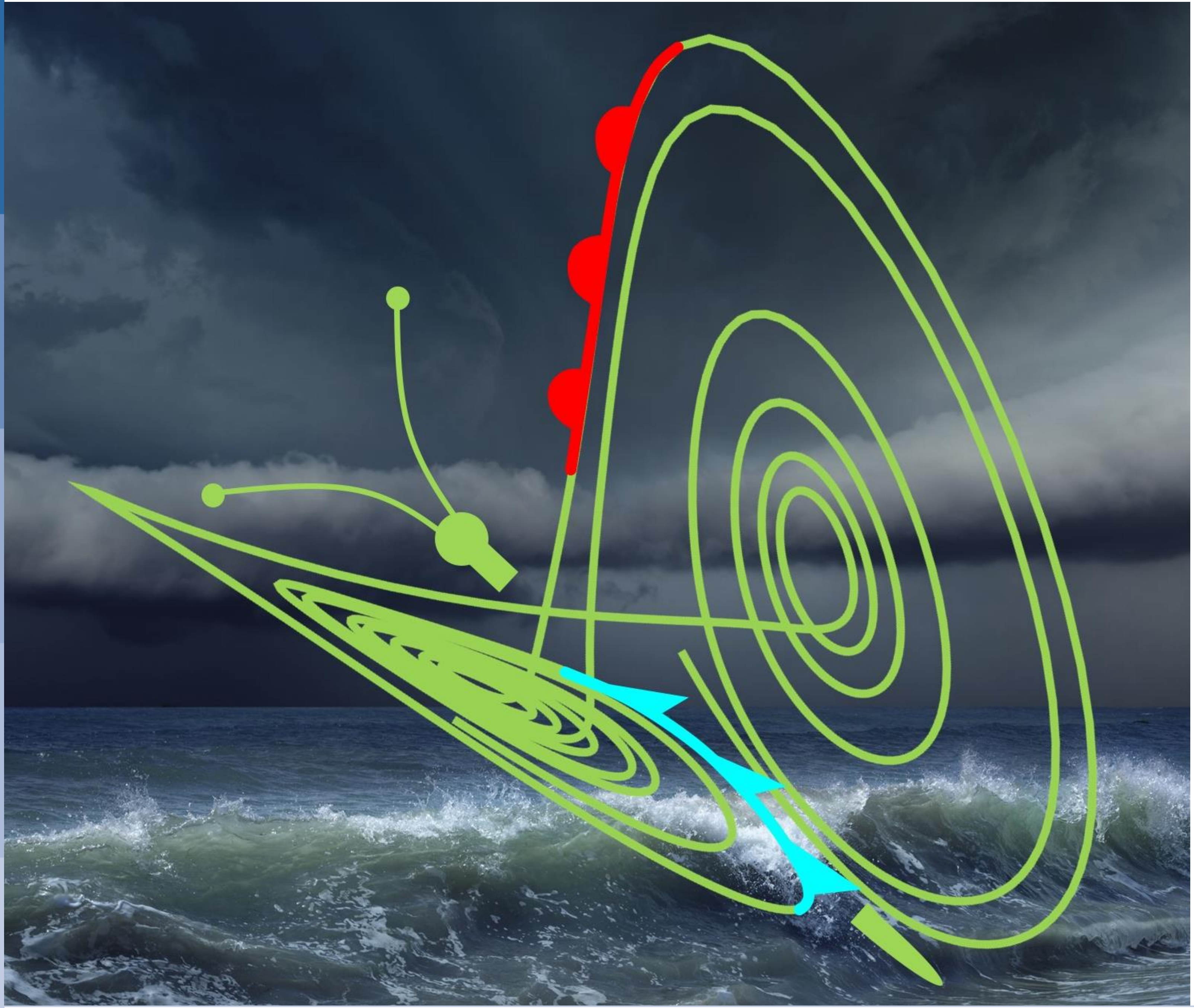

Diagnostics 2

Mark Rodwell

ECMWF Training Course on Predictability

29 November 2023, ECMWF Reading

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Discussion

- Tropical forcing of midlatitude Rossby waves
- Predictability, reliability and sharpness

Discussion

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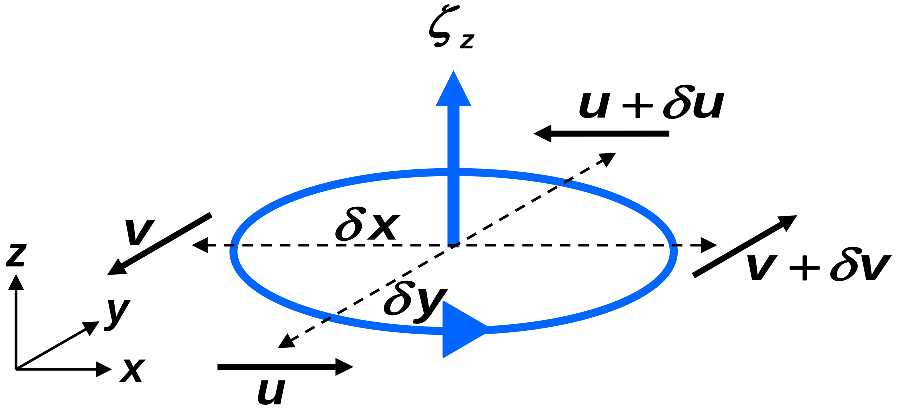
The Vorticity Equation

Motivation (2D flow) :

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

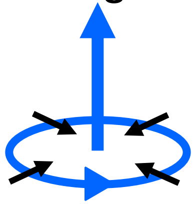
$\underline{\hat{k}}$ is the unit “vertical” vector and
$\underline{\nabla}_z \times$ is the horizontal curl operator

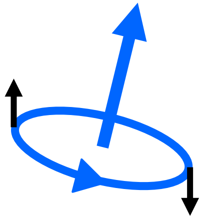


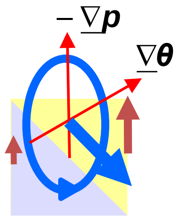
Curl of the 3D momentum equation in absolute frame of reference:

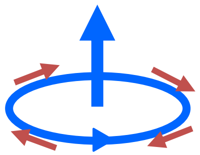
$$\frac{d\underline{\zeta}}{dt} = -\underline{\zeta}(\underline{\nabla}\cdot\underline{u}) + (\underline{\zeta}\cdot\underline{\nabla})\underline{u} + \frac{1}{\rho^2}\underline{\nabla}\rho\times\underline{\nabla}p + \underline{\nabla}\times\underline{F}_u$$

Lagrangian tendency in absolute vorticity | **Divergence** | **Tilting** | **Baroclinic** | **Friction**









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

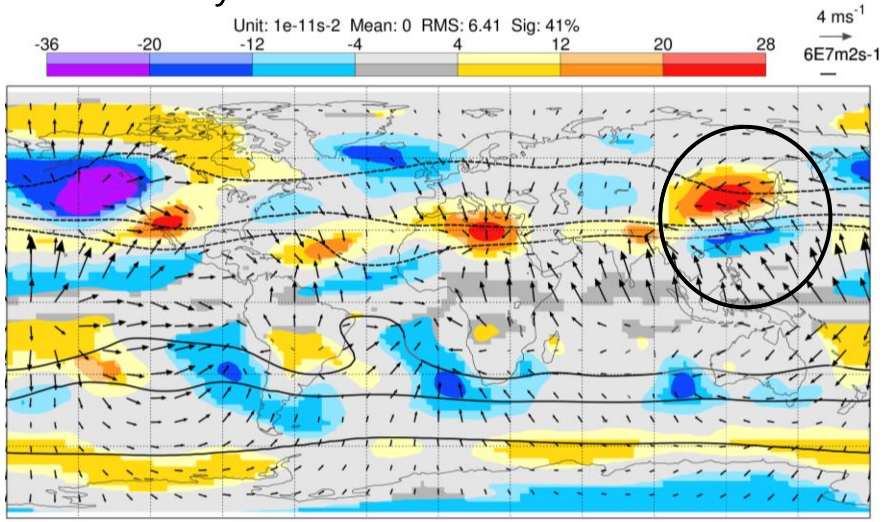
$$\frac{\partial\zeta}{\partial t} + \underline{v}_\psi\cdot\underline{\nabla}\zeta = -\underline{v}_\chi\cdot\underline{\nabla}\zeta - \zeta\underline{\nabla}\cdot\underline{v}_\chi$$

$$= -\underline{\nabla}\cdot(\underline{v}_\chi\zeta) \quad \text{"Rossby Wave Source"}$$

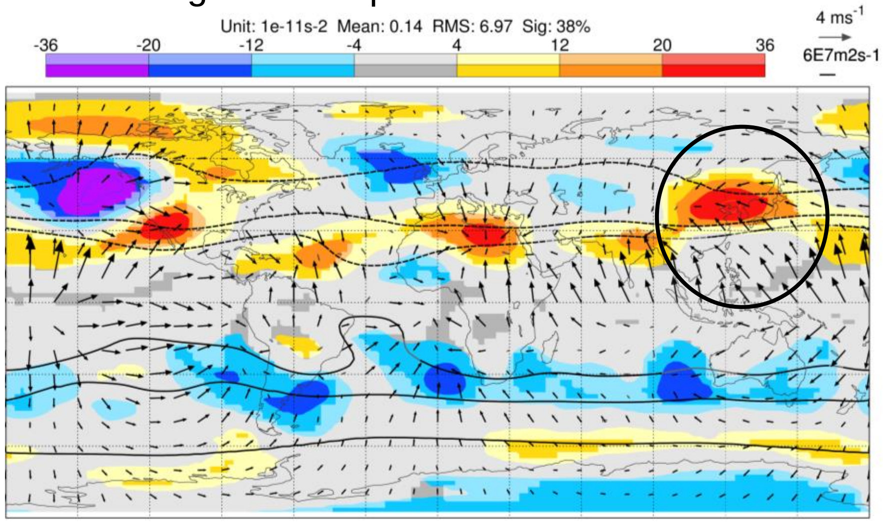
Terms in the Vorticity Equation (upper troposphere)

Shading: Terms
Contours: Streamfunction
Vectors: Divergent winds

Mean Rossby Wave Source

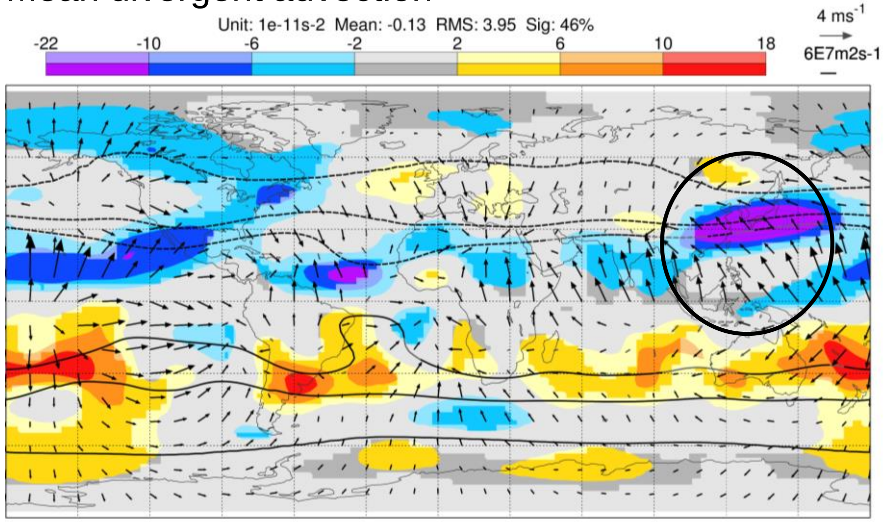


Mean divergence component



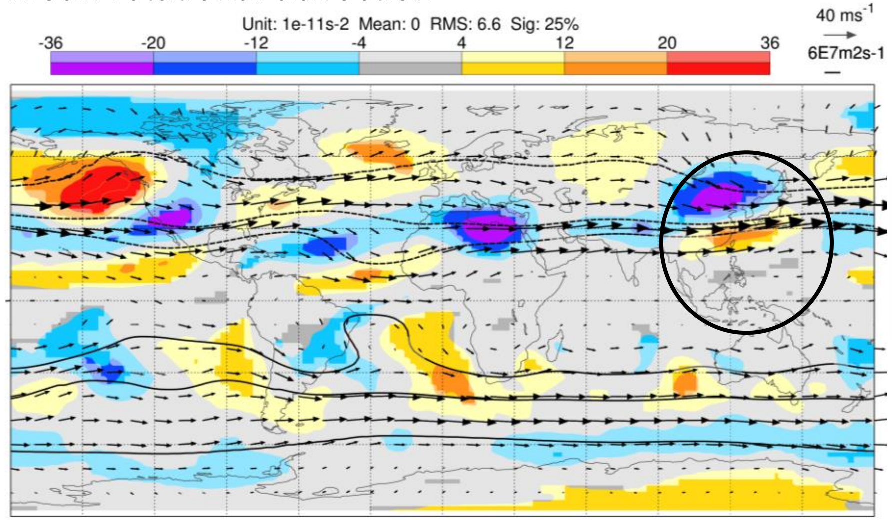
Convergence associated with “stretching”

Mean divergent advection



Advection of low planetary vorticity by divergent outflow

Mean rotational advection

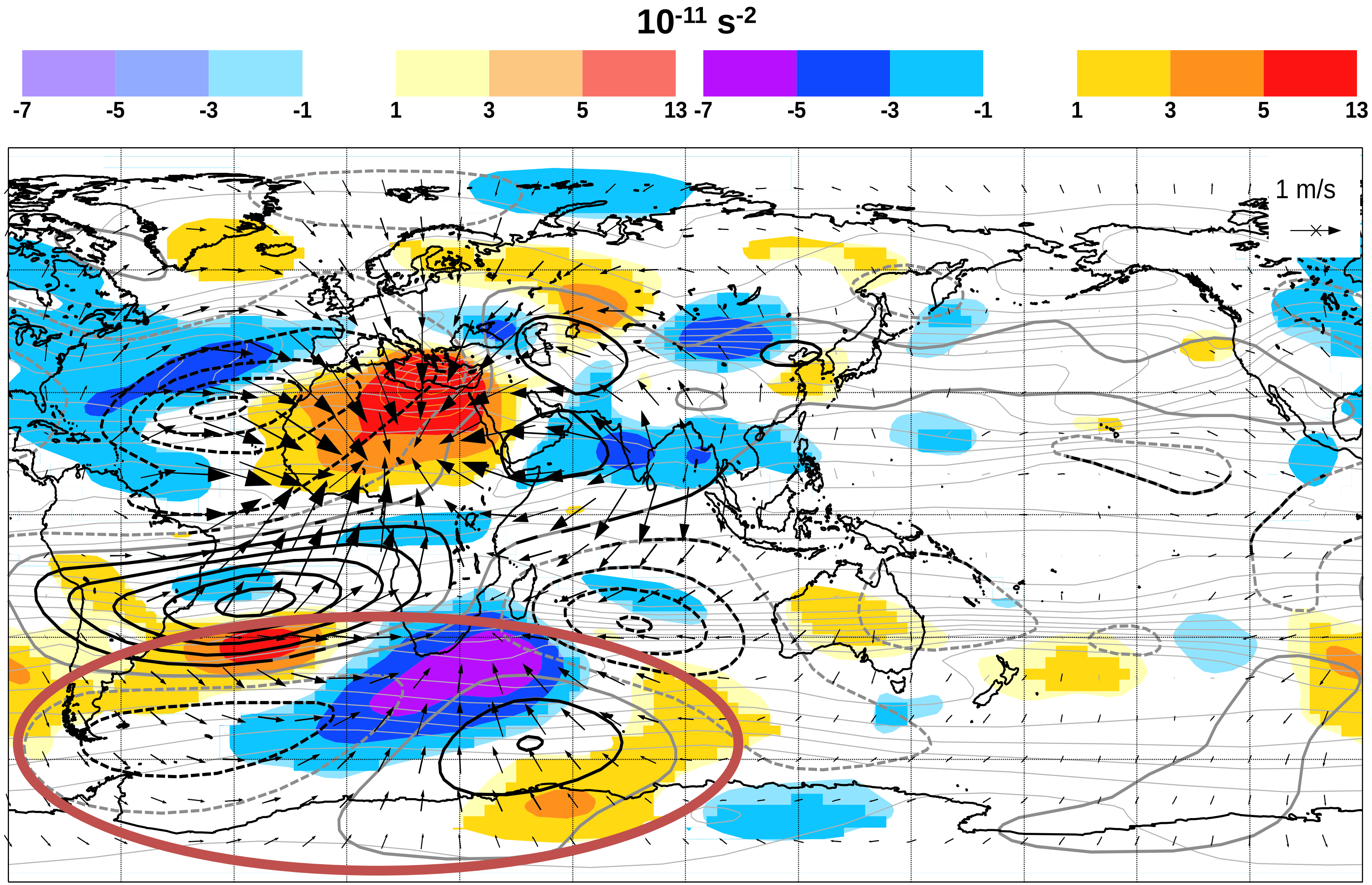


Adjustment of rotational flow balances RWS

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)

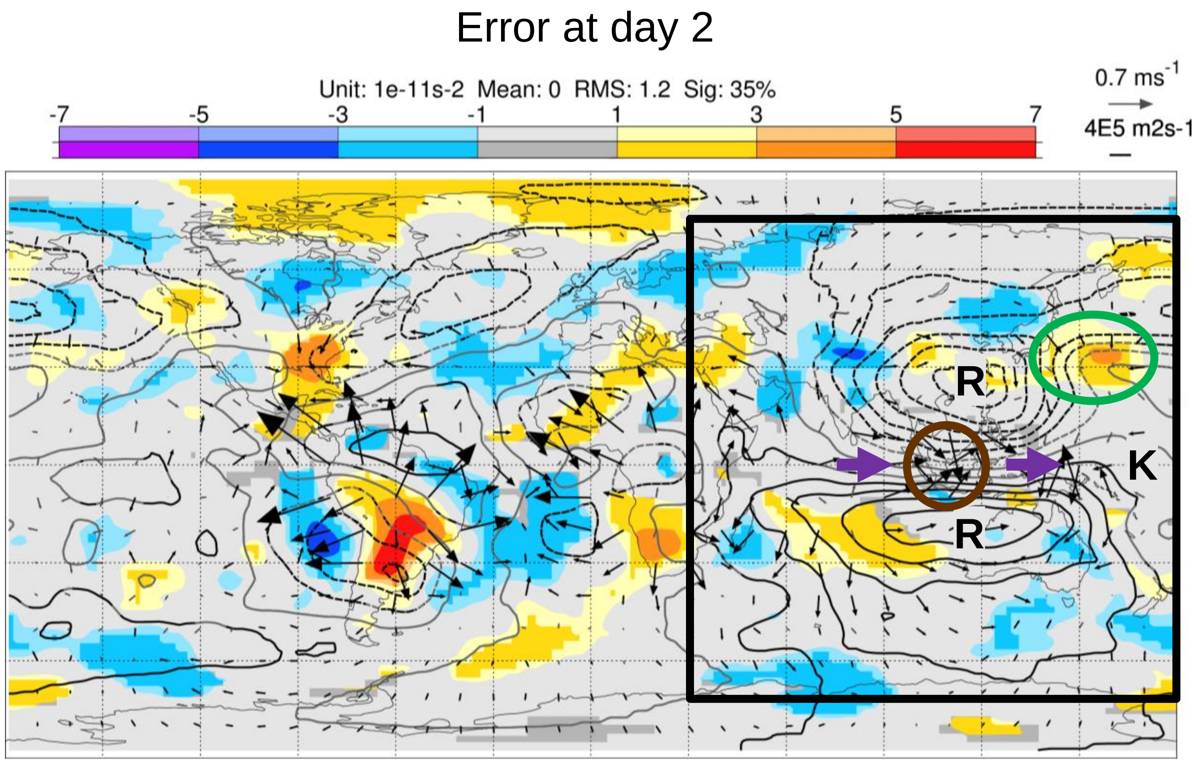


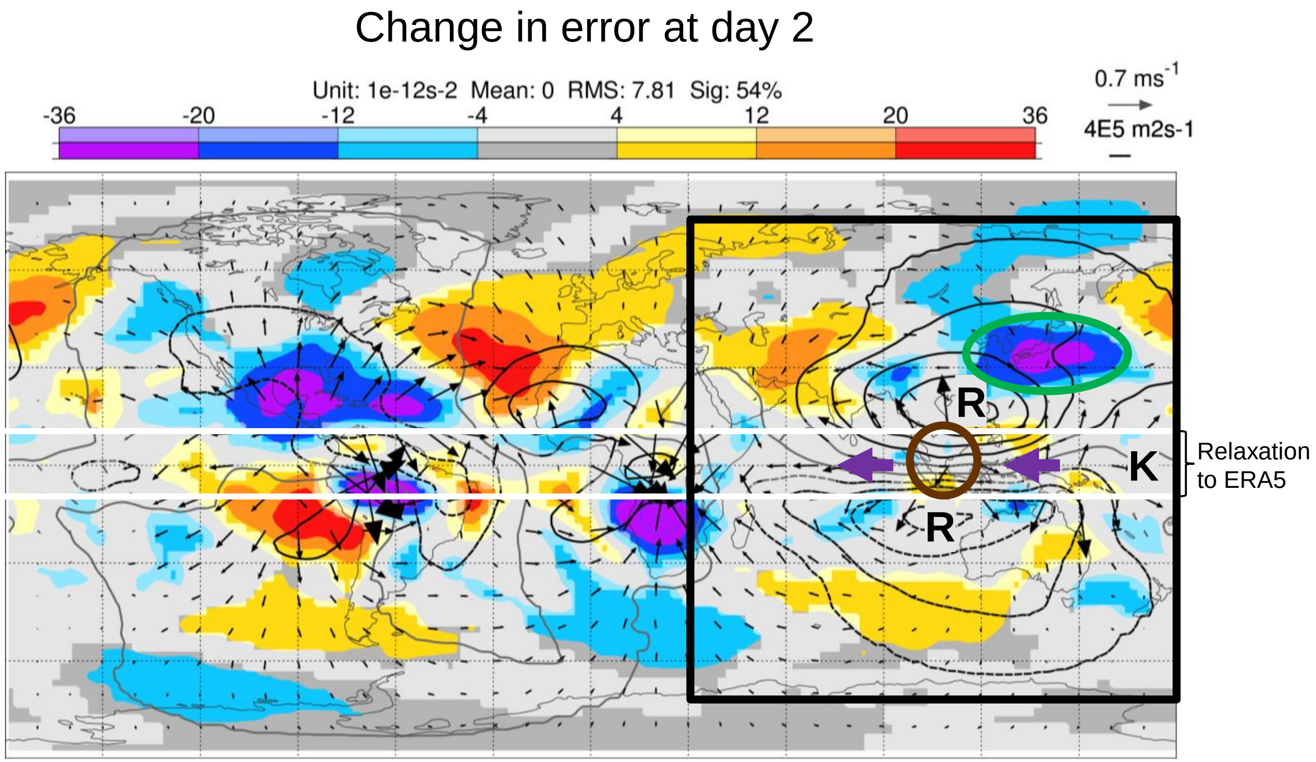
Shading: RWS
Thick contours: Streamfunction
Vectors: Divergent winds

(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 mean D+2 error, and response to tropical relaxation (nudging)





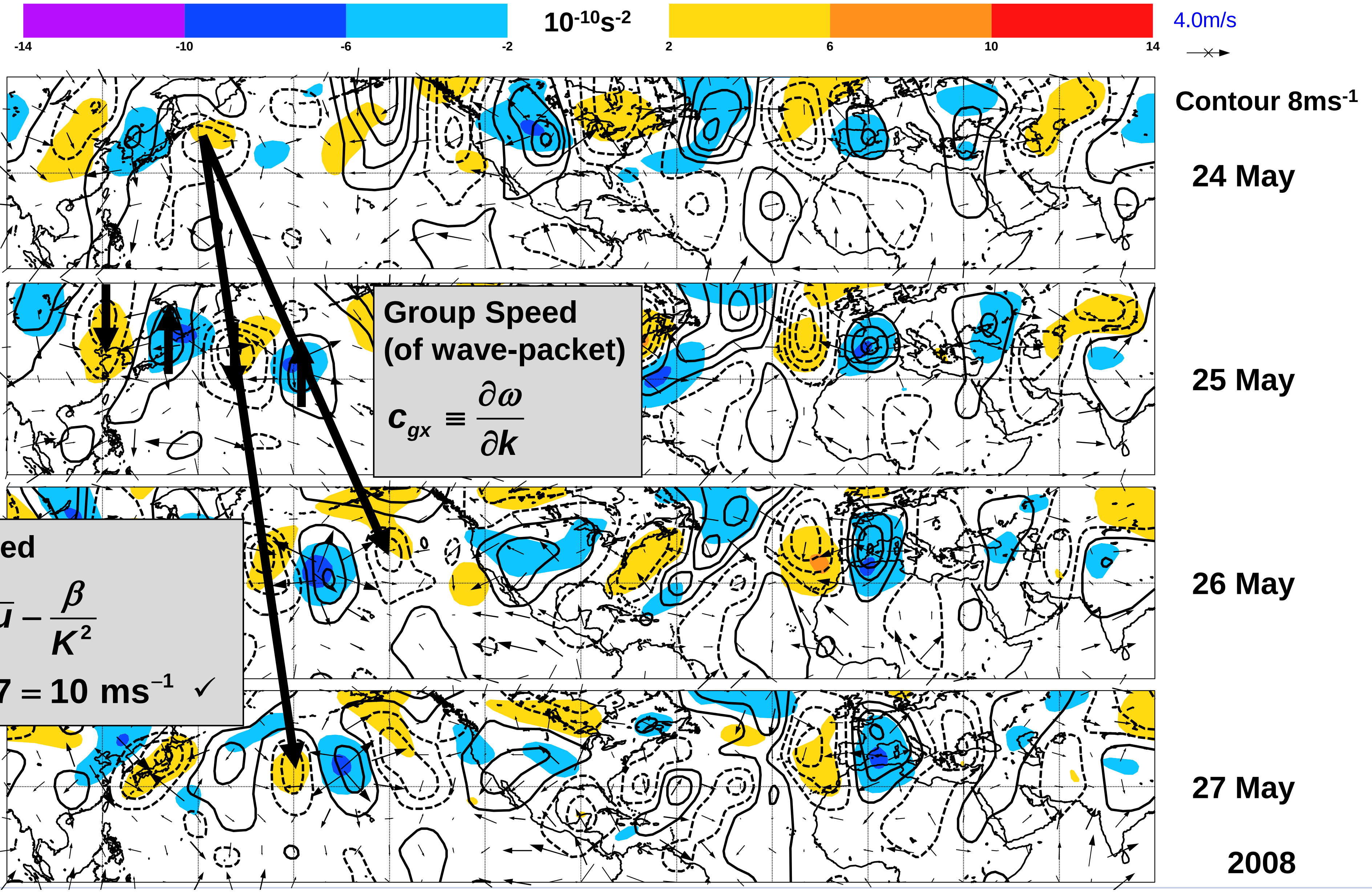
Shading: Rossby Wave Source
Contours: Streamfunction
Vectors: Divergent winds

- Convergence error over 'Warm Pool' (too little convective heating) corrected by relaxation to ERA5 between 10ºS-10ºN
- Streamfunction dipole error (equatorial Rossby Wave **R**) corrected even in the mid-latitudes
- Important improvement in Rossby Wave Forcing at head of Pacific Stormtrack?
- Also a strong reduction in tropical westerly error and Kelvin Wave error **K** to the east (not so clear here)

DJF 2000-2016 (47r1), fields integrated over upper-troposphere, relaxation is of winds and temperatures (runs by Frederic Vitart)

Extra-tropical Rossby waves

100–300 hPa
v_ψ, $\underline{v}_\chi$, RWS



Group Speed (of wave-packet)

$$c_{gx} \equiv \frac{\partial \omega}{\partial k}$$

Phase Speed

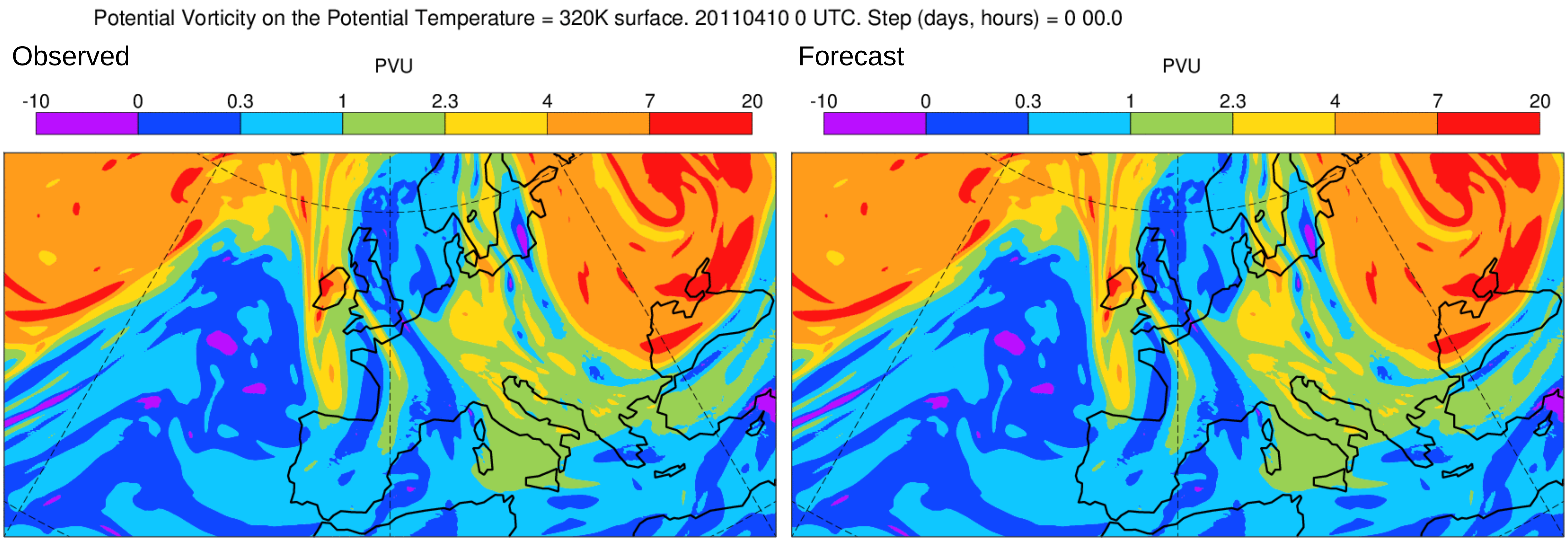
$$c_x \equiv \frac{\omega}{k} = \bar{u} - \frac{\beta}{K^2}$$

$$\approx 17 - 7 = 10 \text{ ms}^{-1} \quad \checkmark$$

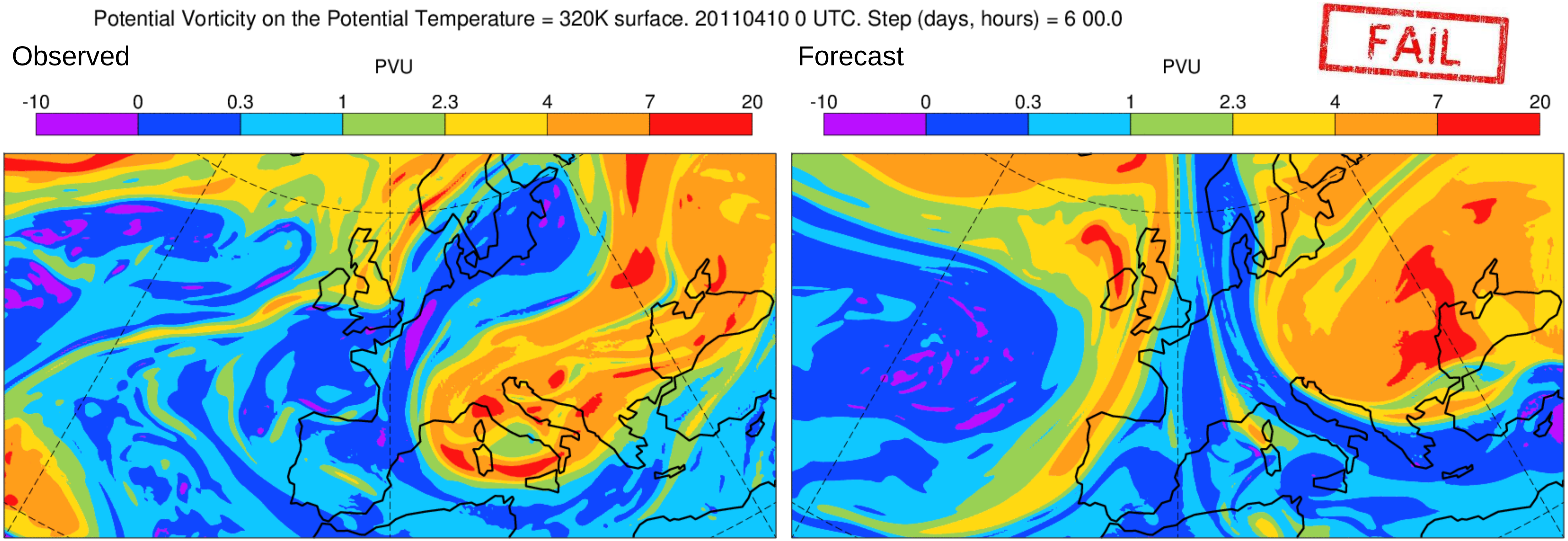
Discussion

- Tropical forcing of midlatitude Rossby waves
- Predictability, reliability and sharpness

Animation of a very poor medium-range single forecast



Animation of a very poor medium-range single forecast

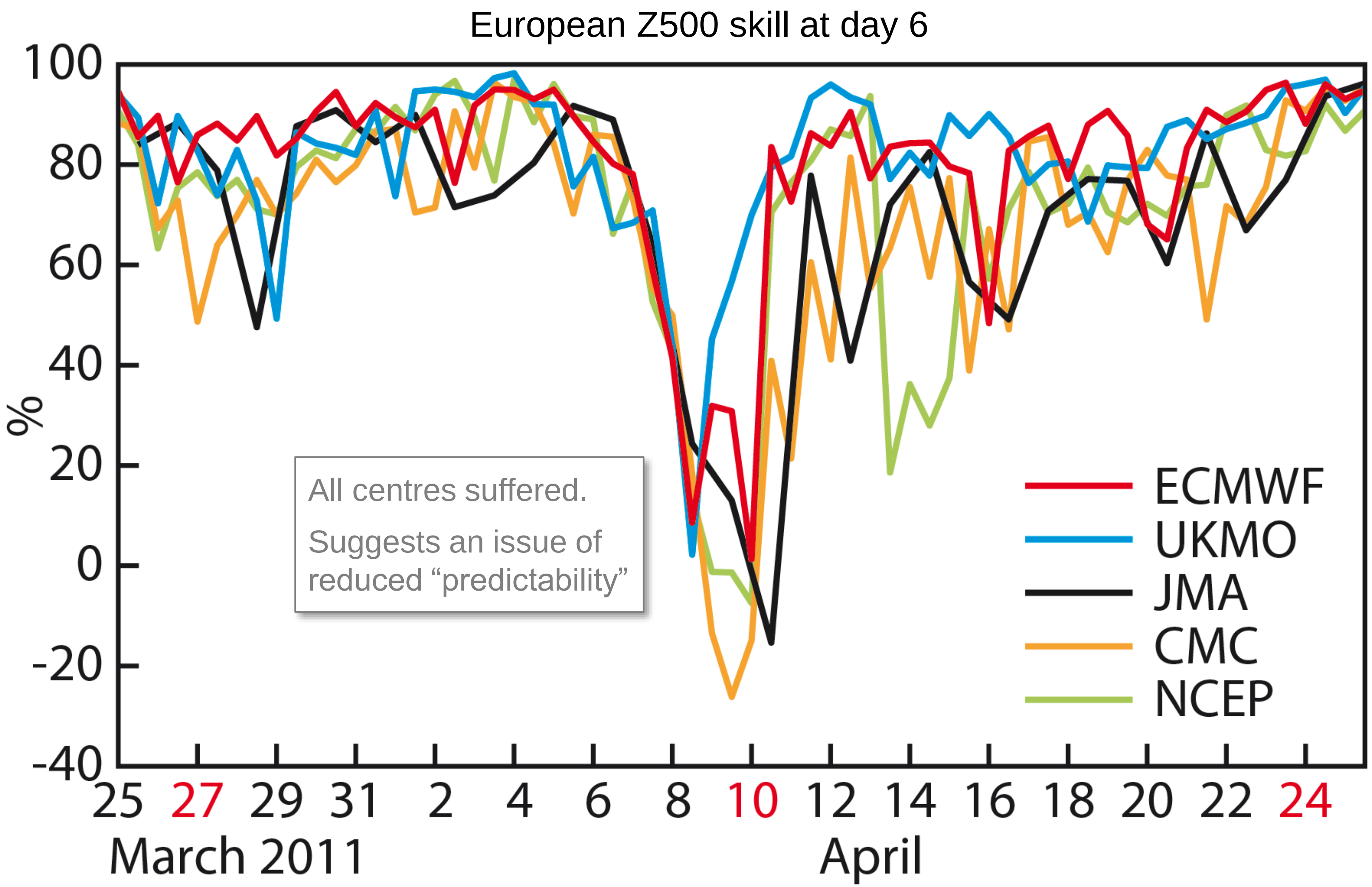


We see the mixing of air masses. The eventual block (high pressure) over Northern Europe is not well predicted

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

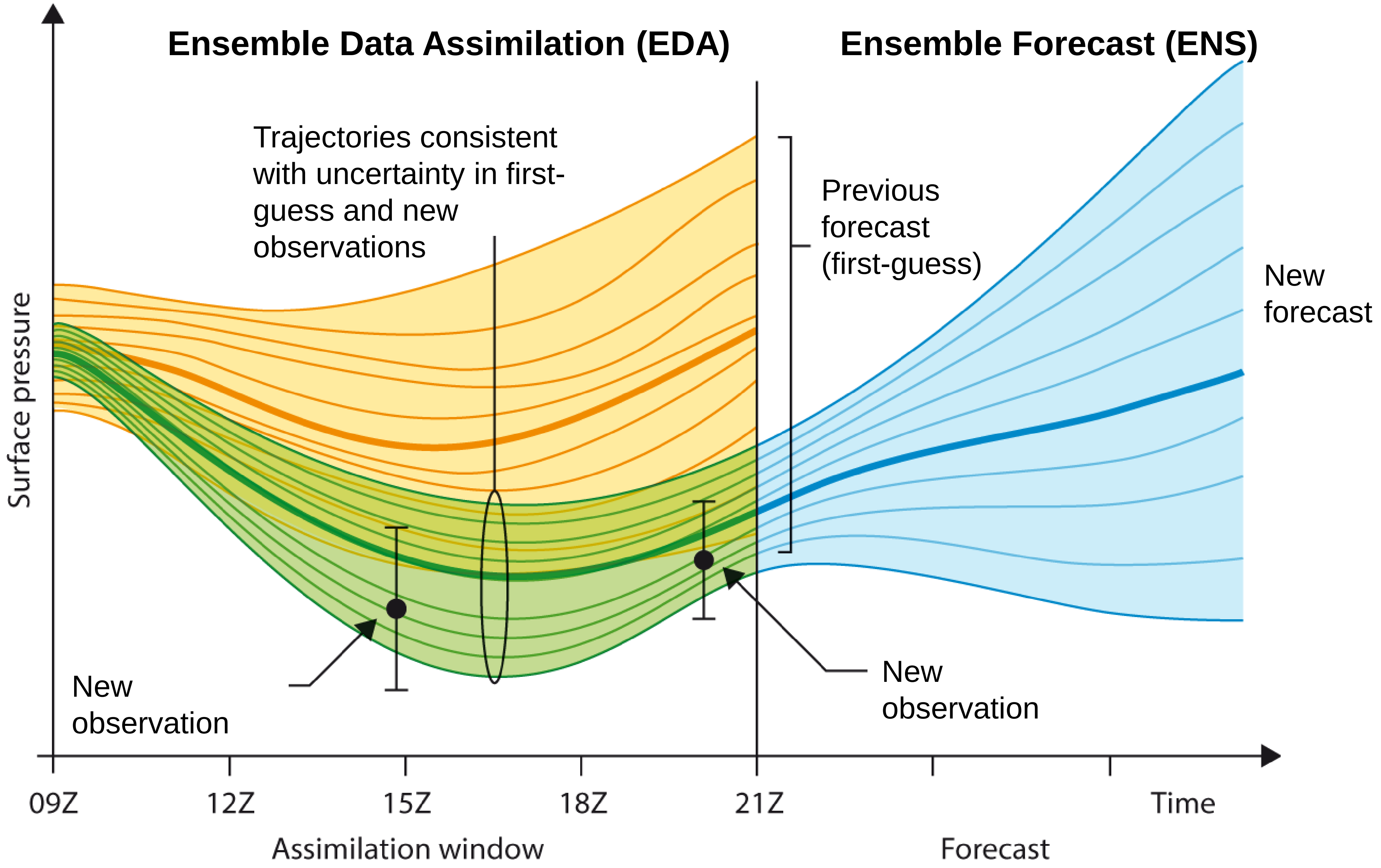


Spatial Anomaly Correlation Coefficient for 500 hPa geopotential height in [12.5ºW –42.5ºE, 35ºN–75ºN]. Date is forecast start

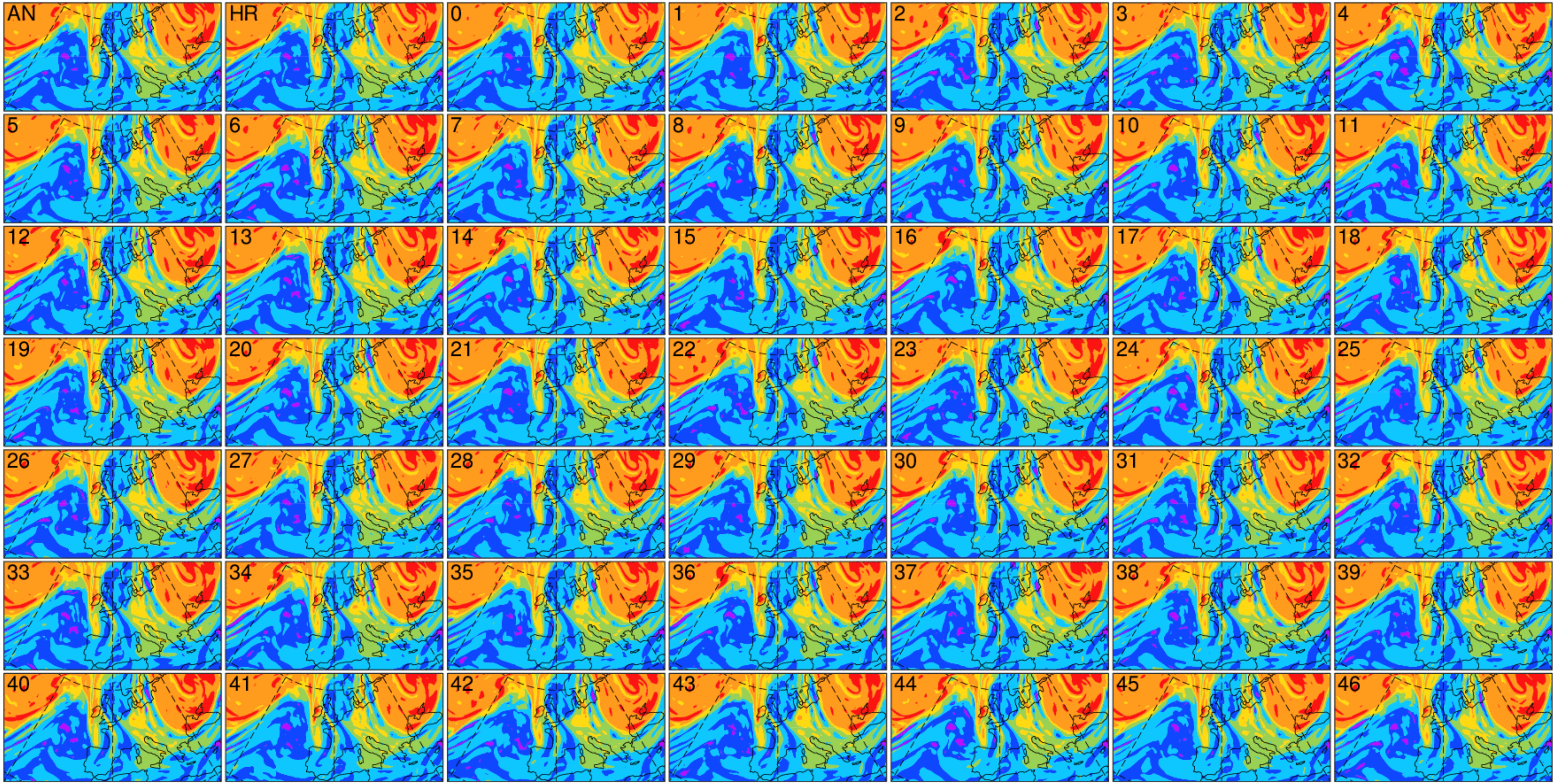
Traditional Ensemble Weather Prediction (ECMWF)

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

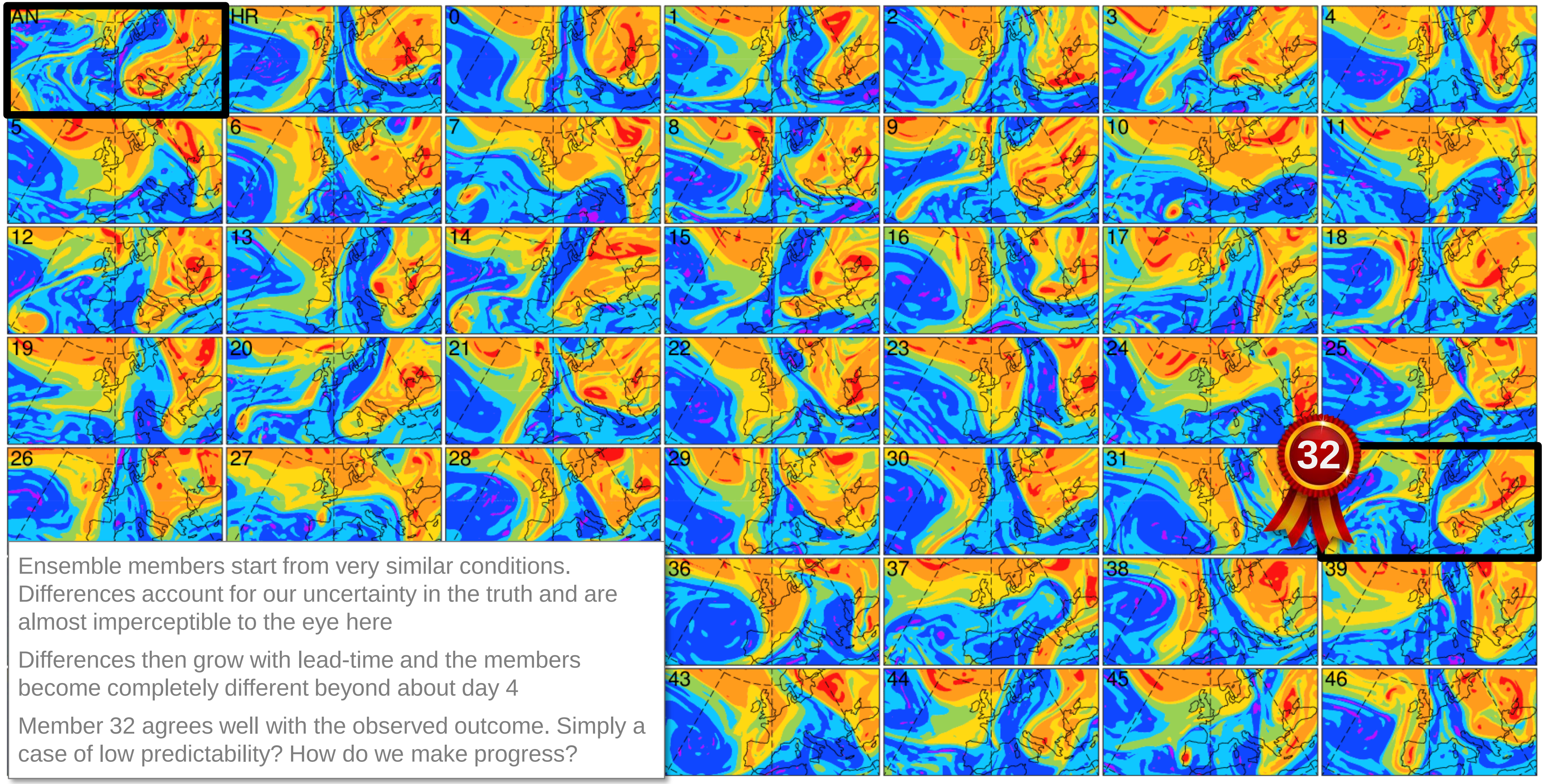
ENS spread arises from chaotic growth of EDA uncertainty, model uncertainty and singular vector perturbations



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

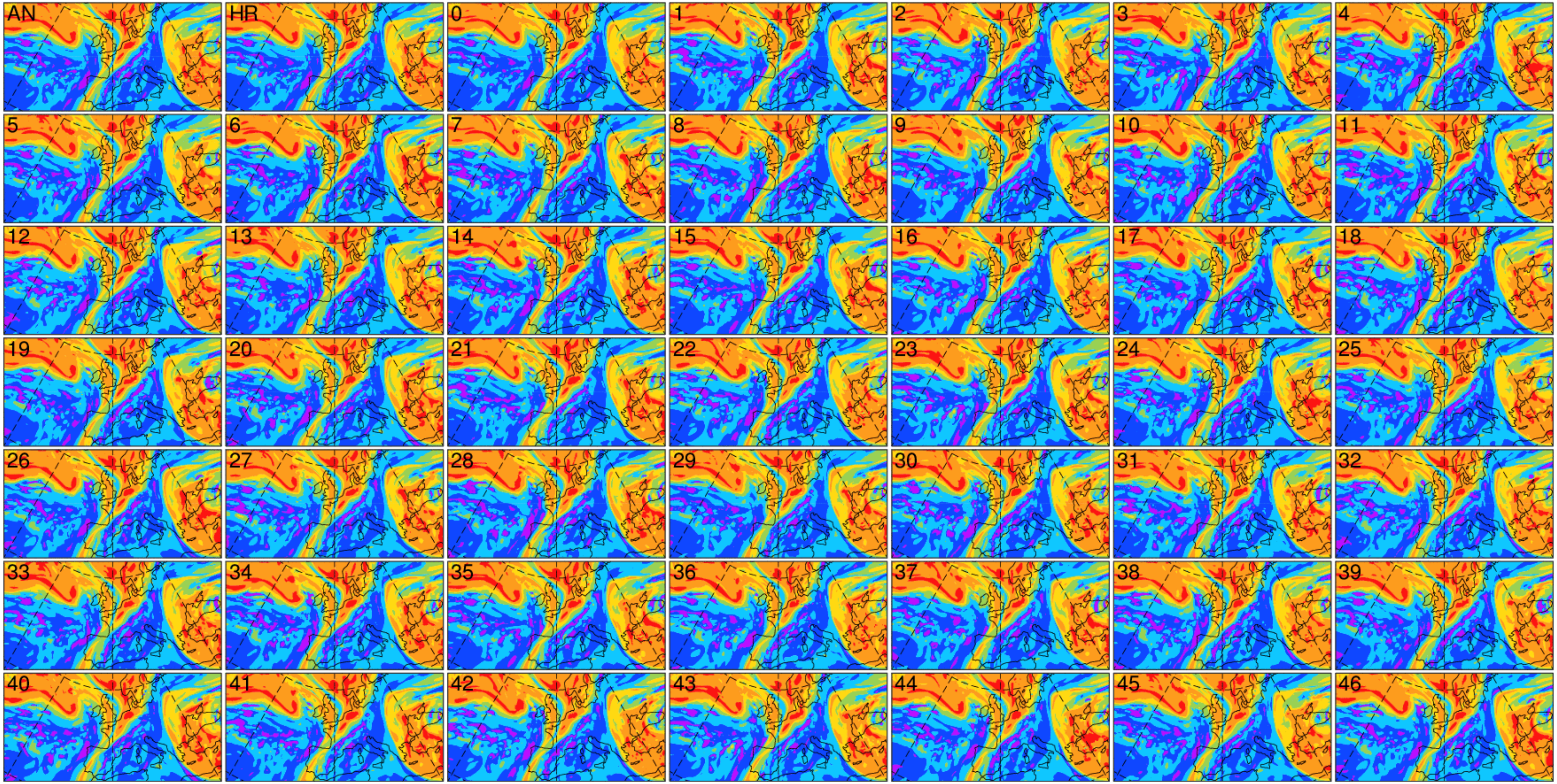


Ensemble members start from very similar conditions. Differences account for our uncertainty in the truth and are almost imperceptible to the eye here

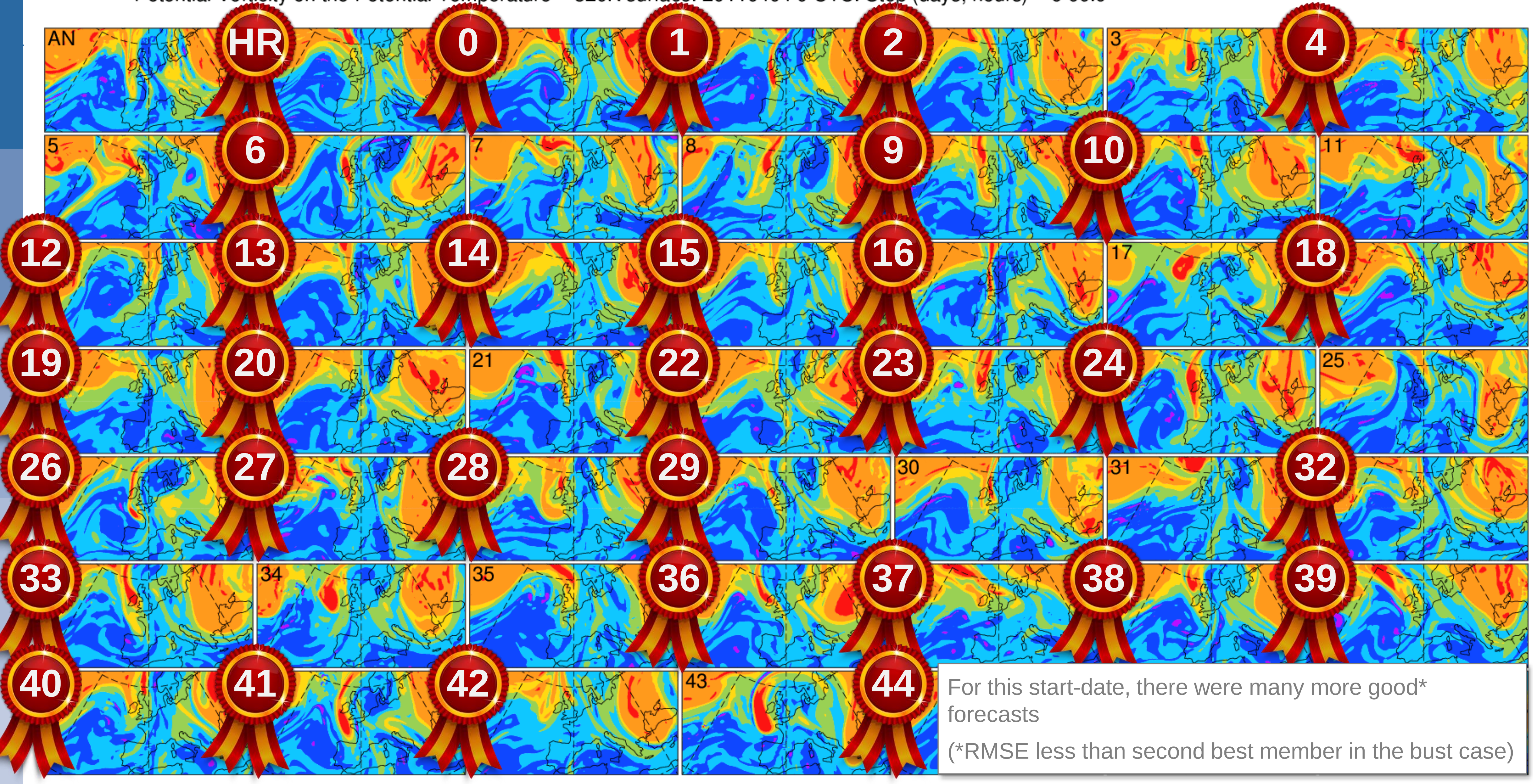
Differences then grow with lead-time and the members become completely different beyond about day 4

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



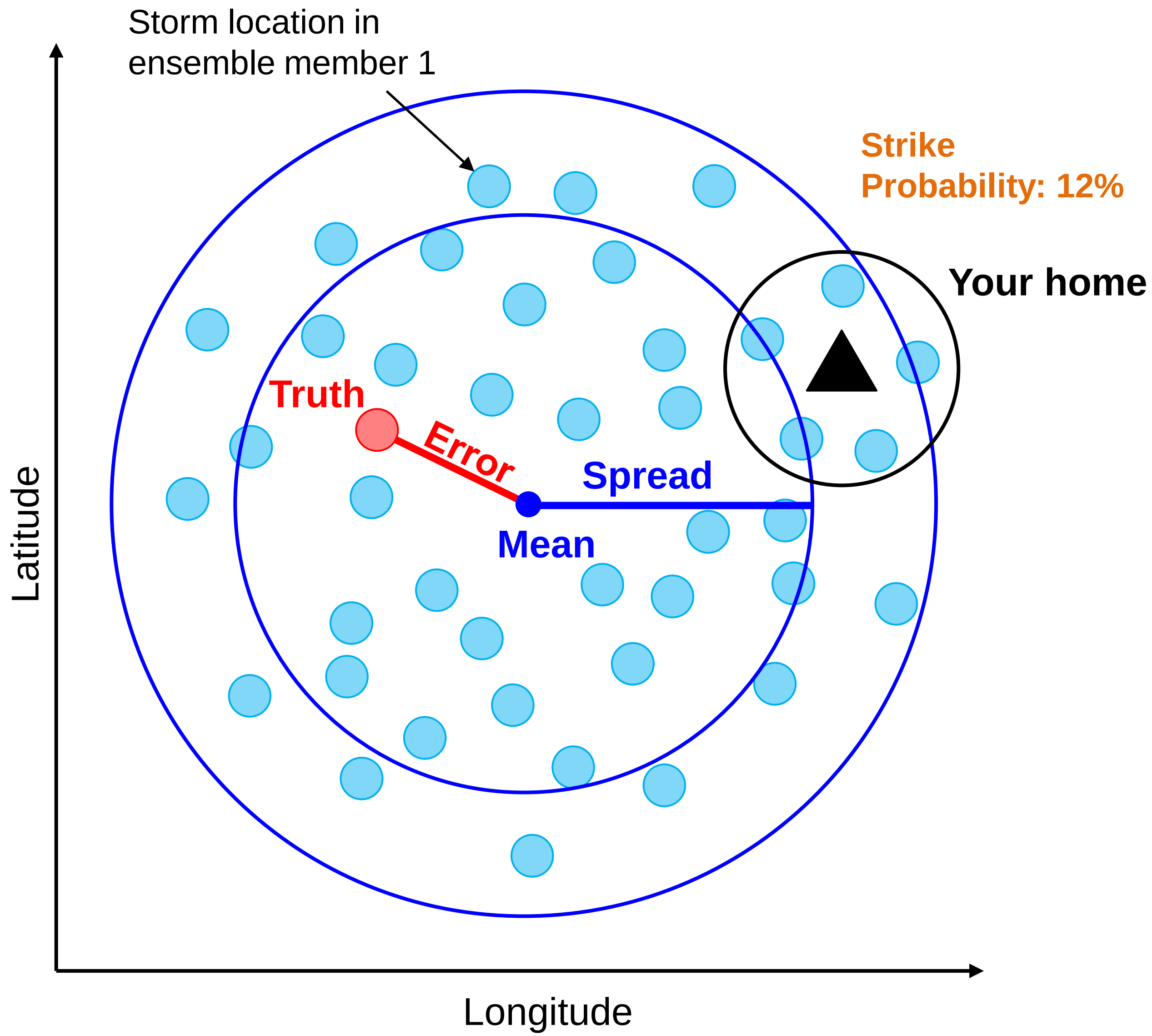
Potential Vorticity on the Potential Temperature = 320K surface. 20110404 0 UTC. Step (days, hours) = 6 00.0



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

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

The aims of 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

Ensemble spread and error

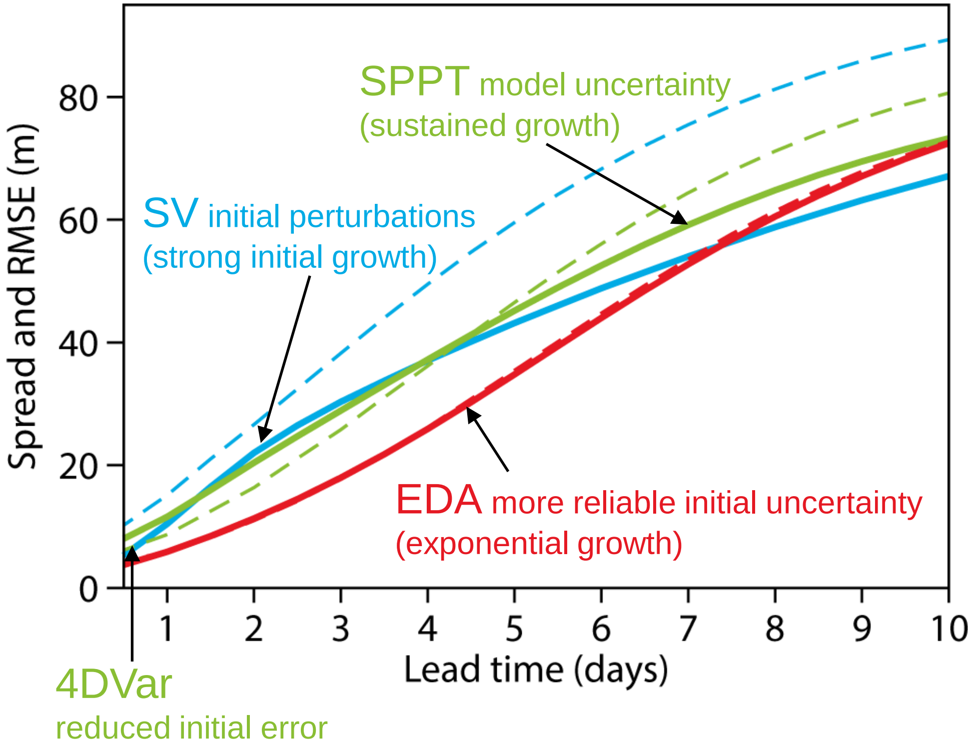
Z500

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

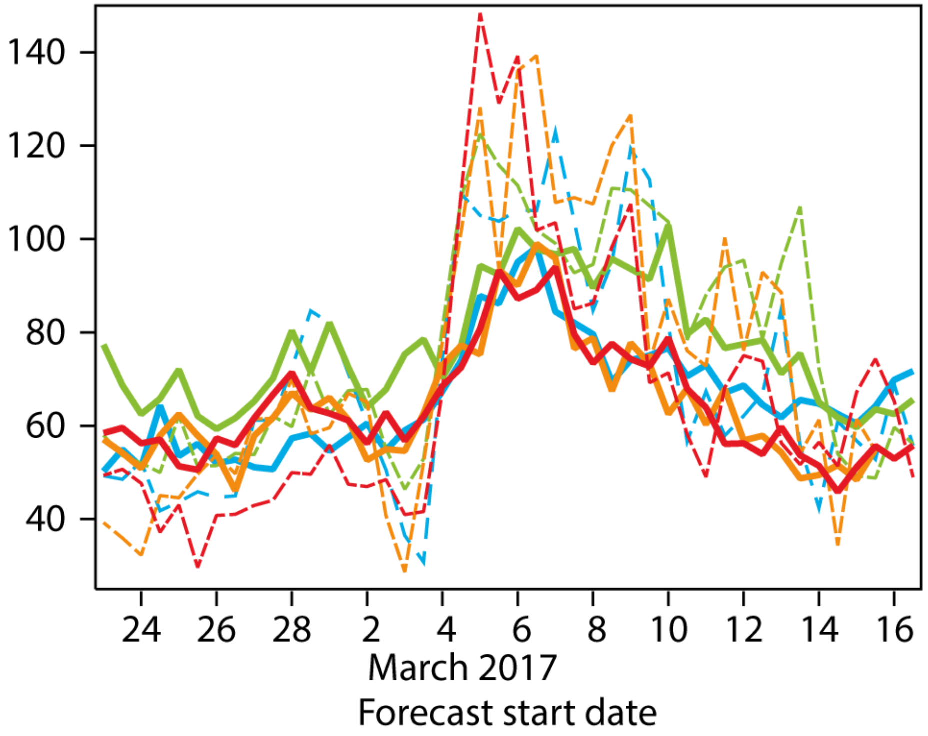
…but we make ensemble forecasts to represent the day-to-day variations in predictability and uncertainty. Can we evaluate it in our forecasts?

Annual means N.Hem. (ECMWF)



	1996	2005	2014
Spread	— (blue)	— (green)	— (red)
Error	- - - (blue)	- - - (green)	- - - (red)

Timeseries for Europe at D+6 (TIGGE)



	ECMWF	UKMO	JMA	NCEP
Spread	— (red)	— (orange)	— (green)	— (blue)
Error	- - - (red)	- - - (orange)	- - - (green)	- - - (blue)

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

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

Power Spectra view of the EDA and ENS: Z250 DJF 2023

Largest variance contributions

EDA: 500 – 3000 km

D+0: 1000 – 4000 km

D+1: ~3500 km

D+2: ~4000 km

D+5: ~4500 km

D+10: ~5000 km

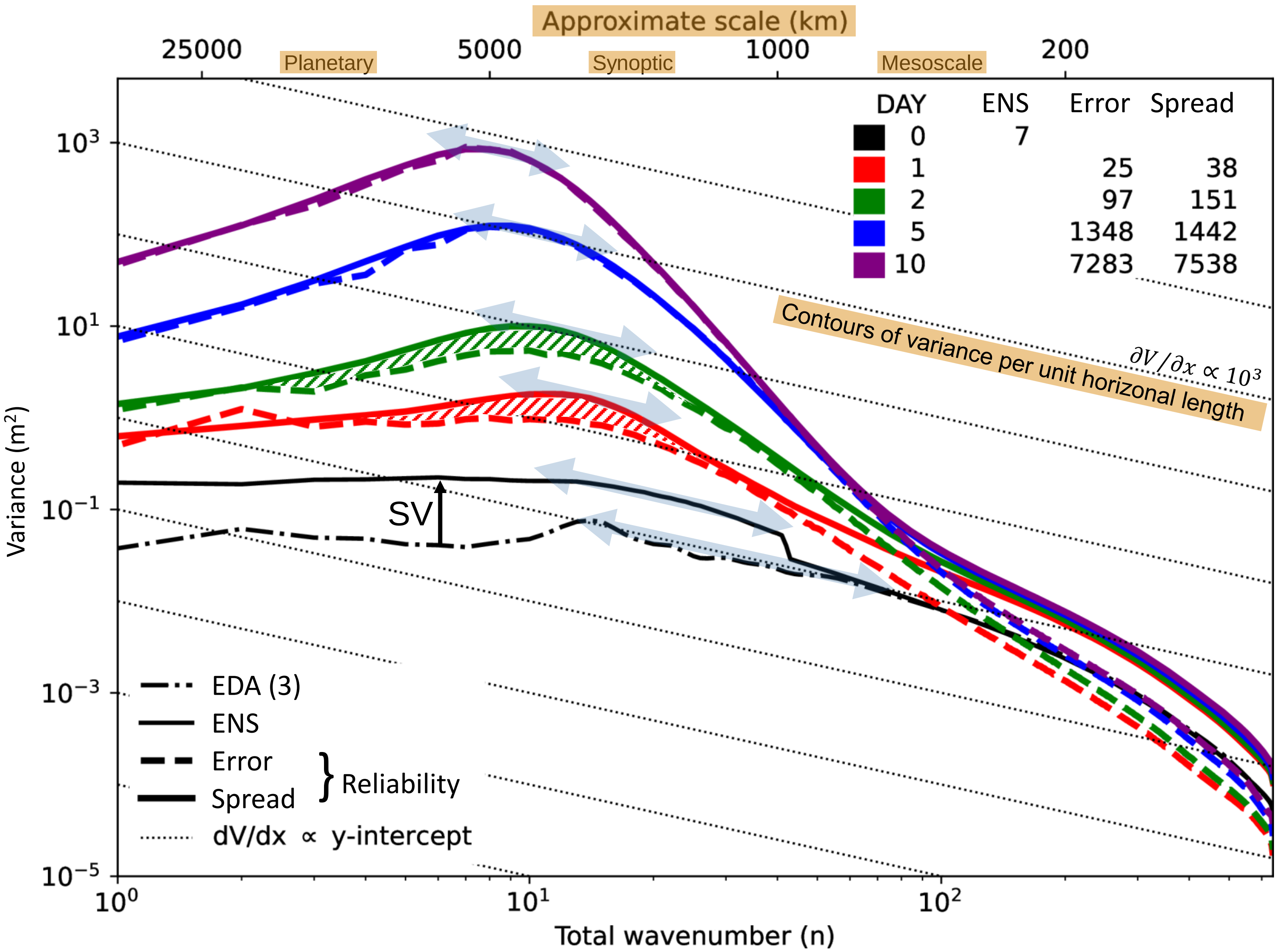
Logarithmic y-axis emphasizes important "exponential growth"

A lot of the eventual skill relies on the seemingly small details of the initialization

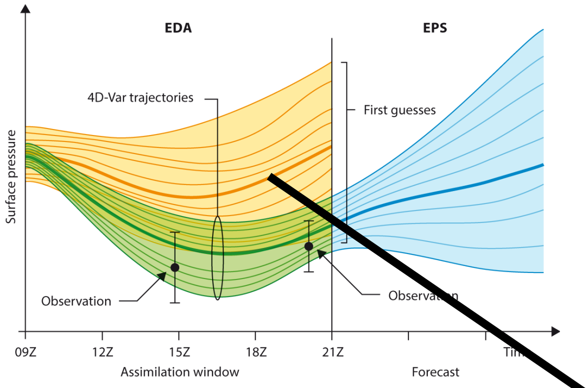
Singular vectors double the initial variance

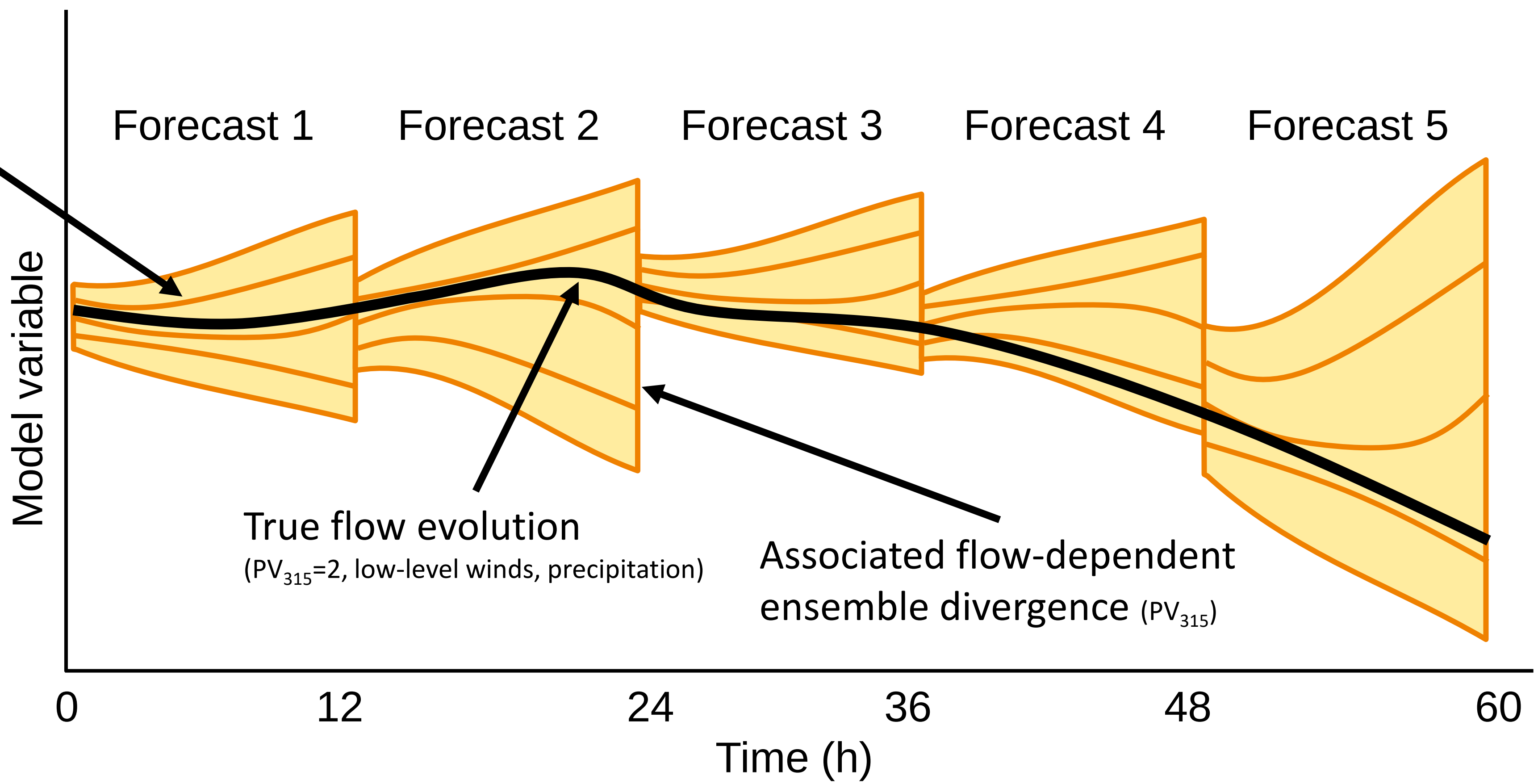
ENS is currently over-spread at D+1 & 2 (compared to the errors)

Important to understand synoptic-scale uncertainty growth at short lead-times



Animating the true evolution of the flow and associated ensemble divergence





Can animate the shadow trajectory and super-impose uncertainty growth-rates – Focus on synoptic scales as these contribute most to initial growth

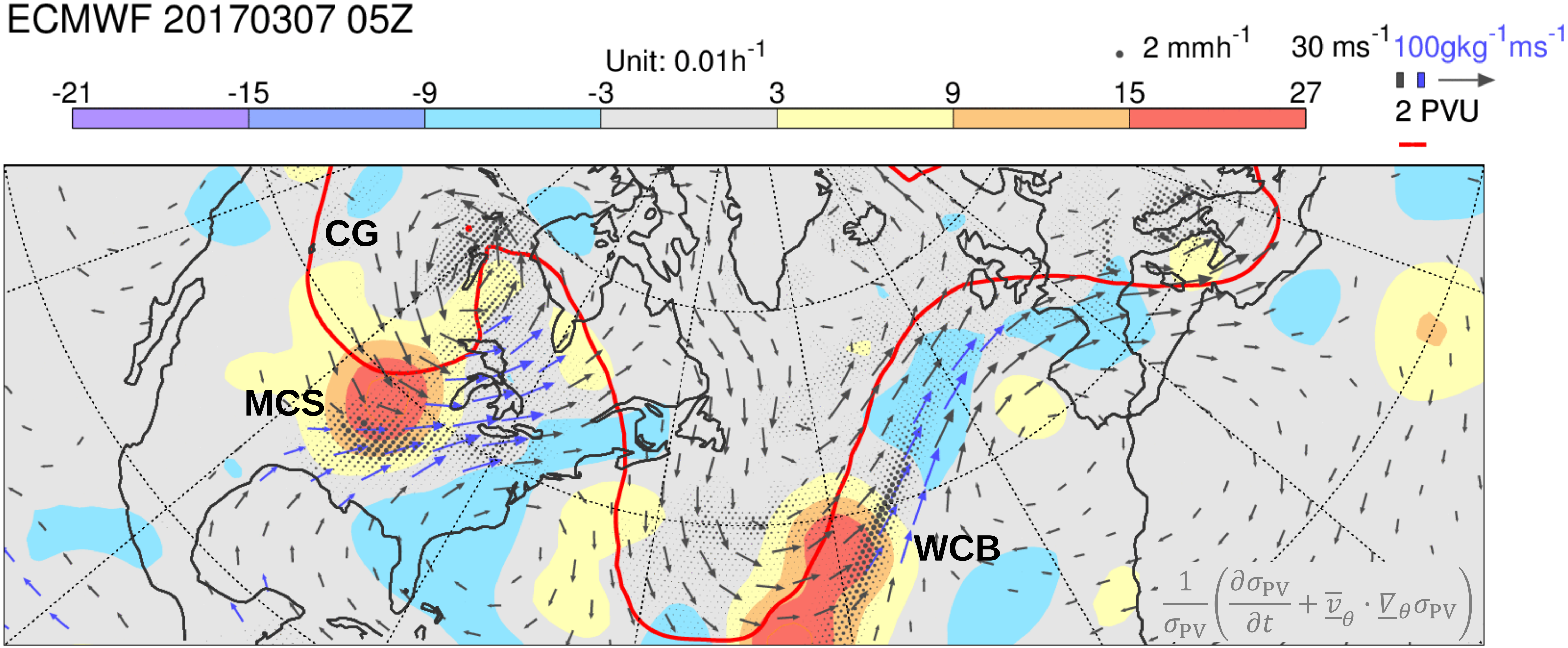
Animation of analysed circulation and corresponding EDA background divergence

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

Aim: Evaluate short-range synoptic flow-dependent representation of uncertainty

Is sensitivity to moist processes real or due to deficiencies in model uncertainty representation?



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)*

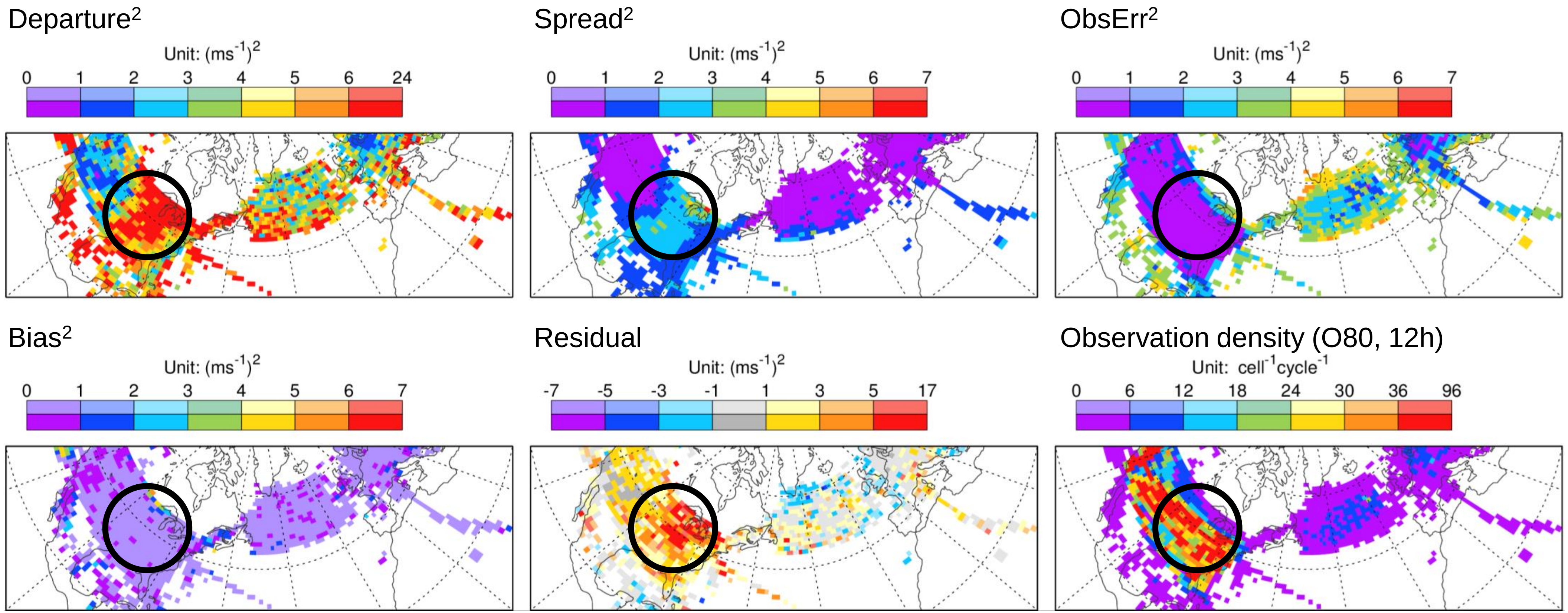
EDA reliability in u_{200} against aircraft observations in MCS situations

Rodwell et al. 2018, BAMS

For more operational diagnostics, see the [Diagnostics Explorer]

$\text{Departure}^2 = \text{Spread}^2 + \text{ObsErr}^2$ (+ Bias^2 + Residual)

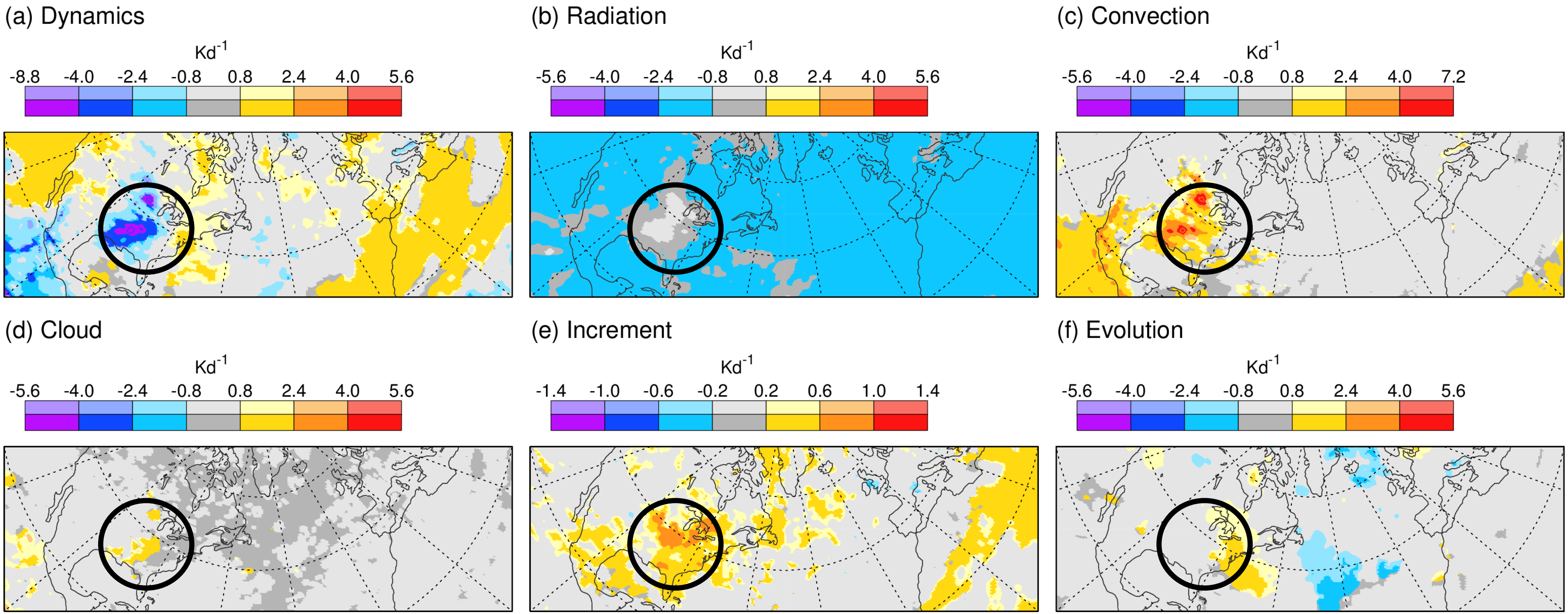
54 cases, 12h window



Enhanced spread (Background variance) in Great Lakes / Mississippi River region
Even larger Departures^2 of the ensemble-mean from the observations ensue
$\text{Bias}^2 \approx 0$ (important for reliability), but Residual $\gg 0$ indicates insufficient Background variance

Uncertain forecasts for Europe may still be over-confident

EDA unperturbed initial tendency budget for T300 in MCS situations



Budget: **Evolution = Dynamics + Radiation + Convection + Cloud micro-physics + analysis Increment** 54 cases, 12h window

Shows how the model represents dynamics and physics of MCS

Positive (and statistically significant) increment suggests that the background forecast is too cold near the top of the convection

The Jetstream and mesoscale convection: “The piano string and hammer”

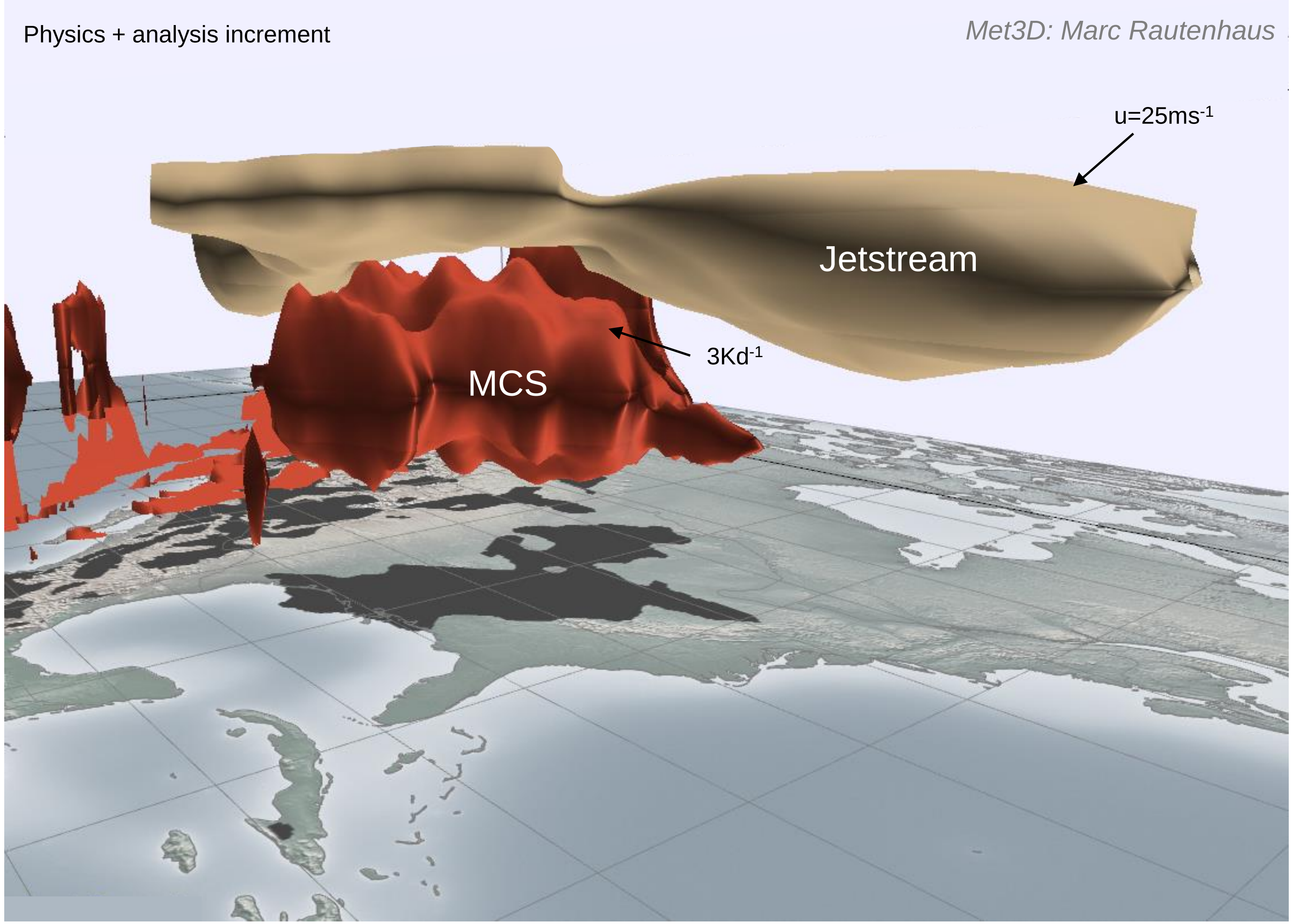
54 cases

If we don’t hit the string hard enough, the wave in the string will be too weak

If we hit the string at the wrong time, the wave will arrive over Europe at the wrong time

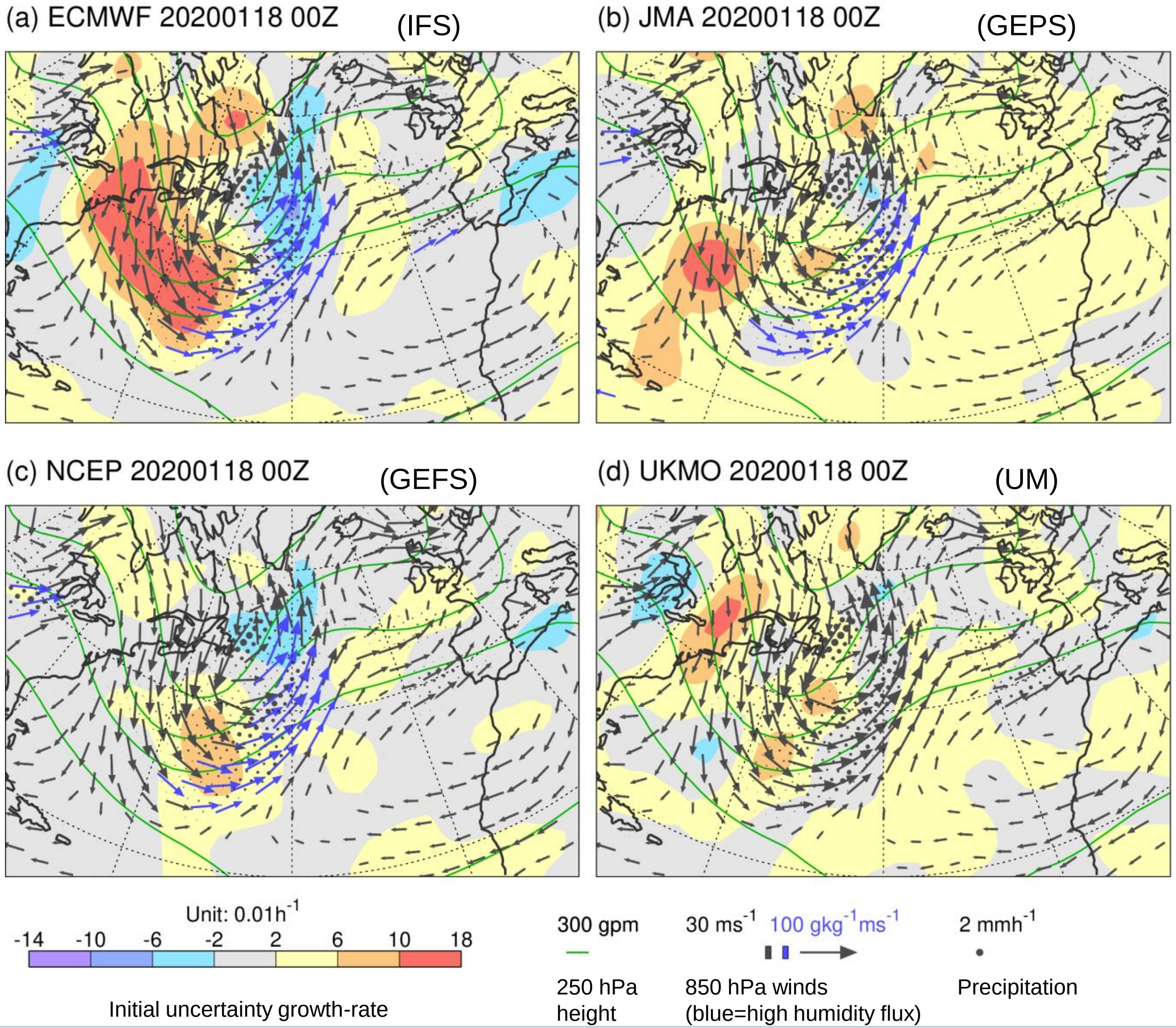
We do not know when to press the key (mesoscale convection itself involves chaotic uncertainty)

What we want is that the ensemble members generate such convection with the “right” uncertainty



Cyclogenesis in different (TIGGE) models

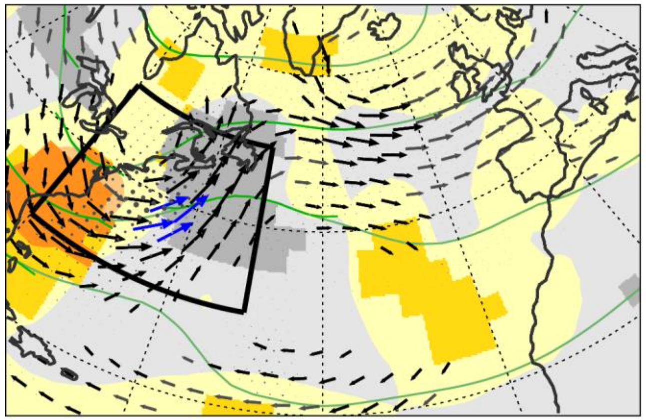
Animation of TIGGE models is a concatenation of 12h forecasts



Compositing on cyclogenesis

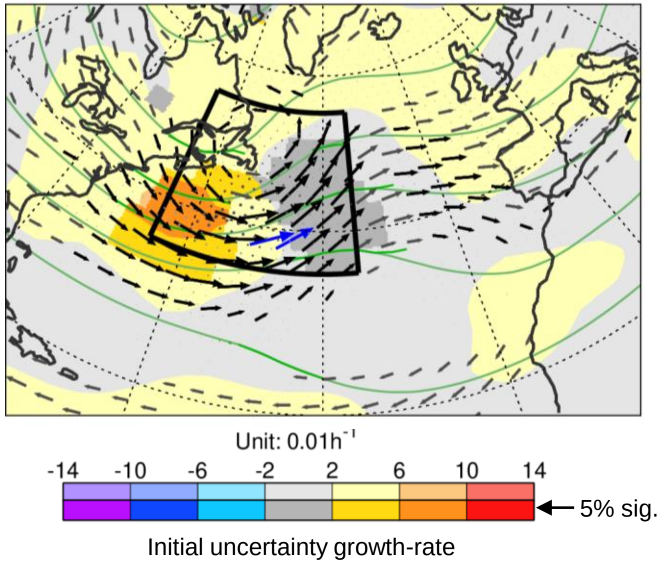
Clustering to identify cyclogenesis events

Clustering region 1 (32 events)



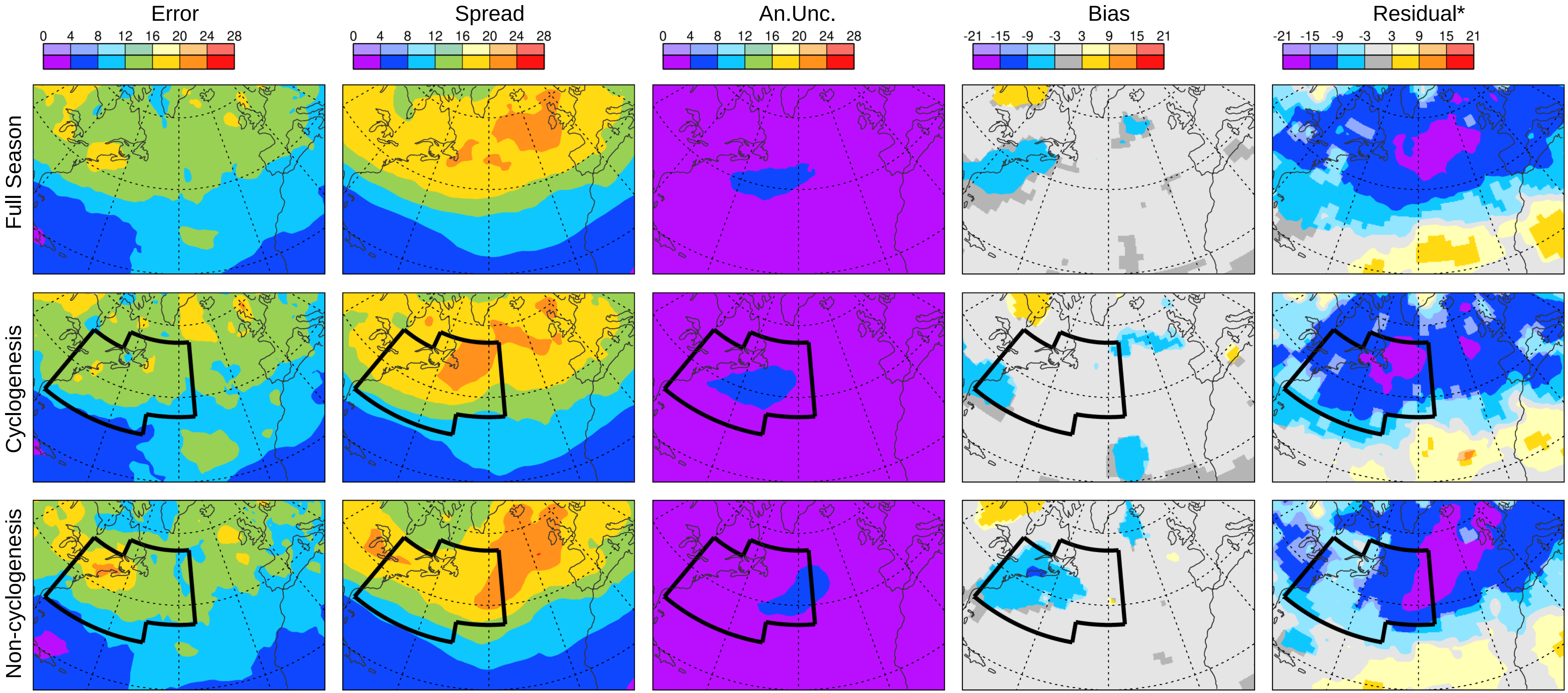
K-means clustering on analyzed Z250, u850, v850, and ensemble-mean 12h precipitation during DJF 2020/21 (not on growth-rate)

Clustering region 2 (+59 events)



ECMWF

Reliability assessment at Day 2 (Z250 DJF 2020/21)



Full Season negative Residual indicates that ensemble is over-spread in the stormtrack
Partitioning into cases of cyclogenesis / non-cyclogenesis in indicated region shows that the overspread is associated with cyclogenesis

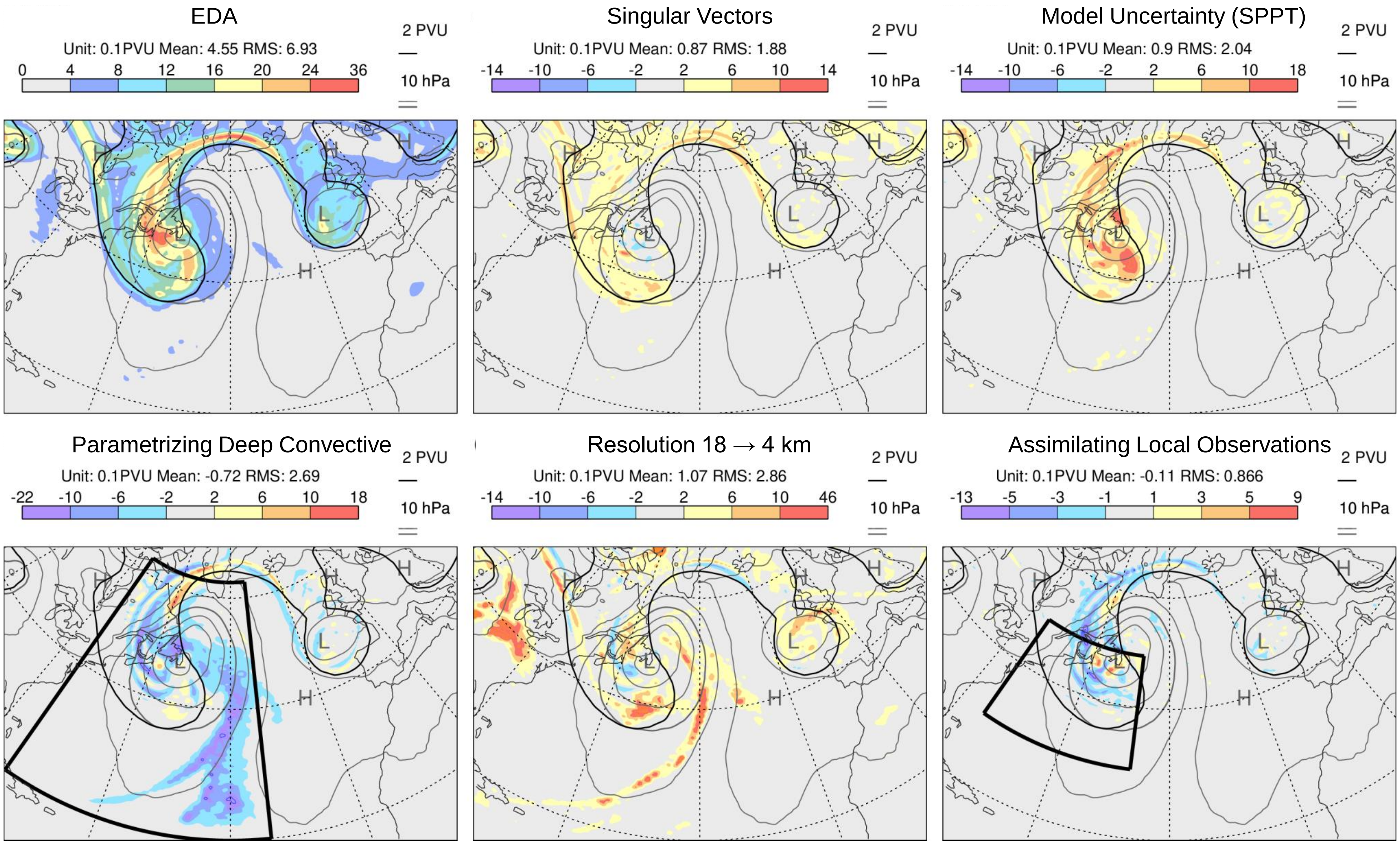
DJF 2020/21 Z250 (m). Shown are the square-roots of the terms in the ensemble reliability budget. Residual = SQRT(|R|)SGN(R)*

Impacts of initialisation and modelling aspects on day-2 spread

Rodwell & Wernli (2023)

20200117 00Z D+2 PV315

- Most spread is from the growth of EDA uncertainty
- Singular vectors and model uncertainty each contribute up to 25% of the total variance
- Parametrizing Deep Convection reduces variance
- Higher resolution increases variance; but not where the model uncertainty places it
- Assimilating local observations has a small mixed impact (note ½ contour interval)
- Results are robust over the 2 case studies considered



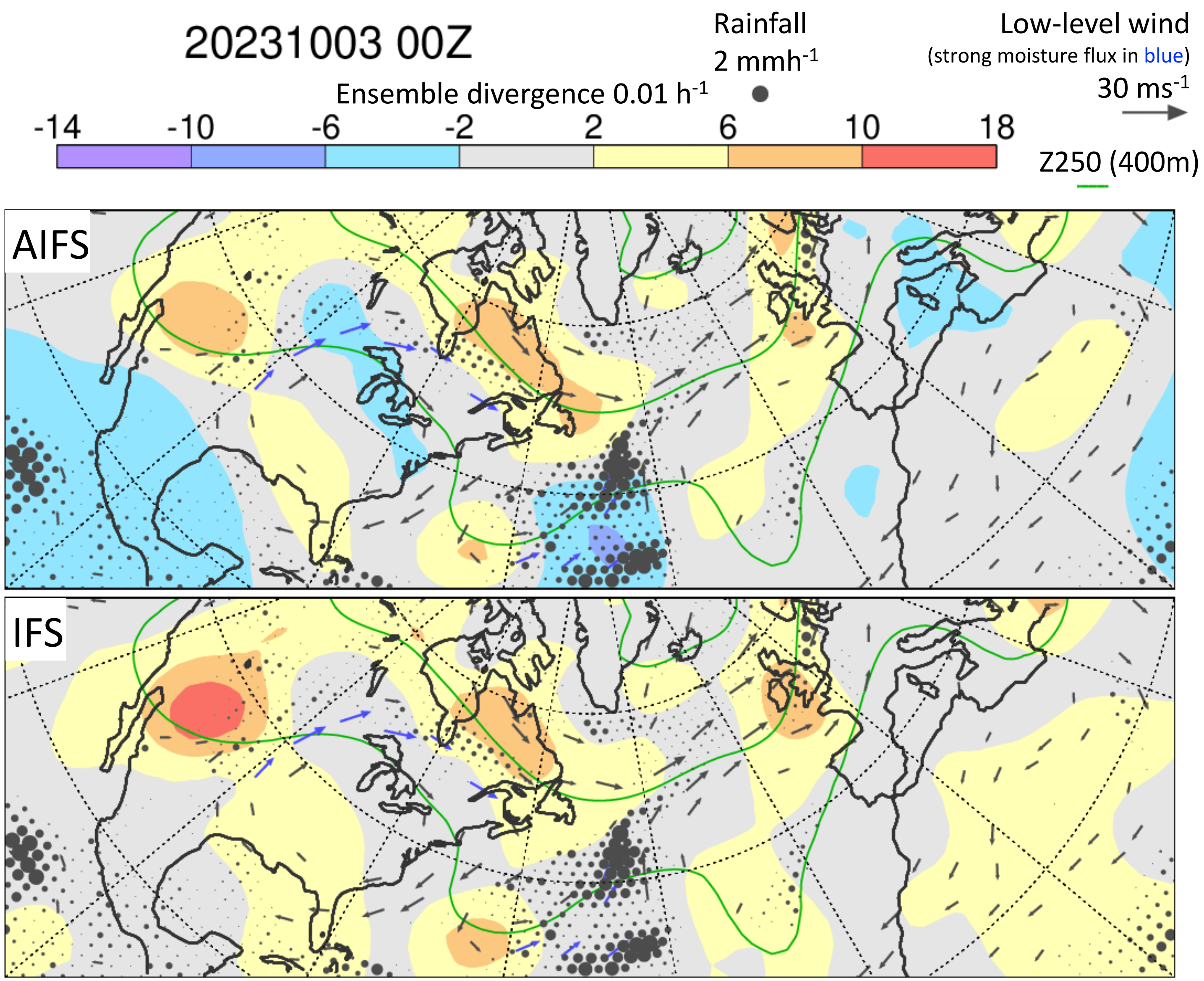
Uncertainty growth-rates in 12h forecasts of AIFS and IFS ensembles (Z250)

A glimpse of the future?:

The ECMWF ‘AIFS’ (Artificial-intelligence IFS) displays similar the patterns of synoptic-scale uncertainty growth to the IFS.

Magnitudes are slightly less, possibly because the AIFS does not include model uncertainty yet.

Does spatial agreement of growth-rates between AIFS and IFS reinforce confidence in both systems?



Uncertainty growth rates from the AIFS and IFS. Both animations show the same circulation and precipitation features, which are based on the operational analysis

Discussion

- Tropical forcing of midlatitude Rossby waves
  - Extended range predictability
- Predictability, reliability and sharpness
  - Uncertainty growth-rates for different synoptic flow-types
  - Flow-dependent reliability as a path to more skilful ensemble forecasts

- ECMWF Workshop on Diagnostics for Global Weather Prediction. 9-12 September 2024

  Novel diagnostics to help improve physics-driven and data-driven systems
  - Diagnostics of predictability
  - Process-oriented diagnostics
  - Data assimilation and ML as diagnostic tools
  - Community diagnostic packages and data archives