Horizontal Mixing in the WRF-ARW Model

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Overview

- Description of implicit and explicit horizontal mixing in WRF
- Evaluation of WRF's implicit mixing
- Model options for explicit mixing & filters
- 2D and 3D Smagorinsky schemes

Introduction

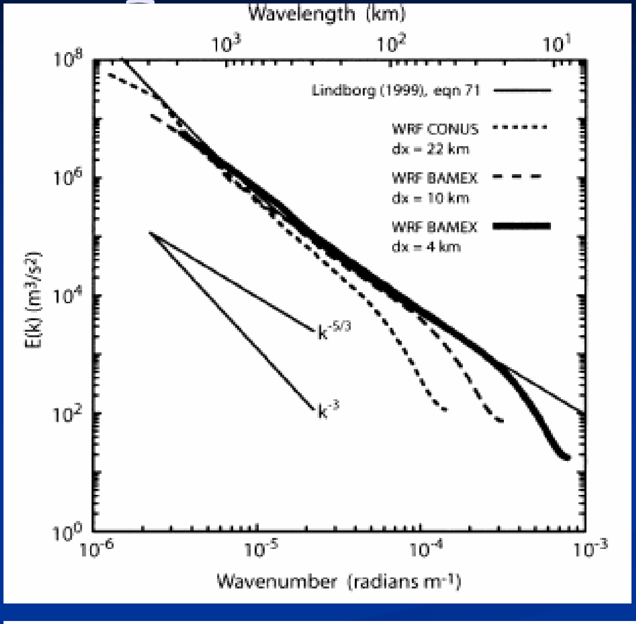
- Most mesoscale models use a turbulence closure scheme to represent subgrid-scale effects – these schemes are based in part on turbulence theory and observations
- As we learned in our HW assignment, finite-difference advection schemes also introduce computational errors, especially at small scales
- To remove these small-scale perturbations, additional artificial mixing is sometimes added (usually via a scale-selective spatial filter)
- Artificial filters are necessary in models with centered-in-space advection, but artificial filters for diffusion are not standard nor necessary in WRF (some have experimented with their use, however)
- WRF does use artificial filters for acoustic and external modes

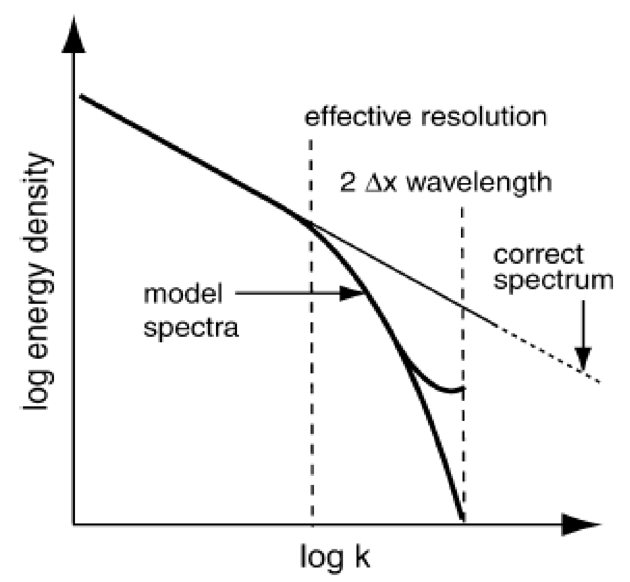
Implicit mixing in WRF

- The 3rd-order Runge-Kutta (RK3) time integration scheme used in WRF can be used stably with high-order approximations to the advection equation
- If an odd-ordered advection approximation is used, the RK3 scheme has a built-in filter of the next-highest order
  - If using 5th-order advection approximation, a 6th-order filter is included
- The implicit filter damps small-scale oscillations with a coefficient proportional to the Courant number (C/60 for the 5th-order advection scheme)
- Therefore, WRF can be run without explicit mixing (i.e., no turbulence scheme) – this is recommended for $\Delta x > 10$ km
- However, turbulence closure schemes are also an option in WRF and are generally used for higher-resolution applications (NWP, cloud modeling, etc.)

Evaluation of WRF implicit mixing

- Skamarock (2004) found that the energy spectra produced by WRF compare well with the observed k^{-3} and $k^{-5/3}$ spectra
- He defines the "effective resolution" of a model to be the point at which the model spectrum is damped relative to the correct spectrum
- The tailing-off at high wavenumbers is necessary to avoid energy buildup and unphysical behavior at very small scales
- However, it's undesirable to over-damp physical small-scale features (otherwise, there would be no reason to use smaller grid spacing)

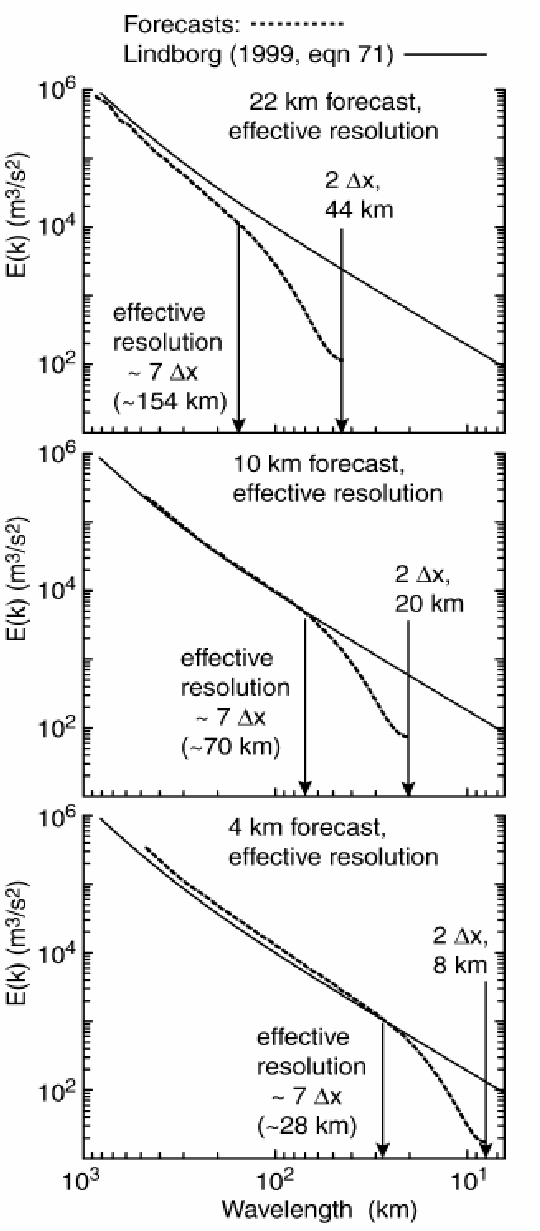




Skamarock (2004)

Evaluation of WRF implicit mixing

- The implicit 6th-order filter in WRF-ARW, compared with explicit filters used in other NWP models, is the most scale selective and the least dissipative
- This means that it only dissipates at the highest wavenumbers, which increases the "effective resolution" of the model
- Skamarock (2004) found WRF's effective resolution to be ~7Δx, compared with ~10Δx for other NWP models
- He suggests that this might be nearing the limit for effective resolution



Skamarock (2004)

Options for explicit mixing

- Diffusion options:
  - No explicit mixing
  - Diffusion evaluated on model coordinate (eta) surfaces
  - Diffusion evaluated in physical (x,y,z) space using stress & deformation tensors
- Options for computation of eddy viscosities (km_opt):
  - **1:** Constant K_h and K_v (specified by user)
  - **2:** 1.5 order prognostic TKE closure
  - **3:** 3D first-order Smagorinsky closure
  - **4:** Horizontal first-order Smagorinsky closure
- If a PBL parameterization is employed, it handles all vertical mixing: all other explicit vertical mixing is disabled (options 1 or 4 are recommended in this case)

Coordinate vs. physical space

- If mixing is done on coordinate surfaces, K_h is allowed to vary in space, but K_v is not
- Since coordinate surfaces follow terrain, the “horizontal” diffusion can introduce vertical diffusion in areas with sloping terrain
- Coordinate-surface diffusion can only be used with km_opt = 1 or 4 (constant K or 2D Smagorinsky)
- For physical-space diffusion, coordinate metrics are computed at each time step using the geopotential:
  - $z_x = g^{-1}\delta_x\varphi$; $z_y = g^{-1}\delta_y\varphi$
- Stress and deformation tensors are calculated in a method similar to that described in Ch. 6 of the book

2D Smagorinsky scheme

- Recall that first-order turbulence closure can be represented using eddy viscosity coefficients:

$$\overline{w''\theta''} = -K_\theta \frac{\partial\bar{\theta}}{\partial z}, \qquad \overline{w''q''_k} = -K_\theta \frac{\partial\bar{q}_k}{\partial z}, \qquad \overline{w''\chi''_m} - K_\theta \frac{\partial\bar{\chi}_m}{\partial z},$$

$$\overline{w''u''} = -K_m \frac{\partial\bar{u}}{\partial z}, \qquad \text{and} \qquad \overline{w''v''} = -K_m \frac{\partial\bar{v}}{\partial z},$$

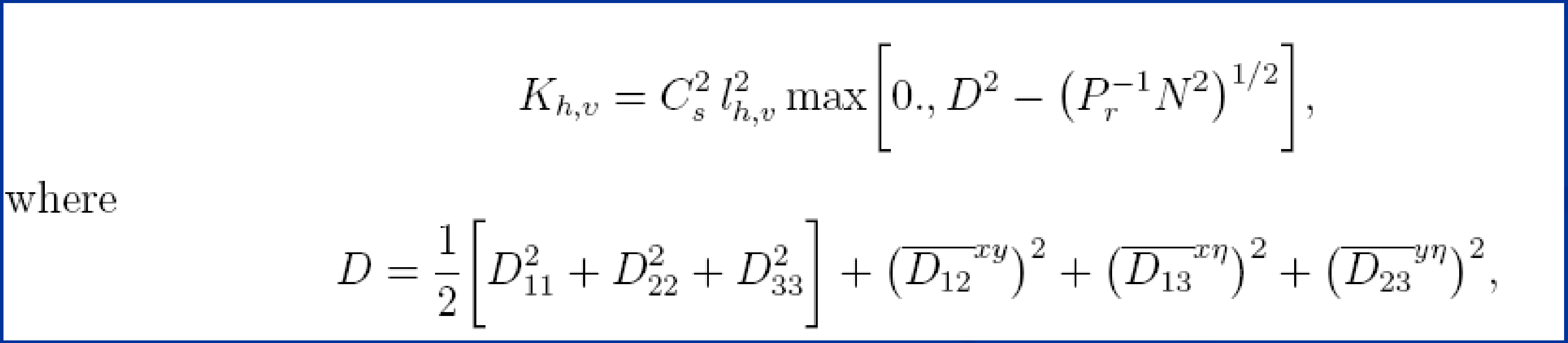
- We then need to calculate the values of K (in WRF K_h and K_v)
- The 2D Smagorinsky scheme calculates only K_h -- it is most often used when a PBL scheme is handling the vertical mixing independently
- It uses the horizontal deformation to calculate K_h, which in WRF is shown by:

$$K_h = C_s^2\, l^2 \left[0.25(D_{11} - D_{22})^2 + \overline{D_{12}^2}^{xy}\right]^{\frac{1}{2}}.$$

C_s = constant (typically 0.25)
l = length scale $(\Delta x\ \Delta y)^{1/2}$
D terms represent deformation
For scalars, K_h divided by Pr =1/3

3D Smagorinsky scheme

- This scheme is similar to the 2D scheme but also includes vertical mixing (used without PBL scheme – mainly for idealized simulations)
- Depends on horizontal and vertical deformation and stability
- Kh and Kv determined by:



$$K_{h,v} = C_s^2\, l_{h,v}^2 \max\left[0.,\, D^2 - \left(P_r^{-1} N^2\right)^{1/2}\right],$$

where

$$D = \frac{1}{2}\left[D_{11}^2 + D_{22}^2 + D_{33}^2\right] + \left(\overline{D_{12}}^{xy}\right)^2 + \left(\overline{D_{13}}^{x\eta}\right)^2 + \left(\overline{D_{23}}^{y\eta}\right)^2,$$

C_s = constant (typically 0.25)

D terms represent deformation

N = Brunt-Vaisala frequency

Pr = Turbulent Prandtl number

For scalars, K divided by Pr =1/3

- User specifies critical length scale: if Δx is less than this length, then $l_h = l_v = (\Delta x\ \Delta y\ \Delta z)^{1/3}$ and $K_h = K_v$; if greater, $l_h = (\Delta x\ \Delta y)^{1/2}$ and $l_v = \Delta z$

Summary and conclusions

- The advection scheme used in WRF includes an implicit scale-selective filter – the model can be run stably without a turbulence closure scheme and without artificial mixing
- This implicit filter is found to increase the effective resolution of the model – it does not overdamp small-scale perturbations
- WRF provides several options for turbulence closure, one of which is usually used when performing high-resolution simulations