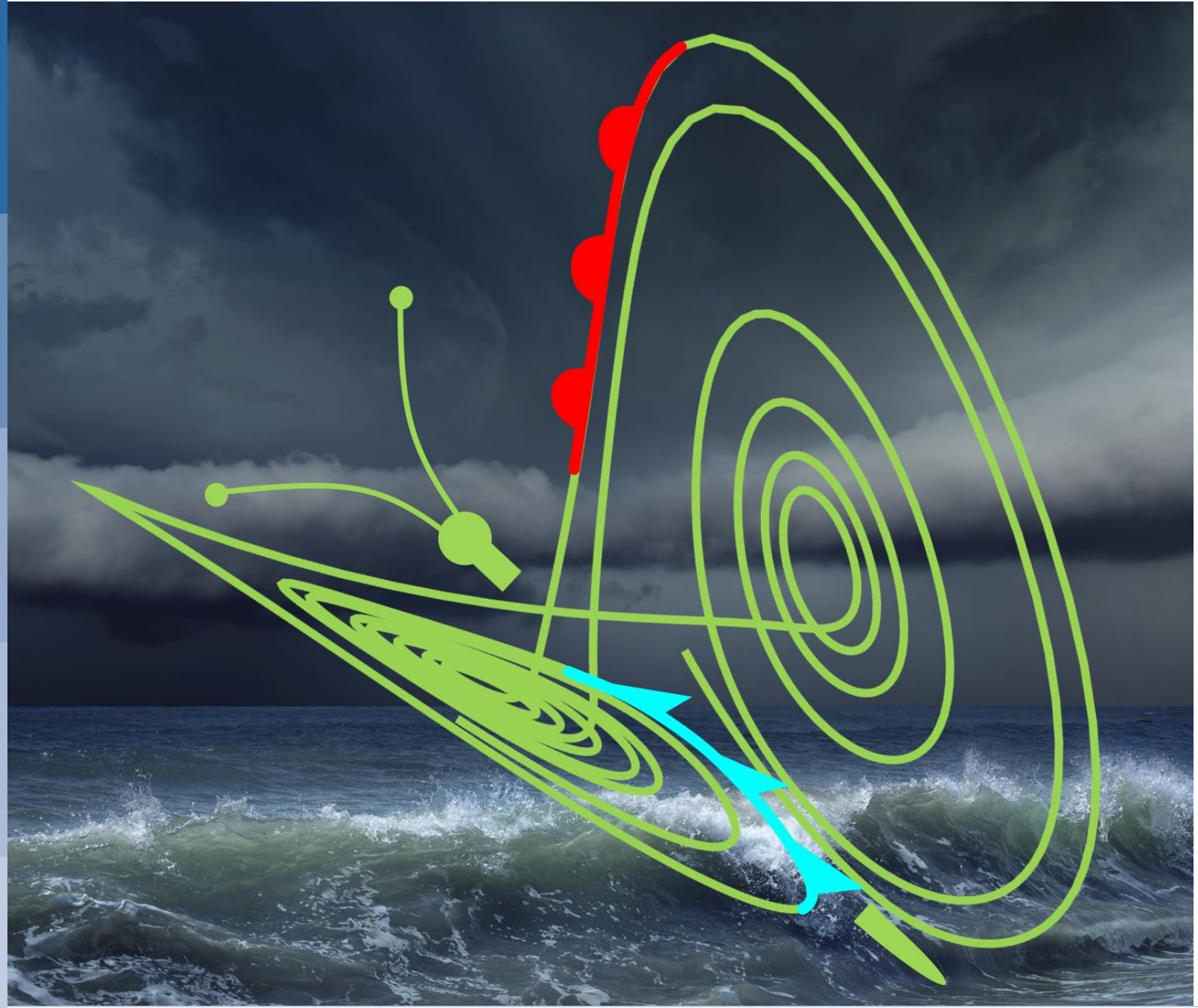


Diagnostics 2

Mark Rodwell

ECMWF Training Course on Predictability

21 October 2026, ECMWF Reading

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Outline

- Tropical forcing of midlatitude Rossby waves
- Predictability, reliability and sharpness
- Mechanisms of uncertainty growth
- The age of AI

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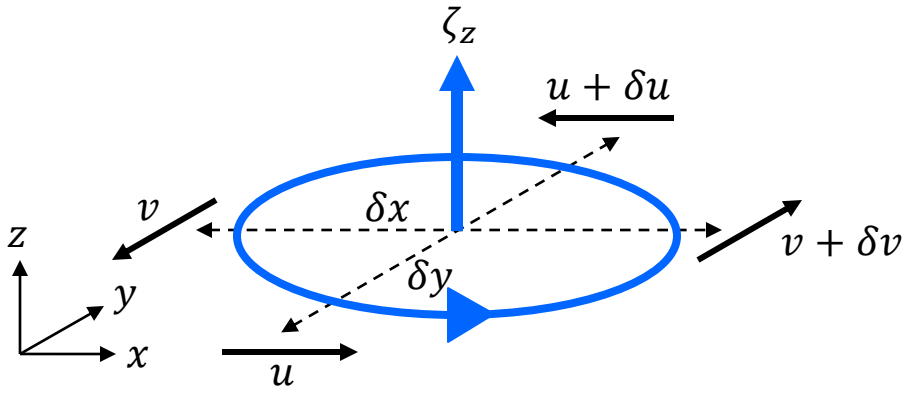
The Vorticity Equation

Motivation (2D flow) :

$\zeta_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad \left(\equiv \hat{\boldsymbol{k}} \cdot \boldsymbol{\nabla}_z \times \boldsymbol{v}\right)$ is the vorticity

$\hat{\boldsymbol{k}}$ is the unit vertical vector

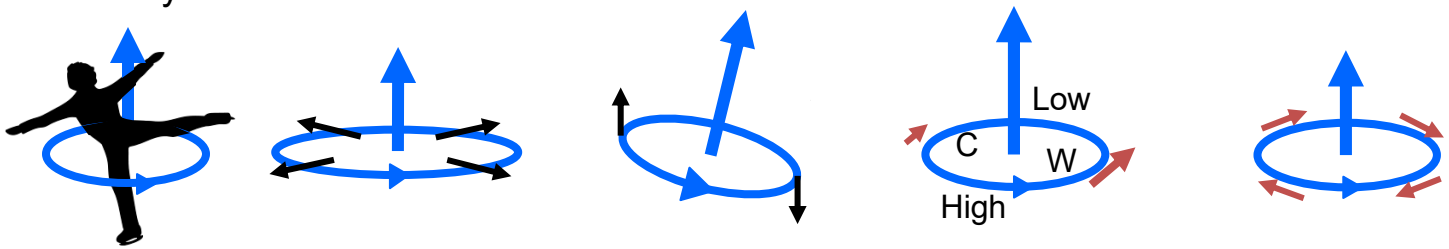
$\boldsymbol{\nabla}_z \times$ is the horizontal curl operator



Curl of the 3D momentum equation in absolute frame of reference:

$$\frac{d\boldsymbol{\zeta}}{dt} = -\boldsymbol{\zeta}(\boldsymbol{\nabla} \cdot \boldsymbol{u}) + (\boldsymbol{\zeta} \cdot \boldsymbol{\nabla})\boldsymbol{u} + \frac{1}{\rho^2}\boldsymbol{\nabla}\rho \times \boldsymbol{\nabla}\boldsymbol{p} + \boldsymbol{\nabla} \times \boldsymbol{F_u}$$

Lagrangian tendency | Divergence | Tilting | Baroclinic | Friction



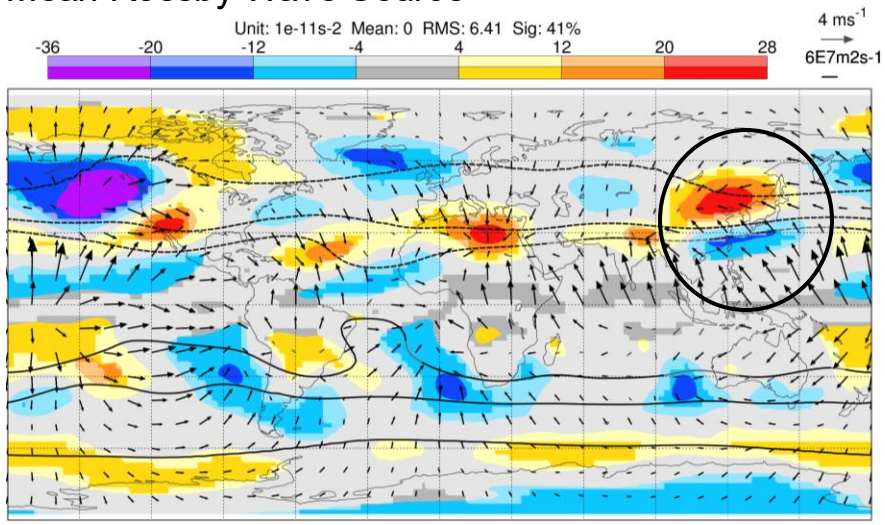
Shallow atmosphere approximation & assuming horizontal, barotropic, frictionless flow:

$$\frac{\partial \zeta}{\partial t} + \boldsymbol{v}_\psi \cdot \boldsymbol{\nabla}\zeta = -\boldsymbol{v}_\chi \cdot \boldsymbol{\nabla}\zeta - \zeta \boldsymbol{\nabla} \cdot \boldsymbol{v}_\chi$$
$$= -\boldsymbol{\nabla} \cdot \left(\boldsymbol{v}_\chi \zeta\right) \quad \text{“Rossby Wave Source”}$$

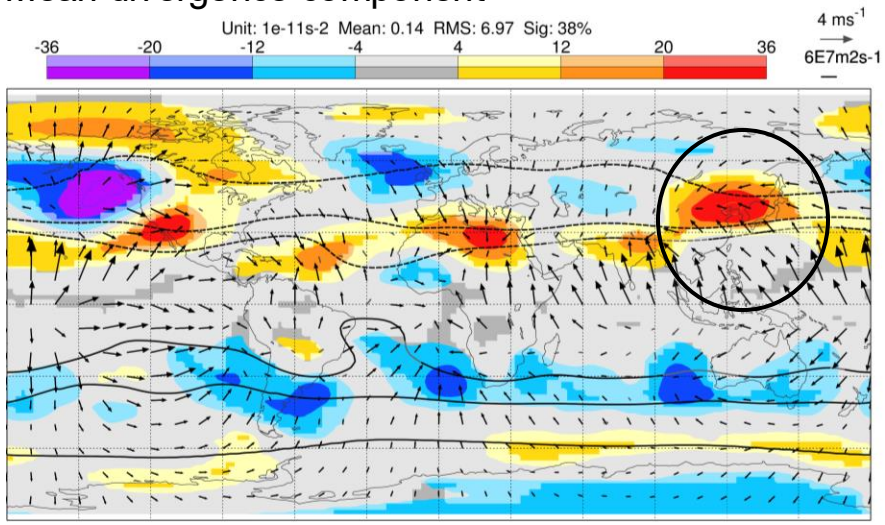
Terms in the Vorticity Equation (upper troposphere)

Shading: Terms
Contours: Streamfunction
Vectors: Divergent winds

Mean Rossby Wave Source

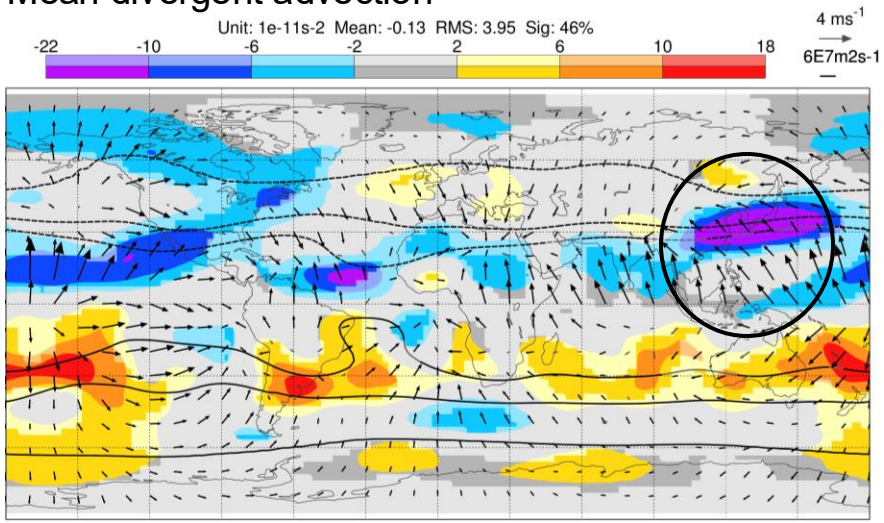


Mean divergence component



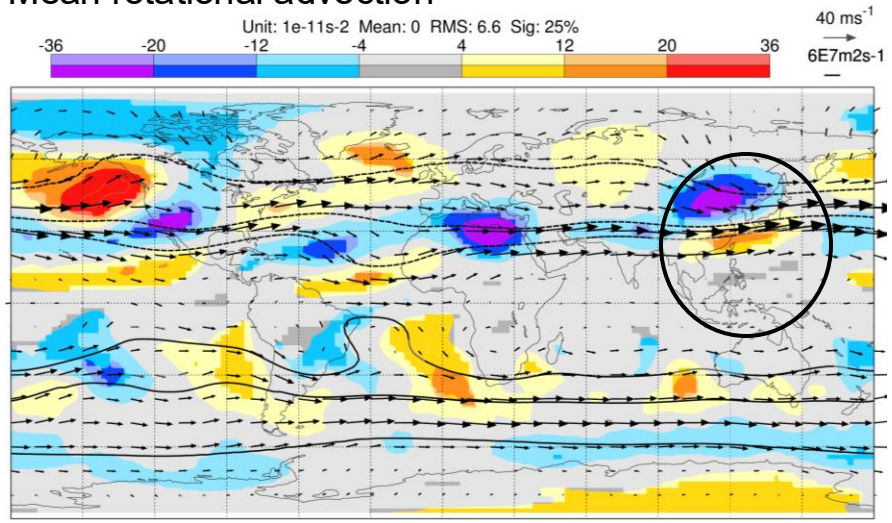
Convergence associated with "stretching"

Mean divergent advection



Advection of low planetary vorticity by divergent outflow

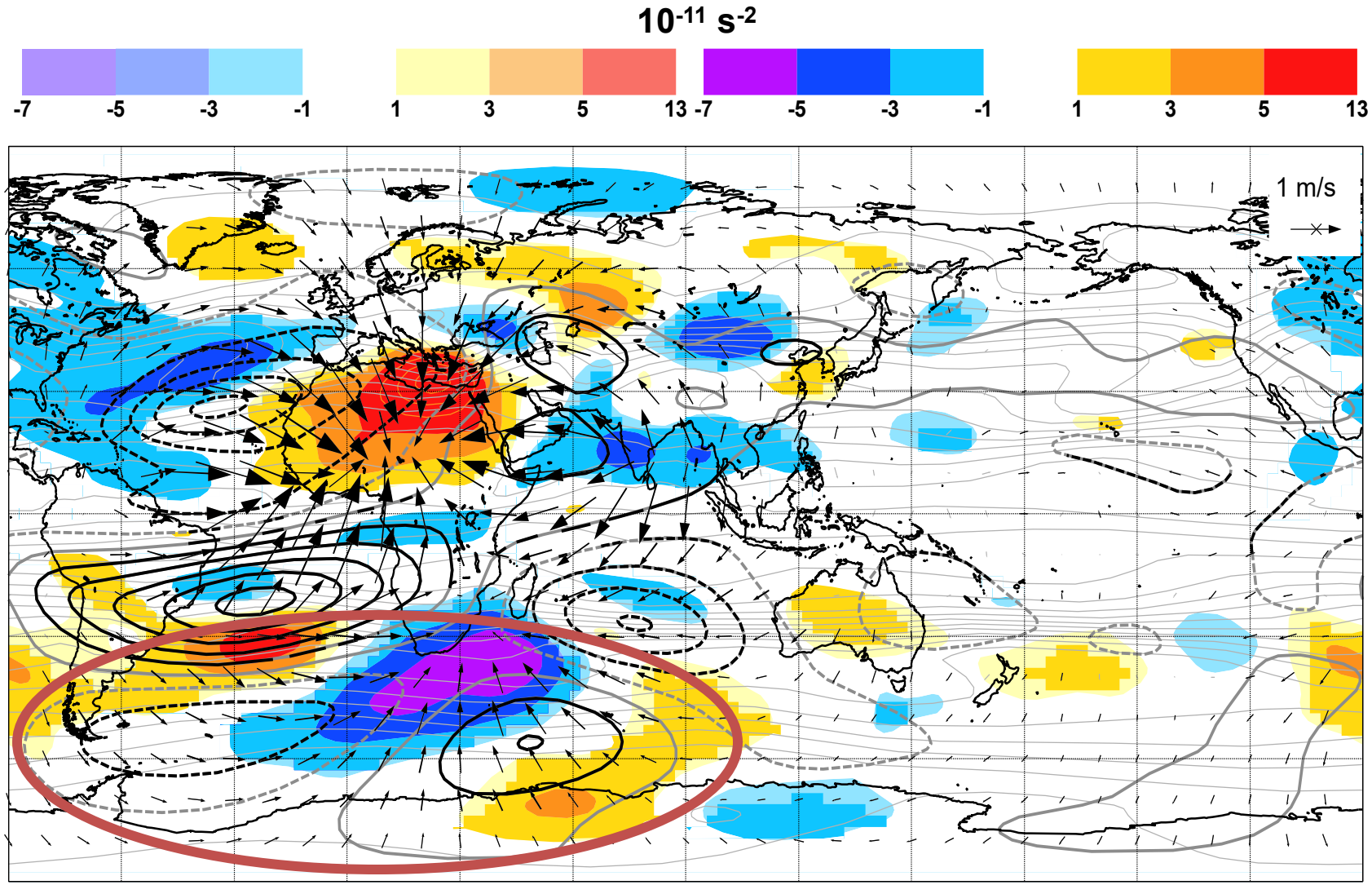
Mean rotational advection



Adjustment of rotational flow balances RWS

Based on operational analyses for the period DJF 2015/16, with terms integrated between 100-300 hPa.

Aerosol impact on RWS, divergent wind & streamfunction



Rodwell and Jung (2008)

Shading: RWS
Thick contours: Streamfunction
Vectors: Divergent winds

(Thin contours: mean absolute vorticity)

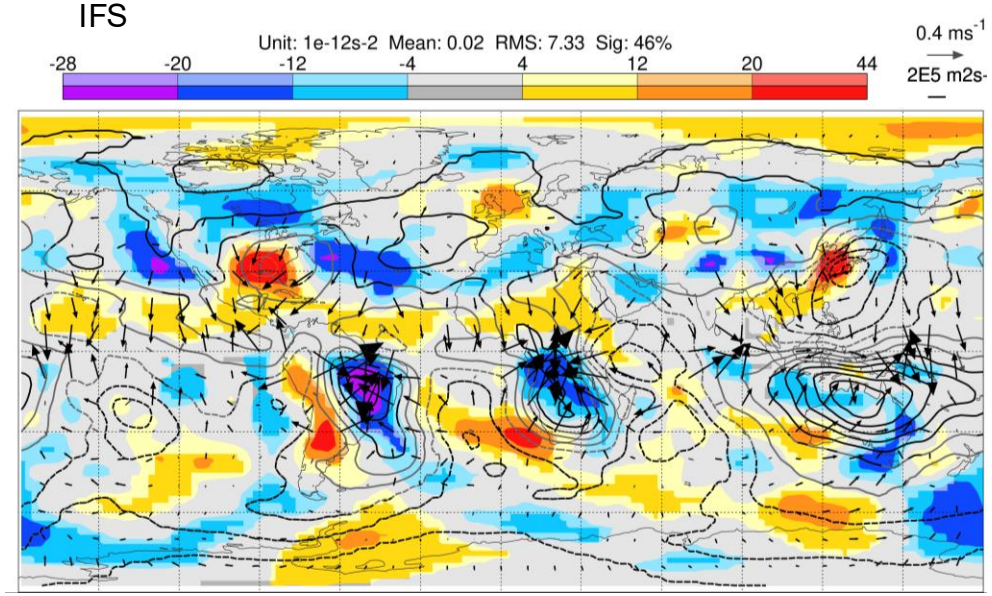
40-year mean JJA response to change in aerosol climatology deduced using seasonal-mean data. Anomalies integrated 100-300 hPa. Southern Hemisphere stationary Rossby wave pattern explains response seen in previous lecture

Upper tropospheric errors in IFS and AIFS (2024 DJF)

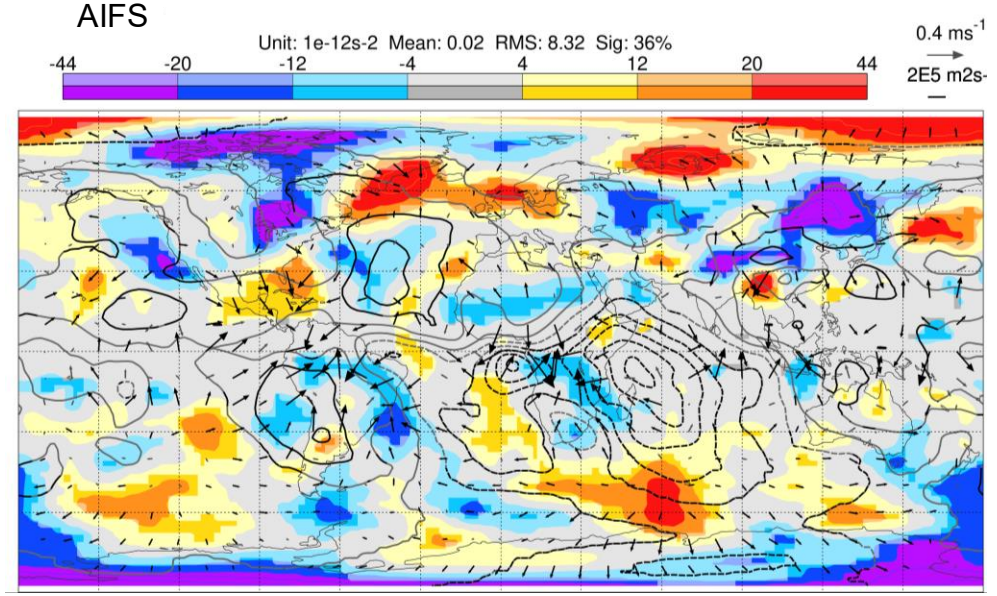
Day 1

Mean errors in streamfunction, divergent winds and Rossby wave source

IFS



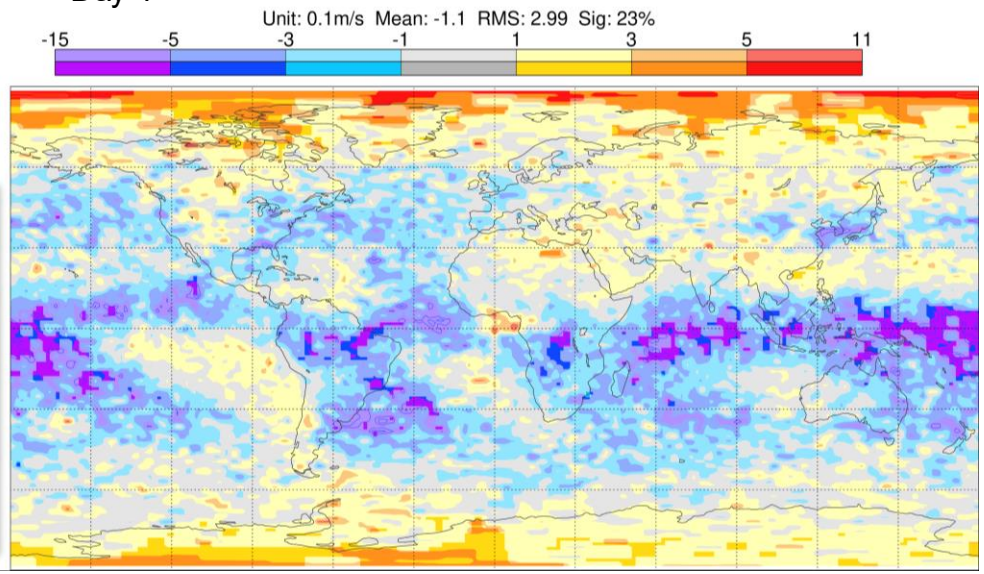
AIFS



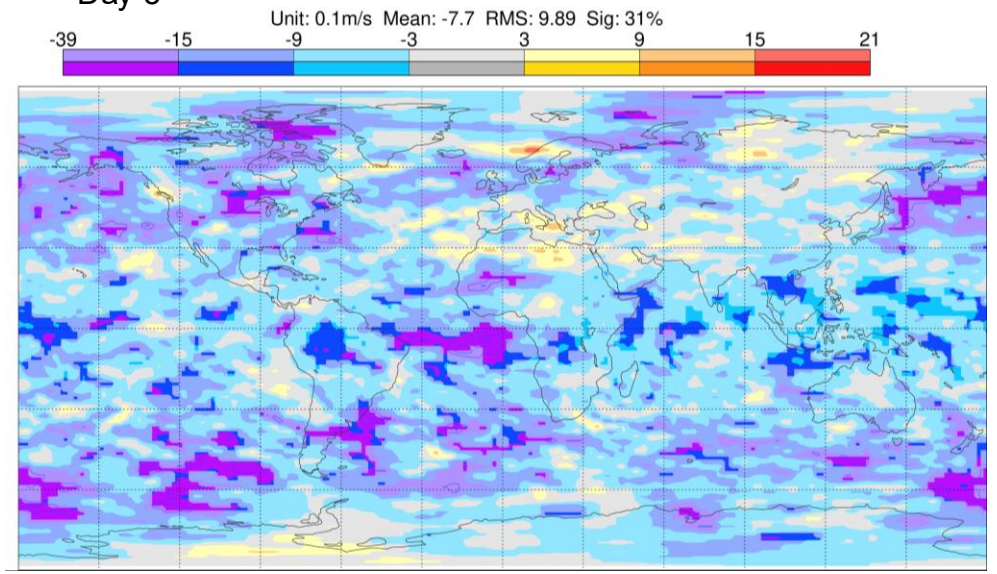
AIFS-IFS

StDev in u250 errors

Day 1



Day 5

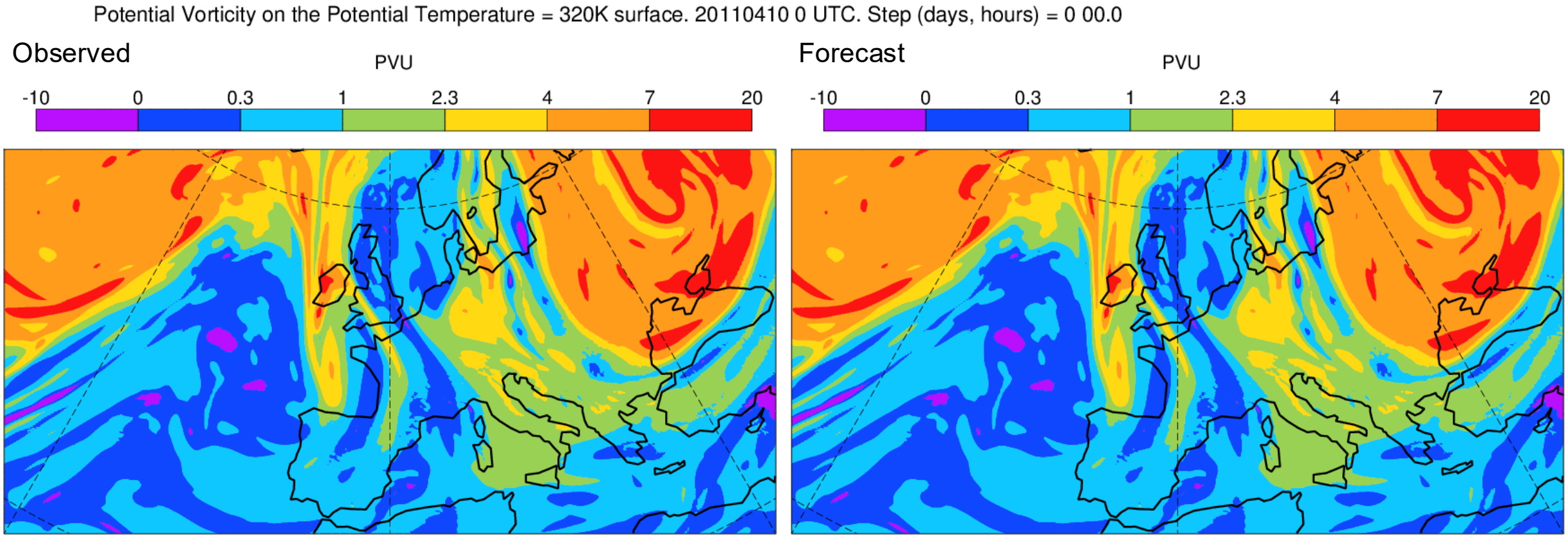


The Artificial Intelligence Forecasting System (AIFS) is trained to follow the 6 hourly analyses (ERA5). Does its predictive advantage come from the resulting reduction in (tropical) short-range error?

Outline

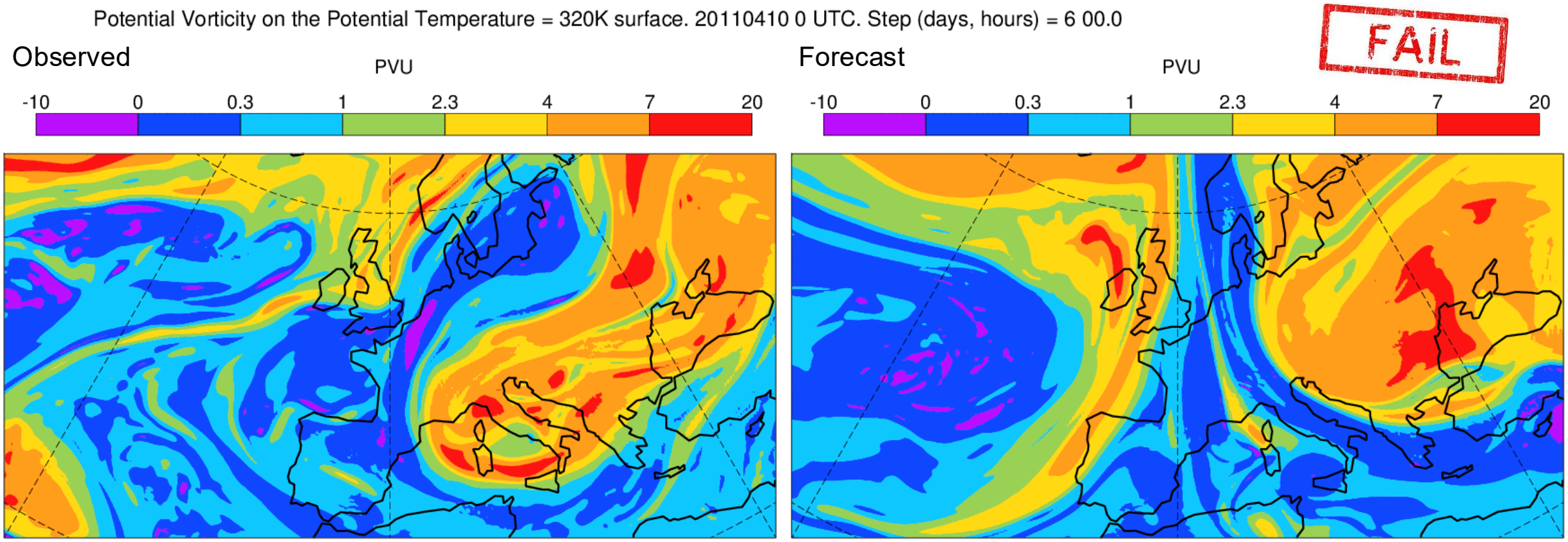
- Tropical forcing of midlatitude Rossby waves
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Animation of a very poor medium-range single forecast



The field plotted is Potential Vorticity (PV). It indicates air masses, with blue being more tropical-tropospheric and red being more polar-stratospheric. PV has other useful properties (some mentioned in the notes)

Animation of a very poor medium-range single forecast

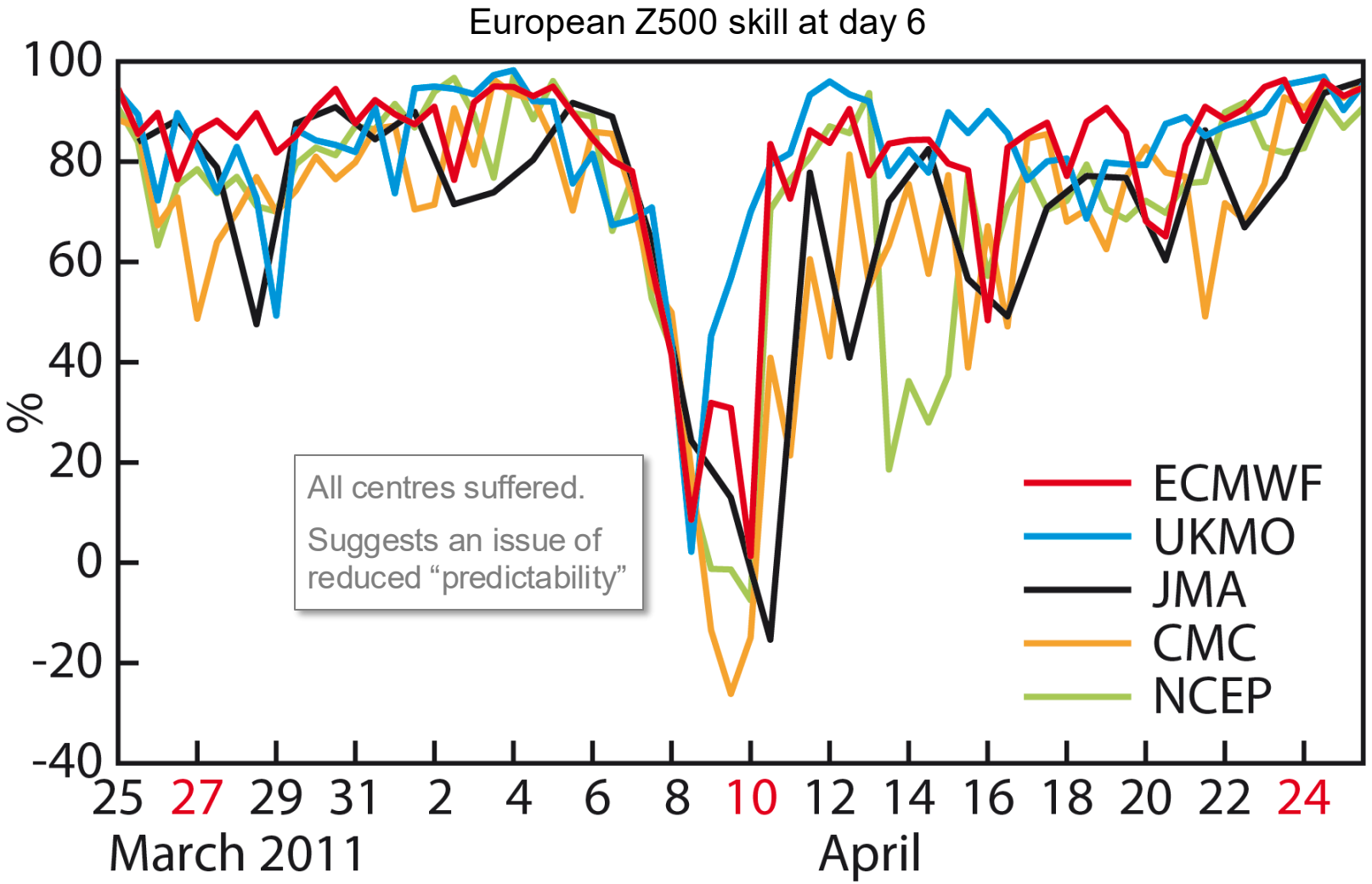


We see the mixing of air masses. The eventual block (high pressure) over Northern Europe is not well predicted

With a single forecast, it is easy to quantify the error (pointwise differences, pattern correlations etc.)

All forecast centres suffered

Rodwell et al, 2013, BAMS

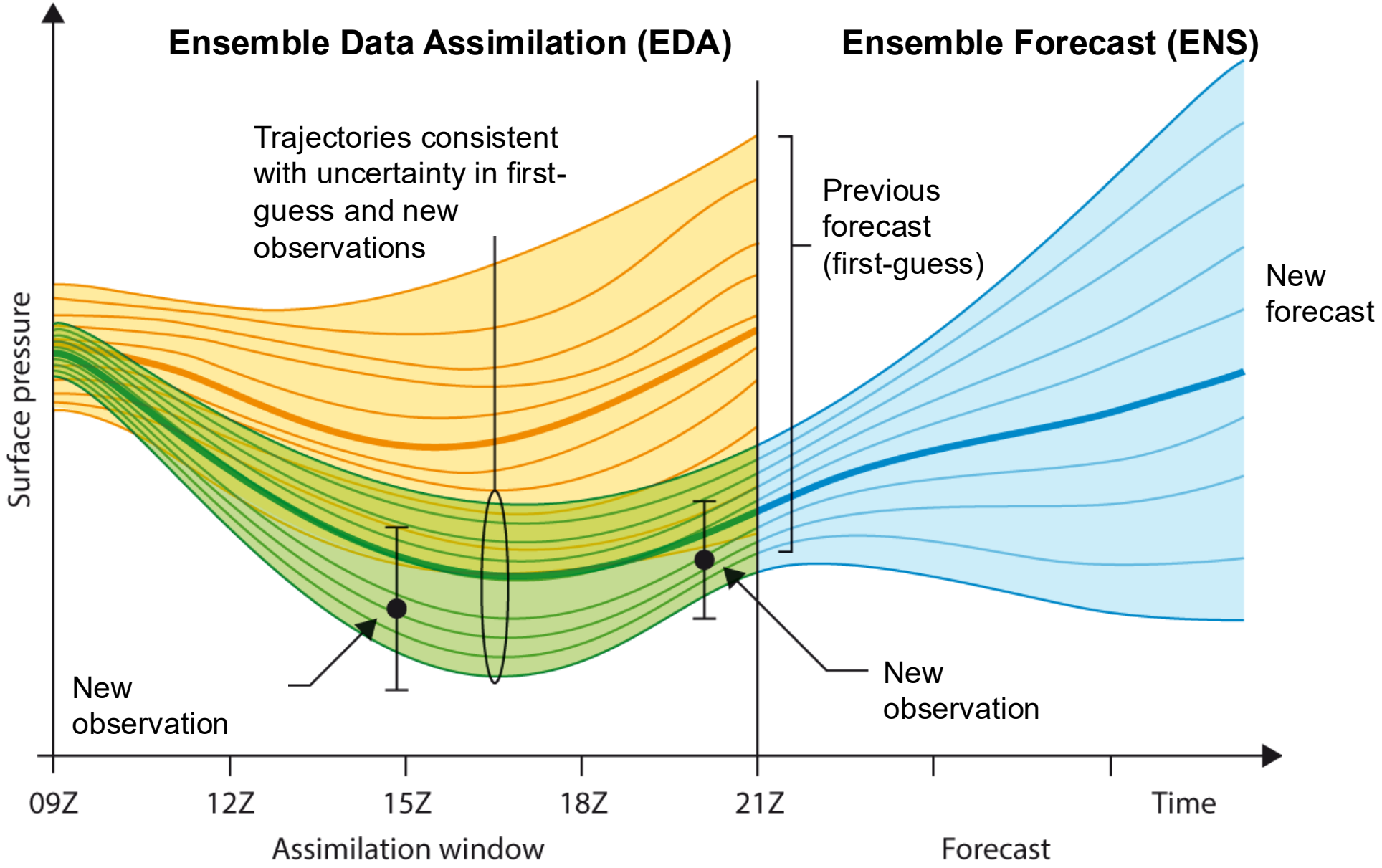


Spatial Anomaly Correlation Coefficient for 500 hPa geopotential height in [12.5°W –42.5°E, 35°N–75°N]. Date is forecast start

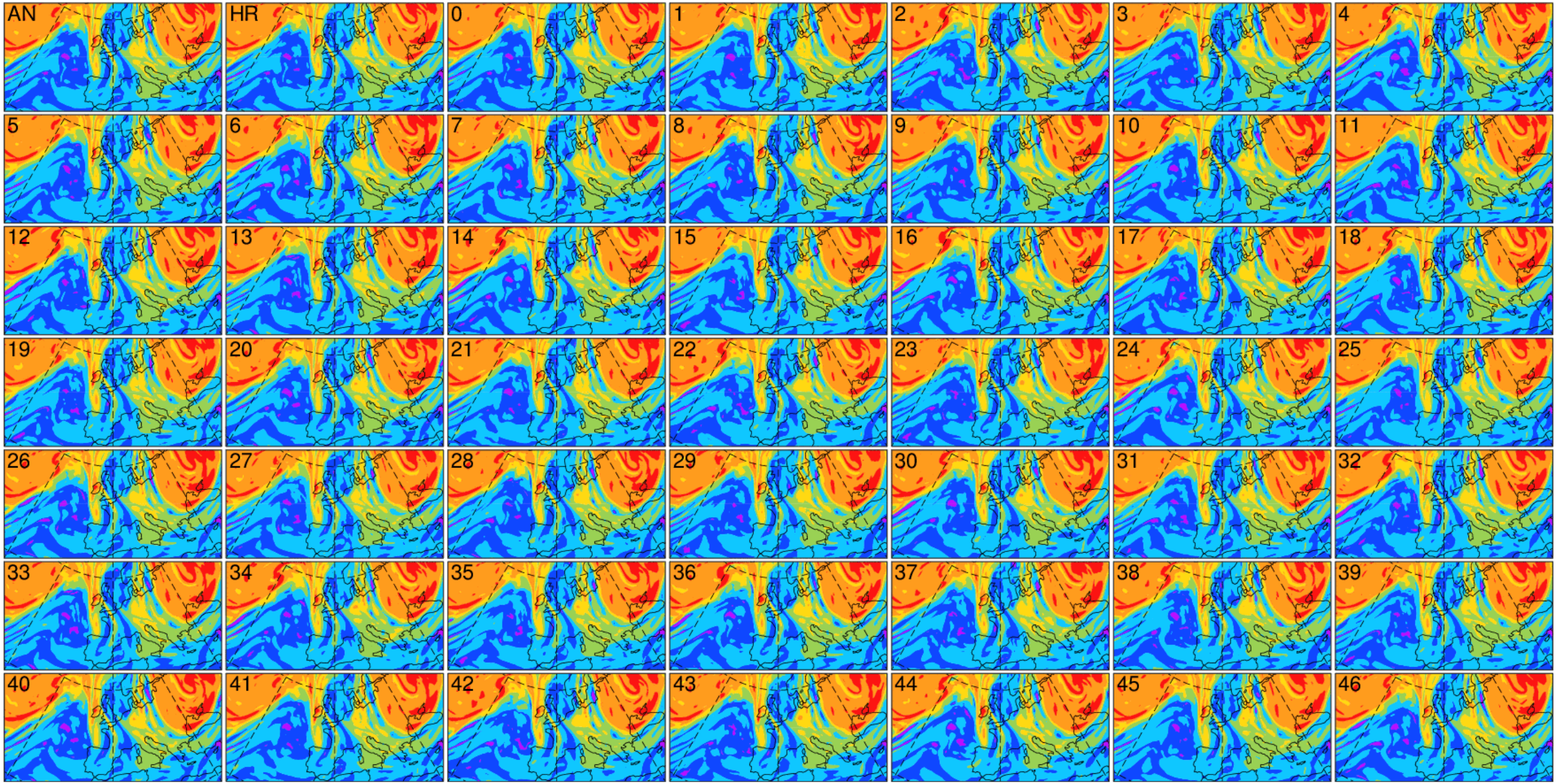
Traditional Ensemble Weather Prediction (ECMWF)

ECMWF global ensemble has 50 members and resolution ~9km. Millions of observations ingested each assimilation cycle.

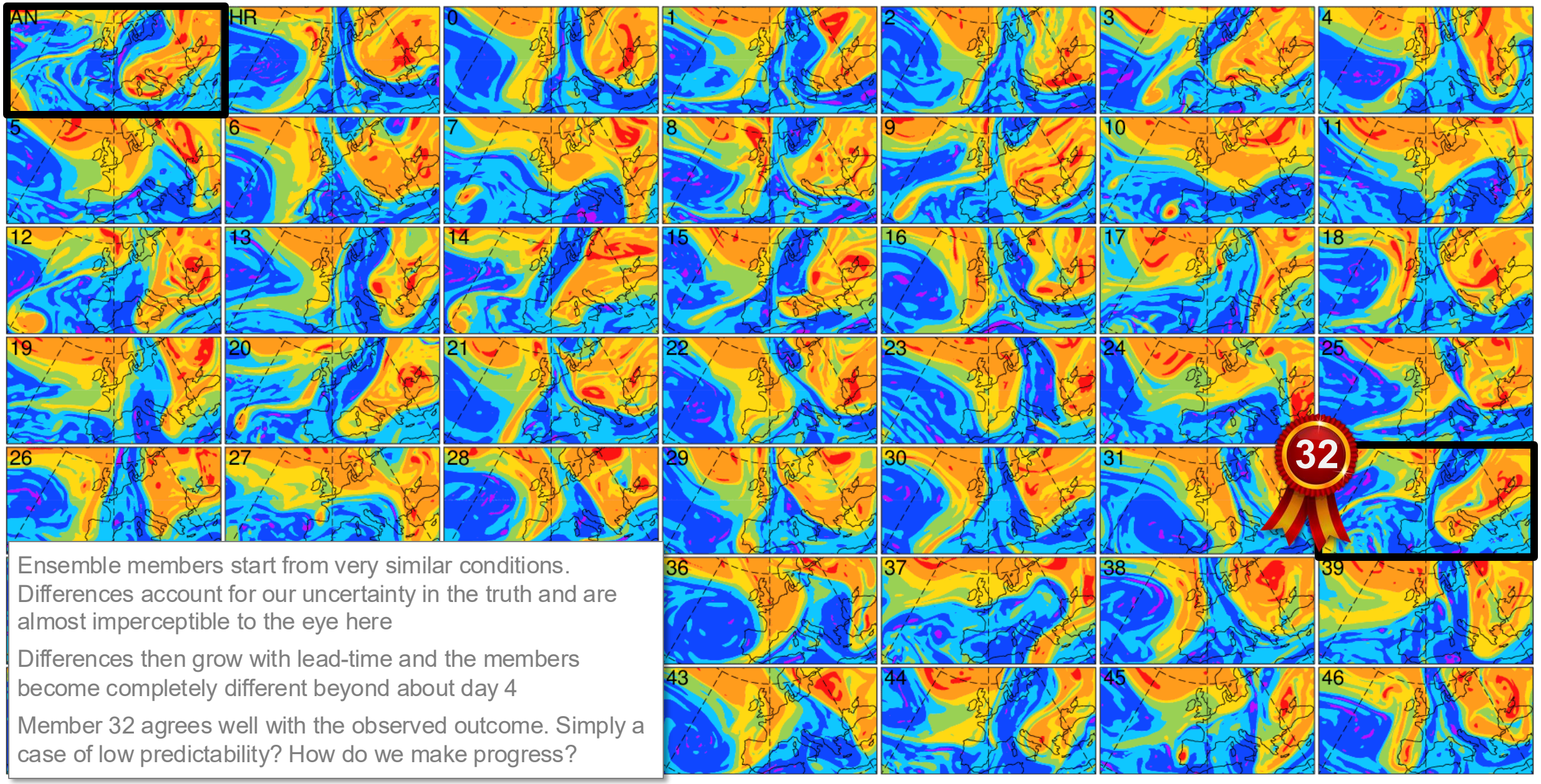
ENS spread arises from chaotic growth of EDA uncertainty, model uncertainty and singular vector perturbations



Potential Vorticity on the Potential Temperature = 320K surface. 20110410 0 UTC. Step (days, hours) = 0 00.0



Potential Vorticity on the Potential Temperature = 320K surface. 20110410 0 UTC. Step (days, hours) = 6 00.0

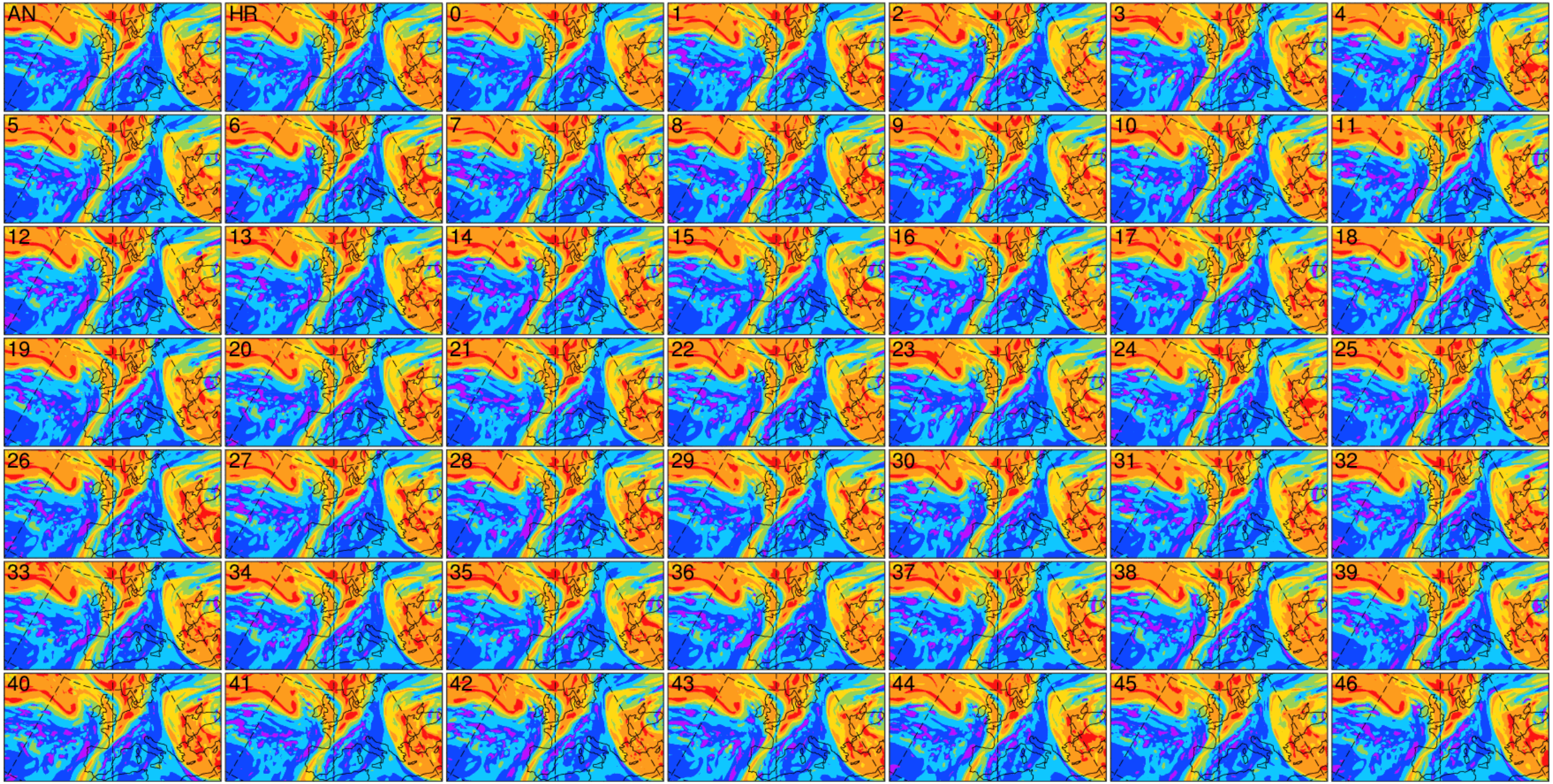


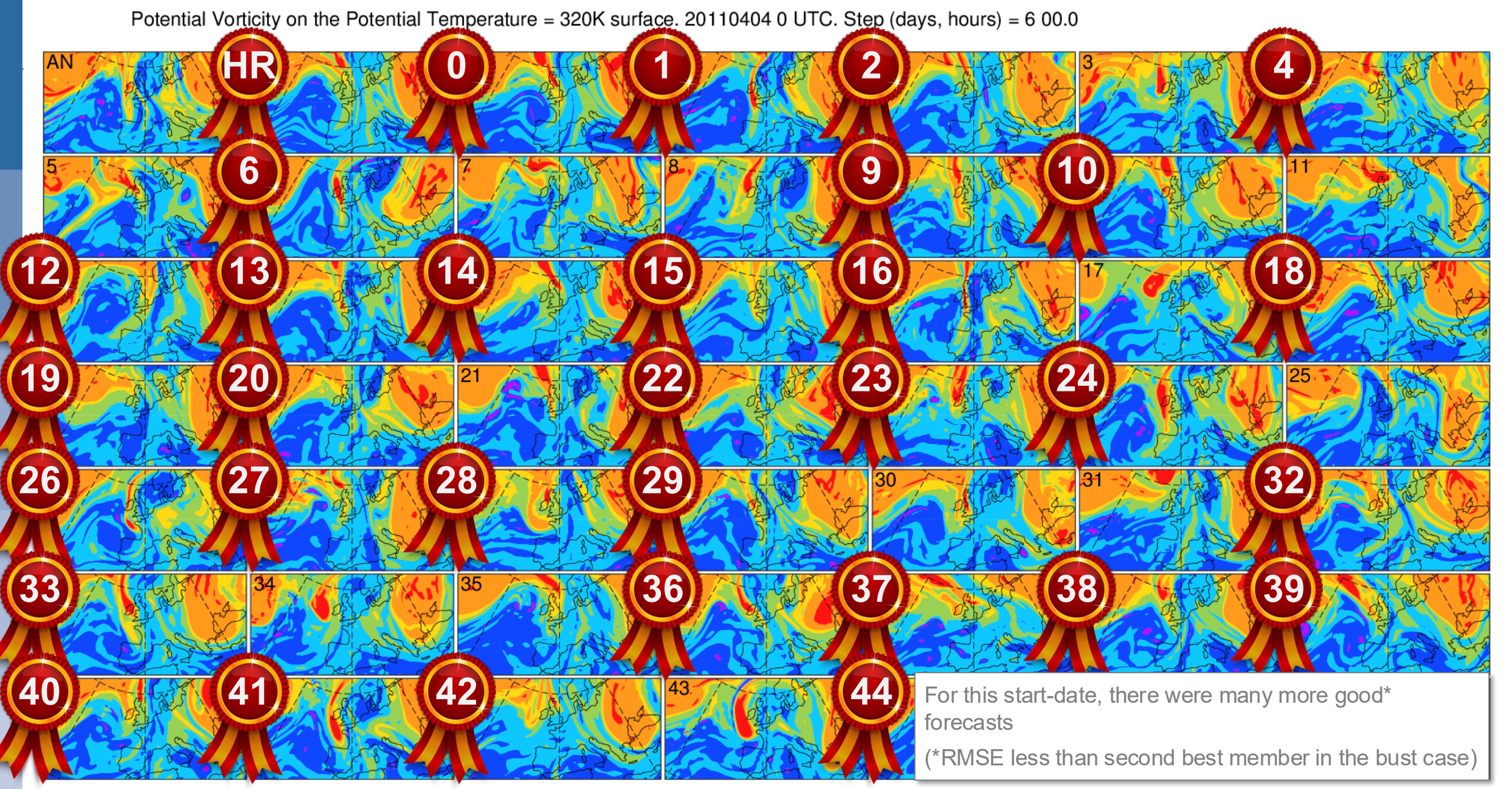
Ensemble members start from very similar conditions. Differences account for our uncertainty in the truth and are almost imperceptible to the eye here

Differences then grow with lead-time and the members become completely different beyond about day 4

Member 32 agrees well with the observed outcome. Simply a case of low predictability? How do we make progress?

Potential Vorticity on the Potential Temperature = 320K surface. 20110404 0 UTC. Step (days, hours) = 0 00.0

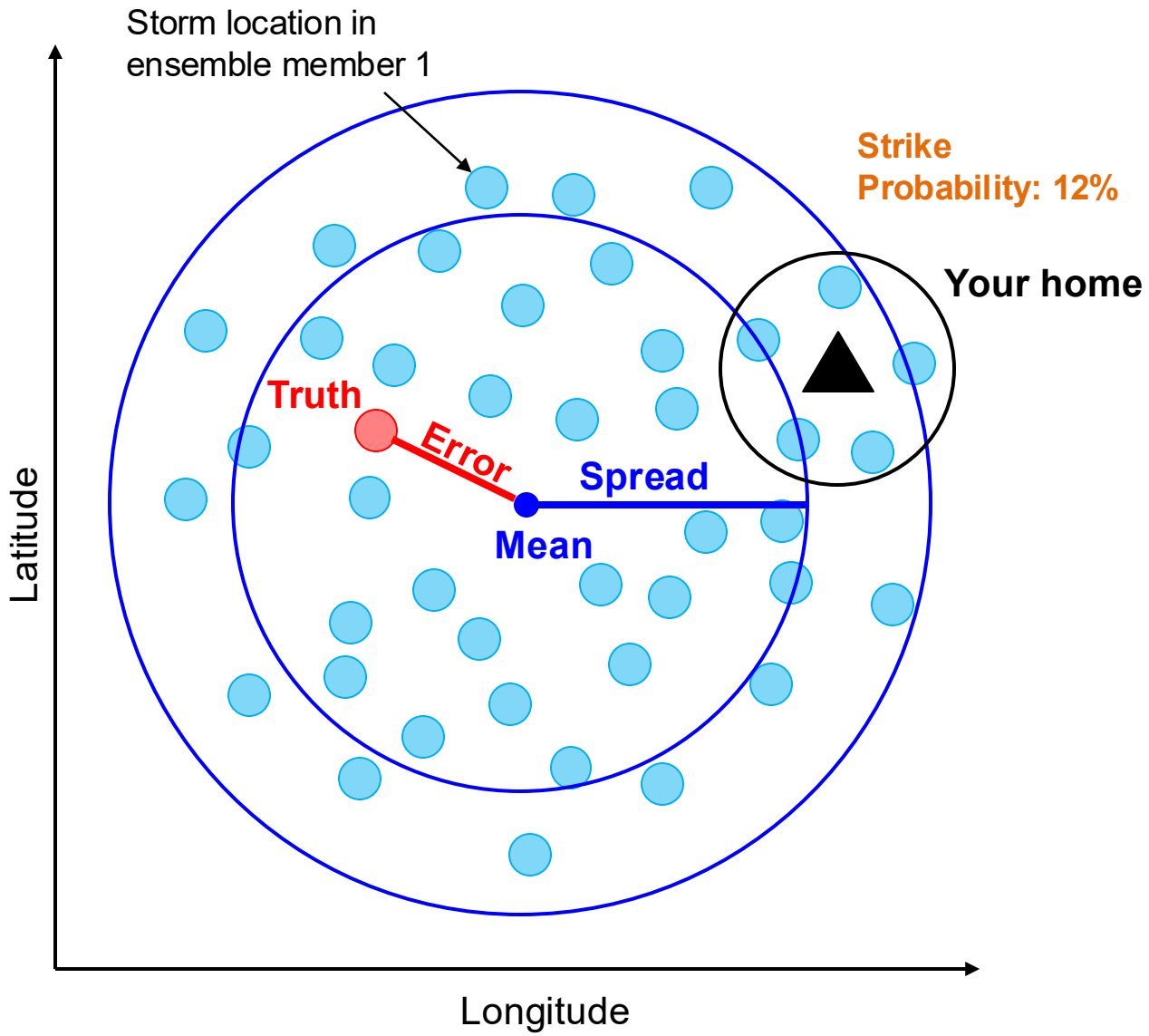




For this start-date, there were many more good* forecasts

(*RMSE less than second best member in the bust case)

The aims of ensemble forecast system development



Aim 1

Improve the forecast model so that the truth* is statistically indistinguishable from any ensemble member (Reliability) ⇒ Unbiased decisions and Error should match Spread, *on average*

* We can take account of our uncertainty in the truth

Aim 2

Reduce uncertainty in the ensemble initial conditions to decrease forecast Spread** (Sharpness) while maintaining Reliability

** Chaos can imply an ulitimate limit to the lead-time for which Spread can be reduced to a useful level

Caution!

Many cases are required to determine reliability. This needs to be assessed and improved in a flow-dependent sense (e.g. using composites)

Ensemble spread and error

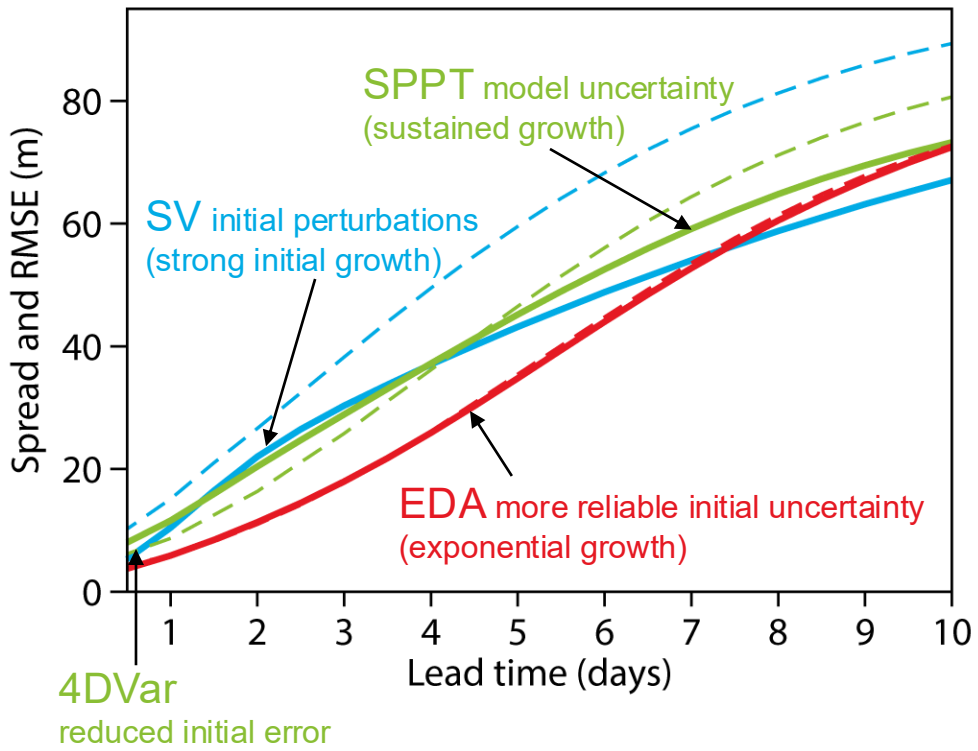
Z500

Rodwell et al. 2018, BAMS

Overall Error and Spread have reduced and come into alignment; due to better observations, initial conditions, forecast model and better representation of uncertainty

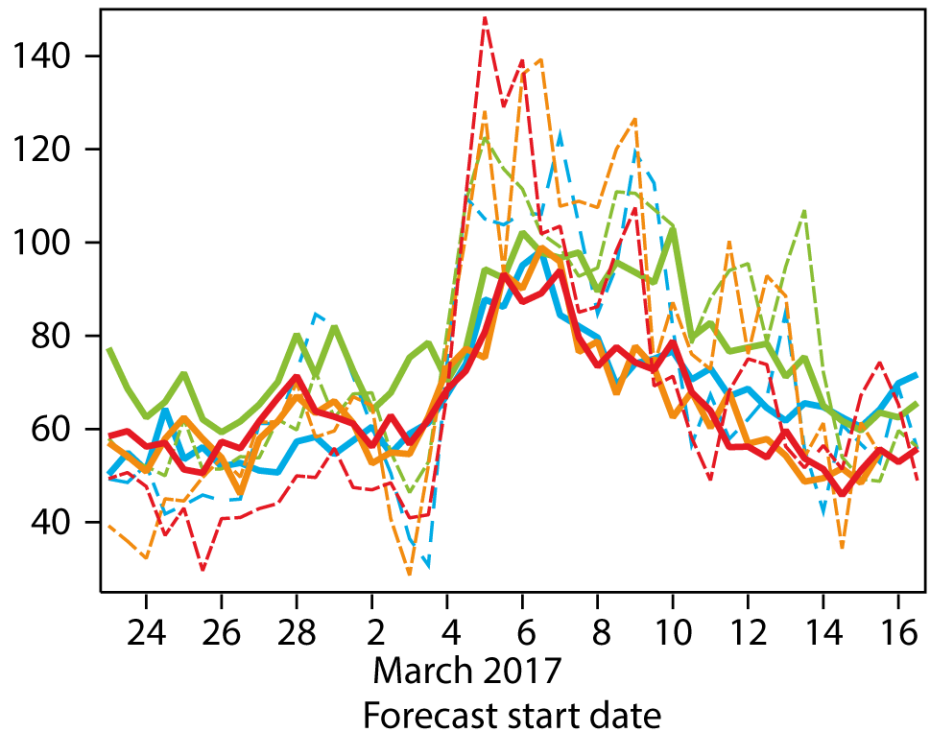
…but we make ensemble forecasts to represent the day-to-day variations in predictability and uncertainty. Can we evaluate it in our forecasts?

Annual means N.Hem. (ECMWF)



	1996	2005	2014
Spread			
Error			

Timeseries for Europe at D+6 (TIGGE)



	ECMWF	UKMO	JMA	NCEP
Spread				
Error				

500 hPa geopotential height (Z500). "Error" is RMS of ensemble-mean error

Spread = ensemble standard deviation (scaled to take account of finite ensemble size)

Outline

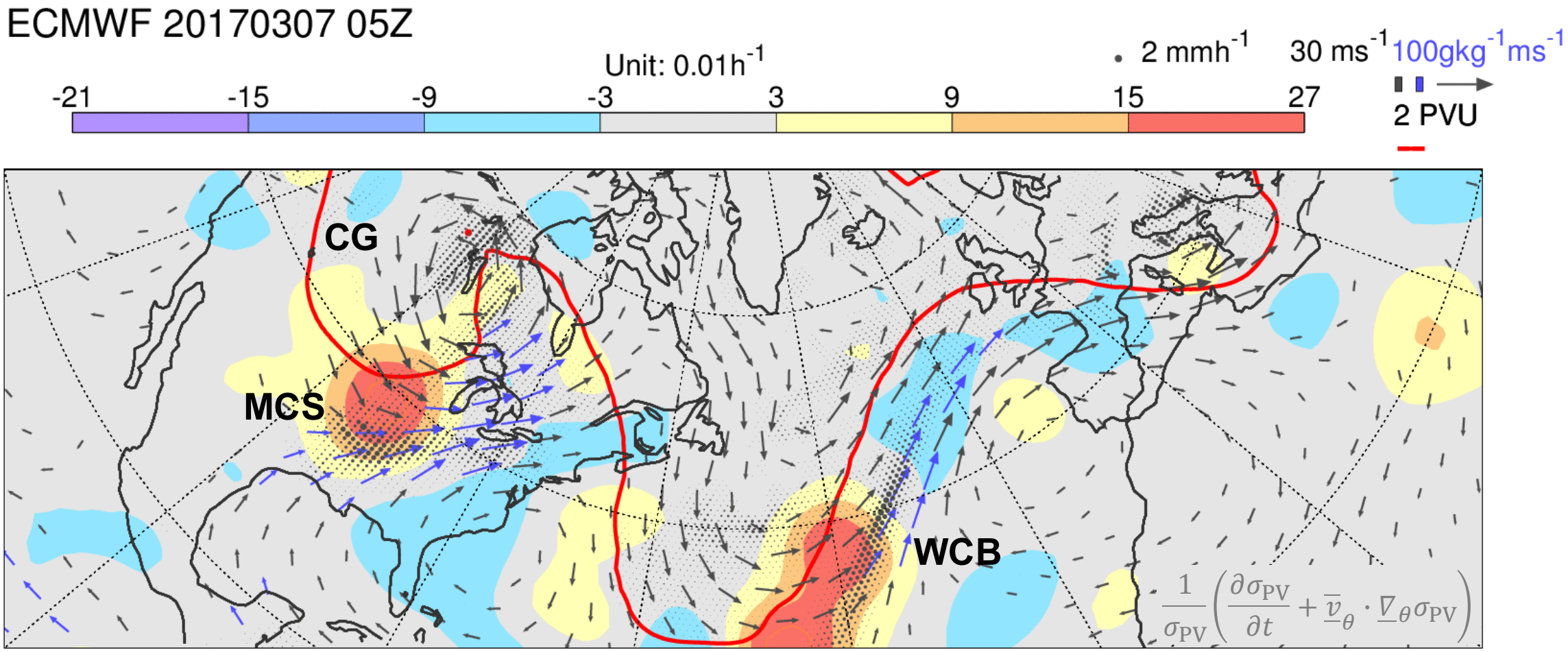
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Animation of analyzed circulation and growth rate of background spread

The "Lagrangian Growth Rate" measures the growth of ensemble spread following the ensemble-mean flow

Much uncertainty growth associated with moist processes: **W**arm **C**onveyor-**B**elts, and **M**eso-**S**cale **C**onvection

Interaction of uncertain features, large ENS spread & poor prediction of Euro blocking at D+6



Control forecast PV_{315}=2, $\underline{v}_{850}$ and $q|\underline{v}|_{850}$, ensemble-mean precipitation. Growth-rate of $\sigma_{PV_{315}}$. Synoptic filter:1d, T21. *Rodwell, Richardson, Parsons and Wernli (2018)*

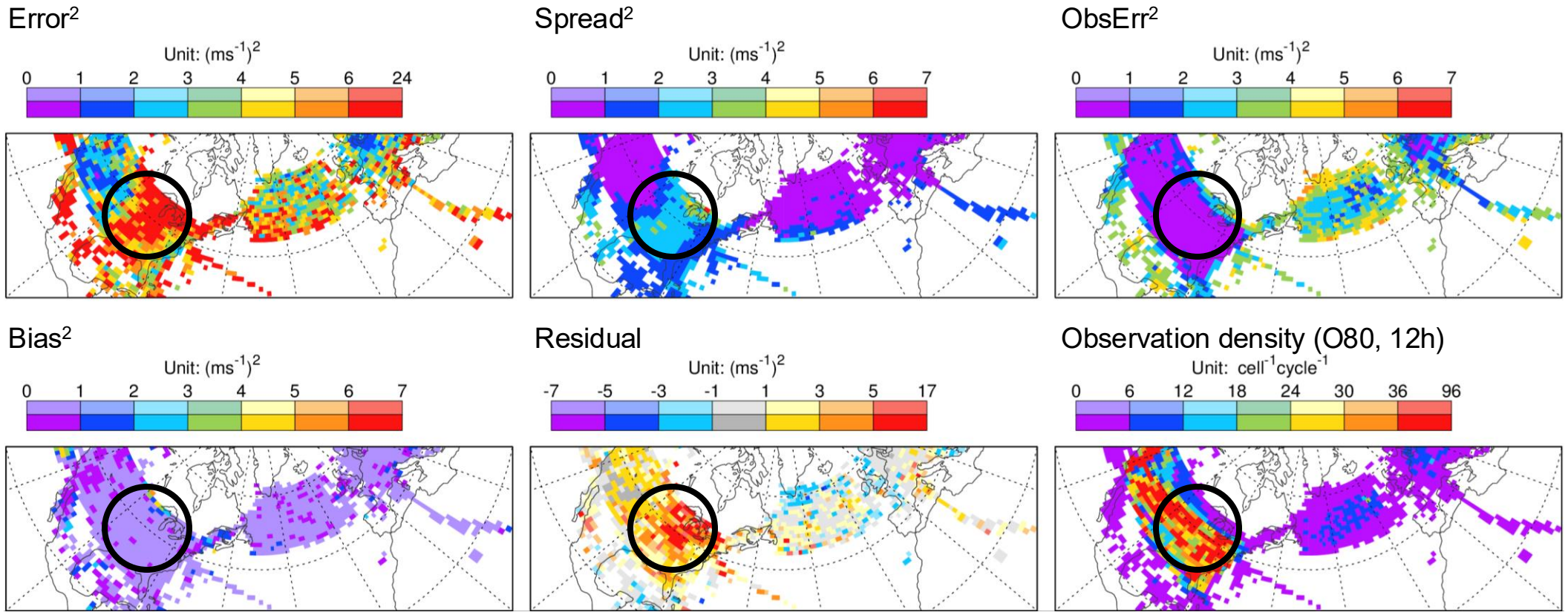
EDA reliability in u_{200} against aircraft observations in MCS situations

Rodwell et al. 2018, BAMS

For more operational diagnostics, see the Diagnostics Explorer

$Error^2 = Spread^2 + ObsErr^2$ (+ $Bias^2$ + Residual)

54 cases, 12h window

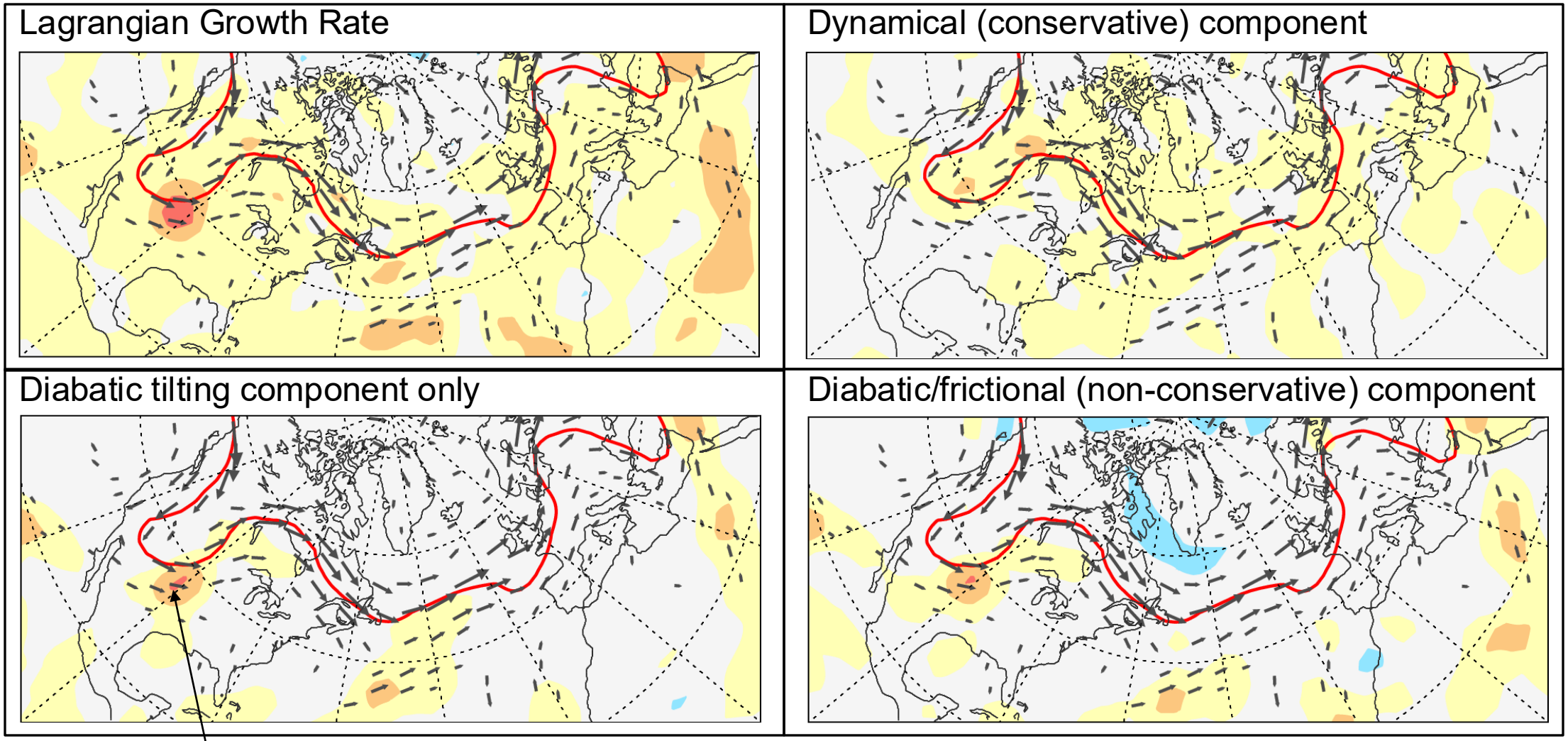


Enhanced spread (Background variance) in Great Lakes / Mississippi River region

Even larger $Error^2$ of the ensemble-mean from the observations

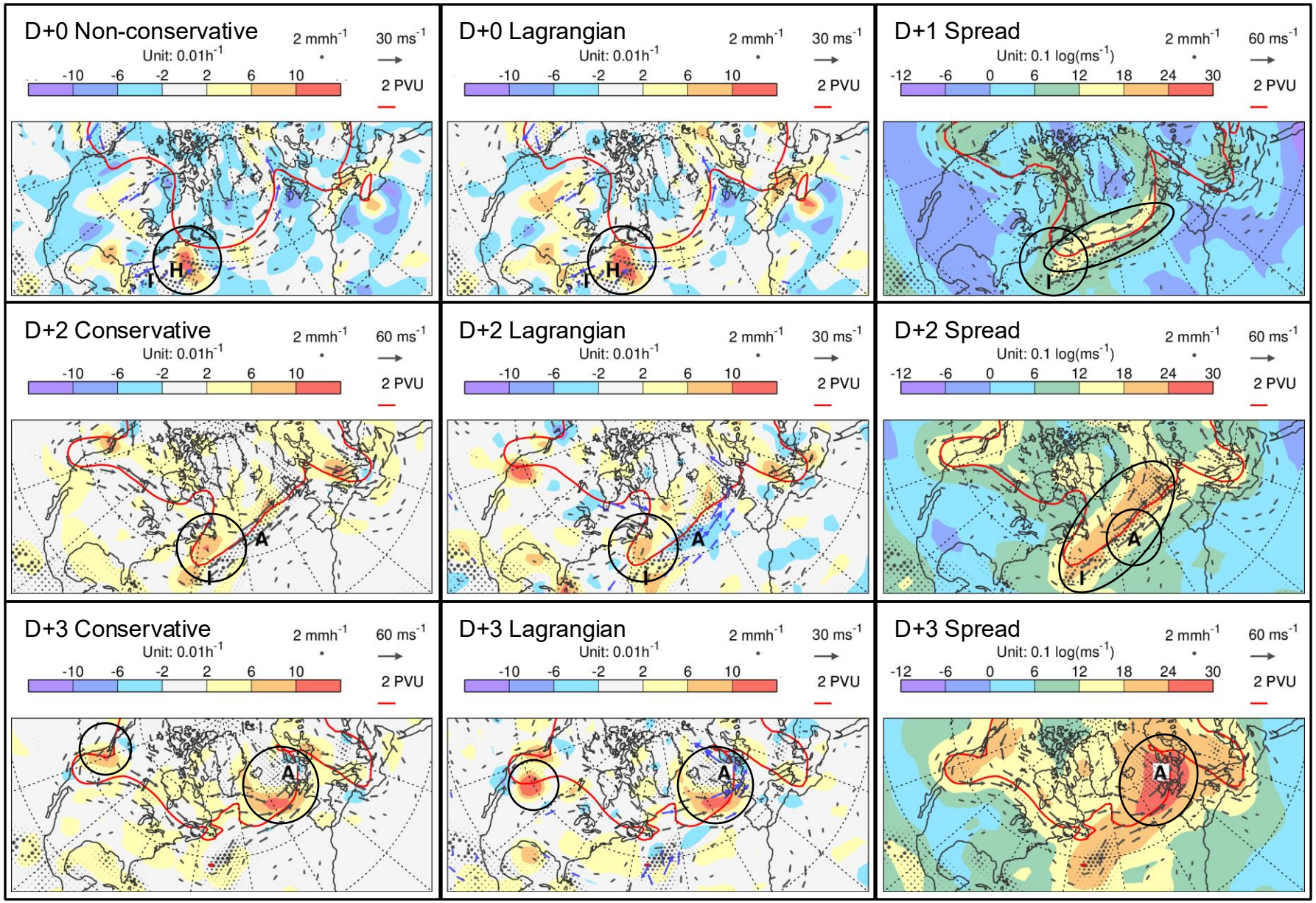
$Bias^2 \approx 0$ (important for reliability), but Residual $\gg 0$ indicates insufficient Background variance

Decomposing the Lagrangian Growth Rate in dynamical and diabatic components



Correlated tilting in mesoscale convection / tornadoes ⇒ strong spread growth ahead of trough. Conservative processes ⇒ weak growth elsewhere

Hurricane interaction with Jet stream, and extratropical storm formation



Non-conservative growth as Humberto interacts with jet (tilting?). Conservative growth in trough (cut-off potential?). Poor Amy wind forecast at D+3

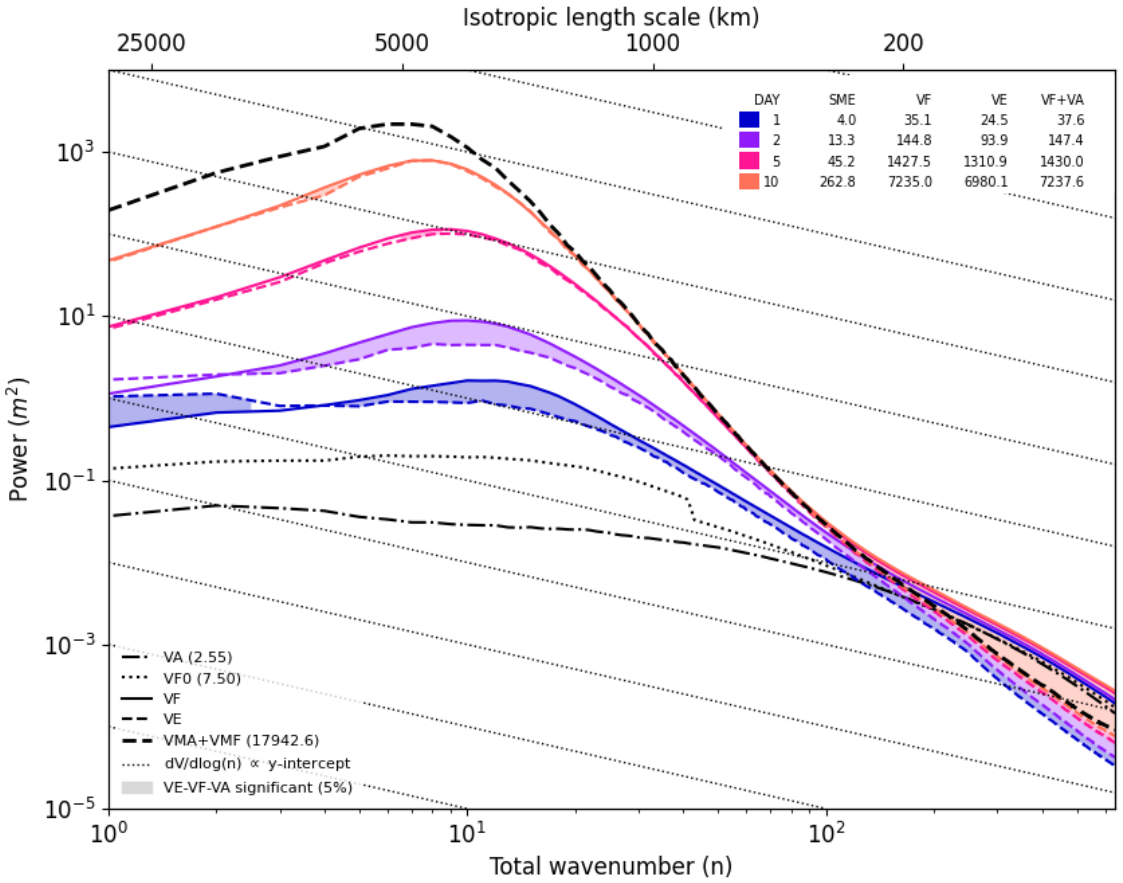
1 October 2025, 0 UTC at D+0 – D+3
Lagrangian & Non-con show v_{850}
Conservative & Spread show $\bar{v}_{330}$
Calculations at 18km, plotted at 800km

Outline

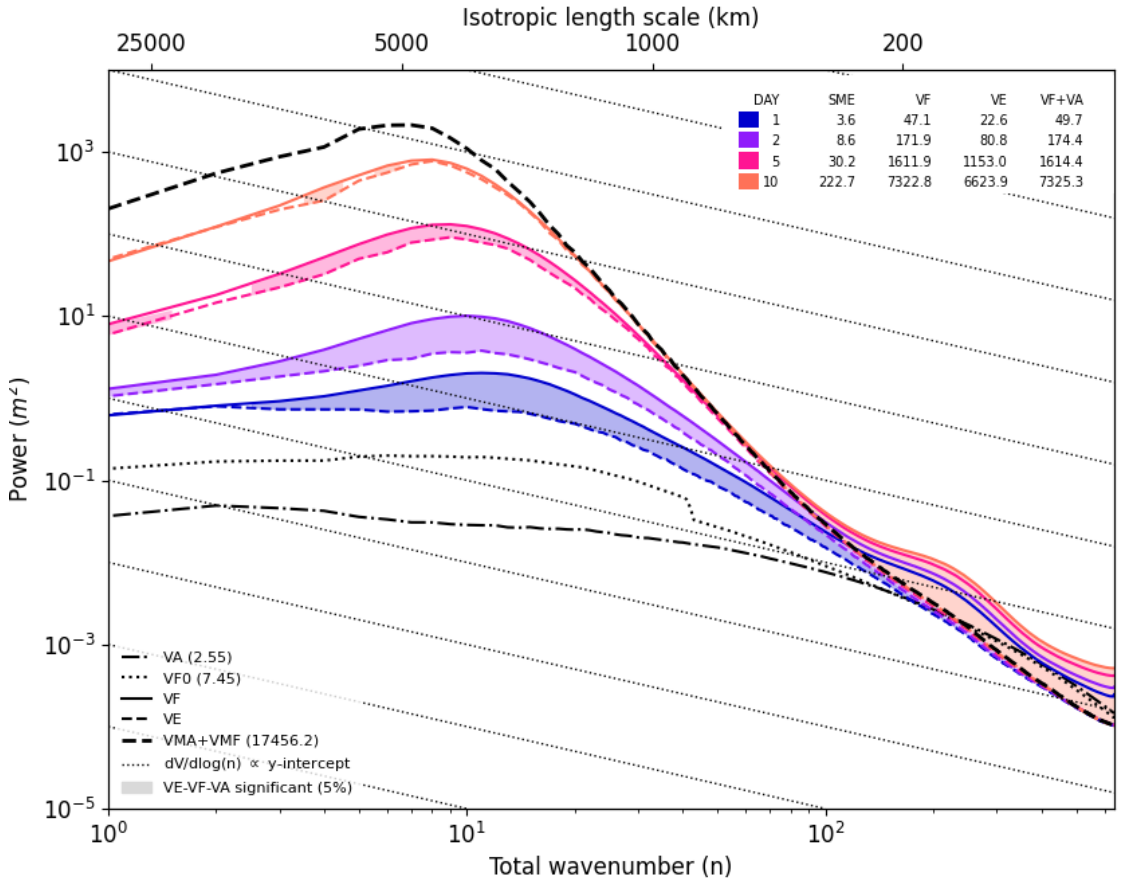
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Ensemble power spectra for physics-based (IFS) and data-driven (AIFS) ensembles

IFS



AIFS



Z250, 2026/07/18 to 2026/10/15

- The largest contribution to initial uncertainty is at scales ~500km.
- The largest contribution to forecast uncertainty grows in scale
- Uncertainty grows exponentially to start with, then asymptotes to the level of atmospheric activity
- Key diagnostic question in the age of machine learning: “Do ML models show the same sequence of growth and how are flow-dependent growth rates represented?”

Discussion

- Tropical forcing of midlatitude Rossby waves
  - Extended range predictability
- Predictability, reliability and sharpness
  - Uncertainty growth-rates for different synoptic flow-types
  - Jet stream uncertainty attribution to dynamical and diabatic processes
  - Flow-dependent reliability as a path to more skilful ensemble forecasts
- Interesting times ahead in terms of AI!