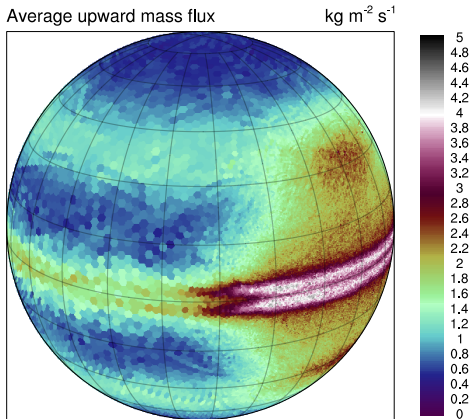


Scale-dependent horizontal velocity fields drive vertical velocity resolution dependence

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CESM AMWG Workshop: February 10, 2014

Resolution dependence in the CESM

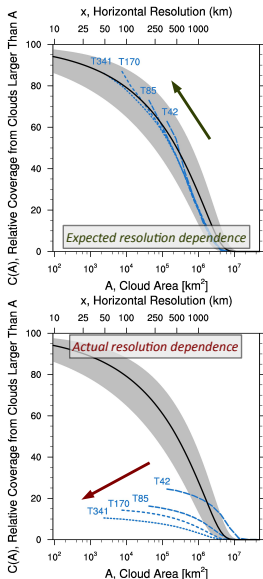


Upward mass flux intensifies as grid cell size decreases.

Is this resolution dependence bad??

Is this resolution-dependence bad??

For clouds, yes.
For other fields...?
(e.g., *O'Brien et al. 2013, J. Clim*)



Why does updraft strength depend on resolution?

The simple and intuitive version: a scale analysis

Express the incompressibility equation in finite-difference form in Cartesian coordinates:

$$\frac{\Delta_x u}{\Delta x} + \frac{\Delta_y v}{\Delta y} + \frac{\Delta_z w}{\Delta z} = 0$$

Replace $\Delta_x u$ and $\Delta_y v$ with a typical cell-to-cell velocity difference, $\overline{\Delta U}$ and solve for Δw :

$$\overline{\Delta w} = -\frac{\overline{\Delta U}}{\Delta x} \cdot \Delta z$$

Can we express $\overline{\Delta U}$ as a function of Δx ???

Yes: it is a *structure function* of a fractal field

Structure functions:

Structure function, $S_U(\Delta x)$ —The average 'gradient' of a field as a function of 'gradient' distance:

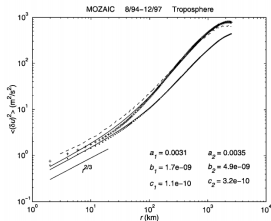
$$S_U(\Delta x) \equiv \overline{|U(x) - U(x + \Delta x)|} = \overline{|\Delta_x U|}$$

Why structure functions???

For fractal fields, structure functions are a power-law of distance:

$$S_U(\Delta x) \propto \Delta x^H$$

Wind is a fractal field



from Cho and Lindborg (2001, JGR)

So for wind, $S_U(\Delta x) \propto \Delta x^{1/3}$

$$\frac{\overline{\Delta U}}{\Delta x} = c \Delta x^{-2/3}$$

$$\overline{\Delta w} = -\frac{\overline{\Delta U}}{\Delta x} \cdot \Delta z \rightarrow$$

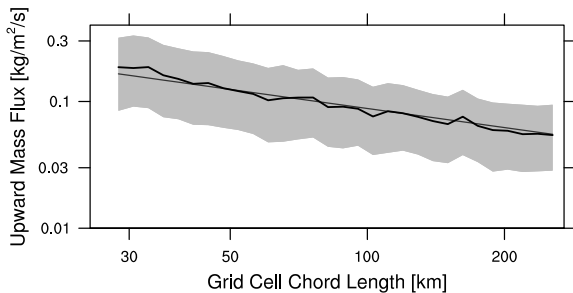
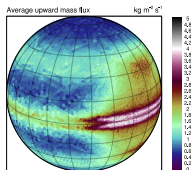
$$\overline{\Delta w} \propto \Delta x^{-2/3}$$

$$S_U^2(\Delta x) \equiv \overline{|U(x) - U(x - \Delta x)|^2}$$

$$\propto \Delta x^{2/3} \rightarrow$$

$$S_U(\Delta x) \approx (S_U^2)^{1/2} \propto \Delta x^{1/3}$$

This $\Delta x^{-2/3}$ dependence appears in CESM

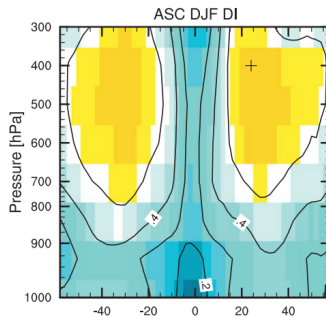


BLACK – Mean upward mass flux

GRAY – $\Delta x^{-2/3}$ power law

But this analysis is unsatisfying...

- It is based on a *scale* analysis: not rigorous
- It assumes equality of the u and v components of the field
- And what if the structure function exponent depends on location in the atmosphere?



Structure function exponent for water vapor field, from AIRS data. Pressel and Collins (2012, J. Clim.)

Overview of a PDF-based derivation

If we do the following:

- Relate the structure functions to the widths of the distribution: $S_x(\Delta U) \rightarrow \sigma_U \sim \Delta x^{H_x}$, $S_y(\Delta V) \rightarrow \sigma_V \sim \Delta y^{H_y}$
- Assume the wind field is statistically isotropic ($P_{uv} = P_{vu}$, $S_u(\Delta x) = S_v(\Delta y)$, $H \equiv H_x = H_y$, and $\Delta x = \Delta y$)
- Assume P_{uv} is a bivariate normal distribution
- Algebra and calculus

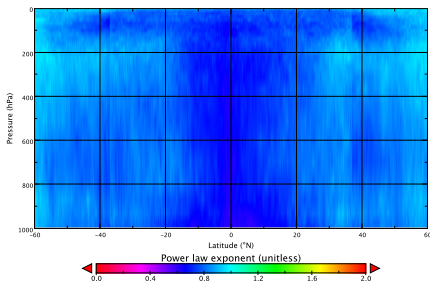
We can analytically map $P_{uv} \rightarrow P_w$, and we find that $P_w(w)$ is a univariate normal distribution with a resolution-dependent width:

$$\sigma_w \propto \Delta x^{H-1}$$

which is analogous to the previous result using scale analysis.

Zonal velocity structure function exponents

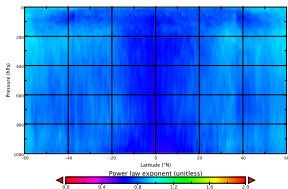
from $\sim 0.25^\circ$ CAM SE aquaplanet



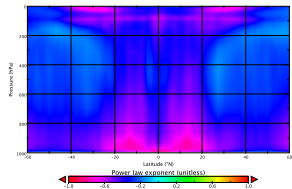
H ranges from ~ 0.4 to 0.9

ω power law exponents

Structure function exponents (H)



ω versus res. exponents



The match isn't perfect, but...?

- The width of the ω PDF increases strongly with decreasing resolution
- One of the physics parameterizations should account for this...
 - Boundary layer?
 - Convection?
 - A new type of *mesoscale eddy flux* parameterization?

Acknowledgements

Thank you to DOE/BER for funding the Frameworks for Robust Regional Modeling Project, on which this work is based.

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This presentation has been authored by an author at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy.

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