The role of mesoscale eddies in the wind-driven Beaufort Gyre variability

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— FAMOS meeting, Nov 2016 —
Ekman pumping and FWC buildup in the BG

“The major cause of the large FWC in the BG is the process of Ekman pumping (EP) due to the Arctic High anticyclonic circulation centered in the BG.” (Proshutinsky et al, JGR, 2009).

Without knowing the process opposing Ekman pumping one can not determine the steady state or variability around it! 

$$\frac{dh}{dt} = W_{Ek} + ?$$
Persistence of the BG as a coherent large-scale circulation despite strong changes in forcing implies that it is a stable dynamical system!

\[
\dot{V} = -\frac{V}{T_E} + W(t)
\]

Bulk gyre characteristic (e.g. FWC)  
Equilibration time scale  
Bulk forcing (Ekman pumping)

Steady state: \( V = T_E \cdot W \)

Variability: \( Var(V) \sim T_E^2 \cdot Var(W) \)

Focus of the scientific community has been on determining the forcing (Ekman pumping), however the physical processes setting the equilibration time scale are poorly understood.
Hypothesis: mesoscale eddies are opposing the Ekman pumping and controlling the gyre stability

Vertically integrated annual average oceanic APE density field based on the PHC (Uotila et al, 2006, Ocean Modeling)

Large APE in the Arctic suggest that eddies fluxes might be important!

- Yang et al, 2016, JGR-Ocn. — potential vorticity budget requires eddy PV fluxes
- Apparent similarities with ACC dynamics (Marshall & Radko, 2003, JPO)
Baroclinic instability (‘in a few words’)
Testing implications in an idealized BG model

- Idealized eddy-resolving simulation of the gyre (MITgcm)
- Azimuthally symmetric closed domain with linear near costal topographic slope
- Resolution: 4x4km horizontal, 10-60m vertical ($R_d \sim 20$km)
- Momentum forcing: time-dependent anticyclonic surface wind stress $\tau(r,t)$
- Fast salinity restoring at the boundaries (equivalent to assuming infinite freshwater reservoir)
- No surface buoyancy fluxes

Statistically equilibrated gyre shows a strong presence of eddies over a large-scale gradient.

Manucharyan & Spall, GRL (2016)
Mesoscale eddies counteract Ekman pumping and constrain FWC even when freshwater is abundant

- **Mesoscale eddies** flatten the halocline in order to release the available potential energy and thus **counteract** Ekman pumping.
- **BG** is **highly sensitive** to surface-stress forcing because the mesoscale eddy diffusivity depends on the halocline slope.

*Manucharyan & Spall, GRL (2016)*

\[
\begin{align*}
\text{FWC} & \sim \tau^{1/3} \\
T & \sim \frac{R^2}{K} \sim \tau^{-2/3}
\end{align*}
\]
Halocline dynamics near equilibrium

Halocline perturbations obey a diffusion equation forced by Ekman pumping

\[ h'_t = \frac{1}{r} \left( nK_0 r h'_r \right)_{r} + \frac{1}{r} \left( r \left( \frac{\tau'}{f} \right) \right)_{r} \]

Eddy diffusion  Ekman pumping

Key implications for FWC dynamics

I. Only large-scale Ekman pumping can efficiently affect FWC

\[ FWC = \sum_{i=1}^{\infty} \frac{W_E^i}{\lambda_i} \approx \frac{W_E^0}{\lambda_0} \]

II. FWC obeys an exponential decay equation

\[ FWC = -\frac{FWC}{T_0} + W_E(t) \]

III. FWC tendency is determined only by boundary processes

\[ GI = 2\pi R \frac{\Delta S}{S_b} \left( nK_0 s' - \frac{\tau'}{f} \right) \bigg|_{r=R} \]

Manucharyan, Spall, & Thompson, 2016, JPO
I. FWC response to spatially inhomogeneous pumping

\[
\frac{1}{r} \left[ r K_0(r) h_i^* \right]_r = -\frac{h_i^*}{T_i}
\]

\[
FWC = \sum_{i=0}^{\infty} \bar{W}_i T_i \approx \bar{W}_0 T_0
\]

- Eddy diffusion operator defines a set of eigenfunctions and associated time scales
- Eddies are most efficient in damping response to inhomogeneous Ekman pumping

Surface-stress eigenfunctions have the same area-averaged Ekman pumping. Only large-scale Ekman pumping distribution can significantly affect FWC.
II. FWC response to periodic Ekman pumping

\[ \frac{dh'}{dt} = -\frac{h'}{T_0} + \delta W \sin \omega t \]

\[ \rightarrow h' = \delta h \sin(\omega t - \phi) \]

- At low frequencies halocline response to periodic pumping is maximized; without eddies the halocline amplitude is unconstrained.
- At high frequencies (e.g. seasonal cycle) there is a quarter of a period lag associated with Ekman advection as eddy effects are negligible.

Theory matches the eddy resolving model
III. Gyre Index for FWC tendency

In the numerical model the GI accurately approximates FWC tendency using observables only at gyre boundaries!

\[ GI = 2\pi R \frac{\Delta S}{S_b} \left( nK_0s' - \frac{\tau'}{f} \right) \bigg|_{r=R} \]

Eddies or Ekman pumping can only redistribute the halocline thickness and the only way to change FWC is via boundary fluxes.
Eddy Memory mode of decadal variability

\[
\overline{v'b'} = K \nabla h^*, \quad h^*(t) = \frac{1}{\tau} \int_{-\infty}^{t} \exp[- \frac{t - t'}{\tau}] h(t') dt' \rightarrow \ddot{a} + \frac{1}{\tau} \dot{a} + \frac{1}{T \tau} a = W(t)
\]

The adjustment to a sudden change in forcing is not an exponential spin-up. Instead, FWC significantly overshoots its equilibrium value.

The presence of EM-mode implies increased variance at decadal time scales!

Mesoscale eddy field has finite memory of past states!

**Implications**
- The adjustment to a sudden change in forcing is not an exponential spin-up. Instead, FWC significantly overshoots its equilibrium value.
- The presence of EM-mode implies increased variance at decadal time scales!

Manucharyan, Thompson, & Spall, 2016, JPO
Conclusions

- **Mesoscale eddies** play a key role in constraining the Ekman-driven halocline variability of the BG.

- Only **large-scale Ekman pumping** patterns can efficiently change the gyre FWC.

- **Gyre Index** accurately predicts FWC tendency using observables only at boundaries.

- Natural **decadal variability** of FWC is possible via **Eddy Memory** mode.