Latest thoughts on stochastic kinetic energy backscatter - good and bad

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What is Stochastic Kinetic Energy Backscatter ?

- ‘random’ pattern of momentum forcing introduced to represent statistical fluctuations in unresolved momentum transfer
- pattern is designed to give the correct KE input power spectrum (space & time)
- strength of the KE input proportional to some measure of model energy dissipation (or generation by parametrized convection)
- size of the fluctuations set by number of eddies per gridbox (boundary layer eddies ignored for gridlengths > 10 km)

Why do we need it ?

- from a practical viewpoint:
  - to increase ensemble system ‘spread’ which improves skill
  - to reduce systematic error resulting from missing nonlinear rectification effects -> climate error
  - model error representation in data assimilation
- a natural component of eddy viscosity parametrizations (Frederiksen and Davies, 1997)
- or more generally, the governing equations are intrinsically stochastic ?

History of stochastic KE backscatter

Met Office

- use of random noise in the simulation of boundary layer turbulence. Mason and Thomson, 1992
- eddy viscosity and backscatter in 2D turbulence on the sphere. Frederiksen and Davies, 1997
- simple isotropic vorticity forcing noise scheme tested in the Met Office Unified Model (1998)
- ECMWF develop simple parametrization tendency perturbation scheme (Buizza et al, 1999)
- Stochastic KE Backscatter (SKEB) scheme developed at ECMWF (Shutts, 2005)
- SKEB scheme developed and operational in Met Office MOGREPS (2006)
- SKEB implemented in Environment Canada EPS (2007)
- SKEB implemented in ECMWF IFS (2009)

SKEB - Spectral Kinetic Energy Backscatter

- Rationale: A fraction of the dissipated energy is backscattered upscale and acts as streamfunction forcing for the resolved-scale flow (Shutts and Palmer 2004, Shutts 2005, Berner et al 2009)
- Streamfunction forcing is given by:

$$F_{\Psi}(\lambda, \mu, \eta, t) = \sqrt{b_R D_{tot}} F(\lambda, \mu, \eta, t)$$

Streamfunction forcing

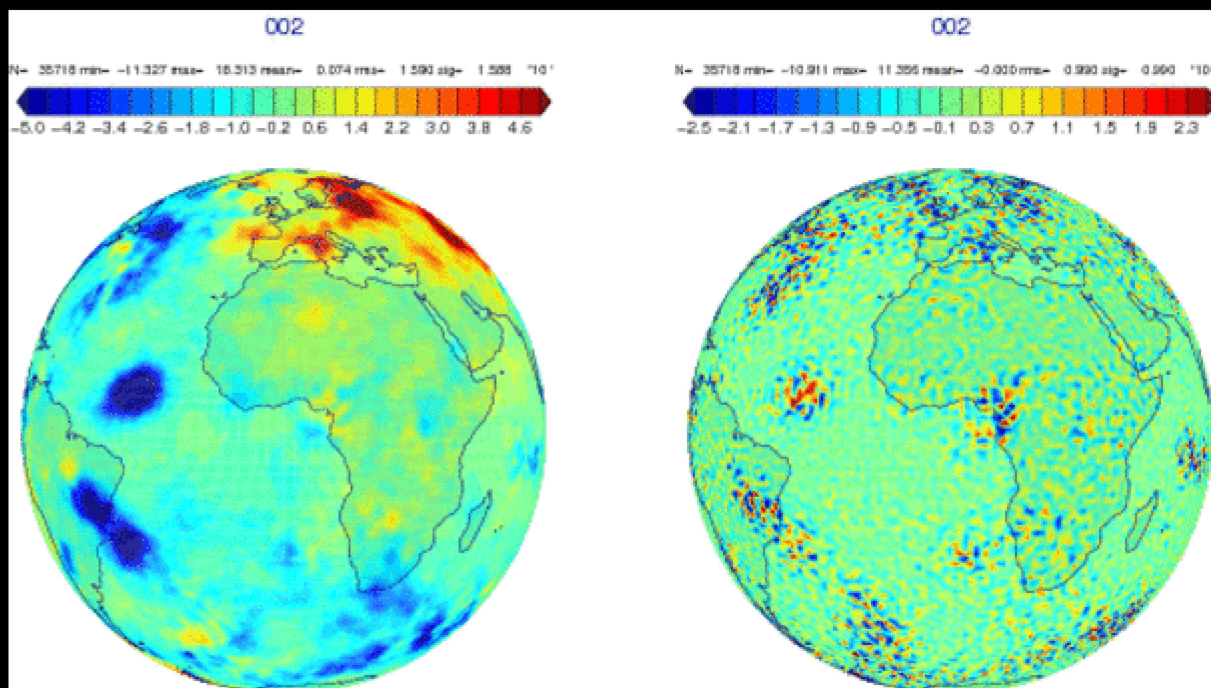
Backscatter ratio

Total dissipation rate

Pattern generator

SKEB pattern

Streamfunction forcing **Vorticity forcing**



SKEB – The total dissipation rate

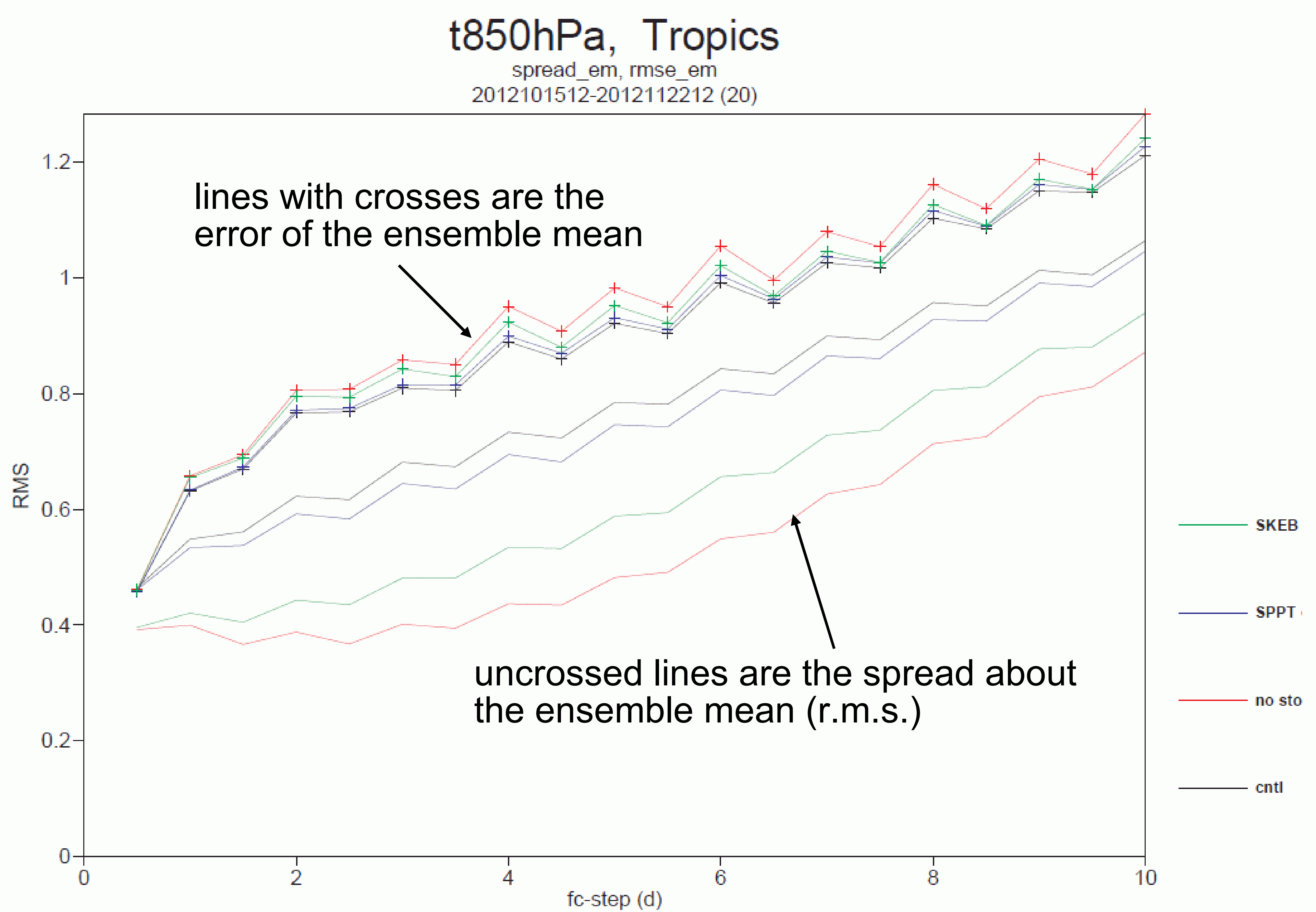
- the total dissipation rate is the sum of
  - “Numerical” dissipation (loss of KE by numerical diffusion + interpolation in semi-Lagrangian advection)
  - Dissipation from gravity wave/orographic drag parametrization (not included in Met Office SKEB)
  - Deep convective KE production
- spatial smoothing required

Impact of stochastic parametrizations in T399 EPS (20 cases)

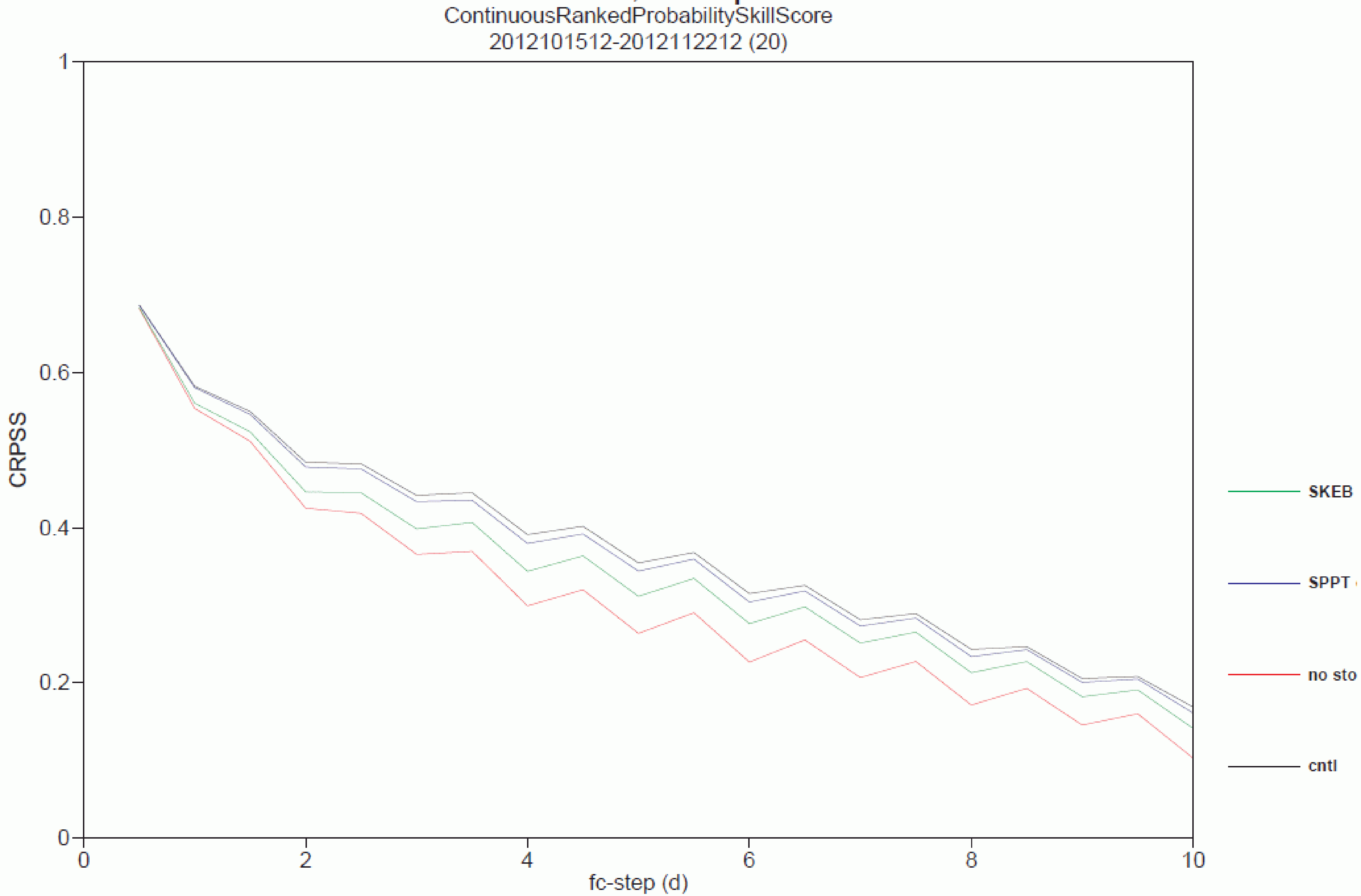
1. no stochastic physics (red curve)
2. SKEB only (green curve)
3. SPPT only (blue curve)

(i.e. the perturbed parametrization tendency scheme)

1. SKEB + SPPT

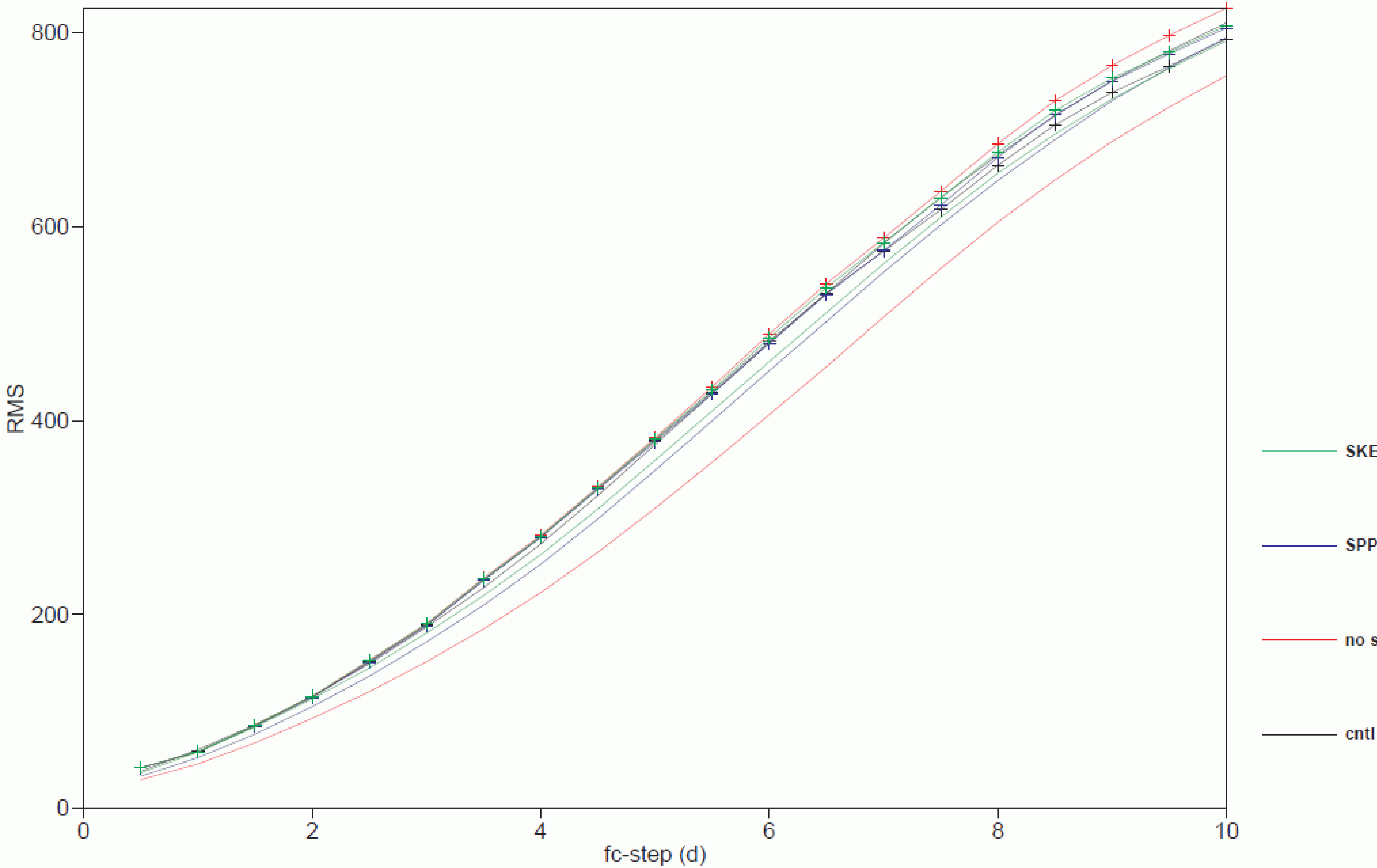

t850hPa, Tropics
spread_em, rmse_em
2012101512-2012112212 (20)
RMS
fc-step (d)
lines with crosses are the error of the ensemble mean
uncrossed lines are the spread about the ensemble mean (r.m.s.)
SKEB
SPPT
no sto
cntl
0
0.2
0.4
0.6
0.8
1
1.2
0
2
4
6
8
10

t850hPa, Tropics



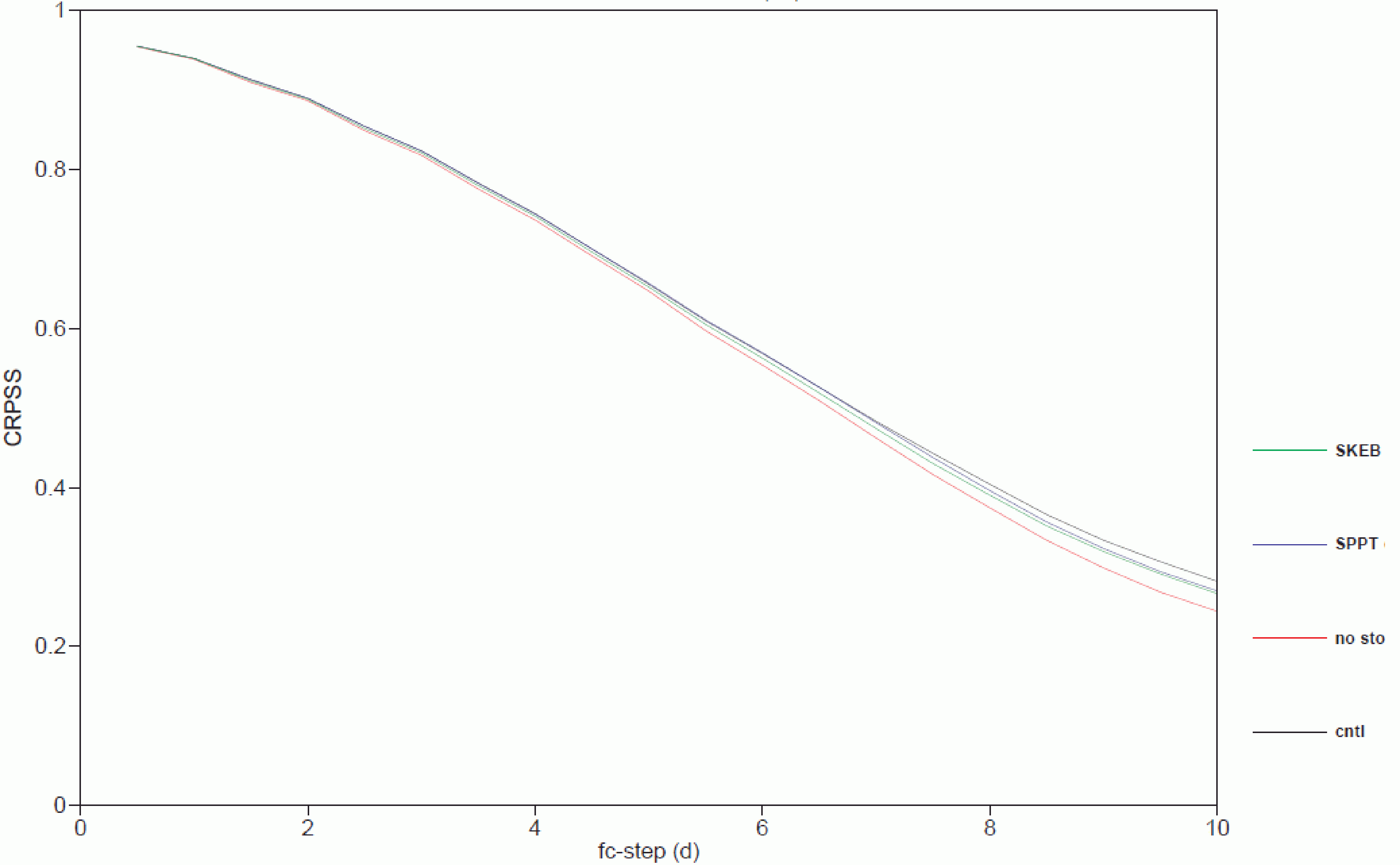
z500hPa, Northern Extra-tropics

spread_em, rmse_em
2012101512-2012112212 (20)



z500hPa, Northern Extra-tropics

ContinuousRankedProbabilitySkillScore
2012101512-2012112212 (20)



Coarse-graining the vorticity equation in the ECMWF forecast model

- Use the IFS's spectral-gridpoint transforms to compute terms in the vorticity equation at :
    - Full resolution (e.g. T1279) – to be regarded as 'truth'
    - A lower 'target' resolution (e.g. T159)
- Define error in the target resolution to be the difference
- Compute the KE input spectrum implied by the error (or residual) forcing function
- Gives the KE input from scales for $159 < n < 1279$

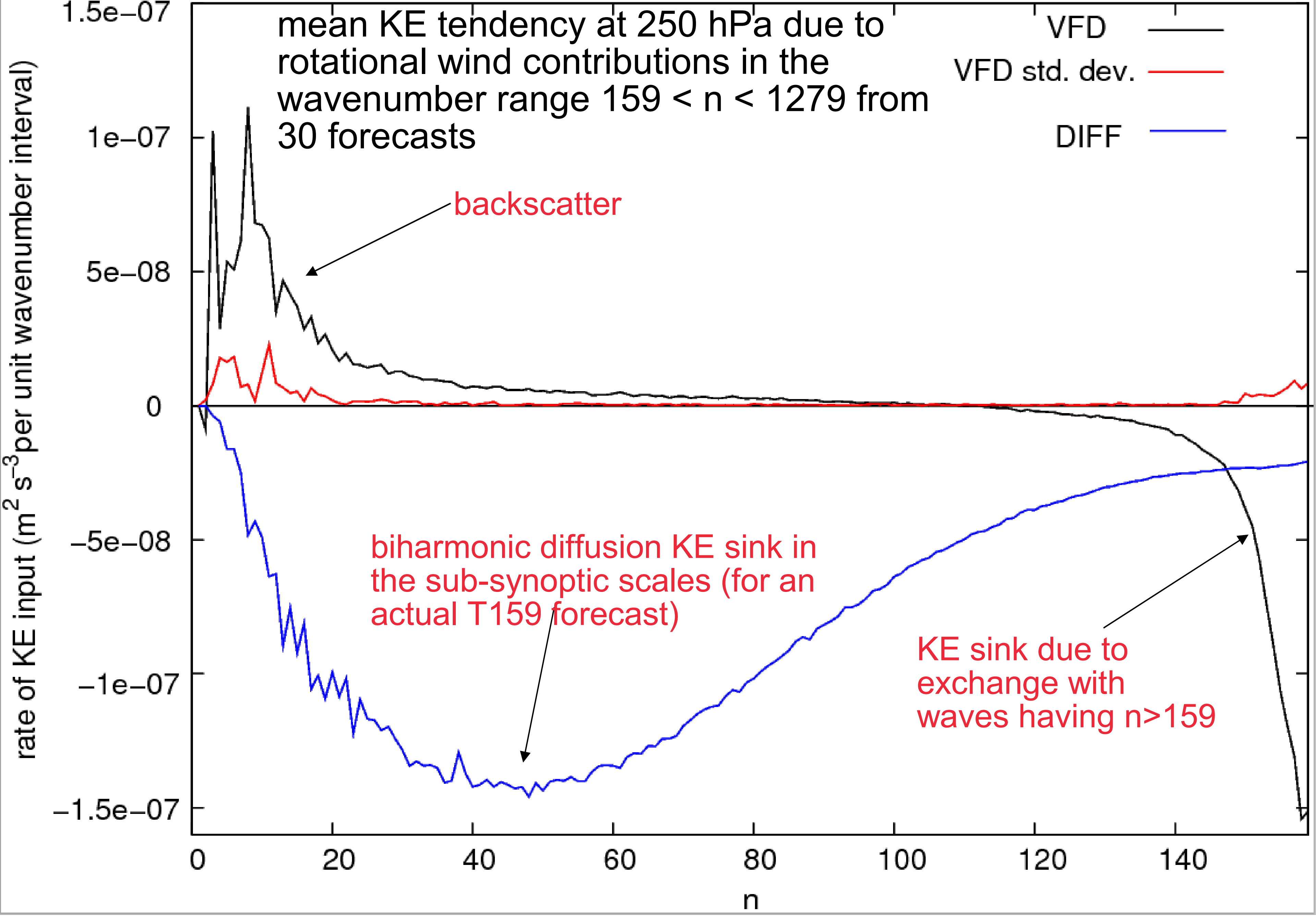
Vorticity equation terms

Vorticity Flux Divergence by the rotational wind (VFD)

Vorticity flux divergence by the divergent wind (Rossby Wave Source or RWS)

Curl (vertical advection of momentum) – called ‘TIP’ here

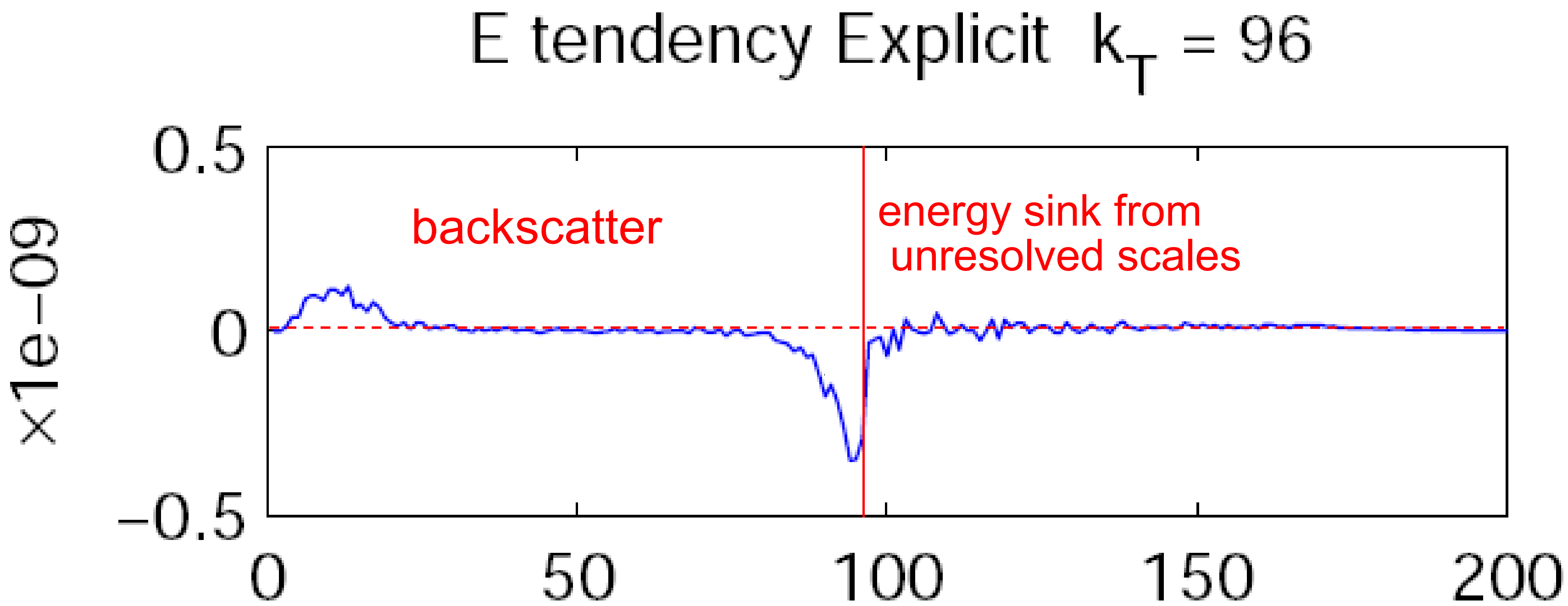
biharmonic horizontal diffusion - DIFF



mean KE tendency at 250 hPa due to rotational wind contributions in the wavenumber range 159 < n < 1279 from 30 forecasts
VFD
VFD std. dev.
DIFF
backscatter
biharmonic diffusion KE sink in the sub-synoptic scales (for an actual T159 forecast)
KE sink due to exchange with waves having n>159
rate of KE input (m^2 s^{-3} per unit wavenumber interval)
n
1.5e−07
1e−07
5e−08
0
−5e−08
−1e−07
−1.5e−07
0
20
40
60
80
100
120
140

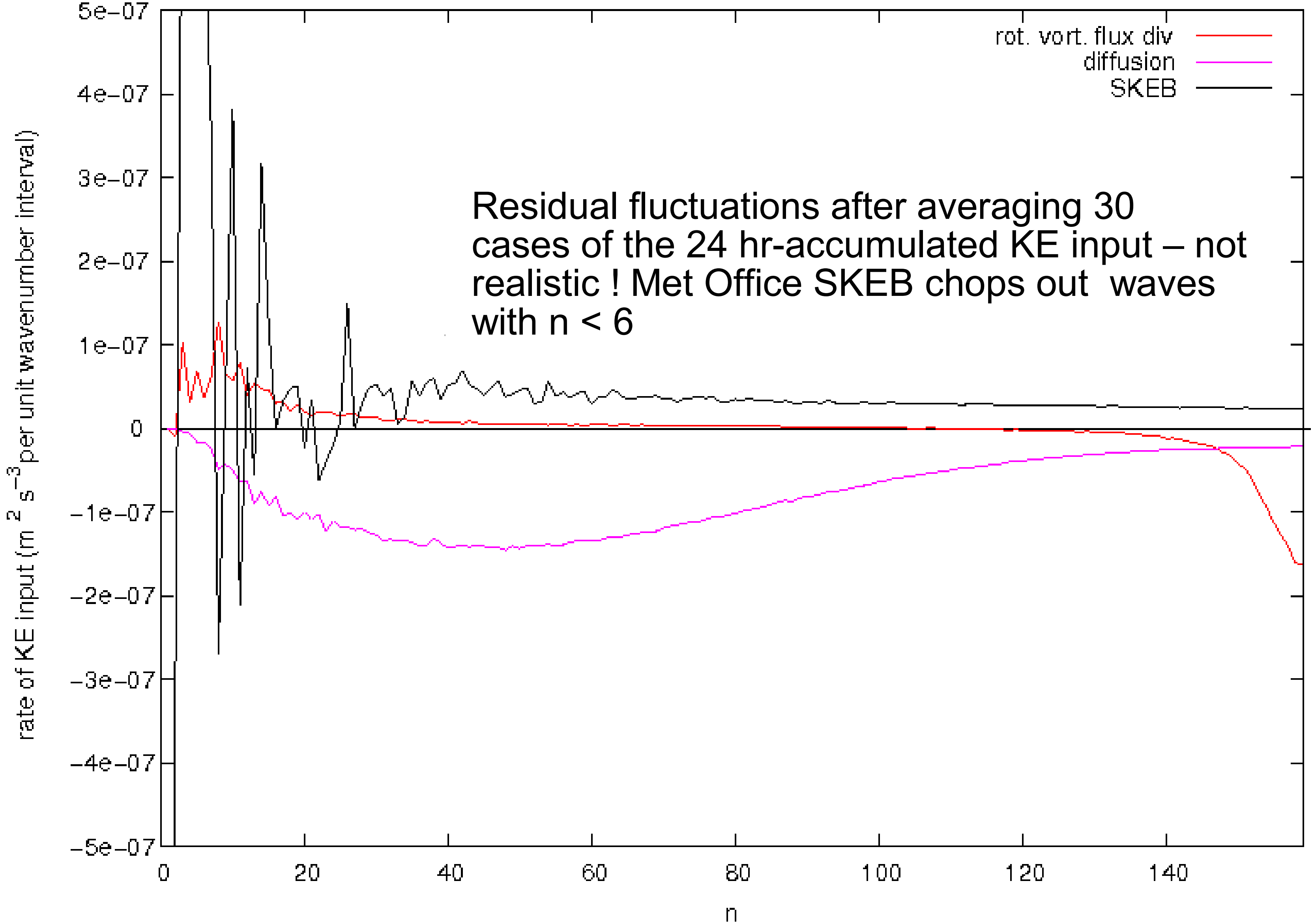
Work by Thuburn et al (2011)
(ECMWF workshop on model error)

Use barotropic vorticity equation – looked at the effect of spectral truncation w.r.t a reference solution

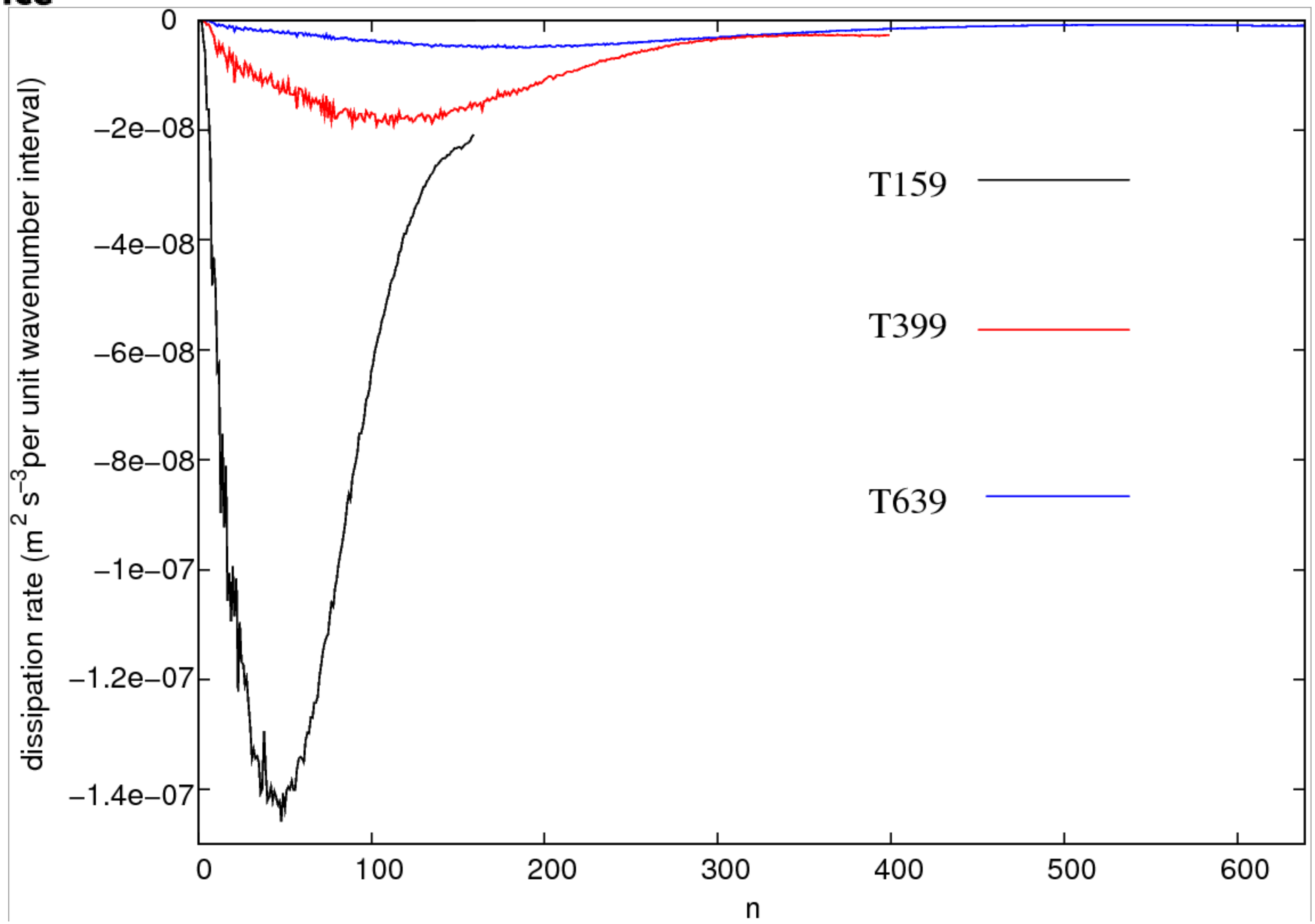


KE input from SKEB at 250 hPa

(using default settings for T159)

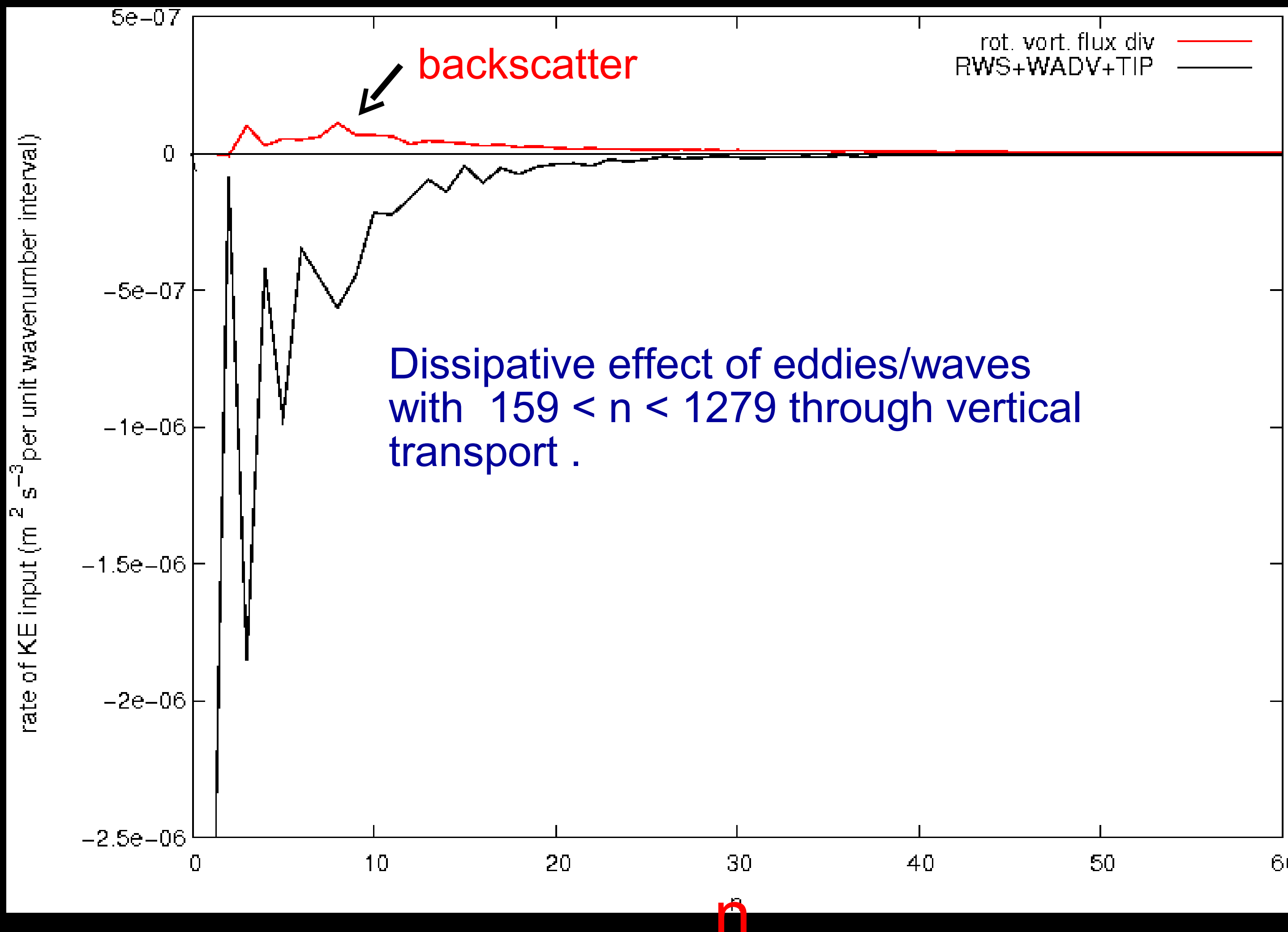


spectrum of KE dissipation due to biharmonic diffusion versus horizontal resolution

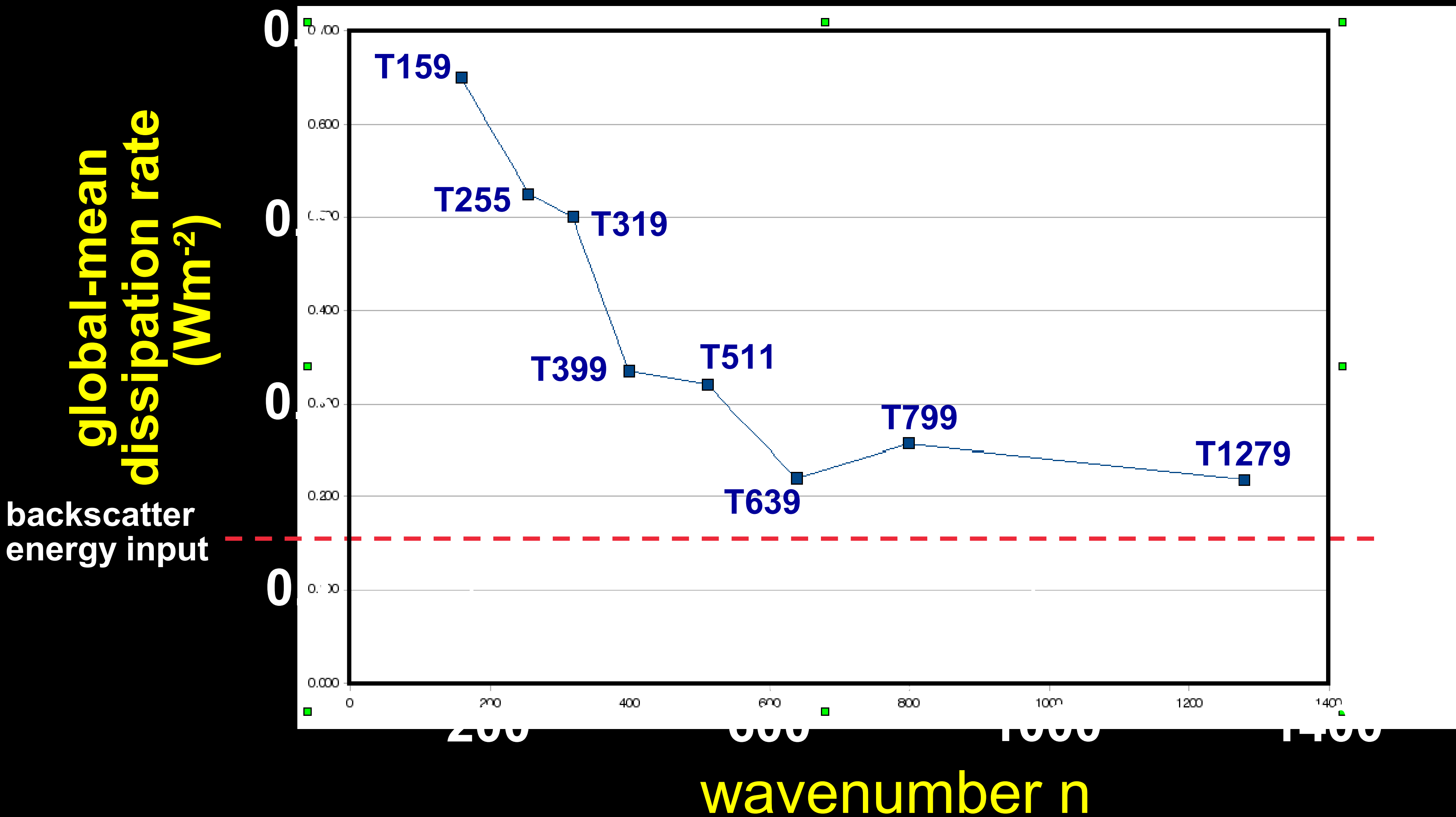


Backscatter by rotational wind *vs* the sum of RWS and TIP

Met Office



Resolution dependence of dissipation rate



summary of current view of SKEB

- heuristic formulation that doesn't derive from theory
- independent phases of waves in the spherical harmonic pattern generator
- current formulations don't scale with resolution properly
- coarse-graining suggests 2D turbulence backscatter should be small for resolution higher than T159
- global-mean numerical dissipation rate drops sharply from T159 to T511
- perturbed parametrization tendency scheme seems more effective but questions remain concerning its justification

short-term plan for SKEB in the Met Office

- move low wavenumber limit for the pattern generator from n=5 to 20 (avoid low wavenumber noisy KE input)
- include a variant of the vorticity confinement scheme to represent the deterministic component of backscatter and counteract numerical diffusion
- extend the SKEB formulation to include temperature increments (already successfully tested by Warren Tennant)

why **IS** EPS spread too small ?

- where does the greatest uncertainty lie in current NWP/climate model ?
  - tropical convection ?
  - cloud variability e.g. thin medium-level cloud ?
  - radiation stress from inertia-gravity waves ?
- convection parametrization is a likely candidate
  - insufficiently sensitive to environmental state
  - KE generated by buoyancy forces is ‘lost’
  - PV generation by convective mass transfer deficient ?
  - include slantwise convection ?

new SKEB scheme based on convective backscatter alone

- provides divergence or vorticity forcing field

random numbers

M_c =convective mass flux

α fixes the memory time scale

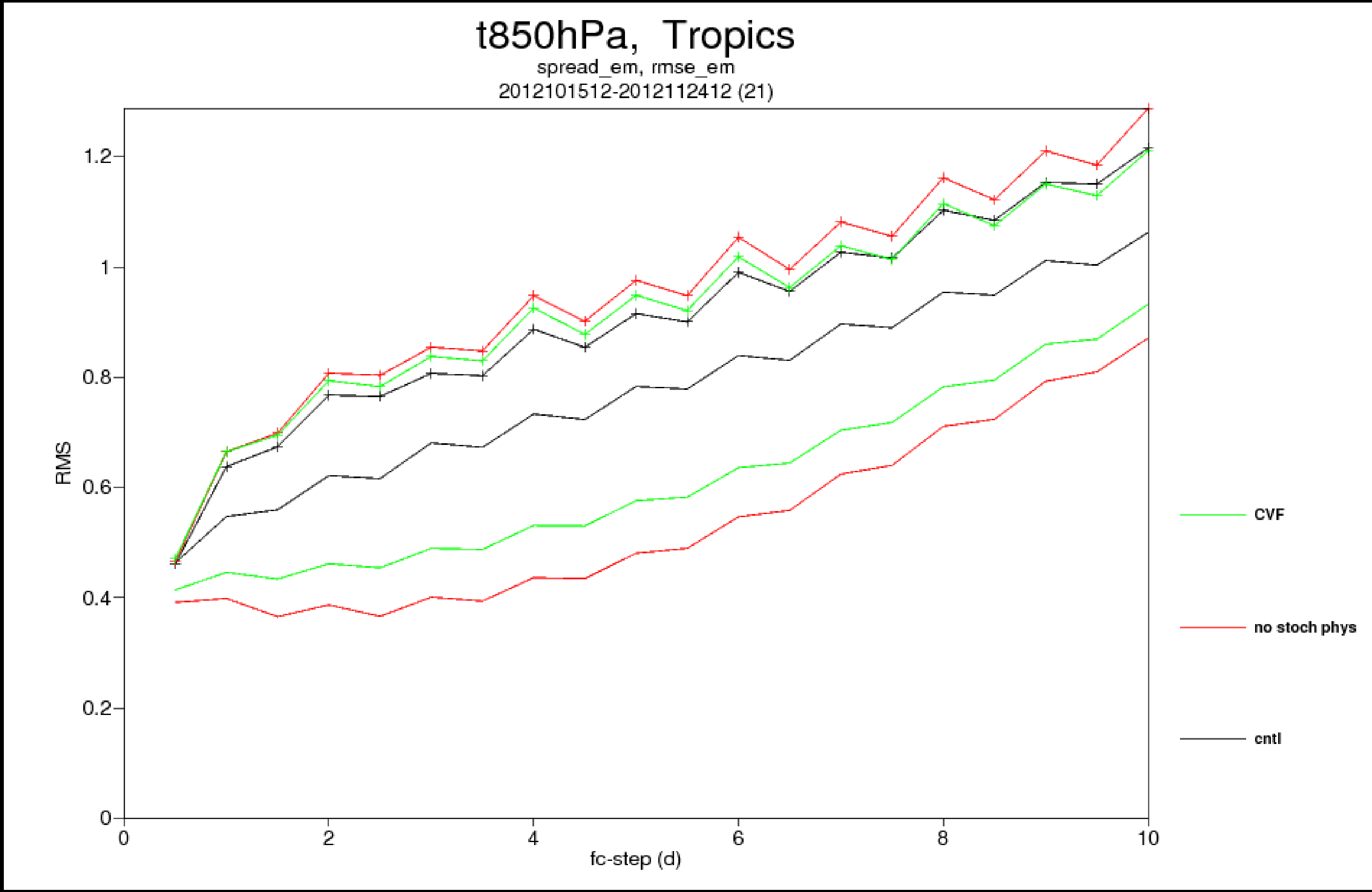
O[..] is a spatial transformation operator
(like those in image processing)

evolve the model vorticity field
(done in spectral space in the
ECMWF IFS)

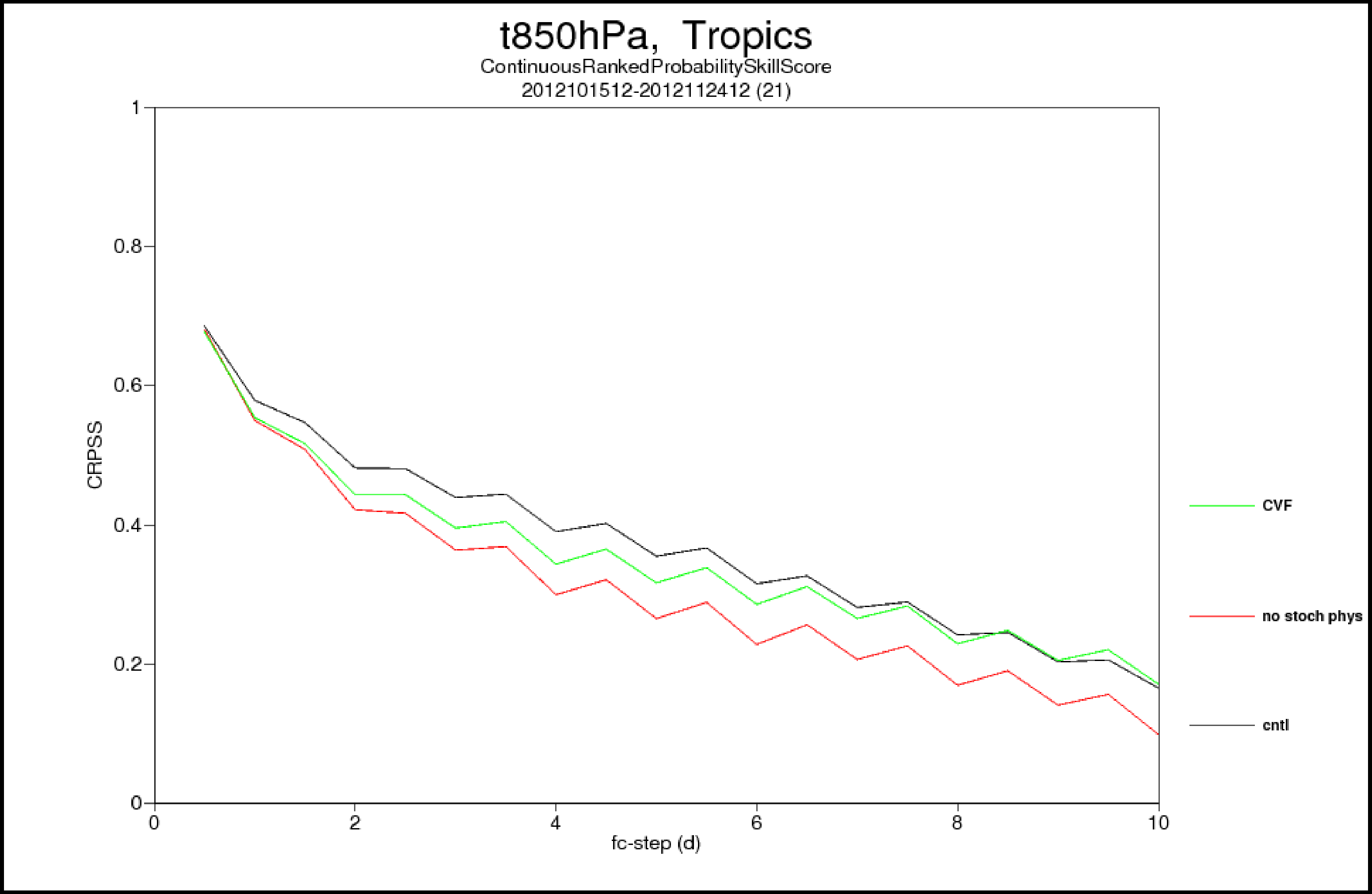
impact of Convective Vorticity Forcing (CVF) scheme on spread and ensemble-mean error for T850 in the tropics

Met Office

ECMWF EPS
T399 51 members 21 cases



impact of Convective Vorticity Forcing (CVF) scheme on Continuous Ranked Probability Skill Score



preliminary conclusions from convective divergence/vorticity forcing tests

- non-stochastic convective divergence forcing version can reduce r.m.s. error in T399 forecasts
- stochastic divergence forcing ineffective in generating spread
- stochastic convective vorticity forcing is effective at generating spread and improving probabilistic skill

Conclusions: backscatter

- 2D turbulent backscatter to low wavenumbers evident at T159 though rather weak
- ECMWF SKEB has a weak wavenumber dependence and crudely counteracts the diffusion
- KE backscatter to low wavenumbers is dominated by a non-random element that is poorly represented by SKEB (-> remove for $n < 20$ and use vorticity confinement)
- SKEB formulation should focus on convective vorticity generation with more realistic representation of associated error structure

Questions and answers