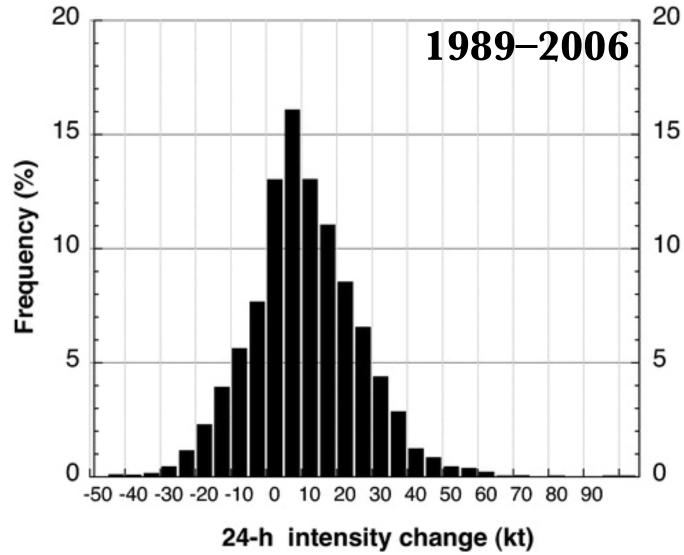
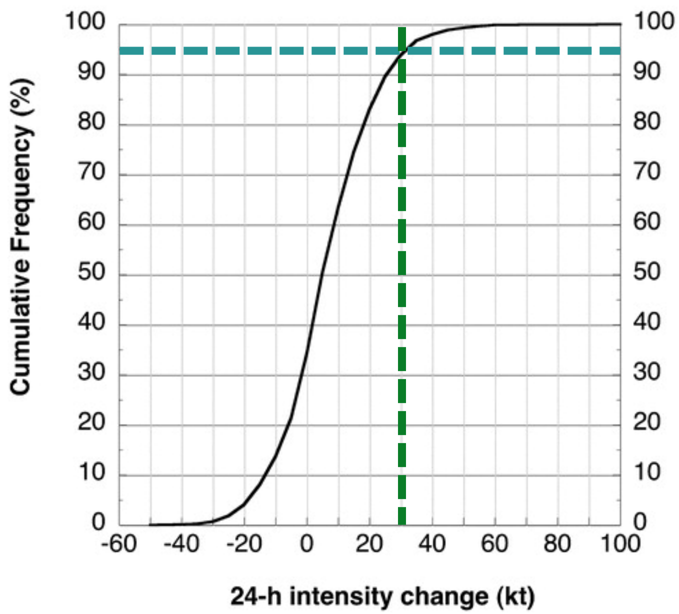
Rapid intensification: What is it?



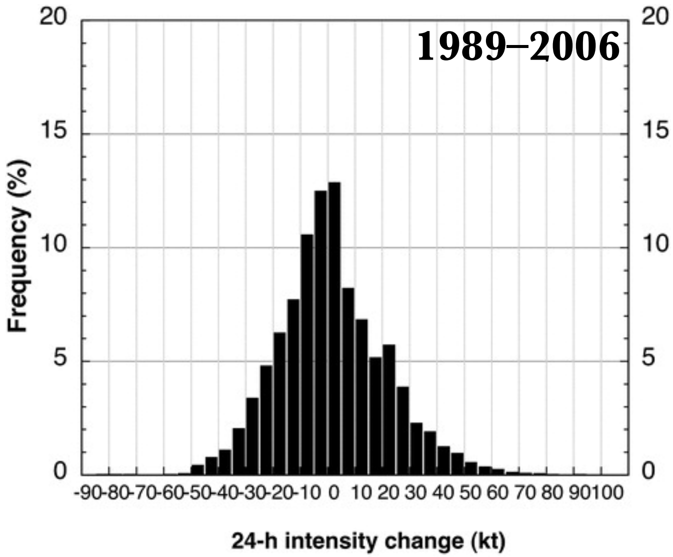


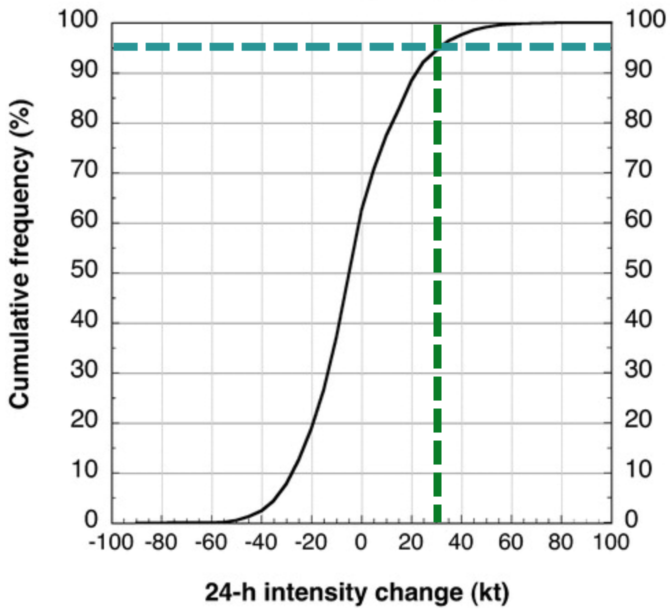
Kaplan & DeMaria (2003)
Kaplan et al. (2011):

~95th percentile
of over water
24-h intensity change
in *Atlantic basin* TCs

30 kt (15.4 m s^{-1})

Rapid intensification: What is it?



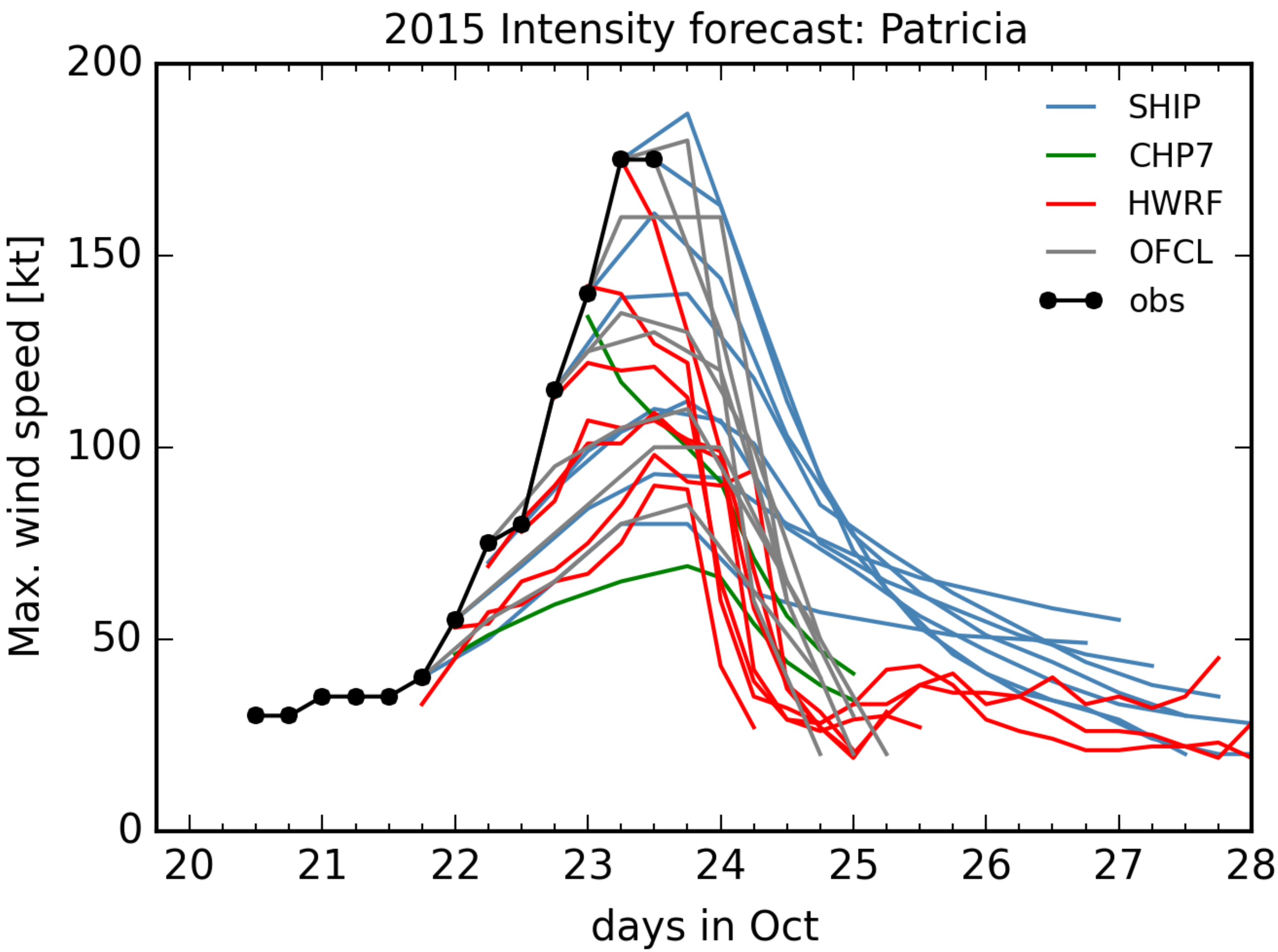


Kaplan & DeMaria (2003)
Kaplan et al. (2011):

~95th percentile
of over water
24-h intensity change
in *eastern Pacific basin* TCs

30 kt (15.4 m s^{-1})

Rapid intensification: Why do we care about it?



Wing and Lee (2015)

Rapid intensification: Crappy forecasts ☹

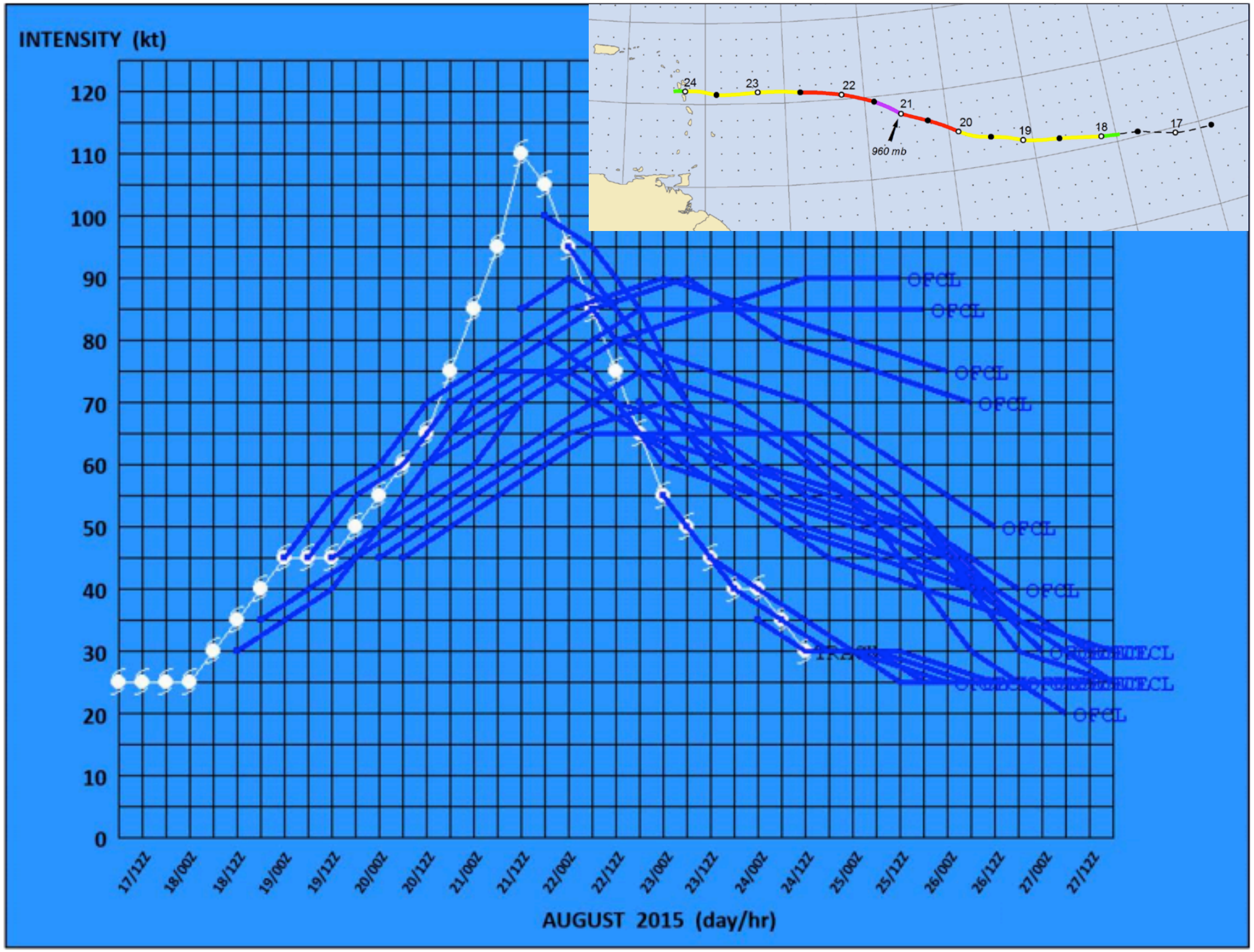
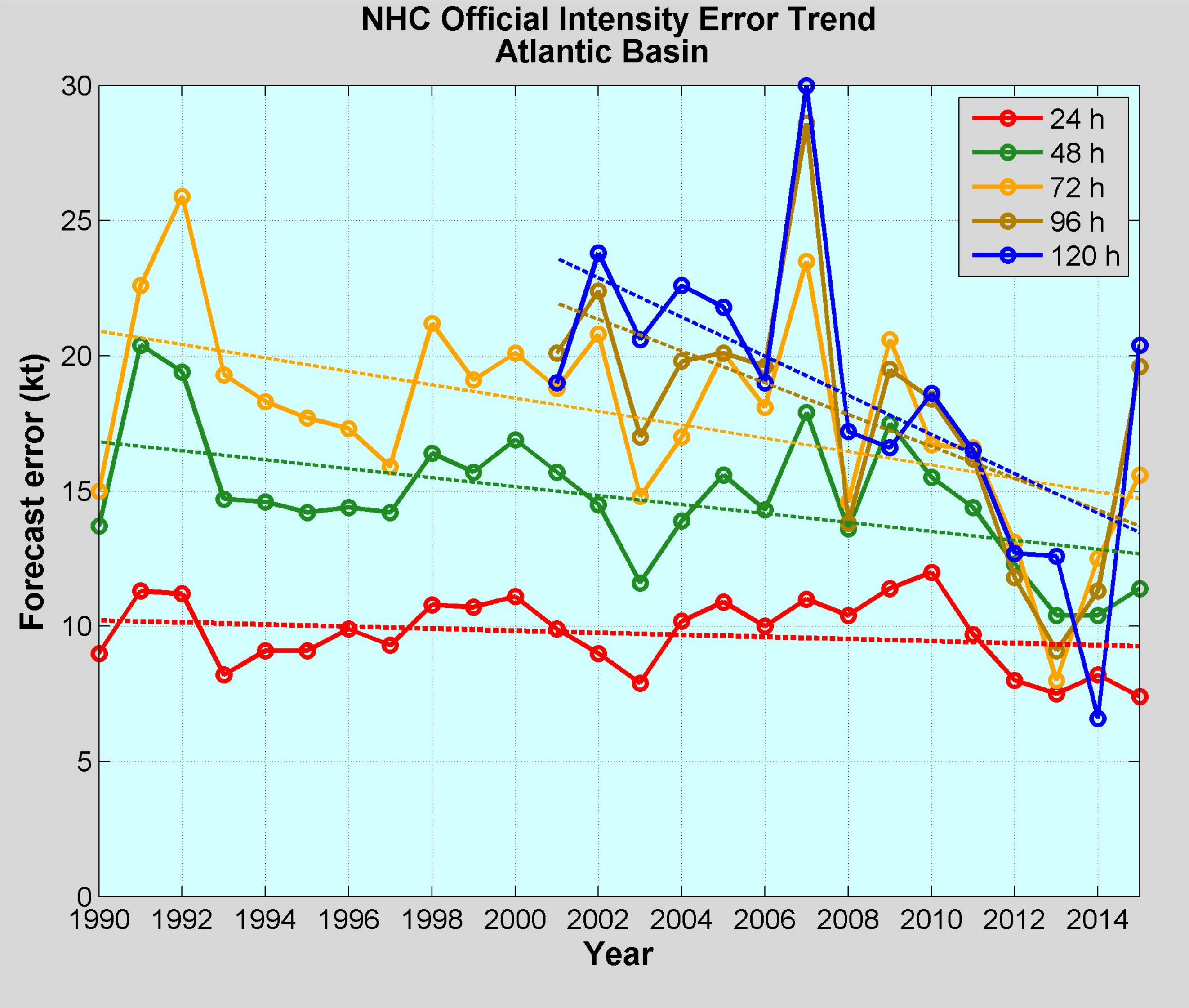
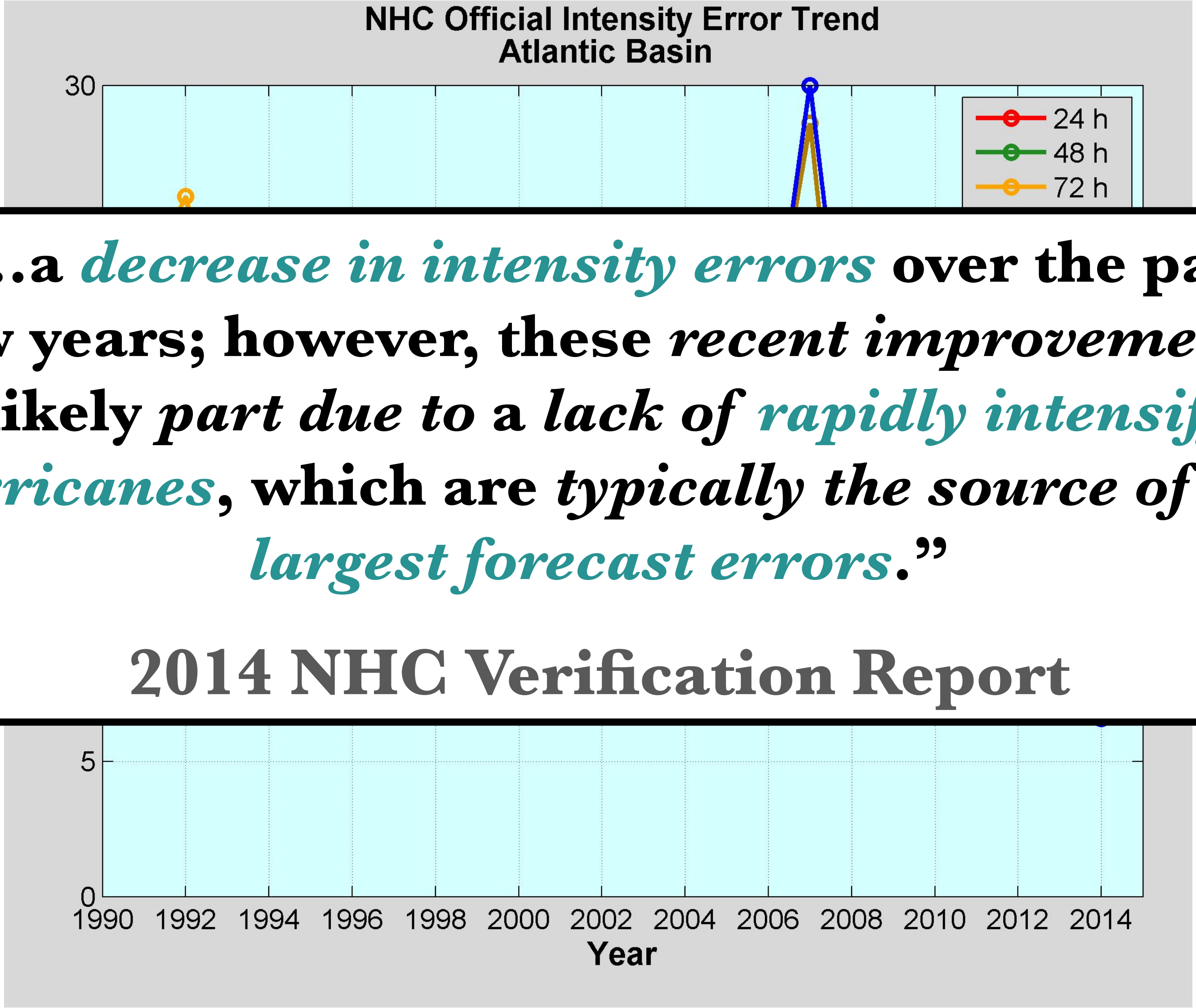


Figure 6. NHC official intensity forecasts (solid light blue lines) plotted against official intensity 'best track' (solid white line with tropical cyclone symbols) for Hurricane Danny, 18-24 August 2015.

Rapid intensification: Crappy forecasts ☹



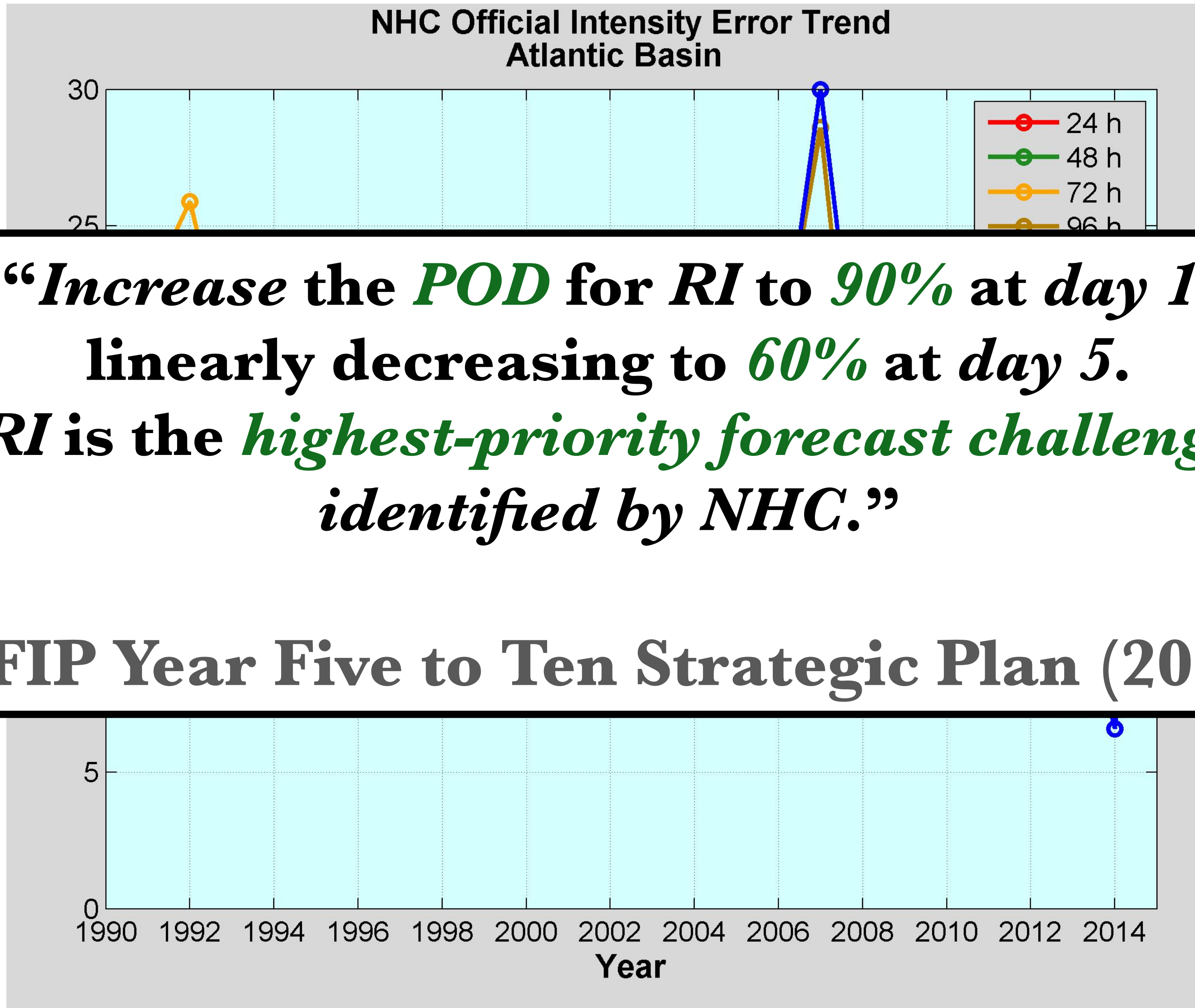
Rapid intensification: Crappy forecasts ☹



"…a *decrease in intensity errors* **over the past few years; however, these** ***recent improvements*** **are likely** ***part due to a lack of rapidly intensifying hurricanes*****, which are** ***typically the source of the largest forecast errors*****."**

2014 NHC Verification Report

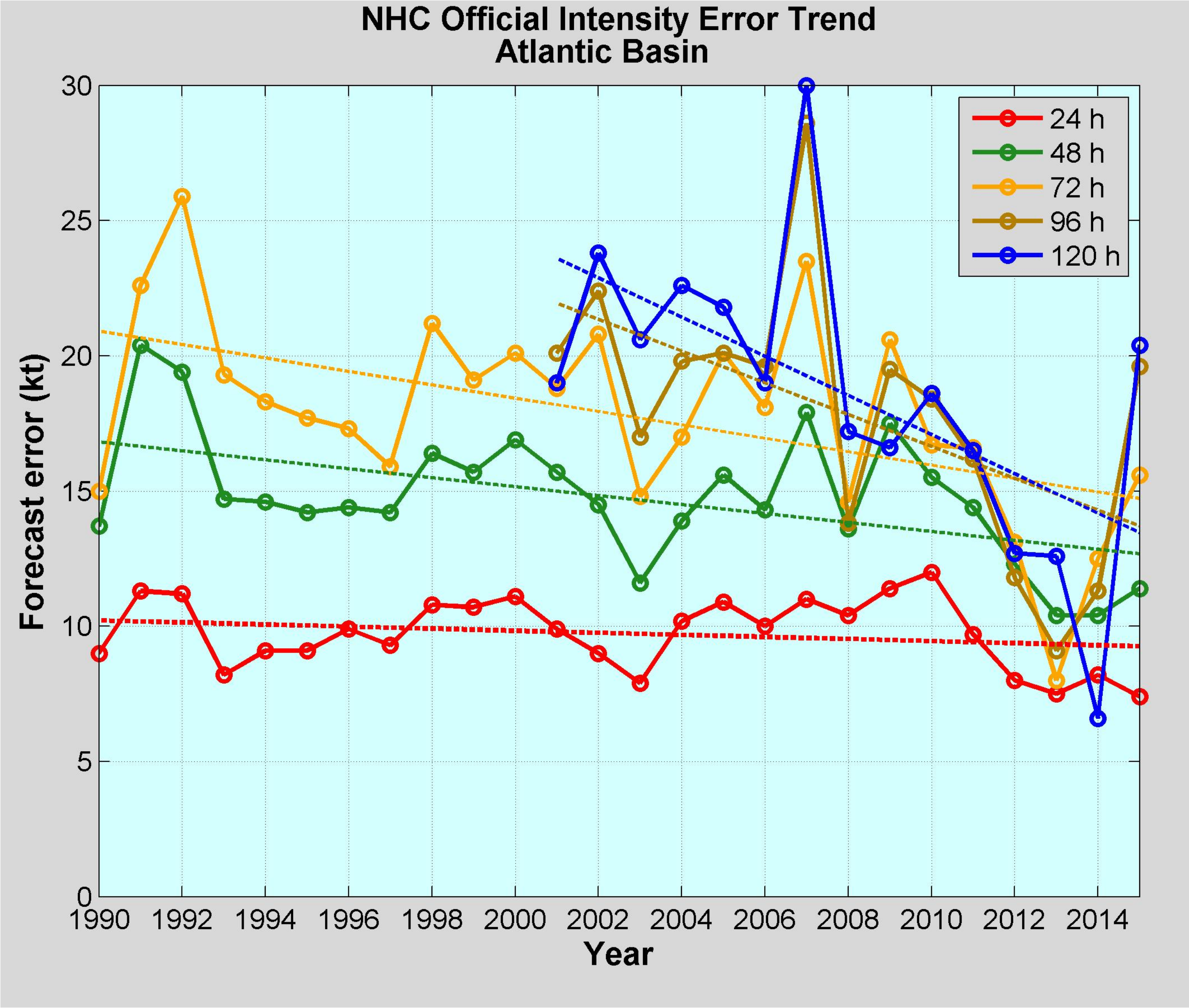
Rapid intensification: Crappy forecasts ☹



***"Increase* the *POD* for *RI* to *90%* at *day 1*, linearly decreasing to *60%* at *day 5*. *RI* is the *highest-priority forecast challenge identified by NHC*."**

HFIP Year Five to Ten Strategic Plan (2014)

NHC intensity verification: Going no where fast…



Late 1980's intensity forecasting: Very little guidance

Late 1980's intensity forecasting: Very little guidance

To help forecast…

Late 1980's intensity forecasting: Very little guidance

NATIONAL HURRICANE CENTER
MIAMI FLORIDA

To help forecast…

We can do better!

Late 1980's intensity forecasting: SHIPS is born!

The Statistical Hurricane Intensity Prediction Scheme (SHIPS)

Combines *predictors* from *climatology*, *persistence*, the *atmosphere*, and the *ocean* to *estimate changes* in *TC intensity*

DeMaria and Kaplan (1994)

Late 1980's intensity forecasting: SHIPS is born!

```
                      * ATLANTIC      SHIPS INTENSITY FORECAST          *
                      * IR SAT DATA AVAILABLE,       OHC AVAILABLE      *
                      *  ALEX         AL012016  01/14/16  18 UTC        *

TIME (HR)         0     6    12    18    24    36    48    60    72    84    96   108   120
V (KT) NO LAND   75    78    80    82    85    89    92    93    92    90    88    83    76
V (KT) LAND      75    78    80    82    85    89    92    93    92    90    88    83    76
V (KT) LGE mod   75    78    76    73    71    66    60   DIS   DIS   DIS   DIS   DIS   DIS
Storm Type     TROP  TROP  TROP  TROP  EXTP  EXTP  EXTP   N/A   N/A   N/A   N/A   N/A   N/A

SHEAR (KT)        9    17    16    14    17    29    28   N/A   N/A   N/A   N/A   N/A   N/A
SHEAR ADJ (KT)    4     3     3     6    12    20    23   N/A   N/A   N/A   N/A   N/A   N/A
SHEAR DIR       300   262   253   209   189   161   147   N/A   N/A   N/A   N/A   N/A   N/A
SST (C)        19.8  18.5  16.9  15.6  14.7  10.4   5.7   N/A   N/A   N/A   N/A   N/A   N/A
POT. INT. (KT)   82    78    76    75    75    73    71   N/A   N/A   N/A   N/A   N/A   N/A
ADJ. POT. INT.   76    73    72    72    72    72    71   N/A   N/A   N/A   N/A   N/A   N/A
200 MB T (C)  -59.9 -61.0 -62.4 -63.3 -63.6 -62.7 -63.1   N/A   N/A   N/A   N/A   N/A   N/A
TH_E DEV (C)      2     1     0     0     0     0     0   N/A   N/A   N/A   N/A   N/A   N/A
700-500 MB RH    55    53    57    59    64    67    69   N/A   N/A   N/A   N/A   N/A   N/A
MODEL VTX (KT)   28    29    30    33    36    39    39  LOST  LOST  LOST  LOST  LOST  LOST
850 MB ENV VOR  109   110    83    62    92   152   170   N/A   N/A   N/A   N/A   N/A   N/A
200 MB DIV       24    21    58   121   144   119    53   N/A   N/A   N/A   N/A   N/A   N/A
700-850 TADV     -2    26    42    70   108    99    49   N/A   N/A   N/A   N/A   N/A   N/A
LAND (KM)      1504  1592  1648  1609  1552  1404  1499   N/A   N/A   N/A   N/A   N/A   N/A
LAT (DEG N)    32.6  34.6  36.5  39.3  42.0  49.2  57.1   N/A   N/A   N/A   N/A   N/A   N/A
LONG(DEG W)    28.0  27.8  27.7  27.8  28.0  29.7  33.3   N/A   N/A   N/A   N/A   N/A   N/A
STM SPEED (KT)   19    20    23    28    32    39    40   N/A   N/A   N/A   N/A   N/A   N/A
HEAT CONTENT      0     0     0     0     0     0     0     0     0     0     0     0     0

  FORECAST TRACK FROM OFCI      INITIAL HEADING/SPEED (DEG/KT): 15/ 19      CX,CY:   5/ 18
  T-12 MAX WIND:  55            PRESSURE OF STEERING LEVEL (MB):  710  (MEAN=624)
  GOES IR BRIGHTNESS TEMP. STD DEV.  50-200 KM RAD:  13.8 (MEAN=14.5)
  % GOES IR PIXELS WITH T < -20 C    50-200 KM RAD:  77.0 (MEAN=65.0)

                       INDIVIDUAL CONTRIBUTIONS TO INTENSITY CHANGE
                        6   12   18   24   36   48   60   72   84   96  108  120
                       ----------------------------------------------------------
  SAMPLE MEAN CHANGE    1.   2.   3.   4.   6.   8.   9.  11.  12.  12.  13.  14.
  SST POTENTIAL        -4.  -8. -13. -17. -24. -30. -35. -39. -42. -44. -45. -45.
  VERTICAL SHEAR MAG    0.  -1.   0.   0.   0.   1.   1.   2.   2.   3.   2.   1.
  VERTICAL SHEAR ADJ    0.   0.  -1.  -2.  -4.  -8. -10. -11. -12. -11. -10.  -8.
  VERTICAL SHEAR DIR    0.   1.   1.   2.   3.   4.   5.   6.   7.   8.   9.   9.
  PERSISTENCE           4.   5.   5.   5.   5.   5.   5.   4.   2.   1.   0.  -1.
  200/250 MB TEMP.      3.   7.  11.  16.  26.  35.  41.  48.  54.  59.  61.  63.
  THETA_E EXCESS       -1.  -2.  -3.  -5.  -7. -11. -14. -18. -23. -27. -30. -32.
  700-500 MB RH         0.   0.   0.   0.  -1.  -1.  -2.  -2.  -2.  -2.  -2.  -1.
  MODEL VTX TENDENCY    0.   1.   2.   5.   9.  10.  10.  10.   9.   8.   8.   7.
  850 MB ENV VORTICITY  1.   1.   1.   2.   3.   5.   7.   8.   9.  10.  11.  11.
  200 MB DIVERGENCE     0.   0.   1.   2.   4.   4.   5.   6.   5.   5.   4.   3.
  850-700 T ADVEC       0.   0.  -1.  -2.  -3.  -2.  -1.  -1.  -2.  -3.  -6. -12.
  ZONAL STORM MOTION    0.   0.   0.  -1.  -1.  -2.  -3.  -3.  -4.  -5.  -6.  -6.
  STEERING LEVEL PRES   0.   0.   0.   0.  -1.  -1.  -1.  -1.  -2.  -1.  -1.  -1.
  DAYS FROM CLIM. PEAK  0.   0.   0.   0.   0.  -1.  -1.  -1.   0.   0.   0.  -1.
  GOES PREDICTORS       0.   0.   0.   1.   1.   1.   1.   1.   1.   1.   1.   1.
  OCEAN HEAT CONTENT    0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.
                       ----------------------------------------------------------
  TOTAL CHANGE          3.   5.   7.  10.  14.  17.  18.  17.  15.  13.   8.   1.
```

DeMaria and Kaplan (1994)

Rapid intensity forecasting: SHIPS was bad ☹

Kaplan and DeMaria (2003)

During the development of SHIPs, TCs with the *largest 48-h intensity change*:

1) **were *smaller***
2) **experienced *weaker shear***
3) **had *less upper-level forcing***
4) **were *further from* their *MPI***

Rapid Intensity Index (RII)

Rapid intensity forecasting: The RII

TABLE 3. The predictors used in the revised Atlantic RII index.

Predictor	Definition
PER	Previous 12-h intensity change
SHRD	850–200-hPa vertical shear of the horizontal wind from the 0–500-km radius
D200	200-hPa divergence from the 0–1000-km radius
RHLO	850–700-hPa relative humidity from 200–800-km radius
PX30	Percent area from 50 to 200 km covered by $\leq -30°C$ IR cloud-top brightness temperatures
SDBT	Std dev of 50–200-km IR cloud-top brightness temperatures
POT	Potential intensity (current intensity − maximum potential intensity)
OHC	Ocean heat content

Kaplan et al. (2010)

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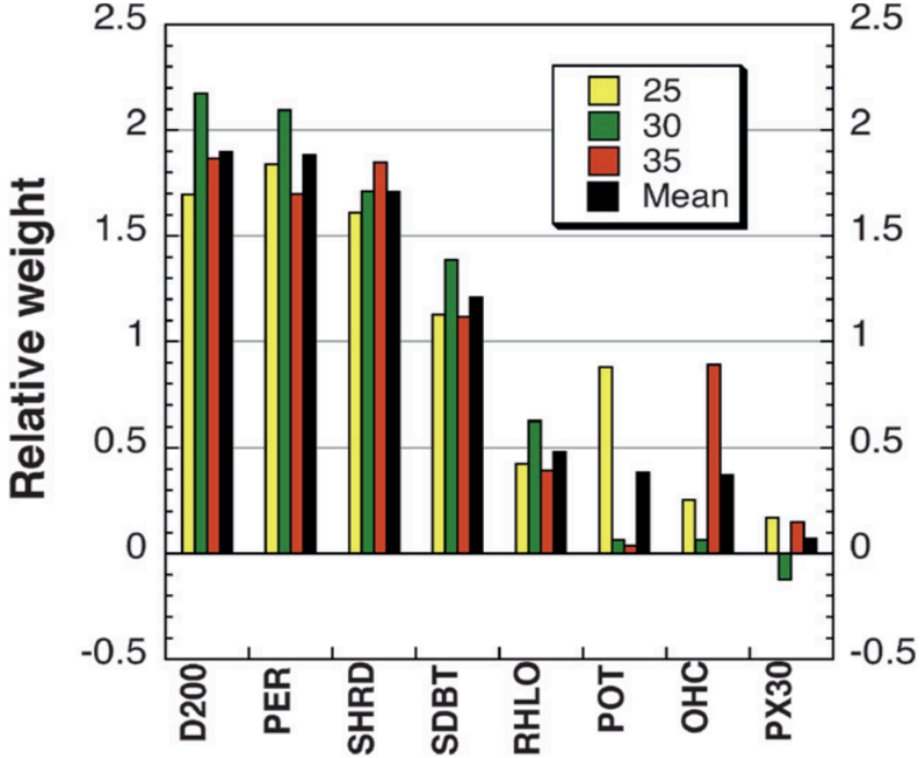
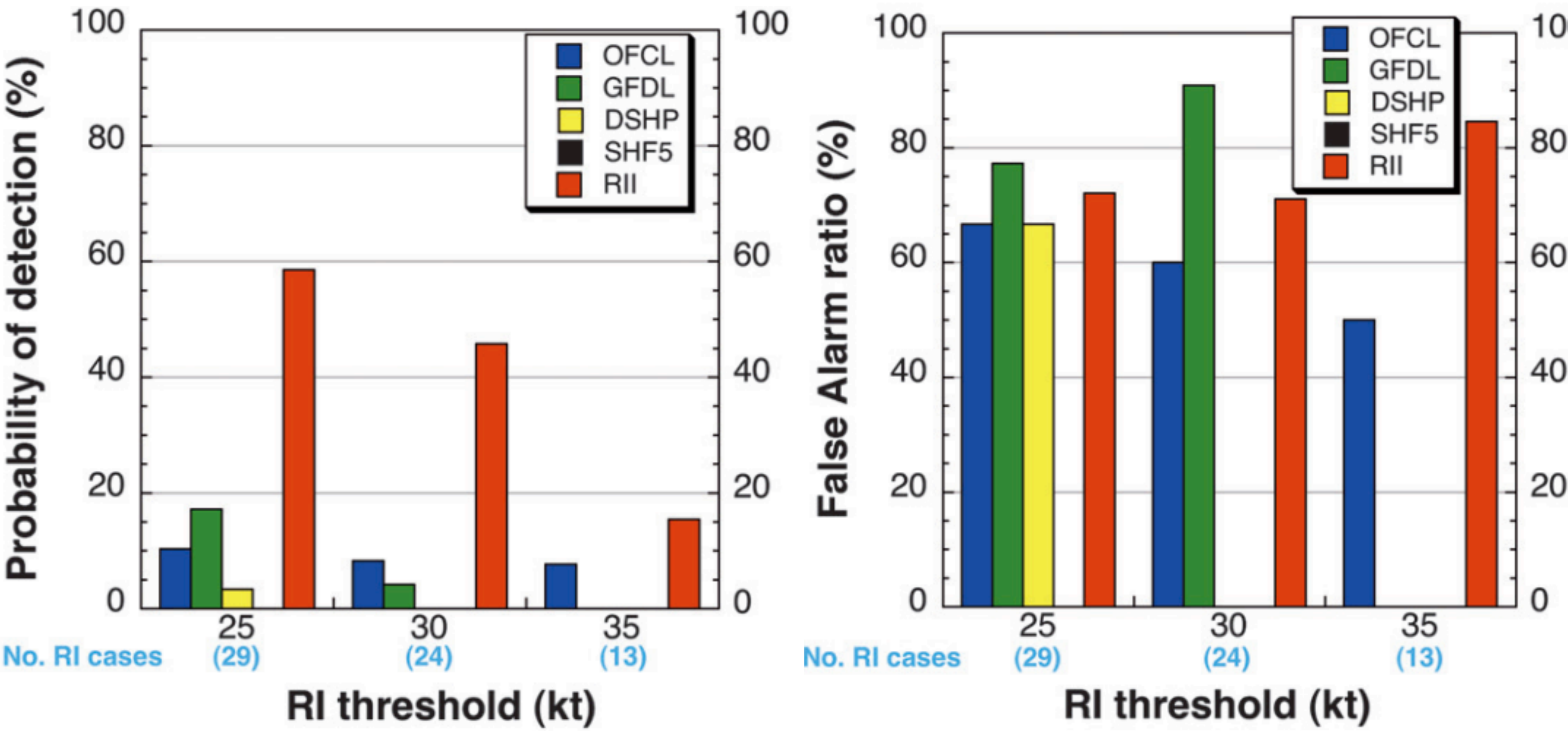


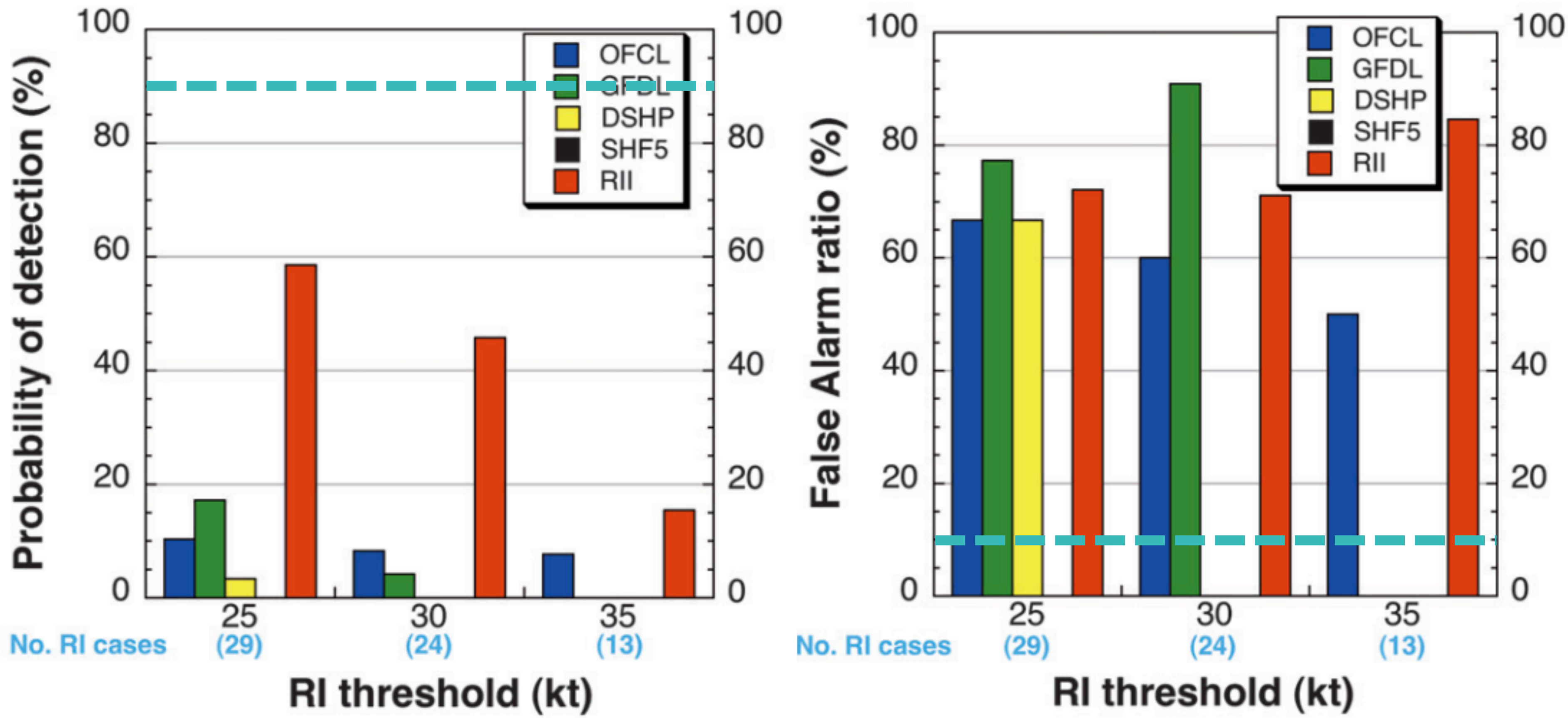
Kaplan et al. (2010)

Rapid intensity forecasting: Verification



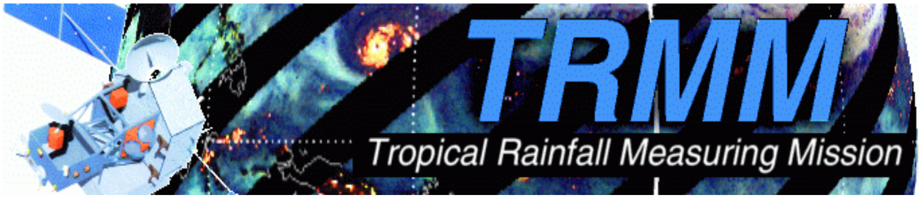
Kaplan et al. (2010)

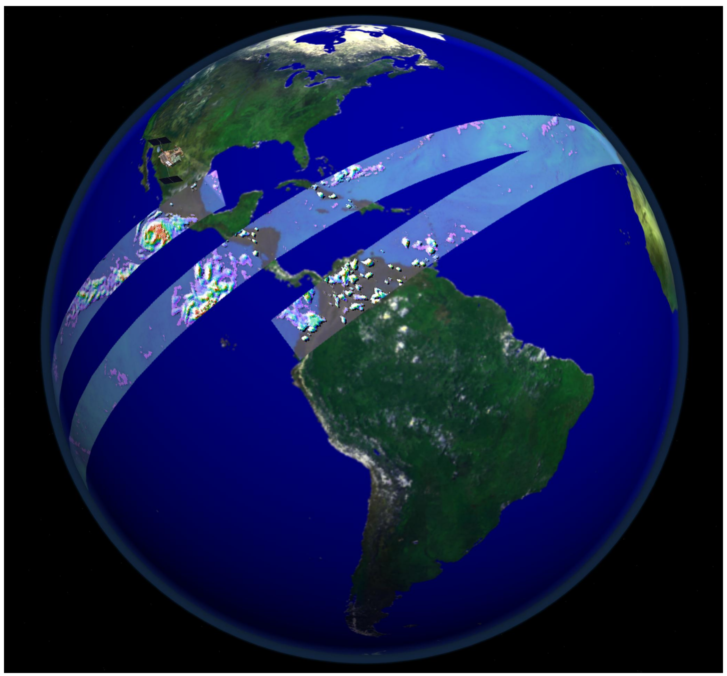
Rapid intensity forecasting: A long way from HFIP goals



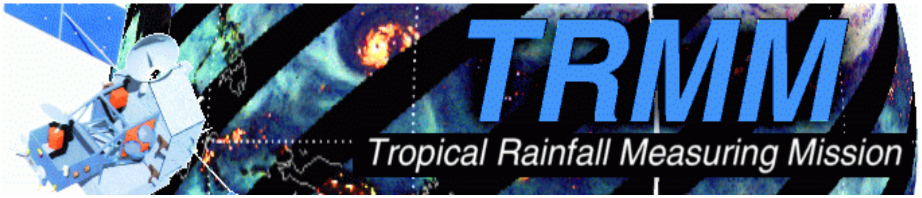
Kaplan et al. (2010)

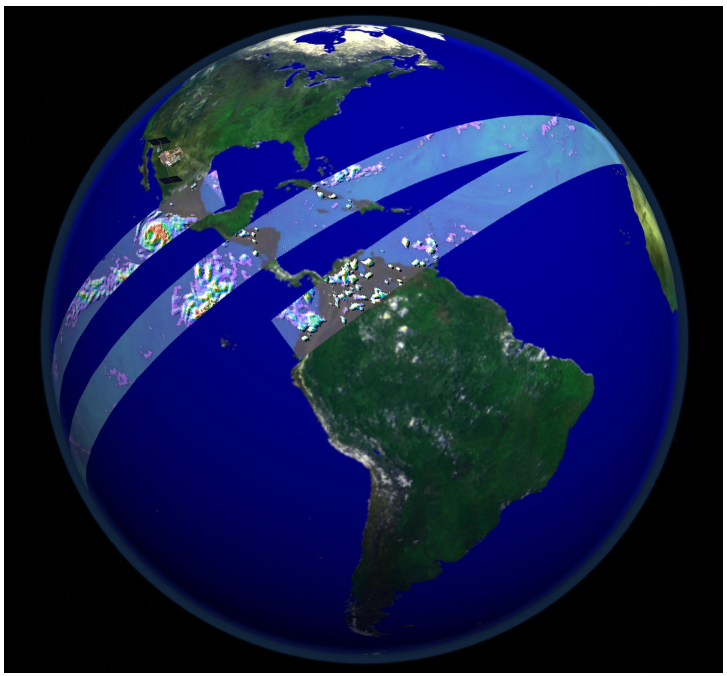
Rapid intensity forecasting: Microwave data

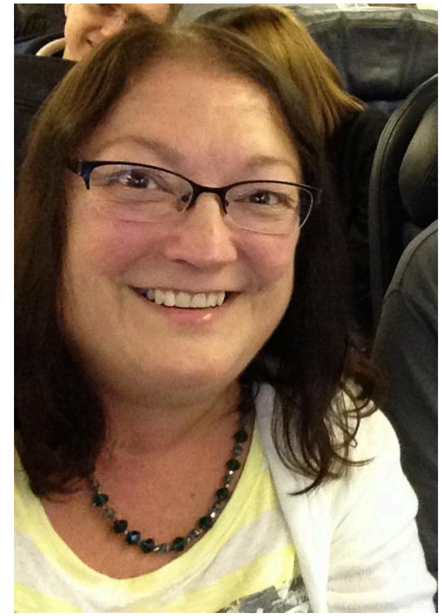


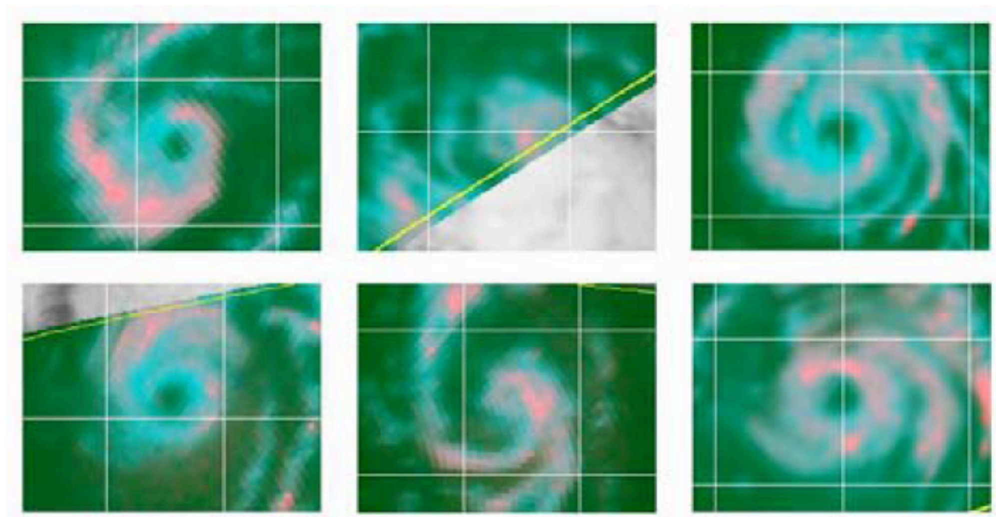


Rapid intensity forecasting: Microwave data



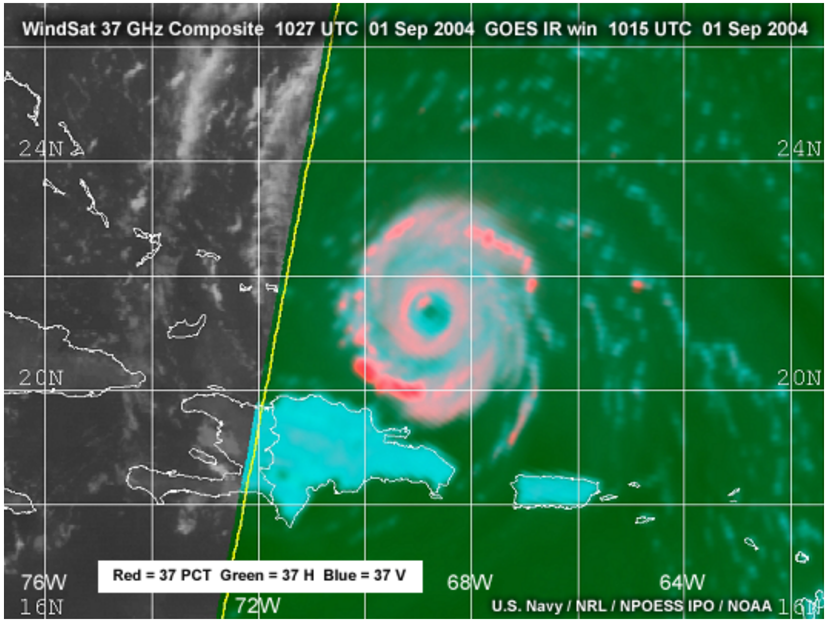






Kieper (2008)

Rapid intensity forecasting: Microwave data



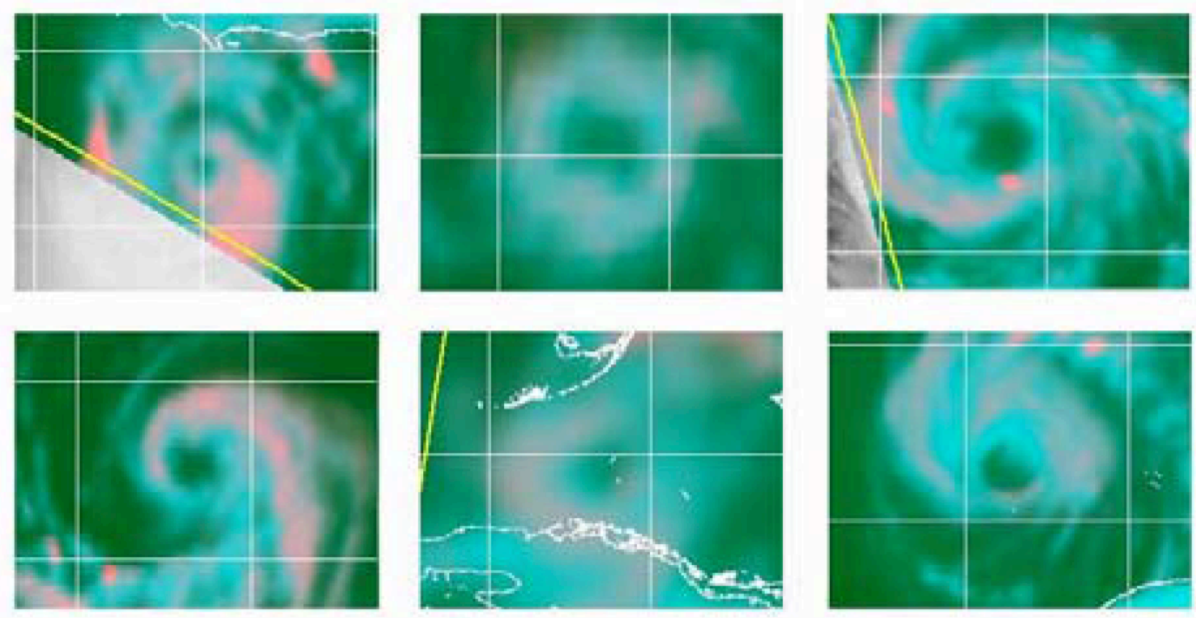
NRL-developed 37 GHz color composite

Polarization correction temperature (*PCT*) of the vertical and horizontal 37 GHz channels

Warm ocean (green), cold ice (pink), shallow clouds (cyan)

Lee et al. (2002); Kieper and Jiang 2012

Rapid intensity forecasting: Improvements using microwave data



37 GHz ring **is a *good predictor* of *RI* when the *environment* is *favorable* (SHIPS)**

82% of *RI cases* have a *ring* at, or before, the start of RI

Ring* is *precipitative*, mainly *shallow convection

Kieper and Jiang 2012; Tao and Jiang (2015)

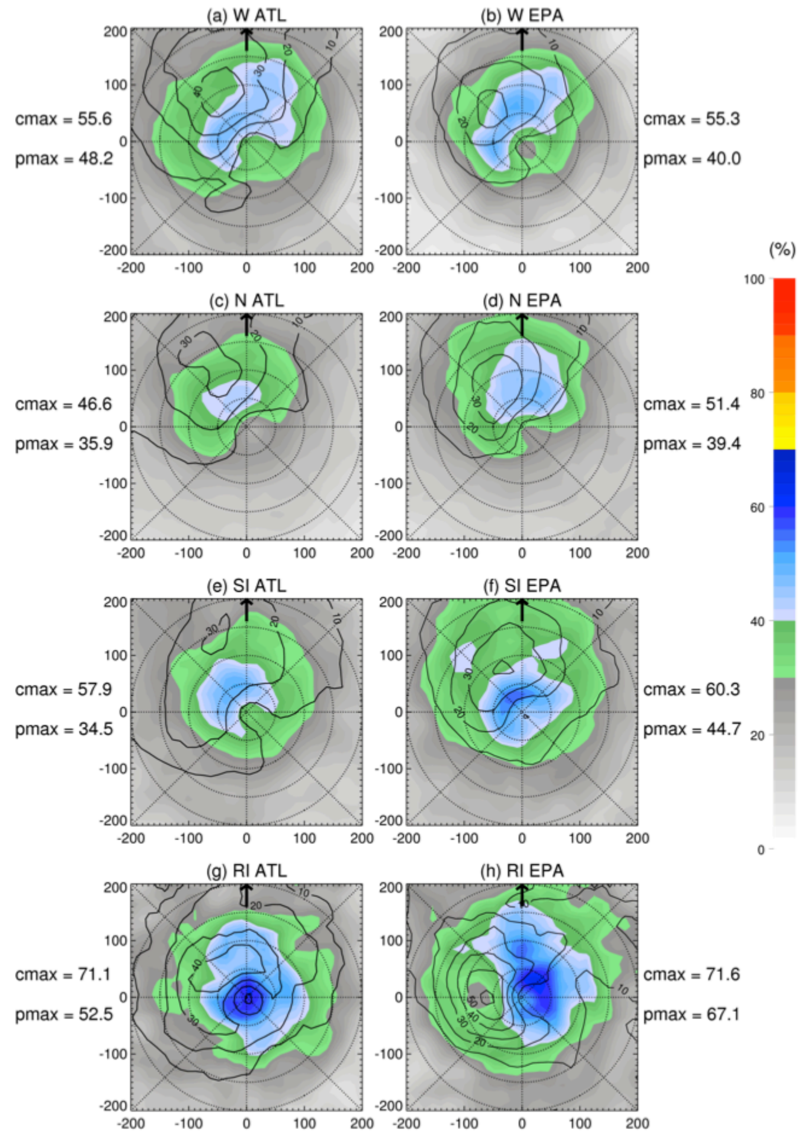
Rapid intensification: Microwave-based signals

Weakening

Neutral

Slowly intensifying

Rapidly intensifying



Downshear

% Cyan

% Pink

Fischer et al. (2014); Zagrodnik and Jiang (2014); Tao and Jiang (2015)

Rapid intensification: Microwave-based signals

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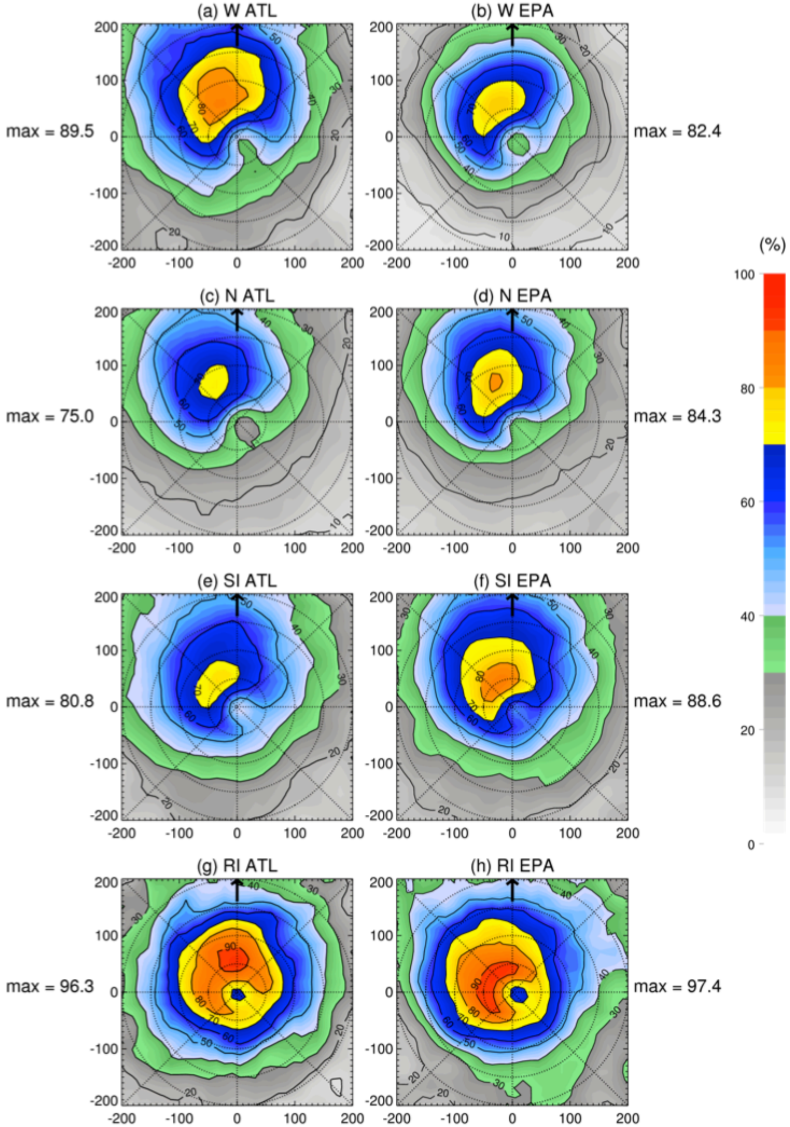

Downshear

% Cyan and Pink

Fischer et al. (2014); Zagrodnik and Jiang (2014); Tao and Jiang (2015)

Rapid intensification: Microwave-based signals

Weakening

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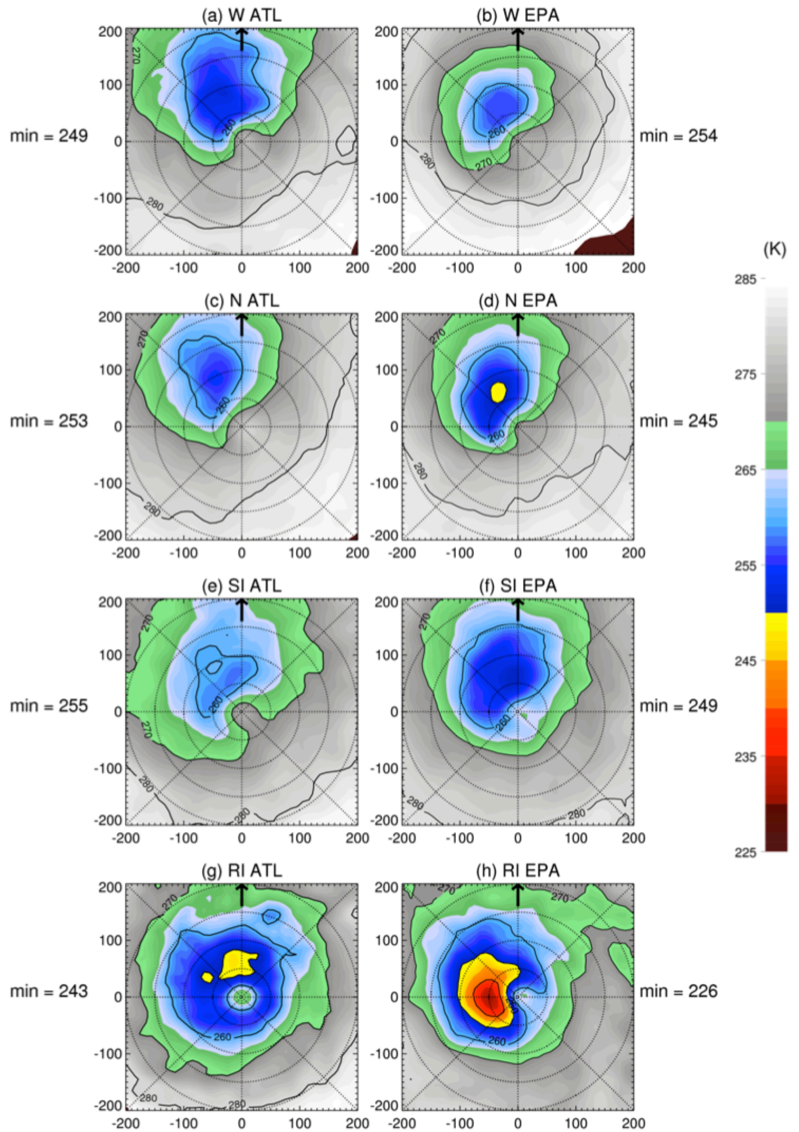
Rapidly intensifying

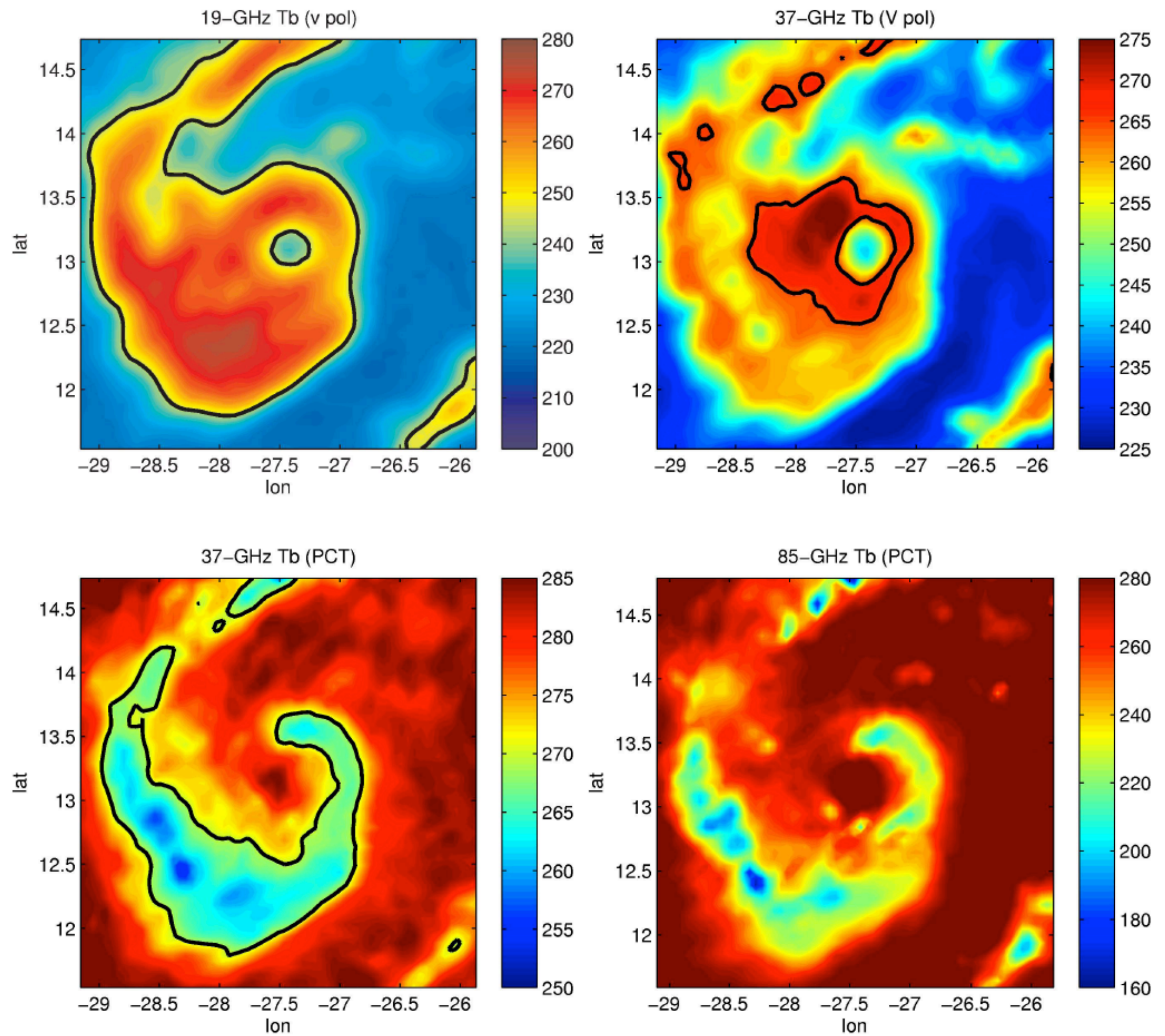


Downshear

85 GHz PCT

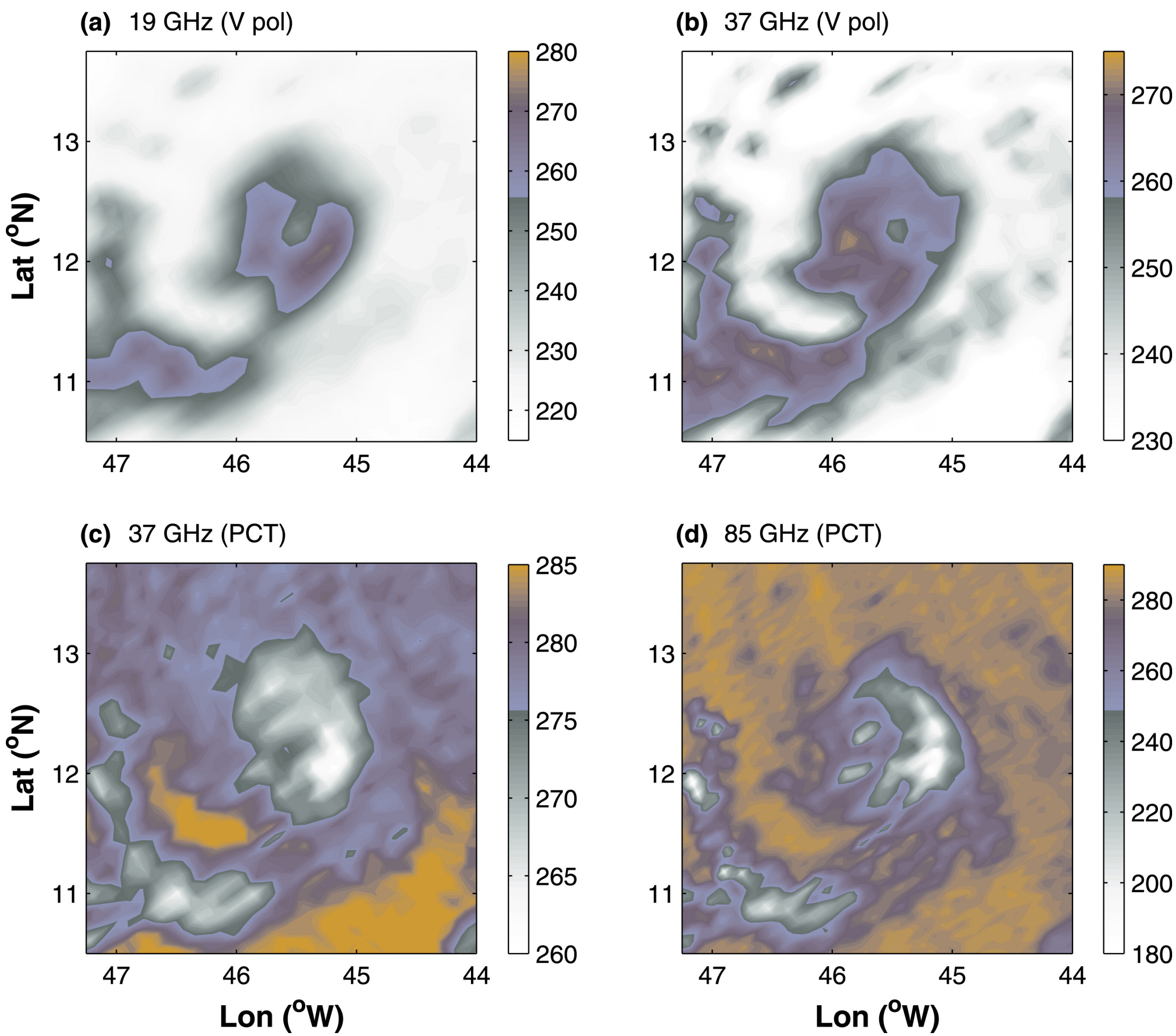
Fischer et al. (2014); Zagrodnik and Jiang (2014); Tao and Jiang (2015)

Rapid intensity forecasting: Welcome Badgers!



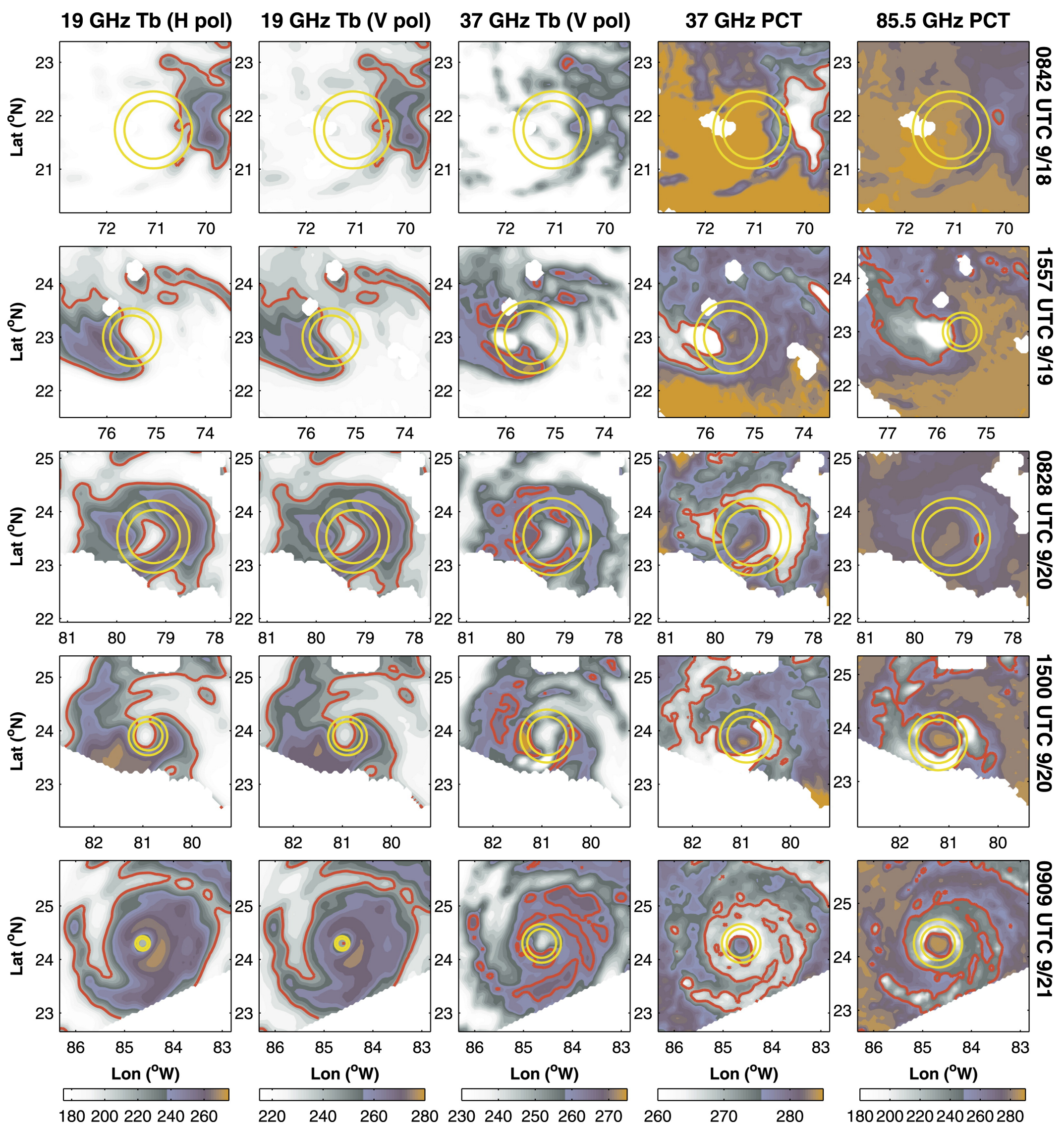
Rozoff et al. (2014, 2015)

Rozoff et al. (2015): Change of color table ☹



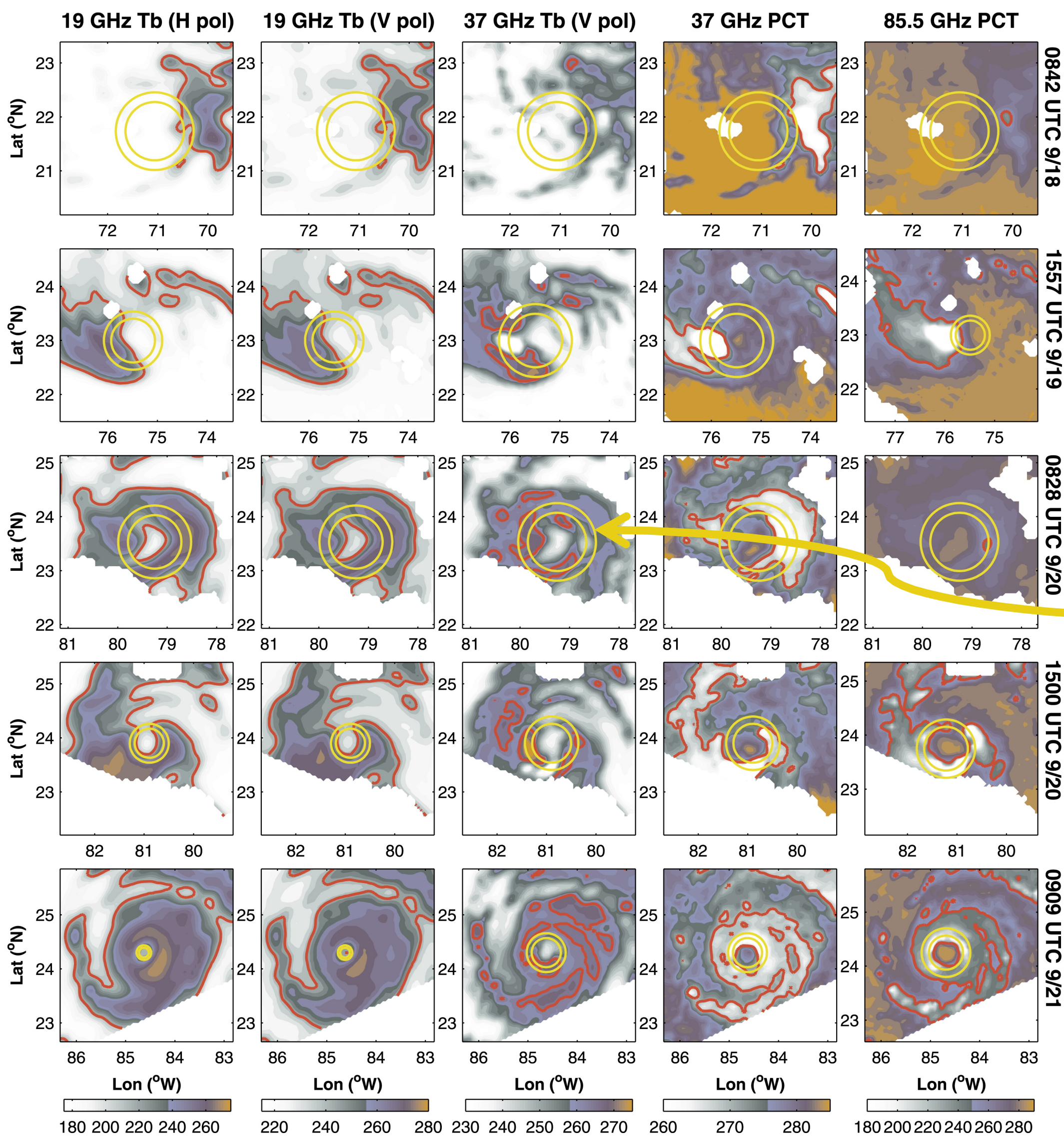
Rozoff et al. (2015)

Rapid intensity forecasting: Rozoff et al. (2015)



Intensification

Rapid intensity forecasting: Rozoff et al. (2015)



MIPA

Maximum inner-core precipitation annulus

Rapid intensity forecasting: RI model with microwave predictors

Model	Definition	Mean value of RI cases vs non-RI cases
ATL	Mean 37.0-GHz T_b (H pol) within the MIPA	Higher
ATL	Max 85.5-GHz PCT in region interior to the MIPA	Lower
ATL	Radius of max 37.0-GHz T_b (V pol) found within r = 30–130 km	Smaller
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Rozoff et al. (2015)

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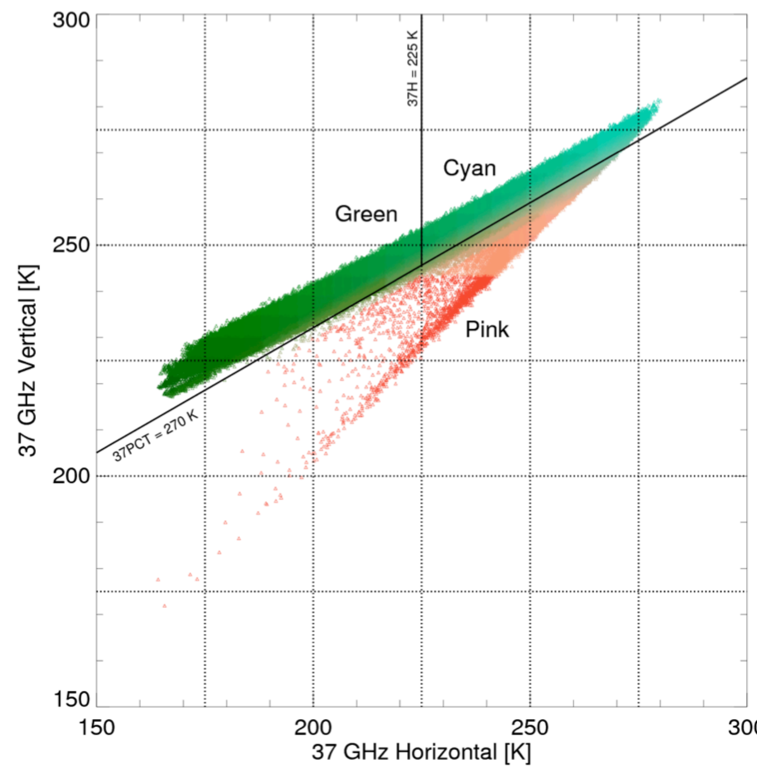
Deeper convection in the MIPA (ring)



Rozoff et al. (2015)

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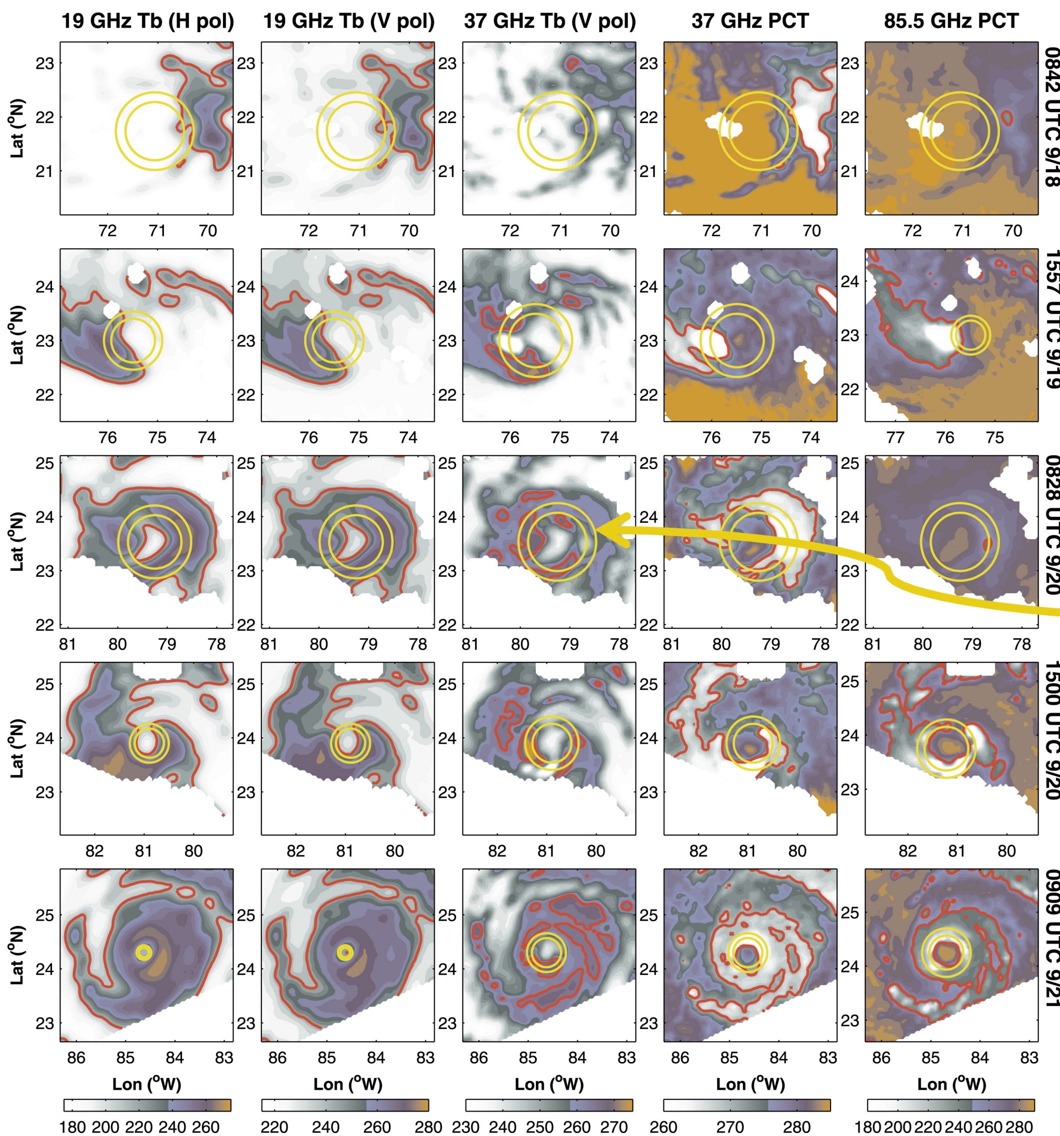
Rozoff et al. (2015)

Rapid intensity forecasting: Rozoff et al. (2015)



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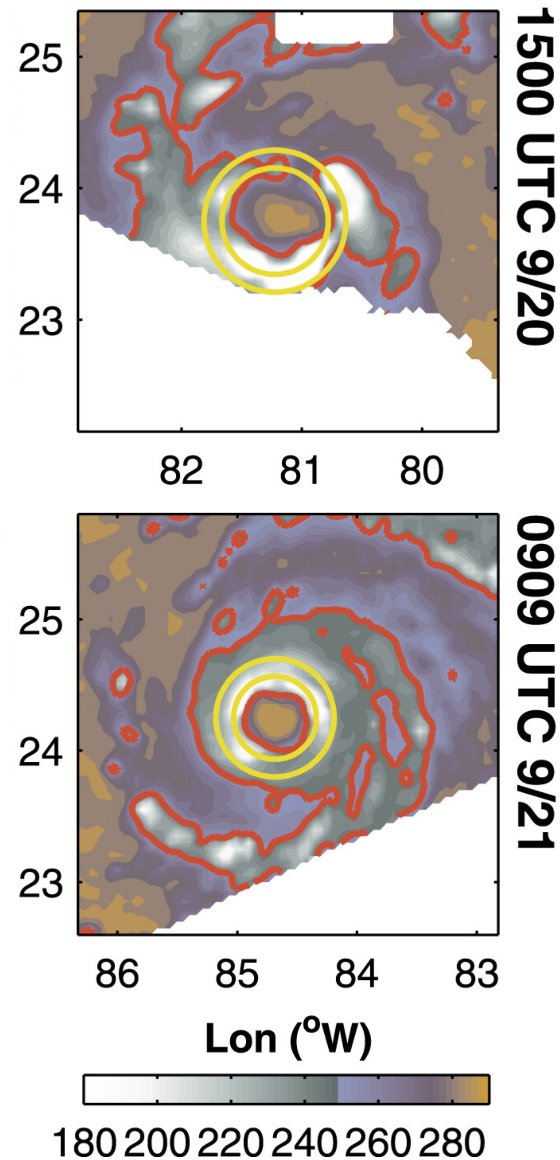
Less warm in the eye???



Rozoff et al. (2015)

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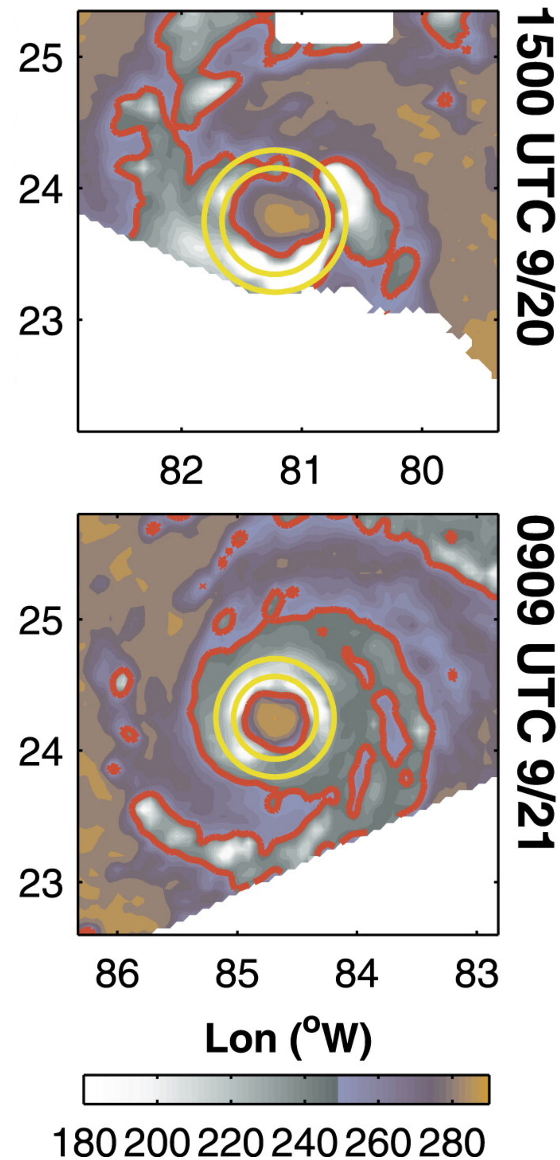
Less warm in the eye???

Storm doesn't yet have an eye?

Further from MPI?



Rozoff et al. (2015)

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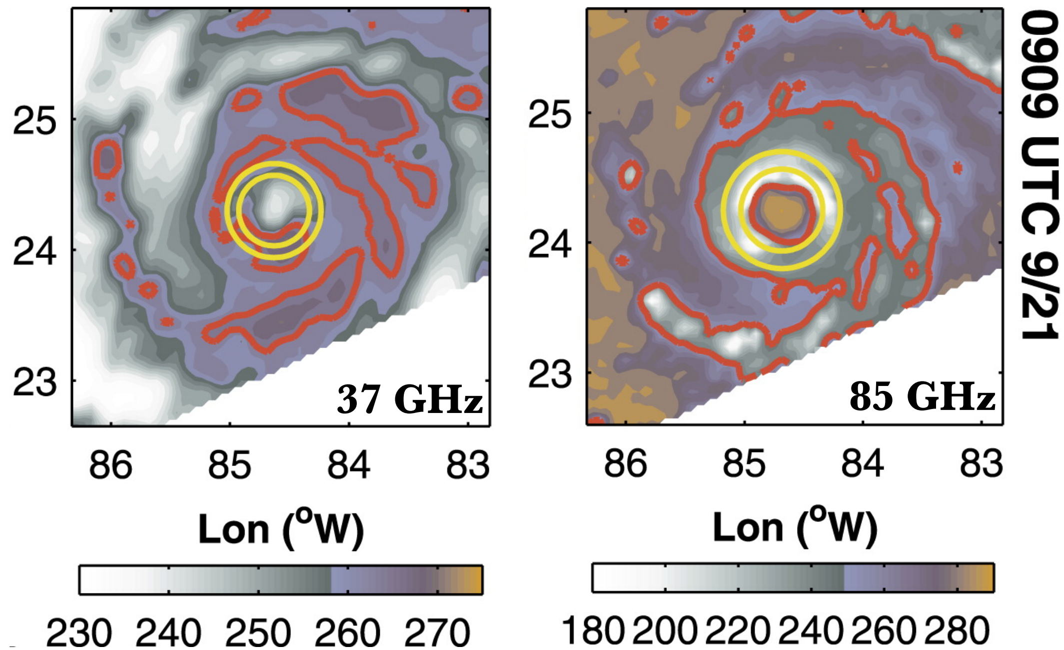
Rozoff et al. (2015)

Rapid intensity forecasting: RI model with microwave predictors

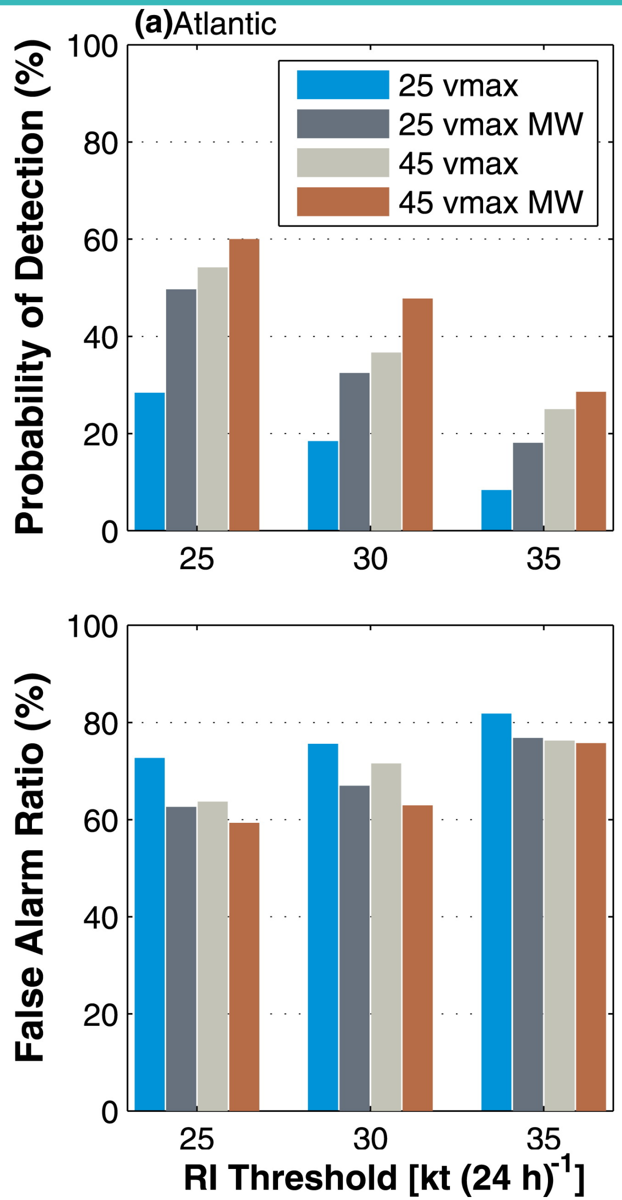
Model	Definition	Mean value of RI cases vs non-RI cases
ATL	Mean 37.0-GHz T_b (H pol) within the MIPA	Higher
ATL	Max 85.5-GHz PCT in region interior to the MIPA	Lower
ATL	Radius of max 37.0-GHz T_b (V pol) found within r = 30–130 km	Smaller
ATL	Radius of min 85.5-GHz T_b (H pol) found within r = 30–130 km	Smaller

Small radius of maximum convection



Rozoff et al. (2015)

RI model with microwave predictors: Still crappy forecasts!



Rozoff et al. (2015)

Rapid intensity forecasting: Improvements to RII

Predictor	Definition
PER	Previous 12-h intensity change
SHRD	850–200-hPa vertical shear within a 500-km radius after vortex removal (time avg)
D200	200-hPa divergence within a 1000-km radius (time avg)
RHLO	850–700-hPa relative humidity within a 200–800-km radius (time avg)
PX30	Percentage of area with −30°C GOES-IR brightness temp ($t = 0$ h) within a 50–200-km radius
SDBT	Std dev of GOES-IR brightness temp ($t = 0$ h) within a 50–200-km radius
POT	Potential intensity (current intensity − max potential intensity) (time avg)
OHC	Oceanic heat content (time avg)

Kaplan et al. (2015)

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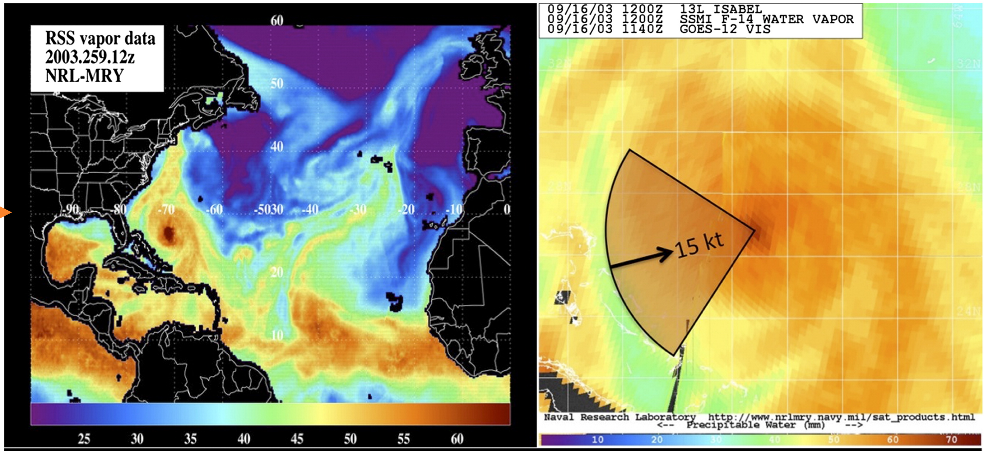

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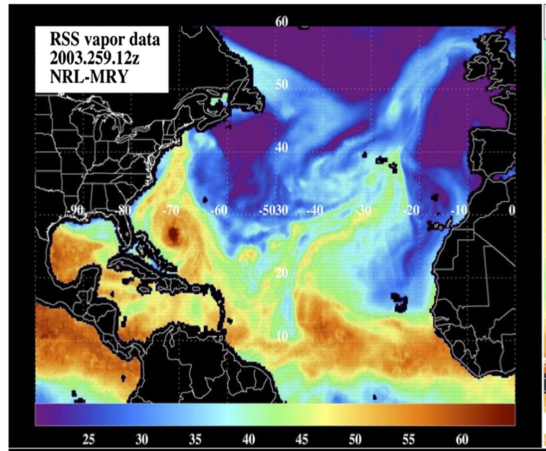

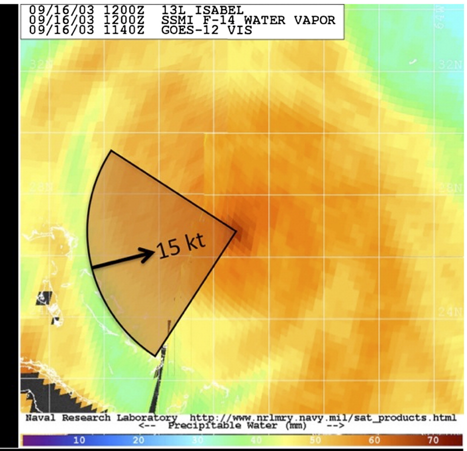

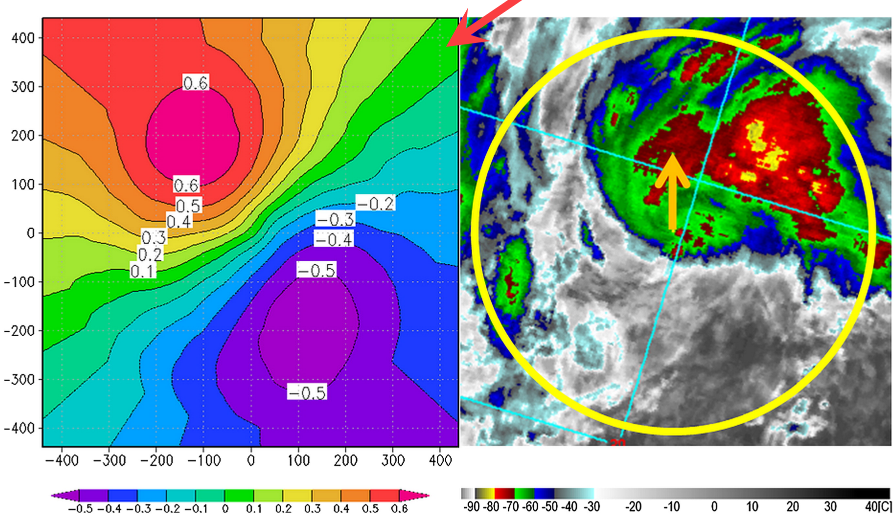

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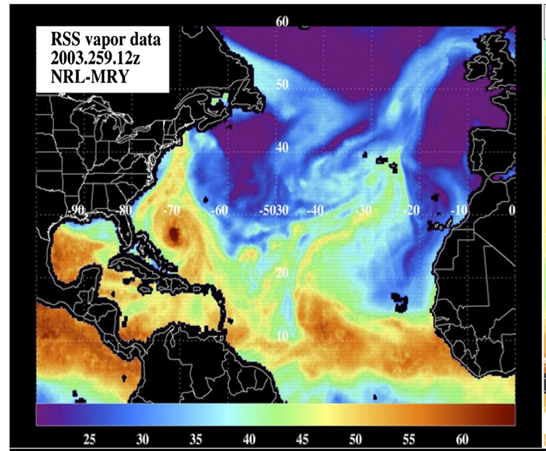
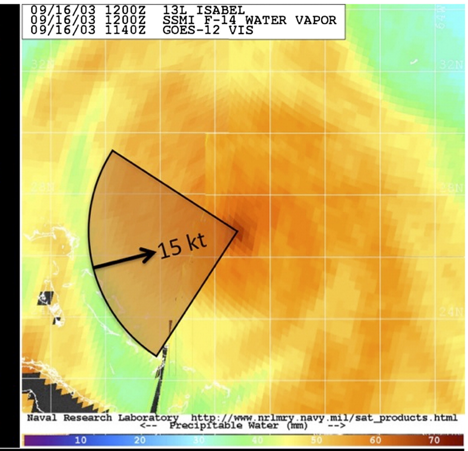
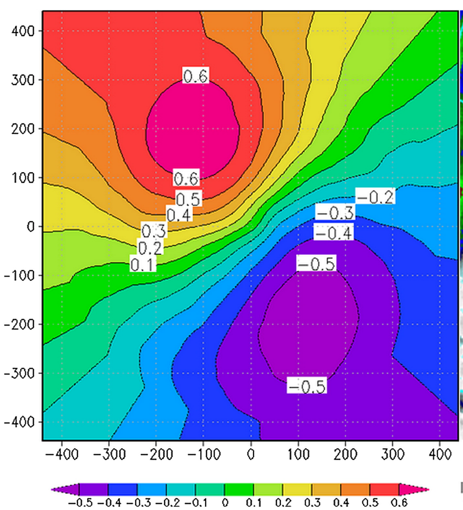
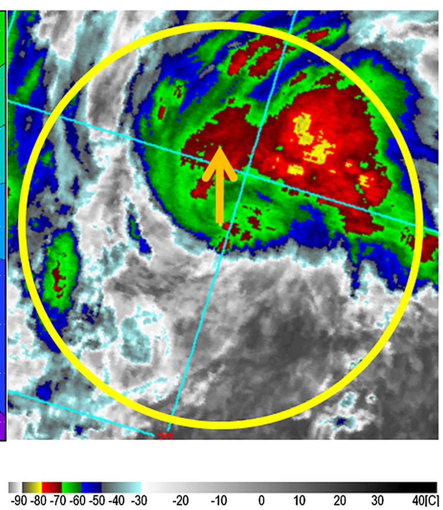








Inner core dry air predictor:

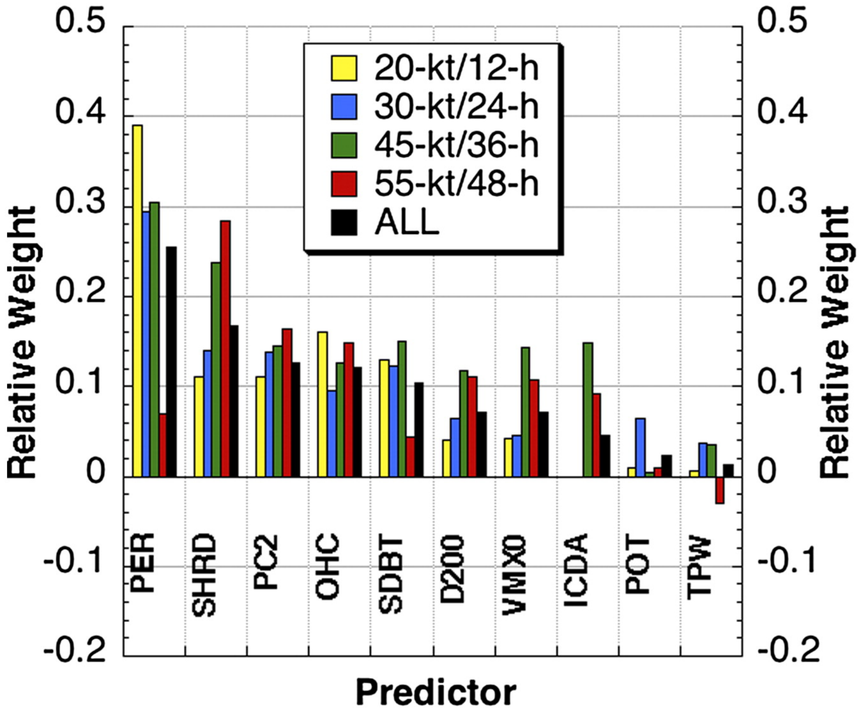
$$(q10_{layer} - q10) * VMAX_0$$

Dry air **mixing** ***down to*** **the** ***surface***

Kaplan et al. (2015)

Rapid intensity forecasting: Improvements to RII

Predictor	Definition
PER	Previous 12-h intensity change
SHRD	850–200-hPa vertical shear within a 500-km radius after vortex removal (time avg)
D200	200-hPa divergence within a 1000-km radius (time avg)
TPW	Percentage of area with TPW < 45 mm within a 500-km radius and ±45° of the upshear SHIPS wind direction (t = 0 h)
PC2	Second principal component of GOES-IR imagery within a 440-km radius (t = 0 h)
SDBT	Std dev of GOES-IR brightness temp (t = 0 h) within a 50–200-km radius
POT	Potential intensity (current intensity − max potential intensity) (time avg)
OHC	Oceanic heat content (time avg)
ICDA	Inner-core dry-air predictor (time avg)
VMX0	Max sustained wind (t = 0 h)



Kaplan et al. (2015)

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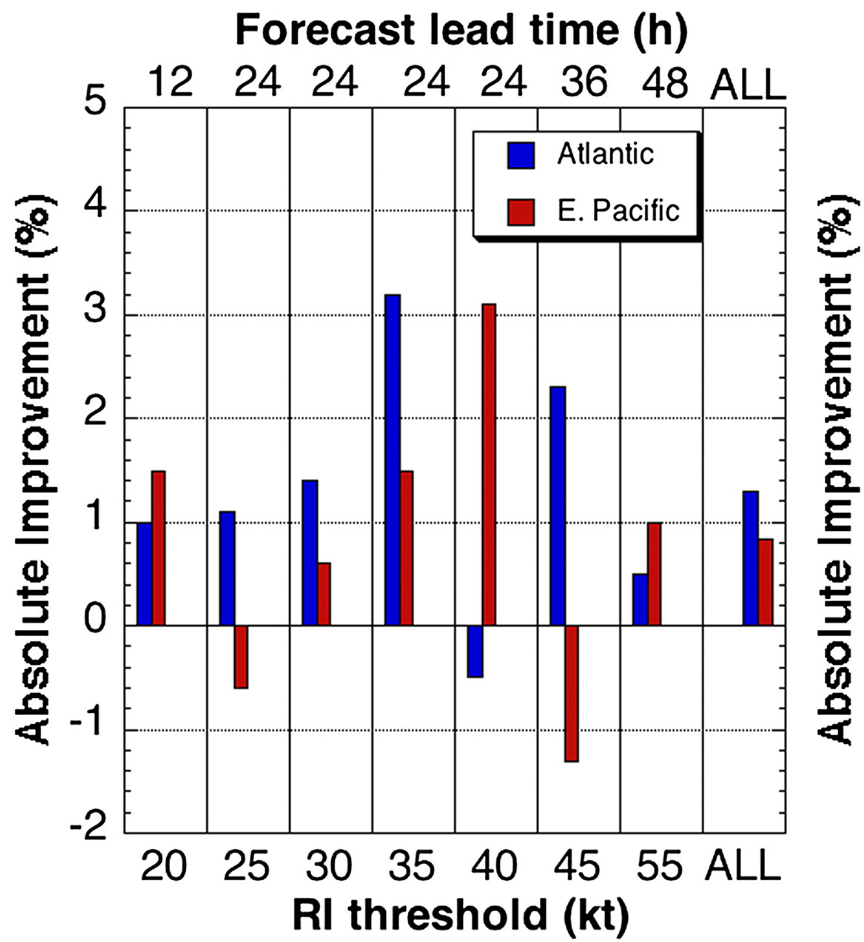
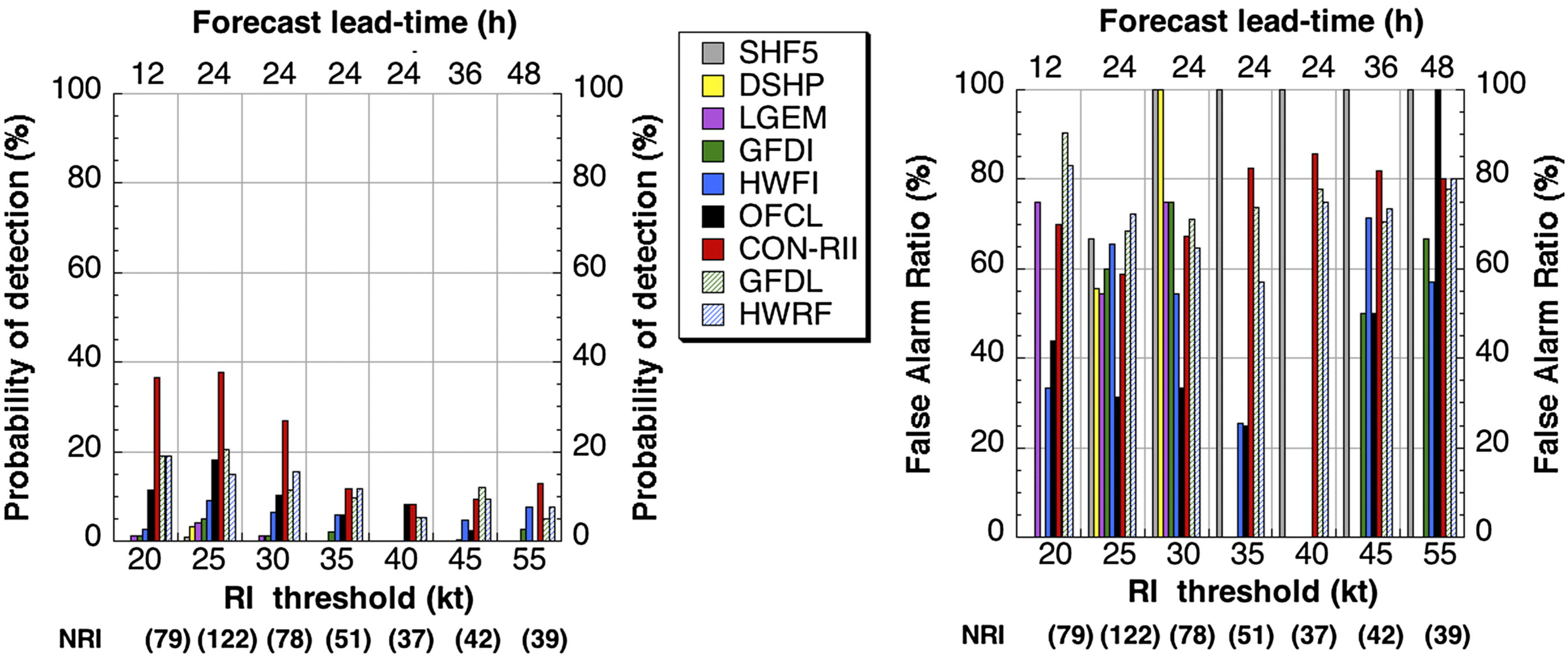


Kaplan et al. (2015)

Rapid intensity forecasting: Still crappy after all these years…☹



Kaplan et al. (2015)

Rapid intensity forecasting: Still crappy after all these years…☹

Forecast lead-time (h)

Forecast lead-time (h)

Why **are** ***forecasts*** **of** ***RI so poor*****?**

What **is** ***missing from*** **the** ***models*****?**

Are there ***observational signals*** **of** ***RI*** **of which** ***forecasters*** **are** ***not taking notice*****?**

RI threshold (kt)

NRI (79) (122) (78) (51) (37) (42) (39)

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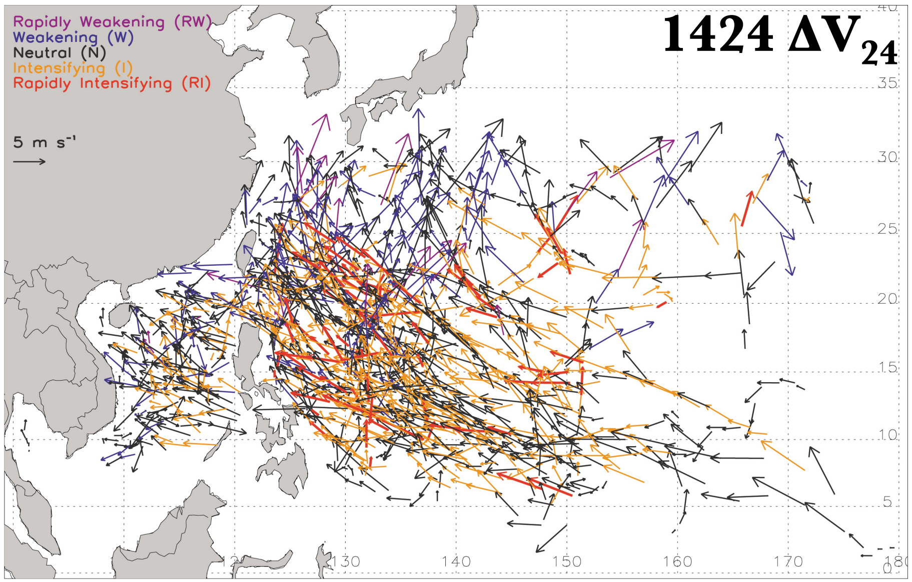
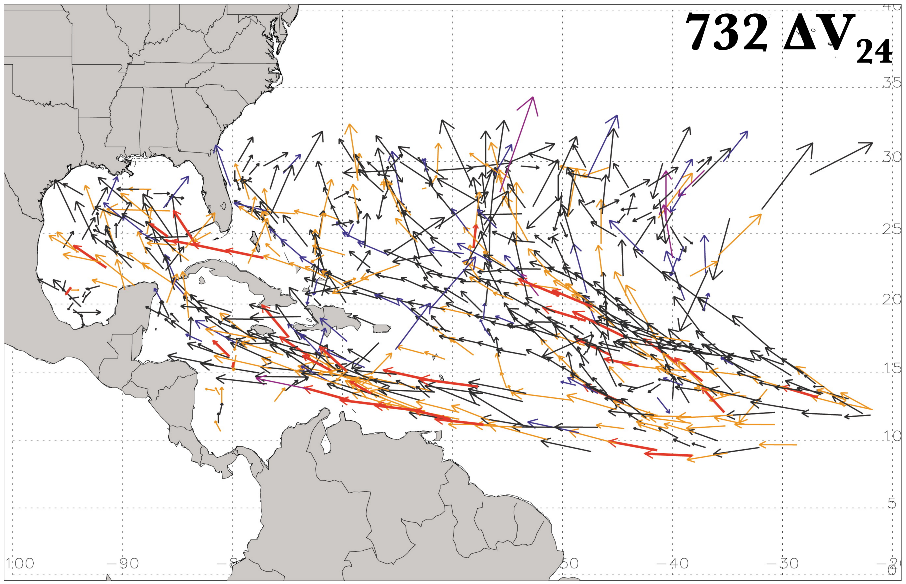
Kaplan et al. (2015)

Rapid intensity forecasting: Why are models so crappy?





Hendricks et al. (2010)

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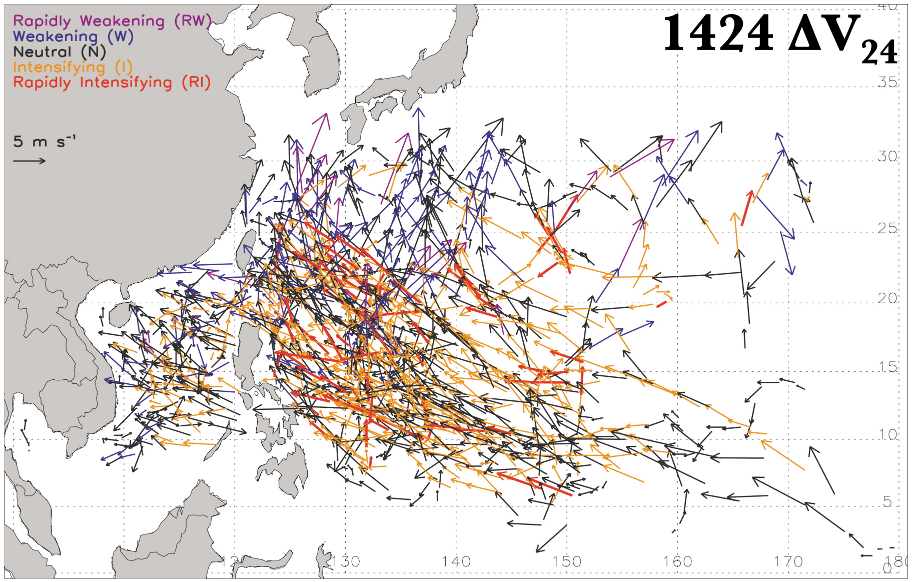

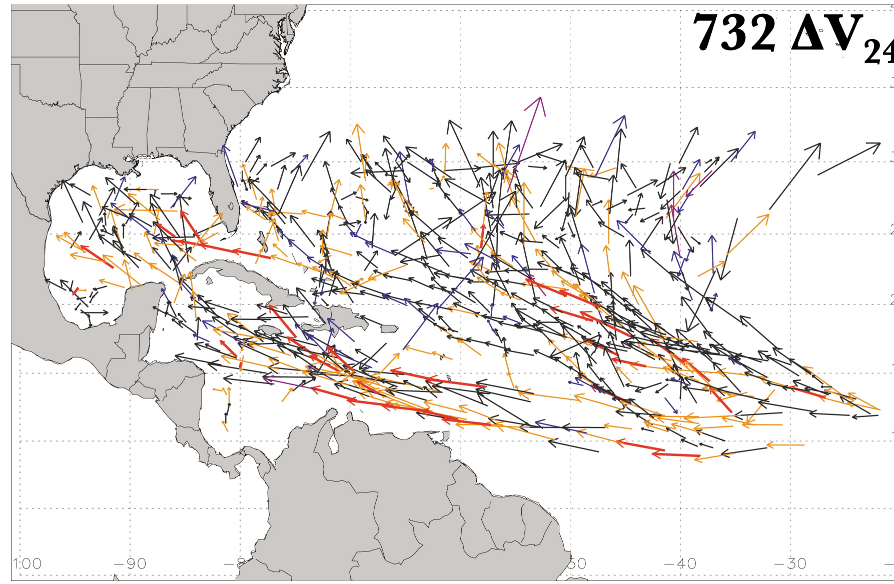

<u>*Hendricks et al. (2010)*</u>:

"While *some environmental differences* were found *between RI* and *weakening/neutral TCs*, an interesting result is that the *environment* of *RI TCs* and *intensifying TCs* is *quite similar*."

Why are models so crappy?
RI environments aren't so different

Quantity	Basin	W	N	I	RI	RI - W	RI - N	RI - I
Deep-layer shear (m s^{-1})	ATL	11.24	11.80	9.89	8.24	**−3.00**	**−3.56**	**−1.65**
SST (°C)	ATL	28.23	27.96	28.58	28.93	**0.70**	**0.97**	0.35
850-hPa relative humidity (%)	ATL	73.93	76.27	76.12	76.45	**2.52**	0.18	0.33
500-hPa relative humidity (%)	ATL	48.83	50.98	52.43	53.97	**5.14**	**2.99**	1.54
850-hPa divergence (10^{-6} s^{-1})	ATL	−1.63	−1.19	−1.40	−1.25	0.38	−0.06	0.15
200-hPa divergence (10^{-6} s^{-1})	ATL	4.61	3.02	3.37	2.84	**−1.77**	−0.18	−0.53
$\partial\theta_E/\partial p$ (10^3 K Pa^{-1})	ATL	0.35	0.28	0.32	0.31	−0.04	0.03	−0.01
850-hPa vorticity (10^{-6} s^{-1})	ATL	7.71	6.91	6.48	5.00	−2.71	−1.91	−1.48

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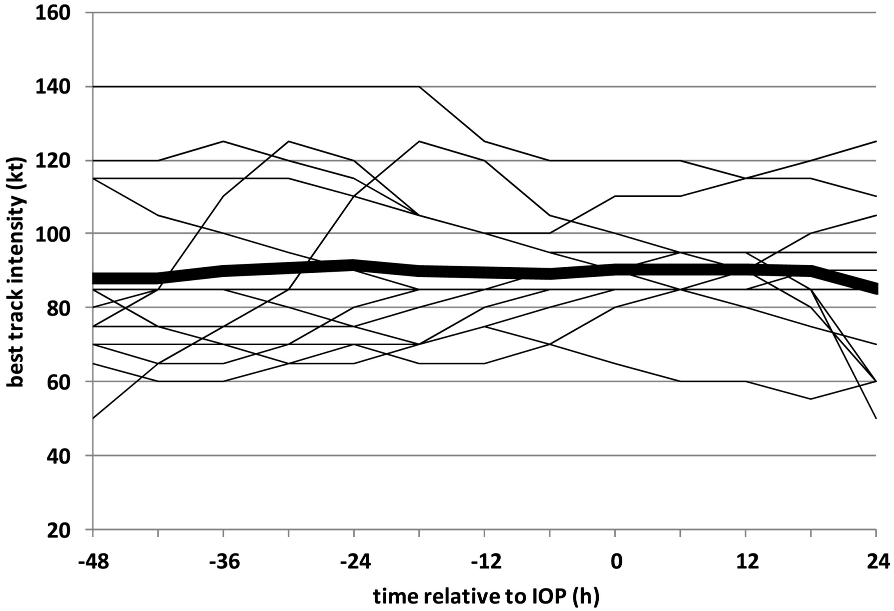
<u>Hendricks et al. (2010)</u>:

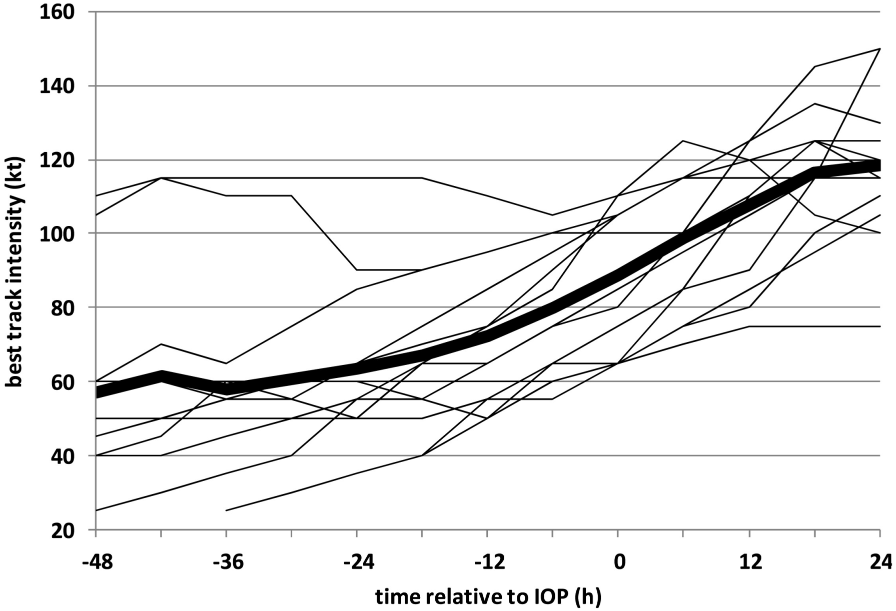
"…*RI* is mostly *controlled by internal* dynamical *processes*. These processes are *inherently less predictable*; therefore, *RI may never be well predicted by mesoscale models*."

Rapid intensification: Internal dynamical processes

Steady State (±10 kt in 24 h)



Intensifying (≥ 20 kt in 24 h)



Rogers et al. (2013)

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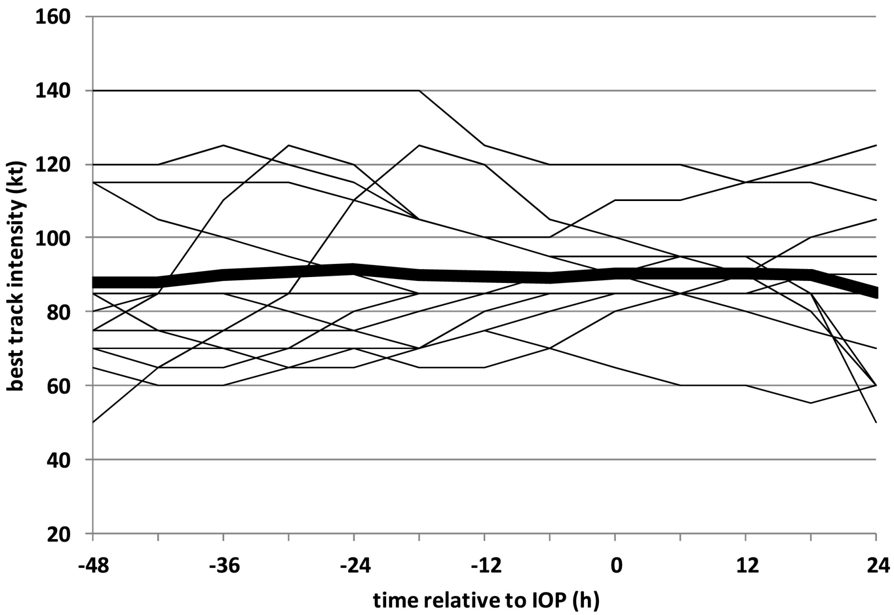

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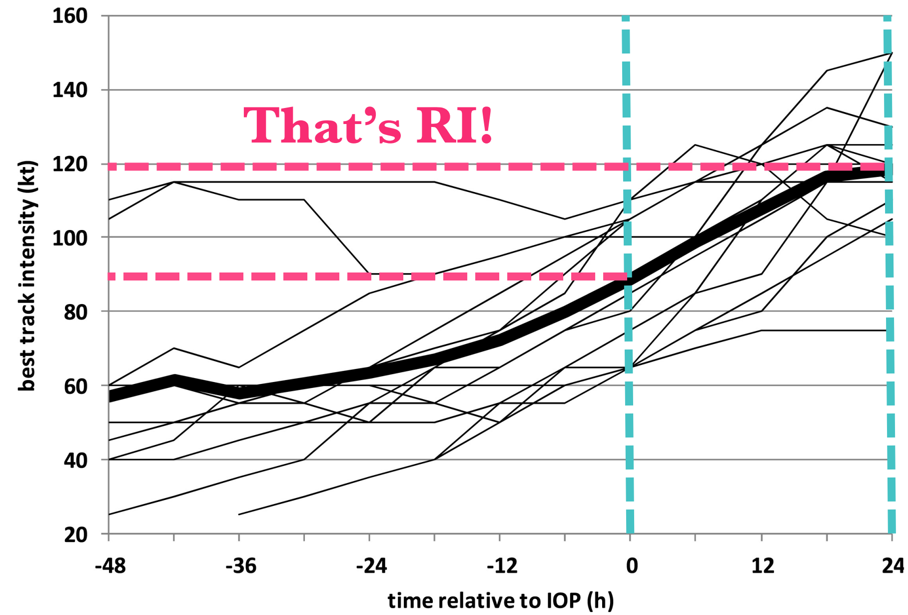

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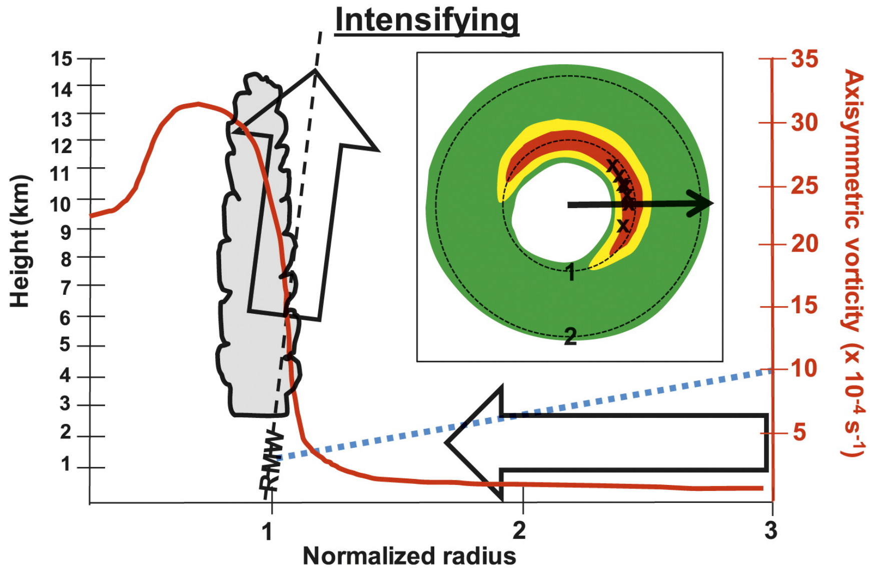
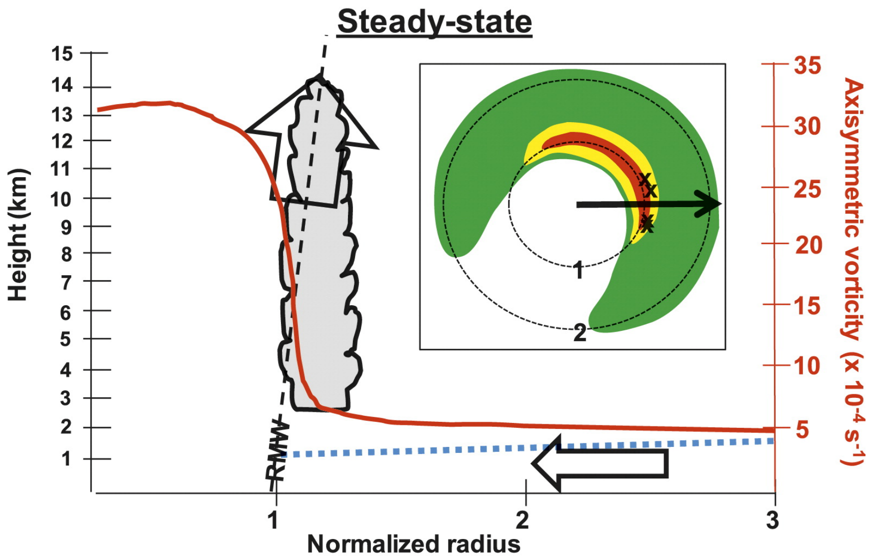
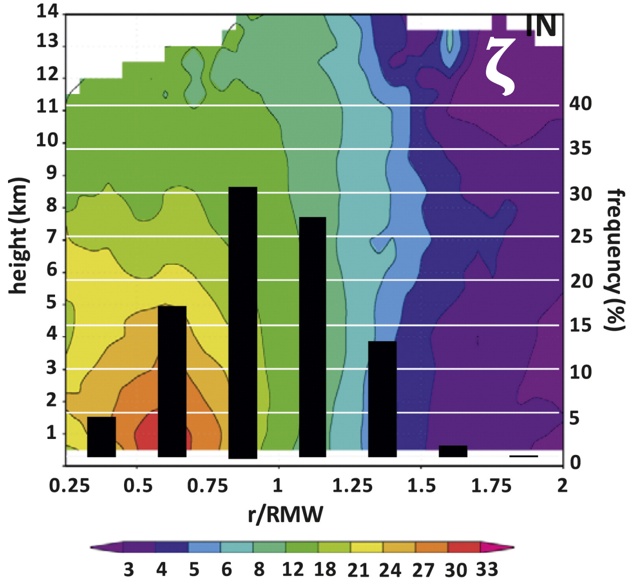
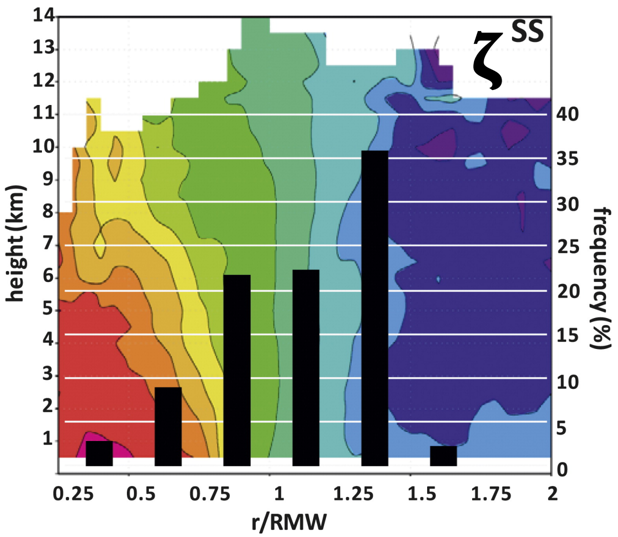




Rogers et al. (2013)

Internal dynamical processes: Convective bursts





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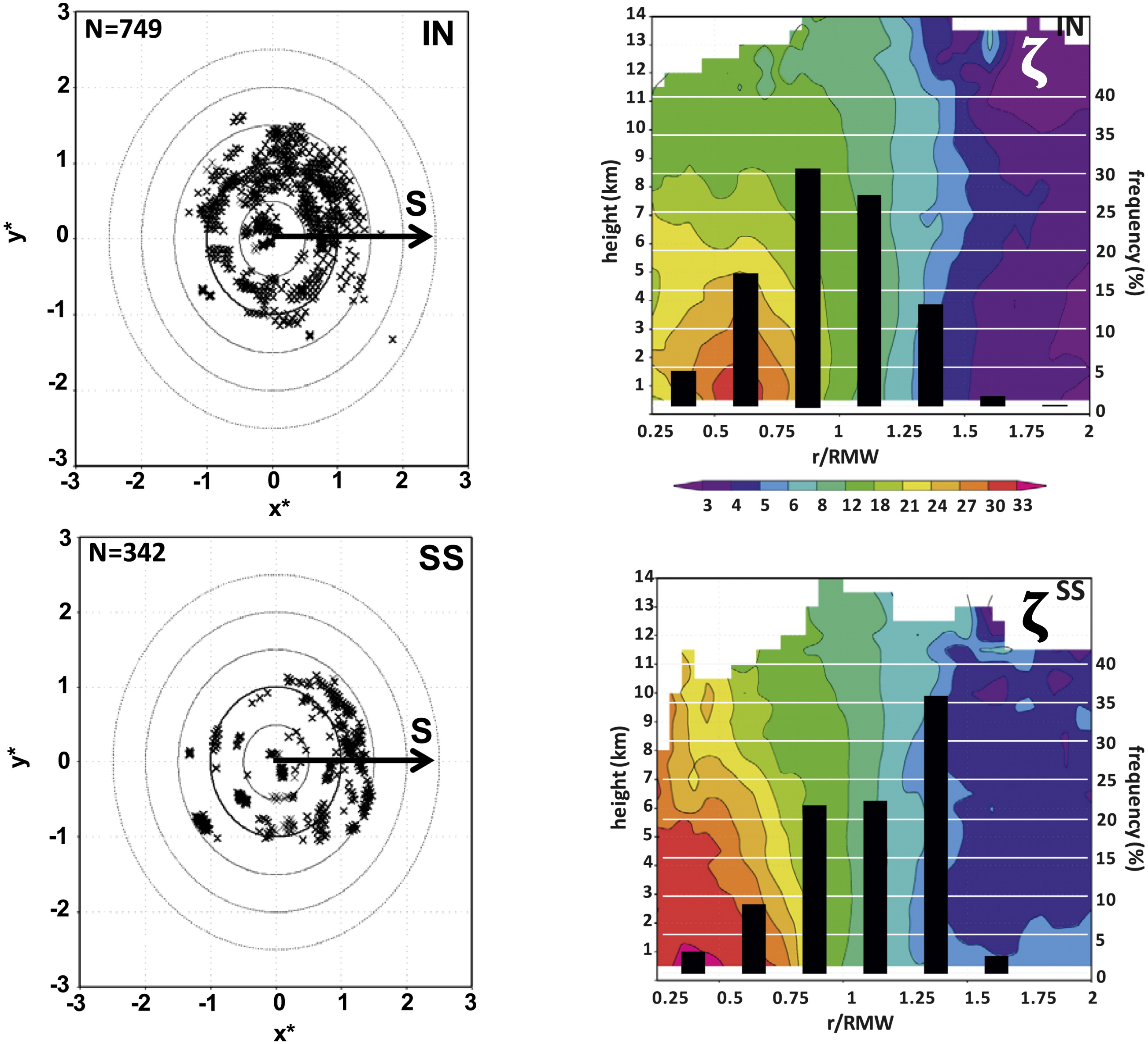

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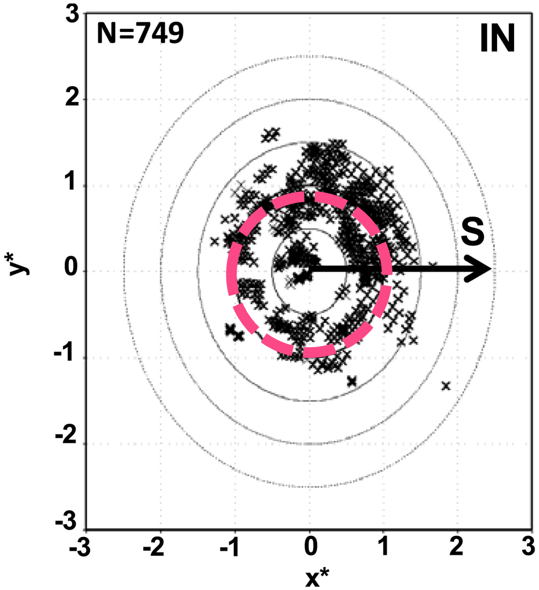
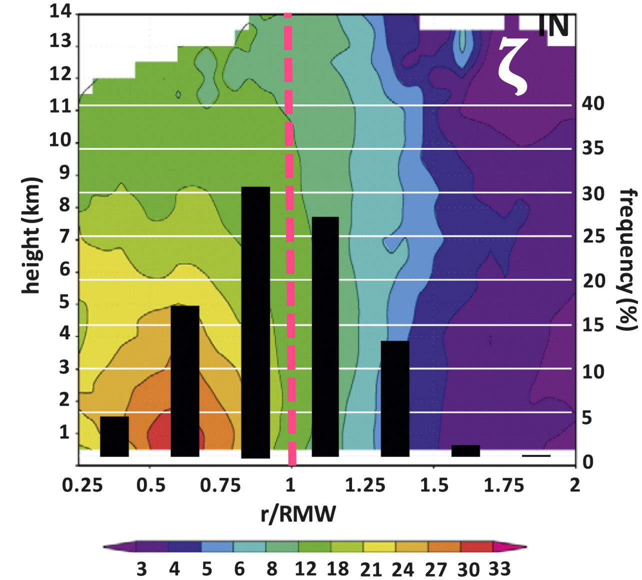
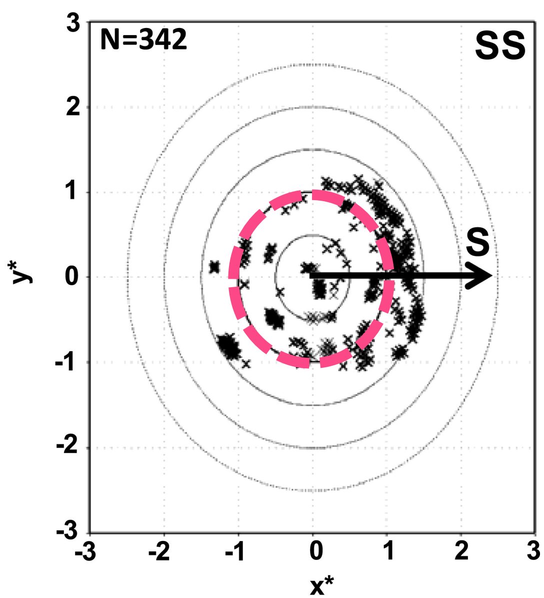
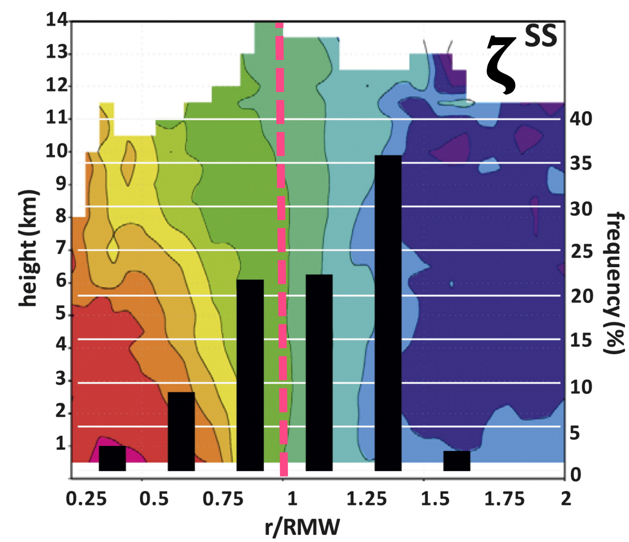


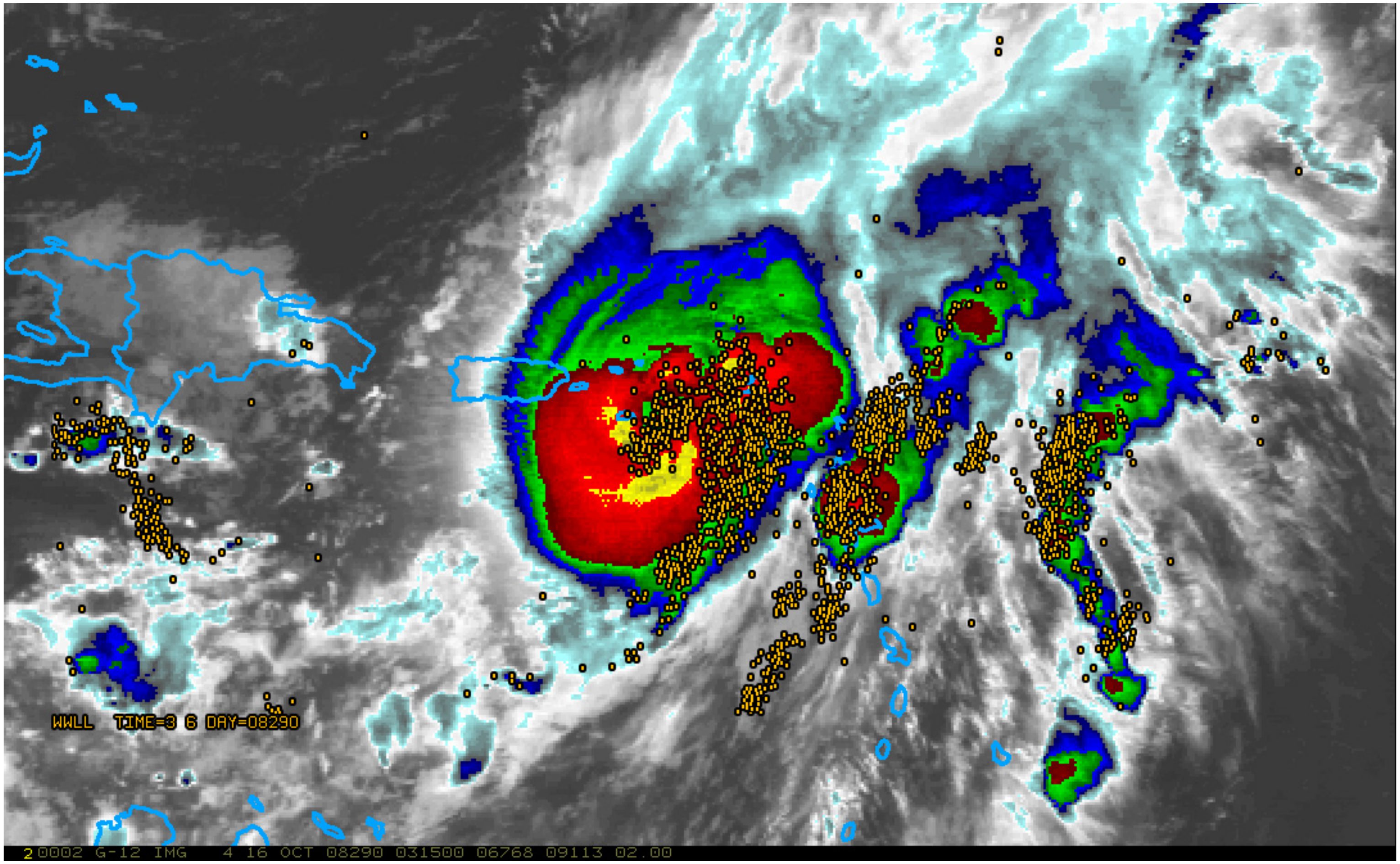




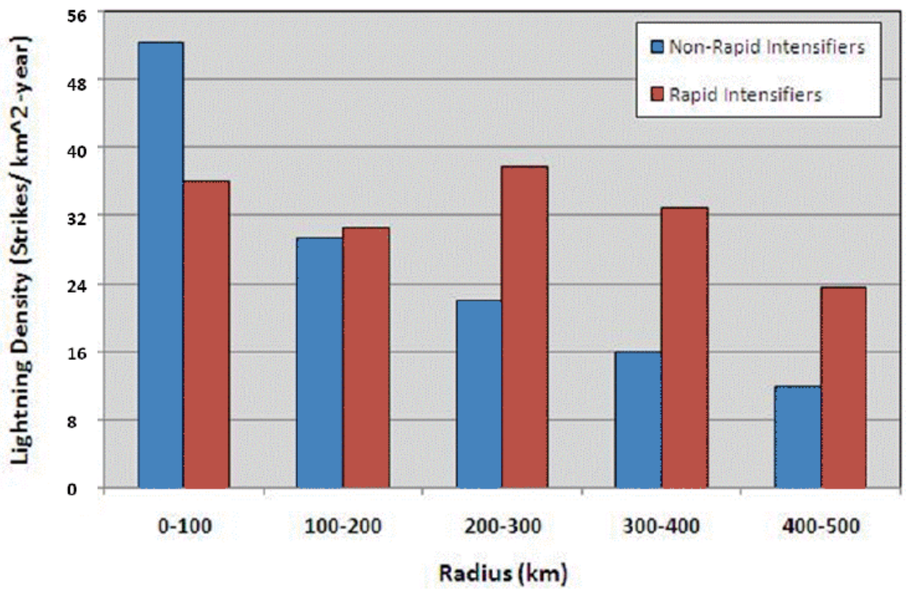


Rogers et al. (2013)

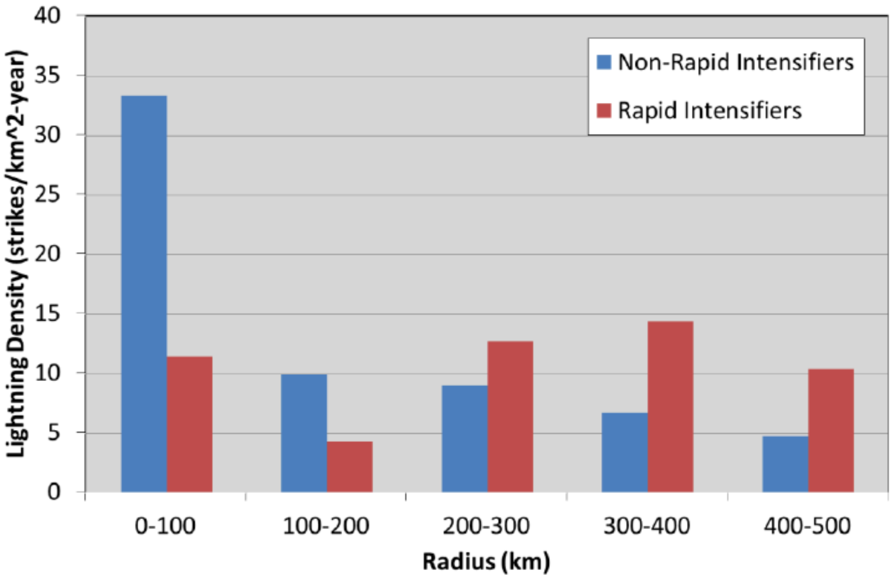
Convective bursts: Lightning!



Convective bursts: Inner core discrepancy…?



Atlantic

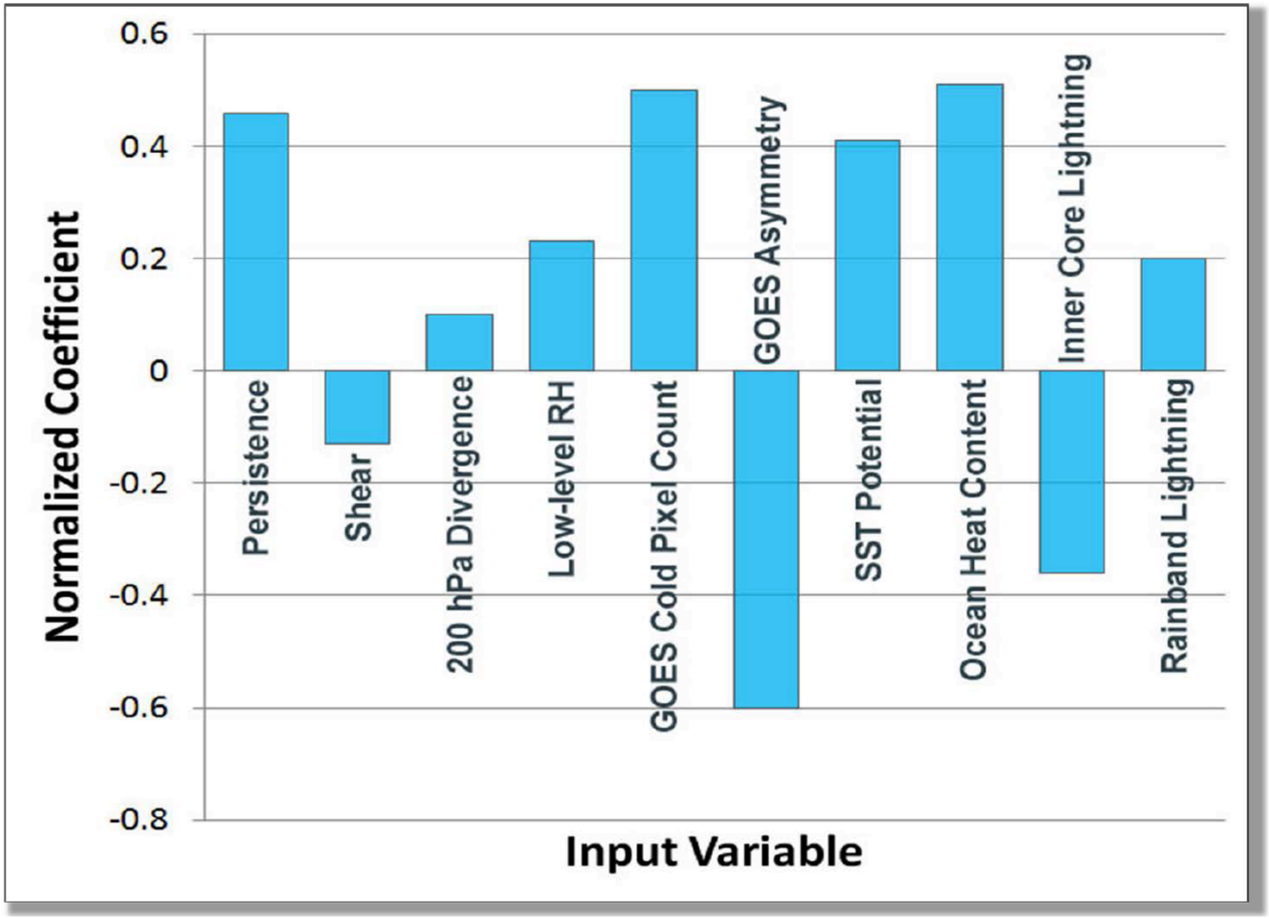


East Pacific

DeMaria (2012)

The RII:
Lightning predictors have an impact

Normalized Discriminant Weights (Atlantic RII Algorithm)



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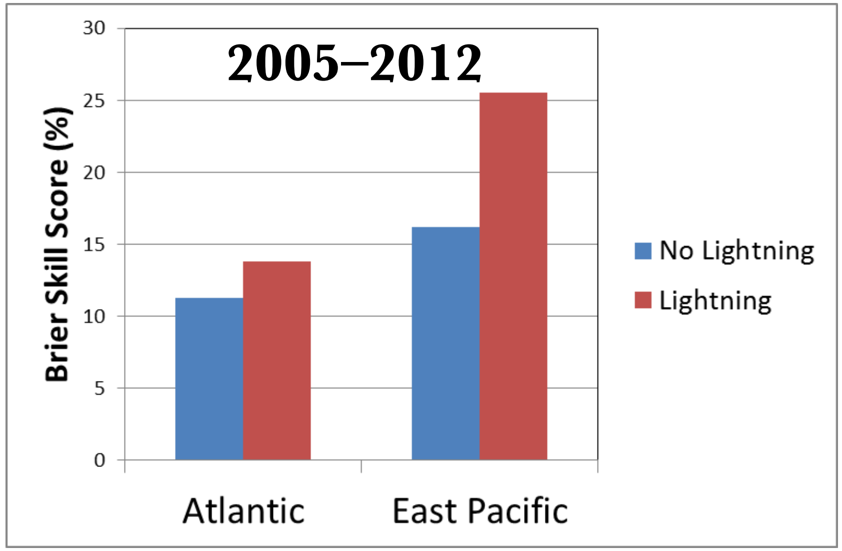
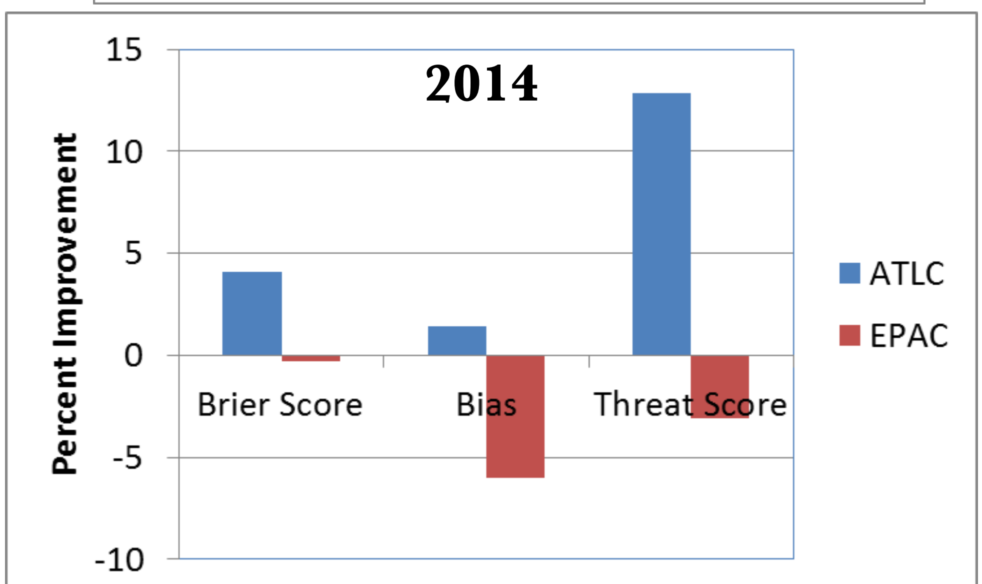




DeMaria (2013)
Schumacher and DeMaria (2015)

TC lightning: Forecasters are willing to use it!

NATIONAL HURRICANE CENTER
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

ANALYSES & FORECASTS ▾ DATA & TOOLS ▾ EDUCATIONAL RESOURCES ▾ ARCHIVES ▾ ABOUT NHC ▾ SEARCH ▾

Tropical Storm CRISTINA

ZCZC MIATCDEP3 ALL
TTAA00 KNHC DDHHMM

TROPICAL STORM CRISTINA DISCUSSION NUMBER 6
NWS NATIONAL HURRICANE CENTER MIAMI FL EP032014
800 PM PDT TUE JUN 10 2014

Cristina is intensifying this evening. The compact central dense overcast has become more circular, and hints of an eye have been apparent in geostationary satellite images. The initial intensity is increased to 55 kt, in agreement with unanimous Dvorak classifications of 3.5/55 kt from TAFB, SAB, and UW-CIMSS ADT.

Although the curved bands beyond the inner-core region remain fragmented, a considerable amount of lightning has been occurring in a rain band located about 120 n mi to the south-southwest of the center. Recent research has documented that lightning in the outer bands of the tropical cyclone circulation is often a precursor of significant intensification. The only apparent factor that could limit strengthening during the next couple of days is mid-level dry air, which has been an issue for Cristina during the past day or so. In about 3 days, Cristina is expected to move into an environment of stronger southwesterly shear and over cooler waters, which should end the strengthening trend and cause the cyclone to weaken. The NHC intensity forecast is slightly higher than the previous one, and is pretty close to the intensity model consensus IVCN.

Cristina has wobbled a little south of due west during the past 6 hours, and the latest initial motion estimate is 265/5. A westward to west-northwestward motion is forecast during the next day or so while the cyclone remains on the south side of a mid-level ridge over northwestern Mexico. After that time, a turn to the northwest is predicted when the ridge weakens and shifts eastward. The NHC track forecast is an update of the previous one, and close to a consensus of the GFS and ECMWF models.

FORECAST POSITIONS AND MAX WINDS

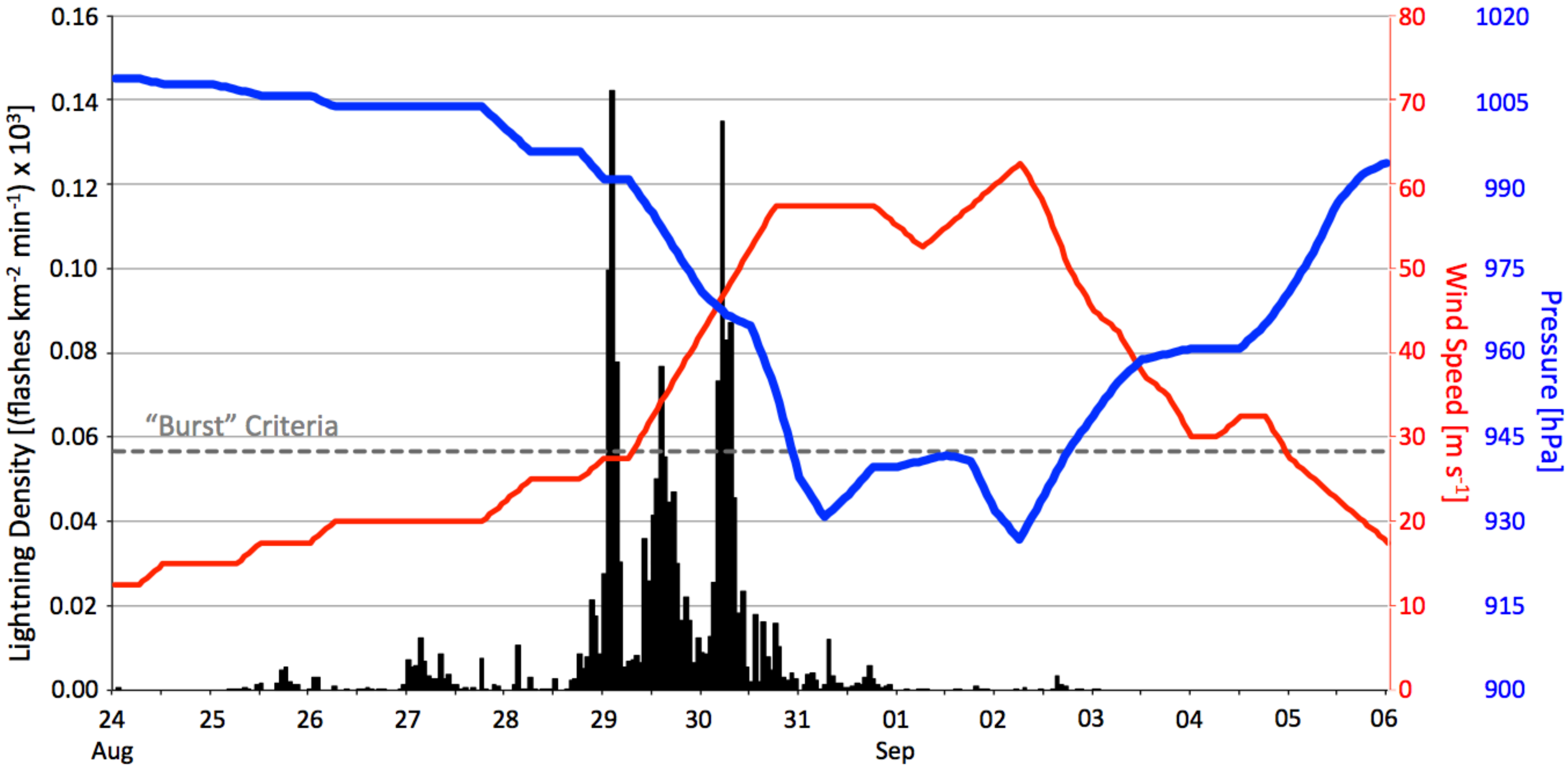
INIT	11/0300Z	15.2N	103.9W	55	KT	65	MPH
12H	11/1200Z	15.4N	105.0W	65	KT	75	MPH
24H	12/0000Z	15.8N	106.4W	70	KT	80	MPH
36H	12/1200Z	16.5N	107.7W	75	KT	85	MPH
48H	13/0000Z	17.2N	109.0W	75	KT	85	MPH
72H	14/0000Z	18.7N	111.5W	70	KT	80	MPH
96H	15/0000Z	19.6N	113.5W	55	KT	65	MPH
120H	16/0000Z	20.0N	115.5W	35	KT	40	MPH

$$
Forecaster Cangialosi

NNNN

Lightning in TCs:
Beyond DeMaria et al. (2014) and GOES-R

Hurricane Earl (2010)



Stevenson (2015, 2016)

Lightning in TCs:
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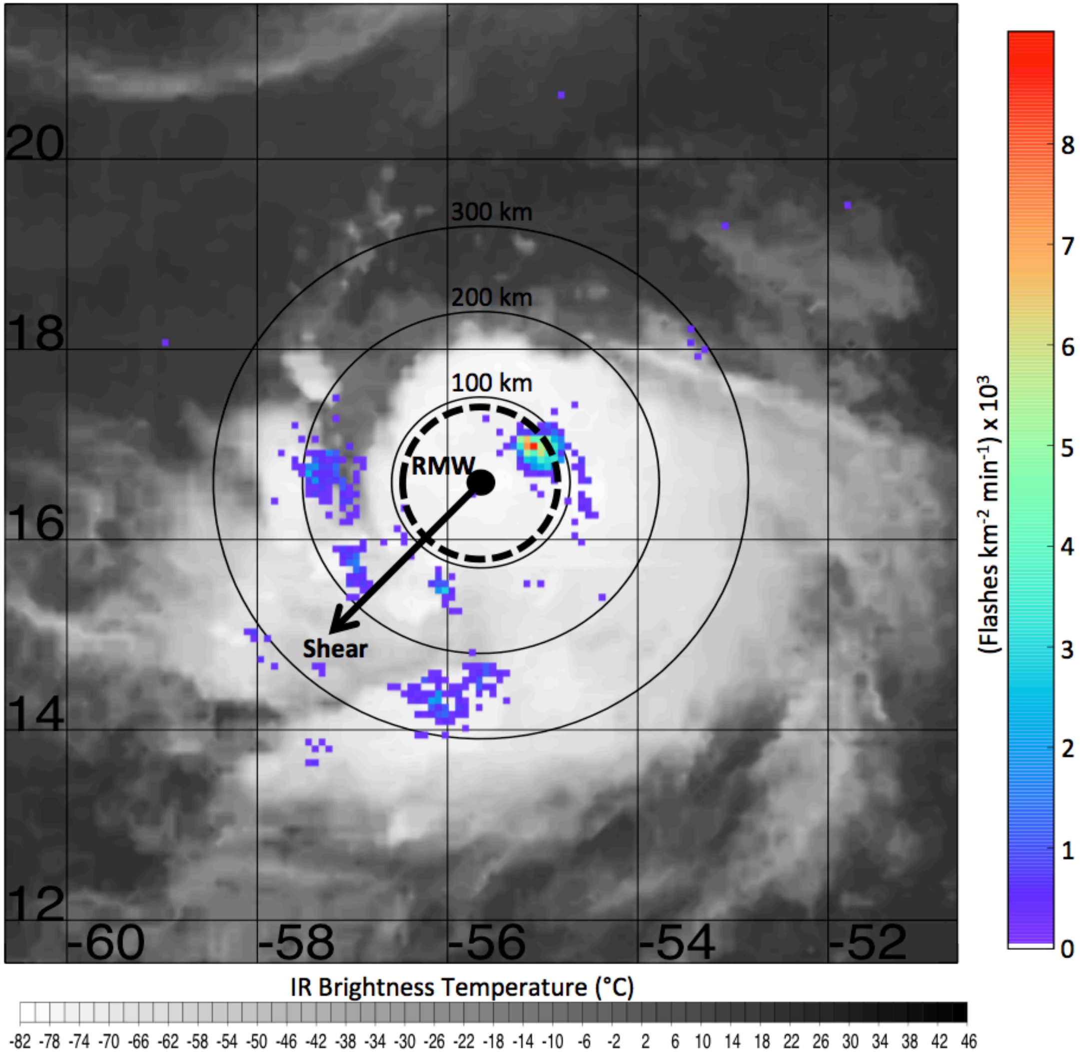
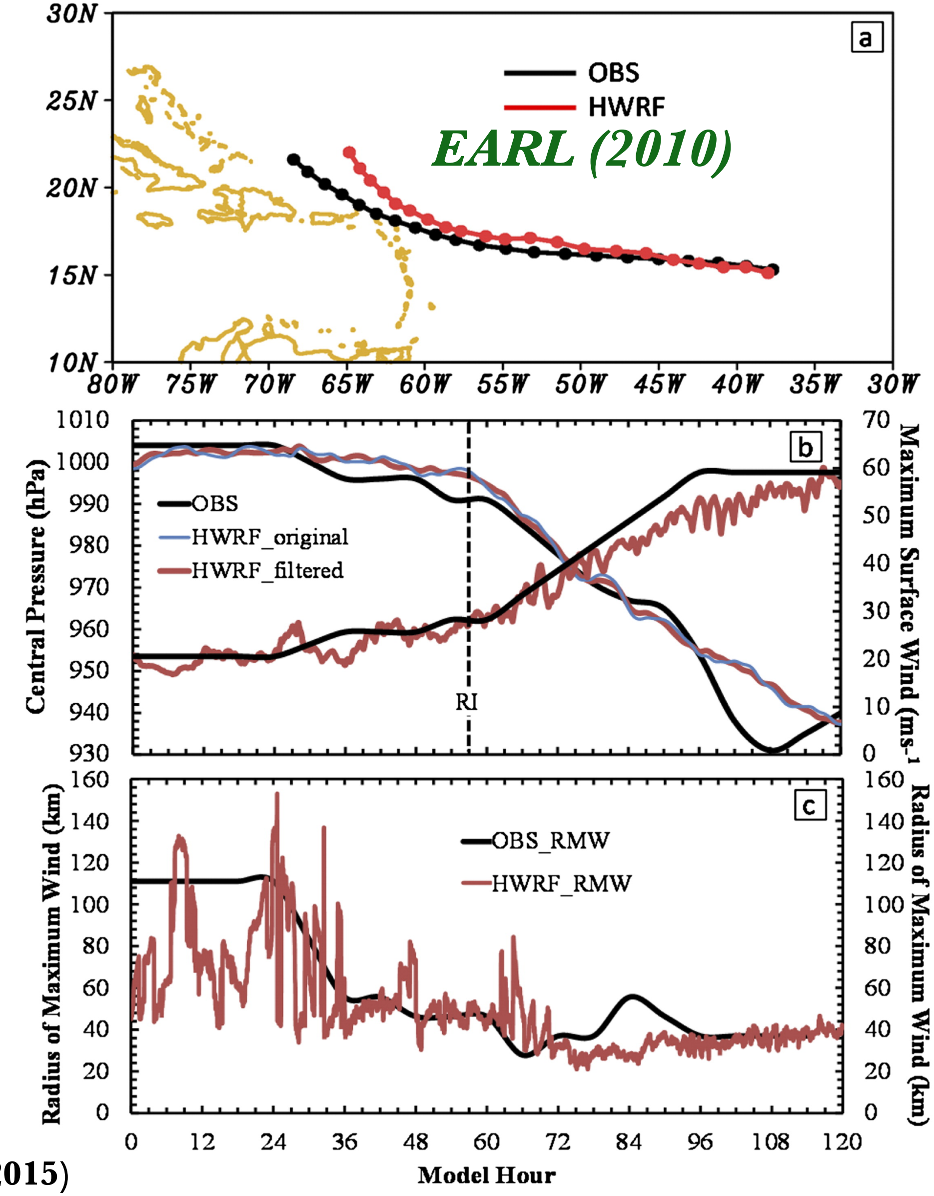


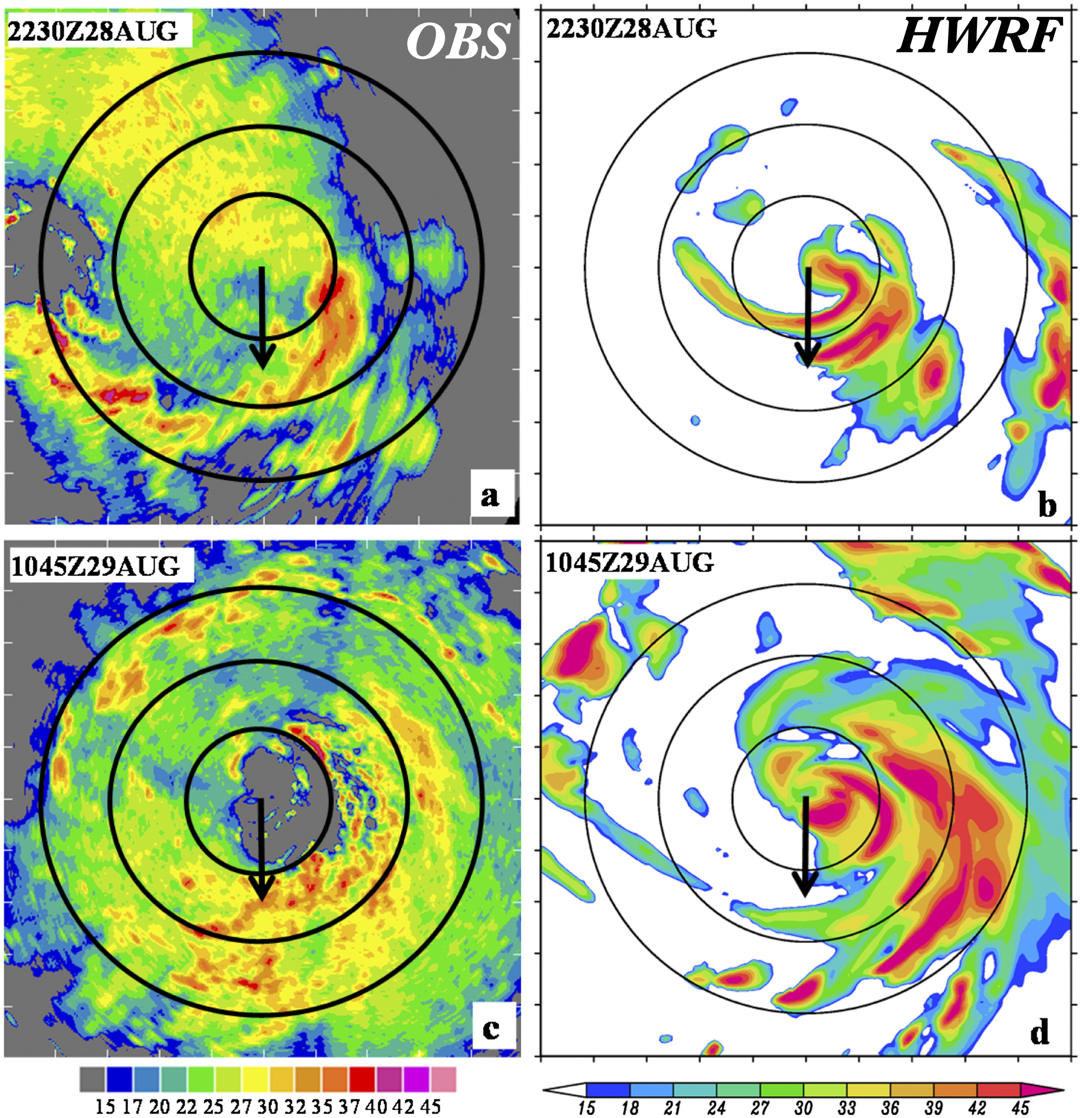
Stevenson (2015, 2016)

Convective bursts: HWRF



Chen and Gopalakrishnan (2015)

Convective bursts: HWRF

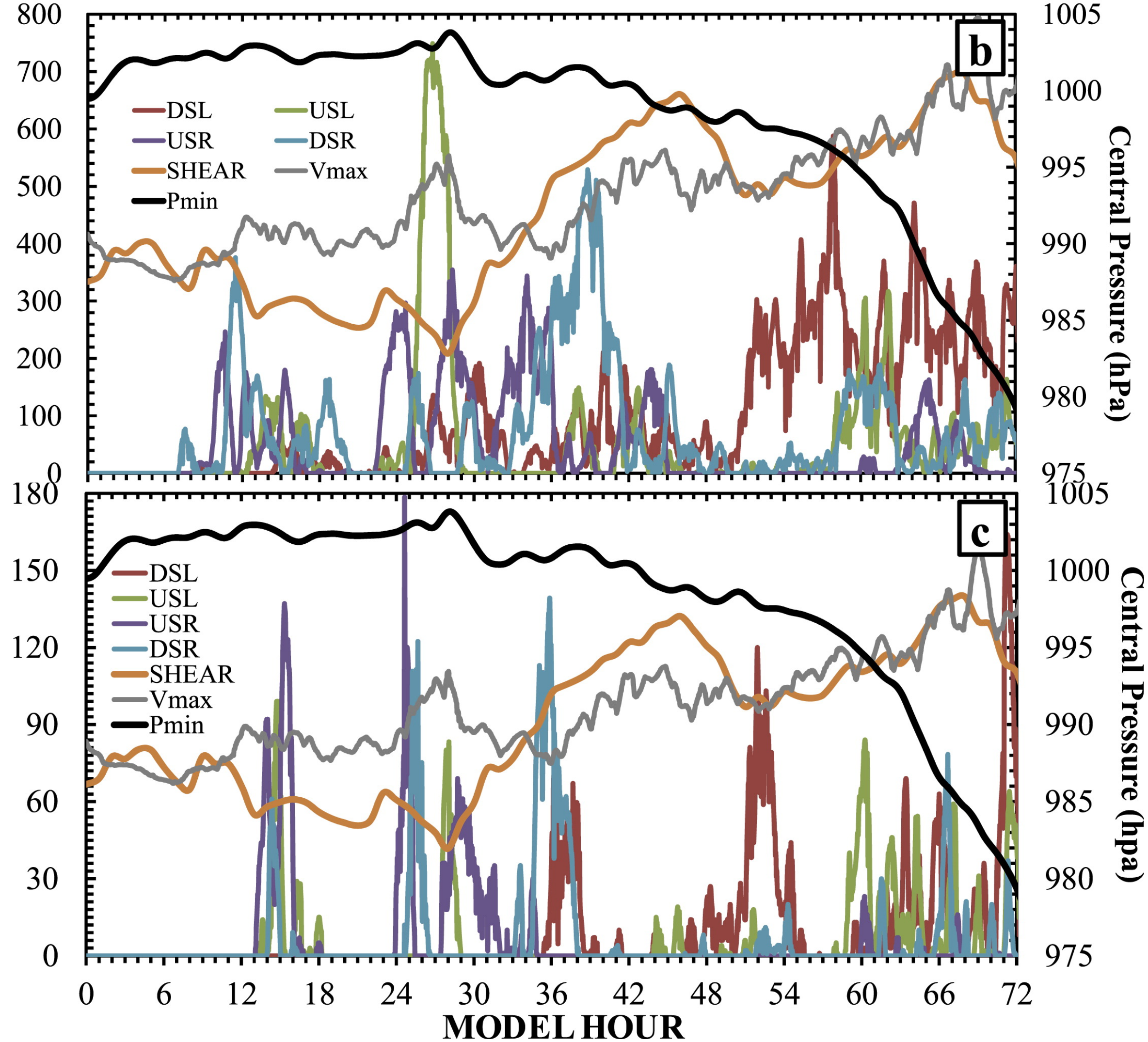


Chen and Gopalakrishnan (2015)

Convective bursts: HWRF

Inner 200 km

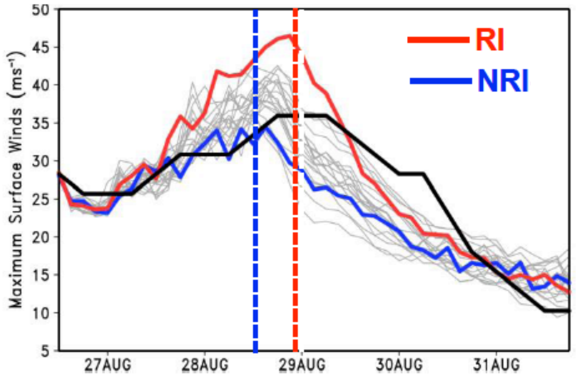
Inner 50 km

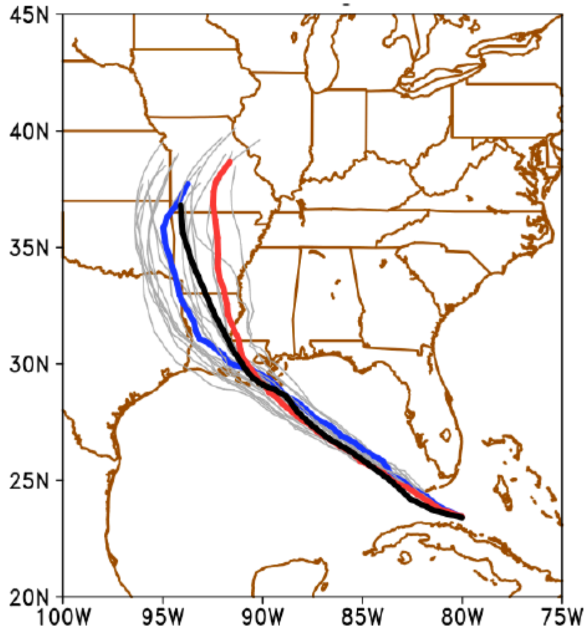


Chen and Gopalakrishnan (2015)

Convective bursts: HWRF

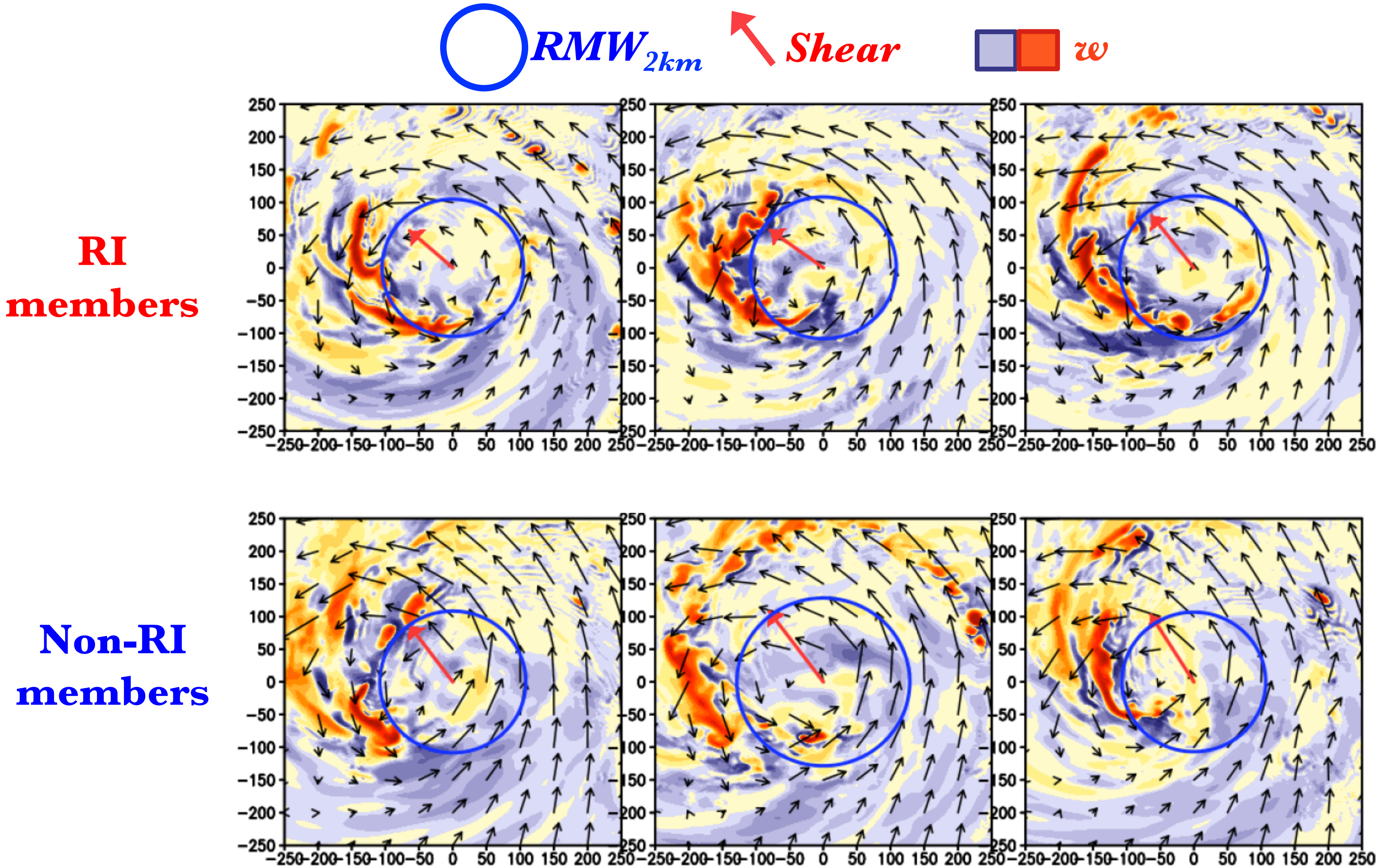
HWRF ensemble forecasts of Hurricane Issac (2012)





Chen and et al. (2016)

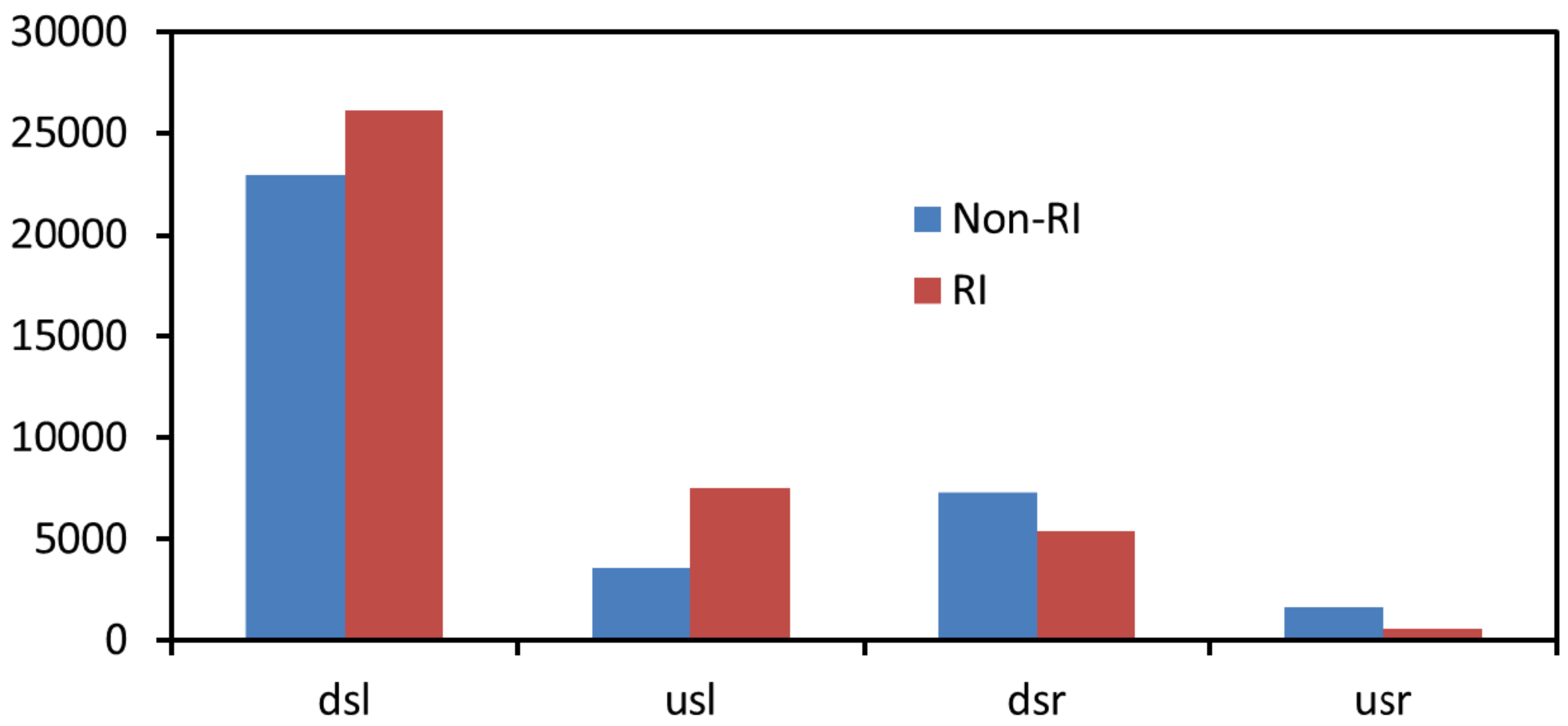
Convective bursts: HWRF



Chen and et al. (2016)

Convective bursts: HWRF

Counts of convective bursts



Chen and et al. (2016)