Representation of model uncertainty in the ECMWF ensembles

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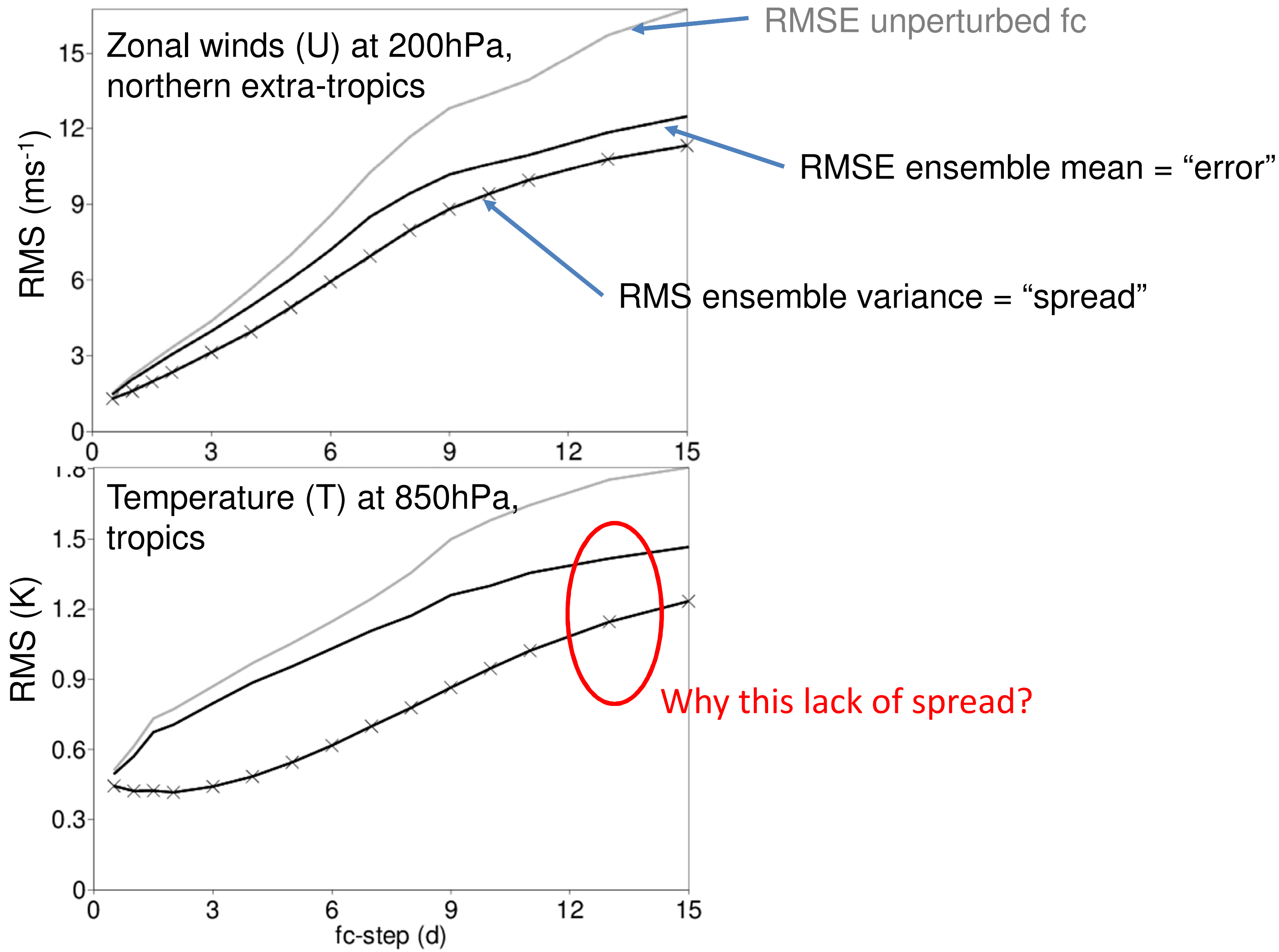
… and with thanks to many others!

Ensemble forecasts with only initial state perturbations

Ensemble mean RMSE ("Error") & standard deviation ("Spread")



Experiment details:

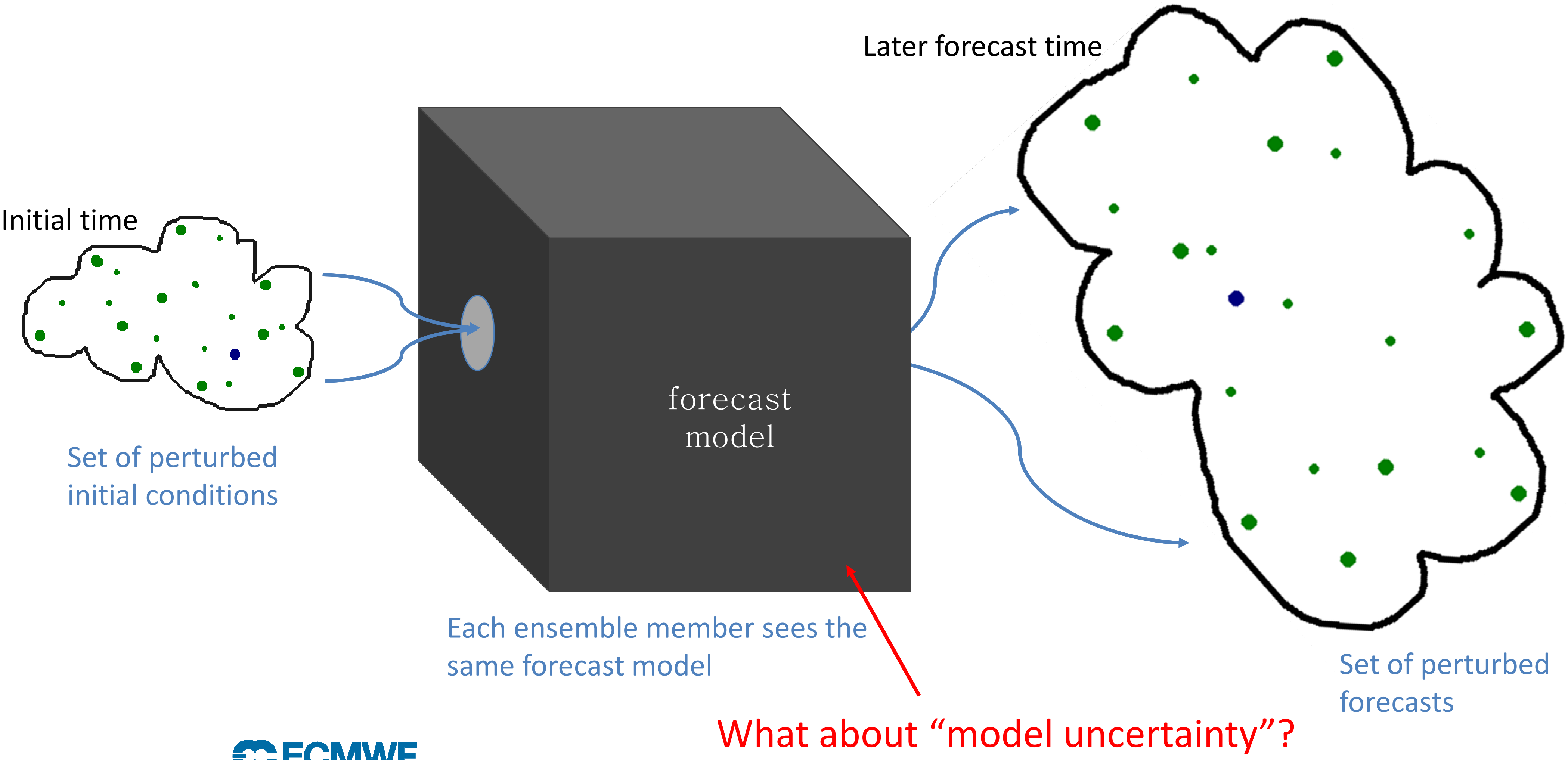
CY43R1

TCo399, dt=900s,

23 dates (2015),

20 perturbed fcs

When only initial uncertainty is represented in the forecast ...



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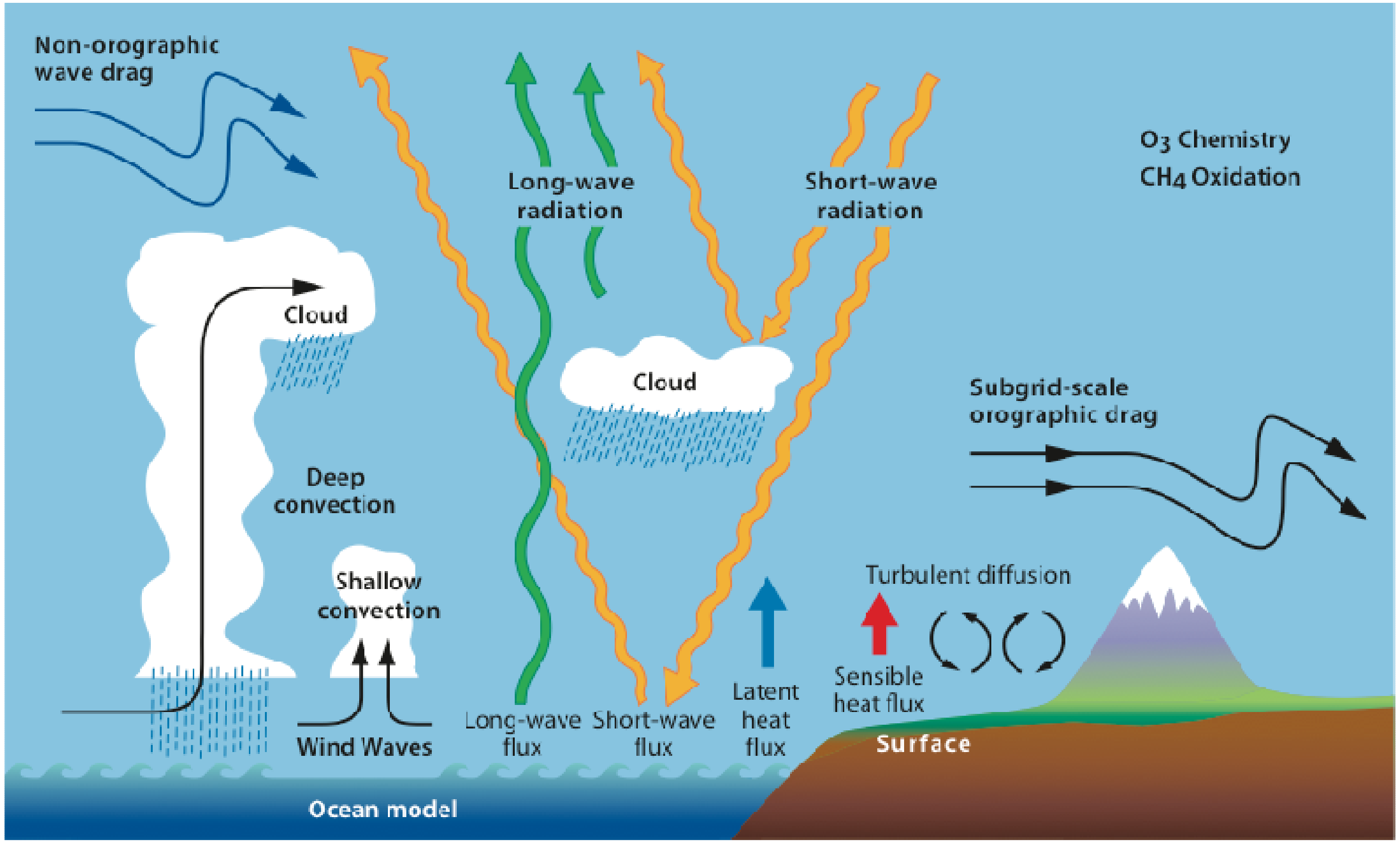
Model uncertainty: parametrized atmospheric physics processes



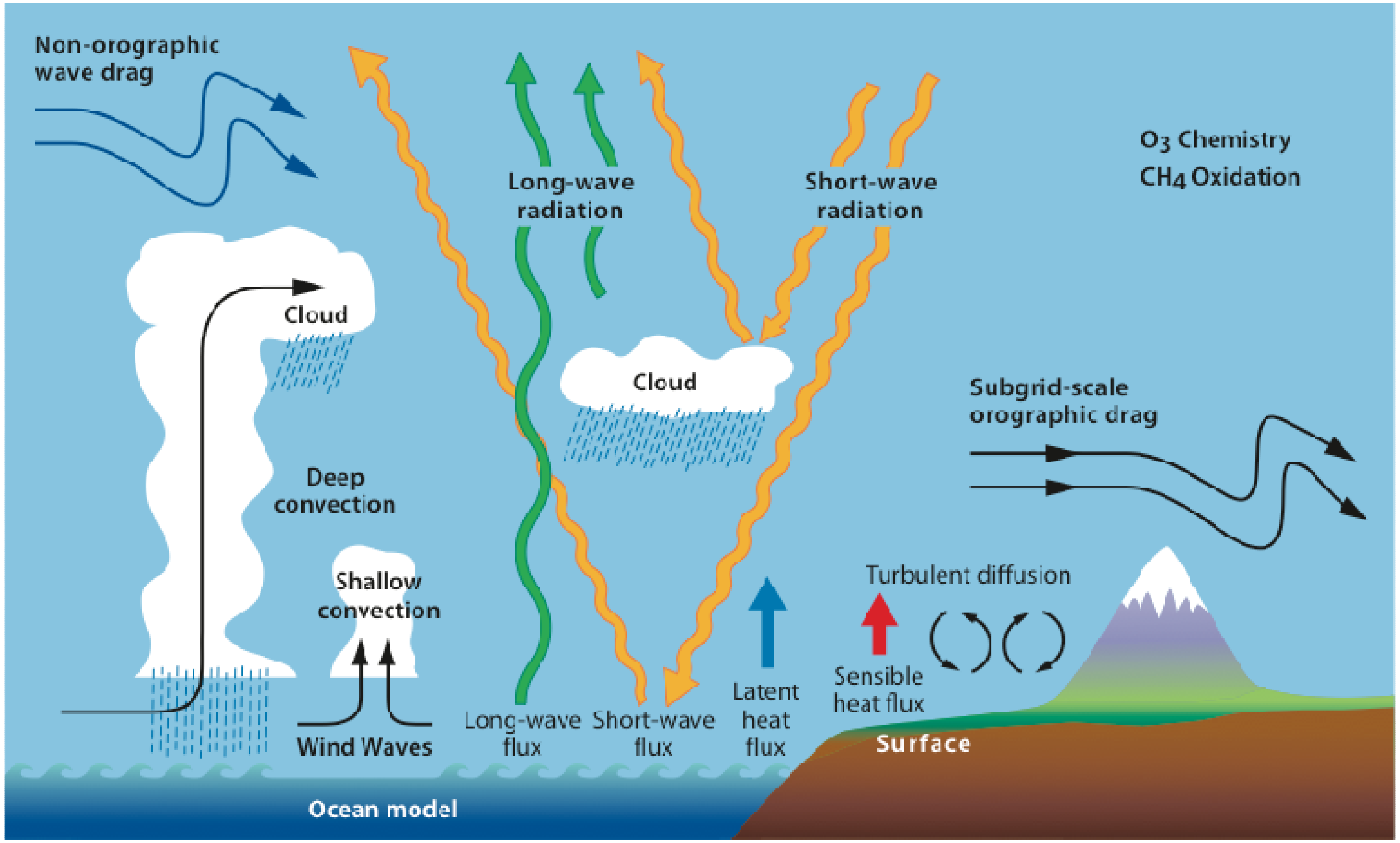
Uncertainties arise due to:

- Inability to resolve sub-grid scales
- Poorly constrained parameters or processes

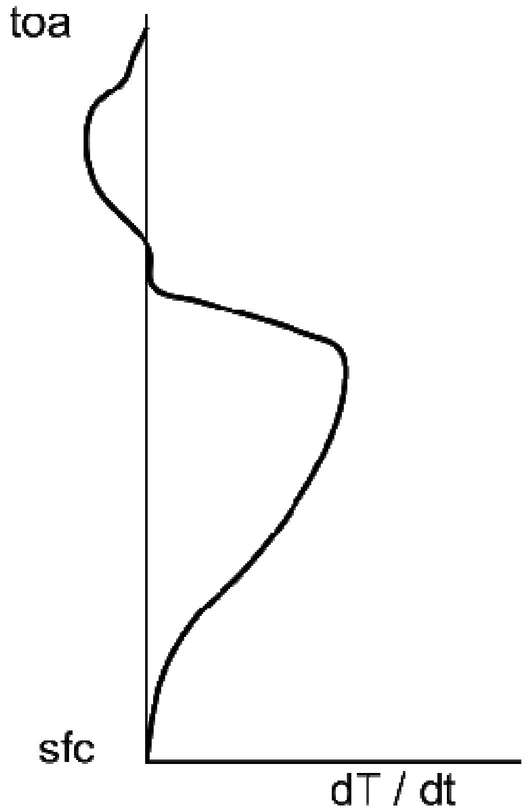
To represent those uncertainties:

- Seek a description that retains consistencies derived within the physics schemes

Model uncertainty: Stochastically Perturbed Parametrisation Tendencies (SPPT)



Consider a profile of heating rates from physics parametrisations:



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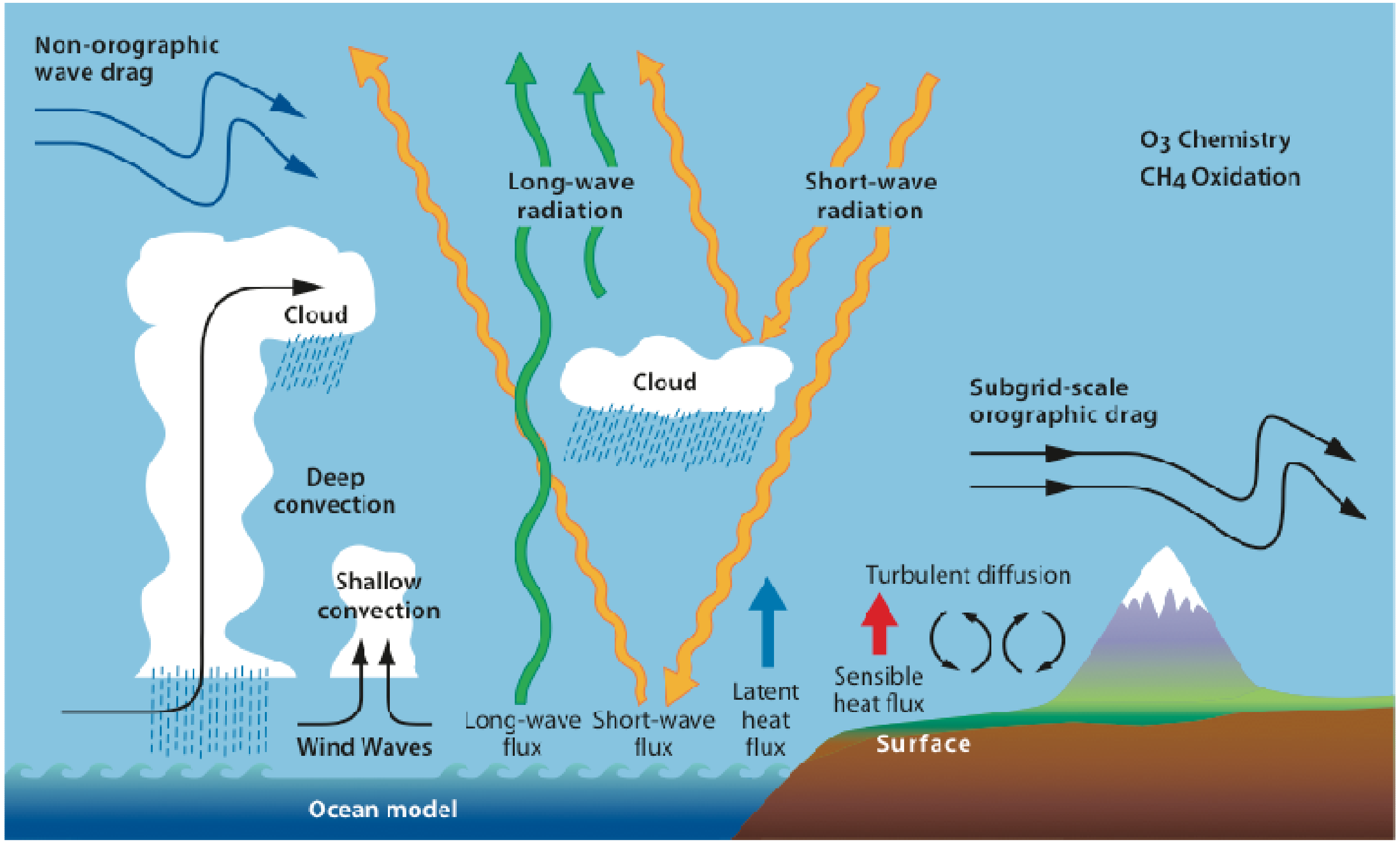
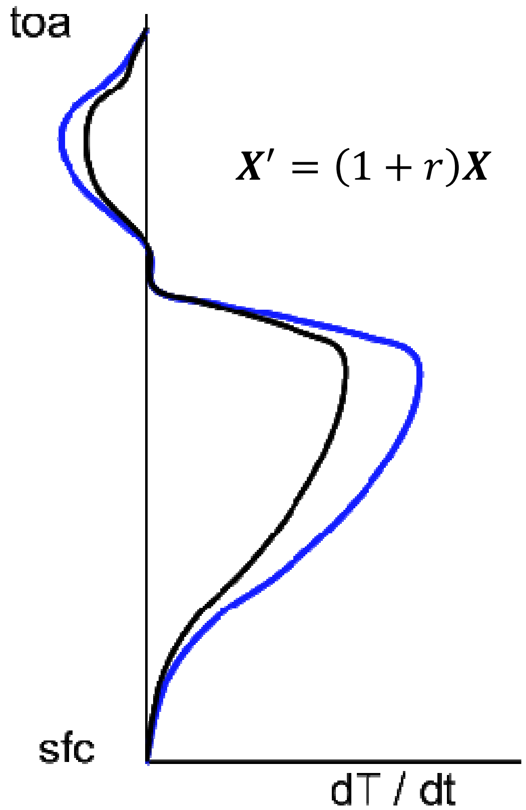
Model uncertainty: Stochastically Perturbed Parametrisation Tendencies (SPPT)



Represent uncertainties with a perturbation proportional to the profile of net physics tendencies



$$X' = (1 + r)X$$

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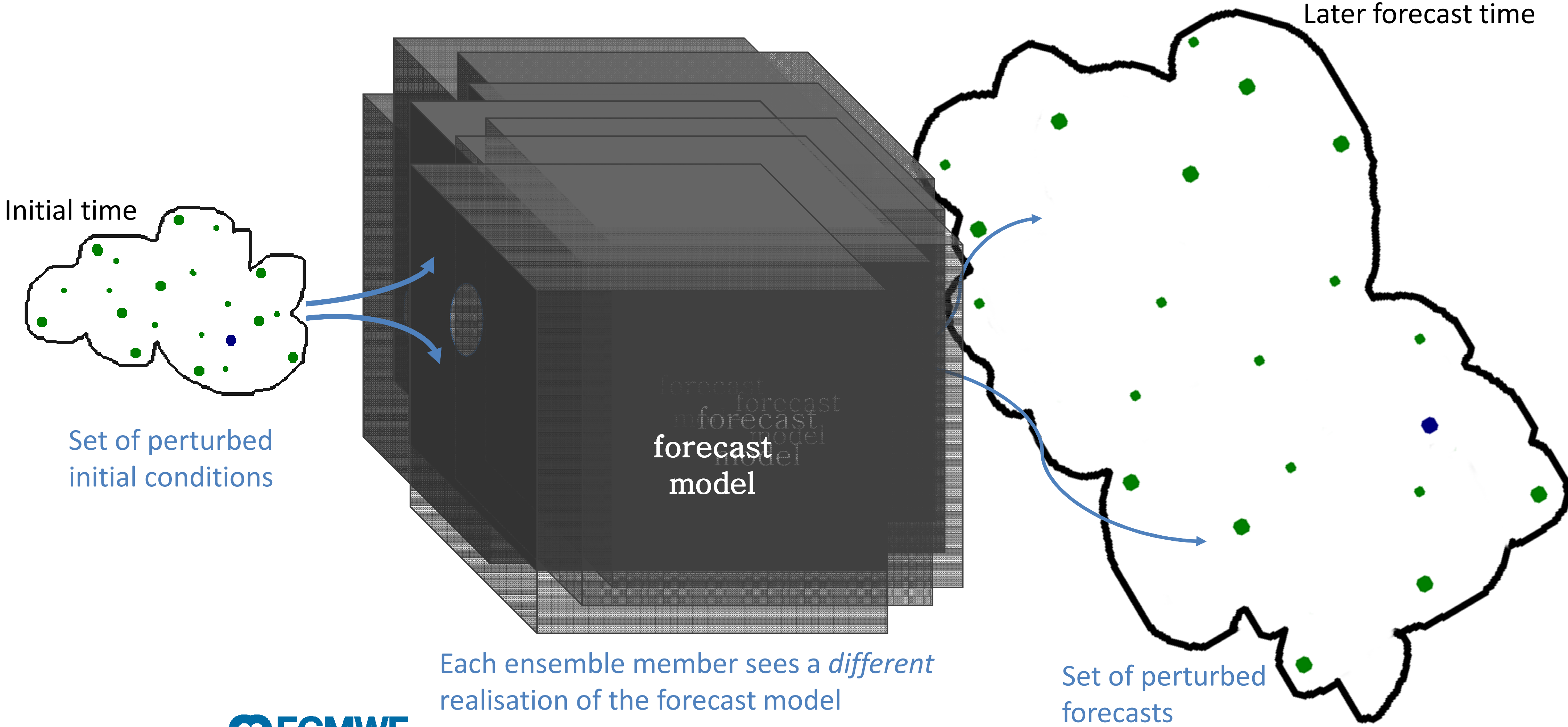
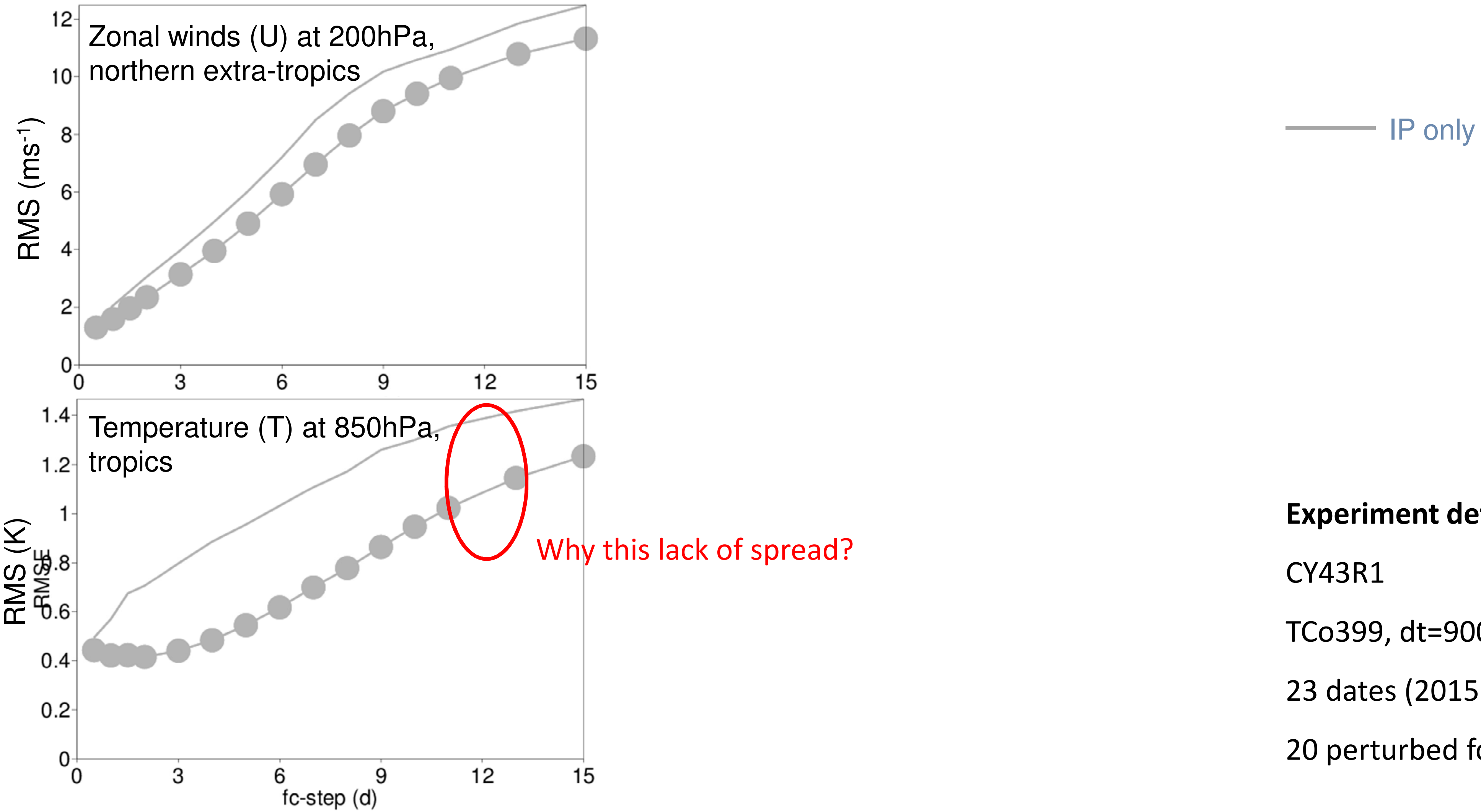
When the forecast also includes a representation of model uncertainty …



ECMWF

Recall: Ensemble forecasts: with initial conditions perturbations (IP) only

Ensemble mean RMSE ("Error") & standard deviation ("Spread")



Experiment details:

CY43R1

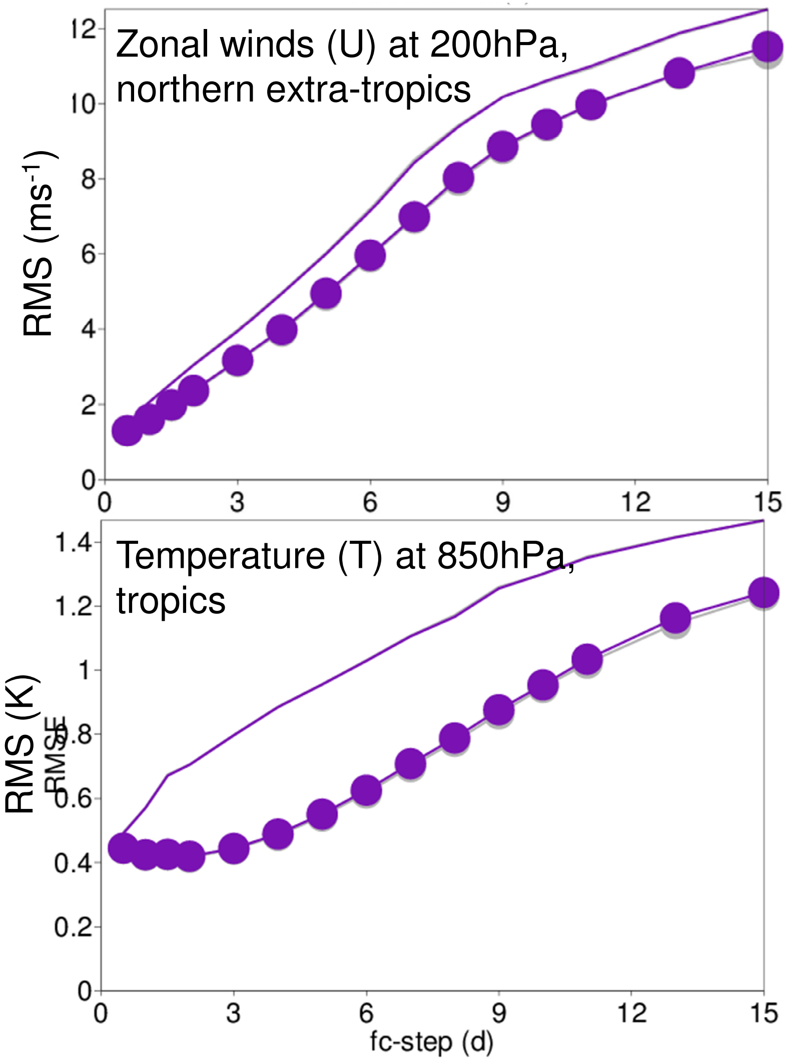
TCo399, dt=900s,

23 dates (2015),

20 perturbed fcs

Ensemble forecasts: with **grid-scale** model uncertainty perturbations (SPPT)

Ensemble mean RMSE ("Error") & standard deviation ("Spread")



Include model uncertainty perturbations via SPPT:

$$X' = (1 + r)X$$

where the noise term

$$r = r(x,t)$$

represents grid-scale noise

IP only

IP + SPPT*
(*grid-scale noise)

Result:
Adding grid-scale noise yields little benefit

Experiment details:

CY43R1

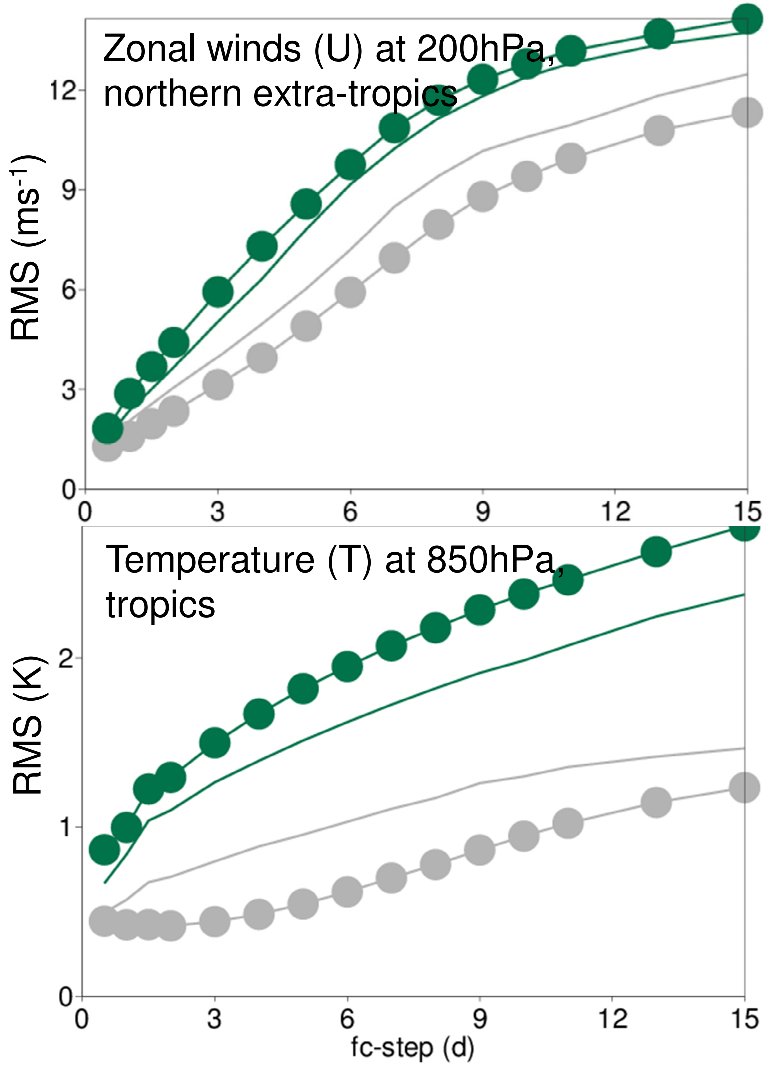
TCo399, dt=900s,

23 dates (2015),

20 perturbed fcs

Ensemble forecasts: with **static** model uncertainty perturbations (SPPT)

Ensemble mean RMSE (“Error”) & standard deviation (“Spread”)



Include model uncertainty perturbations via SPPT:

$$X' = (1 + r)X$$

where the noise term, *r*, is constant in time and space

IP only

IP + SPPT*
(*static perturbations wrt time/space)

Result:
Static perturbations yield increased errors

Experiment details:

CY43R1

TCo399, dt=900s,

23 dates (2015),

20 perturbed fcs

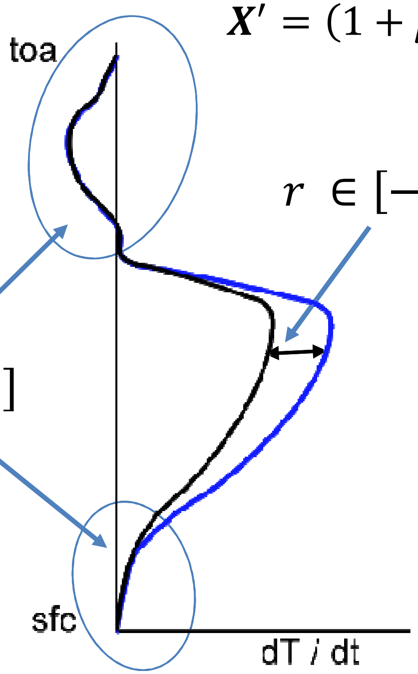
Stochastically Perturbed Parametrisation Tendencies (SPPT) scheme

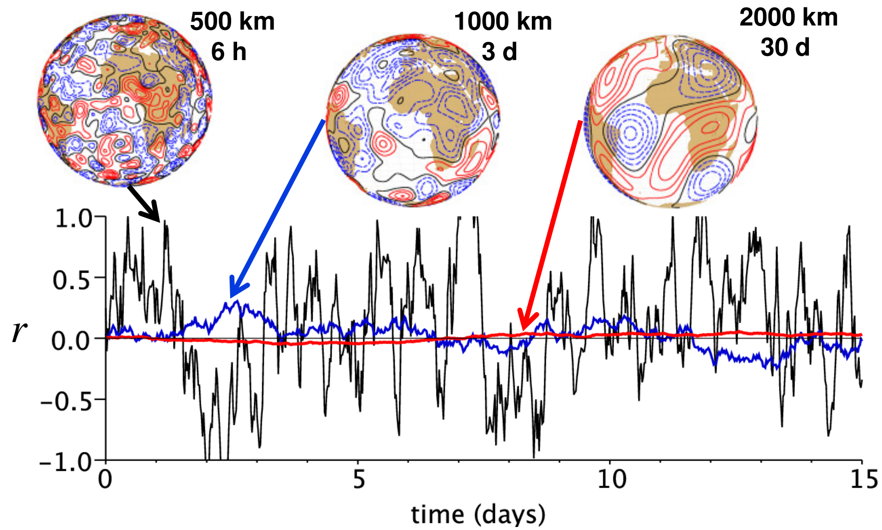
- Used in IFS ensemble forecasts and ensemble of data assimilations
- Initially implemented in IFS, 1998 (Buizza et al., 1999; Palmer et al., 2009; Shutts et al., 2011)

$$X' = (1 + \mu r)X$$

$$r \in [-1, +1]$$

$$\mu \in [0,1]$$





- Column of net tendencies from parametrised atmospheric physical processes multiplied with a 2D random field
- Multi-scale pattern: largest/slowest scale with least variance
- Perturbations are tapered (μ) to zero in the stratosphere and near the lower boundary

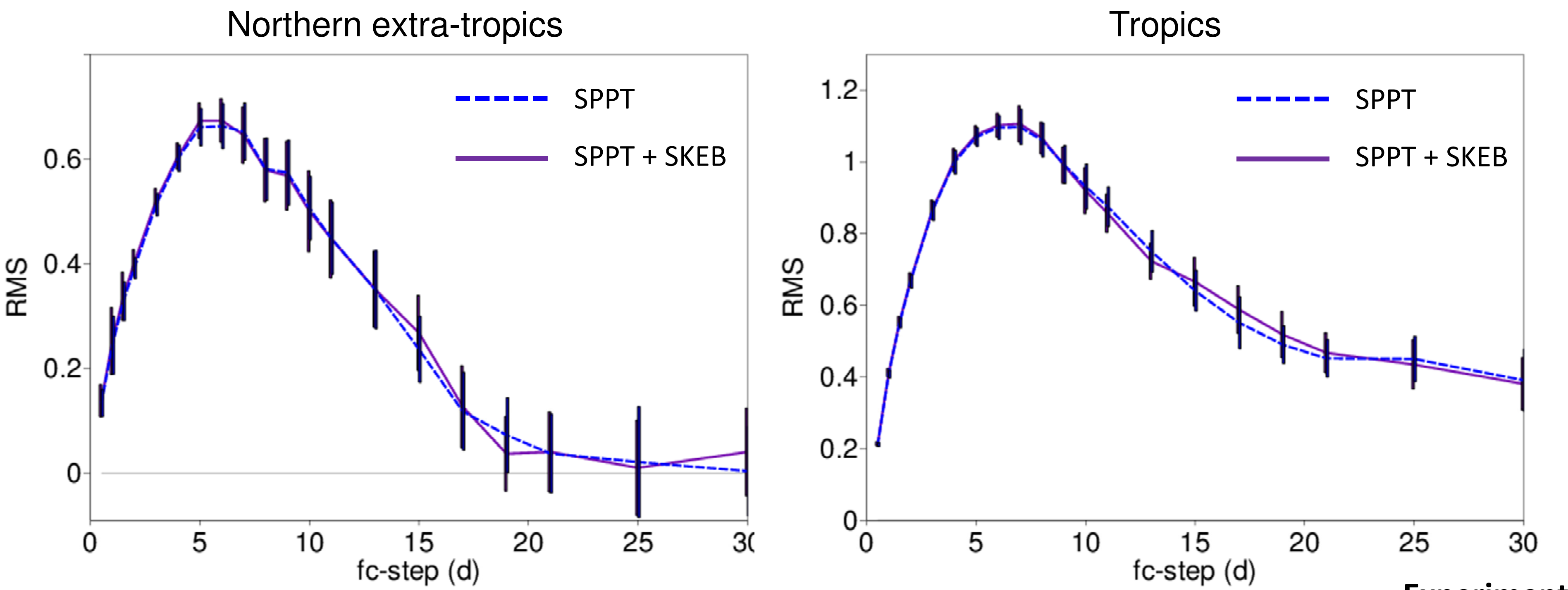
Stochastic representations of model uncertainty in ECMWF ensembles

IFS ensemble forecasts (ENS and SEAS) include 2 model uncertainty schemes:

1. Stochastically perturbed parametrisation tendencies (**SPPT**) scheme
   - SPPT scheme: simulates model uncertainty due to sub-grid parametrisations
2. Stochastic kinetic energy backscatter (**SKEB**) scheme
   - real world: upscale propagation of kinetic energy (KE) at all scales
   - SKEB simulates upscale propagation from unresolved scales to resolved scales
   - streamfunction is perturbed with noise from a 3D random field, modulated by an estimate of local dissipation rate (Berner et al., 2009; Palmer et al., 2009; Shutts et al., 2011)
   - recent revisions to dissipation rate estimate: now only depends on that due to deep convection
   - implemented only in forecasting system (not assimilation)

Ensemble forecasts: SPPT & SKEB

Ensemble standard deviation ("Spread") – 200hPa zonal wind (ms^{-1})



Differences with respect to an experiment with initial perturbations only

Experiment details:

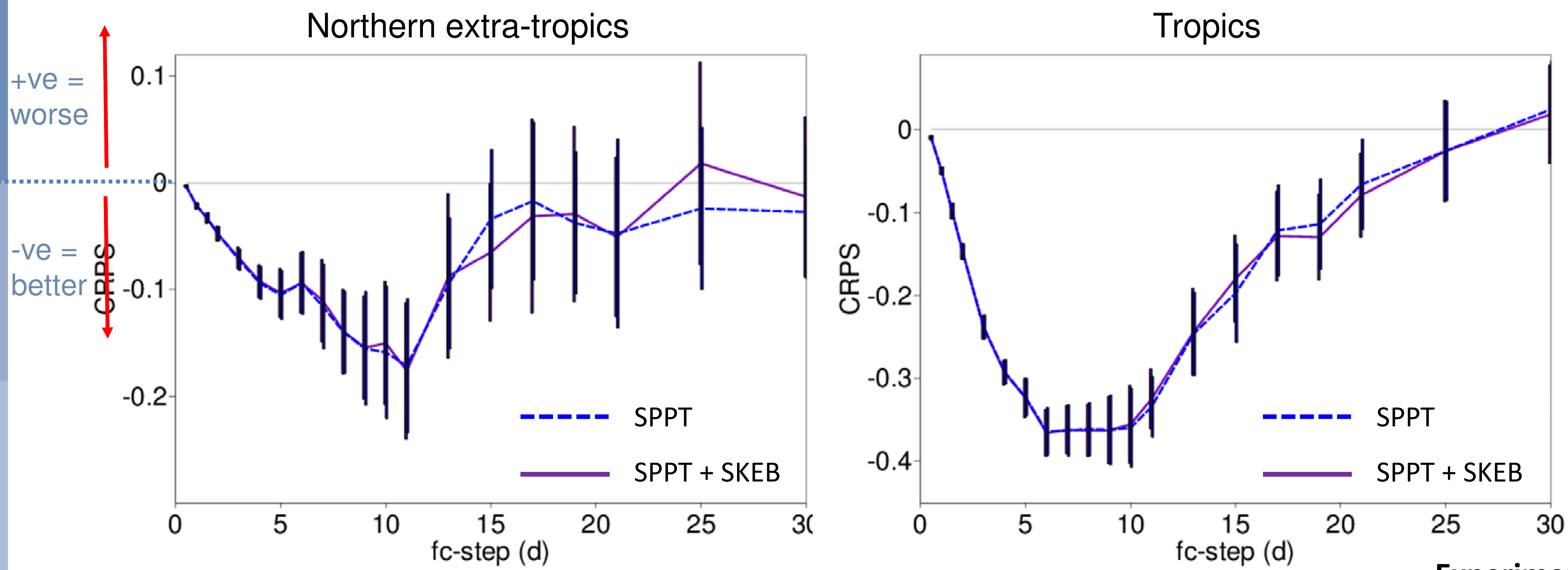
TCo255/TCo159

46 dates (2013-2014),

20 perturbed fcs

Ensemble forecasts: SPPT & SKEB

Continuous Ranked Probability Score – 200hPa zonal wind (ms^{-1})



Differences with respect to an experiment with initial perturbations only

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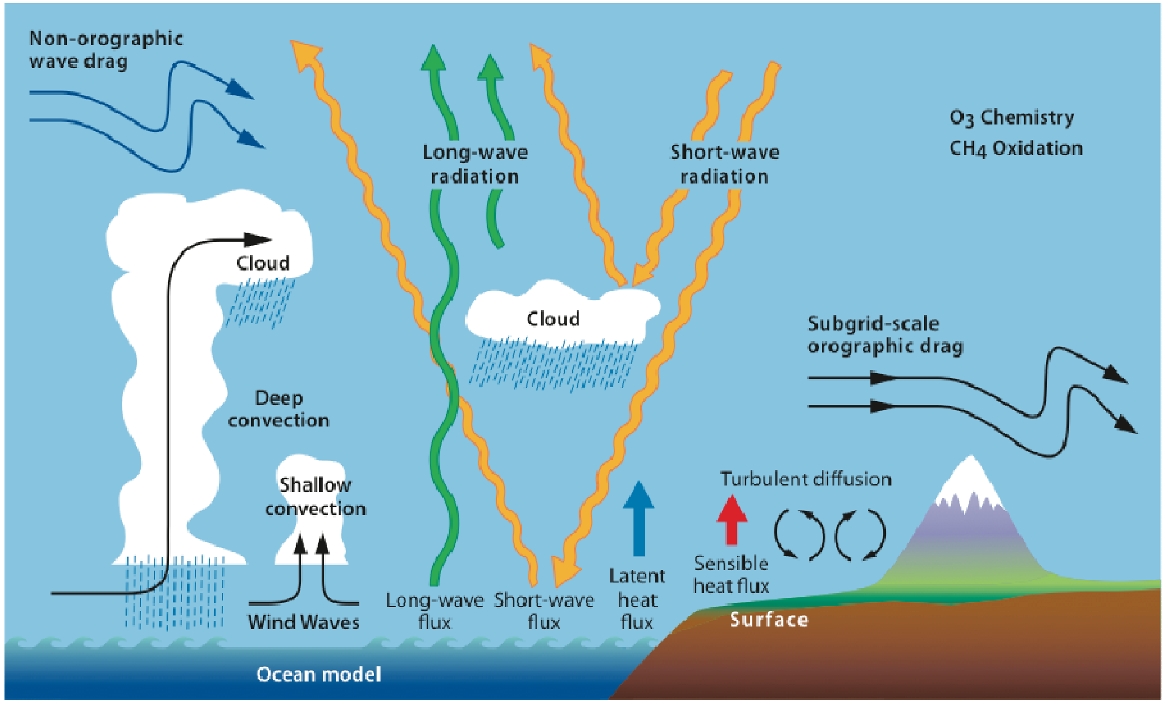
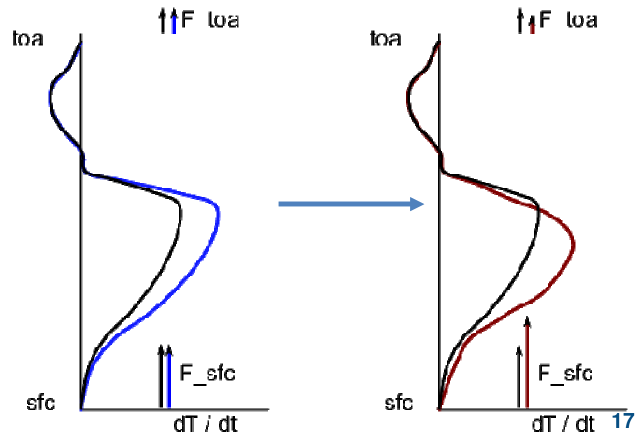
ECMWF

Stochastic representations of model uncertainty: looking ahead

Towards process-level model uncertainty representation

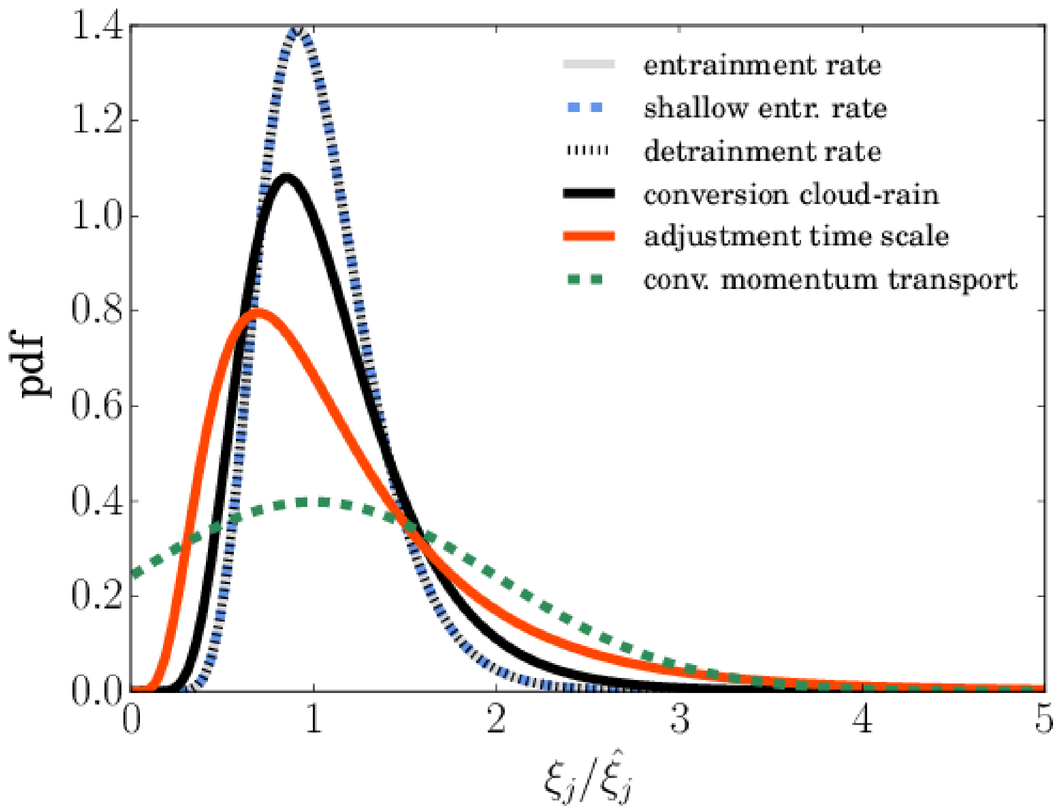


- **Aim: to improve the physical consistency**
- Remove ad hoc tapering in boundary layer and stratosphere
- Preserve local energy/moisture budgets through consistent flux perturbations at the upper and lower boundaries
- Represent uncertainty close to assumed sources of errors
- Include multi-variate aspects of uncertainties



Stochastic physics in the IFS: looking ahead

Towards process-level model uncertainty representation



Stochastically Perturbed Parametrisations (SPP)

(Ollinaho et al., 2017, QJRMS)

Quantities within parametrisation schemes are multiplied with noise from a 2D random pattern:

$$\xi = r\hat{\xi}$$

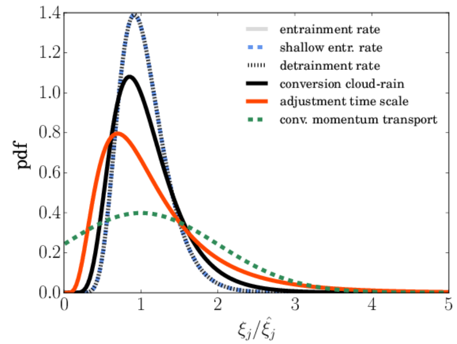
correlated in space (2000 km) and time (72 h).

e.g. convection scheme parameters are perturbed with numbers drawn from distributions shown

Currently: **20 independent perturbations** of quantities in:

- boundary layer
- radiation
- cloud and large-scale precipitation
- convection

SPP: perturbed physics quantities



Turbulent diffusion & sub-grid orography

- transfer coecient for momentum
- coeff. in turb. orographic form drag scheme
- stdev of subgrid orography
- vertical mixing length scale (stable BL)

Radiation

- cloud vert. decorrelation height in McICA
- fractional stdev of horizontal distrib. of water content
- effective radius of cloud water and ice
- scale height of aerosol norm. vert. distrib.
- optical thickness of aerosol

Convection

- entrainment rate
- shallow entrainment rate
- detrainment rate for penetrative convection
- conversion coefficient cloud to rain
- conv. momentum transport (meridional/zonal)
- adjustment time scale in CAPE closure

Cloud & large-scale precipitation

- RH threshold for onset of stratiform cond.
- diffusion coeff. for evap. of turb. mixing
- critical cloud water content
- threshold for snow autoconversion

Stochastically Perturbed Parametrisations (SPP) scheme

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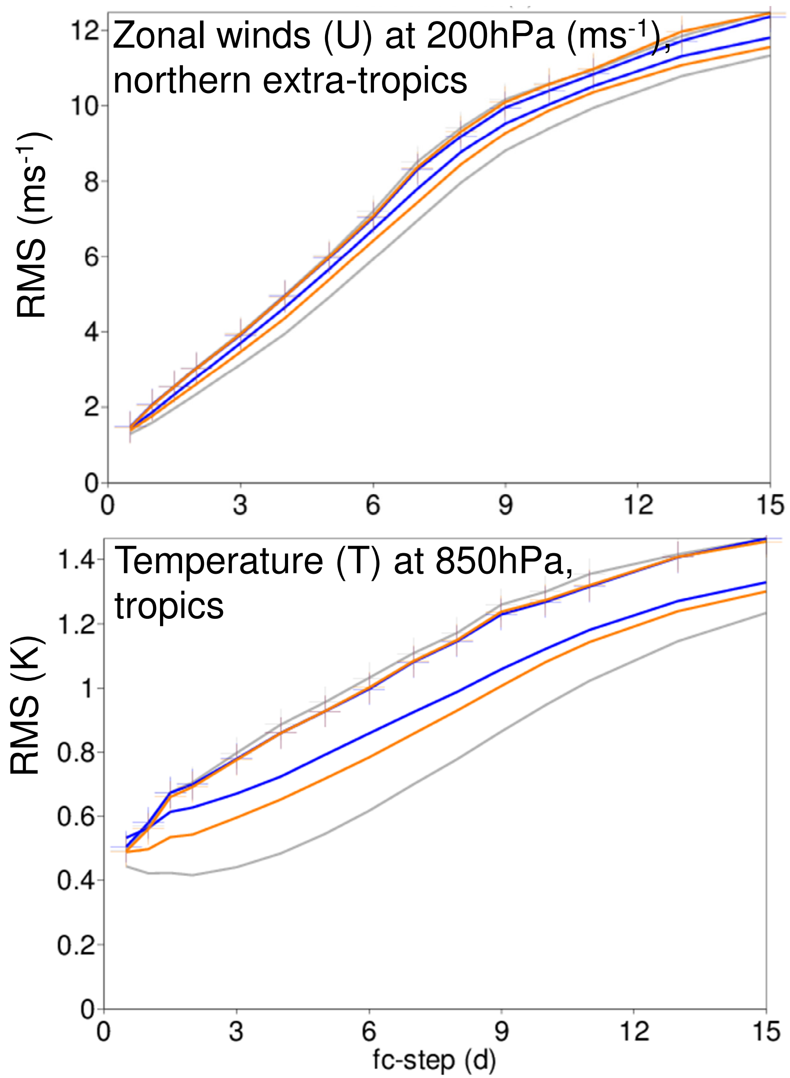

Include model uncertainty perturbations via

i) SPPT:

$$\boldsymbol{X}' = (1 + r)\boldsymbol{X}$$

acting on physics tendencies

ii) SPP:

$$\xi = r\hat{\xi}$$

acting on 20 parameters/variables

IP only

IP + SPPT

IP + SPP

Result:
Currently, SPP generates less spread (& skill) than SPPT
=>
Some model uncertainty sources missing from SPP

More work to do!

Experiment details:

CY43R1

TCo399, dt=900s,

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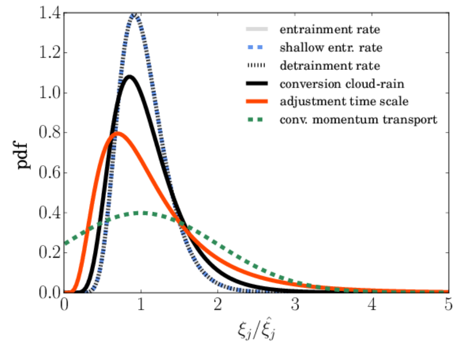
SPP: ongoing work



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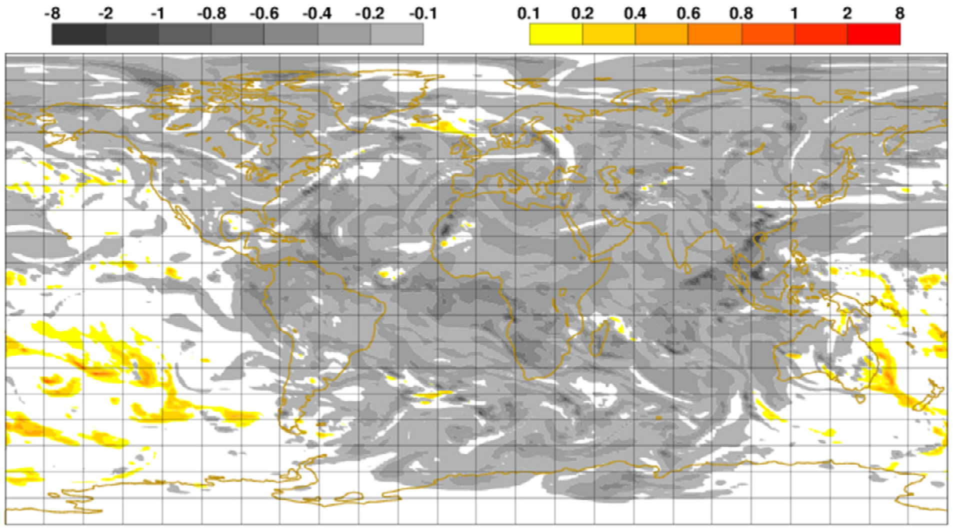
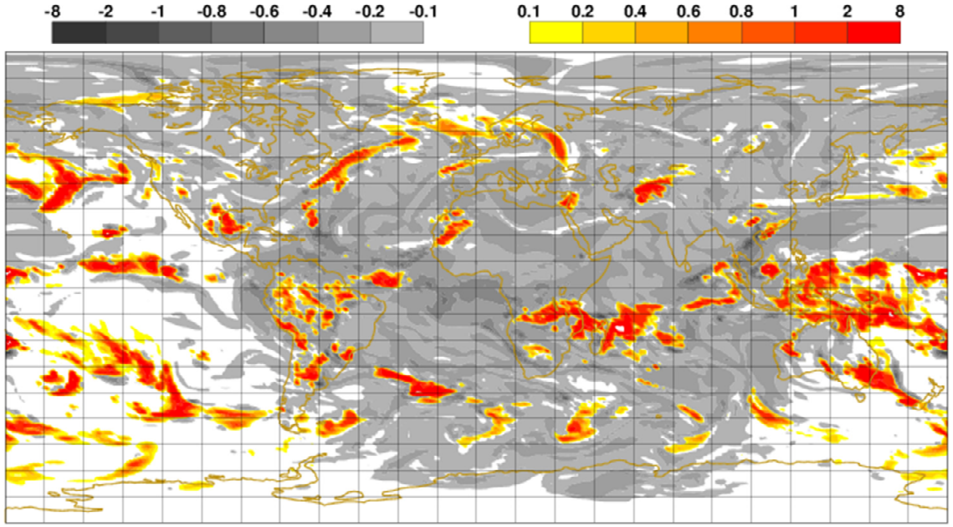
A look at the physical tendencies and processes

Ensemble mean of tendencies, 21-24h

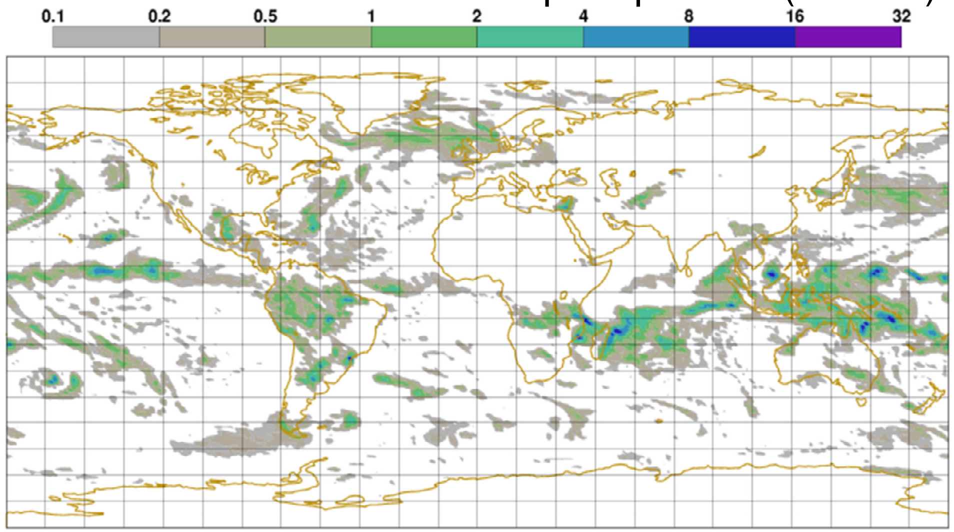
T tendencies from radiation (K/3h)
@ model level 64 (~500 hPa)



Net physics temperature (T) tendencies (K/3h)
@ model level 64 (~500 hPa)



Convective precipitation (mm/3h)

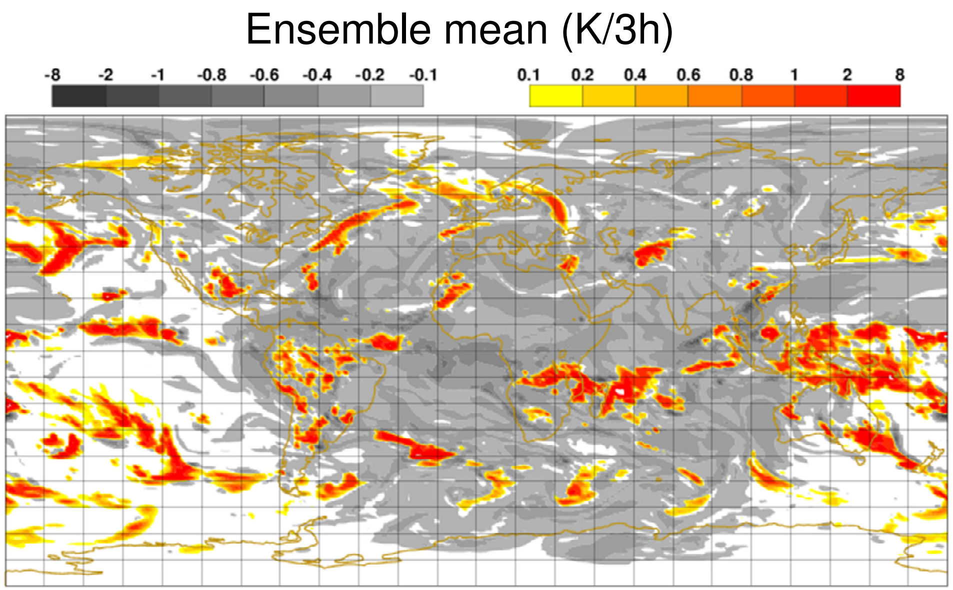


From a 20-member ensemble forecast:
starting 00:00,10-01-2015
with identical initial conditions

ECMWF

And a look at the tendency perturbations

T tendencies, 21-24h @ model level 64 (~500 hPa)



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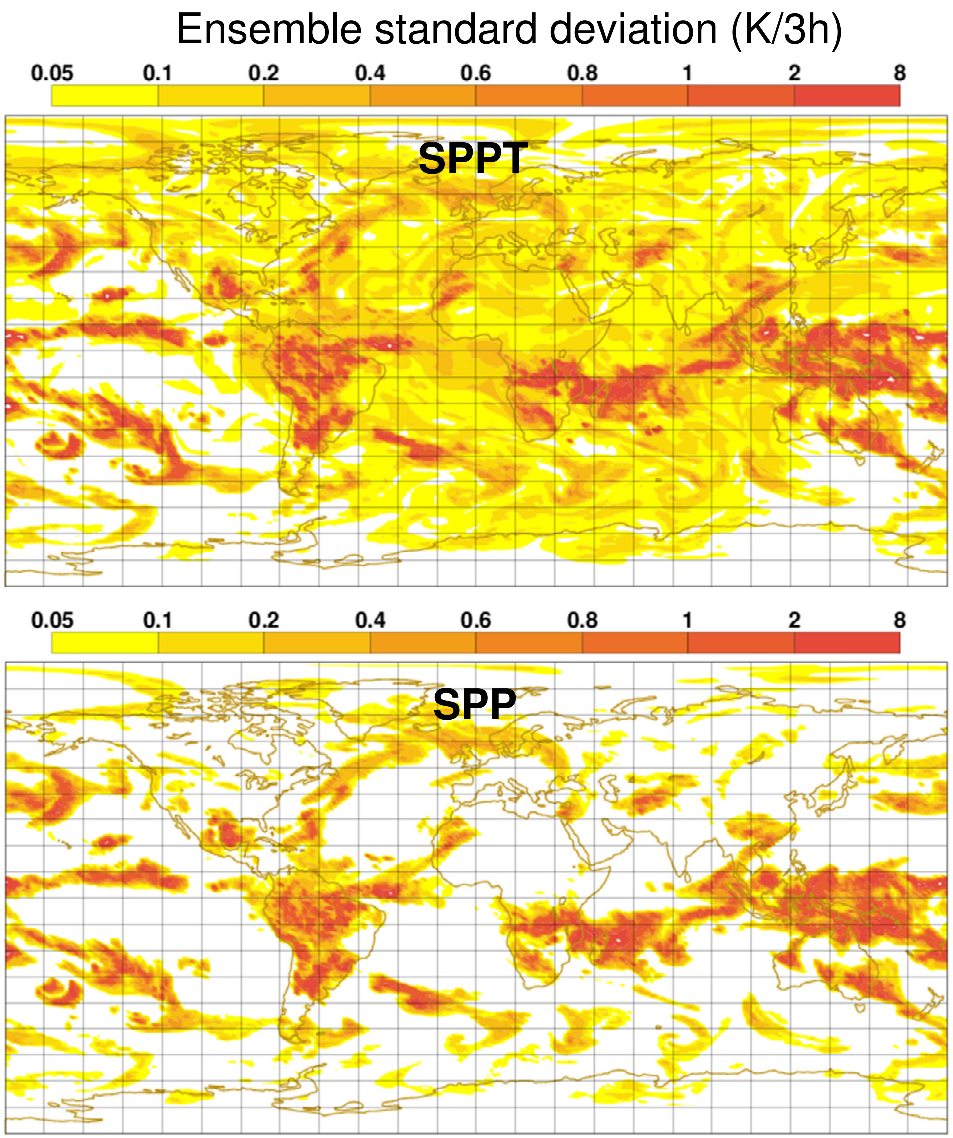
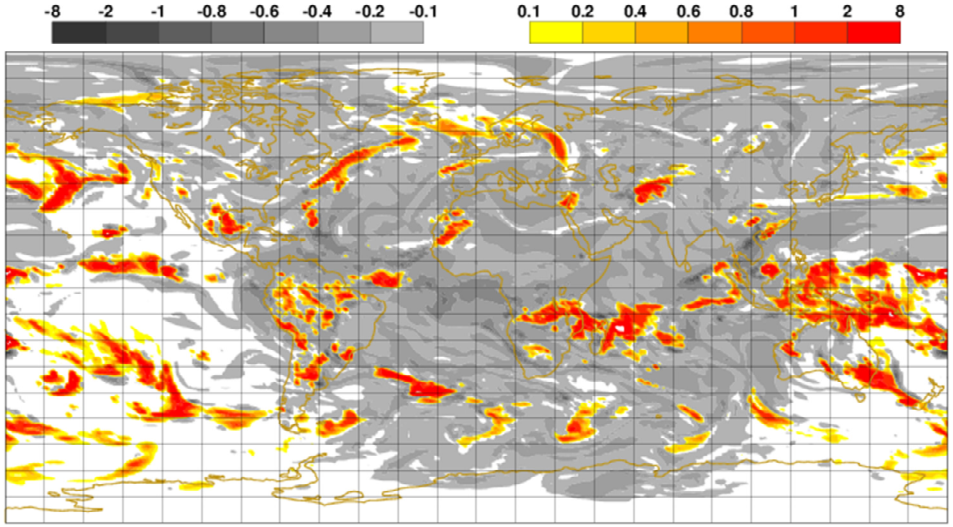
ECMWF



And a look at the tendency perturbations

T tendencies, 21-24h @ model level 64 (~500 hPa)

Ensemble mean (K/3h)



From a 20-member ensemble forecast:
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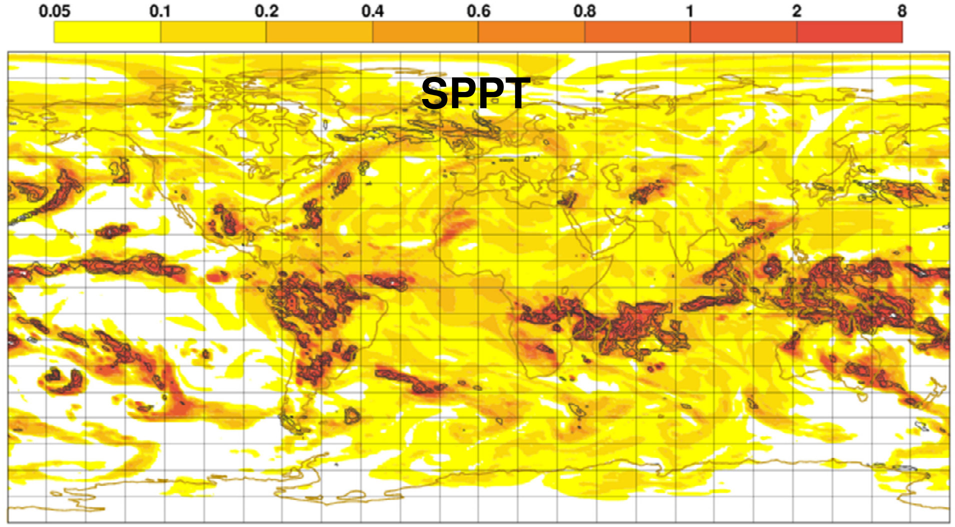
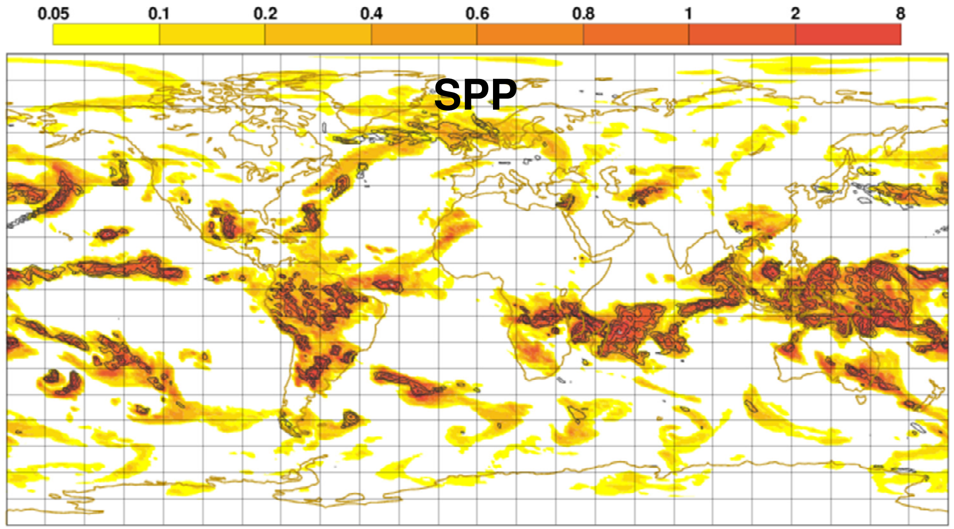
Ensemble standard deviation (K/3h)



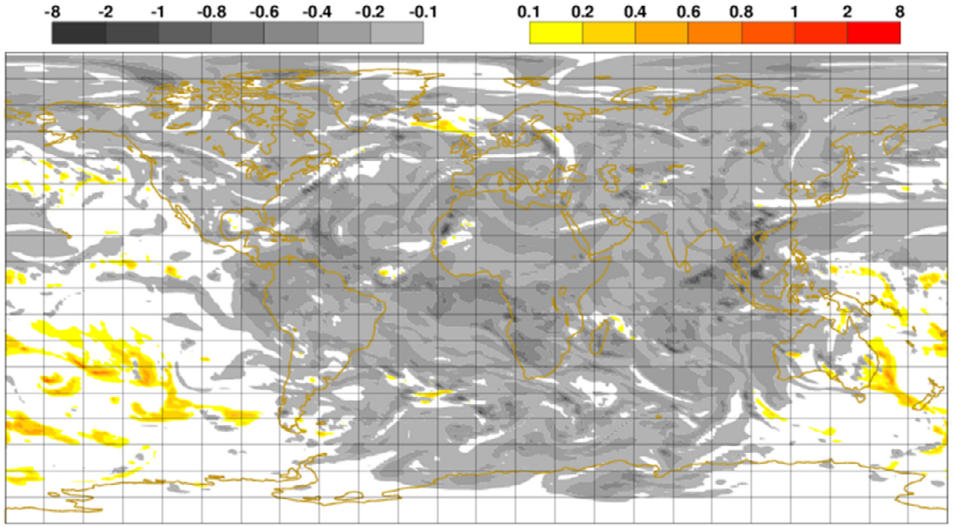


Ensemble mean convective precipitation (mm/3h)

And a look at the tendency perturbations

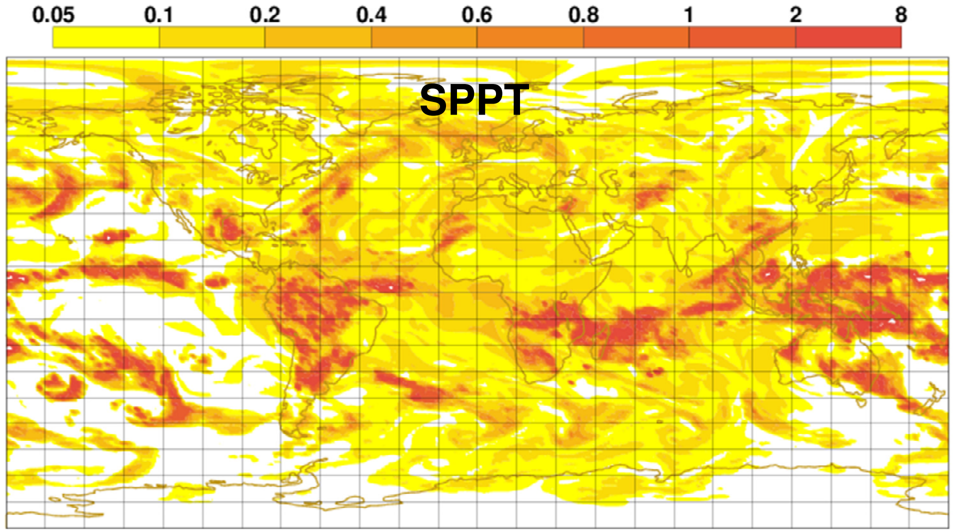
T tendencies, 21-24h @ model level 64 (~500 hPa)

Ensemble mean: radiation tendencies (K/3h)



From a 20-member ensemble forecast:
starting 00:00,10-01-2015
with identical initial conditions

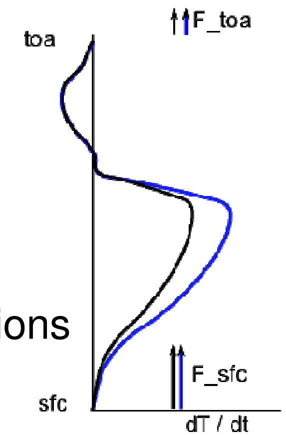
Ensemble standard deviation (K/3h)



=> **Revise SPPT**

Remove perturbations to clear skies heating rates (radiation)

- Remove stratospheric tapering
- Reduce amplitude of the perturbations
- Revise boundary layer tapering

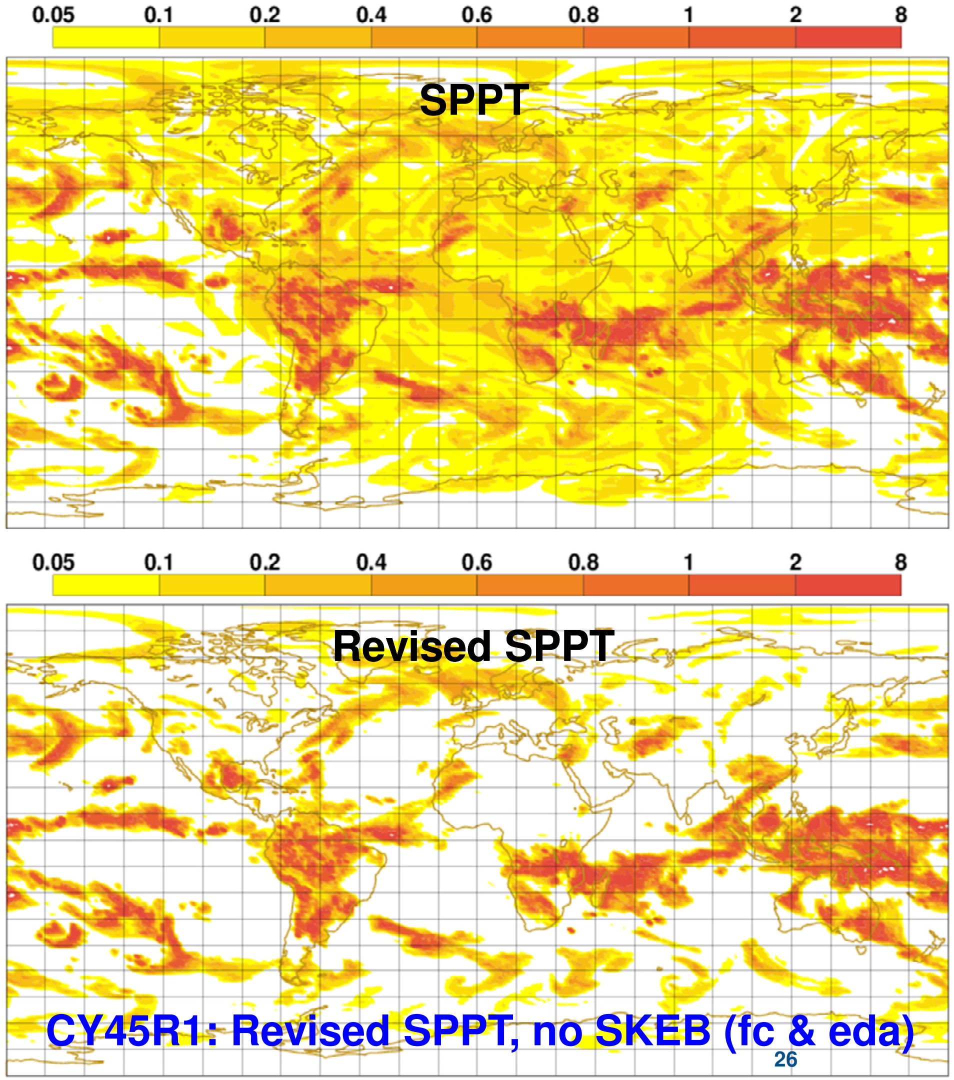


ECMWF

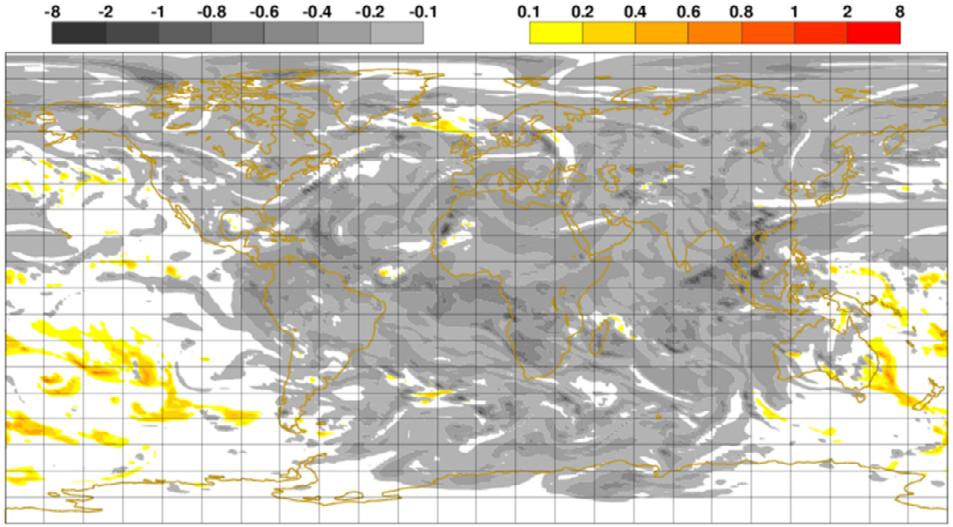
And a look at the tendency perturbations

T tendencies, 21-24h @ model level 64 (~500 hPa)

Ensemble standard deviation (K/3h)



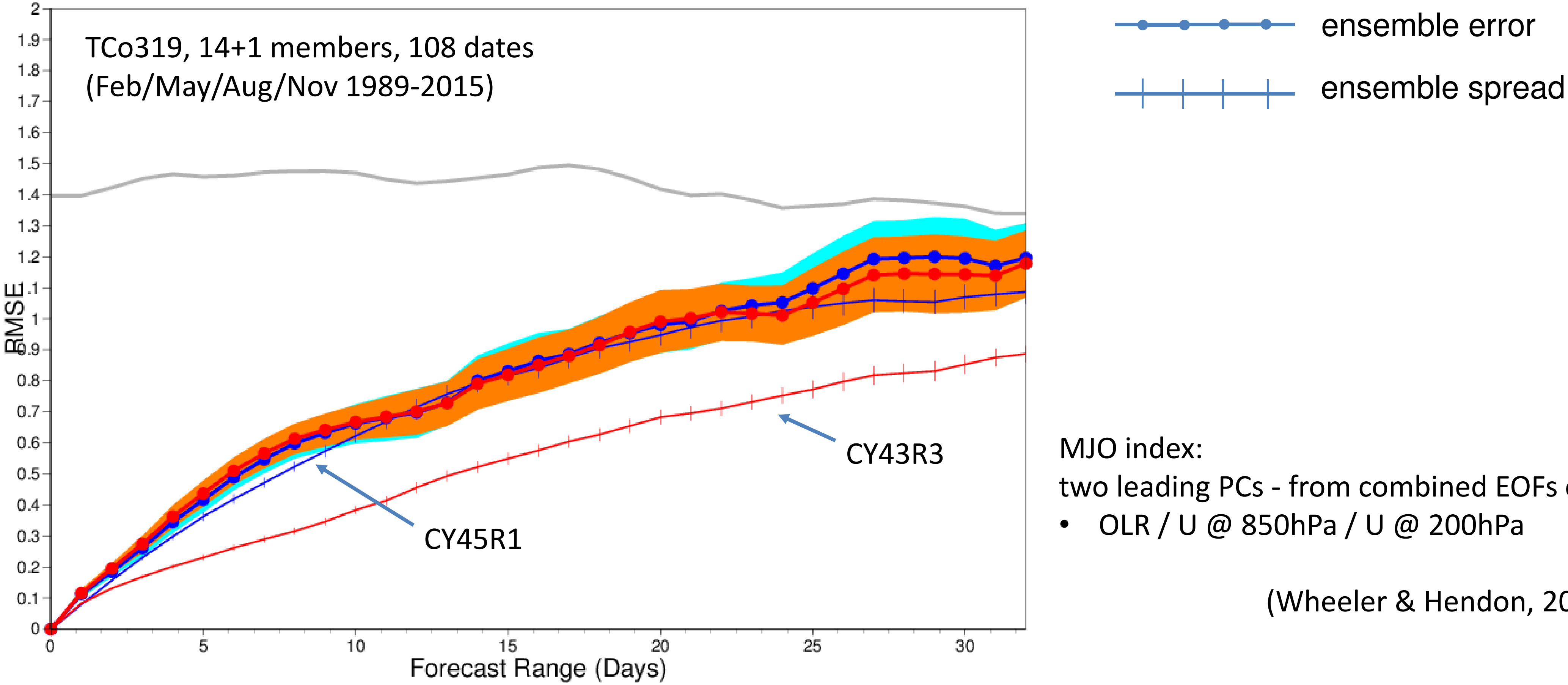
Ensemble mean: radiation tendencies (K/3h)



From a 20-member ensemble forecast:
starting 00:00,10-01-2015
with identical initial conditions

Impact for the extended range: MJO index

... HOT OFF THE PRESS! ...



MJO index:

two leading PCs - from combined EOFs of:

- OLR / U @ 850hPa / U @ 200hPa

(Wheeler & Hendon, 2004)

Representation of model uncertainty in the ECMWF ensembles

Present and future – much greater detail and discussion in:

Leutbecher et al., 2017 (QJRMS, DOI: 10.1002/qj.3094)

Take a look …

&

thanks for your attention!

ECMWF

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RMetS
Royal Meteorological Society

Stochastic representations of model uncertainties at ECMWF: state of the art and future vision

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Members in ensemble forecasts differ due to the representations of initial uncertainties and model uncertainties. The inclusion of stochastic schemes to represent model uncertainties has improved the probabilistic skill of the ECMWF ensemble by increasing reliability and reducing the error of the ensemble mean. Recent progress, challenges and future directions regarding stochastic representations of model uncertainties at ECMWF are described in this article. The coming years are likely to see a further increase in the use of ensemble methods in forecasts and assimilation. This will put increasing demands on the methods used to perturb the forecast model. An area that is receiving greater attention than 5–10 years ago is the physical consistency of the perturbations. Other areas where future efforts will be directed are the expansion of uncertainty representations to the dynamical core and other components of the Earth system, as well as the overall computational efficiency of representing model uncertainty.