

A Mechanical Energy Budget and Evaluation of an Eddying Global Ocean Model with a Wave Drag Parameterization

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LOM Meeting, 2013

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE MAY 2013		2. REPORT TYPE		3. DATES COVERED 00-00-2013 to 00-00-2013	
4. TITLE AND SUBTITLE A Mechanical Energy Budget and Evaluation of an Eddying Global Ocean Model with a Wave Drag Parameterization				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Michigan-Ann Arbor, Department of Earth & Environmental Sciences, Ann Arbor, MI, 48109				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Layered Ocean Model Workshop, Ann Arbor, MI, 21-23 May 2013.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Outline

- 1 Introduction**
 - Motivation and what wave drag is
 - The model and observations for comparison
- 2 Putting wave drag into an ocean model**
 - Wave drag scheme choices
- 3 Energy budget**
 - Mechanical energy budget from the continuity and momentum equations
- 4 Model evaluation**
 - Taylor diagrams of all five diagnostics

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A truncated history of topographic wave drag studies

Previous studies

- Atmospheric general circulation models improved with wave drag (e.g., *Palmer et al.*, 1986)

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- Wave drag boosts vertical diffusivity (e.g., *St. Laurent et al.*, 2002) and improves all considered tidal constituent amplitudes (e.g., *Jayne and St. Laurent*, 2001) in barotropic tidal models

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- Wave drag boosts vertical diffusivity (e.g., *St. Laurent et al.*, 2002) and improves all considered tidal constituent amplitudes (e.g., *Jayne and St. Laurent*, 2001) in barotropic tidal models
- Offline estimates suggest wave drag dissipates energy at 0.2 – 0.49 TW in abyssal hill regions (e.g., *Nikurashin and Ferrari*, 2011; *Scott et al.*, 2011)

A history of topographic wave drag improving models (contd...)

Our goals

- How do we insert wave drag into an eddying global ocean model (**without tides**)?

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- How does wave drag impact the stratification, kinetic energy, and the input and output terms in the kinetic energy equation?

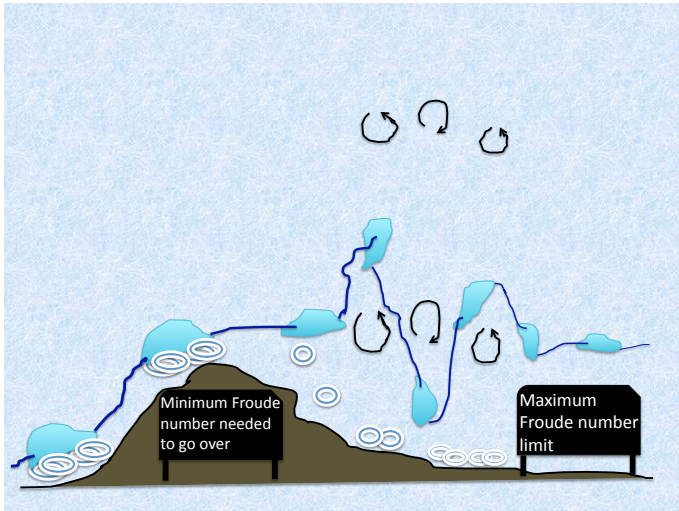
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Our goals

- How do we insert wave drag into an eddying global ocean model (**without tides**)?
- How does wave drag impact the stratification, kinetic energy, and the input and output terms in the kinetic energy equation?
- Are general circulation ocean models forced only by winds and air-sea fluxes improved when wave drag is included?

Motivation and what wave drag is

What is topographic wave drag? (Froude number = U/NH)



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The model and observations for comparison

Our models

HYbrid Coordinate Ocean Model (HYCOM)

- 32 hybrid layers
- $1/12.5^\circ$, $1/25^\circ$ resolutions

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Parallel Ocean Program (POP) component of the Community Earth System Model (CESM) 1.1

- 62 z-layers
- $1/10^\circ$ resolution

The model and observations for comparison

Energy Inputs and Outputs

Inputs

- **Air-sea fluxes** - monthly mean ECMWF Re-Analysis (ERA-40; *Kallberg et al.*, 2004) for HYCOM, Coordinate Ocean Reference Experiment (CORE 2.0; *Large and Yeager*, 2009) for POP

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Dissipators

- **Horizontal viscosity** - ($\sim 10^2 - 10^3 \text{ m}^2 \text{ s}^{-1}$) includes the maximum of a Laplacian and a *Smagorinsky* (1993) parameterization with an additional biharmonic term for HYCOM, biharmonic term for POP

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- **Bottom drag** - quadratic in the momentum equations with coefficient, $C_d = 2.5 \times 10^{-3}$ for HYCOM, 10^{-3} for POP (*Taylor*, 1919; ...; *Arbic et al.*, 2009)

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- **Wave drag** - *Garner* (2005) scheme is used (see later)

The model and observations for comparison

Diagnostics informed by observations and compared with model output

**Current meters (Global Multi-Archive Current Meter Database;
<http://stockage.univ-brest.fr/~scott/GMACMD/updates.html>)**

- Mean vertical structure of kinetic energy

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- Mean vertical structure of kinetic energy

Satellite altimetry (Archiving, Validation and Interpretation of Satellite Oceanographic;

<http://www.aviso.oceanobs.com/es/data/index.html>)

- Surface kinetic energy
- Eddy length scales (inverse first centroid of kinetic energy power spectrum)
- Sea surface height variance
- Intensified jet positions (via *Kelly et al.*, 2007)

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1) What is the range of wavenumbers over which the internal waves are not evanescent?

$$f/U \sim 10^{-4} m^{-1} < |\vec{k}| < N/U \sim 10^{-1} m^{-1}. \quad (1)$$

Here,

- f is the Coriolis parameter
- N is the buoyancy frequency
- U is the velocity near the seafloor
- $|\vec{k}|$ is the wavenumber of the internal wave

Scott et al. (2011) used a range that went down to $f/U \sim 10^{-6} m^{-1}$.

2) Which wave drag parameterizations are there to choose from?

Using a momentum sink:

- Implement in wavenumber space; e.g., *Bell* (1975)
- Implement in physical space; e.g., *Garner* (2005)

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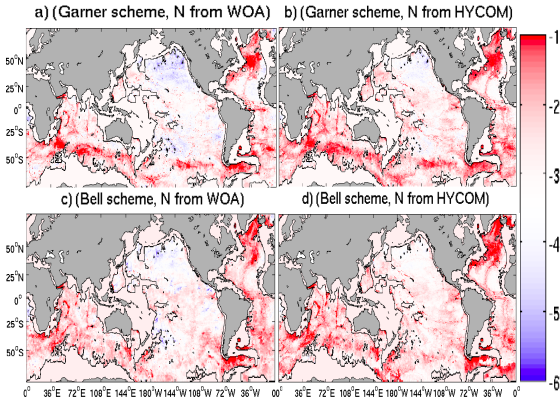
Features of *Garner* (2005) vs those of *Bell* (1975)

- *Garner* (2005) - allows for topographic blocking, but does not depend on Coriolis
- *Bell* (1975) - does not allow for topographic blocking, but does depend on Coriolis
- Both schemes - depend on stratification, velocity, and underlying topographic features and assume $f \ll N$

Wave drag scheme choices

2) (cont...) Comparison of the *Bell* (1975) and *Garner* (2005) schemes

We choose to use the *Garner* (2005) scheme, but the *Bell* (1975) scheme yields similar results (offline)



3) Where do we apply wave drag?

- Is the model numerically stable when wave drag is applied everywhere?
- Is it possible and does it make sense to apply wave drag everywhere?

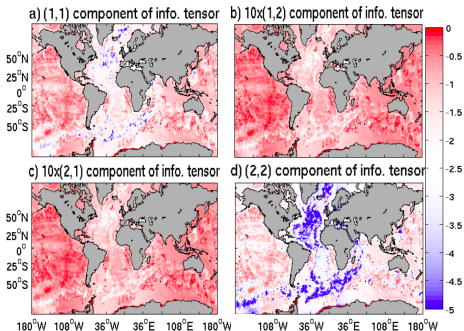
Interpolate over topographic slopes that are supercritical?

Apply wave drag only in abyssal hill regions? Apply wave drag only in regions deeper than 500 meters? ...

Wave drag scheme choices

4) Estimate the input parameters for the wave drag scheme of your choice

- Integrate *Goff and Jordan* (1988) abyssal hill power spectrum, weighted by wavenumbers from **(1)**
- parameters for power spectrum from *Goff and Arbic* (2010) and *Goff* (2010) in abyssal hill regions
- use a machine learning algorithm (*Wood*, 2006) to fill in the non-abyssal hill regions



5) How should the momentum be deposited vertically?

- Is there observational evidence for enhanced turbulence, if not lee wave drag, in the bottom, say, 500 meters? (see *Naveira-Garabato et al.*, 2012)
- Is there evidence that there needs to be a depth-dependent vertical deposition of momentum? (*Polzin* (2009) suggests that there is and the *Garner* (2005) scheme is capable of doing this)
- Are there locations where a non-trivial vertical deposition of momentum is important? (will not be addressed here)

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Mechanical energy budget from the continuity and momentum equations

Momentum equations → kinetic energy equation

$$\begin{aligned}
 & \frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \vec{\nabla}) \vec{u} + \frac{1}{\rho} \vec{\nabla} p + f \hat{k} \times \vec{u} + g \hat{k} = & (2) \\
 & \frac{\delta_s}{\rho} \frac{\vec{\tau}_{wind}}{H_s} - \delta_{b,H_{BD}} \frac{C_d}{H_{BD}} |\vec{u}| \vec{u} - \delta_{b,H_{WD}} \frac{|r_{drag}|}{H_{WD}} \vec{u} \\
 & - \frac{\partial}{\partial z} \left(\nu_z \frac{\partial}{\partial z} \vec{u}_H \right) - \vec{\nabla} \cdot (\nu_{h,2} \vec{\nabla} \vec{u}_H + \nu_{h,4} \vec{\nabla} \nabla^2 \vec{u}_H)
 \end{aligned}$$

Mechanical energy budget from the continuity and momentum equations

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Multiply the momentum equations by ρ and take a dot product with velocity, \vec{u} ; then integrate over the globe

Mechanical energy budget from the continuity and momentum equations

Momentum equations → **kinetic energy equation**

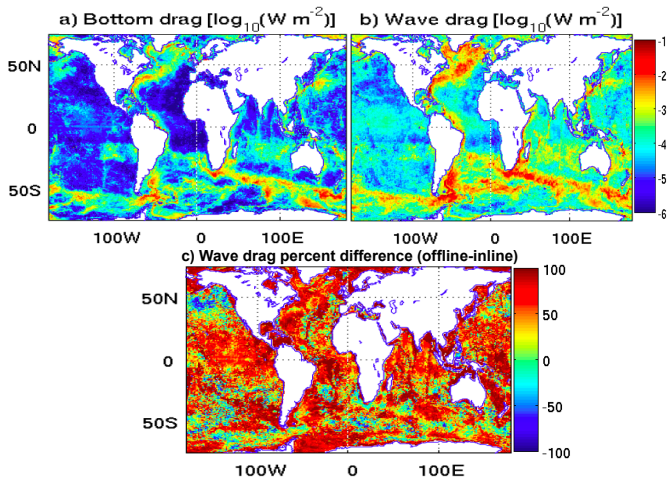
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$$P_{E_K time} + P_{E_K advection} = P_{pressure} + P_{input} - P_{output} + C_{E_K \rightarrow E_P} \quad (3)$$

Mechanical energy budget from the continuity and momentum equations

Bottom and wave drag



Mechanical energy budget from the continuity and momentum equations

Global Integrals of Input/Output Terms in $TW = 10^{12}W$

$$P_{E_K time} + P_{E_K advection} = C_{E_K \rightarrow E_P} + P_{pressure} \quad (4)$$

$$+ P_{Wind} - P_{BD} - P_{WD} - P_{VV} - P_{HV}$$

WD?	Wind	Buoy	BD	WD	VV	HV
no	0.87	0.066	0.31	N/A	0.29	0.29
yes	0.87	0.066	0.14	0.40	0.28	0.26

Inputs vs Outputs:

- 5% imbalance (outputs less than inputs) without wave drag
- 15% imbalance (inputs less than outputs) with wave drag

Mechanical energy budget from the continuity and momentum equations

Mass conservation equation → potential energy equation

$$\int dV \frac{d(\rho g z)}{dt} = \int dV \left[\frac{\partial(\rho g z)}{\partial t} + \vec{u} \cdot \vec{\nabla}(\rho g z) \right] \quad (5)$$

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$$P_{E_P \text{ time}} + P_{E_P \text{ advection}} = P_{\text{diffusive}} + C_{E_P \rightarrow E_K} + C_{E_I \rightarrow E_P} \quad (7)$$

Mechanical energy budget from the continuity and momentum equations

Global Integrals of Mechanical Energy Budget Terms in

$TW = 10^{12}W$

$$P_{E_{Ktime}} + P_{E_{Ptime}} + P_{E_{Kadvection}} + P_{E_{Padvection}} = \quad (8)$$

$$P_{pressure} + P_{diffusive} + P_{input} - P_{output} + C_{E_I \rightarrow E_P}$$

<i>KEadv.</i>	<i>PEadv.</i>	<i>press.</i>	<i>diffuse</i>	$E_I \rightarrow E_P$	<i>input</i>	<i>output</i>
-0.00284	.174	< .001	.00309	.0865	.868	1.06

7% imbalance of mechanical energy budget we ignore:

- partial time derivatives of KE and PE
- along-isopycnal contributions to power associated with buoyancy diffusion
- compressibility

Taylor diagrams of all five diagnostics

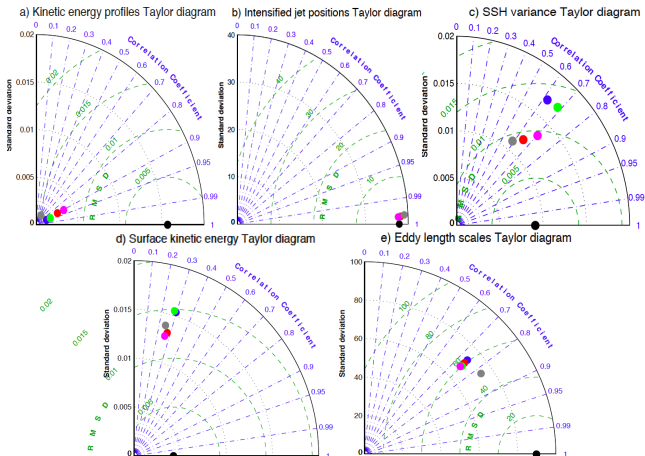
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Does wave drag ever make the model simulations in worse agreement with diagnostics informed by observations?

Observations, 1/12° HYCOM without wave drag, 1/12° HYCOM with wave drag, 1/25° HYCOM without wave drag, 1/25° HYCOM with wave drag, 1/10° POP without wave drag (*Taylor, 2001*)



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There are several details that could use some work when putting wave drag into a model like:

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- what's the more appropriate wave drag scheme to use and in what context?
- use of the full wave drag tensor that *Garner* (2005) formulated?
- use of a depth-dependent momentum deposition procedure that *Garner* (2005) formulated?
- use of an alternative, non-local momentum deposition procedure?

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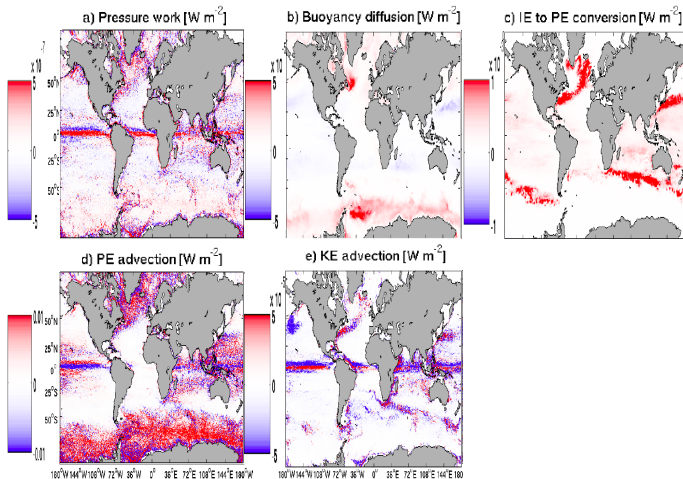
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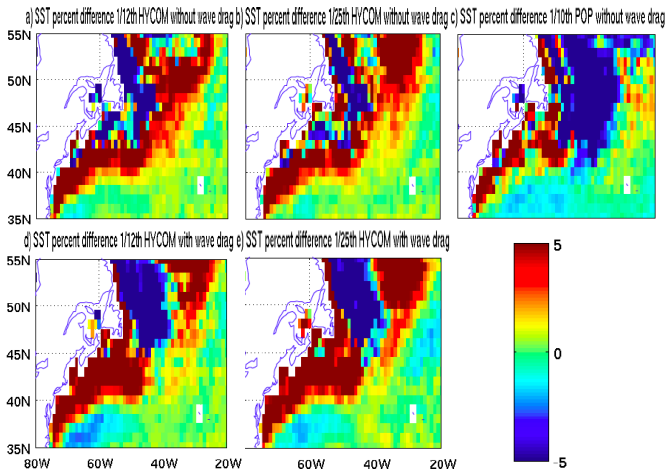
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- substantially less bottom drag dissipation with wave drag, and wave drag cannot be substituted for by boosting bottom drag
- all other mechanical energy budget terms are spatially altered, but changed by little in their global integrals
- wave drag either improves the model or does not make the model worse

Non-input/output mechanical energy budget terms



SST bias



SSH variance

