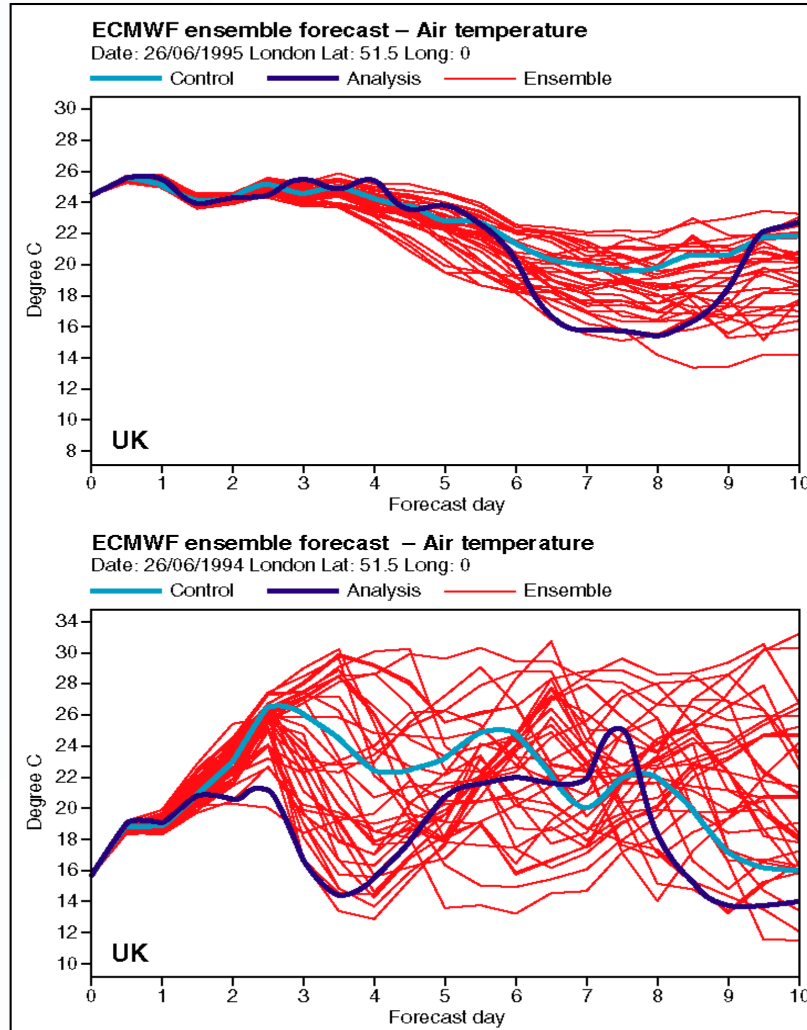
Ensemble Forecasts
Initial Perturbation 1

ECMWF

Chaos and weather prediction

The atmosphere is a chaotic system

- Small errors can grow to have major impact (butterfly effect)
- We can never perfectly measure the current state of the whole atmosphere



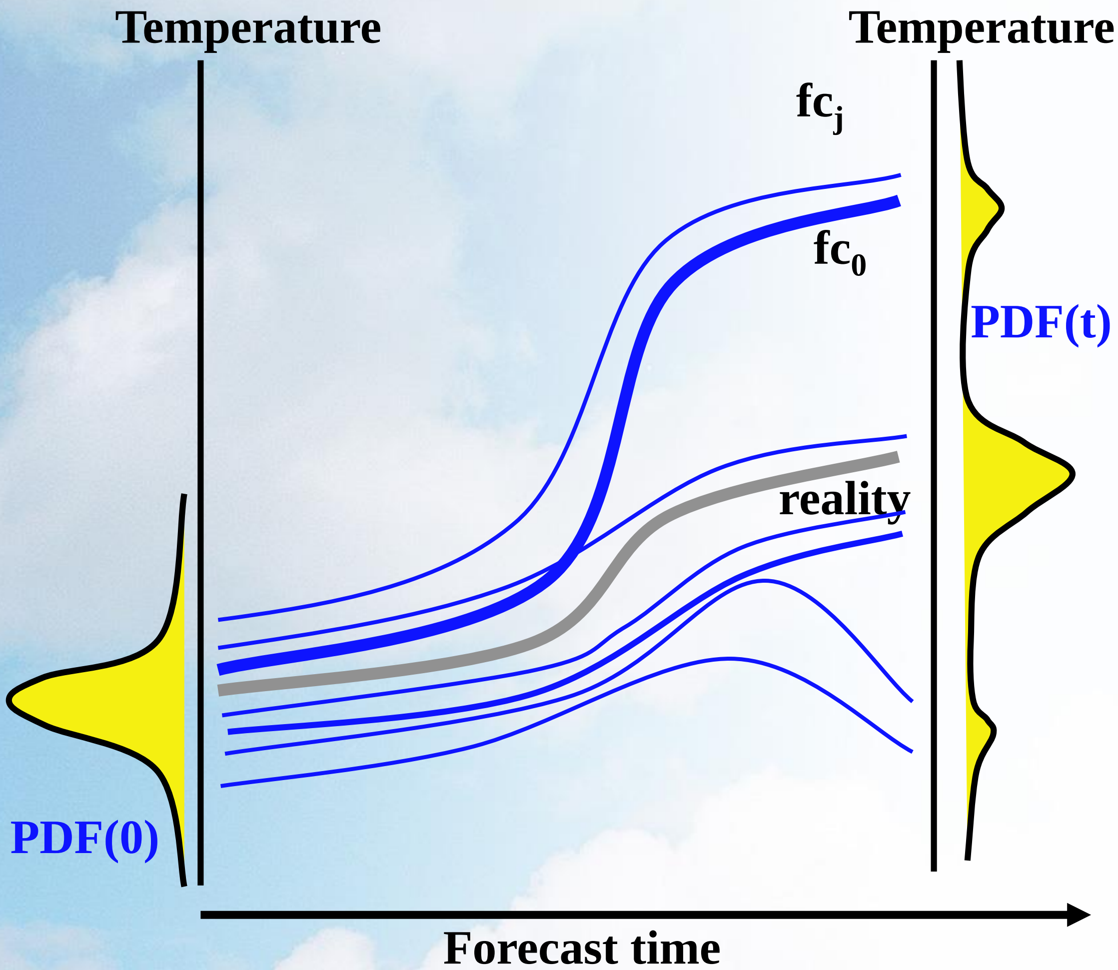
Ensemble Forecasts

- Parallel set of forecasts from very slightly different initial conditions and model formulation
- Assess uncertainty of today's forecast

The ECMWF Ensemble:

- 51 Members (50 perturbed + control member without perturbations), TCo639 (~ 16 km) to day 15
- 91 vertical levels
- Coupled to NEMO ocean model (1/4 degree) and LIM2 ice model
- Initial perturbation via an ensemble of data assimilations and singular vectors, 5 member ocean data assimilation
- Model error representation (SPPT, SKEB)

3. Ensemble prediction systems



Sources of Uncertainty:

- **Initial Conditions**
- **Model Formulation**

from R. Buizza

Reliability of the ensemble spread

- Consider ensemble variance ("spread") for an M-member ensemble

$$\frac{1}{M}\sum_{j=1}^{M}(x_j - \overline{x})^2$$

and the squared error of the ensemble mean

$$(\overline{x} - y)^2$$

- Average the two quantities for many locations and/or start times.
- The averaged quantities have to match for a reliable ensemble (within sampling uncertainty).

From Martin Leutbecher's lecture "Ensemble Verification 1" (tomorrow)

How to construct initial perturbations:

Methods that rely on the dynamics only, e.g.:

- **bred vectors**
- **singular vectors**

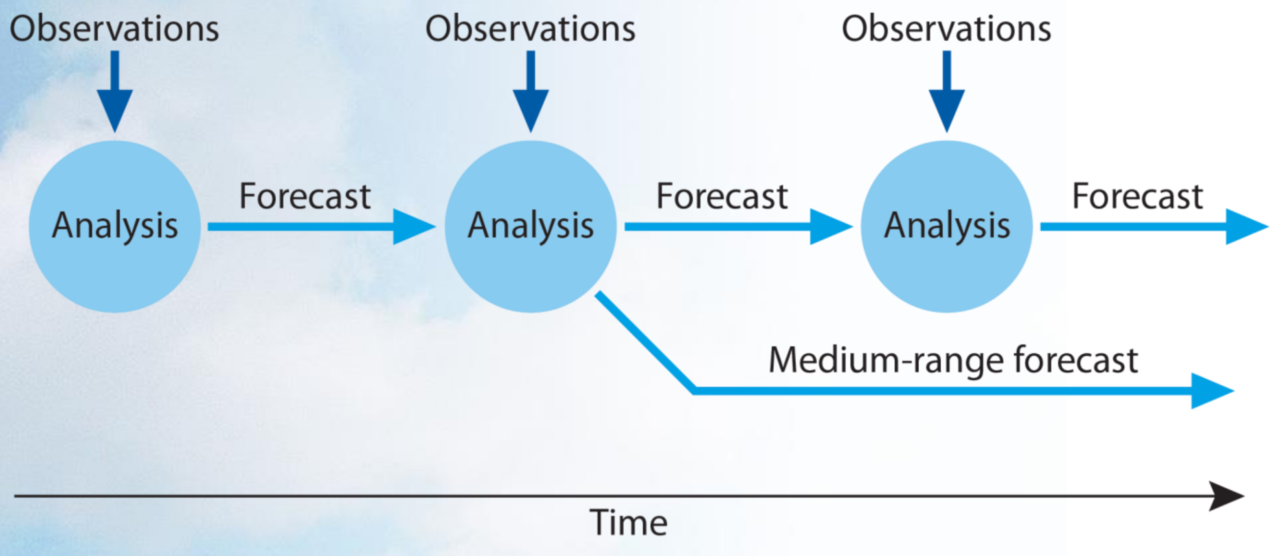
Ensemble data assimilation methods, e.g.:

- **Ensemble of 4D-Var data assimilations (EDA)**
- **Ensemble Kalman Filter**

ECMWF: combination of EDA and singular vectors

Starting the Medium-Range Forecast – the 'Analysis'

Analysis: 3 dimensional virtual image of the atmosphere at a given time.

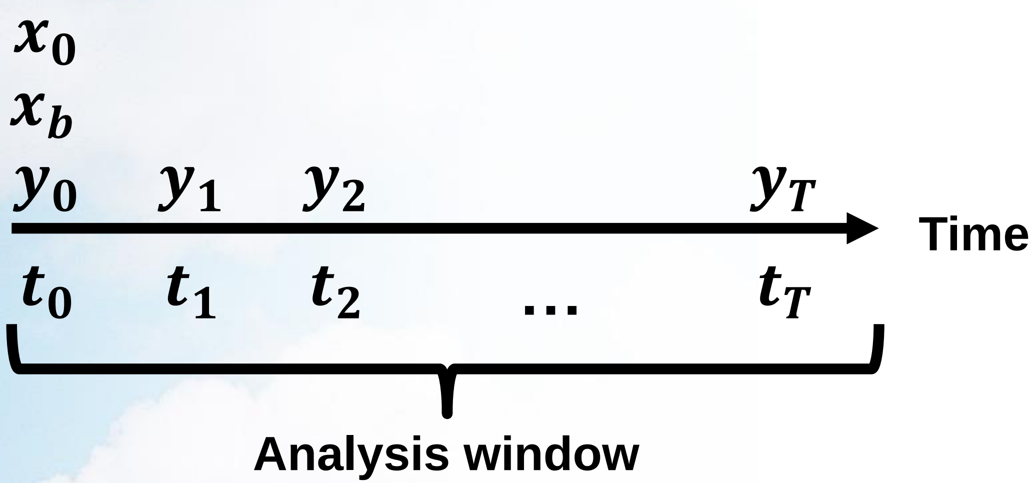


- The short range forecast from the previous analysis is our 'first estimate' of the current state of the atmosphere.

4D-Var assimilation

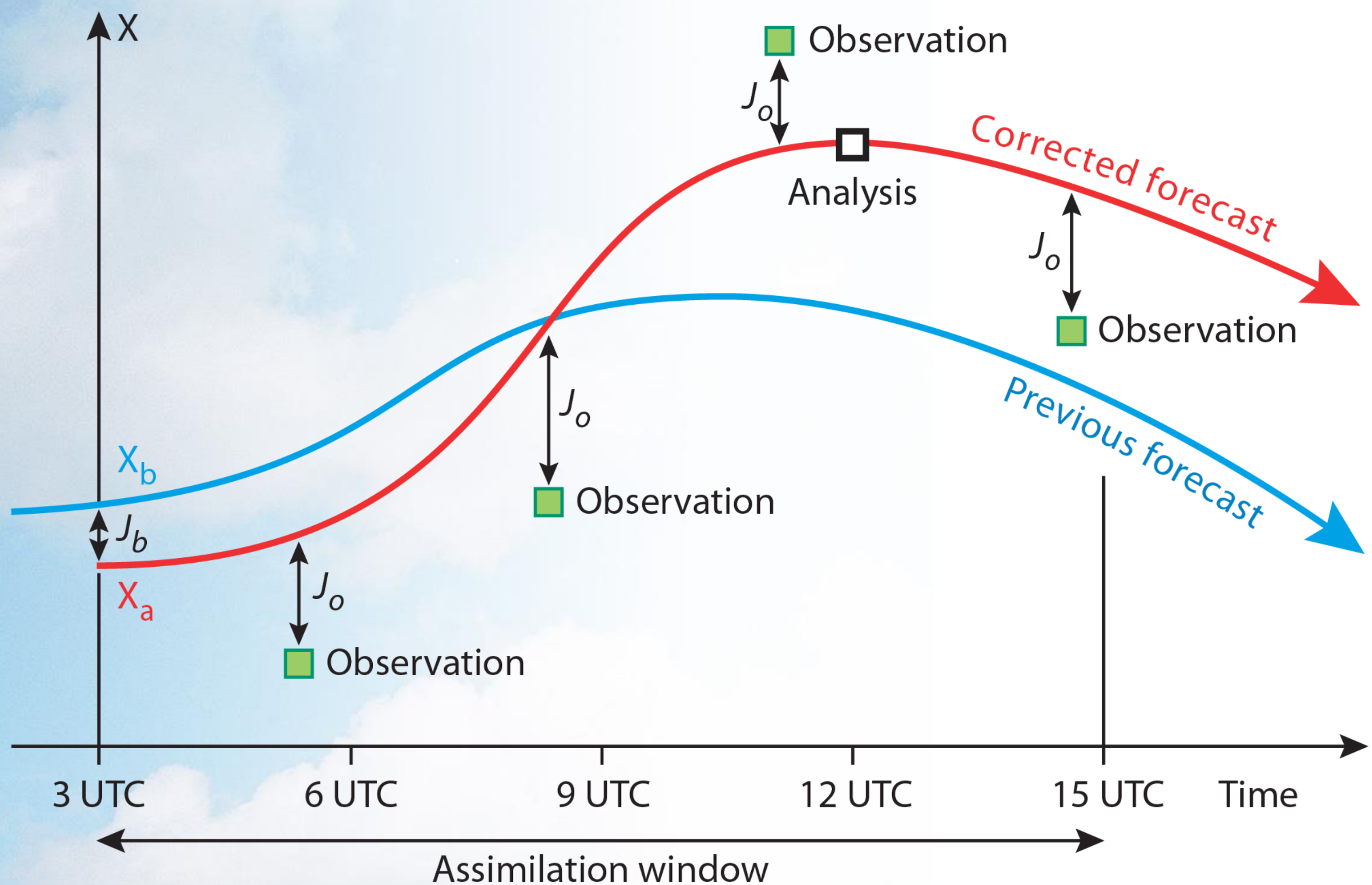
- To find model trajectory that best fits the observations over an assimilation interval (t=0,1,…,T) - > finding the minimum of the 4DVar cost function:

$$J(\mathbf{x}_0)=(\mathbf{x}_b-\mathbf{x}_o)^T(\mathbf{P}^b)^{-1}(\mathbf{x}_b-\mathbf{x}_o)+\sum_{t=0}^{T}\left(\mathbf{y}_t-H_tM_{0\rightarrow t}(\mathbf{x}_0)\right)^T\mathbf{R}_t^{-1}\left(\mathbf{y}_t-H_tM_{0\rightarrow t}(\mathbf{x}_0)\right)$$



See also Massimo Bonavita’s Talk in DA Training

4D-Var assimilation



The Ensemble of Data Assimilations

- 25 perturbed ensemble members + 1 control, TCo639 outer loops, 137 levels, TL191/TL191 inner loops. (HRES DA: TCo1279 outer loops, TL255/TL319/TL399 inner loops).
- Observations randomly perturbed according to their estimated error covariances (R)
- SST perturbed with climatological error structures
- Model error representation via Stochastically Perturbed Parametrization Tendencies (SPPT, see Sarah-Jane's Talk)

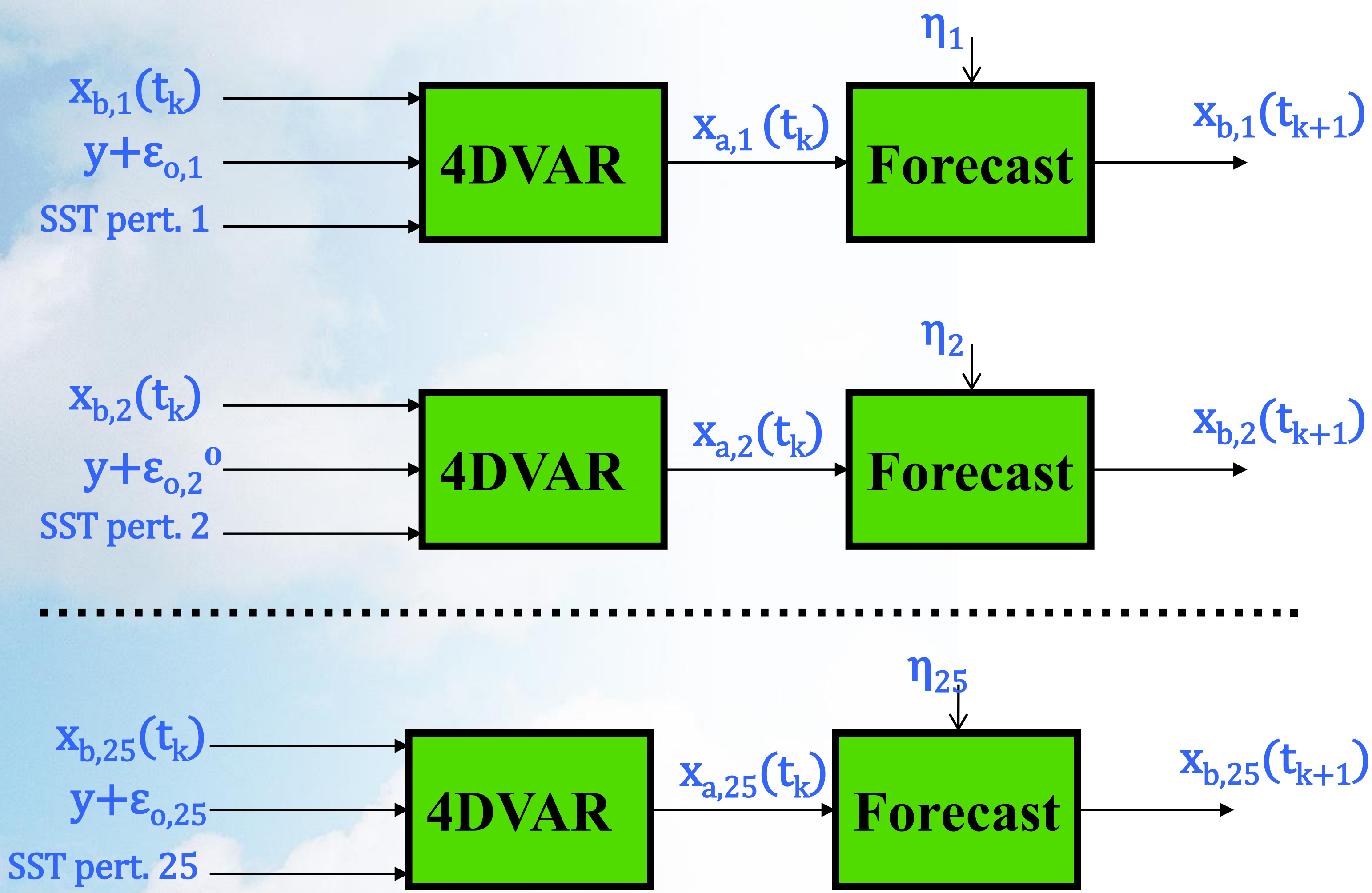
The EDA simulates the error evolution of the 4DVar analysis cycle:

→ uncertainty estimates to initialize ensemble forecasts

→ Flow dependent estimates of background error covariances for use in 4D-Var

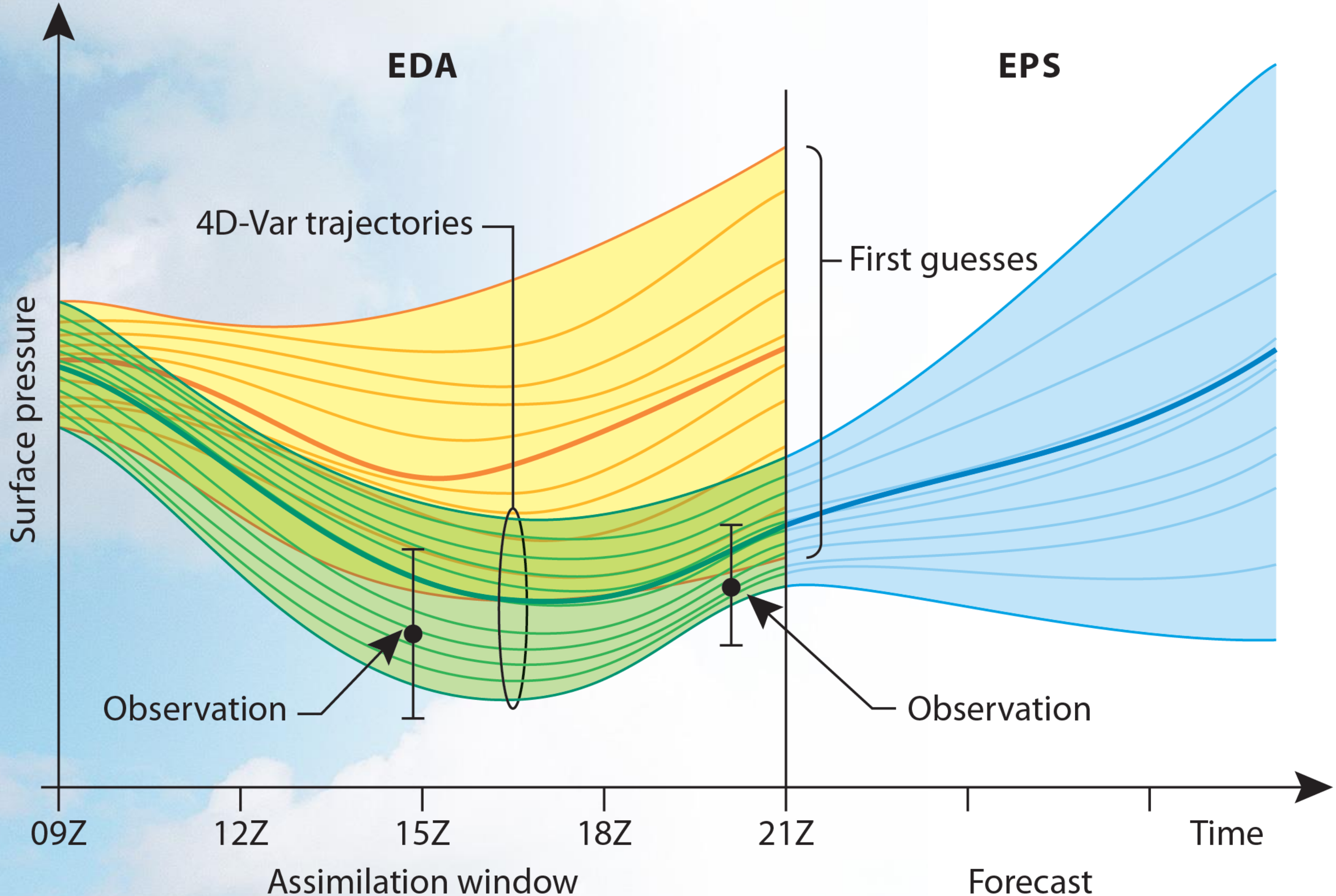
See also Massimo Bonavita's Talk in DA Training

The Ensemble of Data Assimilations



See also Massimo Bonavita's Talk in DA Training

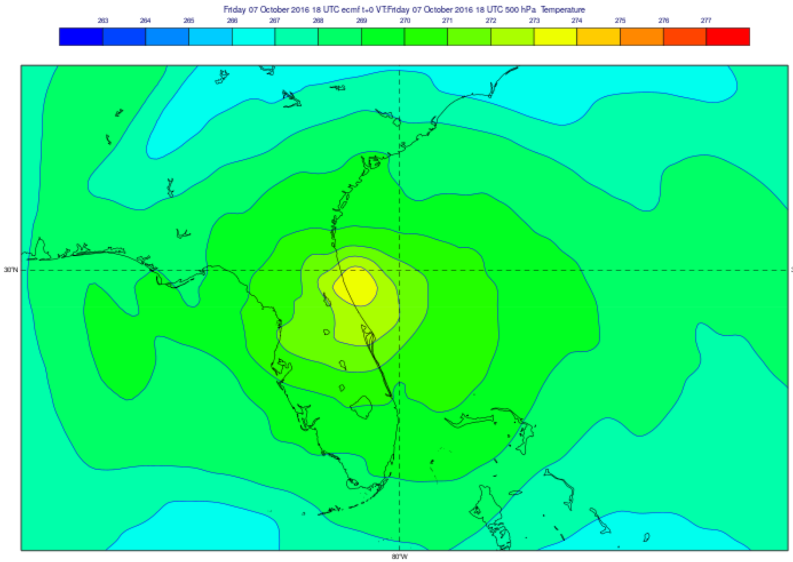
Ensemble assimilation and prediction



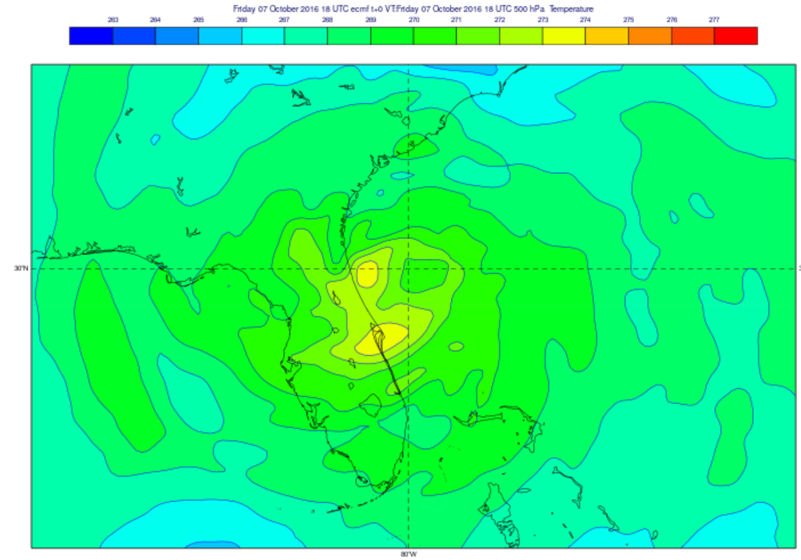
ECMWF

T 500hPa

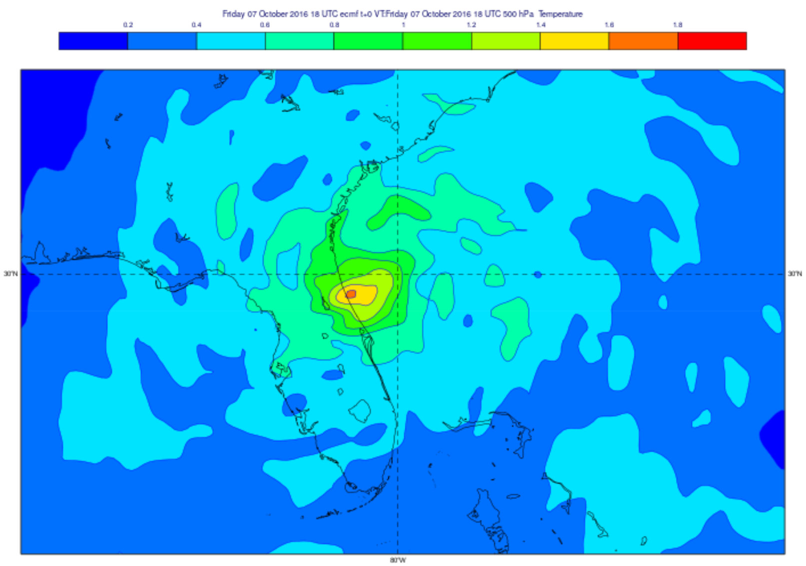
EDA Mean



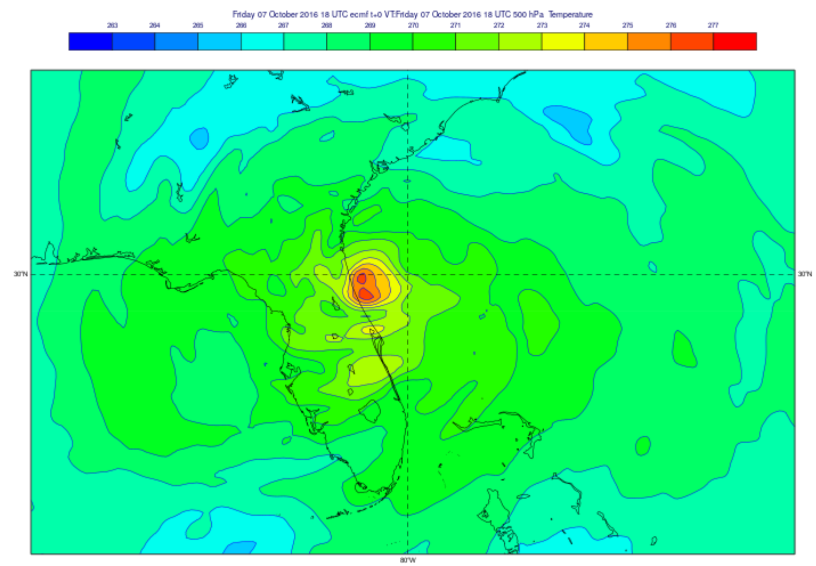
EDA Control member



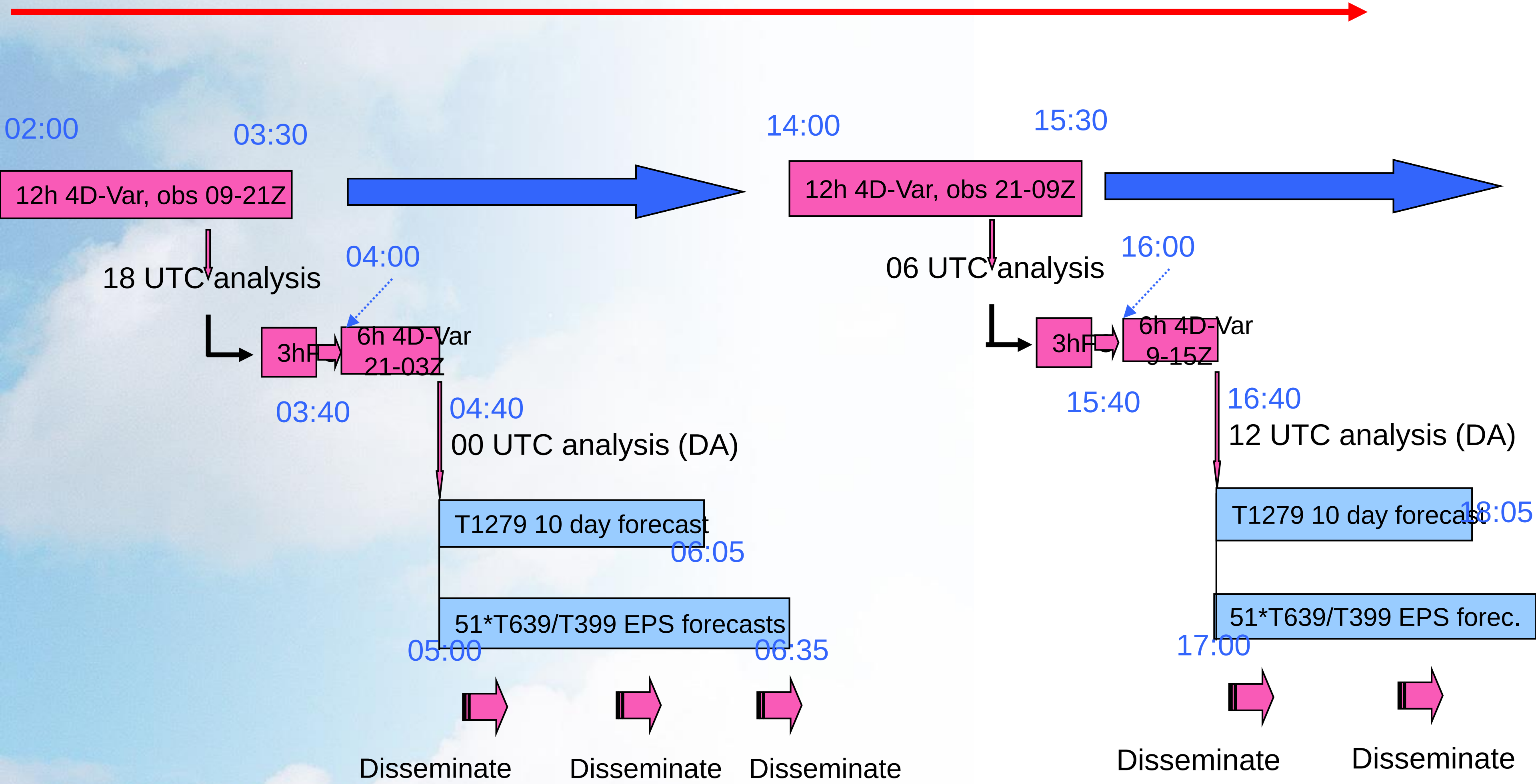
EDA StDev



HRES Analysis



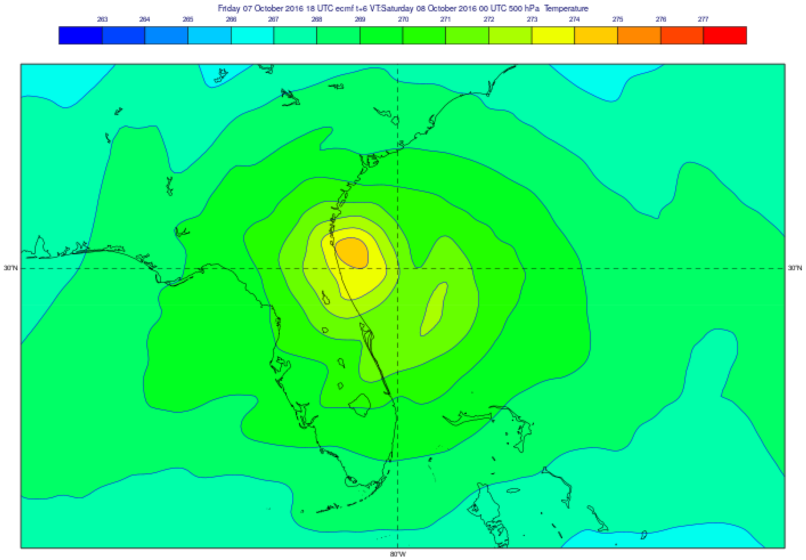
Operational schedule
Early delivery suite introduced June 2004



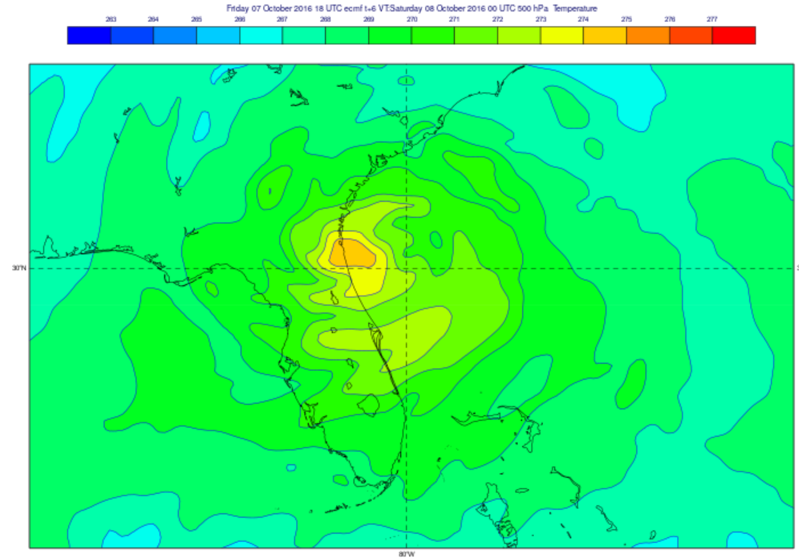
from L. Isaksen

T 500hPa

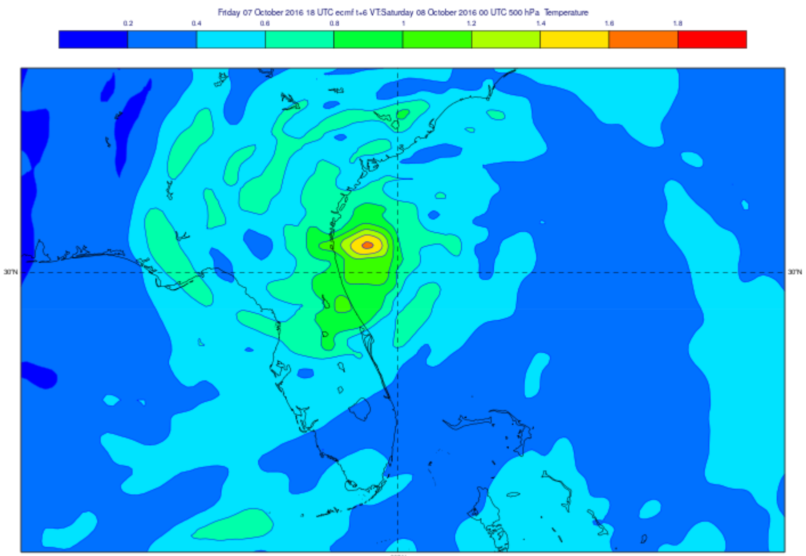
EDA Mean 18 UTC + 6h



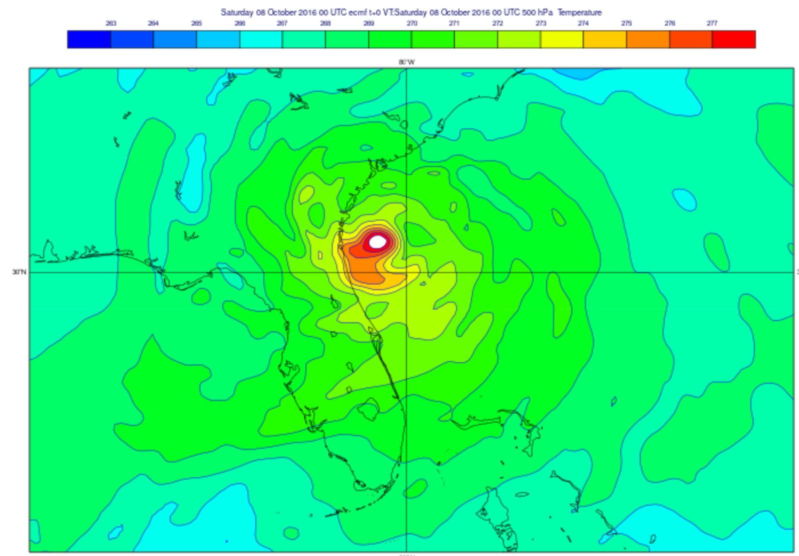
EDA Control 18 UTC + 6h



EDA StDev 18 UTC + 6h



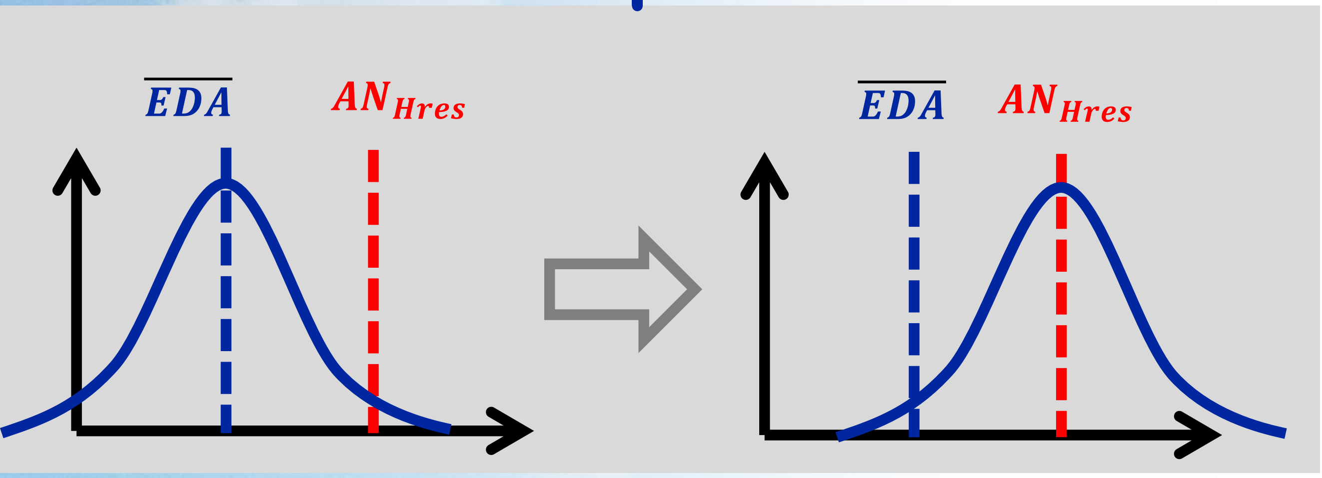
HRES Analysis 00 UTC



Generation of initial conditions for the ensemble:

$$AN_{pf} = AN_{Hres} \pm \left(EDA_i - \overline{EDA}\right) \pm SVPERT_j$$

$$i = 1..25$$
$$j = 1..25$$



EDA : 6h Forecasts

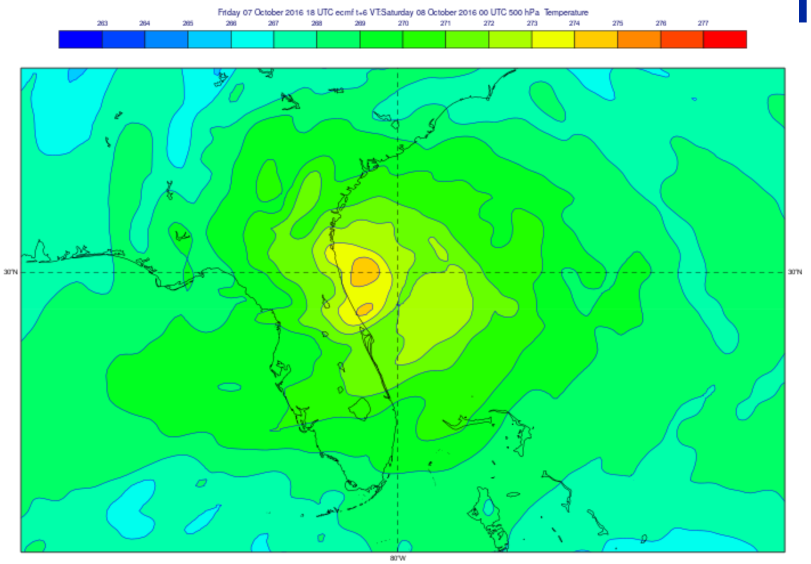
Re-centre EDA-Distribution on Hres-Analysis

$$SVPERT_j = \sum_{l}^{NSET} \sum_{k}^{NSV_l} \alpha_{lk} \, SV_{lk}$$

α **random number drawn from Truncated gaussian**

NSET : nhem, shem, TCs1-6
NSV : 50 for nhem and shem, 5 for TCs

EDA Mem 1 18 UTC + 6h



T 500hPa

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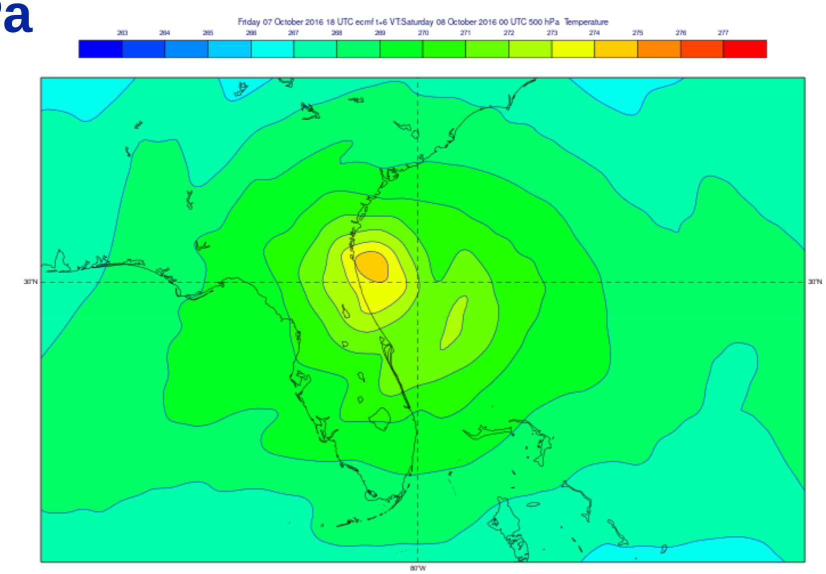
EDA Mean 18 UTC + 6h



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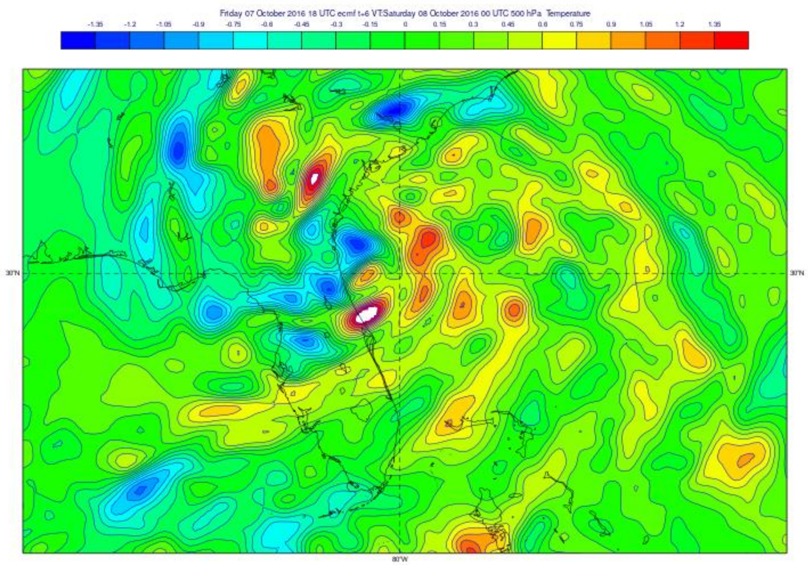
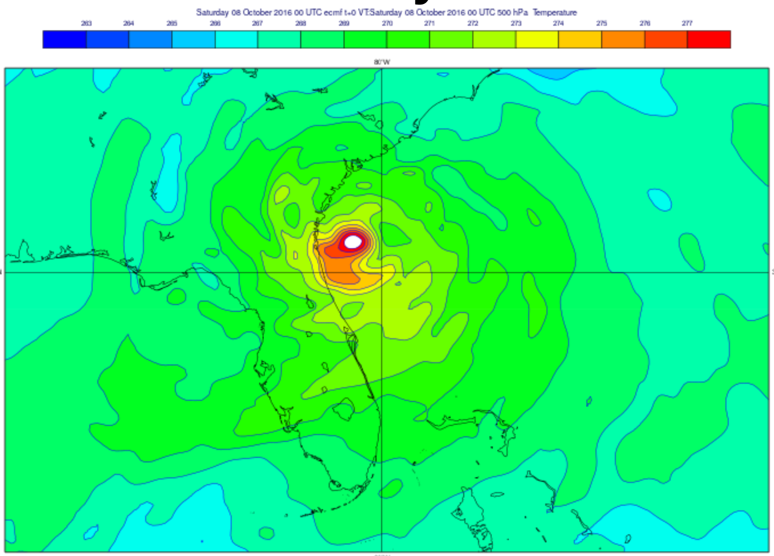
EDA Pert1 18 UTC + 6h



HRES Analysis 00 UTC

T 500hPa

Singular Vector Pert 1



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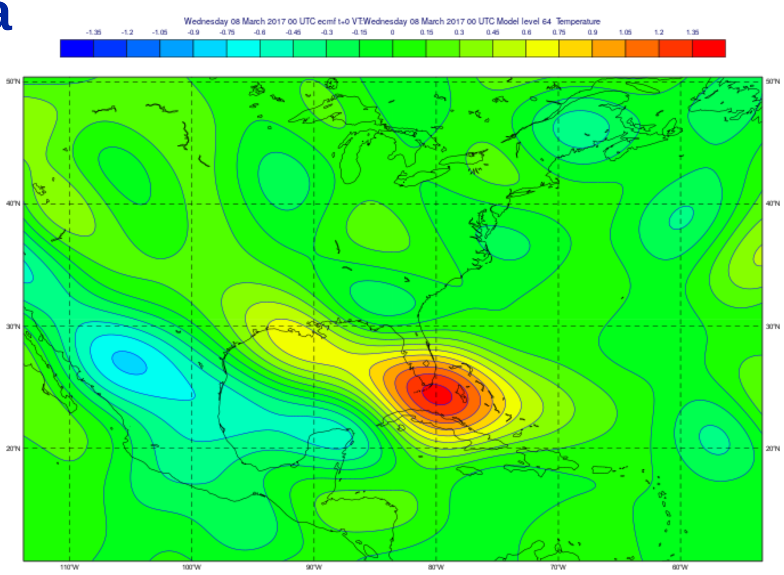

EDA Pert1 18 UTC + 6h

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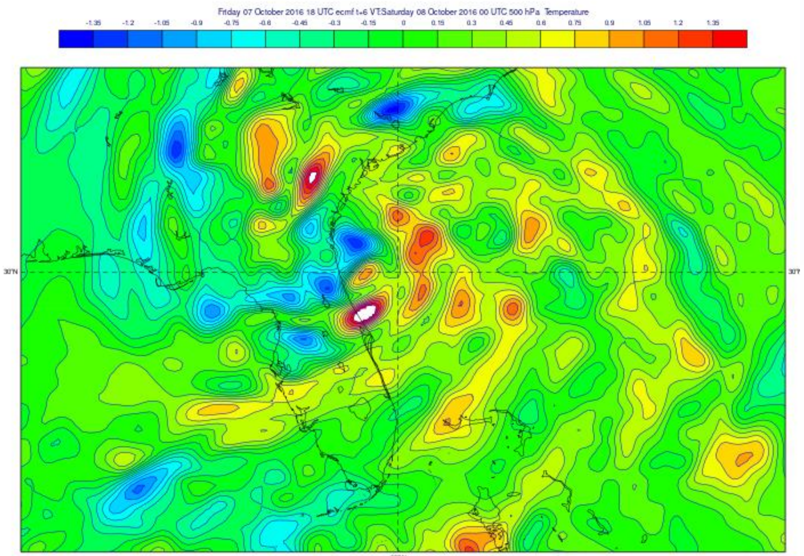

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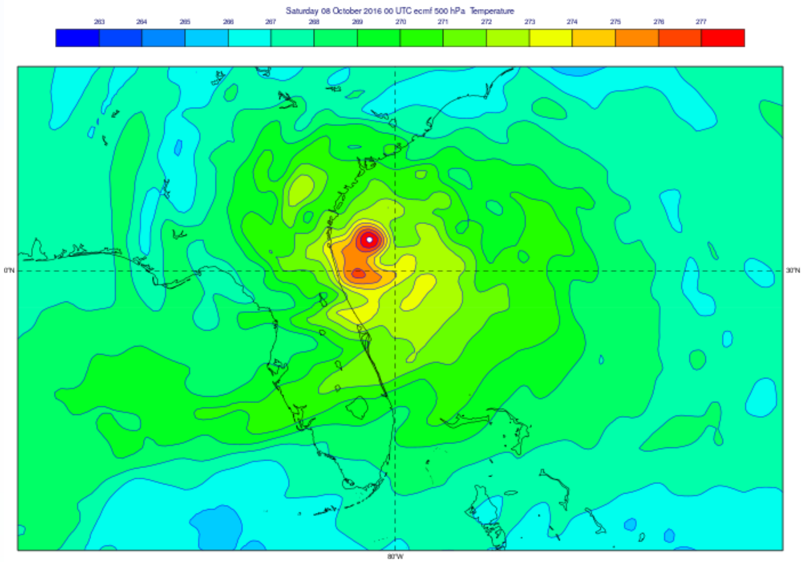
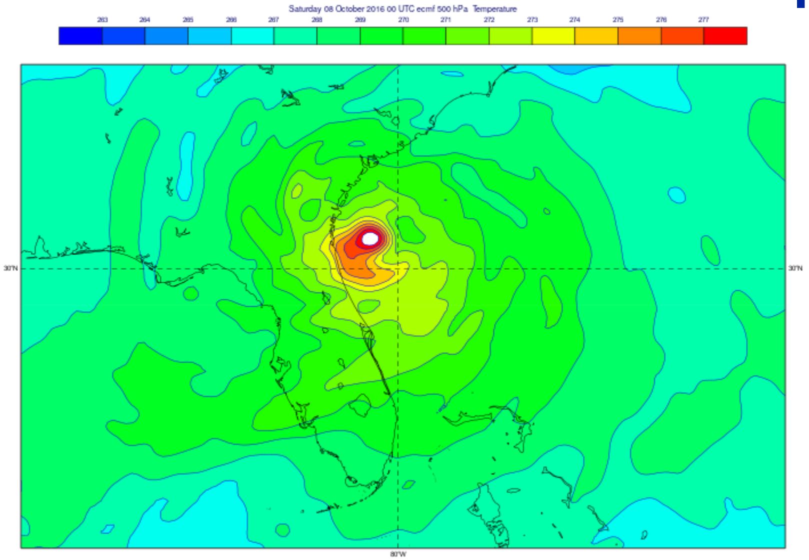
ENS Mem 1 00 UTC

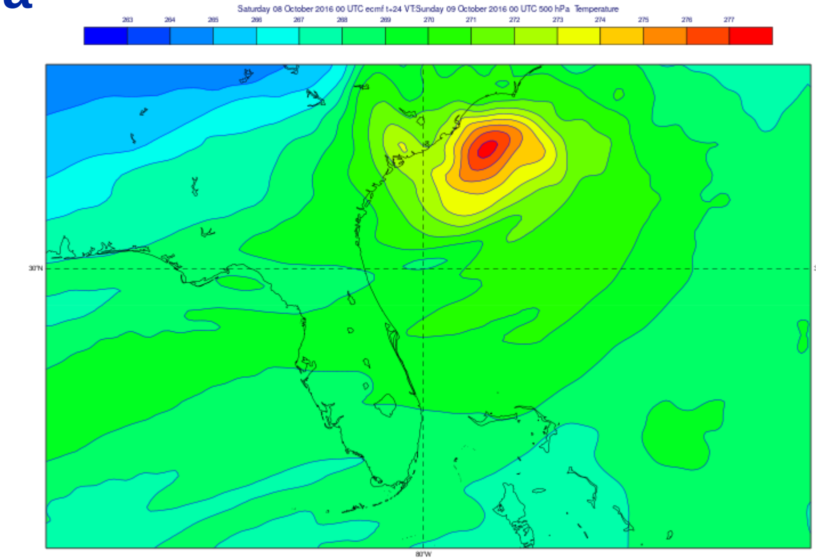


T 500hPa

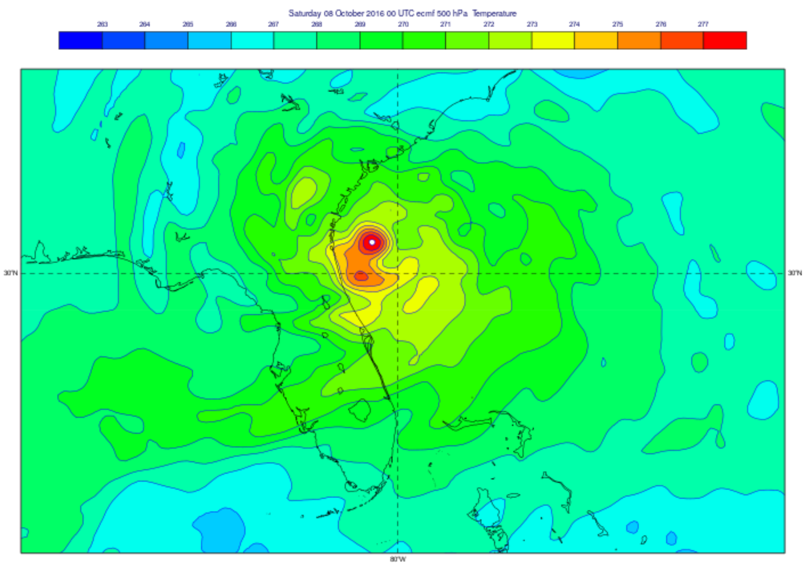
ENS Control 00 UTC



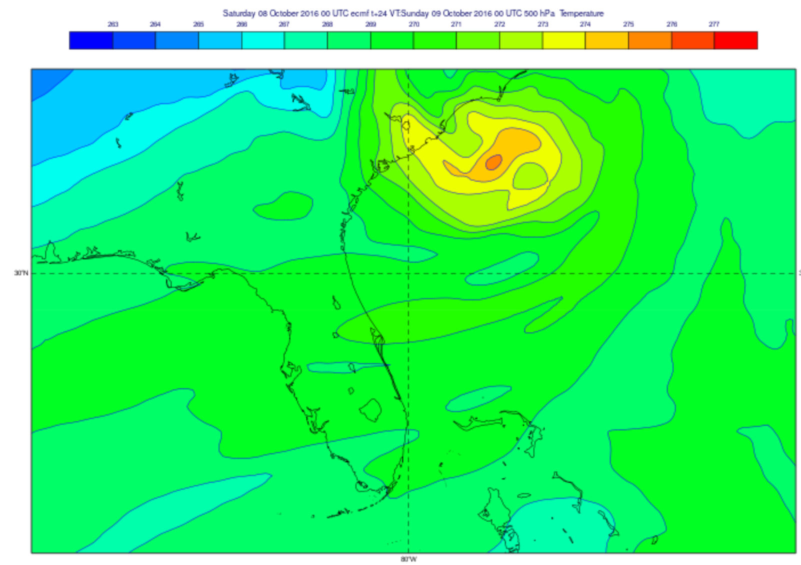
ENS Control 00 UTC + 24h



ENS Mem 1 00 UTC

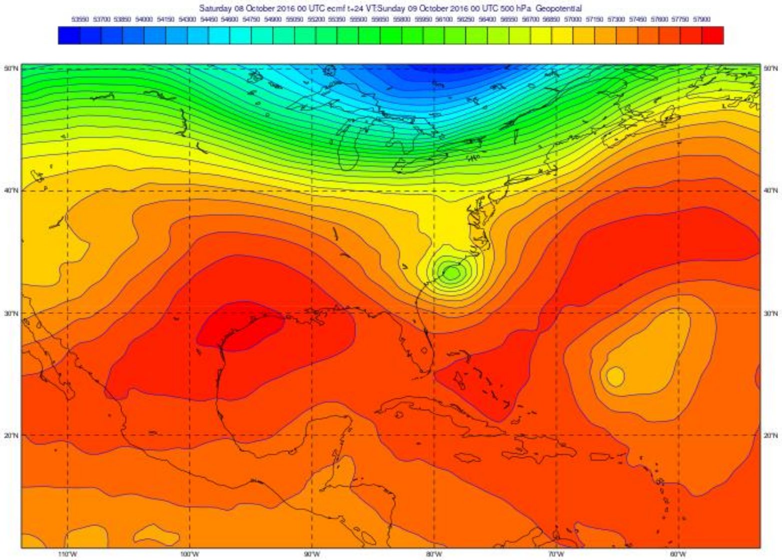


ENS Mem 1 00 UTC + 24h

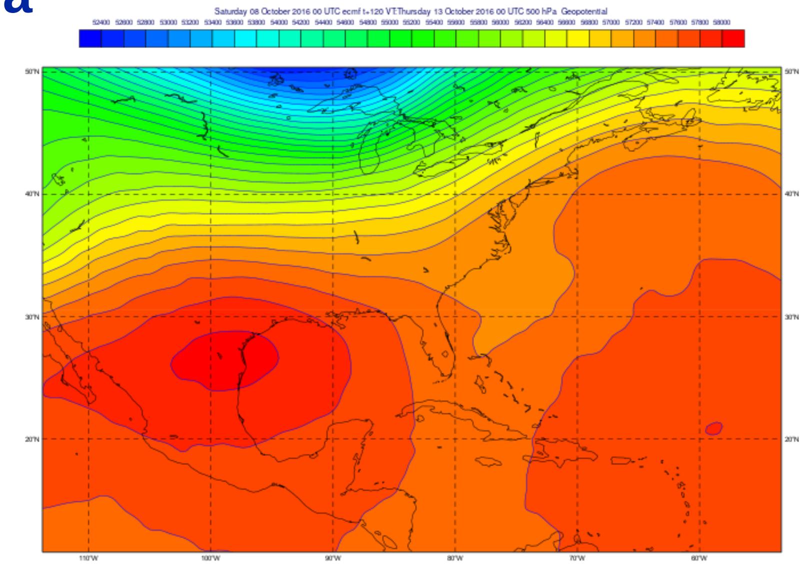


z 500hPa

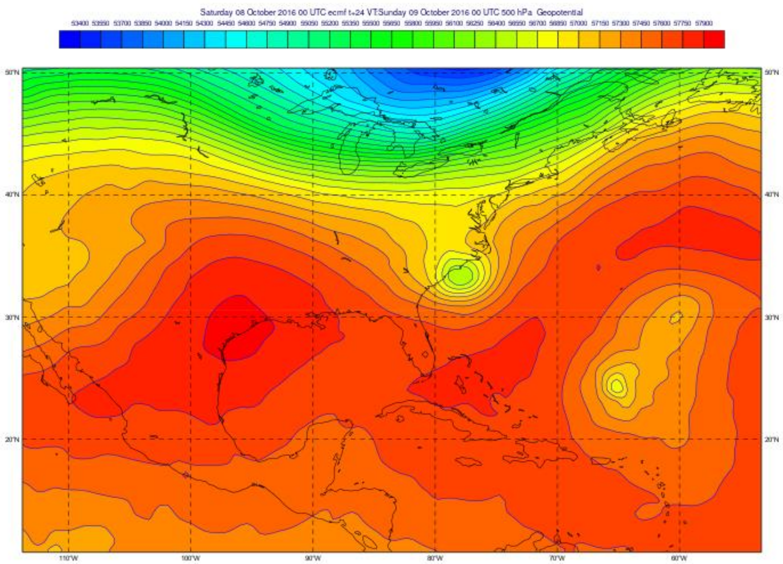
ENS Control 00 UTC + 24h



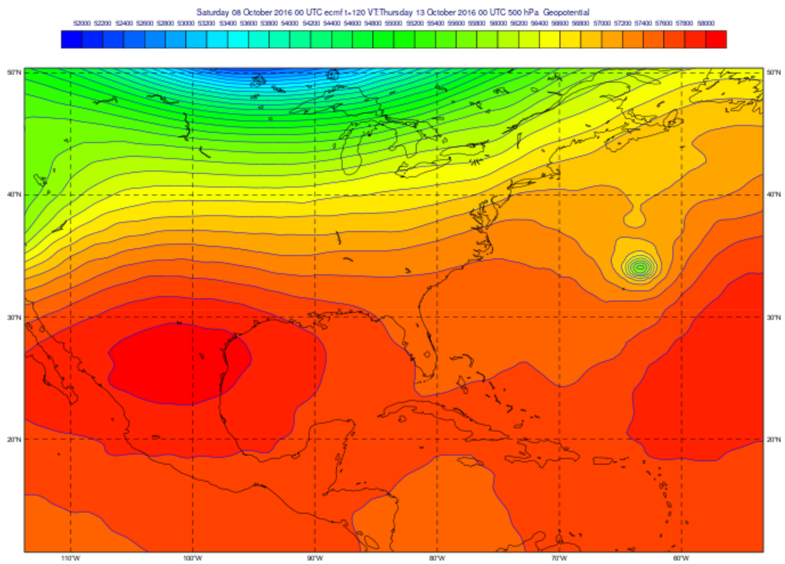
ENS Control 00 UTC + 120h



ENS Mem 1 00 UTC + 24h

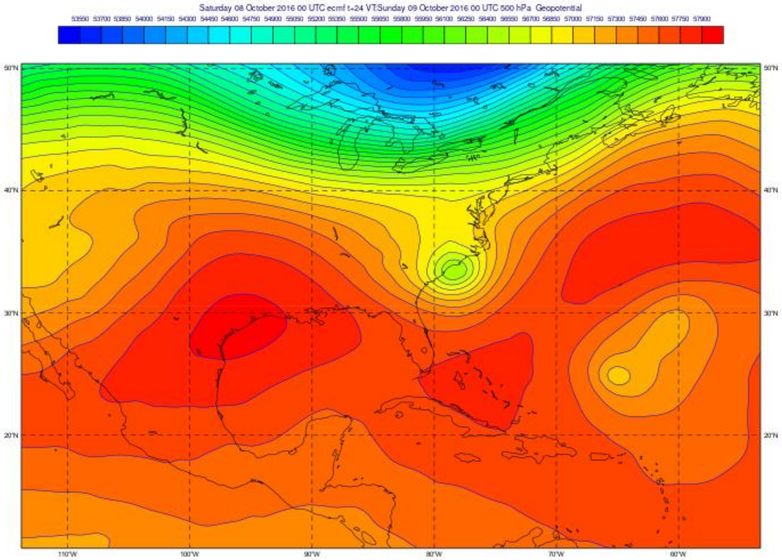


ENS Mem 1 00 UTC + 120h

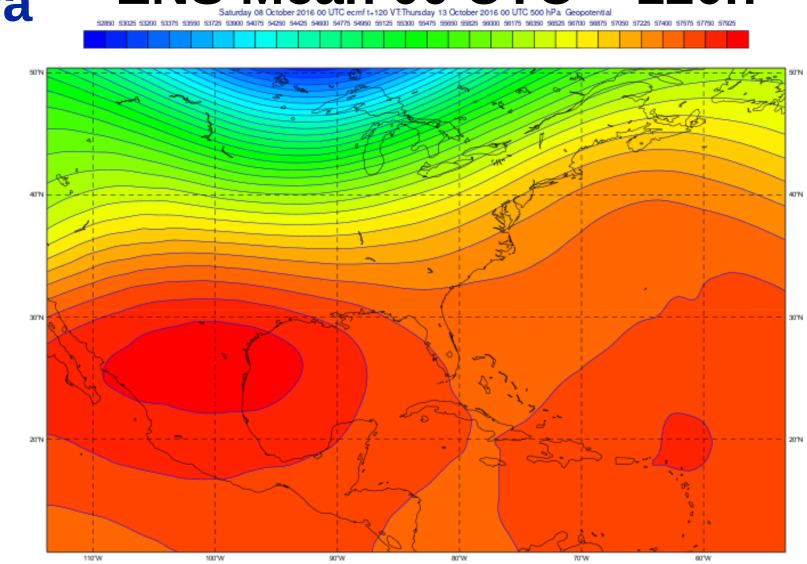


ENS Mean 00 UTC + 24h

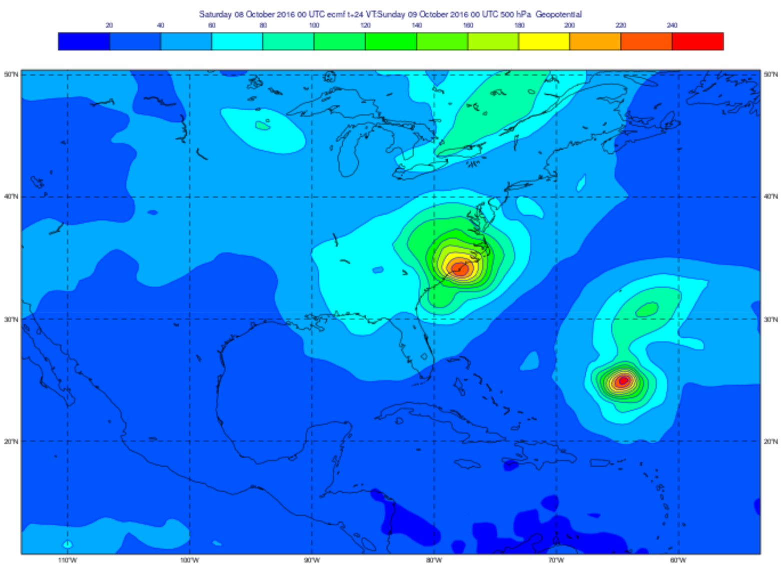
z 500hPa



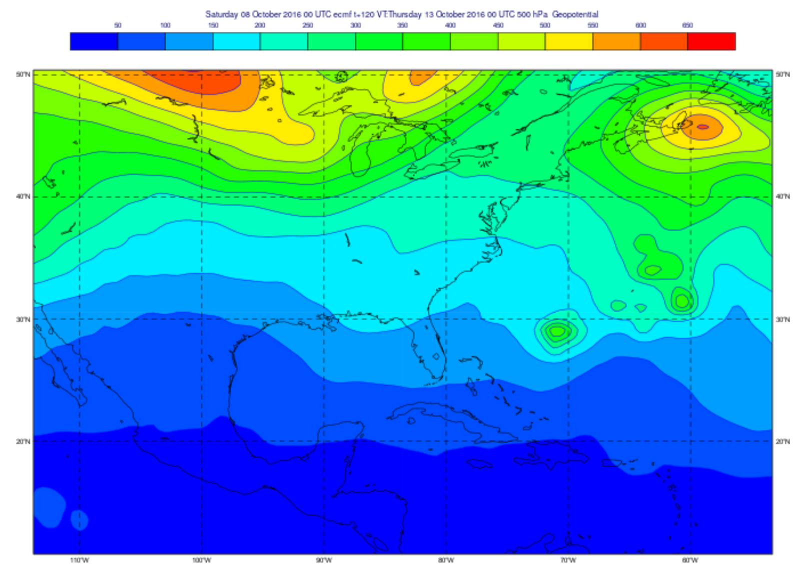
ENS Mean 00 UTC + 120h



ENS StDev 00 UTC + 24h



ENS StDev 00 UTC + 120h



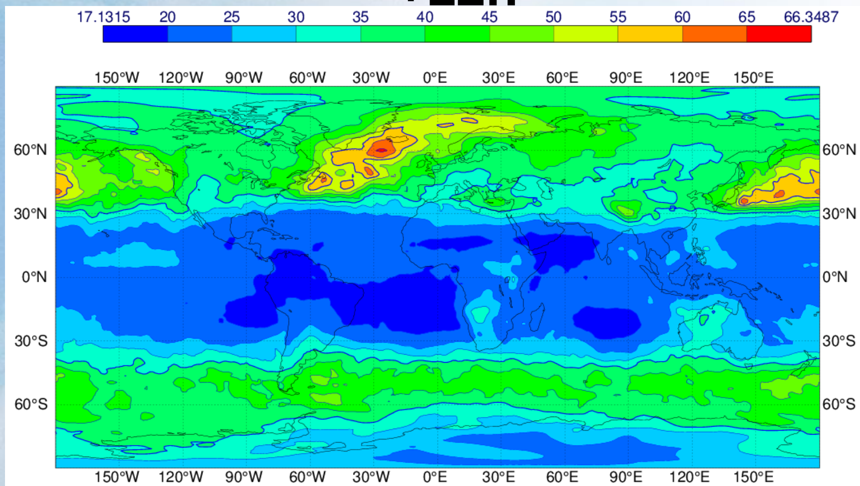
Ocean initial state:

50 Members + 1 Control, 5 Ocean analyses

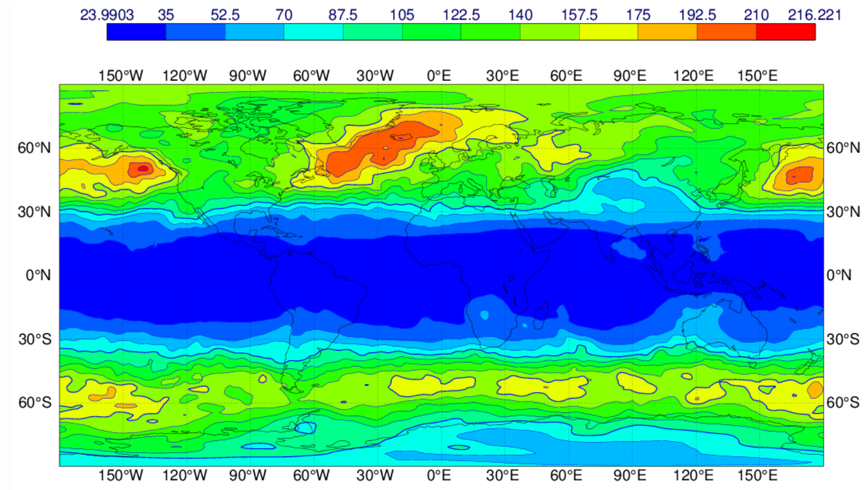
Member	Ocean analysis
Control	1
Member 1	2
Member 2	3
Member 3	4
Member 5	5
Member 6	1
Member 7	2
…	
Member 50	1

z500 hPa Ensemble StDev, averaged 2016112200 – 2017021300, 00 UTC Run

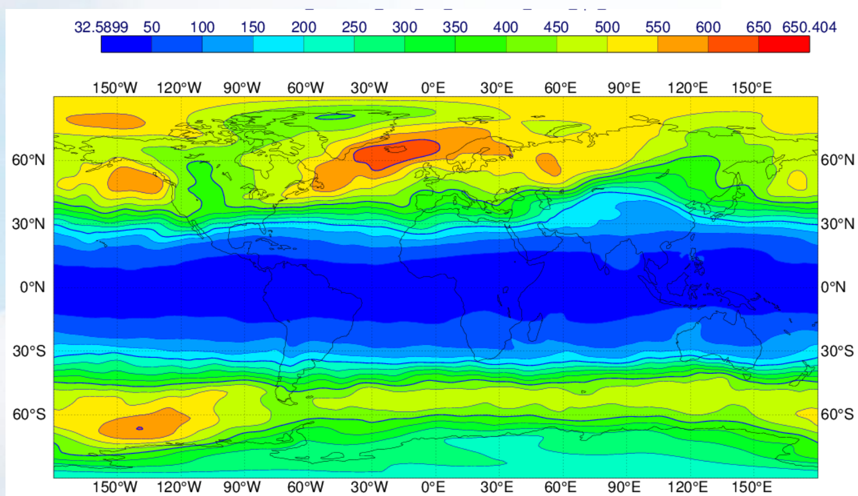
+12h



+48h

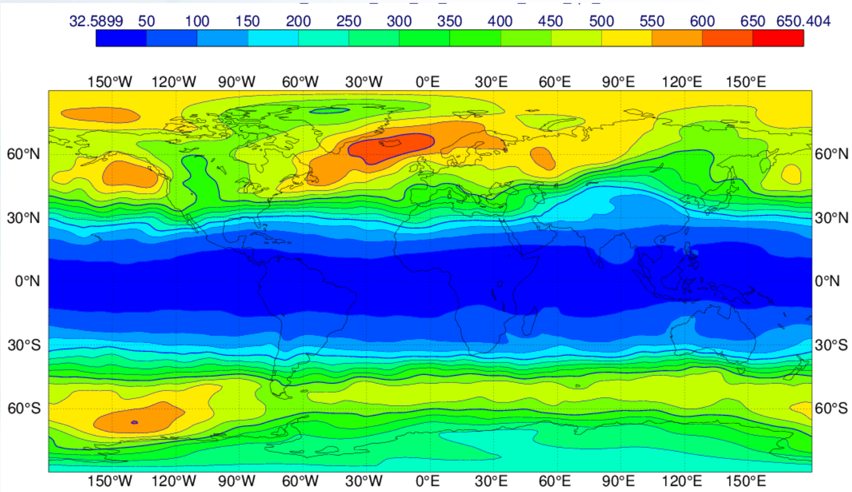


+120h

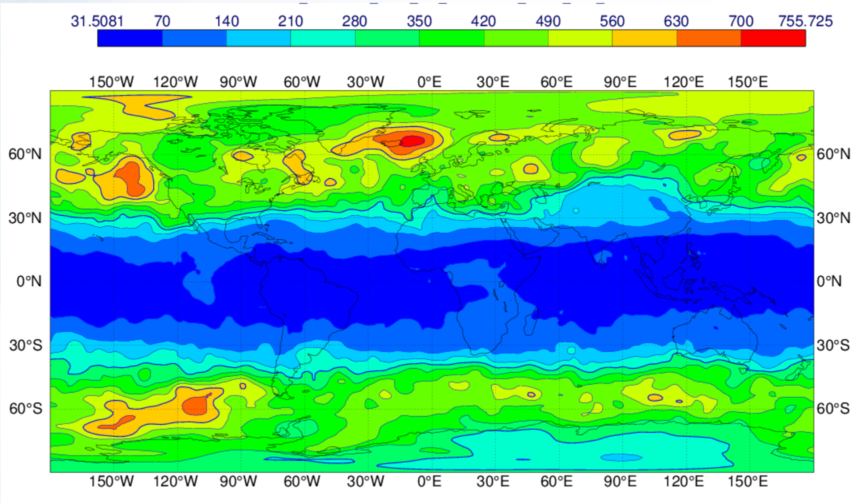


z500 hPa Ensemble StDev and Ensemble Mean RMSE, averaged 2016112200 – 2017021300, 00 UTC Run

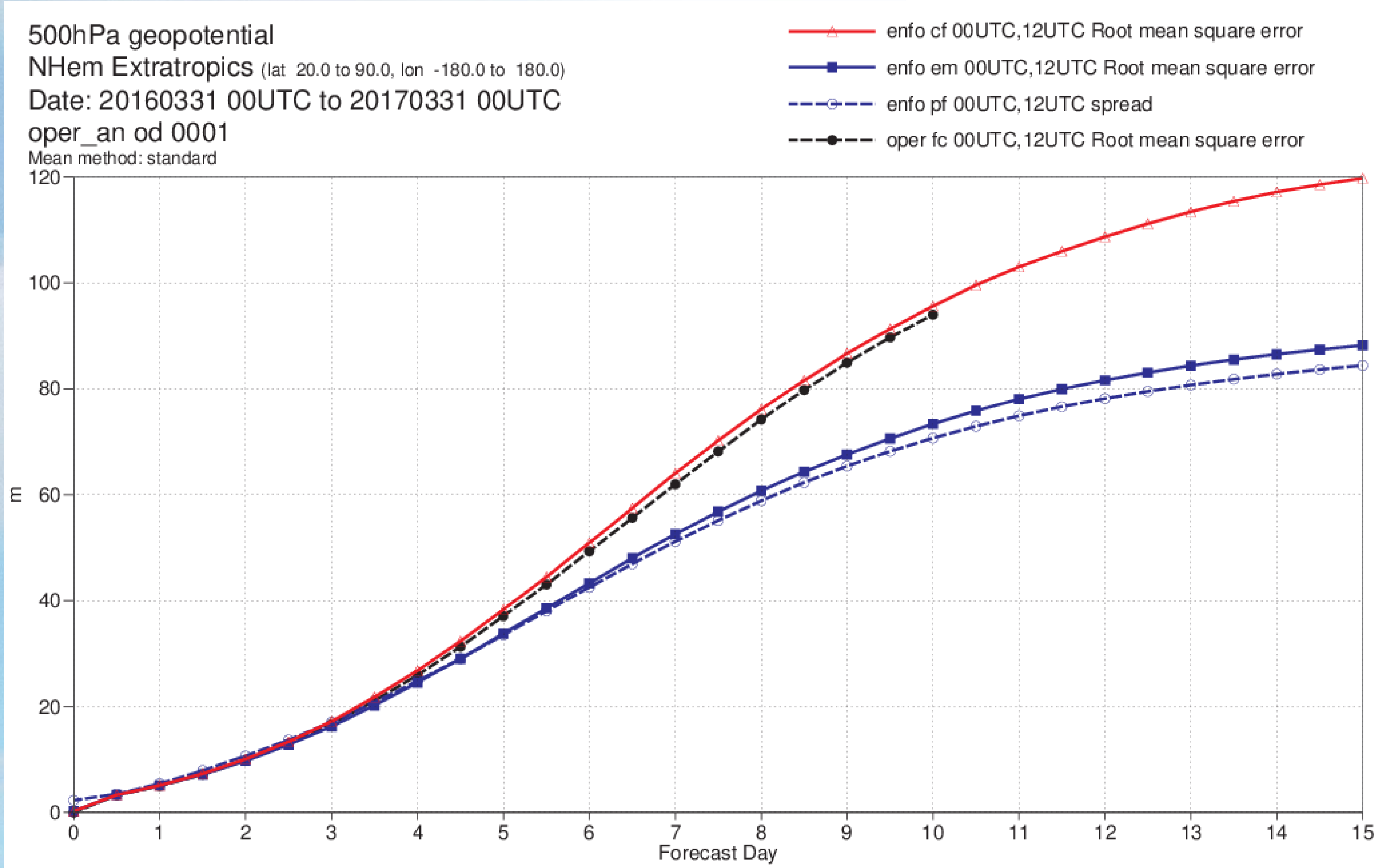
StDev+120h



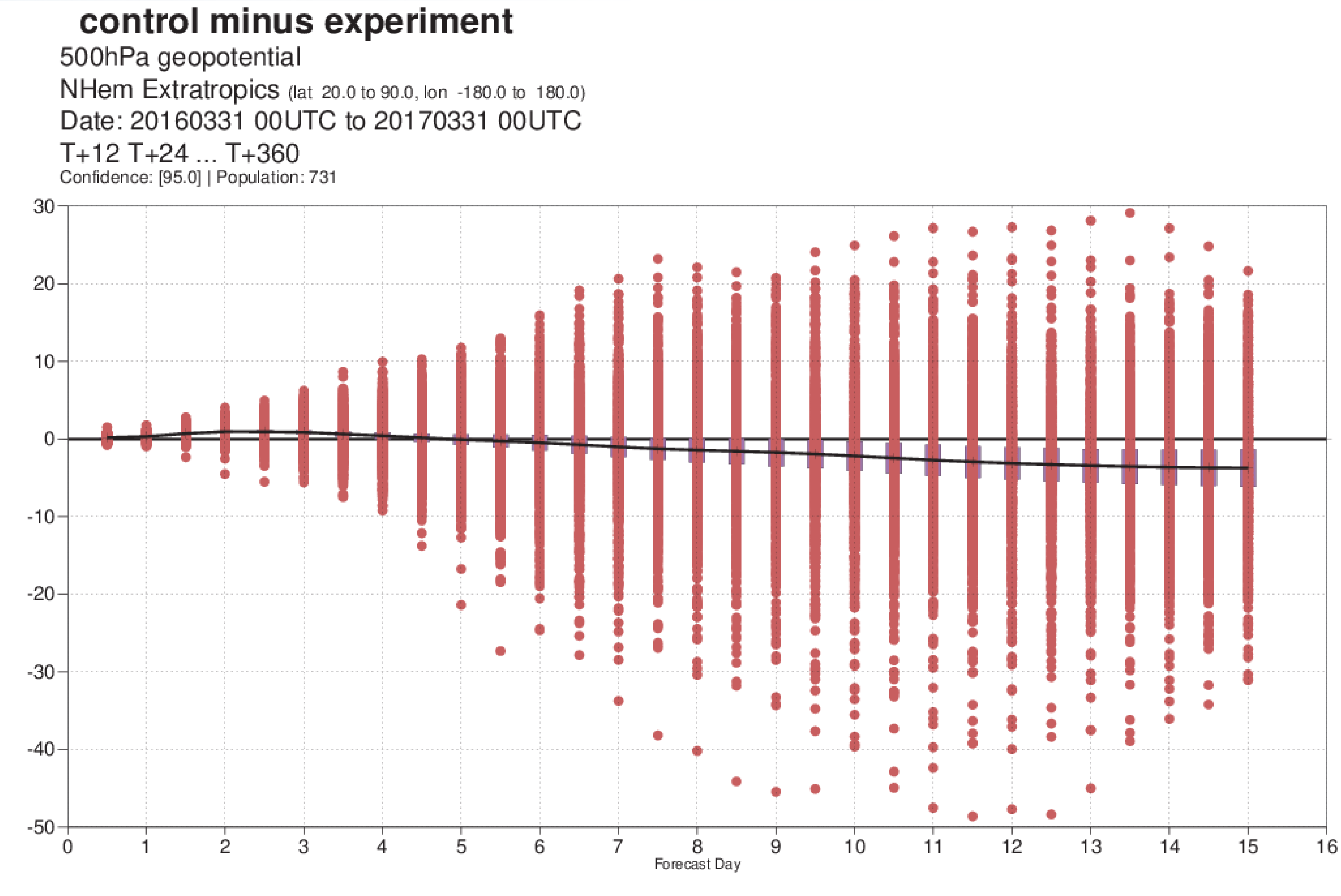
RMSE+120h



Ensemble Spread vs Error

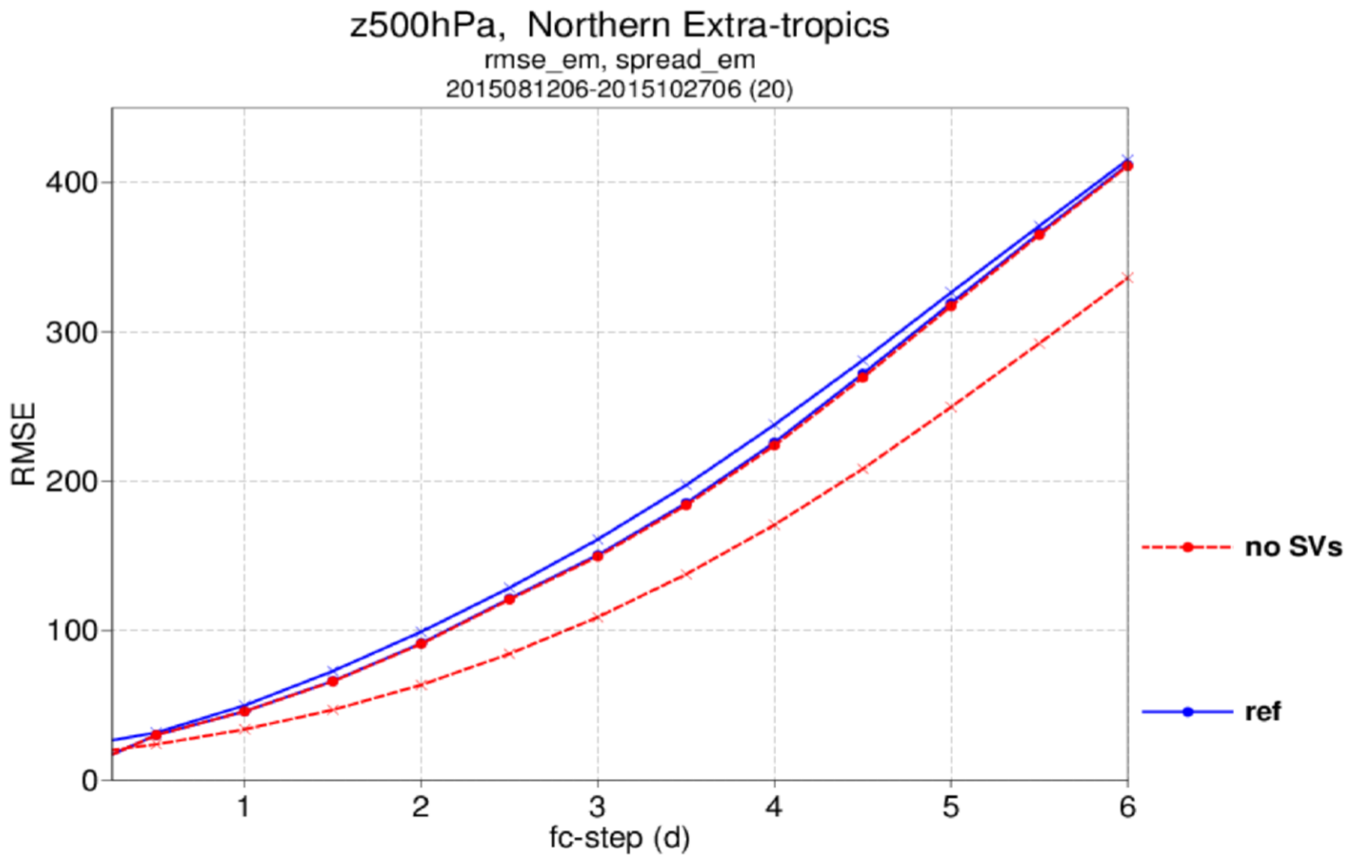


Ensemble Spread vs Error



Why SVs?

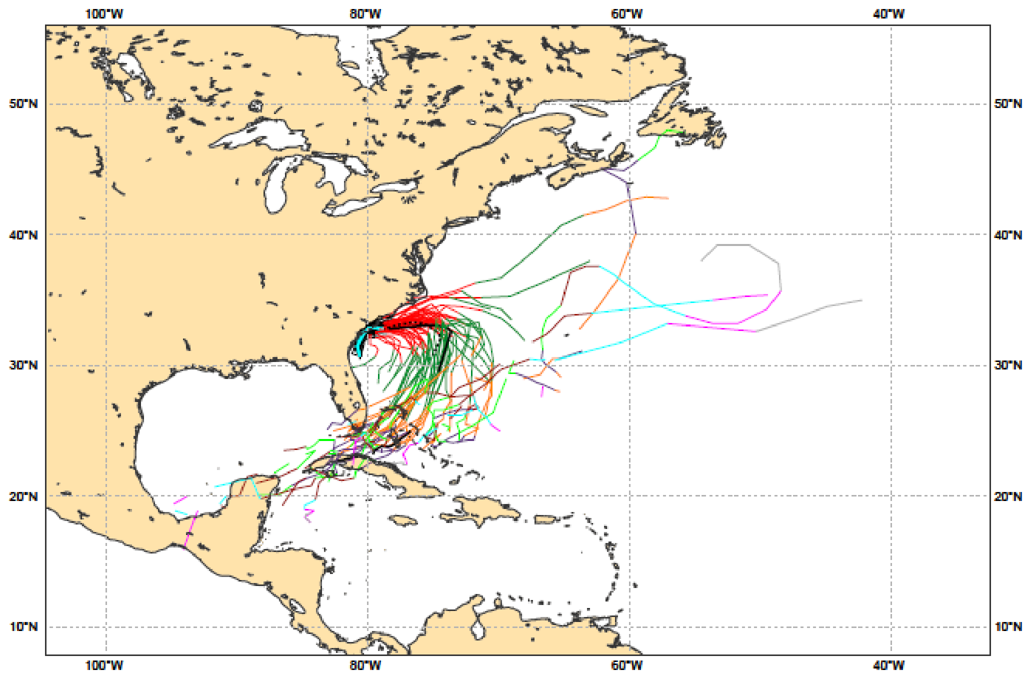
Impact of SVs on ENS



Oper like setup, TCo399, 20 Initial dates

Thank You!

Date 20161008 00 UTC @ECMWF
Individual trajectories for **MATTHEW** during the next **240** hours
tracks: **thick solid**=HRES; **thick dot**=CTRL; **thin solid**=EPS members [coloured]
0-24h 24-48h 48-72h 72-96h 96-120h 120-144h 144-168h 168-192h 192-216h 216-240h



List of ensemble members numbers forecast Tropical Cyclone
Intensity category in colours: TD[up to 33] TS[34-63] HR1[64-82] HR2[83-95] HR3[> 95 kt]

+024 h : hr ct 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50
+048 h : hr ct 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 47 48 49 50
+072 h : 01 02 06 07 10 11 15 16 17 18 19 21 23 26 27 28 29 30 31 33 35 36 39 40 41 43 44 46 47 49 50
+096 h : hr 06 08 09 10 12 13 14 15 16 20 21 25 26 27 28 30 31 33 35 37 40 41 42 43 44 46 47 49 50
+120 h : hr 08 09 13 14 15 16 17 20 25 26 27 28 29 31 33 35 37 40 41 43 44 47
+144 h : 02 08 09 13 15 17 20 28 30 31 33 35 37 41 42 44 47 50
+168 h : 14 16 17 20 22 28 31 35 37 43 47 50
+192 h : 14 15 17 20 31 37 43 50
+216 h : 15 31 37 40 43 50
+240 h : 31 37