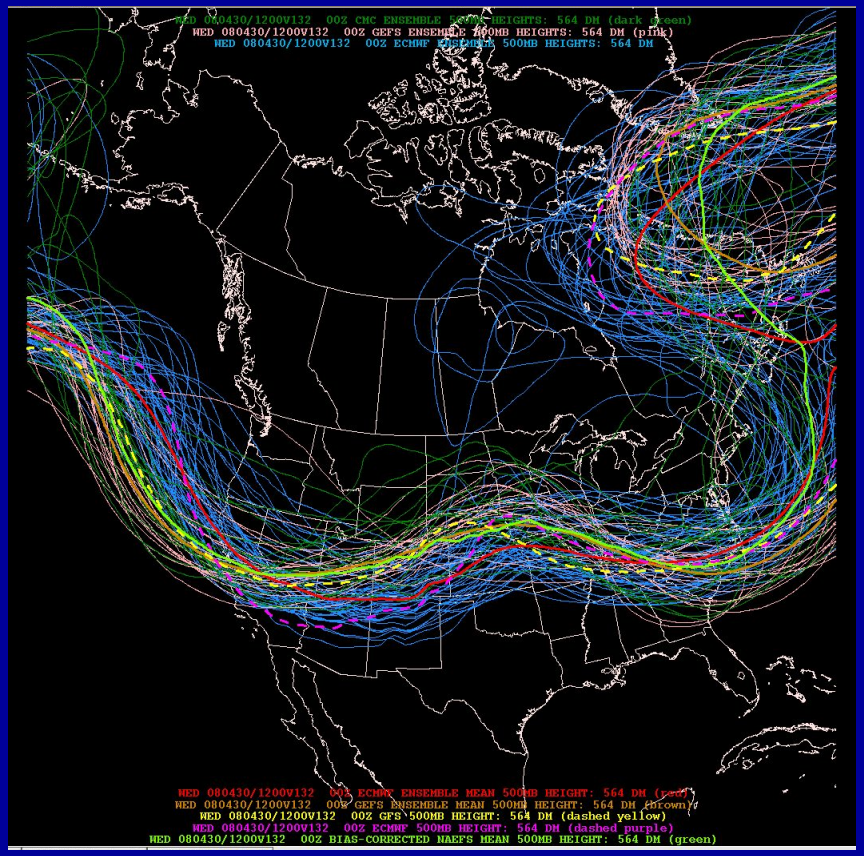
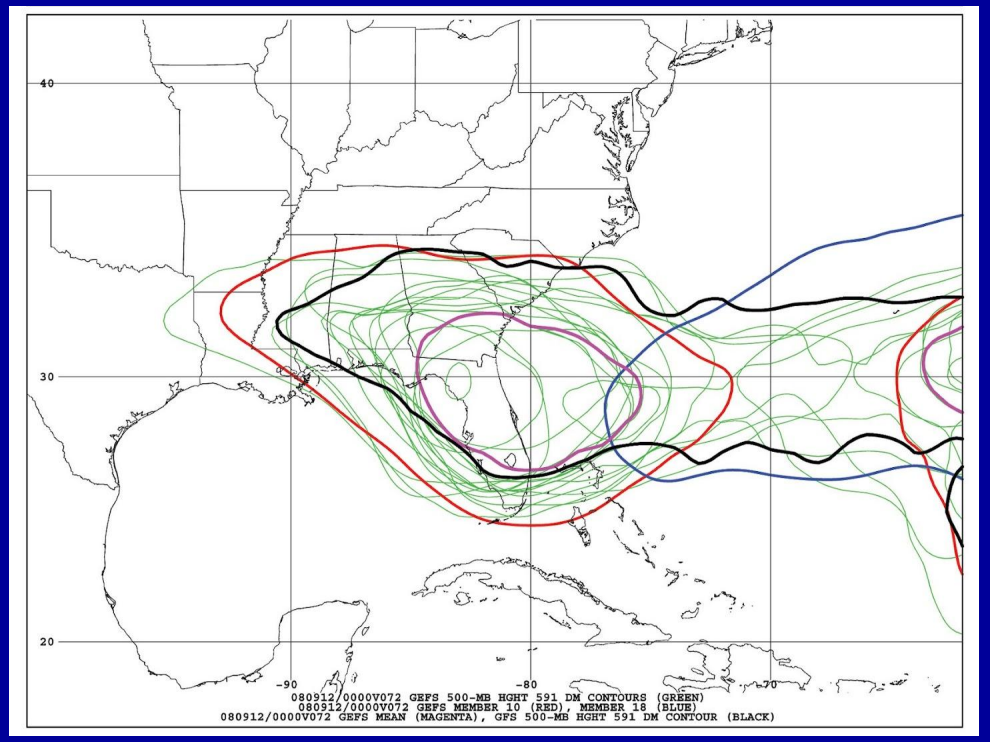
Ensemble Prediction Systems





Eric Blake
National Hurricane Center
2024

Acknowledgements to Dr. Michael Brennan

What are some current advantages of using single-model ensembles? Select all that apply.

0

Estimates of uncertainty	0%
TC intensity model spread	0%
Alternative TC-track solutions	0%
The correct track will always be within the spread	0%

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

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*

Deterministic vs Ensemble

- **Deterministic** - single forecast from one forecast model or method using a single set of initial conditions
  - Examples: GFS, ECMWF, UKMET, HMON, HWRF, HAFS
- **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

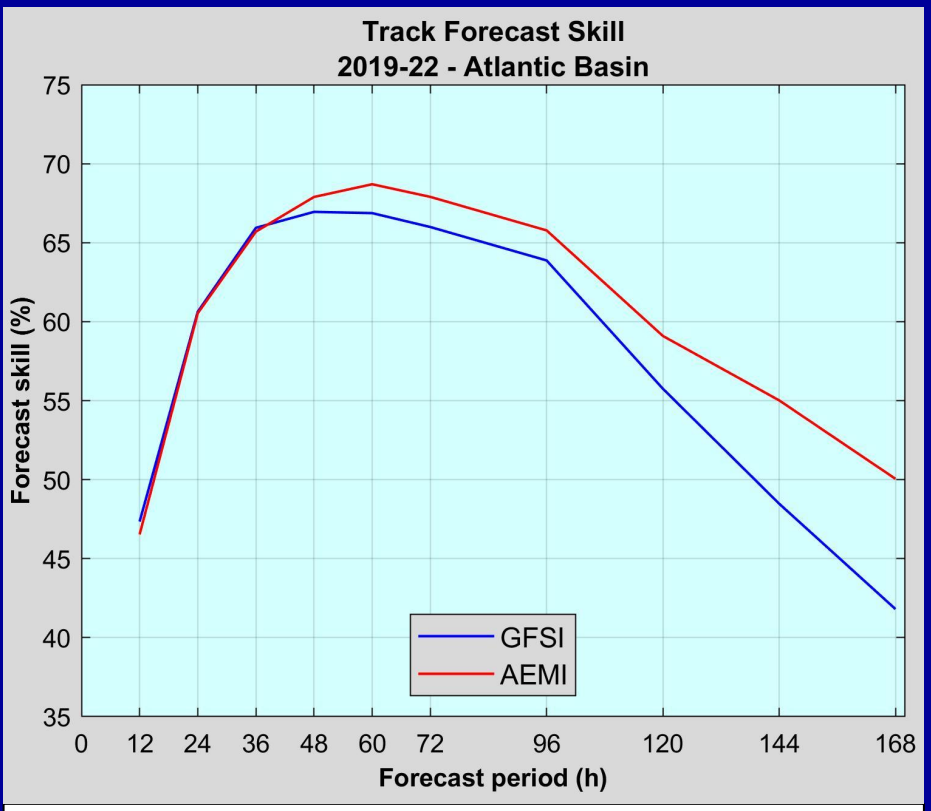
Definitions

- **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 (EPS)
- **Control Run** – for dynamical model ensembles, usually 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

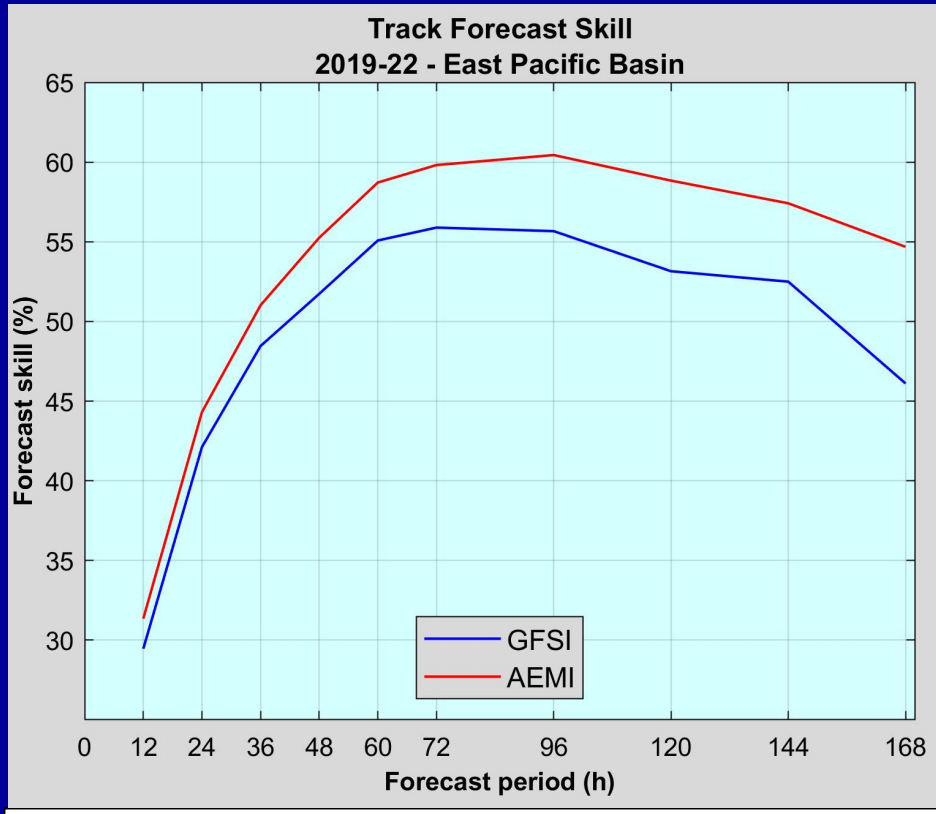
Ensemble Mean vs. Deterministic

- 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

GEFS Mean vs. GFS (2019-2022)

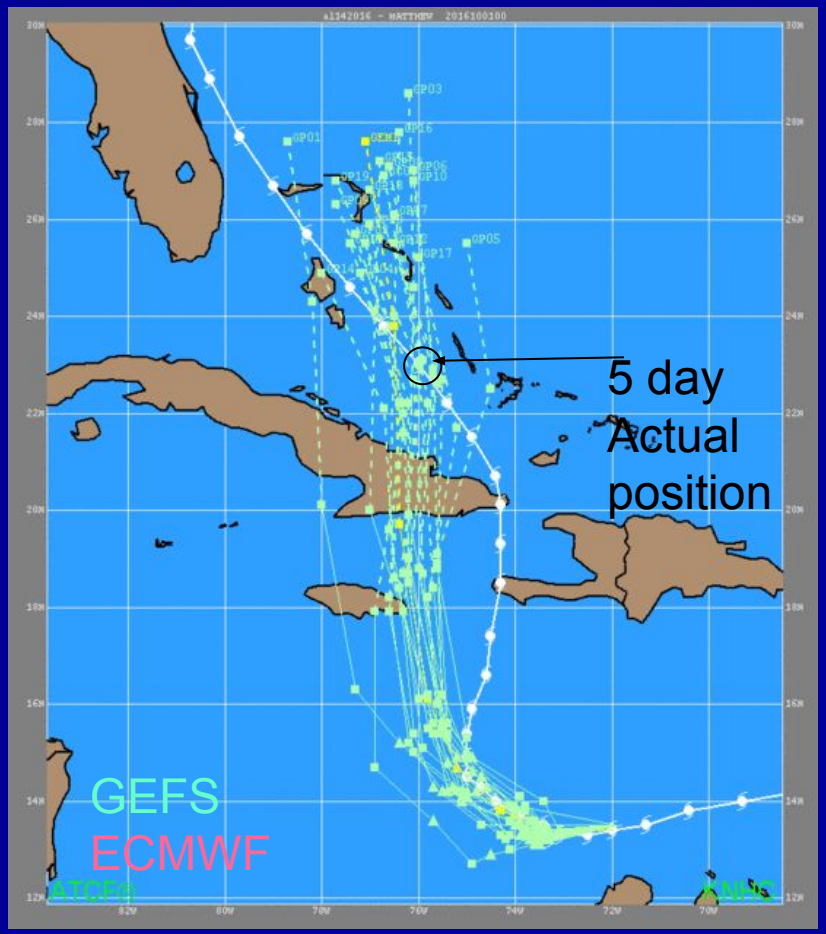


In the Atlantic, the GEFS ensemble mean track forecast (AEMI) is competitive with the deterministic GFS (GFSI) through 36 h and better afterward



Eastern Pacific – ensemble better at all times

Matthew ensemble guidance 1 Oct 00 UTC

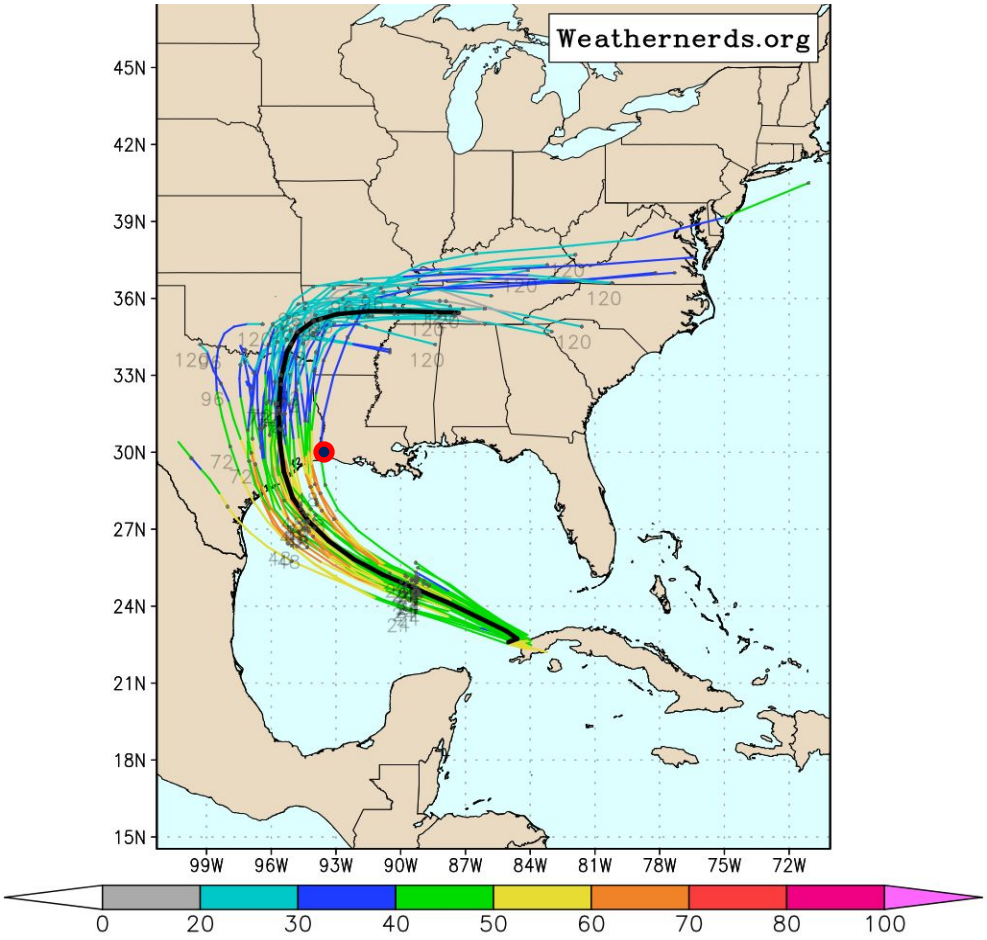


Old GEFS pre-2020 (blue) too underdispersive, especially in Caribbean

Every single GEFS member also too fast at 5 days

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

ECMWF ensemble tracks for Laura at Aug 25 0000 UTC



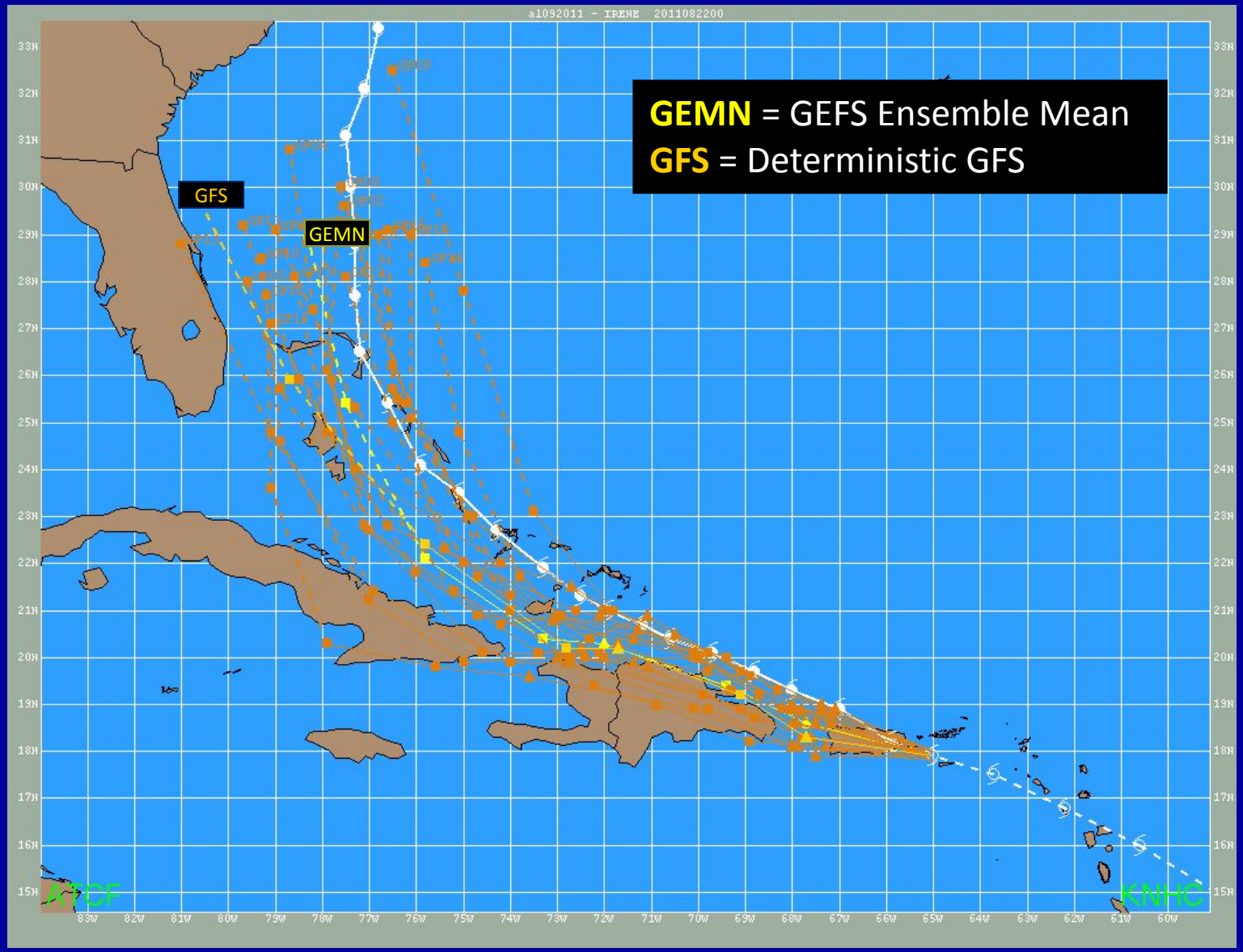
Every member was too far west

Don’t just worship at the altar of the ECMWF!

Single-Model Ensembles for TC Track Forecasting

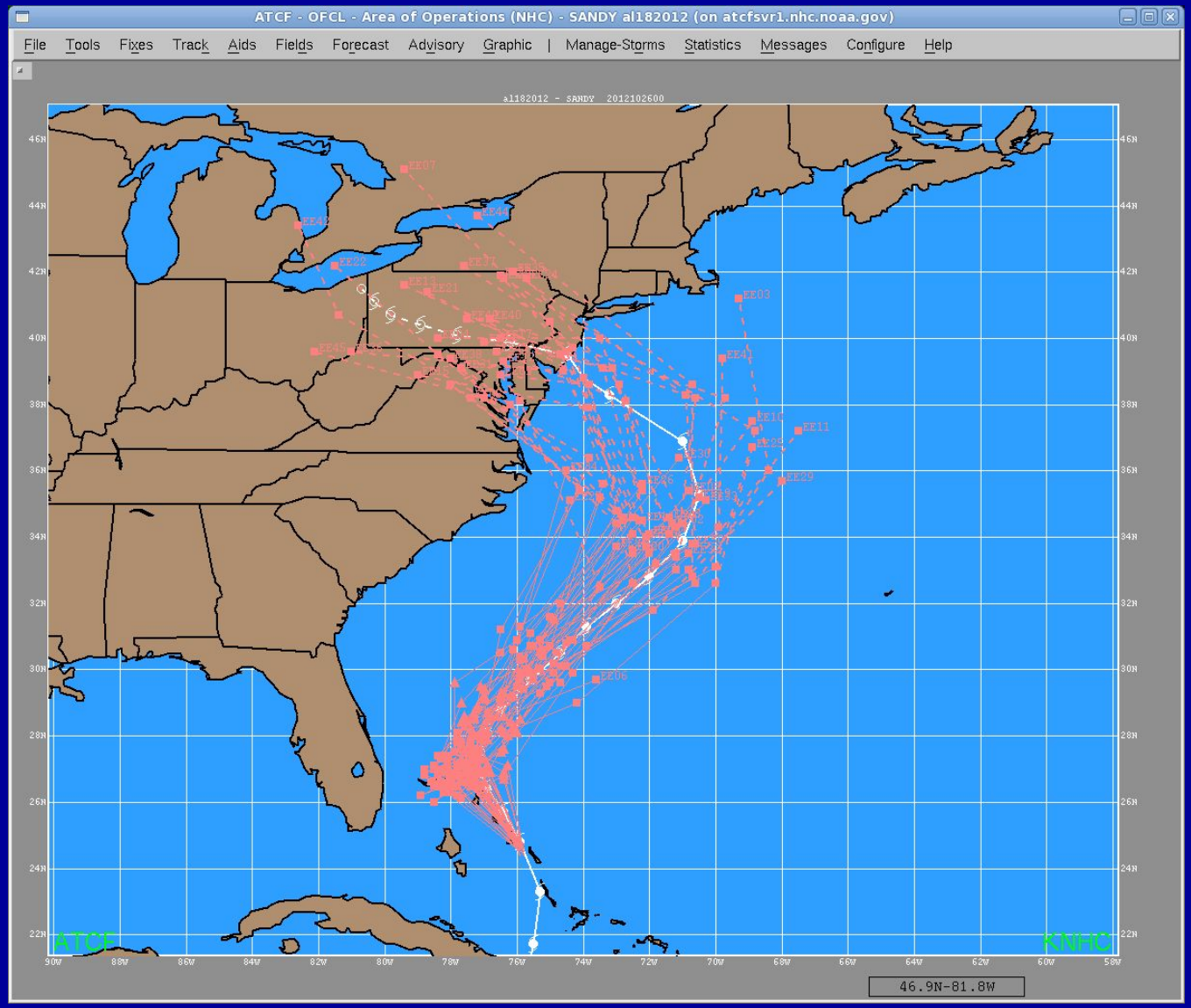
NCEP Global Ensemble Forecast System

Tropical Cyclone Track Forecast Guidance

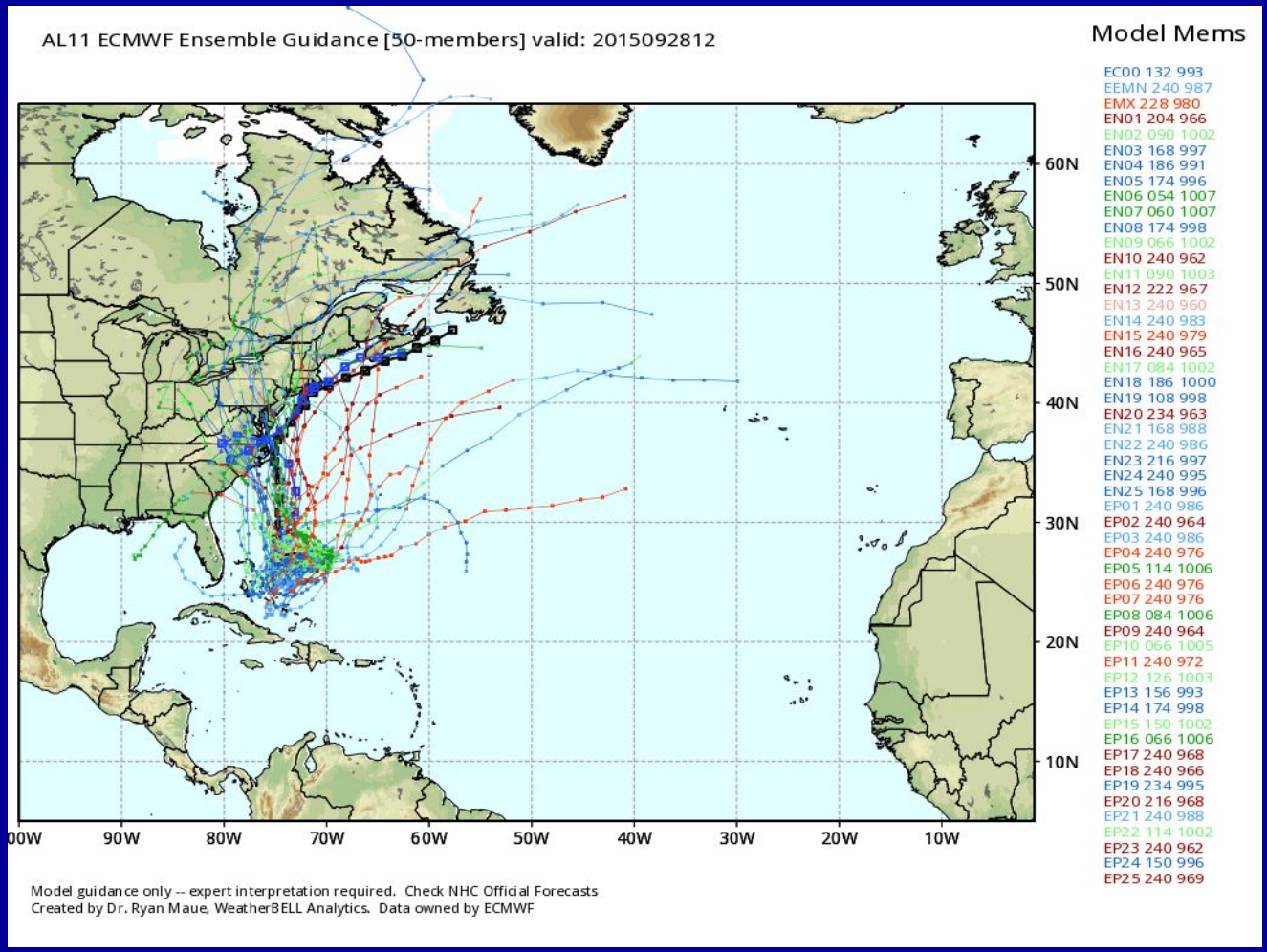


ECMWF Ensemble

Sandy example of desirable spread/verification



Track dependent on intensity?



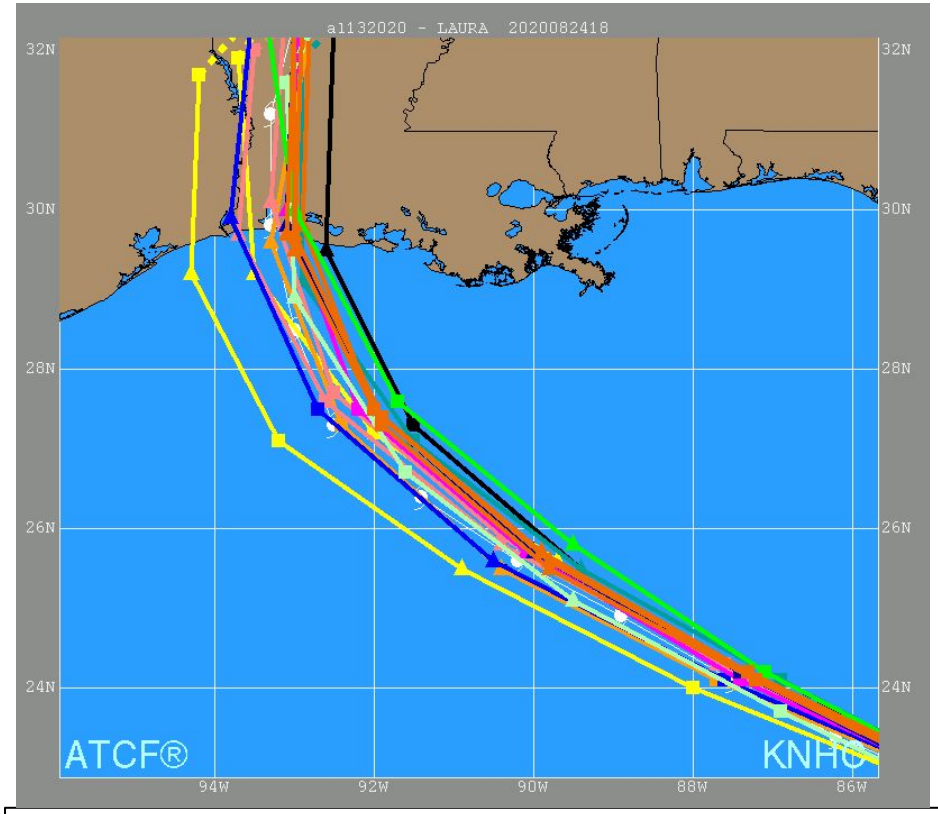
-Stronger members farther right

-Weaker members farther north

Ensemble Problems

- Need a properly calibrated system
  - GEFS used to be underdispersive (much better since upgrade)
  - This problem results in an overconfident forecast (UKMet ensemble has this more than EPS/GEFS now)
  - 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

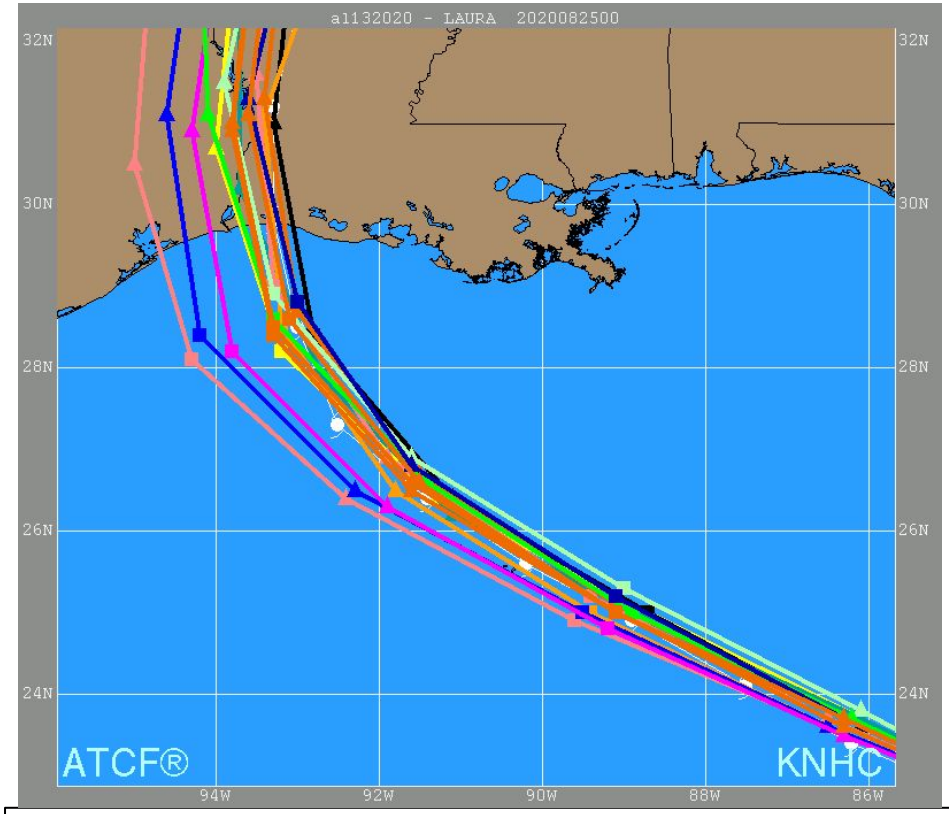
Incorrect Model Trends Near Landfall - Laura



Laura guidance 1800 UTC Aug 24

Guidance almost perfectly centered around the Louisiana landfall

Incorrect Model Trends Near Landfall - Laura

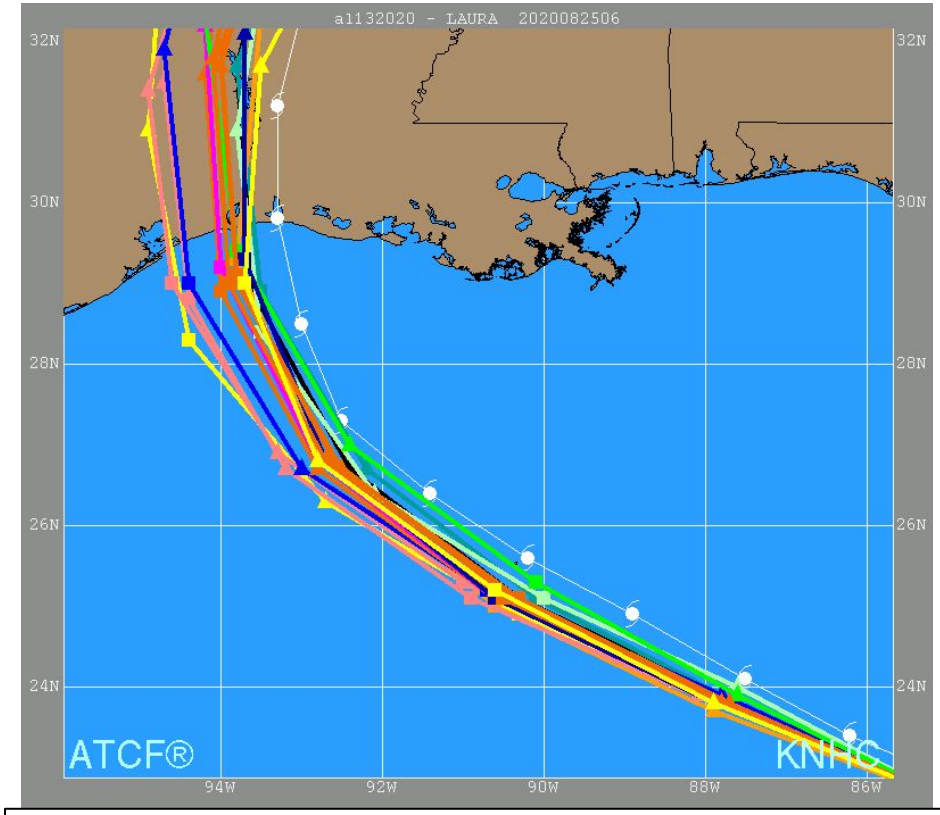


Laura guidance 0000 UTC Aug 25

6 hours later- trouble.

Notable westward shifts of ECMWF ensemble and corrected-consensus aids

Incorrect Model Trends Near Landfall - Laura



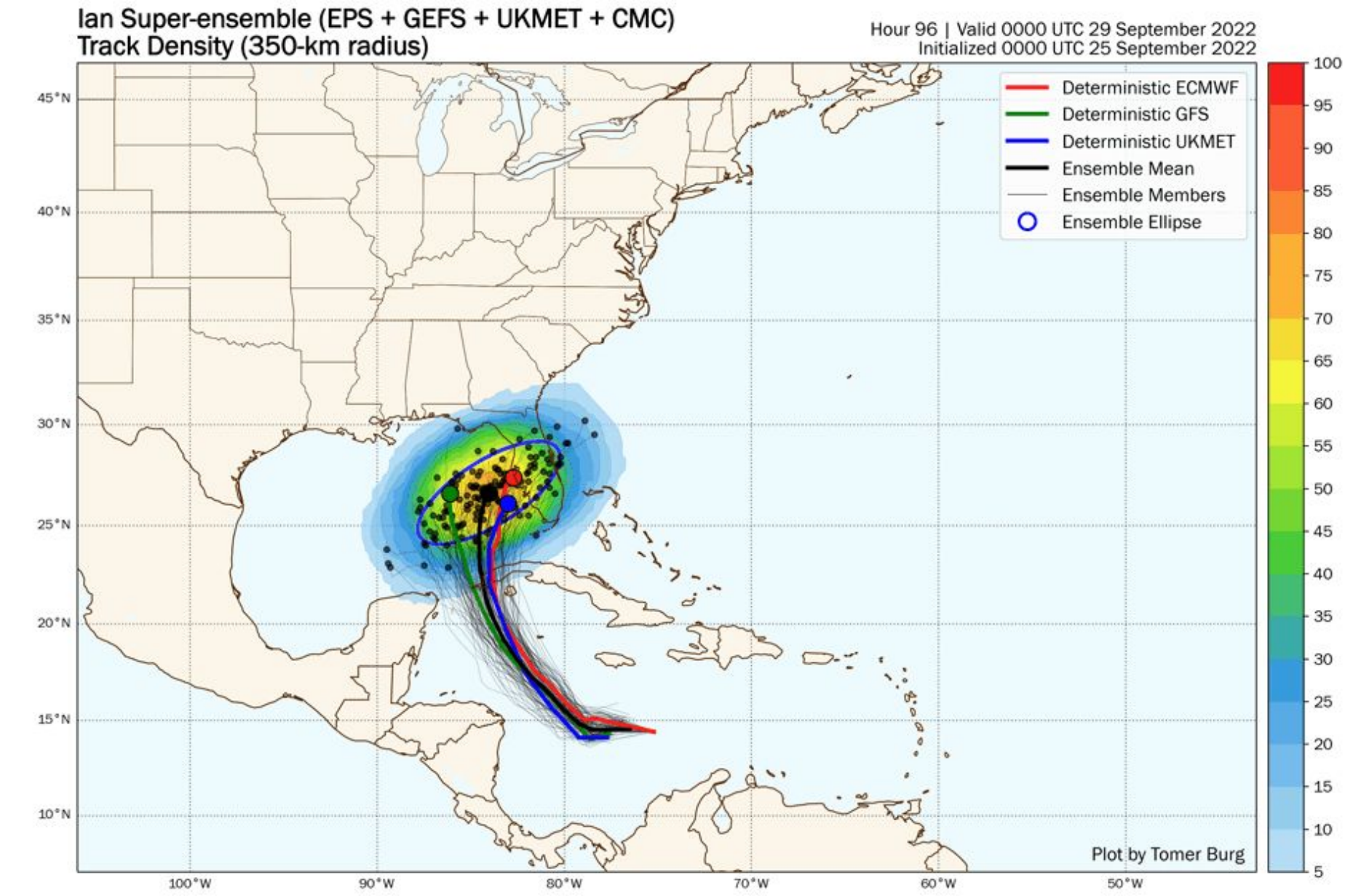
Laura guidance 0600 UTC Aug 25

Lots of models shifted west

NHC fcst did not leave LA

Expectation of a deep hurricane/SW winds in high-levels led NHC to stay on the E side of the guidance

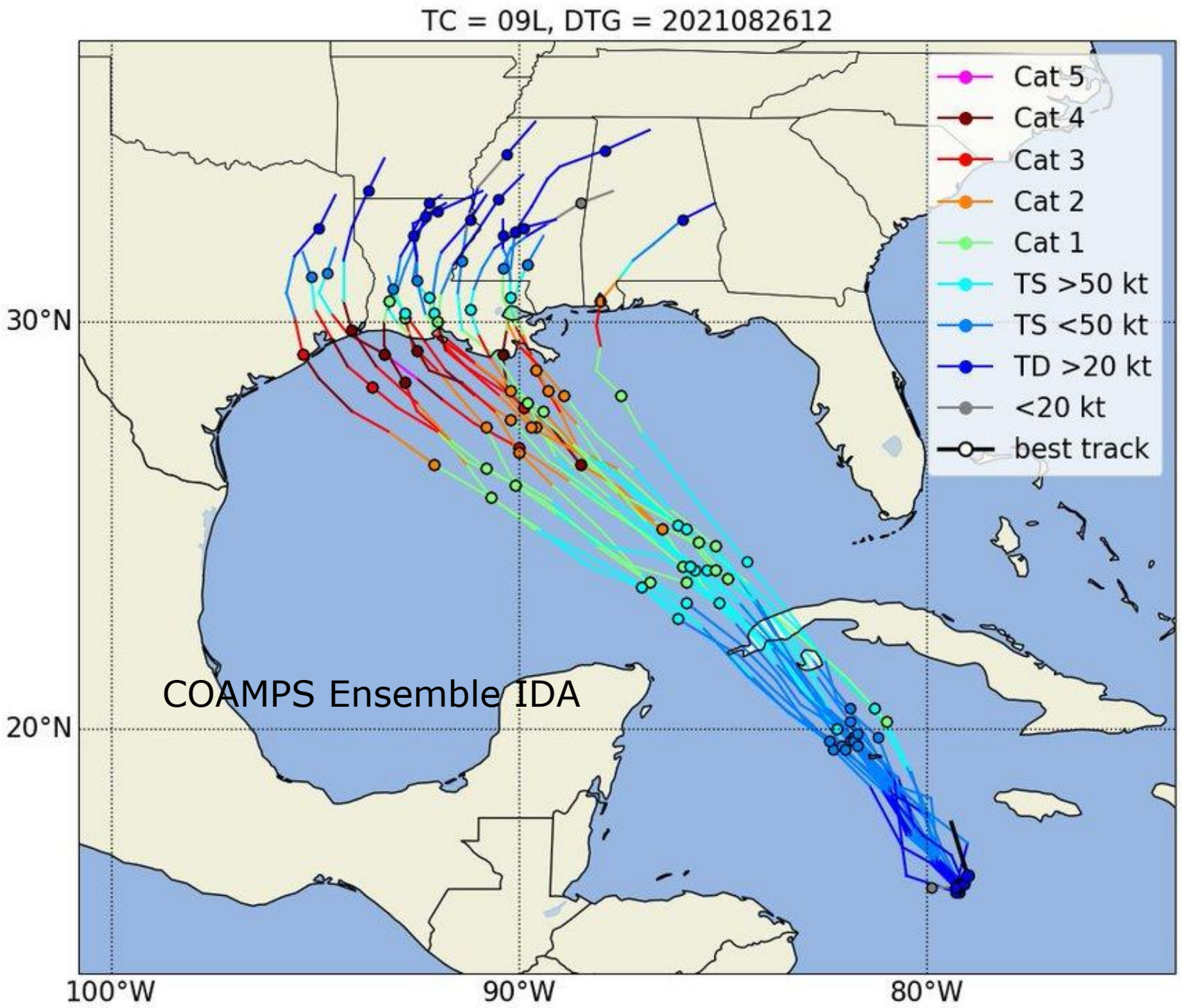
Huge Houston evacuation implications



Wave of the future – put all systems together and use probabilities?

TC Intensity Ensemble Forecasting

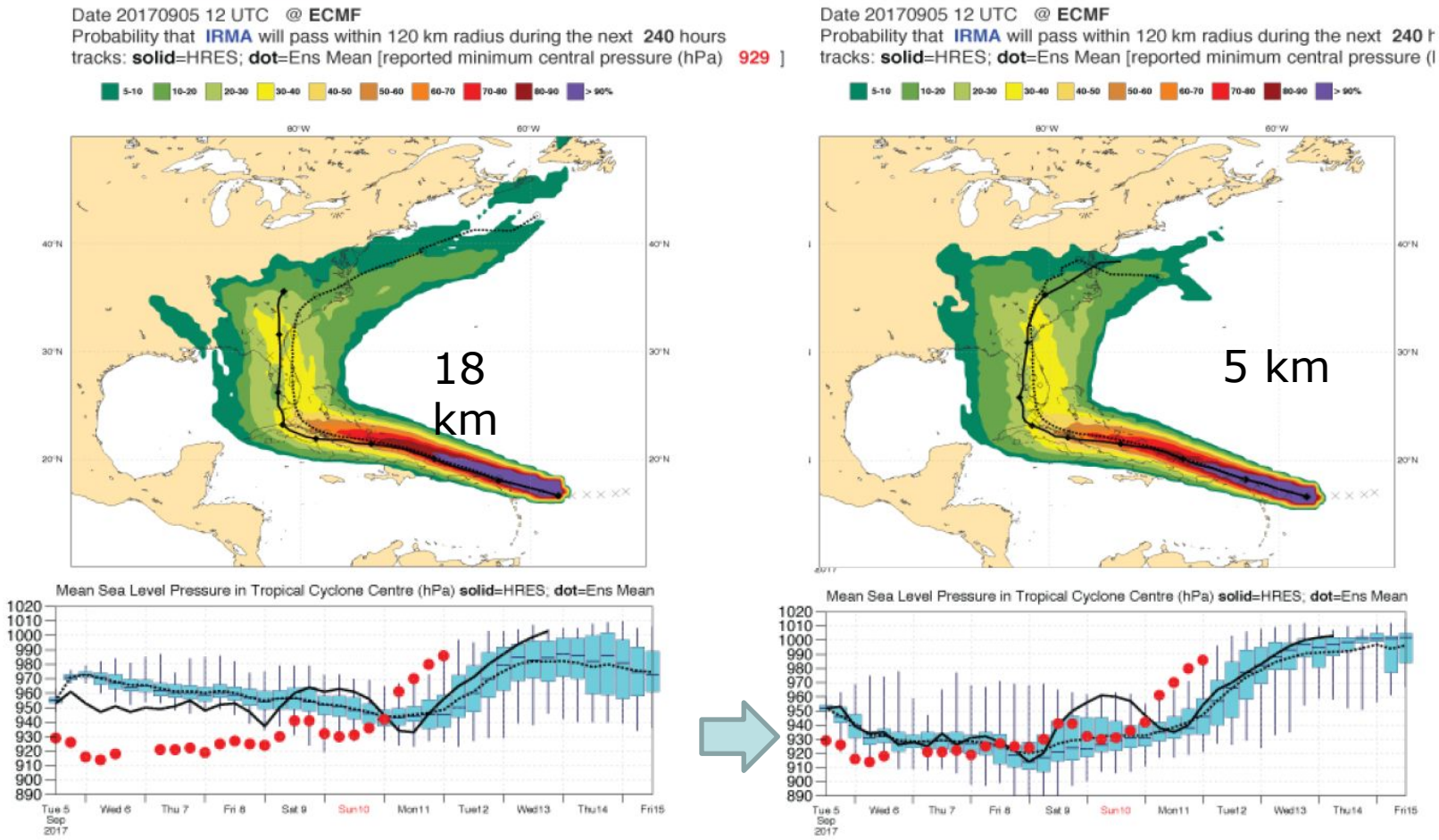
- Some skill above single-model deterministic
- Very computational expensive to run high-resolution (<3 km) intensity ensembles
- HFIP is funding efforts to find products that could be operationally useful


TC = 09L, DTG = 2021082612
Cat 5
Cat 4
Cat 3
Cat 2
Cat 1
TS >50 kt
TS <50 kt
TD >20 kt
<20 kt
best track
30°N
20°N
100°W
90°W
80°W
COAMPS Ensemble IDA

ECWMF experiment, 2030 desired resolution

Richardson, ECMWF, 2018

IRMA operational v. **5km**



Online Access to Ensemble Output and Training Resources

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

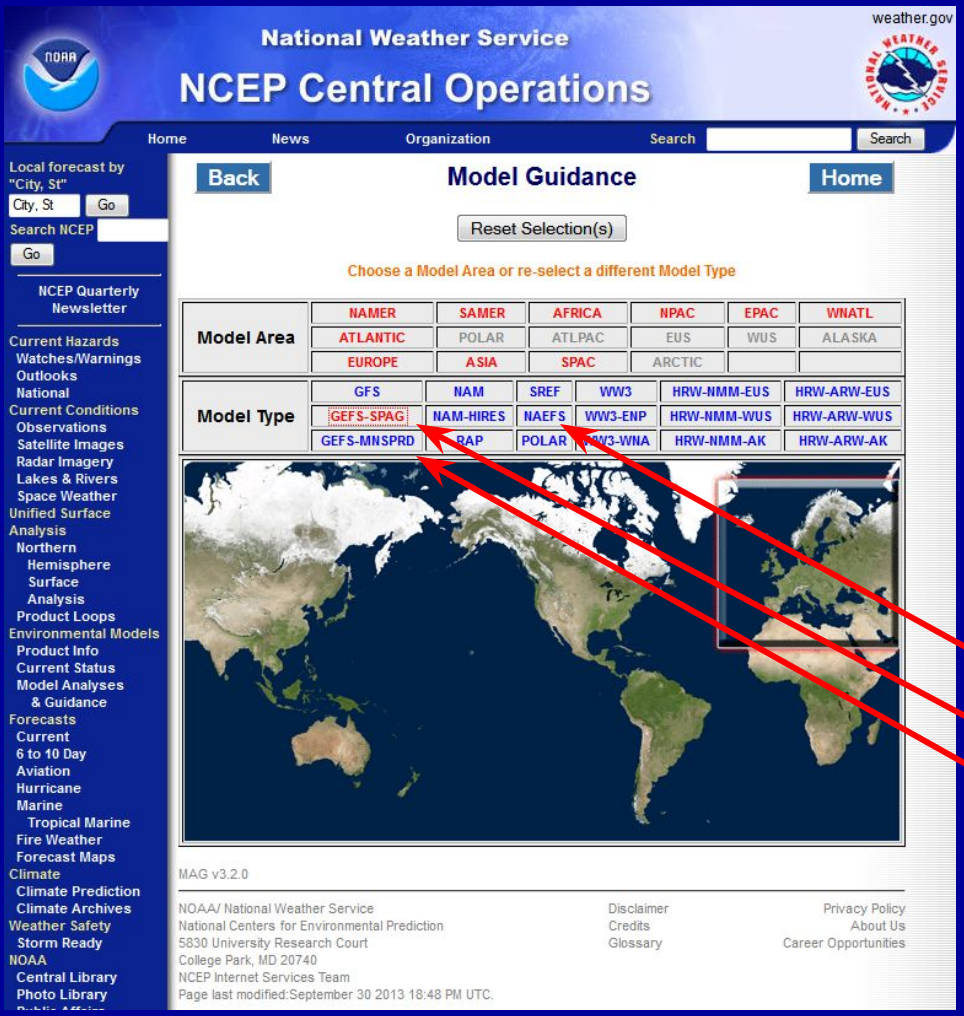
- Introduction to Ensemble Prediction: http://www.meted.ucar.edu/nwp/pcu1/ensemble_webcast/
- Ensemble Forecasting Explained: http://www.meted.ucar.edu/nwp/pcu1/ensemble/
- Ensemble Prediction System Matrix: Characteristics of Operational Ensemble Prediction Systems (EPS): http://www.meted.ucar.edu/nwp/pcu2/ens_matrix/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

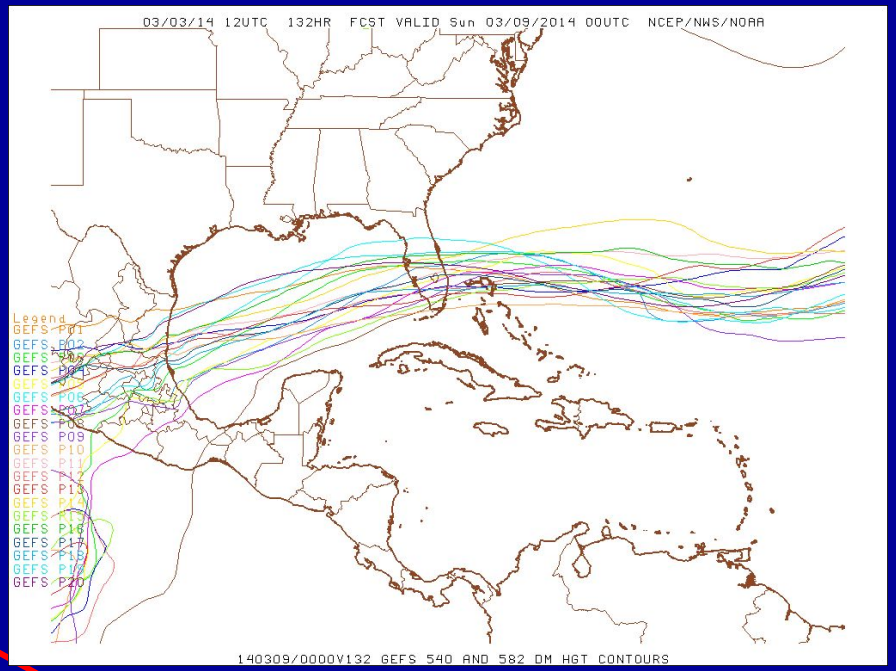
Thank you

Questions?

Access to Ensemble Output

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





Access to ensemble mean, spread, and spaghetti plots

"Good" and "Bad" Ensembles

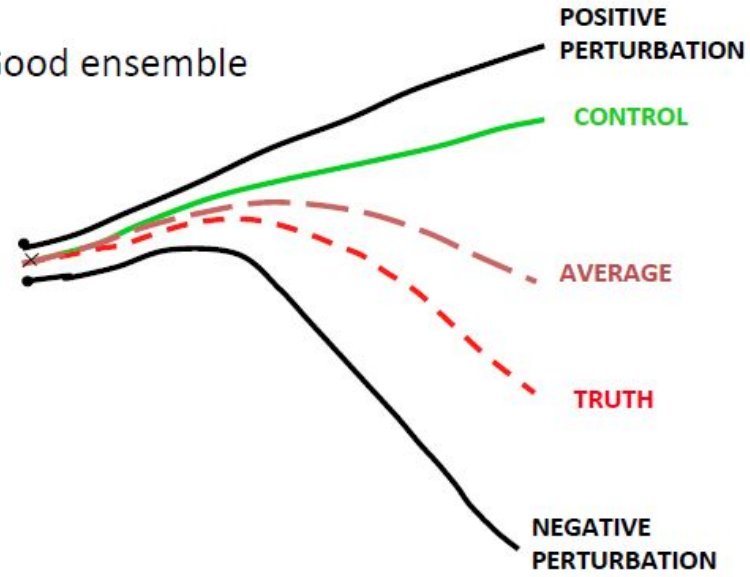
An ensemble forecast starts from initial perturbations to the analysis…

In a good ensemble "truth" looks like an member of the ensemble (Toth, 1992)

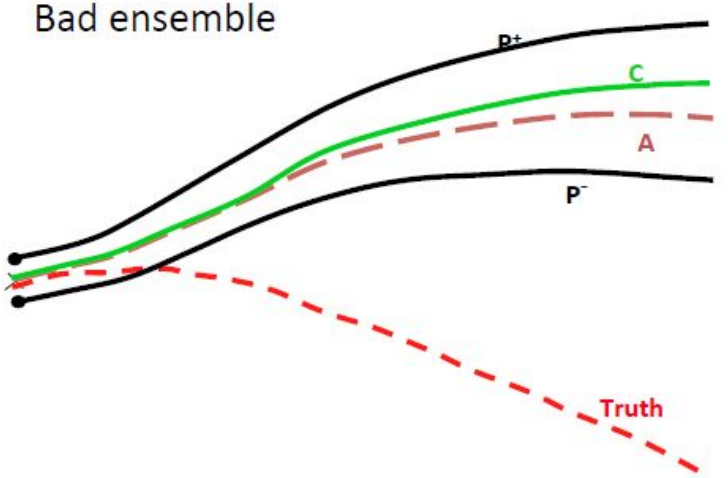
The initial perturbations should reflect the analysis "errors of the day"

A bad ensemble is still useful (implies there is a bug in the system)

Good ensemble



Bad ensemble



Kalnay 2019

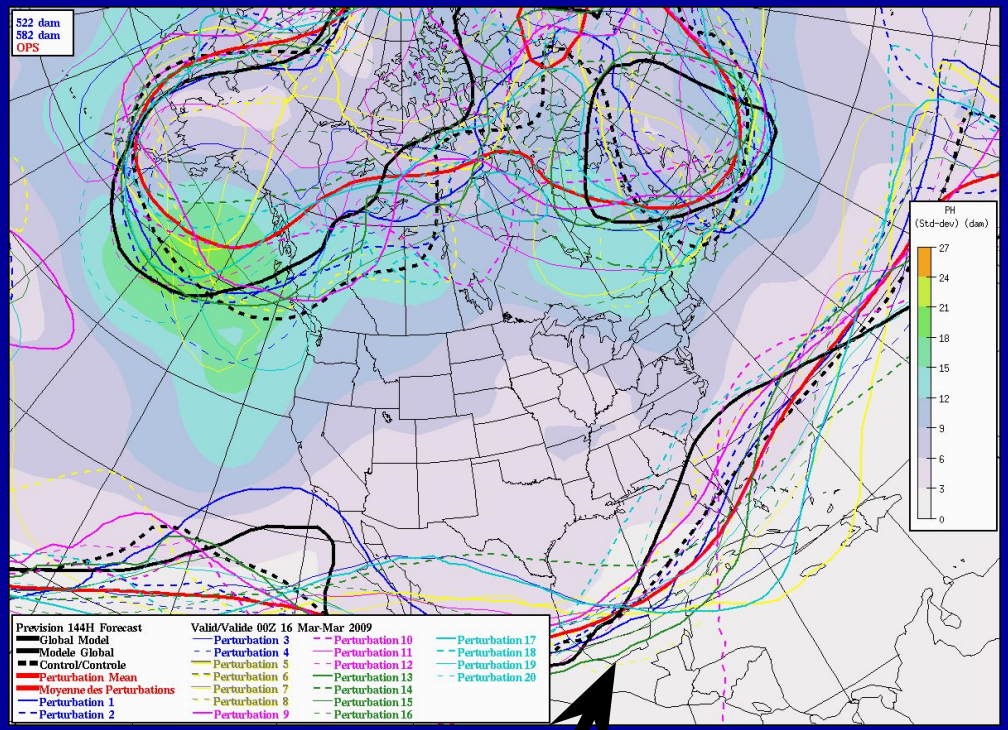
Question 1

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

Canadian Ensembles

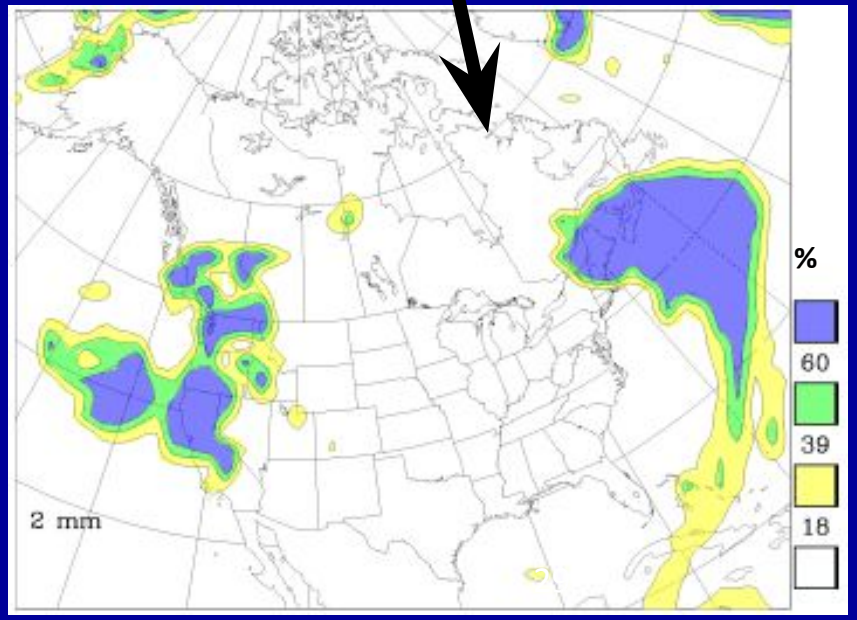
http://weather.gc.ca/ensemble/index_e.html



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

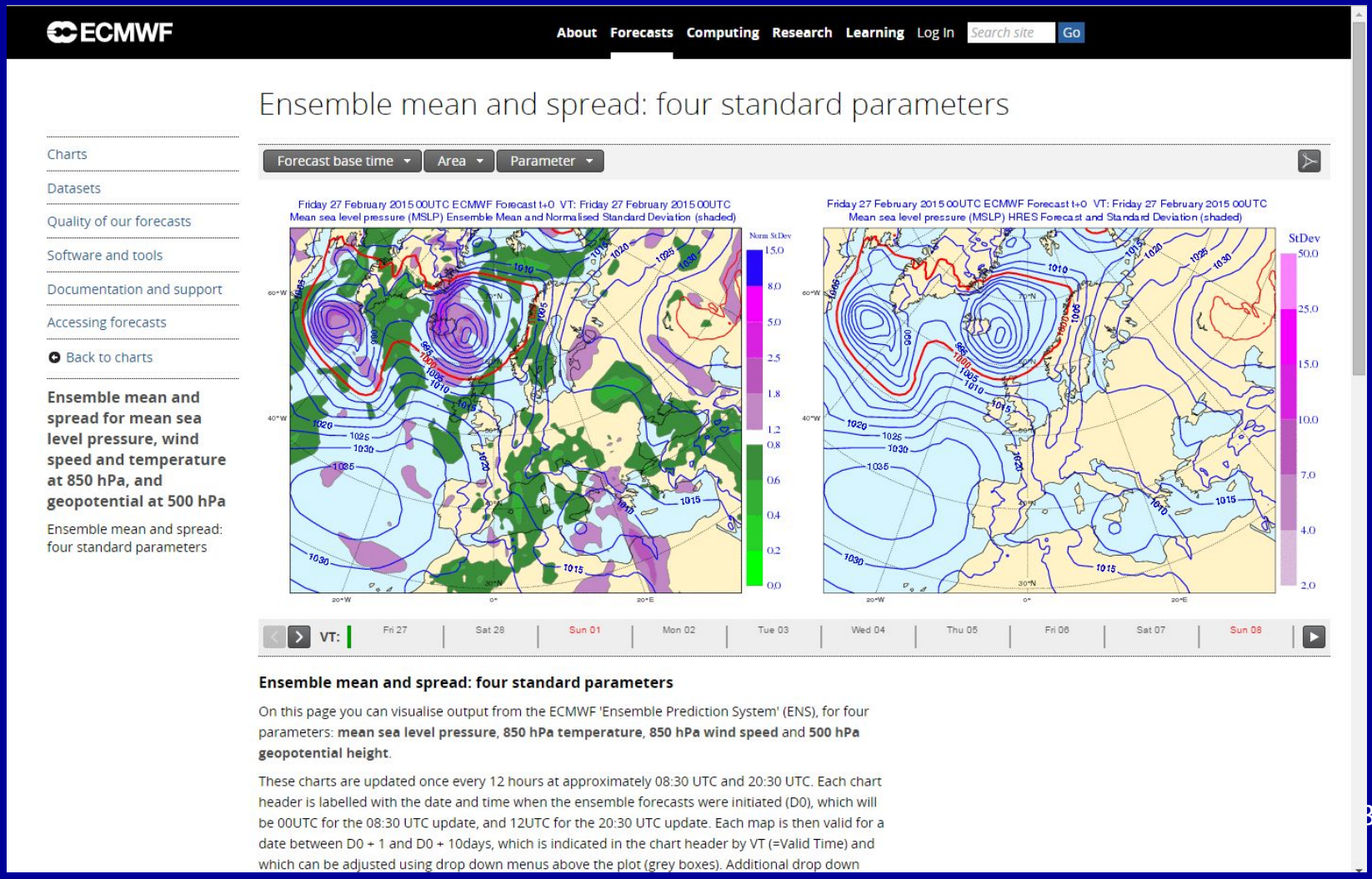
FHR 72 forecast of the probability that the 12 hour accumulation exceeds 2 mm

(The 12-h accumulation period immediately precedes the valid time)



Access to Ensemble Output

- ECMWF Ensembles:
  https://www.ecmwf.int/en/forecasts/charts



Question 1

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

A. Estimates of uncertainty
B. TC intensity model spread
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D. All of the above
E. A & C

ECMWF Ensemble Prediction System

- 51 members (1 control+50 perturbed members)
- Run twice daily (00 and 12 UTC) out to 15 days, 6/18 UTC 144h
  - T639 (~ 18 km) to 15 days
  - 137 vertical levels

Perturbations:

- Generated using singular vectors and stochastically Perturbed Parameterization Tendencies Scheme (SPPT)

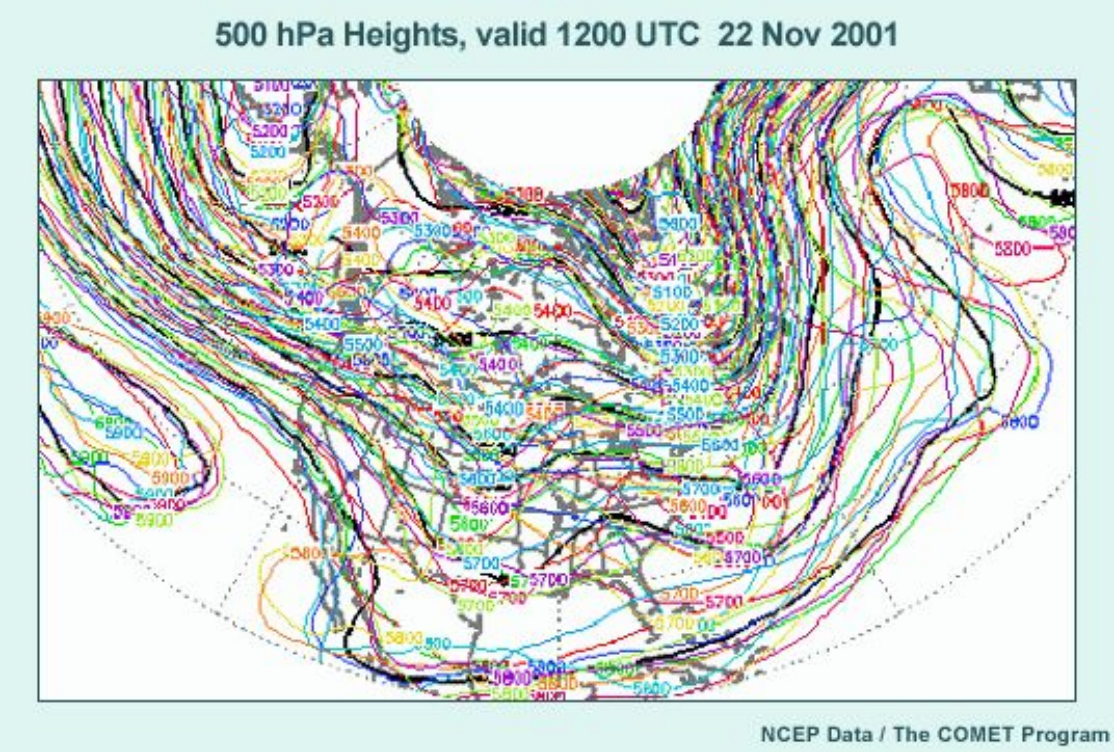
Deterministic ECMWF

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

Big ensemble upgrade coming in June for horizontal resolution to match deterministic!

Ensemble Display and Interpretation

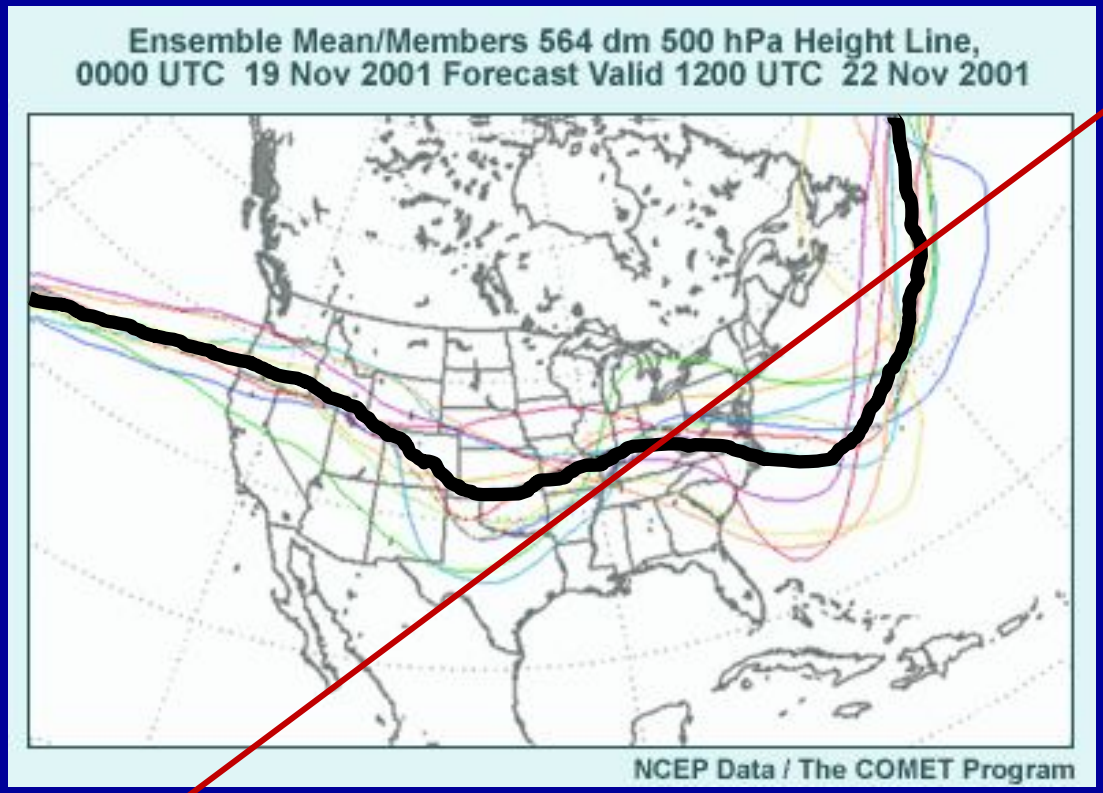
Displaying Ensembles



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

Credit: COMET

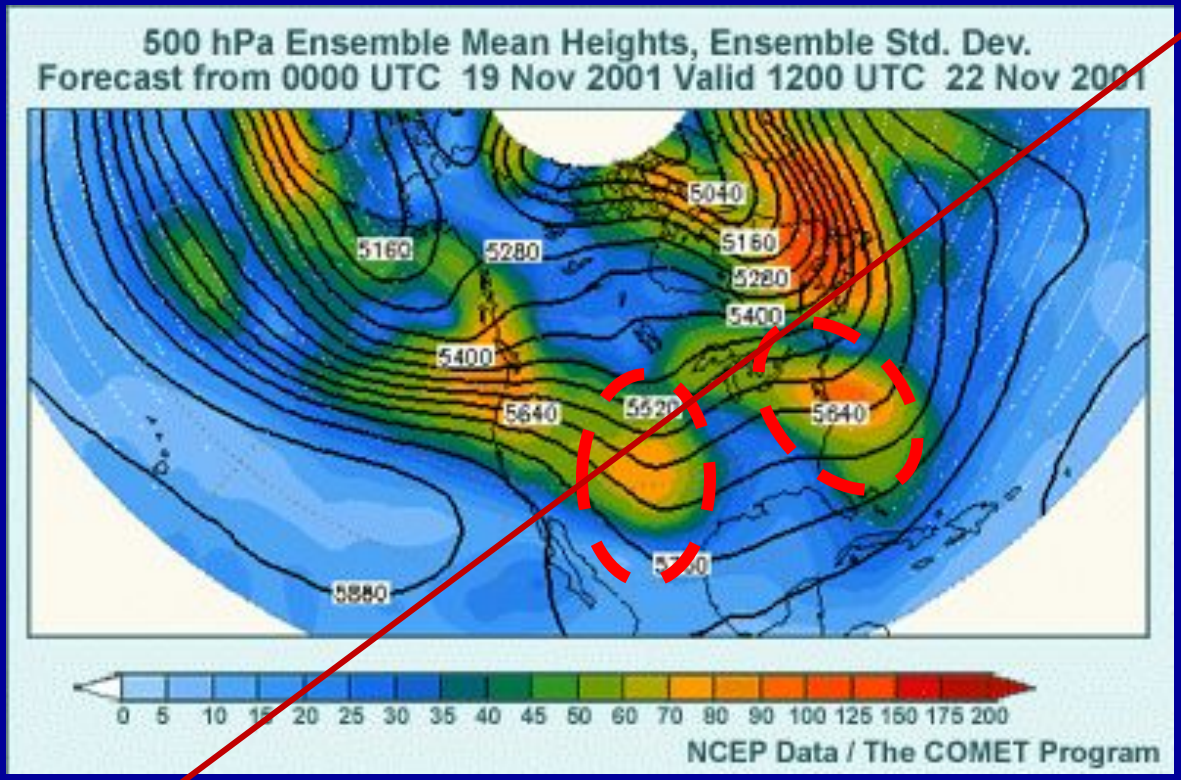
Displaying Ensembles



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

Credit: COMET

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

Credit: COMET

Displaying Ensembles
Ensemble Mean and Spread

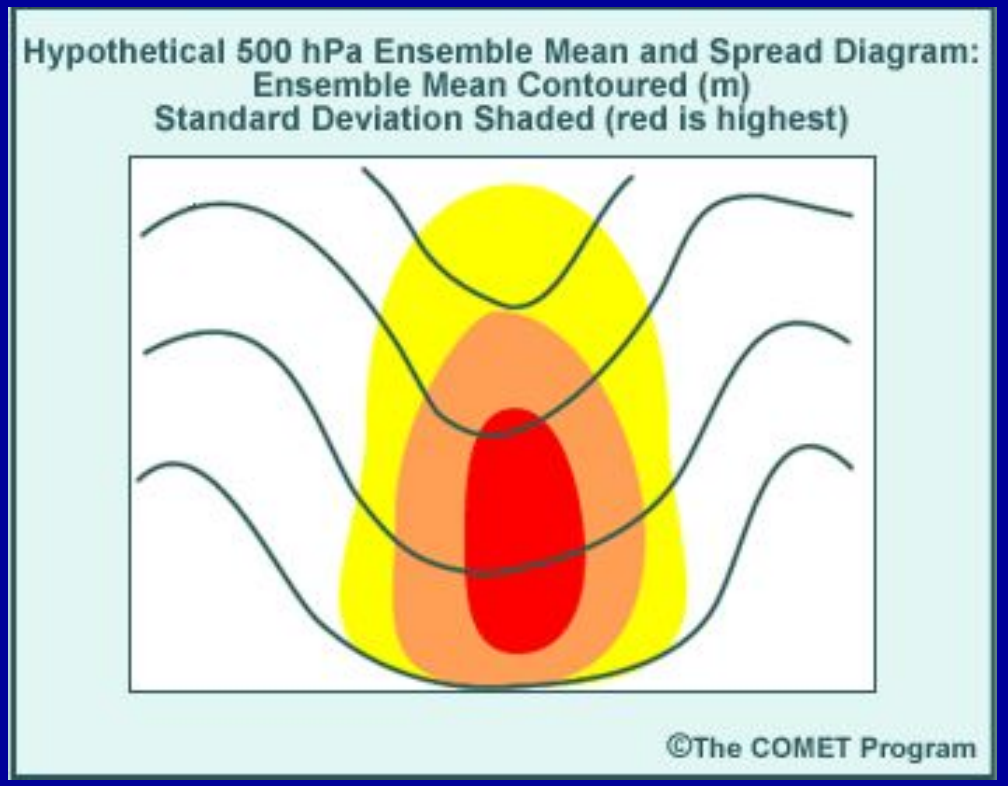
- Advantages
  - Summarizes data in easy to interpret form
  - Information provided for the entire domain
  - Low predictability features smoothed out by the ensemble mean and easily identifiable using spread
- Disadvantages
  - Ensemble mean can be misleading (and may not be the best forecast) if multiple 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?



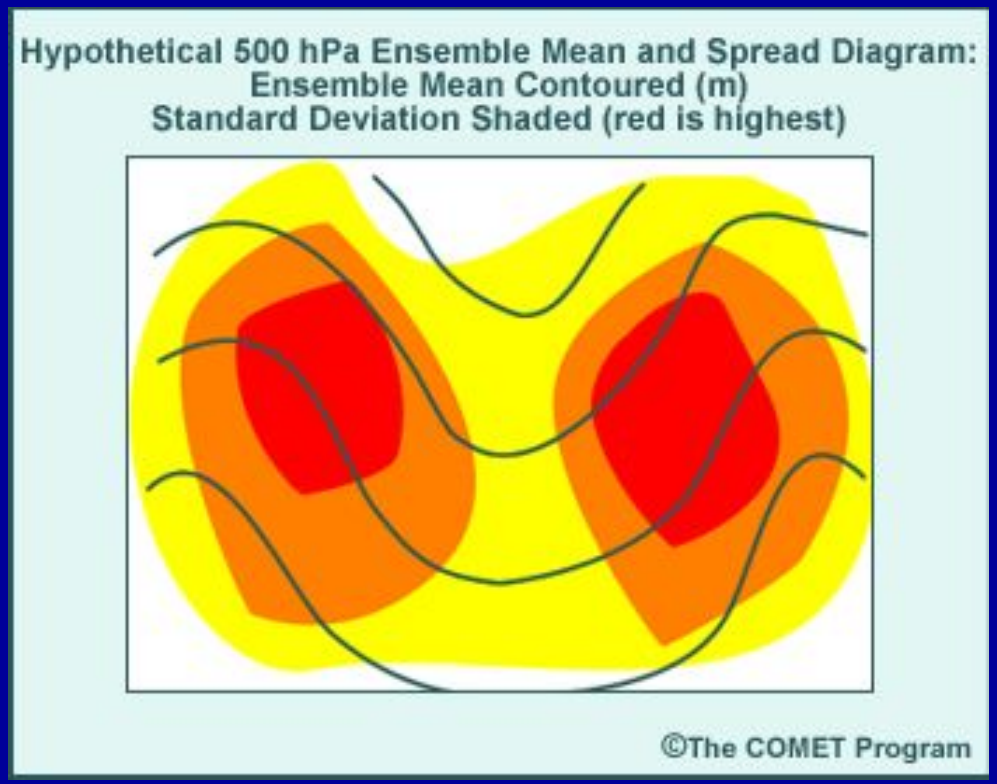
Credit: COMET

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?



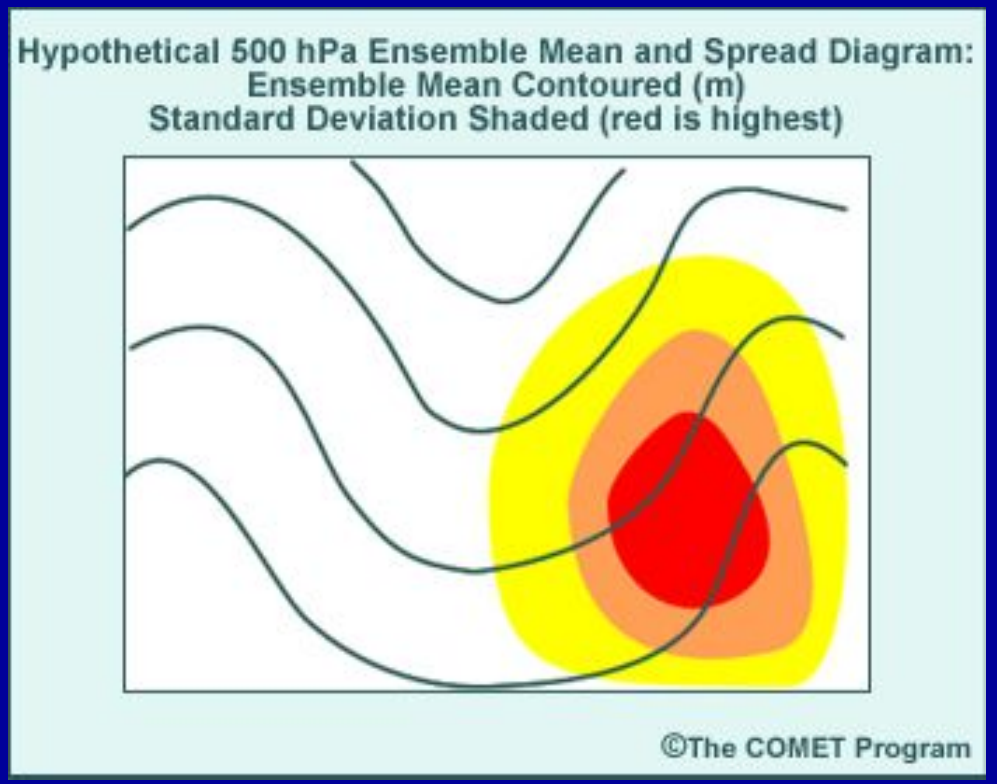
Credit: COMET

Interpreting Mean and Spread

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

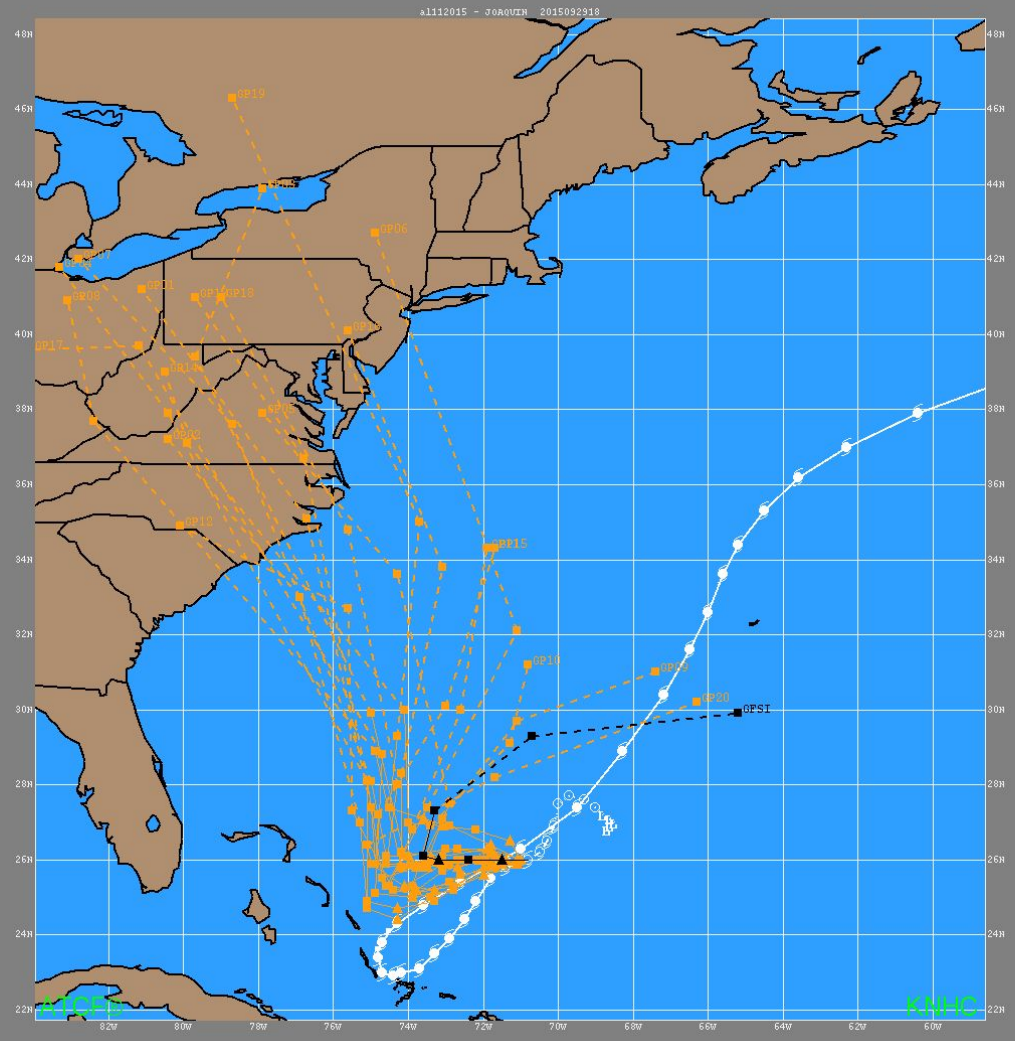
•In this case, the spread indicates greater potential for the trough axis to be east of the ensemble mean trough than to the west

•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?

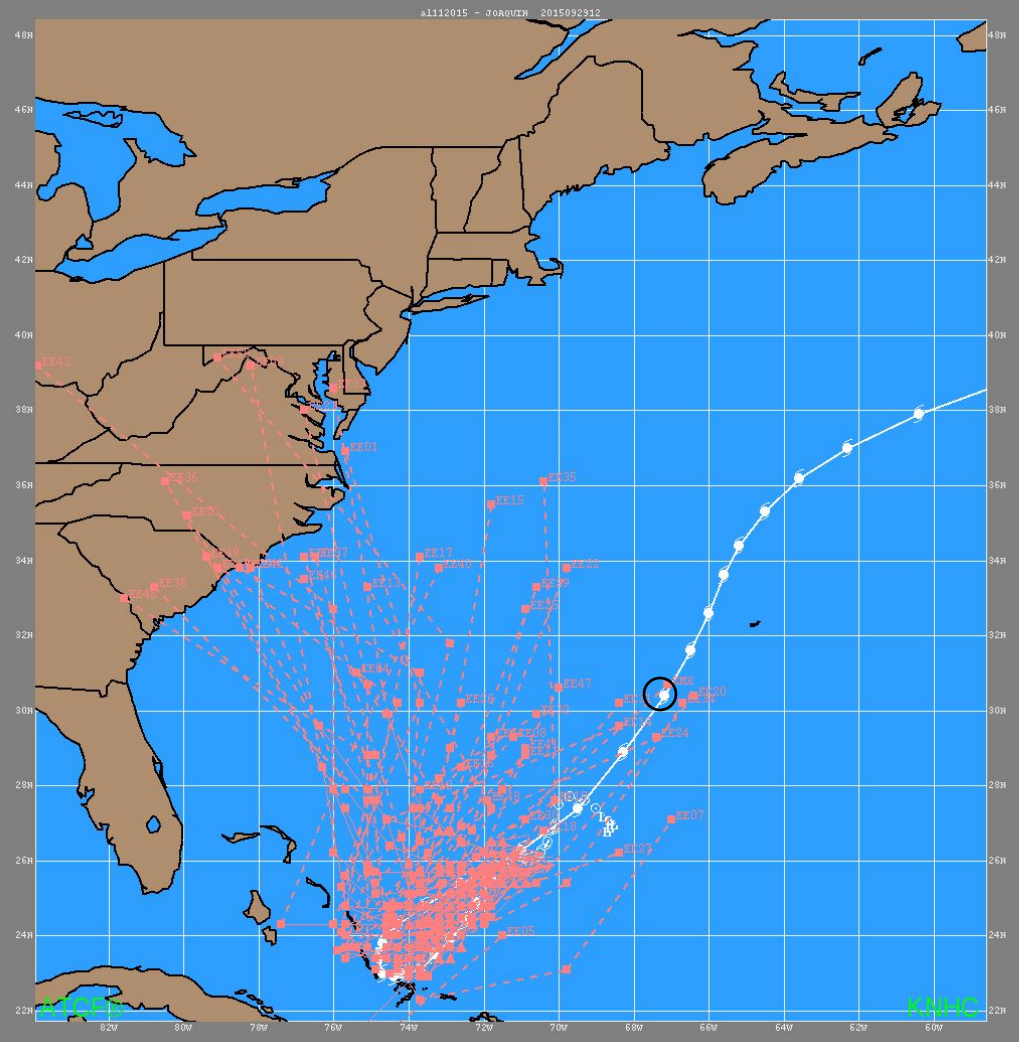


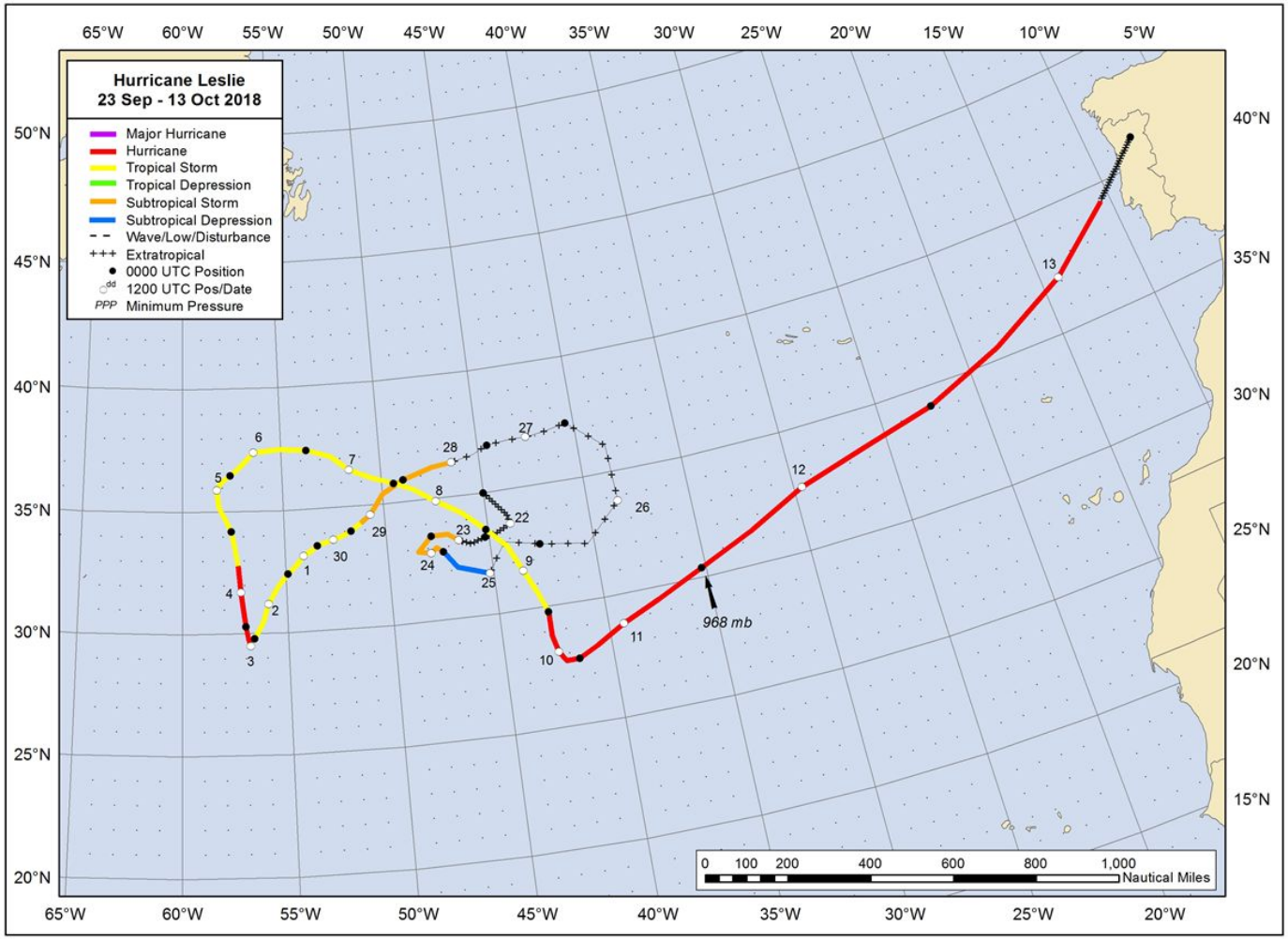
Credit: COMET

GFS Joaquin ensembles 29 Sep 1200 UTC



ECMWF Joaquin ensembles 29 Sep 1200 UTC

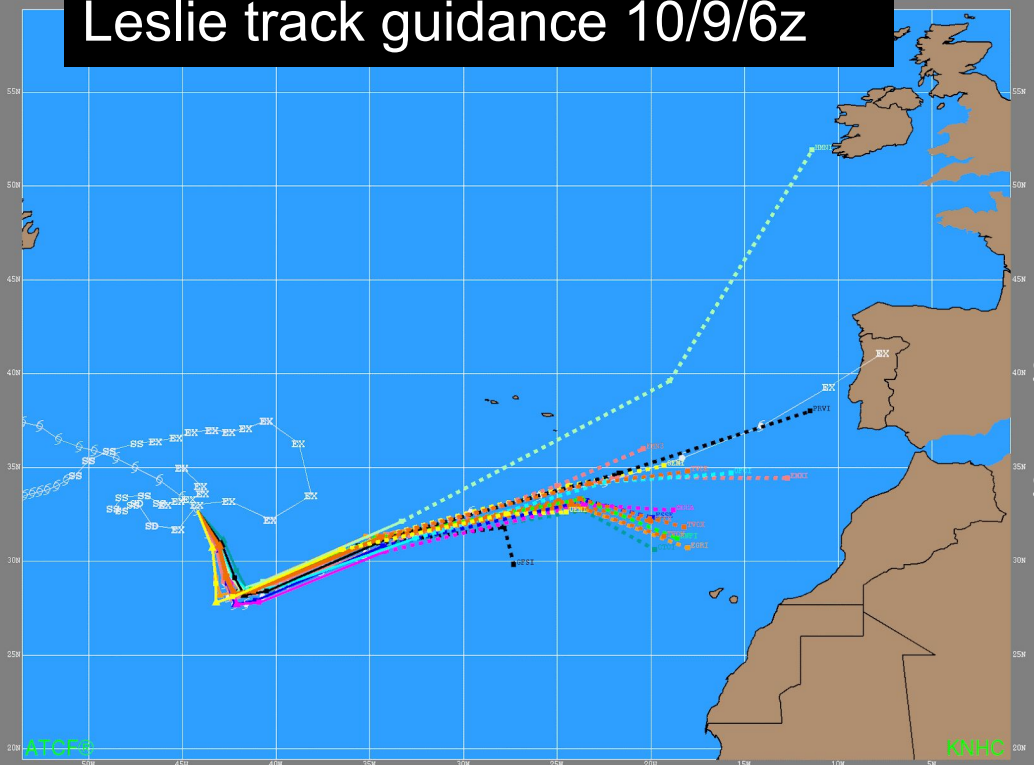




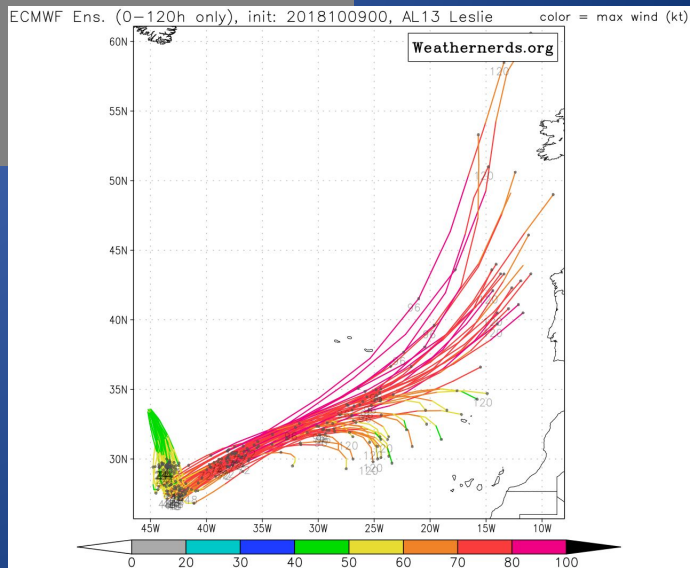
Hurricane Leslie

Long lasting and ***highly*** annoying

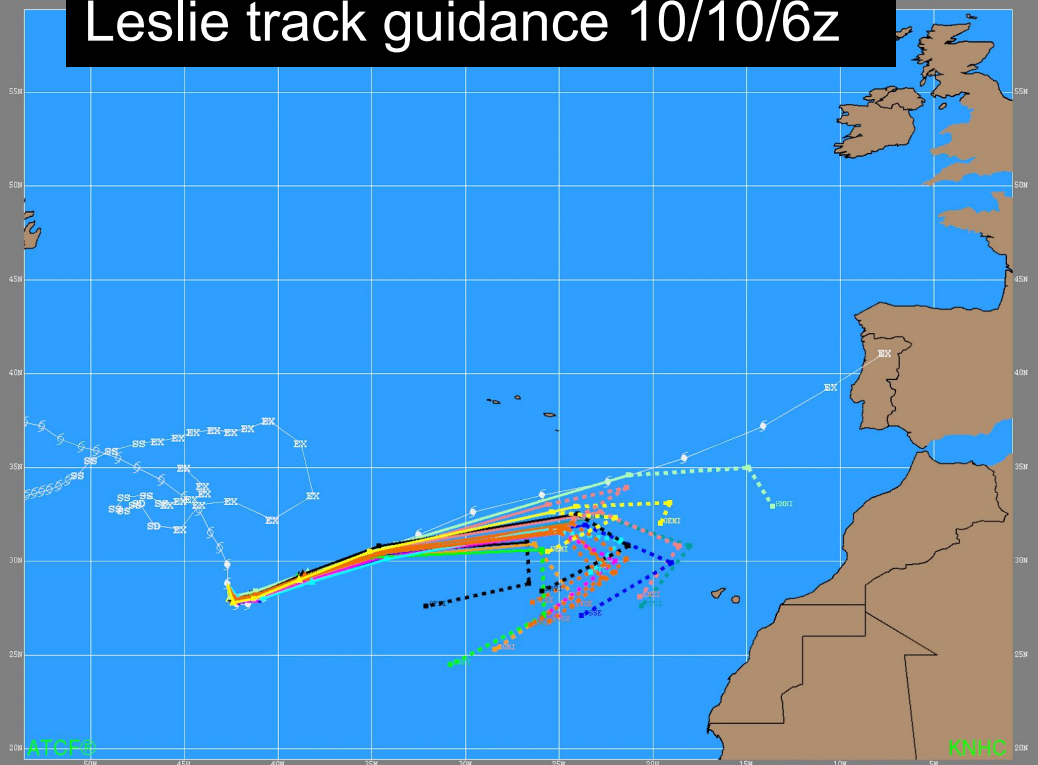
Leslie track guidance 10/9/6z



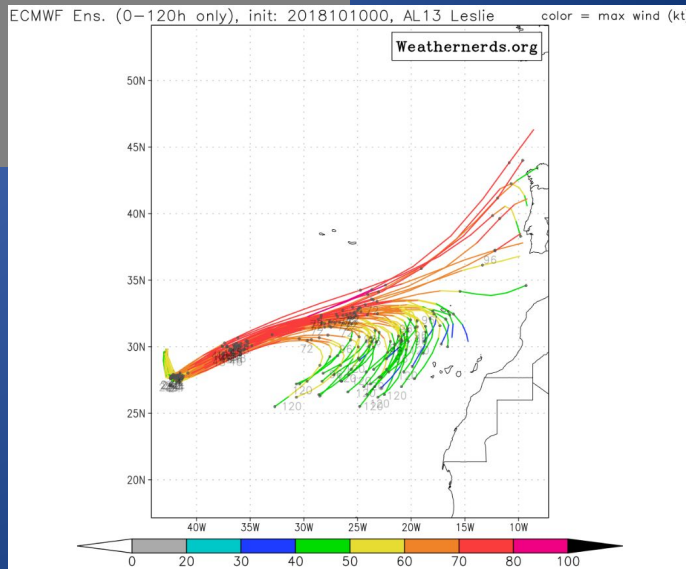
Major model spread, but best models farthest south



Leslie track guidance 10/10/6z



EC ensemble not as definitive



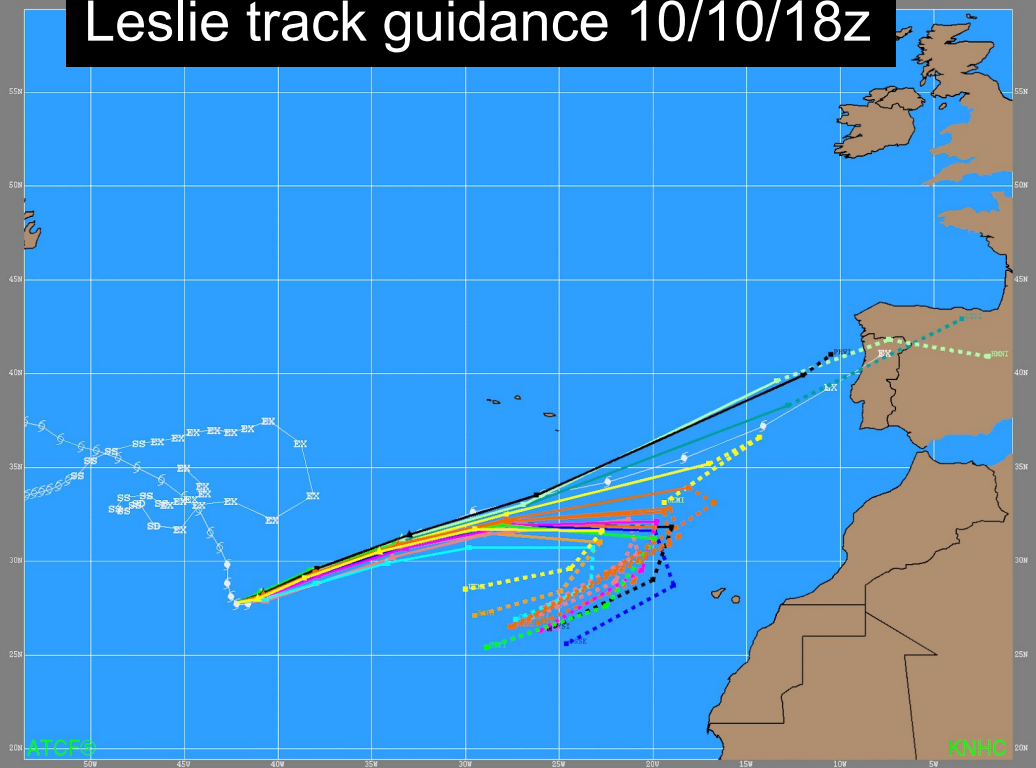
Leslie track guidance 10/10/12z

72 hour zoom

–

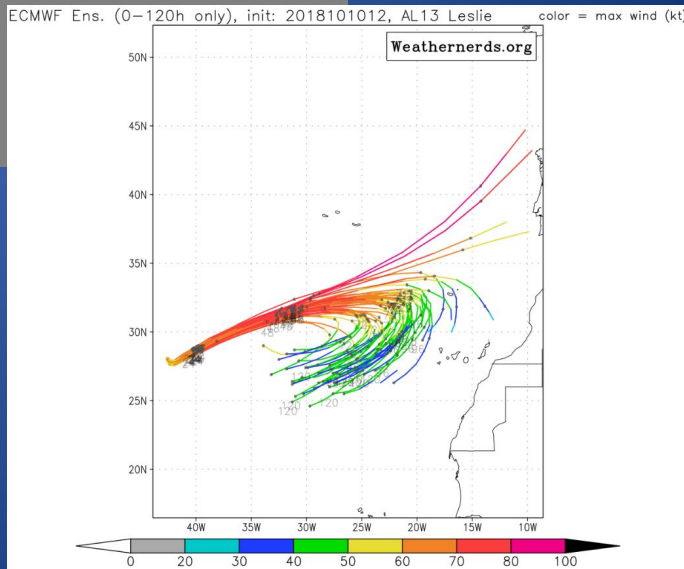
All models have a 400- 600 n mi error

Leslie track guidance 10/10/18z

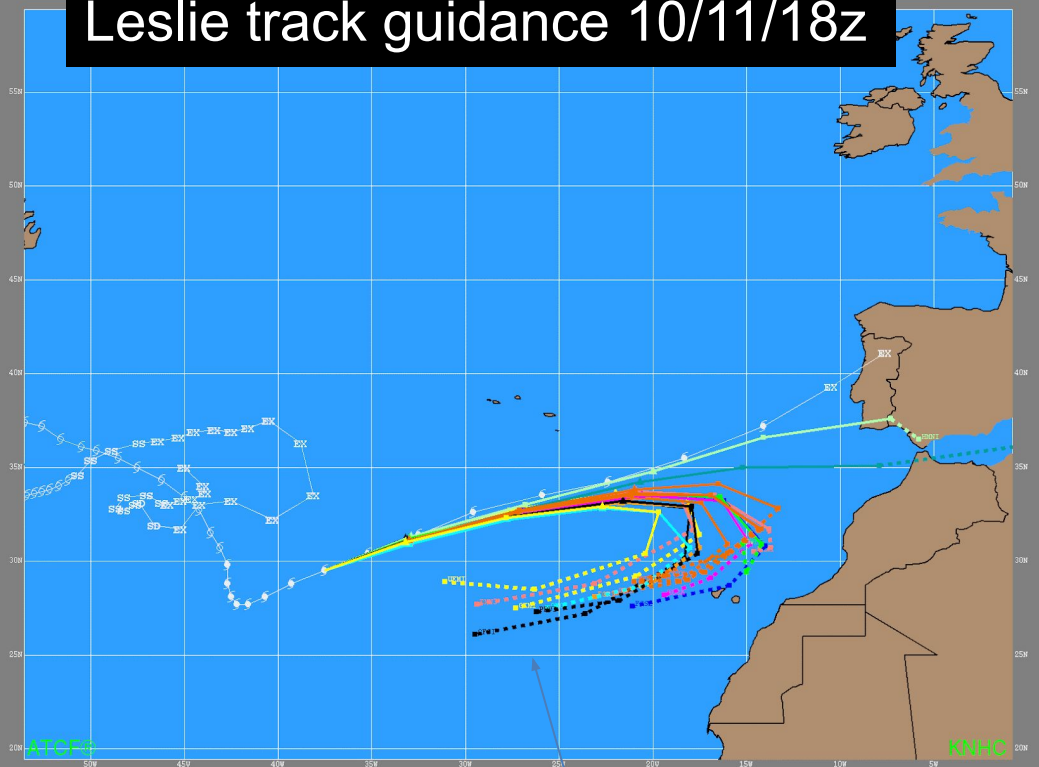


Few more models shift north, but most still miss the trough

EC ensemble continues to shift south



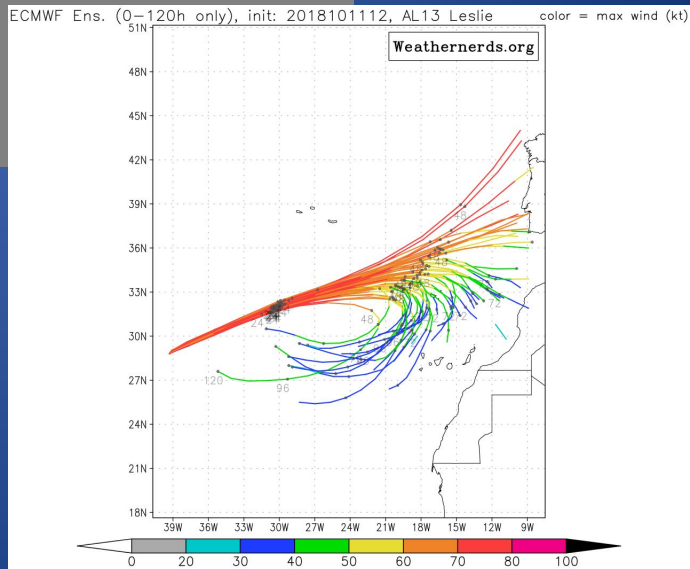
Leslie track guidance 10/11/18z



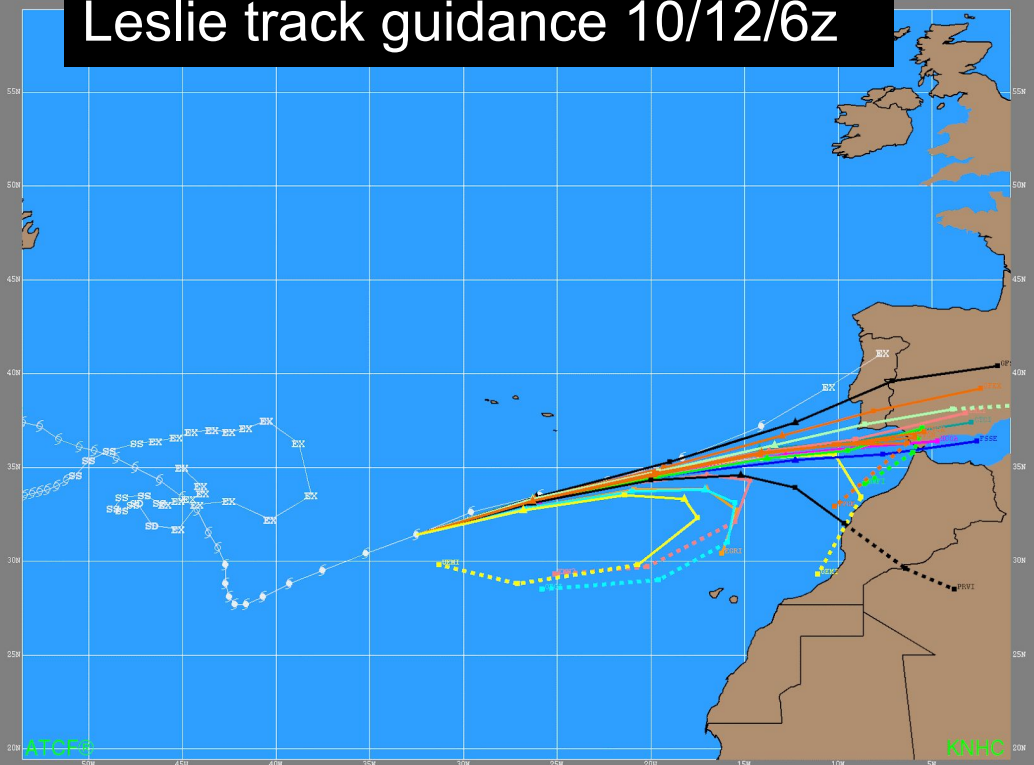
Deterministic models shift south, but little change in EC ensemble

~400 n mi errors in < 48 h

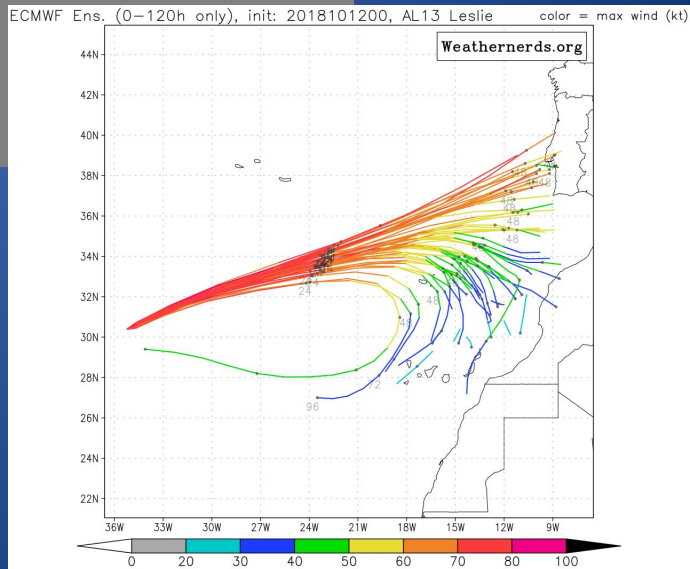
GFS shifts over 1500 n mi



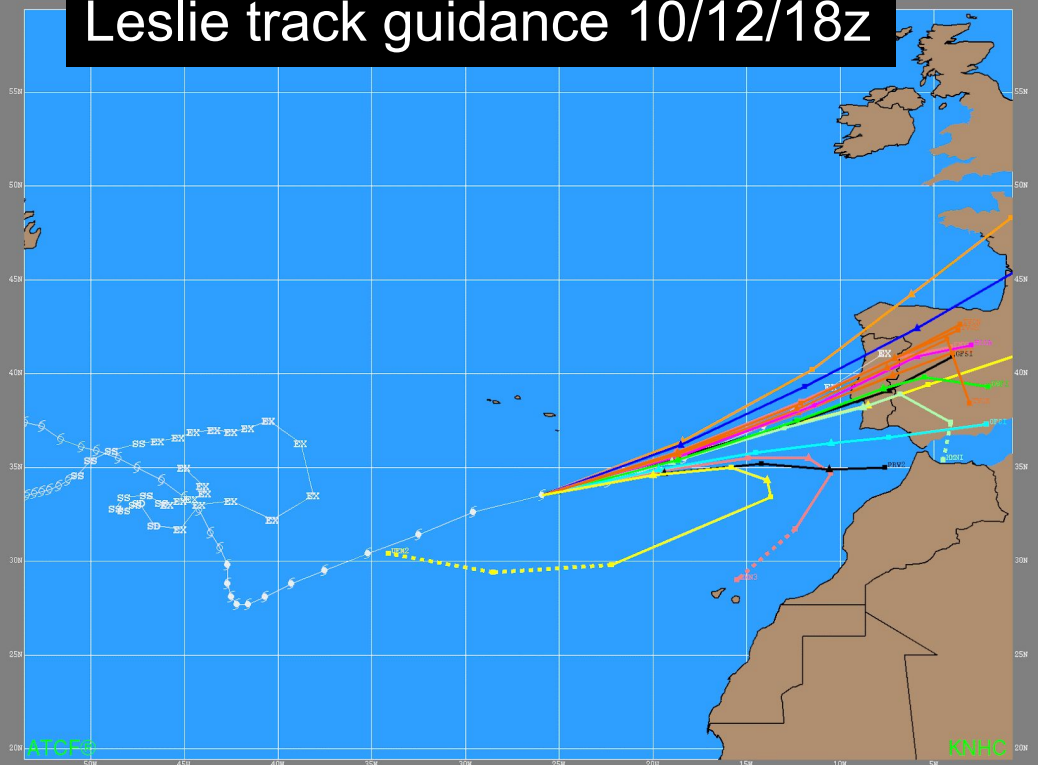
Leslie track guidance 10/12/6z



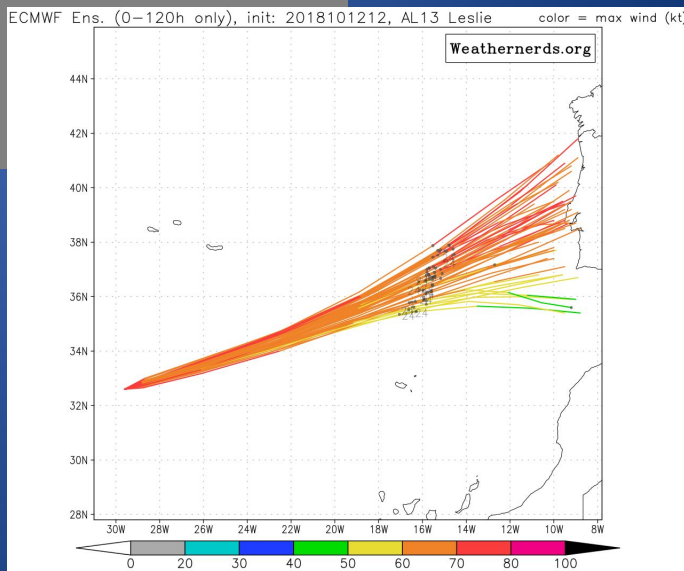
Models mostly jump northward



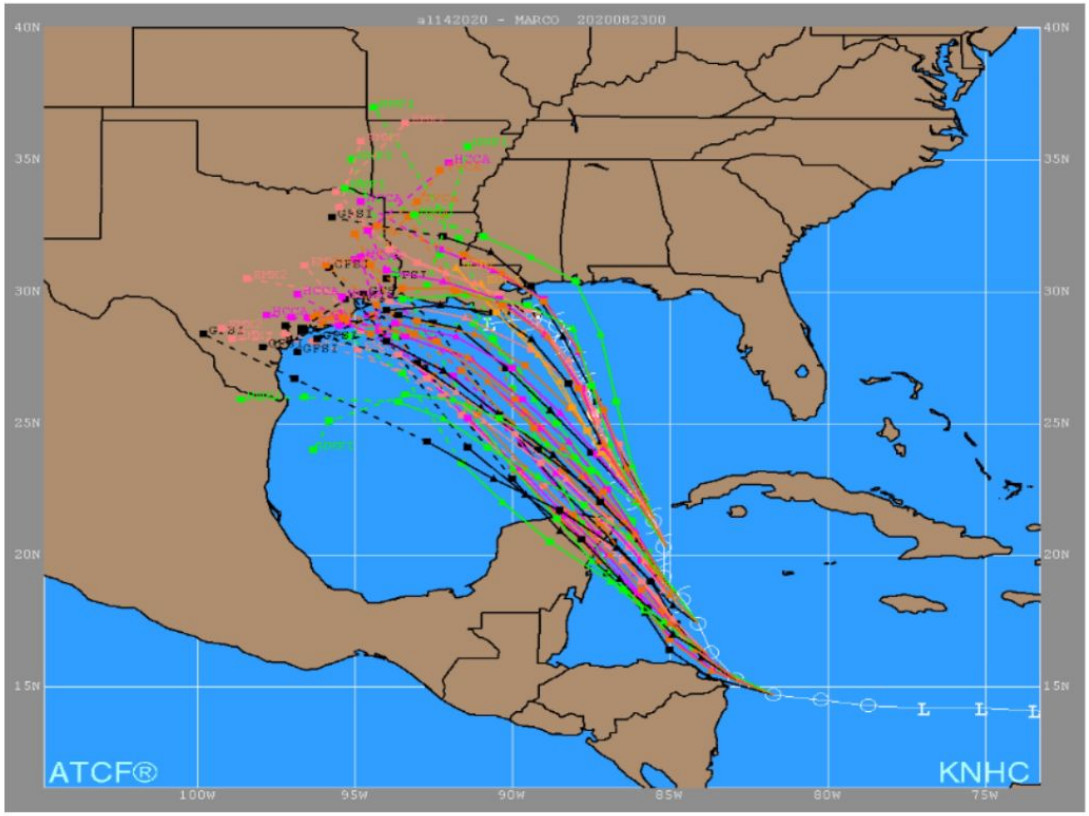
Leslie track guidance 10/12/18z



Finally!



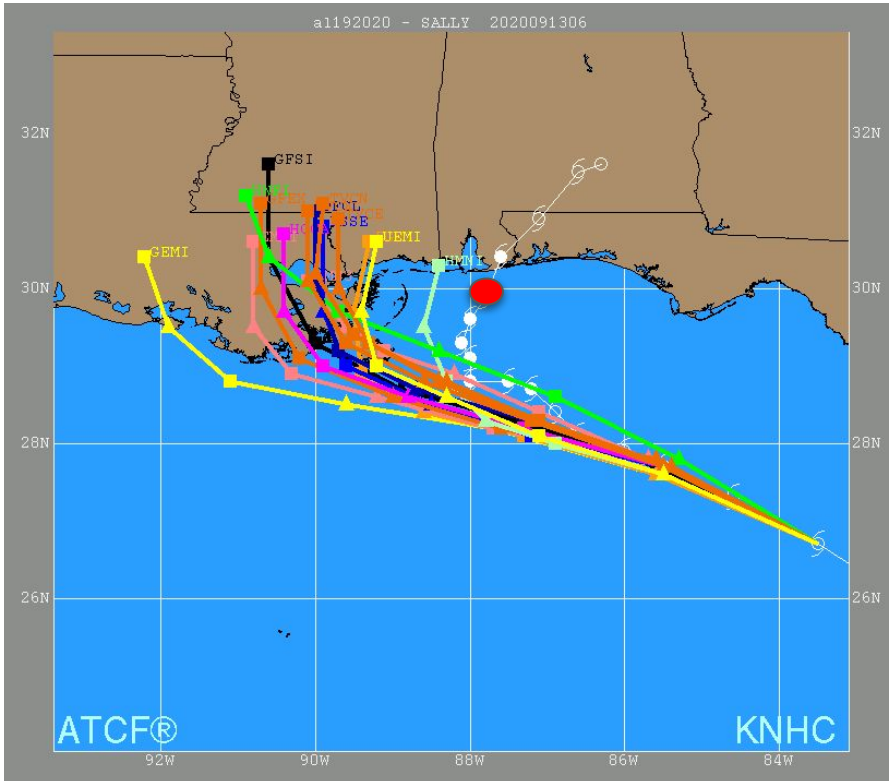
Track Forecast Challenges - Marco



Marco track guidance 21-23 August 2020

Potential interaction between Marco and Laura as well as uncertainty about Marco's intensity led to huge variability in track guidance for Marco and poor forecasts

Track/Warning Forecast Challenges - Sally



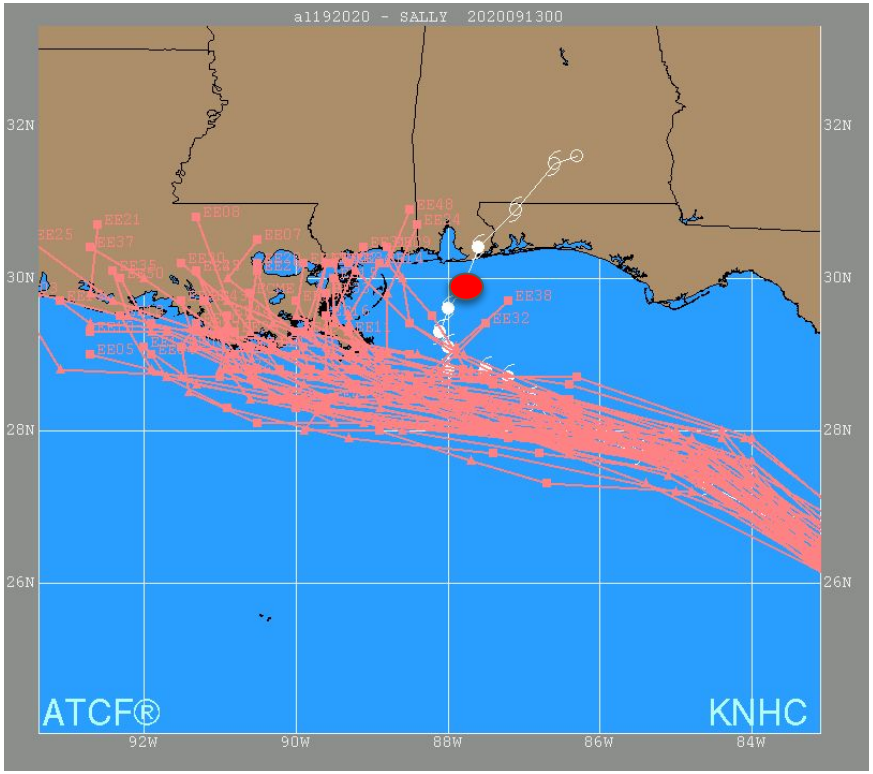
Track guidance 0600 UTC 13 September 2020

Track guidance whiffed when it the Hurricane Warning was put up

Resulted in a clear-sky bust for Louisiana

Note HMNI closest - yet it had a NE bias for Marco. Recent past does affect forecaster perceptions

Track/Warning Forecast Challenges - Sally



ECMWF Ens 0600 UTC 13 September 2020

No help from the best ensemble system either

If anything you might suspect the forecast would bust left, not right

Some stronger members on right side, but intensity skill lags

Genesis Guidance

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

In-house product

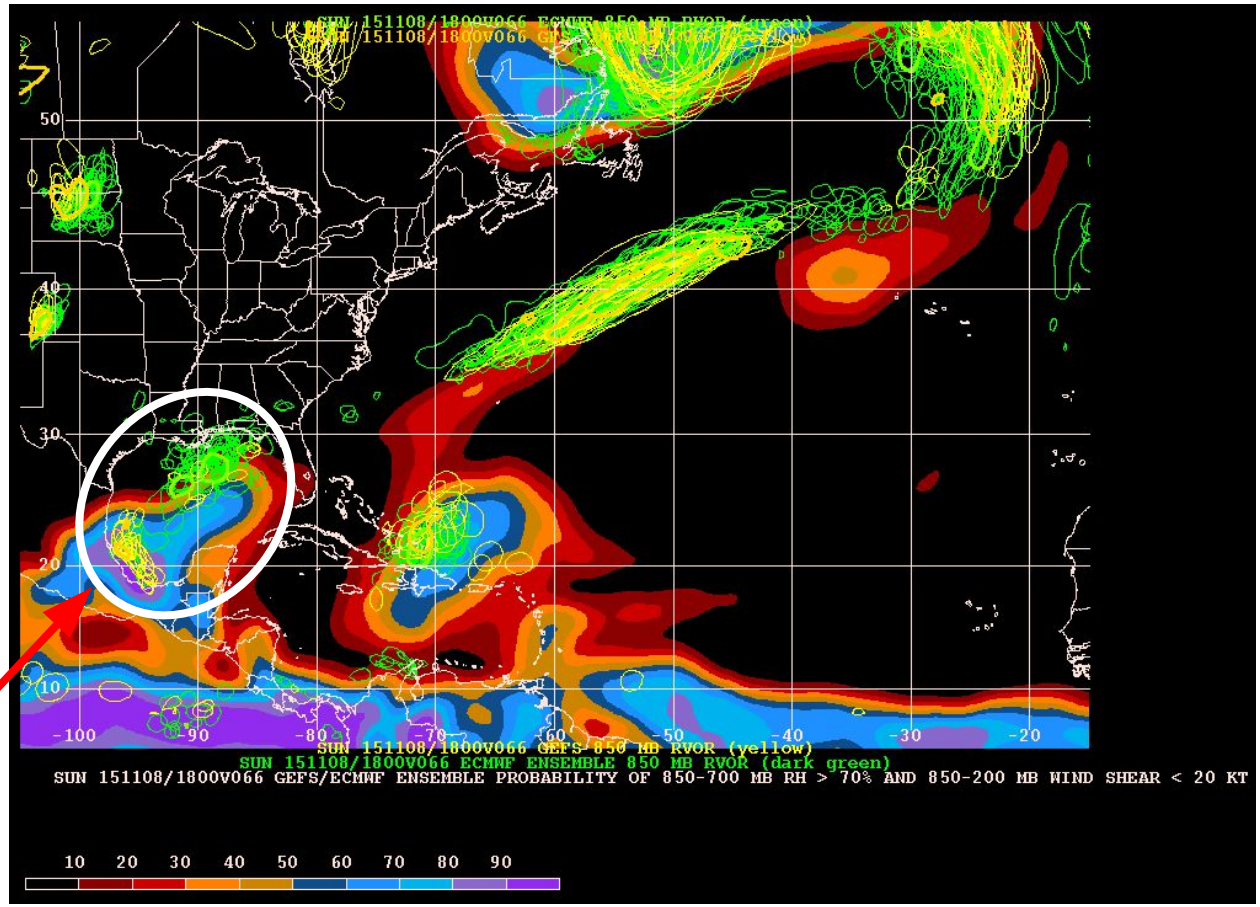
shading: combined probability of 70 ensemble members (GEFS + ECENS):

- 850 – 700 hPa RH > 70%
- 200 – 850 hPa vertical wind shear < 20 kt

contours: 850 hPa relative vorticity (8 x 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**

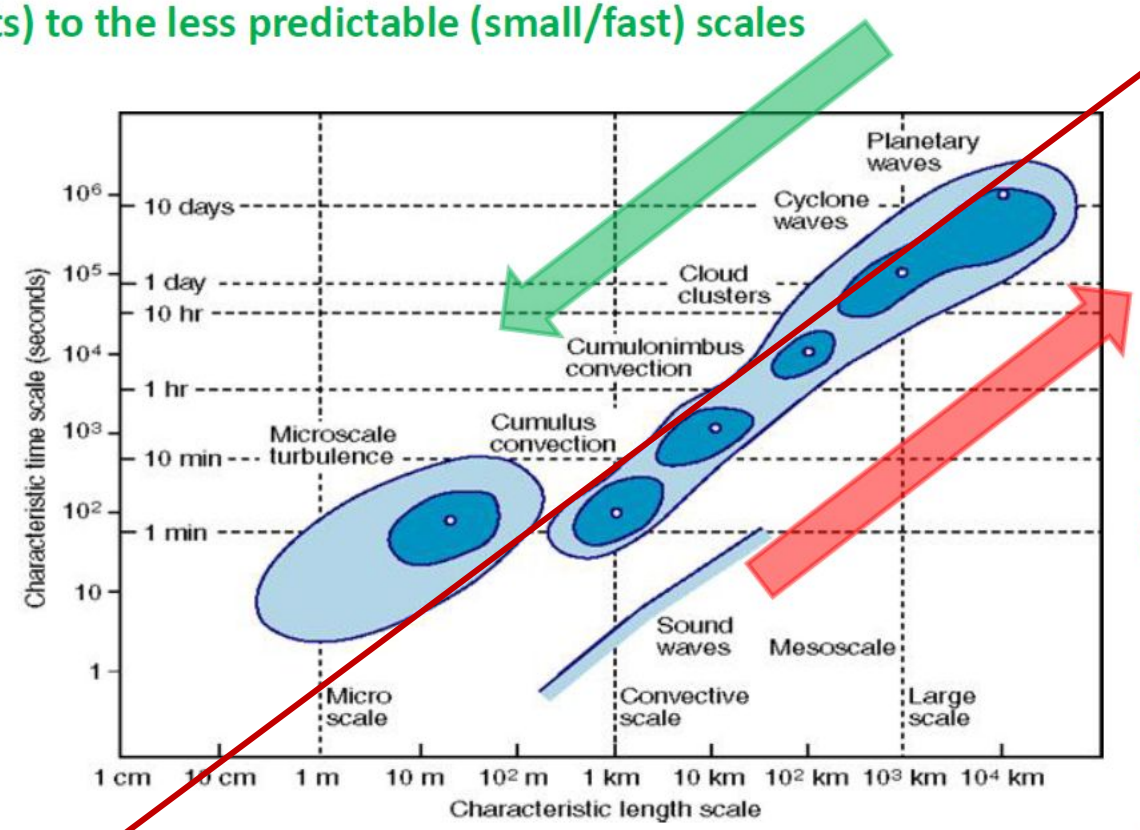


Learning Objectives

- Explain the value of ensembles
- Explain how NHC incorporates ensembles into their forecast products
- Correctly interpret the uncertainty NHC forecast products
- Evaluate ensemble guidance to estimate the uncertainty in TC track or intensity forecasts

How did we manage to extend the FSH beyond 2 weeks?

Predictable signals propagate from the better-initialized and more predictable scales ('mainly' the large scales, the slowly evolving components) to the less predictable (small/fast) scales



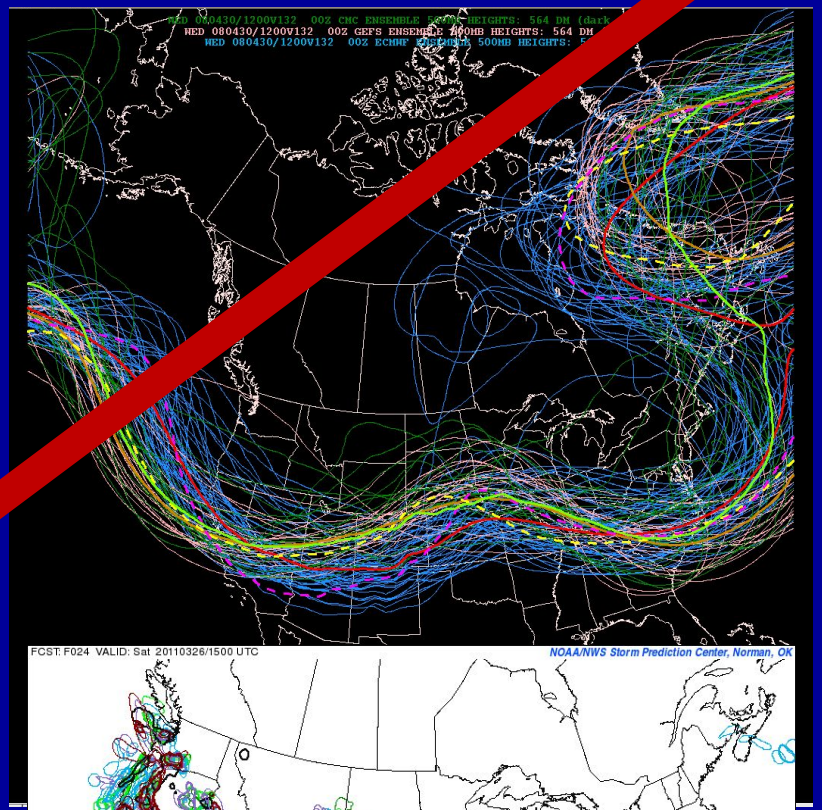
Errors propagate from poorly initialized scales ('mainly' the smaller scales) thus reducing the predictive skill

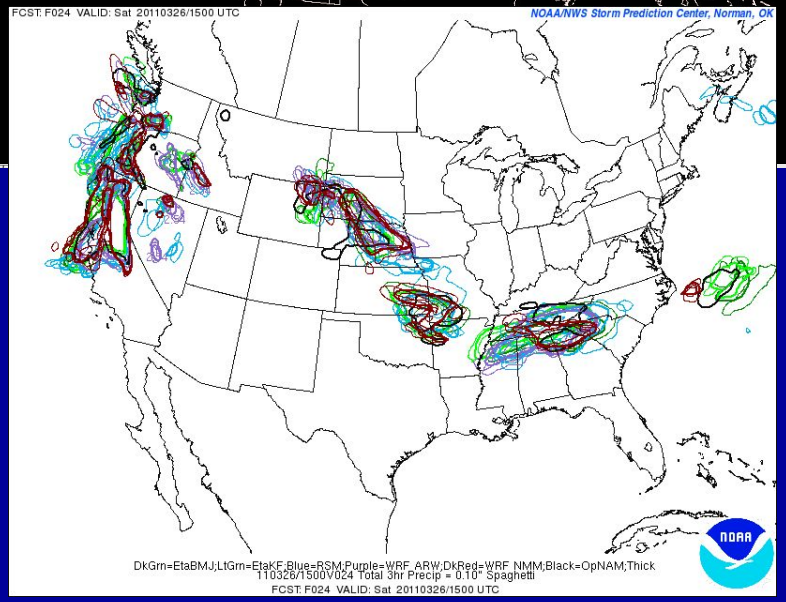
(Buizza and Leutbecher 2015, QJRMS)

ECMWF

Ensemble Use

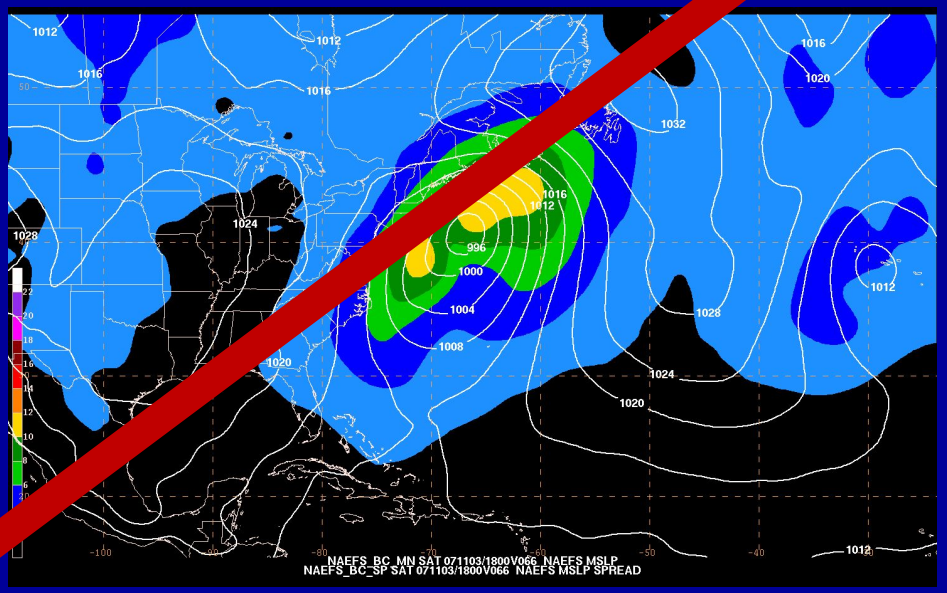
- Originally used for medium- to long-range forecasting of the large-scale pattern
- Uses have grown to encompass all temporal and spatial scales down to convective storm scale
- Address uncertainty particularly those leading to rapidly diverging solutions
  - Initial conditions, model physics, resolution, model numerics

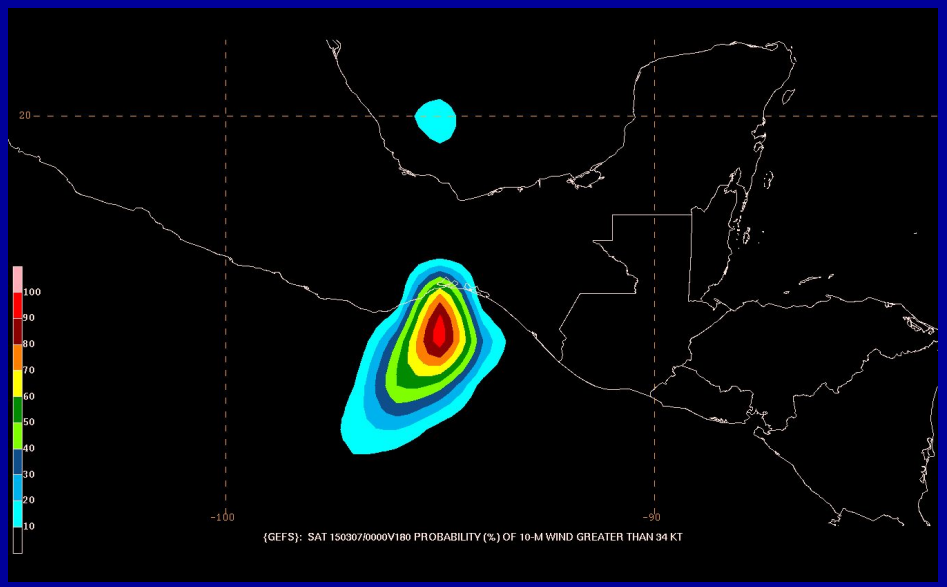




Ensemble Use

- Estimate rate of skill loss with time
  - Spread of solutions generally increases with time
- Compute probabilities for 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 (next week Ryan Torn's talk)

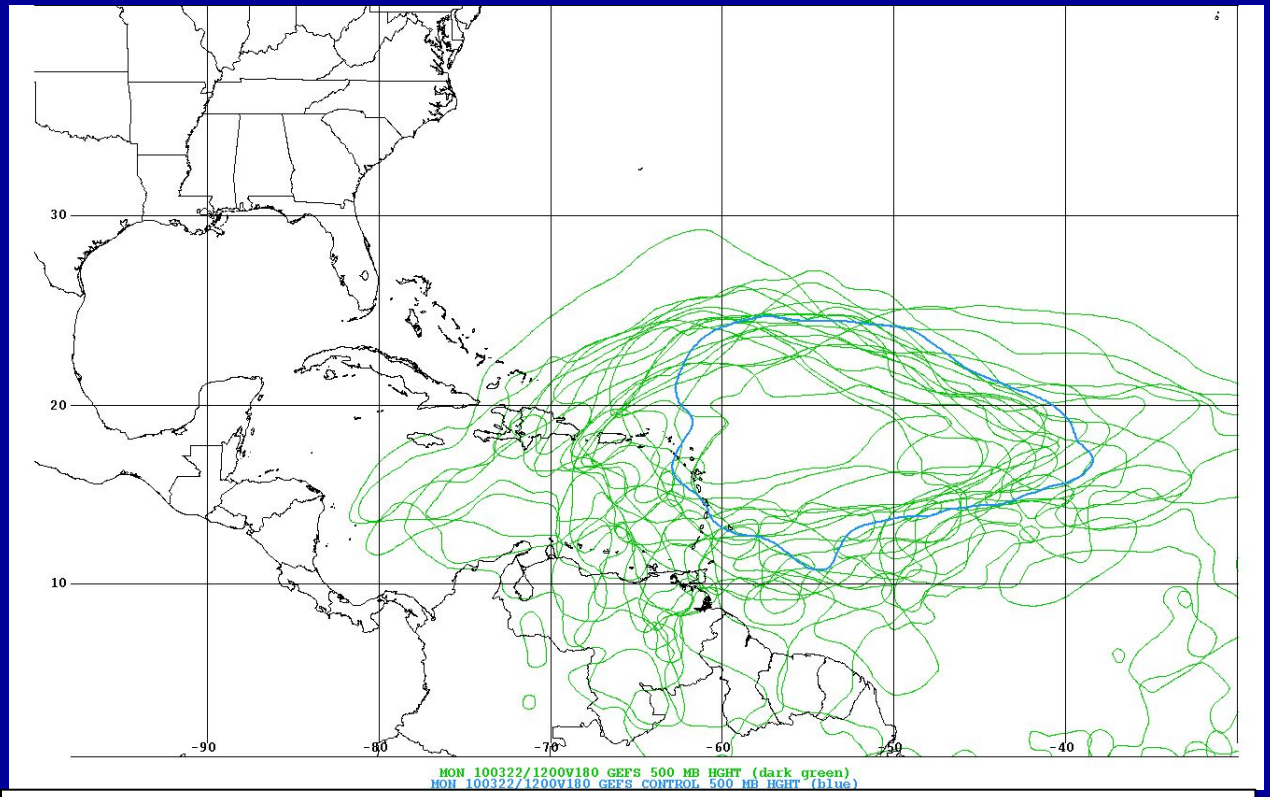




Current Global Ensemble Systems that NHC uses most frequently

NCEP Global Ensemble Forecast System (GEFS)

- 4 cycles per day (00, 06, 12, 18 UTC)
- 31 members (1 control + 30 perturbed)
- Forecast extends out to 384 hours (16 days)



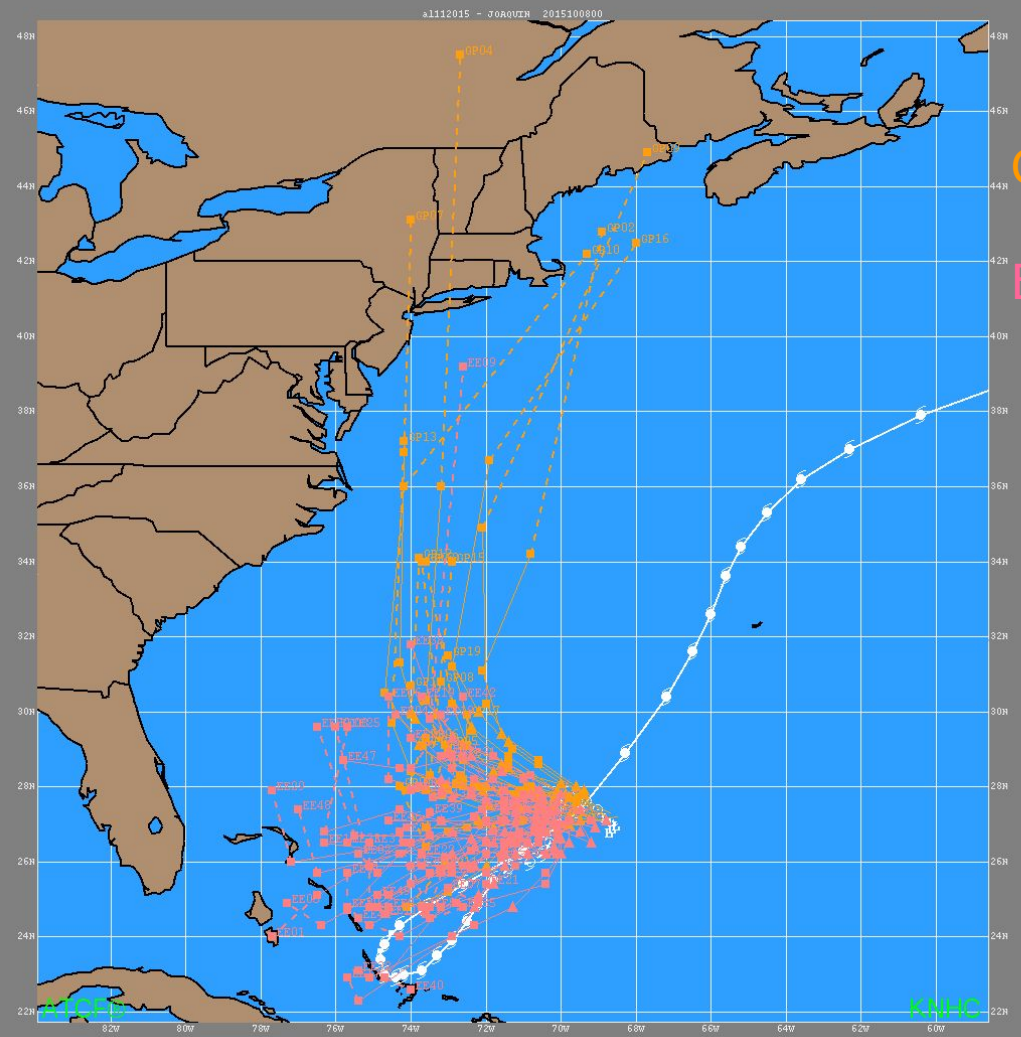
180-h forecast of 588 dm 500-mb height contour valid at 1200 UTC 22 March 2010

NCEP GEFS

- Current Configuration (last upgrade Sep 2020)
  - ~25 km resolution, run to 35 days at 00Z
  - 64 vertical levels
- Ensemble members
  - 30 members generated using EnKF
  - Uses stochastically perturbed physics tendencies (SPPT) scheme and stochastic kinetic energy backscatter (SKEB) scheme for perturbations
  - Model physics consistent with GFS
- Deterministic GFS (2024 upgrade coming?)
  - ~13 km resolution for full run (16 days)
  - 127 vertical levels

Maybe shorten and summarize GEFS/ ECMWF including #members and resolution. No Kalman Filters

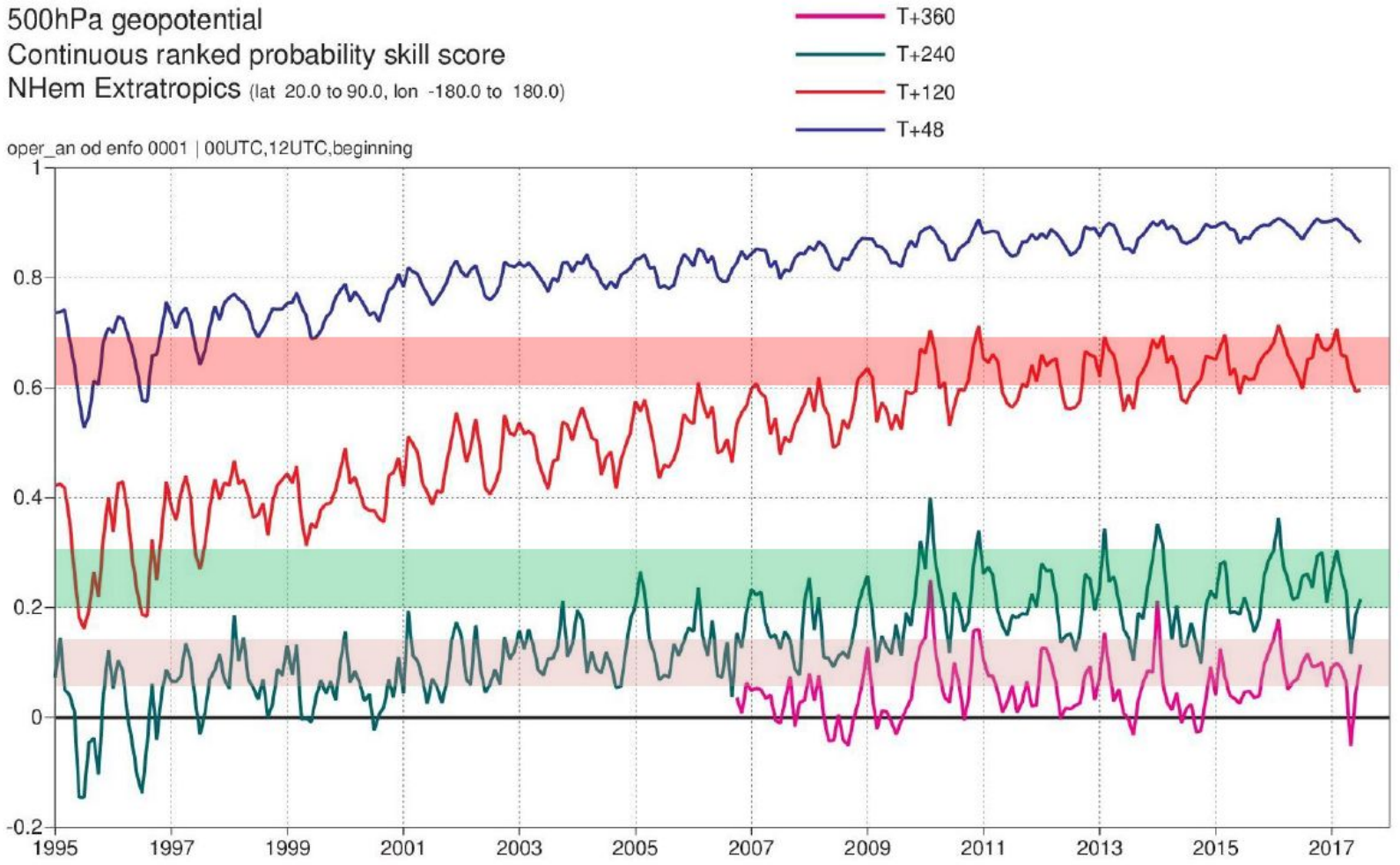
Joaquin ensemble guidance



GEFS

EC Ensemble

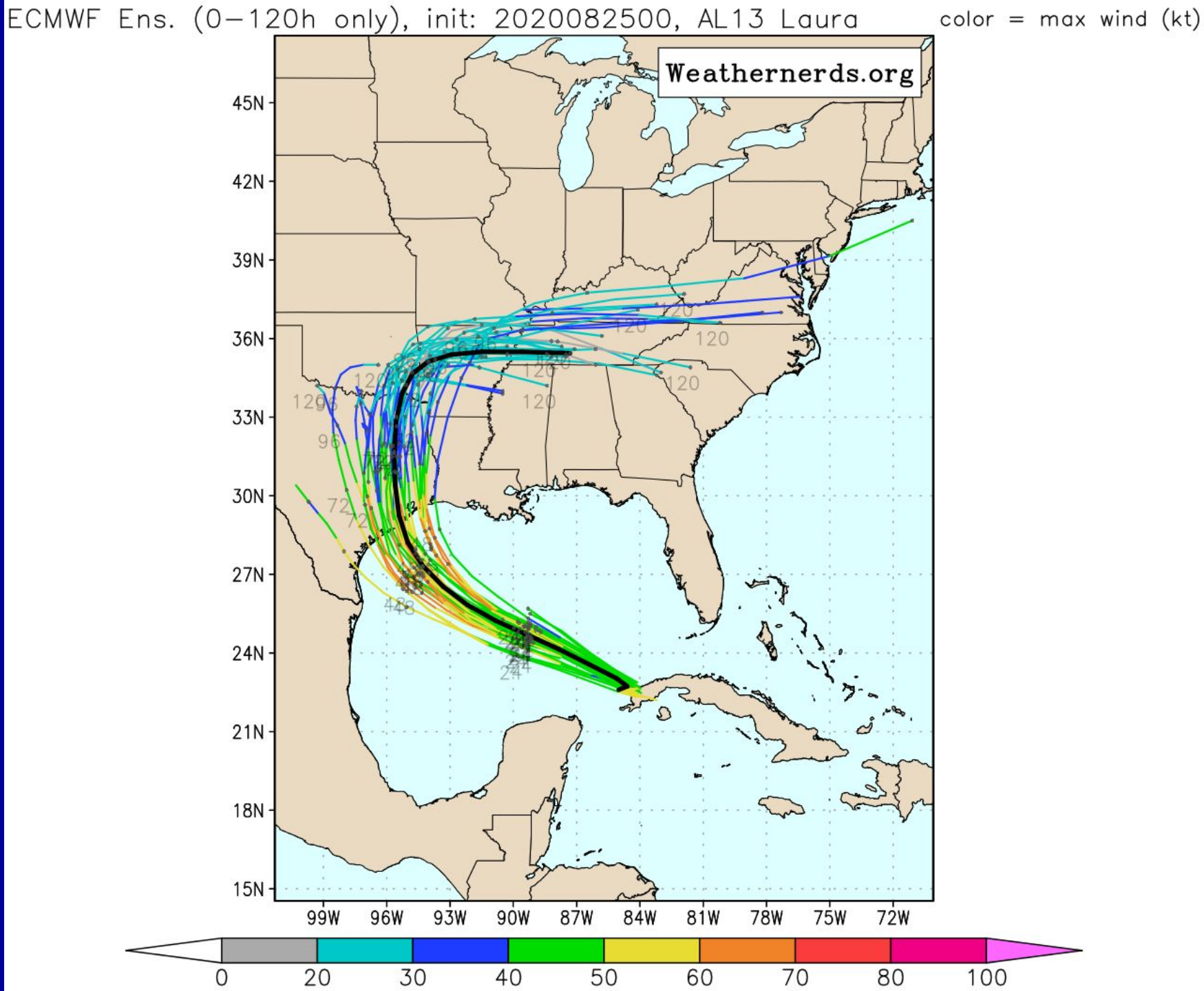
The continuous improvement of ENS fcs of ~2 days/decade



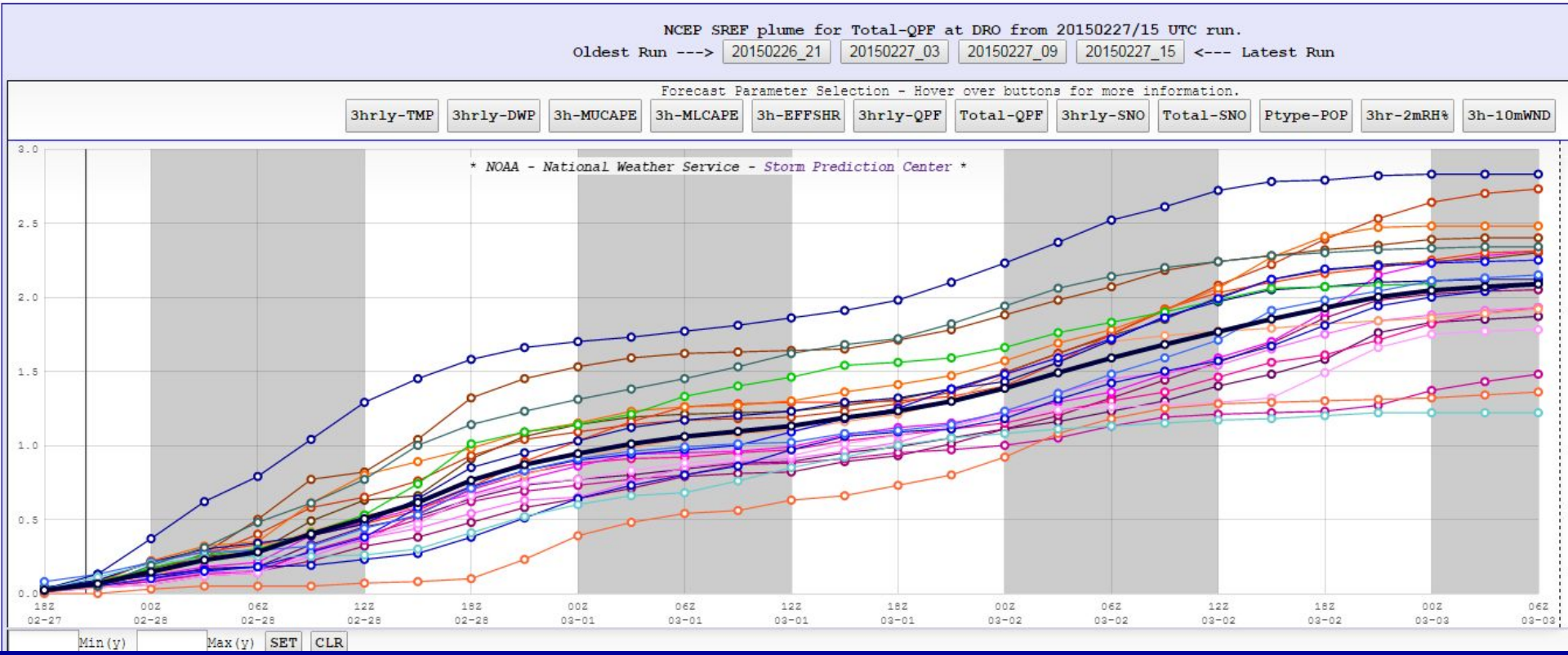
ECMWF

Buizza 2019

Case Example

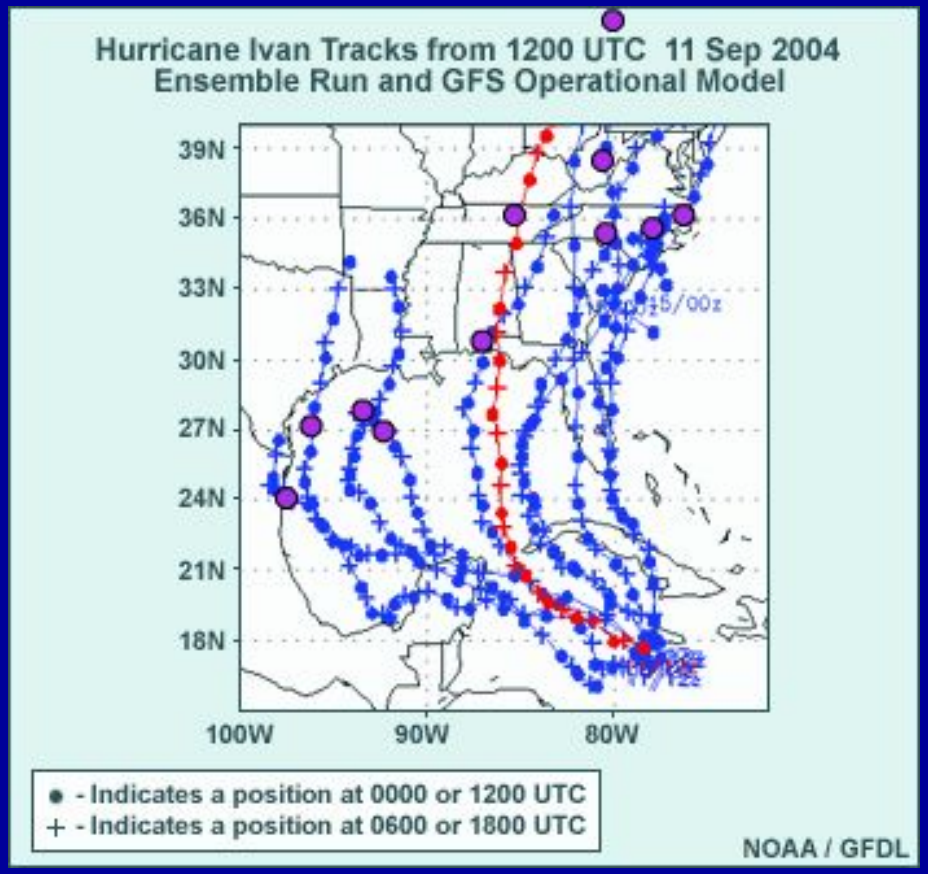

ECMWF Ens. (0–120h only), init: 2020082500, AL13 Laura
color = max wind (kt)
Weathernerds.org
45N
42N
39N
36N
33N
30N
27N
24N
21N
18N
15N
99W
96W
93W
90W
87W
84W
81W
78W
75W
72W
0
20
30
40
50
60
70
80
100

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)

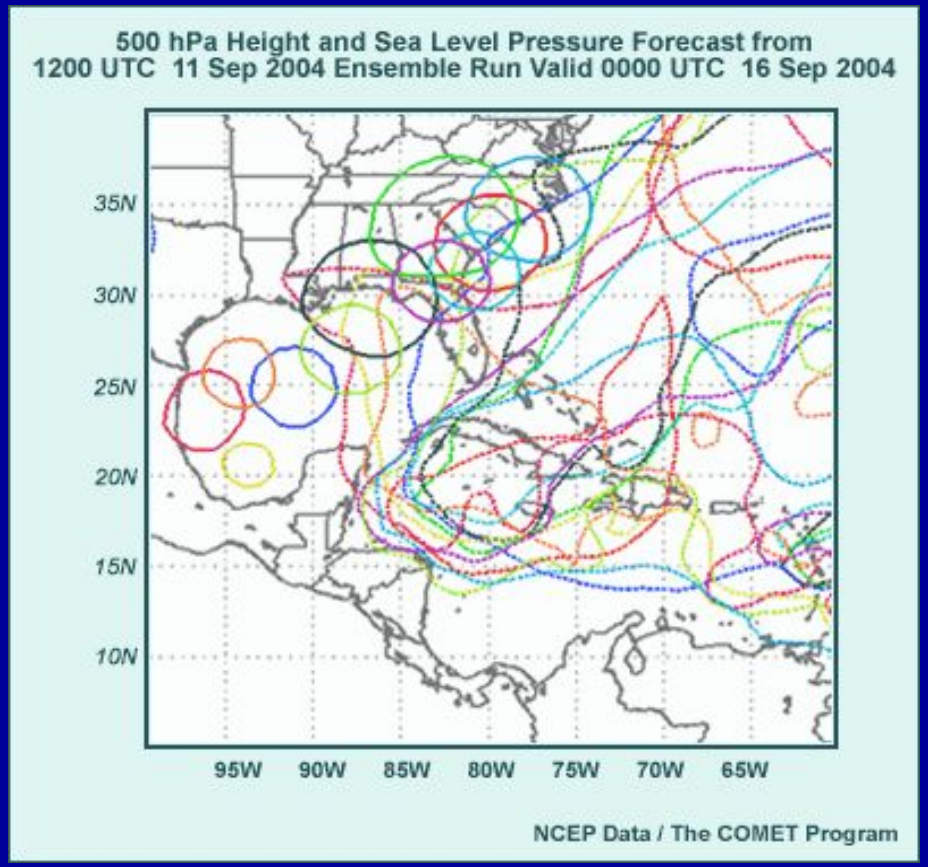
Ensemble Forecast Example



- **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

Credit: COMET

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

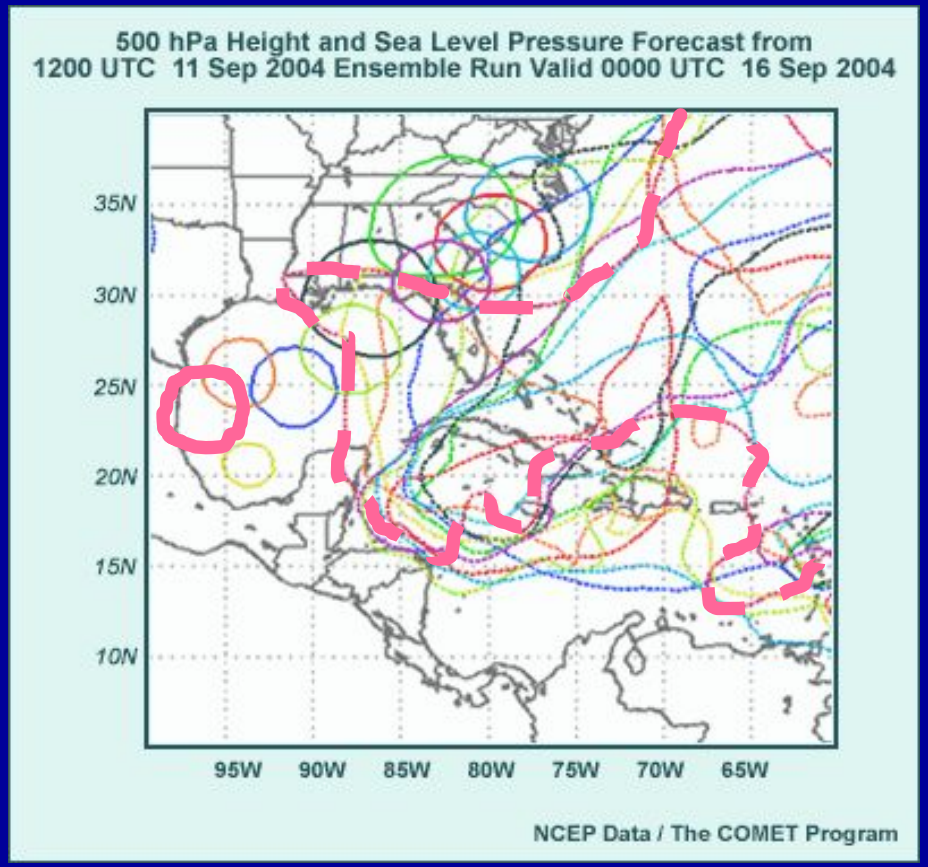
Credit: COMET

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

Ensemble Forecast Example



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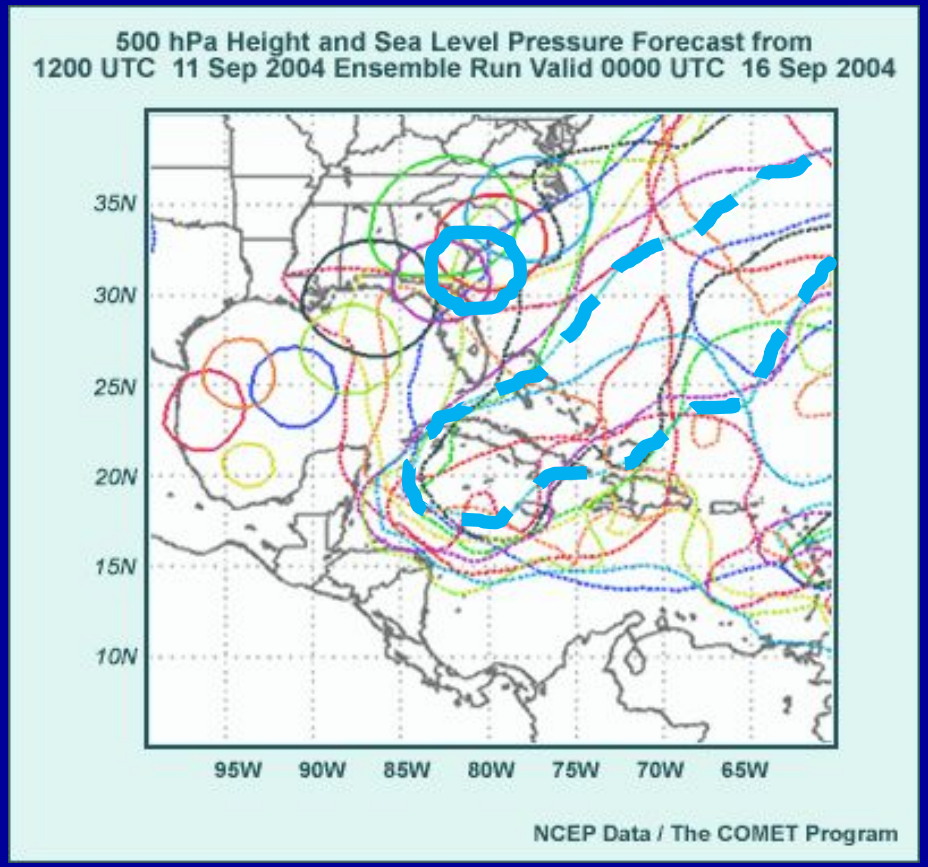
Credit: COMET

Ensemble Forecast Example



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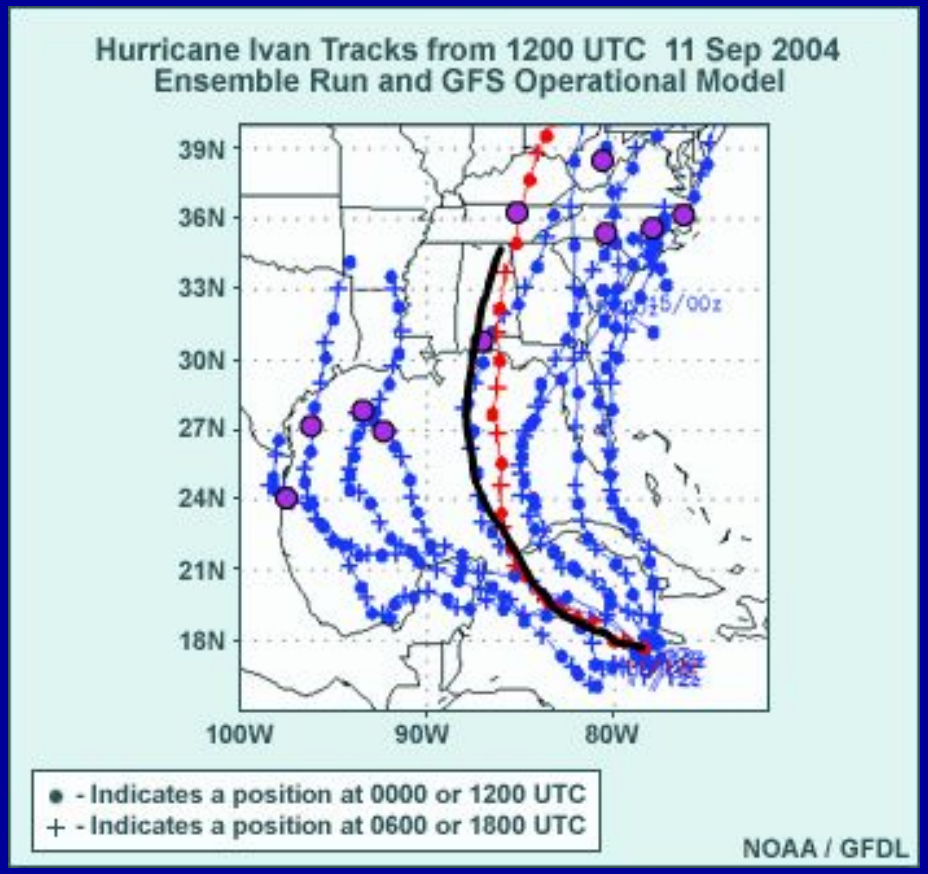
Credit: COMET

Ensemble Forecast Example

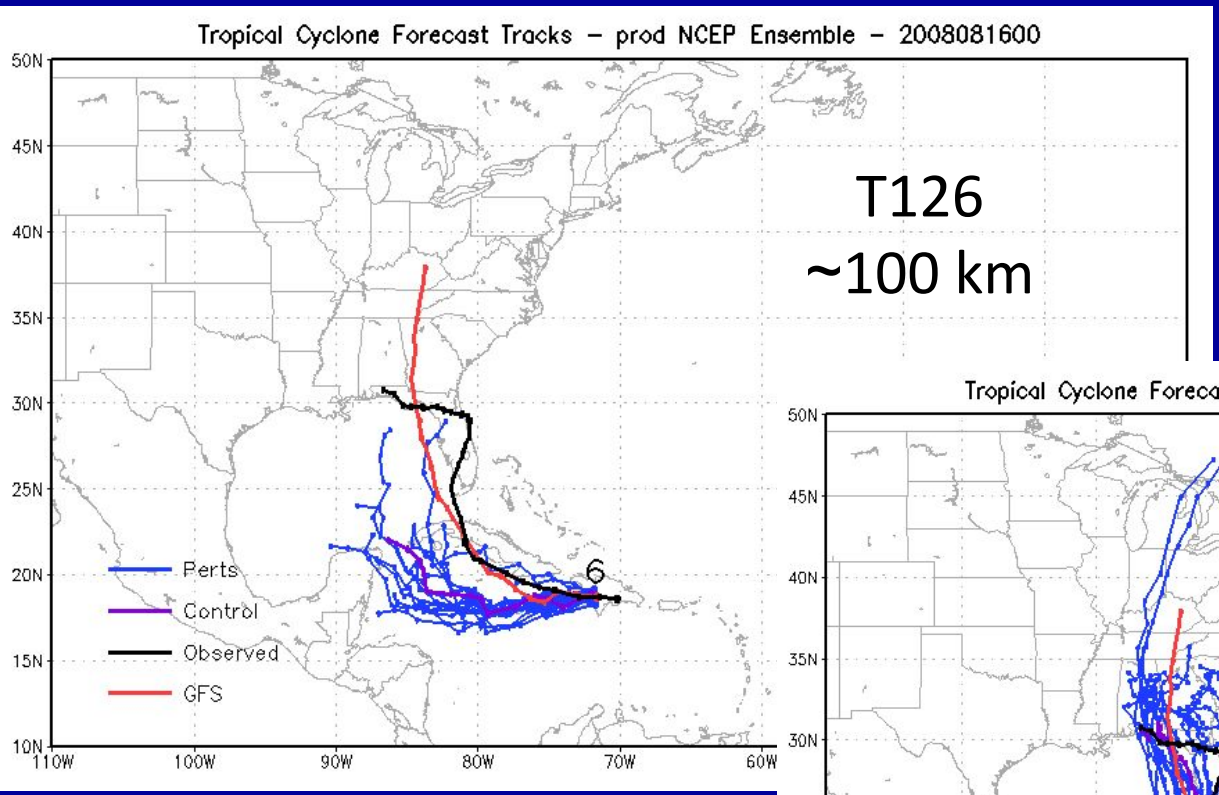


- **Ultimate path for Hurricane Ivan (black) - not too far from GFS and in the middle of the ensemble envelope of solutions**
  - Wide envelope of possible tracks
  - Because of uncertainty in the weakening of the Atlantic ridge, it turned out to be the best solution
  - Typically, one would be wary 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

Credit: COMET

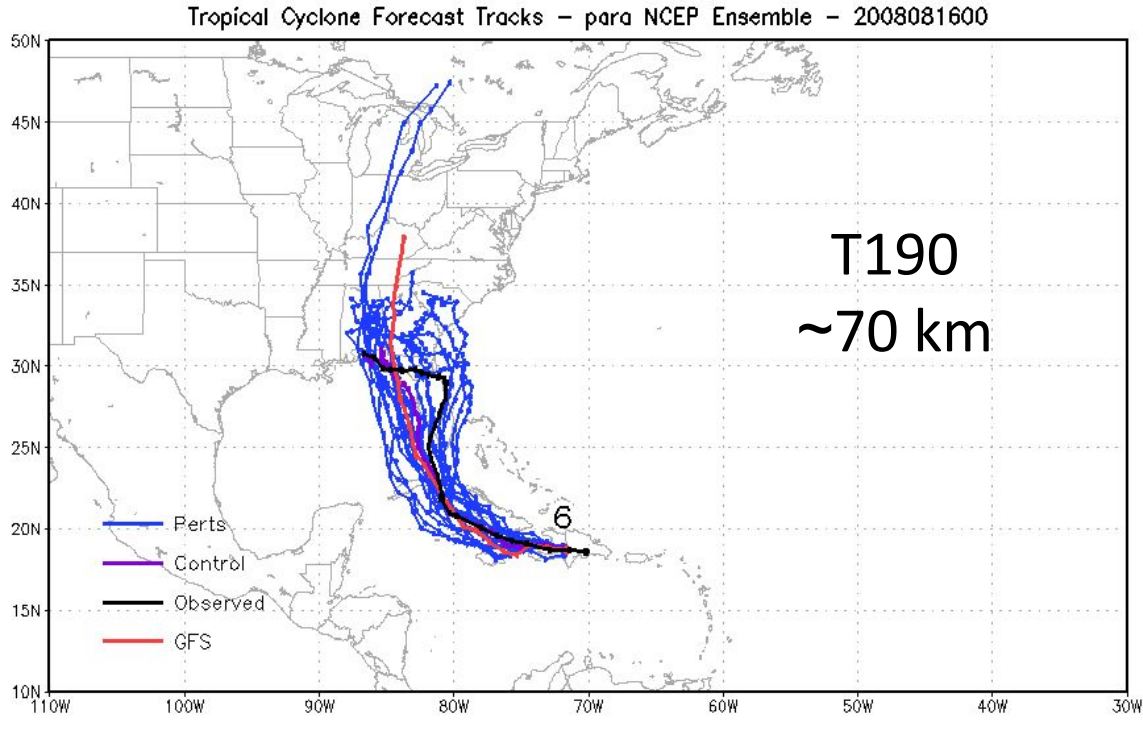
Improvements to Global Ensemble TC Track with Increasing Horizontal Resolution

Tropical Storm Fay 00Z – 16 Aug 2008



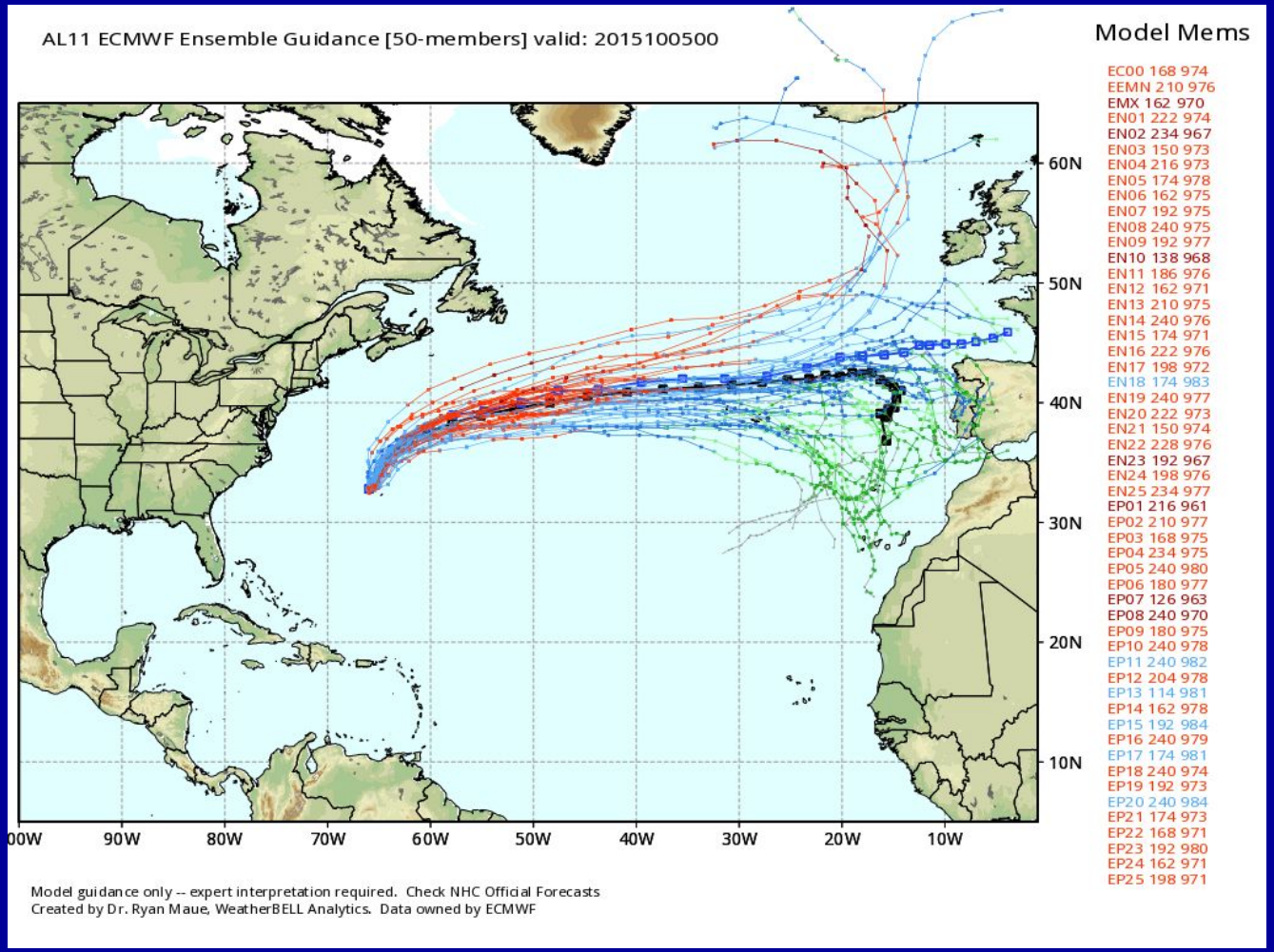
T126
~100 km

More members retain the TC and track forecasts are much improved

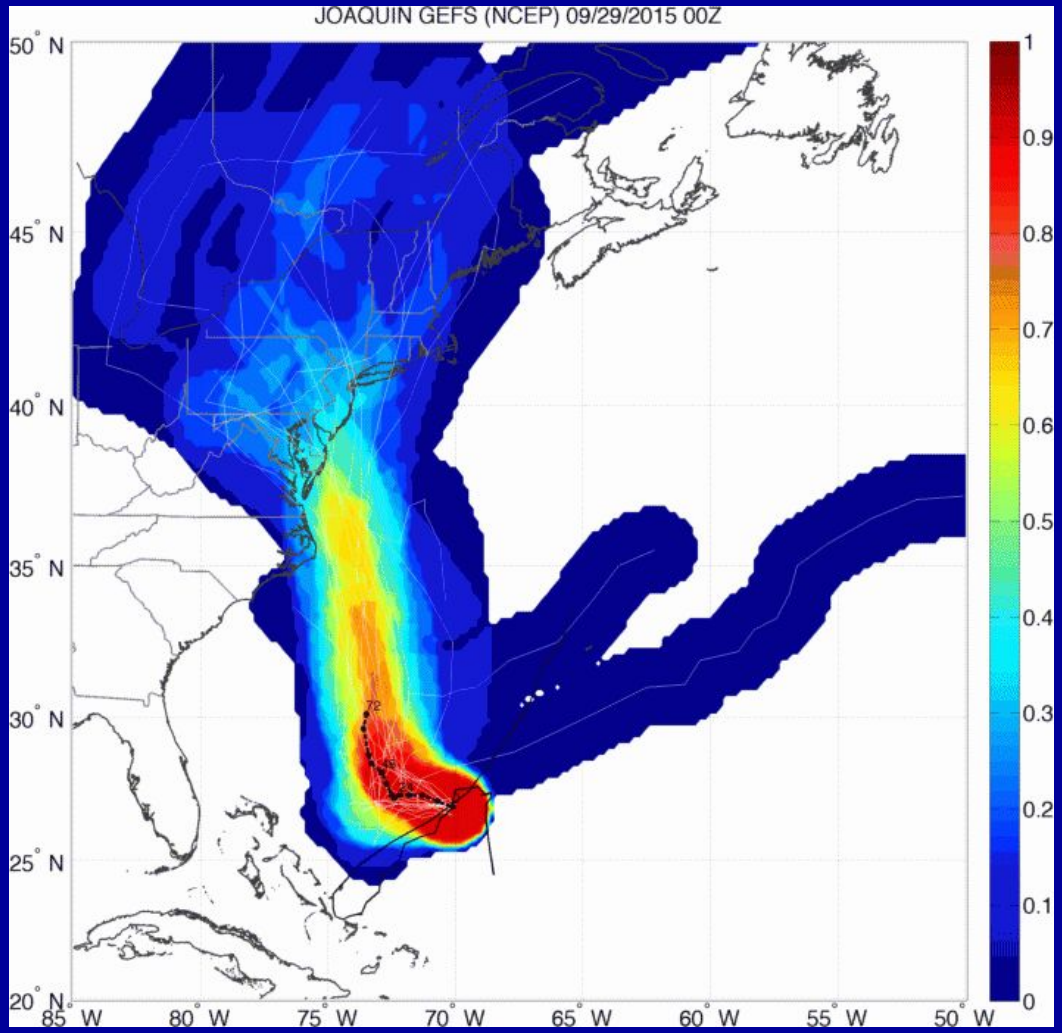


T190
~70 km

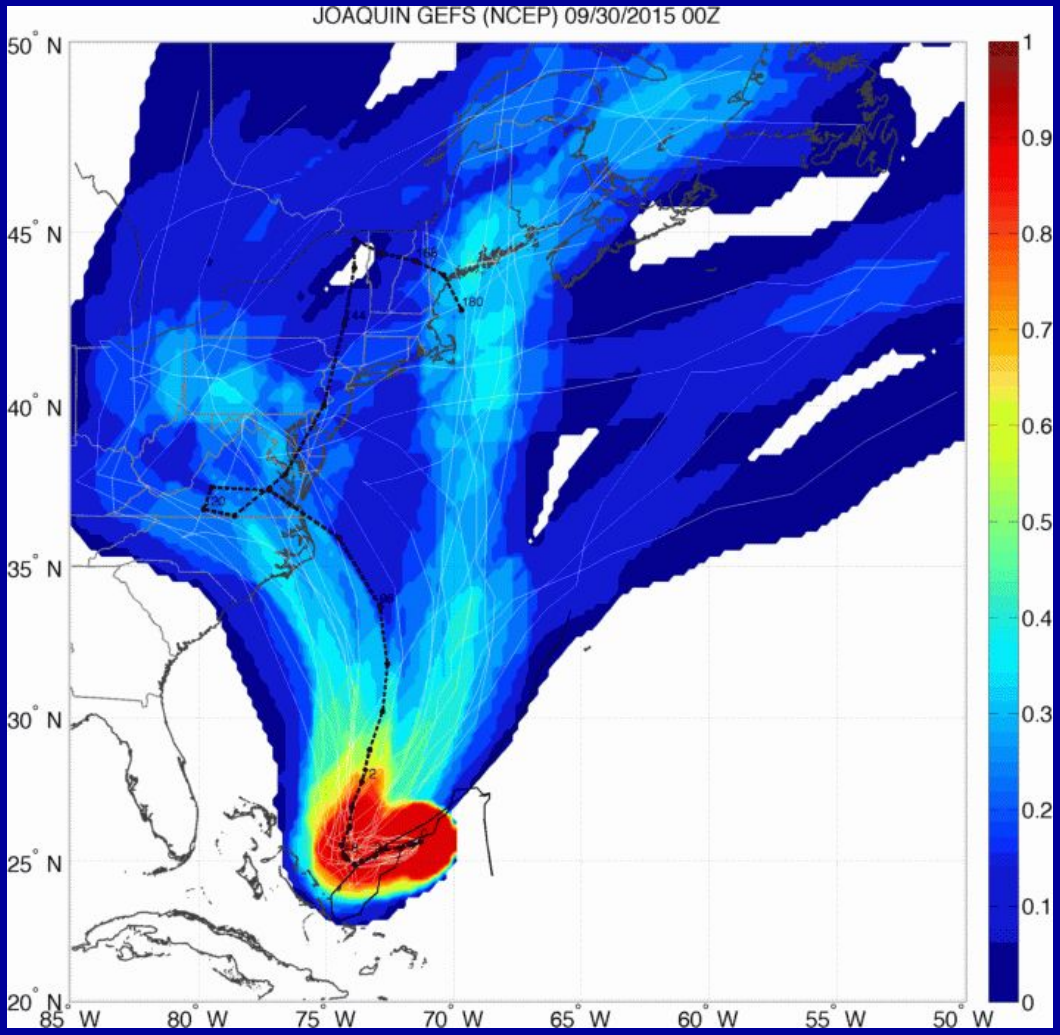
ECMWF ensemble colored by intensity



GEFS vs EC Ensemble 29 Sep 0000 UTC

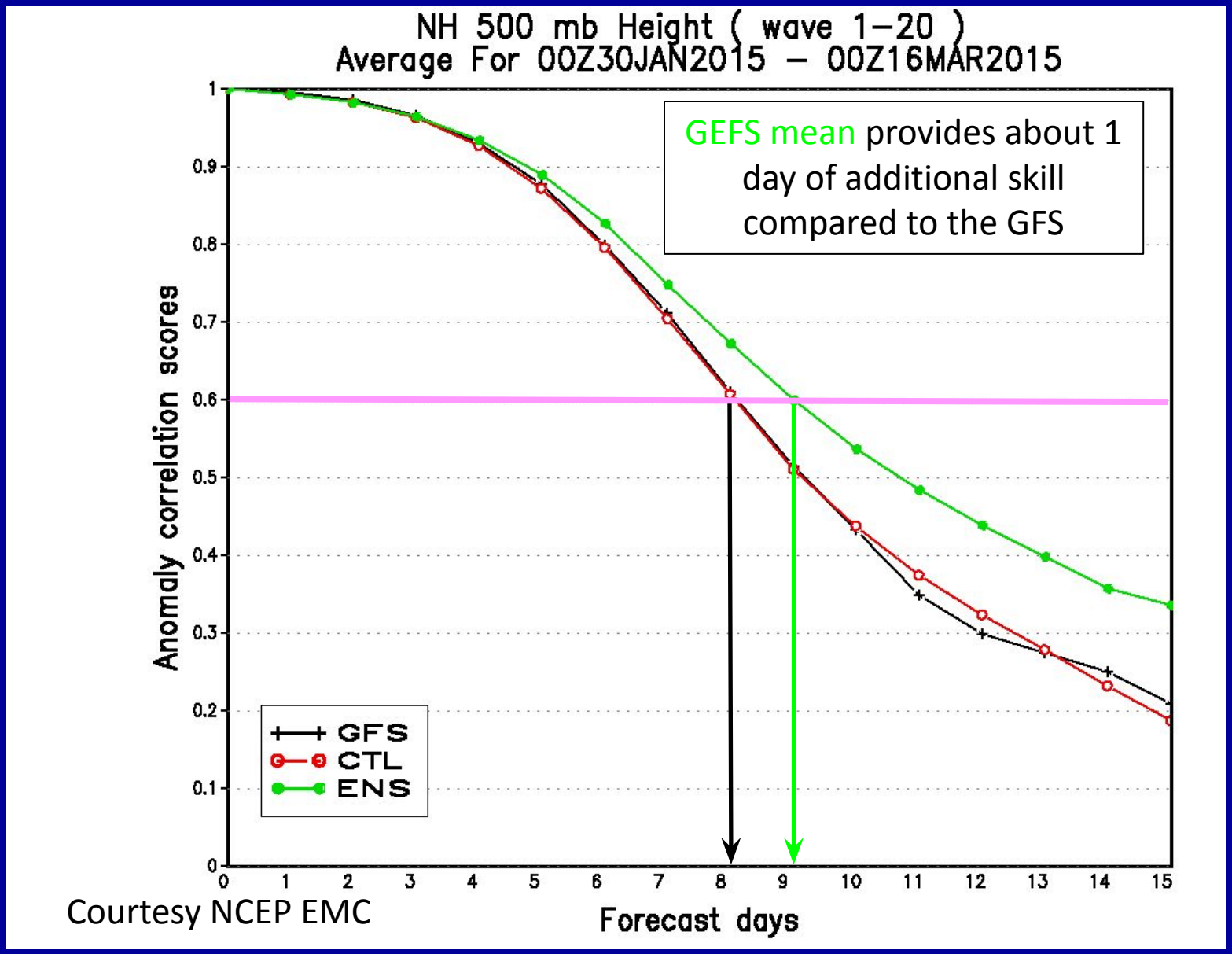


GEFS vs EC Ensemble 30 Sep 0000 UTC



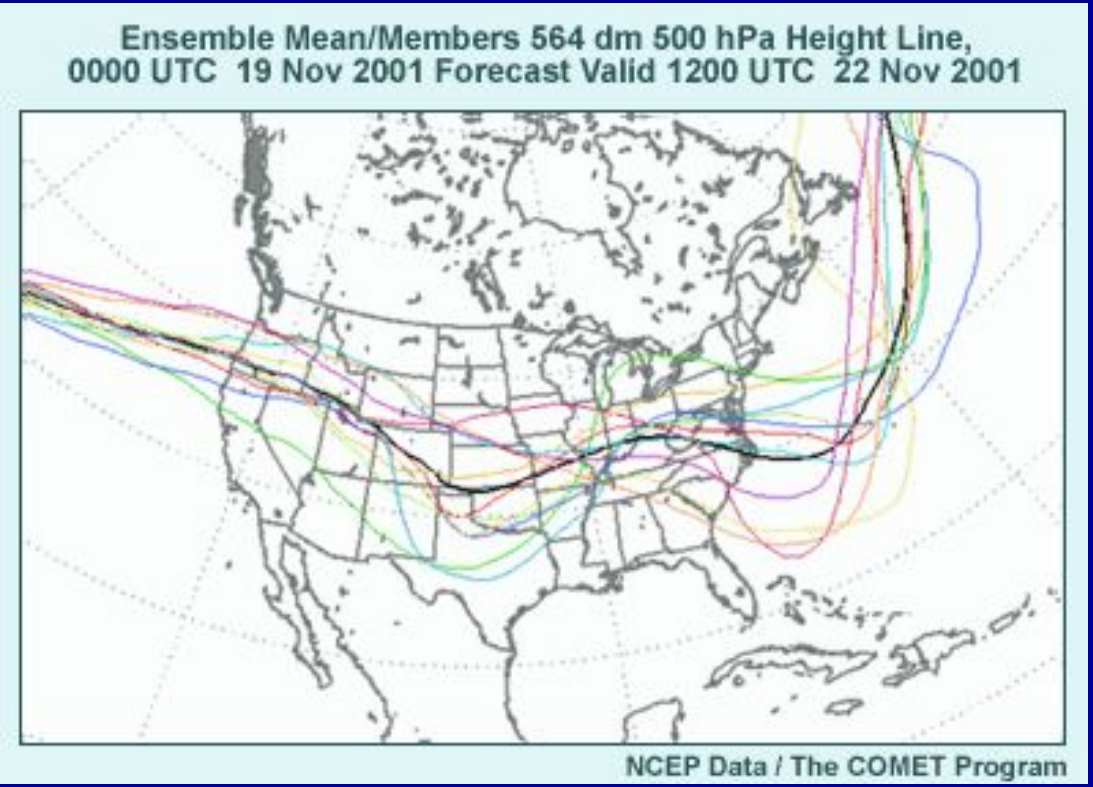
Ensemble Mean vs. Deterministic

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



Courtesy NCEP EMC

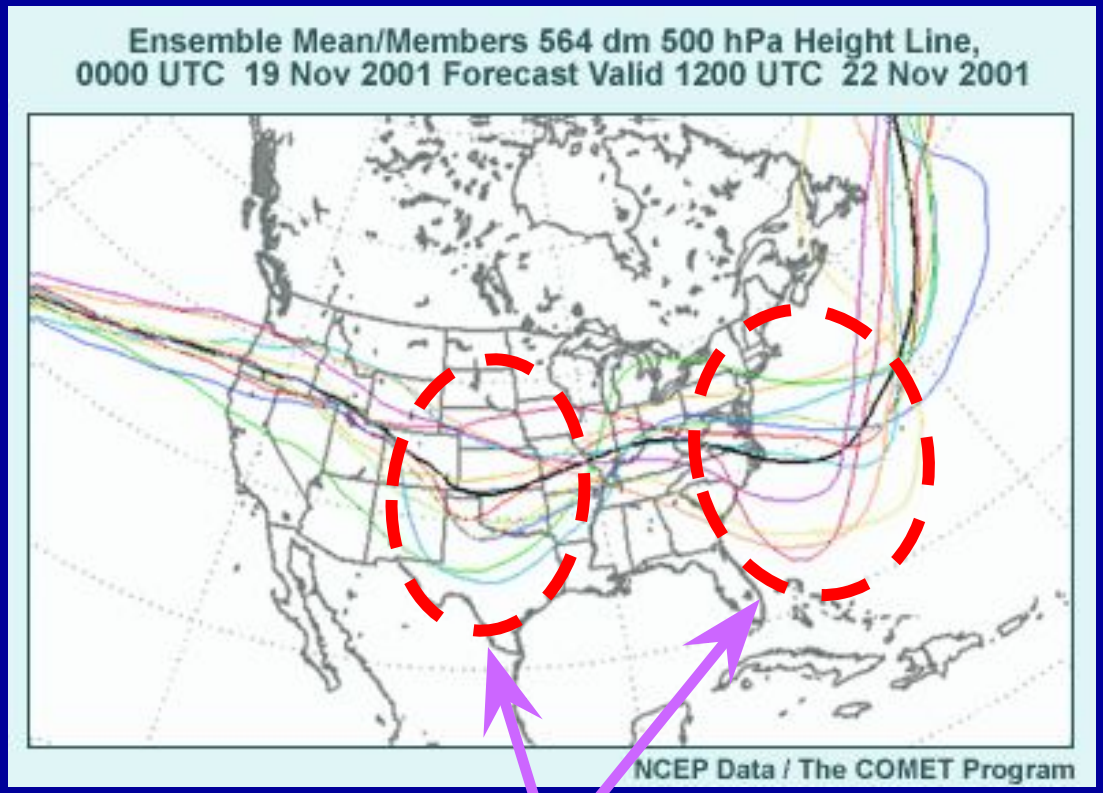
Displaying Ensembles



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

Credit: COMET

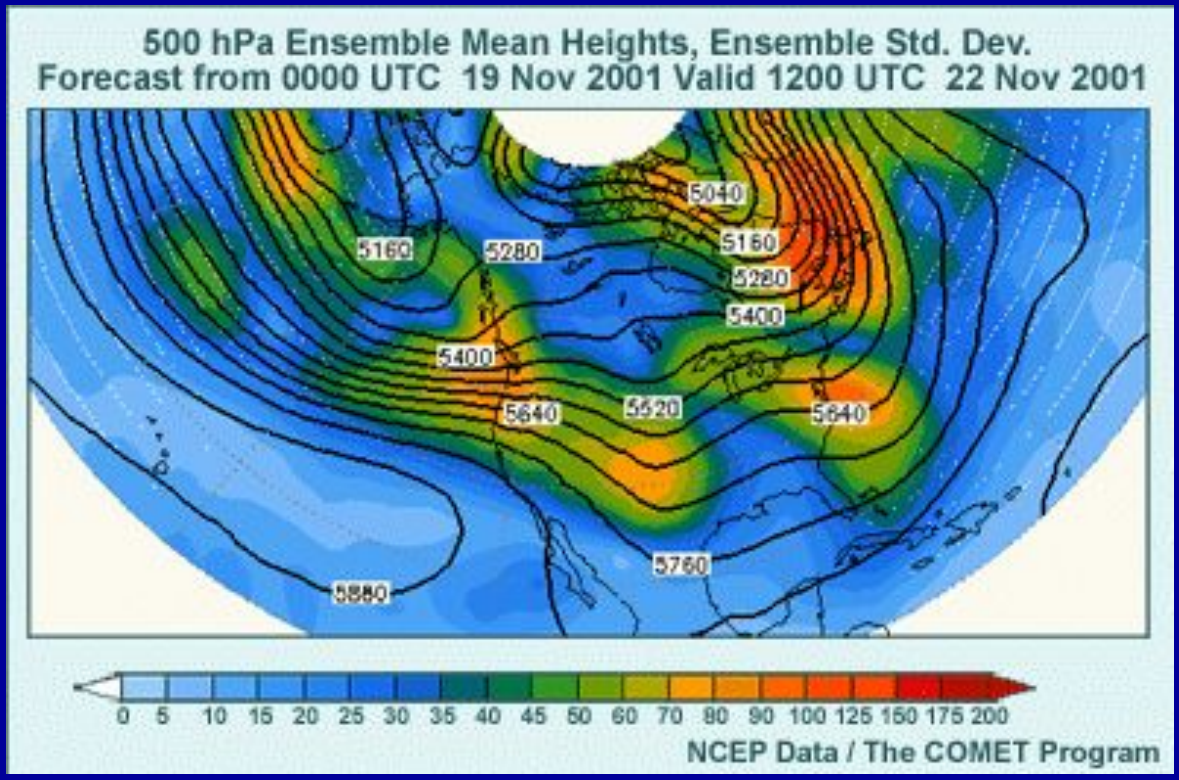
Displaying Ensembles



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

Credit: COMET

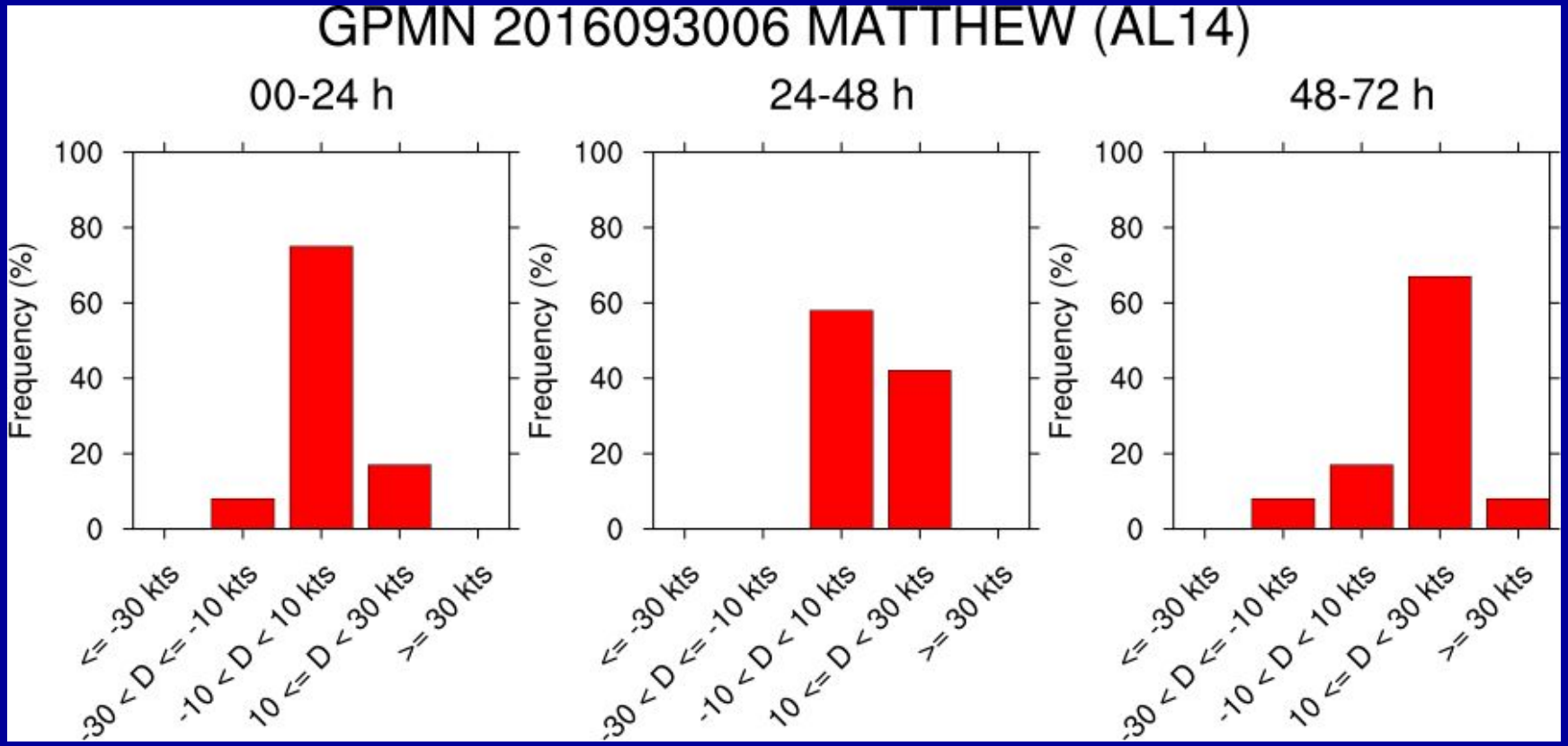
Displaying Ensembles



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

Credit: COMET

Intensity Change Probability Distributions



Poll 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. The correct track will always be within the spread

ECMWF Ensemble Prediction System

- 51 members (1 control+50 perturbed members)
- Run twice daily (00 and 12 UTC) out to 15 days, 6/18 UTC 144h
  - T639 (~ 18 km) to 15 days
  - 137 vertical levels

Perturbations:

- Generated using singular vectors and stochastically Perturbed Parameterization Tendencies Scheme (SPPT)

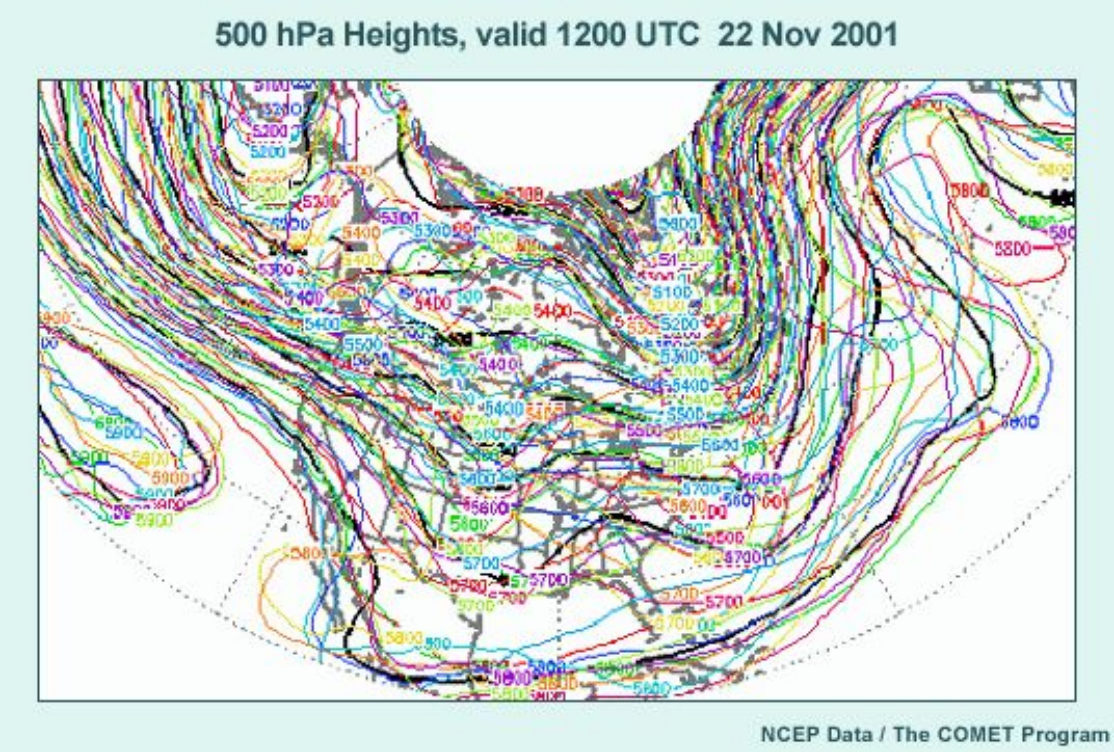
Deterministic ECMWF

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

Big ensemble upgrade coming in June for horizontal resolution to match deterministic!

Ensemble Display and Interpretation

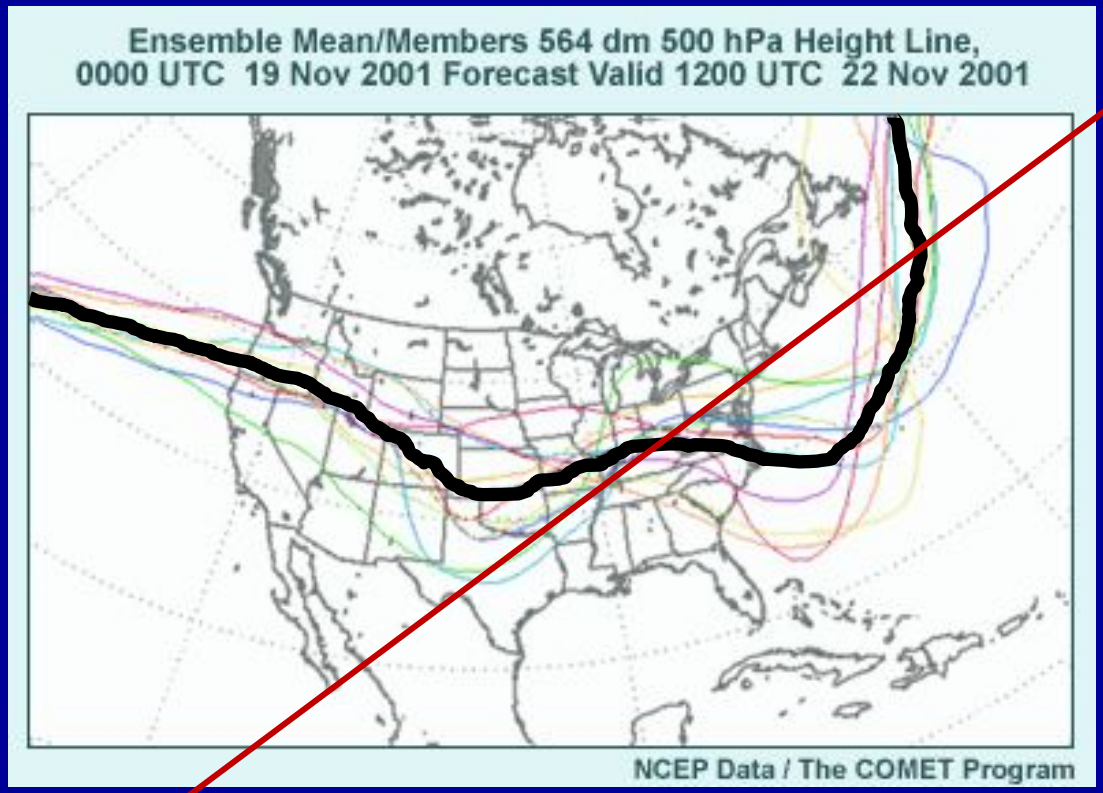
Displaying Ensembles



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

Credit: COMET

Displaying Ensembles

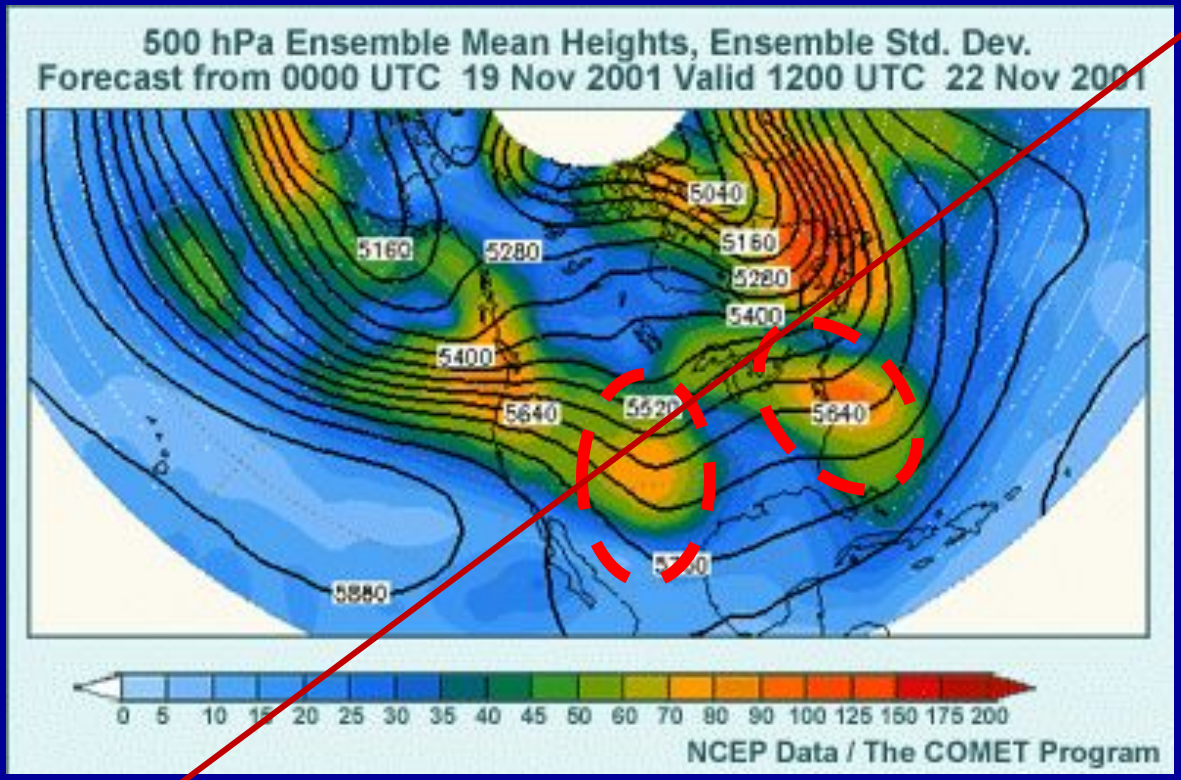


Ensemble Mean - average of multiple forecast members verifying at same time

Credit: COMET

Displaying Ensembles

Ensemble Mean and Spread



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  - Orange/Red – little agreement between members
  - Blue – good agreement between members

Credit: COMET

Displaying Ensembles
Ensemble Mean and Spread

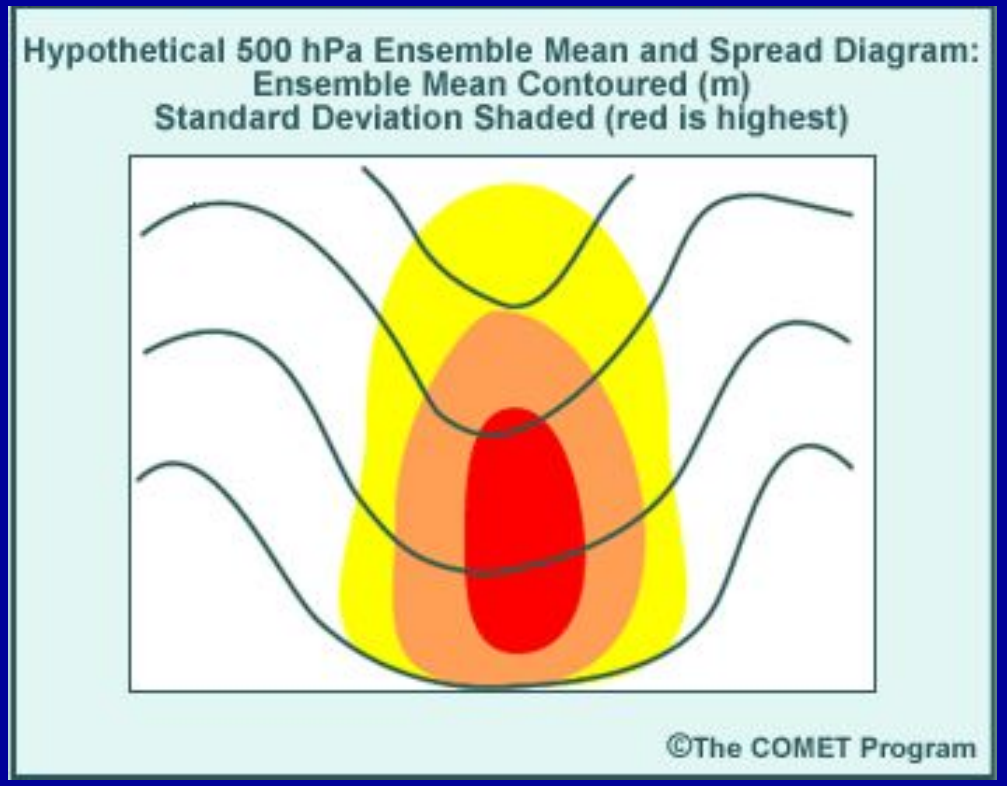
- Advantages
  - Summarizes data in easy to interpret form
  - Information provided for the entire domain
  - Low predictability features smoothed out by the ensemble mean and easily identifiable using spread
- Disadvantages
  - Ensemble mean can be misleading (and may not be the best forecast) if multiple 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?



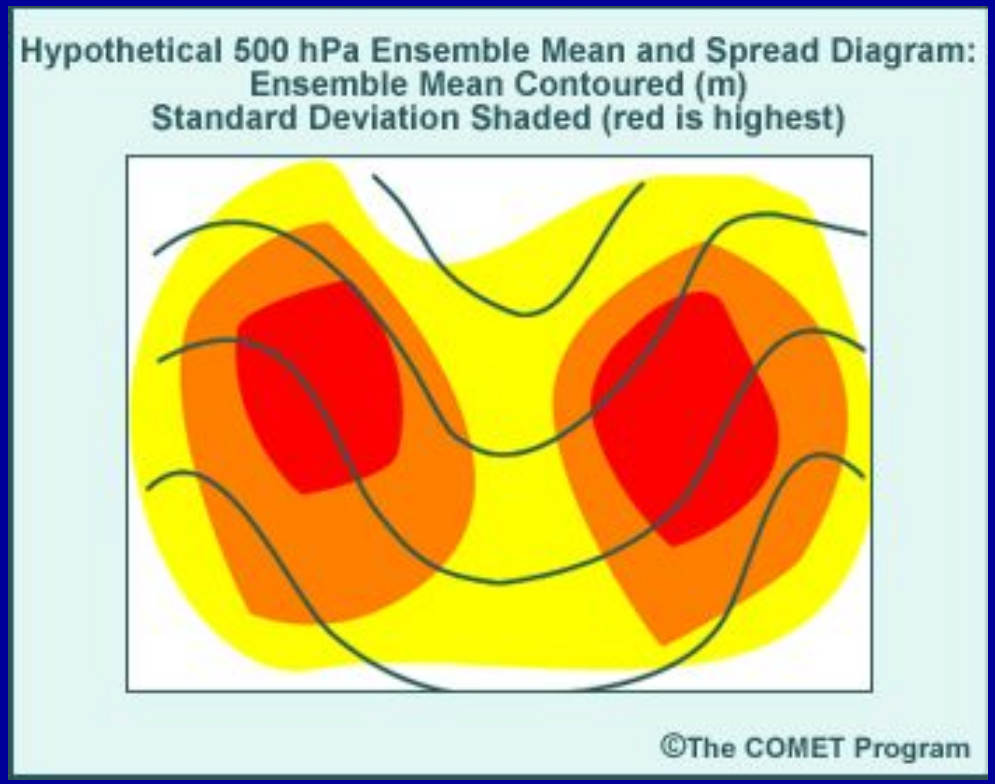
Credit: COMET

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?



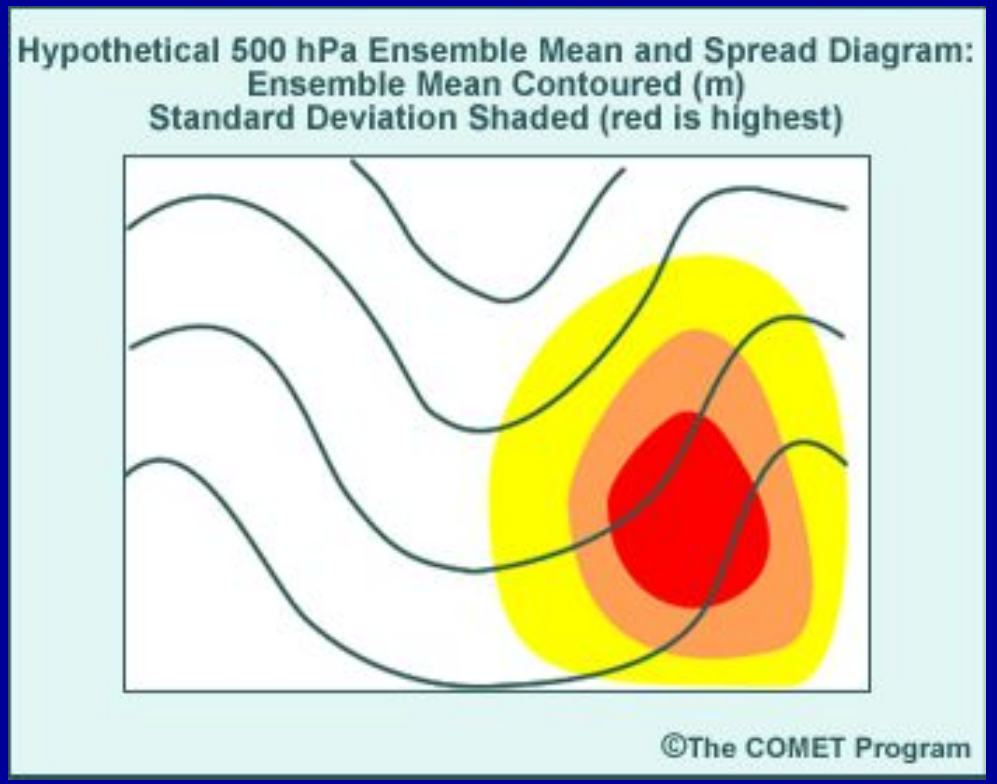
Credit: COMET

Interpreting Mean and Spread

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

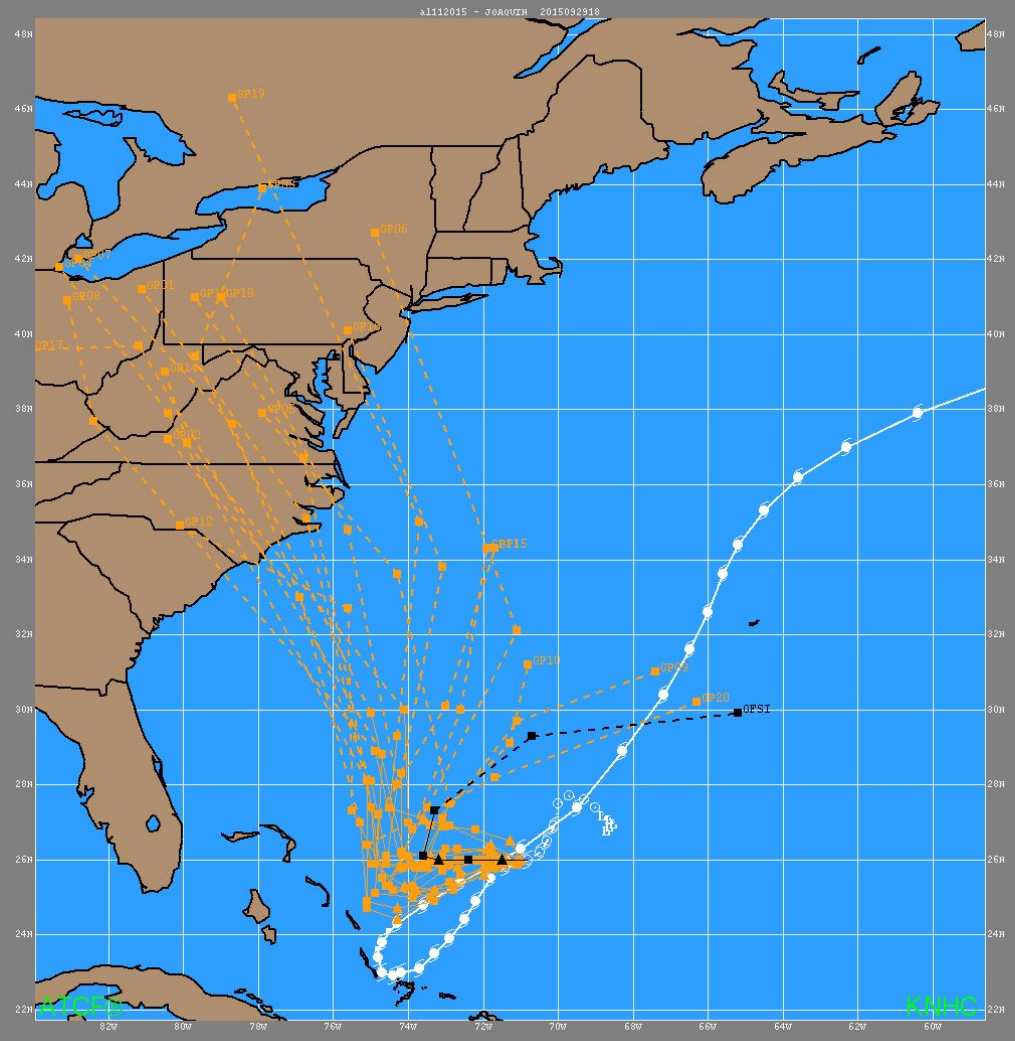
•In this case, the spread indicates greater potential for the trough axis to be east of the ensemble mean trough than to the west

•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?

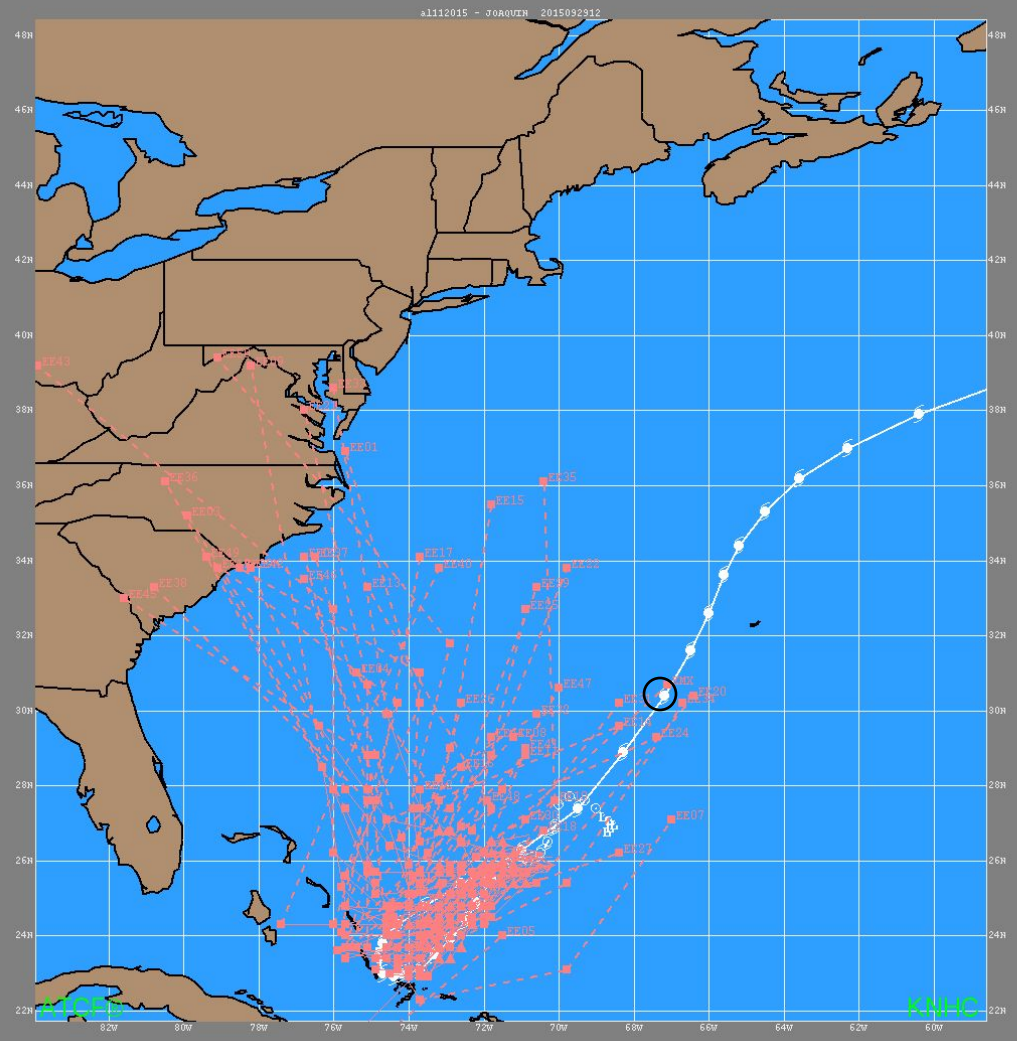


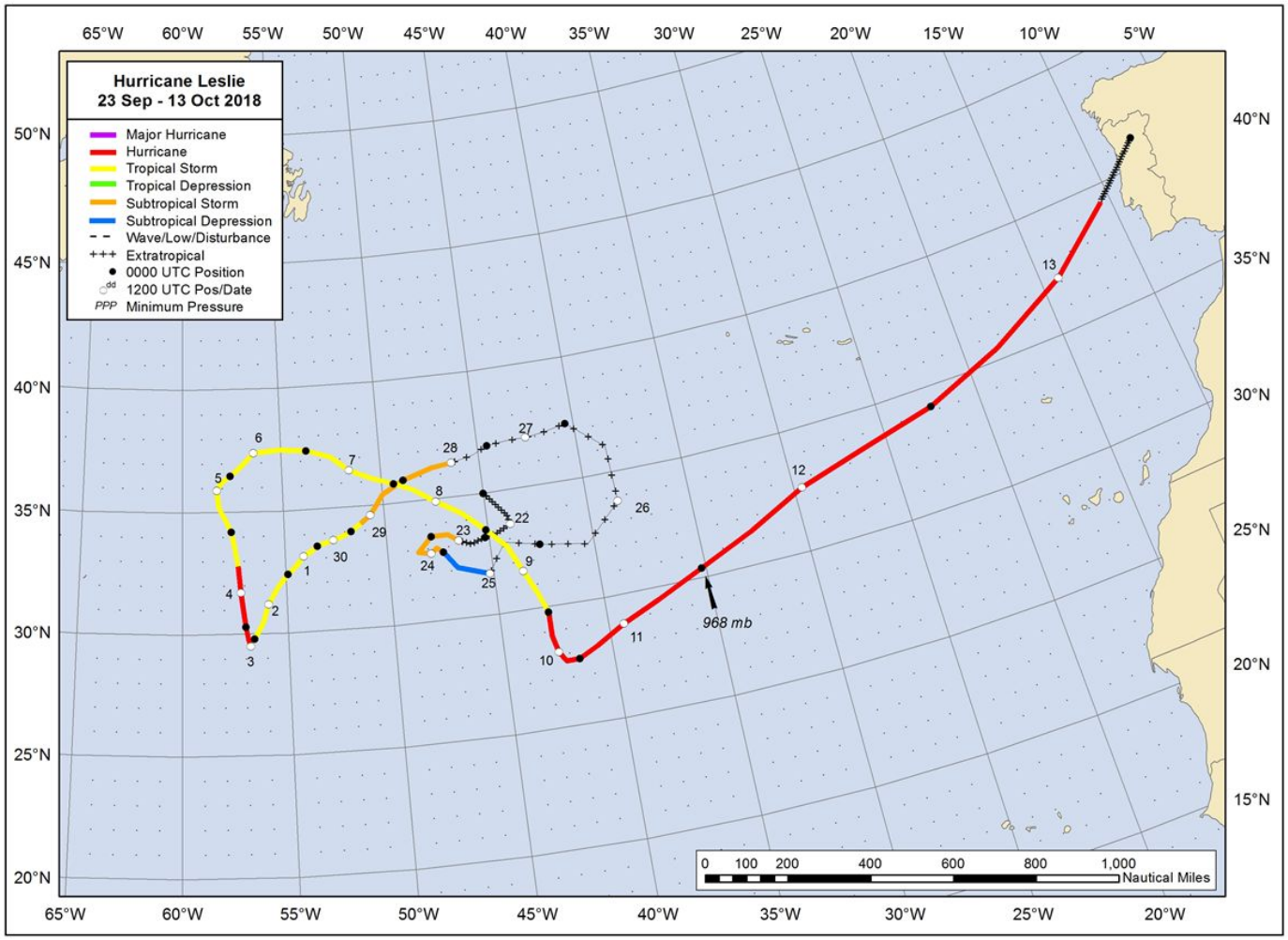
Credit: COMET

GFS Joaquin ensembles 29 Sep 1200 UTC



ECMWF Joaquin ensembles 29 Sep 1200 UTC

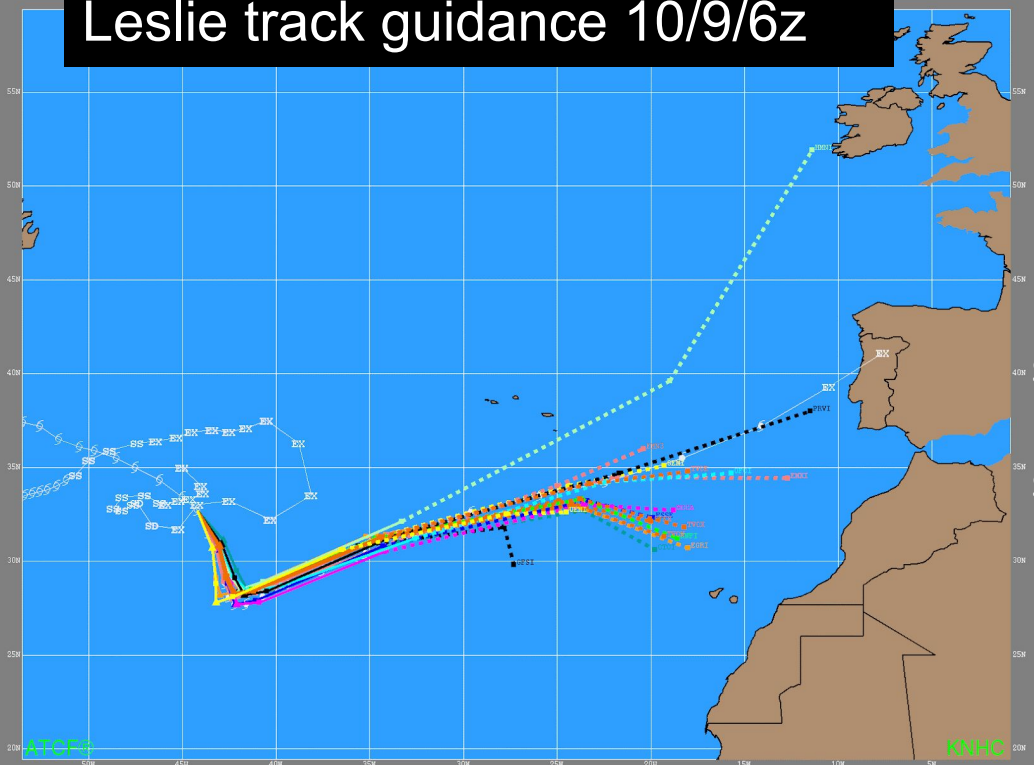




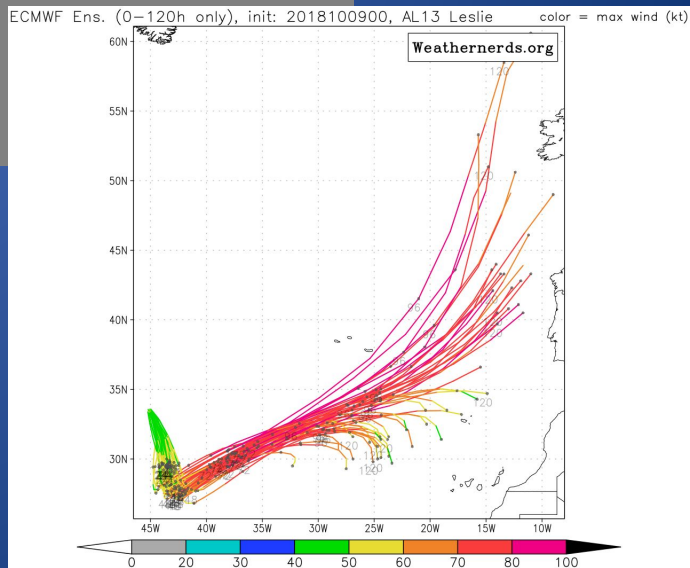
Hurricane Leslie

Long lasting and ***highly*** annoying

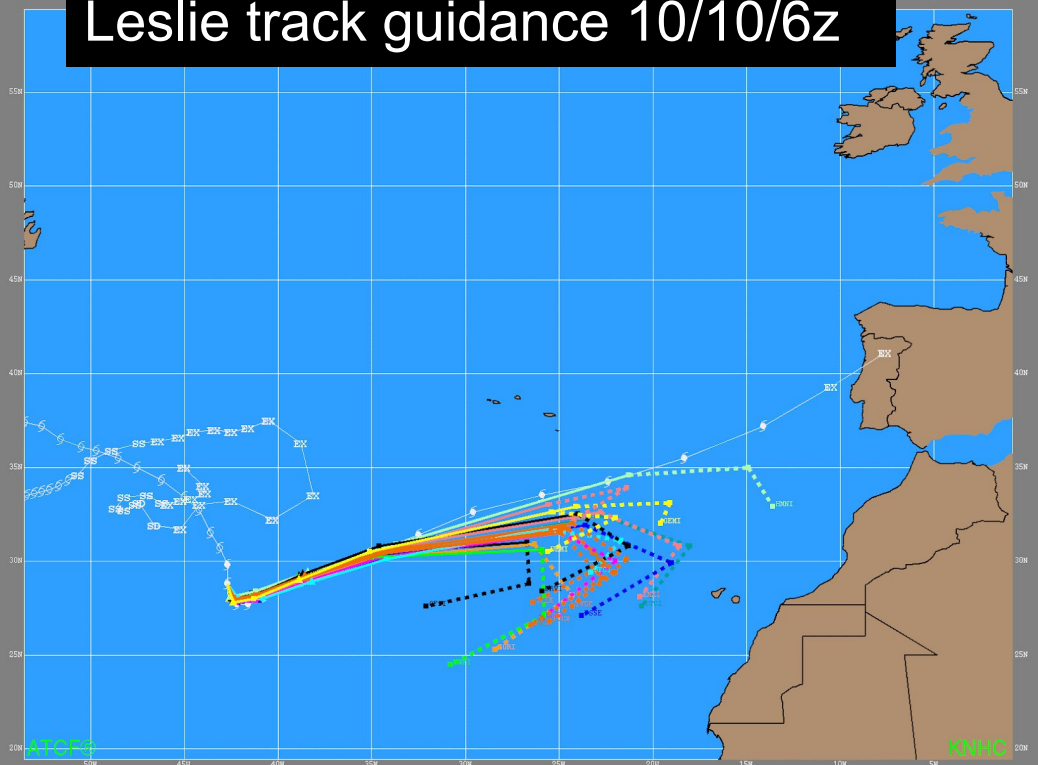
Leslie track guidance 10/9/6z



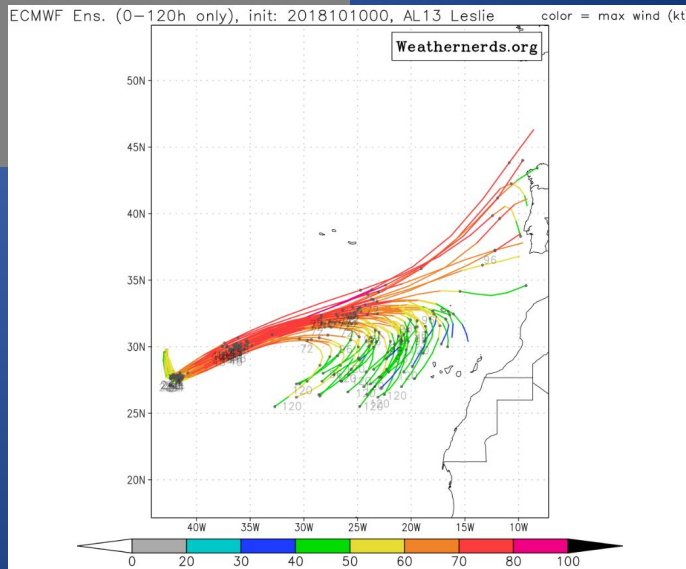
Major model spread, but best models farthest south



Leslie track guidance 10/10/6z



EC ensemble not as definitive



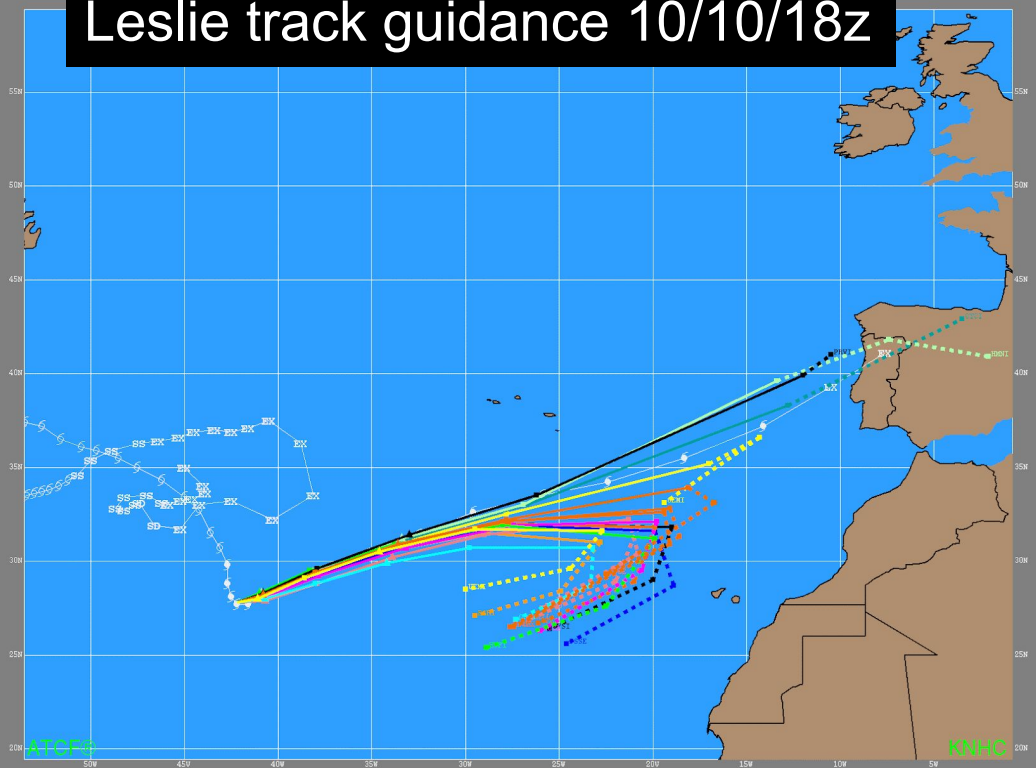
Leslie track guidance 10/10/12z

72 hour zoom

–

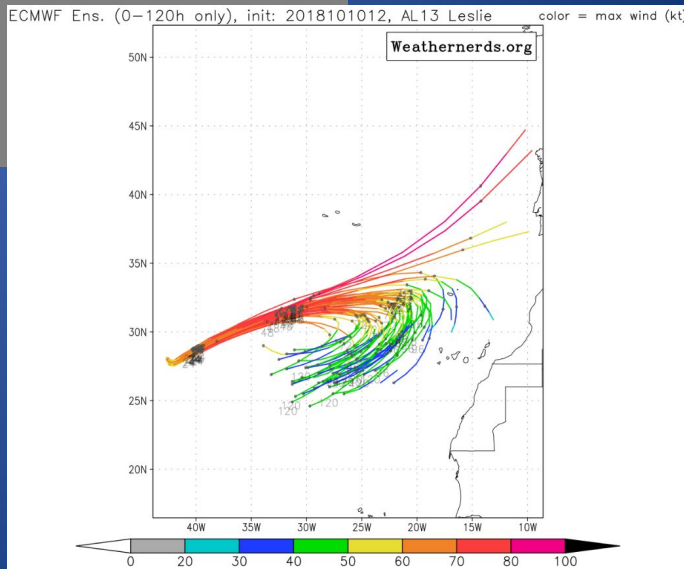
All models have a 400- 600 n mi error

Leslie track guidance 10/10/18z

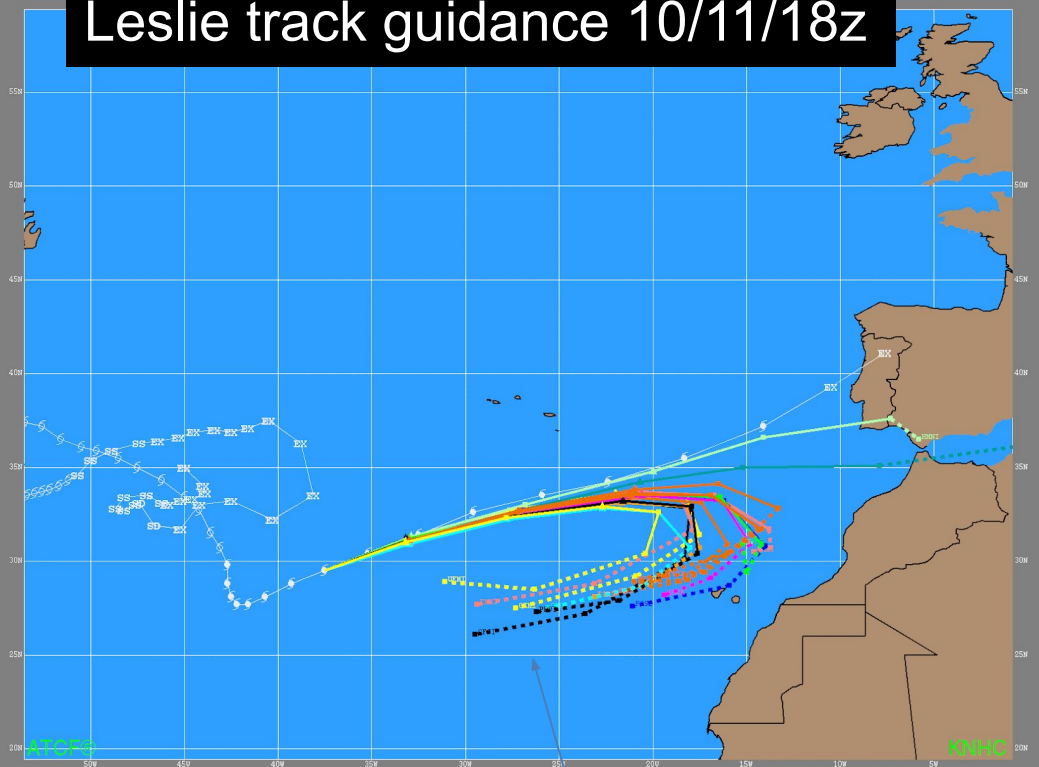


Few more models shift north, but most still miss the trough

EC ensemble continues to shift south



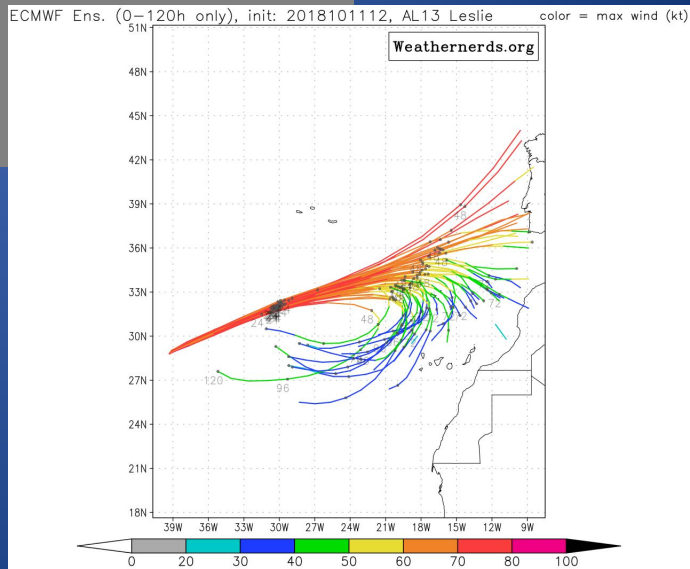
Leslie track guidance 10/11/18z



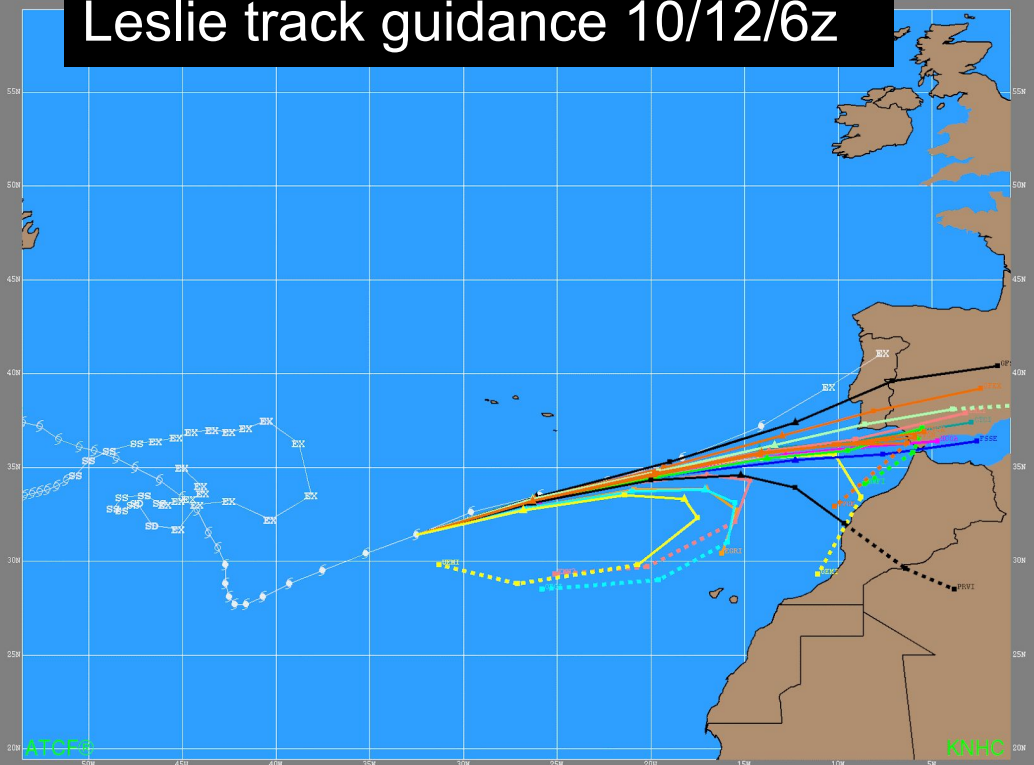
Deterministic models shift south, but little change in EC ensemble

~400 n mi errors in < 48 h

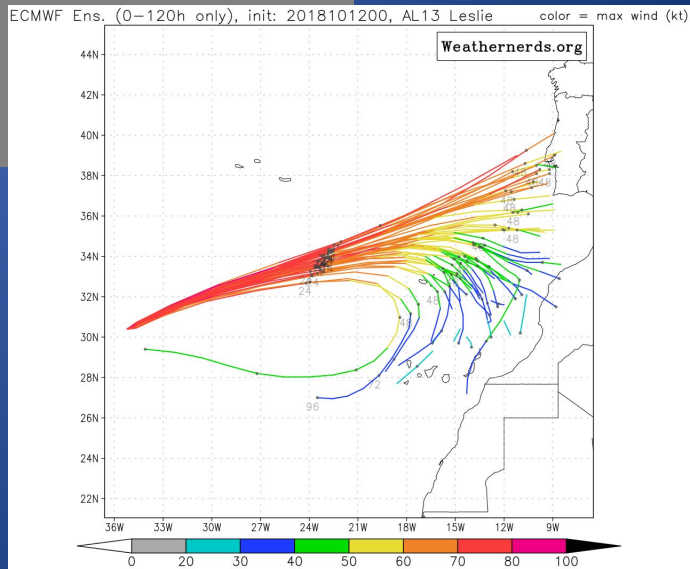
GFS shifts over 1500 n mi



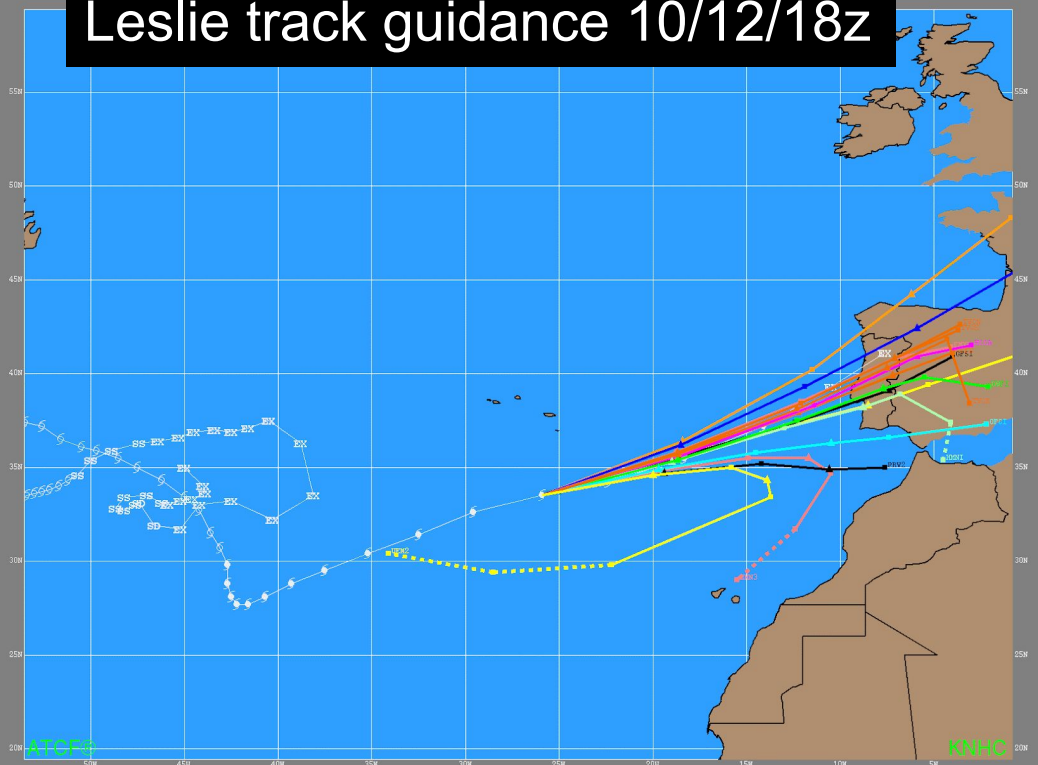
Leslie track guidance 10/12/6z



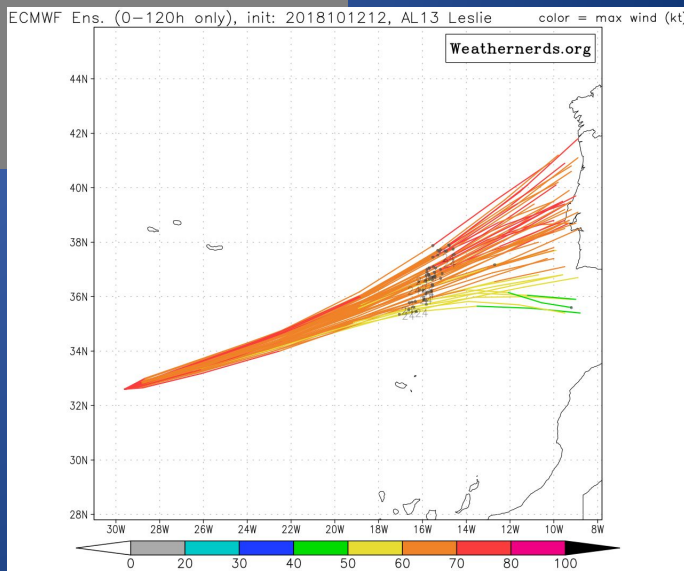
Models mostly jump northward



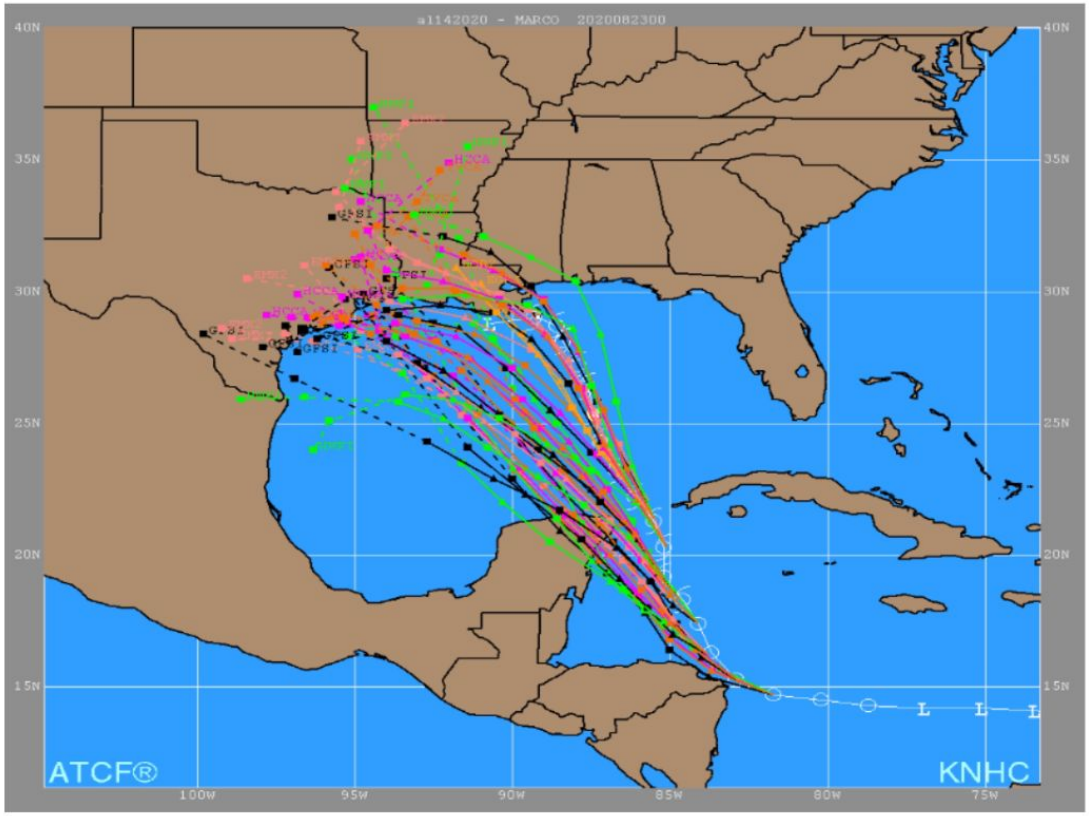
Leslie track guidance 10/12/18z



Finally!



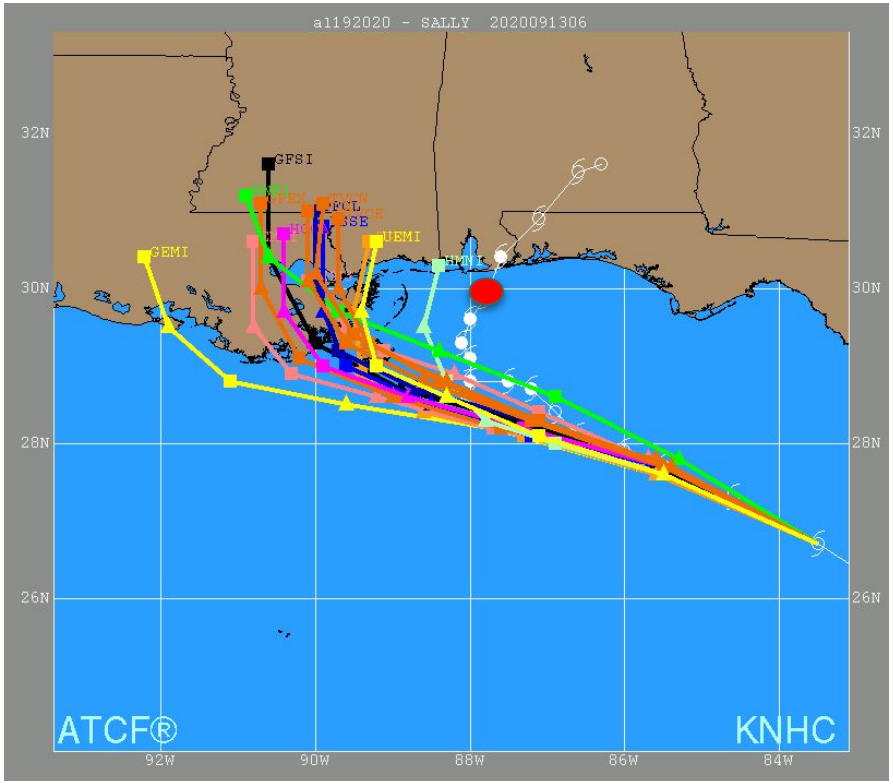
Track Forecast Challenges - Marco



Marco track guidance 21-23 August 2020

Potential interaction between Marco and Laura as well as uncertainty about Marco's intensity led to huge variability in track guidance for Marco and poor forecasts

Track/Warning Forecast Challenges - Sally



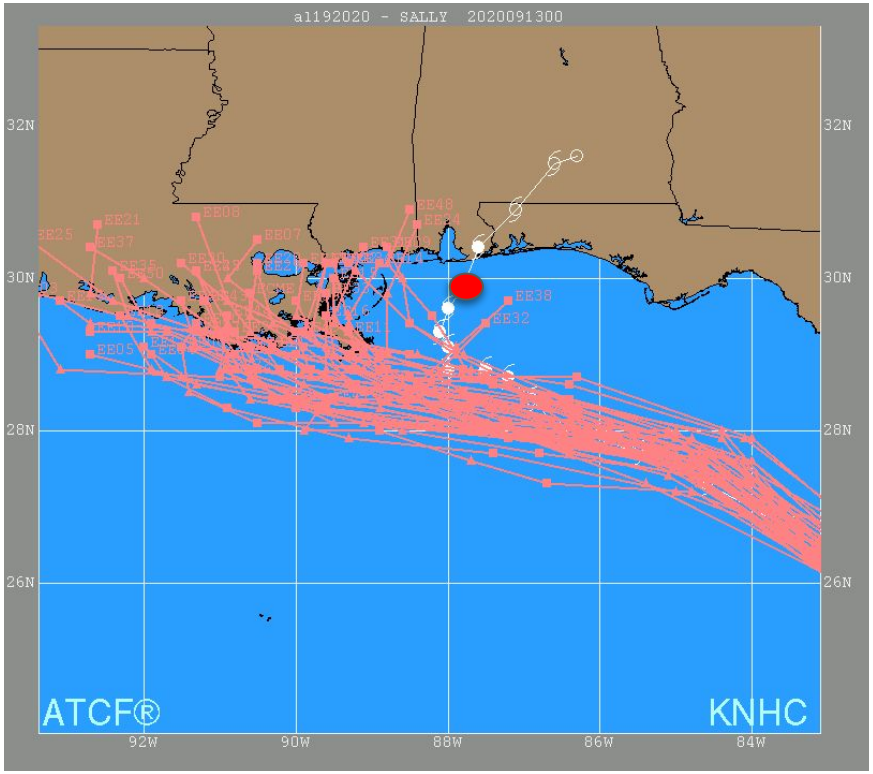
Track guidance 0600 UTC 13 September 2020

Track guidance whiffed when it the Hurricane Warning was put up

Resulted in a clear-sky bust for Louisiana

Note HMNI closest - yet it had a NE bias for Marco. Recent past does affect forecaster perceptions

Track/Warning Forecast Challenges - Sally



ECMWF Ens 0600 UTC 13 September 2020

No help from the best ensemble system either

If anything you might suspect the forecast would bust left, not right

Some stronger members on right side, but intensity skill lags

Genesis Guidance

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

In-house product

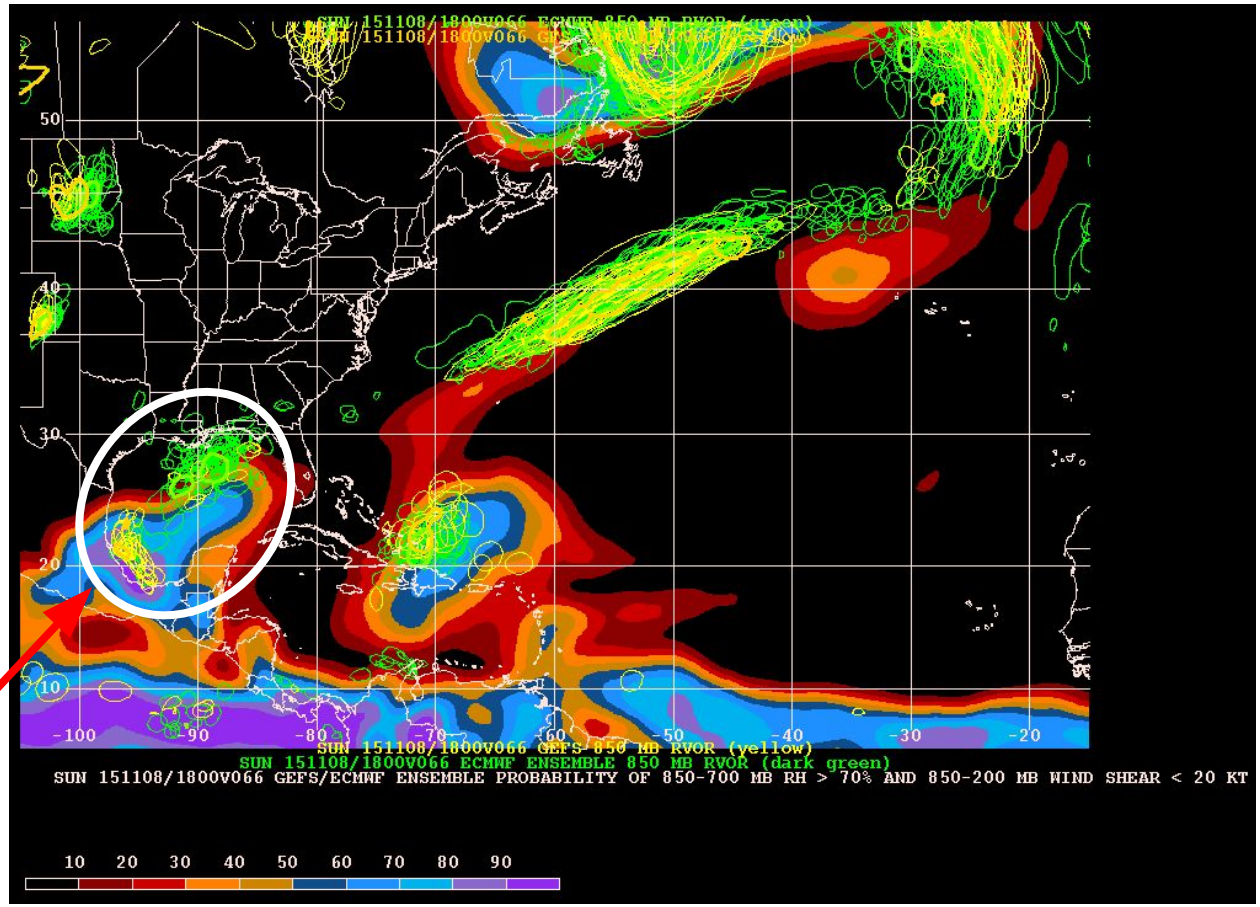
shading: combined probability of 70 ensemble members (GEFS + ECENS):

- 850 – 700 hPa RH > 70%
- 200 – 850 hPa vertical wind shear < 20 kt

contours: 850 hPa relative vorticity (8 x 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**

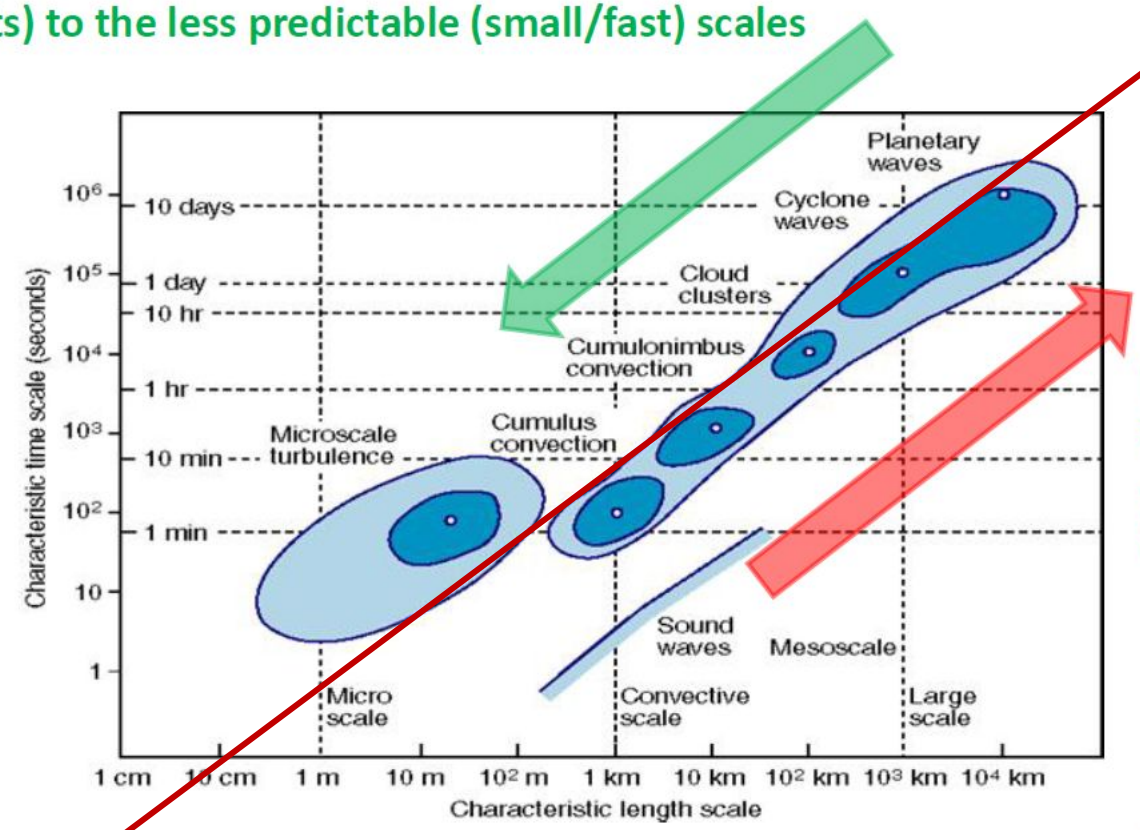


Learning Objectives

- Explain the value of ensembles
- Explain how NHC incorporates ensembles into their forecast products
- Correctly interpret the uncertainty NHC forecast products
- Evaluate ensemble guidance to estimate the uncertainty in TC track or intensity forecasts

How did we manage to extend the FSH beyond 2 weeks?

Predictable signals propagate from the better-initialized and more predictable scales ('mainly' the large scales, the slowly evolving components) to the less predictable (small/fast) scales



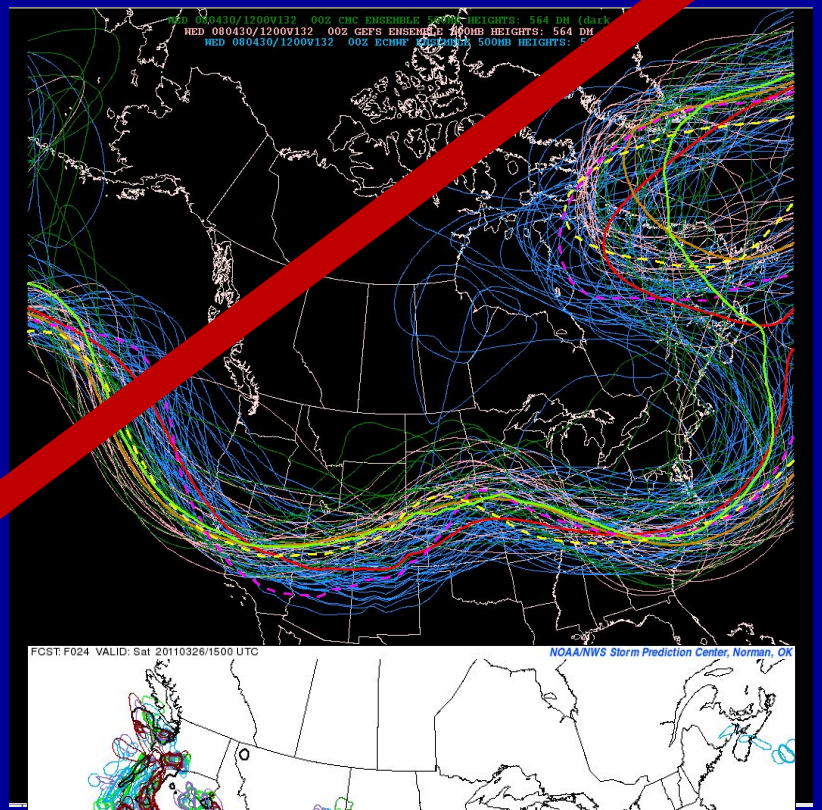
Errors propagate from poorly initialized scales ('mainly' the smaller scales) thus reducing the predictive skill

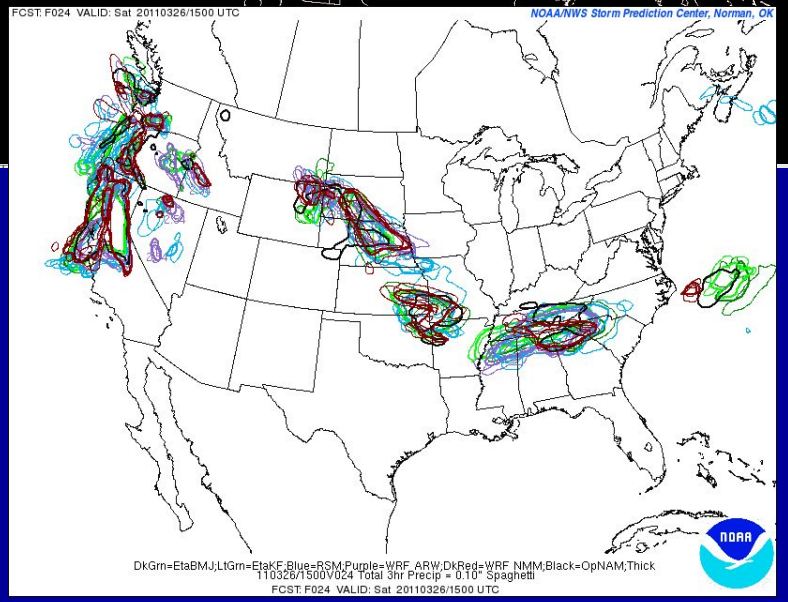
(Buizza and Leutbecher 2015, QJRMS)

ECMWF

Ensemble Use

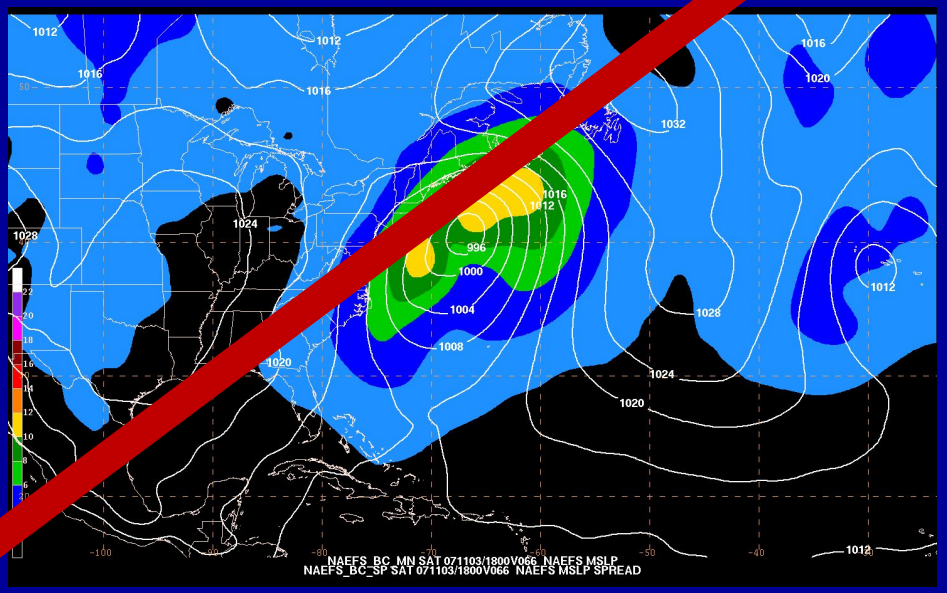
- Originally used for medium- to long-range forecasting of the large-scale pattern
- Uses have grown to encompass all temporal and spatial scales down to convective storm scale
- Address uncertainty particularly those leading to rapidly diverging solutions
  - Initial conditions, model physics, resolution, model numerics

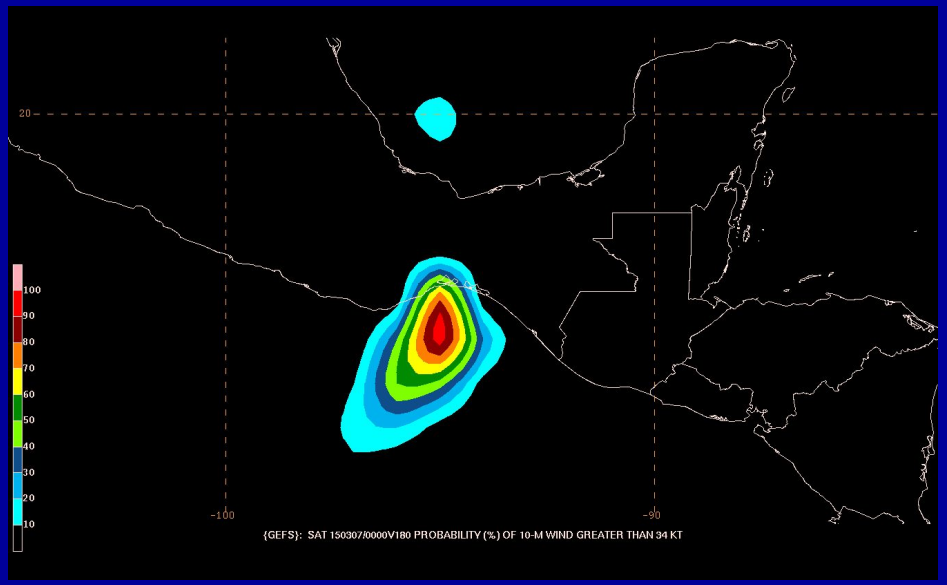




Ensemble Use

- Estimate rate of skill loss with time
  - Spread of solutions generally increases with time
- Compute probabilities for 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 (next week Ryan Torn's talk)

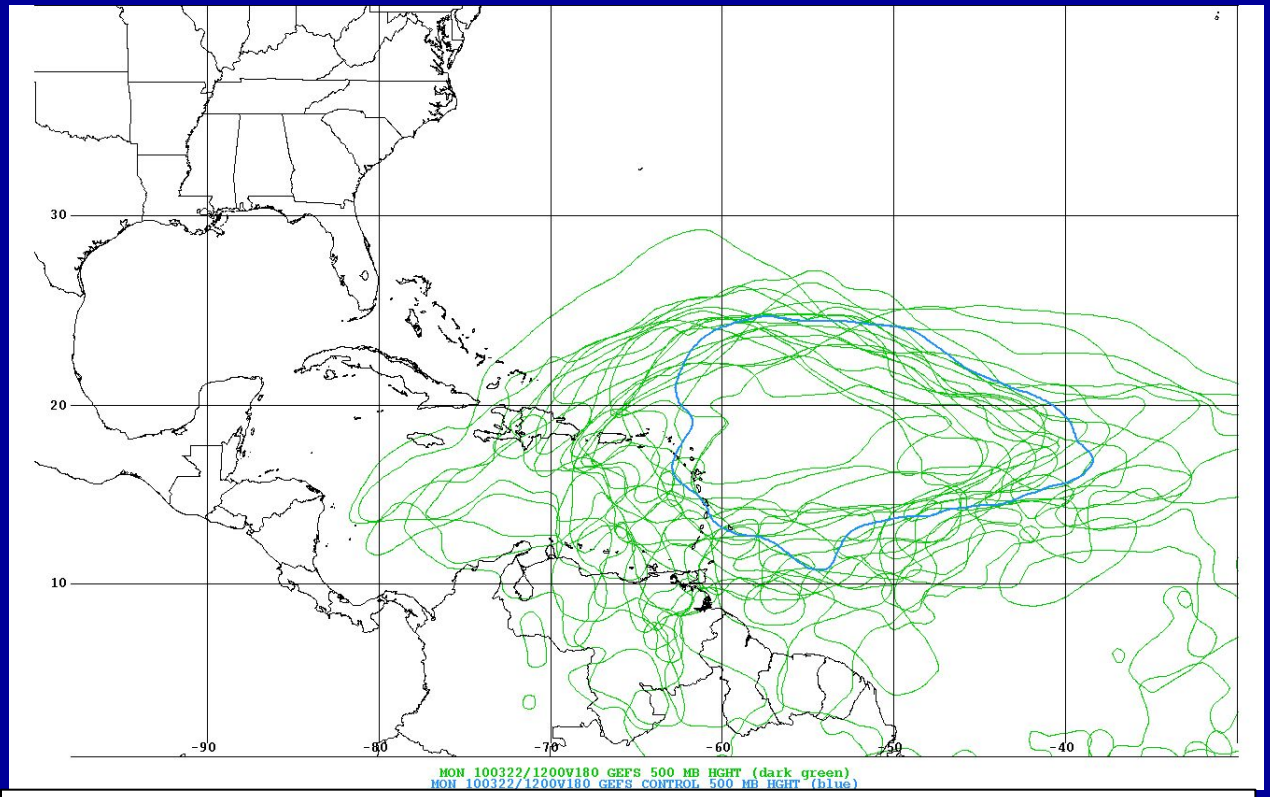




Current Global Ensemble Systems that NHC uses most frequently

NCEP Global Ensemble Forecast System (GEFS)

- 4 cycles per day (00, 06, 12, 18 UTC)
- 31 members (1 control + 30 perturbed)
- Forecast extends out to 384 hours (16 days)



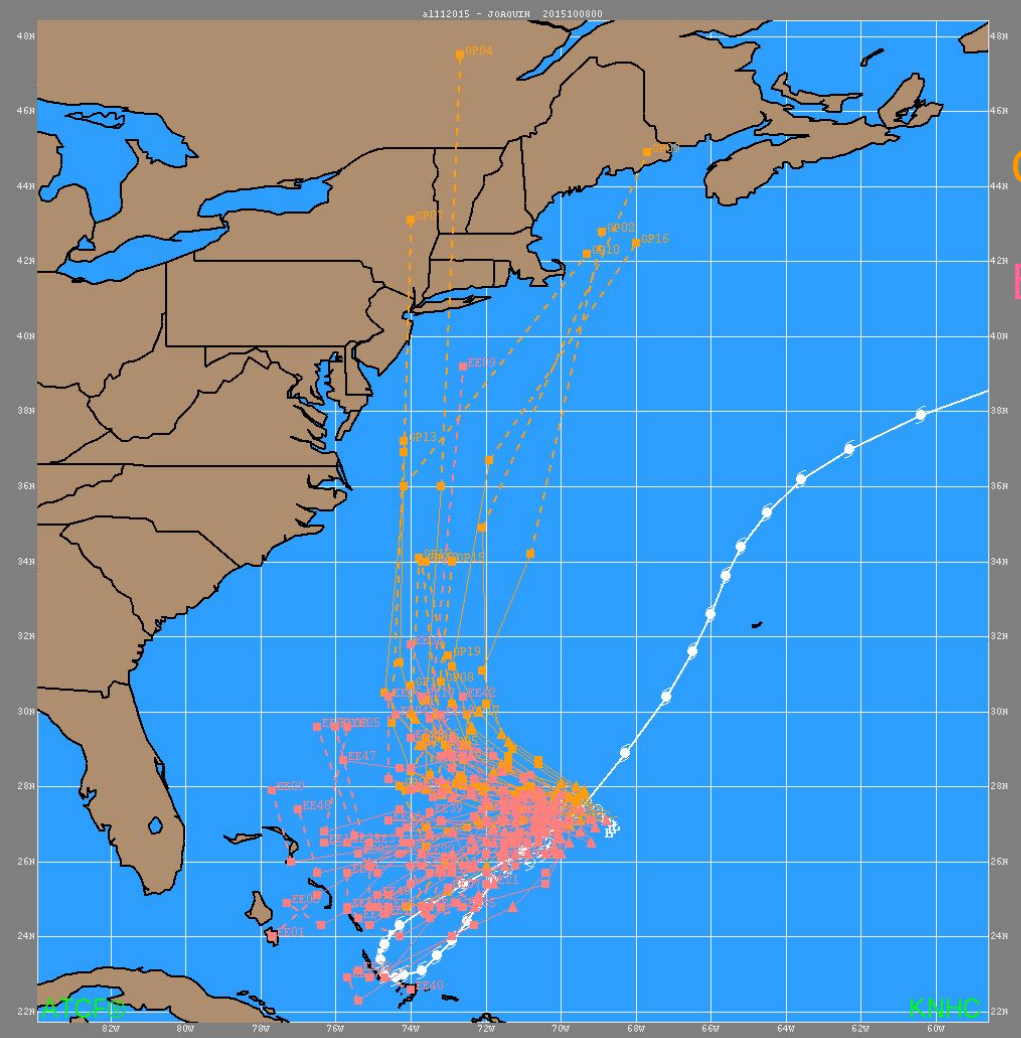
180-h forecast of 588 dm 500-mb height contour valid at 1200 UTC 22 March 2010

NCEP GEFS

- Current Configuration (last upgrade Sep 2020)
  - ~25 km resolution, run to 35 days at 00Z
  - 64 vertical levels
- Ensemble members
  - 30 members generated using EnKF
  - Uses stochastically perturbed physics tendencies (SPPT) scheme and stochastic kinetic energy backscatter (SKEB) scheme for perturbations
  - Model physics consistent with GFS
- Deterministic GFS (2024 upgrade coming?)
  - ~13 km resolution for full run (16 days)
  - 127 vertical levels

Maybe shorten and summarize GEFS/ ECMWF including #members and resolution. No Kalman Filters

Joaquin ensemble guidance



GEFS

EC Ensemble