A New Treatment of Subgrid Mountain Drag in Atmospheric Models

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Mountain drag is a significant part of the momentum budget of the atmosphere. Most of it comes from scales that are still **unresolved** by climate models.

Our new scheme[1] innovates in two ways:

1. Exact linear analysis gives the average orientation of the terrain within a grid cell.

2. The forcing due to wavebreaking is integrated over a distribution of summit heights in a grid cell using an empirical height-width ratio.

From (1), we avoid *ad-hoc* characterizations of the topographic anisotropy, and from (2), we avoid assigning a single RMS amplitude to the terrain, thus broadening the forcing as a function of height.

1. Base-flux computation

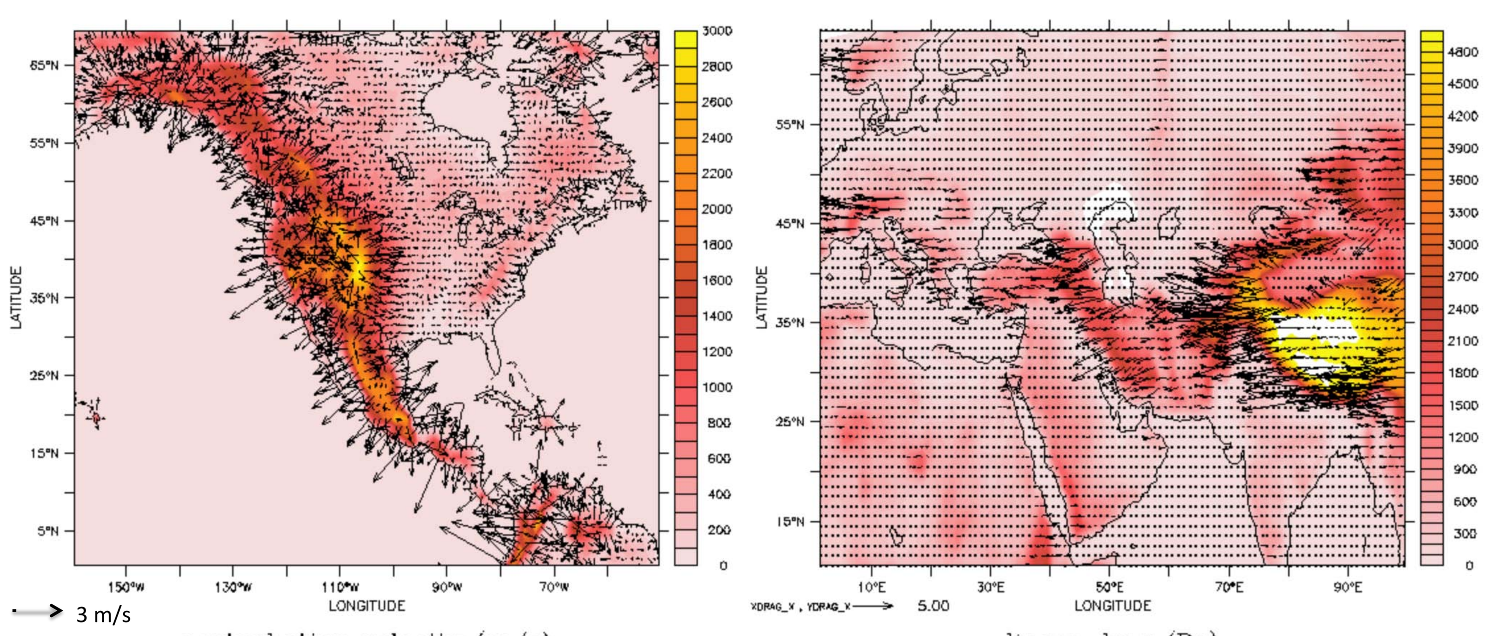
The linear drag (with angle brackets denoting a grid-cell average) is

$$\vec{\tau}_{lin} = \bar{\rho}\langle \vec{V}' w' \rangle = \bar{\rho} \begin{pmatrix} \left\langle u' \frac{\partial h}{\partial x} \right\rangle & \left\langle u' \frac{\partial h}{\partial y} \right\rangle \\ \left\langle v' \frac{\partial h}{\partial x} \right\rangle & \left\langle v' \frac{\partial h}{\partial y} \right\rangle \end{pmatrix} \begin{pmatrix} \bar{u} \\ \bar{v} \end{pmatrix}$$

For $\vec{V}'$, we assume stationary, non-rotating, hydrostatic internal waves. If $\vec{V}' = \nabla\chi$, linear theory gives

$$\chi = (\bar{N}/2\pi) \iint \frac{h(\vec{x}')}{|\vec{x} - \vec{x}'|} dx' dy'$$

The averaging of the 4 matrix elements should be done offline. The input topography *h(x,y)* has to be filtered for physical as well as computational reasons.



perturbation velocity (m/s) linear drag (Pa)

2. Nonlinear extension of base flux

Using dimensional analysis, we write ($\tilde{h}$ is nondimensional height or Froude number)

$$D = \bar{\rho}\frac{\bar{V}^3}{\bar{N}L} \times \begin{Bmatrix} G_0 \tilde{h}^2, & \tilde{h} < \tilde{h}_c \\ G_1 \tilde{h}, & \tilde{h} > \tilde{h}_c \end{Bmatrix}$$

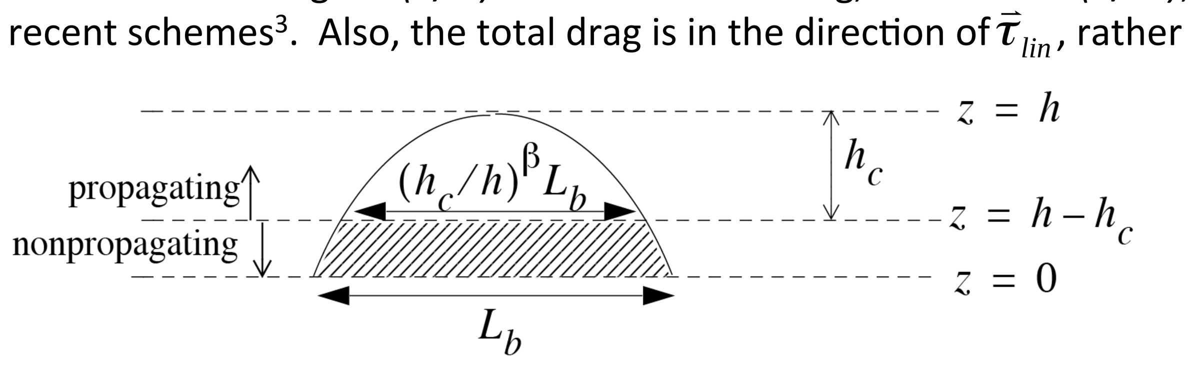
where $\tilde{h}_c$ is a universal threshold and $\bar{V}$ is in the direction opposite $\vec{\tau}_{lin}$. Then for an assumed distribution of individual mountain heights, *h(x,y)*, we integrate *D* over propagating (*p*) and non-propagating (*np*) contributions separately and normalize to match the analytical drag in the linear limit.

$$\vec{\tau} = \left(\frac{\langle D_p \rangle}{D^*} + \frac{\langle D_{np} \rangle}{D^*} \right) \vec{\tau}_{lin}$$

Compare this to the traditional scheme[2]:

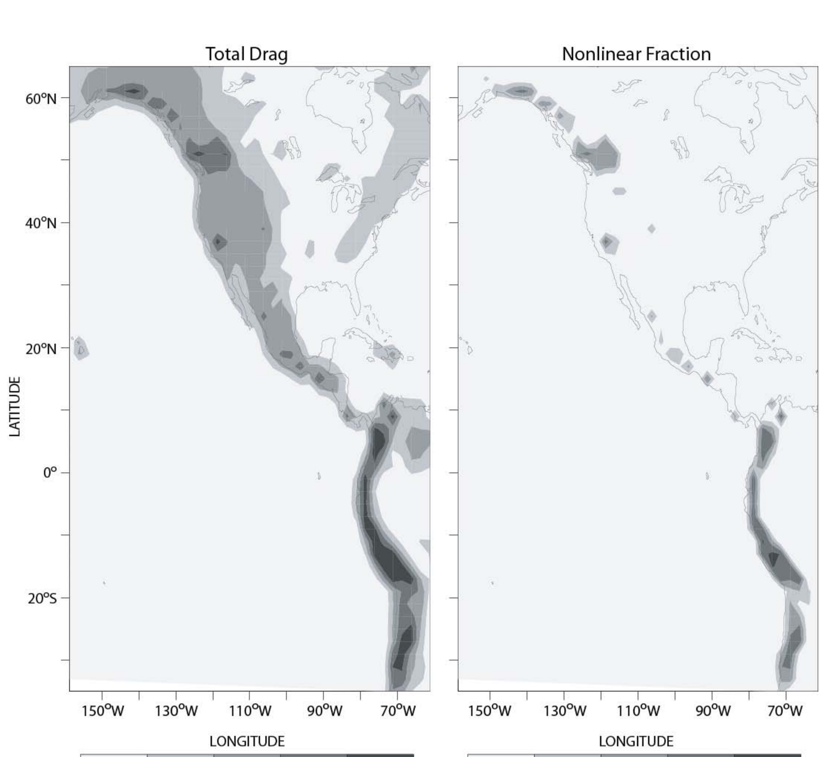
$$D = \bar{\rho}\frac{\bar{V}^3}{\bar{N}L} \times \left(\frac{G_0 \tilde{h}^2}{a^2 + \tilde{h}^2} \right); \qquad \vec{\tau} = -D\,\vec{\bar{V}}/|\vec{\bar{V}}|$$

Our nonlinear drag is $O(1/\tilde{h})$ times the linear drag, instead of $O(1/\tilde{h}^2)$, consistent with other recent schemes[3]. Also, the total drag is in the direction of $\vec{\tau}_{lin}$, rather than $-\bar{V}$.

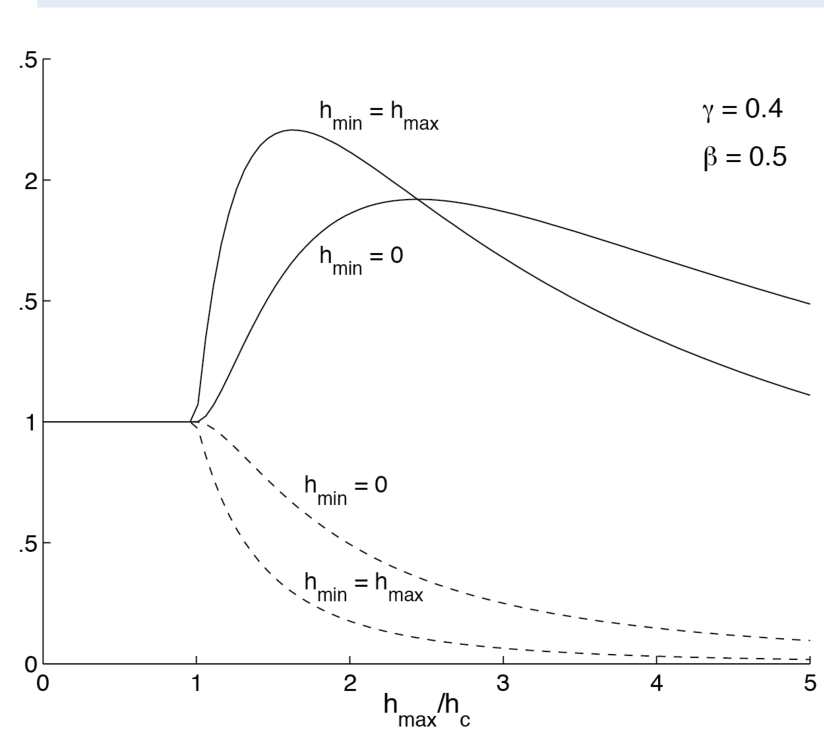


Model of an individual mountain, with parameters h and β.

Normalized total drag (left) and nonlinear fraction over W. Hemisphere for constant U and N, $\tilde{h}_c$ = 0.7.



Examples of the drag <D> averaged between h_{min} and h_{max}, where h is the height of individual mountains in the assumed grid-cell distribution.



[1]Garner, S.T., 2005: A topographic drag closure built on an analytical base flux. *J. Atmos. Sci.*, **62**, 2302-2315.

[2]Pierrehumbert, R.T., and B. Wyman, 1987: An essay on the parameterization of orographic gravity wave drag. *Proc. Seminar/Workshop on Observations, Theory and Modeling of Orographic Effects*, 1, ECMWF, 251-282.

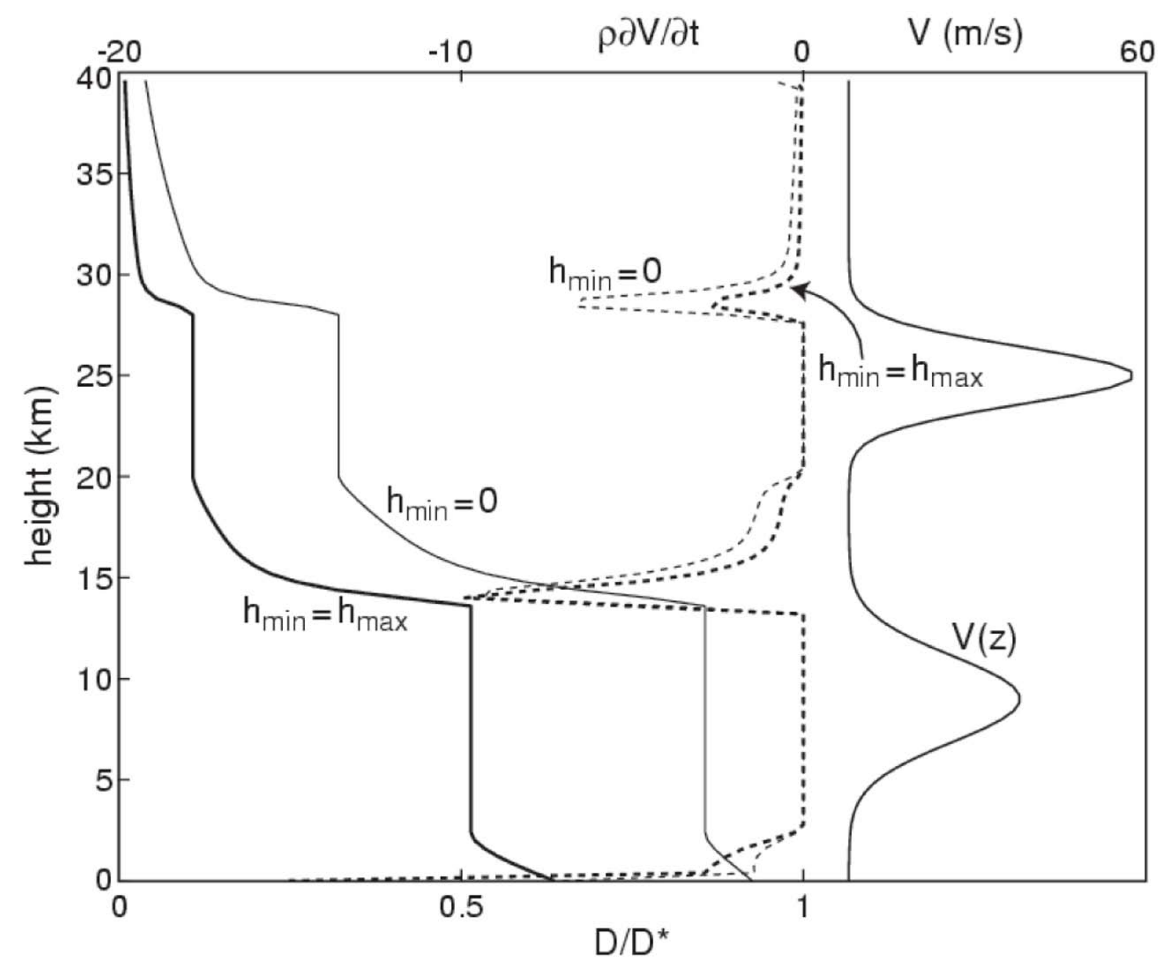
[3]Lott, F., and M.J. Miller, 1997: A new subgrid-scale orographic drag parameterization: its formulation and testing. *Quart. J. Roy. Meteor. Soc.*, **123**, 101-127.

3. Momentum forcing over the atmospheric column

To diagnose wavebreaking as a function of height, we conserve wave activity (pseudomomentum flux),

$$A = \bar{\rho}\bar{N}\bar{V}h^2$$

where *h* is now the wave amplitude, but impose $\tilde{h} < \tilde{h}_c$. The calculation is performed in height bins, followed by averaging. analytically The flux is simply the drag for "topography" *h(z)*. The momentum forcing is the convergence of the flux.



Example for an assumed jet structure *V (z)* (plotted on right):

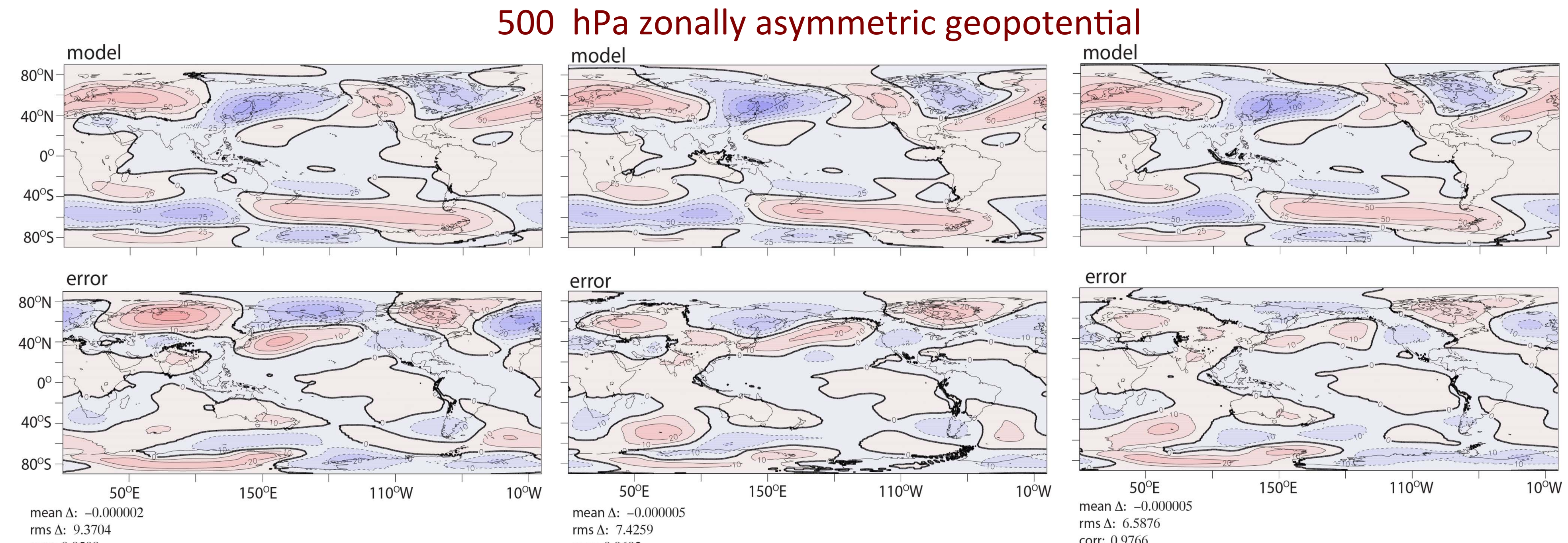
The forcing $\bar{\rho}\partial V/\partial t$ (dashed) is the vertical derivative of the pseudomomentum flux *A* (solid). The flux saturates more gradually when the heights span a range.

4. AMIP runs with monthly climatological SST

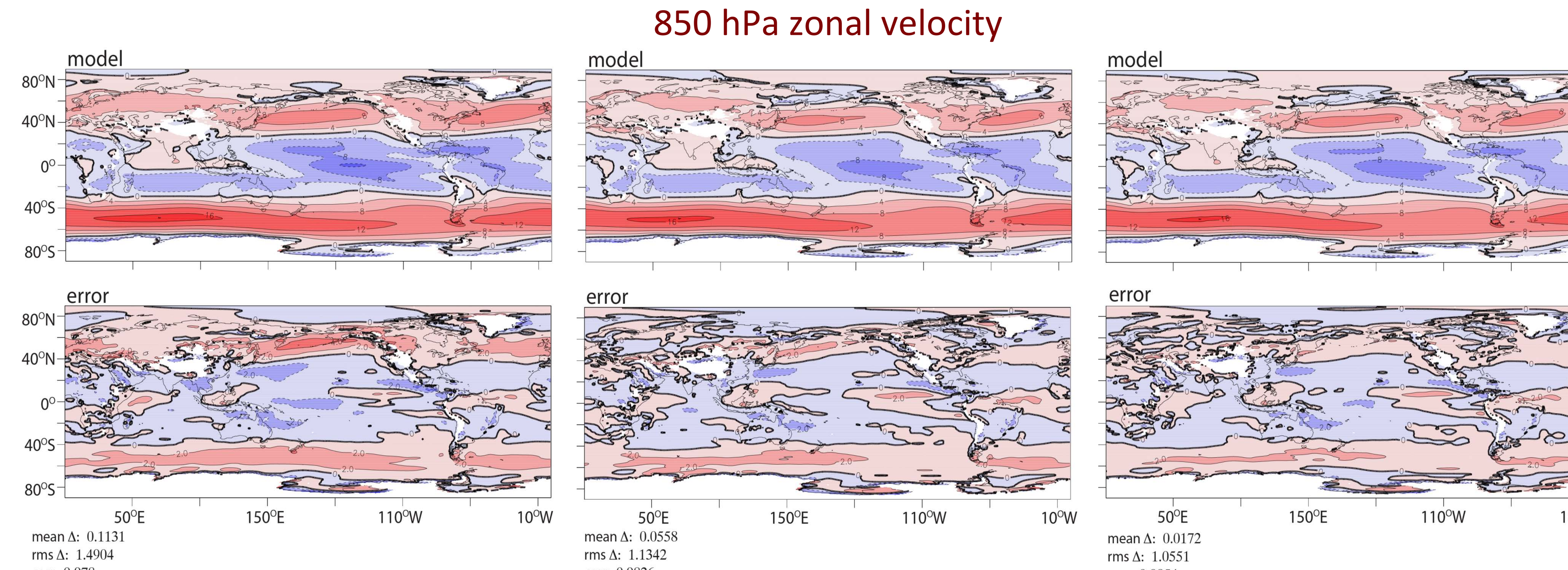
AGCM integrations were carried out at 50-km resolution (C180), averaged over 20 years, and compared to reanalysis.

No drag	Old scheme	New scheme

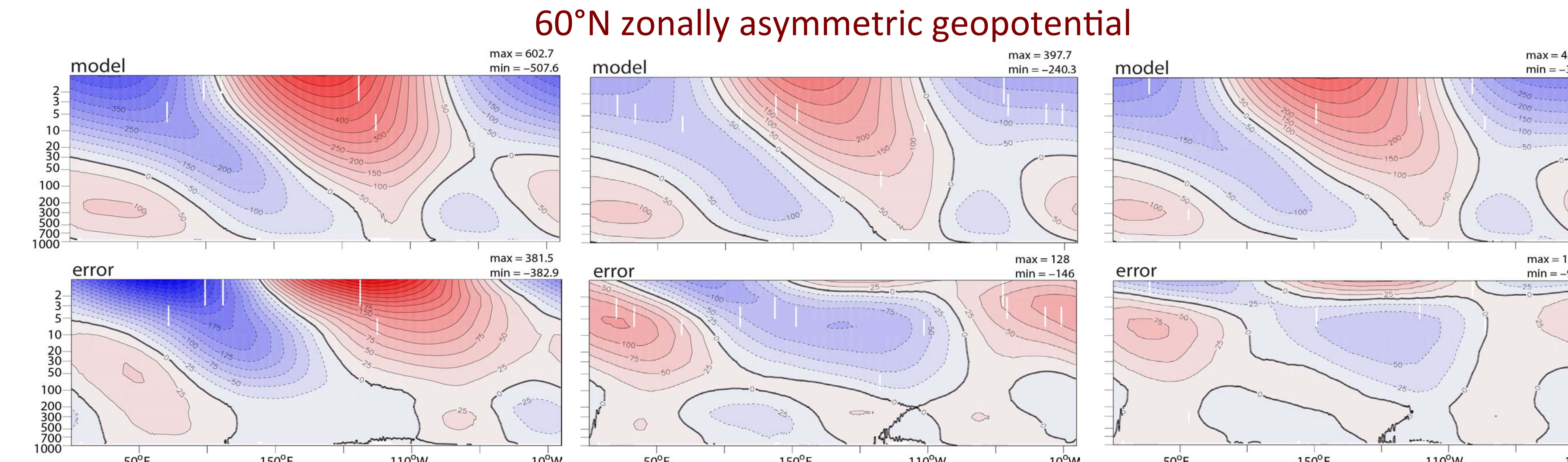
500 hPa zonally asymmetric geopotential



850 hPa zonal velocity



60°N zonally asymmetric geopotential



5. Conclusions

- The new scheme improves the circulation significantly, especially in the lower and middle troposphere and on large scales.
- Improvements in long-time-averaged regional circulations, clouds and precipitation are less significant.
- The zonal wind stress over the oceans is slightly improved compared to ECMWF reanalysis.