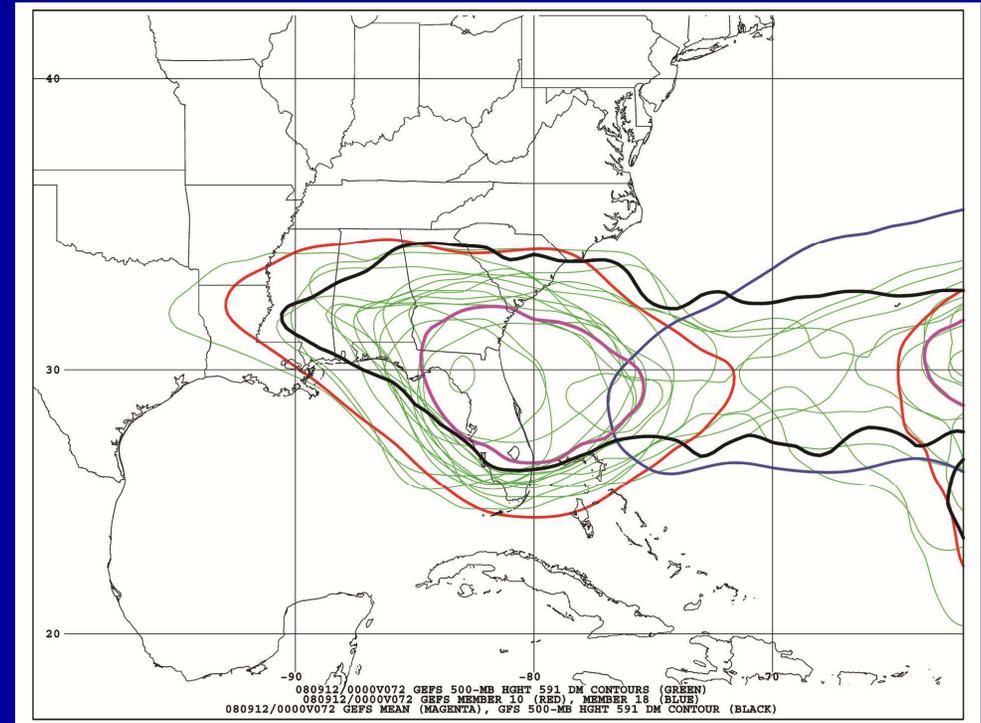
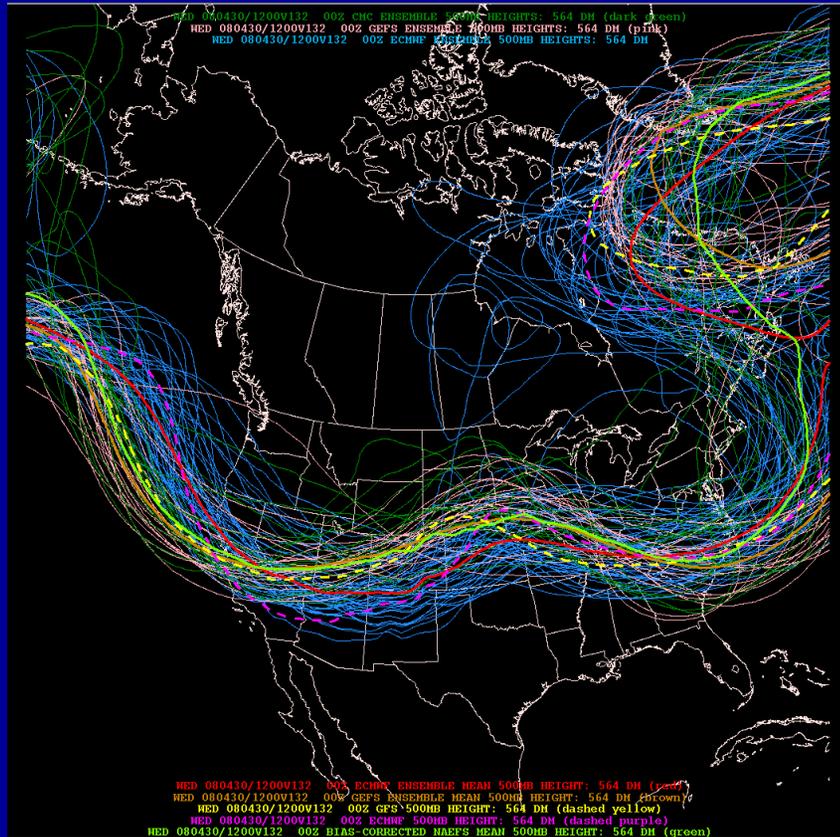


Ensemble Prediction Systems



Eric Blake

National Hurricane Center

March 6, 2018

Acknowledgements to Michael Brennan

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*

Definitions

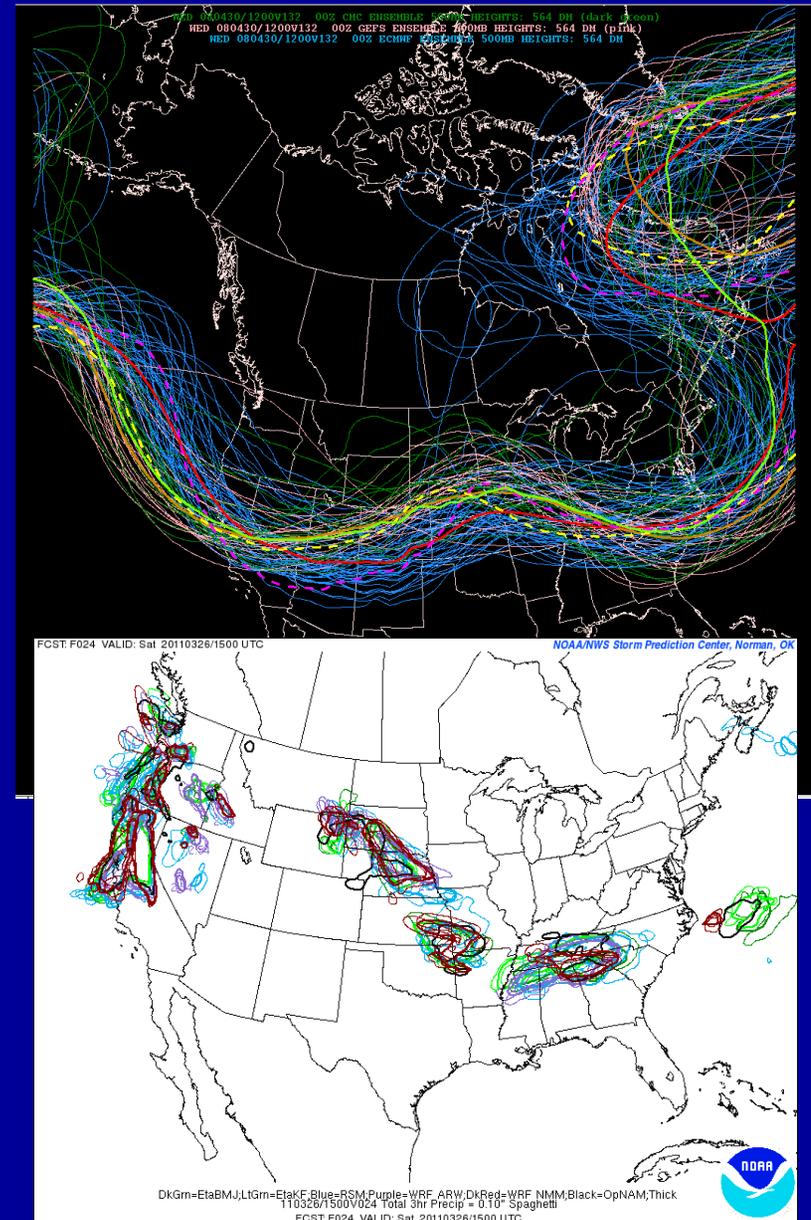
- **Deterministic Model** - single forecast from one forecast model or method using a single set of initial conditions
 - Examples: GFS, ECMWF, UKMET, GFDL, HWRF, BAMS
- **Ensemble** - collection of “member” forecasts verifying at the same time created from:
 - Different but equally viable initial conditions
 - 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

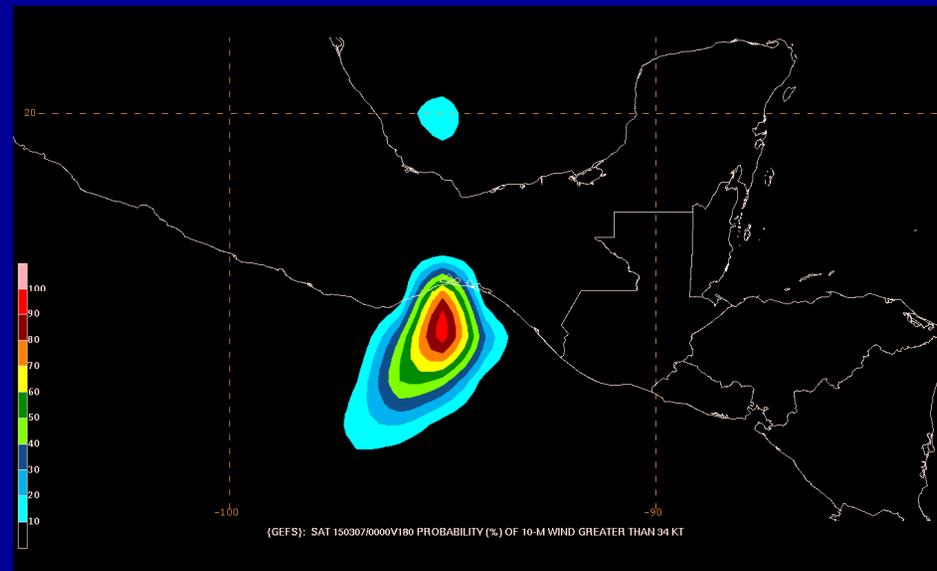
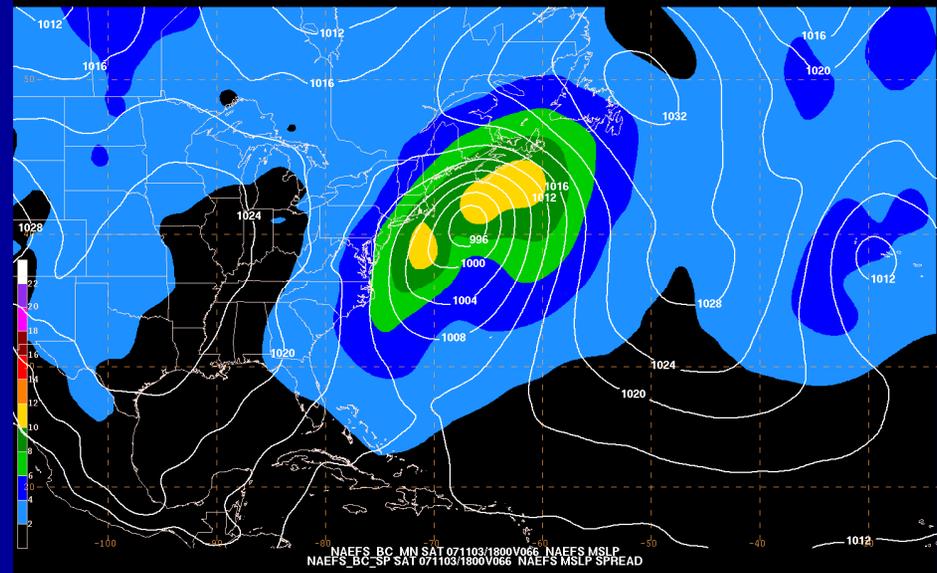
Ensemble Use

- 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

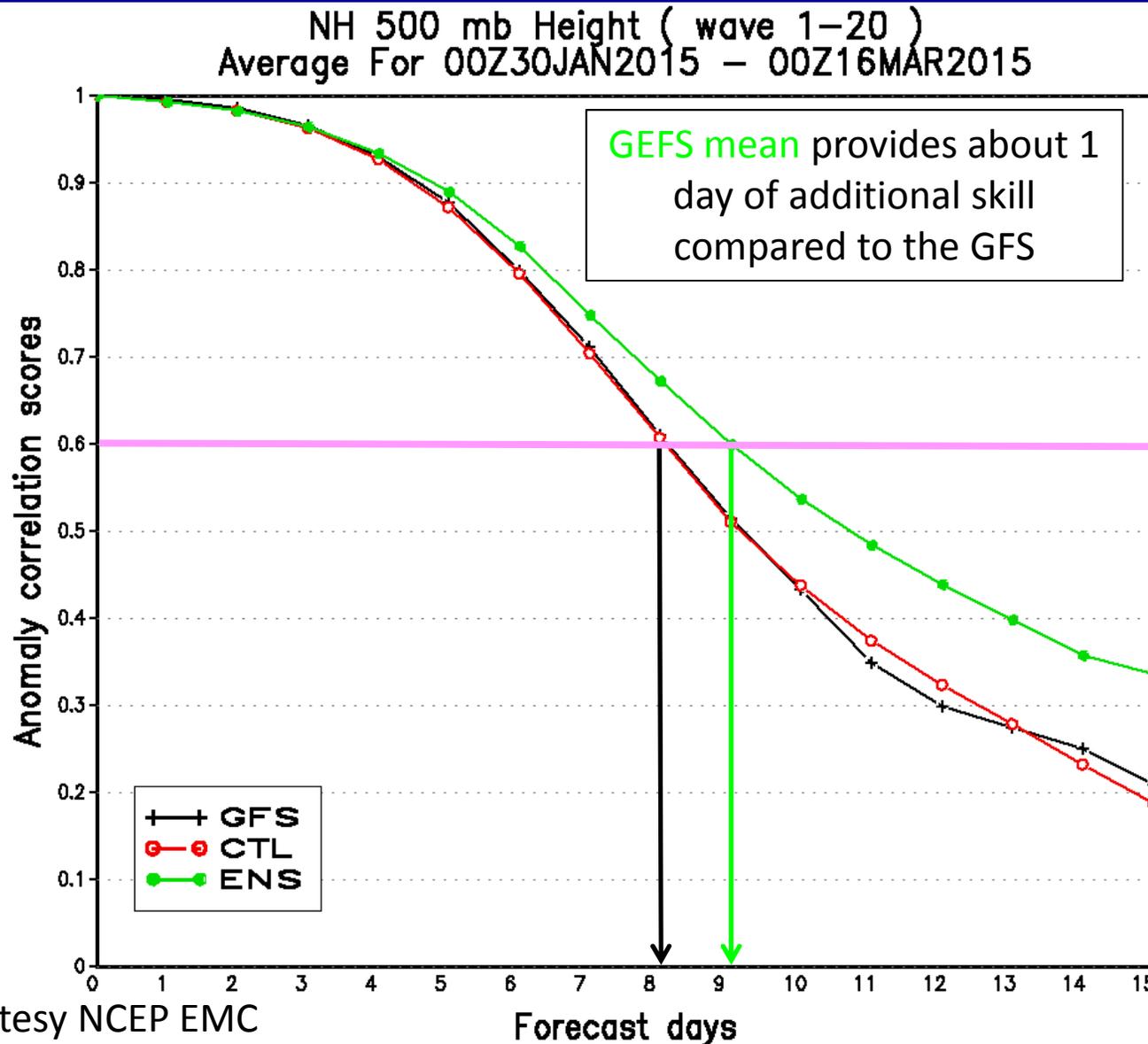


Ensemble Mean vs. Deterministic

- 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

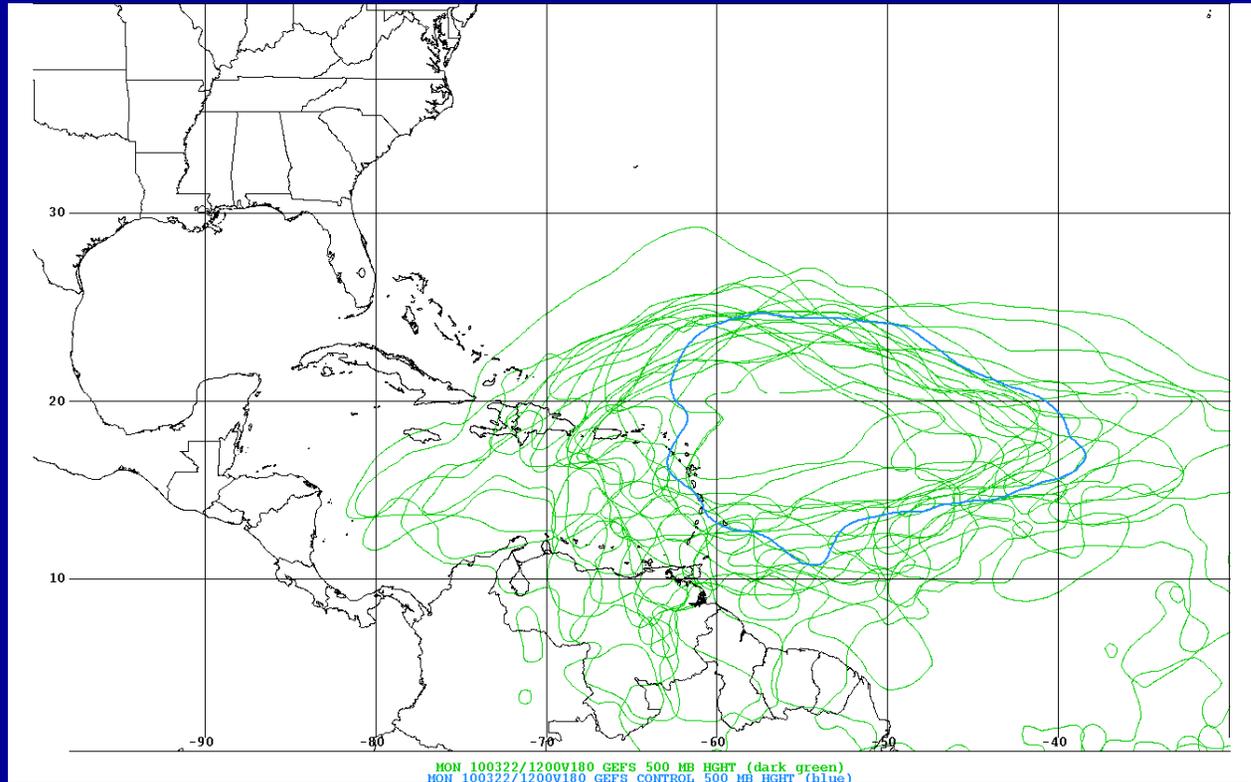


Courtesy NCEP EMC

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)



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

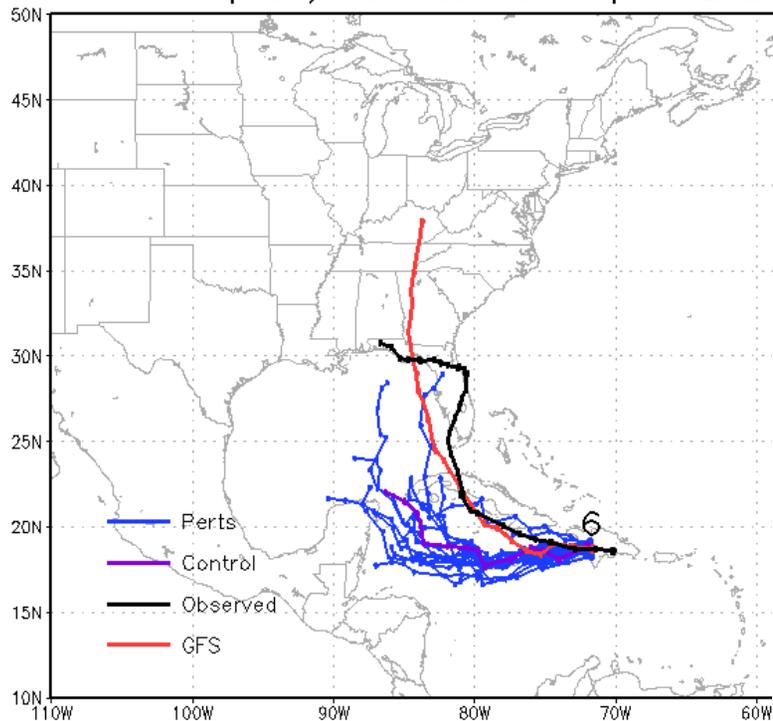
NCEP GEFS

- 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

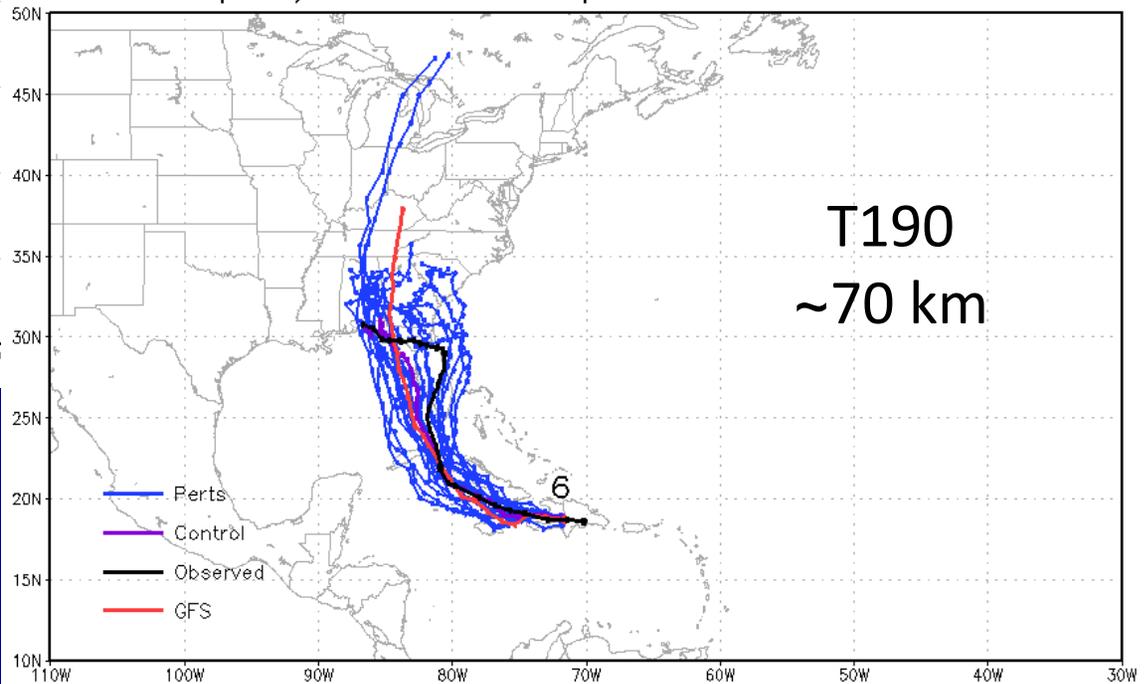
Tropical Cyclone Forecast Tracks – prod NCEP Ensemble – 2008081600



T126
~100 km

More members retain the TC
and track forecasts are much
improved

Tropical Cyclone Forecast Tracks – para NCEP Ensemble – 2008081600



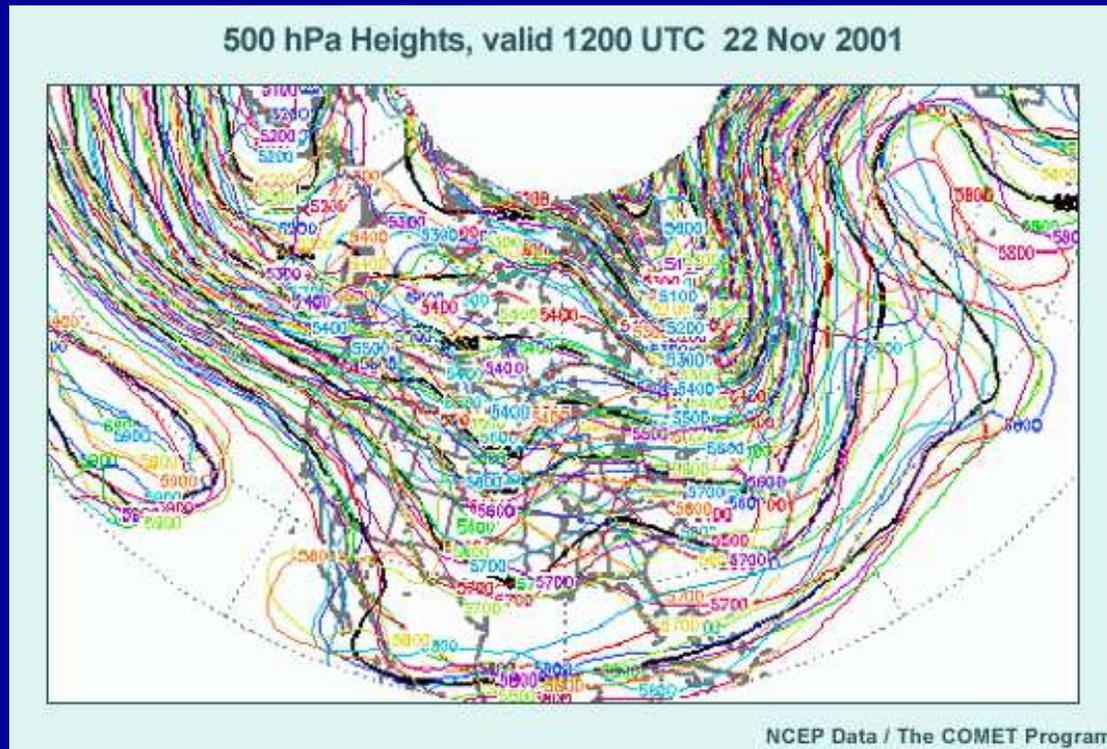
T190
~70 km

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

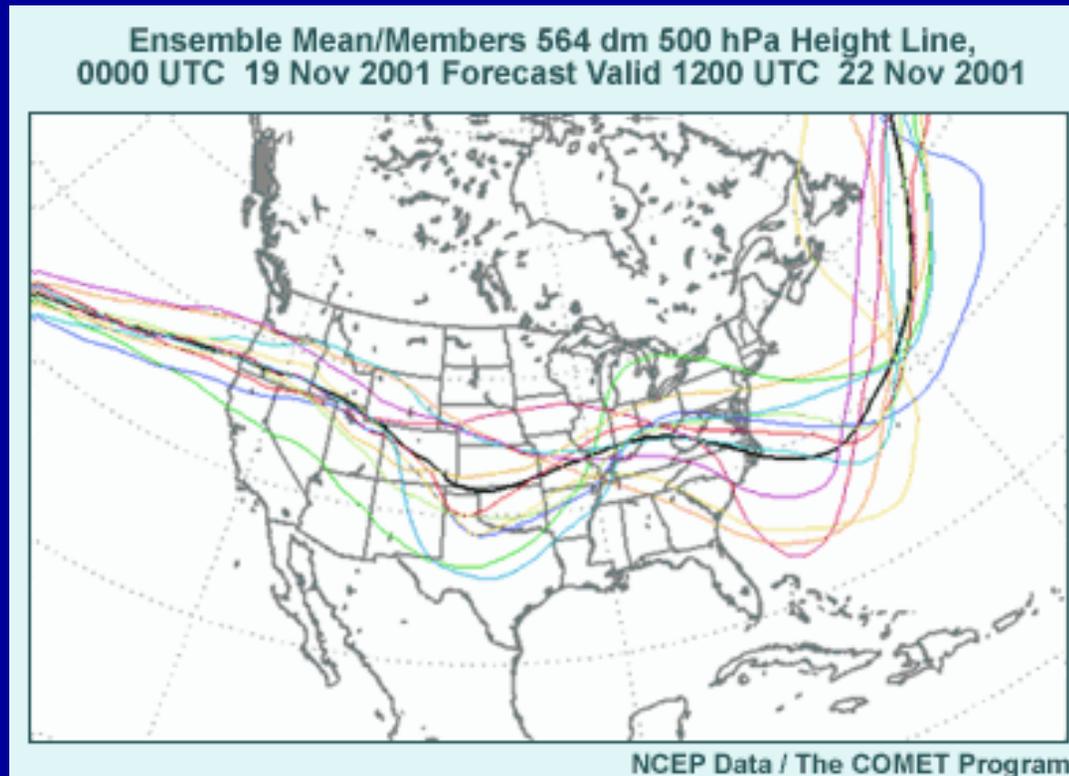
Ensemble Display and Interpretation

Displaying Ensembles



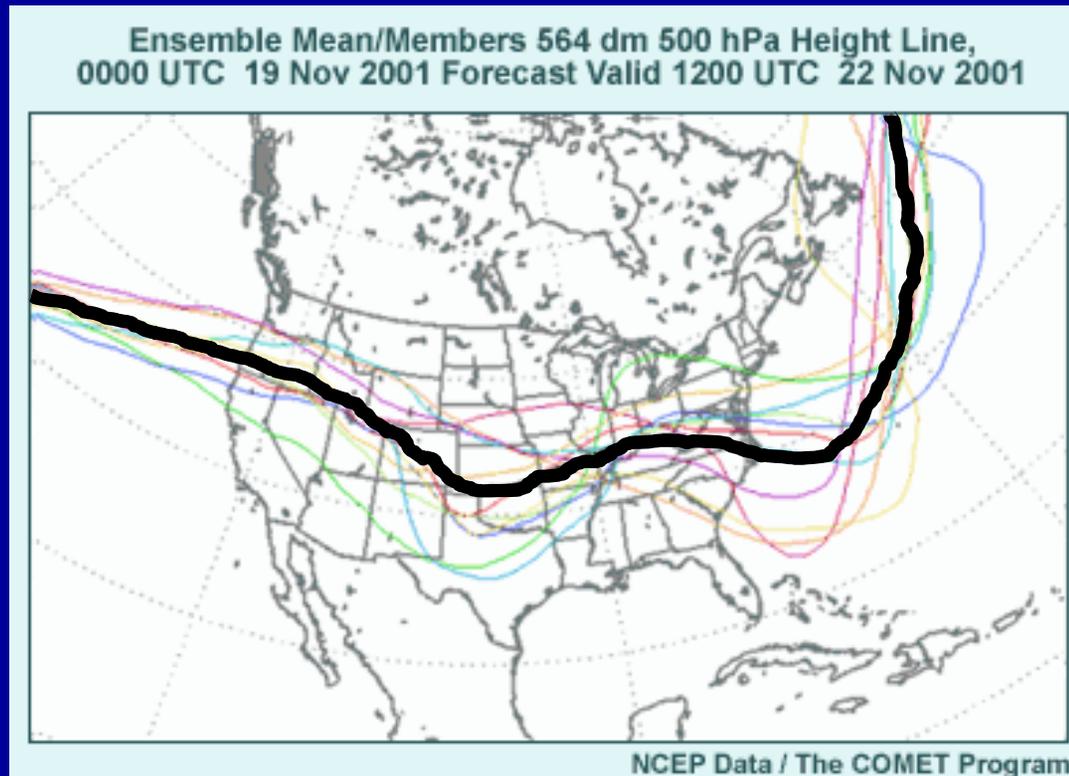
If we try to look at every ensemble member at once, it is messy and difficult to interpret

Displaying Ensembles



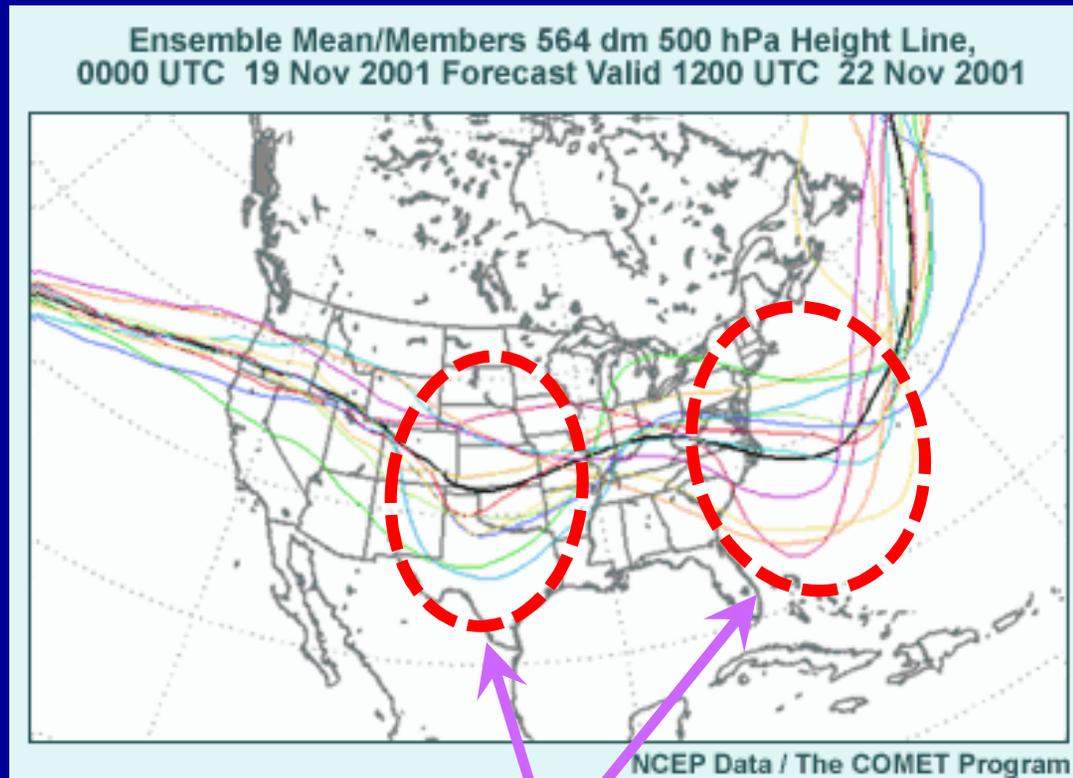
Spaghetti Diagram – displays one isopleth at a time from each ensemble member

Displaying Ensembles



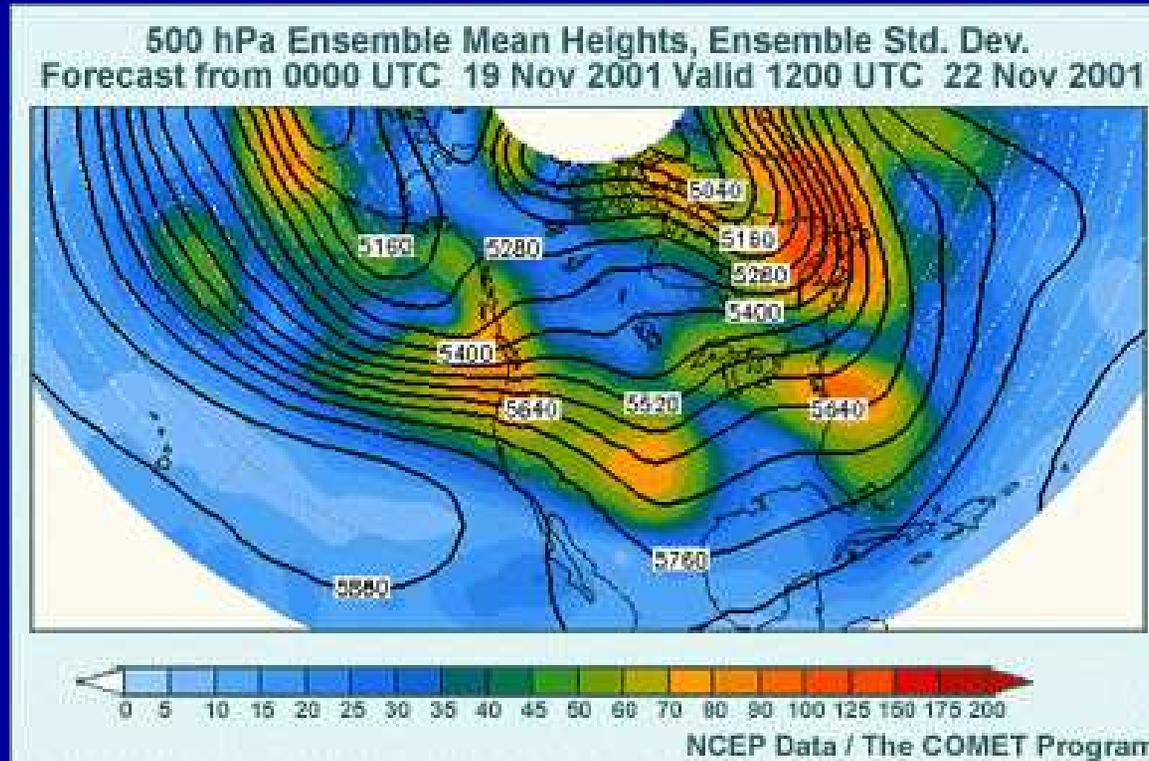
Ensemble Mean - average of multiple forecast members verifying at same time

Displaying Ensembles



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

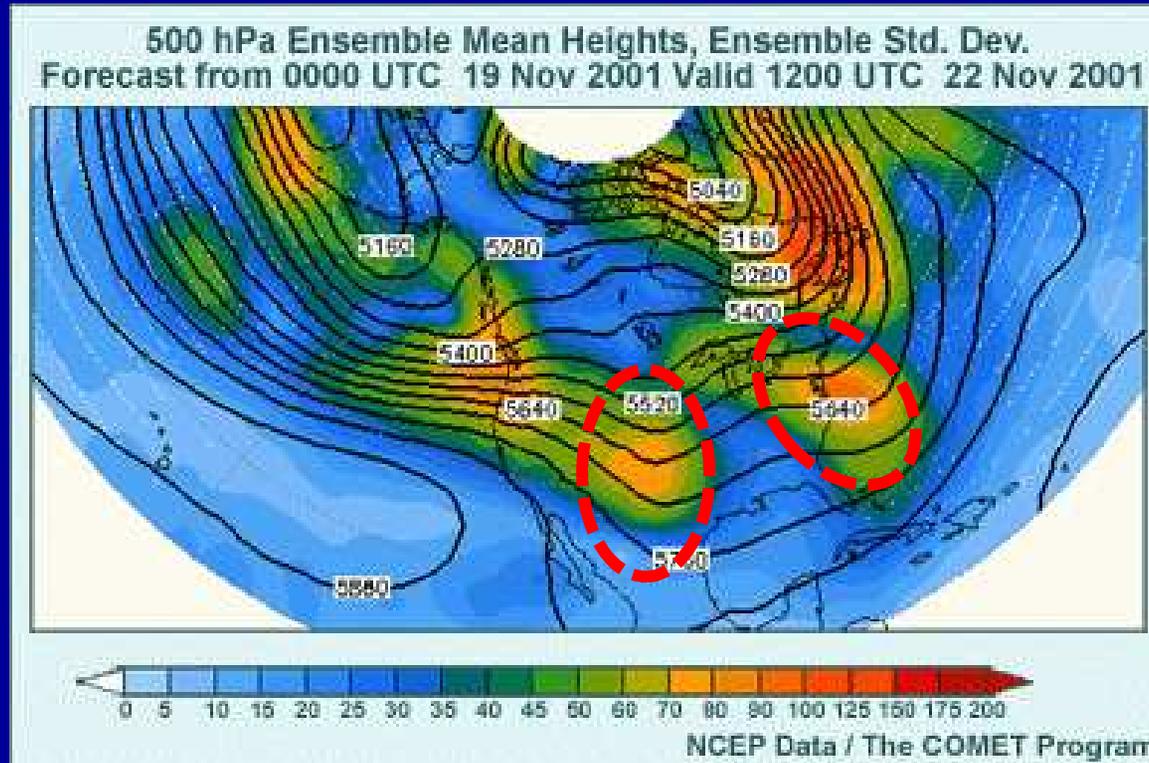
Displaying Ensembles



- **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



- **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

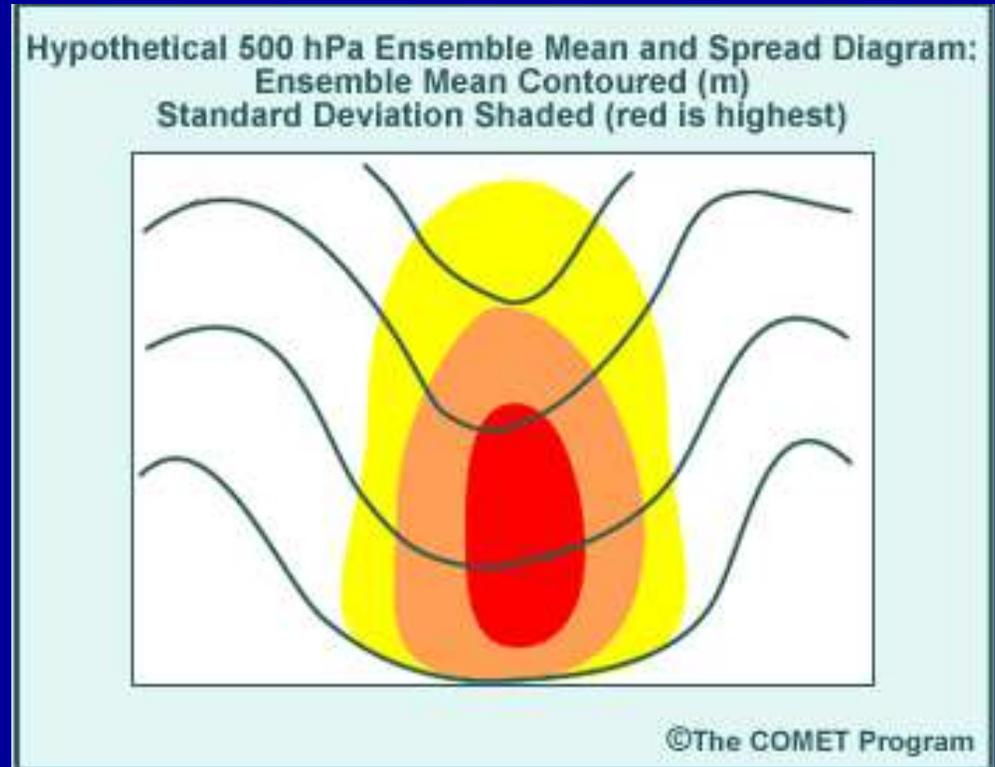
Ensemble Mean and Spread

- 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?

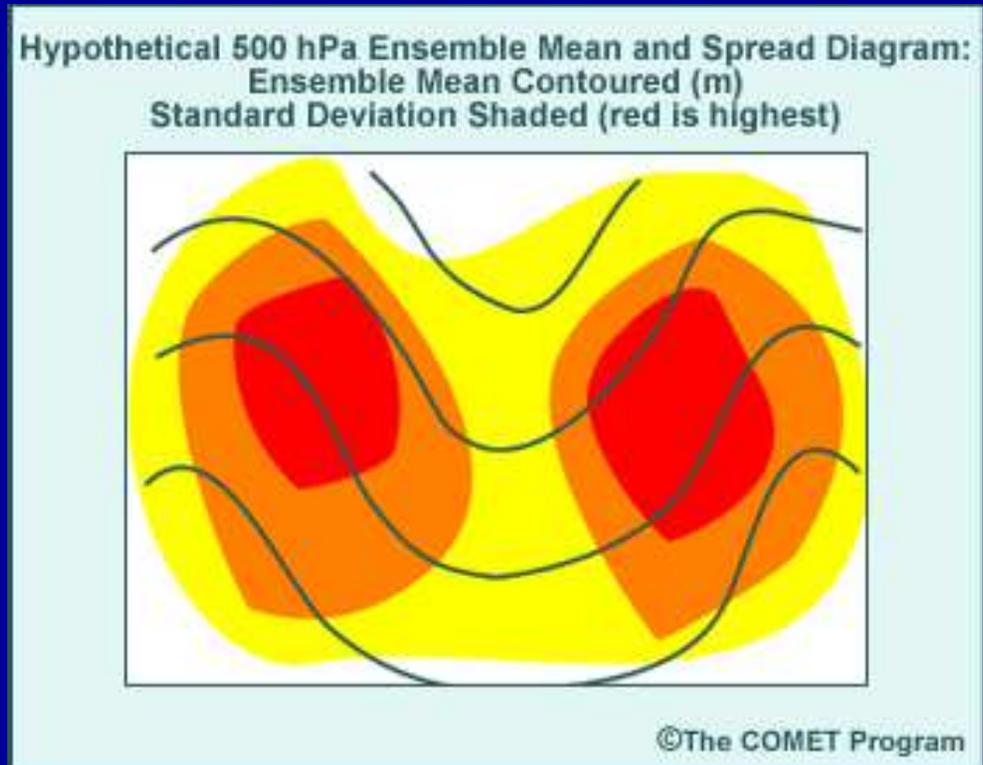


Interpreting Mean and Spread

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

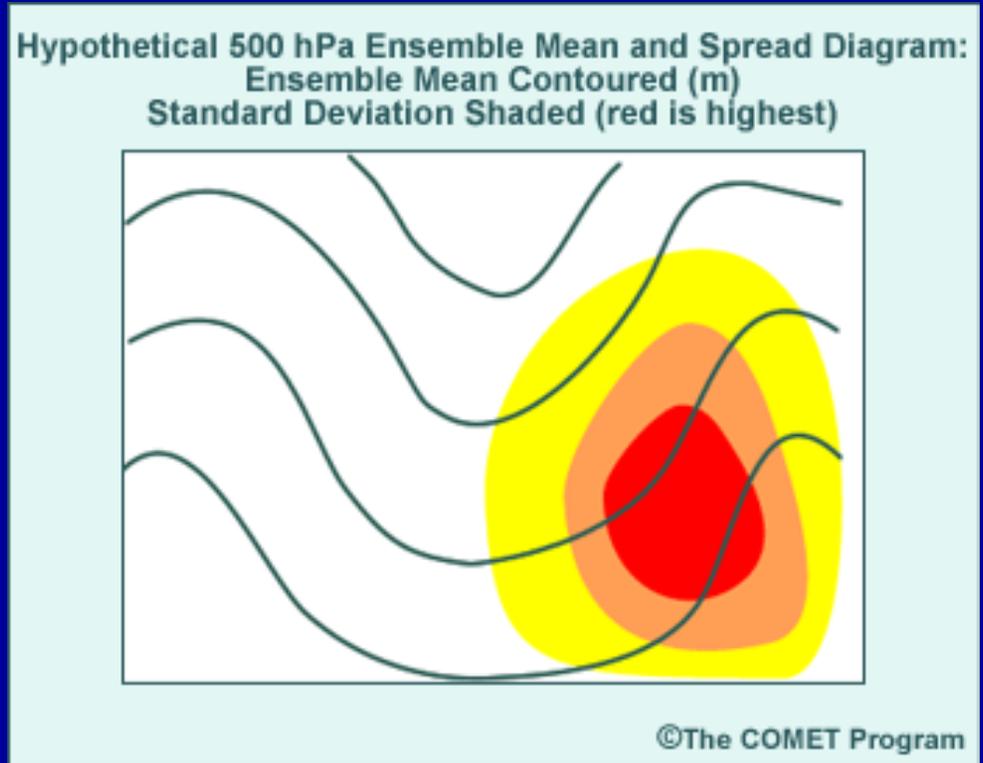
- If a tropical cyclone was located southeast of this trough, at what time will the tropical cyclone begin to be influenced by this trough?



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?



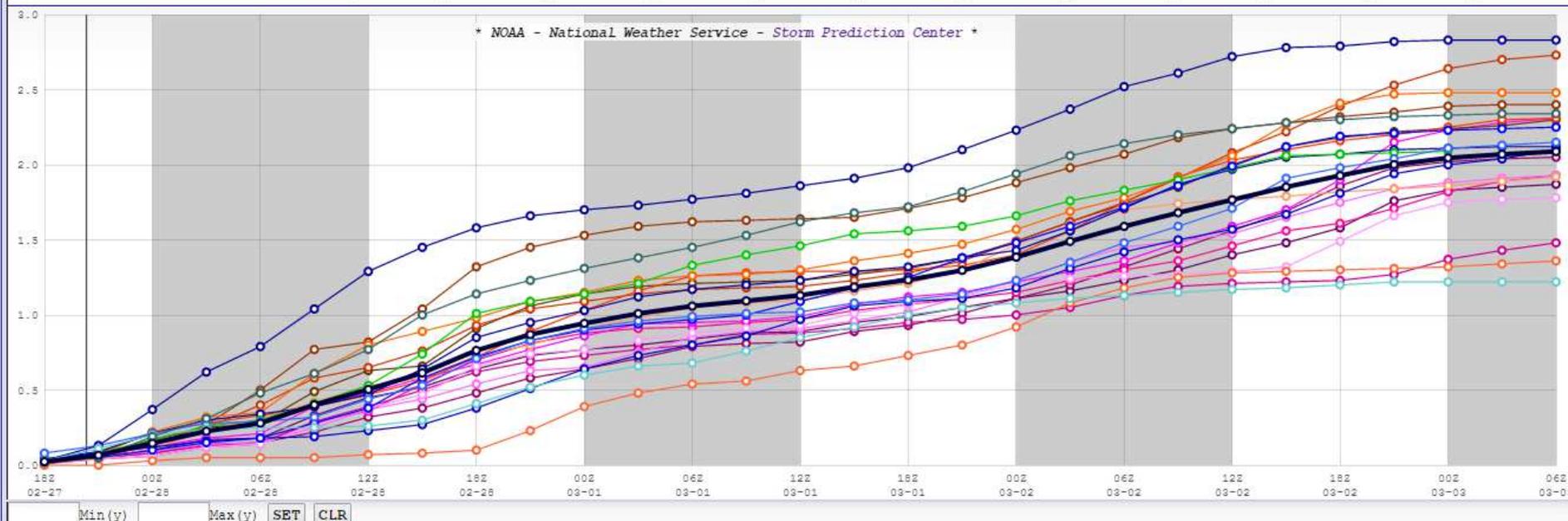
Plume Diagrams

NCEP SREF plume for Total-QPF at DRO from 20150227/15 UTC run.

Oldest Run ---> 20150226_21 20150227_03 20150227_09 20150227_15 <--- Latest Run

Forecast Parameter Selection - Hover over buttons for more information.

3hrly-TMP 3hrly-DWP 3h-MUCAPE 3h-MLCAPE 3h-EFFSHR 3hrly-QPF Total-QPF 3hrly-SNO Total-SNO Ptype-POP 3hr-2mRH% 3h-10mWND



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 ($8 \times 10^{-5} \text{ s}^{-1}$ intervals)

thin green: ECENS members

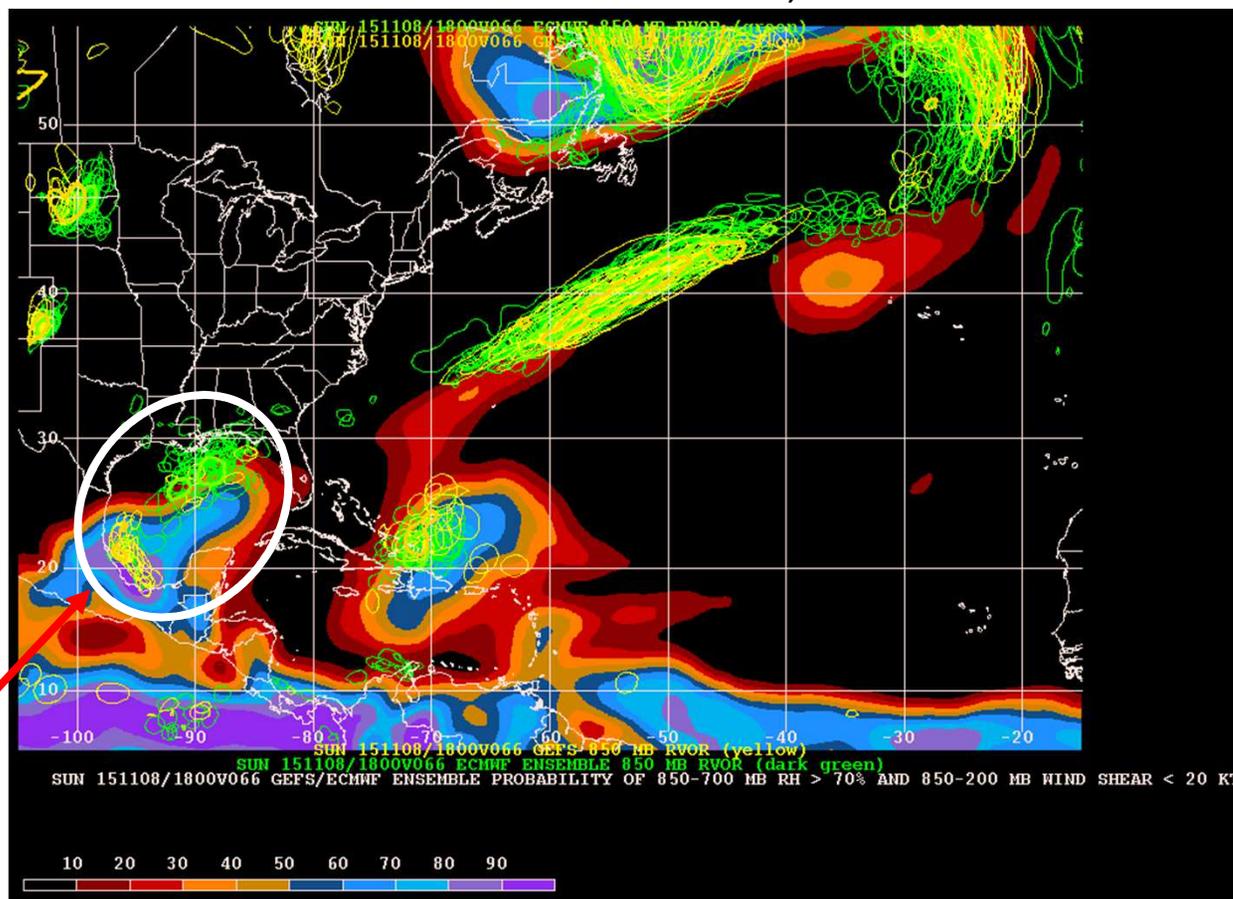
thick green: ECMWF deterministic

thin yellow: GEFS members

thick yellow: GFS deterministic

Invest AL93

0000 UTC November 6, 2015 + 66 h



Ensemble Problems

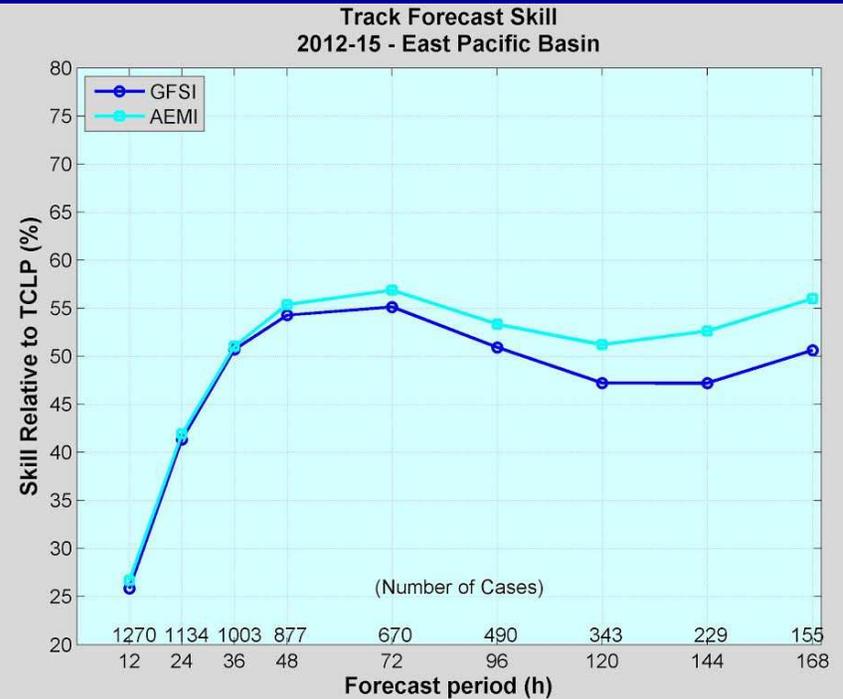
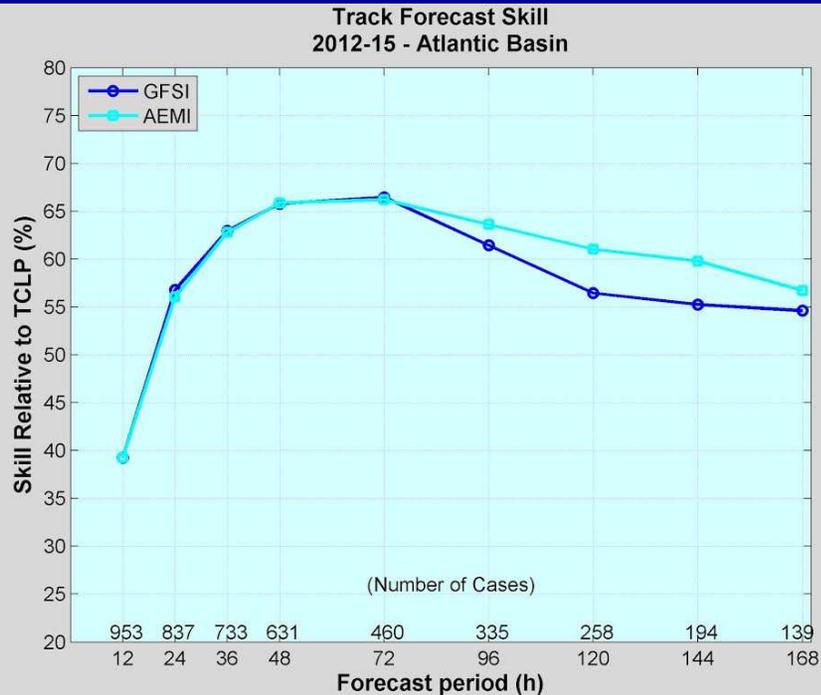
- Need a properly calibrated system
 - GEFS is currently underdispersive
 - This problem results in an overconfident forecast
 - Lower resolution can also hinder a more accurate track forecast (i.e. when track especially dependent on intensity)
- Other issues
 - Ensemble mean can be misleading (and may 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)

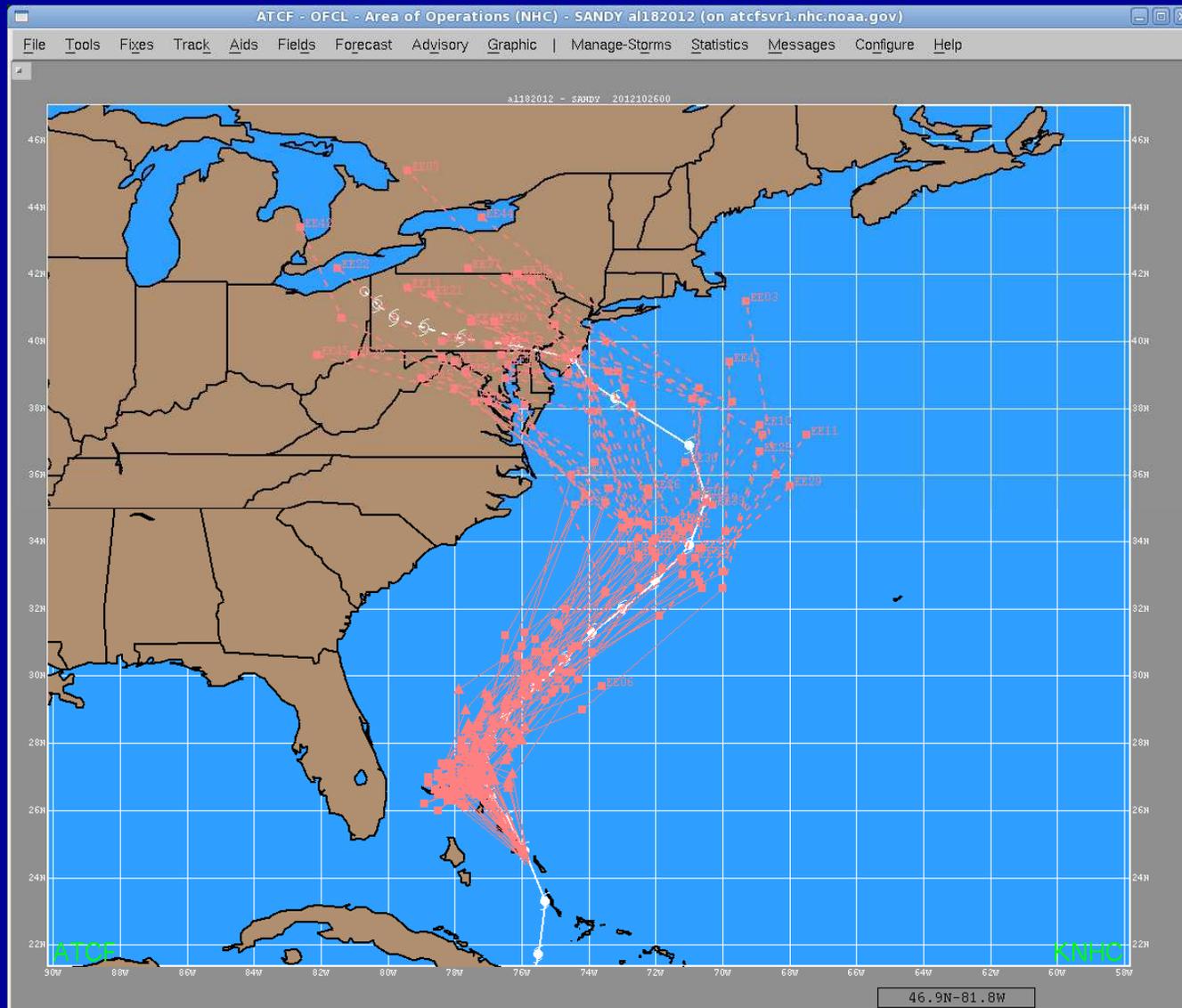


In the Atlantic, the GEFS ensemble mean track forecast (AEMI) is competitive with the deterministic GFS (GFSI) through day 3 and better afterward

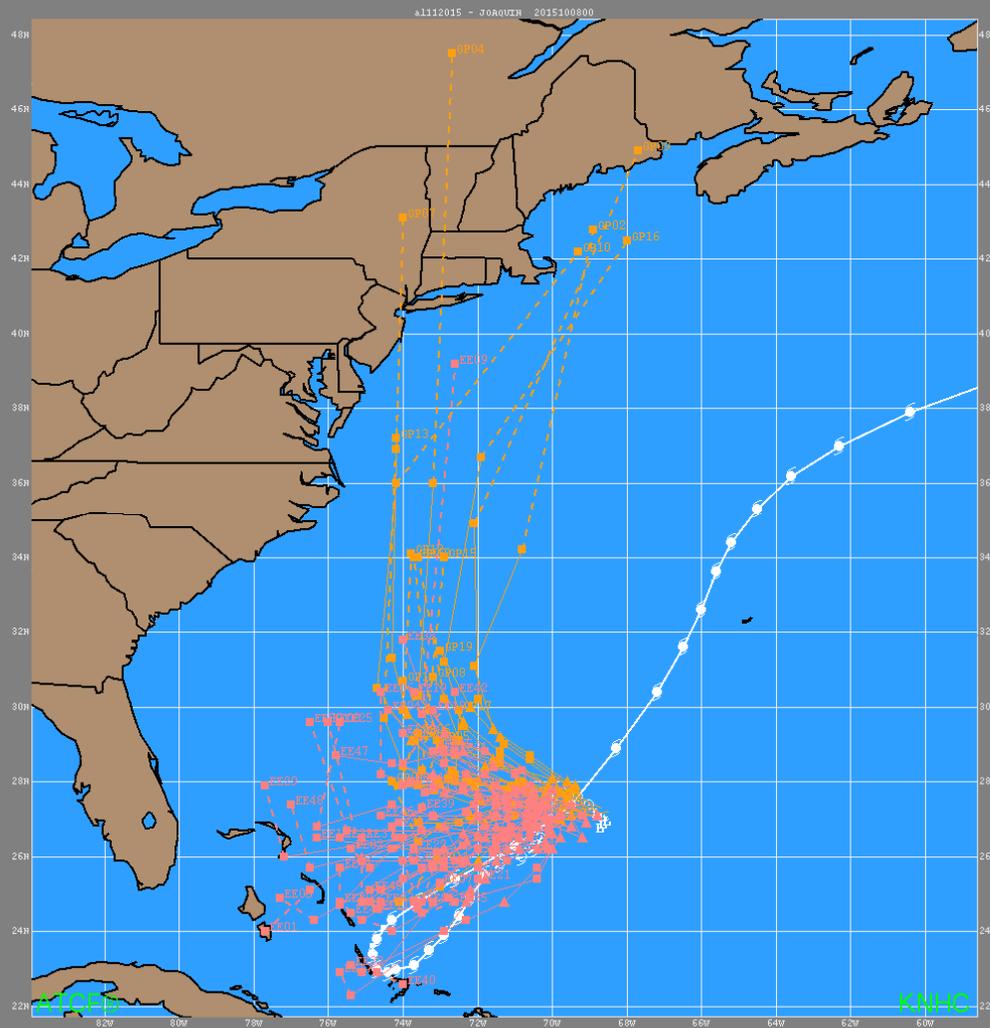
In the east Pacific, AEMI beats GFSI at 48 h and beyond

ECMWF Ensemble

Sandy example of desirable spread/verification



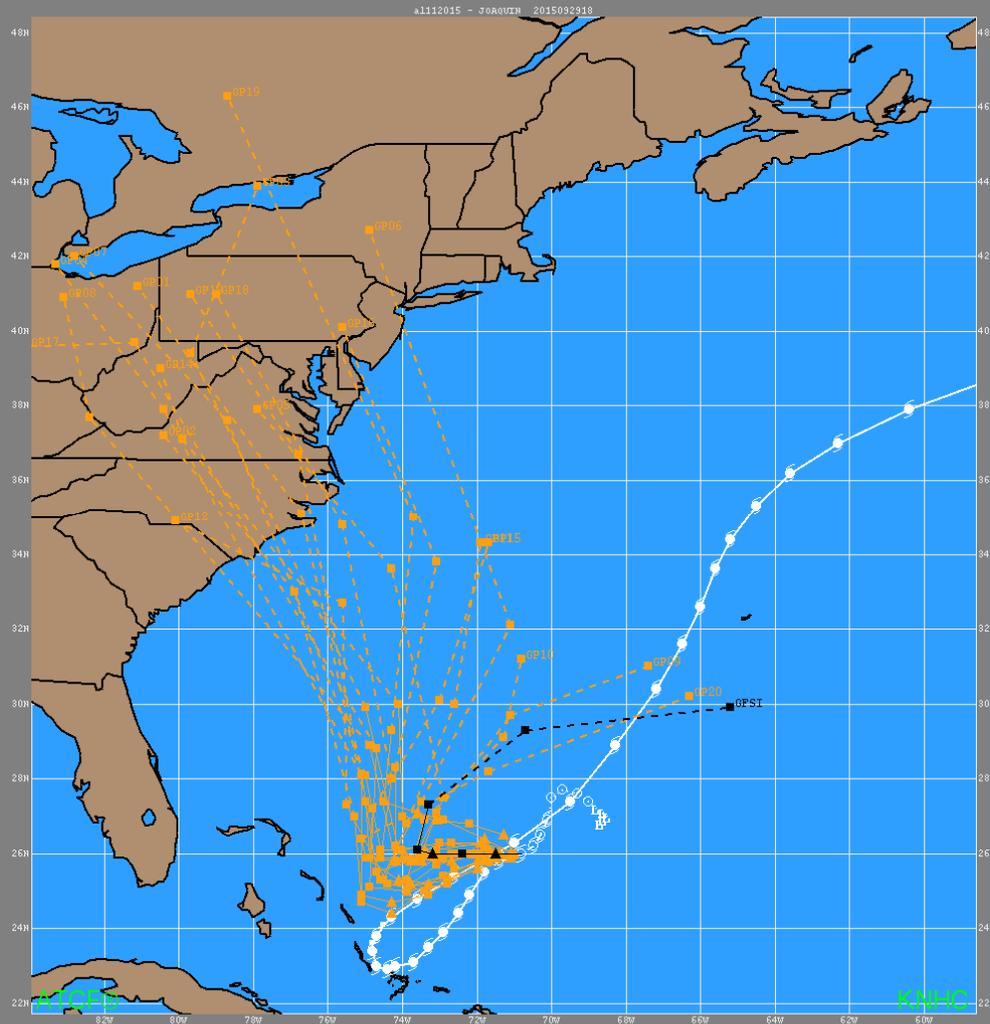
Joaquin ensemble guidance



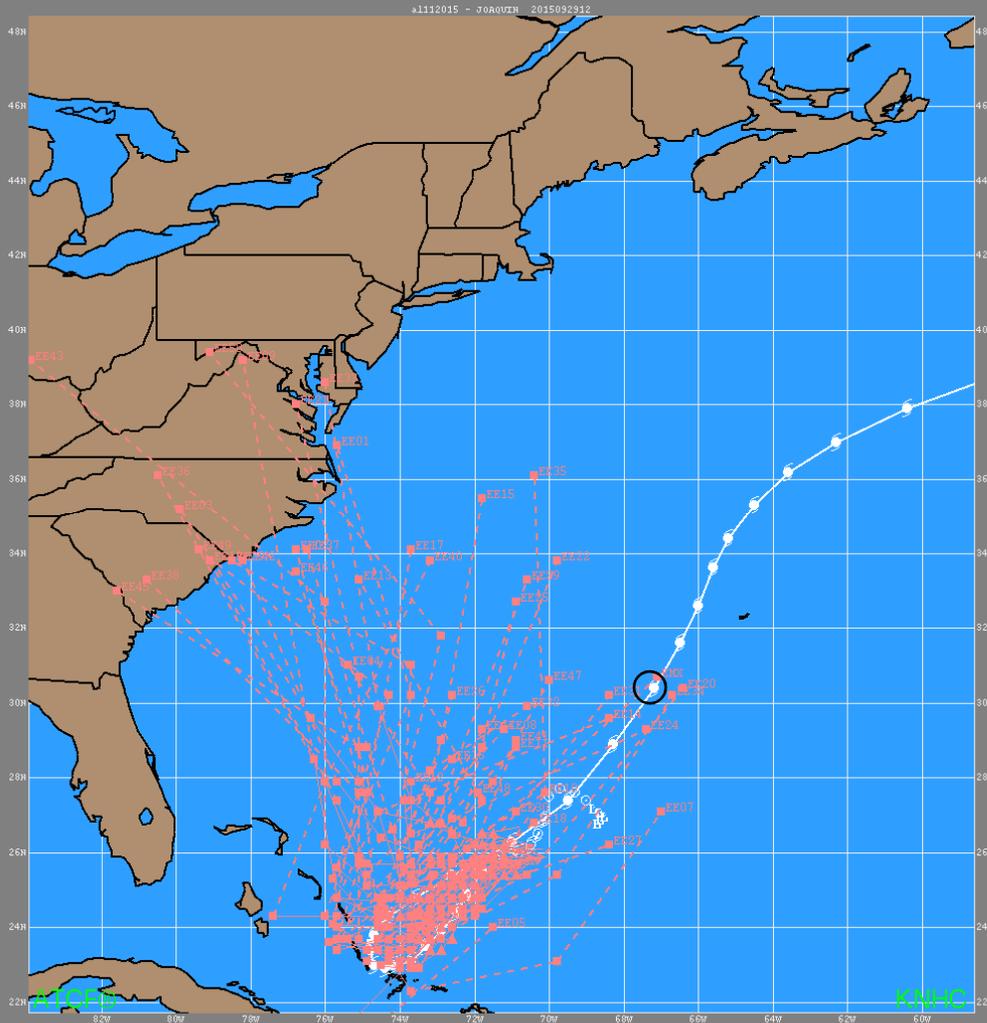
GEFS

EC Ensemble

GFS Joaquin ensembles 29 Sep 1200 UTC

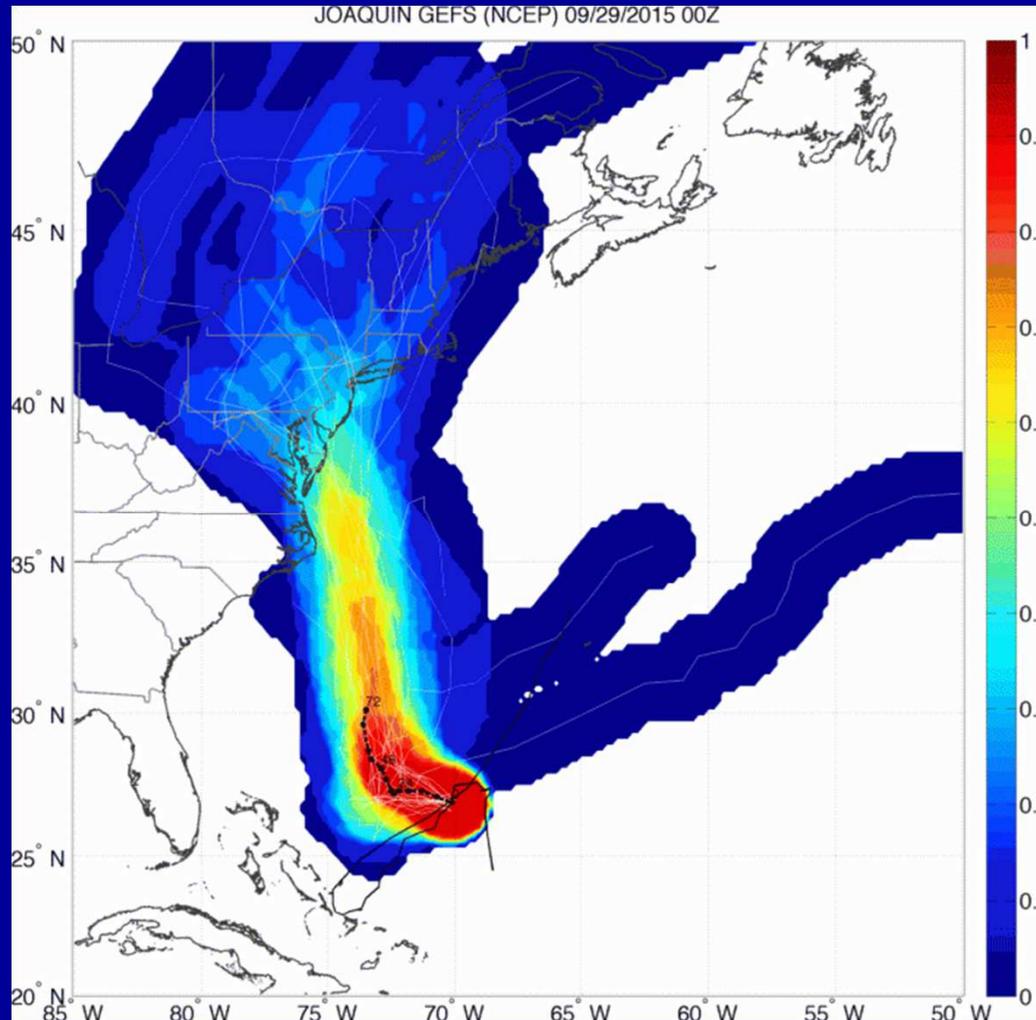


ECMWF Joaquin ensembles 29 Sep 1200 UTC

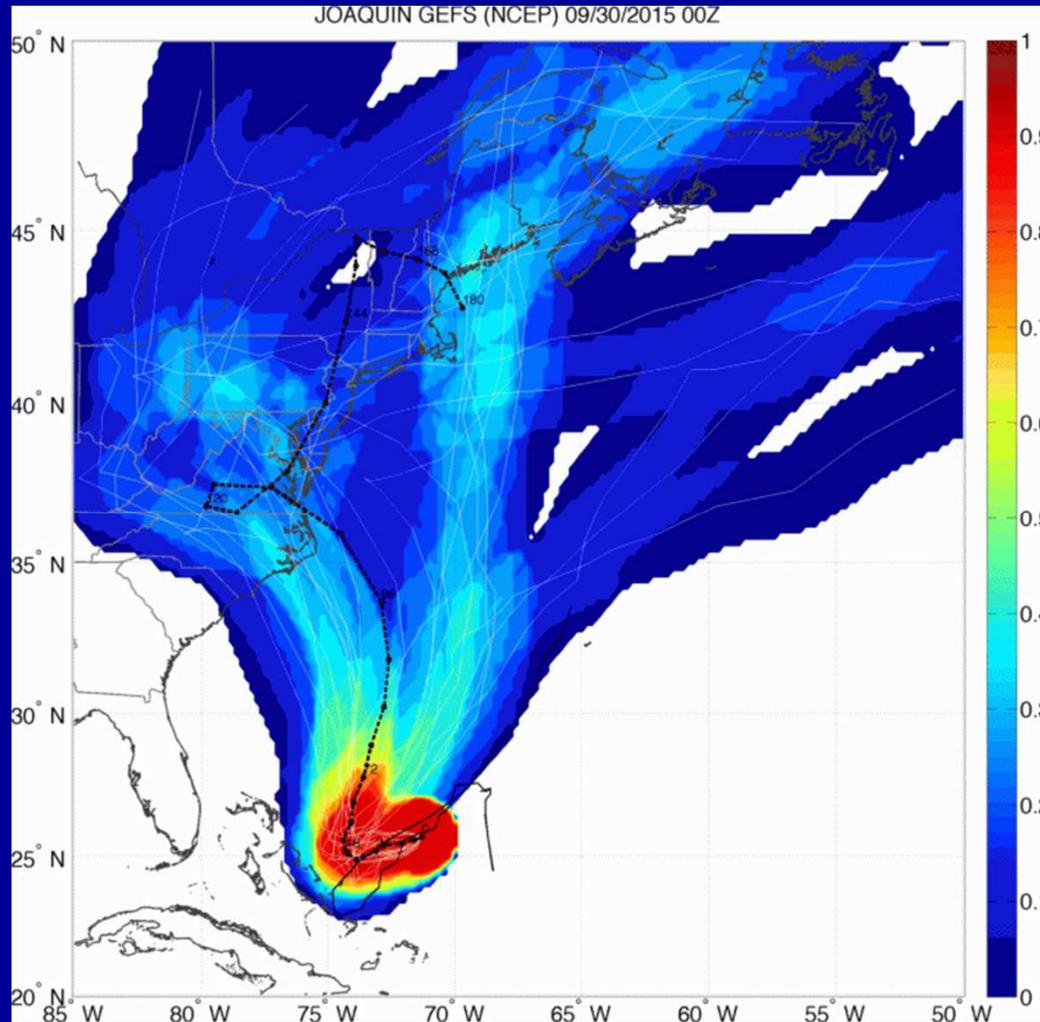


A different way to view the data using probabilities

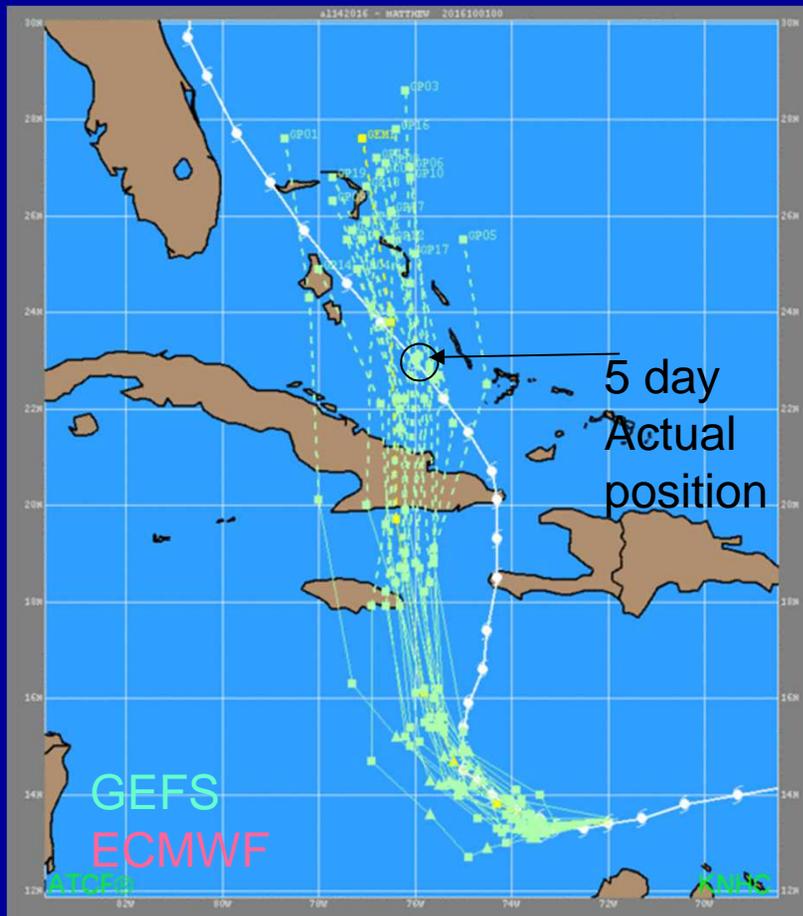
GEFS vs EC Ensemble 29 Sep 0000 UTC



GEFS vs EC Ensemble 30 Sep 0000 UTC



Matthew ensemble guidance 1 Oct 00 UTC

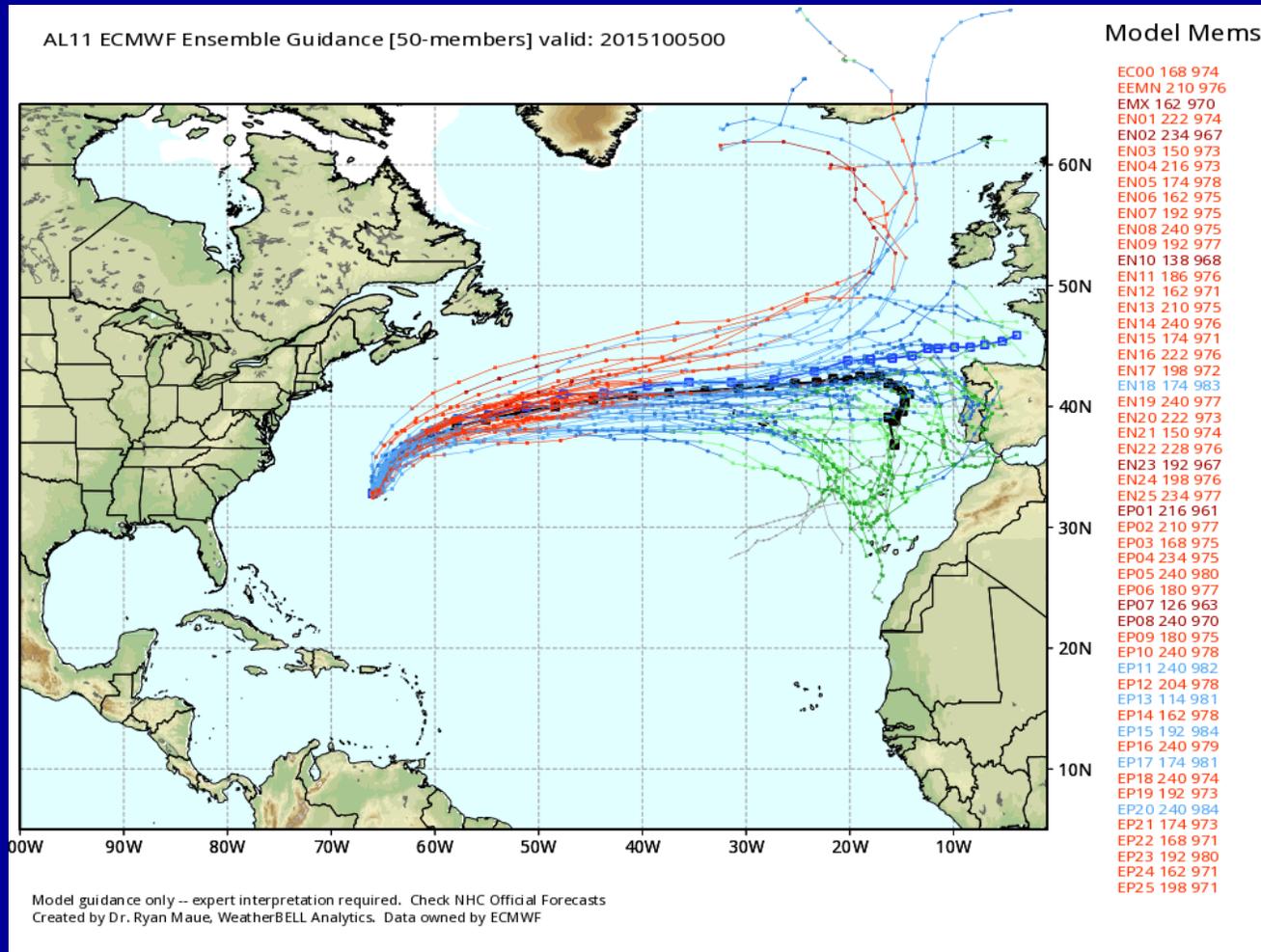


GEFS (blue) too underdispersive,
especially in Caribbean

Every single GEFS member also
too fast at 5 days

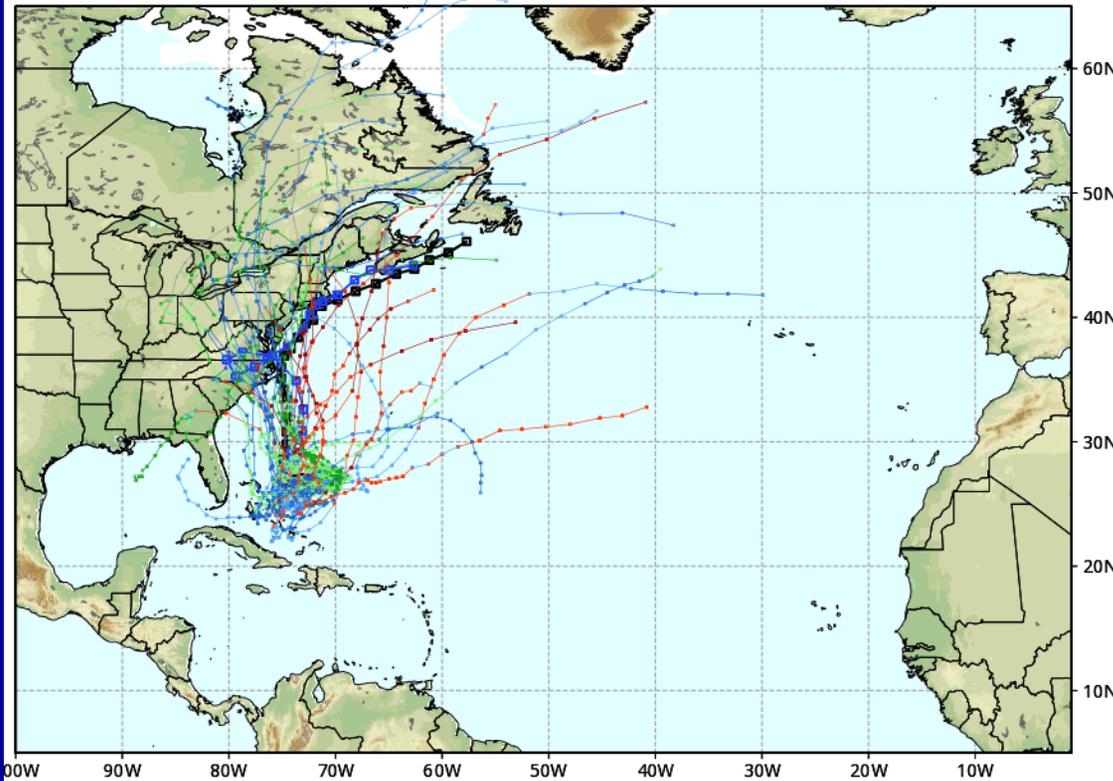
ECMWF (red) has more realistic
spreads, albeit potentially too large

ECMWF ensemble colored by intensity



AL11 ECMWF Ensemble Guidance [50-members] valid: 2015092812

Model Membs



- EC00 132 993
- EEMN 240 987
- EMX 228 980
- EN01 204 966
- EN02 090 1002
- EN03 168 997
- EN04 186 991
- EN05 174 996
- EN06 054 1007
- EN07 060 1007
- EN08 174 998
- EN09 066 1002
- EN10 240 962
- EN11 090 1003
- EN12 222 967
- EN13 240 960
- EN14 240 983
- EN15 240 979
- EN16 240 965
- EN17 084 1002
- EN18 186 1000
- EN19 108 998
- EN20 234 963
- EN21 168 988
- EN22 240 986
- EN23 216 997
- EN24 240 995
- EN25 168 996
- EP01 240 986
- EP02 240 964
- EP03 240 986
- EP04 240 976
- EP05 114 1006
- EP06 240 976
- EP07 240 976
- EP08 084 1006
- EP09 240 964
- EP10 066 1005
- EP11 240 972
- EP12 126 1003
- EP13 156 993
- EP14 174 998
- EP15 150 1002
- EP16 066 1006
- EP17 240 968
- EP18 240 966
- EP19 234 995
- EP20 216 968
- EP21 240 988
- EP22 114 1002
- EP23 240 962
- EP24 150 996
- EP25 240 969

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

-Stronger members farther right
-Weaker members farther north

Question 2

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

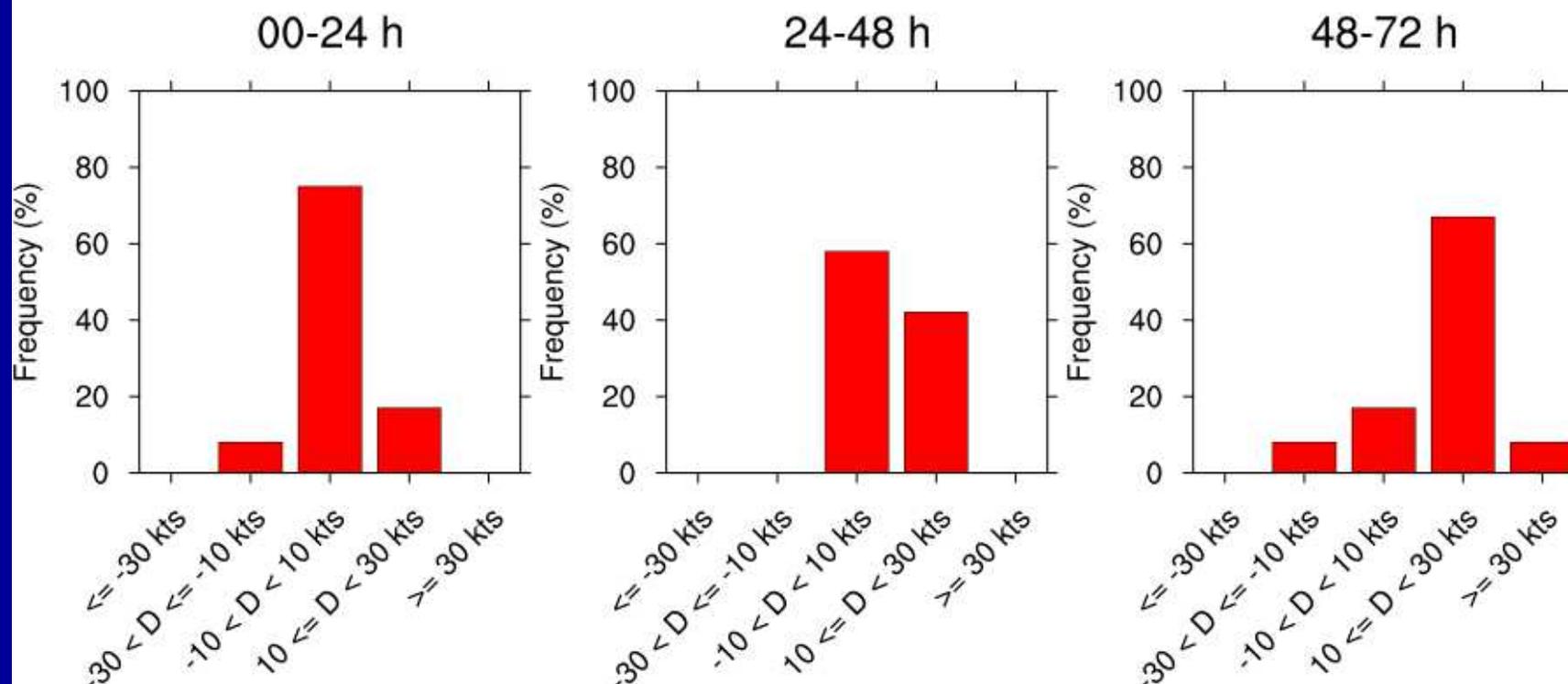
- A. Unusual forecast track cases
- B. When TC track is dependent on intensity
- C. If deterministic models are in poor agreement
- D. All of the above
- E. B & C

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

GPMN 2016093006 MATTHEW (AL14)



Online Access to Ensemble Output and Training Resources

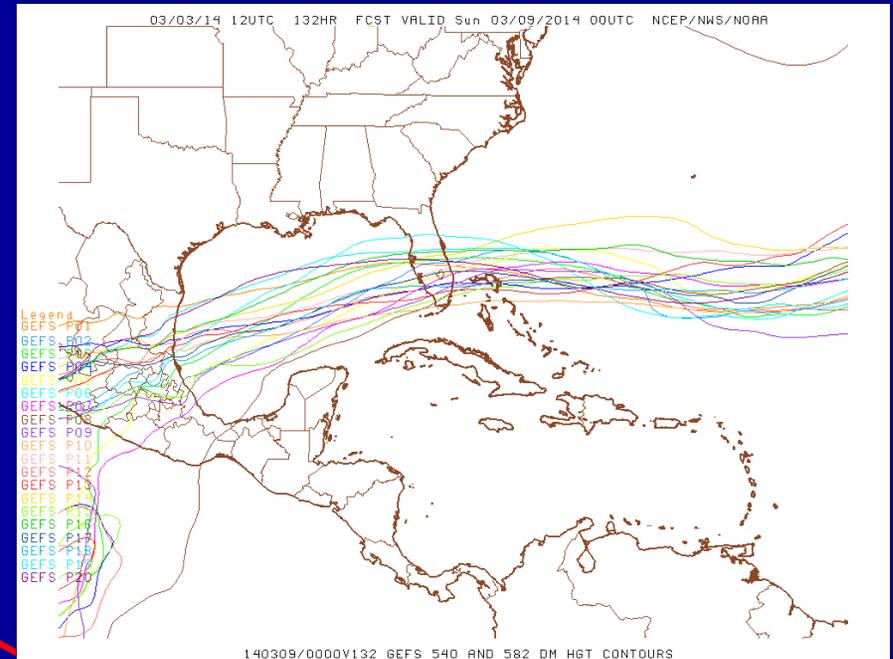
Access to Ensemble Output

NCEP GEFS and NAEFS: <http://mag.ncep.noaa.gov/>

The screenshot shows the National Weather Service (NWS) website interface for NCEP Central Operations. The page title is "Model Guidance". It features a navigation menu on the left with various links like "Local forecast by 'City, St'", "NCEP Quarterly Newsletter", "Current Hazards", "Observations", "Satellite Images", "Radar Imagery", "Lakes & Rivers", "Space Weather", "Unified Surface Analysis", "Northern Hemisphere Surface Analysis", "Product Loops", "Environmental Models", "Product Info", "Current Status", "Model Analyses & Guidance", "Forecasts", "Climate Prediction", "Weather Safety", "Storm Ready", "NOAA Central Library", and "Photo Library". The main content area has a "Back" button, a "Reset Selection(s)" button, and a prompt to "Choose a Model Area or re-select a different Model Type". Below this is a table of model areas and types. A red arrow points from the "NAEFS" link in the table to a spaghetti plot on the right.

Model Area	NAMER	SAMER	AFRICA	NPAC	EPAC	WNATL
	ATLANTIC	POLAR	ATLPAC	EUS	WUS	ALASKA
	EUROPE	ASIA	SPAC	ARCTIC		

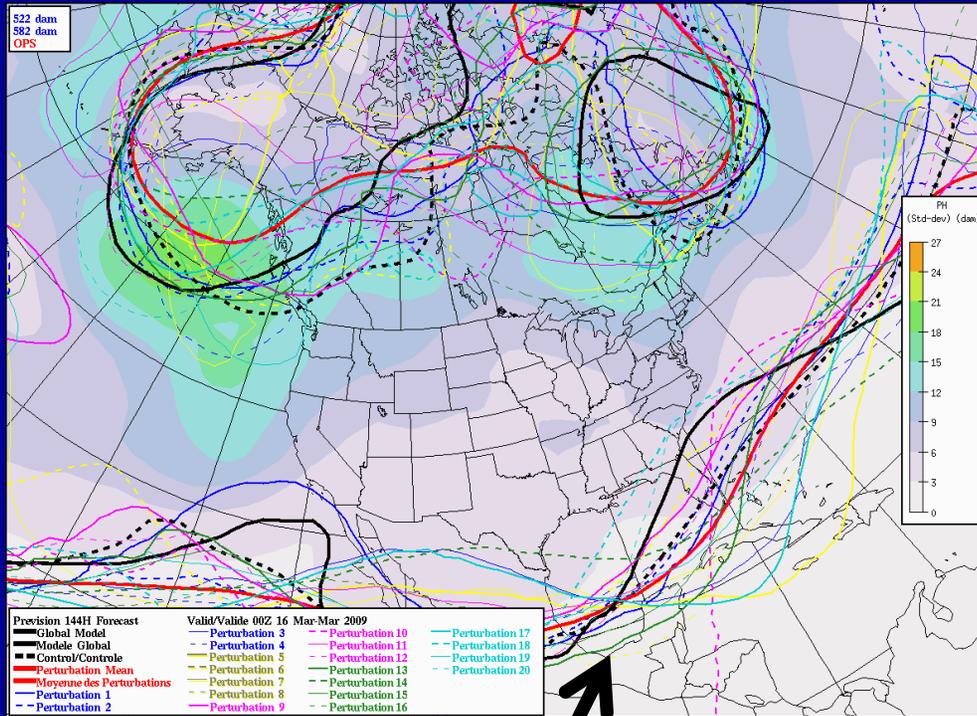
Model Type	GFS	NAM	SREF	WW3	HRW-NMM-EUS	HRW-ARW-EUS
	GEFS-SPAG	NAM-HIRES	NAEFS	WW3-ENP	HRW-NMM-WUS	HRW-ARW-WUS
	GEFS-MNSPRD	RAP	POLAR	WW3-WNA	HRW-NMM-AK	HRW-ARW-AK



Access to ensemble mean, spread, and spaghetti plots

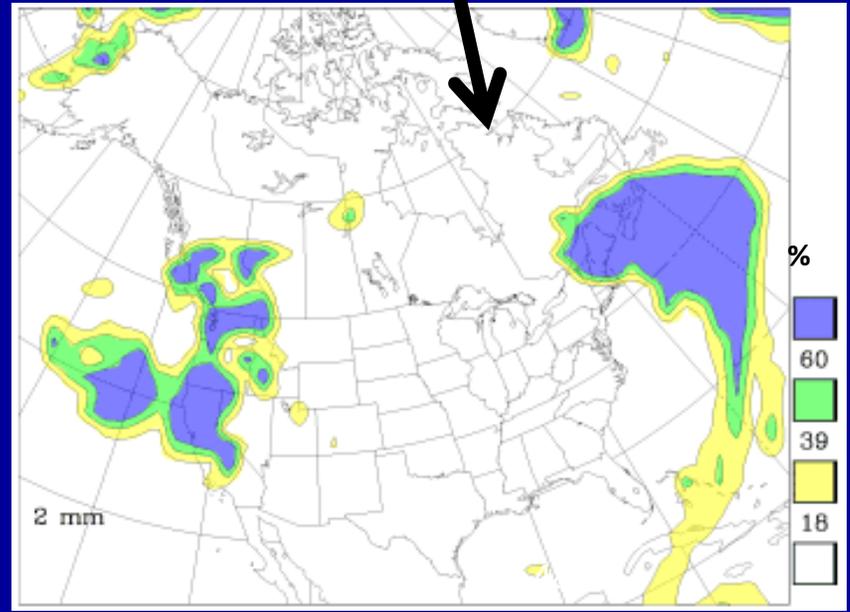
Canadian Ensembles

http://weather.gc.ca/ensemble/index_e.html



Spaghetti diagram of 500-mb 522 and 582 dm height contours

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



Access to Ensemble Output

- ECMWF Ensembles:

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

The screenshot displays the ECMWF website interface. At the top, the ECMWF logo is on the left, and navigation links for 'About', 'Forecasts', 'Computing', 'Research', 'Learning', and 'Log In' are in the center. A search bar is on the right. Below the navigation is the title 'Ensemble mean and spread: four standard parameters'. On the left side, there is a sidebar menu with links: 'Charts', 'Datasets', 'Quality of our forecasts', 'Software and tools', 'Documentation and support', 'Accessing forecasts', and 'Back to charts'. The main content area features two side-by-side maps of the North Atlantic region. The left map is titled 'Friday 27 February 2015 00UTC ECMWF Forecast t+0 VT: Friday 27 February 2015 00UTC Mean sea level pressure (MSLP) Ensemble Mean and Normalised Standard Deviation (shaded)'. The right map is titled 'Friday 27 February 2015 00UTC ECMWF Forecast t+0 VT: Friday 27 February 2015 00UTC Mean sea level pressure (MSLP) HRES Forecast and Standard Deviation (shaded)'. Both maps show contour lines for MSLP and shaded areas representing standard deviation. A color scale for 'Norm StDev' is shown between the maps, ranging from 0.0 to 15.0. Below the maps is a timeline navigation bar with days from Friday 27 to Sunday 08. Below the maps, there is a section titled 'Ensemble mean and spread: four standard parameters' with a paragraph explaining the visualization of the ECMWF Ensemble Prediction System (ENS) output for four parameters: mean sea level pressure, 850 hPa temperature, 850 hPa wind speed, and 500 hPa geopotential height. It also mentions that the charts are updated every 12 hours and provides details on the forecast validity period and update times.

Ensemble mean and spread: four standard parameters

On this page you can visualise output from the ECMWF 'Ensemble Prediction System' (ENS), for four parameters: **mean sea level pressure, 850 hPa temperature, 850 hPa wind speed and 500 hPa geopotential height.**

These charts are updated once every 12 hours at approximately 08:30 UTC and 20:30 UTC. Each chart header is labelled with the date and time when the ensemble forecasts were initiated (D0), which will be 00UTC for the 08:30 UTC update, and 12UTC for the 20:30 UTC update. Each map is then valid for a date between D0 + 1 and D0 + 10days, which is indicated in the chart header by VT (=Valid Time) and which can be adjusted using drop down menus above the plot (grey boxes). Additional drop down

COMET Courses

<http://www.meted.ucar.edu>

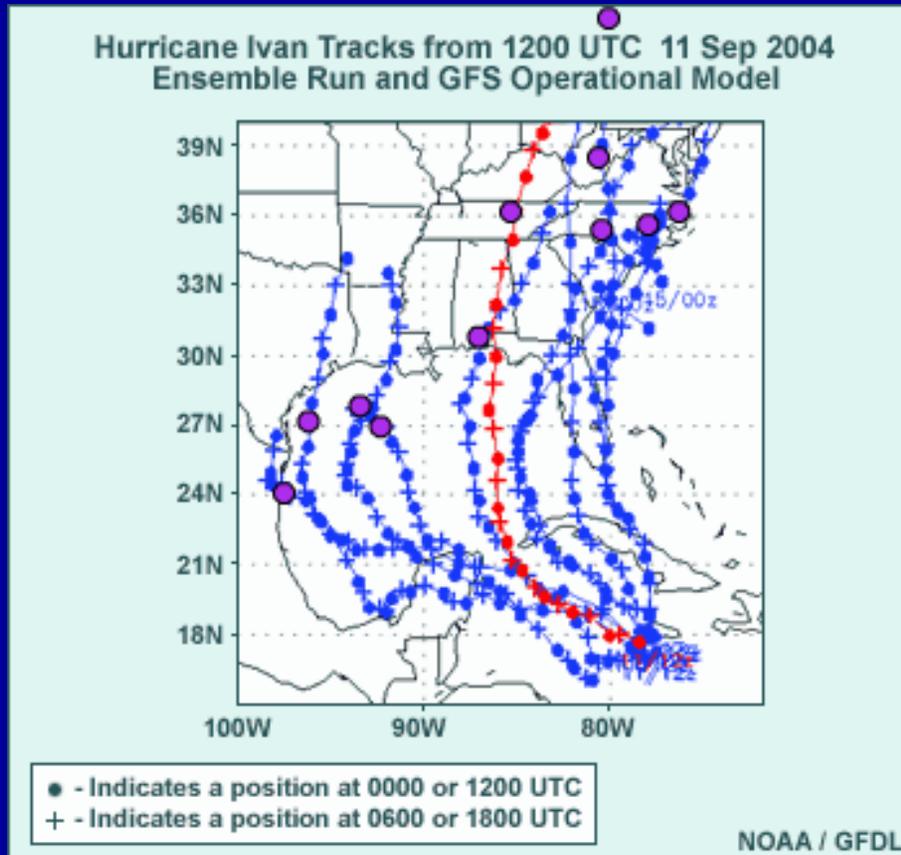
- Introduction to Ensemble Prediction:
http://www.meted.ucar.edu/nwp/pcu1/ensemble_webcast/
- Ensemble Forecasting Explained:
<http://www.meted.ucar.edu/nwp/pcu1/ensemble/>
- Ensemble Prediction System Matrix: Characteristics of Operational Ensemble Prediction Systems (EPS):
http://www.meted.ucar.edu/nwp/pcu2/ens_matrix/
- 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?

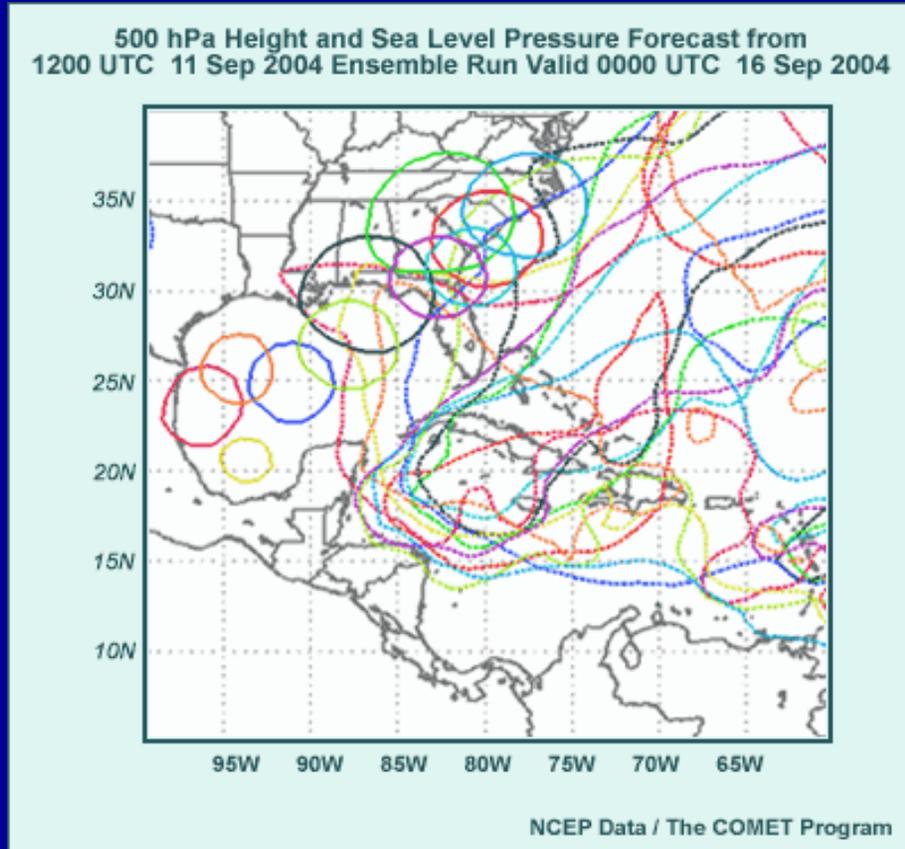
Case Example

Ensemble Forecast Example



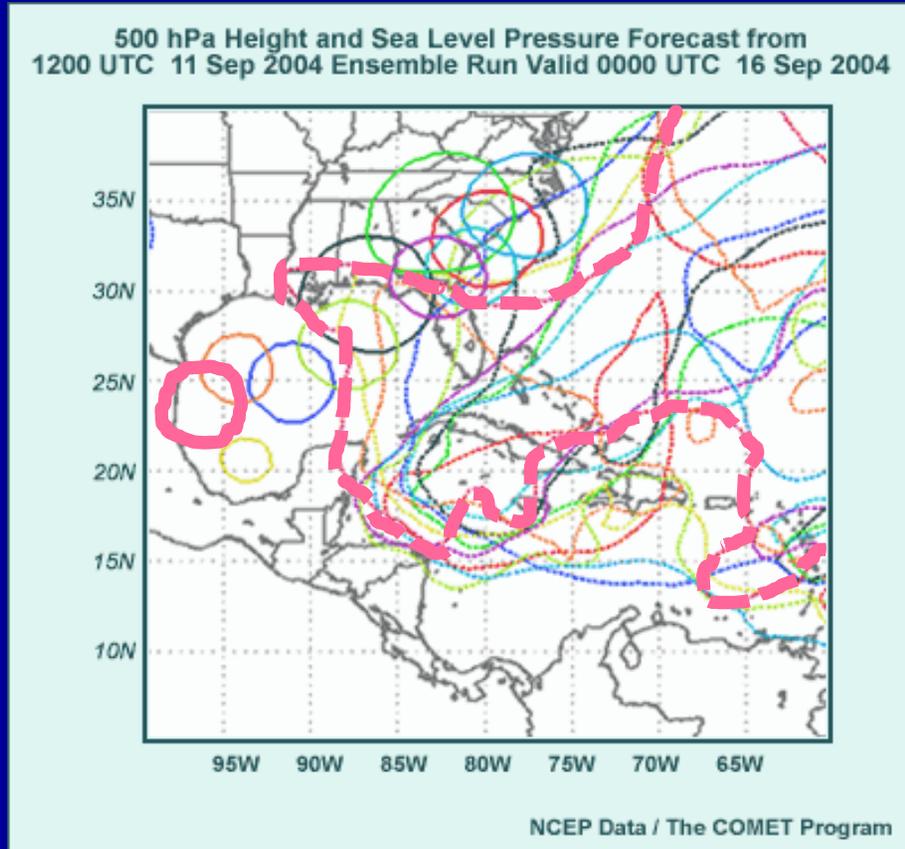
- Initial time: 1200 UTC 11 Sep 2004
NCEP Ensemble members  and operational GFS 
- Purple dots = forecast position at 0300 UTC 17 Sep 2004 (FHR135)
- Ensemble forecast shows large uncertainty in ultimate path of Hurricane Ivan
- Tendency for clustering of tracks
 - 5 members east of the GFS track and faster than GFS at 0300 UTC 17 Sep 2004
 - 4 members west of GFS
 - Operational GFS and 1 member in the middle of the ensemble solutions

Ensemble Forecast Example



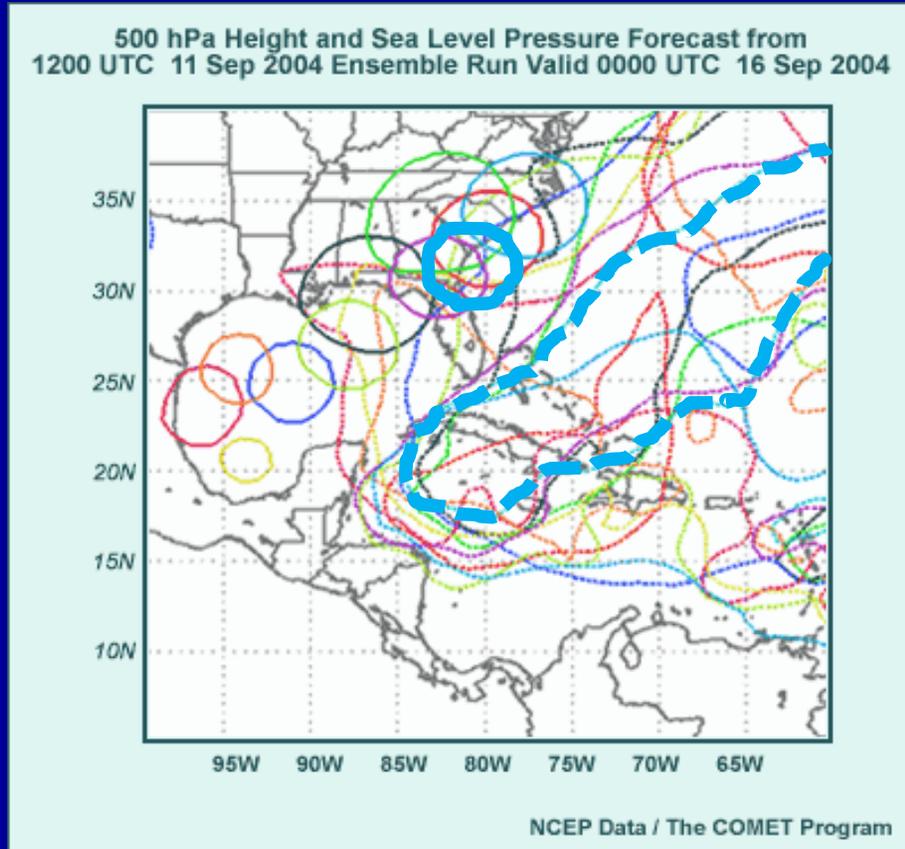
- **Forecast: 0000 UTC 16 Sept 2004
108-hour NCEP ensemble forecast**
- **500-mb 589-dm height (dashed) and
1000-mb PMSL (solid), color coded by
ensemble member**
- **Degree of weakening of western
Atlantic ridge over the northeast Gulf
of Mexico determines position of
Hurricane Ivan**
 - Ridge strongest in pink: Ivan near
northeastern Mexico, 589-dm height
contour in mid-Gulf
 - Ridge weakest in light blue: Ivan over
the Georgia coast, 589-dm height
contour over the western
Atlantic/northwest Caribbean

Ensemble Forecast Example



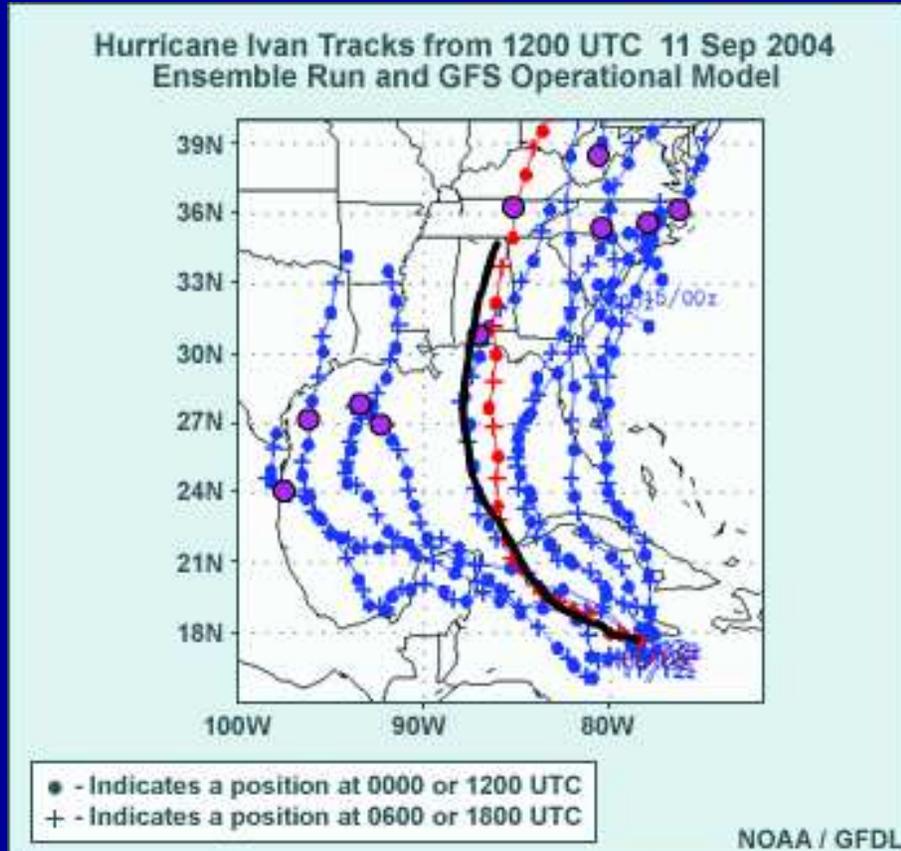
- Forecast: 0000 UTC 16 Sept 2004
108-hour NCEP ensemble forecast
- 500-mb 589-dm height (dashed) and
1000-mb PMSL (solid), color coded by
ensemble member
- Degree of weakening of western
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Ensemble Forecast Example



- Ultimate path for Hurricane Ivan (black) - not too far from GFS and in the middle of the ensemble envelope of solutions
 - Wide envelope of possible tracks
 - Because of uncertainty in the weakening of the Atlantic ridge, it turned out to be the best solution
 - Typically, one would be wary of using the ensemble mean forecast when there is clustering of the solutions
 - Look at the handling of the ridge by the other dynamical models to determine which “cluster” to lean toward