Energetically Consistent Stochastic and Deterministic Kinetic Energy Backscatter Schemes for Atmosphere-Ocean Models

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Outline

- Implementation of energetically consistent stochastic energy backscatter (SEB) and deterministic energy backscatter (DEB) parameterization in a spectral Atmospheric model
- Performance with increasing resolution
- Improved Kinetic Energy-Wavenumber spectrum
- Improved Eddy variability
- Measures of predictability (ACF, EOF)
- Scale Adaptive and computationally efficient

Motivation

- manifold increase in computing power: O(1 km) GCM
- tremendous computational resources and associated data storage capabilities: heavy investments
- even then fail to accurately capture small-scale features (e.g. cloud dynamics, tropical convection, gravity wave drag, other microphysical processes)
- small-scale unresolved (subgrid scale) processes: interact with and influence large-scale resolved processes
- inaccurate representation: error growth, underdispersive ensemble forecasts, uncertainty, and biases (e.g. 500 hPa geopot. height, precip)
- recourse may be taken to stochastic modeling which helps overcome some of these problems
- uncertainty estimation in predictions, model error reduction, triggering noise-induced regime transitions, capturing response to changes in external forcing

Motivation

- Stochastically Perturbed Parametrization Tendency (SPPT) scheme or a Stochastic Kinetic Energy Backscatter Scheme (SKEBS) improve predictability of numerical forecast models

- ***stochastic parametrizations can also be used to improve low resolution atmosphere-ocean models***

- robust and efficient low-resolution models are still of practical interest (long-term climatic processes including paleoclimates, or extreme events)

- helps improving low-resolution atmospheric and oceanic models so that they achieve simulation statistics comparable to high-resolution models

- deterministic energy backscatter schemes have also been used for this purpose

- **novel energetically consistent deterministic backscatter as well as modified SKEBS are used to compensate for the loss of energy due to hyperdiffusion at smaller scales**

Methodology (in brief)

- The nondimensional prognostic equation for vorticity (ζ) in PUMA may be written as:

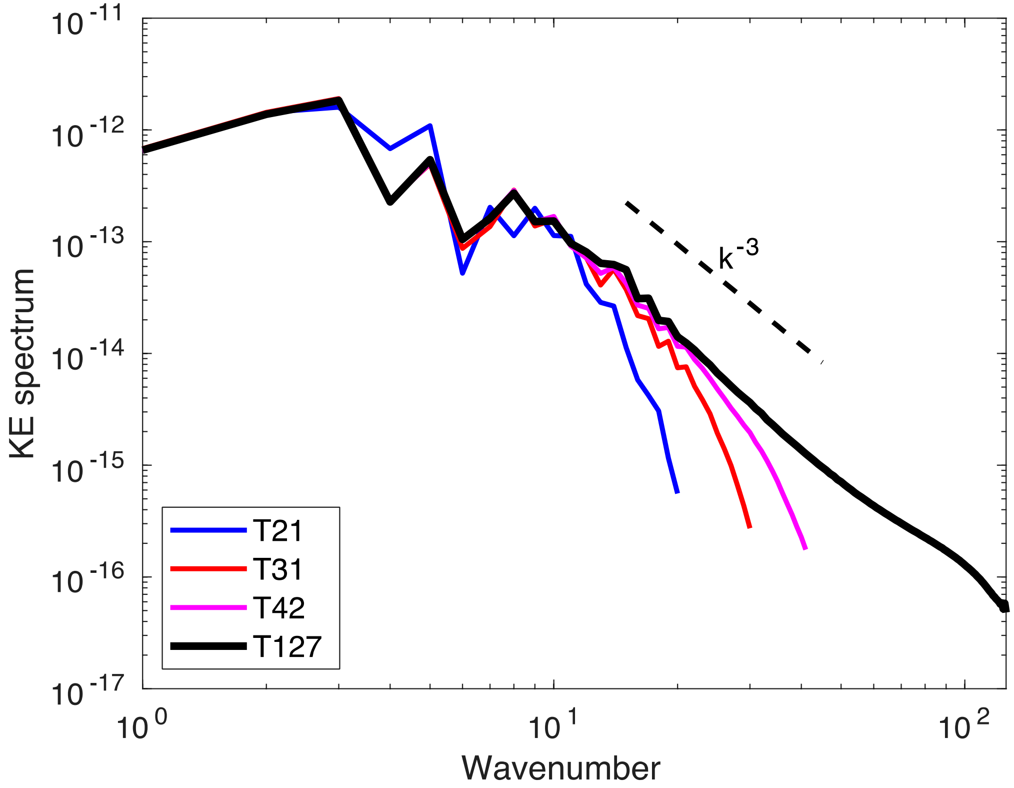
$$\frac{\partial(\zeta + f)}{\partial t} = \frac{1}{(1-\mu^2)}\frac{\partial F_v}{\partial \lambda} - \frac{\partial F_u}{\partial \mu} - \frac{\zeta}{\tau_F} + H_\zeta$$

- Coarse resolution model do not include dissipative range of the wavenumber-energy spectrum

- Hyperdiffusion H_ζ parameterizes both subgrid scale horizontal mixing and energy cascade into these scales and its subsequent dissipation

$$H_\zeta = -(-1)^h K \nabla^{2h} \zeta$$

- At low resolutions, subgrid scale dissipation (due to hyperdiffusion, h=4) seriously affects the quality of simulation



- T21, T31, T42 and T127 resolutions: time-steps of 60 mins, 40 mins, 30 mins, and 4 mins; 10 vertical σ-levels; aqua-planet setup without topography

- *impact of the hyperdiffusion is quite strong at high wavenumbers in low-resolution simulations*: SEB and DEB parameterizations can be used to correct this

- compensate for the loss of KE dissipated at sub-grid scales by injecting back (i.e. backscatter) into the model the KE due to hyperdiffusion

- Berner et al. (2009): SKEBS in NWP: used AR(1) process to generate stochastically perturbed streamfunction forcings

- Jansen & Held (2014): novel energetically consistent stochastic and deterministic backscatter schemes

- hyperviscous closure combined with forcing such that it cancels spurious energy dissipation due to hyperviscosity, while maintaining net dissipation of enstrophy

- We use both SEB and DEB parameterization

- Our modified flow-dependent SEB parameterization: combination of schemes

- Key idea: flow-dependent AR(1) stochastic forcing in which sub-grid scale KE is injected back at each time step to make scheme energetically consistent

- Introduce a stochastic perturbation in the vorticity equation in the form of a first-order autoregressive (AR1) process:

$$\zeta(t+\Delta t) = \varepsilon_1 (1-\alpha)\, \zeta(t) + \varepsilon_2\, \alpha \sqrt{\Delta E}\, n^p\, \eta(0,1)$$

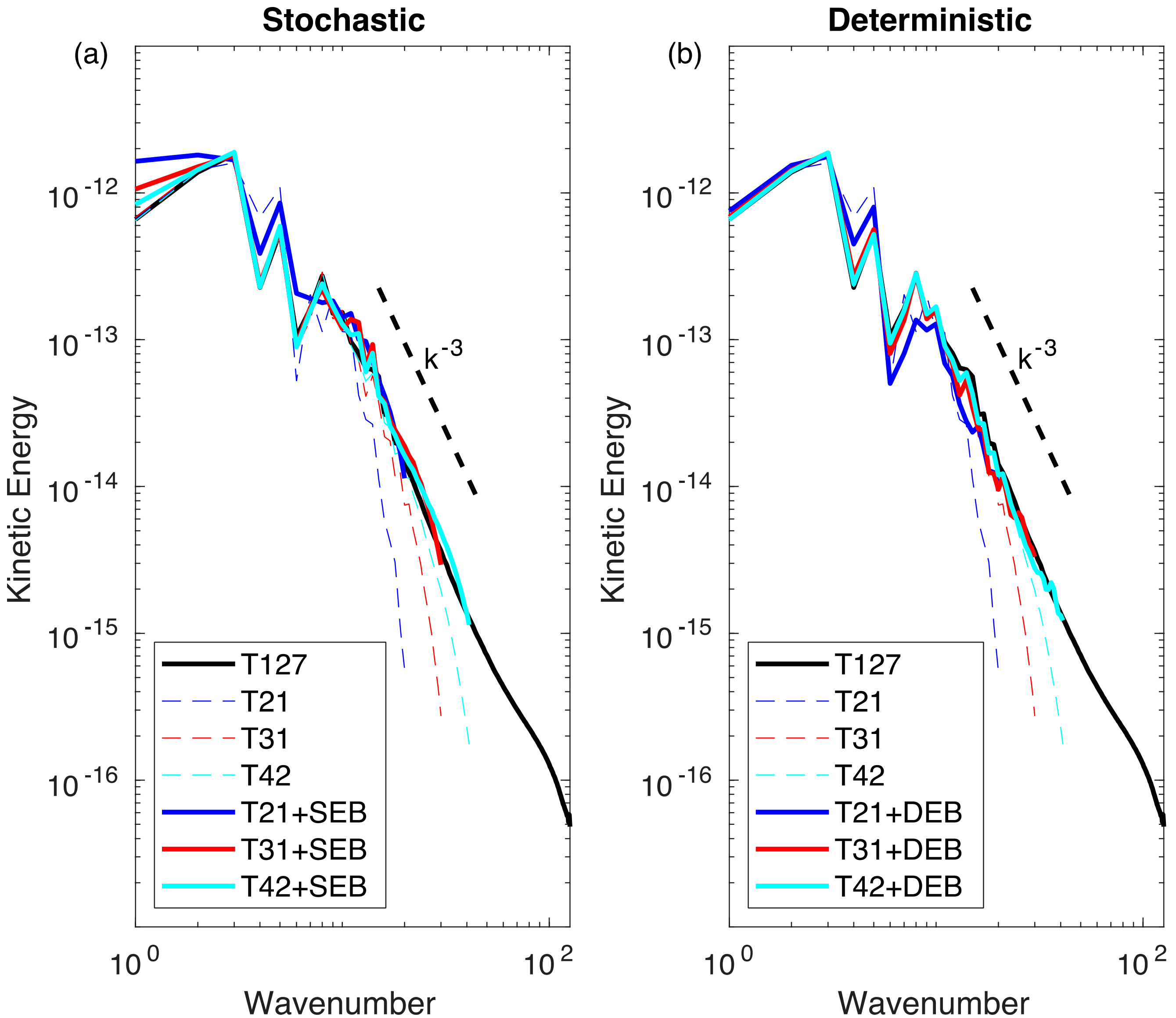
- Perturbation KE input per unit mass (ΔE) (due to sub-grid scale hyperdiffusion) computed at each time step & injected back at run time

- horizontally uniform ΔE at each model vertical level unlike Jansen and Held (2014) who used same ΔE for all vertical levels and Berner et al. (2009) who used a constant ΔE

- DEB parameterization: negative biharmonic hyperdiffusion backscattering term $\varepsilon H_{\zeta DEB}$ in vorticity equation. Net hyperdiffusion:

$$H_{\zeta net} = H_{\zeta} - \varepsilon H_{\zeta DEB}$$

where ε determines the fraction of kinetic energy (ΔE) dissipated by the hyperdiffusion and available for backscatter into the resolved flow



$p = -1.27$
$\alpha = 0.2$

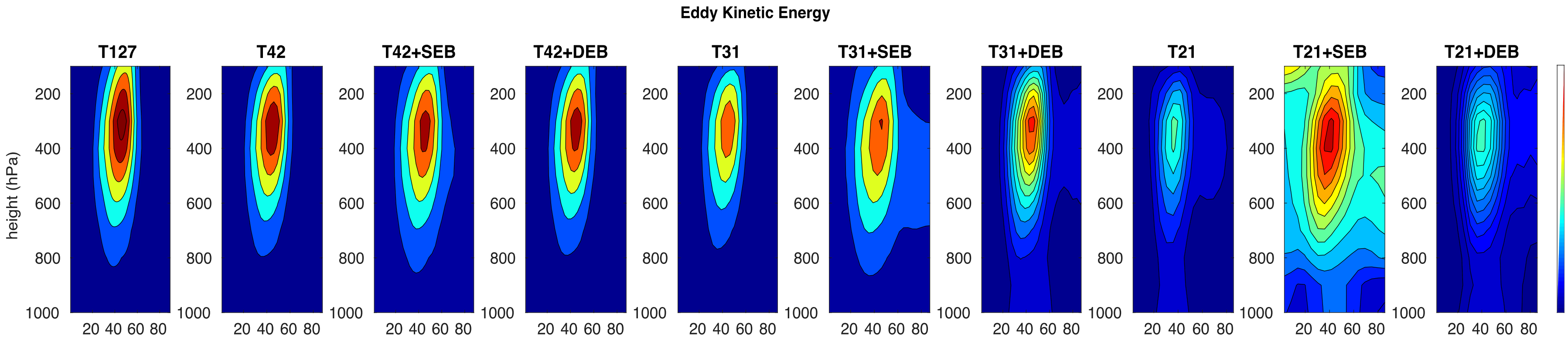
Resolution	ε_1	ε_2	ε
T42	0.051	10	1.0
T31	0.0026	7.1	0.75
T21	0.0001	5.43	0.60

- Interestingly, ε_1 shows an exponential decay, whereas, ε_2 and ε show a power-law scaling with truncation wavenumber N as follows:

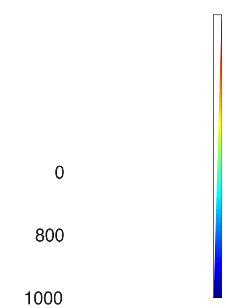
- $\varepsilon_1 = 28\, exp(-\beta_1 N)$, $\varepsilon_2 = 145.5 N^{-\beta_2}$, $\varepsilon = 9.23 N^{-\gamma}$

- Exponents $\beta_1 = 0.3, \beta_2 = 0.88, \gamma = 0.73$; $N = 21, 31, 42$

This suggests that our parameterization schemes are scale adaptive; thus, no re-tuning of the parameters is needed when changing the horizontal resolution

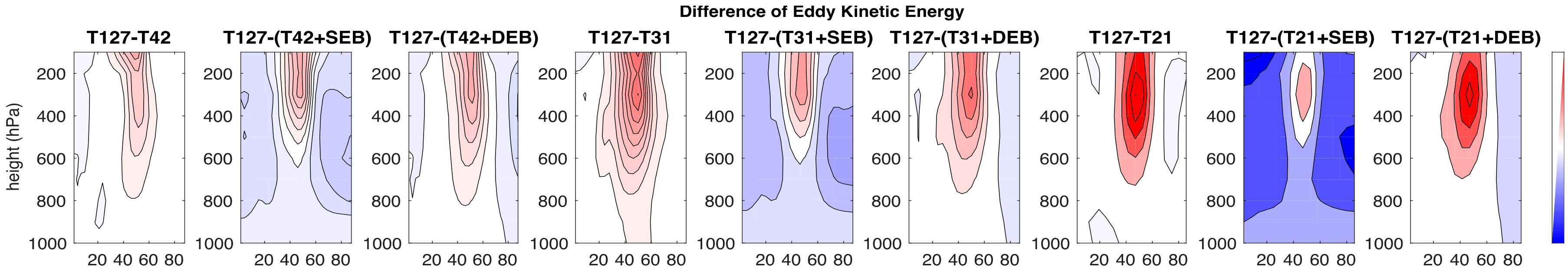


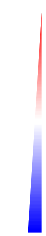
Eddy Kinetic Energy
T127
T42
T42+SEB
T42+DEB
T31
T31+SEB
T31+DEB
T21
T21+SEB
T21+DEB
height (hPa)
200
400
600
800
1000
20 40 60 80



0
800
1000

- EKE, EHF, EMF systematically become weaker as the resolution is reduced
- Eddy variables are especially weak in the T21 model simulation, suggesting that baroclinic instability processes are not well resolved
- Not only the magnitude of the jet is weaker, but also its position is not correct in the T21 simulation
- When applying the SEB scheme, we see a noticeable improvement in the EKE and eddy fluxes in all the low-resolution models with maximum improvement seen in the T21+SEB simulation
- Not only the magnitude of EKE and eddy fluxes have improved significantly, the extra-tropical jets are now located at correct position in the SEB simulations
- Improvements in eddy variability exhibited by low-resolution models when applying the DEB scheme, but not as much as is obtained with SEB scheme



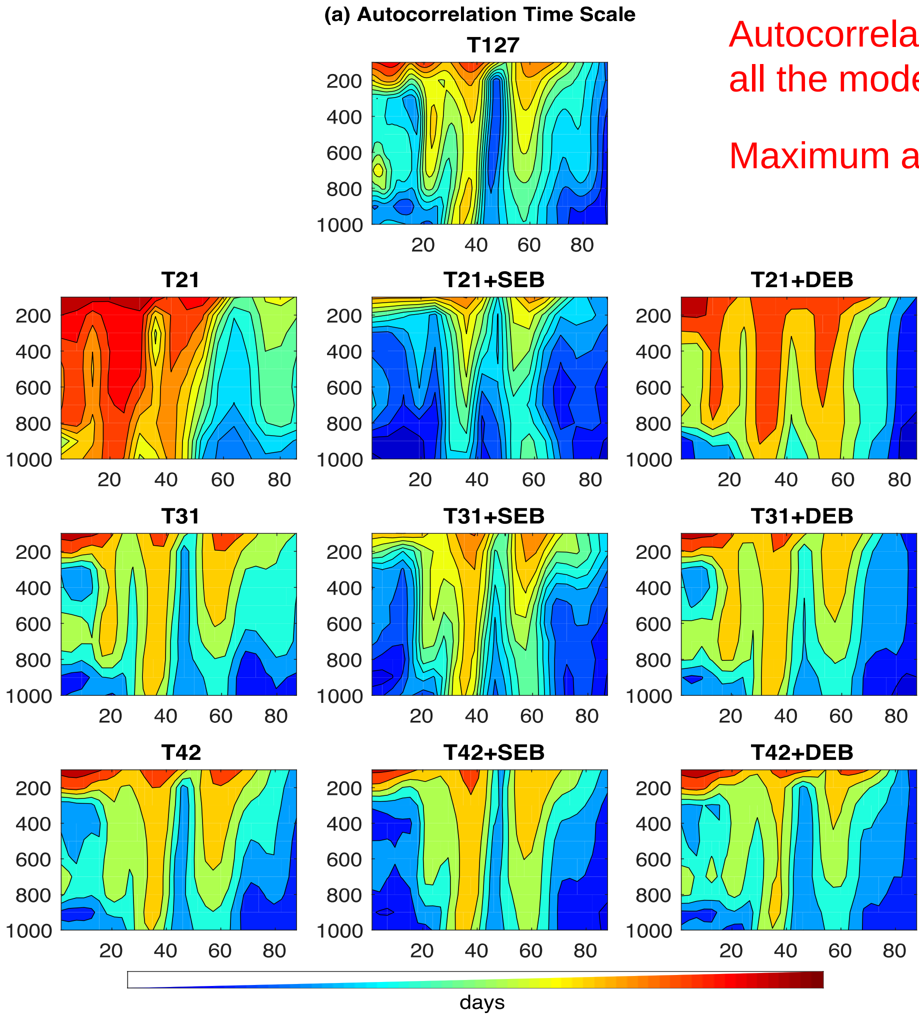


- ✓ *low-resolution simulations (T21 and T31) with the SEB scheme have the highest reduction in biases*
- ✓ *Application of DEB scheme in low-resolution models also reduces the biases, but not as effectively as with the SEB scheme (T21 and T31)*
- ✓ *With increasing resolution, the model runs with SEB and DEB schemes move closer to each other*
- ✓ *Application of the SEB scheme introduces extra energy at those grid points also where it is not desired. This drawback is less pronounced in the model runs with the DEB scheme.*
- ✓ *representation of eddy fluxes also greatly improves in low-resolution models when applying SEB and DEB schemes*

Root Mean Squre Error (rmse) of eddy kinetic energy (EKE), eddy heat flux (EHF) and eddy momentum flux (EMF) between the reference simulation (T127) and simulation experiments with and without energy backscatter at different horizontal resolutions

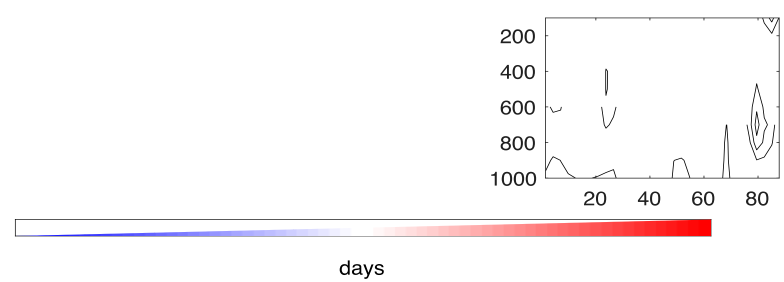
rmse between T127 and	EKE	EHF	EMF
T42	23.06	2.03	2.83
T42+SEB	19.82	1.61	1.82
T42+DEB	18.60	1.71	1.71
T31	44.19	3.66	4.43
T31+SEB	25.08	2.35	2.29
T31+DEB	37.27	3.06	3.13
T21	97.66	11.62	30.65
T21+SEB	44.19	3.05	6.30
T21+DEB	82.36	7.67	9.16

- rmse of perturbed experiments (with SEB and DEB) is less when compared to the unperturbed experiments
- rmse keeps on decreasing as the resolution increases from T21 to T42
- SEB scheme performs better as compared to DEB scheme at T21 and T31 resolutions
- as resolution increases, two schemes become more and more comparable to each other in terms of rmse (for example, at T42)



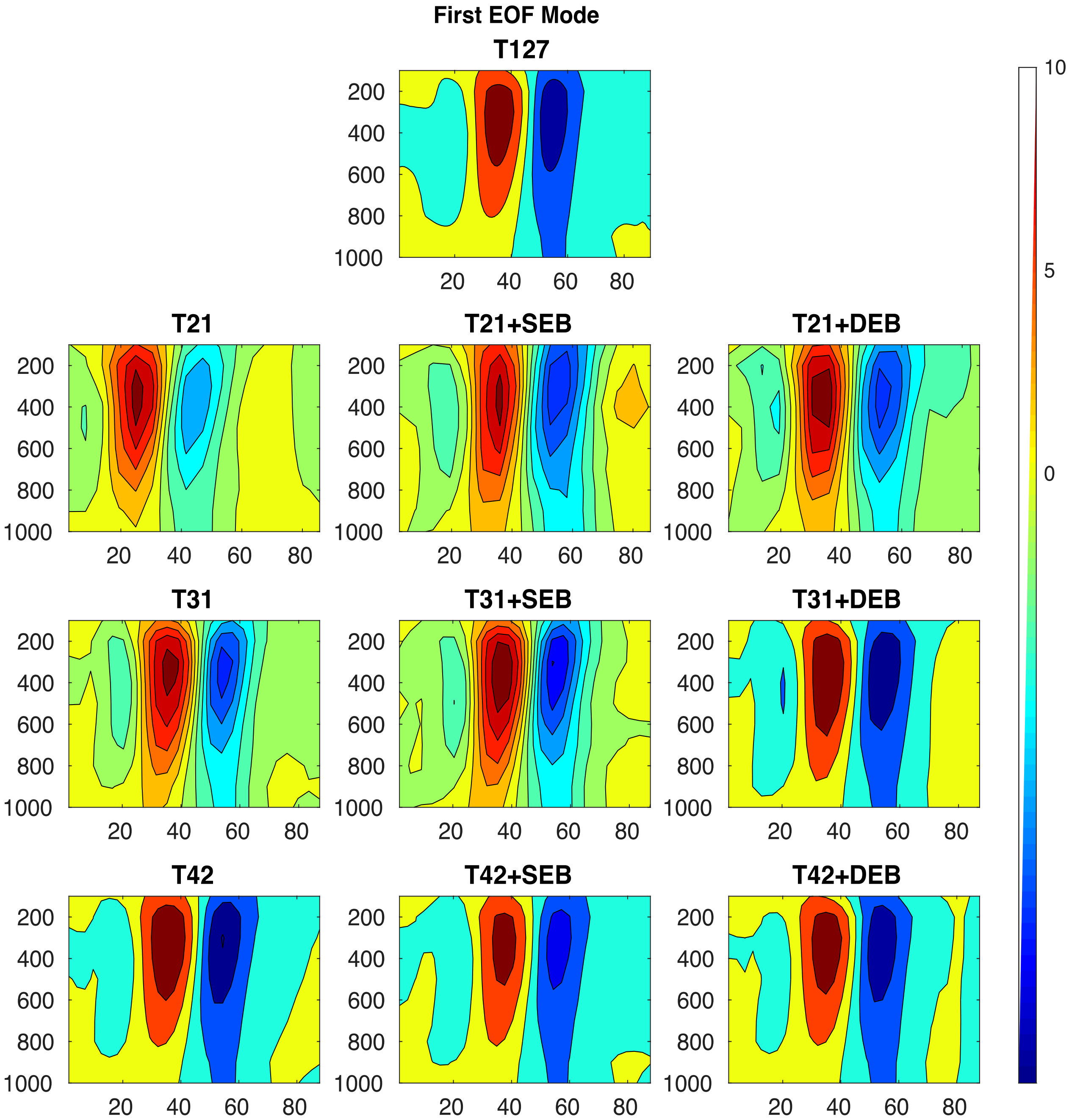
Autocorrelation time scale (integrated autocorrelation function) of all the model simulations at a lag of 15 days

Maximum autocorrelation time is obtained around 35N and 55N



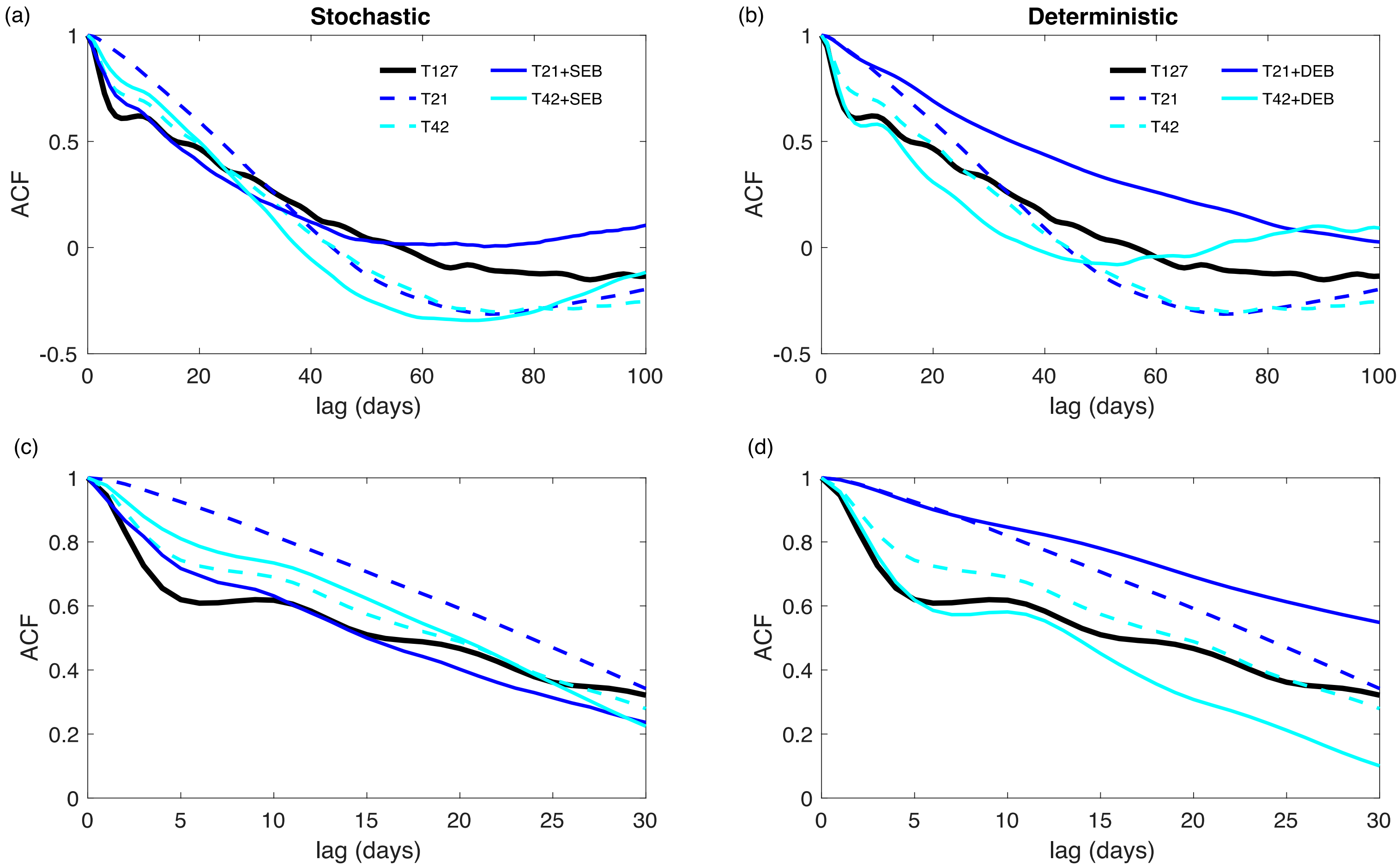
- T21: artificially high autocorrelation time scales (i.e. very long persistence) as compared to reference simulation
- T21+SEB and T21+DEB simulations: improvement (more realistic)
- Increase in horizontal resolution: autocorre. time scale of perturbed simulations moves closer to reference simulation
- Differences: parameterizations improve autocorrelation time scale (hence predictability) of coarse resolution models
- T21 and T31 resolutions: SEB better than DEB; T42 resolution: results are comparable

EOF1 of the zonally averaged zonal wind



effect of energy backscatter on dominant mode of variability

- EOF1 of ref. simulation (T127) shows an annular mode of variability in mid-latitude upper troposphere with a dipole structure centred at approx. 35N and 55N
- low-resolution models capture the dipole structure though with weaker amplitudes as compared to the reference simulation
- position of dipoles in T21: annular mode is shifted equatorwards
- SEB and DEB: position of the annular mode is now correct, magnitude also improves



➢ ACF values of T21 simulation are higher than the reference simulation up to approx. e-folding time scale; become much closer to reference simulation for smaller lags by the use of SEB parameterization

➢ Effect of SEB is less pronounced at T42 resolution

➢ T21+DEB simulation: ACF values represent an unrealistic persistence time-scale

➢ Minima of the T42 ACF curve shift towards lower lags when applying the backscatter schemes (from 70 days to 60 days with SEB and 50 days with DEB): 'return of skill' or 'rebound in predictability' occurs much earlier in the backscatter simulation as compared to without backscatter

Computational Efficiency

- **CPU time for runing PUMA at different horizontal resolutions with and without the energy backscatter scheme**

- **PUMA has been running in parallel on 4 cores**

Intel Xeon E7-8837 Processor @ 2.67GHz			
Resolution	CPU Time for running 1 year of simulation		
	(without backscatter)	(with SEB)	(with DEB)
T127	8278 sec	----	----
T42	69 sec	86 sec	72 sec
T31	27 sec	34 sec	29 sec
T21	8 sec	10 sec	9 sec

Considering robust improvements obtained in coarse resolution simulations using the SEB/DEB schemes, their use in place of higher resolution models can help save a lot of computational time without compromising much of the quality of simulation

Conclusions:

- Low-resolution atmosphere-ocean models suffer from the problem of excessive subgrid scale dissipation

- Construction of robust and realistic low-resolution models is of practical importance

- Energetically consistent subgrid scale KE backscatter parameterization schemes are able to alleviate this problem to a significant extent

- We apply scale adaptive SEB and DEB parameterization schemes in the low horizontal resolution spectral model PUMA

- SEB scheme performs better as compared to the DEB scheme at the low horizontal resolutions; with increasing resolution, the performance of schemes become comparable

- Our schemes are energy consistent, which will be of importance when performing long-term climate simulations.

- Application of schemes in low-resolution models greatly improves the eddy variability: SEB scheme generates better eddy variability as compared to DEB scheme.

- However, this is achieved at the cost of producing extra energy in other areas where it is not desirable.

Conclusions:

- Autocorrelation time scale of low-resolution models becomes more consistent with the reference simulation (T127) when they are run with SEB or DEB schemes.

- Furthermore, dominant mode of variability is realistically reproduced (magnitude as well as location) in model simulations using the SEB and DEB schemes.

- Our future work will focus on combining the stochastic and deterministic energy backscatter schemes.

- We will also see the advantage of these schemes in more realistic models and set-ups for practical applications

S. Dwivedi, C. L. E. Franzke and F. Lunkeit, *Quarterly Journal of the Royal Meteorological Society*, 145, 3376-3386, doi: 10.1002/qj.3625 (2019).