Energy budget-based backscatter in a shallow water model of a double gyre basin

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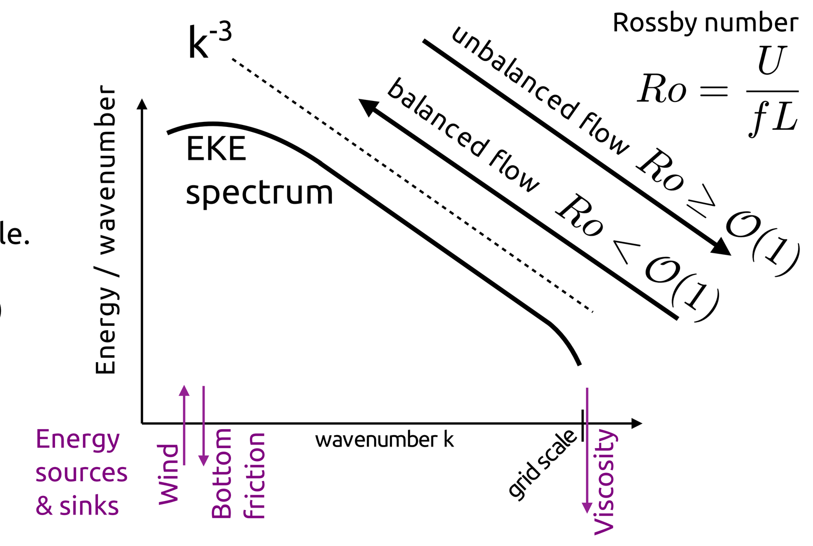
Highlights

- Successful implementation of energy budget-based backscatter in a shallow water model with strong boundary currents.
- Diffusive turbulence closure based on Rossby number-scaling: Balanced flow experiences upscale transfer of energy, Unbalanced flow is dissipated via forward energy cascade.
- Mean and variability of a low resolution model is considerably improved: EKE is virtually identical to high resolution control run. Corrected energy cycle also corrects mean circulation.
- Perspectives for realistic routes to dissipation in circulation models.

Motivation: Energy cascades in geophysical flows

- All circulation models are extremely viscous to satisfy numerical stability.
- Viscosity removes energy and enstrophy from the grid scale.
- Low eddy kinetic energy (EKE) on all spatial scales results due to energy cascades.



- Energy cascades in the real ocean depend on local geostrophic balance (Rossby number), a process not well represented in circulation models close to the grid scale.
- We believe: Successful parameterizations should aim to close the energy cycle by reducing effective viscosity to avoid spurious energy dissipation at the grid scale.

Methods: Shallow water model with energy budget-based backscatter

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} + f\hat{\mathbf{z}}\times\mathbf{u} = -g\nabla\eta + \frac{\mathbf{F}}{\rho h} - \frac{c_D}{h}|\mathbf{u}|\mathbf{u} - \nu\nabla^4\mathbf{u} + \nabla\cdot\nu_{back}\nabla\mathbf{u}$$

Advection, Coriolis, Pressure, Wind forcing, Bottom friction, Viscosity, Backscatter

unbalanced flow → Dissipation

balanced flow

negative viscosity $\nu_{back} \sim -e$

Sub-grid EKE budget
$$\frac{\partial e}{\partial t} = -\dot{E}_{diss} + \dot{E}_{back} + \nu_e\nabla^2 e$$

Backscatter parameterization

- Additional prognostic equation for the sub-grid EKE, parameterizing the diffusive effect of eddies.
- Dissipated energy of balanced flow enters the sub-grid EKE budget. Unbalanced flow is not recycled: forward energy-cascade.
- Backscatter with negative viscosity whose strength depends on sub-grid EKE.
- Remove energy from the resolved flow at small scales (biharmonic viscosity), re-inject at larger scales (Laplacian).
- Satisfy numerical stability via artifical upscale transfer of energy that is physically motivated.
- Tune the backscatter strength with R_{diss}, a cut-off Rossby number to distinguish between balanced and unbalanced flow.
- Parameterization requires 30% more computing time. Negligible compared to x50 for quadrupling the resolution.

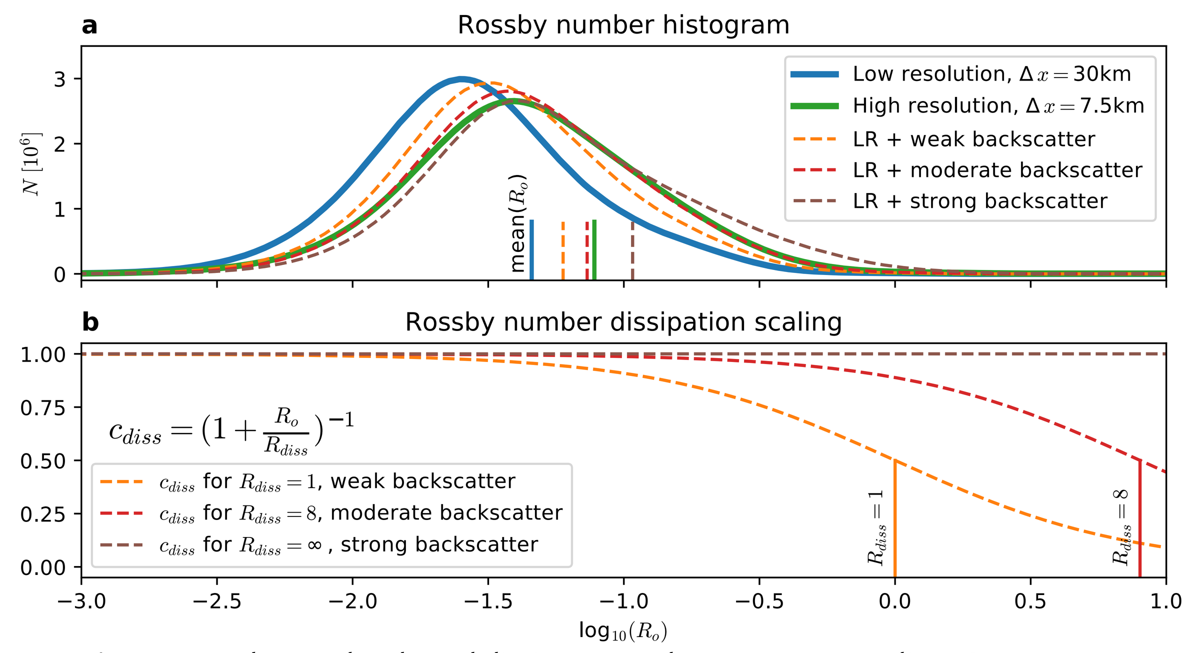


Figure: *Rossby number-based dissipaton scaling. Energy recycling via backscatter for balanced flow, dissipation for unbalanced flow.*

Results

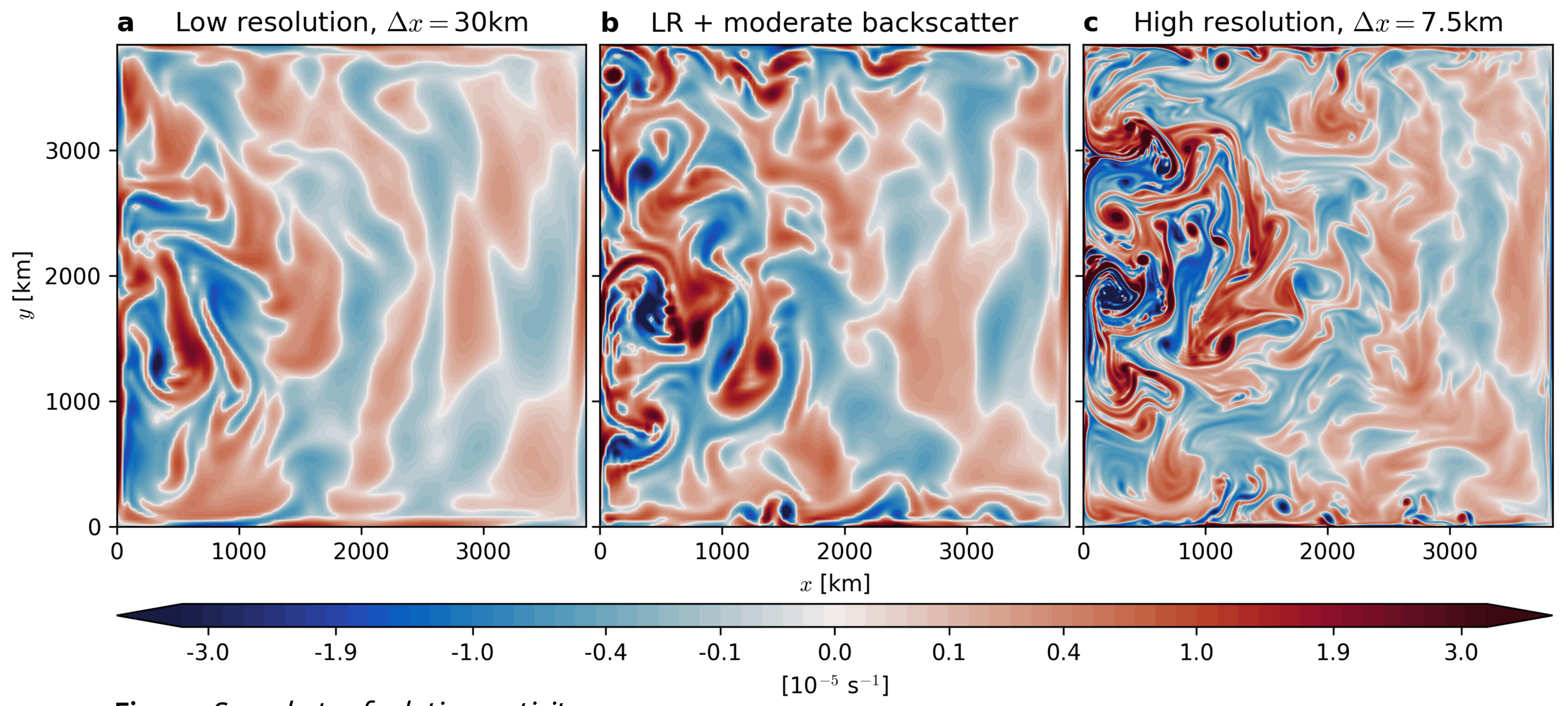


Figure: *Snapshots of relative vorticity.*

- Only large eddies are simulated at low resolution (1/4°). Vigorous turbulence at high resolution (1/16°)
- Backscatter forcing initiates eddies at boundaries that propagate inward.
- Rossby number-scaling of backscatter strength guarantees forward energy-cascade in unbalanced boundary currents.

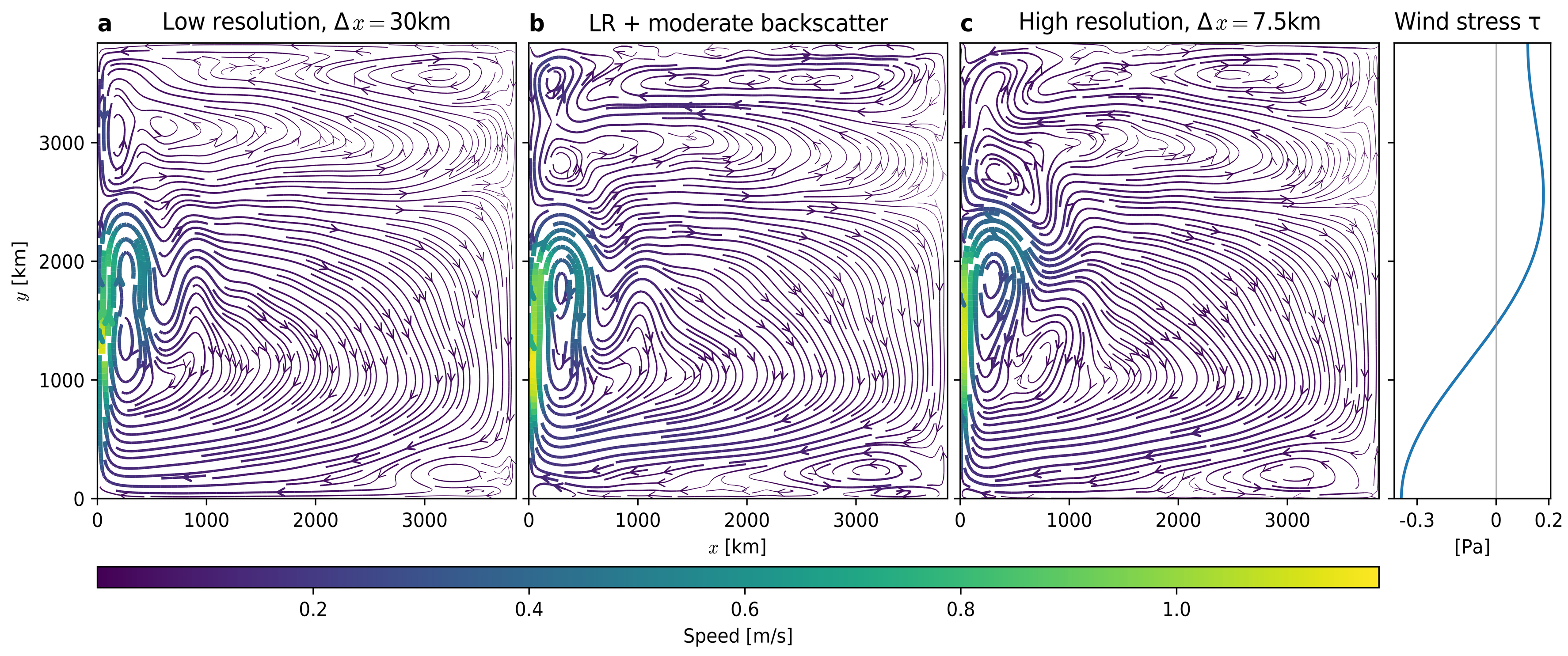


Figure: *Climatological mean circulation. Colour and thickness of stream lines are associated with speed.*

- Limited eddy-mean flow interaction at low resolution. Additional eddy-driven circulation cells at high resolution.
- Backscatter corrects the mean circulation in many but not all regions.
- Only the diffusive effect of eddies is parameterized, not the advection of sub-grid EKE with the resolved flow.

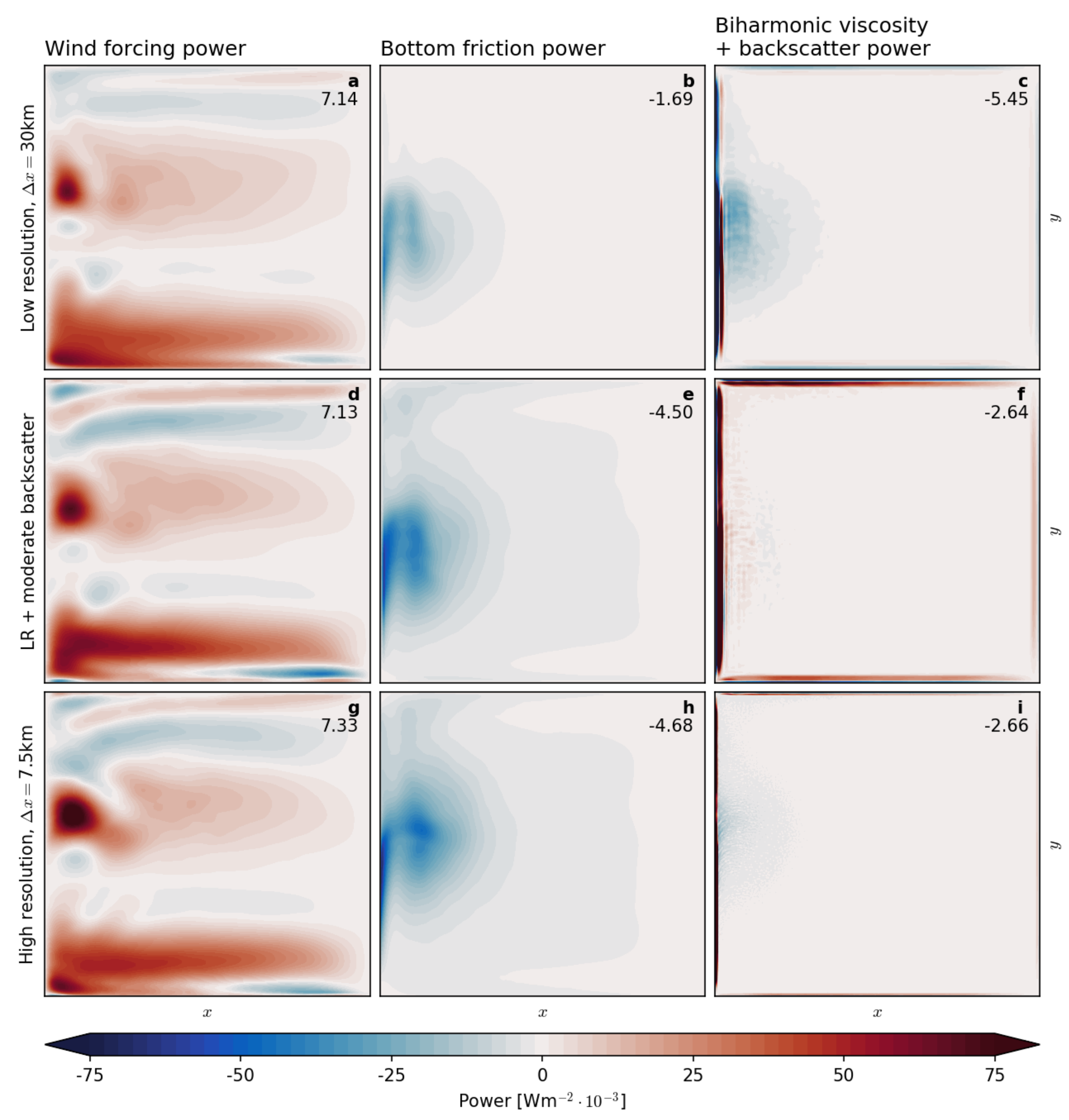


Figure: *Climatological mean of energy sources and sinks. Number in the top-right denotes basin-wide average. Postive: Energy source, Negative: Energy sink.*

- At low resolution 76% of dissipation is via viscosity - spuriously.
- Backscatter reduces the effective viscosity, hence bottom friction accounts correctly for 63% of dissipation
- Negative viscosity forcing at the boundaries creates eddies that have a positive impact on mean flow and variability

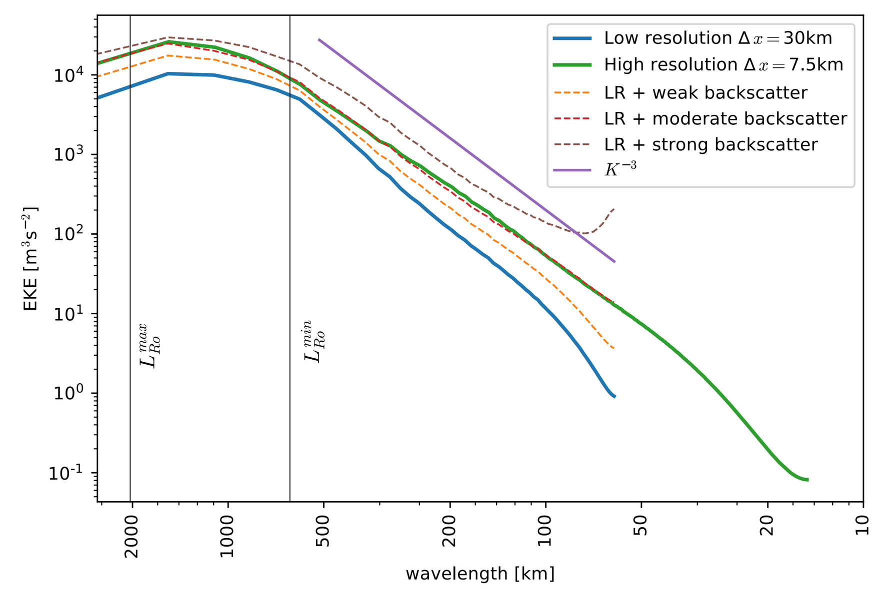


Figure: *Eddy kinetic energy spectrum.*

- Backscatter increases EKE on all spatial scales.
- Easy to tune: Increase backscatter strength to match EKE levels.
- Original Jansen et al (2015) formulation leads to strong energy increase at the grid scale: numerical noise.
- Rossby number-scaling backscatter allows for highly flow- and scale-aware dissipation of unbalanced flow.

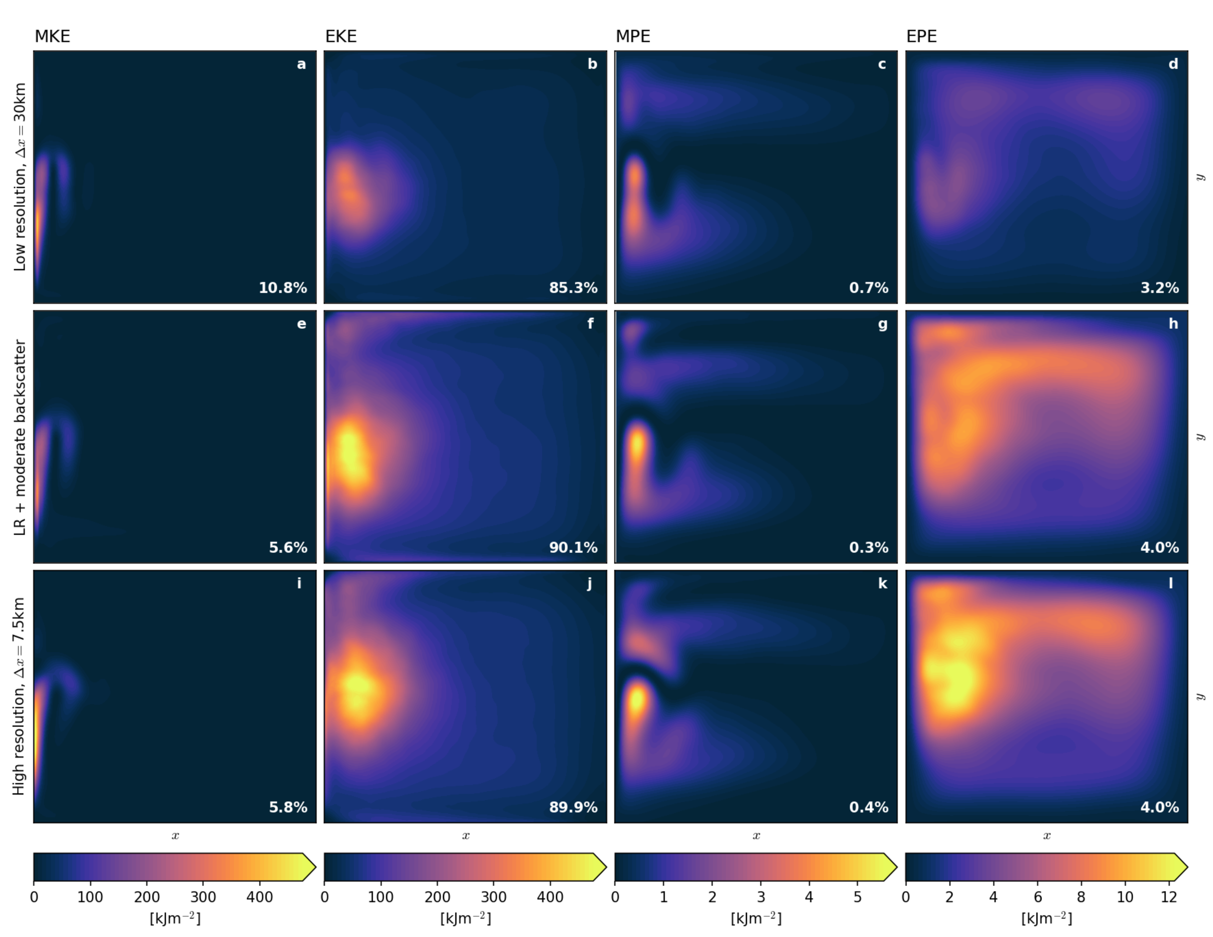


Figure: *Climatological mean of mean kinetic energy (MKE), eddy kinetic energy (EKE), mean potential energy (MPE) and eddy potential energy (EPE). Percent values denote relative contribution to the total energy.*

- EKE and EPE are missing at low resolution due to overly strong viscosity.
- Backscatter re-injects EKE automatically where missing and corrects the relative contributions to total energy.

Discussion

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