Vorticity Budgets and the North Atlantic Gyre/Overturning

Maike Sonnewald (maike_s@mit.edu)[1,2,3], Carl Wunsch[1,2], Patrick Heimbach[3] and the ECCO Consortium

1: Massachusetts Institute of Technology
2: Harvard University
3: University of Texas at Austin

Ocean Sciences Meeting

PL34A-1825

Motivation

- Vorticity and Gyre/Overturning dynamics are linked but remain obscure
  - Vorticity and material transport: **Reconcile theoretical framework/function spaces?**
- Closed global Vorticity Budget in ECCOv4r2 State Estimate allows evaluation.
  - **Focus: North Atlantic**
- Now clear that the ocean has a variety of different dynamical regimes (Sonnewald et al.).
  - Identified regionally and understood?
- Key to understanding and accurately modeling:
  - Deep Convention, Gulf Stream (GS) path and seperation

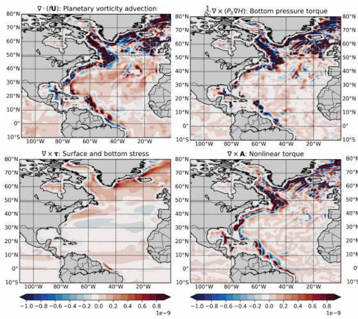


Figure 1: Barotropic Vorticity budget ($10^{-9}ms^{-2}$ eq 1). Global residual is $10^{-11}ms^{-2}$, relevant terms are captured.

Barotropic Vorticity: Buoyancy/Momentum

The depth integrated (Barotropic) vorticity:

$$0 = \underbrace{\nabla\cdot(f\mathbf{U})}_{\text{Planetary vorticity advection}} + \underbrace{\frac{1}{\rho_0}\nabla\times(p_b\nabla H)}_{\text{Bottom Pressure Torque}} + \overbrace{\frac{1}{\rho_0}\nabla\times\tau}^{\text{Wind and bottom stress}} + \underbrace{\nabla\times\mathbf{A}}_{\text{Non-linear torque}} + \overbrace{\nabla\times\mathbf{B}}^{\text{Viscous torque}} \qquad \text{(Eq 1)}$$

Following Mertz and Wright (1992) we distinguish a momentum driven torque of the depth averaged pressure, and the baroclinic Joint Effect of Baroclinicity and Relief (JEBAR) term:

$$\frac{1}{\rho_0}\nabla\times(p_b\nabla H) = \underbrace{\frac{1}{\rho_0}\nabla\times(\overline{p}\nabla H)}_{\text{Torque of depth averaged pressure}} - \underbrace{\nabla\times\left[\frac{\chi\nabla H}{H}\right]}_{\text{JEBAR}} \quad \text{(Eq 2)} \qquad \chi = \frac{g}{\rho_0}\int_H^z z\rho \mathrm{d}z \quad \text{(Eq 3)}$$

The JEBAR term (top right) is associated with changes in buoyancy (Eq 3), acting together with the momentum (bottom right)component in in BPT.

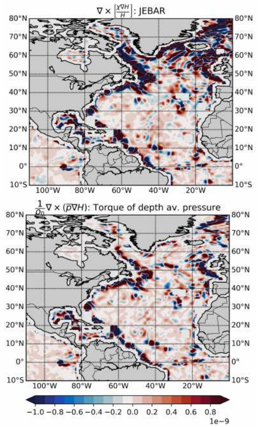


Table below summarizes the dynamical balances (plots below) colours indicate negative (blue) or positive (red):

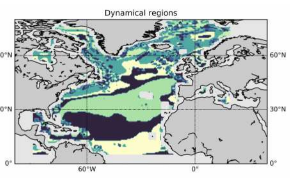
Area, name	Leading terms	Boyancy vs Momentum
12.2%, Quasi-Sverdrupian	$0 \approx \nabla\times\tau_{sb} + \nabla\cdot(f\mathbf{U})$	NA
15.7%, Momentum Dominated	$0 \approx \nabla\cdot(f\mathbf{U}) + \nabla\times\tau_{sb} + \frac{1}{\rho_0}\nabla\times(p_b\nabla \mathrm{H})$	JEBAR $< \frac{1}{\rho_0}\nabla\times(\overline{p}\nabla \mathrm{H})$
61.1%, Transition Zone	$0 \approx \nabla\times\tau_{sb} + \nabla\cdot(f\mathbf{U}) - \frac{1}{\rho_0}\nabla\times(p_b\nabla \mathrm{H})$	JEBAR $\approx \frac{1}{\rho_0}\nabla\times(\overline{p}\nabla \mathrm{H})$
3.6%, Buoyancy Dominated	$0 \approx \nabla\times\tau_{sb} + \nabla\times\mathbf{A} - \frac{1}{\rho_0}\nabla\times(p_b\nabla \mathrm{H})$	JEBAR $>> \frac{1}{\rho_0}\nabla\times(\overline{p}\nabla \mathrm{H})$
≈5.7%, Dominantly non-linear	$0 \approx \nabla\cdot(f\mathbf{U}) + \nabla\times\tau_{sb} + \frac{1}{\rho_0}\nabla\times(p_b\nabla \mathrm{H}) - \nabla\times\mathbf{A}$	JEBAR $>> \frac{1}{\rho_0}\nabla\times(\overline{p}\nabla \mathrm{H})$

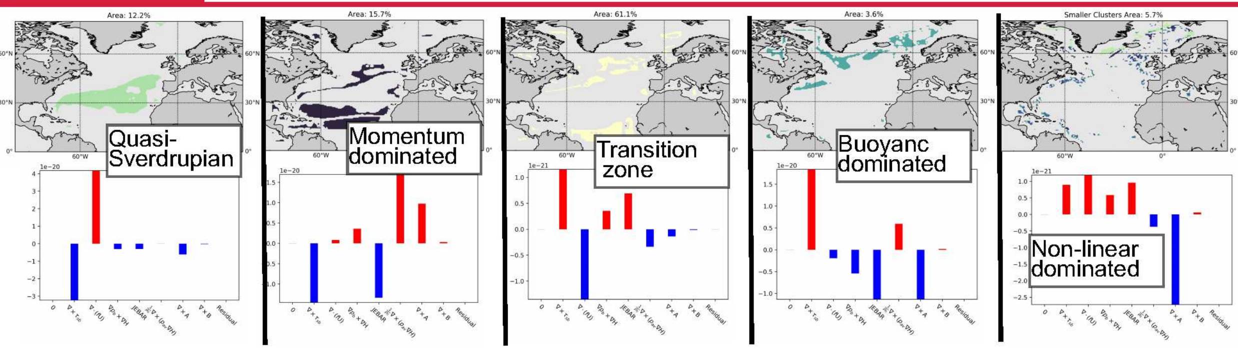
Overturning/Gyre

- JEBAR/buoyancy regions: Key to overturning. (Yeager, 2015)
- Momentum/Quasi-Sverdrupian: Gyre structure.
- Momentum/Transition Zone follows GS path and seperation: Suggests strong sensitivity to bottom boundary parameterisation.
  - Free-slip: BPT ≈ Up-hill flow.
  - No-slip: BPT ≈ Bottom viscous stress divergence. (Hughes and de Cuevas,2001)
  - This framework could offer a concise and computationally cheap way to diagnose what sets the GS path and seperation.
- Areas with strong non-linear contributions likely offer powerful insights, a topic of future work.

Dynamical Regimes

Dynamical regimes are found identifying configurations of terms/variability, using unsupervised learning algorithm K-Means (MacQueen, 1967)





Take Home

- A closed Barotropic Vorticity budget is presented
- The budget allows identification of dynamical regions using a clustering algorithm.
- Vorticity is shown to be a useful diagnostic and prognostic quantity by:
  - Distinguishing regions important for overturning and for gyre circulation
  - Highlighting key dynamical regions associated with GS path and seperation suggest where careful attention to parameterisation is nessesairy
- This interpretation could elucidate the link between the transport of material and vorticity, a key step towards reconciling theoretical frameworks.
- Future work will assess this globally.

For further details: paper in prep+poster

github.com/maikejulie/publications

- Hughes and de Cuevas, 2001: Why Western Boundary Currents in Realistic Oceans are Inviscid: A Link between Form Stress and Bottom Pressure Torque. JPO
- MacQueen, 1967: Some methods for classification and Analysis of Multivariate Observations. Berkley Symposium Proceedings.
- Mertz and Wright, 1992: Interpretations of the JEBAR term. JPO
- Sonnewald et al: Objectively Classified Dynamics: A Global Assessment of Barotropic Vorticity.
- Yeager, 2015: Topographic Coupling of the Atlantic Overturning and Gyre Circulations. JPO