = 0.032
GSS = 0.028

ERI: 60 kt / 24 h

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CLIMO = 0.86%

CHP6			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	42	544	
No	122	18320	
Total Obs			19028

FMEAN = 3.1%
FBIAS = 3.57
POD = **0.256**
POFD = 0.029
FAR = 0.928
CSI = **0.059**
GSS = **0.053**

HWRF			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	1	6	
No	163	18858	
Total Obs			19028

FMEAN = 0.04%
FBIAS = 0.043
POD = 0.006
POFD = **0.000**
FAR = **0.857**
CSI = 0.006
GSS = 0.006

		Base Rate	Prob. of Detection	False Alarm Rate	Equitable Threat Score
30 kt / 12 h	VRI	2.3%	0.302 0.042	0.885 0.891	0.074 0.025
40 kt / 12 h	ERI	0.7%	0.189 0.023	0.951 0.875	0.034 0.019
30 kt / 24h	RI	7.7%	0.434 0.186	0.729 0.646	0.157 0.112
45 kt / 24 h	VRI	6.3%	0.352 0.037	0.850 0.814	0.099 0.028
60 kt / 24 h	ERI	0.9%	0.256 0.006	0.928 0.857	0.053 0.006

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CHP6 HWRF

Conclusions

- In terms of guidance for estimating the upper bound of intensification, CHP6 outperforms all other numerical models.
  - Far superior probability of detection
  - Modestly higher False Alarm Rate compared
  - HWRF and OFCL have some skill at RI threshold, however HWRF only retains slight skill at VRI and ERI thresholds.

Conclusions, cont'd

- The dynamics of VRI/ERI are primarily axisymmetric and do not require a 3D full-physics framework.

- These successful CHP6 predictions suggest that the general pathway of ERI can be captured by an axisymmetric numerical model.

Hypothesis

The upper intensification limit, which can be considered the *Maximum Potential Intensification Rate*, or MPIR, may be achieved when the storm structure and latent heating distribution are axisymmetric in a favorable environment. When the MPIR limit is high for a given storm, ERI becomes possible.

Future Work

NCAR

- Explore how the upper bound on a TC's intensification rate depends on the storm's predicted environment and initial vortex structure.
- Next steps:
  - Examine high-resolution flight level observations from several ERI cases to learn how the TC's physical scale (RMW), inertial stability, dynamic efficiency, and column-integrated latent heating evolve during ERI.
  - Create and evaluate an initial forecast aid for the upper bound intensity forecast

Acknowledgments

- We thank Zhan Zhang (NCEP/EMC) for providing some of the a-decks used in the verification.

- NCAR is sponsored by the National Science Foundation.

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Questions?

National Center for Atmospheric Research

CHP6 vs. COTC

- This 2hd verification only covers the Northern Hemisphere storms.

30 kt / 24 h

Hits

False Alarms

CHP6

RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	763	2187	2950
No	1304	27595	28899
Total Obs	2067	29782	31849

Misses

Correct Nulls

COTC

RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	242	726	968
No	1824	28857	30681
Total Obs	1546	29583	31649

30 kt / 24 h

NCAR

CHP6			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	763	2187	2950
No	1304	27595	28899
Total Obs	2067	29782	31849

BASER = 0.065
FMEAN = 0.093
POD = 0.369
POFD = 0.073
FAR = 0.741
CSI = 0.179

COTC			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	242	726	968
No	1824	28857	30681
Total Obs	1546	29583	31649

BASER = 0.065
FMEAN = 0.031
POD = 0.117
POFD = 0.025
FAR = 0.750
CSI = 0.087

50 kt / 24 h

NCAR

CHP6			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	114	1055	
No	370	30310	
Total Obs			

BASER = 0.015
FMEAN = 0.037
POD = 0.236
POFD = 0.034
FAR = 0.903
CSI = 0.074

COTC			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	2	56	
No	482	31109	
Total Obs			

BASER = 0.015
FMEAN = 0.002
POD = 0.004
POFD = 0.002
FAR = 0.966
CSI = 0.004

50 kt / 48 h

NCAR

CHP6			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	374	1047	
No	739	18315	
Total Obs			

BASER = 0.054
FMEAN = 0.069
POD = 0.336
POFD = 0.054
FAR = 0.737
CSI = 0.173

COTC			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	101	278	
No	1012	18934	
Total Obs			

BASER = 0.055
FMEAN = 0.019
POD = 0.091
POFD = 0.015
FAR = 0.734
CSI = 0.073

80 kt / 48 h

NCAR

CHP6

RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	27	298	
No	99	20051	
Total Obs			

BASER = 0.006
FMEAN = 0.016
POD = 0.214
POFD = 0.014
FAR = 0.917
CSI = 0.064

COTC

RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	1	5	
No	125	20194	
Total Obs			

BASER = 0.006
FMEAN = 0.0003
POD = 0.008
POFD = 0.0002
FAR = 0.833
CSI = 0.008

80 kt / 72 h

NCAR

CHP6			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	24	224	
No	97	11546	
Total Obs			

BASER = 0.010
FMEAN = 0.021
POD = 0.198
POFD = 0.019
FAR = 0.903
CSI = 0.070

COTC			
RI Forecast	RI Observed		
	Yes	No	Total Forecasts
Yes	6	6	
No	115	11665	
Total Obs			

BASER = 0.010
FMEAN = 0.001
POD = 0.050
POFD = 0.001
FAR = 0.500
CSI = 0.047