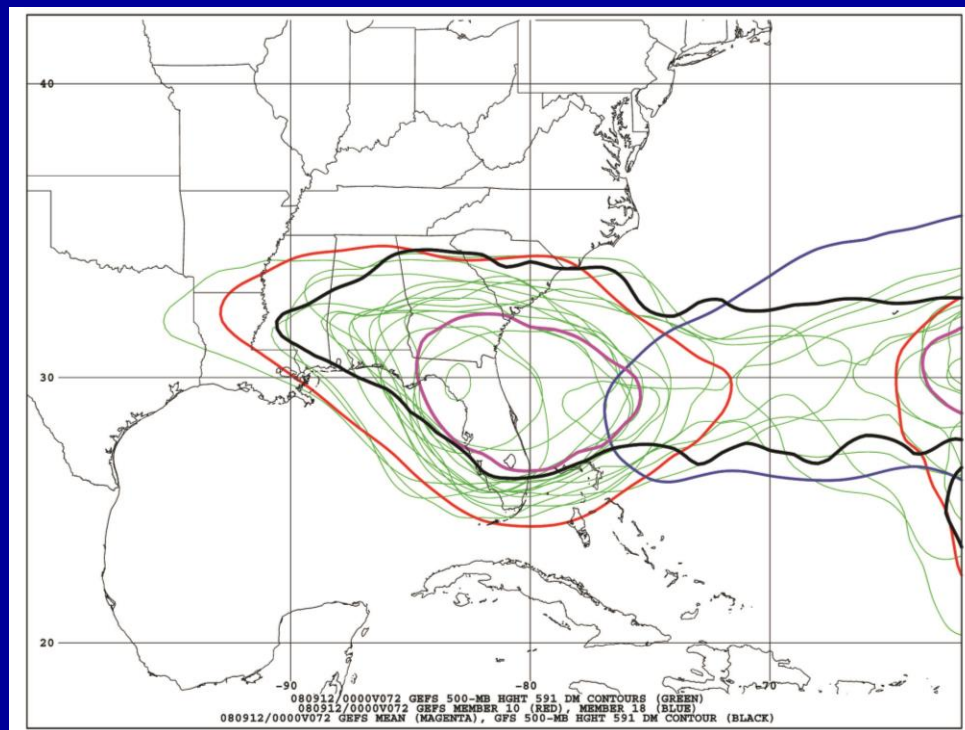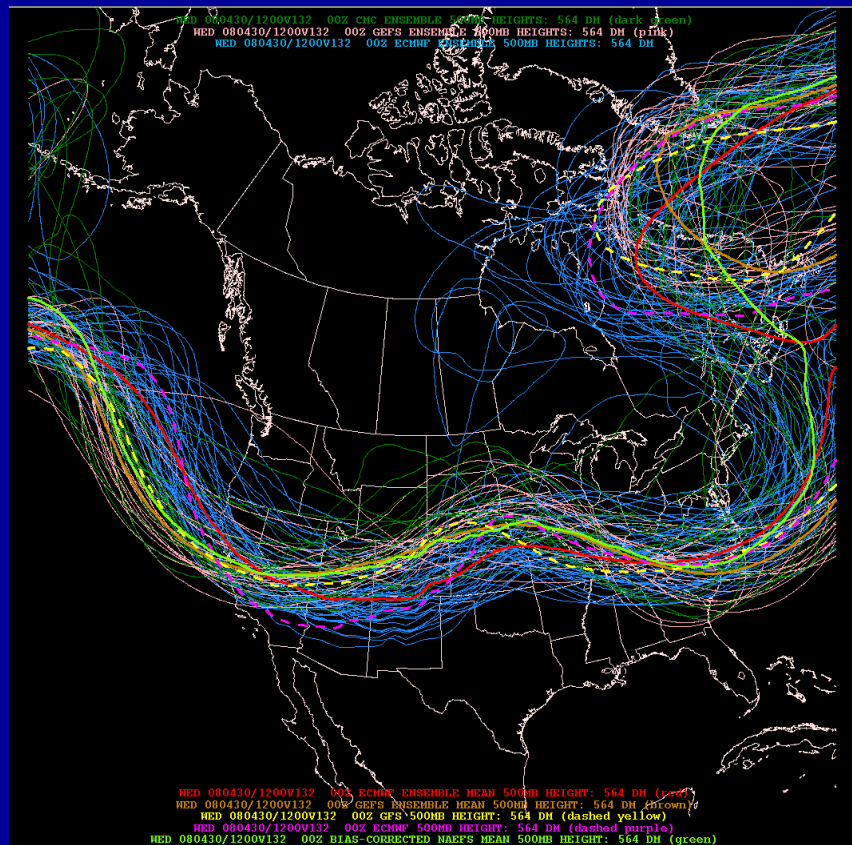# Ensemble Prediction Systems

Eric Blake

National Hurricane Center
7 March 2017

Acknowledgements to Michael Brennan

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Question 1

What are some current advantages of using single-model ensembles?

A. Estimates of uncertainty

B. TC intensity model spread

C. Alternative TC-track solutions

D. All of the above

E. A & C

Why Aren't Models Perfect?

- Atmospheric variables cannot be measured to an infinite degree of accuracy or precision (measurement error)

- Models' initial state never matches the real atmosphere (analysis error)

- Initial condition errors grow with model integration time, most rapidly at smaller scales (error growth)

- Model equations do not fully represent all of the processes in the atmosphere (model error)

- Model grid cannot explicitly resolve all features and processes in the atmosphere (model error)

Options?

- Increase our understanding of physical processes and how models represent them (research)

- More accurate and numerous observations with greater coverage (expensive)

- Improved data assimilation methods (4-D Variational Data Assimilation, Ensemble Kalman Filter)

- Faster computers and more complex models (many programs competing for resources)

- *Probabilistic forecasting with ensembles*

4

Definitions

- **Deterministic Model** - single forecast from one forecast model or method using a single set of initial conditions

  - Examples: GFS, ECMWF, UKMET, GFDL, HWRF, BAMS

- **Ensemble** - collection of "member" forecasts verifying at the same time created from:

  - Different but equally viable initial conditions

  - Different forecasting methods and/or models that (ideally) statistically represent nearly all forecast possibilities

Definitions

- **Dynamical Model Ensemble** –based on perturbation of initial conditions of a single model or different models to create "member" forecasts

  - Examples: NCEP Global Ensemble Forecast System (GEFS), ECMWF Ensemble Prediction System

- **Control Run** – for dynamical model ensembles, the member of the ensemble run with the "best" initial analysis

  - The analysis used by the control run is usually perturbed to produce initial conditions for the remaining ensemble members

- **Spread** – measure of the degree of disagreement (i.e., standard deviation) between ensemble members
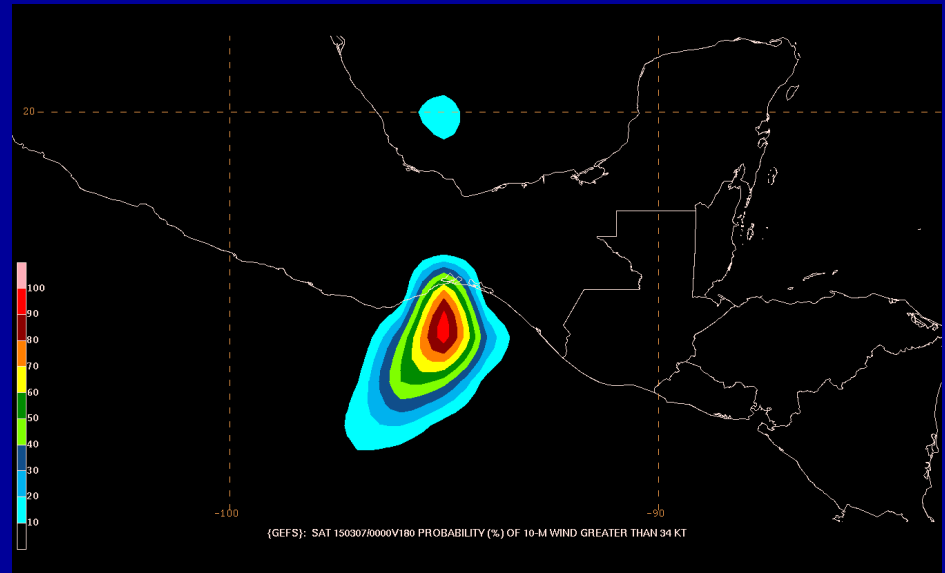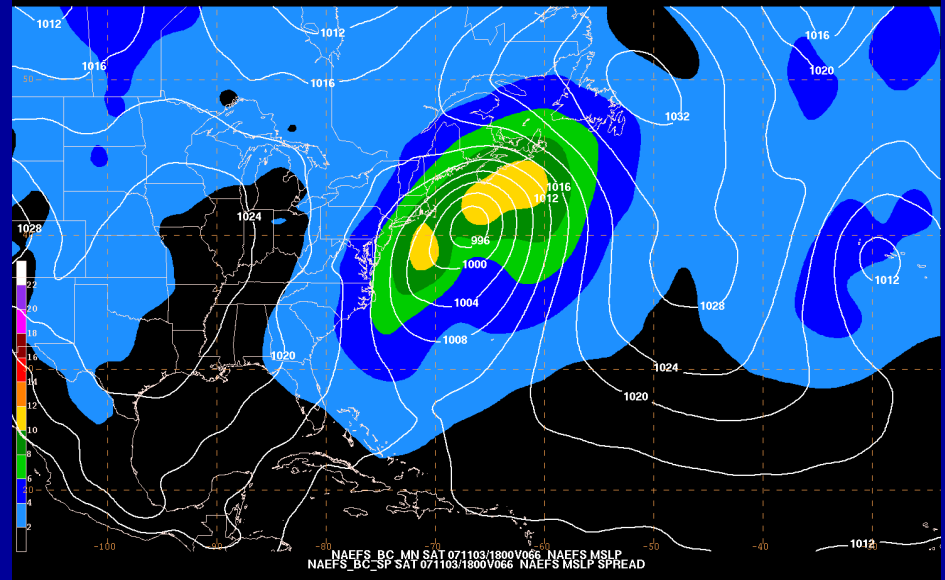
Ensemble Use

- Originally used for medium- to long-range forecasting of the large-scale pattern

- Uses have grown to encompass all temporal and spatial scales down to convective storm scale

- Address uncertainty, particularly those leading to rapidly diverging solutions

  – Initial conditions, model physics, resolution, model numerics
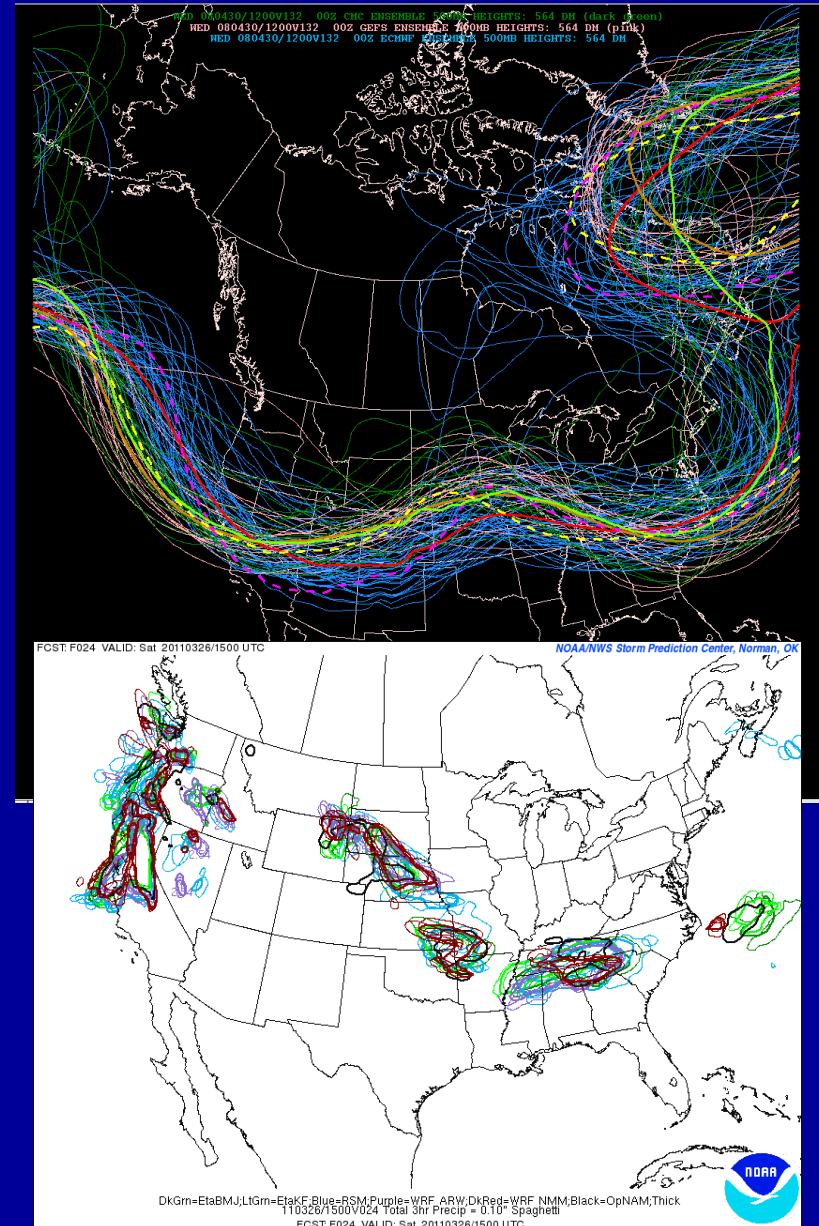
Ensemble Use

- Estimate rate of skill loss with time

  – Spread of solutions generally increases with time

- Compute probabilities of occurrence of a particular event or condition

  – 25 mm of precipitation, winds > 34 kt

- Identify regions where the analysis and forecast are sensitive to additional data in the analysis

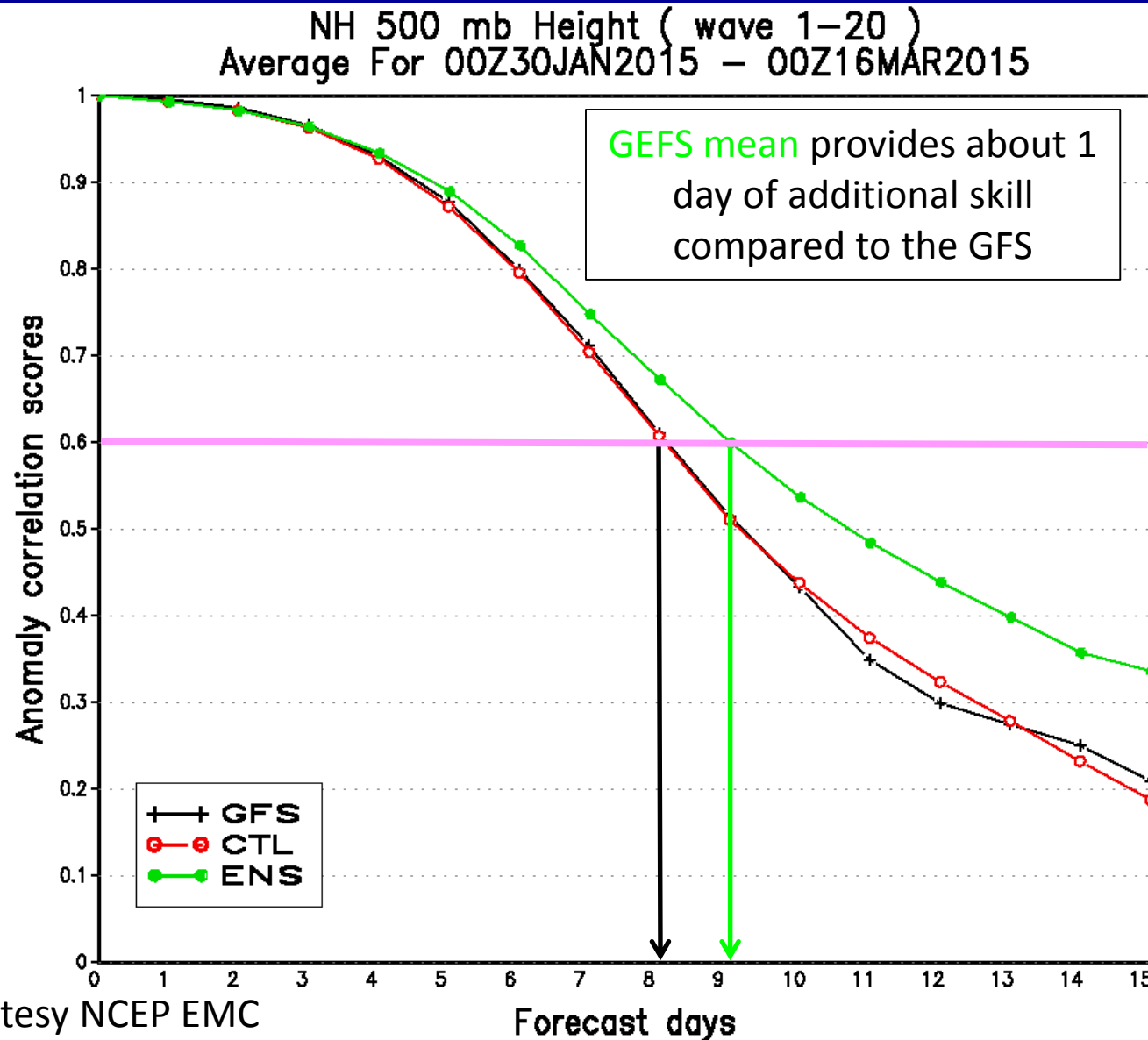 – Ensemble Kalman Filter, targeted observations

Ensemble Mean vs. Deterministic

- Deterministic runs (e.g., GFS) usually have more skill than any *individual ensemble member* due to superior resolution

- Ensemble mean usually has at least as much skill as an *equal-resolution control run*

- Ensemble mean can be more skillful than a *higher-resolution deterministic run*, especially beyond ~3 days
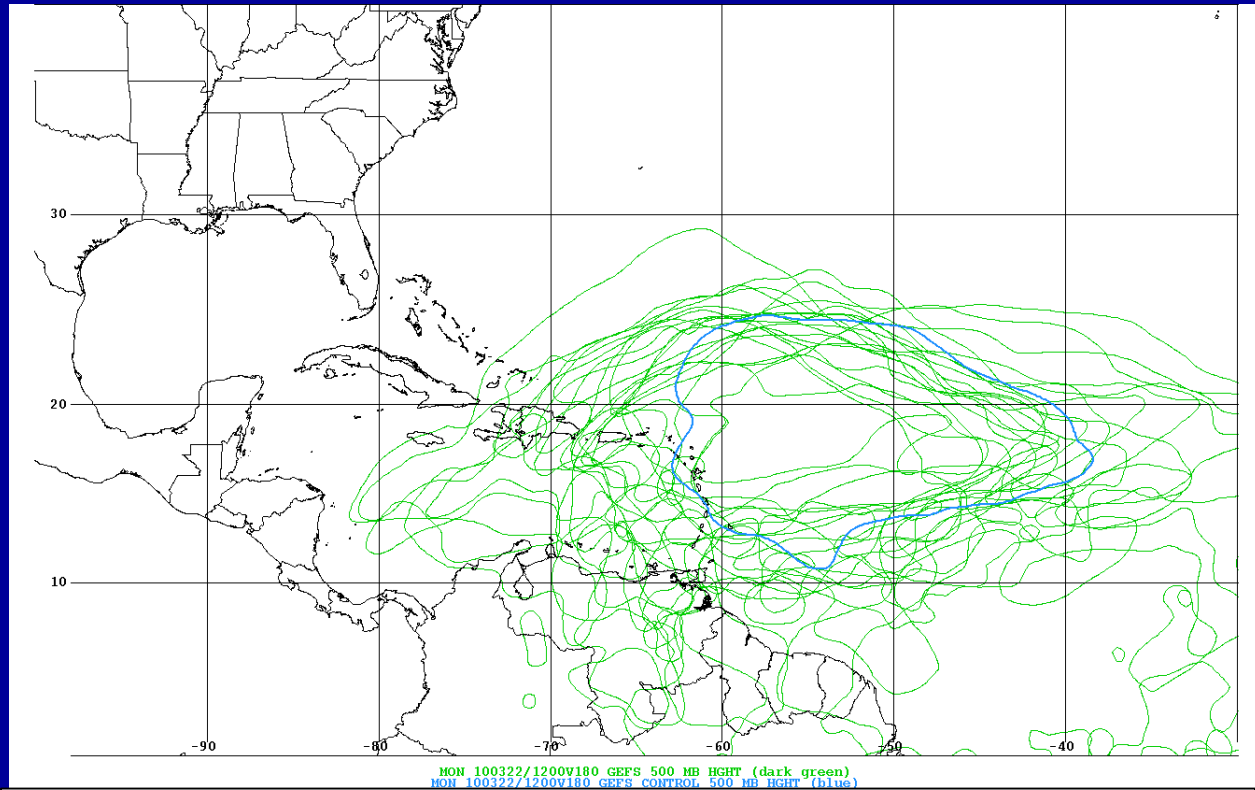
Ensemble Mean vs. Deterministic

500-mb height anomaly correlation die-off chart – 30 Jan-16 Mar 2015

NH 500 mb Height (wave 1-20)
Average For 00Z30JAN2015 – 00Z16MAR2015

GEFS mean provides about 1 day of additional skill compared to the GFS

Anomaly correlation scores

GFS
CTL
ENS

Forecast days

Courtesy NCEP EMC

Current Global Ensemble Systems that NHC uses most frequently

NCEP Global Ensemble Forecast System (GEFS)

- 4 cycles per day (00, 06, 12, 18 UTC)

- 21 members (1 control + 20 perturbed)

- Forecast extends out to 384 hours (16 days)

MON 100322/1200V180 GEFS 500 MB HGHT (dark green)
MON 100322/1200V180 GEFS CONTROL 500 MB HGHT (blue)

180-h forecast of 588 dm 500-mb height contour valid at 1200 UTC 22 March 2010

NCEP GEFS

- Current Configuration (last upgrade 2015)
  - T574 (~ 34 km) through 8 days, T328 (~ 52 km) days 8-16
  - 64 vertical levels

- Ensemble members
  - 20 members generated using Bred Vector and Ensemble Transform methods to address uncertainties in the initial conditions
  - Stochastic (statistical) perturbations try to address model uncertainty
  - Includes vortex relocation to NHC/CPHC/JTWC analyzed position for tropical cyclones in each ensemble member
  - Model physics consistent with GFS

- Deterministic GFS
  - T1534 (~ 13 km) through 10 days, T574 (~ 35 km) days 10-16
  - 64 vertical levels

Improvements to Global Ensemble TC Track with Increasing Horizontal Resolution
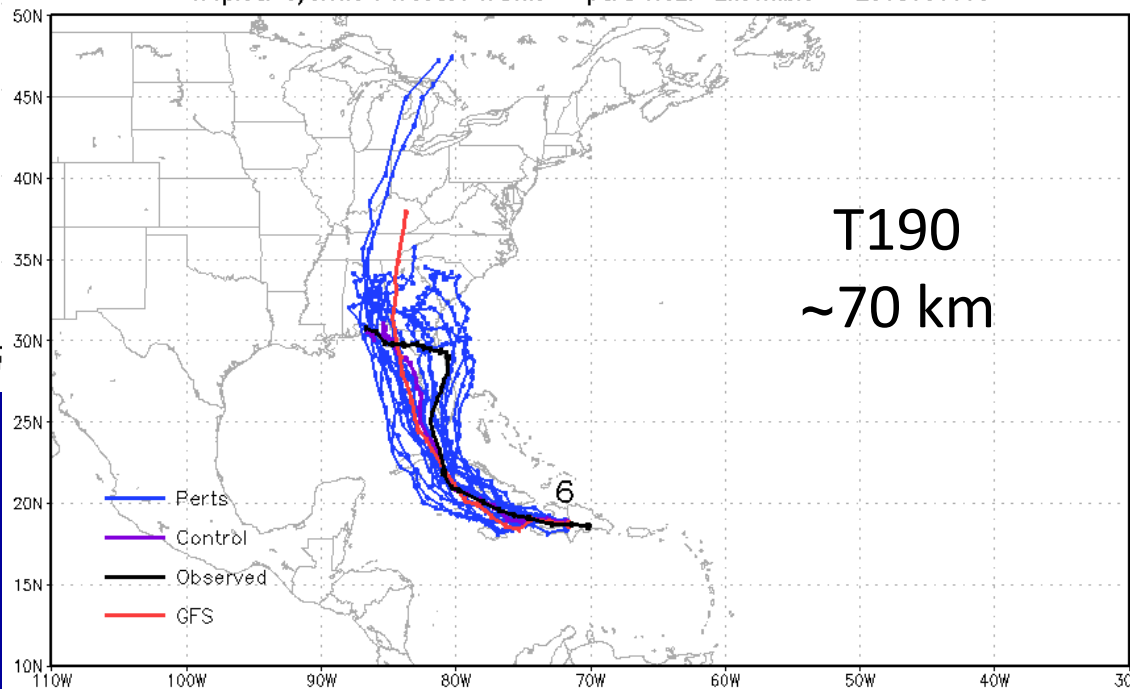
Tropical Storm Fay 00Z – 16 Aug 2008

Tropical Cyclone Forecast Tracks – prod NCEP Ensemble – 2008081600

T126
~100 km

Tropical Cyclone Forecast Tracks – para NCEP Ensemble – 2008081600
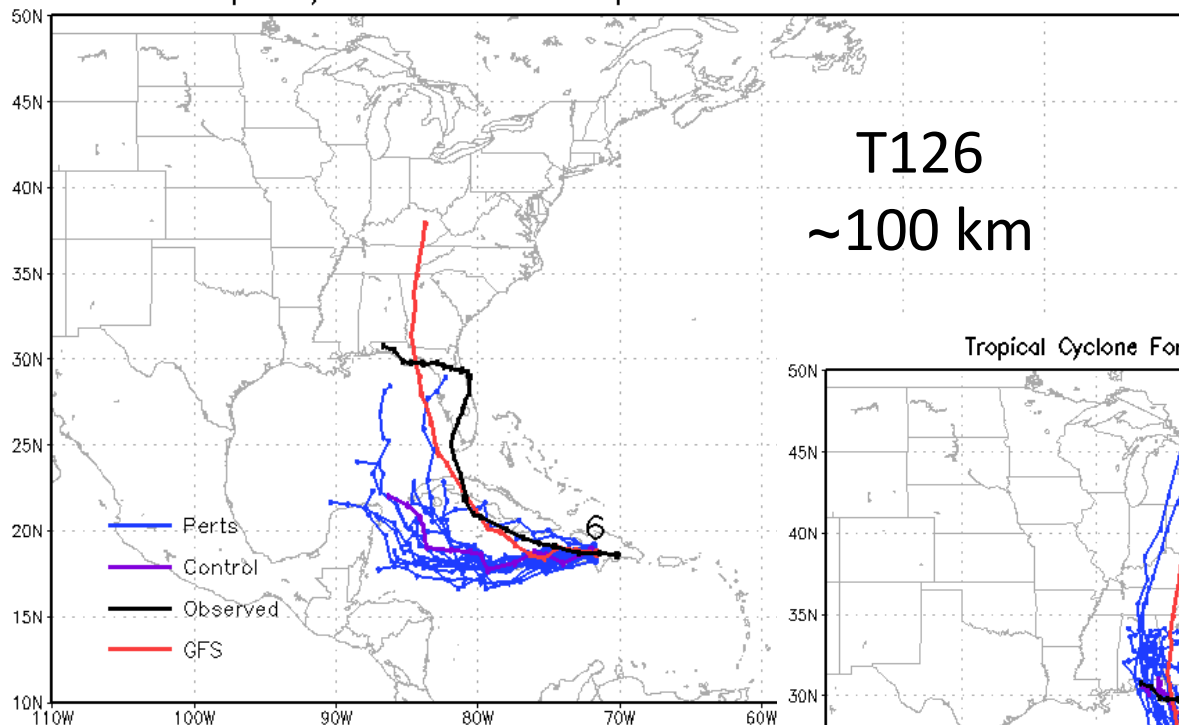
T190
~70 km

More members retain the TC and track forecasts are much improved

ECMWF Ensemble Prediction System

- 51 members (1 control+50 perturbed members)

- Run twice daily (00 and 12 UTC) out to 15 days

  – T639 (~ 18 km) to 15 days

  – 91 vertical levels

  – Perturbations:

  – Initial condition: generated using singular vectors and perturbations from an ensemble of data assimilations

  – Physics: generated by two stochastic parameterization schemes

- Deterministic ECMWF

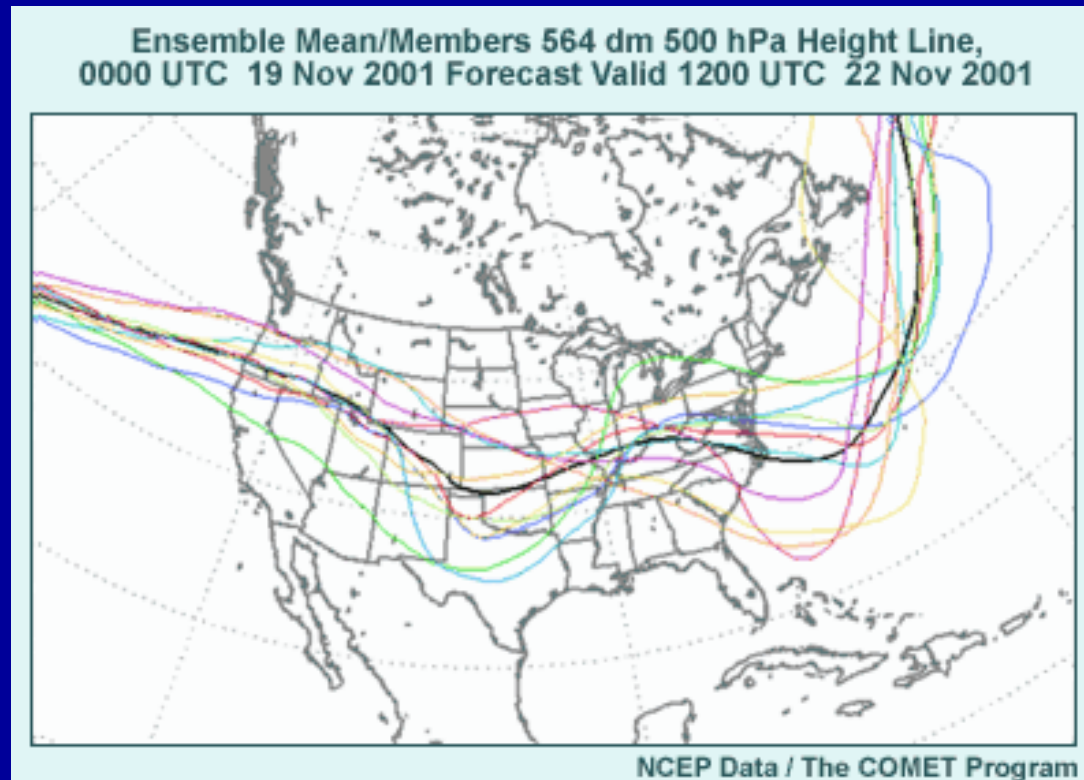 – Horizontal grid resolution T1279 (~9 km) out to 10 days with 137 vertical levels

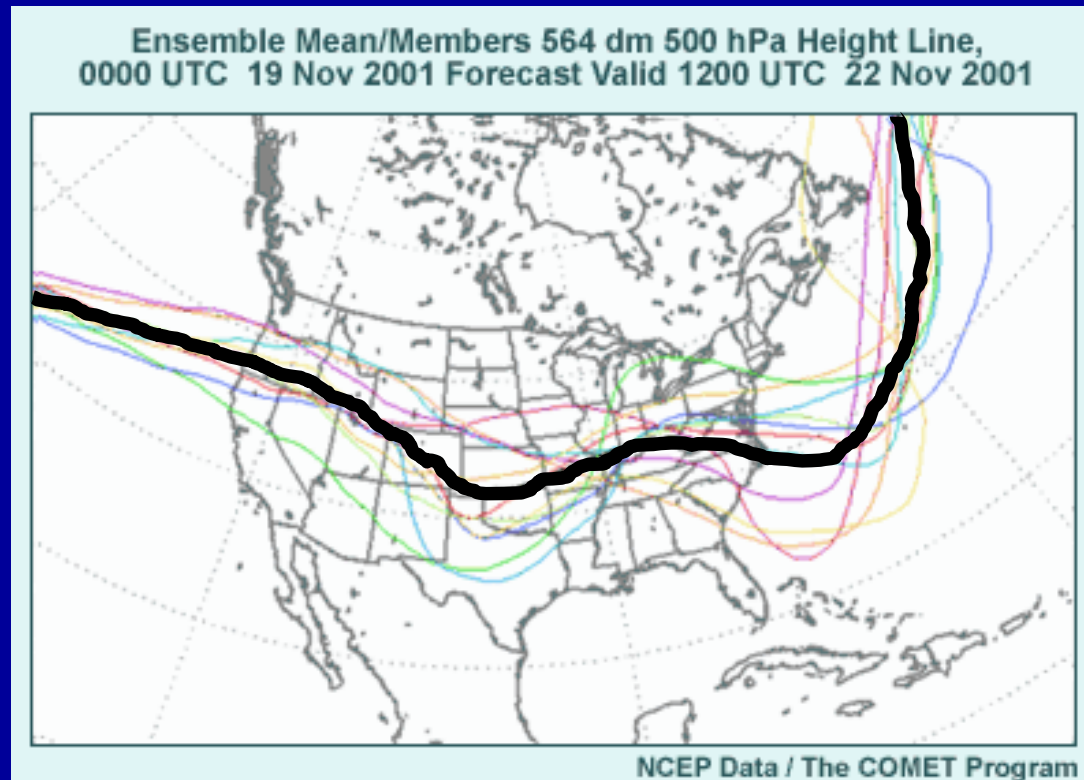# Ensemble Display and Interpretation

Displaying Ensembles

500 hPa Heights, valid 1200 UTC 22 Nov 2001

NCEP Data / The COMET Program
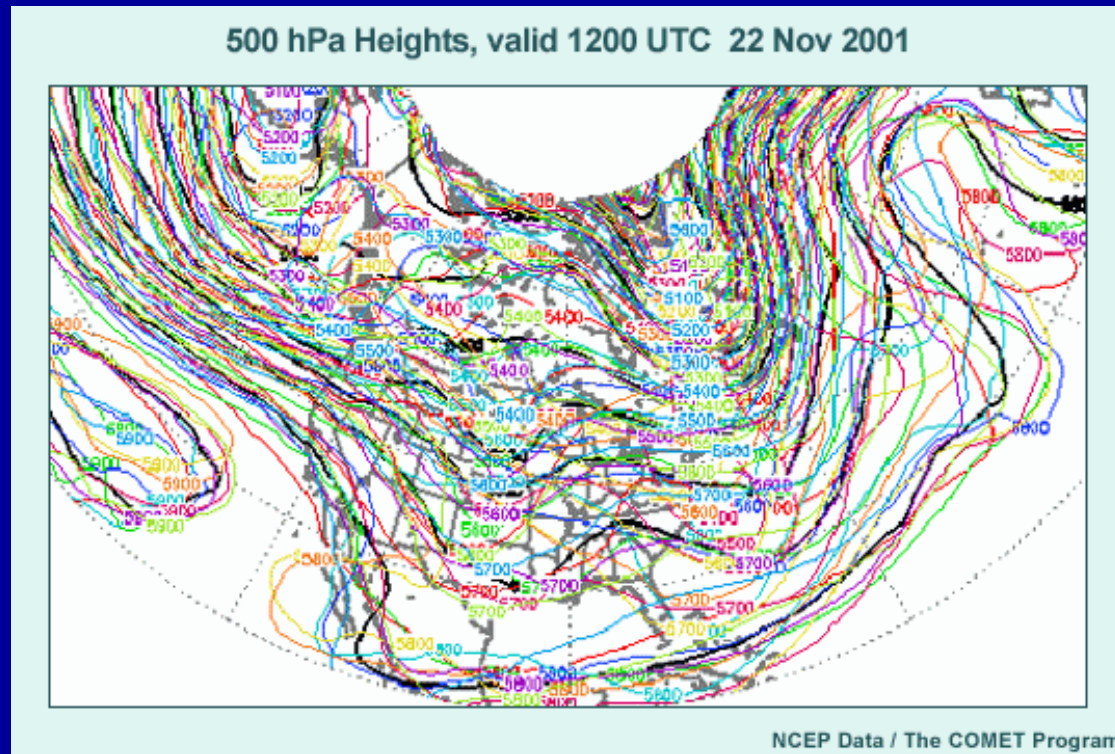
If we try to look at every ensemble member at once, it is messy and difficult to interpret

Credit: COMET

Displaying Ensembles

Ensemble Mean/Members 564 dm 500 hPa Height Line,
0000 UTC 19 Nov 2001 Forecast Valid 1200 UTC 22 Nov 2001

NCEP Data / The COMET Program

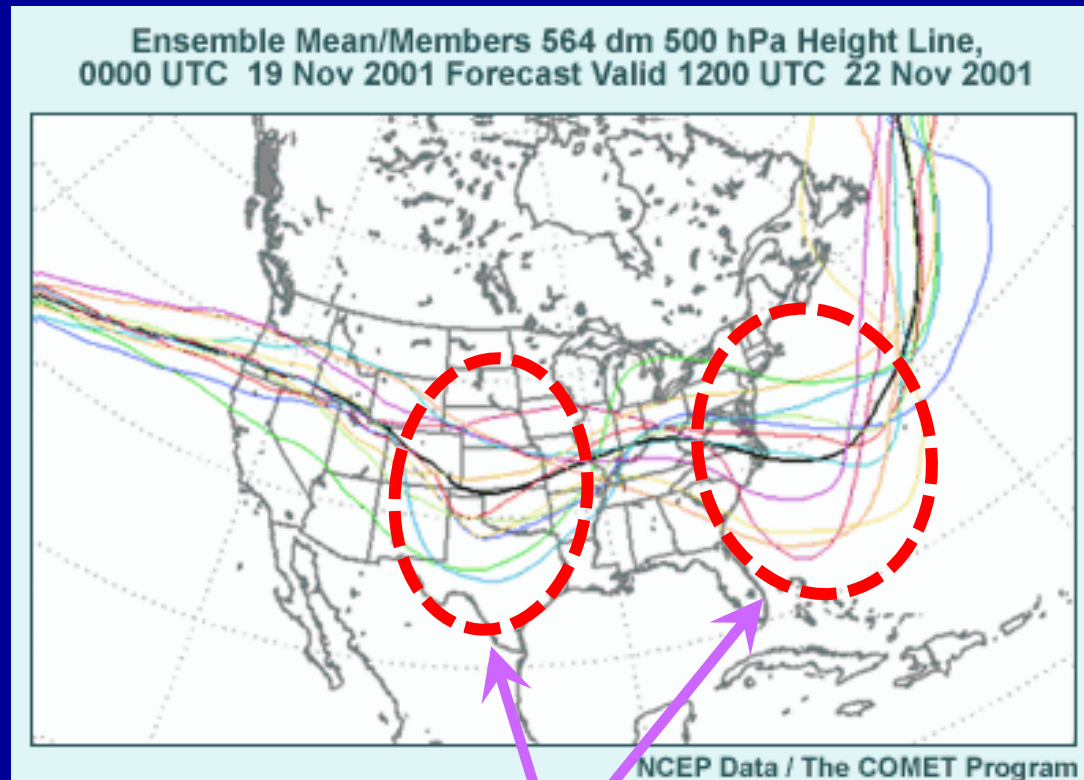**Spaghetti Diagram** – displays one isopleth at a time from each ensemble member

Displaying Ensembles

Ensemble Mean/Members 564 dm 500 hPa Height Line,
0000 UTC 19 Nov 2001 Forecast Valid 1200 UTC 22 Nov 2001

NCEP Data / The COMET Program

Ensemble Mean - average of multiple forecast members verifying at same time

Displaying Ensembles

Ensemble Mean/Members 564 dm 500 hPa Height Line,
0000 UTC 19 Nov 2001 Forecast Valid 1200 UTC 22 Nov 2001

NCEP Data / The COMET Program

Disagreement, or **spread**, between ensemble members

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Displaying Ensembles

500 hPa Ensemble Mean Heights, Ensemble Std. Dev.
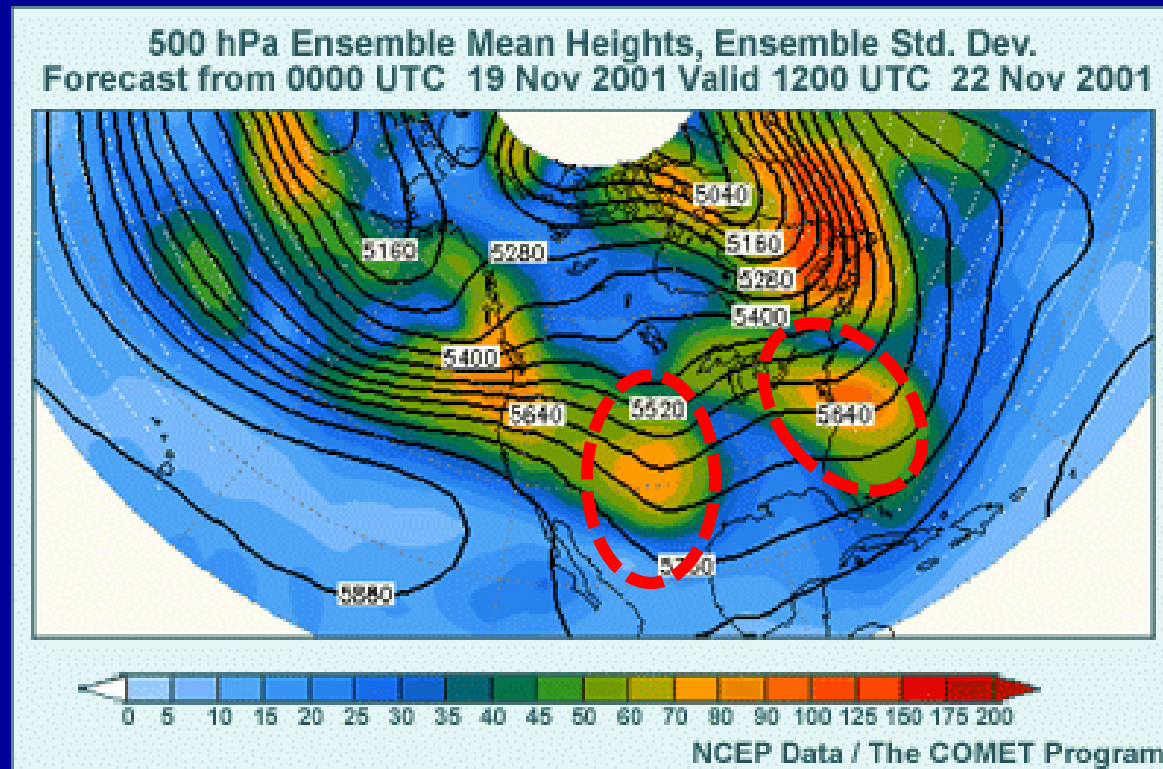Forecast from 0000 UTC 19 Nov 2001 Valid 1200 UTC 22 Nov 2001

NCEP Data / The COMET Program

- Black lines = ensemble mean 500-mb height forecast

- Spread indicated by shading (meters)
  - Orange/Red – little agreement between members
  - Blue – good agreement between members

Displaying Ensembles
Ensemble Mean and Spread

500 hPa Ensemble Mean Heights, Ensemble Std. Dev.
Forecast from 0000 UTC 19 Nov 2001 Valid 1200 UTC 22 Nov 2001

NCEP Data / The COMET Program

- Black lines = ensemble mean 500-mb height forecast
- Spread indicated by shading (meters)
  - Orange/Red – little agreement between members
  - Blue – good agreement between members

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Displaying Ensembles
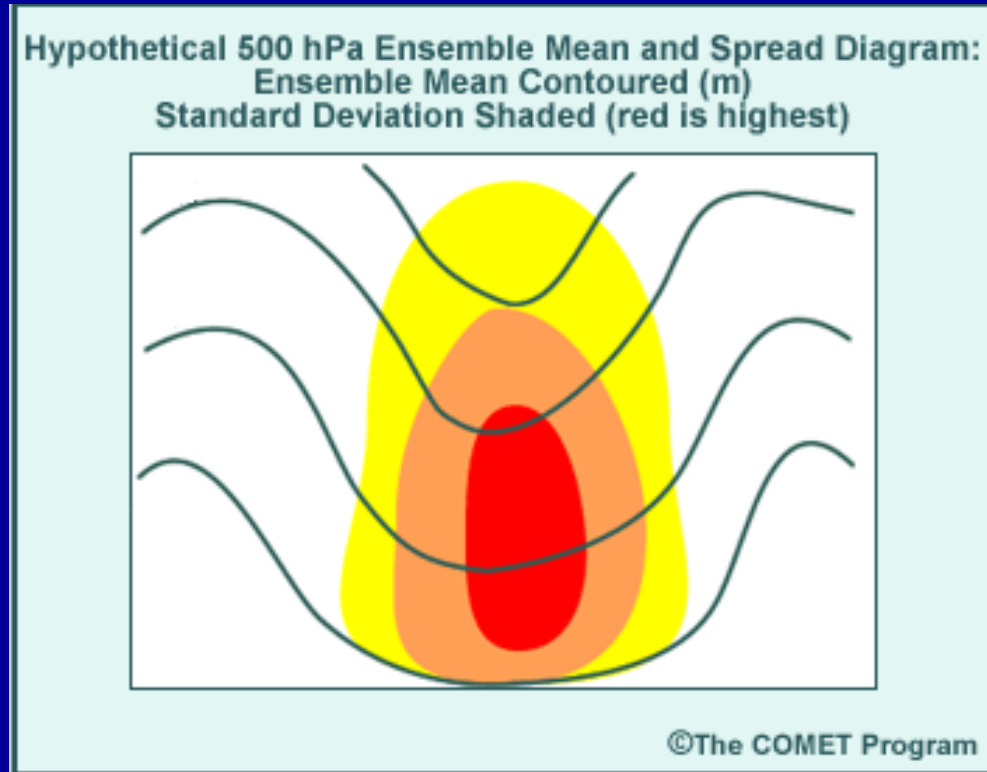## Ensemble Mean and Spread

- Advantages

  - Summarizes data in easy to interpret form

  - Information provided for the entire domain

  - Low predictability features smoothed out by the ensemble mean and easily identifiable using spread

- Disadvantages

  - Ensemble mean can be misleading (and may not be the best forecast) if multiple clusters of nearly equal probability forecast outcomes exist (i.e., bi-modal distribution)

  - May not reveal extreme outlier solutions

Interpreting Mean and Spread

Large spread within the ensemble mean feature → Uncertainty in amplitude of the feature

• In this case, there is uncertainty in the **depth** (not the location) of this 500-mb trough

• If there were a tropical cyclone located southeast of this trough, would the trough be deep enough to recurve the tropical cyclone?
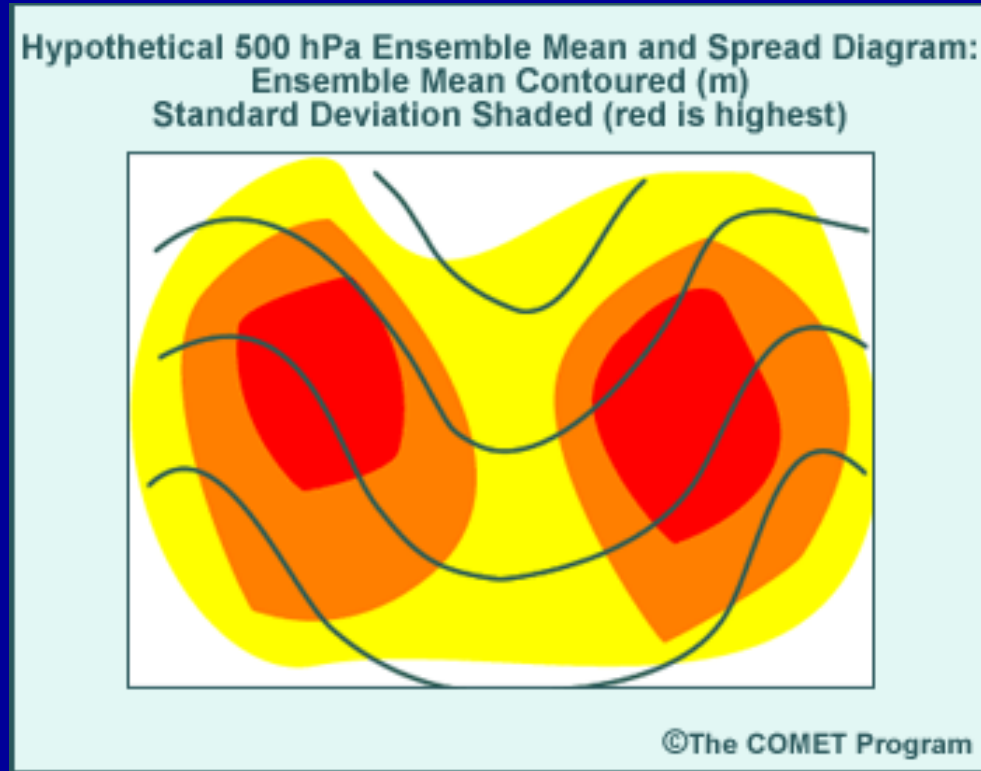

Hypothetical 500 hPa Ensemble Mean and Spread Diagram:
Ensemble Mean Contoured (m)
Standard Deviation Shaded (red is highest)

©The COMET Program

Interpreting Mean and Spread

Large spread upstream or downstream of an ensemble mean feature → Uncertainty in the location of the feature

•In this case, there are nearly equal chances that the 500-mb trough will be east or west of the position shown by the ensemble mean trough

•If a tropical cyclone was located southeast of this trough, at what time will the tropical cyclone begin to be influenced by this trough?
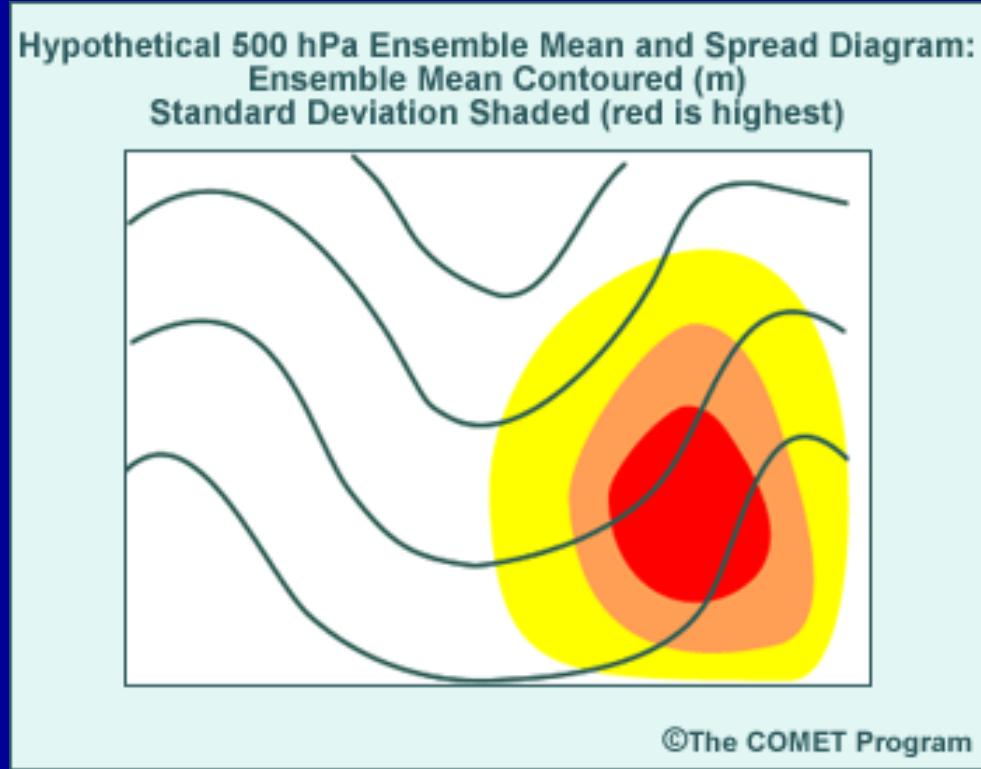

Hypothetical 500 hPa Ensemble Mean and Spread Diagram: Ensemble Mean Contoured (m) Standard Deviation Shaded (red is highest)
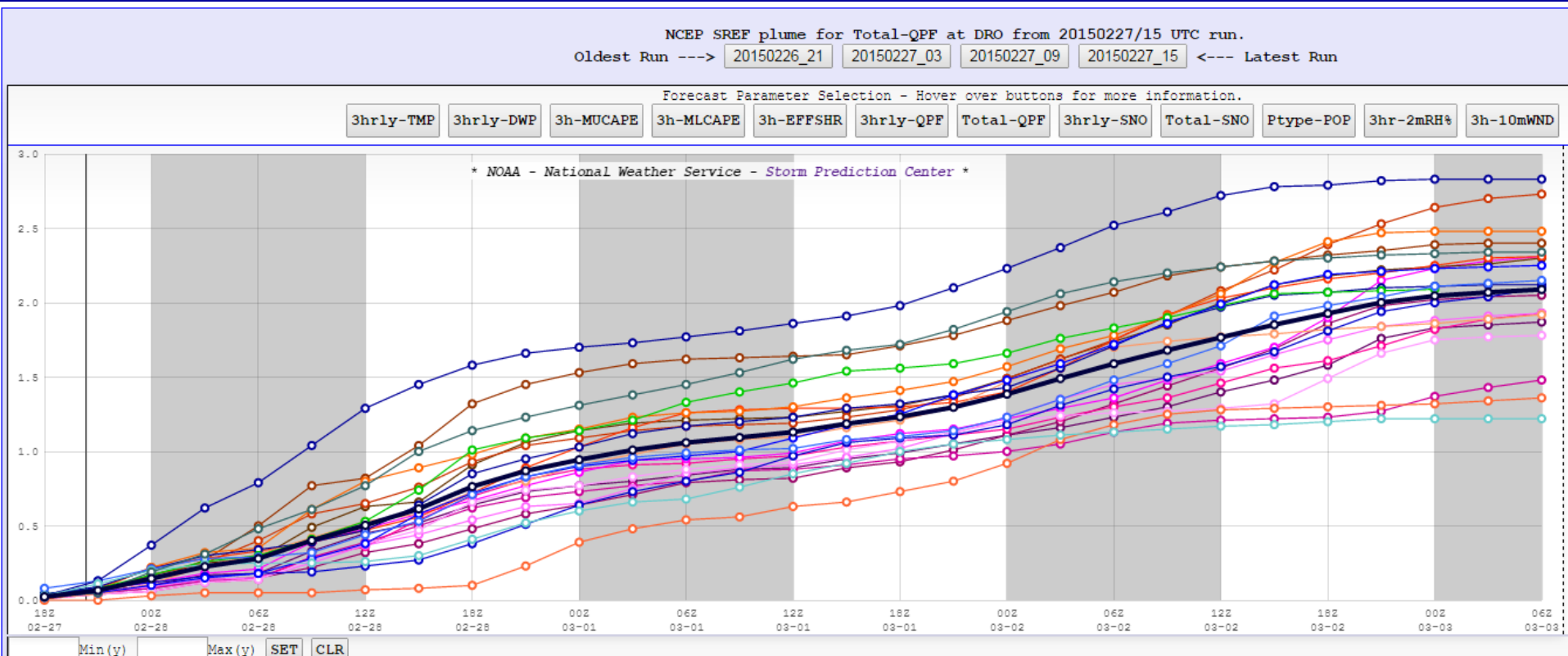
©The COMET Program

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Interpreting Mean and Spread

Large spread on one side of an ensemble mean feature → A cluster of ensemble members different from the ensemble mean

• In this case, the spread indicates greater potential for the trough axis to be east of the ensemble mean trough than to the west

• If there was a tropical cyclone located southeast of this trough, at what time will the tropical cyclone begin to be influenced by this trough?

Hypothetical 500 hPa Ensemble Mean and Spread Diagram:
Ensemble Mean Contoured (m)
Standard Deviation Shaded (red is highest)

©The COMET Program

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Plume Diagrams

NCEP Short Range Ensemble Forecast System (SREF) plume diagram for total precipitation at Durango, Colorado, starting at 15Z 27 Feb 2015 (courtesy NWS SPC)

Genesis Guidance

Little objective guidance is seen with ensembles now, though they help subjectively.

In-house product→

shading: combined probability of 70 ensemble members (GEFS + ECENS):
- 850 – 700 hPa RH > 70%
- 200 – 850 hPa vertical wind shear < 20 kt

contours: 850 hPa relative vorticity (8×10^{-5} s^{-1} intervals)

thin green: ECENS members
thick green: **ECMWF deterministic**
thin yellow: GEFS members
thick yellow: **GFS deterministic**

Invest AL93

0000 UTC November 6, 2015 **+ 66 h**
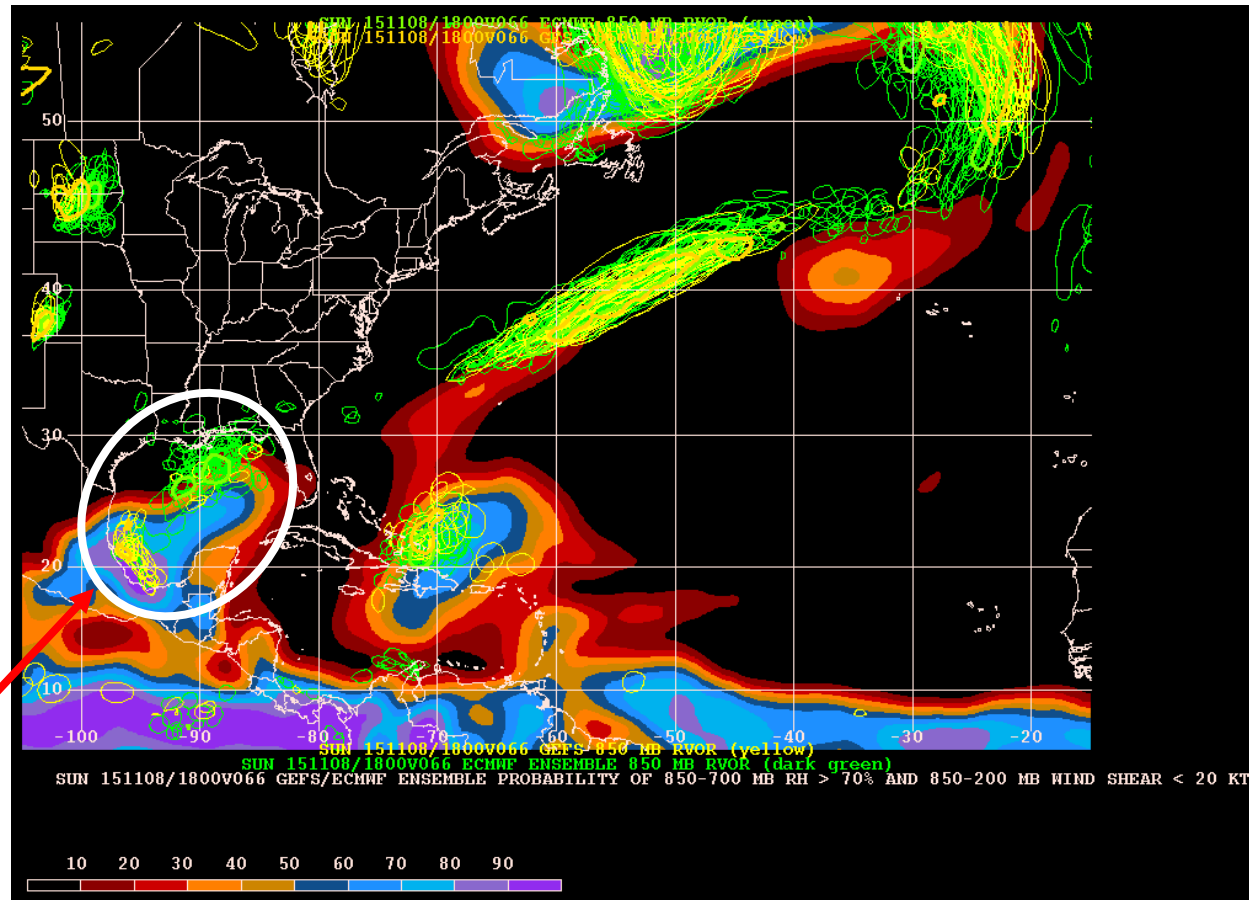
Ensemble Problems

- Need a properly calibrated system

  - GEFS is currently underdispersive

  - This problem results in an overconfident forecast

  - Lower resolution can also hinder a more accurate track forecast (i.e. when track especially dependent on intensity)

- Other issues

  - Ensemble mean can be misleading (and may not be the best forecast) if multiple clusters of nearly equal probability forecast outcomes exist (i.e., bi-modal distribution)
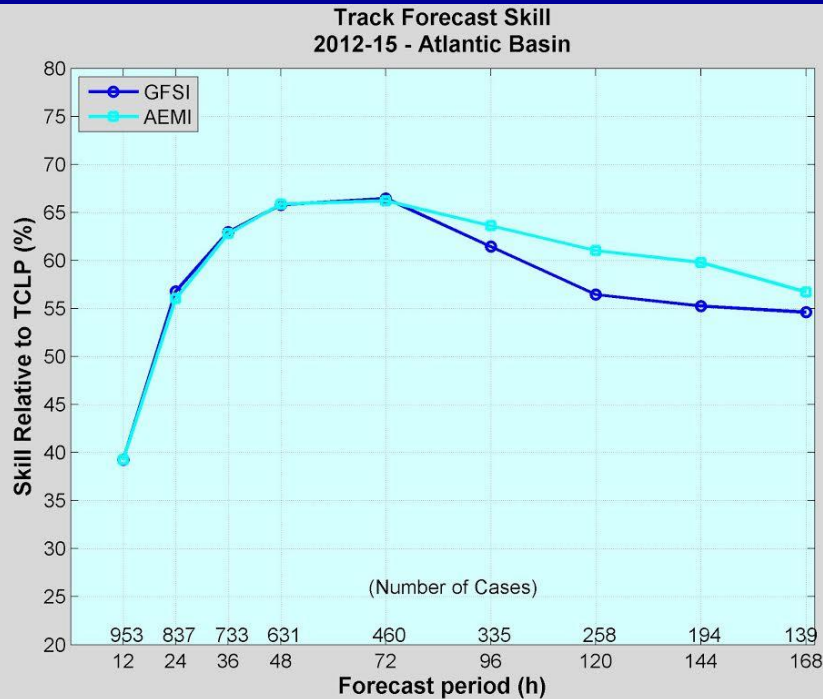
  - May not reveal extreme outlier solutions

Single-Model Ensembles for TC Track Forecasting

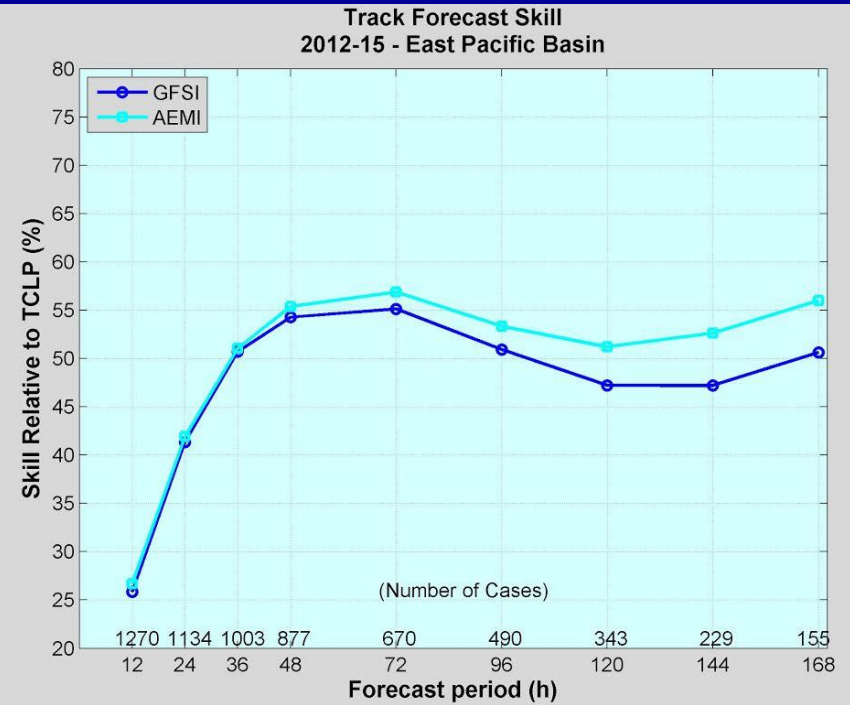# NCEP Global Ensemble Forecast System
Tropical Cyclone Track Forecast Guidance

GEFS Mean vs. GFS (2012-2015)

Track Forecast Skill
2012-15 - Atlantic Basin

Track Forecast Skill
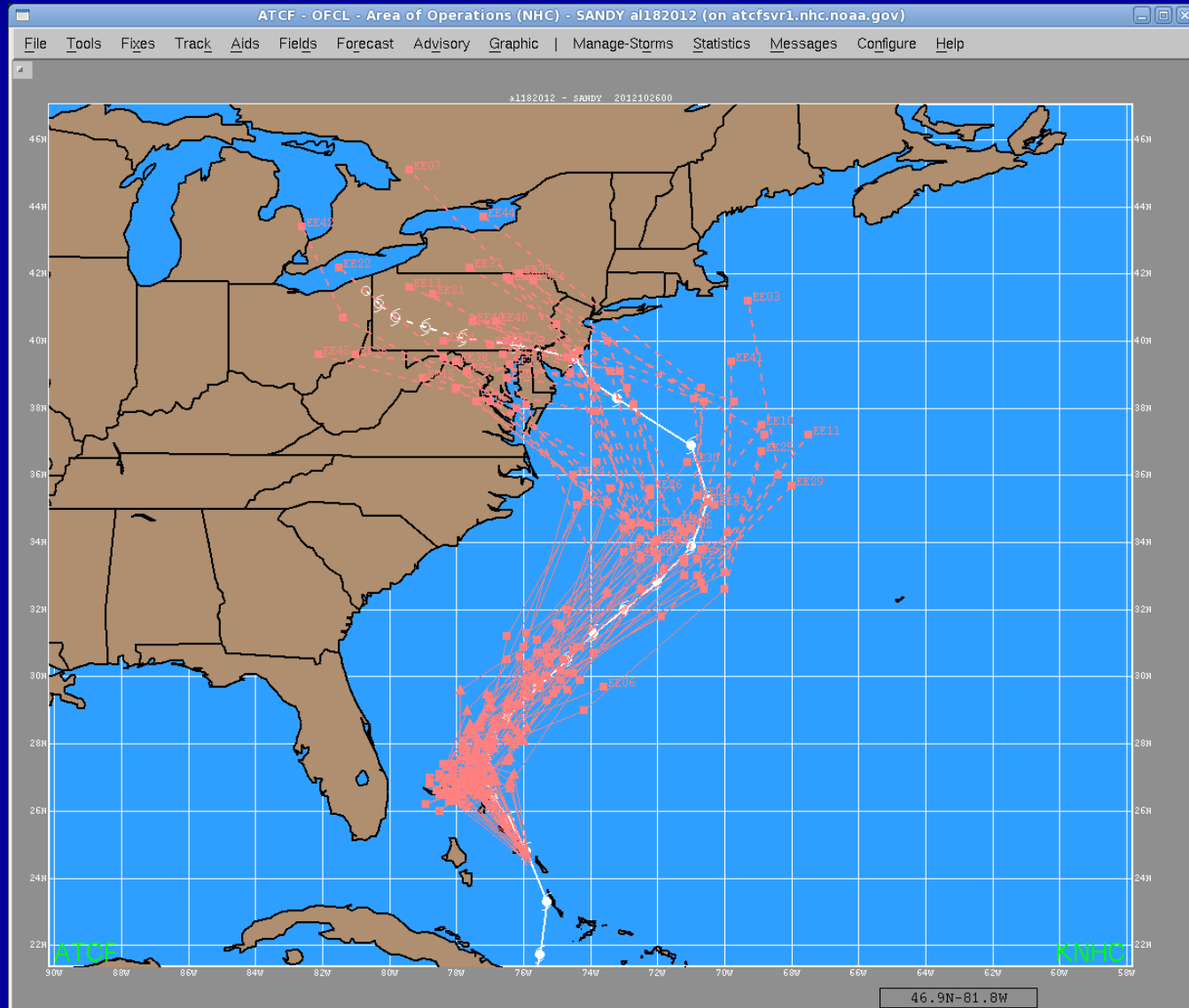2012-15 - East Pacific Basin

In the Atlantic, the GEFS ensemble mean track forecast (AEMI) is competitive with the deterministic GFS (GFSI) through day 3 and better afterward
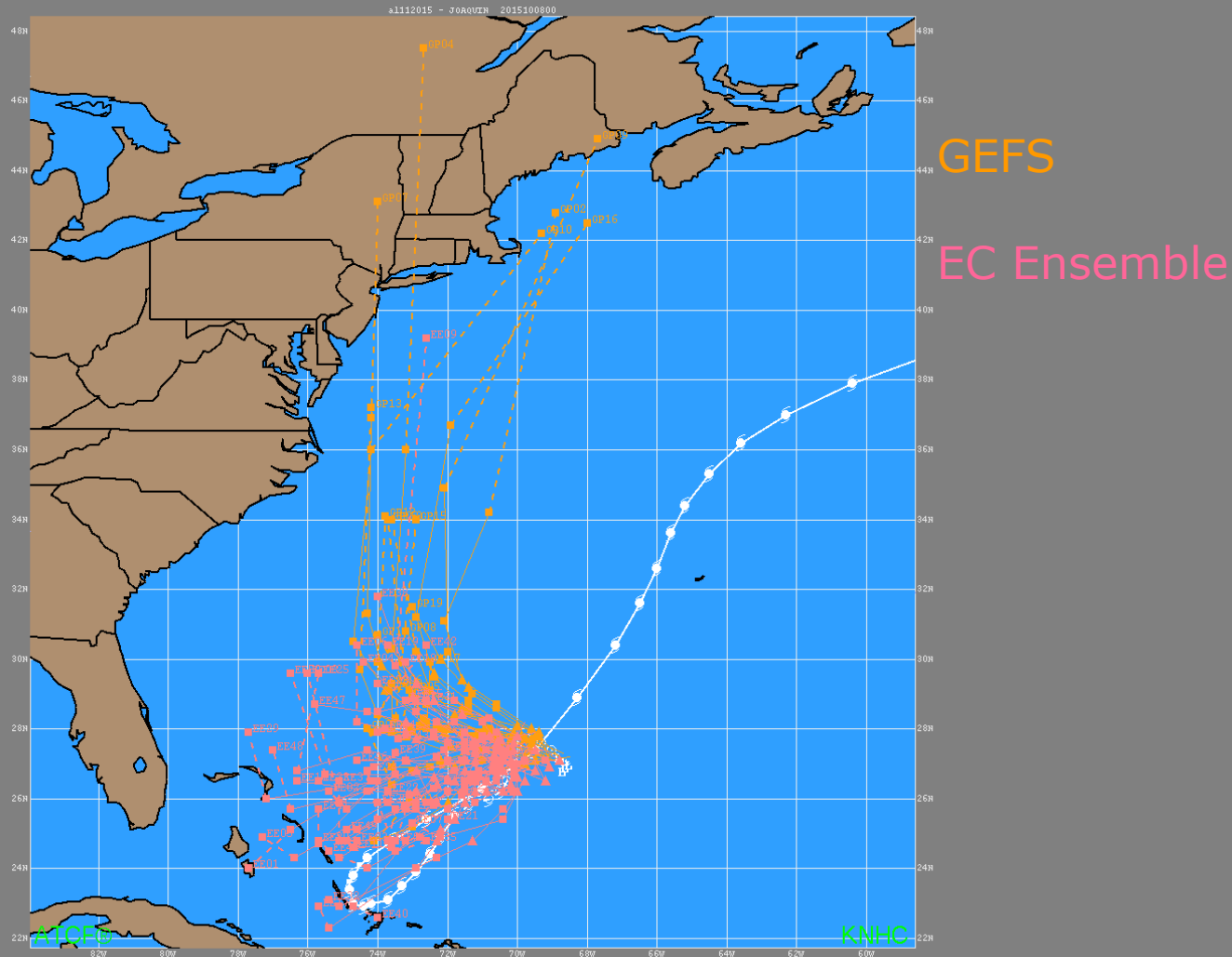
In the east Pacific, AEMI beats GFSI at 48 h and beyond
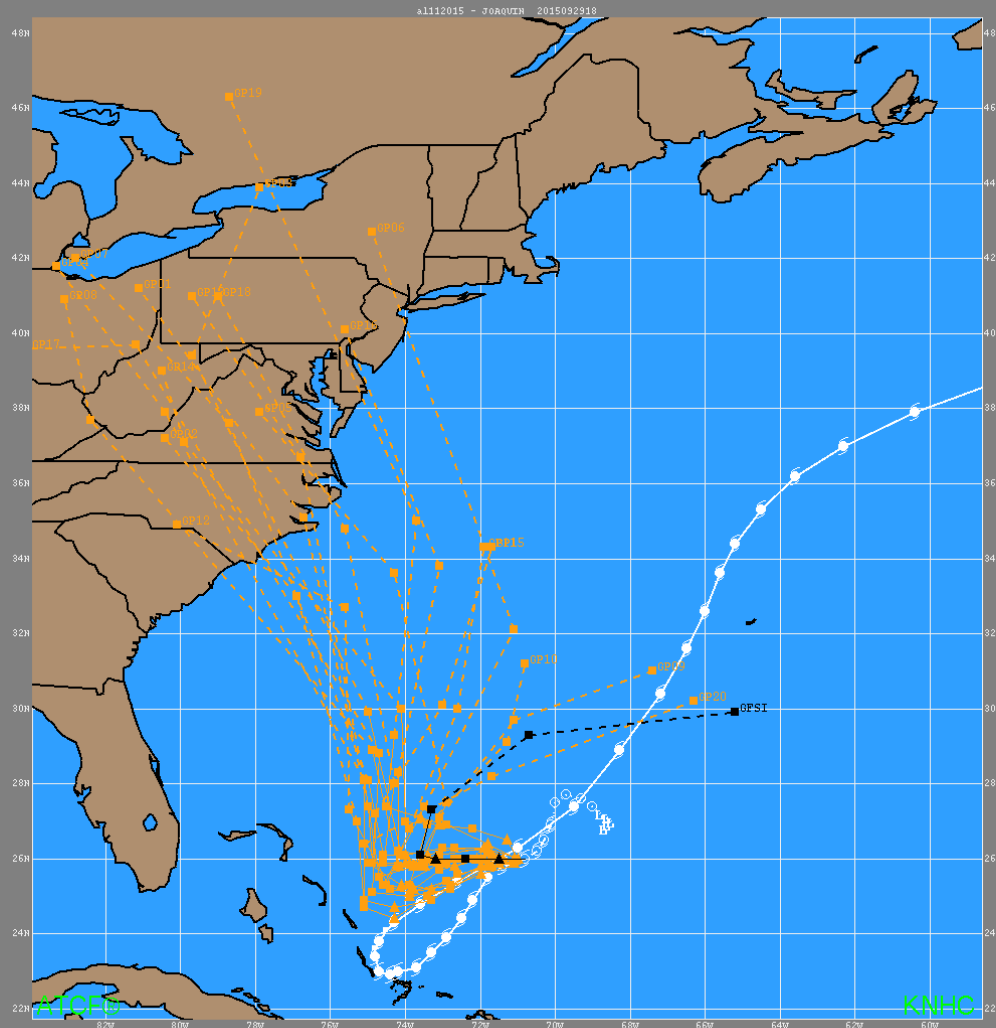
ECMWF Ensemble
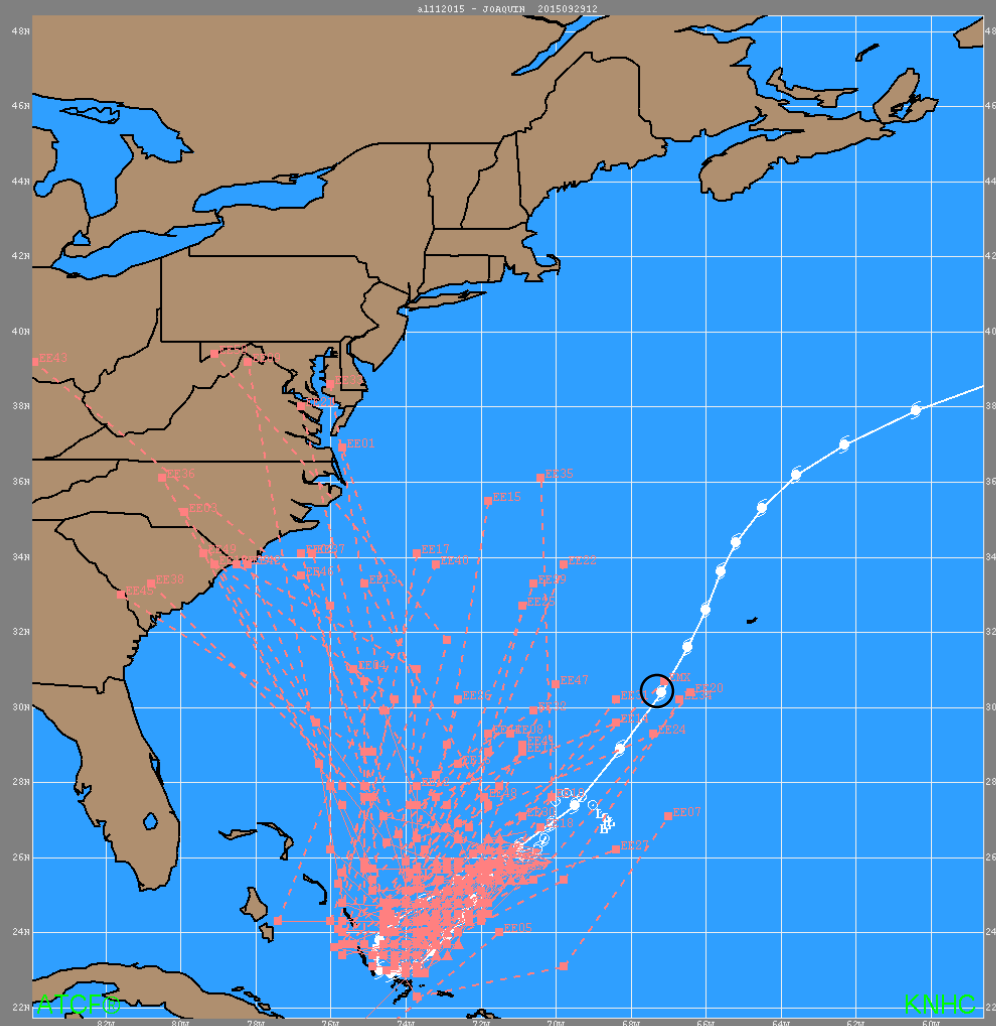## Sandy example of desirable spread/verification

Joaquin ensemble guidance
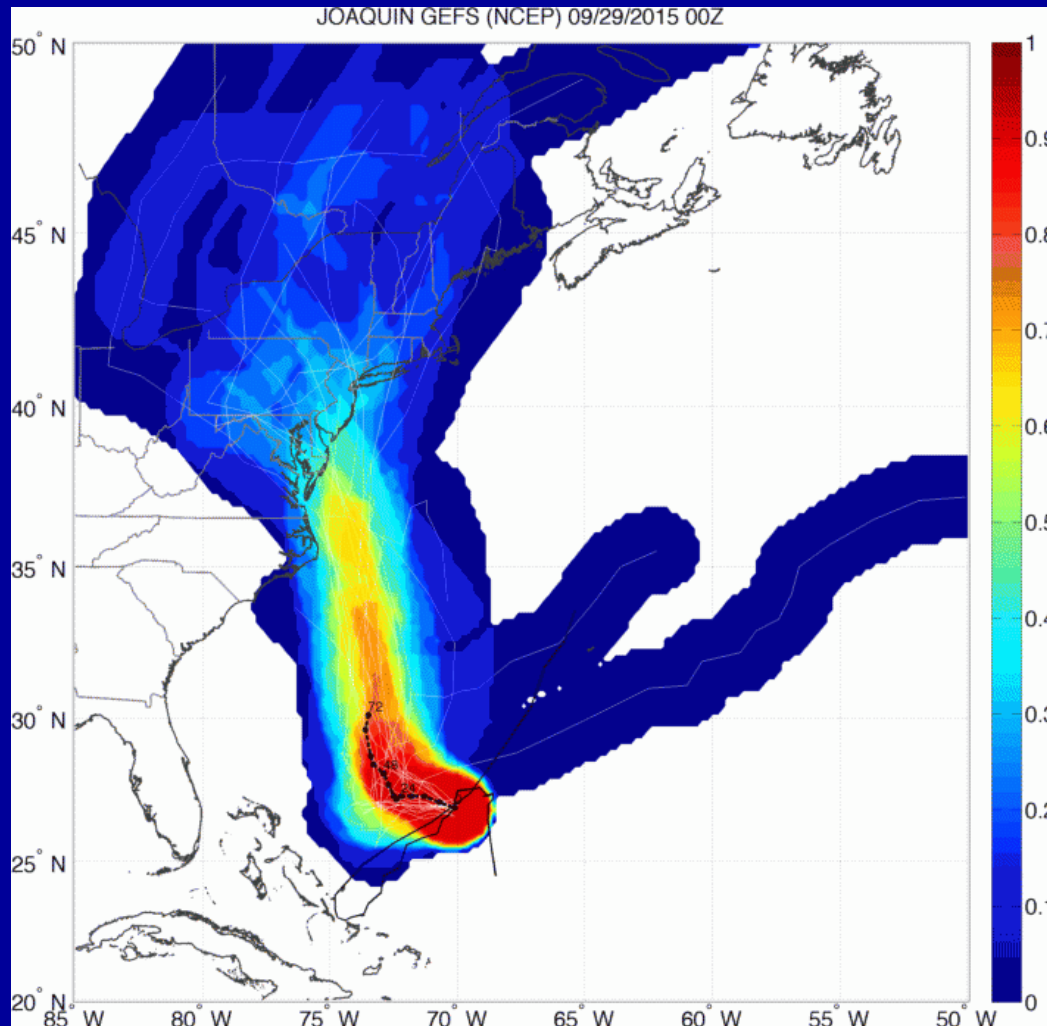

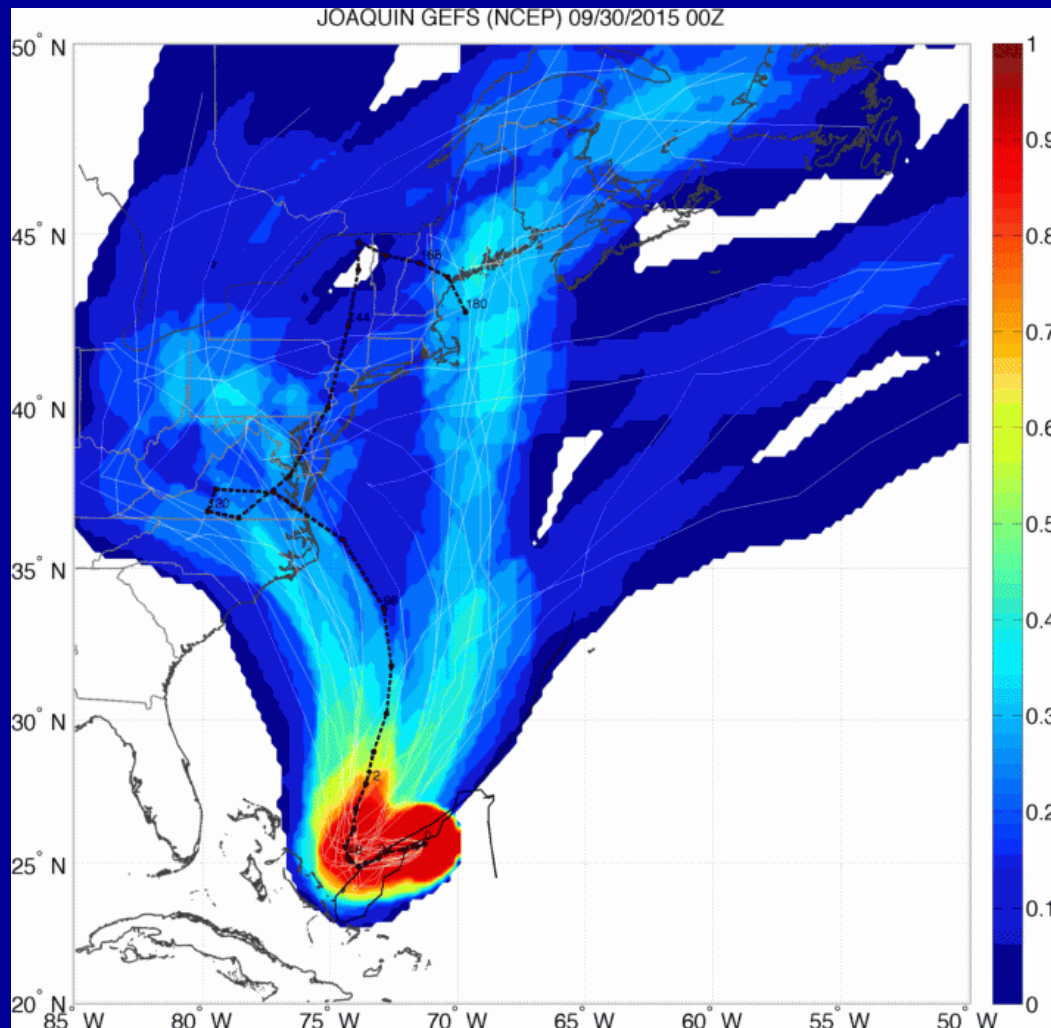
GEFS

EC Ensemble

GFS Joaquin ensembles 29 Sep 1200 UTC

ECMWF Joaquin ensembles 29 Sep 1200 UTC
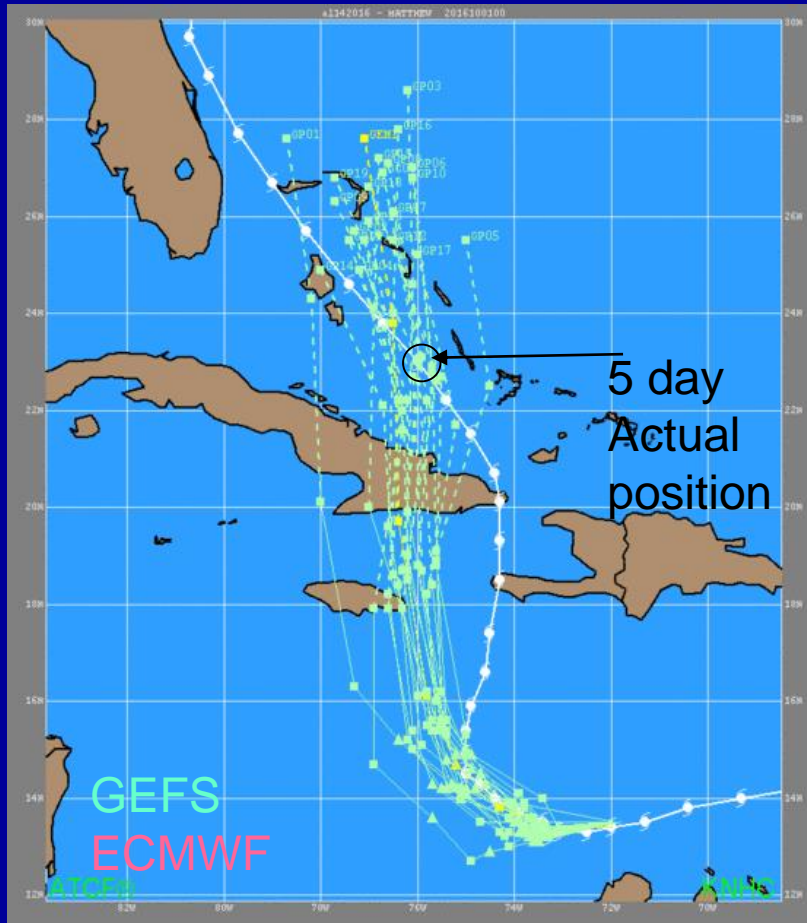
A different way to view the data using probabilities

GEFS vs EC Ensemble 29 Sep 0000 UTC

JOAQUIN GEFS (NCEP) 09/29/2015 00Z

GEFS vs EC Ensemble 30 Sep 0000 UTC

JOAQUIN GEFS (NCEP) 09/30/2015 00Z

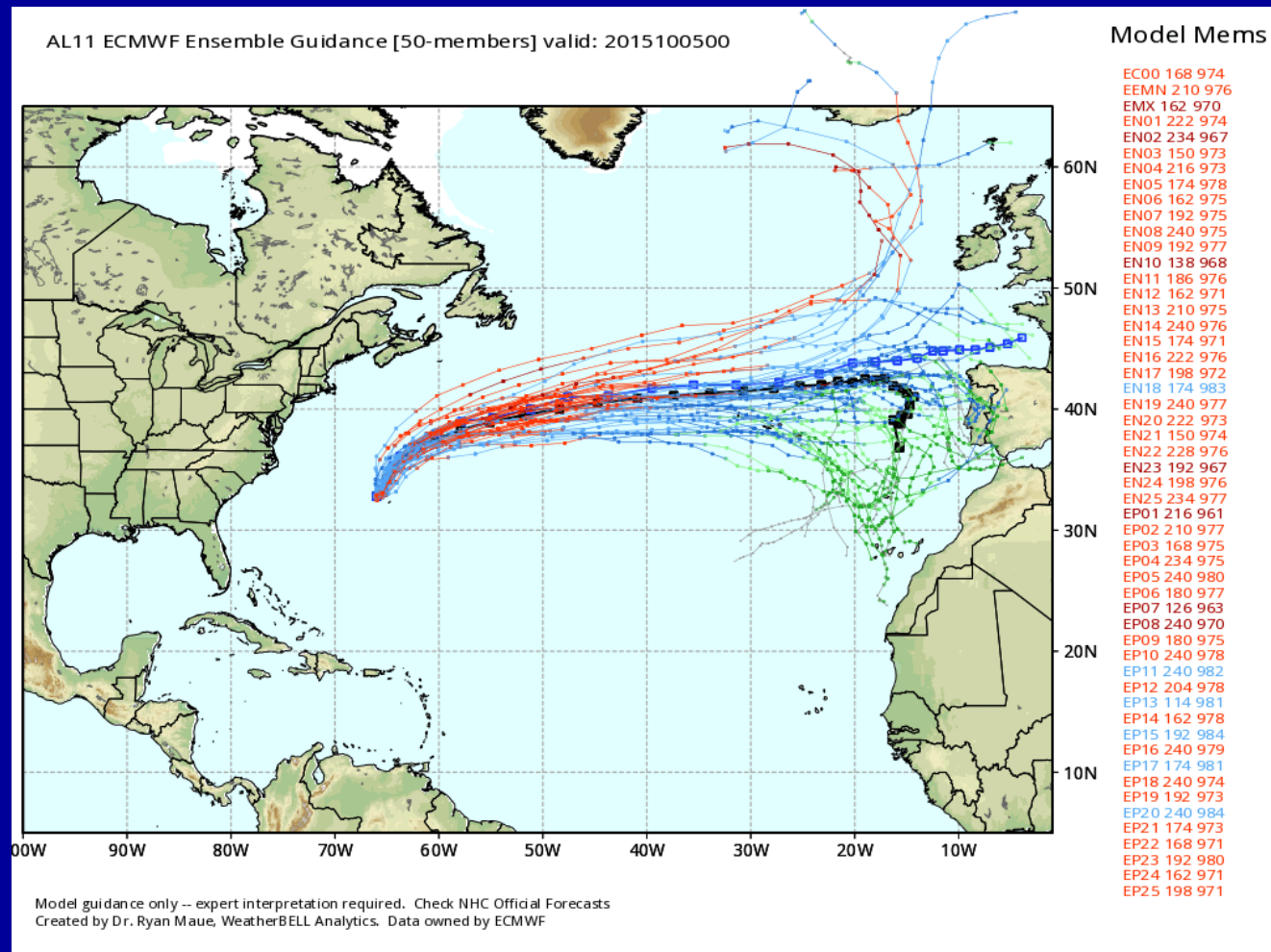# Matthew ensemble guidance 1 Oct 00 UTC

GEFS (blue) too underdispersive, especially in Caribbean

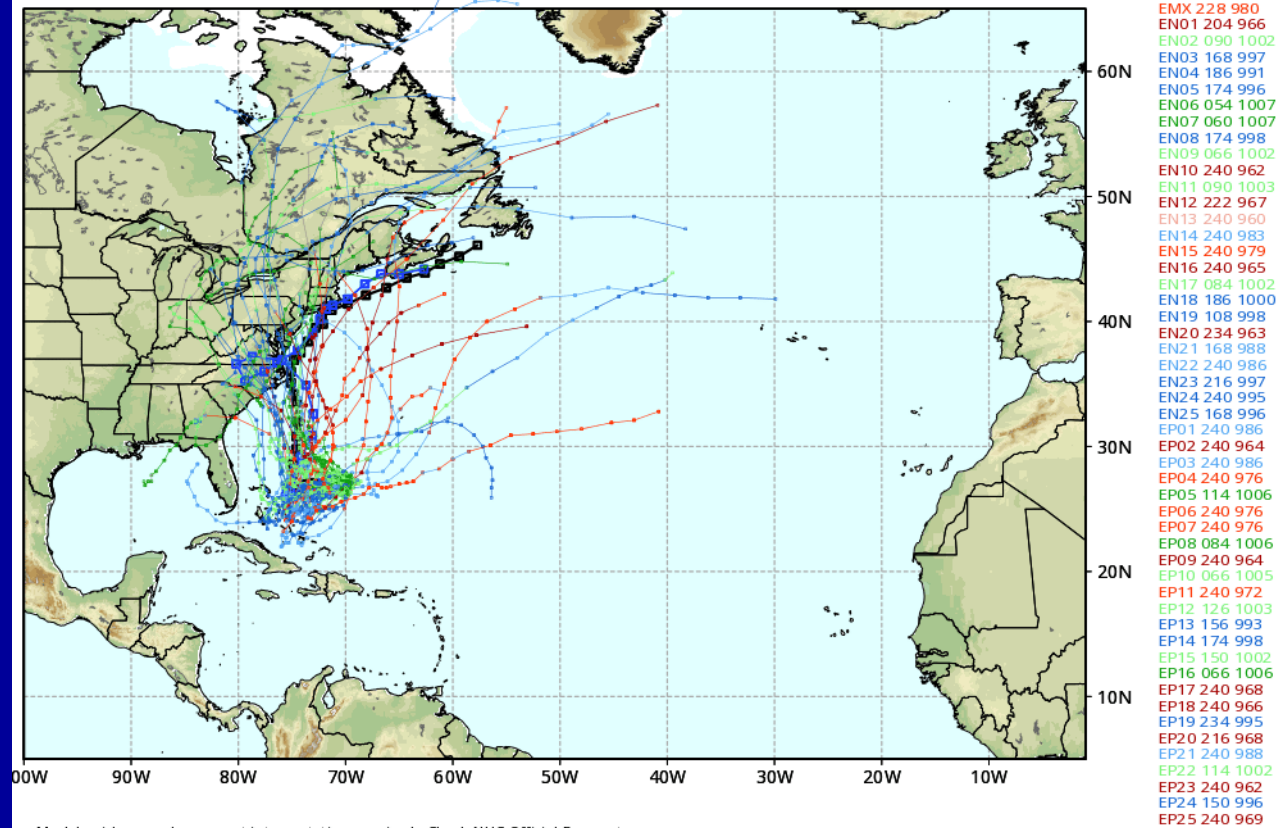Every single GEFS member also too fast at 5 days

ECMWF (red) has more realistic spreads, albeit potentially too large

ECMWF ensemble colored by intensity

AL11 ECMWF Ensemble Guidance [50-members] valid: 2015100500

Model guidance only -- expert interpretation required. Check NHC Official Forecasts
Created by Dr. Ryan Maue, WeatherBELL Analytics. Data owned by ECMWF

Model Mems

EC00 168 974
EEMN 210 976
EMX 162 970
EN01 222 974
EN02 234 967
EN03 150 973
EN04 216 973
EN05 174 978
EN06 162 975
EN07 192 975
EN08 240 975
EN09 192 977
EN10 138 968
EN11 186 976
EN12 162 971
EN13 210 975
EN14 240 976
EN15 174 971
EN16 222 976
EN17 198 972
EN18 174 983
EN19 240 977
EN20 222 973
EN21 150 974
EN22 228 976
EN23 192 967
EN24 198 976
EN25 234 977
EP01 216 961
EP02 210 977
EP03 168 975
EP04 234 975
EP05 240 980
EP06 180 977
EP07 126 963
EP08 240 970
EP09 180 975
EP10 240 978
EP11 240 982
EP12 204 978
EP13 114 981
EP14 162 978
EP15 192 984
EP16 240 979
EP17 174 981
EP18 240 974
EP19 192 973
EP20 240 984
EP21 174 973
EP22 168 971
EP23 192 980
EP24 162 971
EP25 198 971

-Stronger members farther right
-Weaker members farther north

Question 2

In which situation(s) is a well-calibrated ensemble system likely to fail?

A. Unusual forecast track cases

B. When TC track is dependent on intensity

C. If deterministic models are in poor agreement

D. All of the above

E. B & C

TC Intensity Ensemble Forecasting

- **Little skill above single-model deterministic at present**

- **Very computational expensive to run high-resolution (<3 km) intensity ensembles**

- **HFIP is funding efforts to find products that could be operationally useful**

Intensity Change Probability Distributions
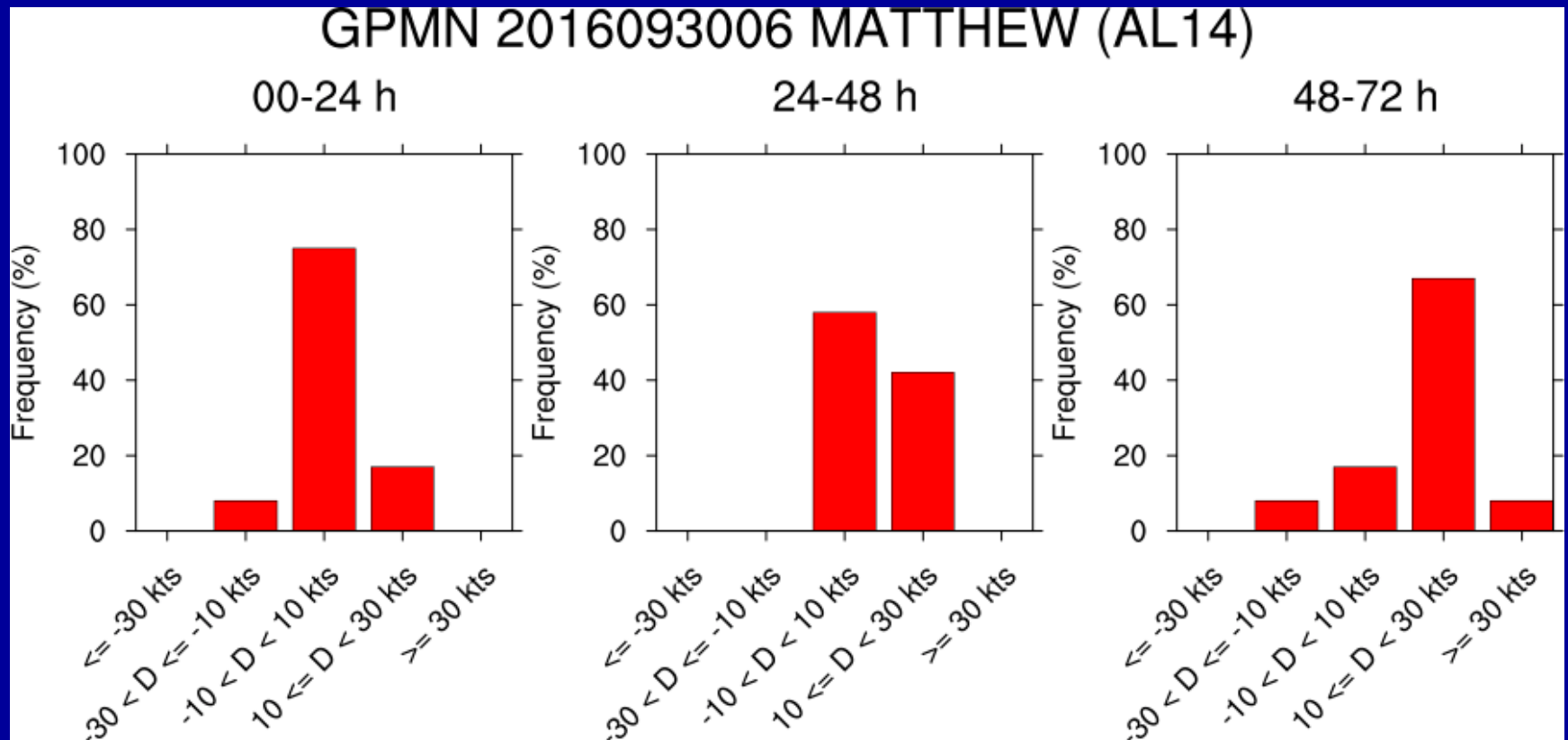
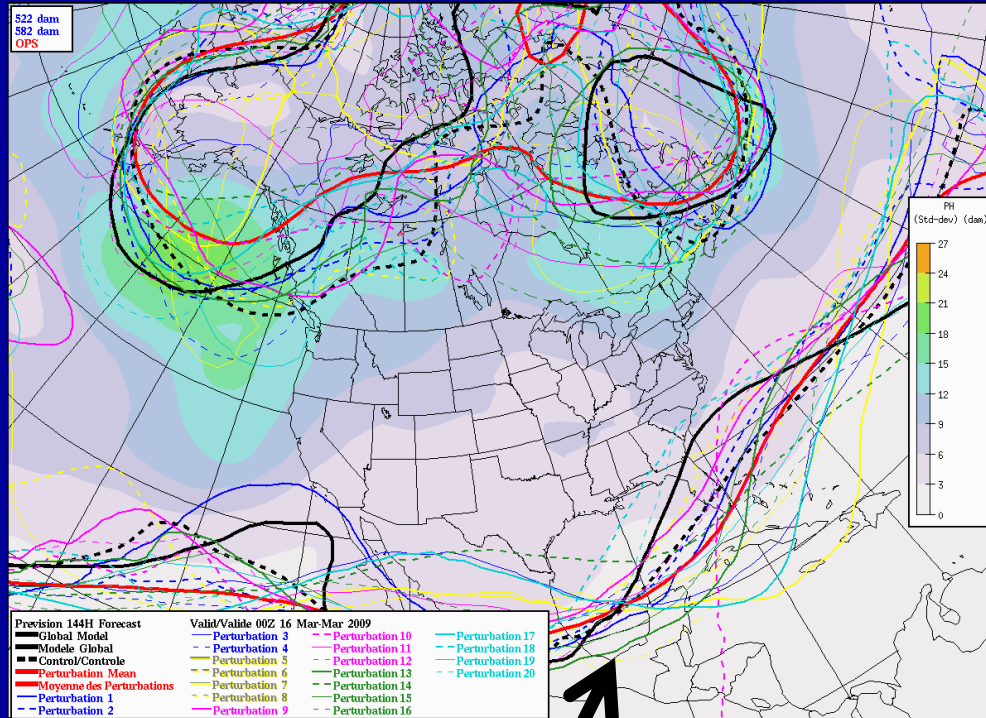# Online Access to Ensemble Output and Training Resources

Access to Ensemble Output

NCEP GEFS and NAEFS: http://mag.ncep.noaa.gov/
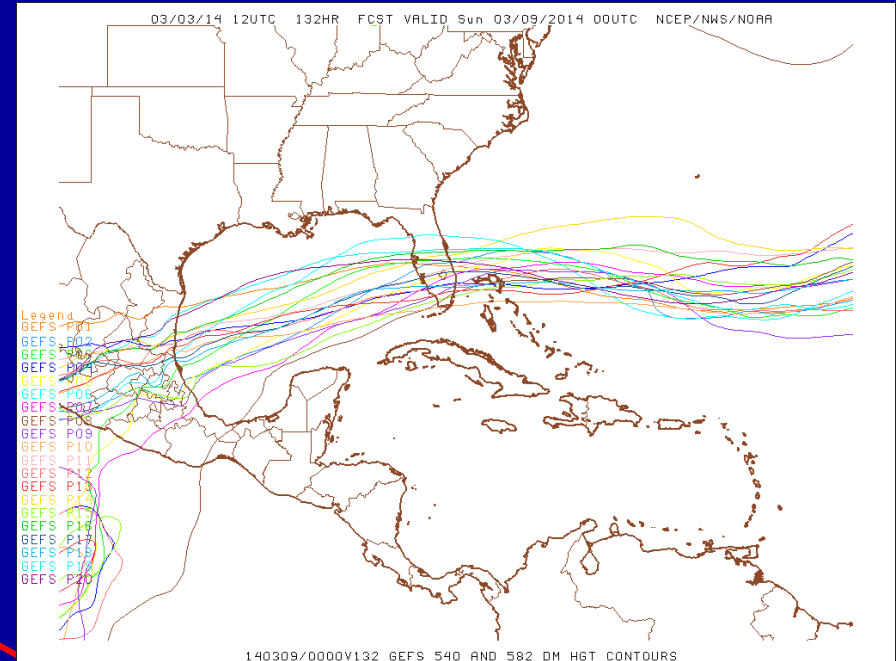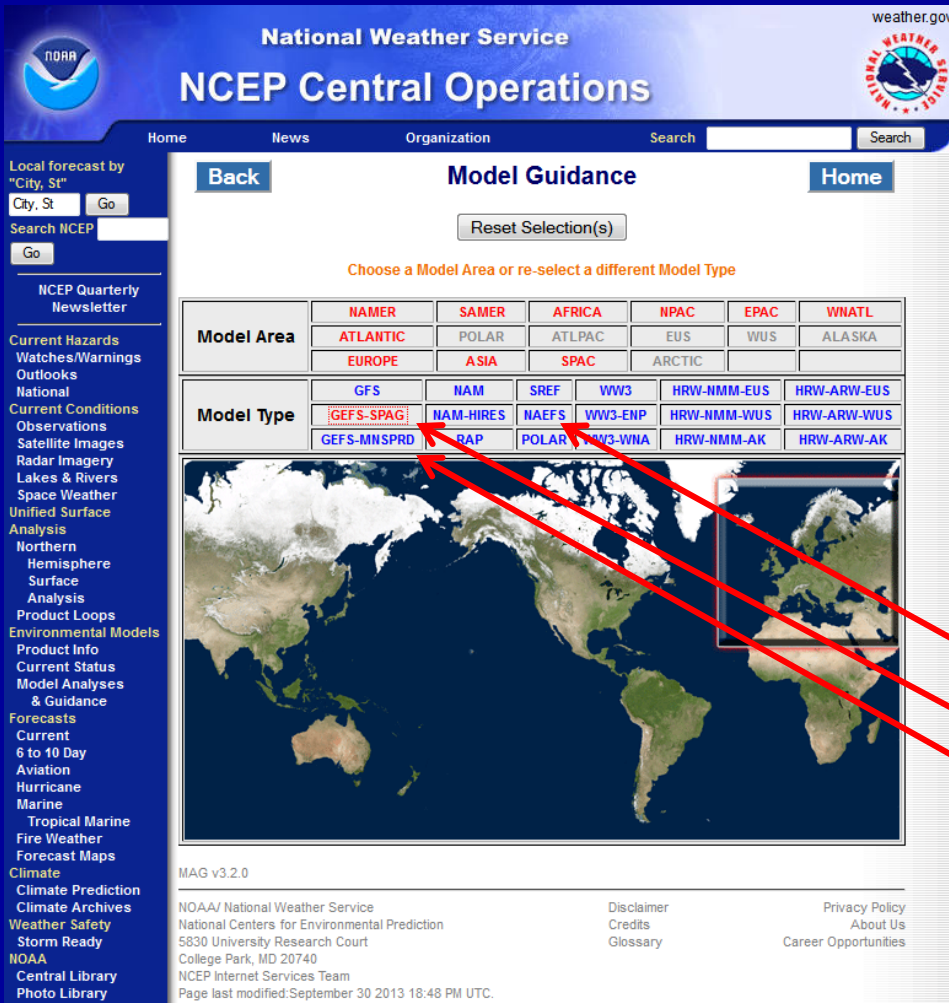
Access to ensemble mean, spread, and spaghetti plots

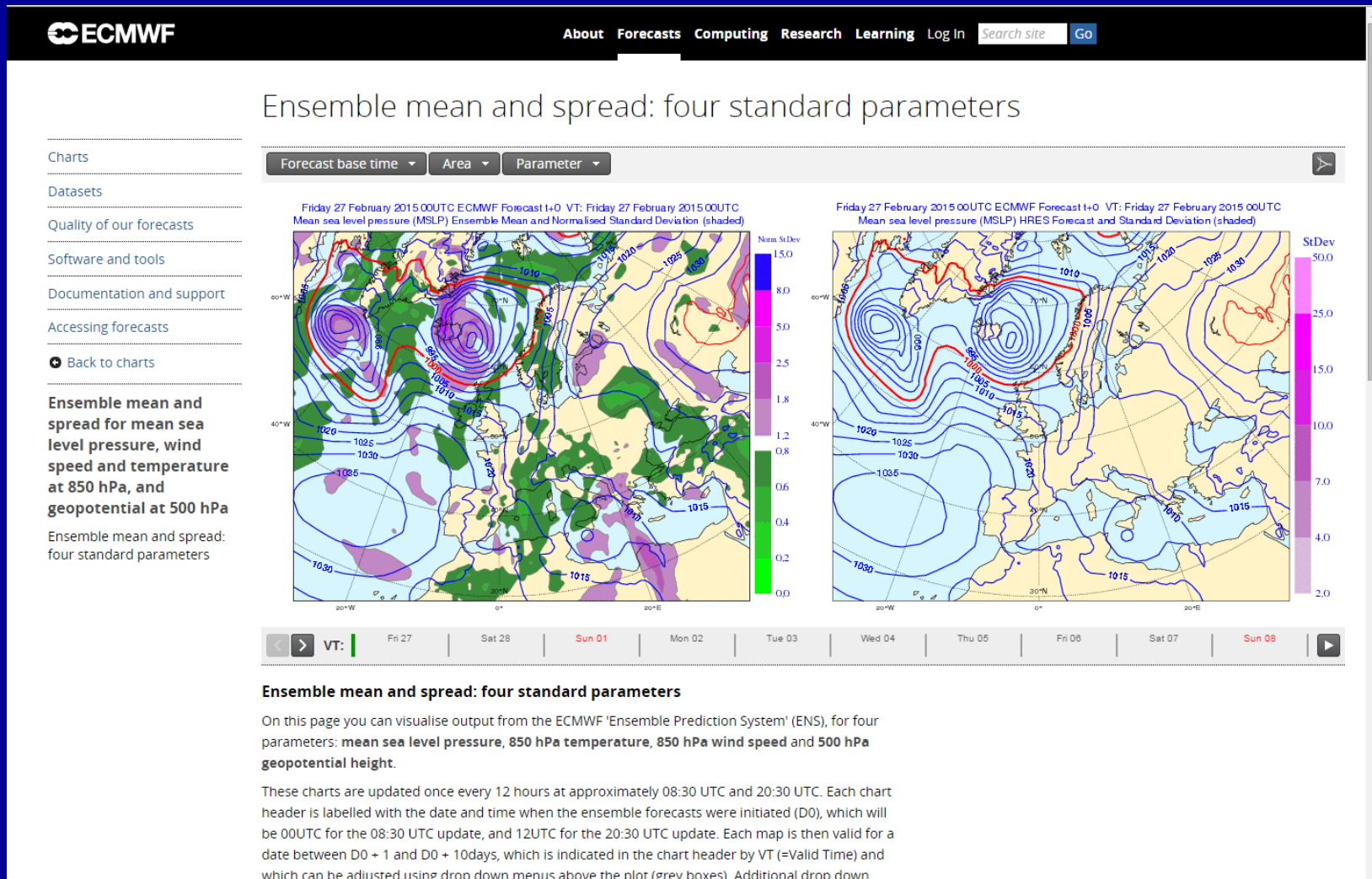# Canadian Ensembles
http://weather.gc.ca/ensemble/index_e.html

FHR 72 forecast of the probability that the 12 hour accumulation exceeds 2 mm
(The 12-h accumulation period immediately precedes the valid time)

Spaghetti diagram of 500-mb 522 and 582 dm height contours
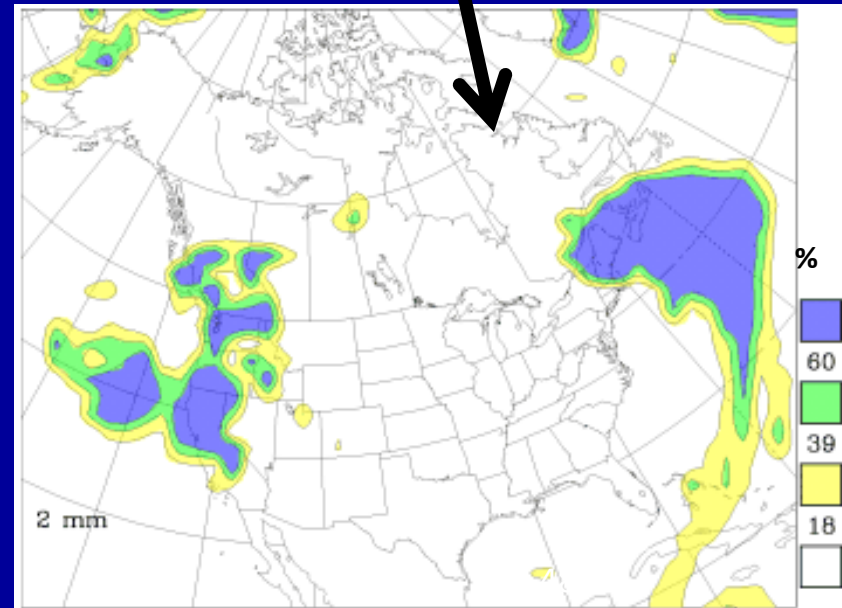
Access to Ensemble Output

- ## ECMWF Ensembles:

  http://www.ecmwf.int/en/forecasts/charts/medium/ensemble-mean-and-spread-four-standard-parameters

COMET Courses
http://www.meted.ucar.edu

- Introduction to Ensemble Prediction:
  http://www.meted.ucar.edu/nwp/pcu1/ensemble_webcast/

- Ensemble Forecasting Explained:
  http://www.meted.ucar.edu/nwp/pcu1/ensemble/

- Ensemble Prediction System Matrix: Characteristics of Operational Ensemble Prediction Systems (EPS):
  http://www.meted.ucar.edu/nwp/pcu2/ens_matrix/

- Wave Ensembles in the Marine Forecast Process:
  http://www.meted.ucar.edu/nwp/WaveEnsembles/

- NWP Workshop on WRF and NAEFS:
  http://www.meted.ucar.edu/s_africa_work/

Thank you

Questions?