Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

cen

Introduction to Data Assimilation, Subgrid-Scale Parameterization and Predictability

Christian Franzke

Meteorological Institute

Center for Earth System Research and Sustainability

University of Hamburg

Email: christian.franzke@uni-hamburg.de

Outline for Today

Stochastic Parameterization Schemes

- ECMWF Model
  - Stochastic Physics
  - Stochastic Backscatter
- Empirical Approach (Wilks model)

Stochastic Physics

In climate models we decompose tendencies into **dynamical** and **physical** components

$$dx = f(x)_{Dyn}dt + f(x)_{Phy}dt$$

- *Dynamical components* from resolved equations of motion
- *Physical components* from parameterizations of unresolved physical processes

ECMWF Stochastic Physics scheme

$\tilde{f}(x)_{Phy} = (1 + r\eta)f(x)_{Phy}$

$\eta\in[-1, +1]$; $r\in[0,1]$ tapers the perturbations to zero near the surface & in the stratosphere

- Stochastically perturbed physics tendencies (SPPT) scheme
- Simulates uncertainty due to sub-grid parametrisations
- Developed by Buizza et al. (1999)
  - Improved in 2009

Buizza et al. 1999

Stochastic Physics

ECMWF Stochastic Physics scheme:

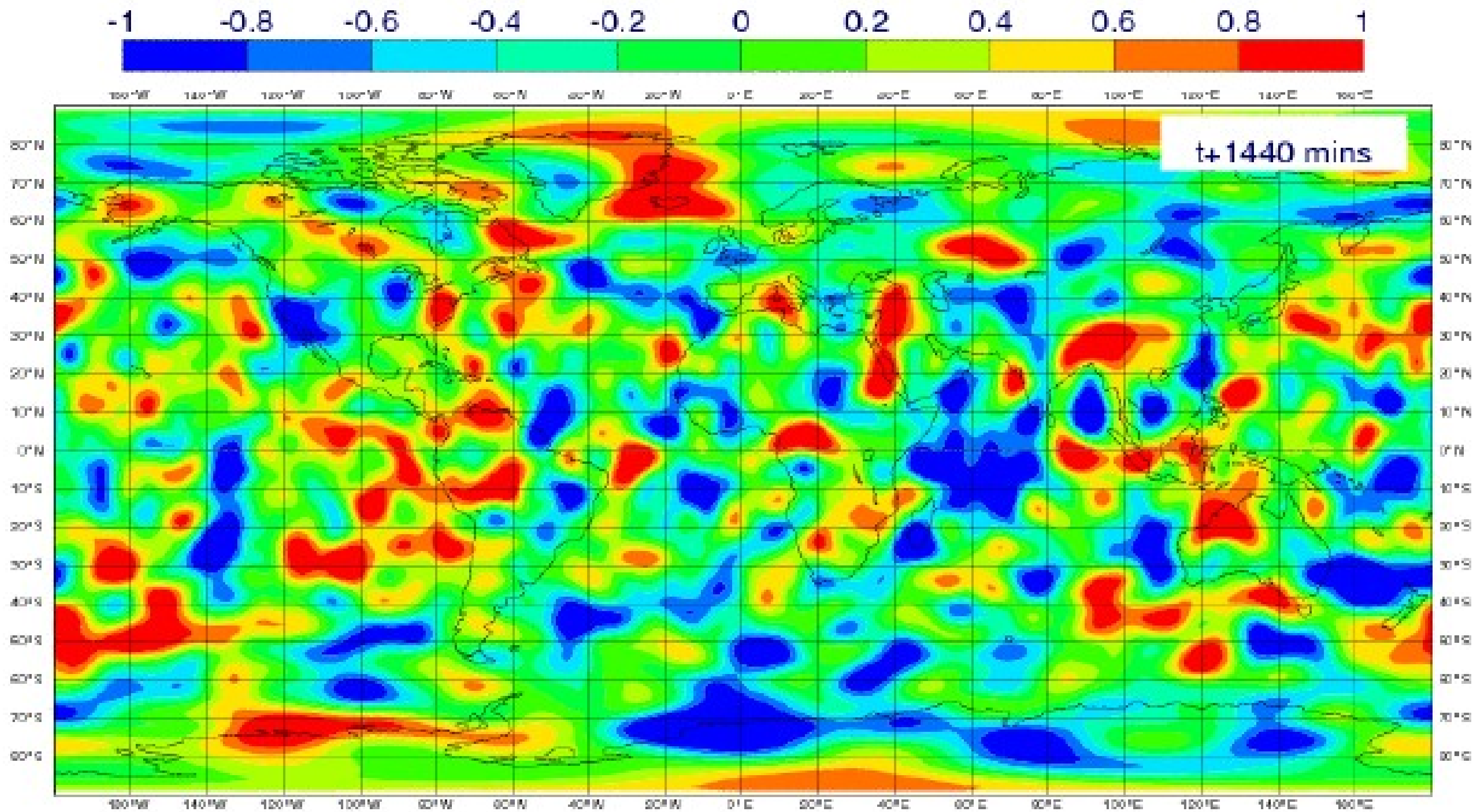
SPPT pattern

- 2D random pattern of spectral coefficients, r
  - Time-correlations: AR(1)
  - Space-correlations: Gaussian
- Applied at all model levels to preserve vertical structures

Buizza et al.

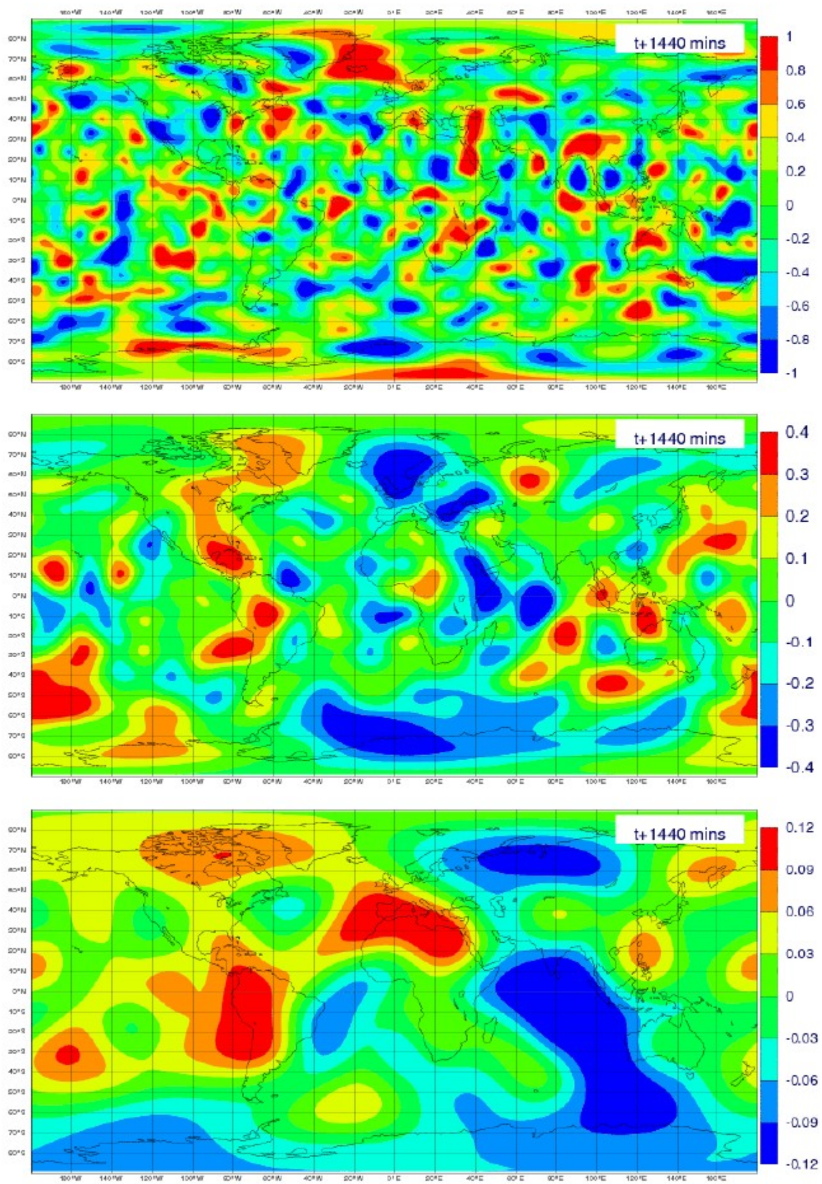
Stochastic Physics

SPPT pattern



Buizza et al.

Stochastic Physics



3 correlation scales:

i) 6 hours, 500 km, σ = 0.52

ii) 3 days, 1000 km, σ = 0.18

iii) 30 days, 2000 km, σ = 0.06

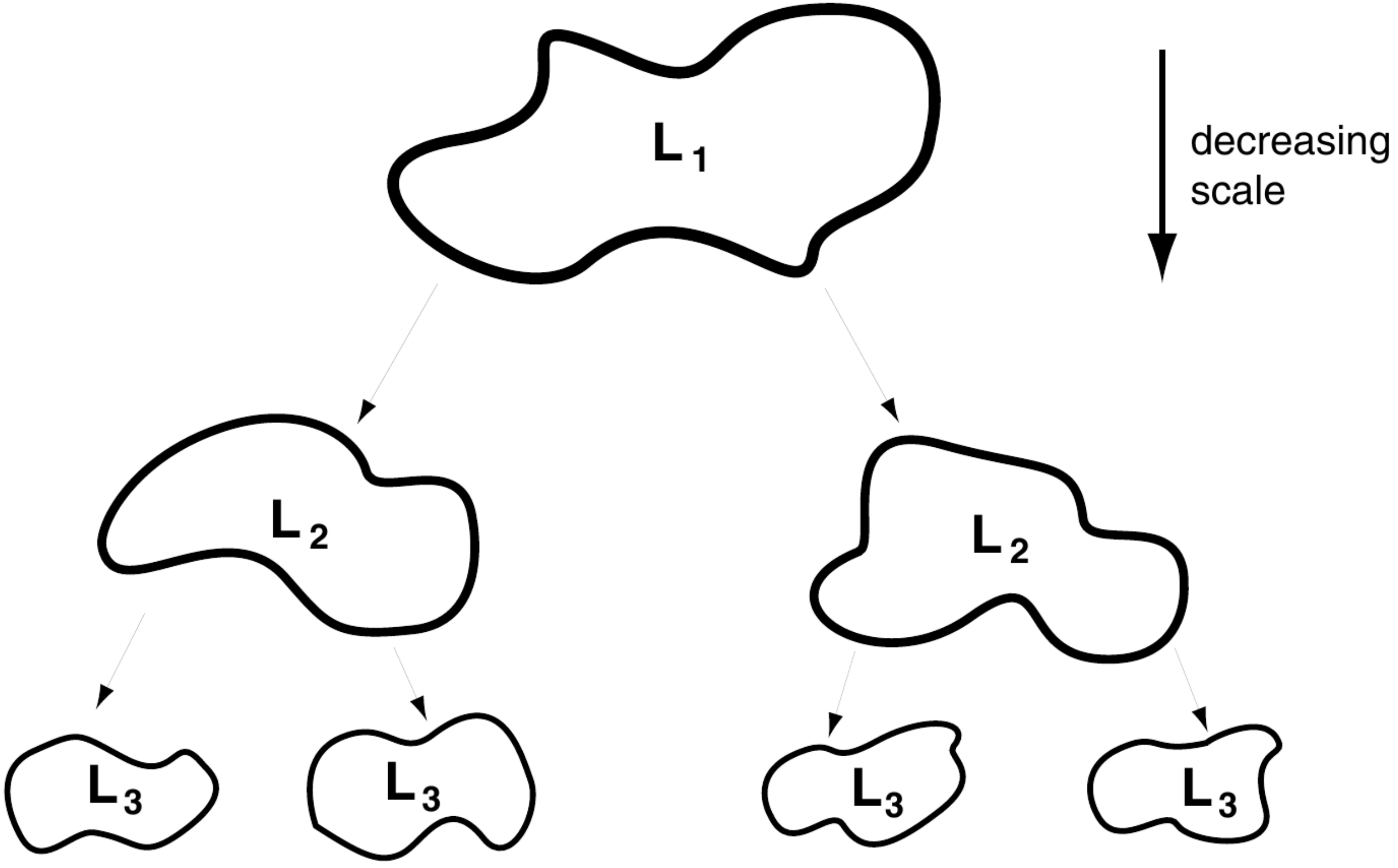
Buizza et al.

ENERGY TRANSFERS IN ATMOSPHERE AND OCEAN

Stochastic Backscatter

Energy Spectra

Energy cascade



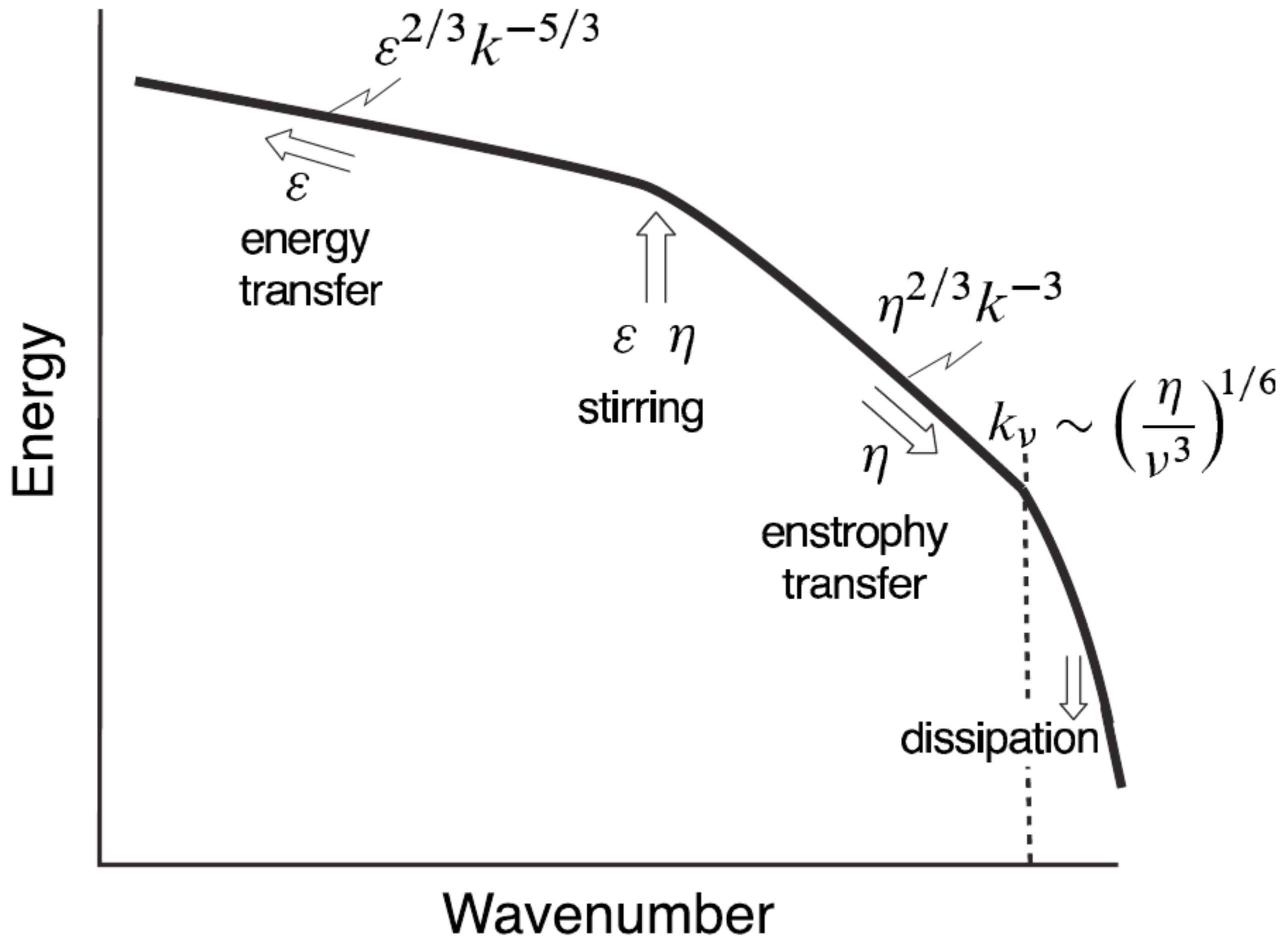
Vallis 2006

ENERGY TRANSFERS IN ATMOSPHERE AND OCEAN

cen

Energy Spectra

Two Dimensional Turbulence



Vallis 2006

Stochastic Backscatter

- Attempting to simulate a process otherwise absent from the model
  - **upscale transfer of energy from sub-grid scales**
- Represents backscatter of Kinetic Energy (KE) by adding perturbations to U and V via a forcing term to the streamfunction

$$F_{\varphi} = \left(\frac{b_R D_{\text{tot}}}{B_{\text{tot}}}\right)^{1/2} F^*$$

Shutts 2005, Berner et al. 2009

Stochastic Backscatter

$$F_\varphi = \left(\frac{b_R D_{\text{tot}}}{B_{\text{tot}}}\right)^{1/2} F^*$$

where

- F^* is a 3D random pattern field,
- B_{tot} is the mean KE input by F^* alone,
- D_{tot} is an estimate of the total dissipation rate due to the model,
- b_R is the backscatter ratio – a scaling factor.

Shutts 2005, Berner et al. 2009

ENERGY TRANSFERS IN ATMOSPHERE AND OCEAN

cen

Stochastic Backscatter

3D random pattern field F* :

- First-order auto-regressive [AR(1)] process for evolving F*
  $F^*(t + \Delta t) = \varphi F^*(t) + \rho\eta(t)$
- where $\varphi = \exp(-\Delta t\ \tau)$ controls the correlation over timestep Δt;
- and spatial correlations (power law) for wavenumbers define ρ for random numbers η
- vertical space-(de)correlations: random phase shift of η between levels

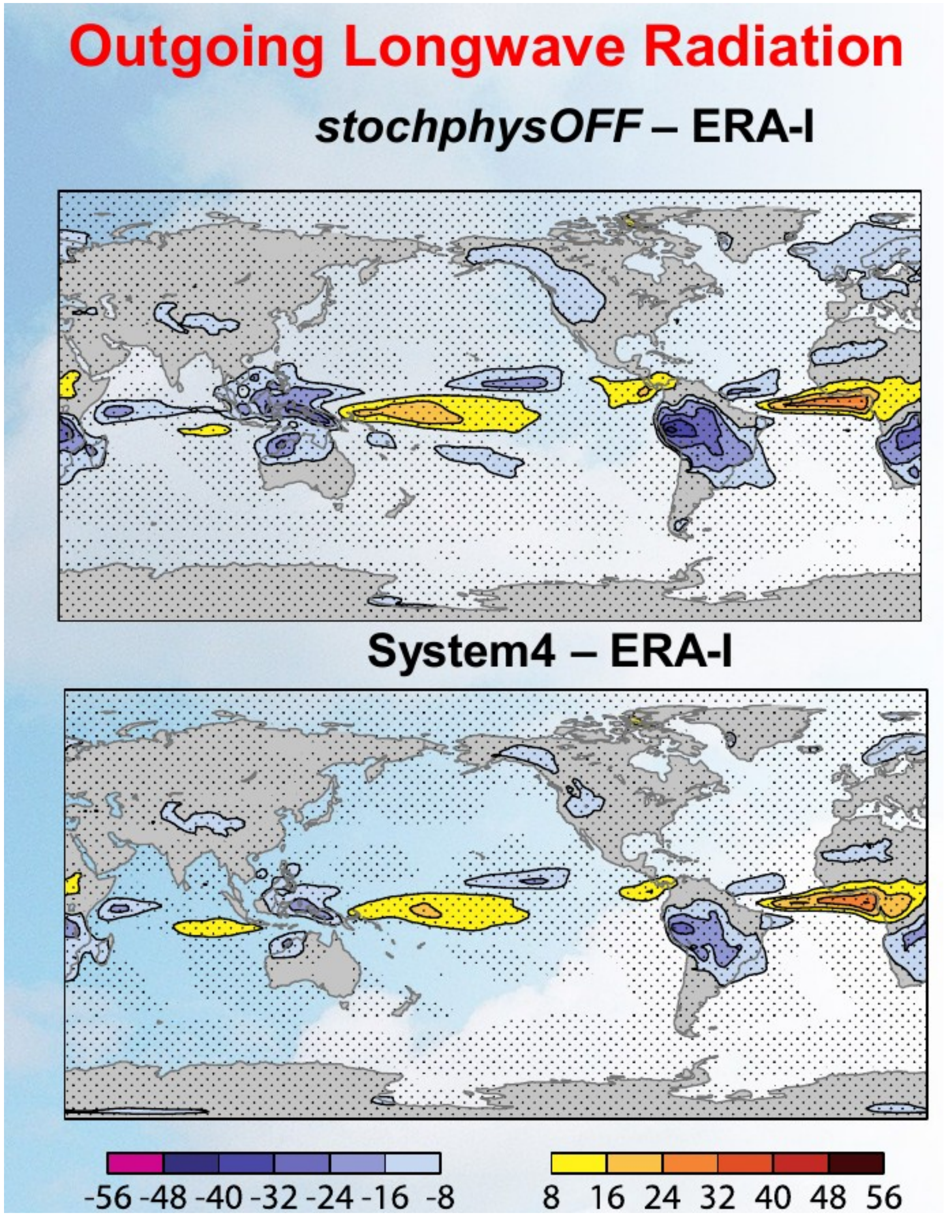
Shutts 2005, Berner et al. 2009

Stochastic Backscatter

- Adding SPPT + SKEB perturbations:
  - increases ensemble “spread” (= ensemble standard deviation), i.e. ensemble members describe greater region of the parameter space
  - some reduced ensemble mean errors
- In the extra-tropics:
  - SPPT and SKEB each have a similar impact, i.e. perturbations are successfully adopted and evolved by the model
  - Experiments: perturbations in days 0-5 contribute most effect

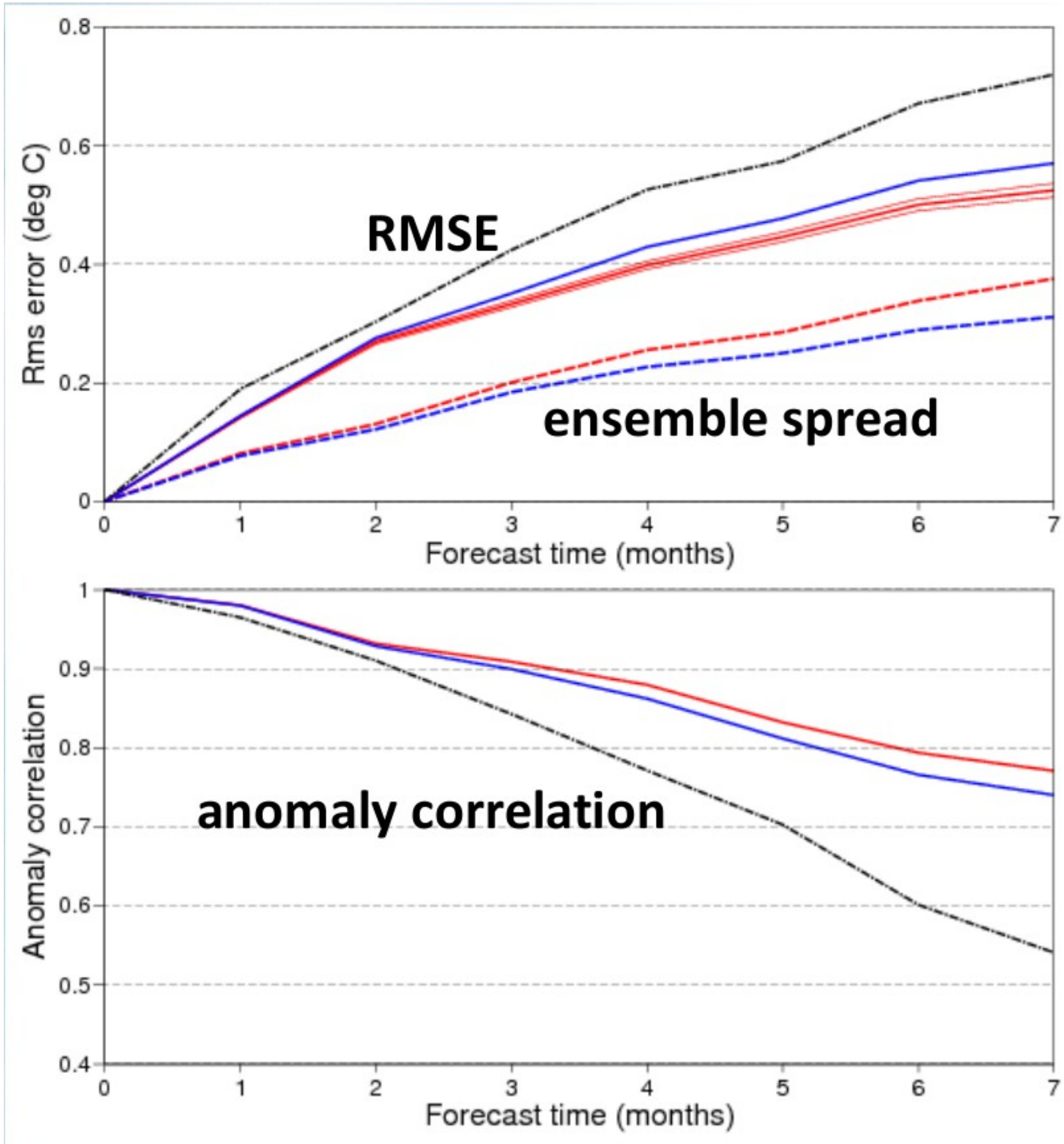
Shutts 2005, Berner et al. 2009

Stochastic Backscatter



Shutts 2005, Berner et al. 2009

Stochastic Backscatter



stochphysOFF

System 4

System 4 has:

- Reduced forecast errors
- Increased ensemble spread
- Improved correlation

From Antje Weisheimer

Shutts 2005, Berner et al. 2009

Empirical Stochastic Scheme

2-Level Lorenz-96 Model

$$\frac{\mathrm{d}X_k}{\mathrm{d}t} = -X_{k-1}(X_{k-2} - X_{k+1}) - X_k + F - \frac{hc}{b} \sum_{j=J(k-1)+1}^{kJ} Y_j; \quad k = 1, \ldots, K \tag{1a}$$

$$\frac{\mathrm{d}Y_j}{\mathrm{d}t} = -cbY_{j+1}(Y_{j+2} - Y_{j-1}) - cY_j + \frac{hc}{b} X_{\mathrm{int}[(j-1)/J]+1}; \quad j = 1, \ldots, JK. \tag{1b}$$

Wilks 2005

ENERGY TRANSFERS IN ATMOSPHERE AND OCEAN

cen

Empirical Stochastic Scheme

Reduced Lorenz-96 Model

$$\frac{\mathrm{d}X_k^*}{\mathrm{d}t} = -X_{k-1}^*(X_{k-2}^* - X_{k+1}^*) - X_k^* + F - g_U(X_k^*); \quad k = 1, \ldots, K.$$

$$g_U(X_k) = b_0 + b_1 X_k + b_2 X_k^2 + b_3 X_k^3 + b_4 X_k^4 + e_k,$$

Wilks 2005

Empirical Stochastic Scheme

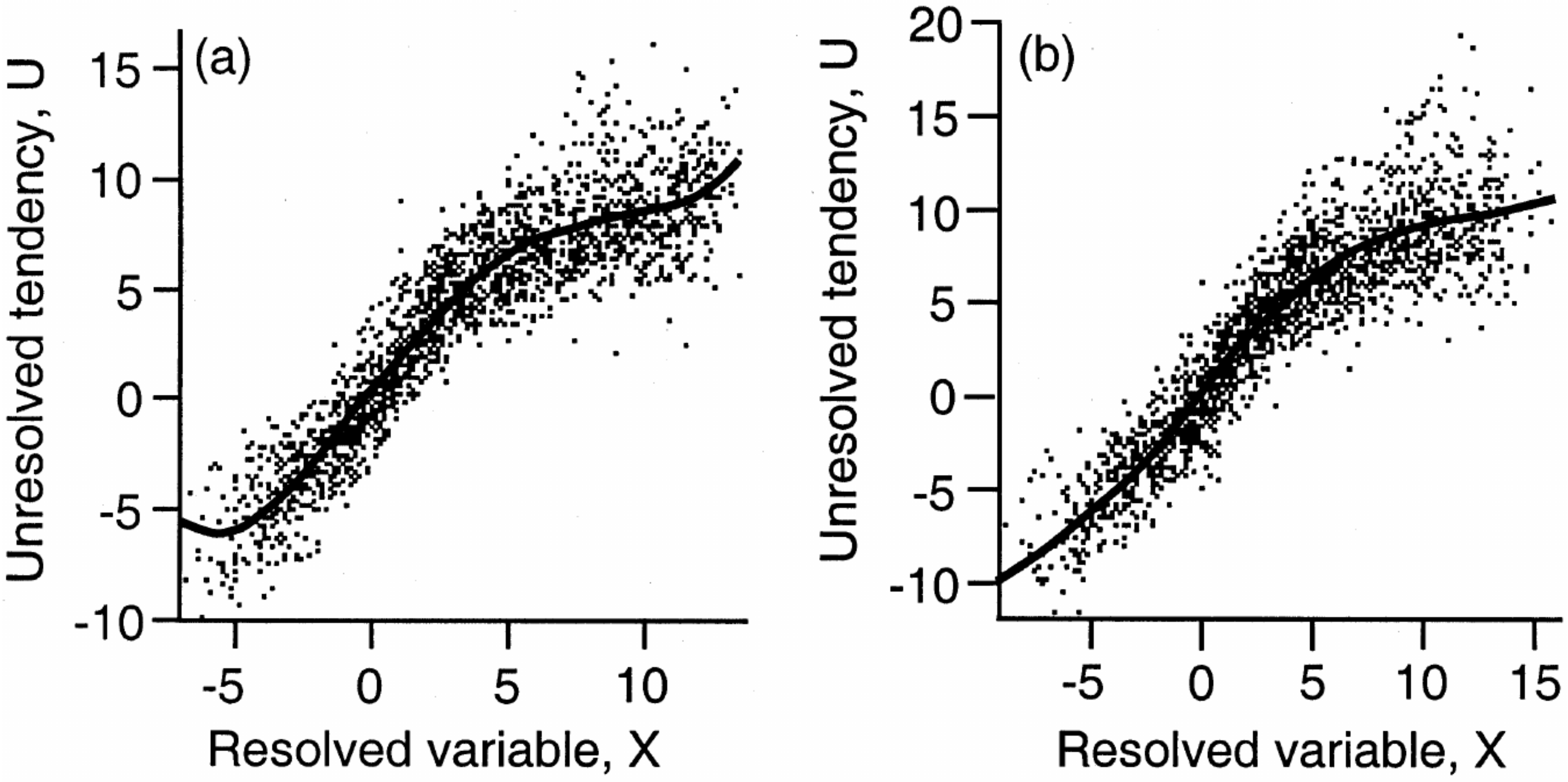


Figure 2. Scatterplots of the unresolved tendency U (Eq. (3)) as a function of the resolved variable X to which it applies, together with the regression functions constituting the deterministic part of the parametrizations $g_U(X)$ (Table 1 and Eq. (4)), for forcings: (a) $F = 18$ and (b) $F = 20$.

Wilks 2005

Empirical Stochastic Scheme

TABLE 1. PARAMETRIZATION REGRESSION PARAMETERS AND DIAGNOSTICS

	b_0	b_1	b_2	b_3	b_4	s_e	R^2
$F = 18$	0.275	1.59	−0.0190	−0.0130	0.000707	1.74	87.6%
$F = 20$	0.262	1.45	−0.0121	−0.00713	0.000296	1.99	86.3%

See text for details.

Wilks 2005

Empirical Stochastic Scheme

Reduced Lorenz-96 Model

$$\frac{\mathrm{d}X_k^*}{\mathrm{d}t} = -X_{k-1}^*(X_{k-2}^* - X_{k+1}^*) - X_k^* + F - g_U(X_k^*); \quad k = 1, \ldots, K.$$

$$g_U(X_k) = b_0 + b_1 X_k + b_2 X_k^2 + b_3 X_k^3 + b_4 X_k^4 + e_k,$$

AR(1) representation

$$e_k(t) = \phi e_k(t - \Delta) + \sigma_e (1 - \phi^2)^{1/2} z_k(t).$$

Wilks 2005

Empirical Stochastic Scheme

Reduced Lorenz-96 Model

$$\frac{\mathrm{d}X_k^*}{\mathrm{d}t} = -X_{k-1}^*(X_{k-2}^* - X_{k+1}^*) - X_k^* + F - g_U(X_k^*); \quad k = 1, \ldots, K.$$

Residuals:

$$U(t) = [-X_{k-1}(t)\{X_{k-2}(t) - X_{k+1}(t)\} - X_k(t) + F] - \left\{\frac{X_k(t+\Delta t) - X_k(t)}{\Delta t}\right\}$$

Wilks 2005

Today's Exercise

Implement Wilks Scheme in Lorenz-96 Model
Compare deterministic with stochastic scheme

K=8; J=32; F=18
h=1; c=10; b=10
Δt=0.0001

TABLE 1. PARAMETRIZATION REGRESSION PARAMETERS AND DIAGNOSTICS

	b_0	b_1	b_2	b_3	b_4	s_e	R^2
$F = 18$	0.275	1.59	−0.0190	−0.0130	0.000707	1.74	87.6%
$F = 20$	0.262	1.45	−0.0121	−0.00713	0.000296	1.99	86.3%

See text for details.

$\sigma_e = s_e$; $\Phi = 0.984$

ENERGY TRANSFERS IN ATMOSPHERE AND OCEAN