Representing uncertainties

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Acknowledgements

- Stephanie Johnson, Massimo Bonavita
- Martin Janousek, Thomas Haiden, Zied Ben Bouallegue
- Scientists, forecasters and users in Member and Co-operating States and beyond
- Past and present ECMWF colleagues and management

ECMWF

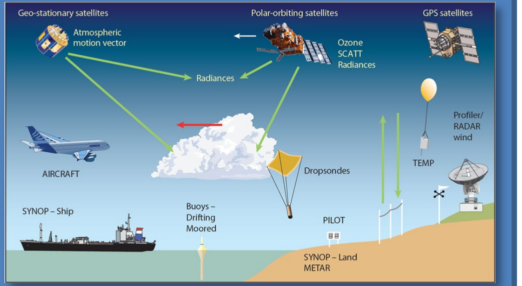
Every ensemble requires representations of uncertainties

AIFS-Diffusion
AIFS-CRPS

at ECMWF: Quantifying uncertainties globally from hours to seasons ahead

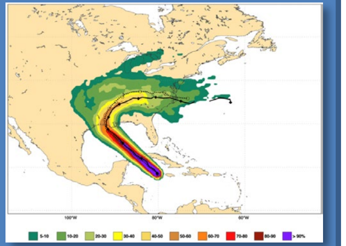
Ensemble of data assimilations

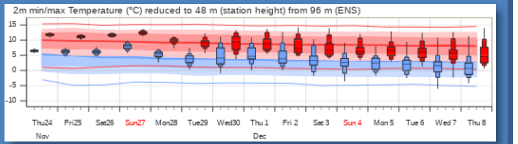
12 hours



Medium-range ensemble

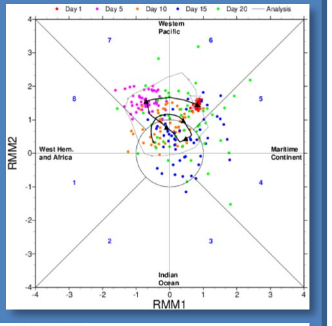
15 days

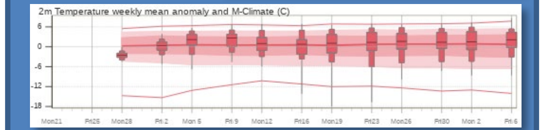




Sub-seasonal ens.

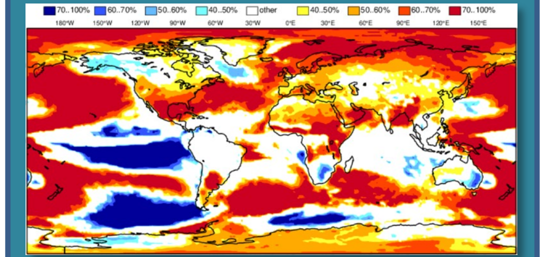
46 days





Seasonal ensemble

7 (13) months

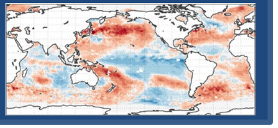


ERA5/6 DA ensembles

reforecast ensemble

reforecast ensemble

ocean analysis ensemble

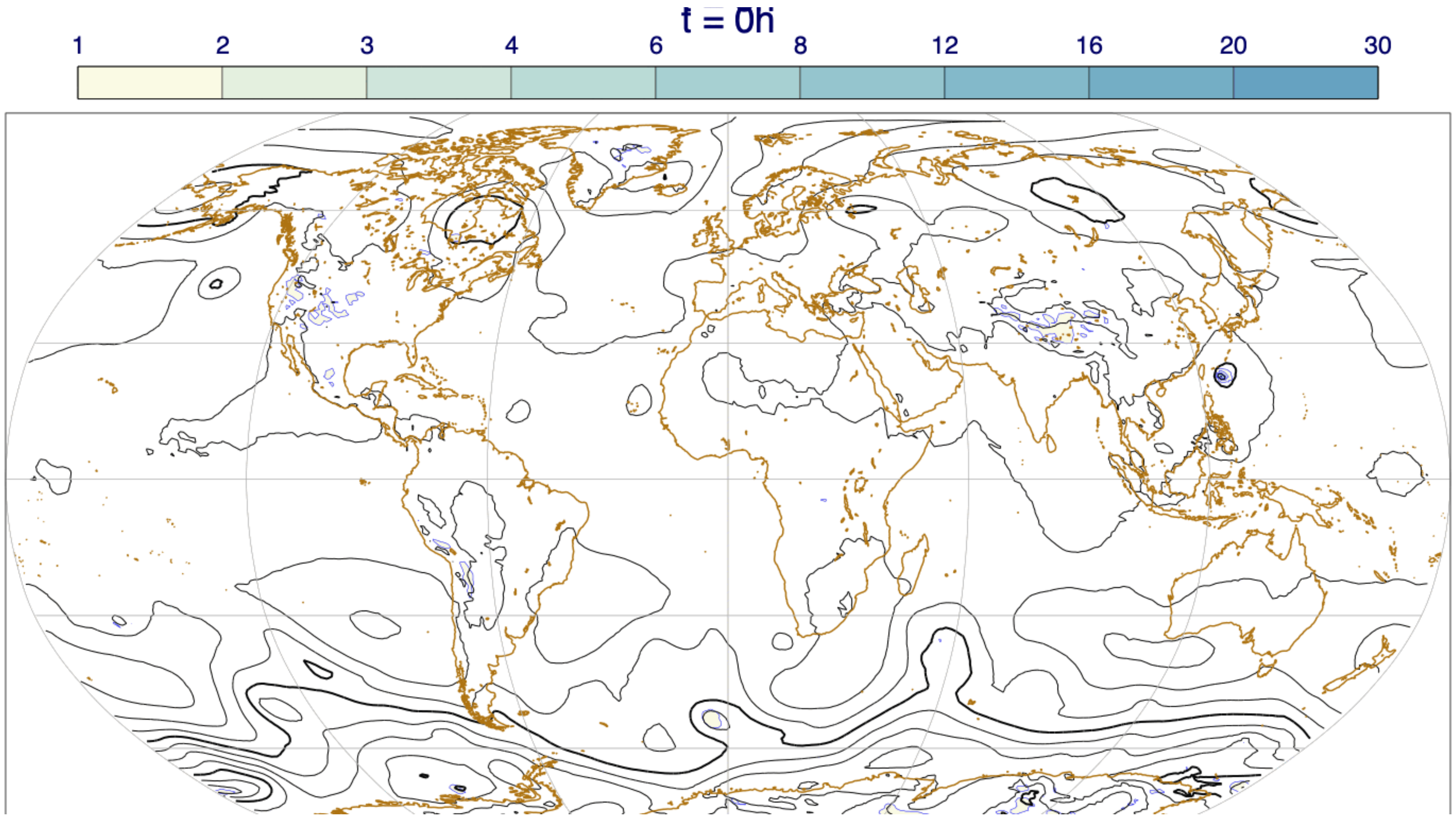


and in our Member and Cooperating States including many limited-area model ensembles

and beyond see, e.g., a dozen global ensembles are now in the [TIGGE] and [S2S] databases

Quantifying forecast uncertainties

- knowing forecast uncertainty helps greatly in decision making
- forecast uncertainty varies
- ensembles predict situation dependent uncertainty



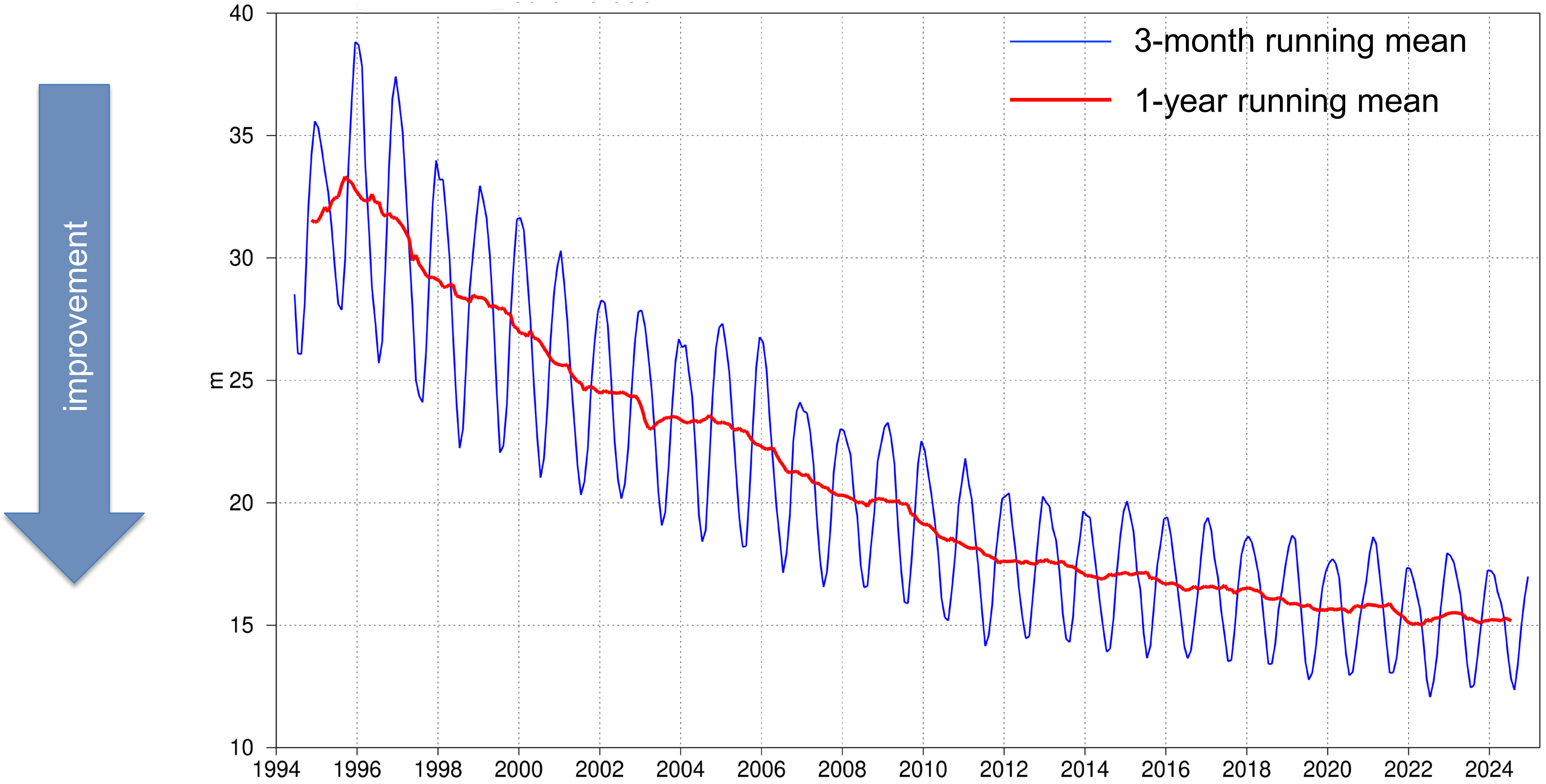
mean sea level pressure, ensemble spread (shading), ensemble mean (contours)
operational medium-range ensemble from 1 Sep 2022, 0 UTC, up to Day 5

Evolution of the improvements over 30 years

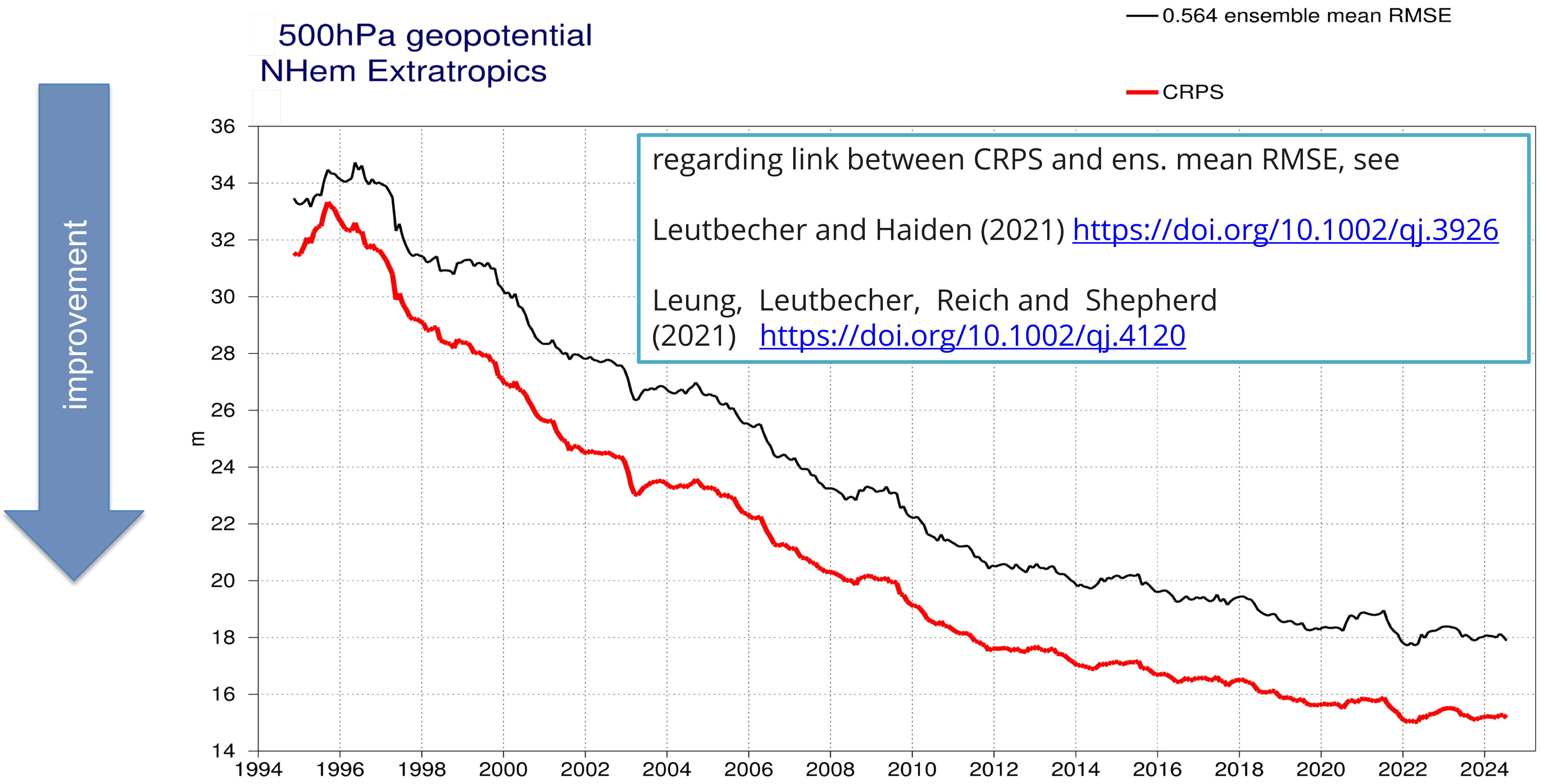
- scores start with the beginning of daily medium-range ensemble forecasts in 1994

- use **Continuous Ranked Probability score (CRPS)**
  - mean squared error of the cumulative distribution
  - skill increases with decreasing CRPS
  - rewards reliability
  - rewards sharpness
  - summary measure used for the ECMWF headline score

Day 5 N-Hem extratropics 500 hPa geopotential probabilistic skill



Day 5 N-Hem extratropics 500 hPa geopotential probabilistic skill

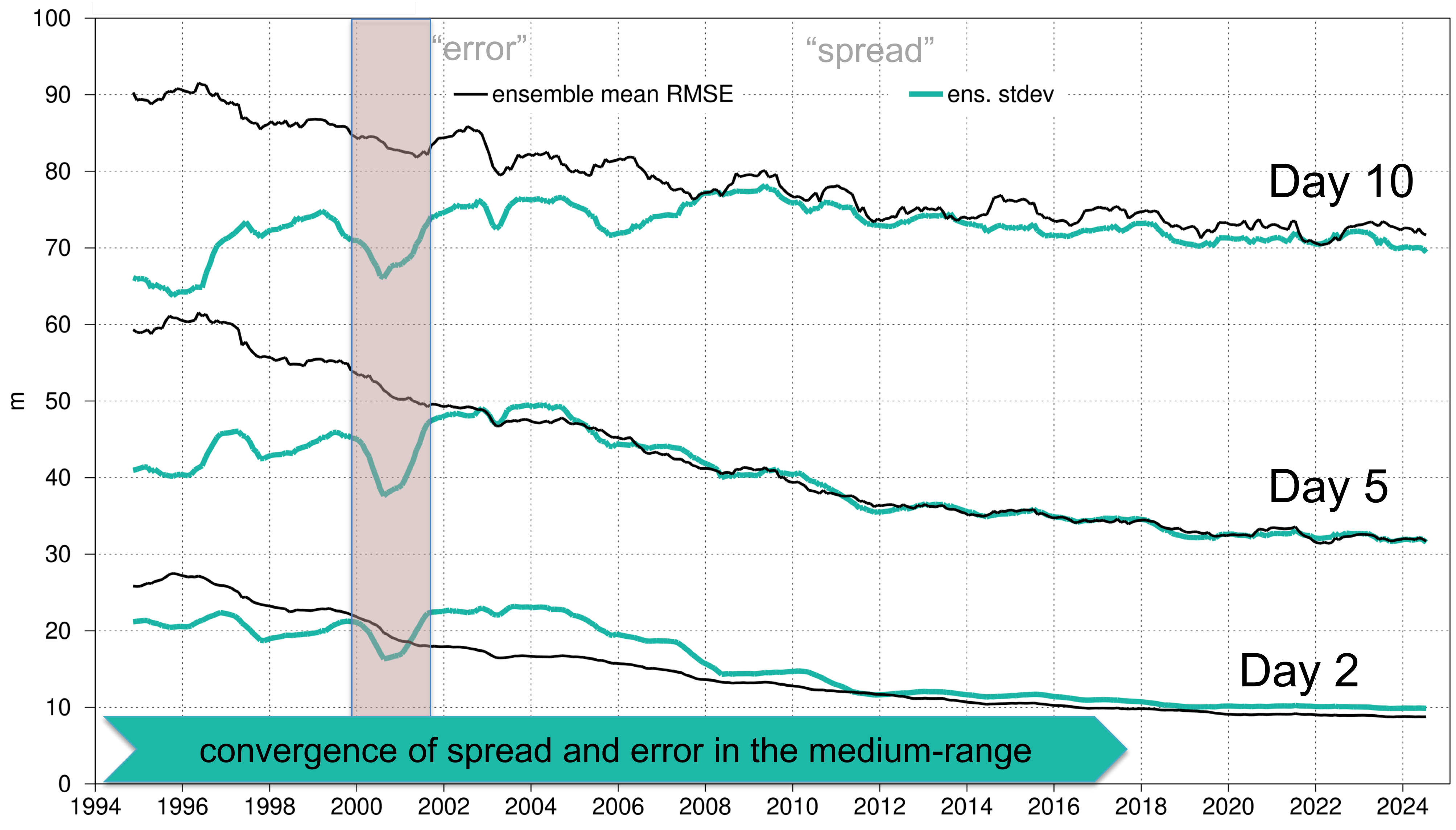


regarding link between CRPS and ens. mean RMSE, see

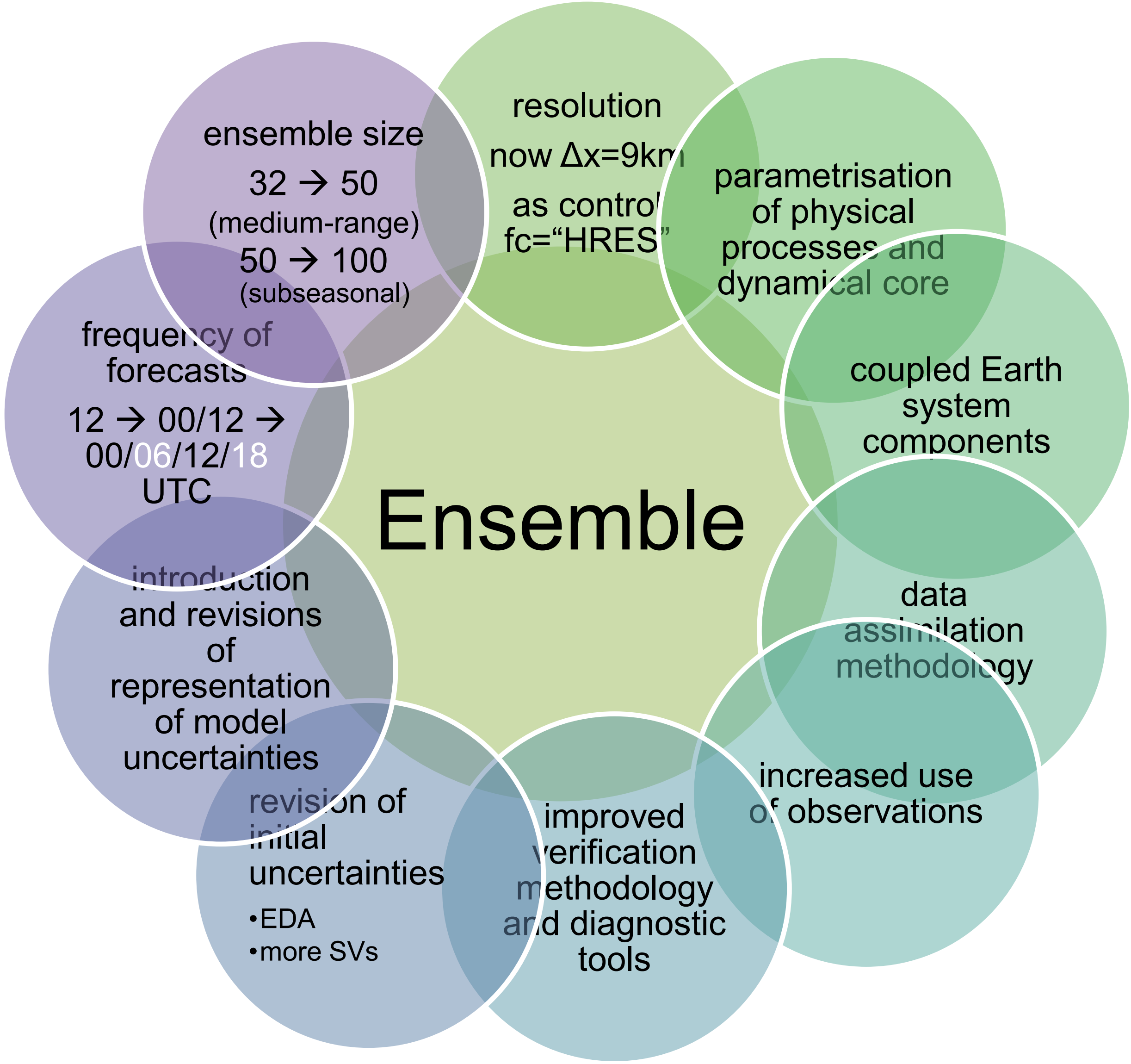
Leutbecher and Haiden (2021) https://doi.org/10.1002/qj.3926

Leung, Leutbecher, Reich and Shepherd (2021) https://doi.org/10.1002/qj.4120

Towards more reliable and sharper forecasts — Z500 N-Hem extratropics



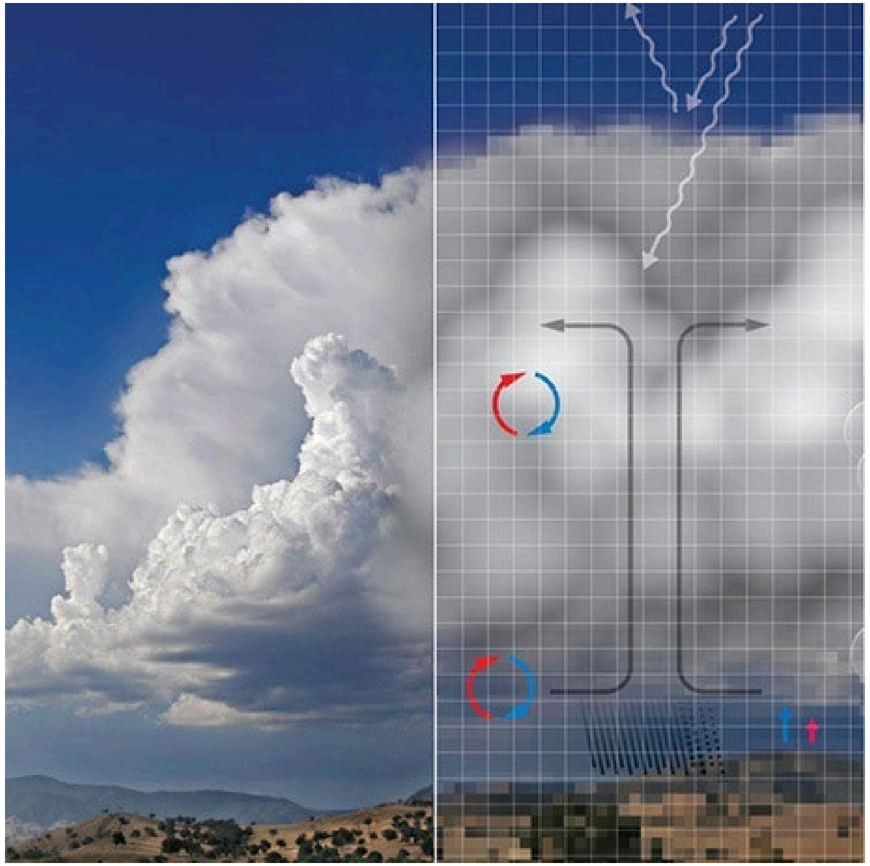
Many different contributions that led to improvements



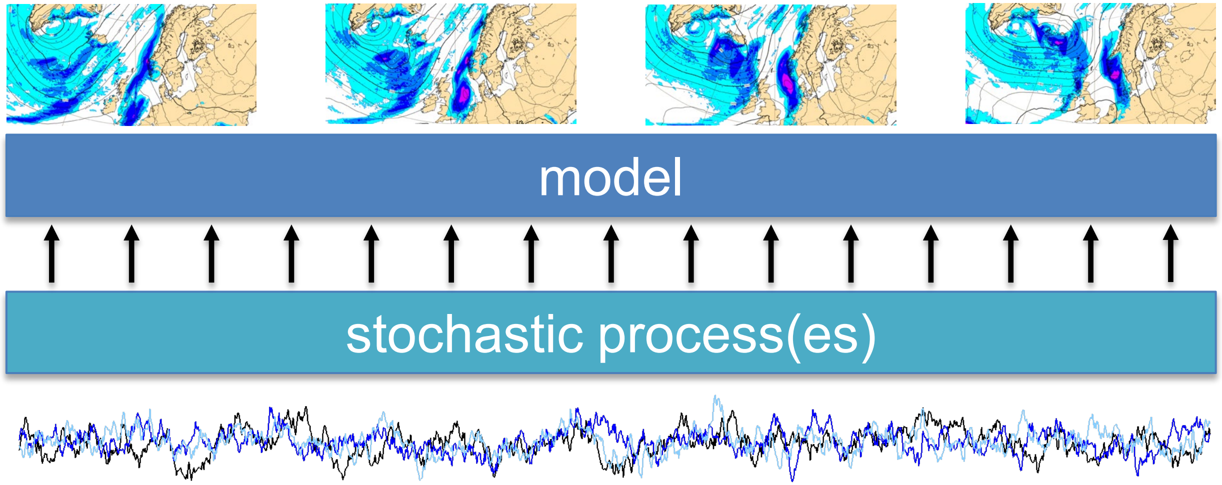
All models are imperfect

Earth System **Model**

$$\mathbf{x}(t) \rightarrow \mathbf{x}_S(t+\Delta t) \qquad \mathbf{x}(t) \rightarrow \mathbf{x}_M(t+\Delta t)$$

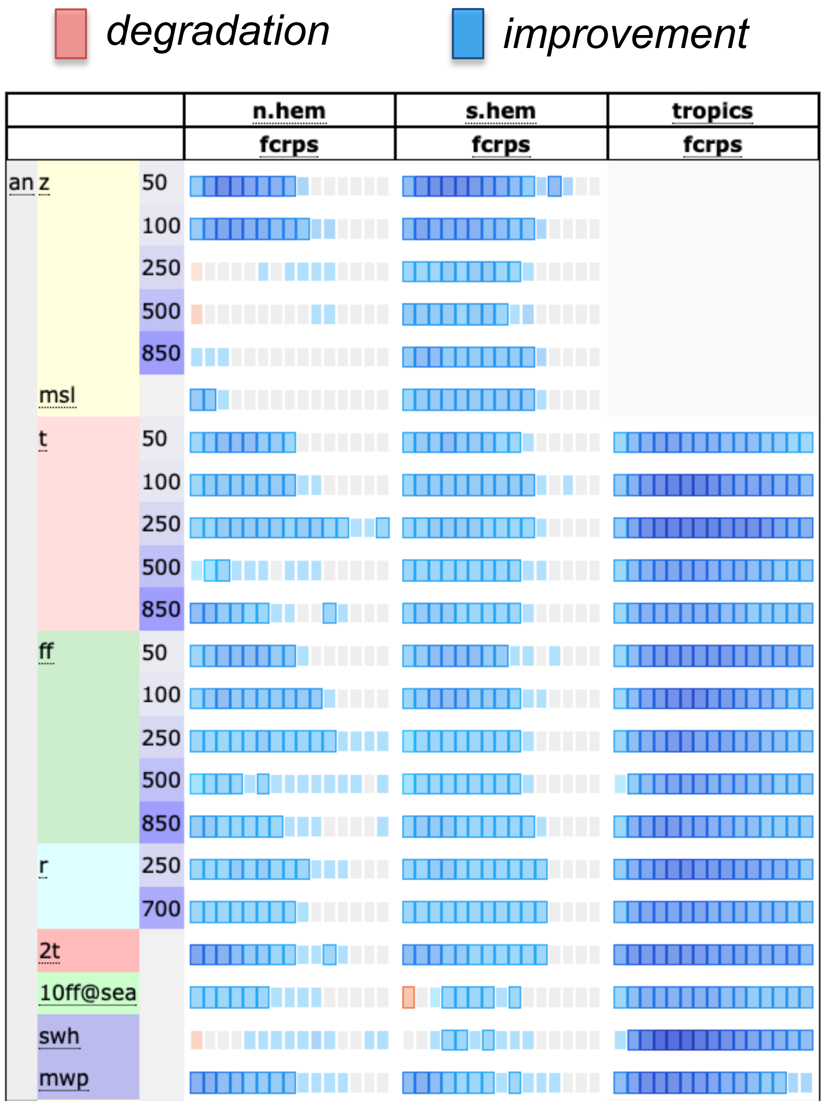


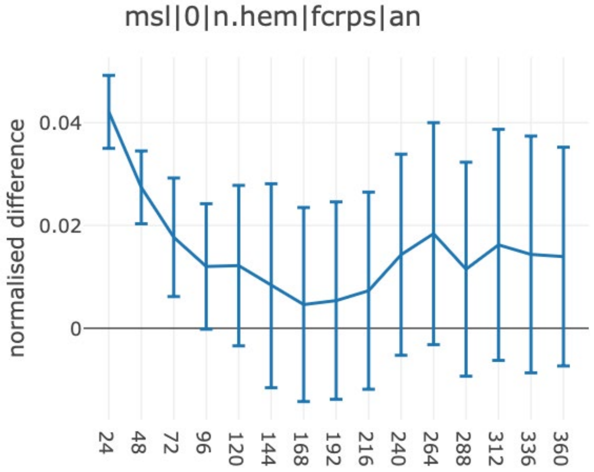
- representing random errors of model improves reliability of ensemble
- Stochastic representation of model uncertainties

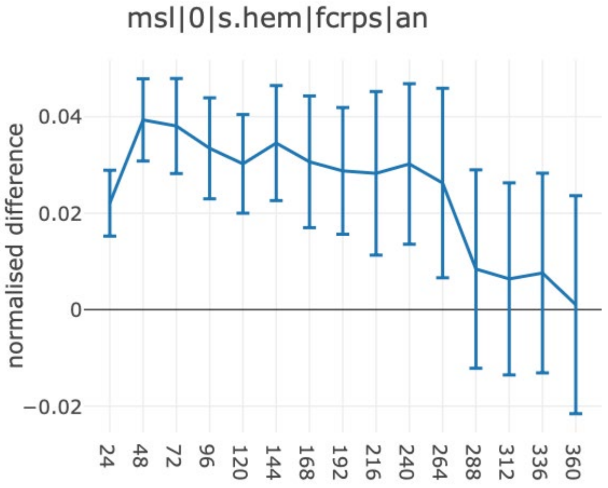


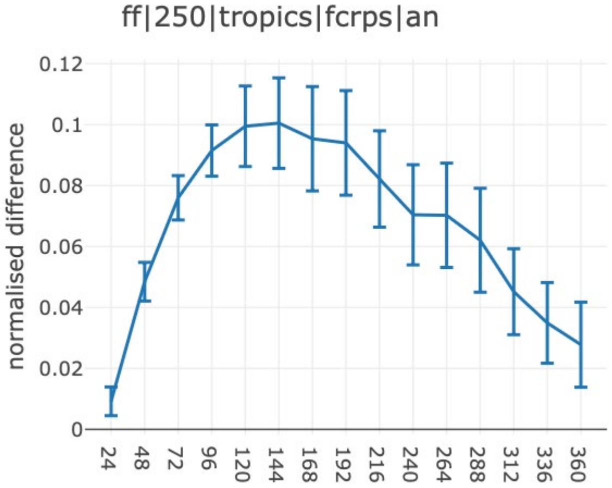
Impact of switching on the model uncertainty representation (SPP)

IC Perts + SPP *versus* IC perts









Experiments

- CY49R1
- 29 km ENS (TCo399)
- 8 ensemble members
- Starts: 00 UTC every day, Dec+Jan+Feb 2022/23
- Forecast period: 15 days
- IC perturbations: EDA (with SPP), SVs, ocean ICs

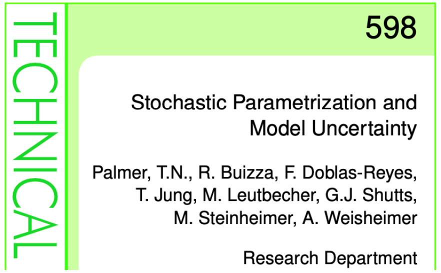
Milestones in representing model uncertainties in the IFS

SPPT, 1998 *Q. J. R. Meteorol. Soc.* (1999), **125**, pp. 2887–2908

Stochastic representation of model uncertainties in the ECMWF Ensemble Prediction System

By R. BUIZZA*, M. MILLER and T. N. PALMER
European Centre for Medium-Range Weather Forecasts, UK

SPPT, 2010


TECHNICAL
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Stochastic Parametrization and Model Uncertainty
Palmer, T.N., R. Buizza, F. Doblas-Reyes, T. Jung, M. Leutbecher, G.J. Shutts, M. Steinheimer, A. Weisheimer
Research Department

SPPT, 2017

Lock et al (2019) https://doi.org/10.1002/qj.3570

SKEB 2010–2017

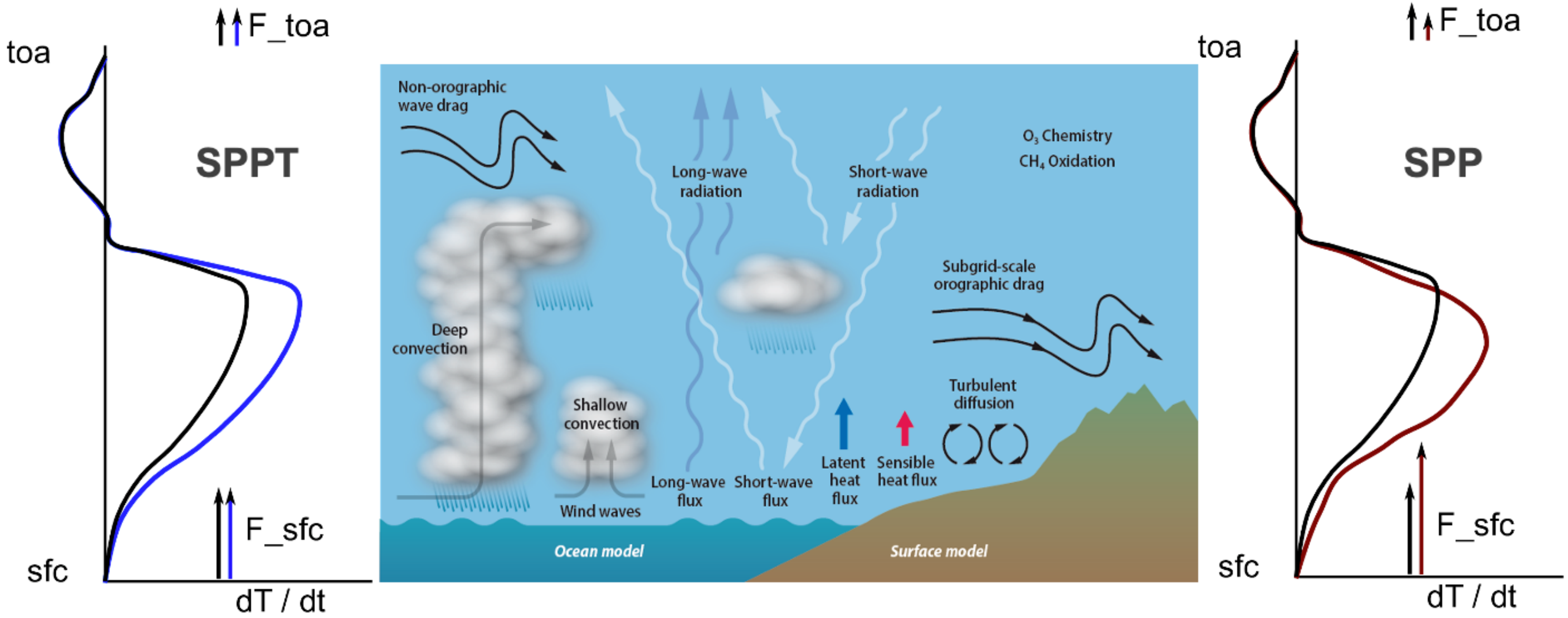
Berner et al (2009) 10.1175/2008JAS2677.1

SPP, 2024

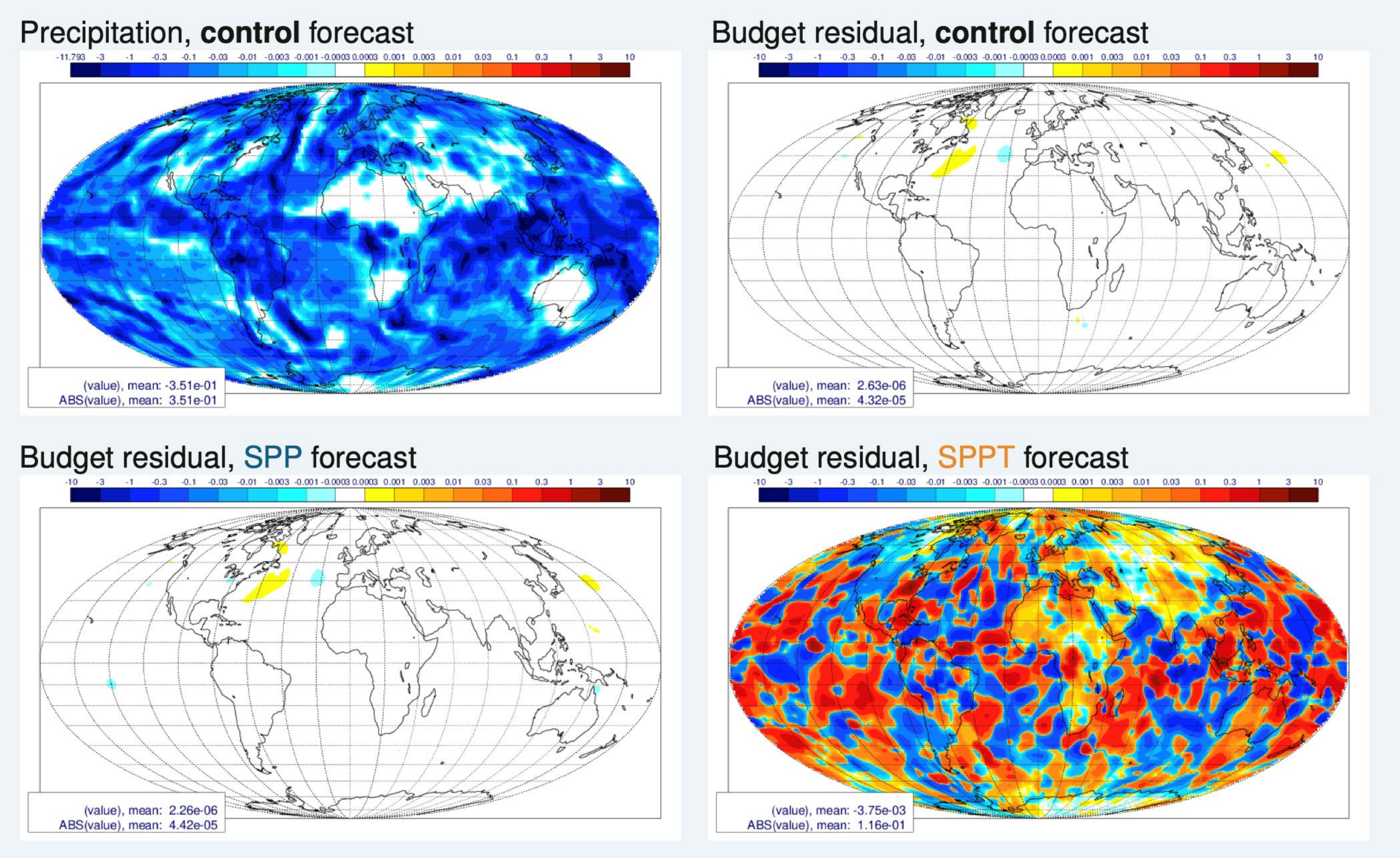
Leutbecher, M., Lang, S., Lock, S.J., Roberts, C.D. and Tsiringakis, A., 2024. Improving the physical consistency of ensemble forecasts by using SPP in the IFS. ECMWF Newsletter **181**

SPP has replaced SPPT

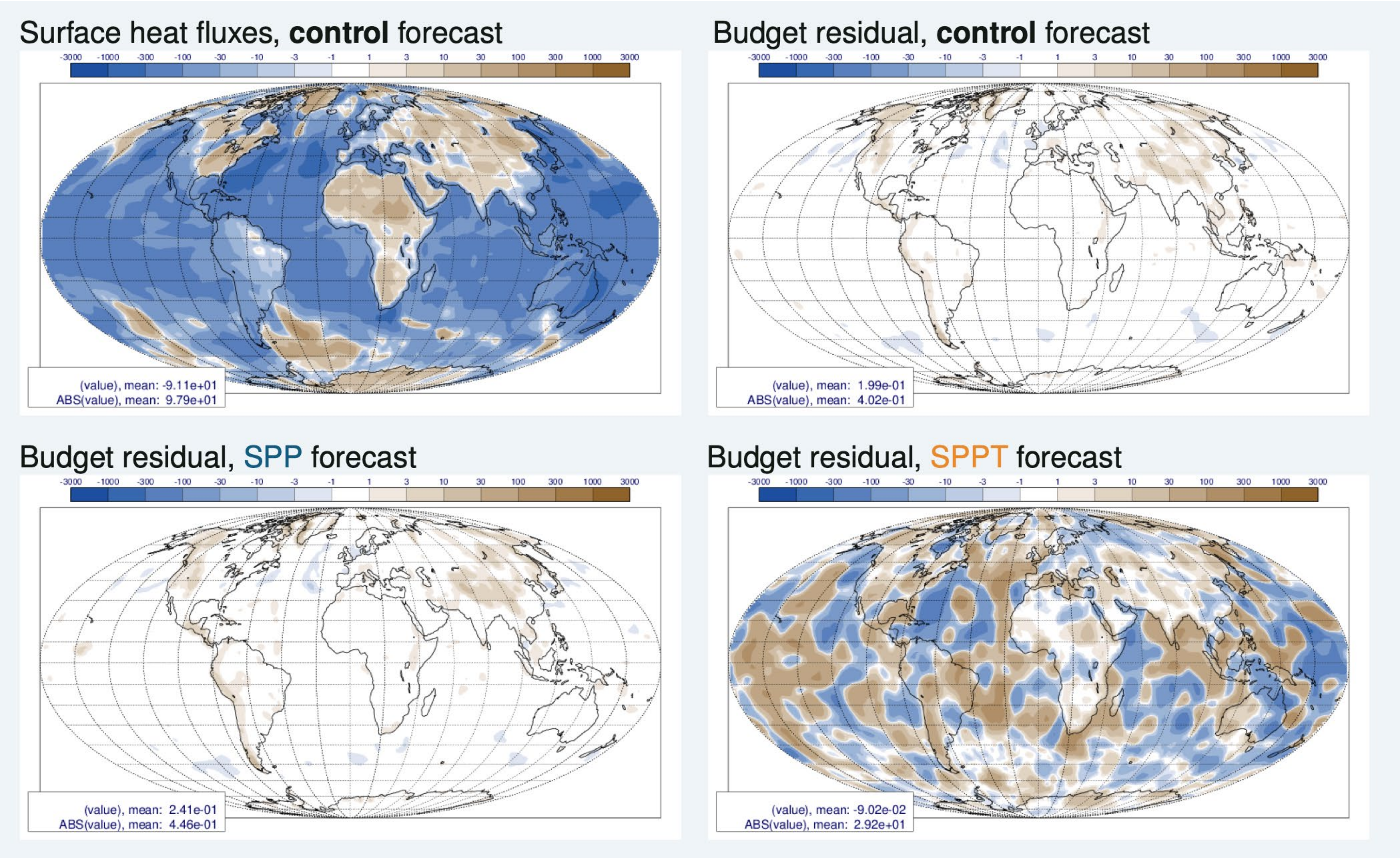
- Great collaboration with Memberstates (ACCORD, Meteo-France) on common code
- SPP represents model uncertainties closer to the assumed sources of the errors
- SPP better maintains physical consistency: e.g. local budgets and flux perturbations
- SPPT represents amplitude errors while SPP also represents errors in the shape of a heating profile



Moisture conservation (mm in 3 h)



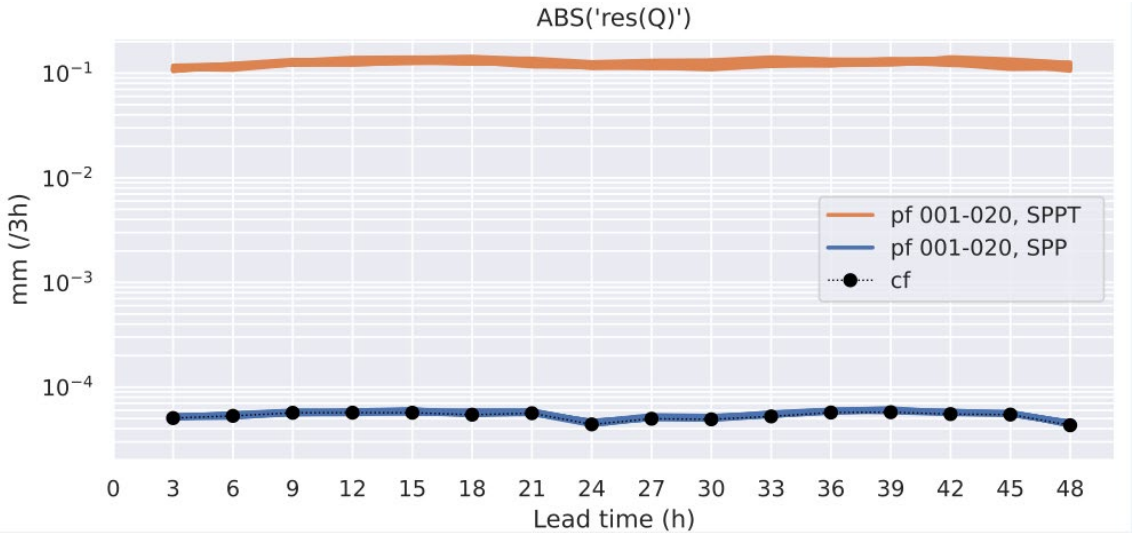
Enthalpy conservation (W/m^2)



Local conservation

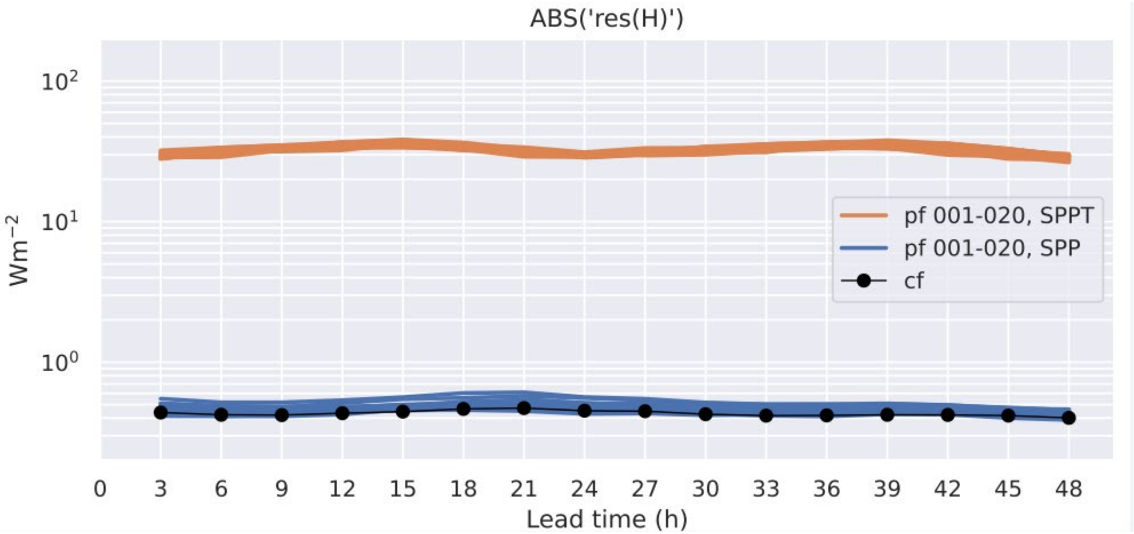
Moisture

$$\frac{1}{g}\int_{p_{\rm surf}}^{0}\left(\frac{dq_{\rm v}}{dt}+\frac{dq_{\rm l}}{dt}+\frac{dq_{\rm i}}{dt}+\frac{dq_{\rm r}}{dt}+\frac{dq_{\rm s}}{dt}\right)dp = F_{\rm prs}+F_{\rm e}$$



Enthalpy

$$\frac{c_{\rm pd}}{g}\int_{p_{\rm surf}}^{0}\frac{dT}{dt}dp+\frac{L_{\rm v0}}{g}\int_{p_{\rm surf}}^{0}\frac{dq_{\rm v}}{dt}dp-\frac{L_{\rm s0}-L_{\rm v0}}{g}\int_{p_{\rm surf}}^{0}\frac{dq_{\rm i}+dq_{\rm s}}{dt}dp = F_{\rm s}+L_{v0}F_{\rm q_v}-\left(L_{s0}-L_{v0}\right)F_{\rm q_s}-F_{\rm rad}^{\rm top}+F_{\rm rad}^{\rm surf}-D_{\rm diss}^{KE}$$



Stochastic representation of model uncertainties: What’s next?

- Revise SPP momentum transport perturbations to reduce 10-metre wind spread
- Extend SPP to coupled processes, e.g. land-surface
- Uncertainty representation in ocean and sea-ice model
- Dynamical core uncertainties, e.g. STOCHDP
- Hybrid uncertainty representation in IFS ensembles nudged with AIFS-CRPS

Milestones in representing initial uncertainties in the IFS

Singular vectors, 1992; see Molteni et al (1996) https://doi.org/10.1002/qj.49712252905

- Evolved singular vectors added,
- Tropical cyclone targeted SV perturbations added
- Number of SVs increase
- Gaussian sampling to create perturbations from SVs

Ensemble of data assimilations EDA, 2010

- Buizza et al (2008), https://doi.org/10.1002/qj.346
- EDA resolution: TL399 in 2010, TCo639 in 2013, **TCo1279** in 2024
- EDA ensemble size: 10 member in 2010, 25 member in 2013, **50 member** in 2019 (exchangeability)
- Consistent representation of model uncertainties in EDA and ensemble forecasts since 2018

Ensemble initial conditions from an EDA and an unperturbed analysis

k-th perturbed IC = AN + k-th EDA member − EDA mean
= k-th EDA member + (AN − EDA mean)
where k=1, 2, … , 50

Quarterly Journal of the Royal Meteorological Society   *Q. J. R. Meteorol. Soc.* (2015) DOI:10.1002/qj.2543

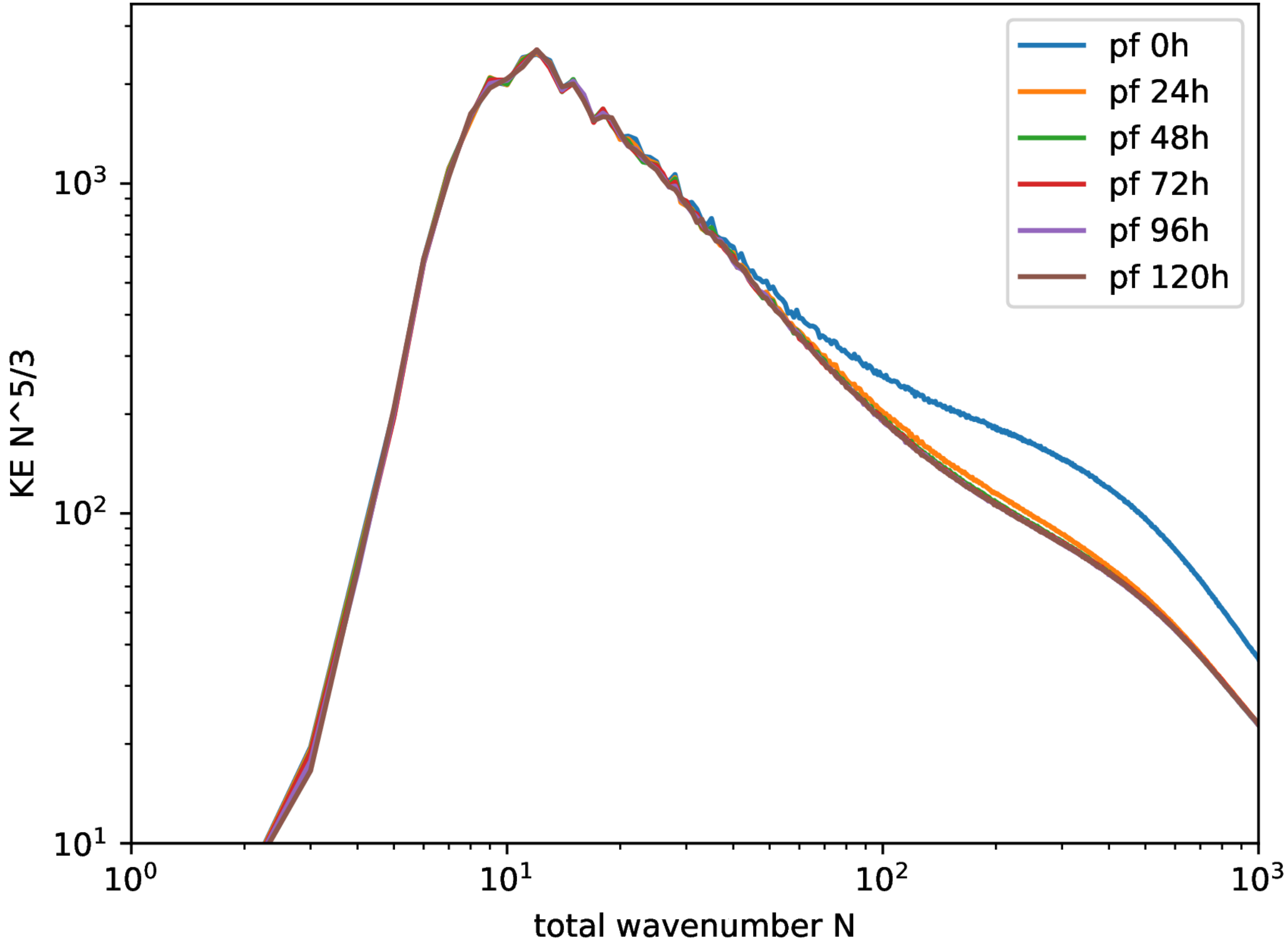
see also

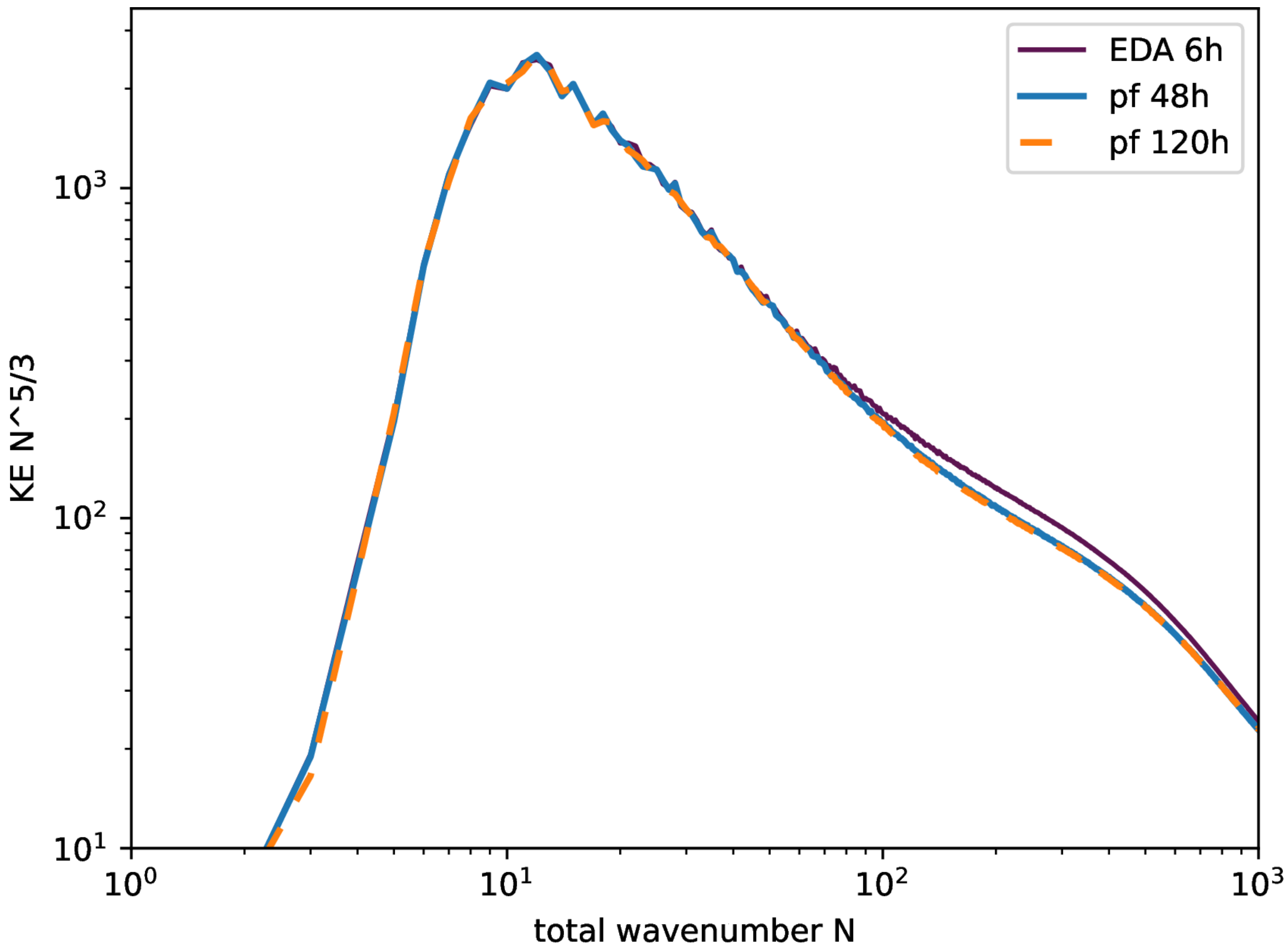
RMetS
Royal Meteorological Society

On the impact of re-centring initial conditions for ensemble forecasts

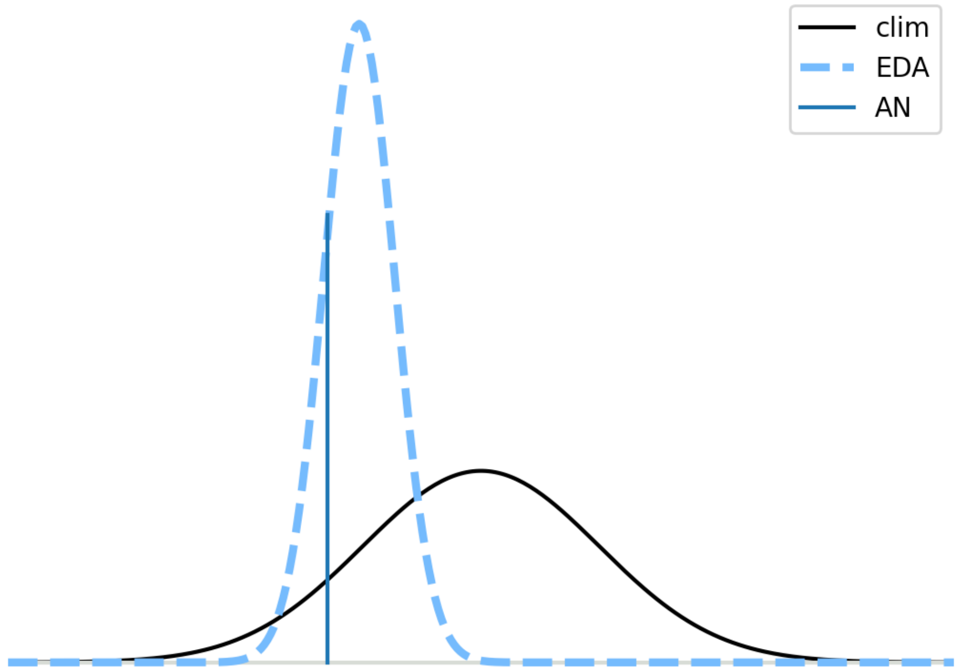
Simon T. K. Lang,* Massimo Bonavita and Martin Leutbecher
European Centre for Medium-Range Weather Forecasts, Reading, UK

Kinetic energy spectra at 250 hPa

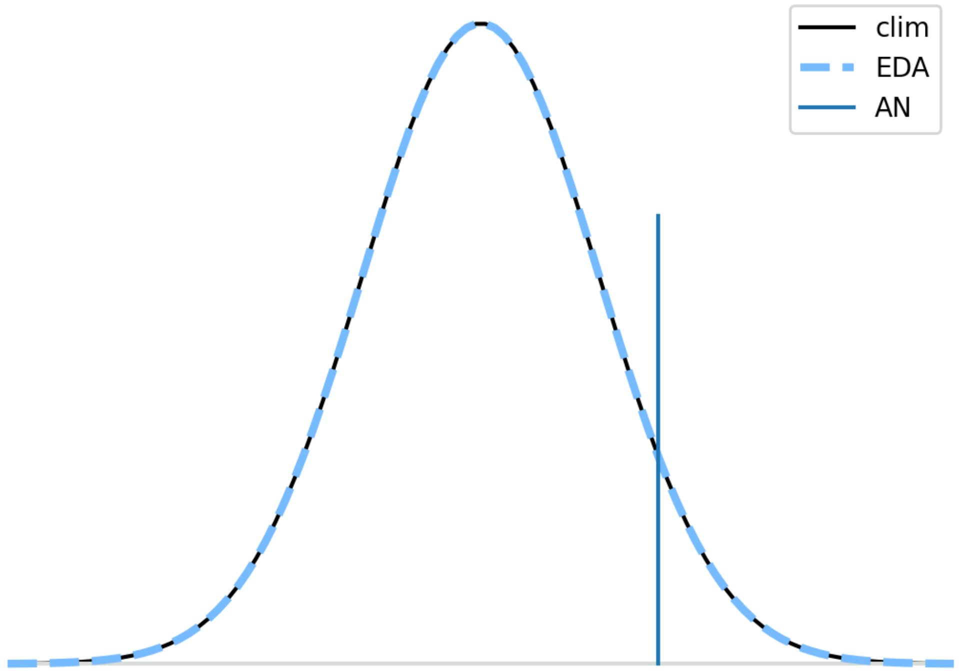




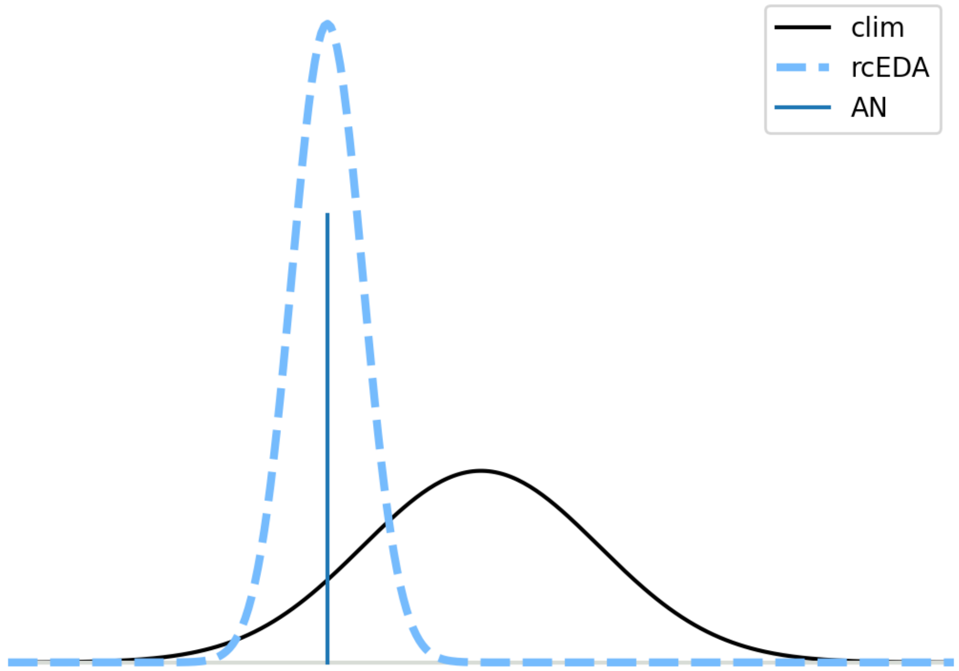
EDA 6h
pf 48h
pf 120h
KE N^5/3
10^1
10^2
10^3
10^0
10^1
10^2
10^3
total wavenumber N

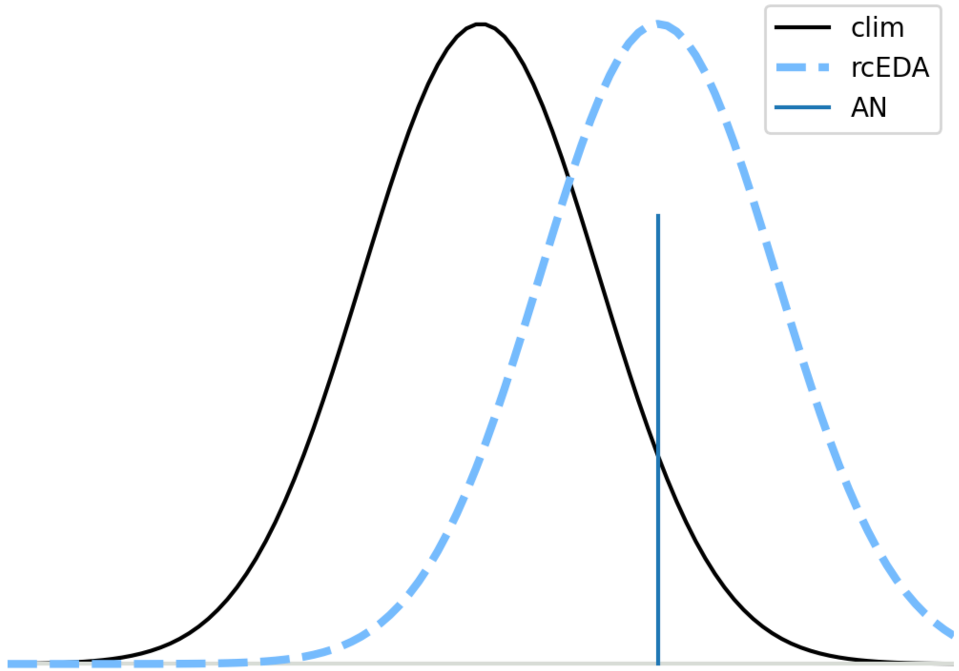


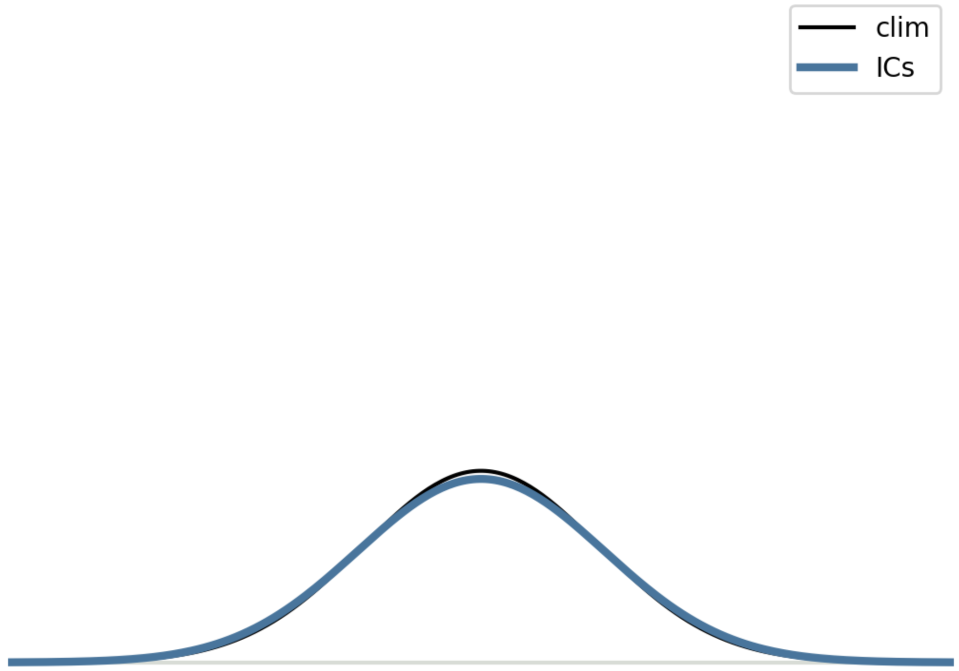
well constrained direction in phase space, e.g. large scales

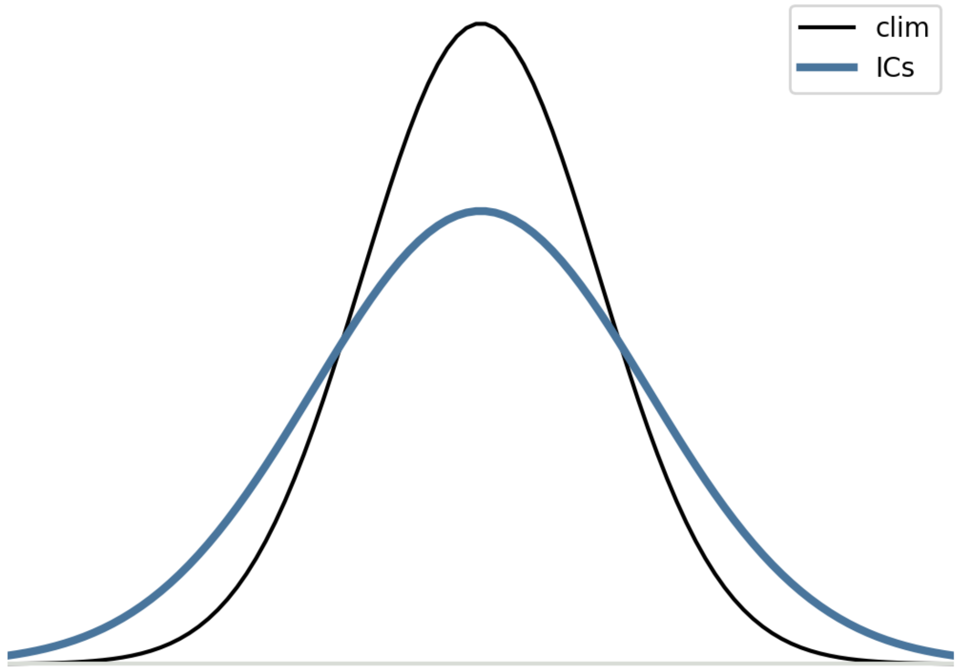


poorly constrained direction in phase space, e.g. small scales

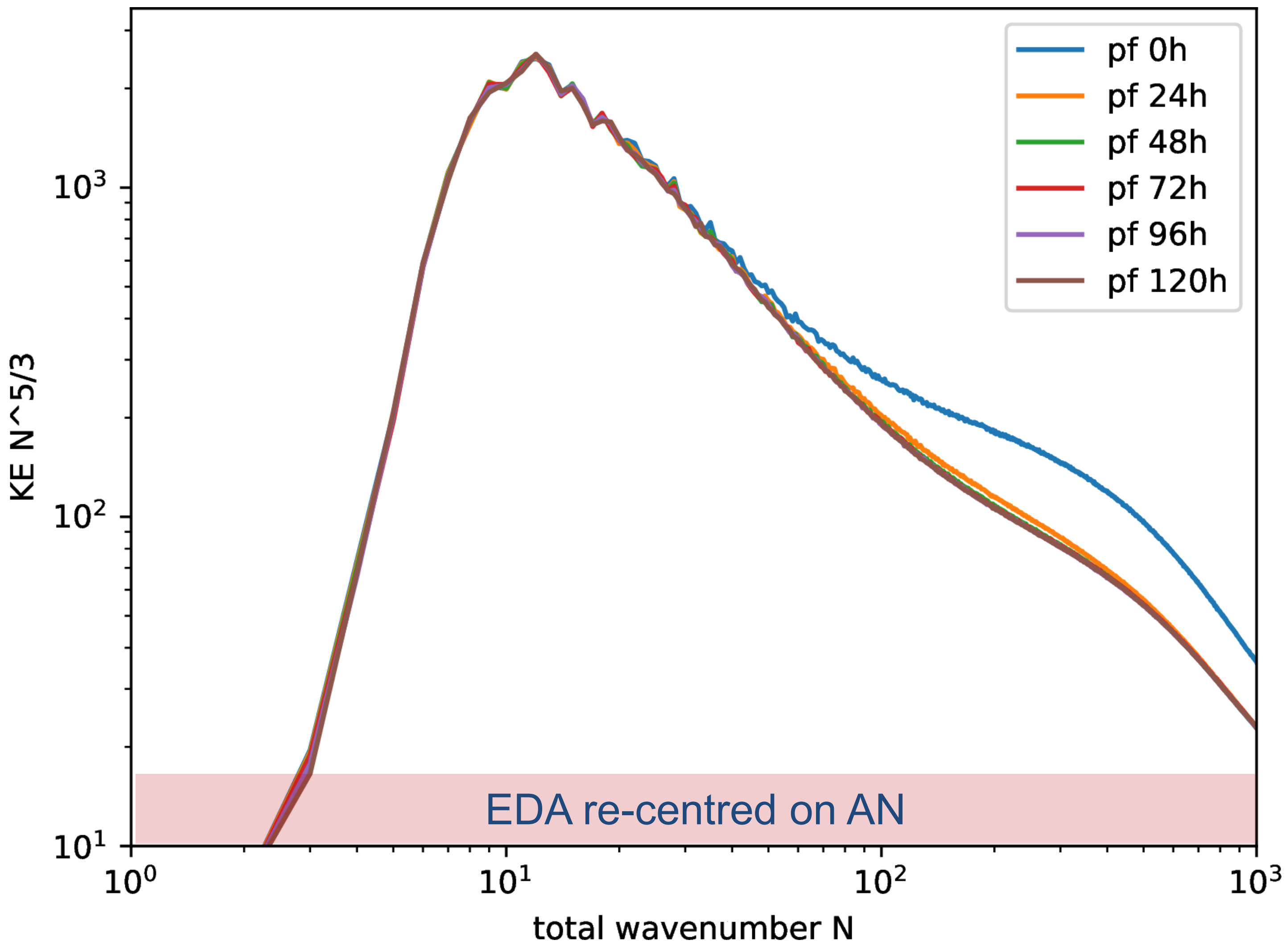

clim
rcEDA
AN


clim
rcEDA
AN

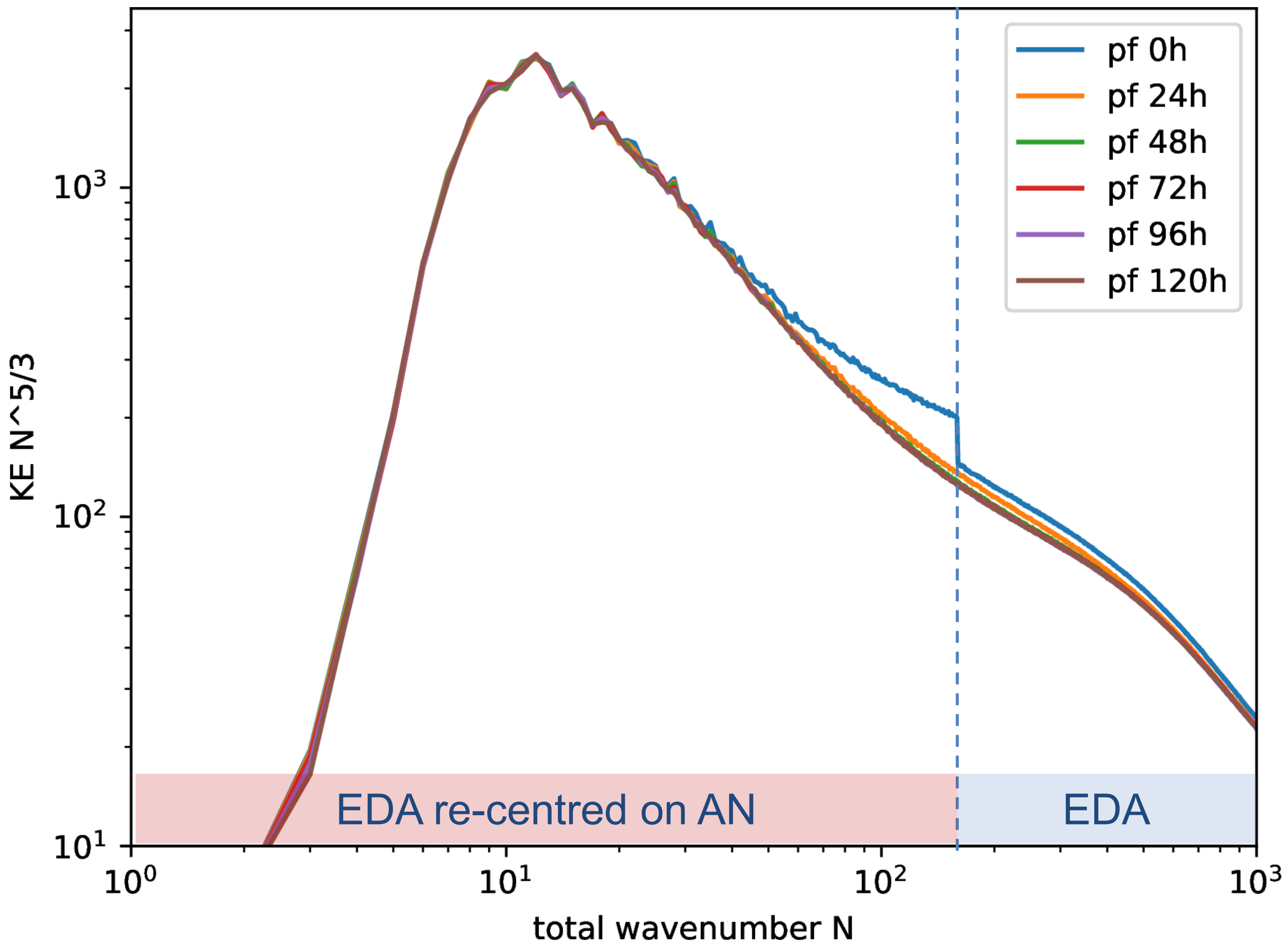

clim
ICs


clim
ICs

Kinetic energy spectra at 250 hPa



Scale-dependent EDA re-centring: KE spectra at 250 hPa



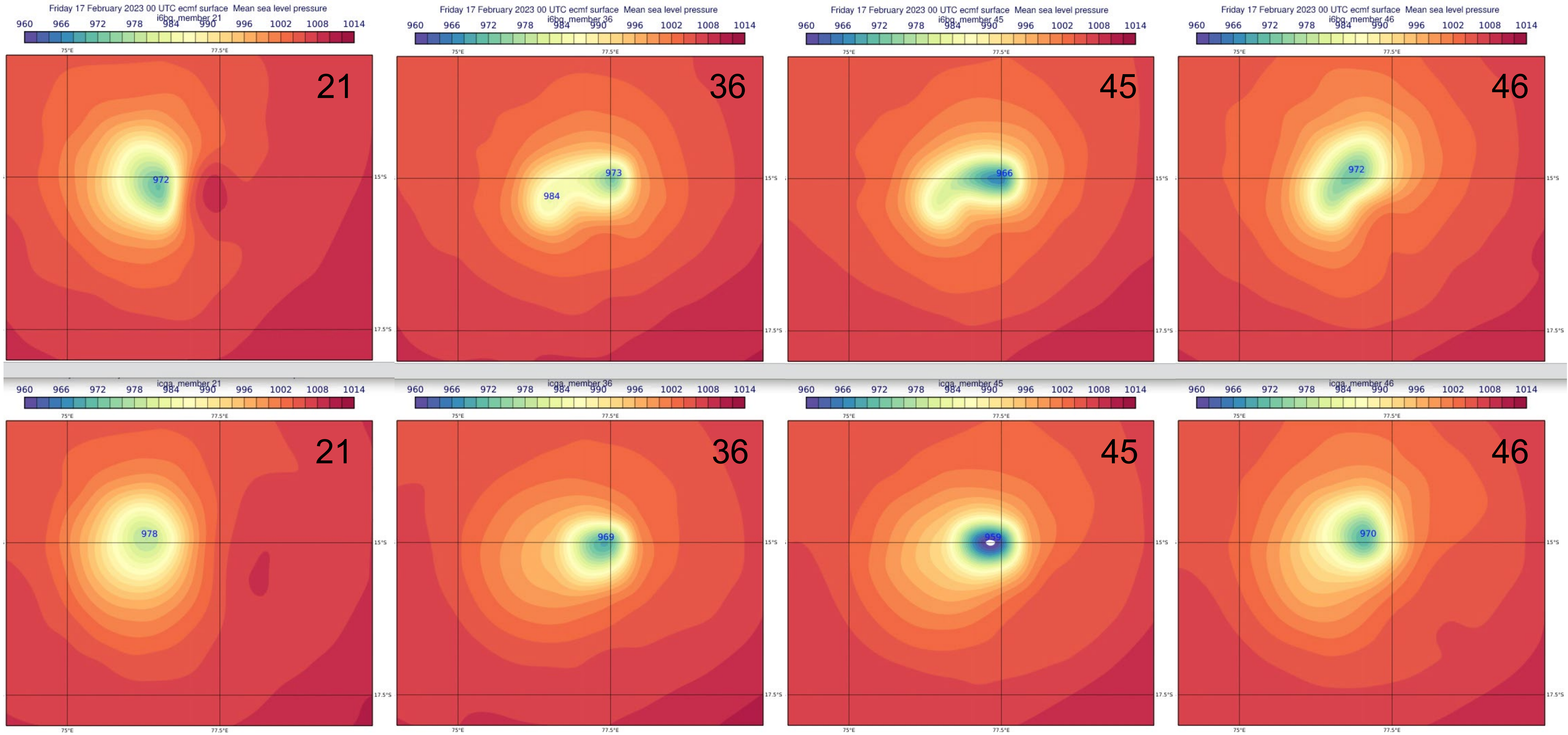
TC Freddy, 17 Feb 2023, 0UTC, mean sea level pressure t=0h

re-centred EDA

49r1

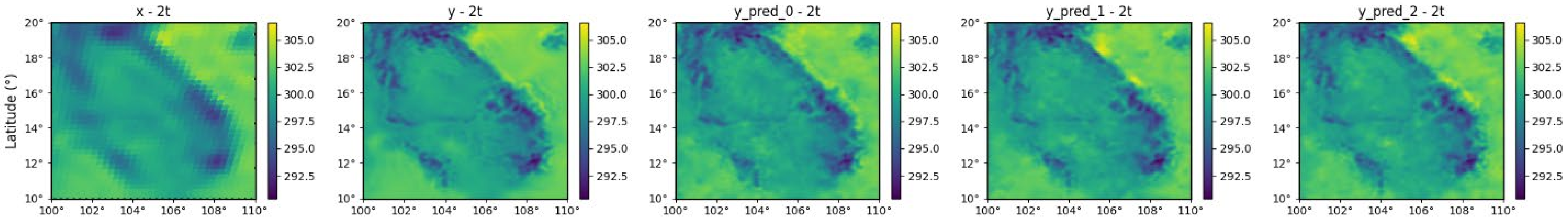
scale-dependent re-centring of EDA

(50r1)



Representing uncertainties at kilometre scale resolutions

- Funded by **Destination Earth**, work is on-going to test and further develop uncertainty representations at high resolution (Δx ≤4.4 km)
- Lack of affordability to run large IFS ensemble at km-scale in the next five to ten years
- Alternative approach: Use ML to learn probabilistic downscaling and assess realism via comparison with IFS km-scale simulations



Input
36 km resol.
subseasonal
hindcast

Target
9 km resol.
medium-range
hindcast

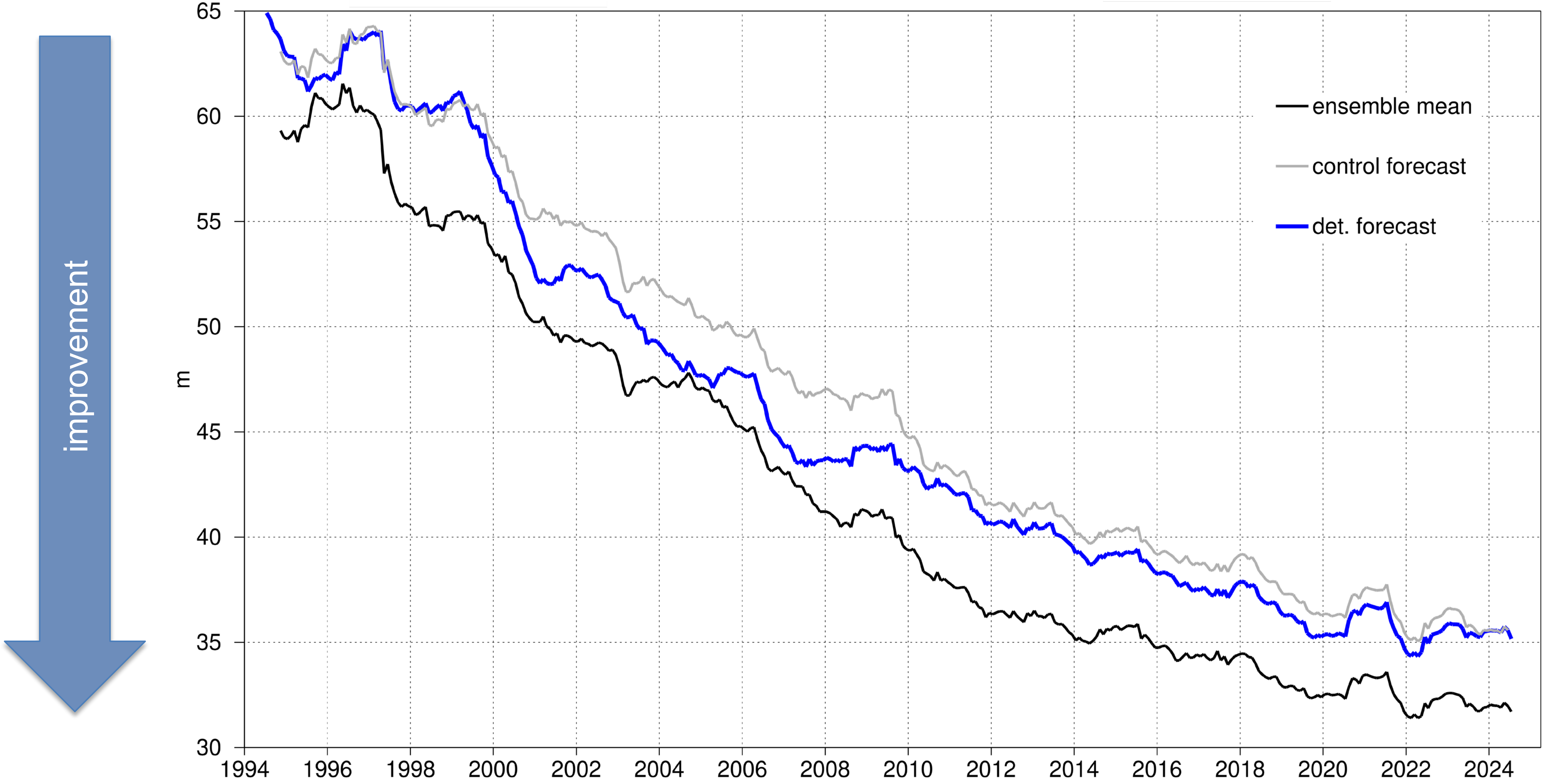
ML Predictions 1, 2, 3
9 km resolution, diffusion approach
using input on the left + noise
zoom on SE Asia, date in 2022 (validation)

Summary/ Discussion

- The evolution of the medium-range verification statistics over the past 30 years nicely documents improvements in probabilistic skill that are due to a large number of contributions to all aspects of the IFS. Too many to describe here.
- The representation of uncertainties is at the core of the ensemble prediction methodology. Recent advances were summarized
  - The introduction of SPP and its local conservation properties which leads to improved physical consistency
  - The revision of the construction of the initial conditions from an EDA and a deterministic higher-quality analysis via a scale-dependent re-centring
  - Harnessing machine learning for uncertainty quantification at high resolution via downscaling of a lower-resolution ensemble
- Ensemble forecasts and their uncertainty representations have become central components of weather forecasting during the last decades. How will ensemble forecasting evolve in the coming 25 years?

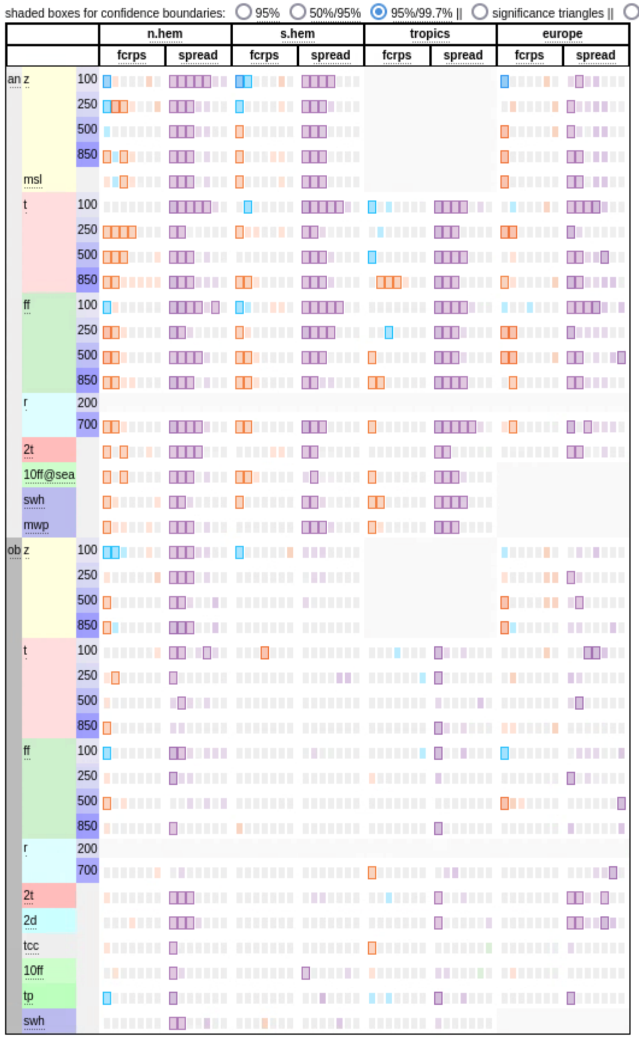
Thank you!

Evolution of Day 5 RMS errors --- N-Hem extratropics Z500

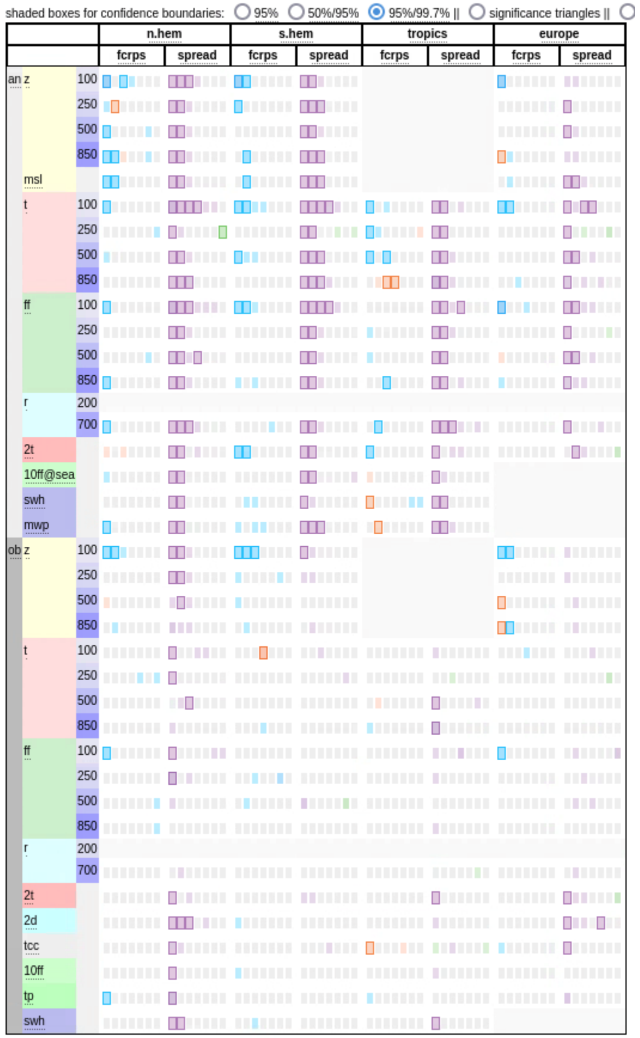


Scale selective re-centring of EDA compared to 49r1

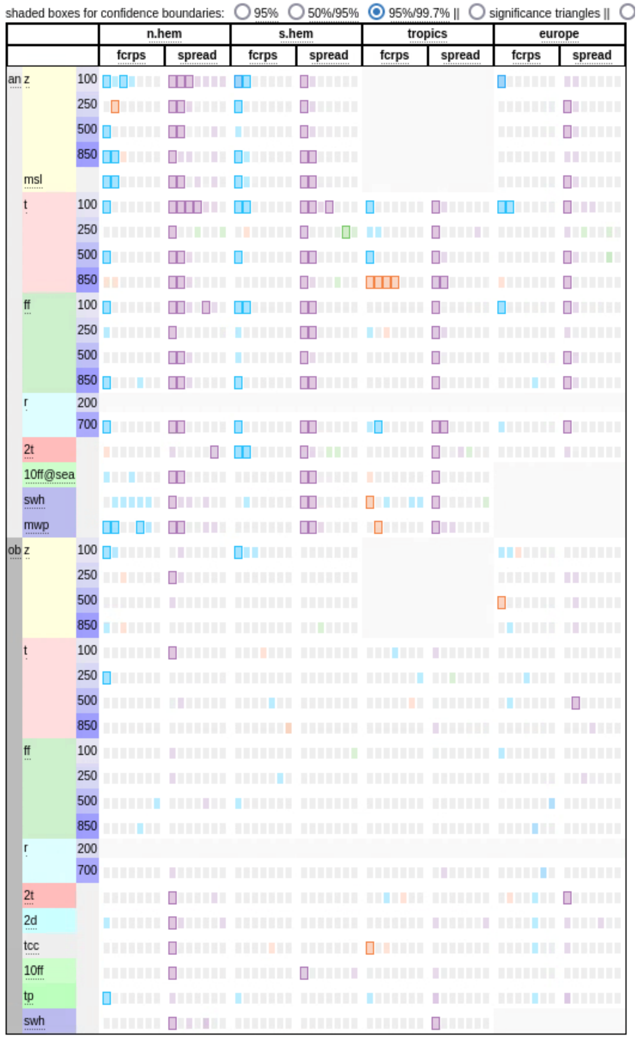
Filter N≤95



Filter N≤ 159



Filter N≤ 255



N: total wavenumber

92 start dates JJA2022