Eyewall Replacement Cycles: Forecasting Onset and Associated Intensity and Structure Changes

A Joint Hurricane Testbed Project

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RAMMB/CIRA team
NHC personnel

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JHT project goals:

- Transition a new model to operations that provides probabilistic forecasts of eyewall replacement cycle events in hurricanes.
- Utilize low-level aircraft reconnaissance data to expand the general climatology of intensity and structure changes associated with eyewall replacement cycles.
- Apply the new climatology toward constructing new operational tools to forecast intensity and wind structure changes associated with eyewall replacement cycles.
- Continue model development toward increasing skill.

Model: probability of ERC onset

$$P(\mathrm{ERC}|\mathbf{F}) = P(\mathrm{ERC})\frac{P(\mathbf{F}|\mathrm{ERC})}{P(\mathbf{F})}$$

Statistical/empirical model transitioned to operations prior to the start of the 2010 hurricane season.

Executes within SHIPS using environmental and satellite-based features ($\mathbf{F}$) as input.

Provides probability of the onset of an eyewall replacement cycle within lead-time periods: 0−12h, 12−24h, 24−36h, 36−48h.

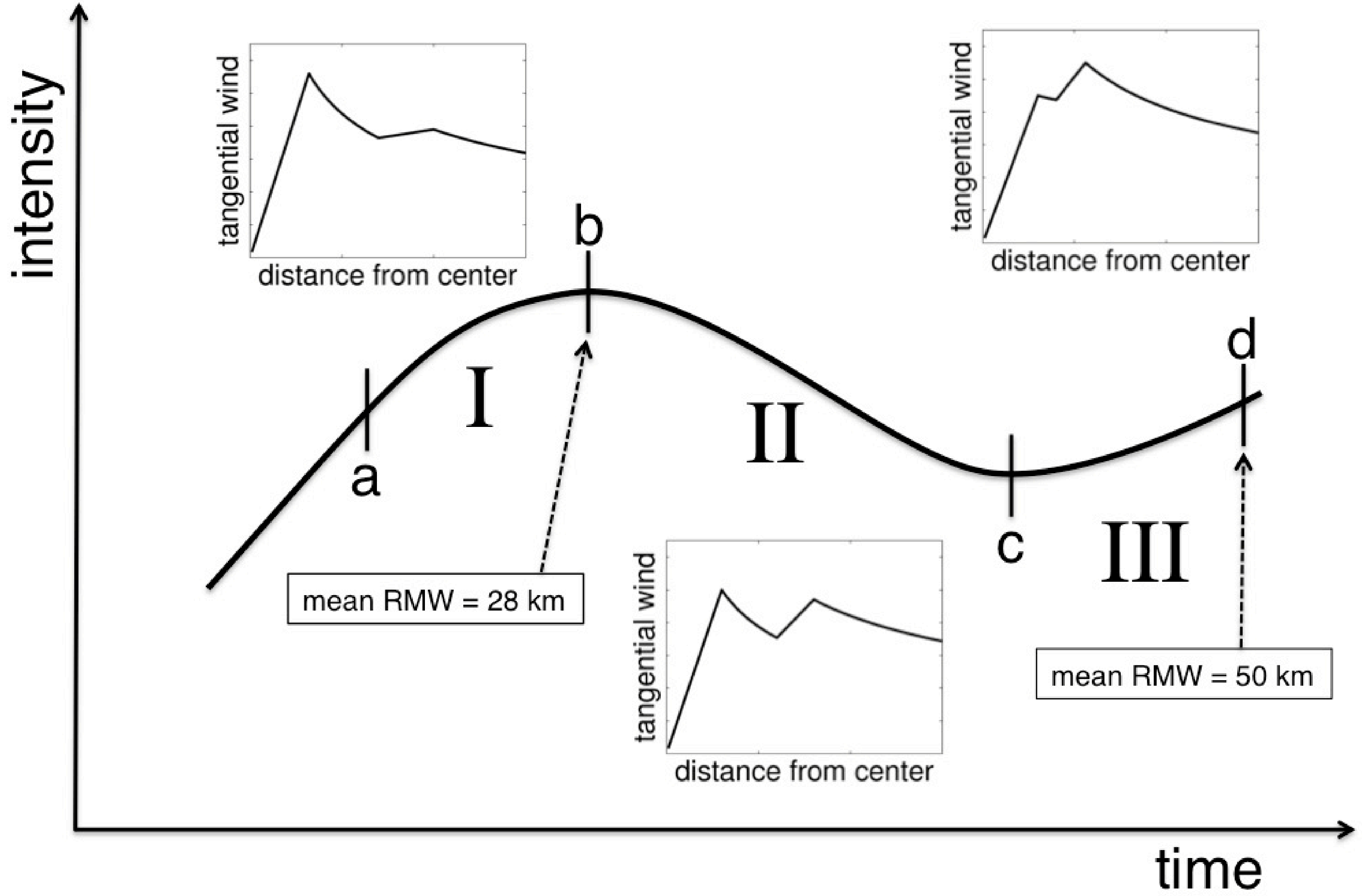
Kossin, J. P., and M. Sitkowski, 2009: An objective model for identifying secondary eyewall formation in hurricanes. *Mon. Wea. Rev.*, **137**, 876-892.

Model verification

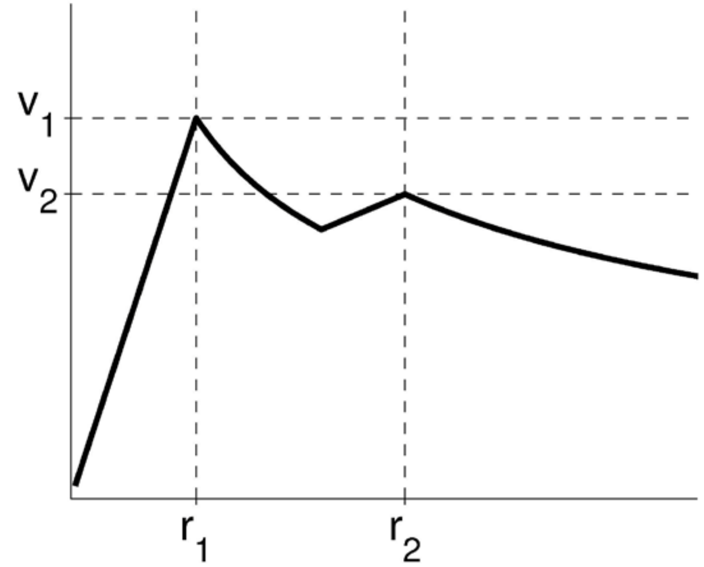
Brier Skill Score (operational)

Year	N (ERC)	00-12 hr	12-24 hr	24-36 hr	36-48 hr
2011	5	+21%	+18%	+14%	+19%

Eyewall replacement cycle climatology: three phases of an ERC



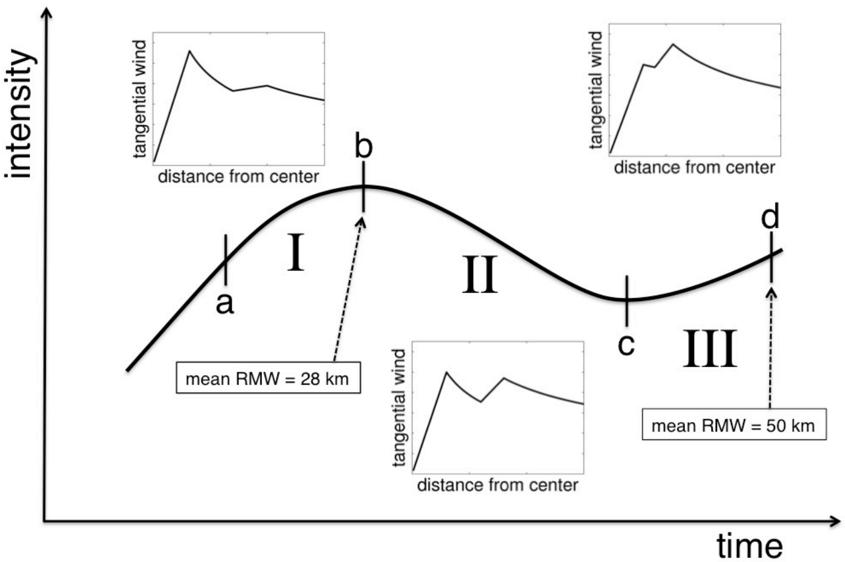
Climatology of intensity and structure changes



	Intensification		Weakening		Reintensification	
	Mean	SD	Mean	SD	Mean	SD
Δv_1 (kt)	+14	18	−20	11	−15	14
Δv_2 (kt)	+9	11	+18	14	+8	8
$\Delta v_{\text{best-track}}$ (kt)	+7	11	−9	12	−2	5
Δr_1 (km)	−7.0	11.5	−1.4	6.9	−2.2	8.0
Δr_2 (km)	−14.8	18.8	−28.8	15.9	−12.7	12.0
Δt (h)	9.4	9.1	16.6	8.6	10.7	12.6

Sitkowski, M., J. P. Kossin, and C. M. Rozoff, 2011: Intensity and structure changes during hurricane eyewall replacement cycles. *Mon. Wea. Rev.*, **139**, 3829-3847.

New models



Predictor	Description
VMX	Current intensity (kt)
LAT	Lat (°)
SHRD	Avg 850–200-hPa shear magnitude (kt) in the annulus r = 200–800 km
VMPI	Max potential intensity (kt) as calculated following Bister and Emanuel (1998)
TWAC	Avg 850-hPa symmetric tangential wind (m s^{-1}) in the annulus r = 0–600 km
IR00_02	Avg GOES channel-4 brightness temperature (°C) in the annulus r = 0–200 km
IR00_17	Radius (km) of min GOES brightness temperature within r = 20–120 km

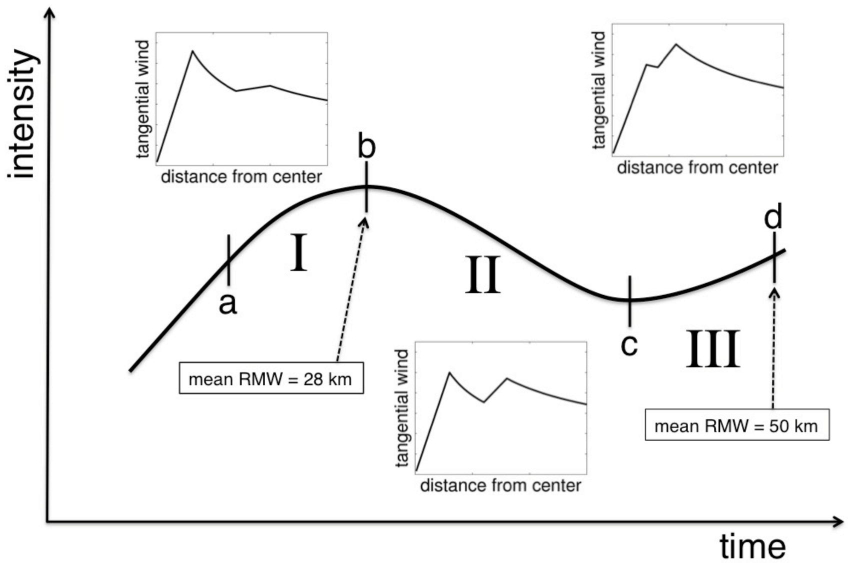
Model 1

Amount of weakening:
$\Delta v_1 = f\,(\text{VMX, LAT, SHRD})$
R^2 = 68%, RMSE = 3.6 kt

Storms that are stronger, or located at higher latitudes, or embedded in higher shear tend to weaken more during an ERC.

Kossin, J. P., and M. Sitkowski, 2012: Predicting hurricane intensity and structure changes associated with eyewall replacement cycles. *Wea. Forecasting*, to appear.

New models



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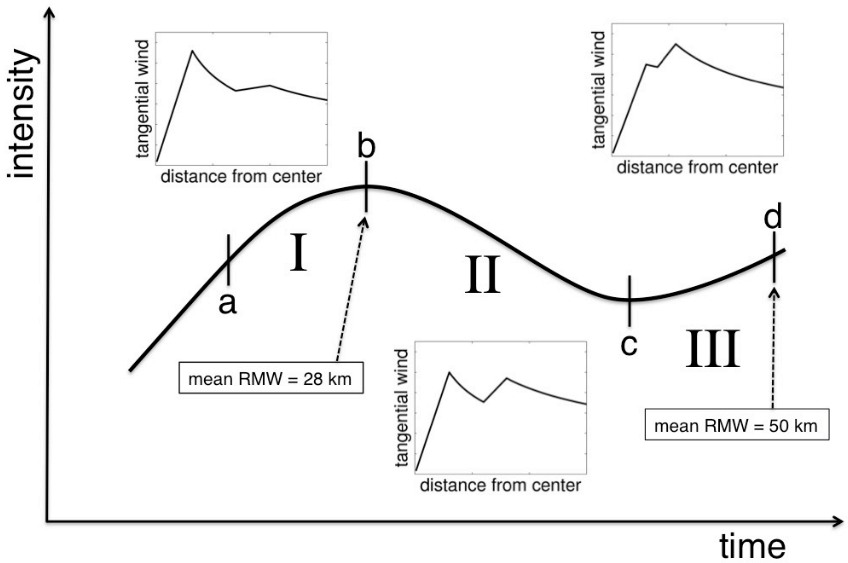
Model 2

Duration of weakening:
$\Delta t = f\,(\mathrm{IR00\_17})$
R^2 = 49%, RMSE = 6.2 hr

The duration is longer when the coldest cloud tops are located farther away from the storm center.

Kossin, J. P., and M. Sitkowski, 2012: Predicting hurricane intensity and structure changes associated with eyewall replacement cycles. *Wea. Forecasting*, to appear.

New models



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Model 3

Rate of re-intensification:

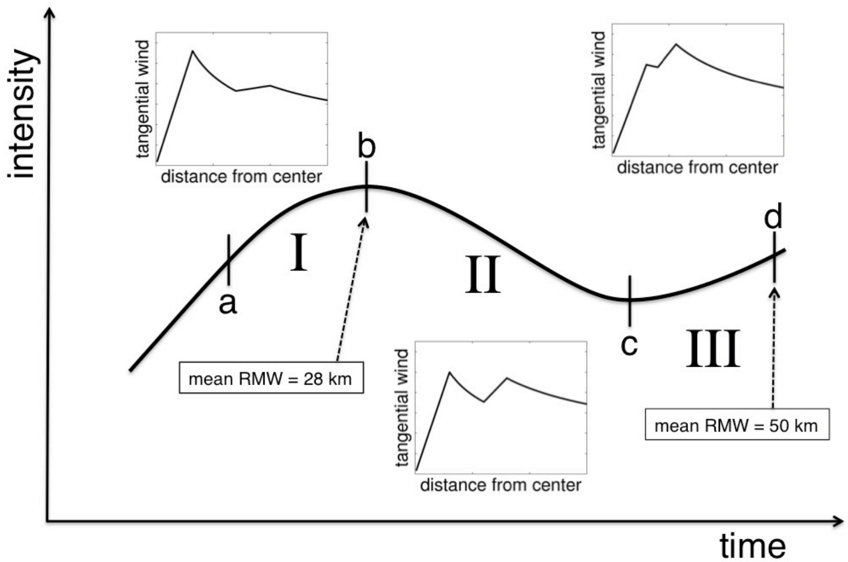
$dv_2/dt = f$ (VMPI, IR00_02)

R^2 = 47%, RMSE = 1.3 kt hr^{-1}

Lower PI and colder cloud tops are associated with faster rates.

Kossin, J. P., and M. Sitkowski, 2012: Predicting hurricane intensity and structure changes associated with eyewall replacement cycles. *Wea. Forecasting*, to appear.

New models



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Model 4

Total expansion of RMW:
ΔRMW = f (VMPI, TWAC)
R^2 = 51%, RMSE = 9.9 km

Higher PI and weaker broad-scale tangential wind is associated with greater expansion. Higher PI may control re-intensification through its effect on RMW.

Kossin, J. P., and M. Sitkowski, 2012: Predicting hurricane intensity and structure changes associated with eyewall replacement cycles. *Wea. Forecasting*, to appear.

Summary

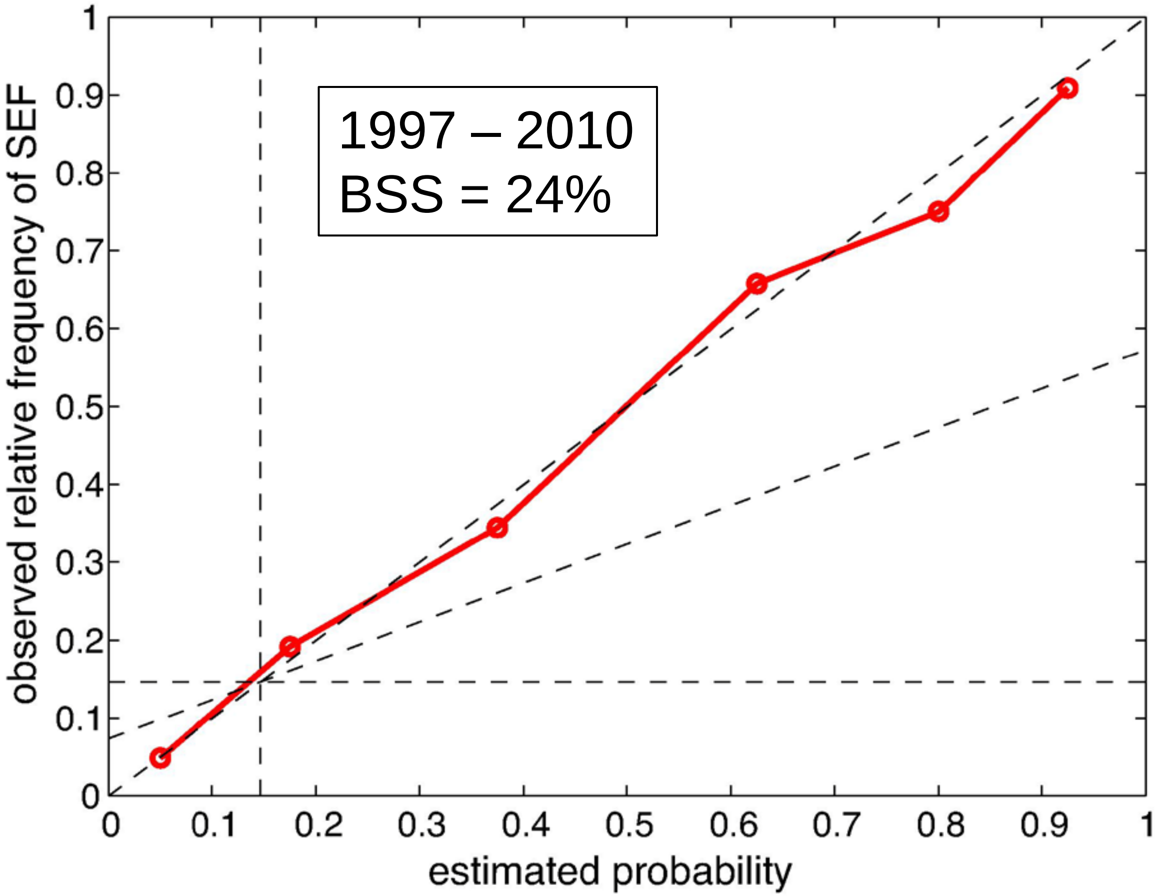
The *P*(ERC)-model was successfully transitioned into NHC operations and has performed skillfully at all lead-times during the 2010 and 2011 seasons. Overall operational skill for the period 2008-2011 is quite good. Improvements to the *P*(ERC)-model improve the skill further.

Flight-level data were used to construct a climatology of intensity and wind structure changes associated with eyewall replacement cycles. This has been used to construct new intensity forecasting tools that are now ready for transition into operational testing.

P(ERC) model improvements:
(optimal feature selection)

<u>Features selected:</u>

measures of
- intensity
- shear
- vertical motion
- relative humidity



In progress: logistic regression and 2-member ensemble

Operational SHIPS text output file

Intensity forecasts

```
          *   ATLANTIC SHIPS INTENSITY FORECAST       *
          *      GOES DATA AVAILABLE                  *
          *      OHC  DATA AVAILABLE                  *
          *  ALEX        AL012010  06/29/10  06 UTC   *

TIME (HR)          0     6    12    18    24    36    48    60    72    84    96   108   120
V (KT) NO LAND    60    64    68    73    76    82    84    85    81    76    70    62    56
V (KT) LAND       60    64    68    73    76    82    73    44    32    28    27    27    27
V (KT) LGE mod    60    65    69    73    77    83    87    45    32    28    27    27    27

SHEAR (KT)        14    12    10     8     7     7     9     5     8     4    10     7    11
SHEAR ADJ (KT)     0     0     0    -3    -3    -4    -5    -1    -3     7    -1     3    -5
SHEAR DIR          4   358     4    32    48    79    23   310    10   345   337   320   349
SST (C)         28.5  28.6  28.8  28.8  28.8  28.6  28.3  28.2  28.1  28.1  27.9  27.6  27.3
POT. INT. (KT)   143   145   148   148   148   144   140   137   136   137   134   129   125
ADJ. POT. INT.   128   131   133   134   133   128   122   119   118   119   116   109   104
200 MB T (C)   -50.2 -50.3 -49.8 -49.1 -49.4 -48.9 -48.9 -48.4 -48.4 -48.8 -48.8 -49.2 -49.2
TH_E DEV (C)       9     8    10    12     9    10    10    11    10    13    10    12    11
700-500 MB RH     77    73    75    76    78    81    80    82    82    80    76    74    71
GFS VTEX (KT)     20    20    23    22    22    22    20    17    10     6     5     2     3
850 MB ENV VOR   123   115   128   140   126   116   100    90    82    41    37     8     9
200 MB DIV        59    50    54    58    43    52    71    66    46     7    15    -5     4
LAND (KM)        161   238   325   426   353   165    -9  -143  -257  -387  -496  -605  -609
LAT (DEG N)     21.4  22.2  22.9  23.5  24.1  24.8  25.4  25.7  25.7  26.3  27.6  28.6  29.5
LONG(DEG W)     91.8  92.3  92.7  93.5  94.2  95.9  97.5  98.8 100.0 101.2 102.4 103.4 103.2
```

```
** PROBLTY OF AT LEAST 1 SCNDRY EYEWL FORMTN EVENT AL012010 ALEX       06/29/2010  00 UTC **
TIME(HR)    0-12   12-24(0-24)   24-36(0-36)   36-48(0-48)
CLIMO(%)      0        3(  3)        5(  8)        8( 15)     <-- PROB BASED ON INTENSITY ONLY
PROB(%)       0        9(  9)       34( 40)        4( 42)     <-- FULL MODEL PROB (RAN NORMALLY)
```

```
   SAMPLE MEAN CHANGE       1.   2.   3.   4.   6.   8.   9.  11.  11.  12.  13.  13.
   SST POTENTIAL            1.   2.   3.   4.   5.   5.   4.   3.   2.   1.   0.  -2.
   VERTICAL SHEAR MAG       0.   0.   1.   2.   4.   6.   9.  11.  13.  13.  13.  14.
   VERTICAL SHEAR ADJ       0.   0.   0.   0.   1.   2.   3.   3.   2.   2.   1.   1.
   VERTICAL SHEAR DIR       0.   0.   1.   1.   1.   2.   2.   2.   2.   2.   2.   2.
   PERSISTENCE              2.   3.   3.   3.   3.   3.   3.   2.   2.   1.   0.   0.
   200/250 MB TEMP.        -1.  -2.  -3.  -3.  -6.  -8. -10. -13. -15. -17. -20. -22.
   THETA_E EXCESS           0.   0.   0.   0.  -1.  -1.  -1.  -1.  -1.  -1.  -1.  -1.
   700-500 MB RH            0.   0.   0.  -1.  -1.  -2.  -2.  -2.  -2.  -2.  -3.  -3.
   GFS VORTEX TENDENCY      0.   1.   1.   1.   1.   0.  -3.  -8. -11. -12. -14. -14.
   850 MB ENV VORTICITY     1.   1.   2.   3.   4.   5.   6.   7.   7.   7.   7.   6.
   200 MB DIVERGENCE        0.   0.   1.   1.   2.   3.   4.   5.   4.   4.   3.   3.
   ZONAL STORM MOTION       0.   0.   0.   0.   0.   0.  -1.  -1.  -1.  -2.  -2.  -2.
   STEERING LEVEL PRES      0.   0.   0.   0.   0.   0.   0.   1.   1.   1.   0.   0.
   DAYS FROM CLIM. PEAK     0.   0.   0.   0.   0.  -1.  -1.  -1.  -1.  -1.   0.  -1.
   GOES PREDICTORS          0.   1.   1.   1.   2.   2.   2.   2.   2.   2.   1.   1.
   OCEAN HEAT CONTENT       0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.
                           ------------------------------------------------------------
   TOTAL CHANGE             4.   8.  13.  16.  22.  24.  25.  21.  16.  10.   2.  -4.

    ** 2010 ATLANTIC RI INDEX AL012010 ALEX      06/29/10  06 UTC **
           ( 30 KT OR MORE MAX WIND INCREASE IN NEXT 24 HR)

  12 HR PERSISTENCE (KT):  10.0 Range:-45.0 to  30.0 Scaled/Wgted Val:  0.7/  1.6
  850-200 MB SHEAR (KT) :  10.3 Range: 26.2 to   3.2 Scaled/Wgted Val:  0.7/  0.8
  D200 (10**7s-1)       :  52.8 Range:-21.0 to 140.0 Scaled/Wgted Val:  0.5/  0.7
  POT = MPI-VMAX (KT)   :  71.8 Range: 33.5 to 126.5 Scaled/Wgted Val:  0.4/  0.3
  850-700 MB REL HUM (%):  80.8 Range: 56.0 to  85.0 Scaled/Wgted Val:  0.9/  0.5
  % area w/pixels <-30 C:  76.0 Range: 17.0 to 100.0 Scaled/Wgted Val:  0.7/  0.1
  STD DEV OF IR BR TEMP :  15.3 Range: 30.6 to   3.2 Scaled/Wgted Val:  0.6/  0.9
  Heat content (KJ/cm2) :  33.2 Range:  0.0 to 130.0 Scaled/Wgted Val:  0.3/  0.0

  Prob of RI for 25 kt RI threshold=   32% is   2.6 times the sample mean(12.6%)
  Prob of RI for 30 kt RI threshold=   22% is   2.8 times the sample mean( 8.1%)
  Prob of RI for 35 kt RI threshold=   12% is   2.5 times the sample mean( 4.8%)
  Prob of RI for 40 kt RI threshold=    9% is   2.7 times the sample mean( 3.4%)

   ##          ANNULAR HURRICANE INDEX (AHI) AL012010 ALEX       06/29/10  06 UTC          ##
   ## STORM NOT ANNULAR, SCREENING STEP FAILED, NPASS=4 NFAIL=3                            ##
   ## AHI=  0   (AHI OF 100 IS BEST FIT TO ANN. STRUC., 1 IS MARGINAL, 0 IS NOT ANNULAR) ##
   ##     ANNULAR INDEX RAN NORMALLY
```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Rapid Intensification Index (RII)

Annular Hurricane Index (AHI)

Probability of Onset of an Eyewall Replacement Cycle