Stochastic methods for representing atmospheric model uncertainties in ECMWF's IFS model

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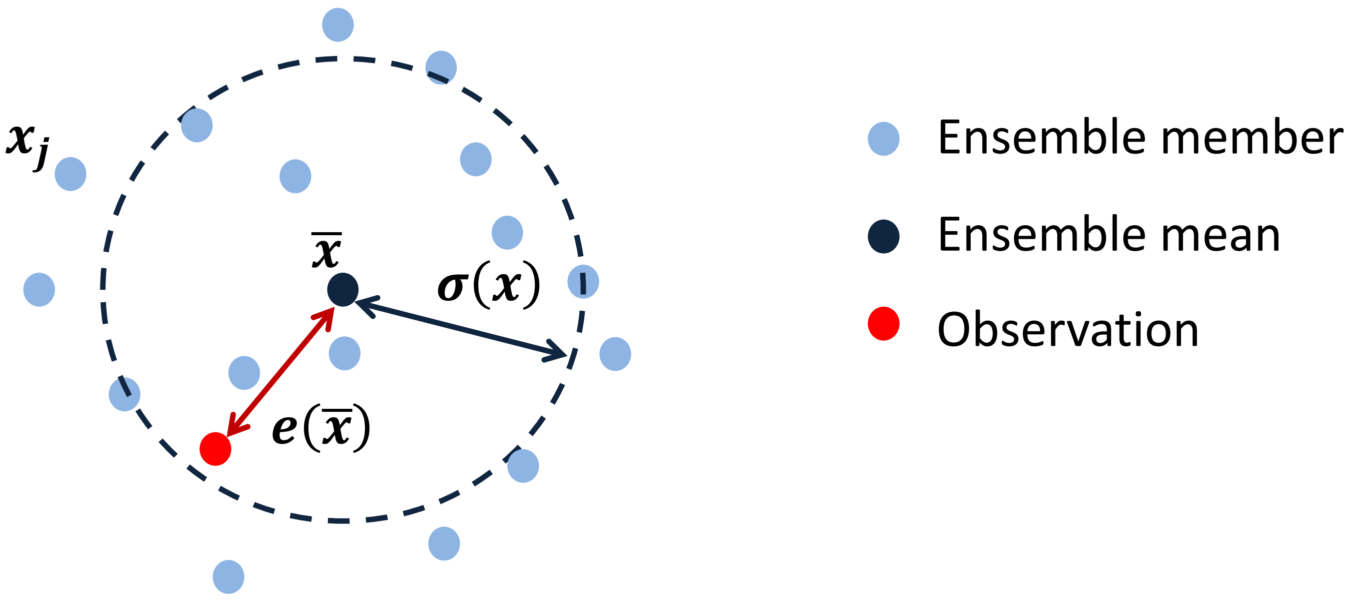
With thanks to Martin Leutbecher, Simon Lang, Pirkka Ollinaho

Some background: ensemble reliability

- In a reliable ensemble, **ensemble spread** is a predictor of **ensemble error**



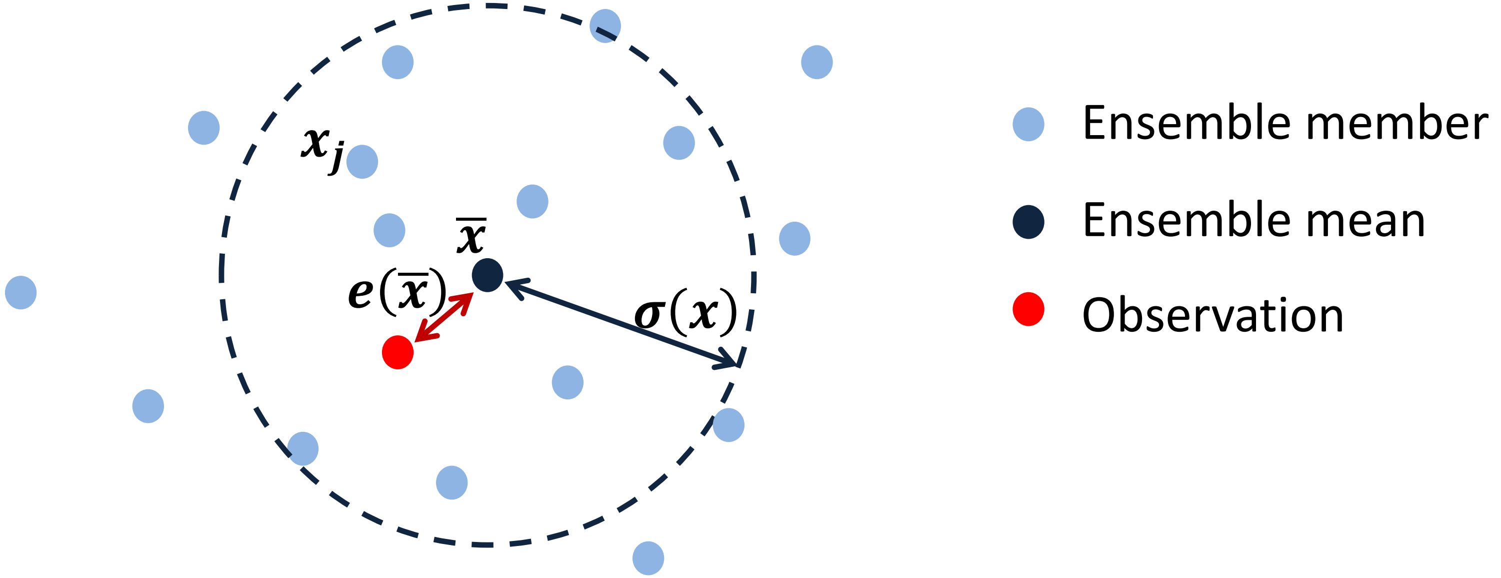
i.e. averaged over many ensemble forecasts,

$$e(\bar{x}) \approx \sigma(x)$$

Some background: ensemble reliability

- In an **over**-dispersive ensemble,

$$e(\bar{x}) \ll \sigma(x)$$



and ensemble spread does not provide a good estimate of error.

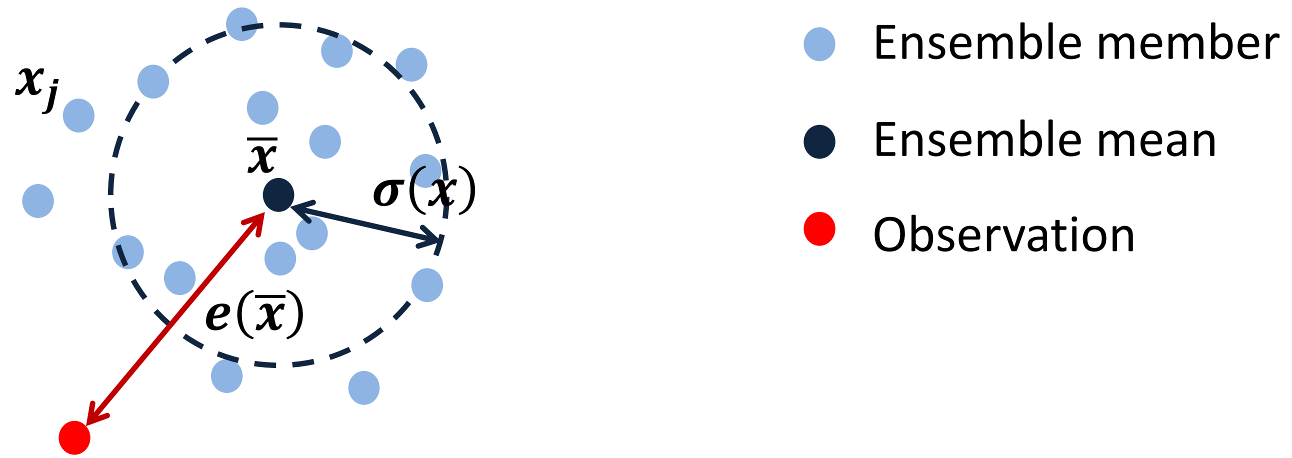
The relatively large spread implies large uncertainty and hence, likely large error:

an “under-confident forecast”

Some background: ensemble reliability

- In an **under**-dispersive ensemble,

$$e(\bar{x}) \gg \sigma(x)$$



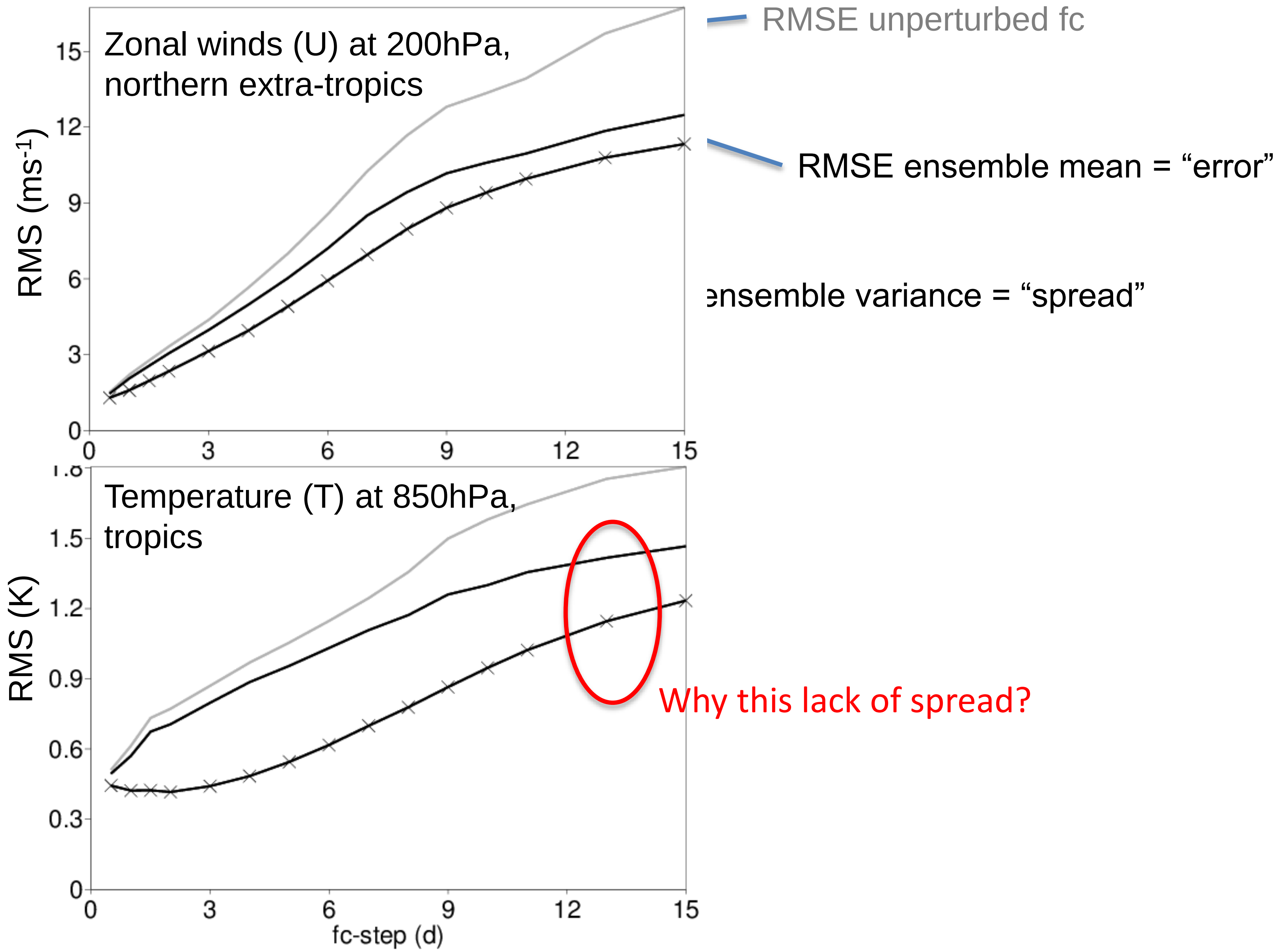
The small spread implies low uncertainty and hence, small errors:

an “over-confident forecast”

What happens when there is no representation of model uncertainty in our ensemble?

Ensemble forecasts with only initial conditions perturbations

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



Experiment details:

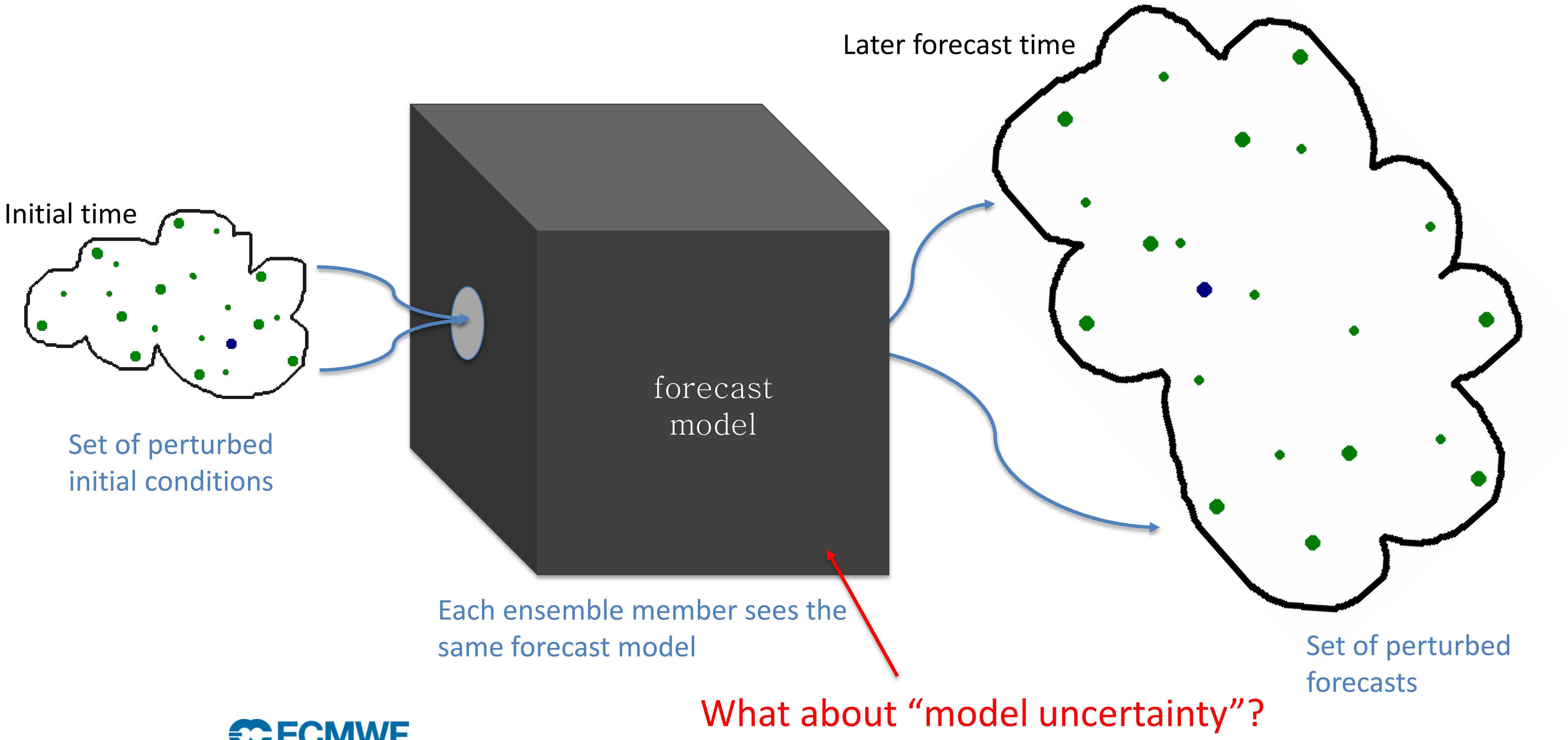
CY43R1

TCo399, dt=900s,

23 dates (2015),

20 perturbed fcs

When only initial uncertainty is represented in the forecast …



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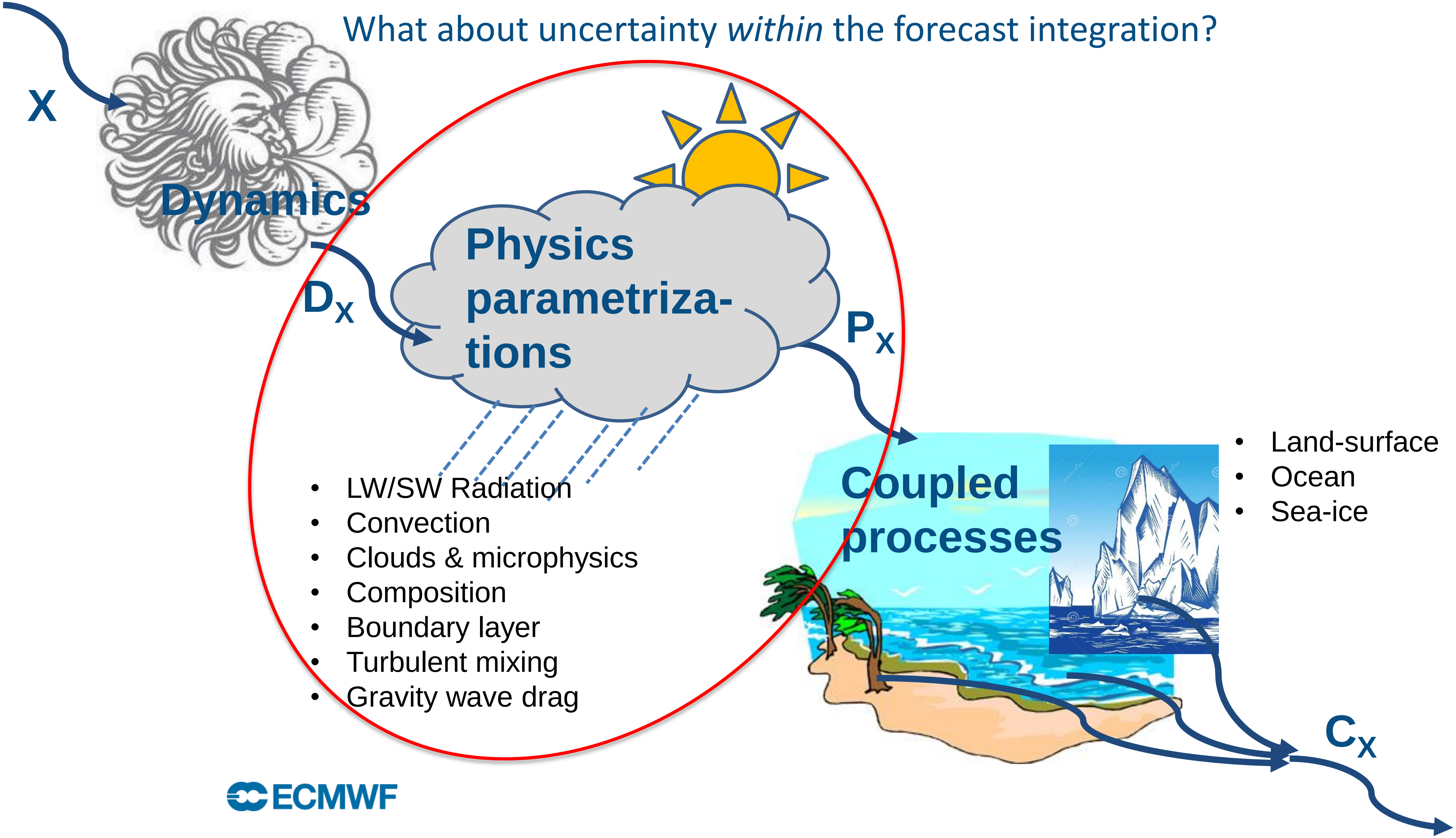
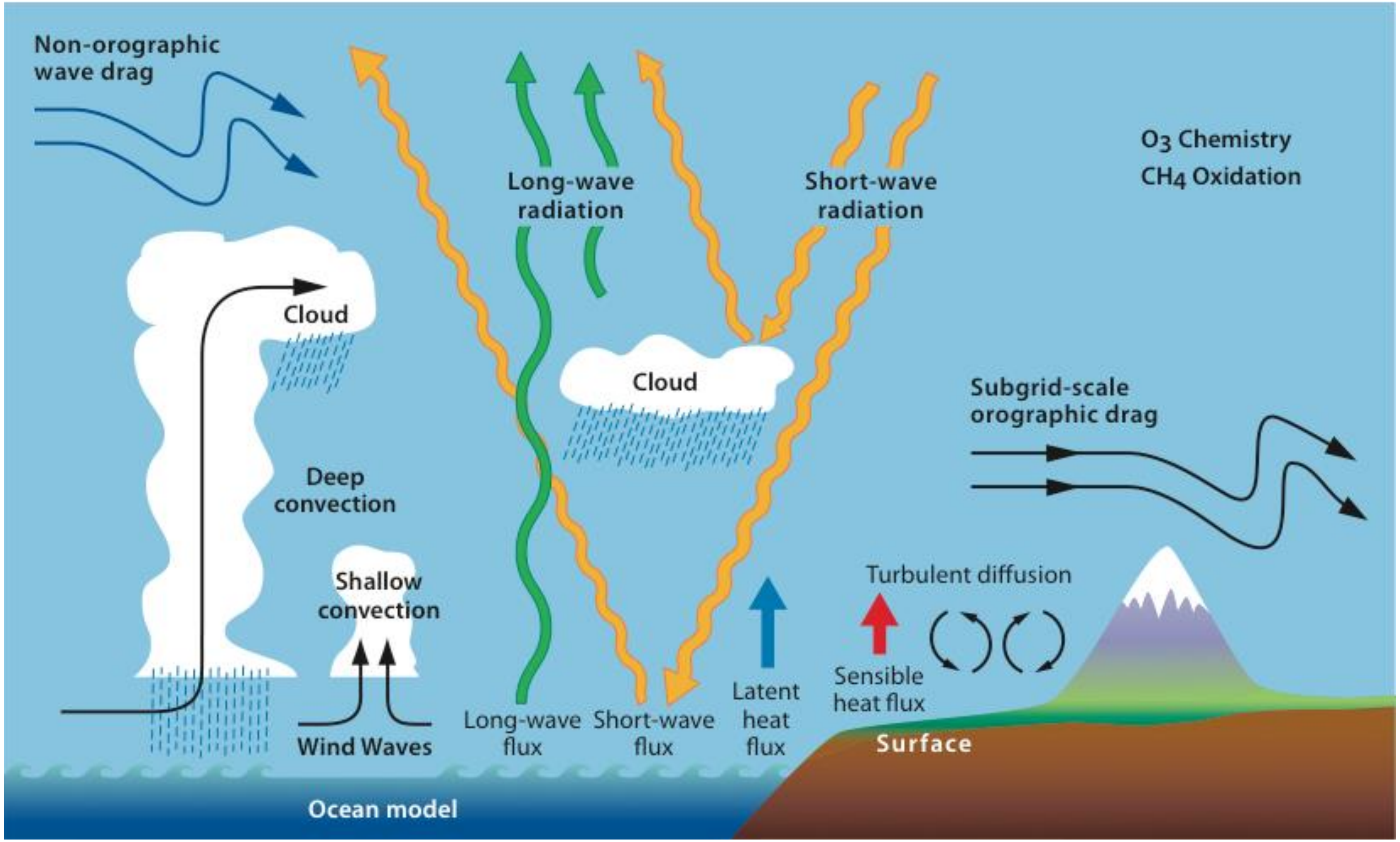
What about uncertainty *within* the forecast integration?



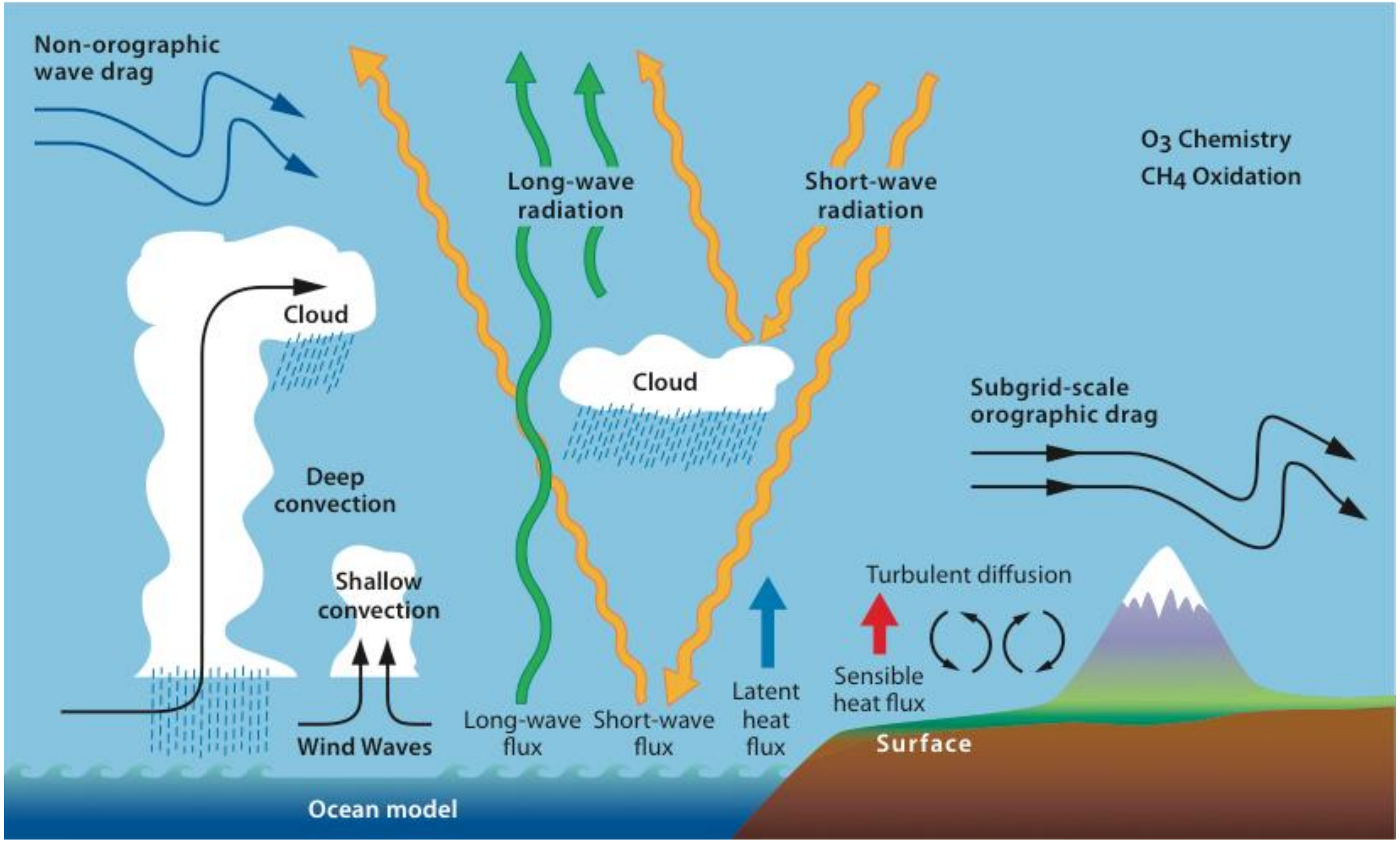
Model uncertainty: parametrized atmospheric physics processes



Uncertainties arise due to:

- Inability to resolve sub-grid scales
  - Surface drag (orography/waves)
  - Convection rates (occurrence / en-/detrainment)
  - Phase transitions
  - Radiation transfer in cloudy skies
- Poorly constrained parameters or processes
  - cloud-water distribution (radiation)
  - Composition
  - Non-orographic drag

Model uncertainty: parametrized atmospheric physics processes

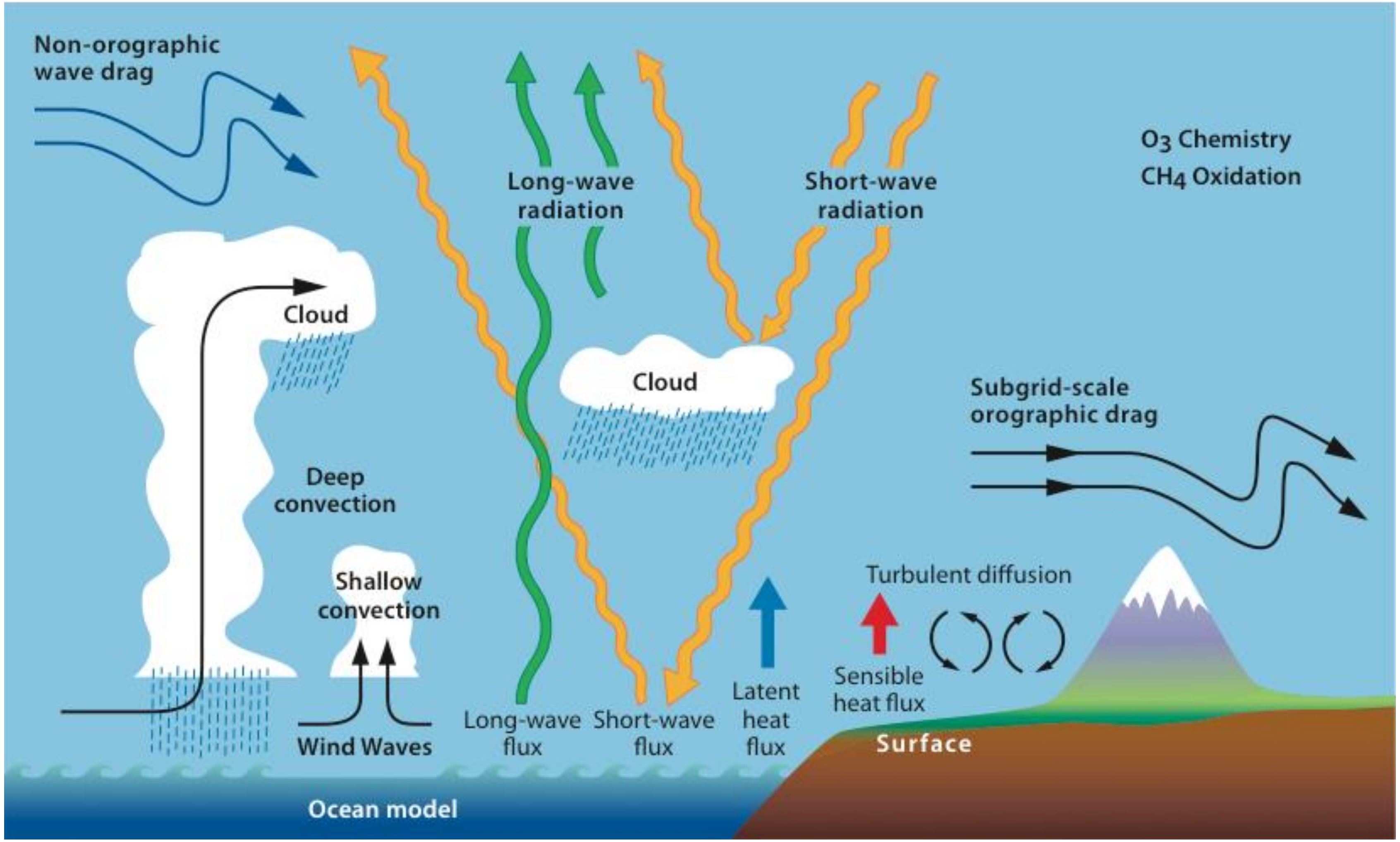


Parametrisation schemes:

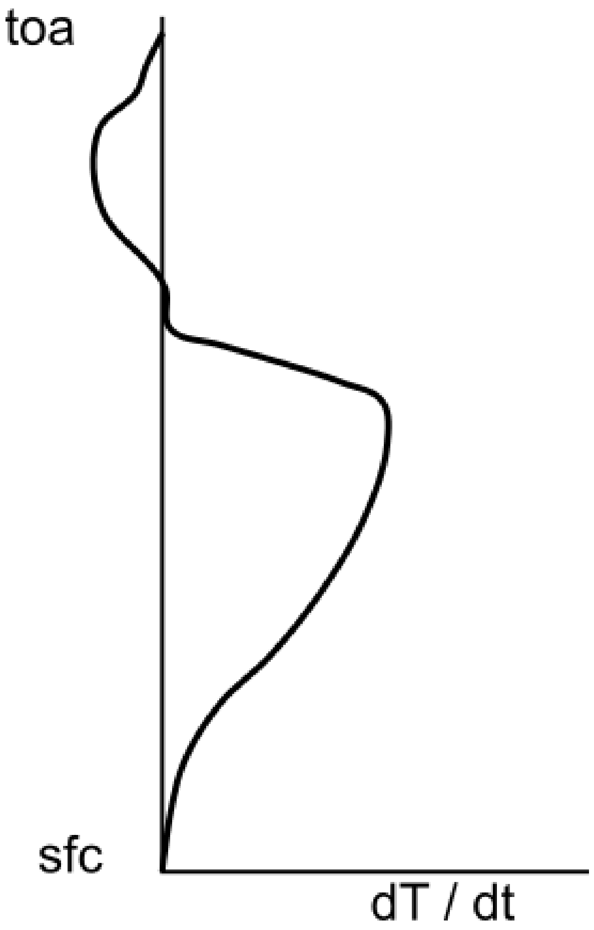
- developed & operate together
- highly tuned for best performance

Seek a description of uncertainty that retains consistencies of the representation of the physical processes.

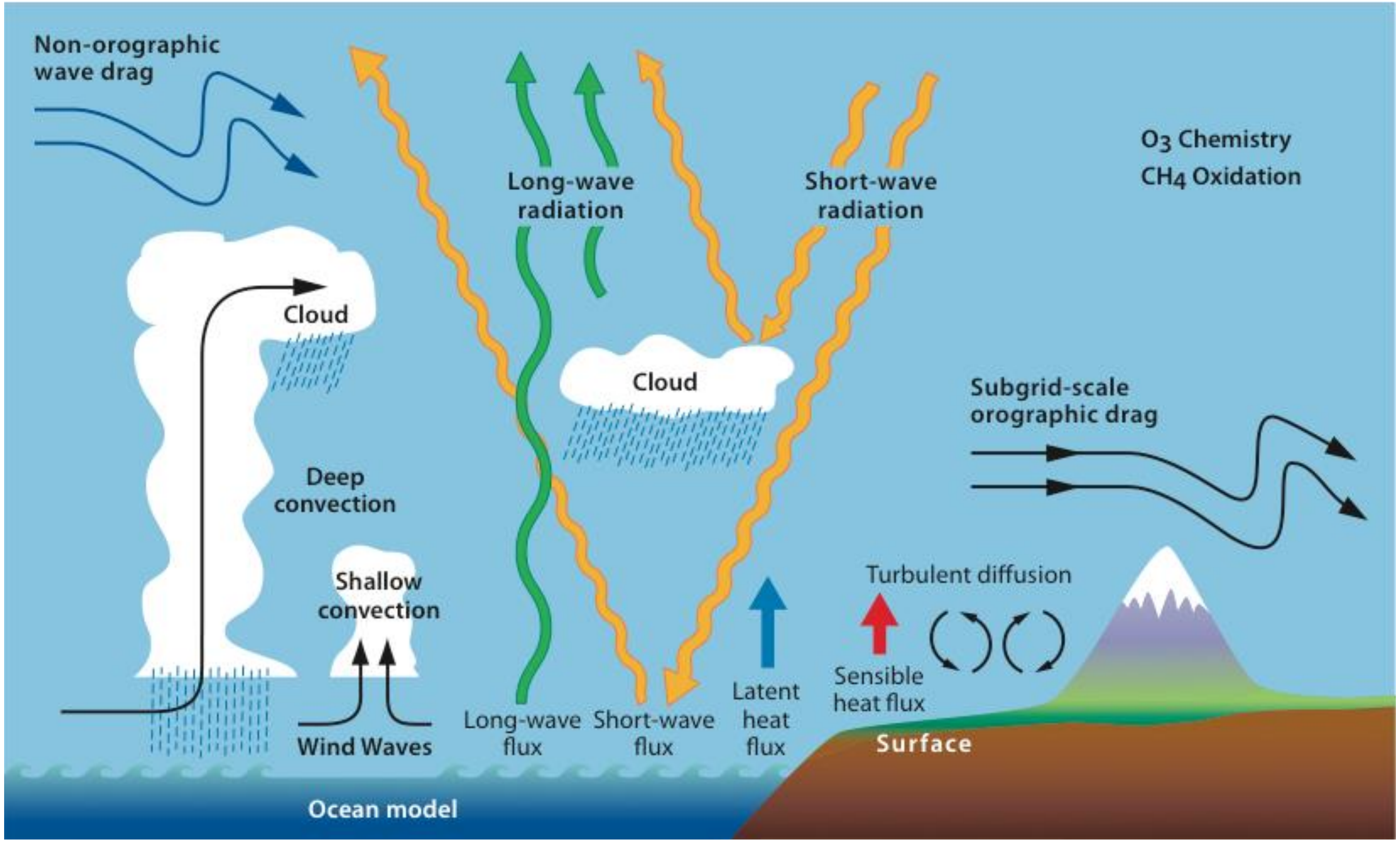
Model uncertainty: parametrized atmospheric physics processes



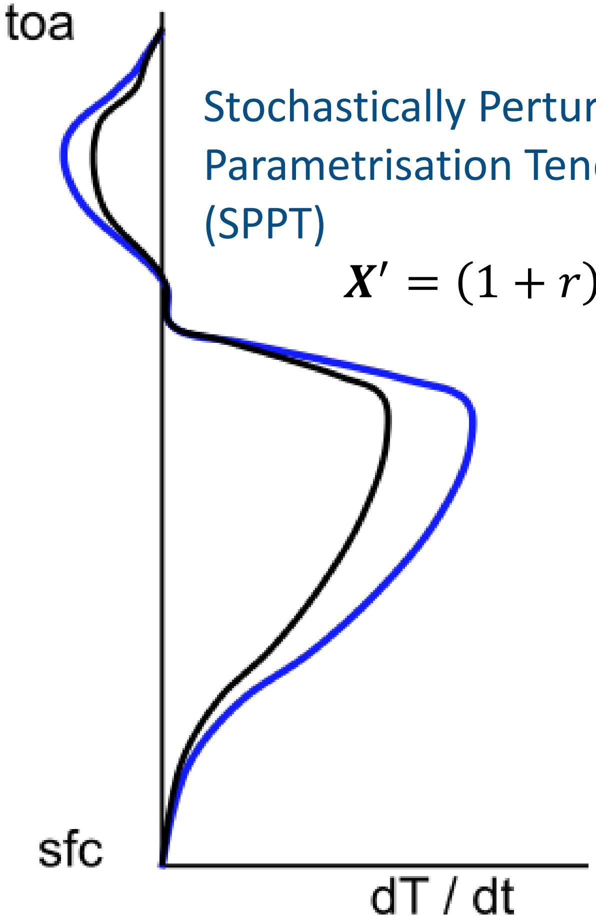
Consider a profile of heating rates from physics parametrisations:



Model uncertainty: parametrized atmospheric physics processes

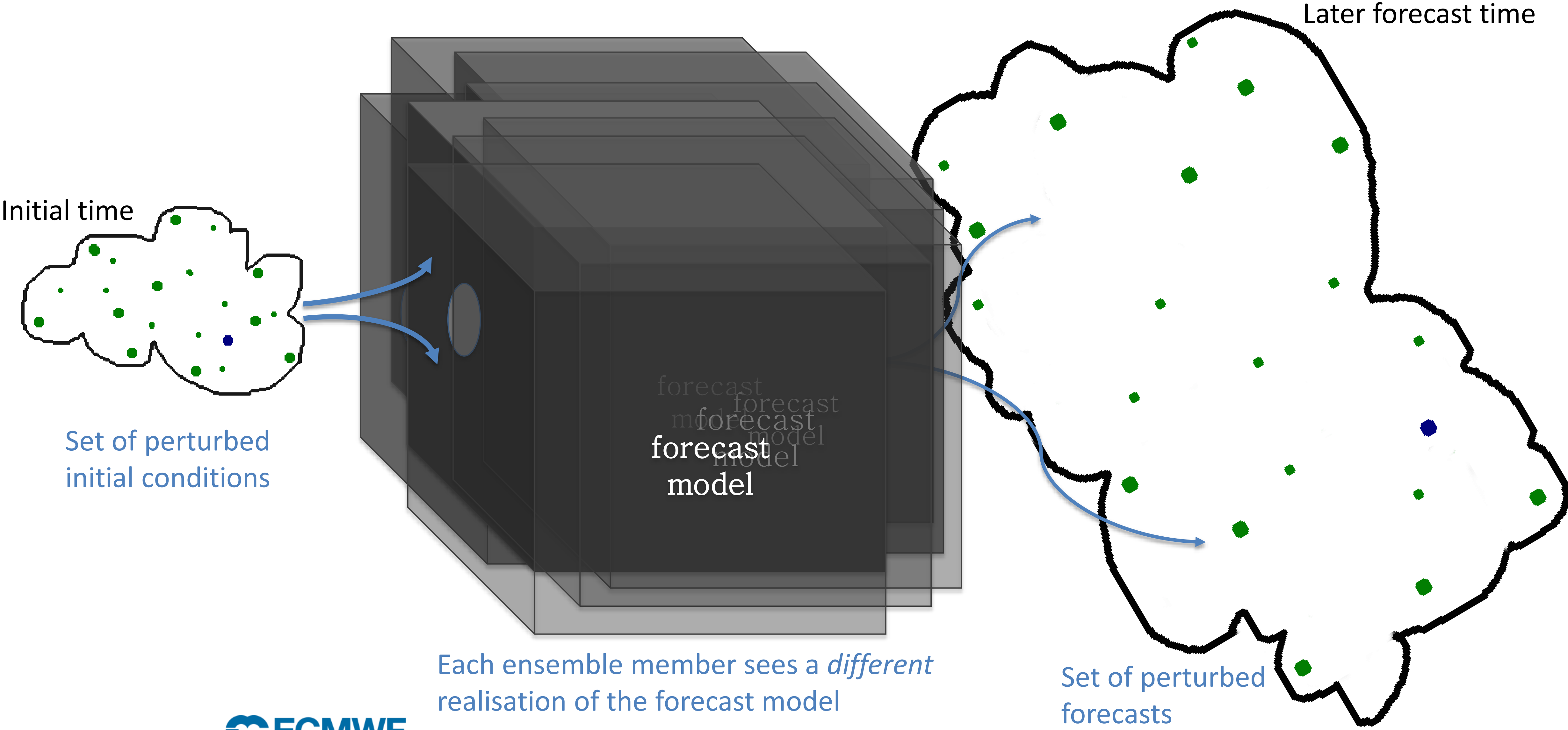


Proposal: represent uncertainties with a perturbation proportional to the profile of net physics tendencies



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

When the forecast also includes a representation of model uncertainty …



Set of perturbed initial conditions

Each ensemble member sees a *different* realisation of the forecast model

Set of perturbed forecasts

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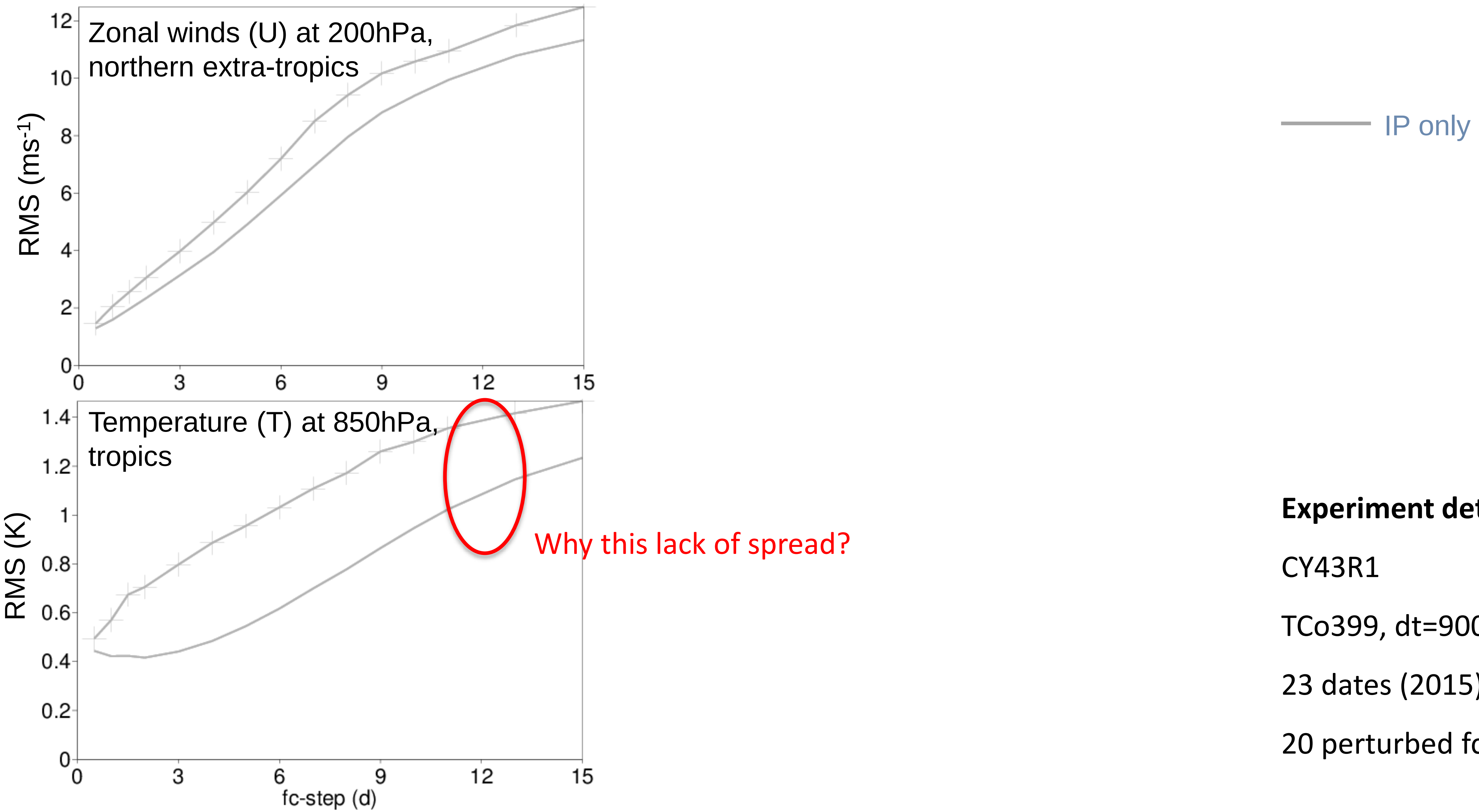
Recall: Ensemble forecasts: with initial conditions perturbations (IP) only

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



Experiment details:

CY43R1

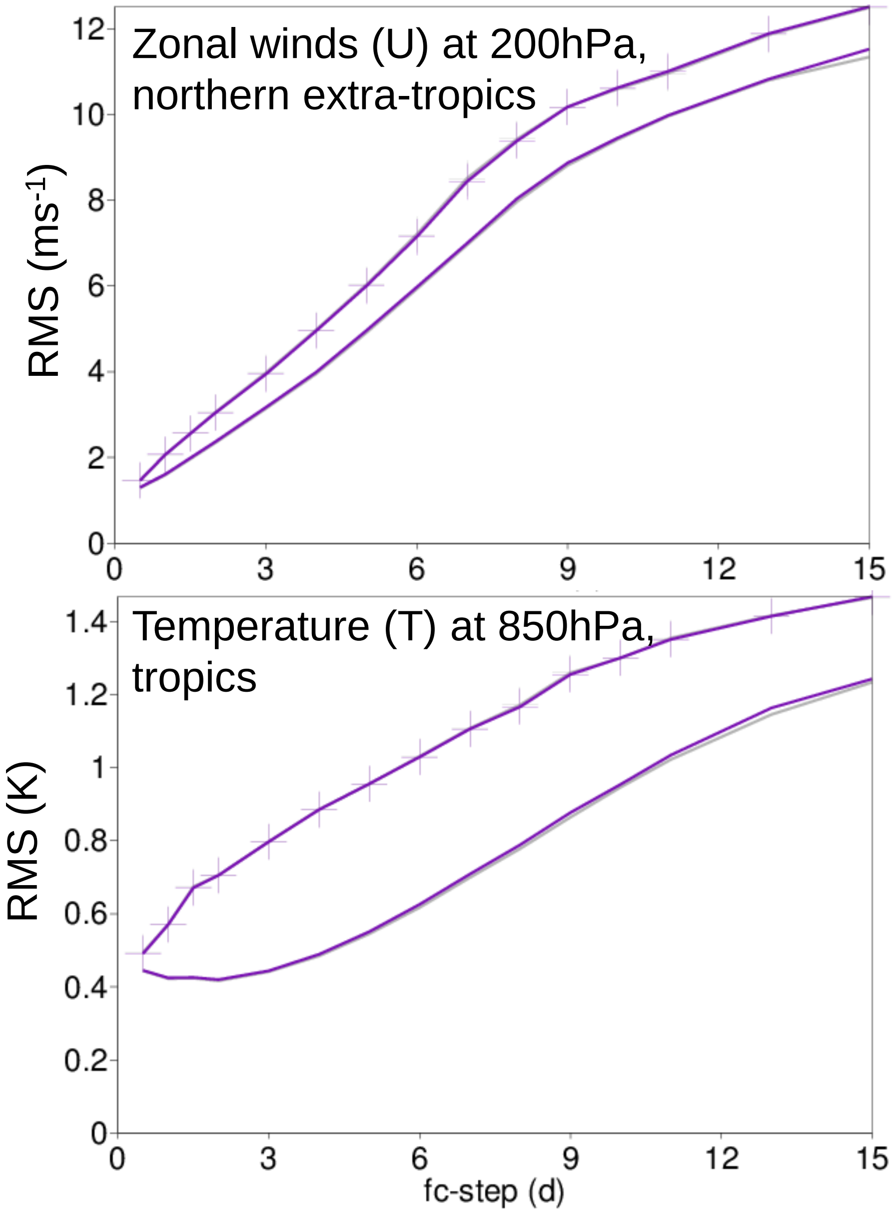
TCo399, dt=900s,

23 dates (2015),

20 perturbed fcs

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

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



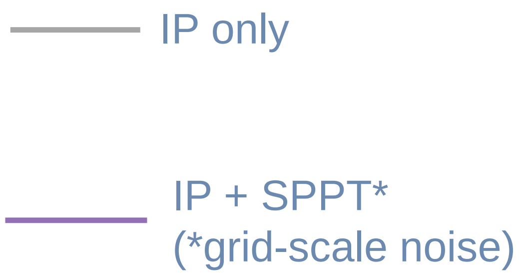
Include model uncertainty perturbations via SPPT:

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

where the noise term

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

represents grid-scale noise



Result:
Adding grid-scale noise yields little benefit

Experiment details:

CY43R1

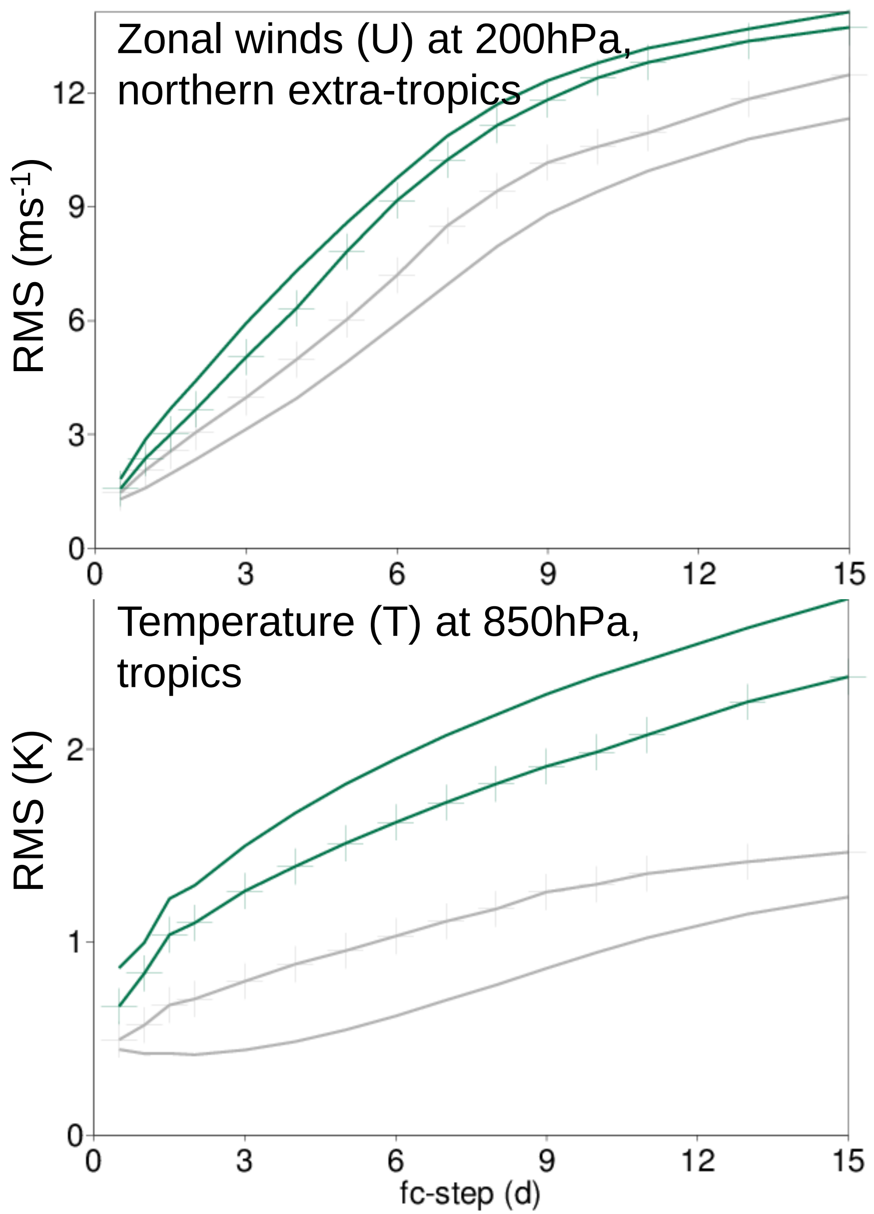
TCo399, dt=900s,

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

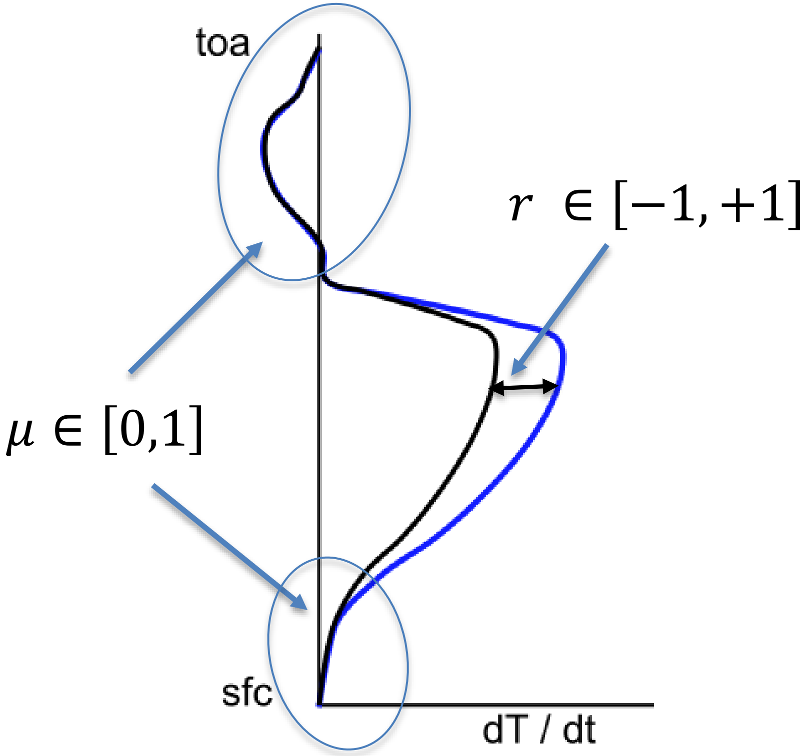
TCo399, dt=900s,

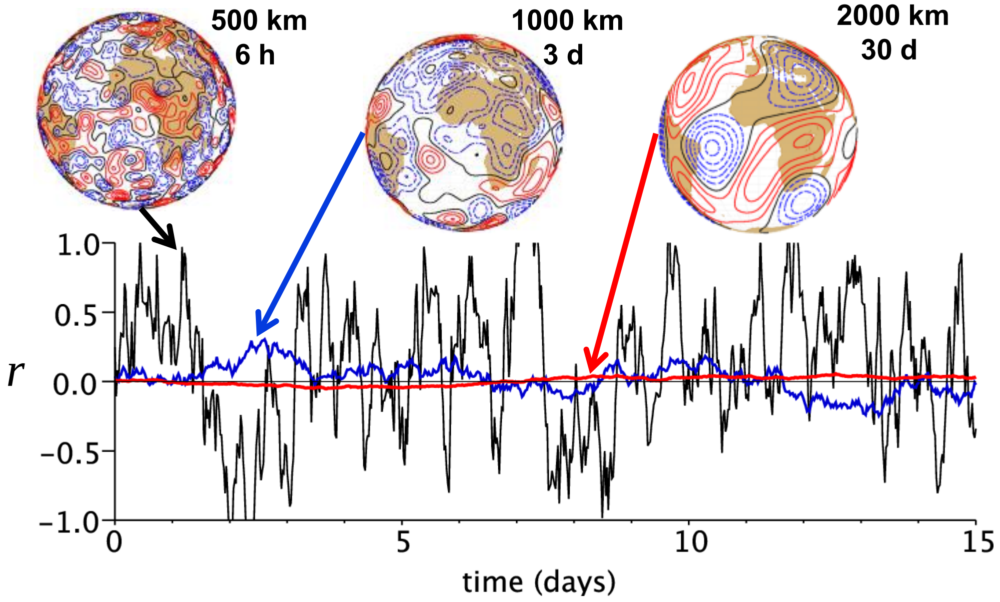
23 dates (2015),

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)

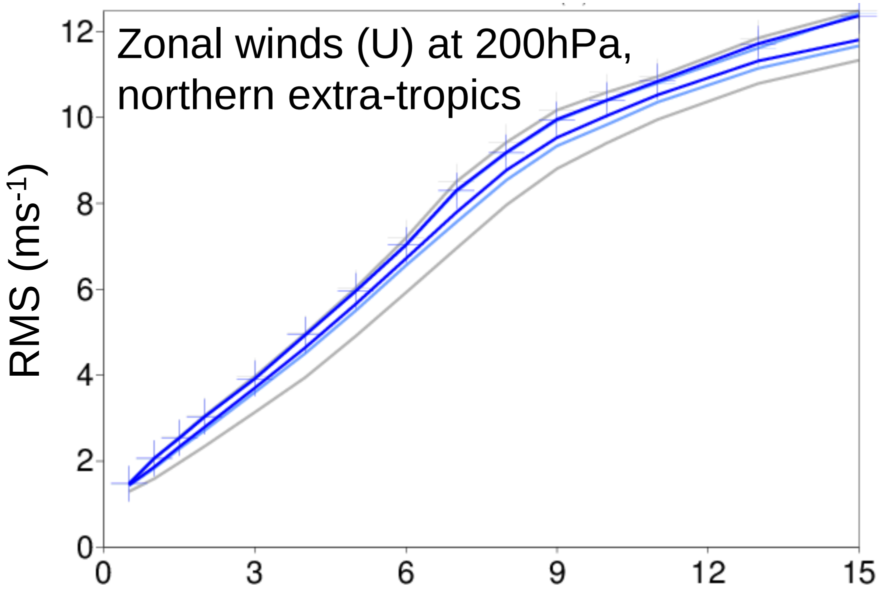


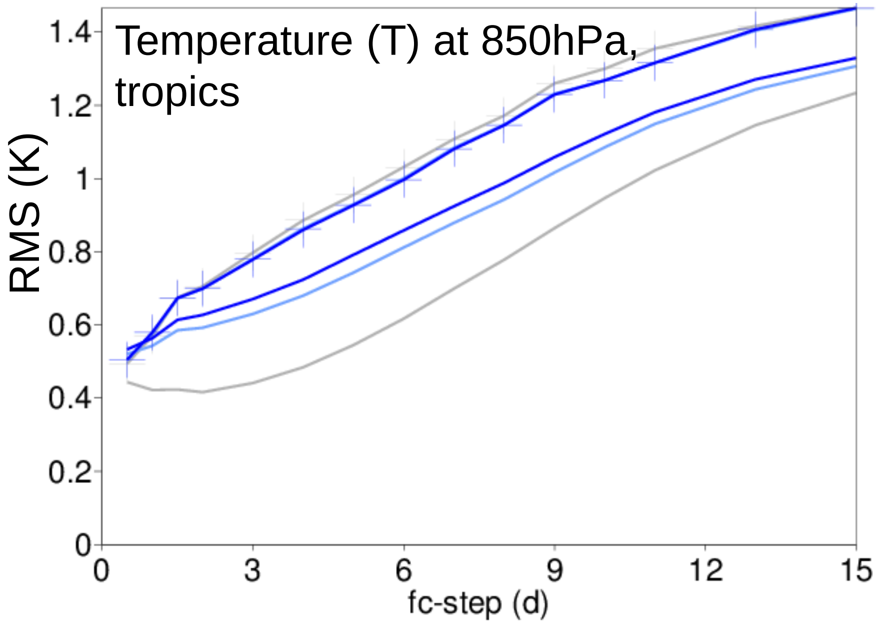


- Column of net tendencies from parametrised atmospheric physical processes multiplied with a 2D random field
- Multi-scale pattern: largest/slowest scale with least variance
- Perturbations are tapered (μ) to zero in the stratosphere and near the lower boundary

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

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





Include model uncertainty perturbations via SPPT:

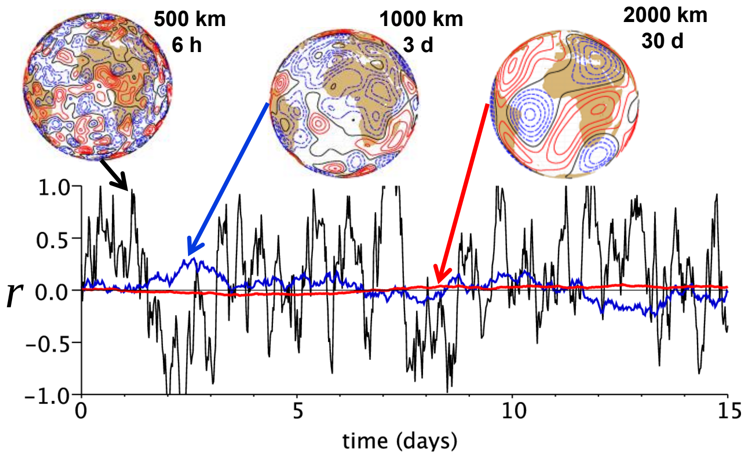
$$X' = (1 + r)X$$

where the noise term

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

1. Includes only shortest-scale correlations
2. Includes multi-scale correlations

Some additional spread from SPPT3



IP only

IP + SPPT1* (*short scales only)

IP + SPPT3** (**3 scales)

Experiment details:

CY43R1

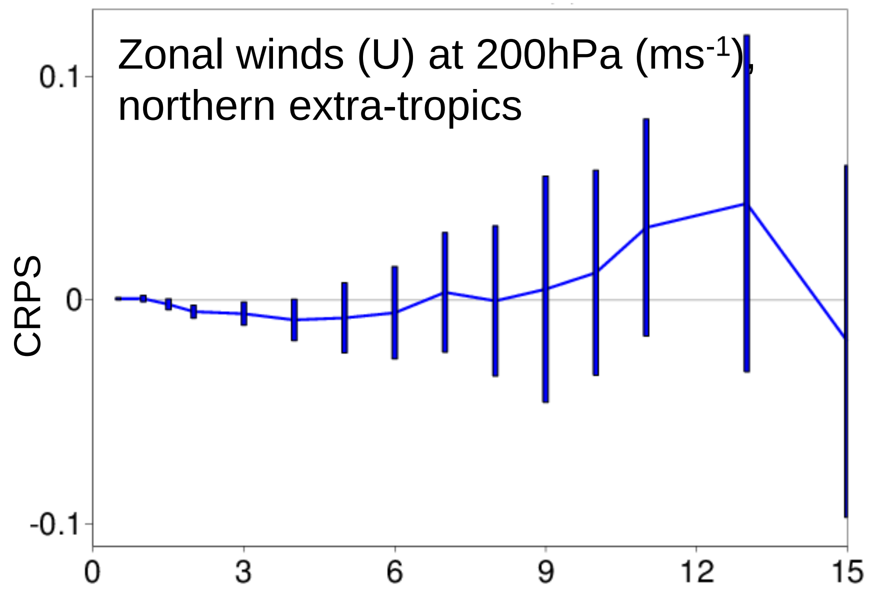
TCo399, dt=900s,

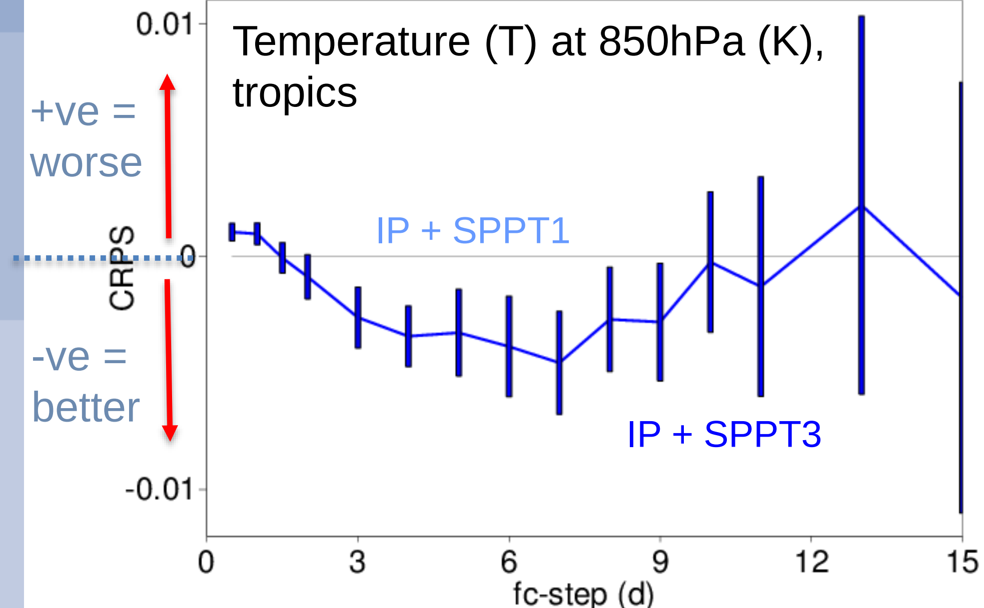
23 dates (2015),

20 perturbed fcs

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

Probabilistic skill (CRPS) – difference from **SPPT3** with respect to **SPPT1**





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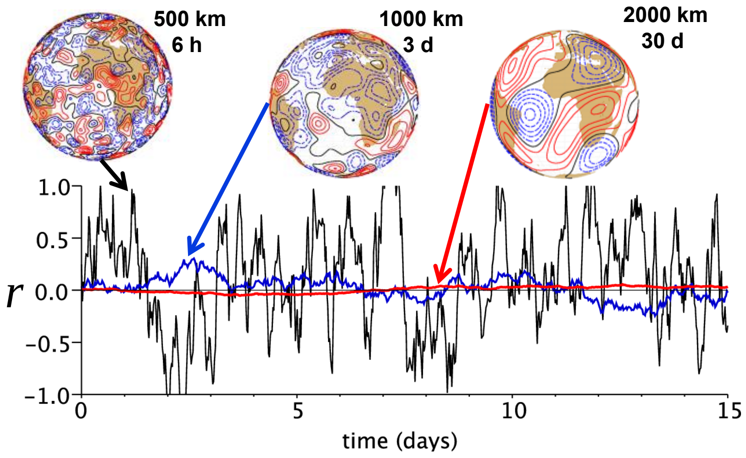


Some additional probabilistic skill from SPPT3

Experiment details:

CY43R1

TCo399, dt=900s,

23 dates (2015),

20 perturbed fcs

Stochastic representations of model uncertainty in IFS

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

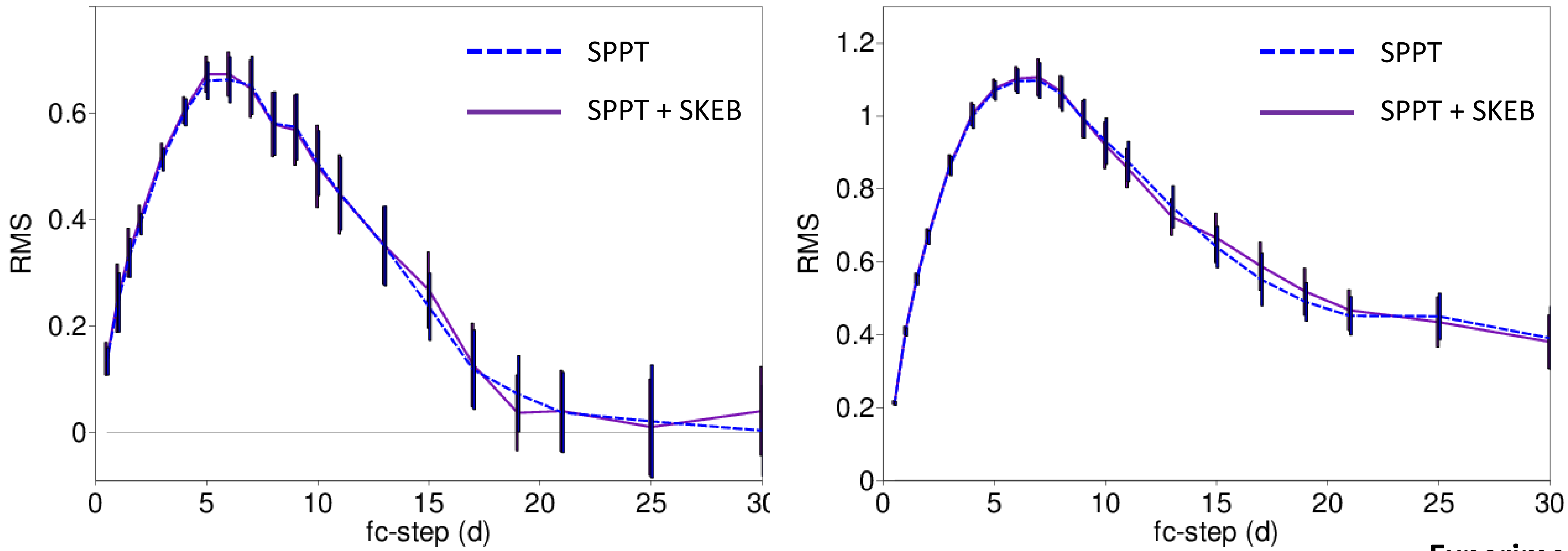
2. Stochastic kinetic energy backscatter (**SKEB**) scheme
   - real world: upscale propagation of kinetic energy (KE) at all scales
   - SKEB simulates upscale propagation from unresolved scales to resolved scales
   - streamfunction is perturbed with noise from a 3D random field, modulated by an estimate 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

Ensemble forecasts: SPPT & SKEB

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

Northern extra-tropics

Tropics



Differences with respect to an experiment with initial perturbations only

Experiment details:

TCo255/TCo159

46 dates (2013-2014),

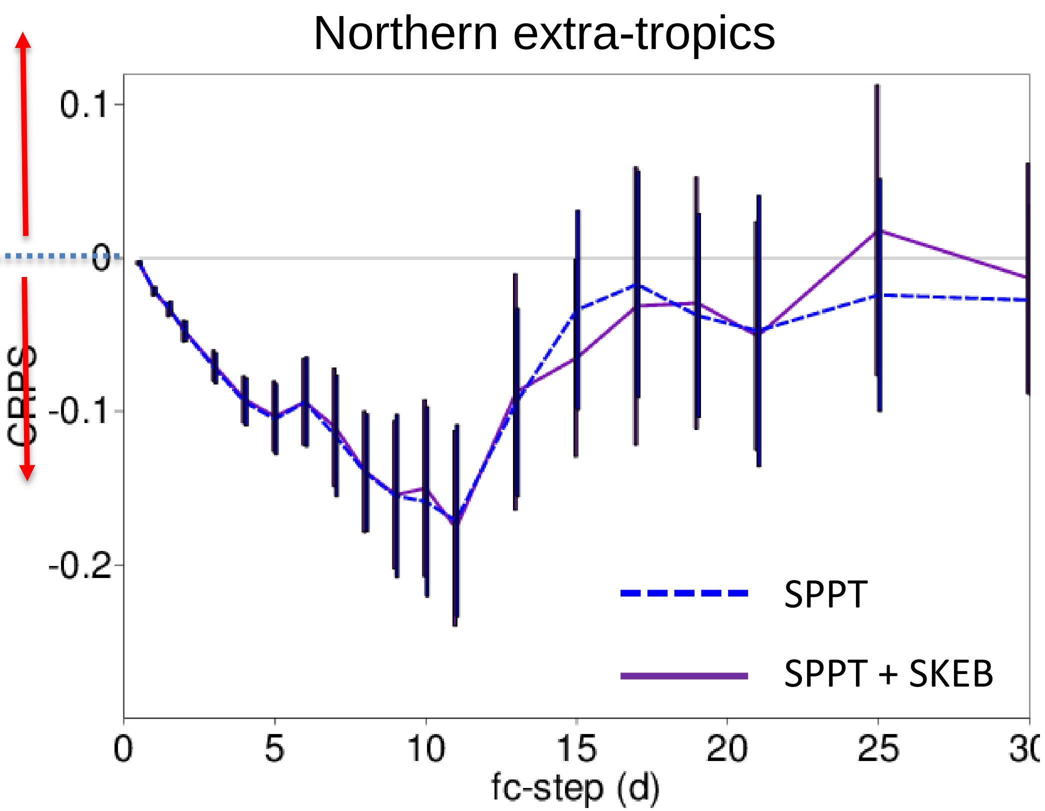
20 perturbed fcs

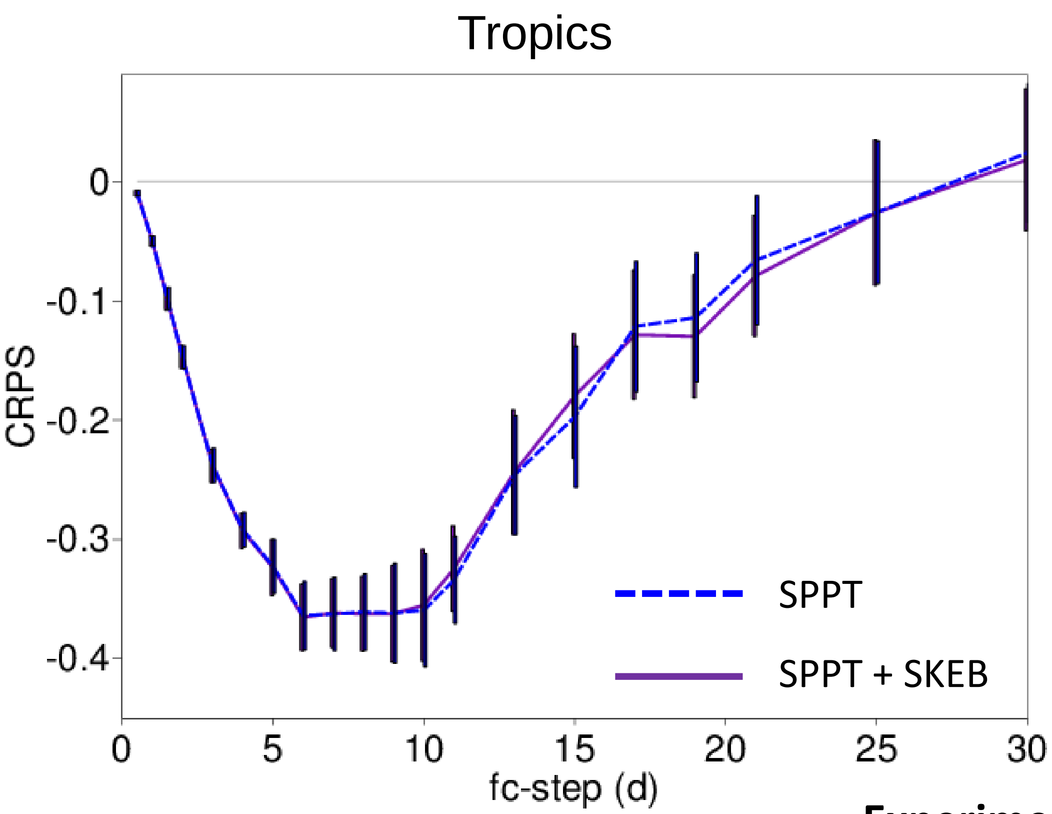
Ensemble forecasts: SPPT & SKEB

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

+ve = worse

-ve = better





Differences with respect to an experiment with initial perturbations only

Experiment details:

TCo255/TCo159

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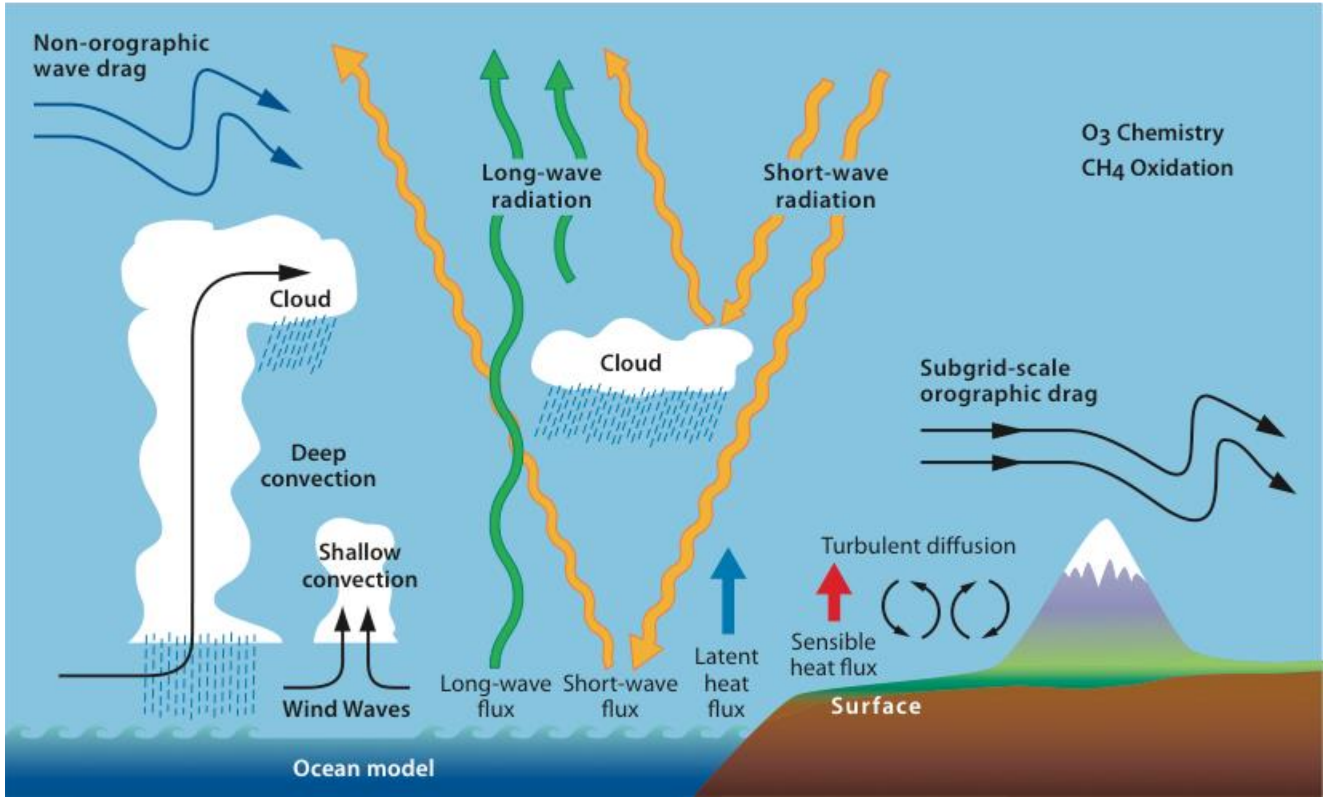
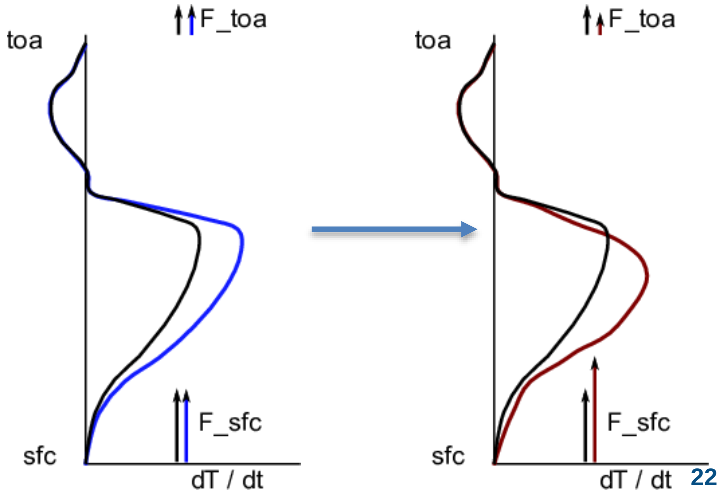
Stochastic representations of model uncertainty: looking ahead

Towards process-level model uncertainty representation

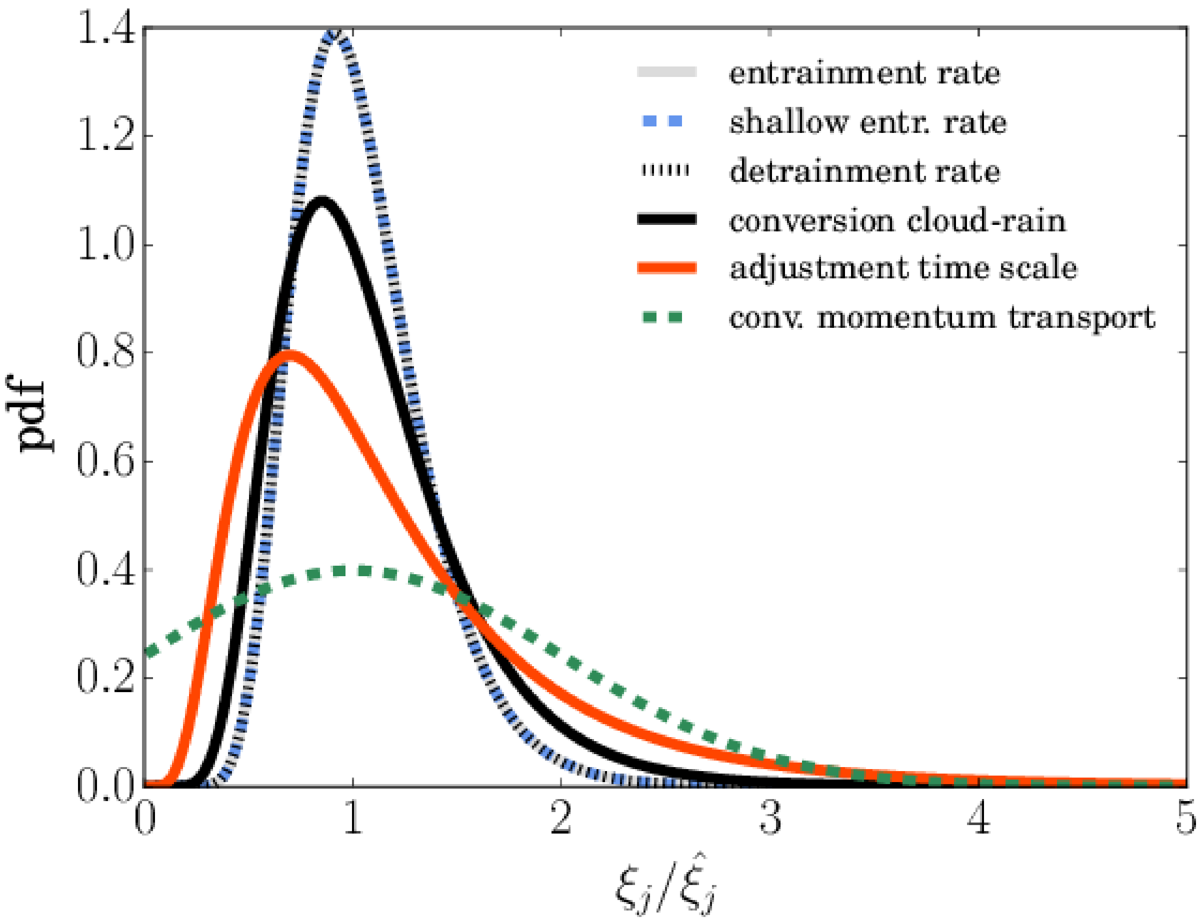


- **Aim**: to improve the physical consistency
- Remove ad hoc tapering in boundary layer and stratosphere
- Preserve local energy/moisture budgets through consistent flux perturbations at the upper and lower boundaries
- Represent uncertainty close to assumed sources of errors
- Include multi-variate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

Parameters/variables within parametrisation schemes are multiplied with noise from a 2D random pattern: $\xi = r\hat{\xi}$

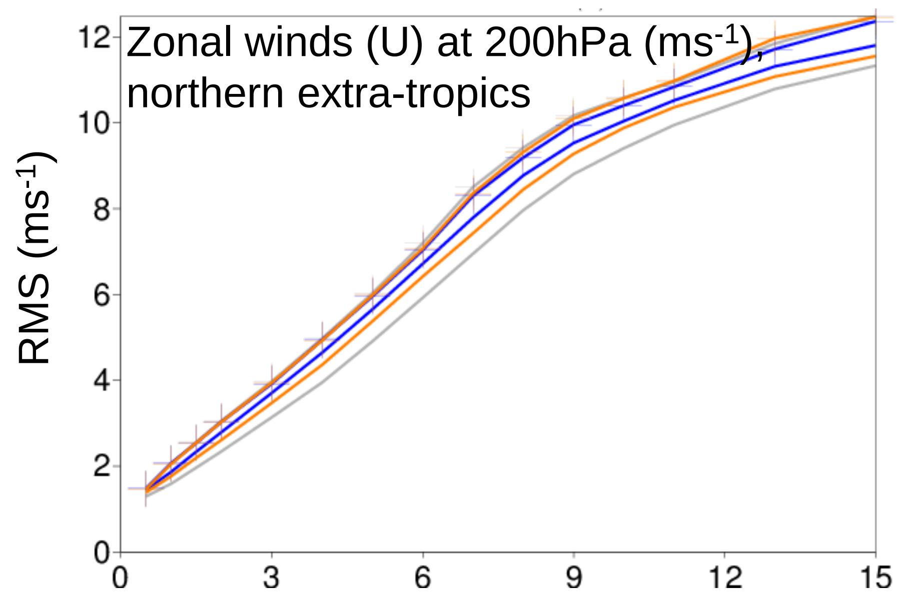
correlated in space (2000 km) and time (72 h).

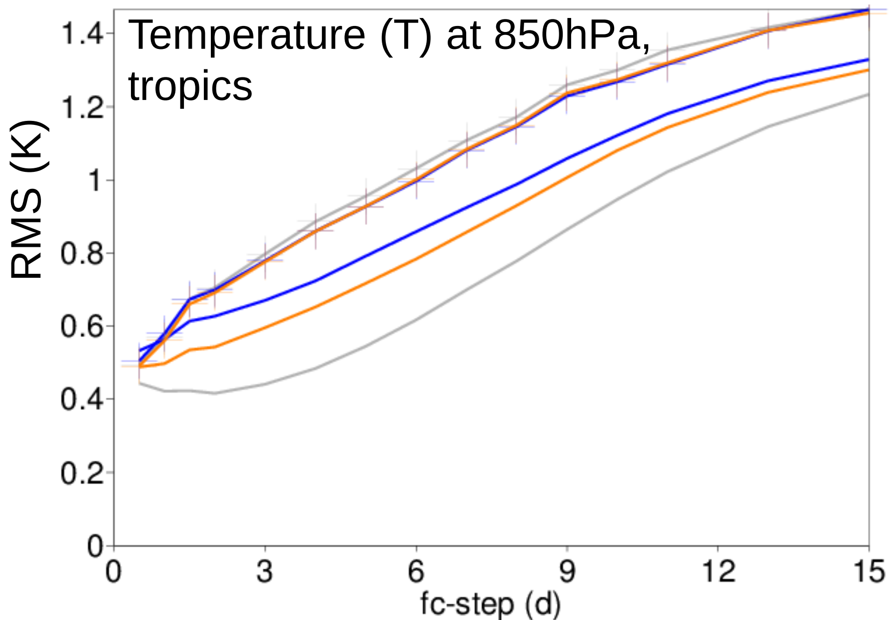
e.g. convection scheme parameters are perturbed with numbers drawn from distributions shown

Currently: **20 independent perturbations** in parametrisations of sub-grid orography and vertical mixing, radiation, cloud and large-scale precipitation and convection

Stochastically Perturbed Parametrisations (SPP) scheme

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





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

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

More work to do!

- IP only
- IP + SPPT
- IP + SPP

Experiment details:

CY43R1

TCo399, dt=900s,

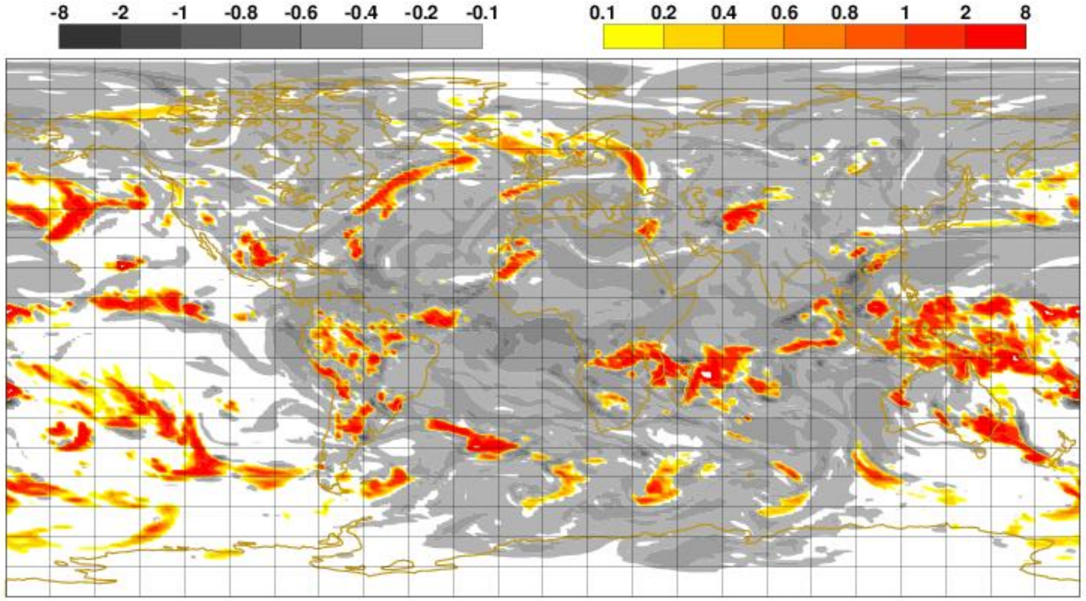
23 dates (2015),

20 perturbed fcs

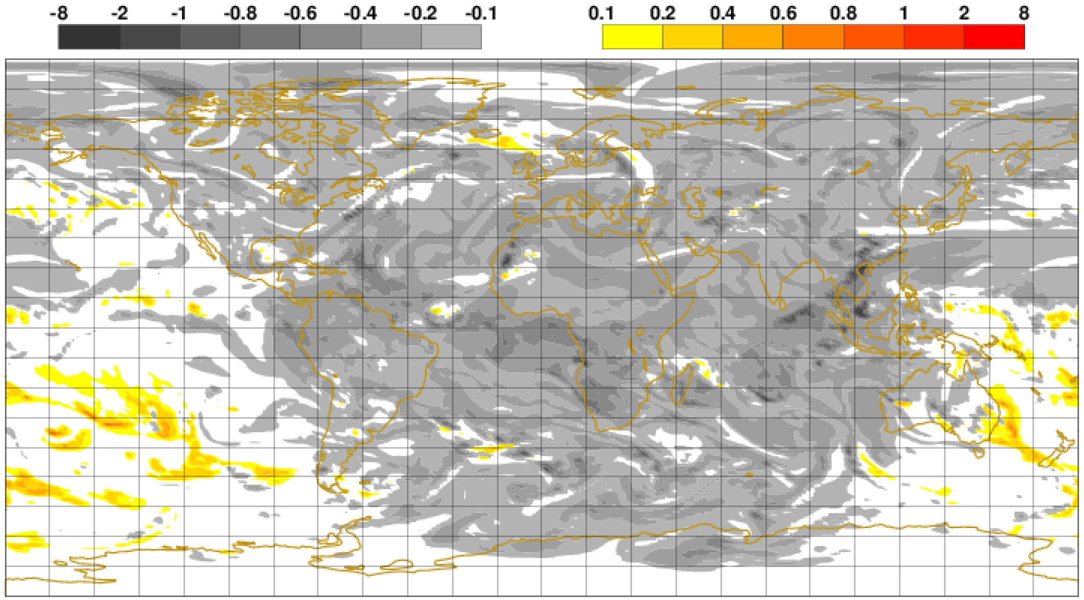
A look at the physical tendencies and processes

Ensemble mean of tendencies, 21-24h

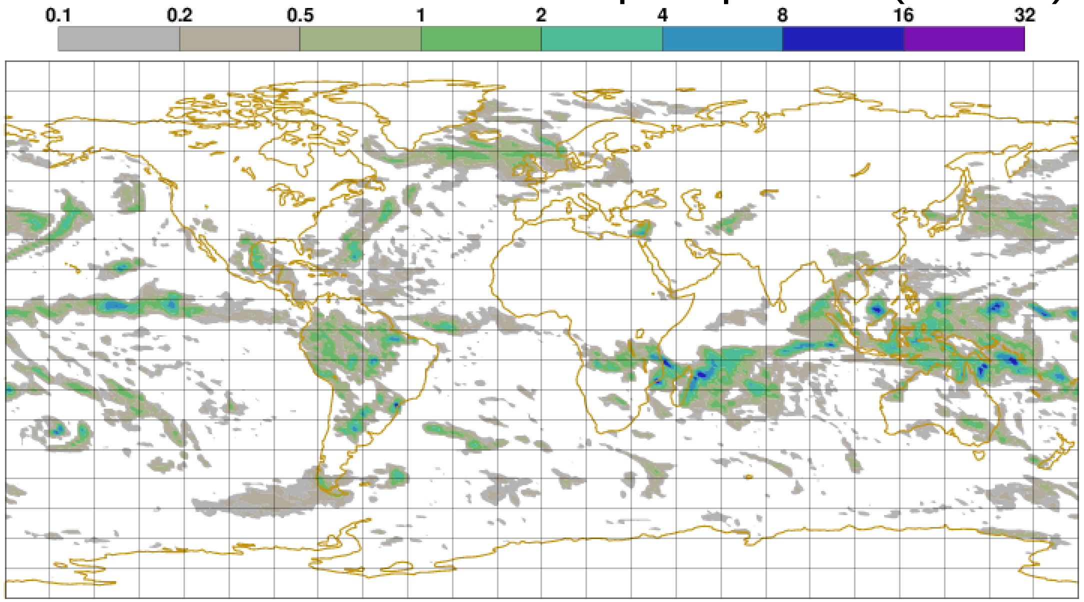
Net physics temperature (T) tendencies (K/3h)
@ model level 64 (~500 hPa)



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



Convective precipitation (mm/3h)



From a 20-member ensemble forecast:
starting 00:00,10-01-2015

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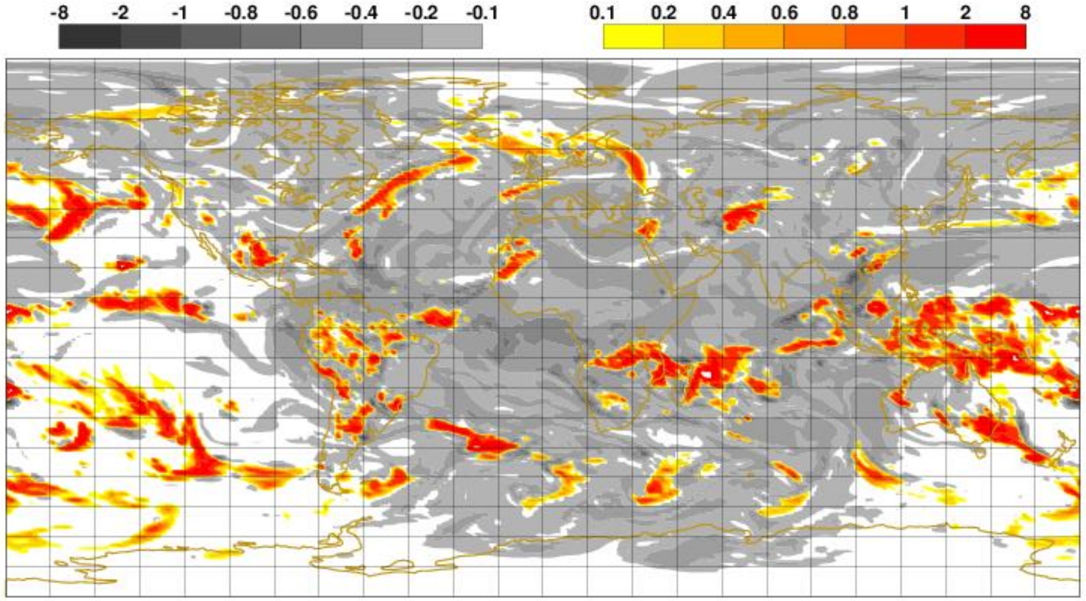
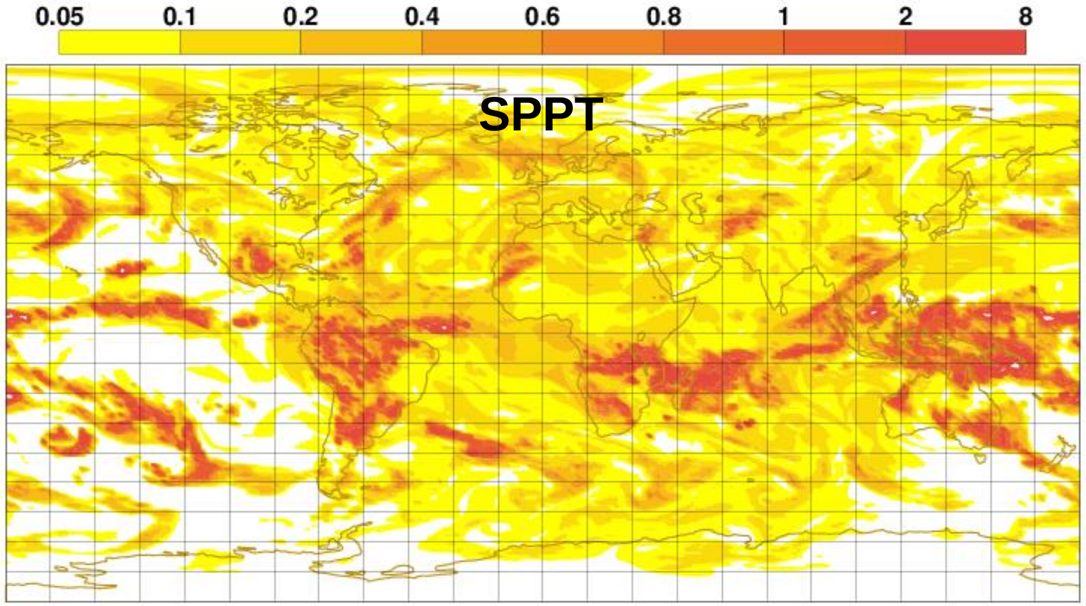
And a look at the tendency perturbations

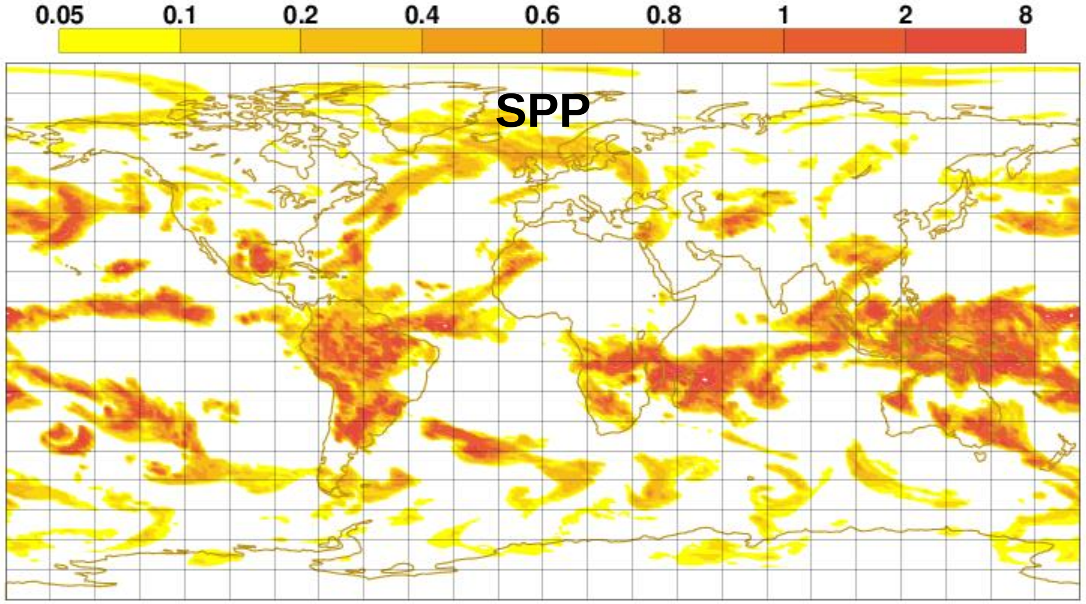
T tendencies, 21-24h @ model level 64 (~500 hPa)

Ensemble mean (K/3h)



Ensemble standard deviation (K/3h)





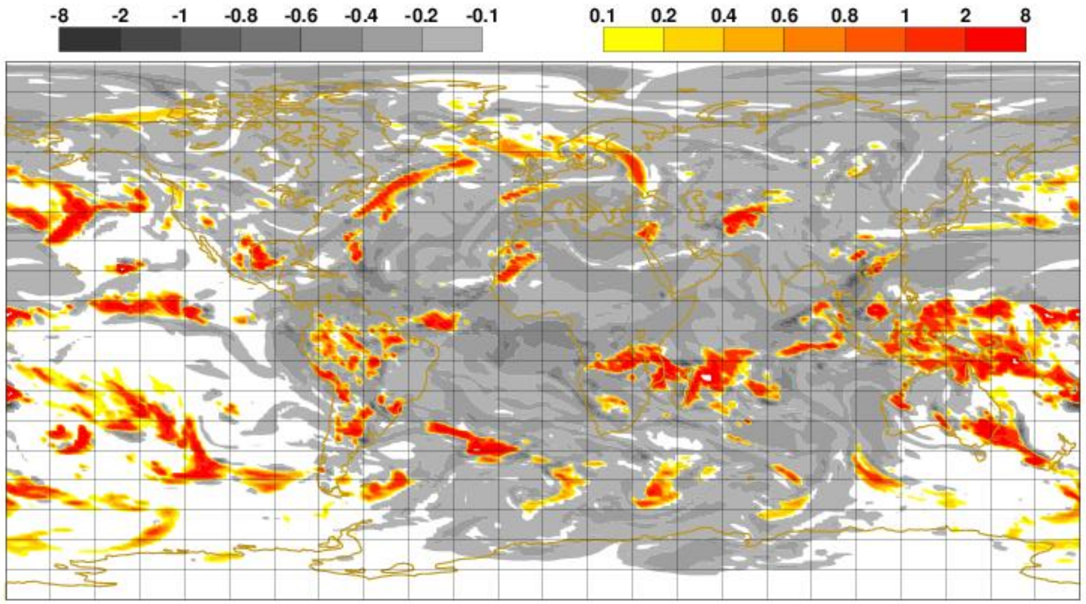
From a 20-member ensemble forecast:
starting 00:00,10-01-2015
with identical initial conditions

ECMWF

And a look at the tendency perturbations

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

Ensemble mean (K/3h)



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

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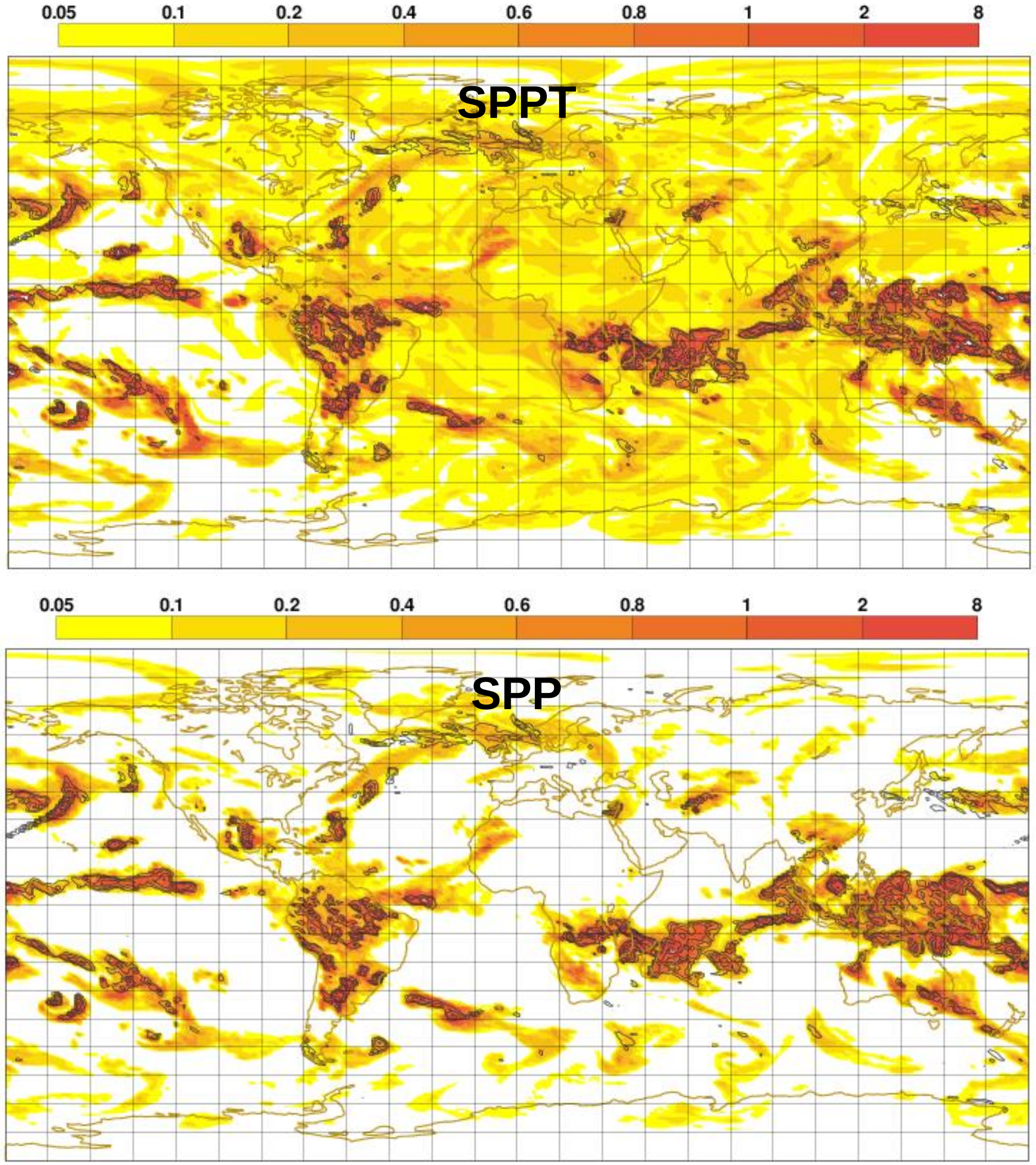
Ensemble standard deviation (K/3h)

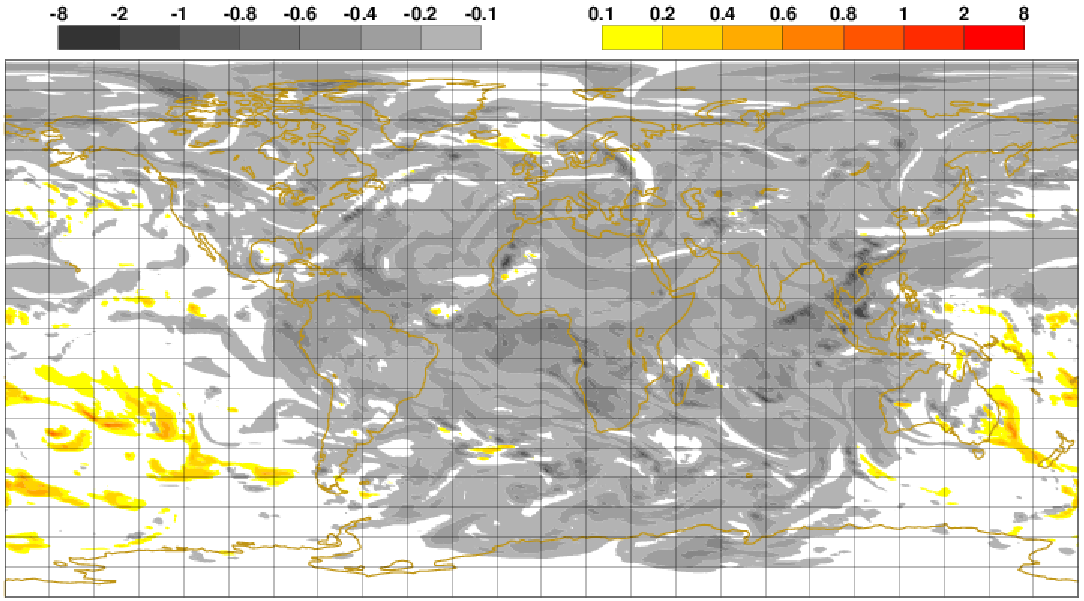


Ensemble mean convective precipitation (mm/3h)

And a look at the tendency perturbations

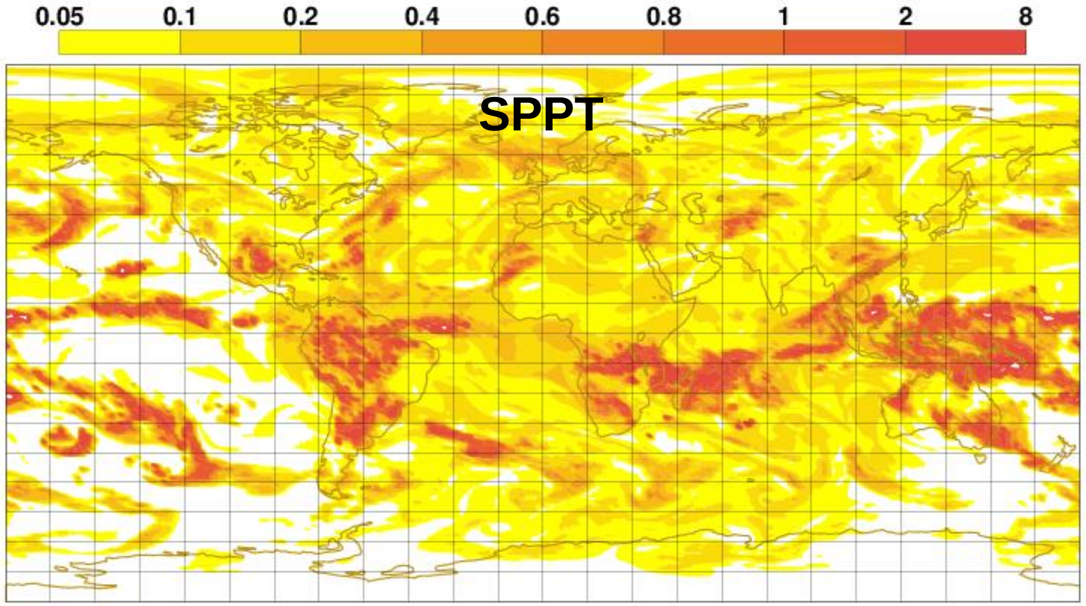
T tendencies, 21-24h @ model level 64 (~500 hPa)

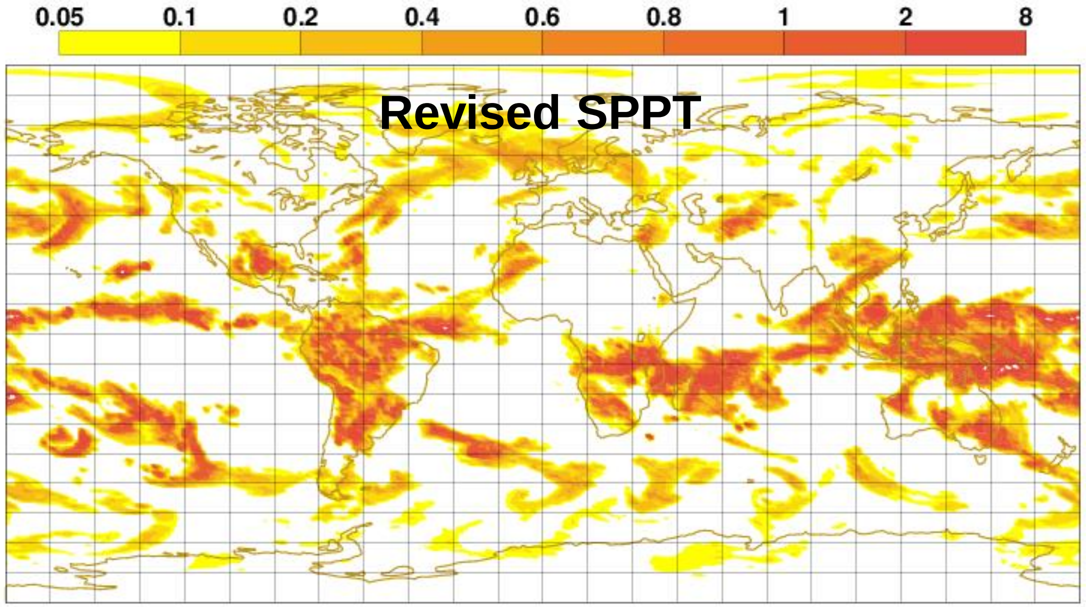
Ensemble mean: radiation tendencies (K/3h)



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

Ensemble standard deviation (K/3h)

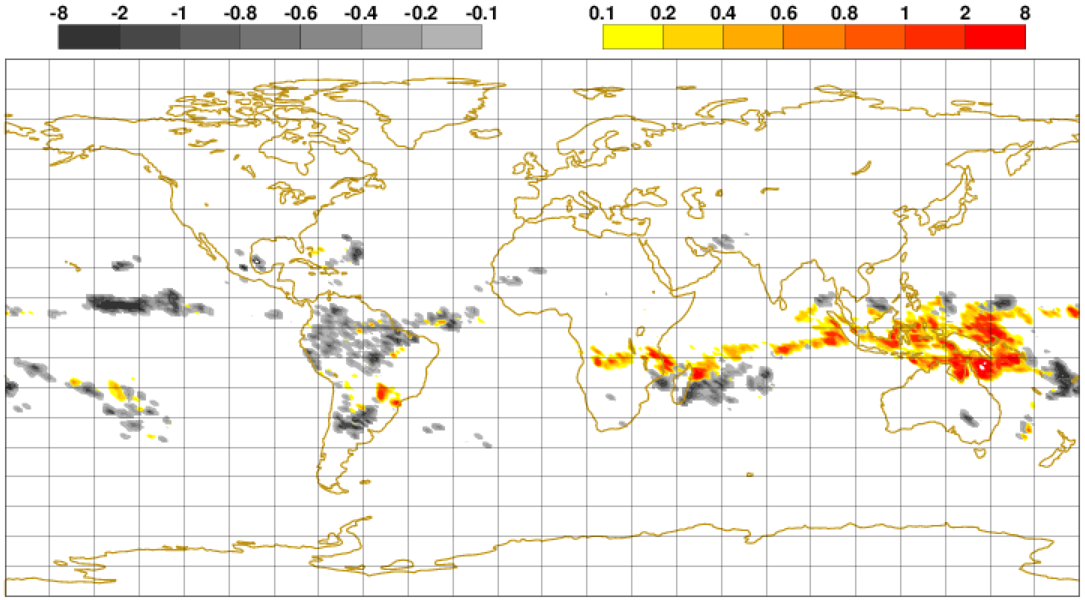




A look at the physical tendencies and processes (II)

U tendencies, 0-3h @ model level 49 (~200 hPa)

Ensemble mean: convection tendencies ($ms^{-1}/3h$)



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

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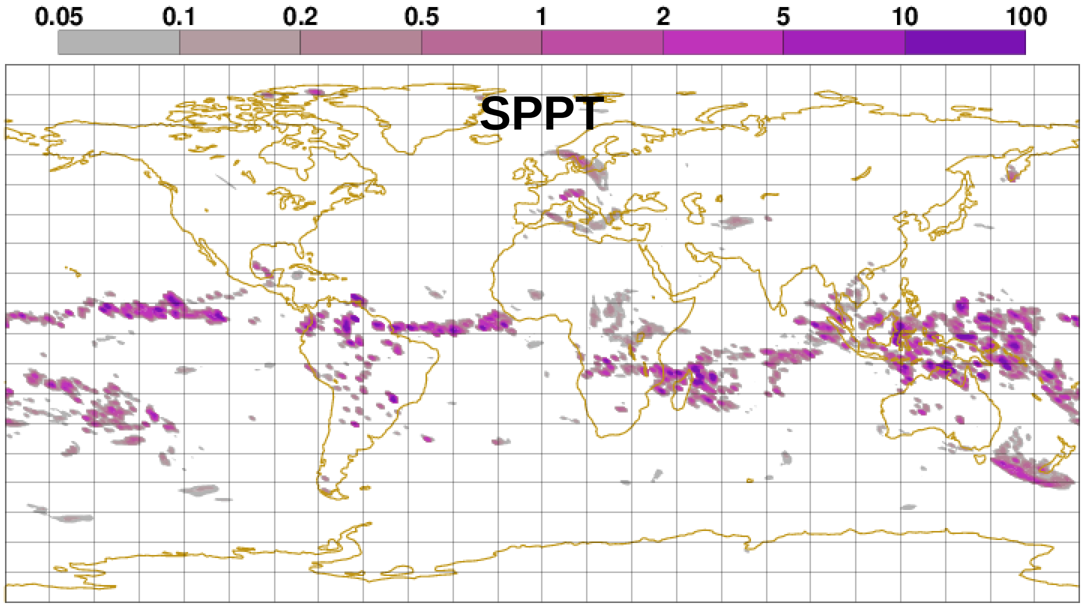
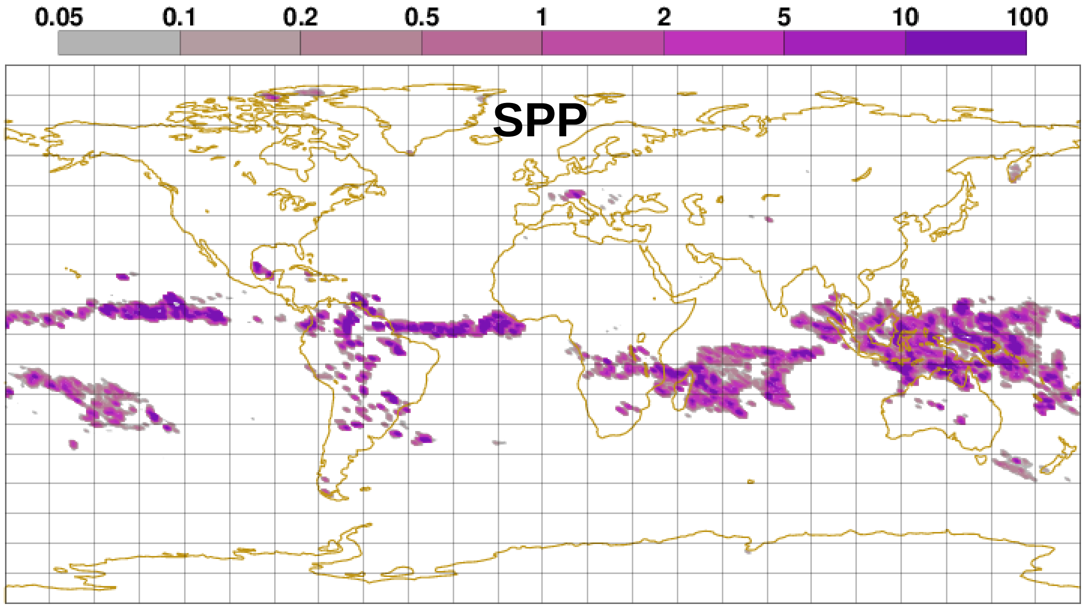
Ensemble variance $(ms^{-1}/3h)^2$

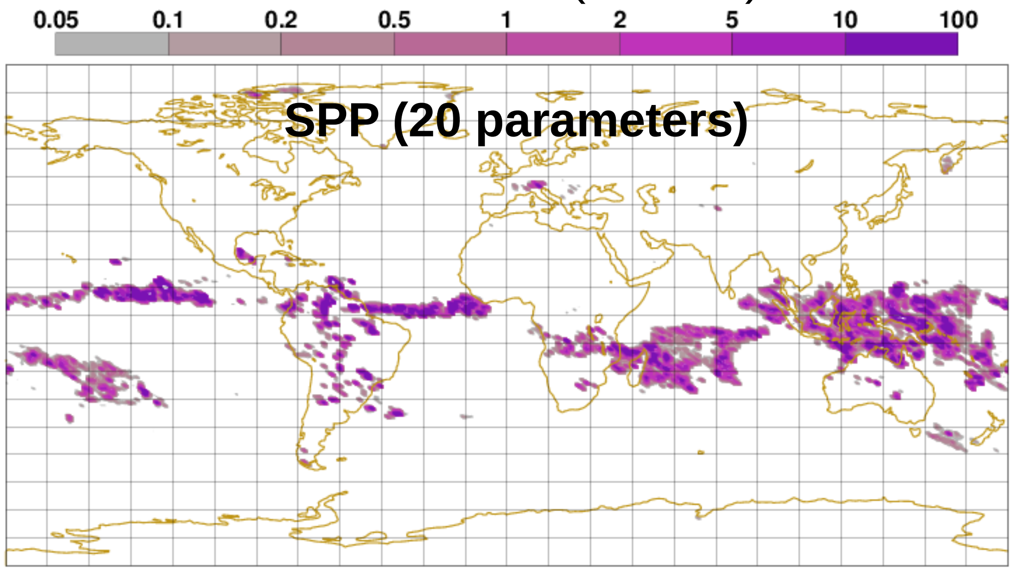


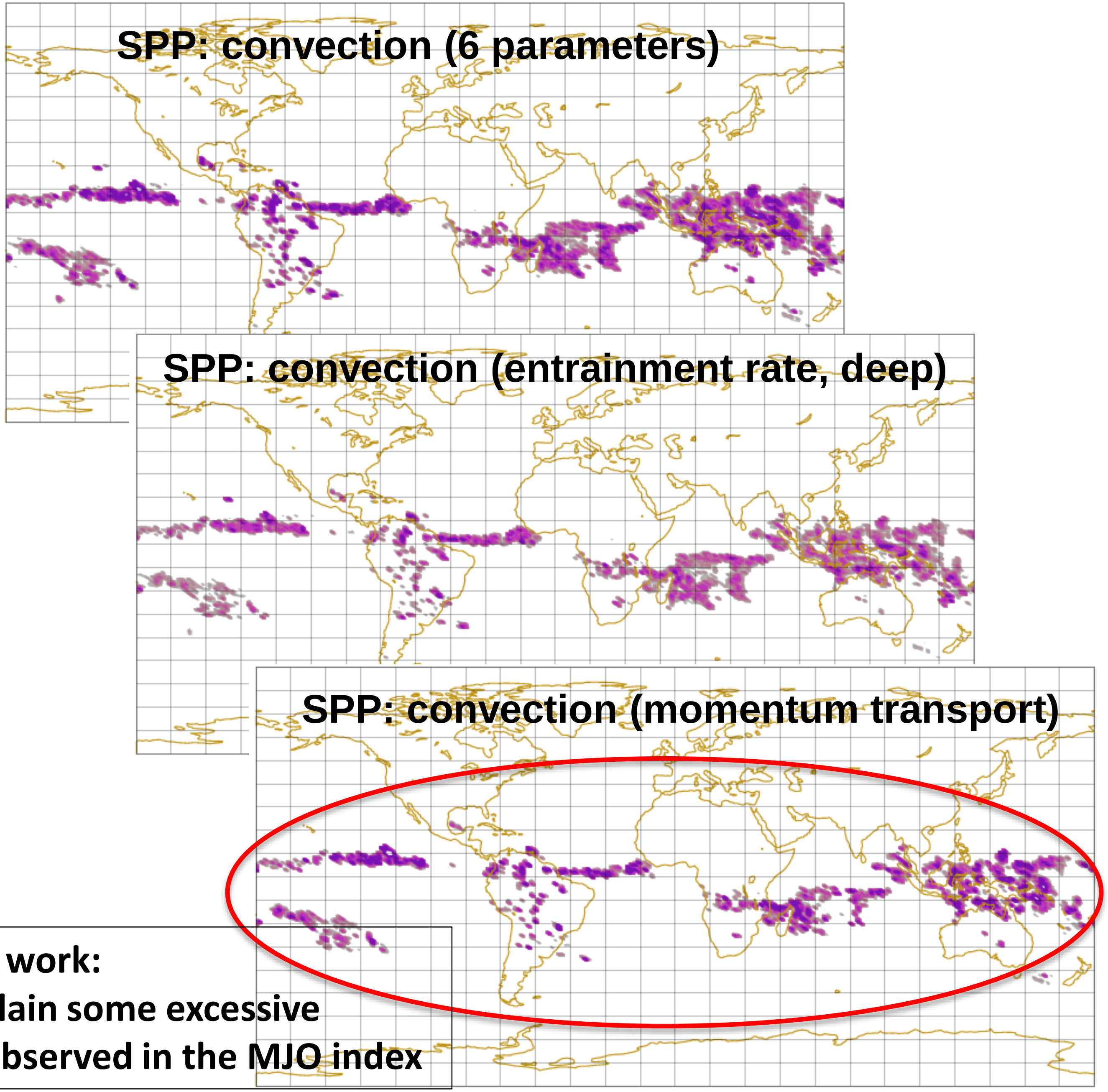


And a look at the tendency perturbations (II)

U tendencies, 0-3h @ model level 49 (~200 hPa)

Ensemble variance $(ms^{-1}/3h)^2$



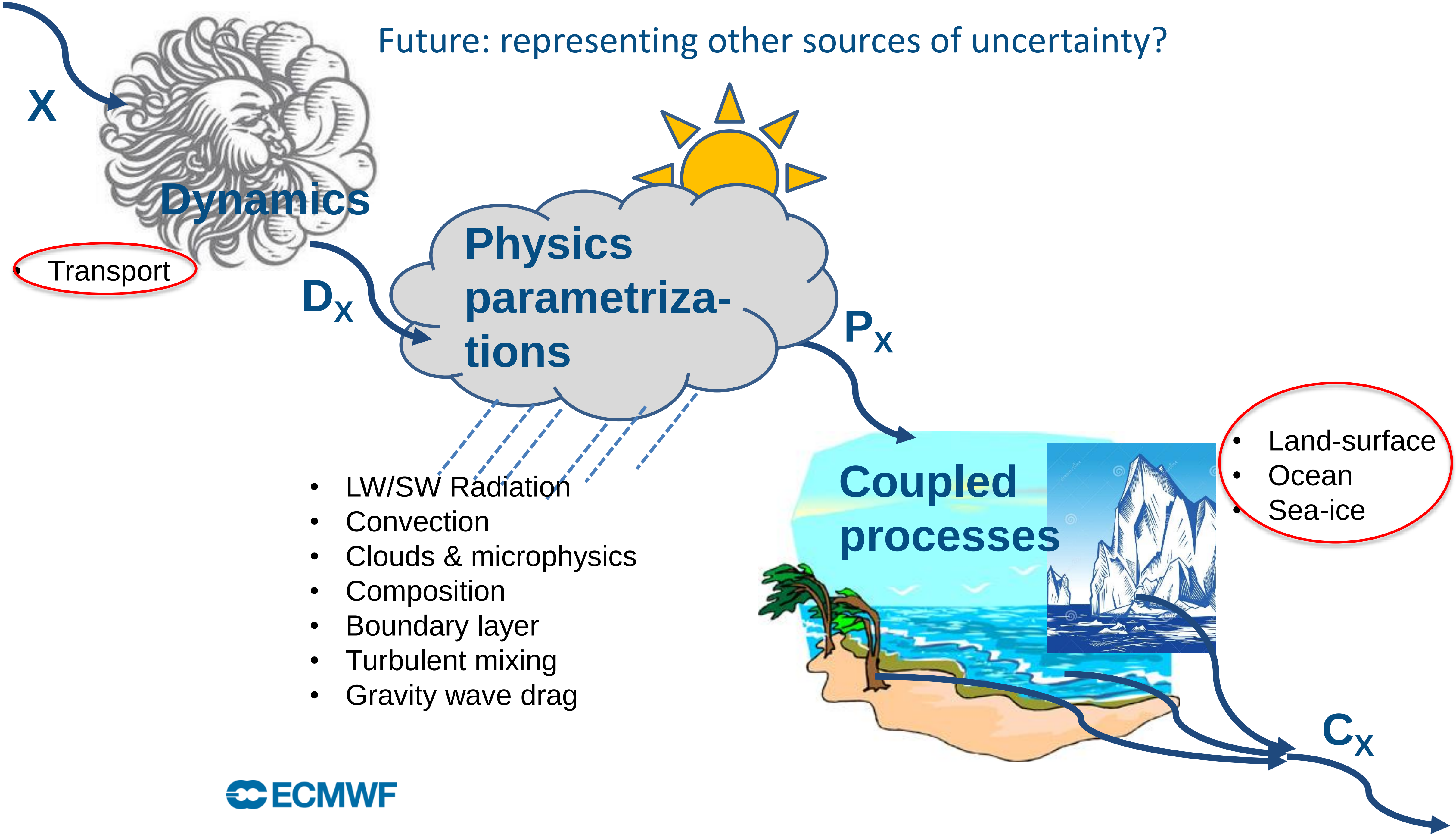


From a 20-member ensemble forecast:
starting 00:00,10-01-2015
with identical initial conditions

Ongoing work:
may explain some excessive spread observed in the MJO index

ECMWF

Future: representing other sources of uncertainty?



Stochastic methods for representing atmospheric model uncertainties in ECMWF's IFS model

Present and future – much greater detail and discussion in:

Leutbecher et al., 2017: Stochastic representations of model uncertainties at ECMWF: State of the art and future vision, QJRMS, DOI: 10.1002/qj.3094

Take a look …

&

thanks for your attention!

ECMWF