# Evaluating the effectiveness of stochastic perturbations to represent model error

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## Introduction

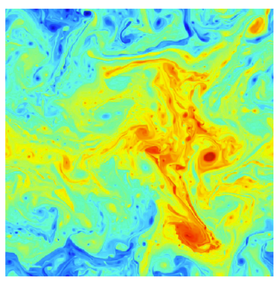
- Ensemble forecasts are typically under dispersive (ensemble spread is less than root-mean square error of ensemble mean forecasts)
- Stochastic physics, which in intended to represent model error, typically increases the ensemble spread and allows for reliable ensemble systems
- But are we getting the ensemble spread for the right reasons?

## Idealized Model Setup

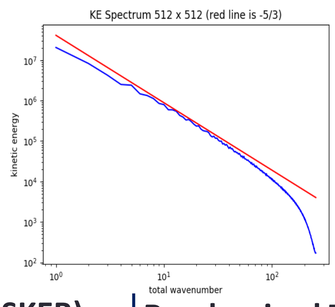
Surface quasi-geostrophic dynamic (SQG- Held et al 1995)

- Two rigid boundaries (z=0 and z=H) with constant potential vorticity (PV) in the interior
- Dynamics is basically advection of PV at boundaries, interior solution is analytic.
- Square doubly-periodic domain (20000 km on a side).
- Linear thermal relaxation of cos(2*pi*y/L) boundary θ field with a time scale of 10 days.
- 8th-order hyper-diffusion of boundary θ.
- Fourier spectral method with RK4 time differencing – nonlinear terms de-aliased using 3/2 rule.
- Written with a few hundred lines of python (including model uncertainty parameterizations, see *https://github.com/jswhit/sqgturb*).

**$512^2$ solution: θ at z=H for 20 days**



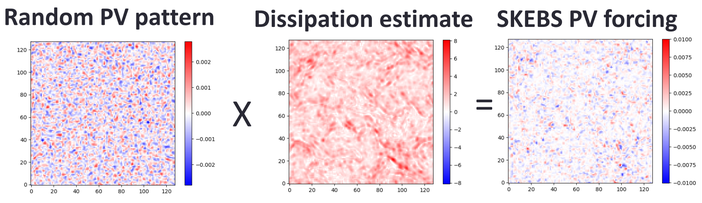
**Kinetic Energy Spectrum**




Turbulence is 3D like, with a shallow -5/3 spectrum

### Stochastic Kinetic Energy Backscatter (SKEB)

**Random PV pattern** X **Dissipation estimate** = **SKEBS PV forcing**



### Randomized Transport (RNDT)

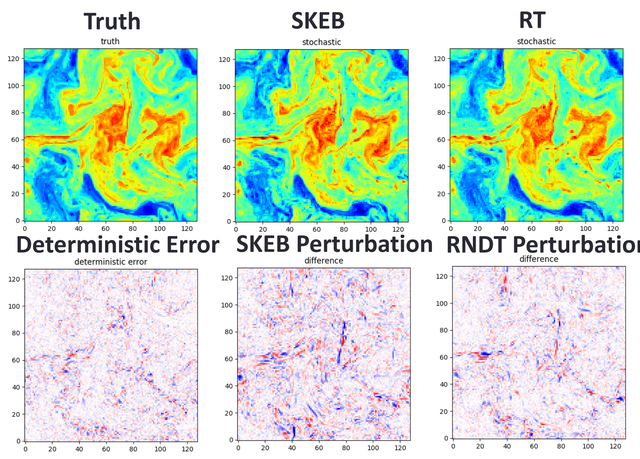
Advection of tracer Θ

$$\frac{D\Theta}{Dt} = 0$$

- Adding white random velocity

$$\boldsymbol{v} = \boldsymbol{w} + \sigma\dot{\boldsymbol{B}}$$

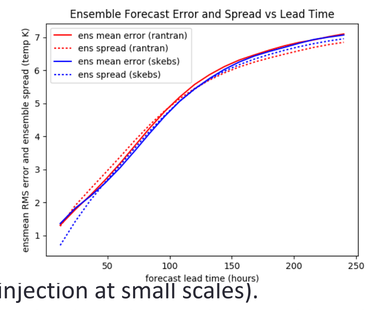
Example 1-day forecast at $126^2$, initialized by coarse graining $512^2$ solution




Perturbations are largest where gradients (and errors) are largest

## Idealized Model Experiments

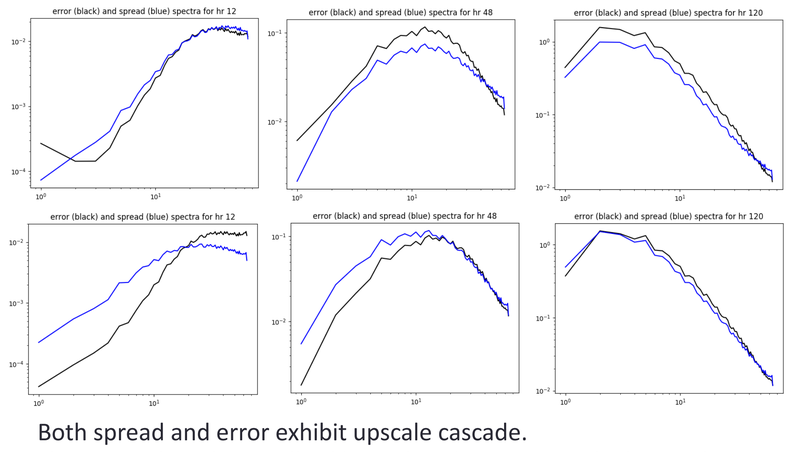
**Ens mean error and spread (10 members)**
temporal corr = 3h, horizontal corr = 2Δx
amplitudes tuned to calibrate spread/error at day 4




- Faster initial spread growth for SKEBs (due to energy injection at small scales).
- Difficult to calibrate spread/error at both long and short leads with a single spatial length scale in covariance. Longer lengths increase (decrease) spread at long (short) leads.

KE Spectrum of Error and Spread for RNDT experiments

12-hours 48-hours 120-hours



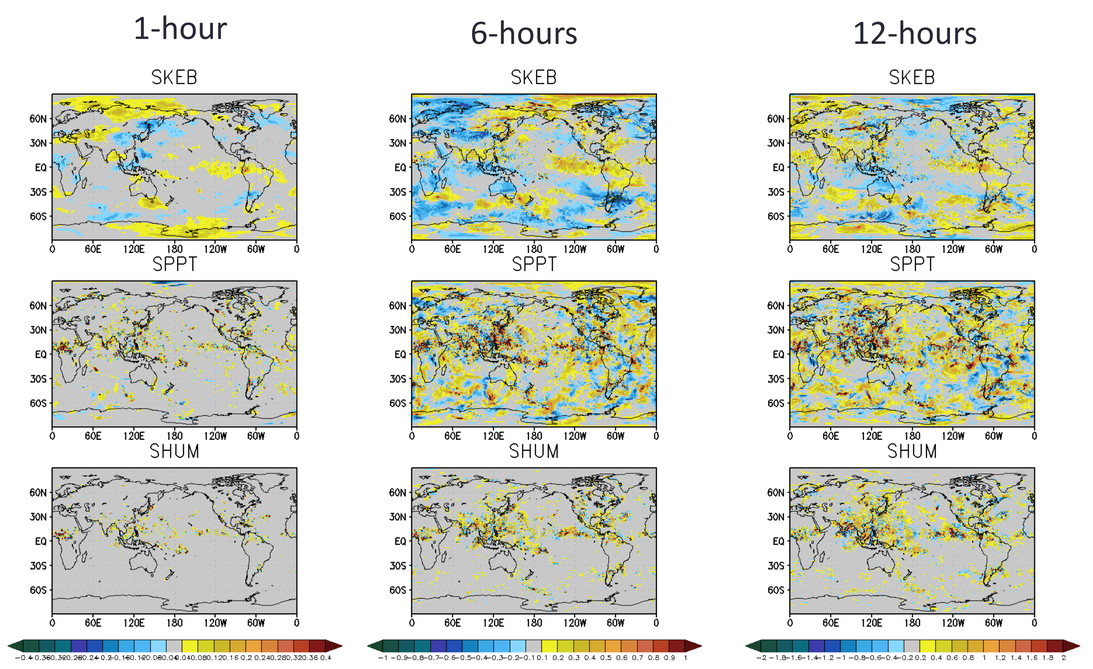

hcorr=1Δx

hcorr=3Δx

Both spread and error exhibit upscale cascade.
Short Length scale is well calibrated at short time-scale, but under-spread at 5-days
Long length scale is over-spread at 12-hours, but is good at 5-days.

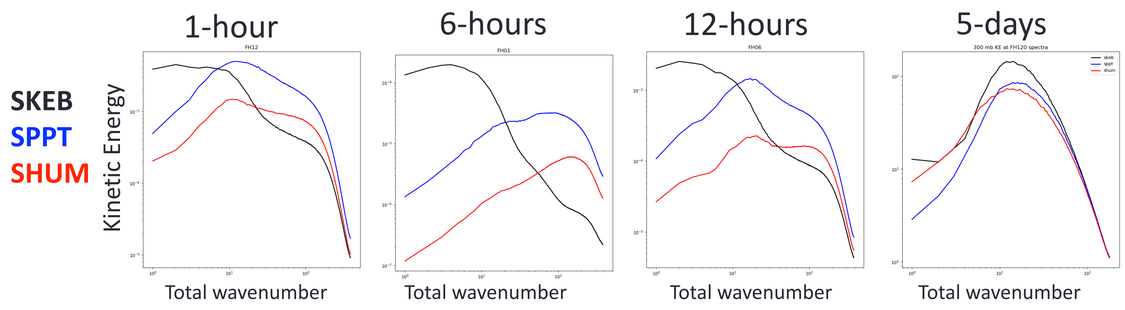
## Real world results

**FV3-GFS**: Non-hydrostatic global model, full physics.
Currently has 3 stochastic physics parameterizations
**SKEB** – Stochastic Energy Backscatter (Shutts 2005)
**SPPT** – Stochastically Perturbed Physics Tendencies (Buizza et al. 1999)
**SHUM** – Stochastically Perturbed Boundary Layer Humidity (inspired by Tompkins and Berner 2008)




Sample perturbations evolution of 300 hPa zonal wind from stochastic physics schemes currently available in the FV3-GFS model

### 300 hPa KE spectra of stochastic physics perturbations



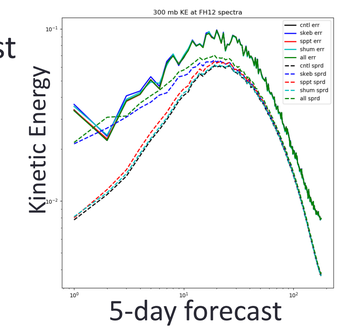

Initially, SHUM has the smallest perturbations, but by day-5 those perturbations have cascaded to the largest waves.

### Ensemble Forecast Verification

300 hPa KE Spectra of Spread and Error

12-hour forecast

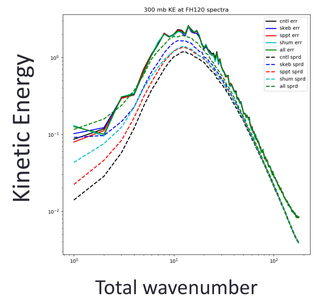
- 20-member ensemble forecast
- initialized with GFS operational analysis every 5th day at 00z in August 2014.
- C192 (~60km) resolution
- Verified again ERA-Interim reanalysis




5-day forecast

SKEB produces a lot of ensemble spread at large scales, which is needed.

Forecast system is under-spread at most wavenumbers.




SHUM's perturbations grow more than SPPT by day-5.

The combination of all 3 stochastic physics parametrization produces a well calibrated forecast at all wavenumbers by day-5.

## Conclusions

- SQG model provides a simple framework to test model uncertainty parameterizations
- Both SKEBs and randomized transport appear to simulate model uncertainty due to unresolved dynamics well in this simple (but high-dimensional) model.
- Randomized transport does not require a dissipation estimate (which can be expensive to compute every time-step, especially when a lot of smoothing is desired).
- Both require amplitude, spatial scales to be tuned carefully to get accurate calibration for short and long forecast leads (need multiple scales?). Relatively insensitive to temporal scale (if >> Δt).
- Will test in FV3 model once SKEBs baseline is established.
- SKEB in FV3 is operating at a much longer length-scale than theory suggests, but model does need the spread at these scale. What is this source of model error?
- Difficult to get a well calibrated system at all forecast leads.