Stochastic representations of uncertainty in operational ensemble forecasting systems

by
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Talk presented at Deutscher Wetterdienst, Offenbach, Germany Nov 26 2013

Talk Outline

- the case for and against stochastic parametrization
- current operational numerical weather prediction model implementations of stochastic parametrization
- experimental/research stochastic schemes
- horizontal coarse-graining of ‘truth’ simulations
- impact of stochastic parametrization on global energetics
- summary

The case for stochastic parametrization

(Palmer, 2001) 

- deduced from the lack of spread in ensemble prediction systems

- related to statistical equilibrium assumption in model parametrization schemes

- long-standing systematic errors in climate models due to above assumption ?

- potential benefits arising from nonlinear rectification associated with stochastic fluctuations

The case against stochastic parametrization (Devil's advocate slide)

Shutts, 2013

• developing weather systems don't 'see' short time-scale, sub-gridscale fluctuations

• *stochastic* parametrization merely emulates the time/space variability that an environmentally-sensitive *deterministic* parametrization could more realistically provide

• there is no resolution barrier beyond which the deterministic equations used for weather prediction fail to provide improved forecasts – geophysical processes 'fundamentally uncertain' ?

• random model error should reside at the grid scale or sub-grid scale yet current stochastic parametrization schemes force synoptic and planetary scales

• meteorologists have considerable understanding of the small-scale processes deemed to contribute to forecast model uncertainty. No need for voodoo/black magic...

Why do ensemble forecasts fail to produce enough spread ?

- initial state uncertainty insufficient

- model doesn't exhibit the same sensitivity as the real world (chaos, too much dissipation etc) Parametrizations are designed and tuned to reproduce climate means.

- tropical convection parametrization fails to generate realistic variability (ensembles are highly underspread)

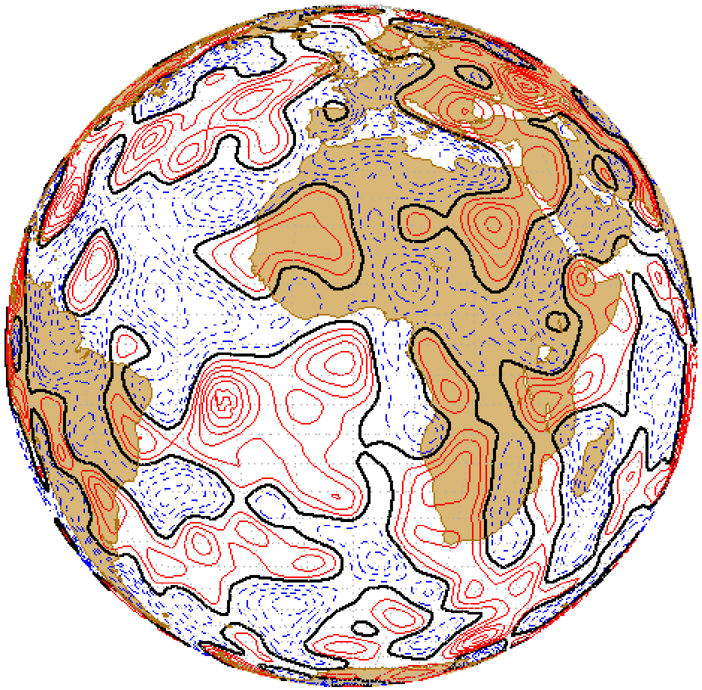
The stochastic devices we use in Ensemble Prediction Systems

- time-dependent random patterns on the sphere are used to orchestrate perturbations to the model's state

- generate perturbations by:
  - perturbing sub-grid scale physical parametrization
    - tendencies *x* pattern (SPPT)
    - critical parameters *x* pattern (RP3)
  - injecting vorticity with the pattern *x* $\sqrt{\text{KE dissipation rate}}$ (SKEB)

SPPT – Stochastic Perturbed Parametrization Tendency
RP(3) – Random Parameters
SKEB – Stochastic Kinetic Energy Backscatter

snapshot of the pattern field used in SPPT



Operational forecast model representations of uncertainty

Random Parameters (Met Office)

'critical' parameters that are highly variable or have fuzzy definitions are forced to vary in time with a 1st-order auto-regressive process e.g. entrainment rate, CAPE removal time-scale, ice crystal fall-speed

Perturbed parametrization tendency schemes (ECMWF, Environment Canada)

tendencies are multiplied by a global random pattern field which has:

- time-mean value of 1 at all points
- specified standard deviation (e.g. 0.5 of the mean tendency)
- specified power spectrum in spatial wavenumber (e.g. Gaussian)
- AR1 process for the time evolution of each spherical harmonic in the random pattern with typical 6 hour decorrelation time

typically applied to the **total** parametrization tendency

representations of uncertainty (continued)

Stochastic kinetic energy backscatter (Met Office, ECMWF, Environment Canada

- counteract the tendency of forecast models to dissipate energy
- convection parametrization tends to destroy APE as well as CAPE !
- KE generated by buoyancy forces assumed to dissipated in parametrization
- SKEB injects vorticity into regions where numerical & convective dissipation is diagnosed (Met Office scheme 'backscatters' horizontal divergence too)

convective 'dissipation' rate (D_c) is meant to represent the rate of supply of KE from the sub-gridscale to the explicitly-resolved scales e.g.

$$D_C = \frac{1}{\rho g}\left|\frac{\partial M_C}{\partial z}\right| \cdot CAPE$$ (used in Met Office MOGREPS)

representations of uncertainty (continued)

Met Office

Stochastic Convection (Naval Research Lab, Monterey; NOGAPS model)

- like the perturbed parametrization tendency scheme except without a pattern generator

$$\left.\frac{\partial \phi}{\partial t}\right|_{conv}^{stoch} = (1+\eta\beta)\left(\frac{\partial \bar{\phi}}{\partial t}\right)_{conv}$$

Teixeira and Reynolds (2008)

η has zero mean and unit standard deviation

$\beta = 1$ in practice

other (non-operational) methods of representing convective uncertainty

Met Office

- statistical formulation of convection parametrization
Plant and Craig (2008)

- stochastic convective vorticity scheme (previously used in the Met Office MOGREPS; new version developed)

- stochastic convection schemes of Lin and Neelin (2000, 2002)

- multi-cloud/multiscale models of Majda and co.
e.g. Khouider, Biello and Majda (2010)

- probabilistic cellular automaton used as a driver for inputs to convection parametrization (Bengtsson et al, 2012)

Impact of the stochastic schemes on model energetics

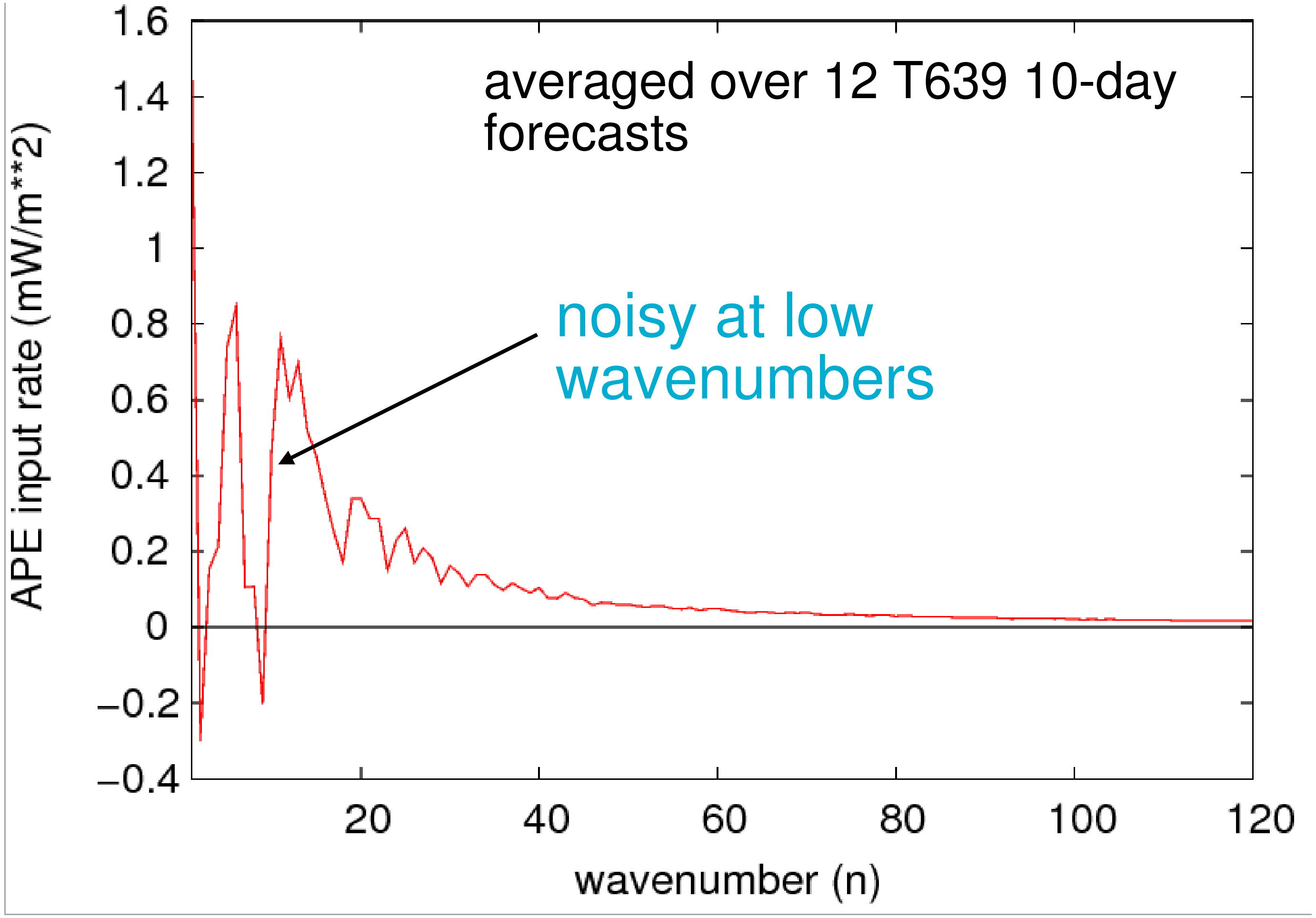
stochastic perturbations inject kinetic energy and available potential energy

But what is their mean effect and how is the energy input distributed across the spatial scales ?

The pattern fields have most of their spectral power in low wavenumbers but the fields they multiply contain much high wavenumber power

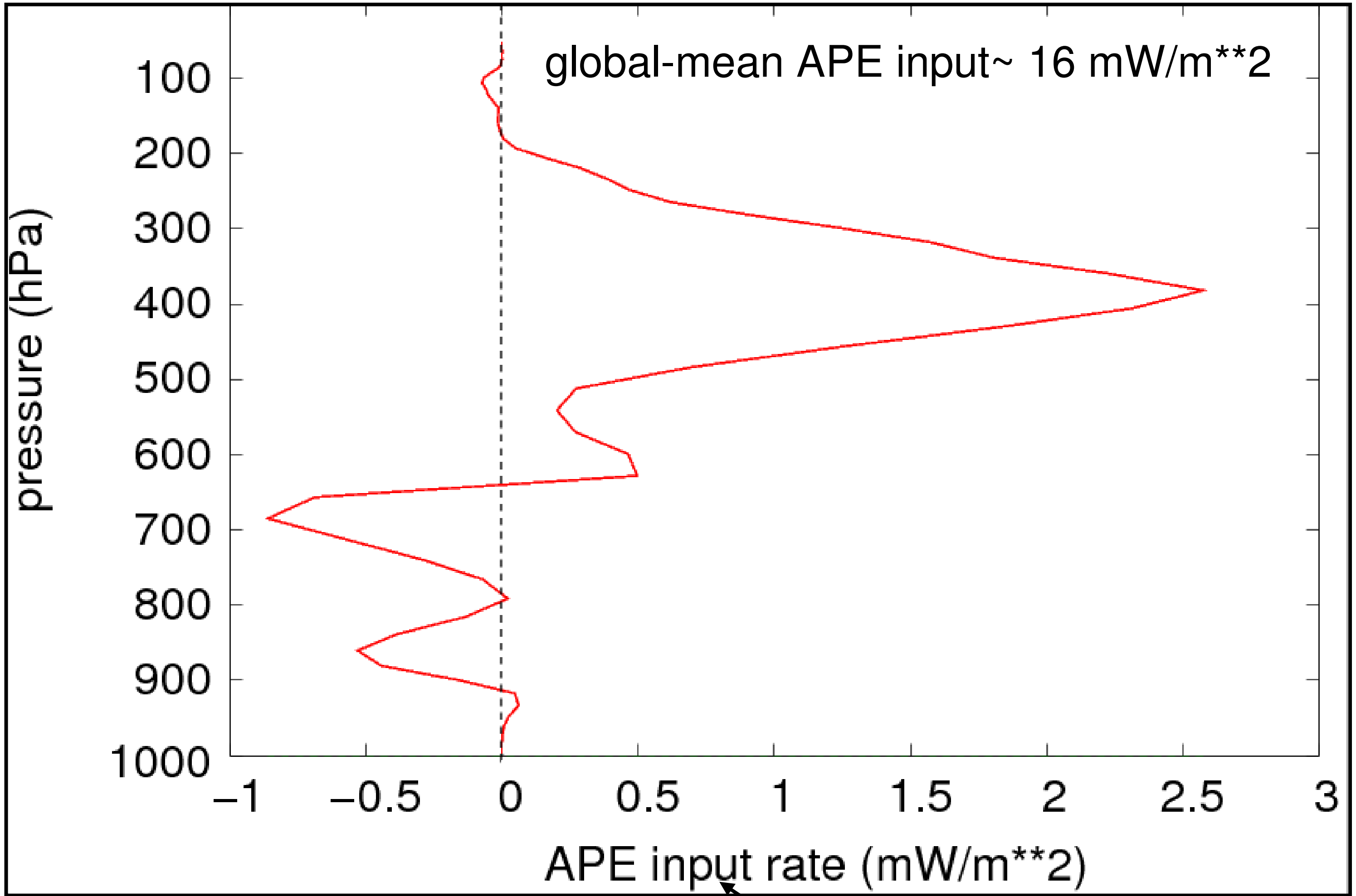
APE input spectrum due to ECMWF perturbed parametrization tendency scheme

(tendencies are multiplied by cos(lat)**2 to isolate the tropics)



APE input profile due to ECMWF perturbed parametrization tendency scheme

(tendencies are multiplied by cos(lat)**2 to isolate the tropics)



per model layer

KE input by backscatter

calculate terms in the vorticity equation in model forecasts at:

- full resolution (T1279) (equivalent to a 16 km grid)
- degraded resolution (T159) (equivalent to a 130 km grid)

compute their differences in spectral space and evaluate KE tendency contributions from wavenumbers 160 to 1279

Vorticity equation terms

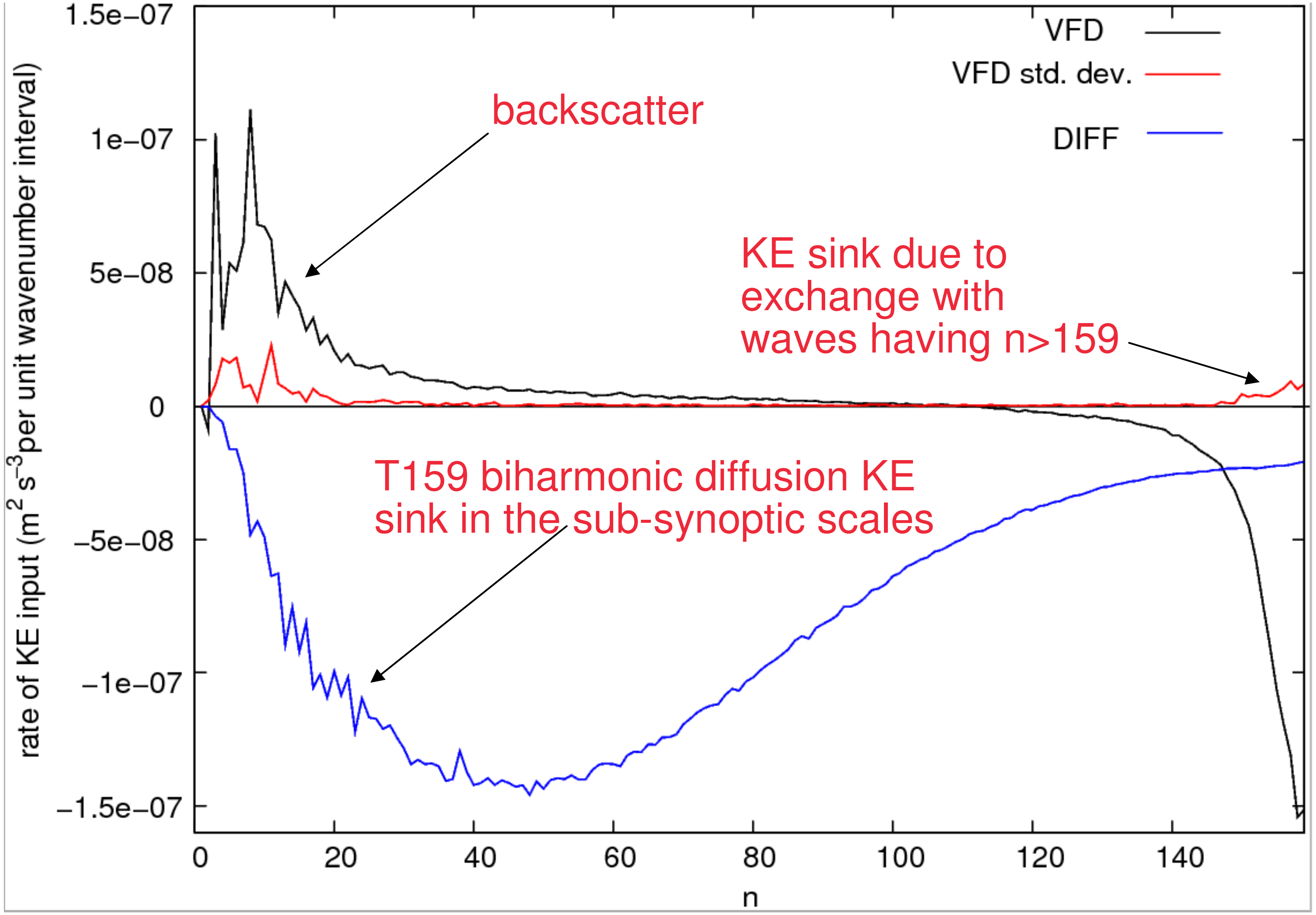
$\nabla \cdot \left(\zeta \mathbf{V}_{\psi}\right)$ Vorticity Flux Divergence by the rotational wind (VFD)

$\nabla \cdot \left(\zeta \mathbf{V}_{\chi}\right)$ Vorticity flux divergence by the divergent wind (Rossby Wave Source or RWS)

$\nabla \times \left(\dot{\eta} \frac{\partial \mathbf{V}}{\partial \eta}\right)$ Curl (vertical advection of momentum) – called 'TIP' here

$\nabla^{4} \zeta$ biharmonic horizontal diffusion - DIFF

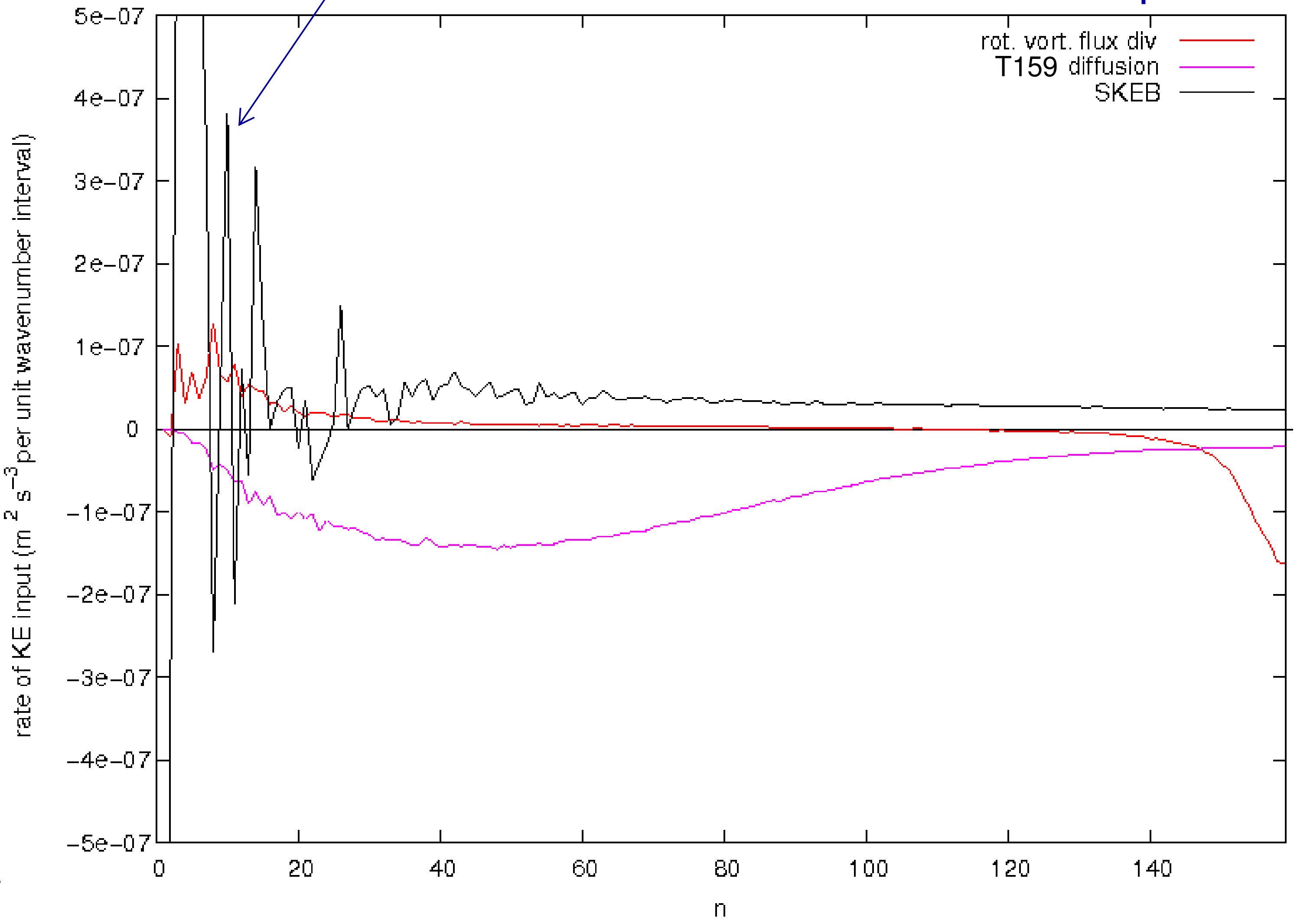
mean KE tendency at 250 hPa due to rotational wind contributions in the wavenumber range 159 < n < 1279 from 30 forecasts



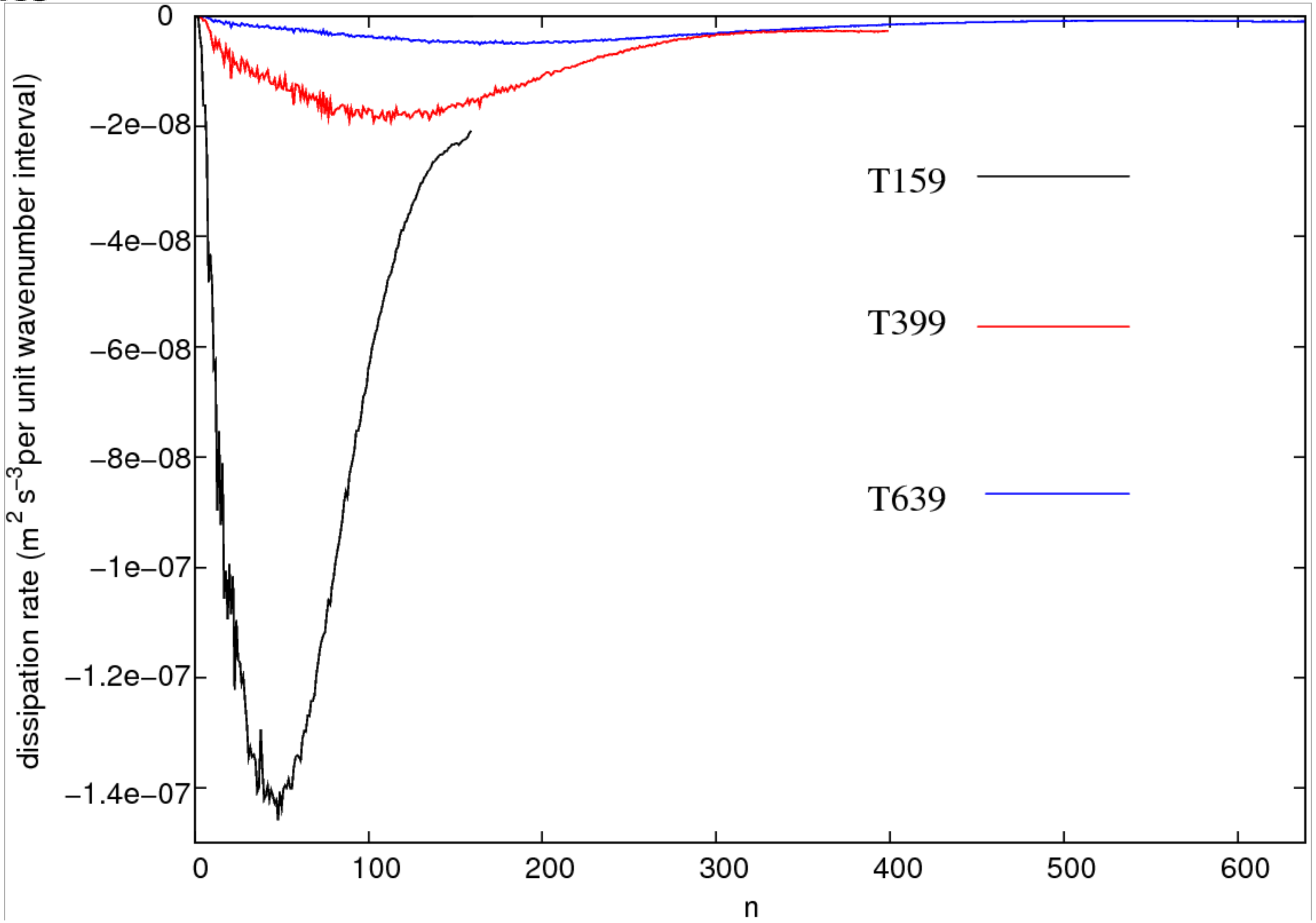
KE input from SKEB at 250 hPa

(using default settings for T159)

Residual fluctuations after averaging 30 cases of the 24 hr-accumulated KE input

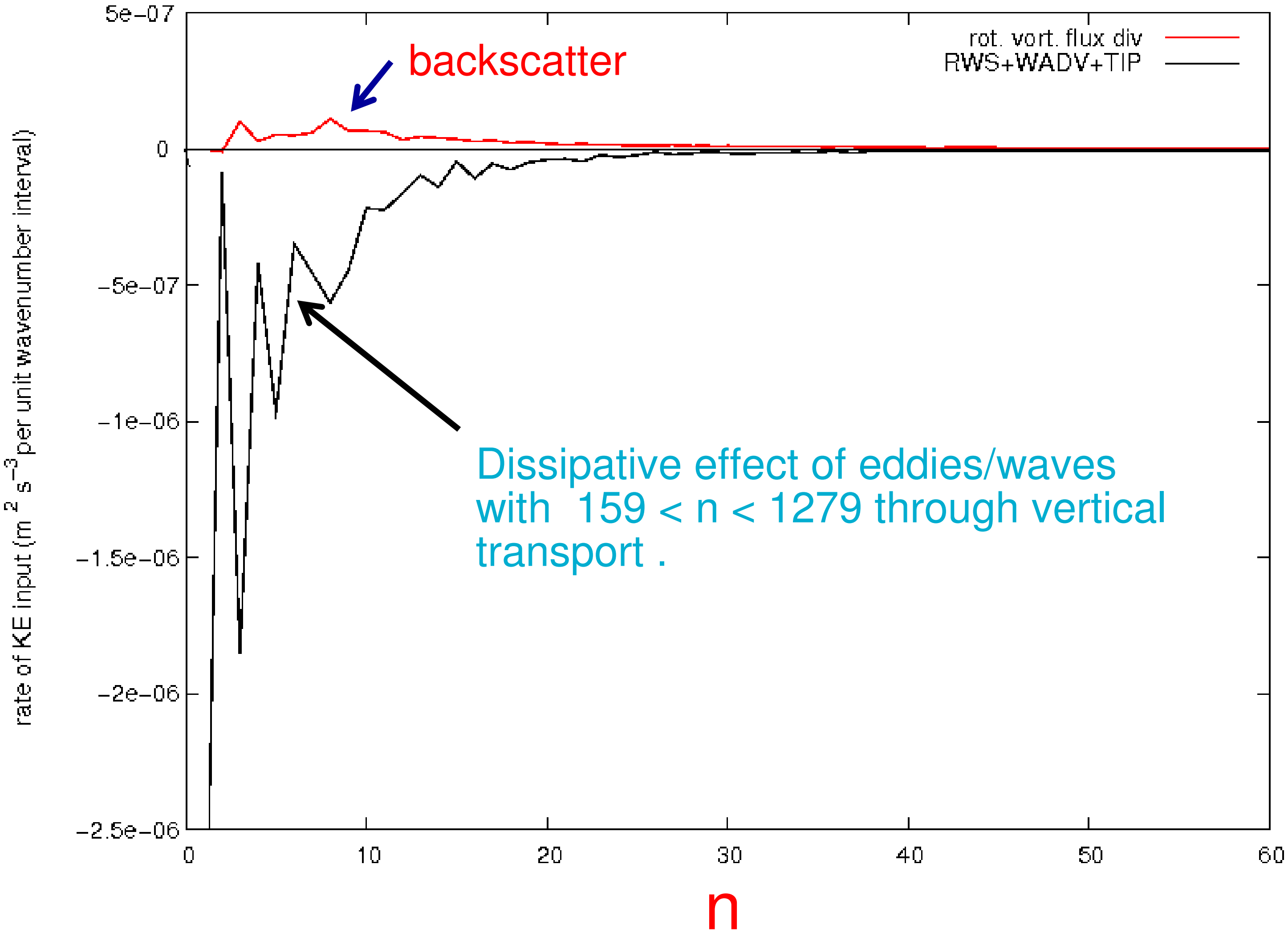


spectrum of KE dissipation due to biharmonic diffusion versus horizontal resolution



Backscatter by rotational wind *vs* the sum of RWS and TIP

Met Office

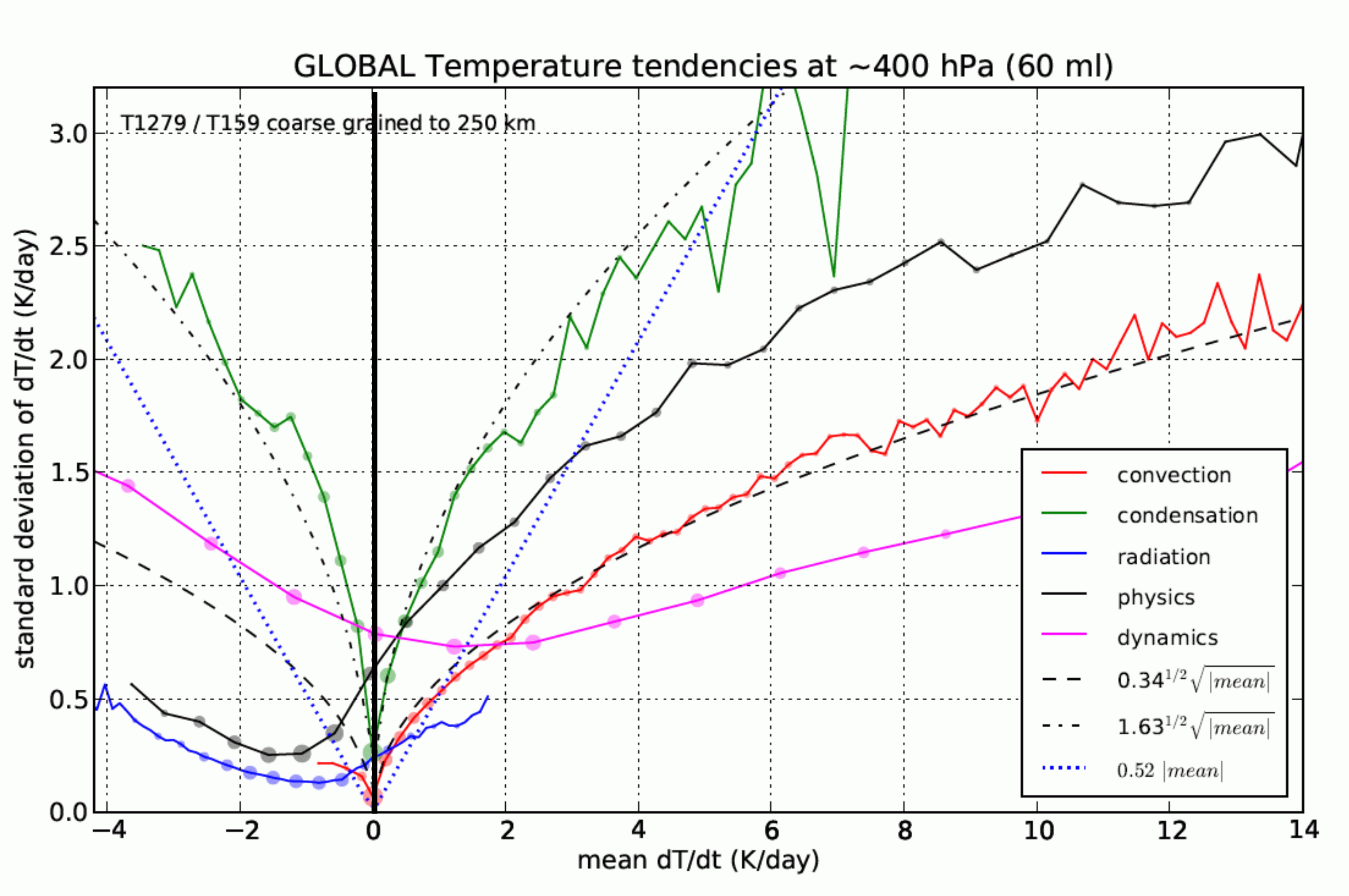


coarse-graining ‘truth’ forecasts

Met Office

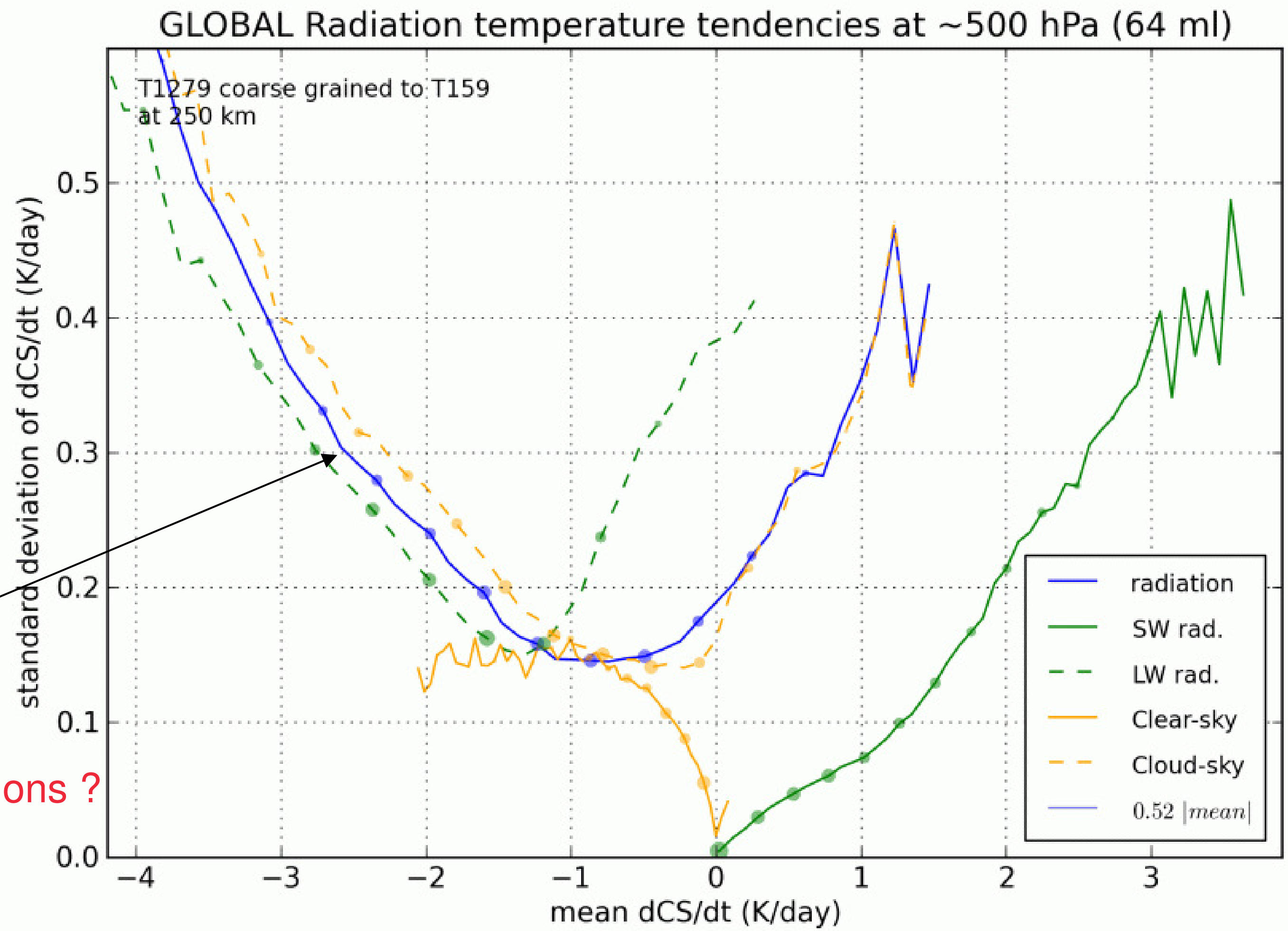
1. use 12-hour forecasts from the ECMWF forecasting system at operational resolution as ‘truth’ (T1279 gridlength ~ 16 km)
2. compare with forecasts from a much lower resolution ‘target resolution’ (T159 gridlength~ 130 km)
3. coarse-grain parametrization tendencies to a common spatial and temporal resolution
4. define ‘error’ at the target resolution to be the difference
5. look at the pdf of the error as a function of tendency in the target forecasts averaged over many cases

standard deviation of model tendency error versus mean tendency



variance proportional to mean tendency

radiation tendency uncertainty

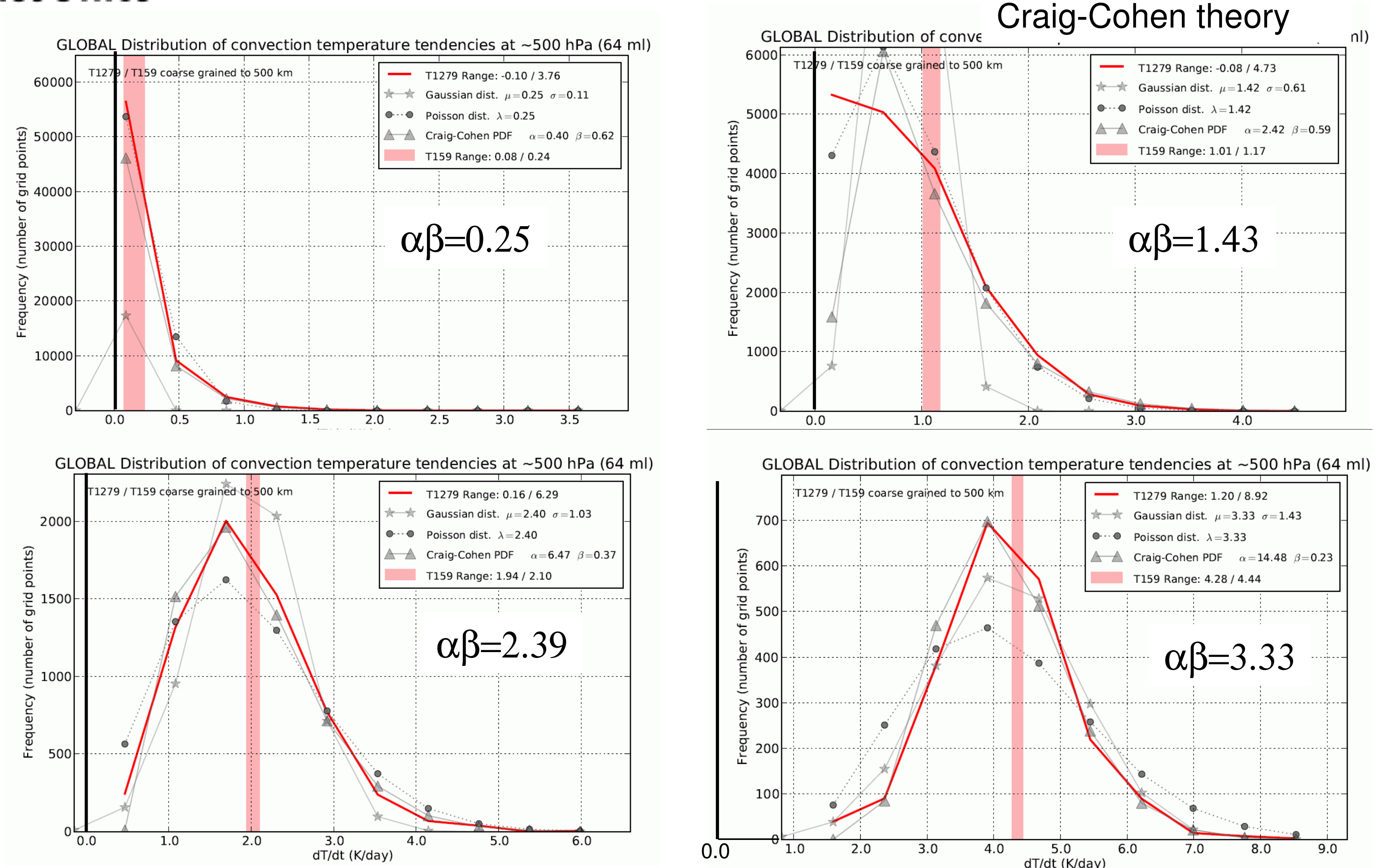


fit a parabola
and use to define
radiative T perturbations ?

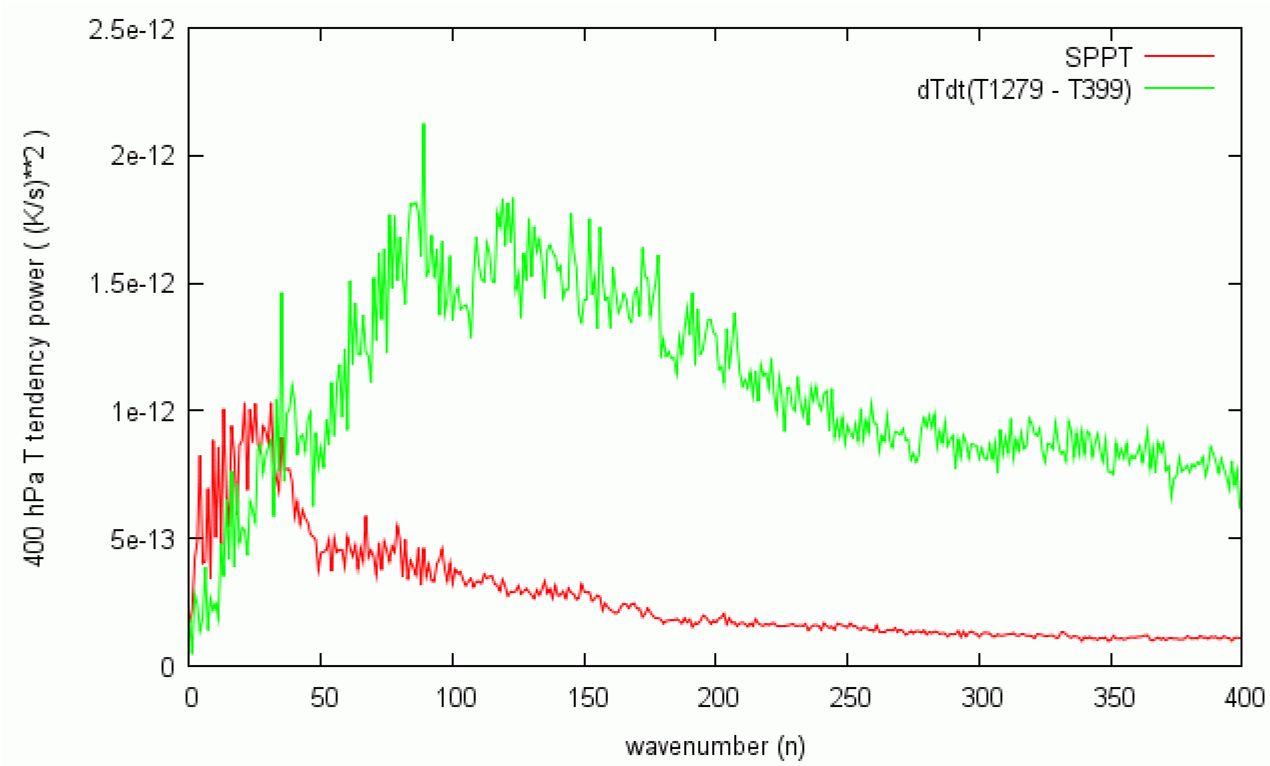
pdf of 'truth' tendencies for narrow ranges of target resolution tendency

(pink strip indicates tendency range)

αβ= mean tendency in Craig-Cohen theory



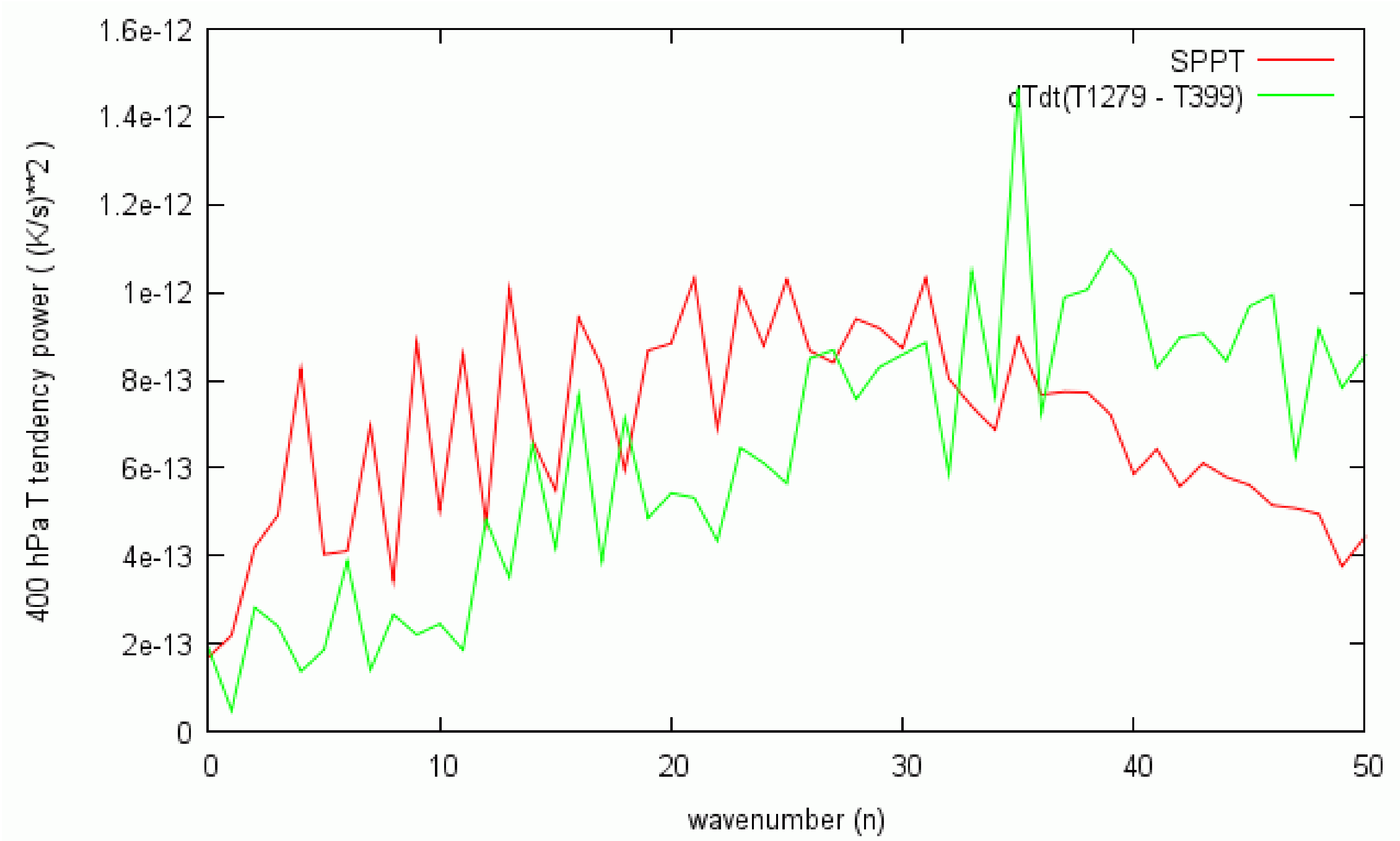
power spectra of SPPT temperature tendencies and coarse-graining tendency errors



Note that experience with the ECMWF model has shown that stochastic forcing in wavenumbers n>60 generates little spread in the EPS

power spectra of SPPT and dTdt ‘error’ – zoomed view

Note: only one case therefore quite noisy



A new perturbed tendency scheme for convection and explicit latent heating/cooling

An AR1 process is defined for every gridpoint by:

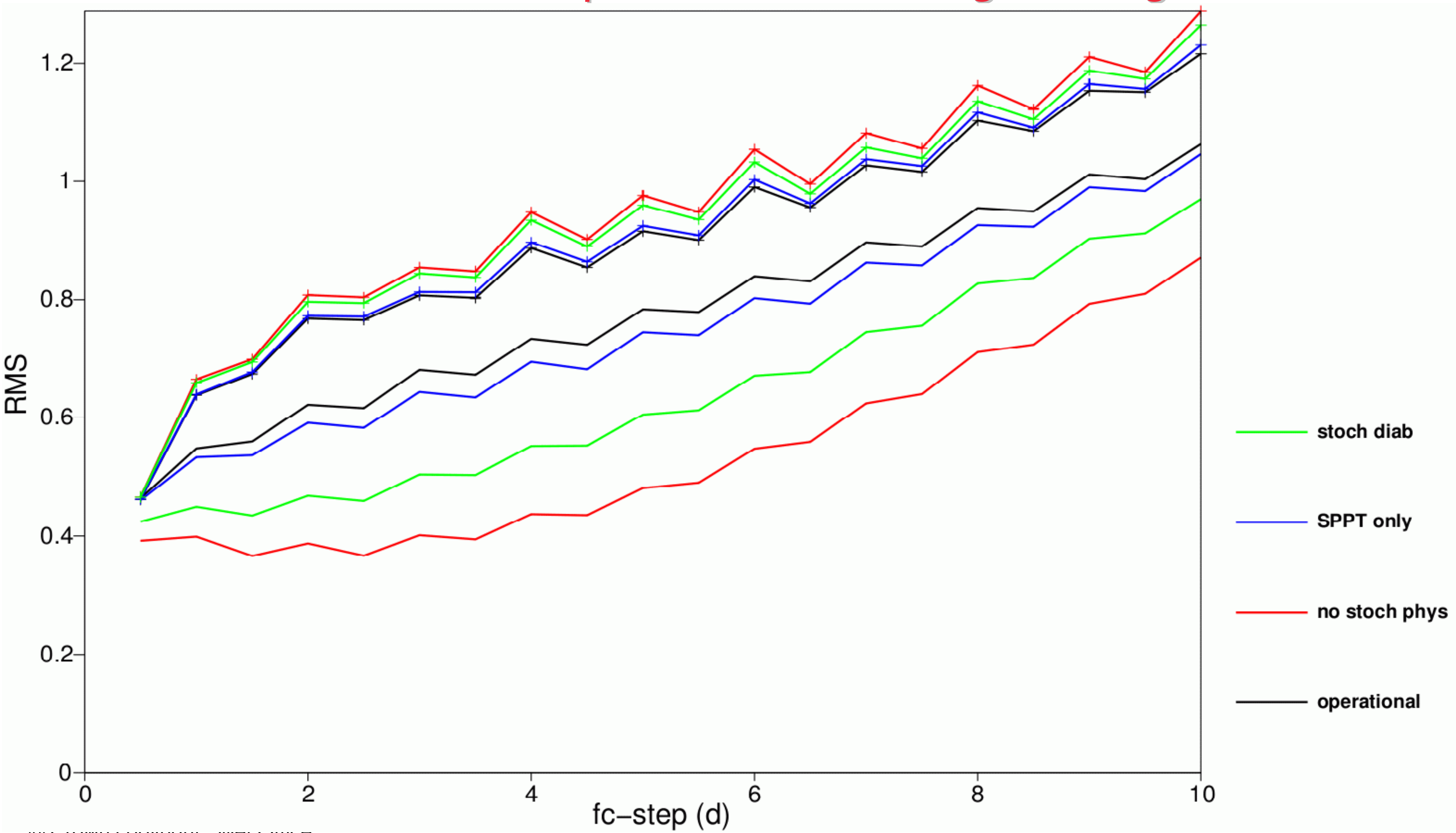
$$\delta \dot{T}^n = \delta \dot{T}^{n-1} \phi + sgn(\dot{T_p^n}) \sqrt{1-\phi^2} S \, r^n \sqrt{\dot{T}_{ref} |\dot{T_p^n}|} \tag{3.2}$$

where $\delta \dot{T}^n$ is the perturbation temperature tendency at time-step n; r^n is a random number with zero mean and unit variance; $\phi = \exp(-\Delta t/\tau)$; Δt is the time step; τ is the temporal decorrelation time; $\dot{T}_{ref}$ is a reference temperature tendency (consistent with the previous section's coarse-graining results); $\dot{T_p^n}$ is the parametrization temperature tendency in the forecast model at time-step n; the smoothing factor S

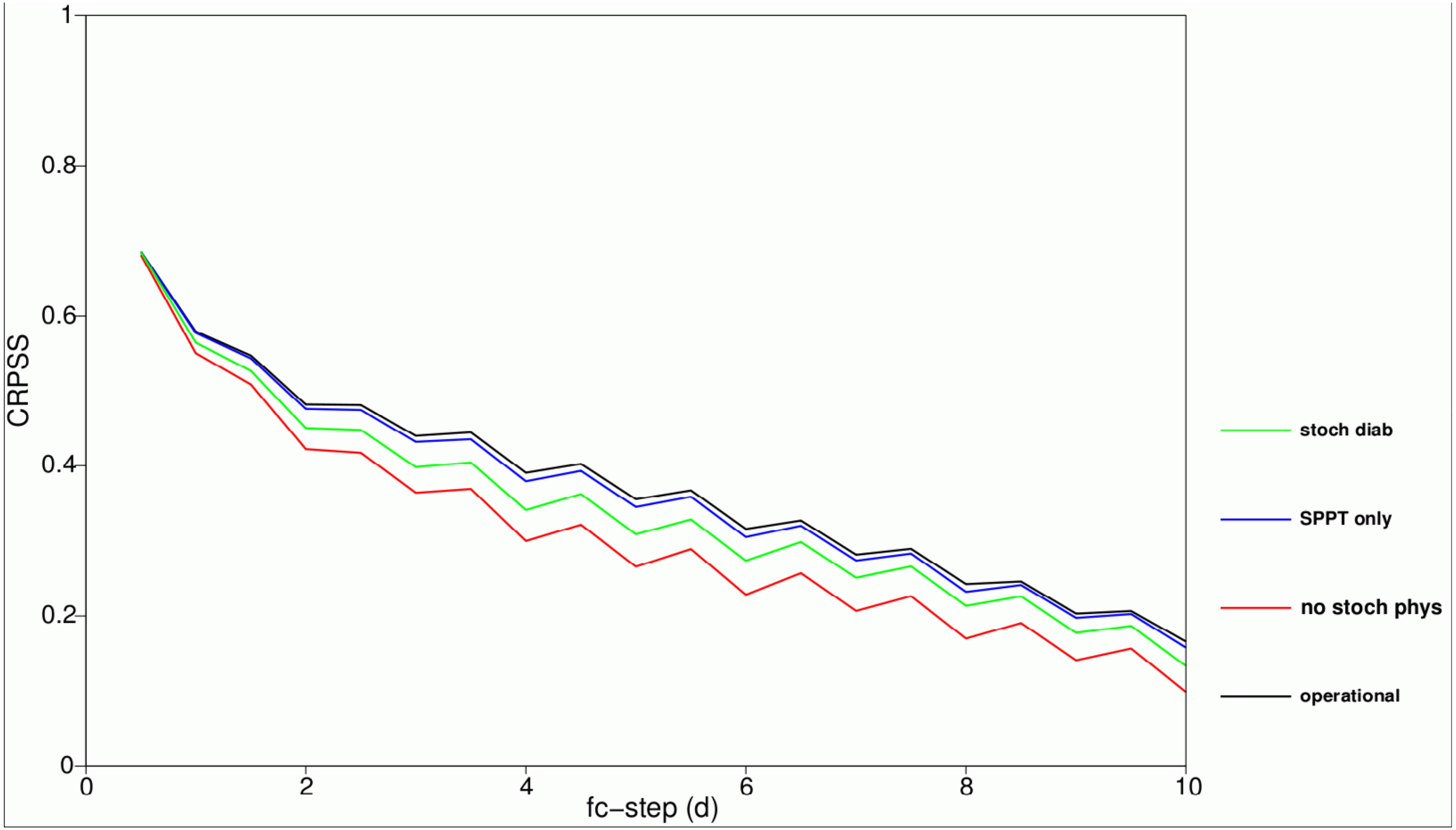
the variance of the spatially-smoothed tendency is given by:

$$\langle var \left[\widehat{\delta \dot{T}^n} \right] \rangle = \dot{T}_{ref} |\dot{T_p^n}|$$

impacts on EPS spread and skill of temperature at 850 hPa in the tropics (for T399 forecast resolution) - only for dT/dt perturbations from convection and explicit latent heating/cooling



impacts on Continuous Ranked Probability Skill Score (CRPSS)



extension of the scheme to wind and humidity perturbations – determining reference tendencies

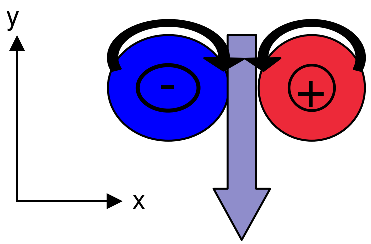
- reference tendencies for u and q can be determined from coarse-graining for each model level

- constant reference tendency for q won't work ! currently trying q_{sat}/τ where τ is a time scale e.g. 10 days

- currently using constant values for T and u/v reference tendencies

another approach:
Stochastic Convective Vorticity Forcing

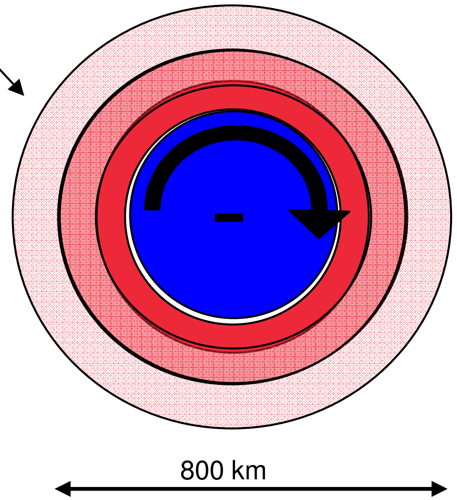
- vertical momentum transport in deep convection tends to create vorticity dipoles
- vertical mass transport in conjunction background rotation generates vertically-orientated potential vorticity dipoles (PV lenses, Gill(1981))



drag force due to vertical momentum transport

Vorticity error structures

mesoscale convective system



Stochastic Convective Vorticity Forcing (SCVF) scheme

Define a stochastic vorticity tendency evolution equation:

$$\delta\dot{\zeta}^{n} = \delta\dot{\zeta}^{n-1}\phi + \sqrt{1-\phi^2}\, r^n \frac{M_{det}}{\tau_c \rho} \qquad (1)$$

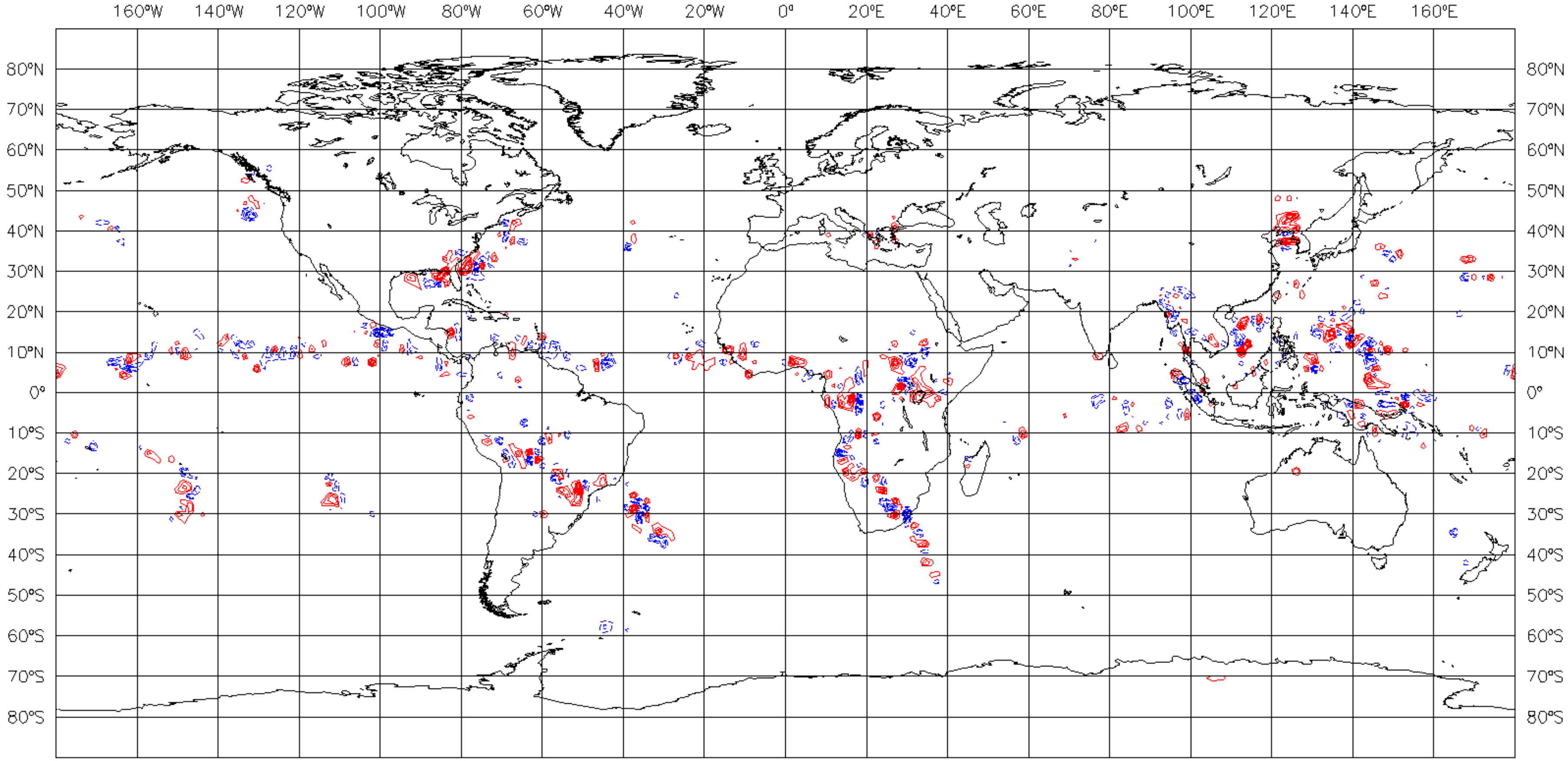
where $\dot{\zeta}$ is the vorticity tendency due to convective mass detrainment rate M_{det} and τ_c is a time scale.

then spectrally filter the tendency field using the filter function F(n) :

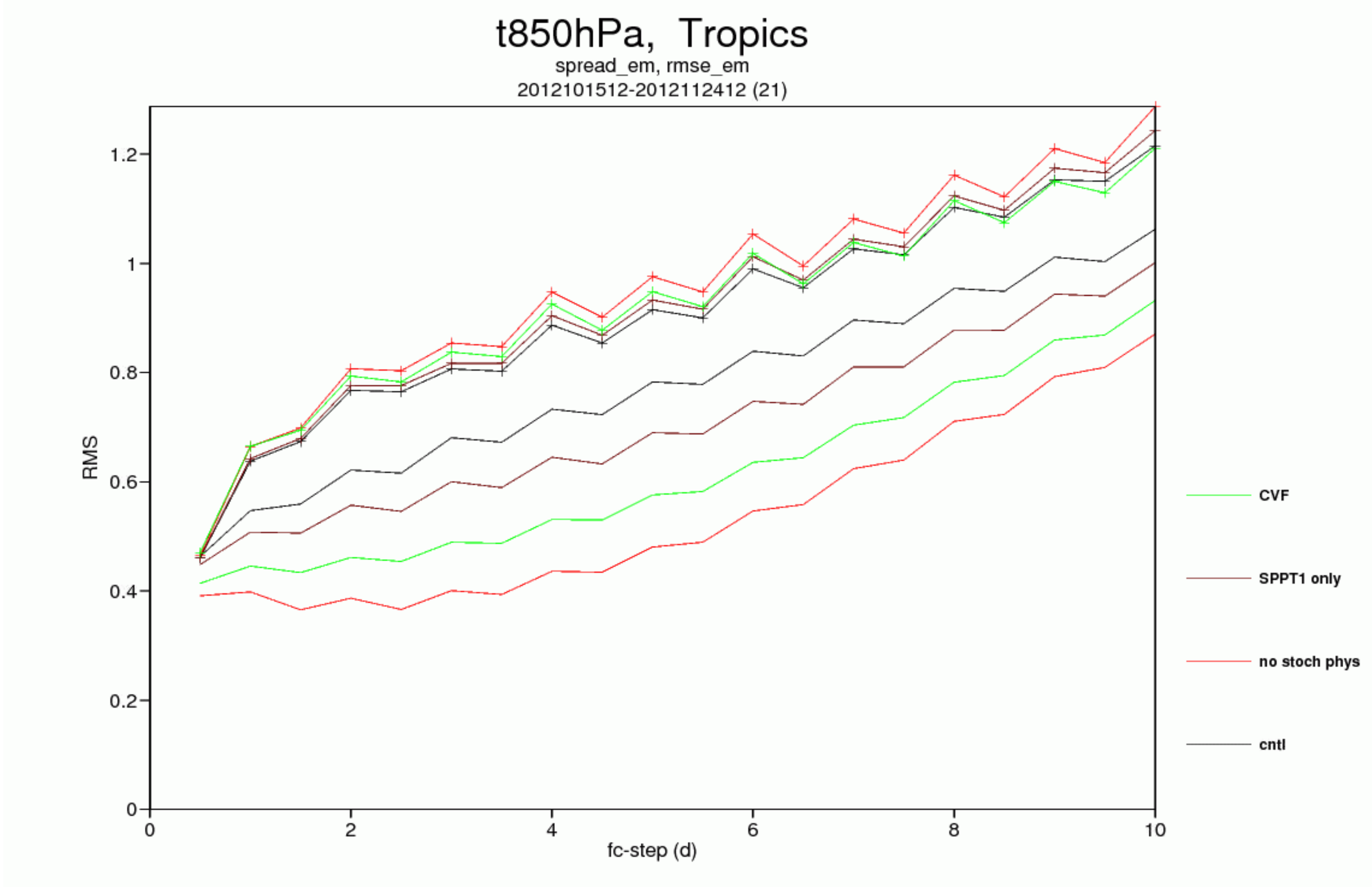
$$F(n) = 1 - \exp\left[-\frac{1}{2}\left(\frac{R_f}{a}\right)^2 n(n+1)\right]$$

where R_f is a filter scale and n is the ‘wavenumber’

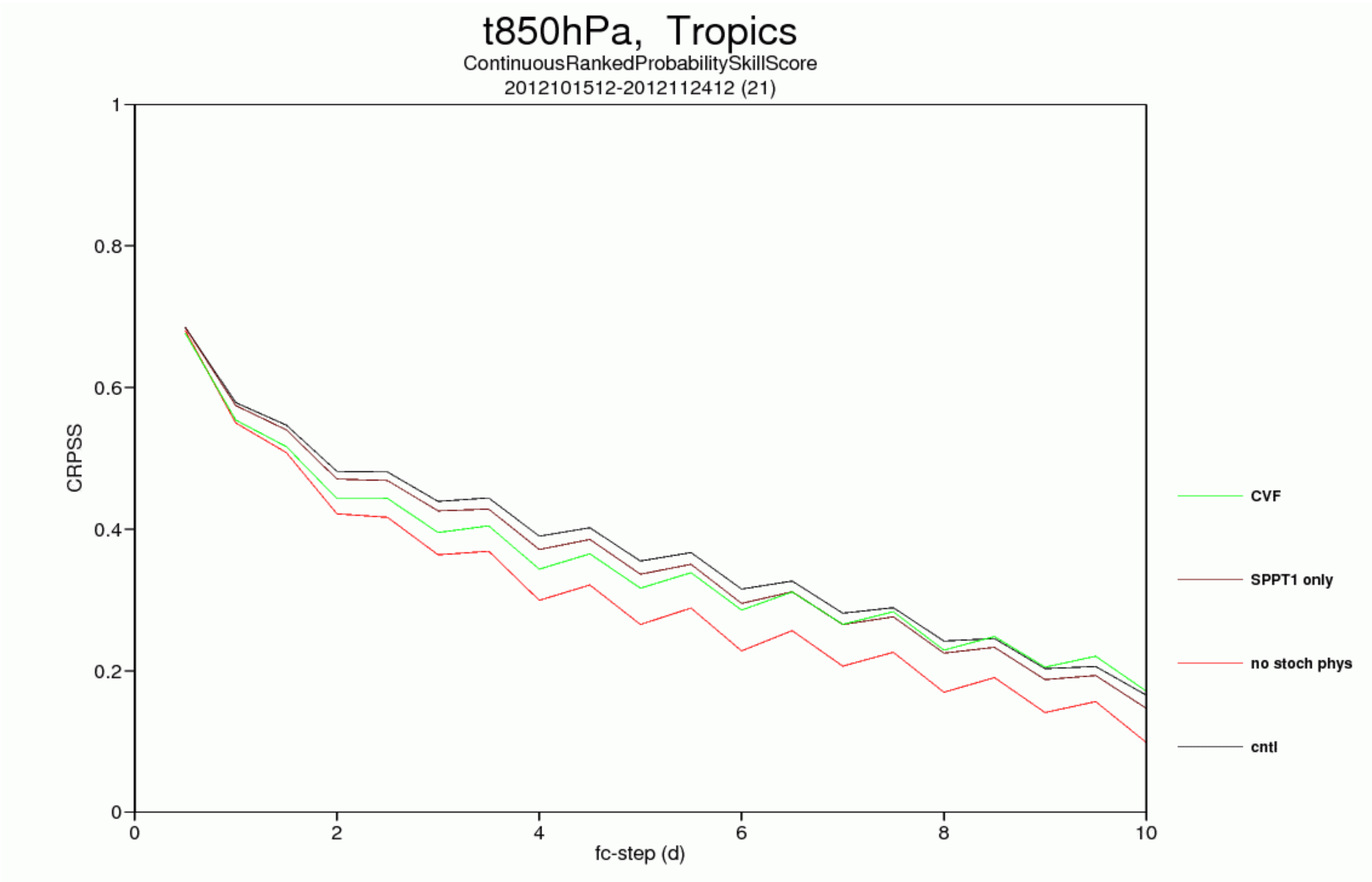
unsmoothed vorticity tendency at 400 hPa



spread/skill plot for T at 850 hPa in the tropics using SCVF scheme



CRPSS for T at 850 hPa in the tropics using SCVF scheme



Summary

- NWP models seem insufficiently sensitive to initial state perturbations
- introduction of stochastic terms into the model equations is seen to be a partial remedy
- stochastic parametrizations are motivated by observational and theoretical insights but remain *ad hoc* at the present time
- *coarse-graining* high resolution 'truth' simulations provides a means for constraining stochastic formulations

Questions and answers