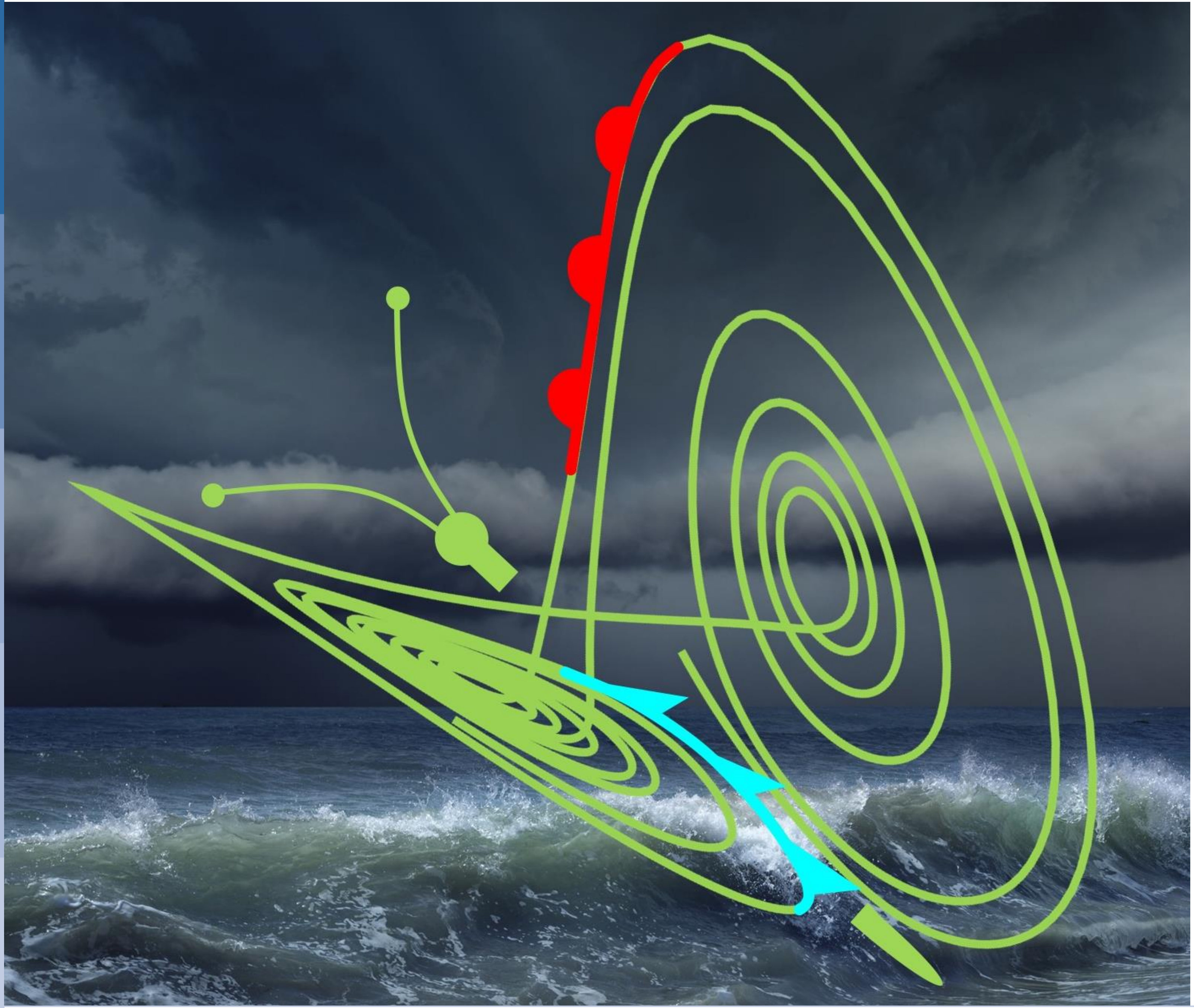

Challenges and Limits in Ensemble Weather Prediction

Mark Rodwell

UEF2019
“The strength of ensembles”

5 June 2019, ECMWF

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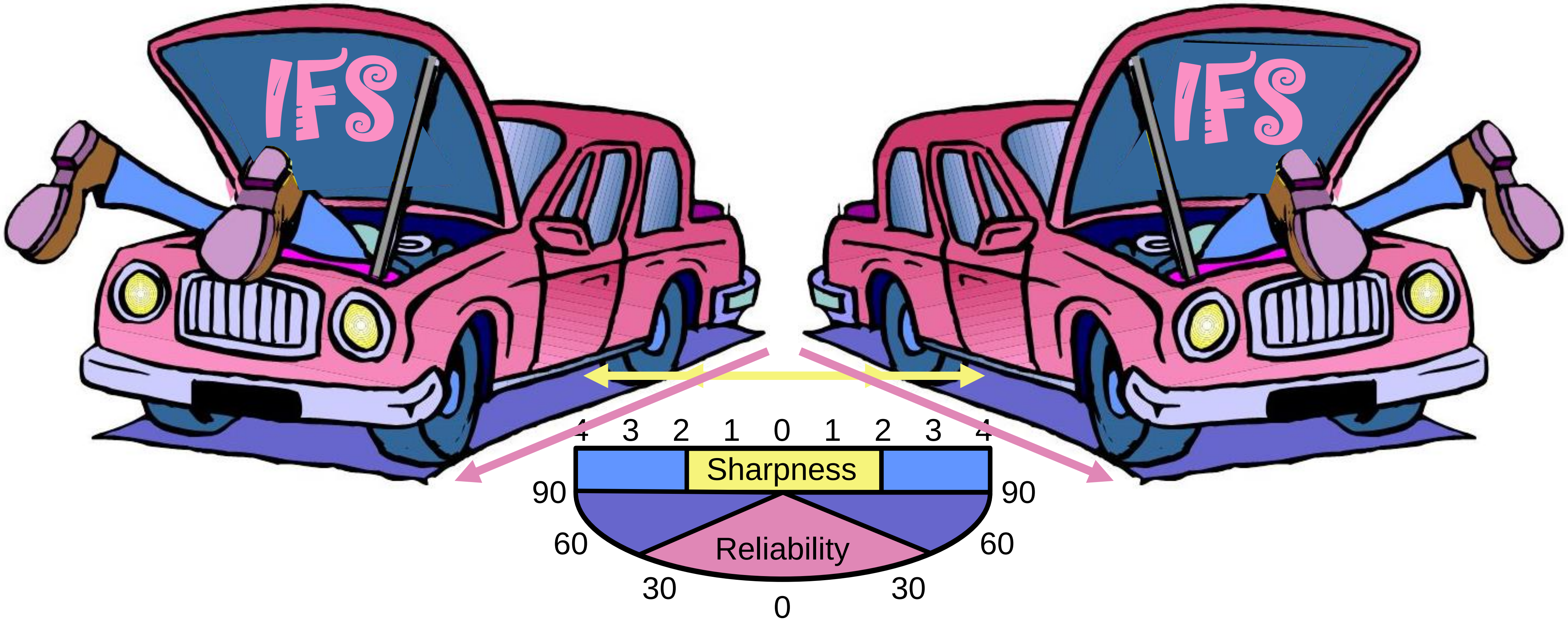
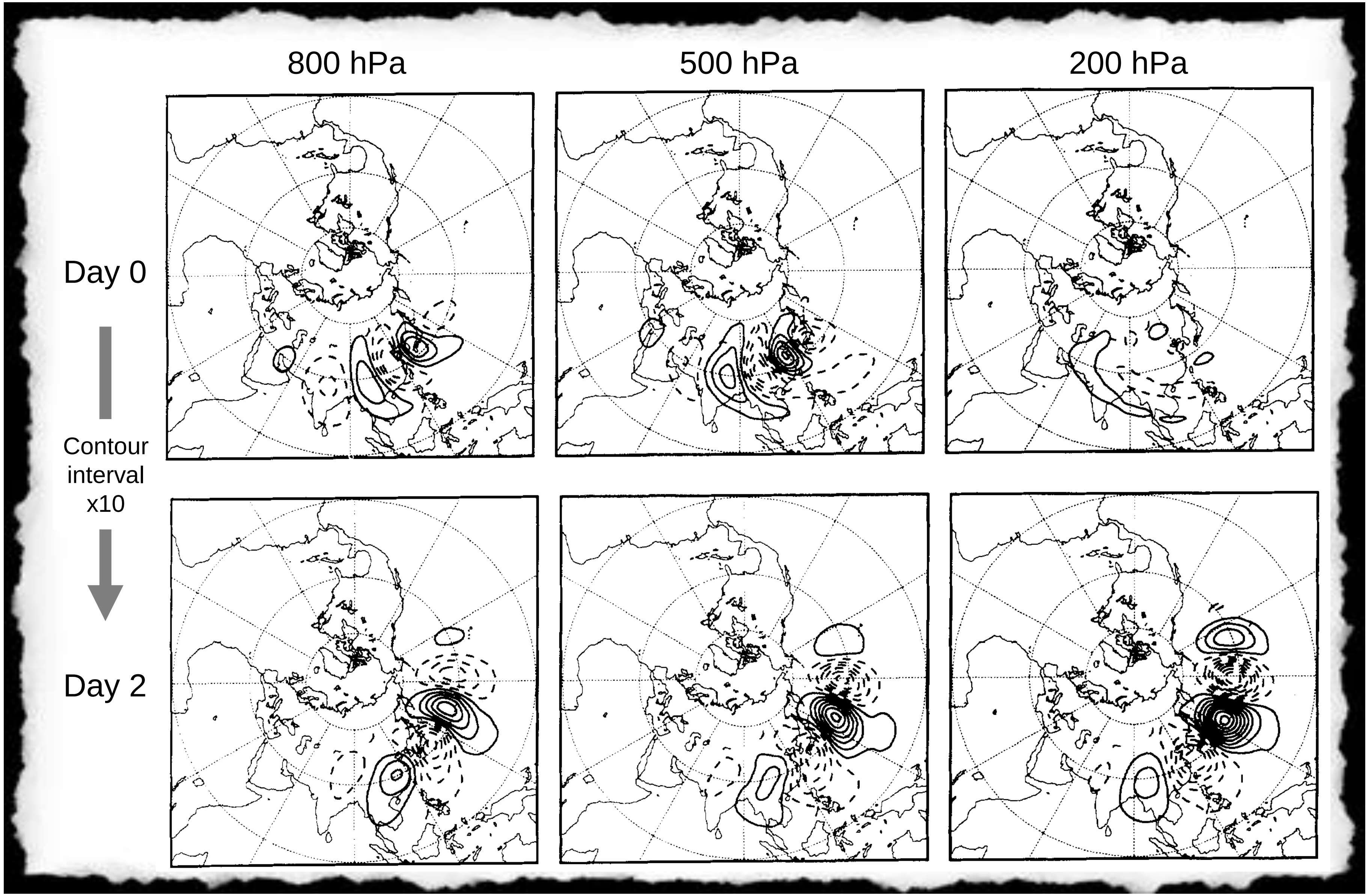
Challenges and Limits in Ensemble Weather Prediction - Outline

- A good ensemble forecast system
  - Reliability and Sharpness
- The Perfect Storm
  - When the going gets tough …
- Representativity
  - The missing variance
- Putting it all together

What makes a good ensemble forecast system?



Chaos and it's flow-dependence



Molteni and Palmer (1993)

A fastest-growing "Singular Vector" (SV)

SVs are dependent on the state of the atmosphere

Here, a westward tilt with height at day 0

The amplitude at the upper tropospheric level grows considerably (x50) over the first 2 days

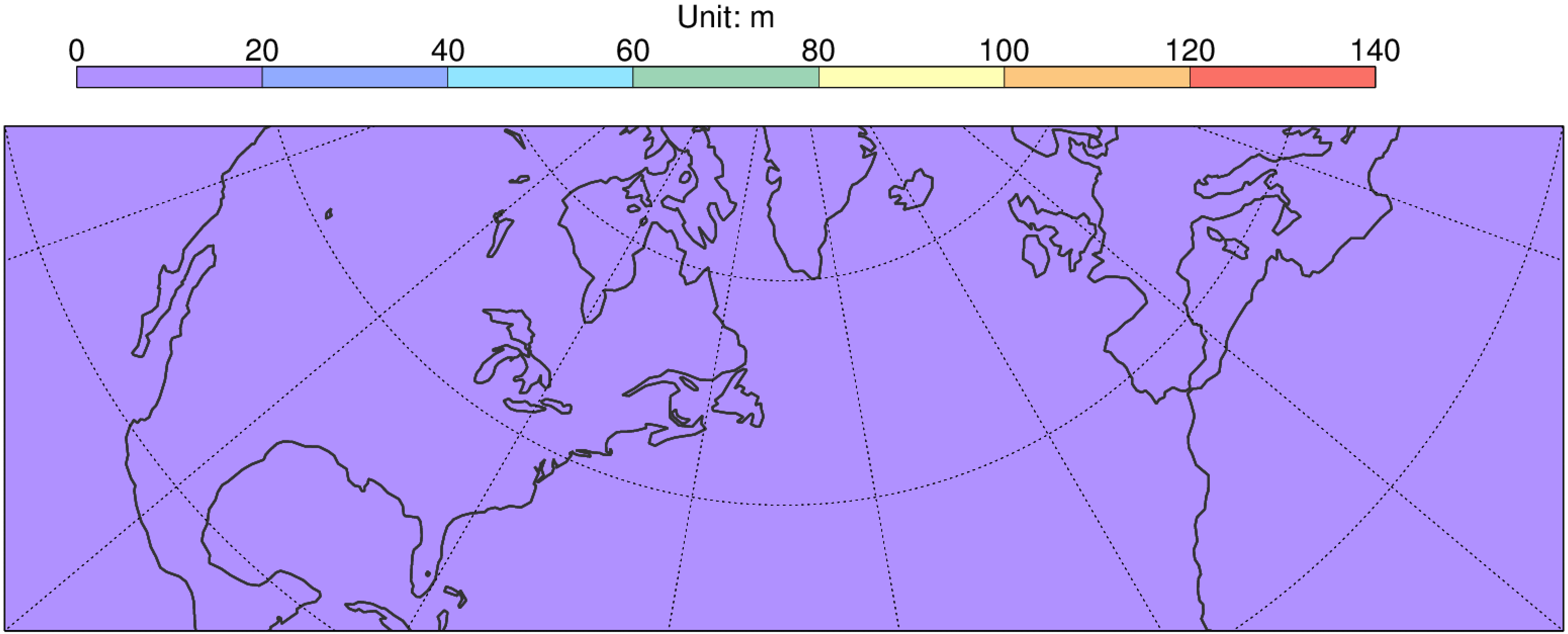
Fastest growing baroclinic 2 day SV on a 6yr Jan-Feb climatology. Streamfunction with intervals (top) 1.5 and (bottom) 7.0 x10^6 m^2s^{-1}. Dry 3-level T21 QG model.

Animation of ECMWF ensemble forecast spread 20170305 12Z D+0 to 6: σ_{Z500}

Uncertainty growing from various sources, is itself advected, and becomes large over Europe by D+6

ECMWF ENS stdev Z_{500hPa} (shaded).

20170305 12Z



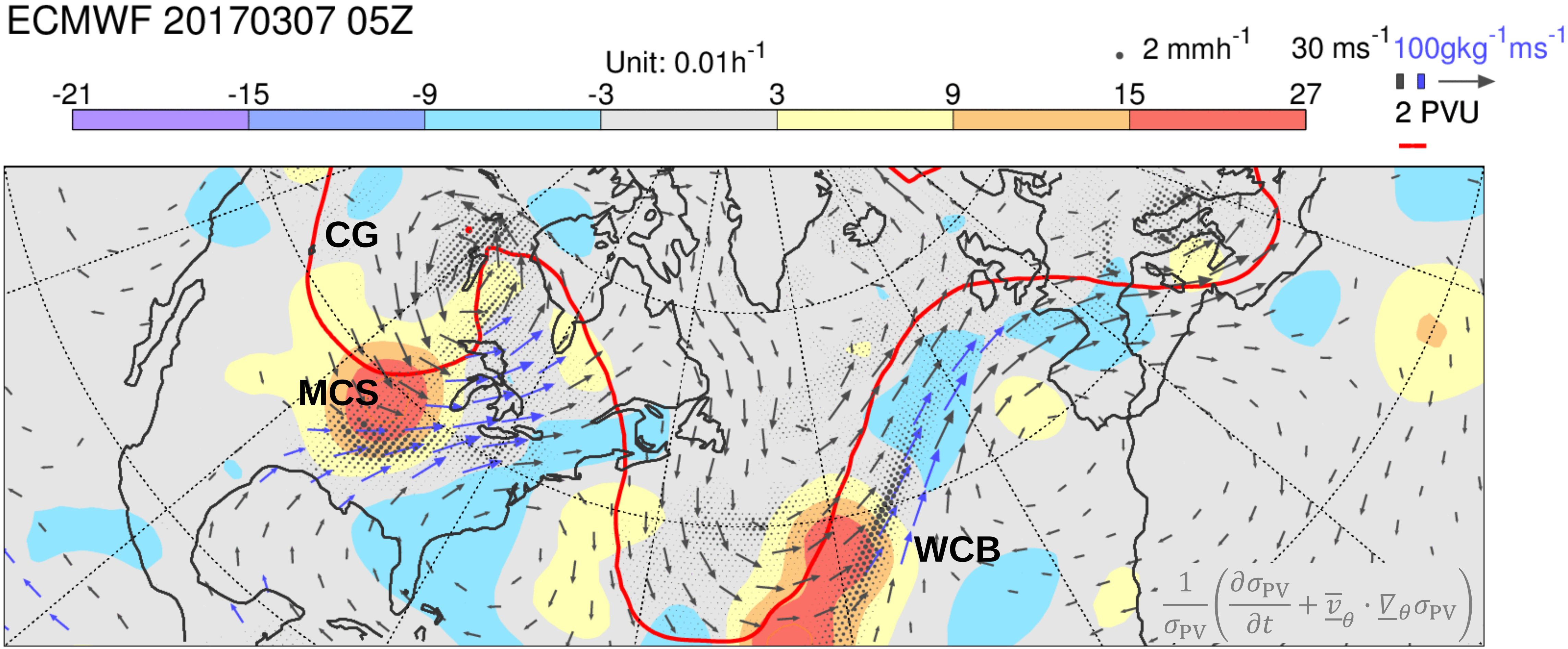
Uncertainty growth-rate along the truth trajectory – Based on EDA background $\sigma_{PV_{315}}$

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

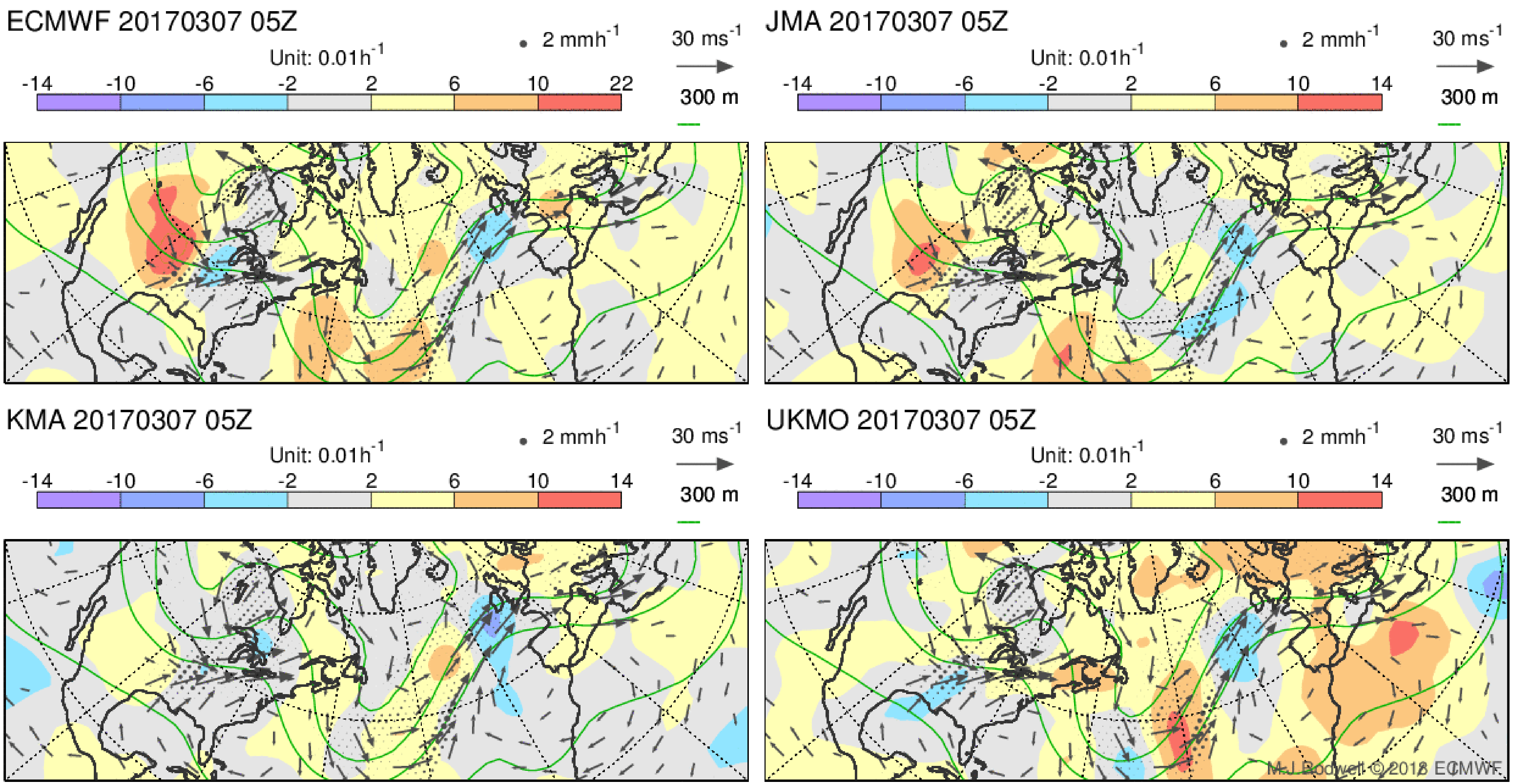
Aim: Evaluate short-range synoptic flow-dependent representation of uncertainty

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



Control forecast PV_{315}=2, $\underline{v}_{850}$ and $q|\underline{v}|_{850}$, Ensemble-mean precipitation. 1d running-mean gives 12h-integrated growth rate with any diurnal cycle removed. T21 smoothed

Uncertainty growth-rate along the truth trajectory - Based on 12h ENS Z_{250hPa} TIGGE



ECMWF:

EDA(PV_{315K}) ≈ ENS(Z_{250hPa}) ≈

JMA:

≈ ECMWF

UKMO:

Stronger growth-rates over Europe/Africa

KMA:

Weaker everywhere

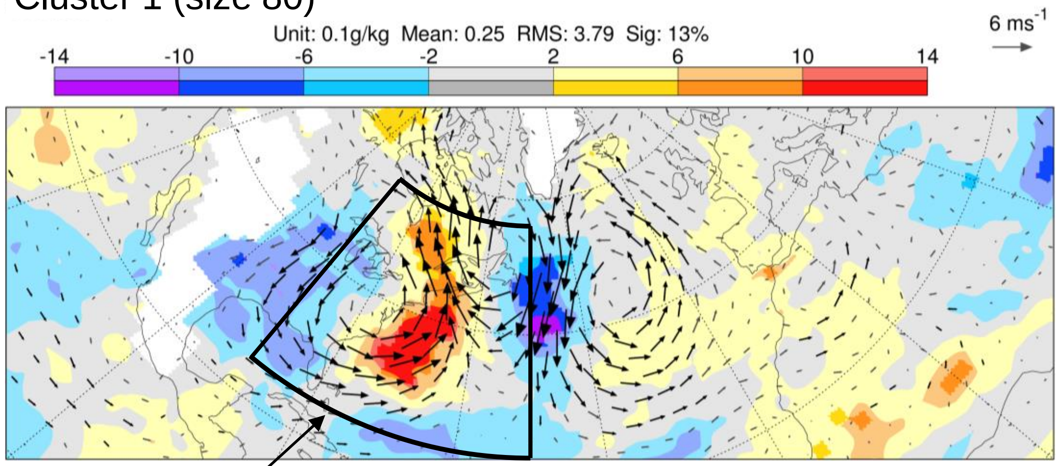
Which is best?

$$\frac{1}{\sigma_Z}\left(\frac{\partial \sigma_Z}{\partial t} + \underline{\overline{v}}_p \cdot \underline{\nabla}_p \sigma_Z\right)$$

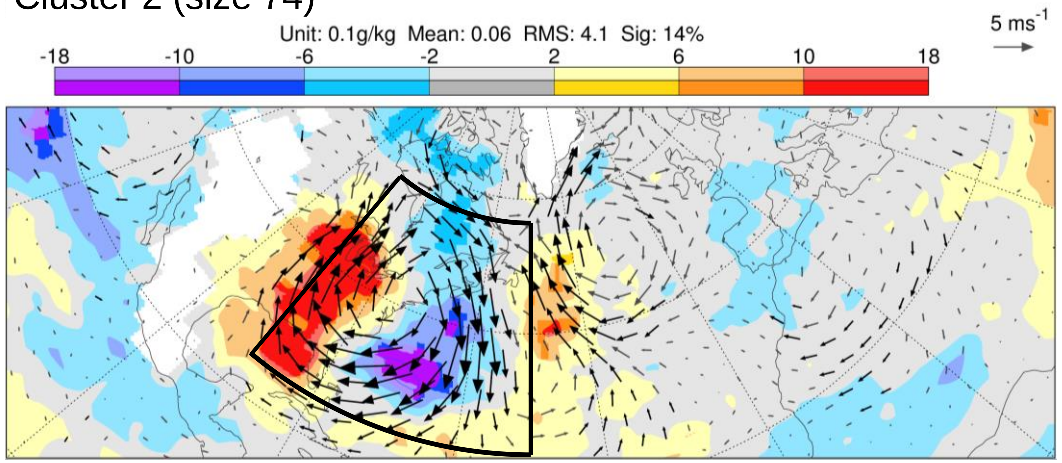
Control forecast Z_{250} (CI=300m) and $\underline{v}_{850}$, Ensemble-mean precipitation. 1d running-mean gives 12h-integrated growth rate with any diurnal cycle removed. T21 smoothed

Synoptic flow clusters - Mean anomalies in low-level humidity and wind (q_{850} and $\underline{v}_{850}$)

Cluster 1 (size 80)

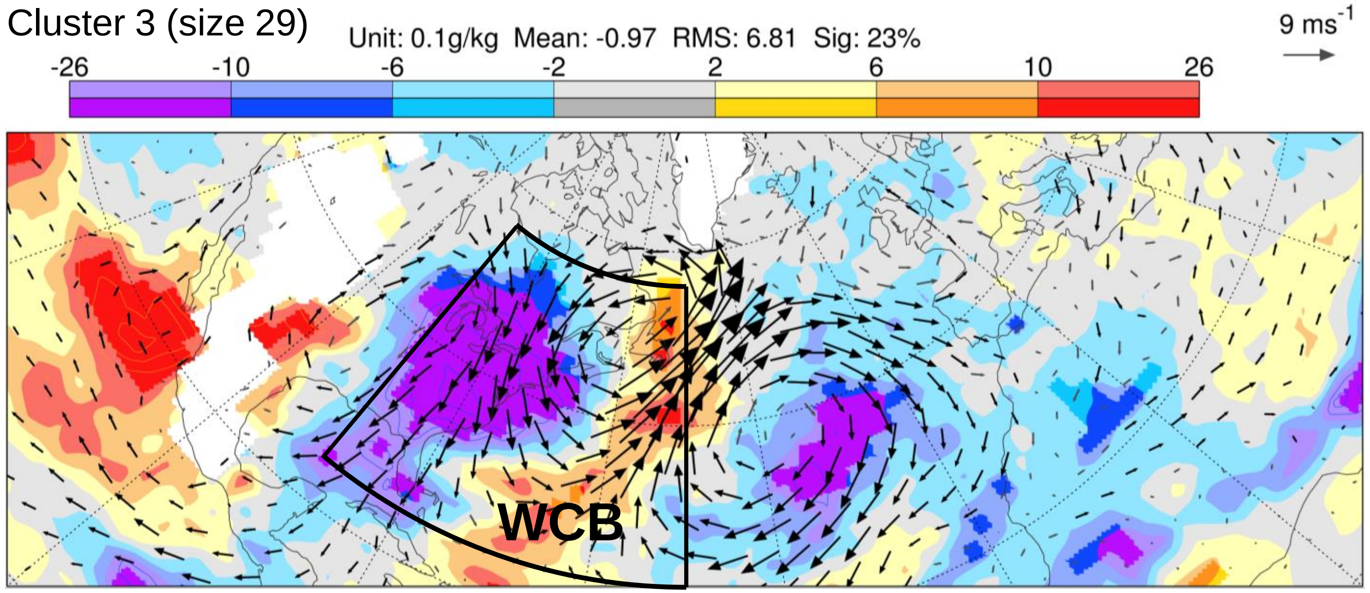


Cluster 2 (size 74)



Clustering region

Cluster 3 (size 29)



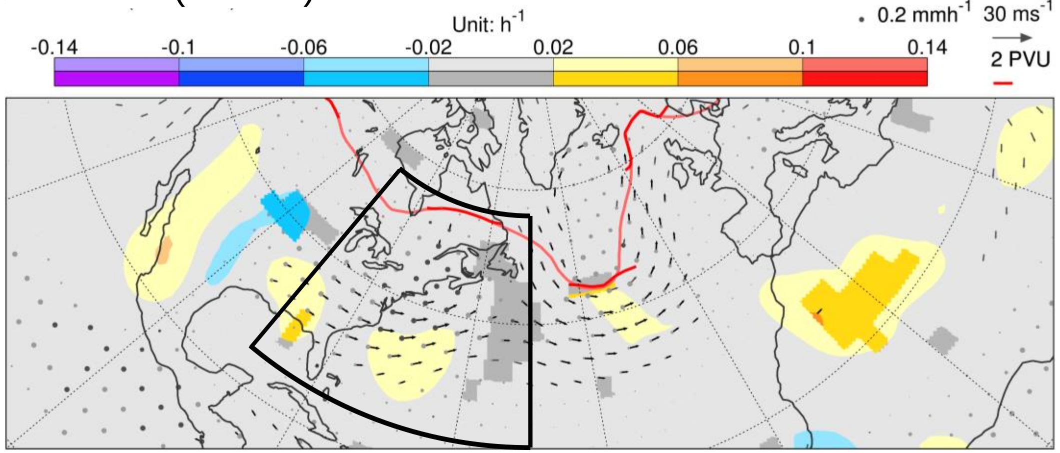
Here, the main focus is on the “Warm Conveyor Belt” cluster, with enhanced uncertainty growth-rates

Note everything is for the single season (MAM 2017) – important for operational development cycle

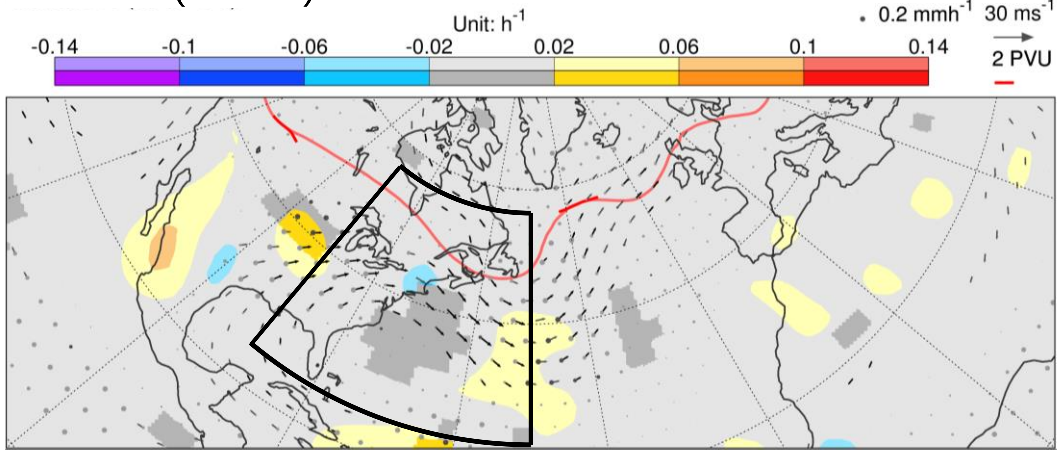
Based on K-means clustering of the synoptically-filtered and normalised fields from the PV animation in the region indicated, for MAM 2017. Bold colors = 5% significance

Synoptic flow clusters - Mean PV_{315}, $\underline{v}_{850}$, Precipitation & PV_{315} growth-rate, EDA

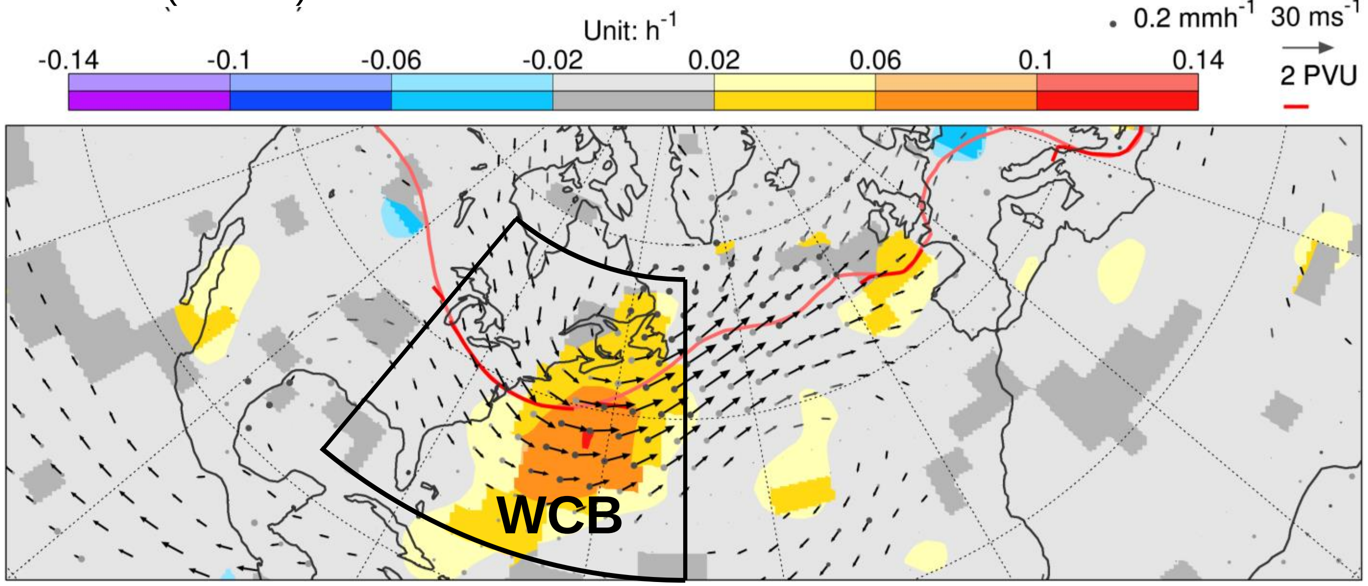
Cluster 1 (size 80)



Cluster 2 (size 74)



Cluster 3 (size 29)

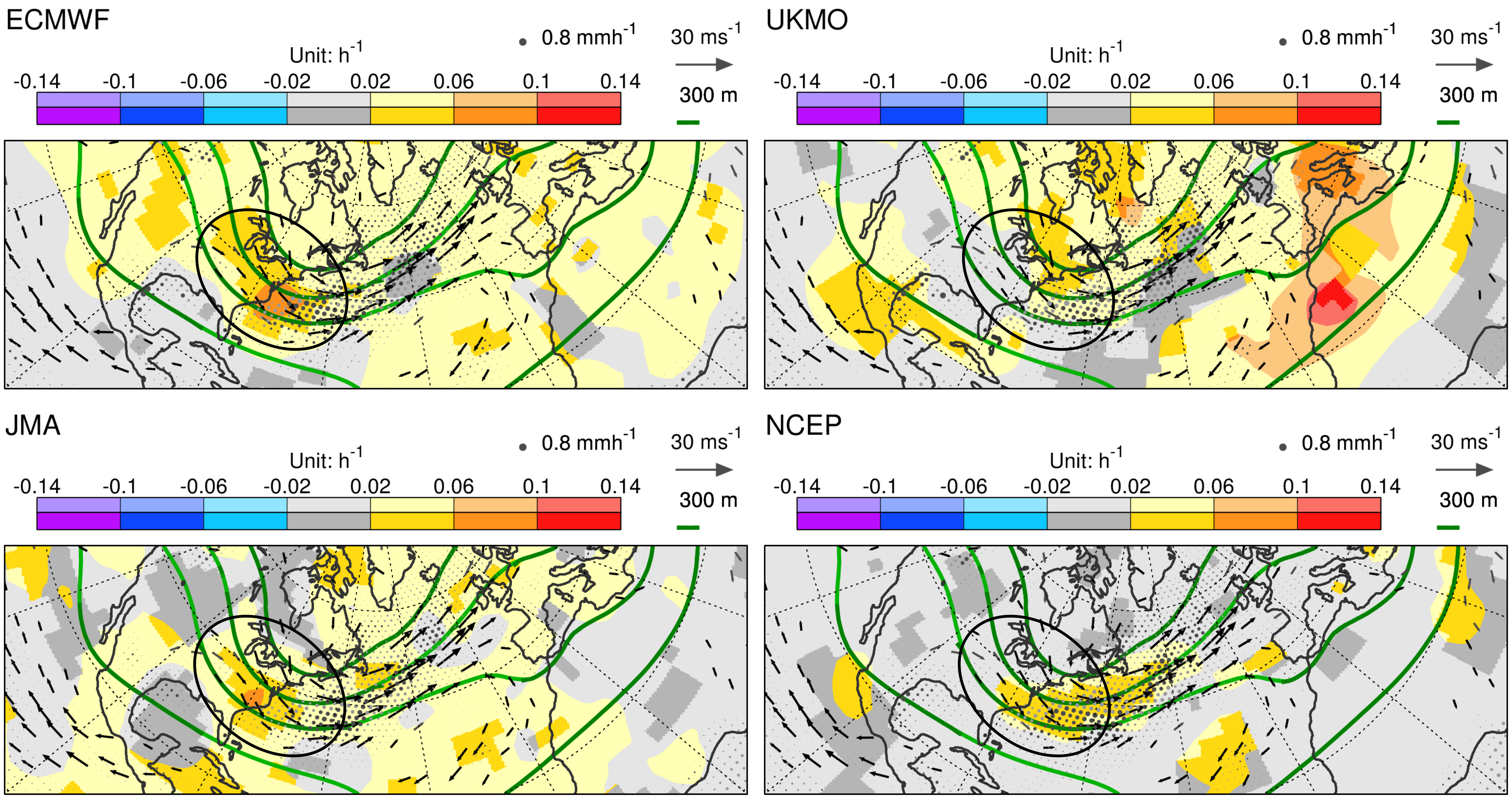


Here, the main focus is on the "Warm Conveyor Belt" cluster, with enhanced uncertainty growth-rates

$$\frac{1}{\sigma_{PV}}\left(\frac{\partial \sigma_{PV}}{\partial t} + \underline{\overline{v}}_{\theta} \cdot \underline{\nabla}_{\theta}\sigma_{PV}\right)$$

Based on K-means clustering of the synoptically-filtered and normalised fields from the PV animation in the region indicated, for MAM 2017. Bold colors = 5% significance

Warm Conveyor Belt cluster - Mean Z_{250}, $\underline{v}_{850}$, precipitation & Z_{250} growth-rate, TIGGE



ECMWF: Substantial growth-rate in trough region.

JMA: ≈ECMWF

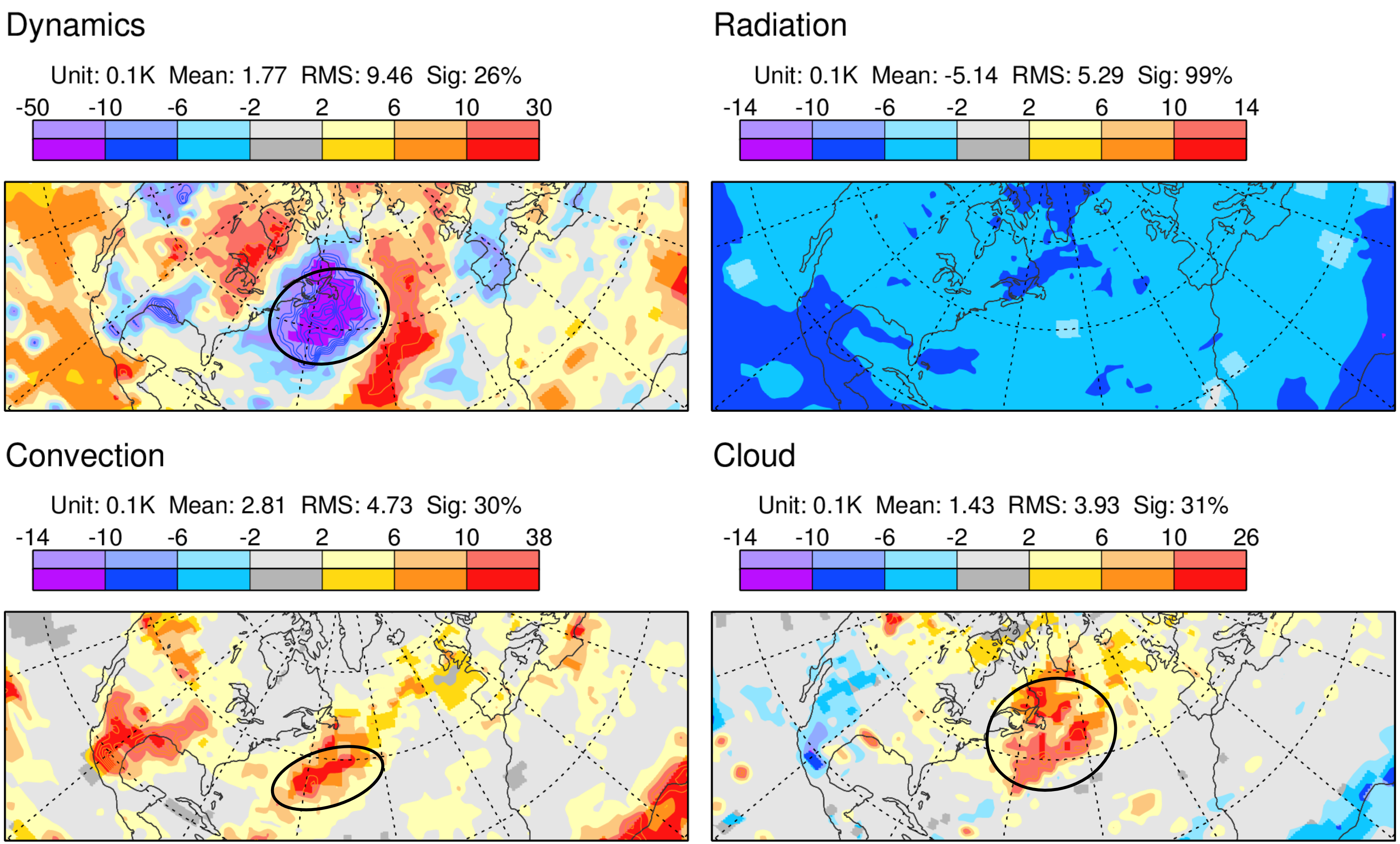
UKMO: Stronger growth-rates over Europe/Africa

NCEP: Generally weaker growth-rate

$$\frac{1}{\sigma_Z}\left(\frac{\partial \sigma_Z}{\partial t} + \underline{v}_p \cdot \underline{\nabla}_p \sigma_Z\right)$$

MAM 2017. Clustered on ψ200 and T850 in same region for clean comparison. Some dates missing from TIGGE archive so WCB cluster includes 25 EDA cycles

Warm Conveyor Belt cluster – Mean T_{500} process tendencies, EDA control



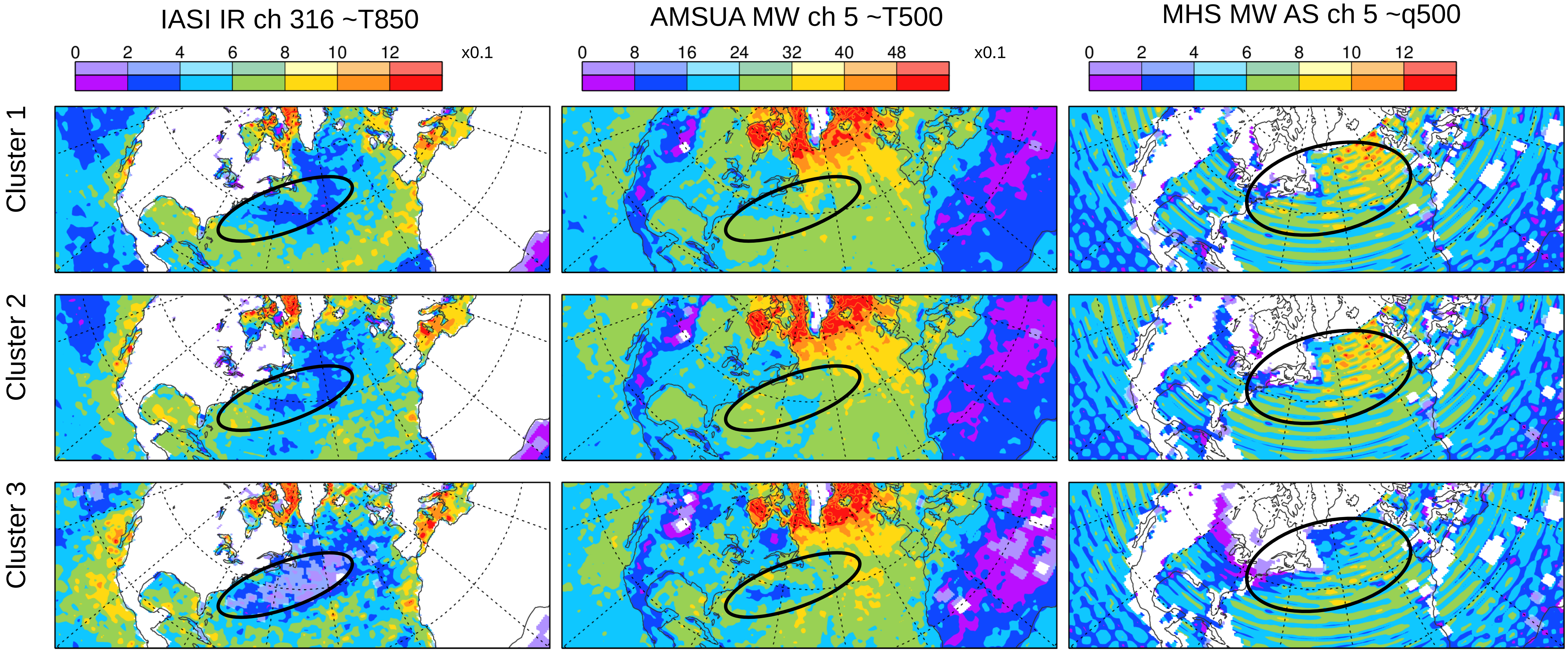
For the "Warm Conveyor Belt" cluster, the ascent leads to a dynamical cooling tendency

The physical processes are particularly active and counter-act some of this cooling

At 500hPa, we see strong warming due to cloud microphysics and embedded convection

Tendencies are from the unperturbed EDA control background forecast. Dates relate to the WCB cluster. Bold colors = 5% significance

Density of observations assimilated for each cluster MAM 2017



unit=cell^{-1}cycle^{-1}≈(125km)$^{-2}$(12h)$^{-1}$

Difficulties in assimilating observations in WCB cluster just when we need them most! Even when assimilated ‘all-sky’ observations are assumed to have very large uncertainties (*e.g.* due to highly non-linear observation operators).

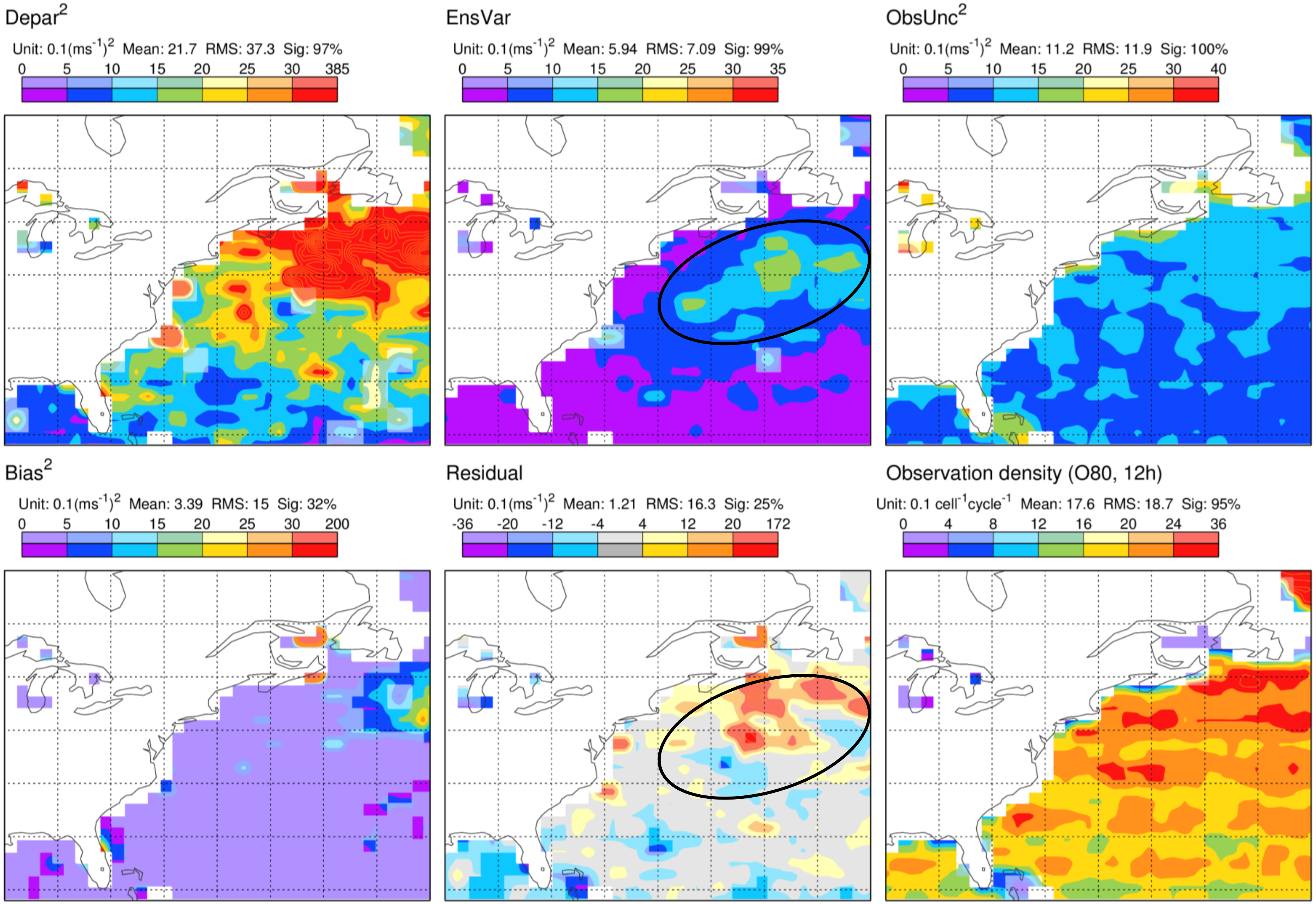
The Perfect Storm

- Large inherent uncertainty growth-rates - LIMIT
- Model physics (and stochastic physics) working at (or beyond?) their limits - CHALLENGE
- Difficulty to observe the truth - CHALLENGE
- Highly non-linear observation operators - CHALLENGE

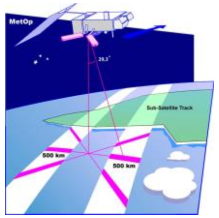
The Diagnostics Toolbox

- A couple of examples of the EDA variance budget tool

Error growth evaluation for WCB cluster based on scatterometer **surface wind** in EDA



MAM 2017



~~Error = Spread~~

Depar^2 = EnsVar + ObsUnc^2 + Bias^2 + Residual
(on average)

Large departures for this WCB case

Observation error variance is over-estimated for this data (not shown)

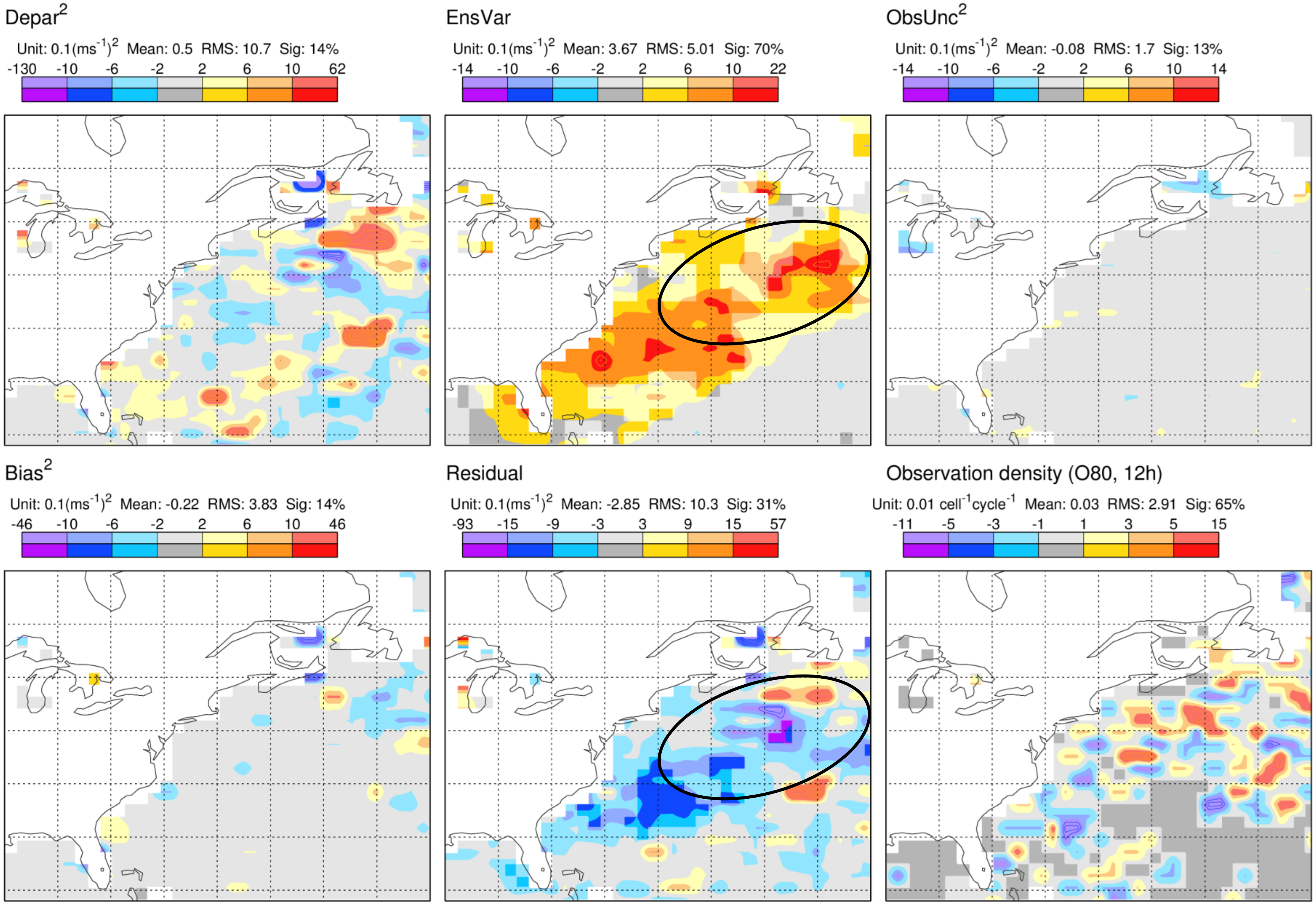
Hence EnsVar is under-represented

What happens if we increase stochastic physics?

Cluster	Size	Residual $(ms^{-1})^2$	(Un)reliability (%)
1	80	0.65	35
2	74	0.67	33
3	29	1.63	32

RMS of residual over the clustering region shows that WCB cluster contributes 1/3 to overall unreliability

Change to WCB cluster EDA variance budget with boundary-layer stochastic physics



MAM 2017

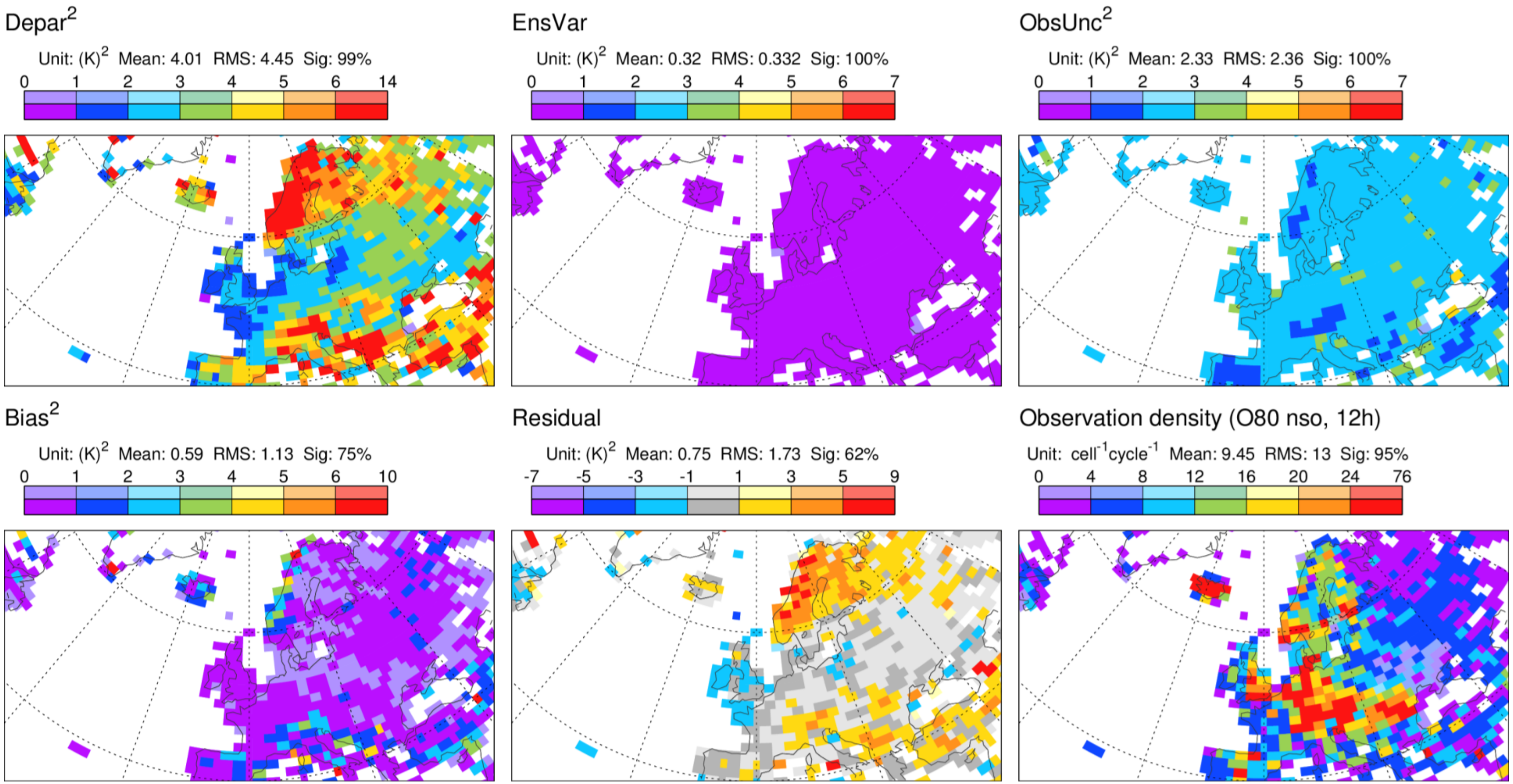
Model cycle 45r1 – cycle 43r1

Removing the boundary-layer tapering of stochastic physics increases background variance (EnsVar) by 60%

Residual is made more negative (an improvement)

A reduction in estimated observation error variance (ObsUnc²) should also improve the Residual

Error growth-rate evaluation. Based on EDA surface assimilation of *in situ* **T2m**



$Depar^2 = EnsVar + ObsUnc^2 + Bias^2 + Residual$
(on average)

IFS cycle 45r1, MAM 2018. No prior aggregation of observations, but Bias^2 will only indicate O80 aggregated bias

Observation uncertainty is a bigger term than ENS variance – even with boundary-layer stochastic physics.

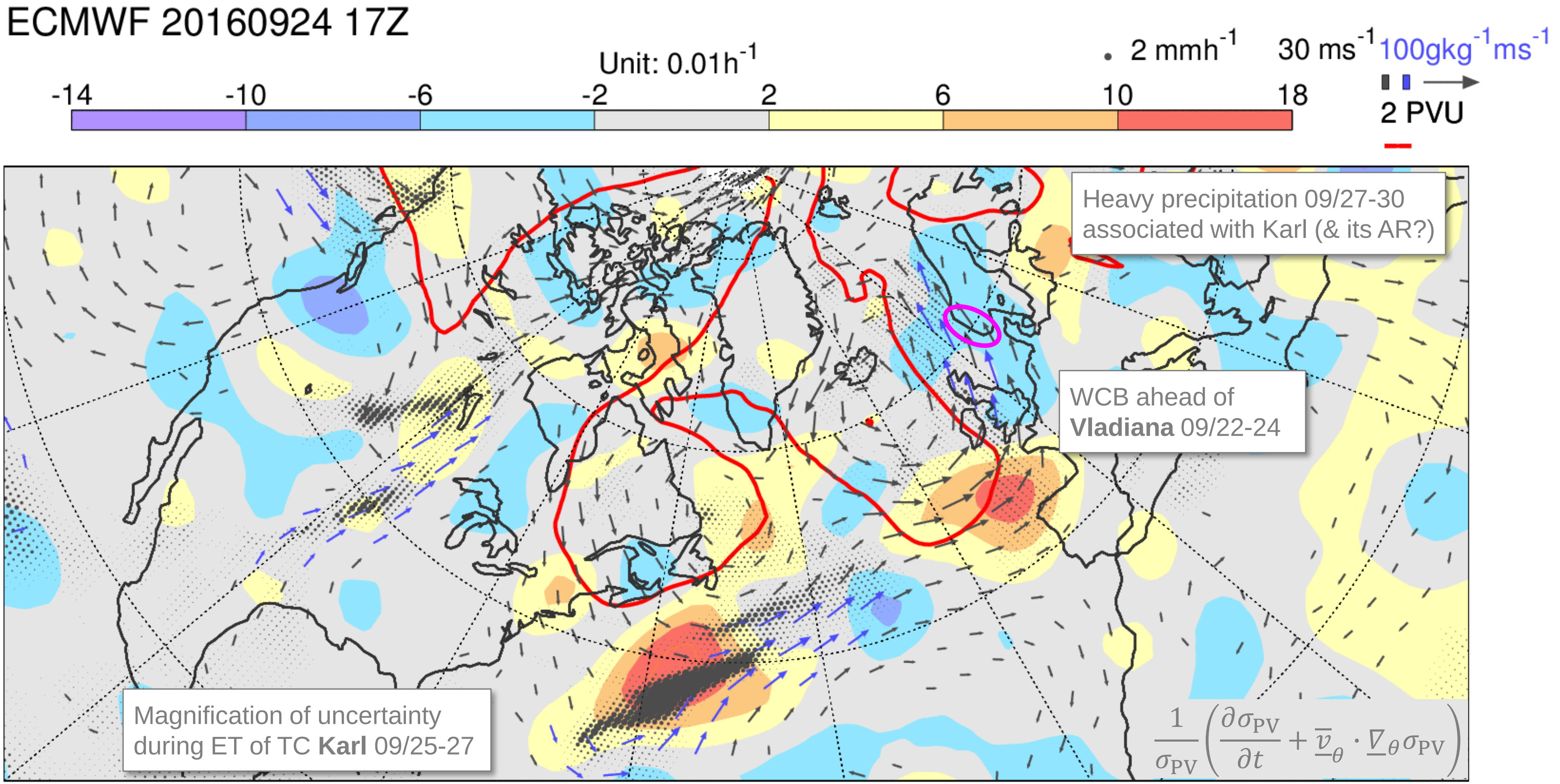
Residual has some blue regions (*e.g.* UK). Hence observation & grid-scale-model uncertainty not under-done.

This suggests that ENS variance deficit associated with lack of representativity of sub-grid-scale variations has an overall upper-bound of $\sqrt{5}$K in Scandinavia and $\sqrt{3}$K in Alps. Could be flow-dependent.

Operative at all lead-times. So smaller contribution to overall errors at longer lead-times

Implications and uses for post-processing (as well as assimilation system)

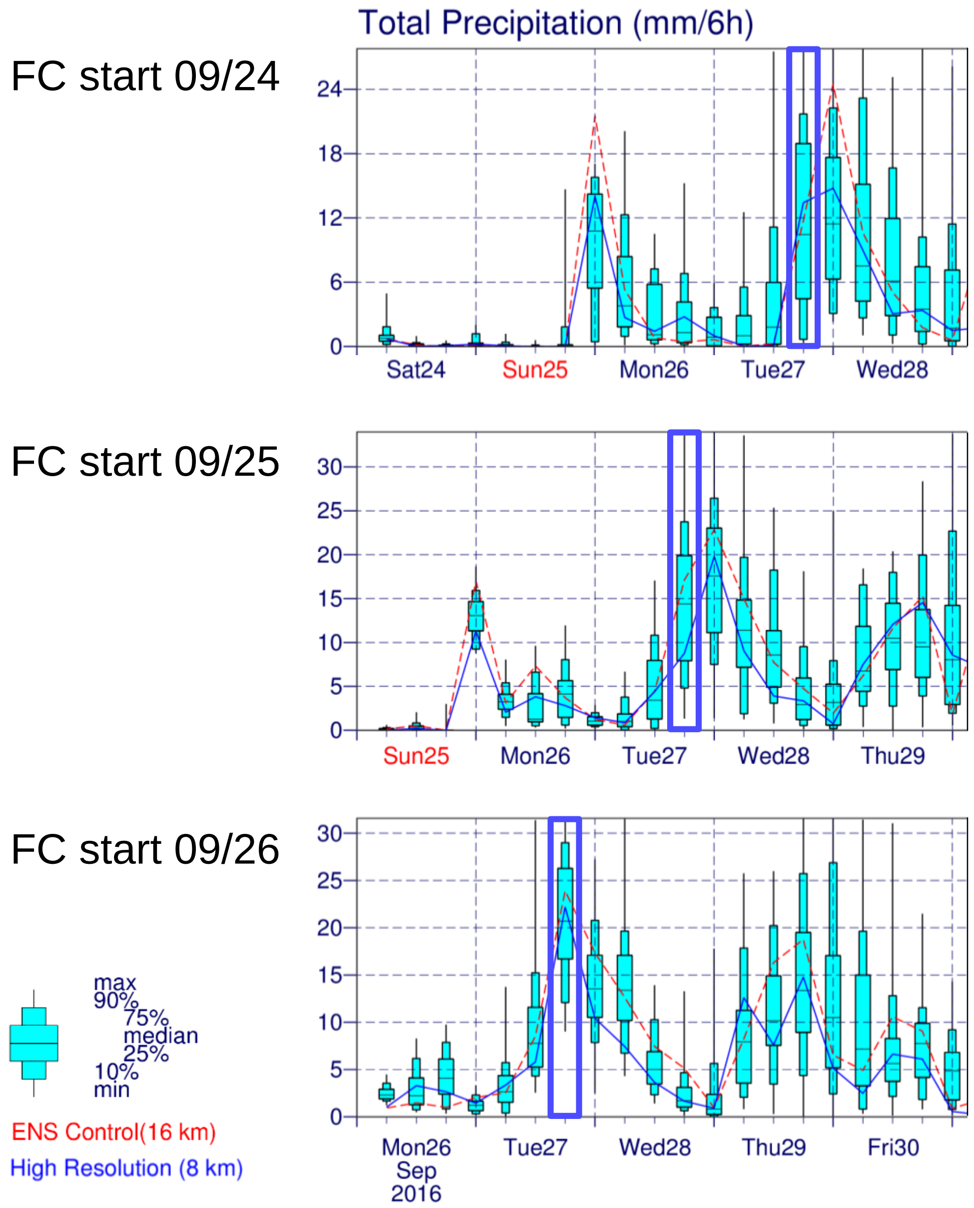
Uncertainty growth-rate along truth trajectory – EDA $\sigma_{PV_{315}}$: NAWDEX Case

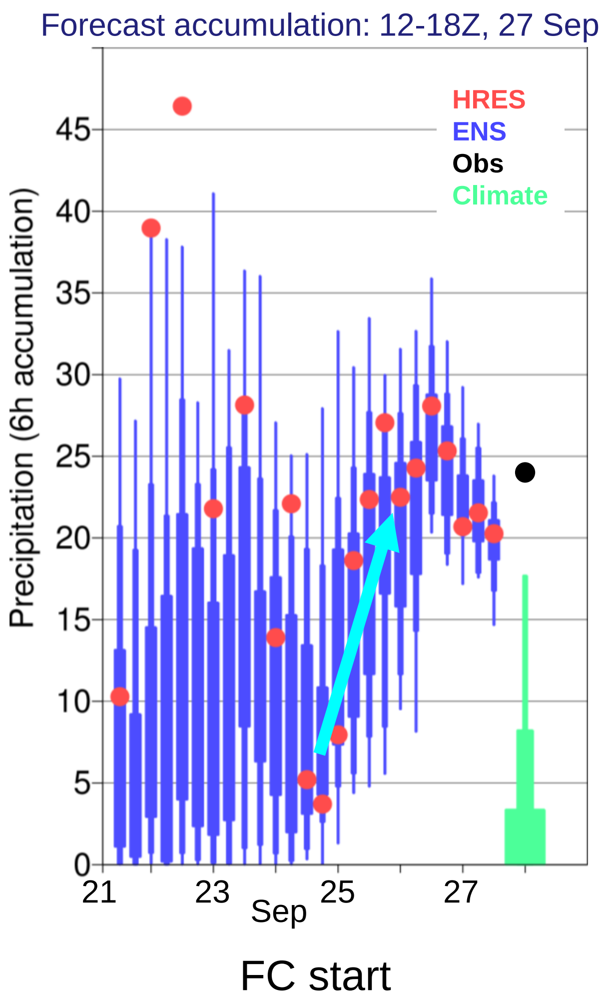


PV_{315}=2 & $\underline{v}_{850}$ from control forecast, precipitation is ensemble-mean. 1d running-mean gives 12h-integrated growth rate with any diurnal cycle removed. T21 smoothed

Forecast for **precipitation** in Bergen, Norway following TC Karl

Right plot from Linus Magnusson





Once uncertainties associated with the extratropical transition of Karl are resolved, the probability for strong precipitation firms-up

In the right panel, note the observation is at the top of the last forecast distribution. This might be fine, but could also reflect issues with model representativity of point observations

Note the different y-axes

Challenges and Limits in Ensemble Weather Prediction

- Reliability and Sharpness $\Rightarrow$ Skill
  - Faithful representation of uncertainty growth-rates (which are flow-dependent) – LIMIT
  - Better estimation of observational error – CHALLENGE

    … and correlated observation error
  - Assimilation of better observational information – CHALLENGE
- "Perfect storms"
  - Large inherent growth-rates – LIMIT

    … $\Rightarrow$ downstream deterministic forecast "Busts"
  - Model physics (and stochastic physics) working at their limits – CHALLENGE

    … beyond their limits $\Rightarrow$ Ensemble Jumpiness* (& Det. Busts) – CHALLENGE
  - Difficulty to observe the truth. Non-linear observation operators – CHALLENGE

    … re-assessment of targeted observations? – CHALLENGE
- Representativity
  - Model representativity of sub-grid-scale (observational) variability – CHALLENGE

    … for data assimilation and post-processing**

** See talk by David Richardson*   *** See talk by Thomas Haiden*

Thank you

Ensemble spread and error

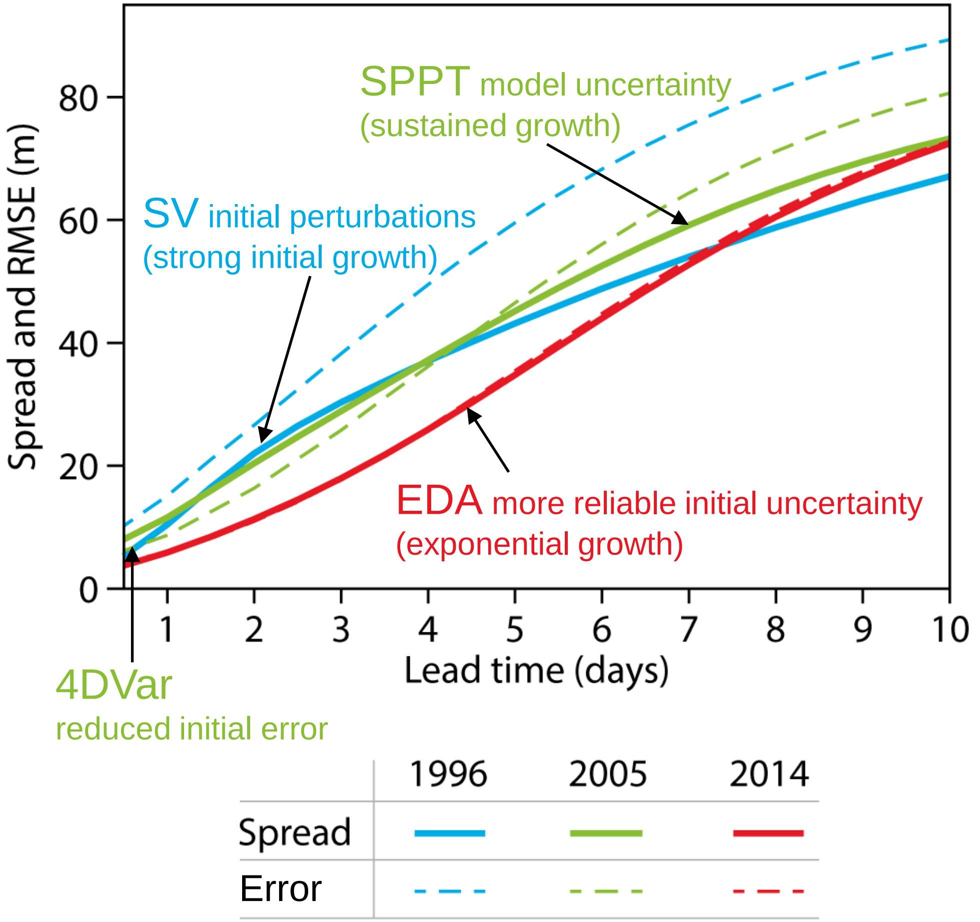
Z500

Rodwell et al. 2018, BAMS

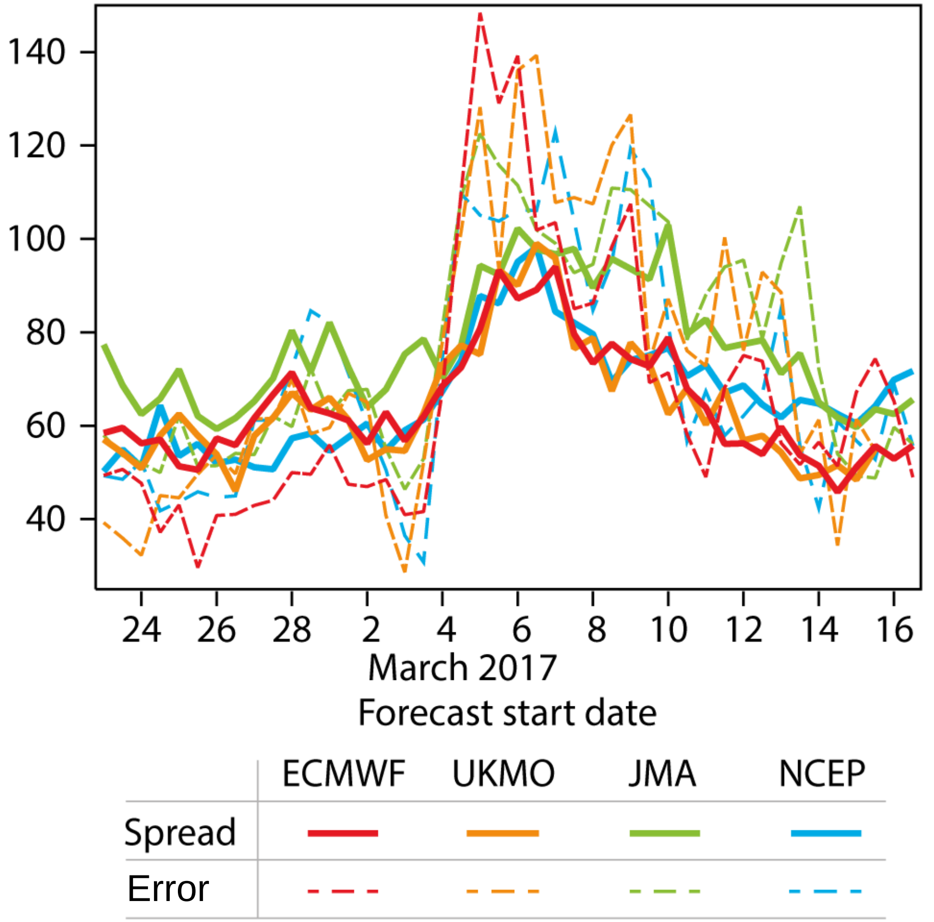
Overall Error and Spread have reduced and come into alignment; due to better observations, initial conditions, forecast model and better representation of uncertainty

…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)



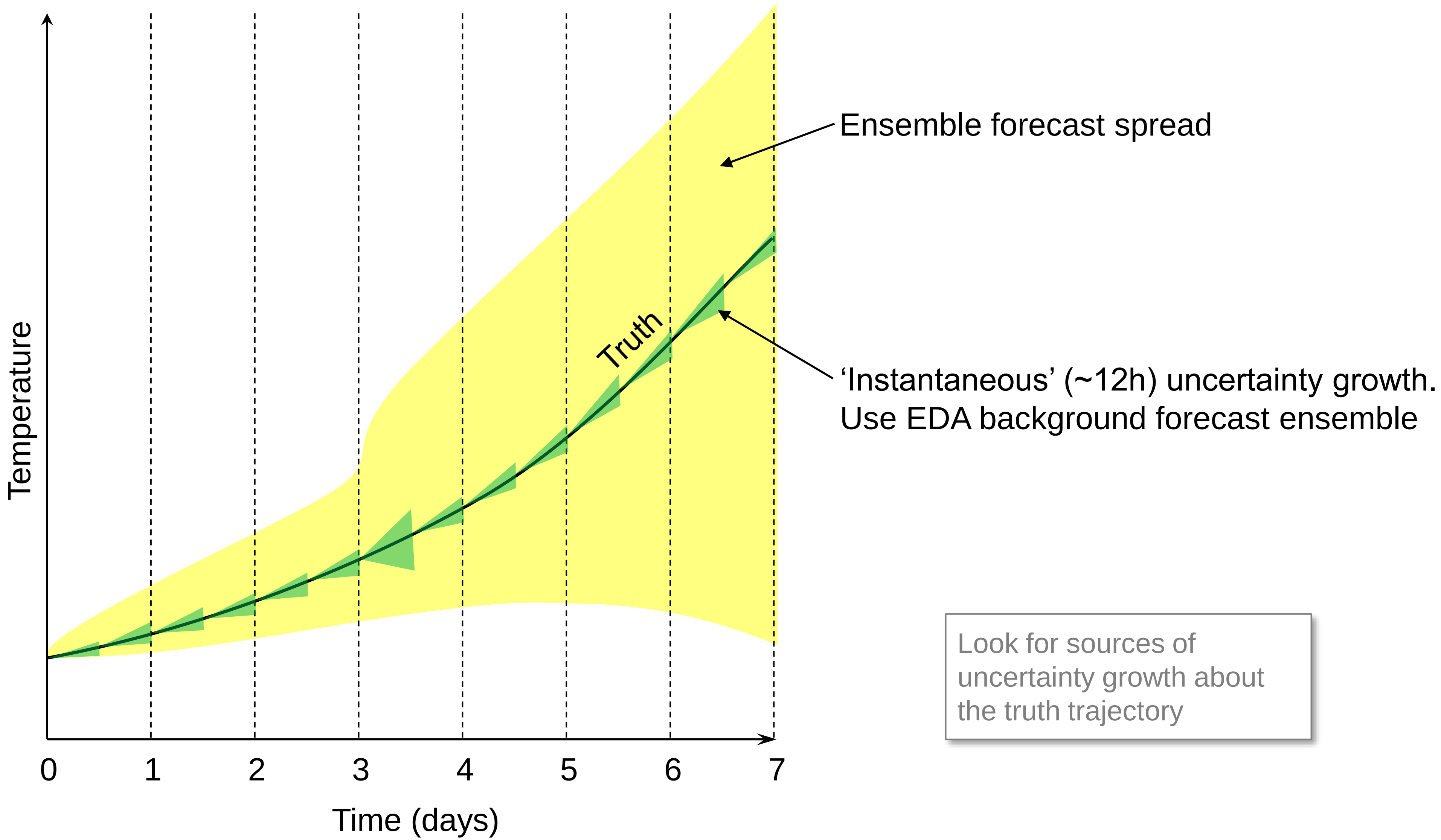
Timeseries for Europe at D+6 (TIGGE)



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

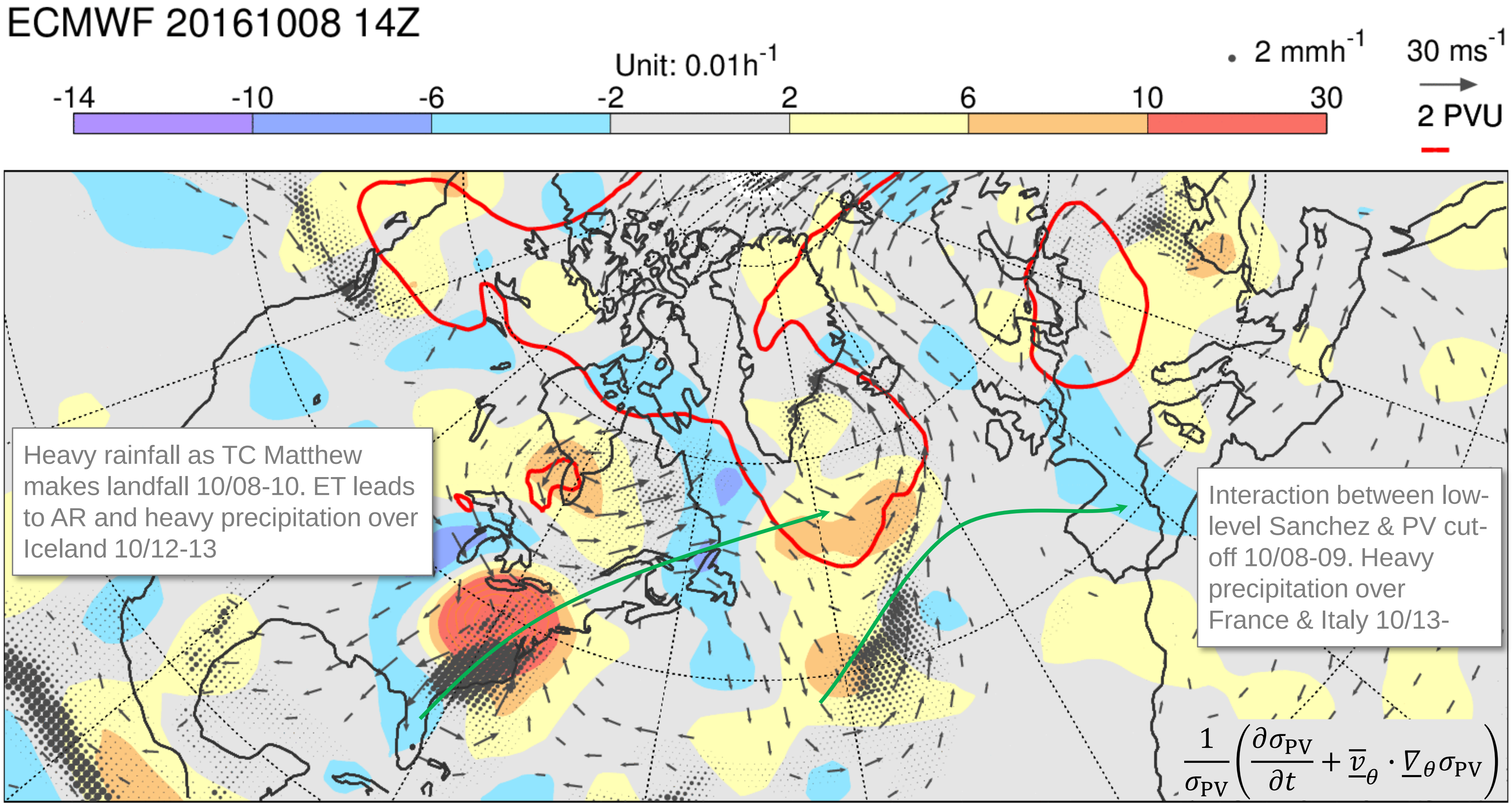
Spread = ensemble standard deviation (scaled to take account of finite ensemble size)

Ensemble forecast spread and the quasi-instantaneous growth of uncertainty



Look for sources of uncertainty growth about the truth trajectory

"Lagrangian" growth-rate for $\sigma_{PV_{315}}$: NAWDEX TC Matthew & cyclone Sanchez

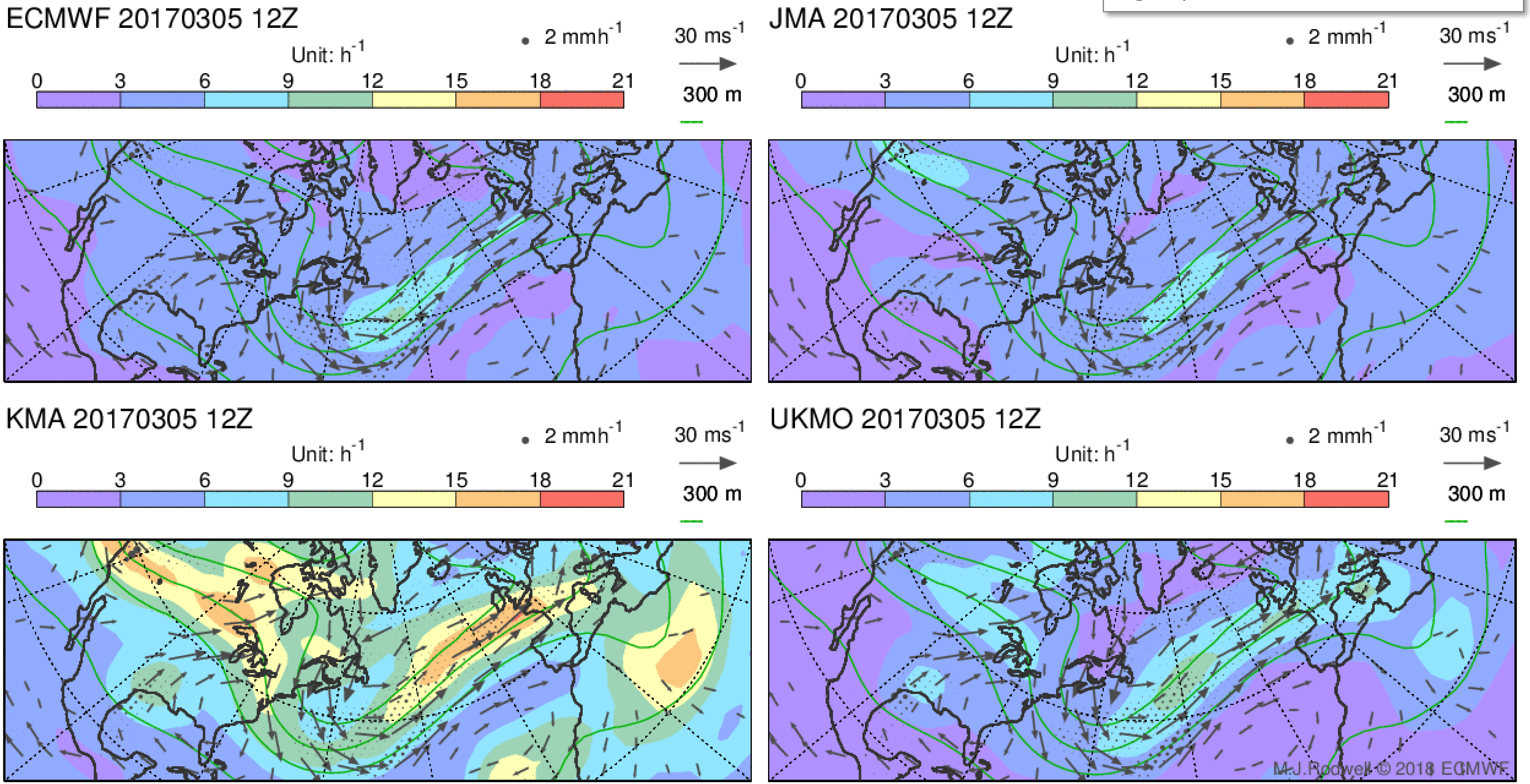


PV_{315}=2 & $\underline{v}_{850}$ from control forecast, precipitation is ensemble-mean. 1d running-mean gives 12h-integrated growth rate with any diurnal cycle removed. T21 smoothed

TIGGE 12h Standard deviation in Z_{250hPa} (shaded) ~Initial uncertainty of ensemble

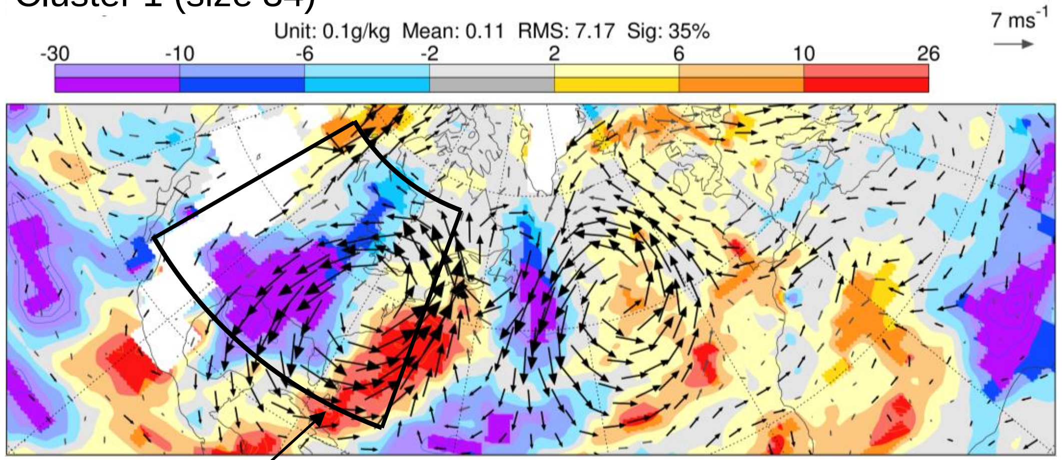
CF 850hPa winds (vectors), CF Z_{250} (green contour) and EM precip (dots). 1d running-mean applied.

Ensembles start from a different initial uncertainties, but growth-rate (in linear regime) should be unaffected

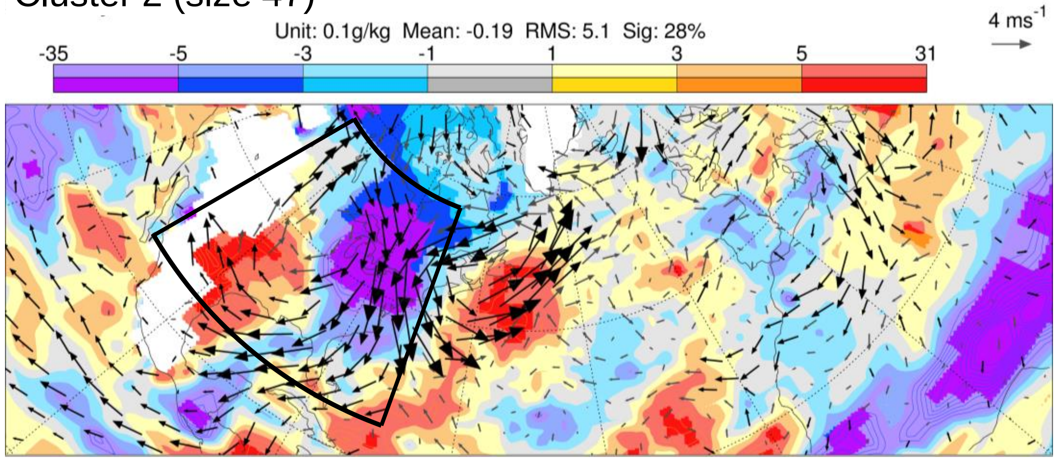


Clustering to identify 3 synoptic flow patterns. Mean anomalies in q850 and v850

Cluster 1 (size 34)

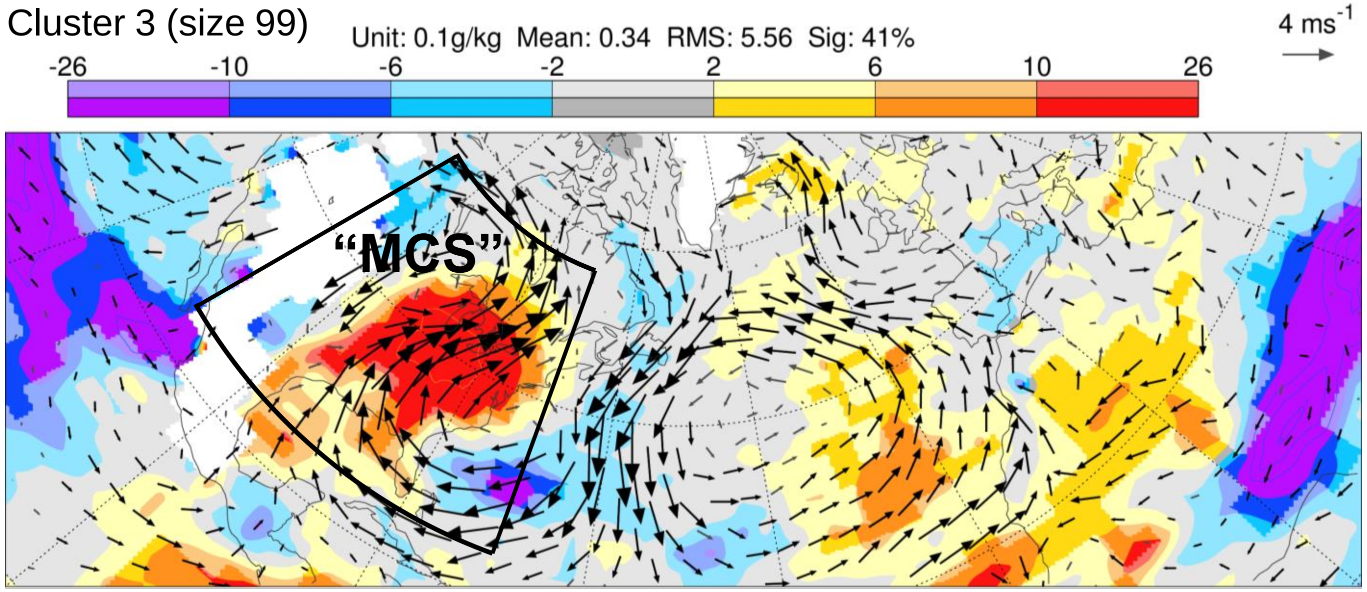


Cluster 2 (size 47)



Clustering region

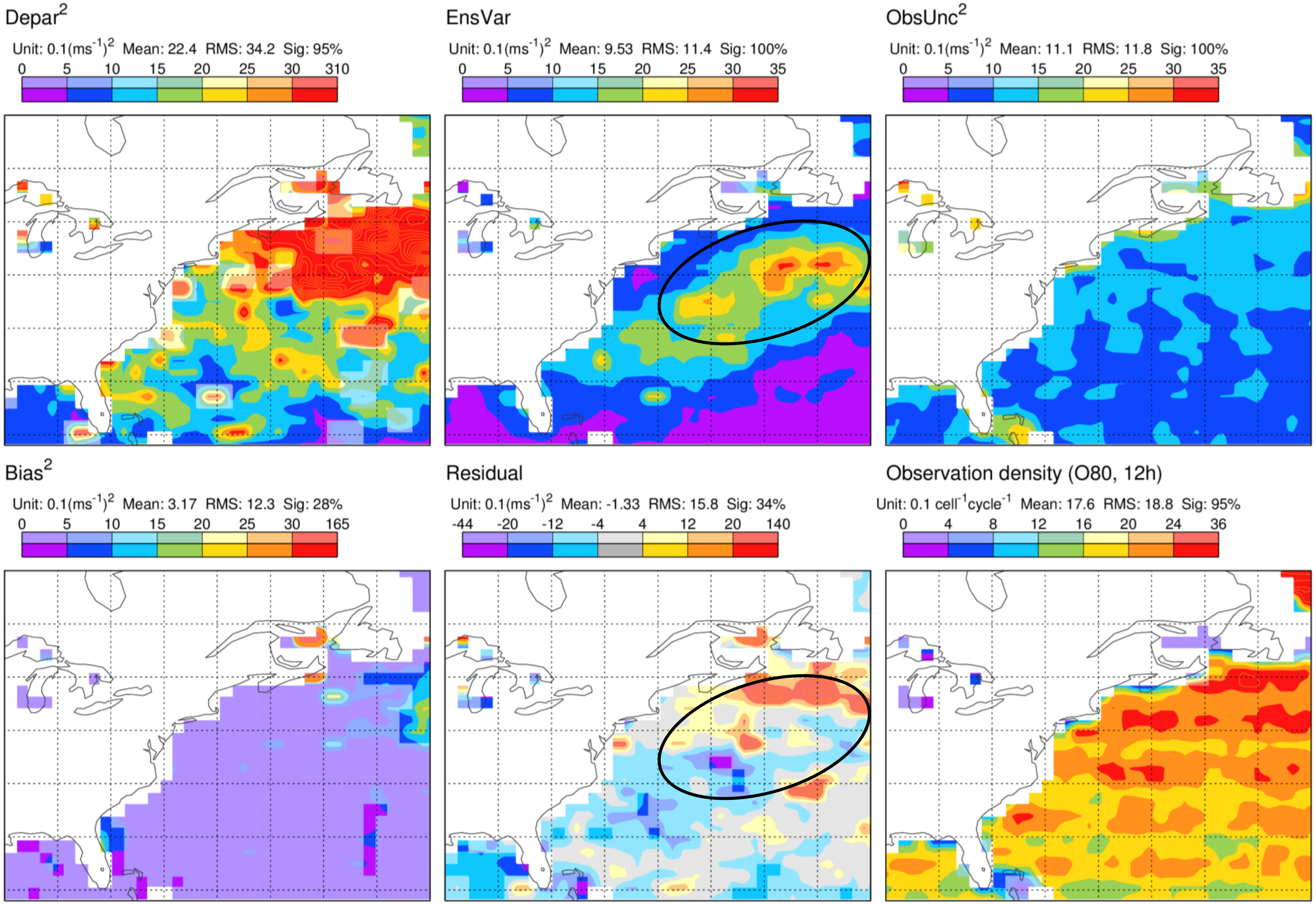
Cluster 3 (size 99)



Here, the main focus is on "Mesoscale Convective System" cluster, which is the most highly populated

Based on K-means clustering of the synoptically-filtered and normalised fields from the PV animation in the region indicated, for MAM 2017. Bold colors = 5% significance

Ensemble Data Assimilation variance budget based on scatterometer winds (45R1)



MAM 2017

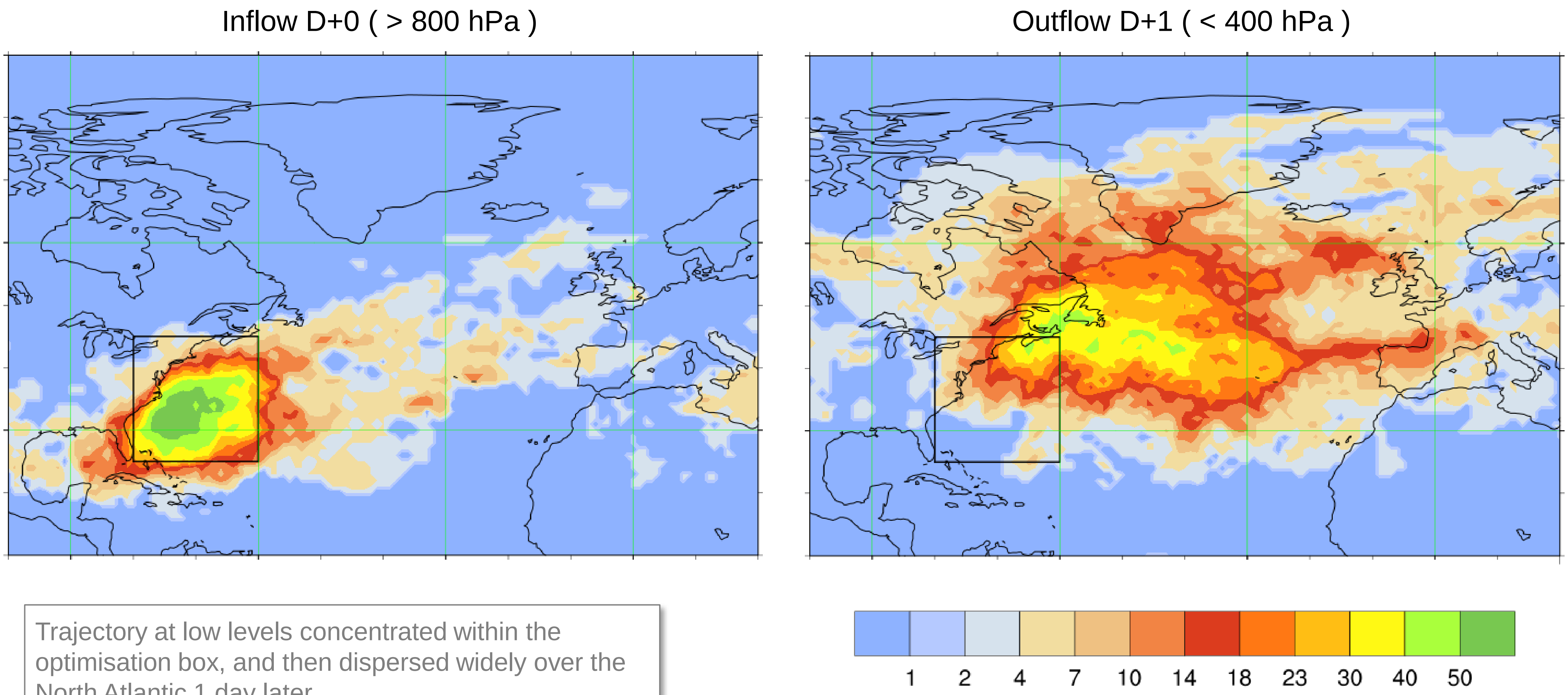
5% improved residual. Mixed signals for squared departures (mean 3% increase, RMS 8% decrease)

Future tuning (down) of observation error variance (ObsUnc²) should act to remove the blue from the Residual

Potential to reduce departures and ensemble variance (in subsequent cycle) …

Top 50 Warm Conveyor Belt inflow events in box indicated from Nov 15 – Oct 16

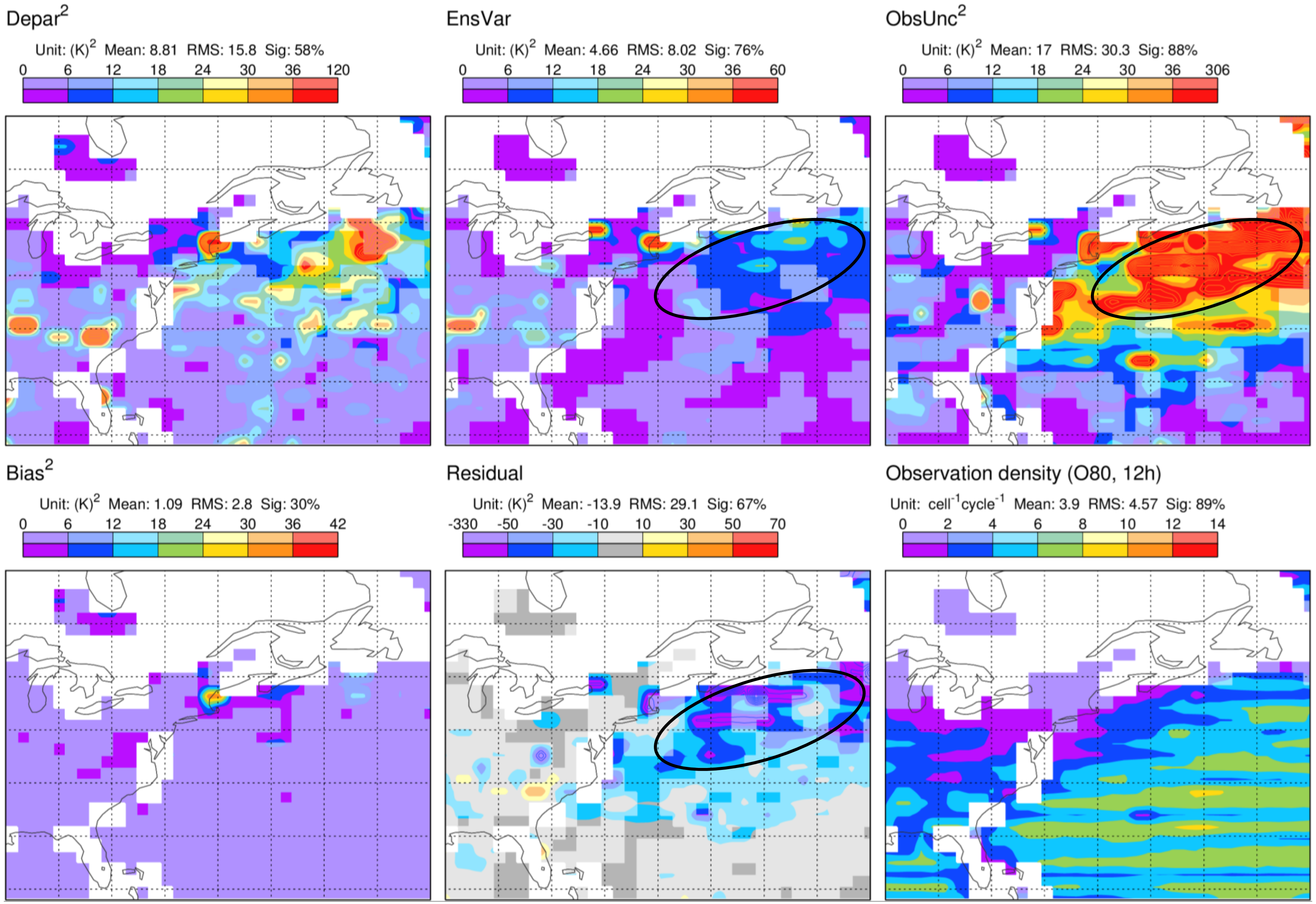
From Heini Werni



Trajectory at low levels concentrated within the optimisation box, and then dispersed widely over the North Atlantic 1 day later

Based on trajectories ascending by more than 600 hPa in 2d

Flow-dependent EDA error growth-rate evaluation using MHS All-Sky channel 5



Warm Conveyor Belt cluster
Sensitive to H_2O 750-400 hPa

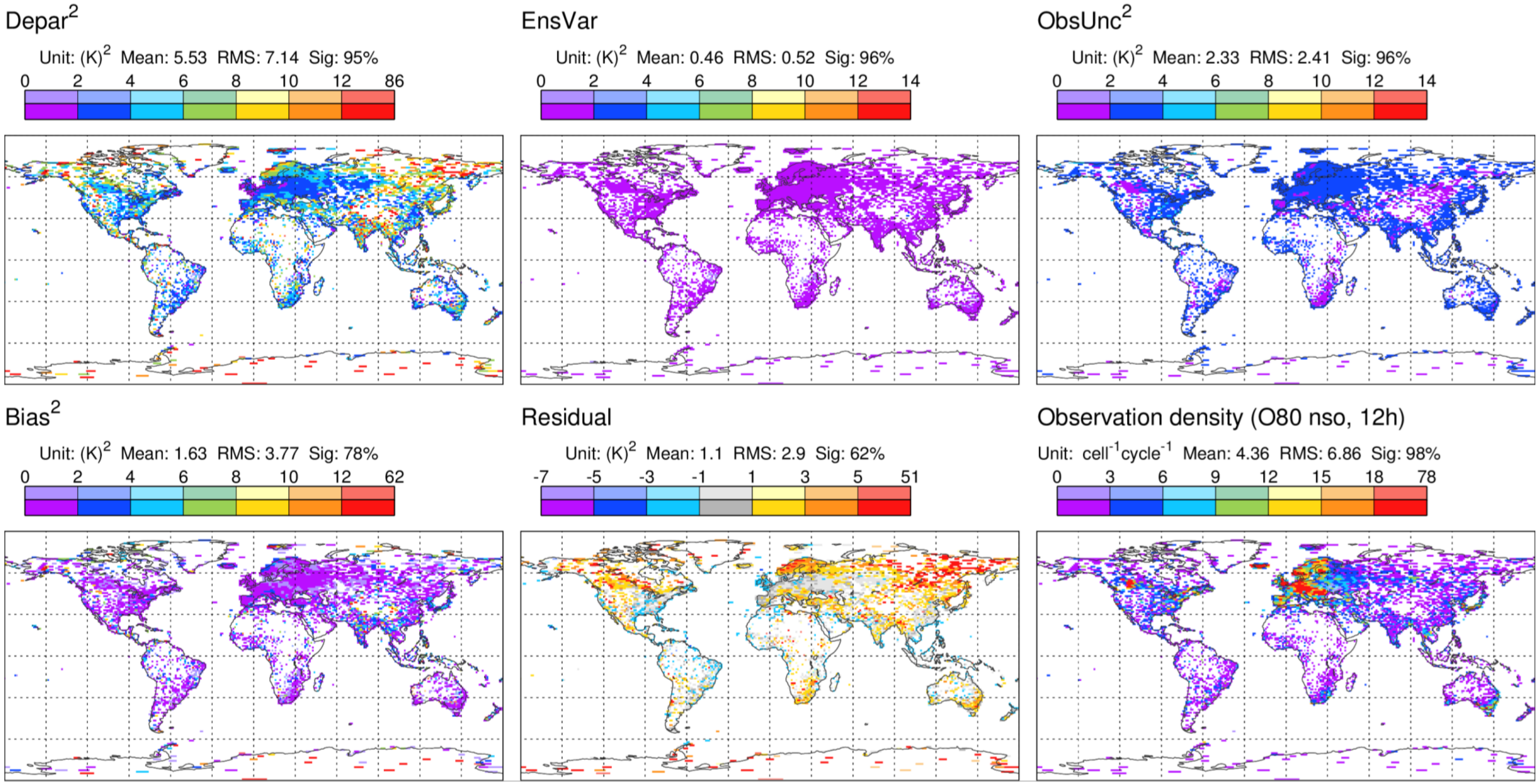
MAM 2017

Budget suggests these observations are currently down-weighted (large ObsUnc^2).

Highly non-linear forward operators in cloudy conditions, and deep weighting functions make it difficult to increase weight given to these observations.

Little physics or observational Bias^2

Error growth-rate evaluation. Based on EDA surface assimilation of *in situ* T2m.



IFC cycle 45r1, MAM 2018. No prior aggregation of observations

Observation uncertainty is a bigger term than ENS variance – even with boundary-layer stochastic physics.

Residual has some blue regions (e.g. UK). Hence observation & grid-scale-model uncertainty not under-done.

Thus indication is that positive residuals in mountainous regions are associated with ENS variance deficit due to lack of representativity of sub-grid variations

Trend in probabilistic forecast performance. Leadtime at which CRPSS drops to 0.1

Continuous Rank Probability Skill Score (CRPSS) for extratropical precipitation verified against 24h observed accumulations