Dynamics II

CAM-SE, kinetic energy spectra and 'water loading'

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Summer school: Introduction to Climate Modeling (University of Stockholm)

1. 1. CAM-SE
   - A non-technical introduction to spectral elements
2. 2. Total kinetic energy (TKE) spectra
   - Observed spectra
   - Idealized turbulence theory
   - Example idealized turbulence simulation
   - Model energy spectra and model filters
3. An example of a challenge as we move to higher resolutions: 'Water loading' in CAM-SE
4. 'Commercial'

Introduction to the spectral element method - 1D

Consider conservation law for variable $U(x,t)$ in one dimension

$$\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} = 0, \quad \text{in } \Omega \times (0, T] \tag{1}$$

where T is total integration time, F is flux function (for linear advection, e.g., $F(U) = c_0 U$).

Partitioning of global domain Ω into N_{elm} non-overlapping elements: $\Omega = \bigcup_{j=1}^{N_{elm}} \Omega_j$

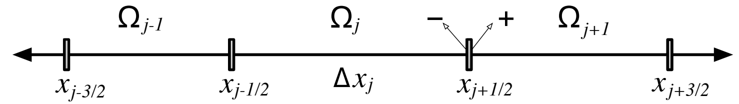


Figure from (Nair et al., 2011)

Weak Galerkin formulation

Multiply (1) with test function $\varphi(x)$ and integrate over element Ω_j

$$\int_{\Omega_j} \left[\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} \right] \varphi(x)\, dx = 0. \tag{2}$$

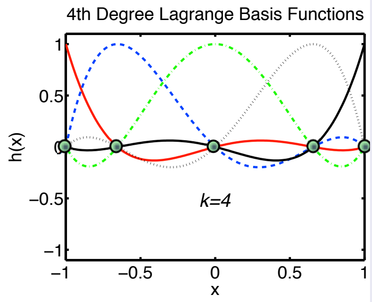
1D spectral element method - spatial discretization

Within each element we represent the solution with polynomials of degree ⩽N, that is, we project the solution onto a polynomial basis within each element:

$$U(x,t) \approx \sum_{k=1}^{N} U_k(t) h_k(x), \tag{3}$$

where $U_k(t)$ is the 'amplitude' or weight for the kth polynomial at time t (similarly for φ).

In default CAM-SE $N = 3$ (degree 3 polynomials; 4^{th}-order accurate)



Note that the degree is $N = 4$ on the Figure (from Nair et al. (2011)) and not N=3 as in CAM-SE

1D spectral element method - spatial discretization

Within each element we represent the solution with polynomials of degree $\leqslant$N, that is, we project the solution onto a polynomial basis within each element:

$$U(x,t) \approx \sum_{k=1}^{N} U_k(t) h_k(x), \tag{3}$$

where $U_k(t)$ is the 'amplitude' or weight for the kth polynomial at time t (similarly for φ).

When substituting (3) into

$$\int_{\Omega_j} \left[\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} \right] \varphi(x)\, dx = 0. \tag{4}$$

Note that we can compute derivatives analytically within each element.

Evaluate integrals using Gauss-Lobatto-Legendre (GLL) quadrature (exact for polynomials of degree $2N-1$):[a]

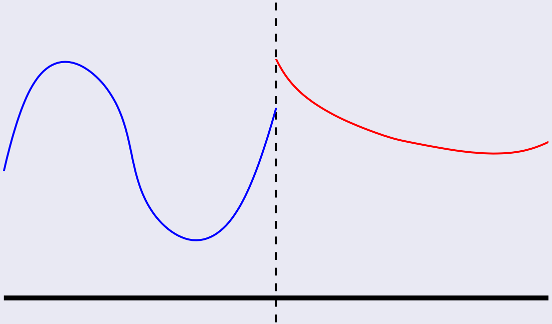
$$\int f\, dx \approx \sum_{n=1}^{N} \omega_n^{(gll)} f(x_n^{(gll)}), \tag{5}$$

where $x^{(gll)}$ are the quadrature points and $\omega^{(gll)}$ the associated weights.

[a] nodal basis function + GLL quadrature $\Rightarrow$ efficient numerical integration

1D spectral element method - coupling of elements

Up until now I have only talked about spectral elements on one element; obviously we need to couple the elements:



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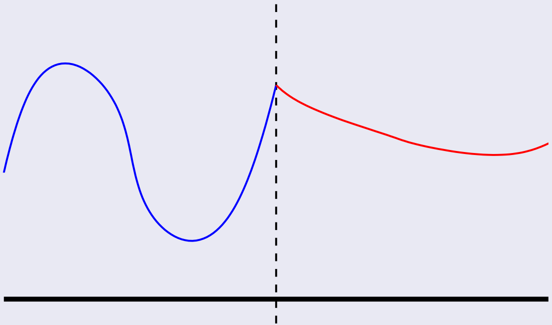


- Continuity is enforced at element boundaries, in other words, we project the solution onto the space of globally continuous piecewise polynomials.
- This is the only mechanism at which neighboring elements ‘feel’ each other
  $\rightarrow$ may be interpreted as the flux between the elements.

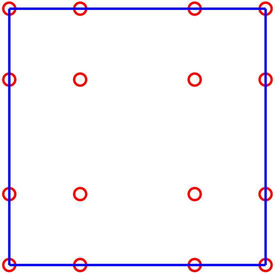
This projection is performed at every Runga-Kutta time-stepping stage!

Extension to 2D: Tensor product approach, that is, we project solution onto polynomial tensor product basis:

$$U(x,y,t) \approx \sum_{\ell=1}^{N} \sum_{k=1}^{N} U_{k\ell}(t) h_k(x)\, h_\ell(y), \tag{6}$$

where $h_k(x)$ and $h_\ell(y)$ are 1D polynomials in x and y, respectively.

Again continuity is enforced on the element boundary $\Rightarrow$ in parallel implementation only the points on the boundary of the elements need to be exchanged between processors, i.e. very little communication between processors!



Extension to the sphere

- Tile the sphere with quadrilateral elements
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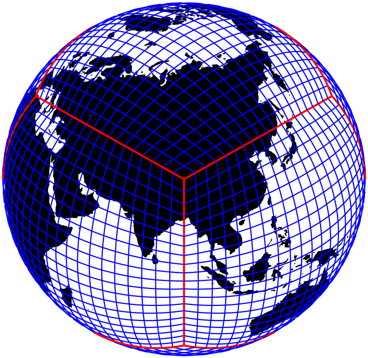

Extension to the sphere

- Tile the sphere with quadrilateral elements
- Physical domain, elements and GLL points
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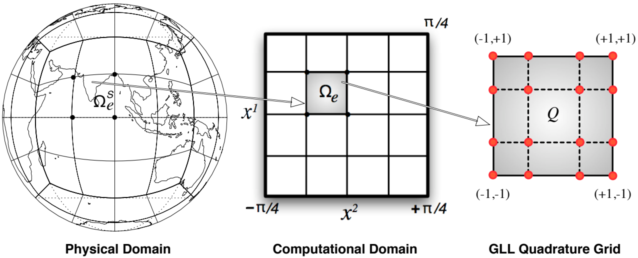


Fig. 9.22 A schematic diagram showing the mapping between each spherical tile (element) Ω_e^S of the physical domain (cubed-sphere) $\mathscr{S}$ onto a planar element Ω_e on the computational domain $\mathscr{C}$ (cube). For a DG discretization each element on the cube is further mapped onto a unique reference element Q, which is defined by the Gauss-Lobatto-Legendre (GLL) quadrature points. The horizontal discretization of the HOMME dynamical cores relies on this grid system.

Figure from Nair et al. (2011)

- Tile the sphere with quadrilateral elements
- Physical domain, elements and GLL points
- Element framework also ‘easily’ allows for mesh-refinement
-

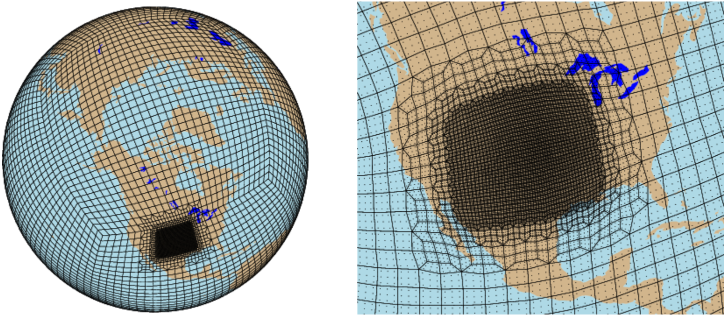


Figure courtesy of Mark Taylor (Sandia)

- Tile the sphere with quadrilateral elements
- Physical domain, elements and GLL points
- Element framework also ‘easily’ allows for mesh-refinement
- Since a quasi-isotropic grid is used there is no need for polar filtering as in CAM-FV + only nearest neighbor communication $\Rightarrow$ highly scalable dynamical core

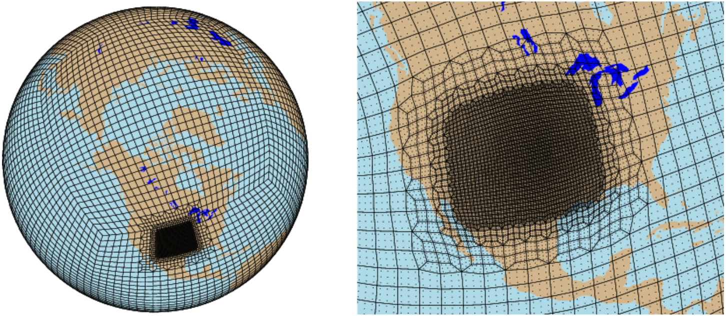


Figure courtesy of Mark Taylor (Sandia)

Highly scalable dynamical core

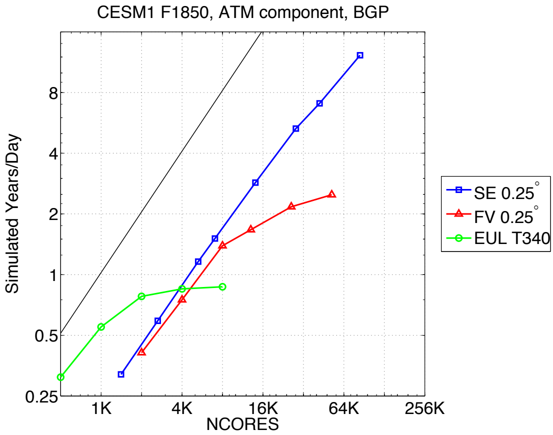


Figure from Dennis et al. (2012)

We can now perform climate simulations at unprecedented resolutions and we are starting to resolve some meso-scale motion (at which scales the dynamics fundamentally changes character!)

Total kinetic energy (TKE) spectra

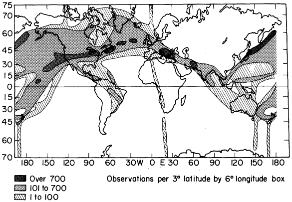


FIG. 1. Geographical distribution of GASP observations from flight segments at least 2400 km long; see text.

Figure from Nastrom and Gage (1985)

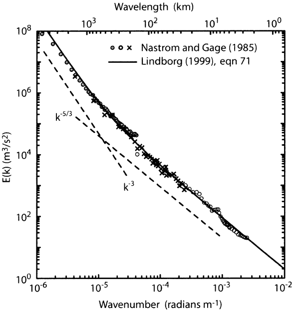


Figure from Skamarock (2004)

Upper Figure

Observational campaign (1975-76) collected wind and temperature data from 6000+ commercial aircraft flights (most measurements at 9-14km);
Figure shows the flight tracks.

Lower Figure

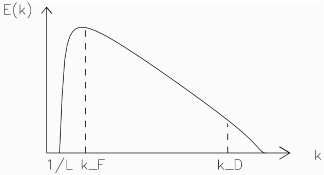
Total kinetic energy (TKE) spectra plotted on log-log scale (x-axis is wavenumber $k = \frac{2\pi}{L}$ and y-axis is TKE)

Despite season, latitude, location in the troposphere and stratosphere data show remarkably 'well-defined' slopes:

- k^{-3} dependence on k at large scales from approximately 1000-3000km
- small transition zone where slope decreases
- $k^{-5/3}$ dependence on k in the range from a few kilometers to 300-400 km
  ($\approx$ meso-scale and smaller).

If I could answer that question and related questions fully ...

In other words, these questions belong to the category of major unanswered questions in atmospheric dynamics!



- Consider three-dimensional, statistically steady, homogeneous and isotropic turbulence in an incompressible constant density fluid
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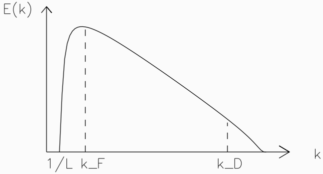
$k^{-5/3}$ spectrum - idealized turbulence theory (following overview by Thuburn (2011))



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- Assume that the fluid is stirred and energy is input on some large scale k_F, and that energy is dissipated by viscosity at some scale k_D.
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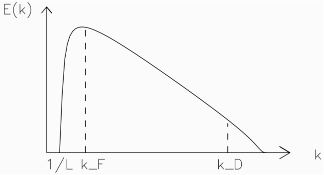

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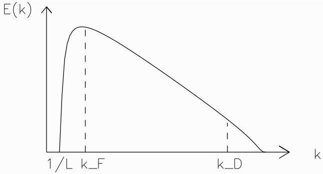

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- Assume, also, that there is some range of scales in between k_F and k_D that is statistically independent of the details of the forcing and dissipation a.k.a. *inertial range*
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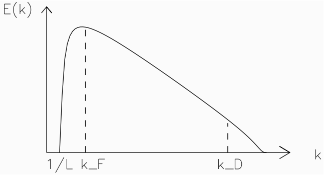

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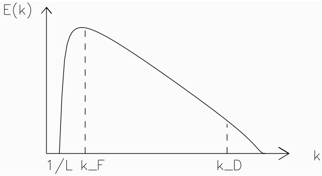
- Assume, also, that there is some range of scales in between k_F and k_D that is statistically independent of the details of the forcing and dissipation a.k.a. *inertial range*
- The rate of energy production ϵ must equal the rate of energy dissipated!
- Moreover, the rate of transfer of energy from wavenumbers smaller than k to wavenumbers greater than k, for any k in the inertial range, must also equal ϵ.

$k^{-5/3}$ spectrum - idealized turbulence theory (following overview by Thuburn (2011))



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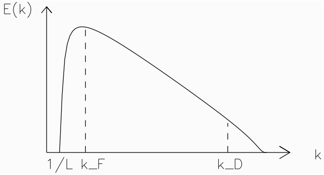

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- The dimension of spectral energy density $\hat{E}(k)$ is

$$\left[\hat{E}(k)\right] = L^3 T^{-2}, \tag{7}$$

  where L stands for length and T stands for time.
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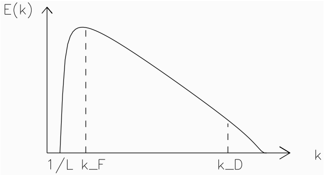

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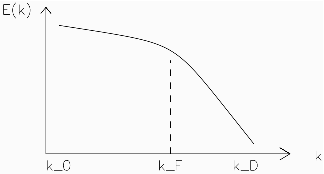
  where L stands for length and T stands for time.
- In the inertial range at wavenumber k, the only quantities are k itself and ϵ

$$[k] = L^{-1} \qquad\qquad [\epsilon] = L^2\, T^{-3} \tag{8}$$

  so the only way to construct a quantity with the same dimensions as $\hat{E}(k)$ is

$$\hat{E}(k) \propto \epsilon^{2/3} k^{-5/3}. \tag{9}$$

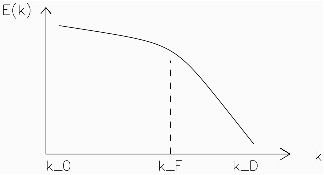
k^{-3} spectrum - idealized turbulence theory (following overview by Thuburn (2011))



- Now consider **two**-dimensional, statistically steady, homogeneous and isotropic turbulence in an incompressible constant density fluid
- In 2D we have another conserved variable: enstrophy ($\propto \zeta^2$ where ζ vorticity), and therefore a cascade of enstrophy at a rate η.
- Typically energy now cascades upscale while enstrophy cascades downscale
- The argument (on the previous slide for the $k^{-5/3}$'s spectrum) did not depend on the number of dimensions nor on the direction of the energy cascade!
- We therefore expect to see a $k^{-5/3}$ spectrum on scales larger than the forcing scale k_F, provided there is a mechanism to provide a sink of energy at very large scales k_0.
- Scaling argument: In the inertial range on the small-scale side of the forcing, the energy density has dimensions (as before)

$$\left[\hat{E}(k)\right] = L^3 T^{-2}, \tag{10}$$

k^{-3} spectrum - idealized turbulence theory (following overview by Thuburn (2011))



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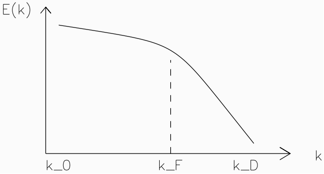
$$[k] = L^{-1} \qquad [\eta] = T^{-3}. \tag{10}$$

k^{-3} spectrum - idealized turbulence theory (following overview by Thuburn (2011))



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- Scaling argument: In the inertial range on the small-scale side of the forcing, the energy density has dimensions (as before) so the only way to construct a quantity with the same dimension as $\hat{E}(k)$ is

$$E(k) \propto \eta^{2/3} k^{-3}. \tag{10}$$

One form of the equations describing 2D incompressible flow is the barotropic vorticity equation

$$\frac{d\zeta}{dt} = 0, \tag{11}$$

where ζ vorticity.

- To dissipate enstrophy that cascade towards the grid scale, a suitable tuned diffusion

$$\kappa \nabla^4 \zeta, \tag{12}$$

  is added to the right-hand side of (11).

Numerically solve

$$\frac{d\zeta}{dt} = \kappa \nabla^4 \zeta, \tag{13}$$

on a double-perodic square Cartesian domain with an initial condition of vorticity alternating sign (see Figure).

Initial condition: ζ, $\hat{E}(k)$ and enstrophy spectrum

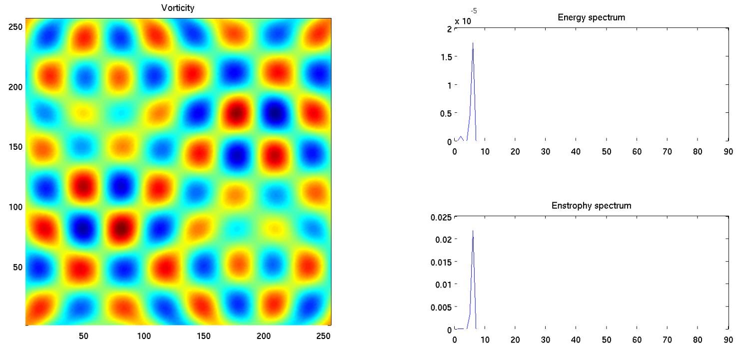


Figure from (Thuburn, 2011)

Solution after a few vortex turn-over times

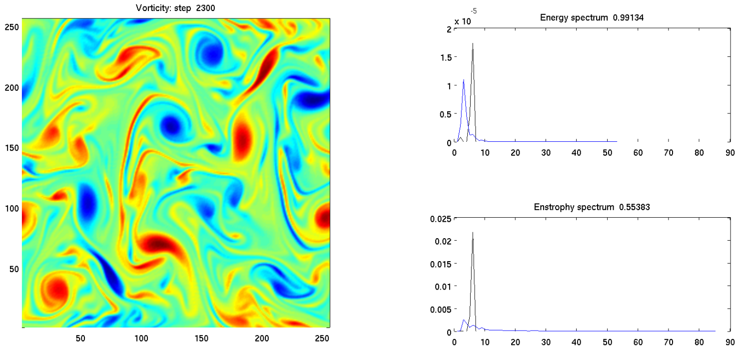


Figure from (Thuburn, 2011)

An idealized example simulation: Barotropic vorticity equation

Solution after a few vortex turn-over times

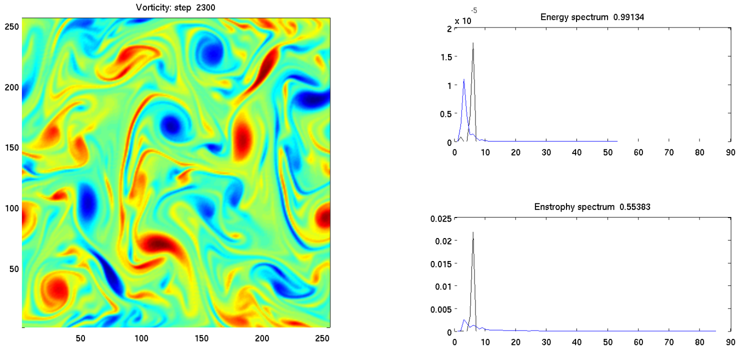
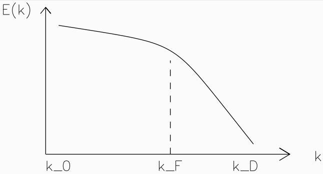


Figure from (Thuburn, 2011)

- Like-signed vortices merge: physical manifestations of upscale energy transfer
- At the same time, fluid has been stripped from edges of most vortices and drawn into thin filaments that fill the space between vortices (physical manifestation of downscale of enstrophy)

What happens if I remove the enstrophy sink term $\kappa\nabla^4\zeta$?



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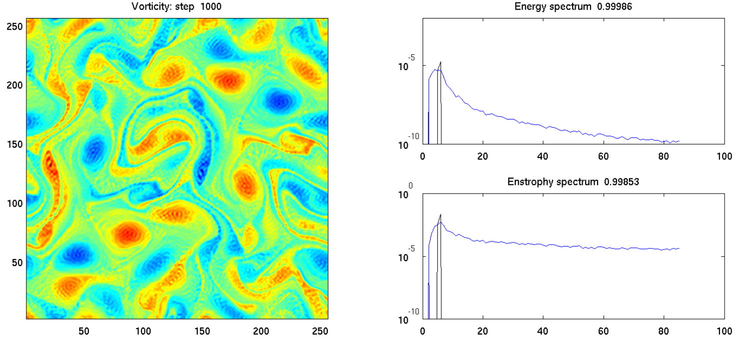


Figure from (Thuburn, 2011)

- Accumulation of enstrophy near the grid scale!!!!

Application to the real atmosphere (following overview by Thuburn (2011))

Scaling arguments and results from the previous slides where based on making very idealized assumptions! Can this be applied to the real atmosphere? There are a number of caveats!

- We neglect intermittency and a spectrum as steep as k^{-3} is barely consistent with a inertial range (large scales begin to dominate the strain rate and interaction will cease to be local in spectral space)
- The atmosphere is not a 2D incompressible fluid although much of the atmosphere is stably stratified and moves approximately layerwise two-dimensionally
- Analysis of global datasets implies that there are significant sources and sinks of energy across a wide range of scales, which is inconsistent with the idea of an inertial range.
- Furthermore, the observed kinetic energy spectrum makes a transition to something close to $k^{-5/3}$ on scales of a few 100 km; this transition is quite different from the transition prediction by two-dimensional turbulence theory and there is currently no widely accepted explanation for it (Lindborg, 2006; Lilly et al., 1998).

However, careful analysis of global datasets implies that the general conclusion of energy cascading predominantly upscale and (potential) enstrophy cascading predominantly downscale does indeed hold!

In any case ...

we may ask the question: Can our models simulate the $k^{-5/3}$'s transition?

Global models can now simulate $k^{-5/3}$'s transition

Some of the first global models to simulate $k^{-5/3}$'s transition: Takahashi et al. (2006); Hamilton et al. (2008)

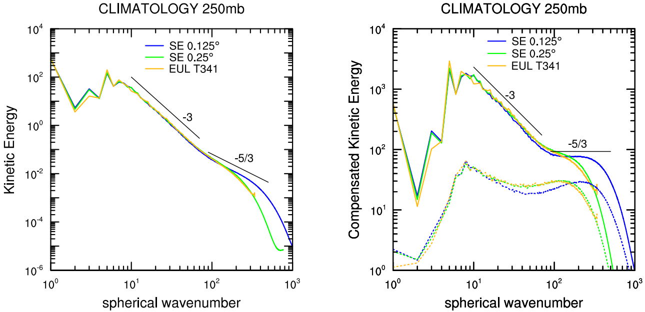
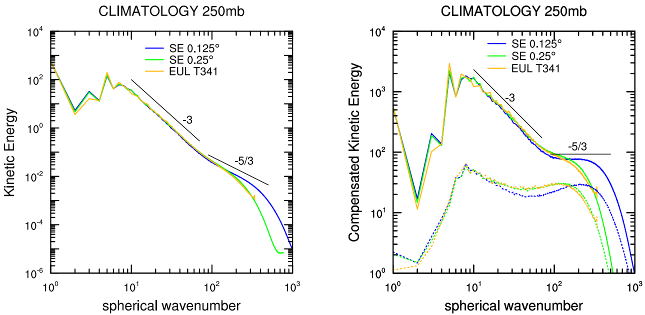


Figure from Evans et al. (2012)

Setup: CAM4 physics, aqua-planet simulation. Solid lines: (left) $E(k)$ and (right) $k^{-5/3}E(k)$. Dotted lines is $E(k)$ including only the divergent component of the winds.

- $1/8^\circ$ resolution: clear transition to $k^{-5/3}$
- Aside: At some wavenumber ($k < 10^2$) the divergent modes have more energy than vortical modes (meso-scale) - has that something to do with the $k^{-5/3}$'s transition?



Note that the tail of the spectrum tails off ... what can we learn from that?

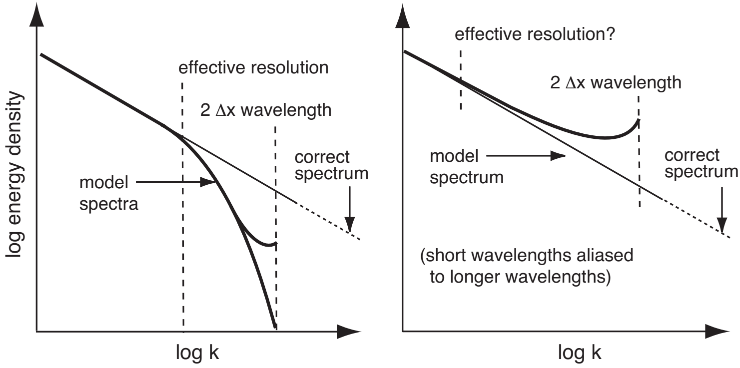


Figure from Skamarock (2011)

Right Figure

As shown for the barotropic voricity equation simulation, if there is not a sink at the grid scale energy will accumulate and contaminate the solution ... here is an example from CAM-FV

Using TKE to 'tune' model dissipation operators

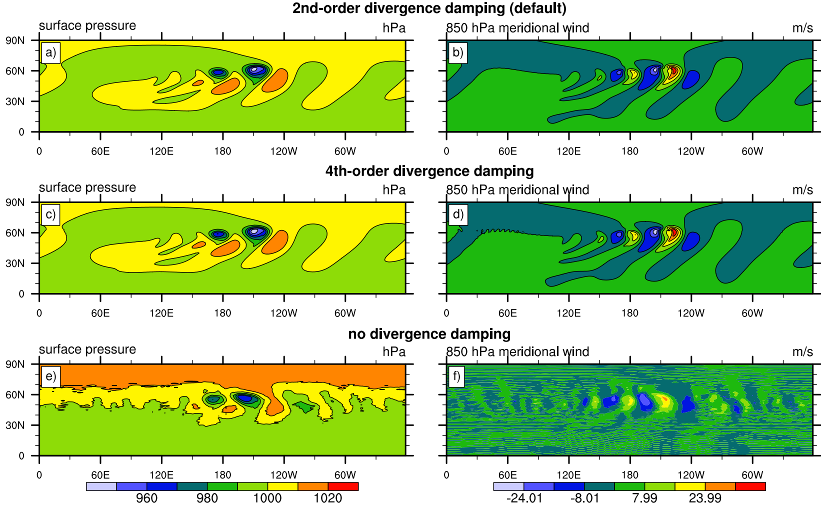


Figure from Jablonowski and Williamson (2011)

Idealized baroclinic wave simulation (Jablonowski and Williamson, 2006) and associated TKE

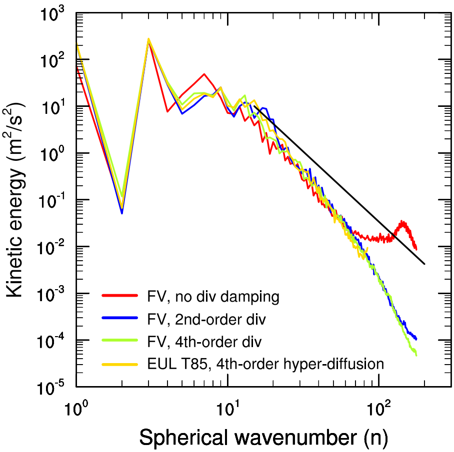


Figure from Jablonowski and Williamson (2011)

Idealized baroclinic wave simulation (Jablonowski and Williamson, 2006) and associated TKE

Using TKE to 'tune' model dissipation operators

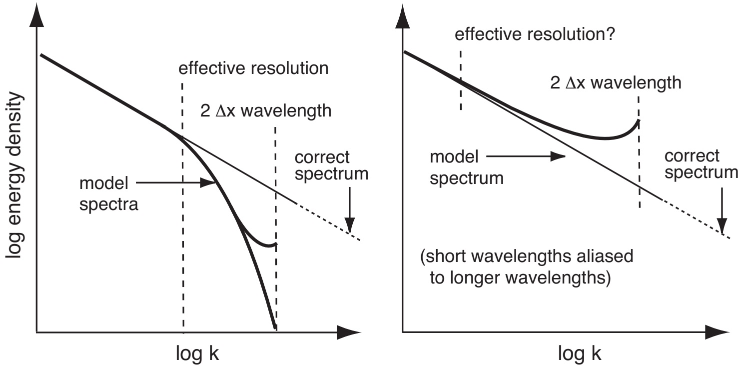


Figure from Skamarock (2011)

Assuming the TKE spectrum 'tails off' (no spurious accumulation of energy near the grid scale), one can argue that the TKE spectrum can be used to define an 'effective' resolution of the model

Using TKE to 'tune' model dissipation operators

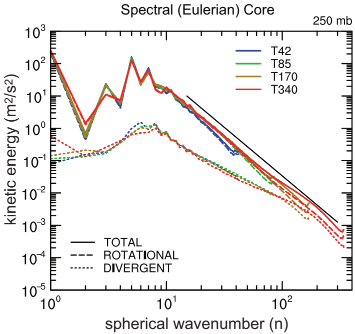


Figure from Skamarock (2011)

Assuming the TKE spectrum 'tails off' (no spurious accumulation of energy near the grid scale), one can argue that the TKE spectrum can be used to define an 'effective' resolution of the model

- Spherical harmonic based dynamical core (CAM-EUL): hint of $k^{-5/3}$'s transition and for $k > 200$ energy is removed
- CAM-FV: no hint of $k^{-5/3}$'s transition and tails off 'already' at $15\Delta x$-$20\Delta x$

Using TKE to 'tune' model dissipation operators

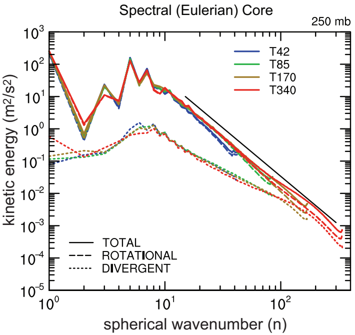


Figure from Skamarock (2011)

Assuming the TKE spectrum 'tails off' (no spurious accumulation of energy near the grid scale), one can argue that the TKE spectrum can be used to define an 'effective' resolution of the model

This is somewhat controversial: from linear analysis we know that waves near the grid-scale are not well-represented and can therefore not be trusted. One may therefore argue that we should damp those waves so that they transition to zero energy at the truncation limit
(M. Blackburn, University of Reading)

Using TKE to 'tune' model dissipation operators

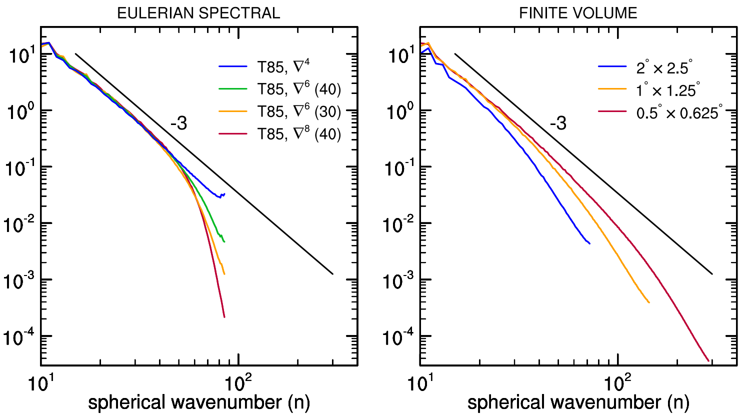
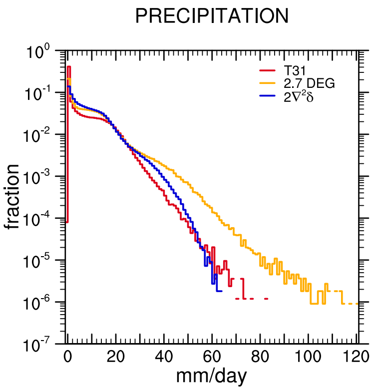


Figure from Jablonowski and Williamson (2011)

- (left) TKE spectrum for CAM-EUL using different orders of hyperdiffusion
- (right) TKE spectrum for CAM-FV

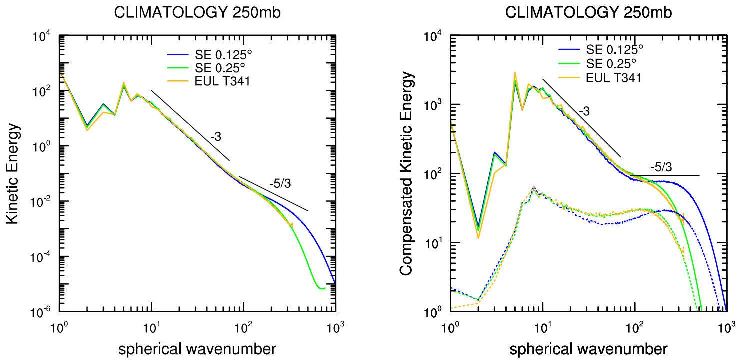
⇒ at increasing orders of hyperdiffusion CAM-EUL starts to 'look like' CAM-FV

Using TKE to 'tune' model dissipation operators



Diffusion mechanisms and their magnitude matters - for example, many extreme events are close to the grid scale and may be affected by diffusive properties of the dynamics near the grid-scale!

Figure: Fraction of time the tropical convection is in 1 mm day^{-1} bins ranging from 0 to 120 mm day^{-1}, calculated for 6h averages for all grid point between $\pm 10^\circ$. Frequency distribution is annual average for CAM-FV and CAM-EUL (low resolution results $\approx 3^\circ$)

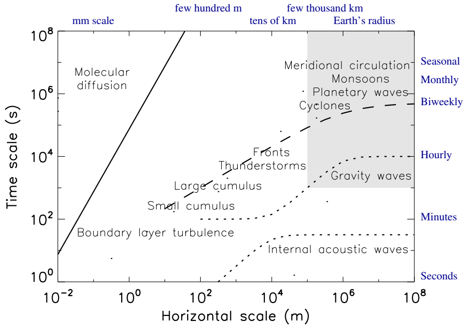


We are now starting to resolve some meso-scale motion ($k^{-5/3}$'s transition)

$\rightarrow$ slowly starting to resolve large-scale convection (since we can resolve large-scale updrafts) but we are certainly not resolving all kinds of convection and associated phenomena: *GREY ZONE*

Are the assumptions we are making in climate models developed for resolutions of $\mathcal{O}(>100km)$ still valid?

Challenges as we move to higher resolution



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Are the assumptions we are making in climate models developed for resolutions of $\mathcal{O}(> 100km)$ still valid?

Are the assumptions we are making in climate models developed for resolution of $\mathcal{O}(> 100km)$ still valid?

- Is the hydrostatic assumption still valid? (*hydrostatic approximation*): Involves ignoring the acceleration term in the vertical component of the momentum equations so that it reads:

$$\rho g = -\frac{\partial p}{\partial z}, \tag{11}$$

  where g gravity, ρ density and p pressure.

- There has been a lot of discussion/focus on developing non-hydrostatic global dynamical cores, however, we argue that there are other processes that become important before we 'hit' the 'hydrostatic limit' (next slide)

Challenges as we move to higher resolution: condensate loading

'Typical' representation of water in climate models

- Prognostic: Water vapor, cloud liquid and cloud ice
- Diagnostic: Rain, snow, graupel (also called soft hail), and hail $\Rightarrow$ if rain, snow, graupel or hail forms it is assumed that it falls to the ground in one time step Δt where Δt is typically $\mathcal{O}(15-30)$ minutes.

Surface-pressure (P_s) is usually computed as the mass of dry air and water vapor in the column, i.e. surface pressure does not 'feel' the weight of the remaining water species. In reality, however, precipitating condensate may exist in a deep column that persists for a significant time ($> \Delta t$); the weight of this column contributes to the pressure field = condensate loading (CL).

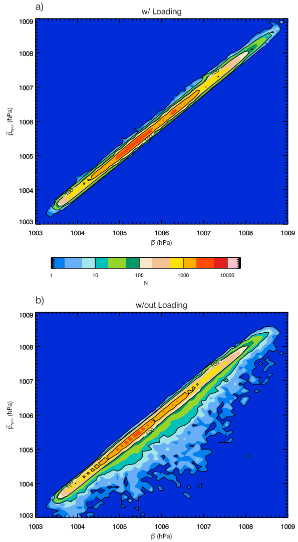
The major contribution to condensate mass comes from precipitating species such as rain, hail, snow, and graupel!

High resolution climate modeling

Not including CL is a justifiable approximation at horizontal resolutions of $\mathcal{O}(100)$ km

... as we move to 25km and higher resolutions this neglect is no longer justified!
(see next slide)

Condensate loading (CL) and surface pressure (P_s) (Bacmeister et al., 2012)



Experiment setup

Model = WRF (NCAR weather research forecast model) with 'all' water variables prognostic as well as non-hydrostatic dynamics; $\Delta x = \Delta y = 500$m horizontal resolution, 5 day simulation.

Non-hydrostatic effects at $\Delta x = 25$km

Figure (upper): Joint frequency distributions of WRF pressure (x-axis) and hydrostatic pressure (y-axis) coarse-grained to 25 km.

Non-hydrostatic effects not significant!

What is the effect of CL on P_s?

Figure (lower): Same as upper but hydrostatic pressure ignores CL (y-axis).

$\Rightarrow$ frequent, large ($\mathcal{O}$(hPa)) underestimates of P_s compared to WRF P_s.

A clear implication of this result is that high-resolution climate model surface pressures in regions of strong precipitation may be systematically underestimated by several hPa.

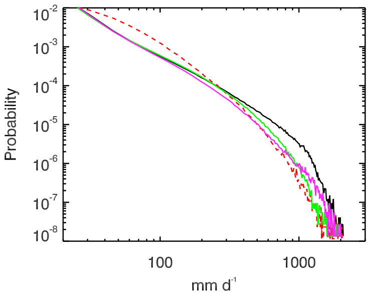
Why don't we 'just' run climate models with prognostic rain, snow, graupel, ...?

High-resolution climate modeling is reaching 'grey zone' resolutions, i.e. we are starting to resolve meso-scale motion but we are not resolving individual updrafts to form hail, snow, graupel, ...

→ having prognostic rain, snow, hail, and graupel is problematic in the 'grey' zone!

But we can parameterize the effect of water loading so that the dynamics 'feels' the weight of all precipitating species such as rain, snow, graupel, ...

Condensate loading (CL) and precipitation (Bacmeister et al., 2012)



CAM5 experiment with water loading

CAM5 physics, run for 8/2005, $\Delta x = 25$km, with two parameterizations for CL (so that P_s 'feels' CL although CAM does not have prognostic graupel, snow, ...).

Figure: probability density functions (PDFs) of precipitation rates, $\theta \in [30^\circ S, 30^\circ N]$

for TRMM (observations), CAM5 with CL1 and CL2, and CAM5 control (no CL)

CAM5 control clearly overestimates the likelihood of precipitation rates greater than 200 mm/d with respect to TRMM. Major improvement with water loading!

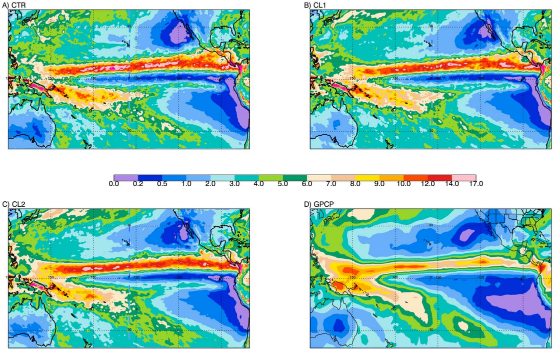


Figure: 12-month mean precipitation from all CAM5 experiments compared with observational estimates from the Global Precipitation Climatology Project (GPCP)

- All CAM5 experiments exhibit positive precipitation biases in the Pacific intertropical convergence zone (ITCZ) with respect to GPCP.
- Modest improvements over CTR (no water loading) are evident in CL1/CL2 (including water loading) particularly South of the Equator where the model's double ITCZ has been reduced

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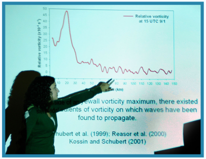
- Atmospheric Chemistry & Biogeochemistry
- Mesoscale Meteorology and Weather Prediction
- Climate Science and Global Change
- Solar Physics and Solar-Terrestrial Interactions



- Atmospheric Physics
- Social Science
- Computational Science, Applied Mathematics, and Numerical Methods
- Technology for Atmospheric and Solar Measurements
- Science Education and Capacity Building

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Questions?

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