# Probabilistic Prediction of Hurricane Intensity with an Analog Ensemble

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Funded by NOAA HFIP

# Motivation & Goal

- Numerical weather prediction is limited by errors in initial conditions, model imperfections, and nonlinearity.
  - Ensembles of an NWP model provide forecast probability density functions (PDFs), useful for guidance
    - Limited computer resources may require sacrifice in resolution
- We investigate a way to generate PDFs from a single deterministic run
  - the HWRF NWP model to exploit its high resolution
  - Using the analog ensemble technique (Delle Monache et al. 2013), one can obtain forecast uncertainty from HWRF

# The Analog Ensemble (AnEn)

Delle Monache et al. (2013; *Mon. Wea. Rev.*)

- The analog ensemble (AnEn) estimates the PDF of an observed future value of the predictand variable (here, TC intensity) given an individual numerical weather prediction (NWP) model forecast.

$$p(y \mid \mathbf{x}^f) \qquad \mathbf{x}^f = \left(x_1^f, x_2^f, \ldots, x_k^f\right)$$

where, at a given time and location, *y* is the unknown observed future value of TC intensity and are the *k* predictors from the deterministic model forecast at the same time.

# The Analog Ensemble
## illustrated

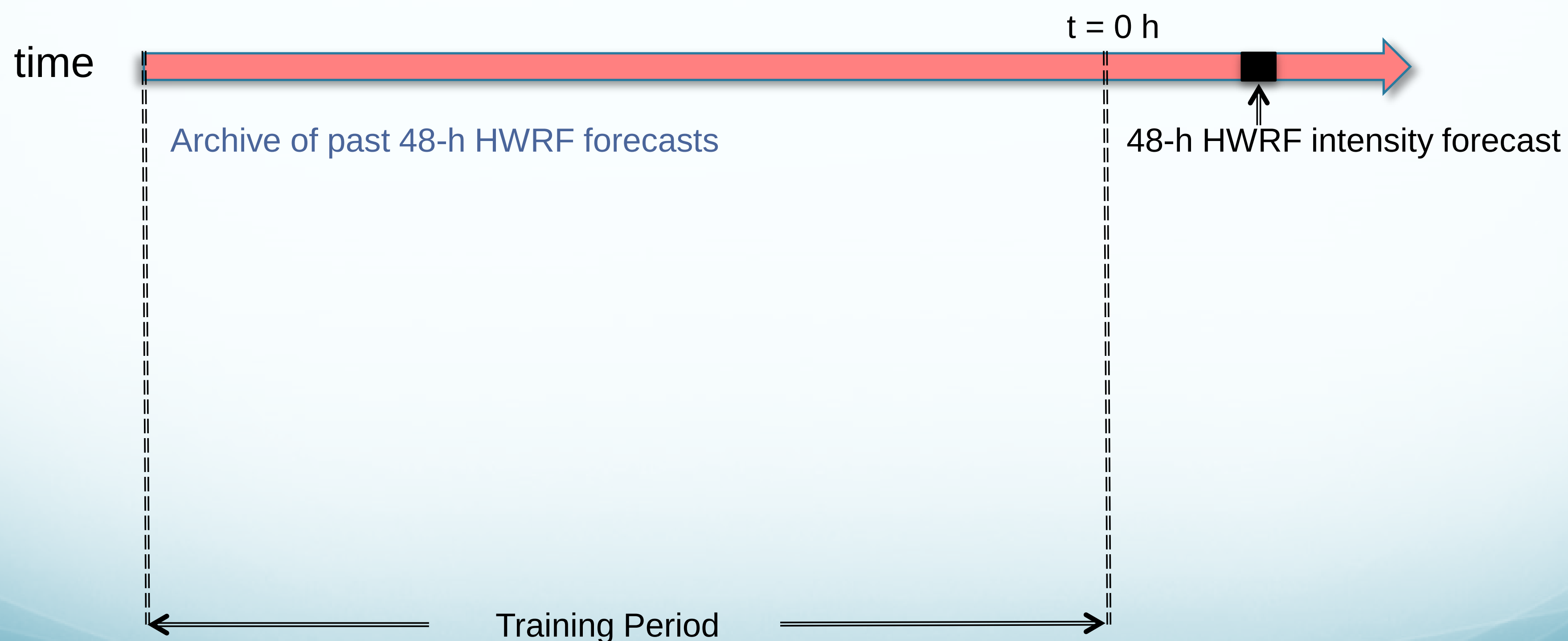
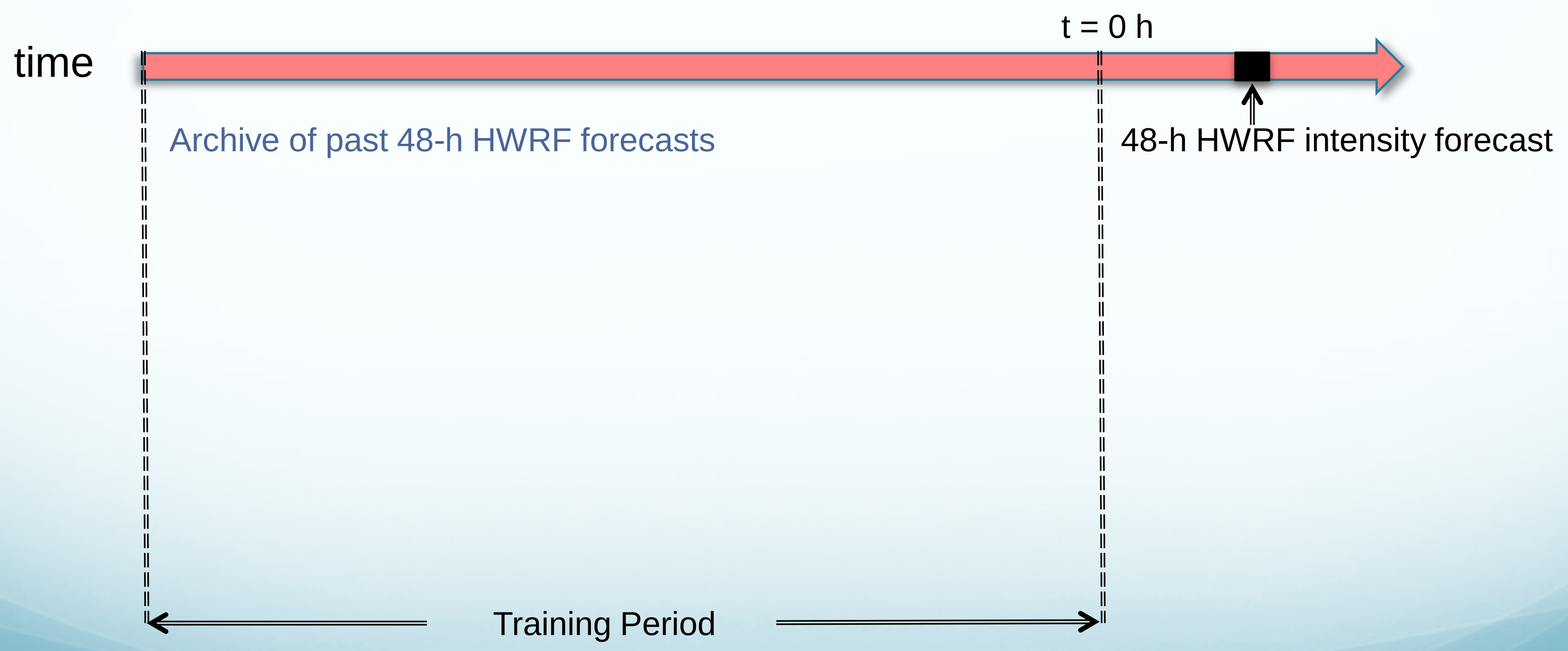



Figure adapted from Delle Monache et al. (2013)

# The Analog Ensemble

## illustrated

Find set number of analogs based on certain predictors

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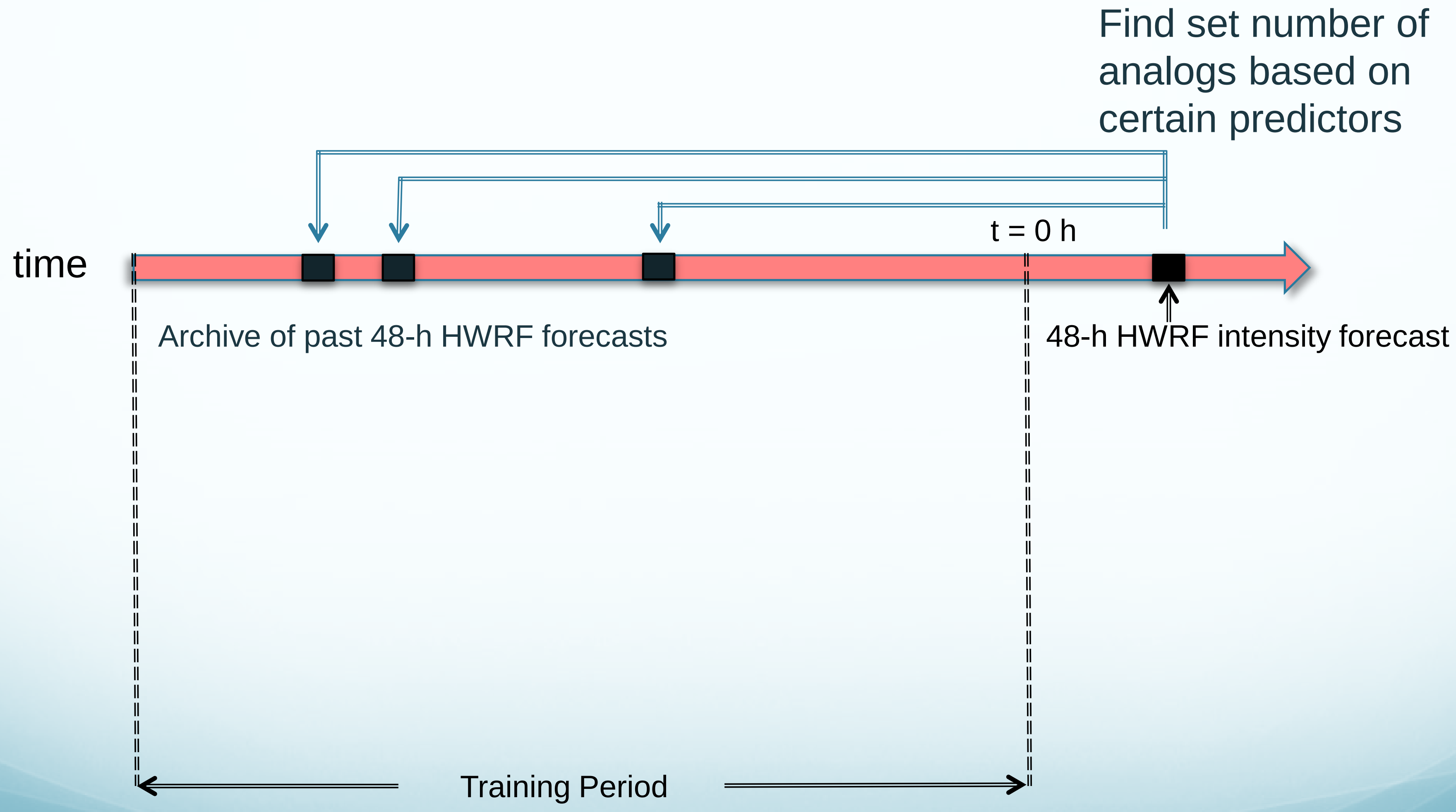


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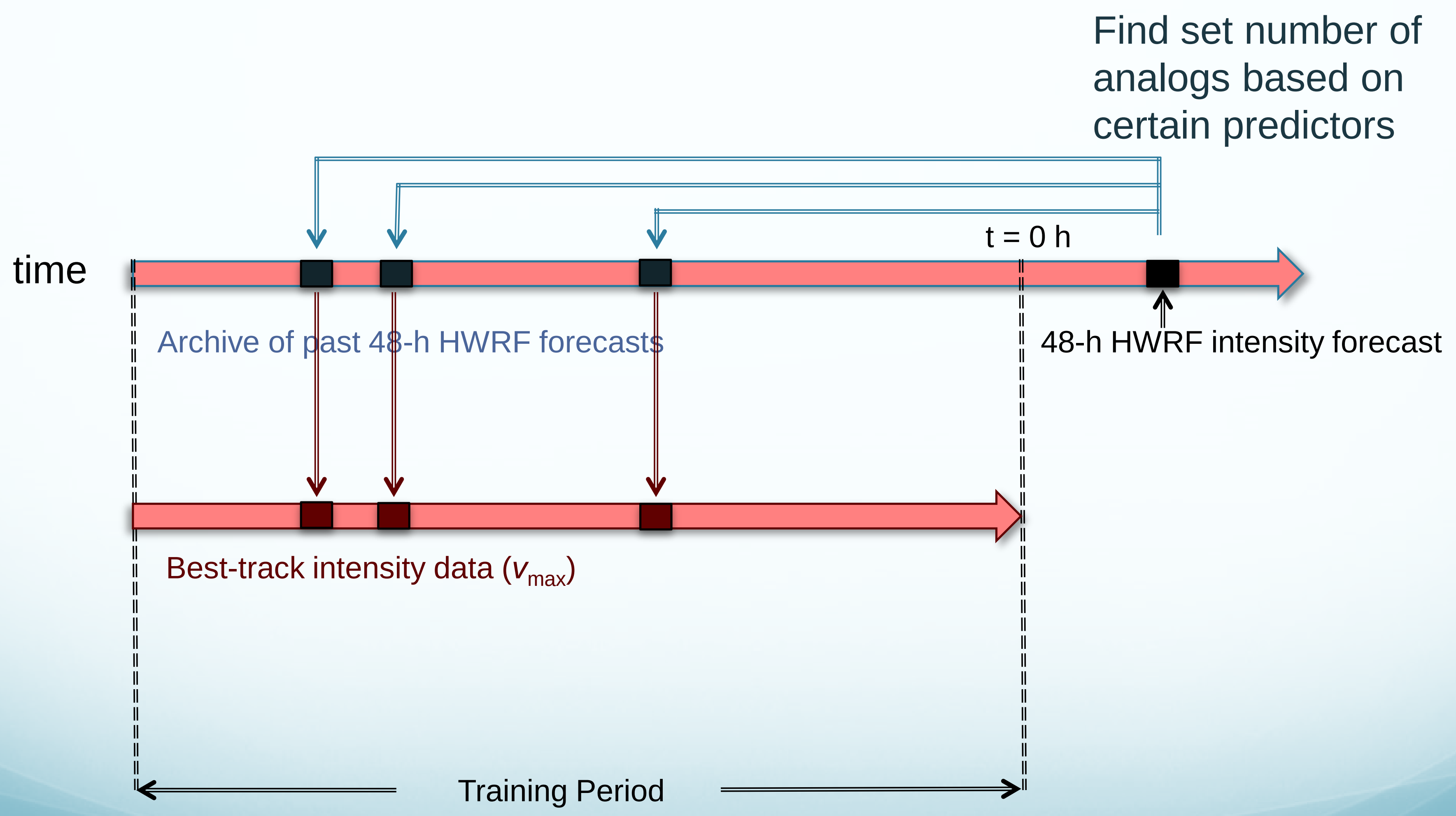


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# The Analog Ensemble

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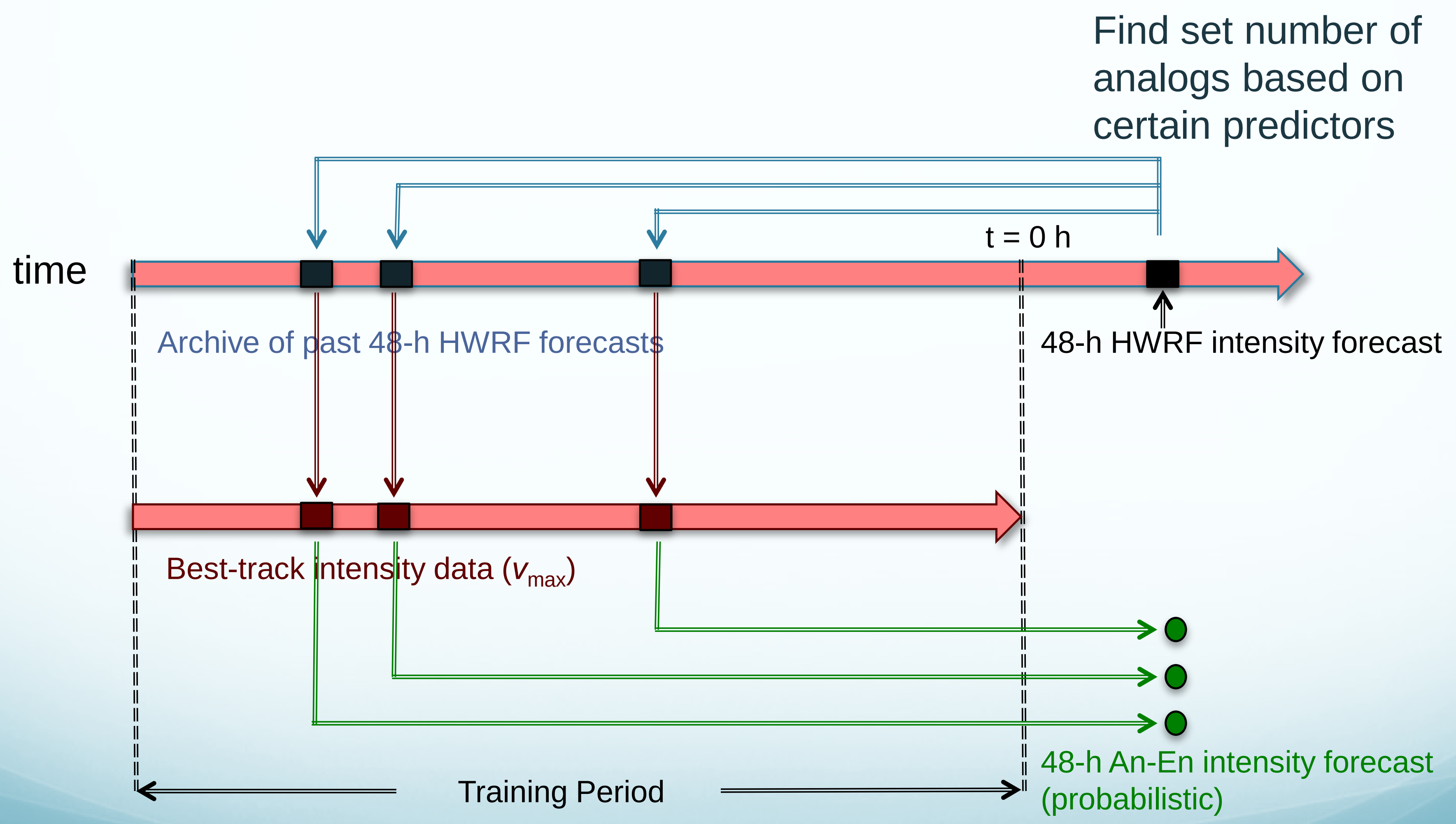



Figure adapted from Delle Monache et al. (2013)

# The Analog Ensemble

- The quality of an analog (i.e., closeness of a match) is determined with the following metric

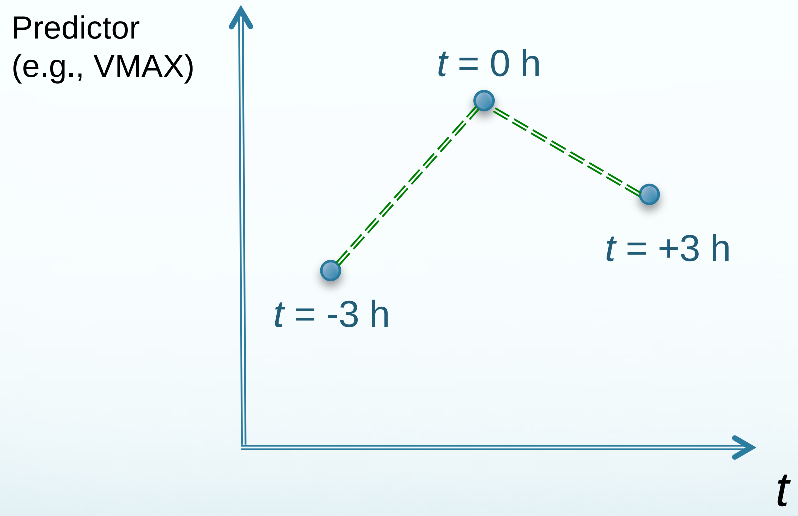
$$\left\| F_t, A_{t'} \right\| = \sum_{i=1}^{N_V} \frac{w_i}{\sigma_{f_i}} \sqrt{\sum_{j=-\tilde{t}}^{\tilde{t}} \left( F_{i,t+j} - A_{i,t'+j} \right)^2}$$

  - $F_t$ is the current HWRF forecast valid at the future time $t$
  - $A_{t'}$ is an analog (a past HWRF forecast from the archive) with the same forecast lead time but valid at a past time $t'$
  - $N_v$ and $w_i$ are the number of predictors and their weights
  - $\sigma_{fi}$ is the standard deviation of the time series of past forecasts of a given predictor for the forecast lead time
  - $\tilde{t}$ is equal to half the number of additional times over which the metric is computed
  - $F_{i,t+j}$ and $A_{i,t'+j}$ are the values of the forecast and the analog in the time window 2 .

# The Analog Ensemble

$$\left\| F_t, A_{t'} \right\| = \sum_{i=1}^{N_V} \frac{w_i}{\sigma_{f_i}} \sqrt{\sum_{j=-\tilde{t}}^{\tilde{t}} \left( F_{i,t+j} - A_{i,t'+j} \right)^2}$$

- $\tilde{t}$ = 1 in our case (3 hourly given HWRF dataset).



# Features of the AnEn

- Can use a higher resolution model for an ensemble prediction (since only one real-time forecast is needed for AnEn)
- No need for initial conditions and model perturbation strategies to generate an ensemble
- Flow-dependent error characteristics can be determined
- The AnEn is well-suited for improving the prediction of rare events since it searches for a small set of best analogs.
  - This may improve HWRF prediction of rapid intensification (RI) forecasts.

# HWRF training data

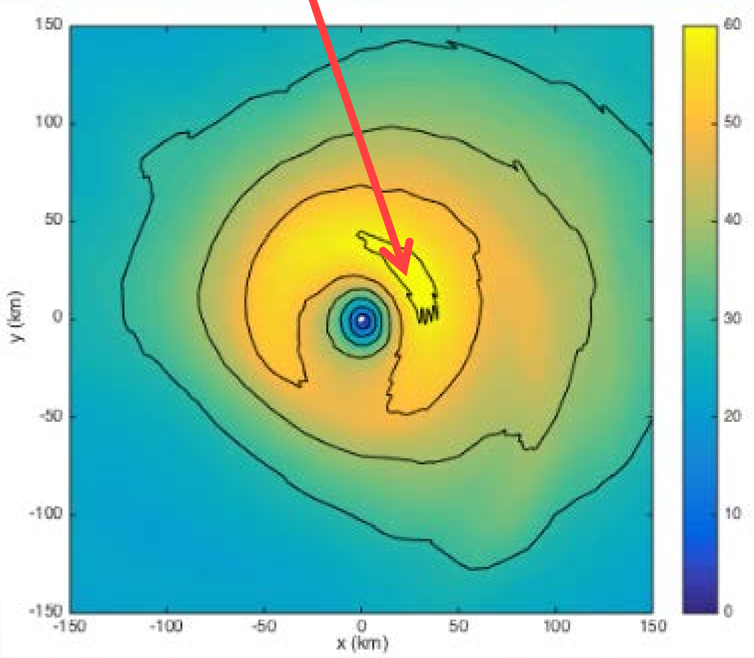
- H214 is used on 2008-2013 reforecast data (Atlantic and eastern Pacific).
  - 3-km nest (7.1 x 7.1$^{o}$) and 9-km nest (12 x 12$^{o}$) within 27 km outer grid.
  - NMM dynamic core
  - Vortex initialization package + GSI data assimilation
  - Princeton Ocean model.
  - Simplified Arakawa Schubert with shallow convection cumulus scheme on outer domains
  - Ferrier for tropics microphysics
  - GFS PBL parameterization
  - GFDL surface layer, land-surface model and radiation schemes.

# Available HWRF Forecasts

- 2023 HWRF runs, with 0 – 126 h lead-times (at 3 h increments) [77 tropical cyclones]
  - **2008:** Storm nos. 2 – 9, 11, 15, 17
    - **11 storms: 3 TS, 2 cat 1, 1 cat 2, 2 cat 3, 3 cat 4**
  - **2009:** Storm nos. 3, 5, 6, 11
    - **4 storms: 2 TS, 1 cat 2, 1 cat 4**
  - **2010:** Storm nos. 4, 6 – 8, 10 – 16
    - **11 storms: 5 TS, 1 cat 1, 1 cat 3, 4 cat 4**
  - **2011:** Storm nos. 1 – 18
    - **18 storms: 1 TD, 11 TS, 2 cat 1, 1 cat 2, 1 cat 3, 2 cat 4**
  - **2012:** Storm nos. 1 – 19
    - **19 storms: 9 TS, 6 cat 1, 3 cat 2, 1 cat 3**
  - **2013:** Storm nos. 1 – 14
    - **14 storms: 1 TD, 11 TS, 2 cat 1**

# HWRF training data

- H214 predicted VMAX
  - Maximum value at forecast time.




HWRF initial analysis tangential wind (m $s^{-1}$) for Hurricane Earl on 06 UTC 2 Sept 2010

# Available Observations

- 77 tropical cyclones in the Atlantic are matched with H214 retrospective runs
  - 2008 – 2013
  - Best track maximum wind speed (VMAX) interpolated to 3-hourly increments to match HWRF.

# Tested Predictors

- A variety of environmental and storm-related predictors are explored.
  - **Thermodynamic (environment*):**
    - SST,
    - TPW,
    - RH,
    - CAPE (inner-core and rainband region),
    - MPI,
    - large-scale temperature gradient

***Note, environmental parameters are obviously influenced by the storm as well.**

# Tested Predictors

- A variety of environmental and storm-related predictors are explored.
  - **Kinematic (environment*):**
    - 850-200-hPa vertical wind shear,
    - storm motion vector,
    - 200-hPa divergence

***Note, environmental parameters are obviously influenced by the storm as well.**

# Tested Predictors

- A variety of environmental and storm-related predictors are explored.
  - **Storm-specific:**
    - Turbulent surface latent & sensible heat fluxes,
    - integrated kinetic energy at 850 hPa,
    - 850-500-hPa latent heating rate (inner-core & rainband regions),
      850-500-hPa inertial stability (inner-core & rainband regions) (i.e., $I^2 = \left(f + \frac{2v}{r}\right)(f + \zeta)$
    - a variety of storm structure and symmetry parameters. For example,

$$s = \frac{\sigma^2_{LRGHR}}{\sigma^2_{LRGHR} + \int_0^{2\pi} \left(\overline{LRGHR} - LRGHR\right)^2 d\lambda}$$

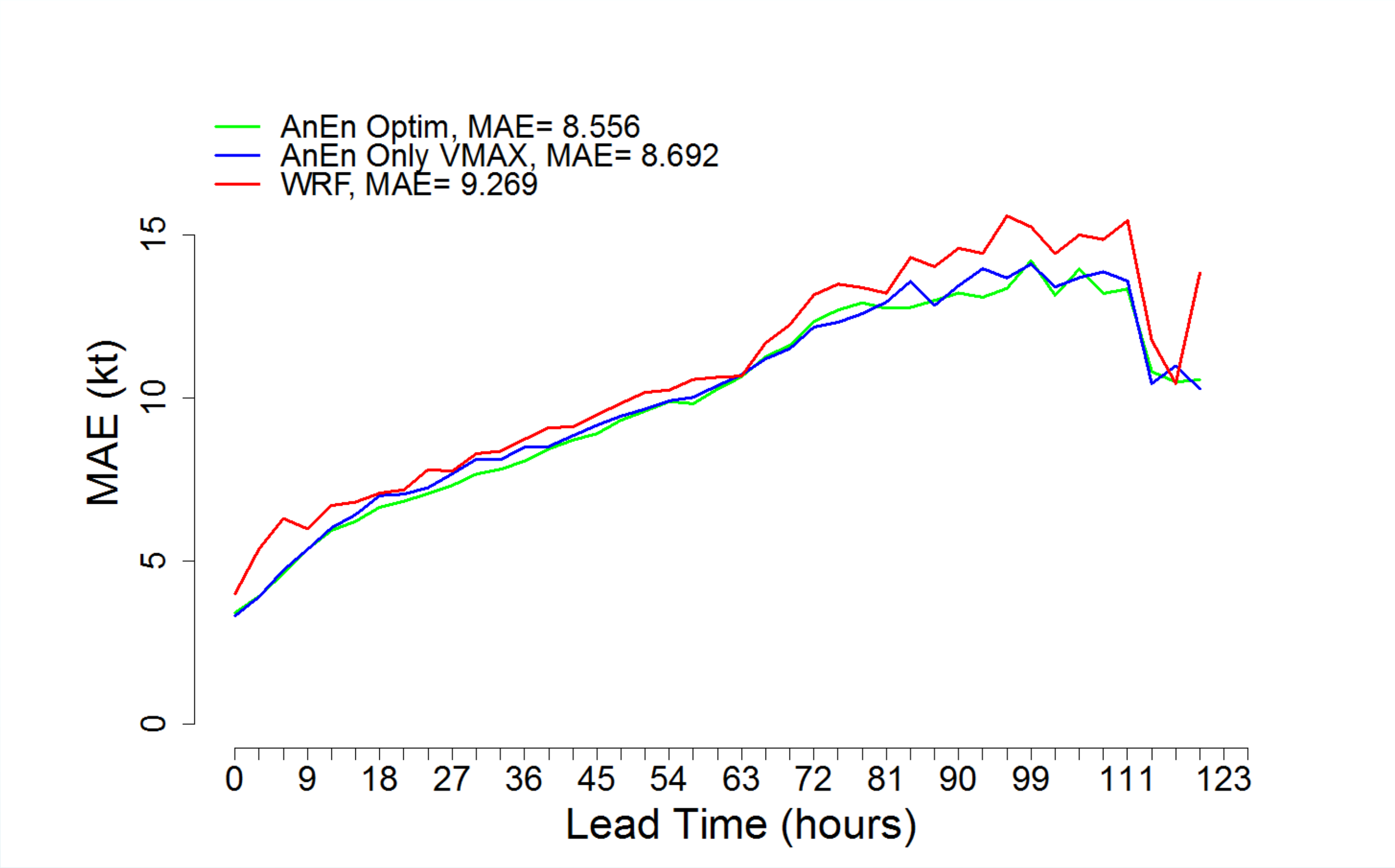
# Verification Period

- 626 runs, from Aug 2012 – Dec. 2013, forecast lead time from 0 – 126 h
- Predictions: VMAX

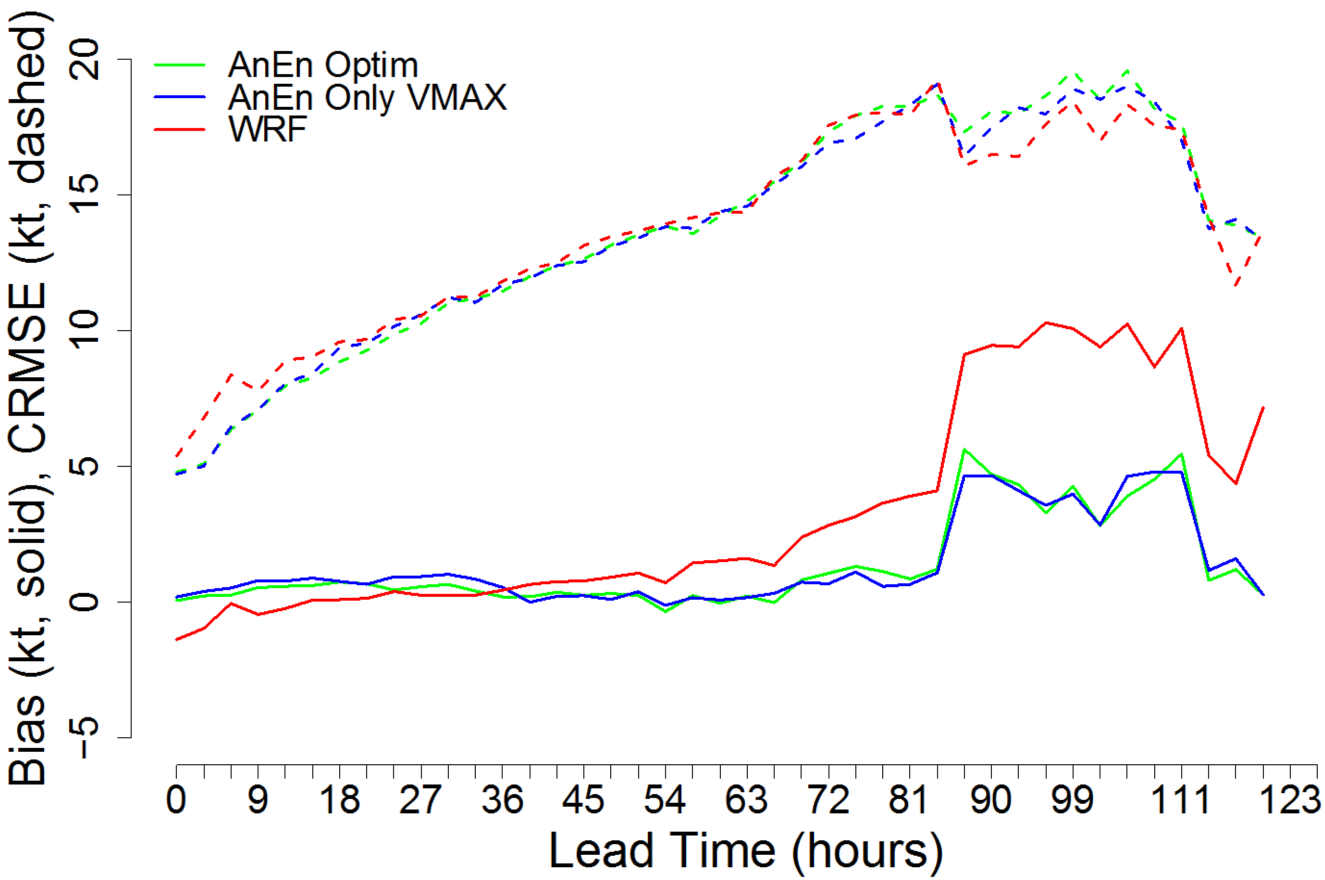
# Optimal Predictors

- Maximum wind speed and 51 of the aforementioned predictors are used for preliminary tests of AnEn predictions of VMAX.
- Optimal weights ($w_i$) of the 51 predictors is defined by choosing the combination minimizing MAE over 2/3 of the Atlantic dataset (not used for the validation.
  - All possible combinations defined with the constraint $\sum_{i=1}^{10} w_i = 1$, where $w_i \in [0\ 1]$ are considered.
  - Weight values greater than 0 result in only 3 predictors:
    Maximum predicted wind speed, inner-core (850-500 hPa) inertial stability, and estimated storm motion direction with weights of 0.4, 0.3, and 0.3.
  - 20 ensemble members are used.

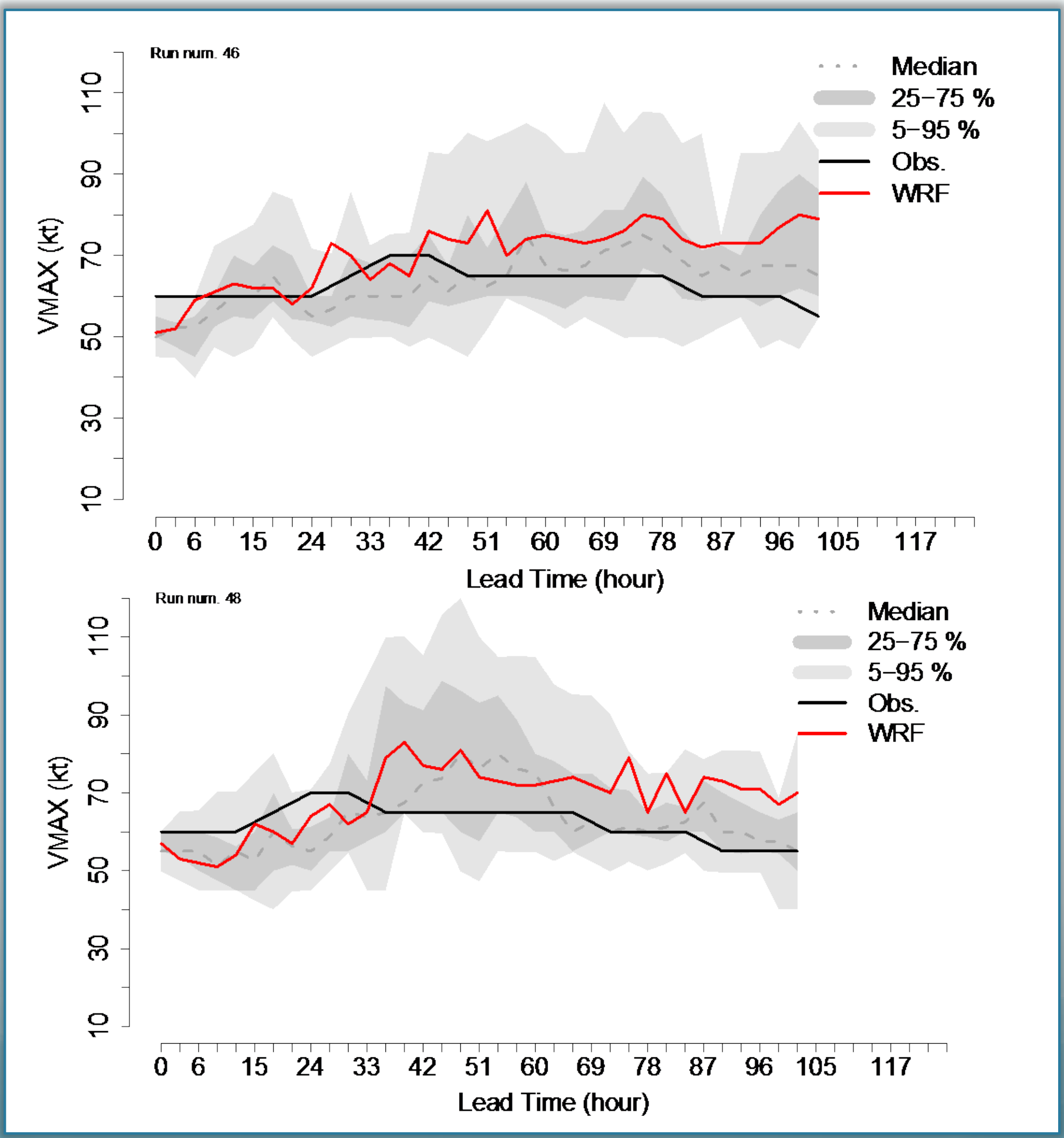
# Maximum Absolute Error (MAE)



# Centered Root Mean Square Error and Bias

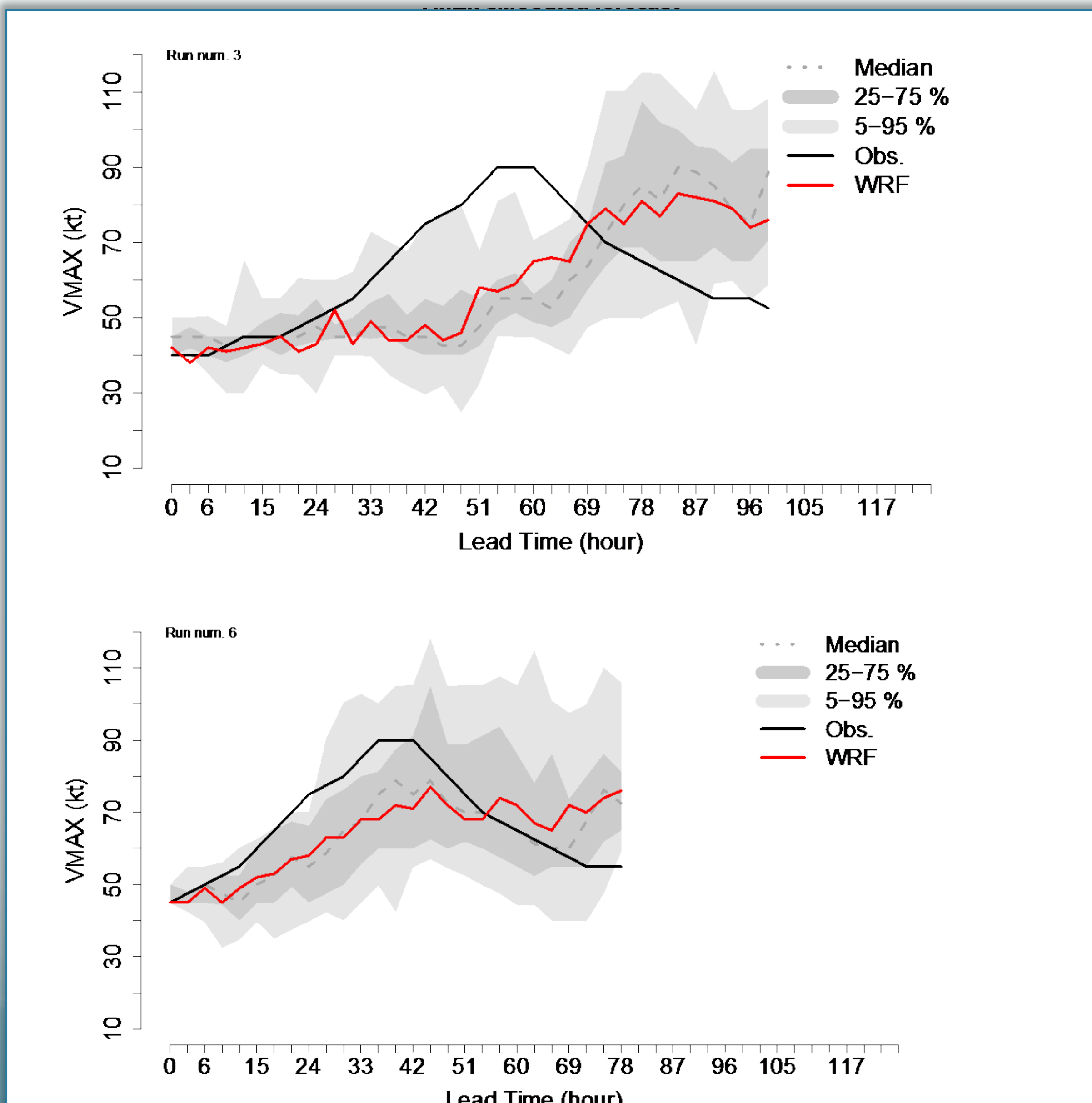


# Case Studies




Hurricane Leslie (2012)

# Case Studies




Hurricane Kirk (2012)

# Summary of ATL 2014 HWRF Results

- AnEn (VMAX predictor only) and the optimally weighted predictor-enhanced AnEn improve the MAE of HWRF by 6.2% and 7.7%, respectively.
  - Excels in reducing bias of forecast
  - Provides an ensemble spread forecast
- Examples show AnEn is particularly useful in the first 48 h, with statistically significant differences in MAE between the HWRF and AnEn.

# Ongoing Efforts

- We acquired 2015 reforecast data from HWRF.
  - Unfortunately, there were only 1110 forecasts available for the Atlantic (compare to 2023 forecasts from the 2014 version of HWRF)
  - There are 1316 forecasts available for the Eastern Pacific
  - Reforecast data are from 2011 – 2014.

# Ongoing Efforts

- The 2015 HWRF grib2 files no longer contain latent heating, which reduced the previous predictor set considerably.
- New predictors have been added for each of the following regions (*r* = 0 – 50, 0 – 100, 100 – 250 km):
  - Average 700-hPa total condensate (10 g $kg^{-1}$)
  - Average 850-500 hPa total condensate (10 g $kg^{-1}$) (+ symmetry predictor)
  - Average 850-500 hPa upward motion (Pa $s^{-1}$)
  - Radial flow @ surface (m $s^{-1}$)
  - 850-500 hPa vertical motion symmetry parameter (10%)
  - Surface Radial flow symmetry parameter (10%)
  - 850-500 hPa inert. stab. + pos. vert. mot. coupling parameter ($10^{-4}$ Pa $s^{-3}$) (+ symmetry predictor)

$$CP = \begin{cases} -I^2 w & \text{if } w < -0.5 \text{ Pa s}^{-1} \\ 0 & \text{otherwise} \end{cases}$$

  - NHC official VMAX forecast

# Eastern Pacific results (2015 HWRF)

3 predictors:

- Maximum predicted wind speed,
- Inner-core inertial stability, and
- 500-250-hPa RH

(Weights of 0.6, 0.3, and 0.1)

671 runs for testing (~1/2 runs) starting after 8/8/2013

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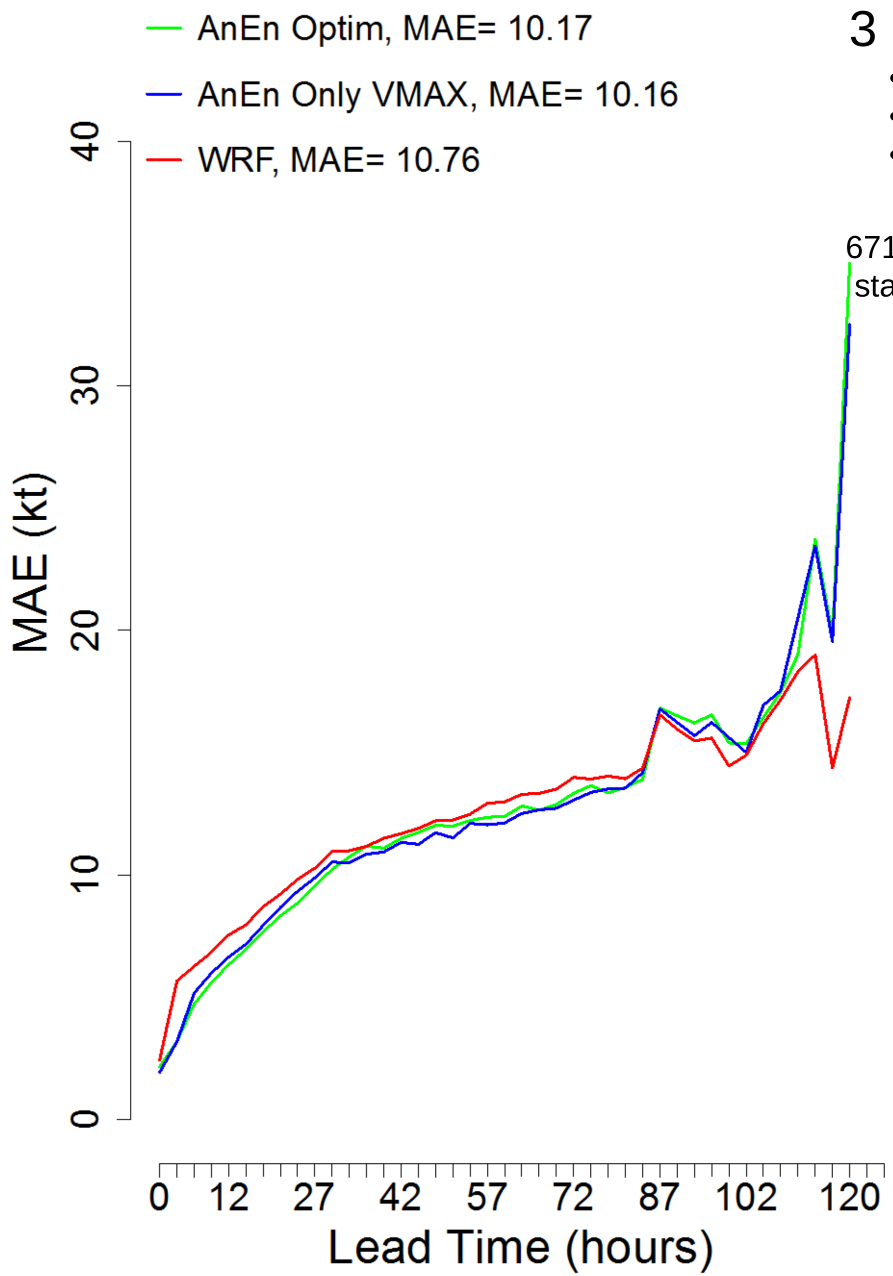


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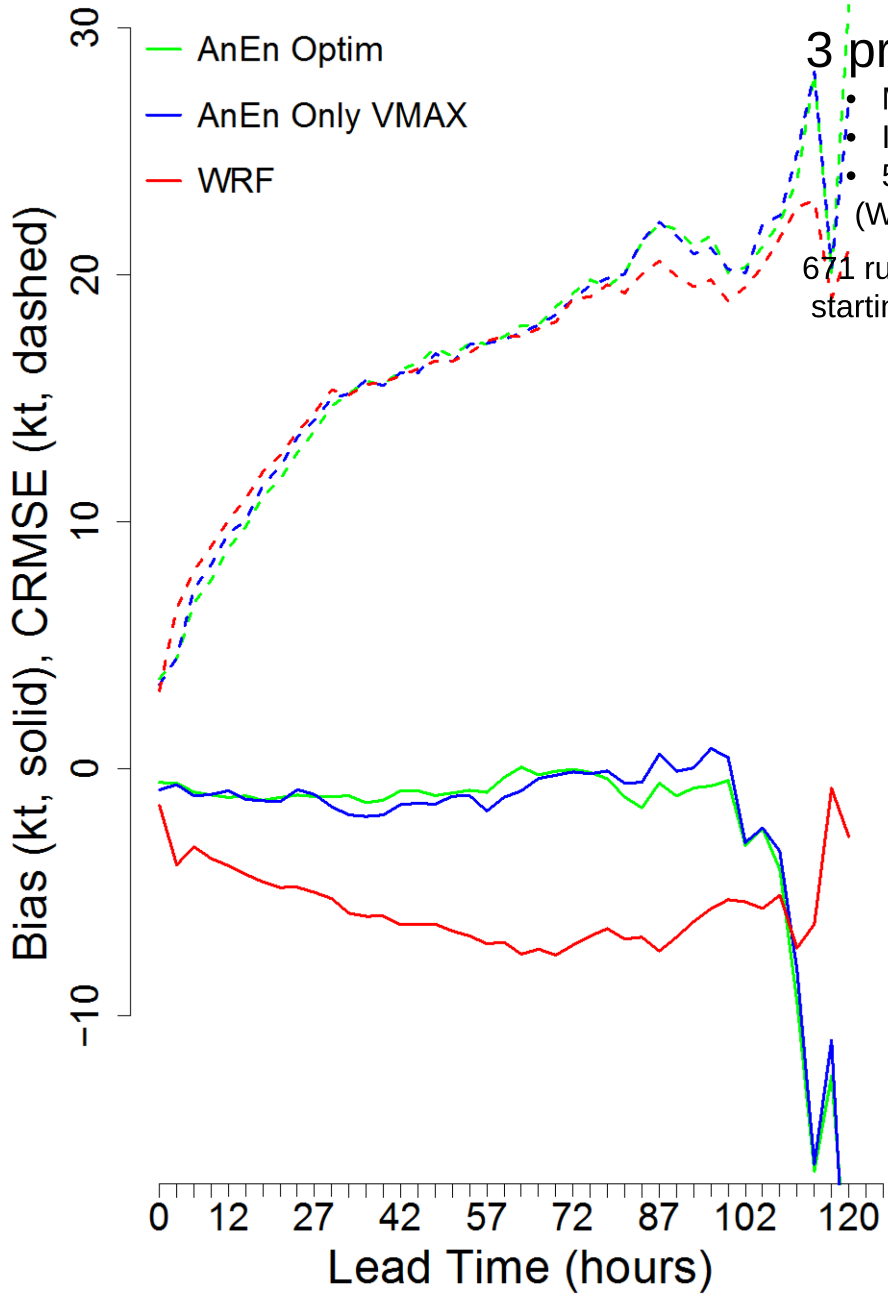


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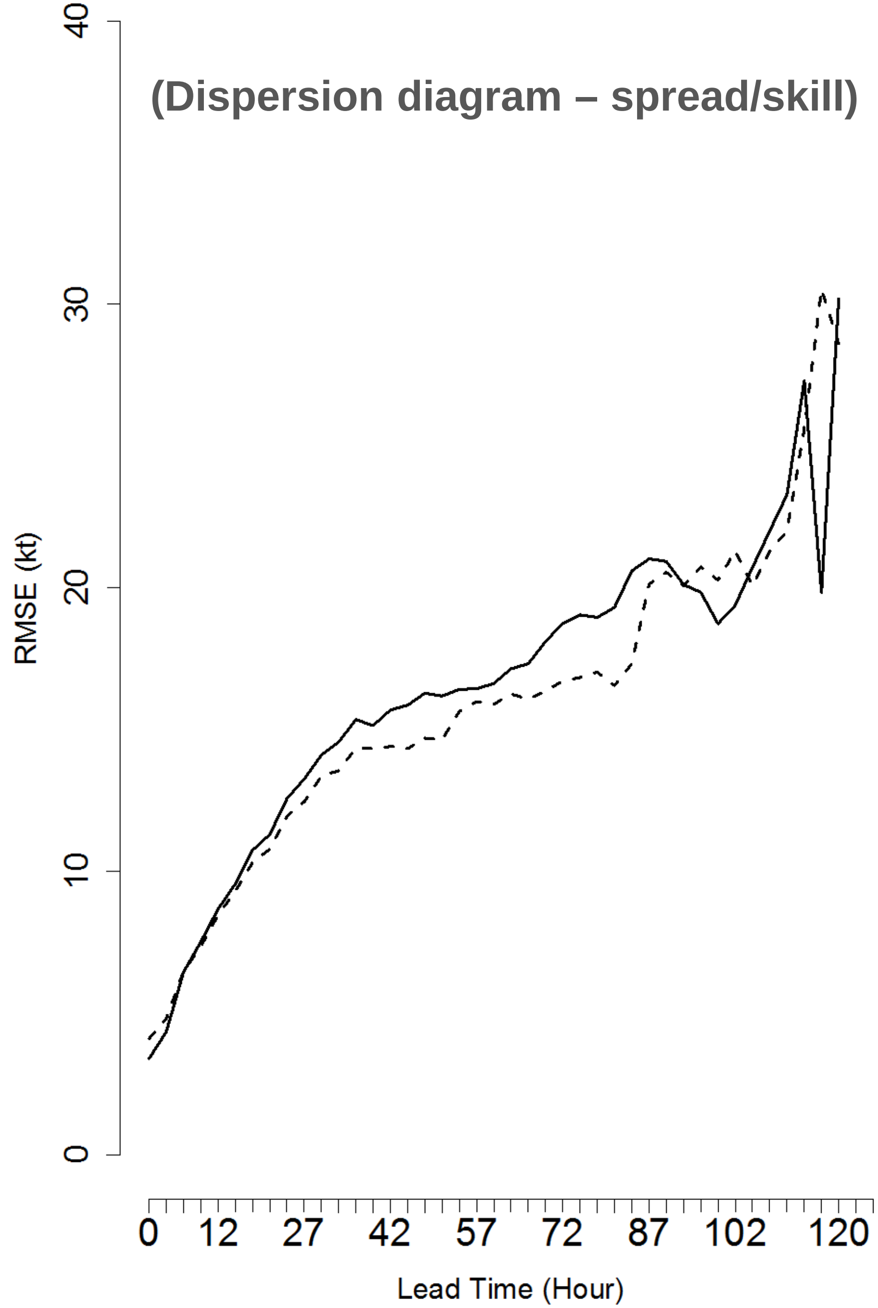
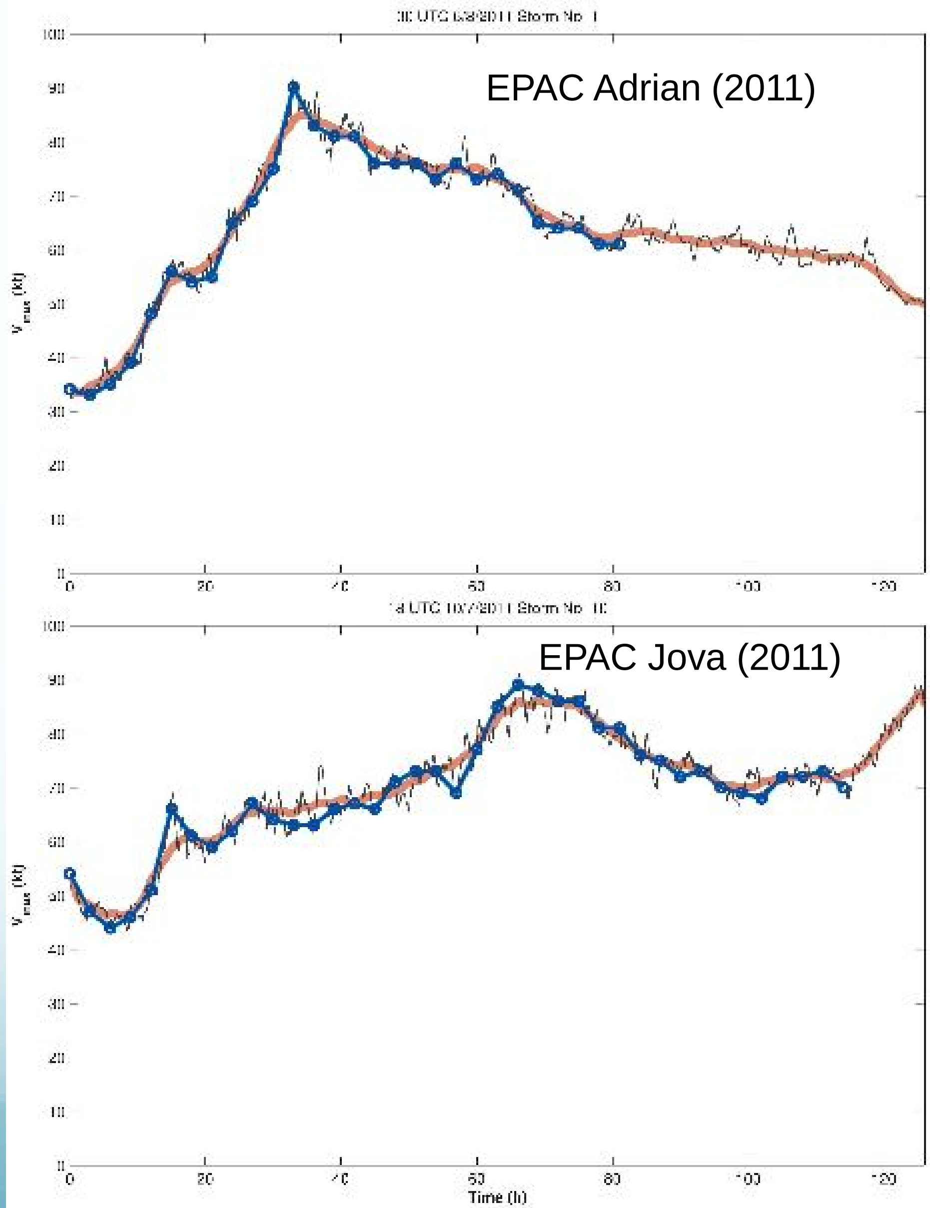
# Eastern Pacific results (2015 HWRF)

**(Dispersion diagram – spread/skill)**



# Ongoing Efforts

- We are now using high resolution HTCF ($\Delta$ *t* ~25.7 s). This can provide smoother VMAX.



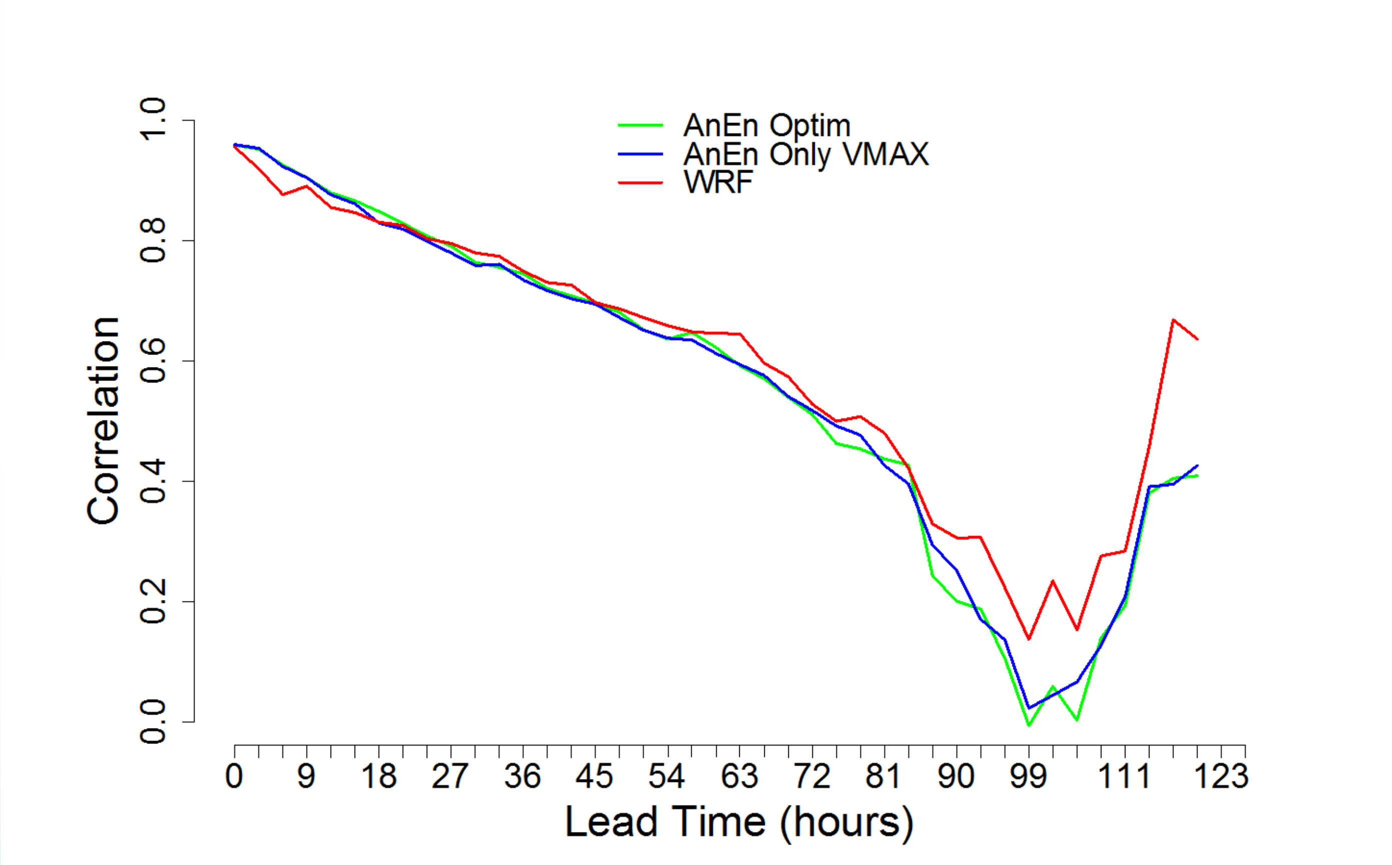

Black: Hi-res VMAX
Orange: Smoothed
Blue: 3-h HWRF GRIB2 derived data

# Next Steps

- Complete / Evaluate AnEn models for 2015 HWRF
- Real-time testing
  - Adapt 2015 version of algorithm for NCEP-ready operations
  - 2015 version test in real-time for 2016 season

# Extra Slides

# Correlation



# Centered Root Mean Square Error and Bias

$$\mathrm{CRMSE} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left[\left(A_t - \bar{A}\right) - \left(O_t - \bar{O}\right)\right]^2}$$

$$\mathrm{Bias} = \bar{A} - \bar{O}$$

where

$A_t = \frac{1}{K}\sum_{k=1}^{K} A_{tk}$ is the average of the K analog VMAX ensemble members for time *t*

$\bar{O} = \frac{1}{T}\sum_{k=1}^{T} O_t$ is the time average of VMAX observations

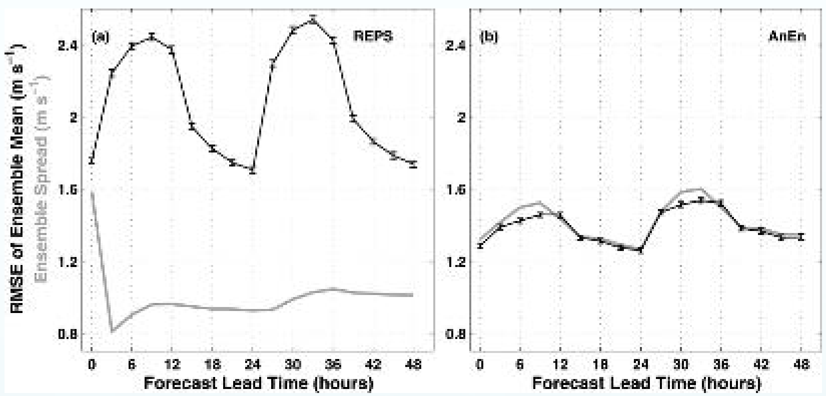
$\bar{A} = \frac{1}{T}\sum_{k=1}^{T} A_t$ is the time average of analog VMAX ensemble members

# Proof of Concept

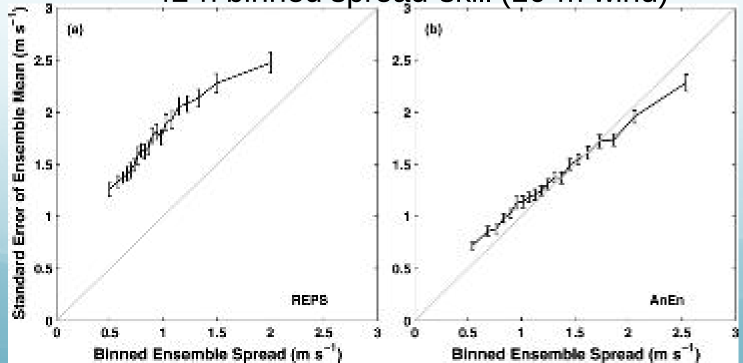
## Dispersion

- Delle Monache et al. (2013) tested the AnEn on 10-m AGL wind speeds and 2-m AGL temperatures at 550 aviation routine weather-reporting stations collected over a 457-day period (verification period was the final 100 days). Canadian GEM is basis. Compared against REPS.

Dispersion diagram for probabilistic prediction of 10-m wind speed




42-h binned spread-skill (10-m wind)




-> AnEn able to capture flow-dependent forecast uncertainty since the AnEn spread reflects forecast error variance

# Proof of Concept

## Reliability

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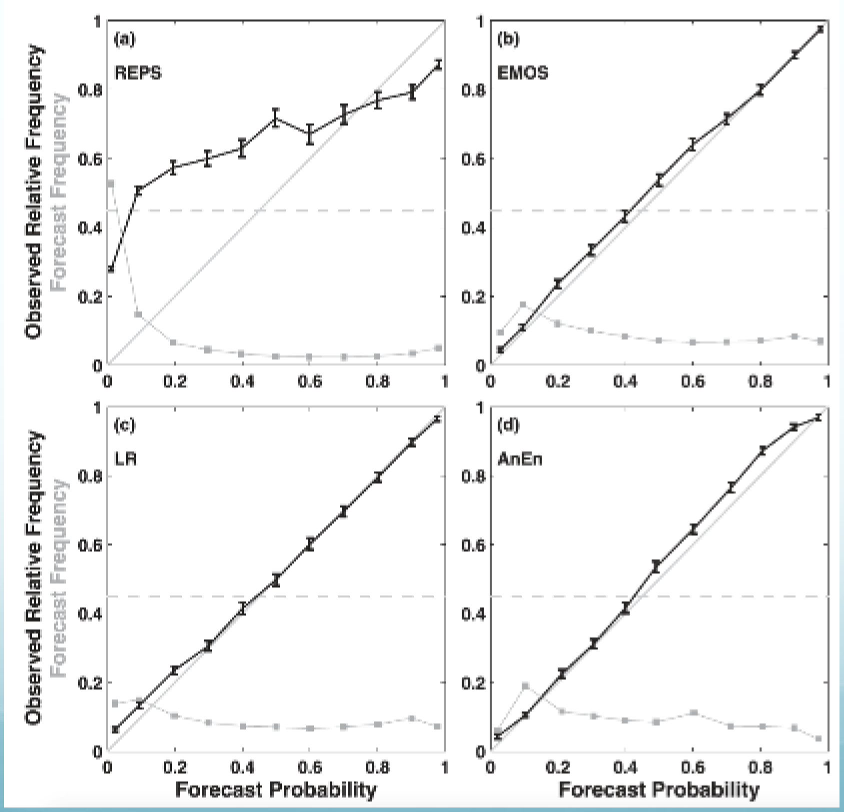
Reliability for probabilistic prediction of 10-m wind speed exceeding 5 m $s^{-1}$ at 9 h lead time



# Proof of Concept

## Discrimination

- Delle Monache et al. (2013) tested the AnEn on 10-m AGL wind speeds and 2-m AGL temperatures at 550 aviation routine weather-reporting stations collected over a 457-day period (verification period was the final 100 days). Canadian GEM is basis. Compared against REPS.

Relative operating characterstic skill score for probabilistic prediction of 10-m wind speed exceeding 5 and 10 m $s^{-1}$