Stressing out the Beaufort Gyre: insights into Arctic upper ocean dynamics from an idealized model

Marta Faulkner, Michael Spall,
Isabela Le Bras
CAMAS Workshop 2025

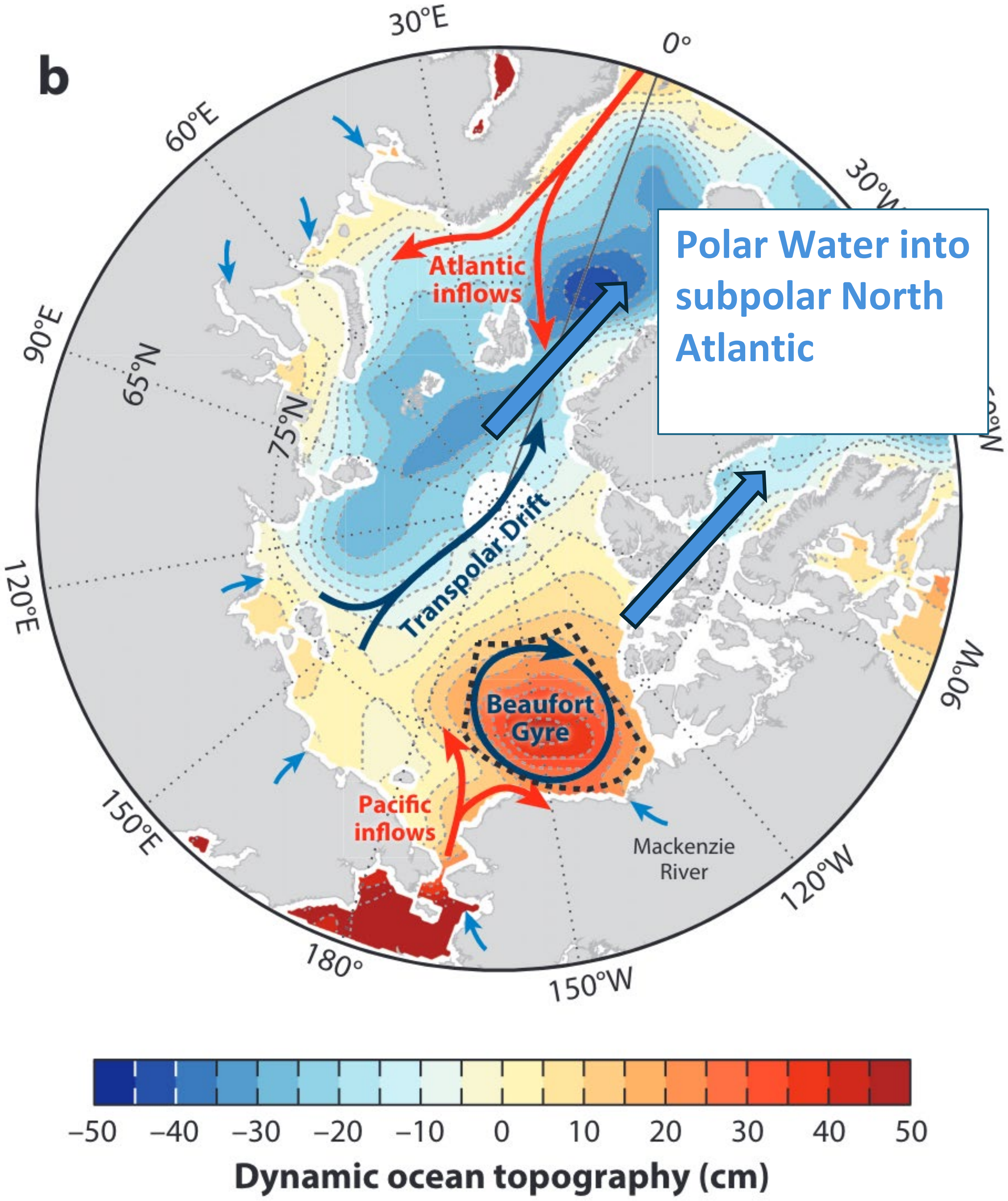
Photo: US Coast Guard

Why care about Arctic circulation?

Arctic freshwater & heat budgets interact with global circulation

Sea ice is influenced by the upper ocean (in particular, Atlantic Water): climate feedbacks, local community/ecosystem effects

Upper Arctic circulation is important on global and regional scales – but our understanding of the dynamics is incomplete

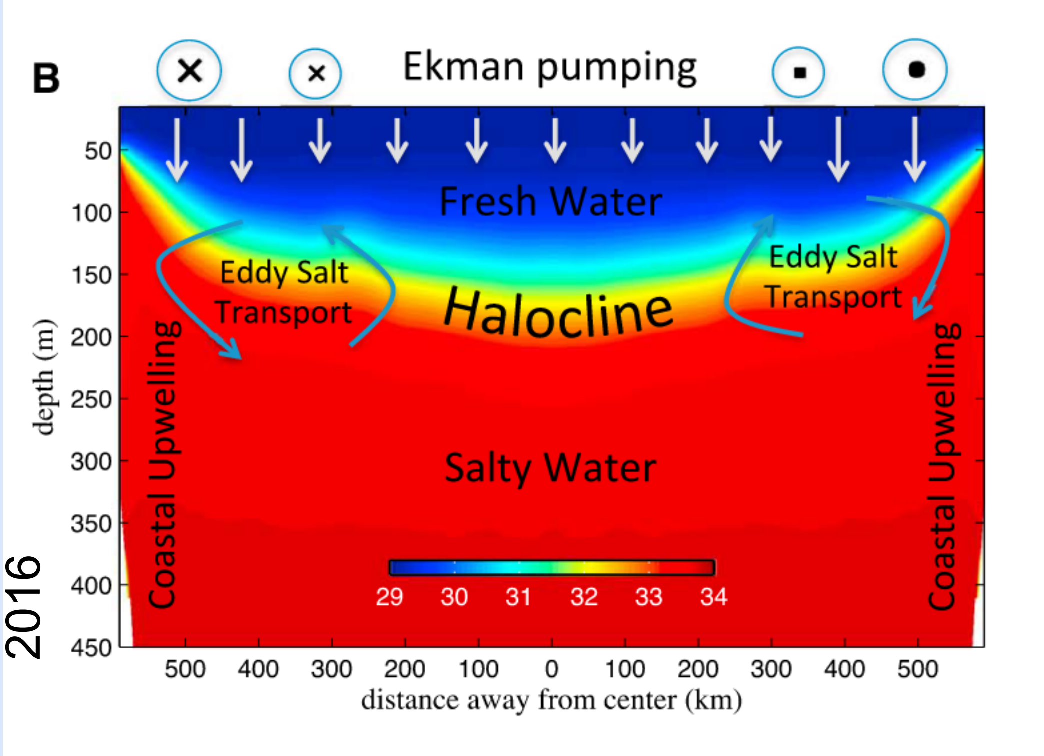


Timmermans & Toole, 2023

A previous idealized model of the Beaufort Gyre

Wind-driven freshwater buildup and release in the Beaufort Gyre constrained by mesoscale eddies

Georgy E. Manucharyan[1] and Michael A. Spall[1]



Manucharyan & Spall 2016

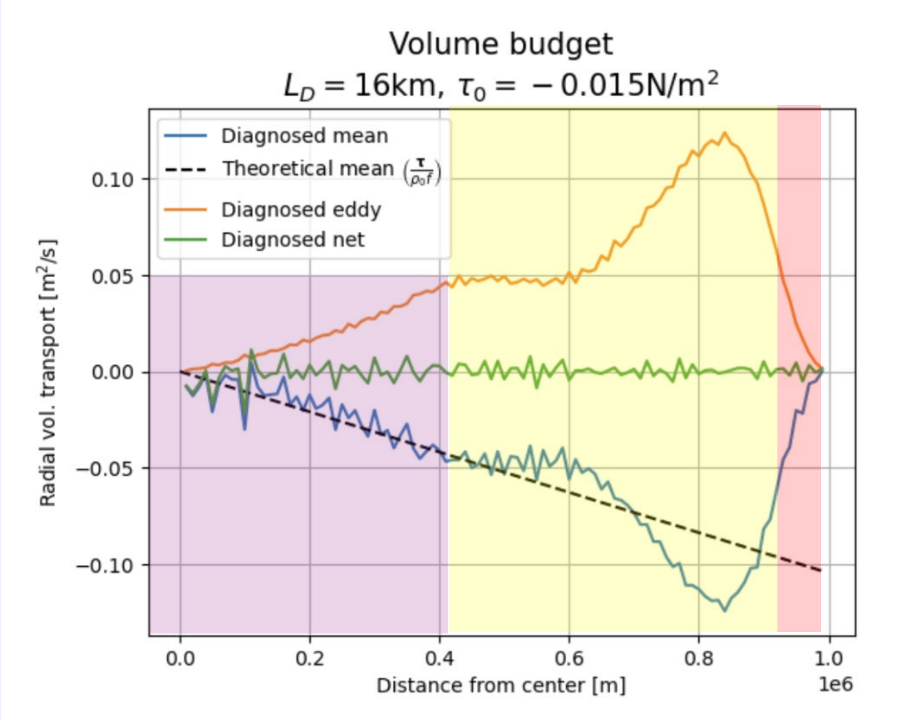
Continuously stratified model of anticyclonic gyre without solid boundaries – circular domain, azimuthally uniform surface stress

Mean inwards Ekman mass transport balanced by outwards eddy mass flux:

$$\frac{\tau_0 r}{f \rho_0 R} + k \left(\frac{\partial h}{\partial r}\right)^2 = 0.$$

Next step: add boundaries to a two-layer version of this model

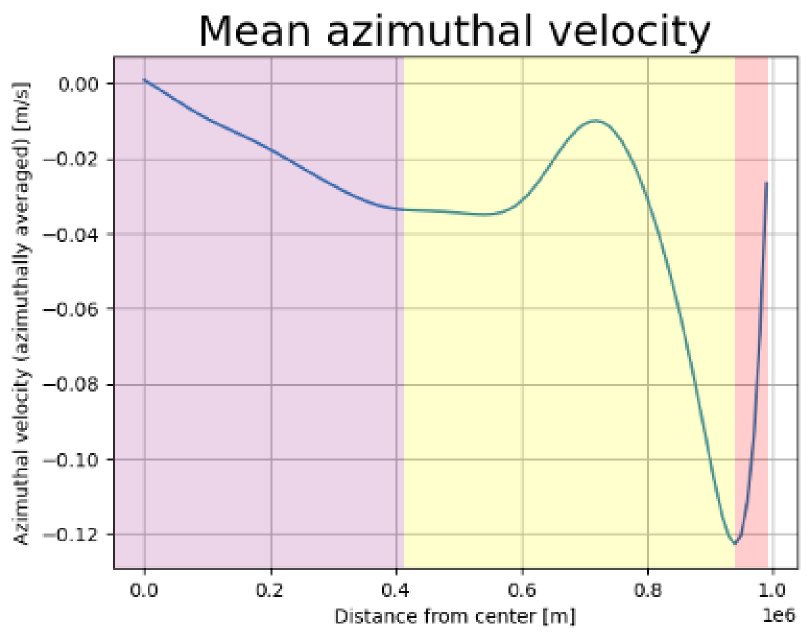
No straits; anticyclonic surface stress: three dynamical regions

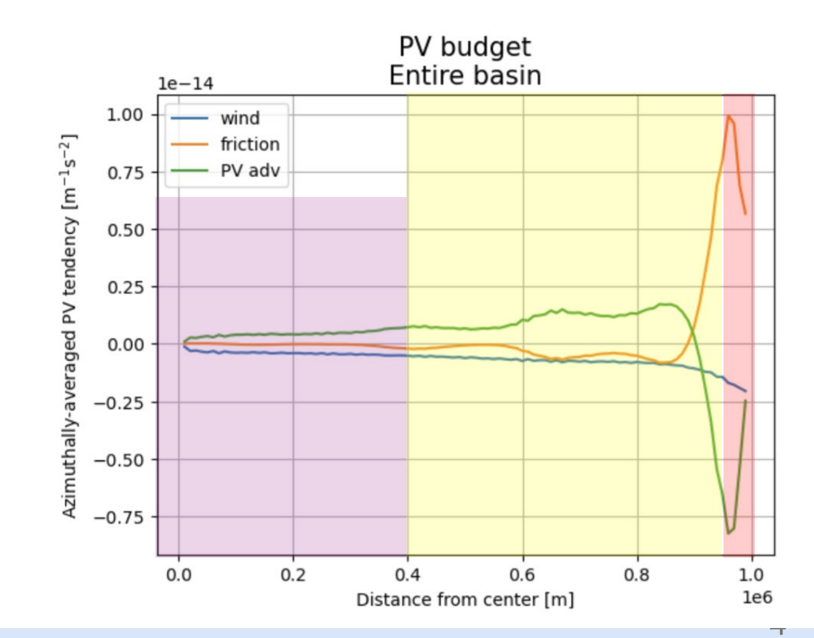


Interior – mass balance as described by M&S

Boundary/frictional region – vorticity advected to the boundary is dissipated

Nonlinear/transition region – departure from interior balance featuring undulations around linear Ekman transport





Parameter	Values
Resting deformation radius L_D [km]	16, 27, 35, 43, 51
Maximum surface stress τ_0 [N/m^2]	0.0025, 0.015, 0. 275, 0.04

No straits; anticyclonic surface stress: Scalings for boundary current

Assume balance between Ekman and friction:

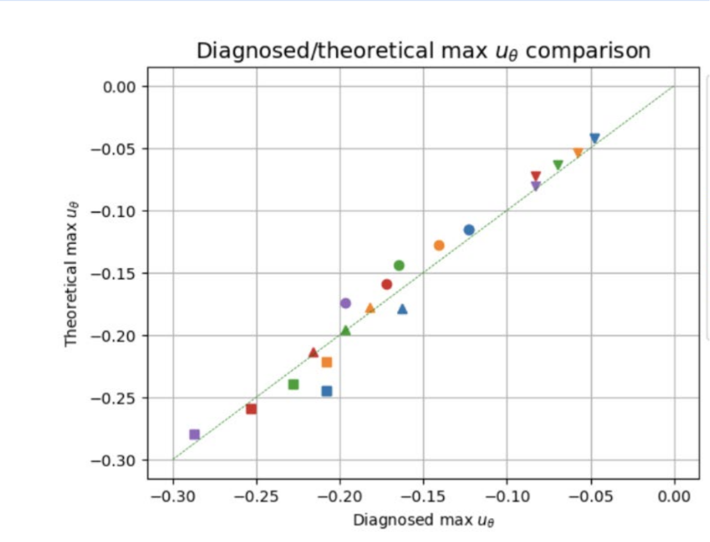
$$0 = \frac{\tau_0 r}{\rho_0 h_1 R} + A\frac{\partial^2 u_\theta}{\partial r^2} \approx \frac{\tau_0}{\rho_0 h_b} + A\frac{|U_\theta^{max}|}{L_b^2}.$$

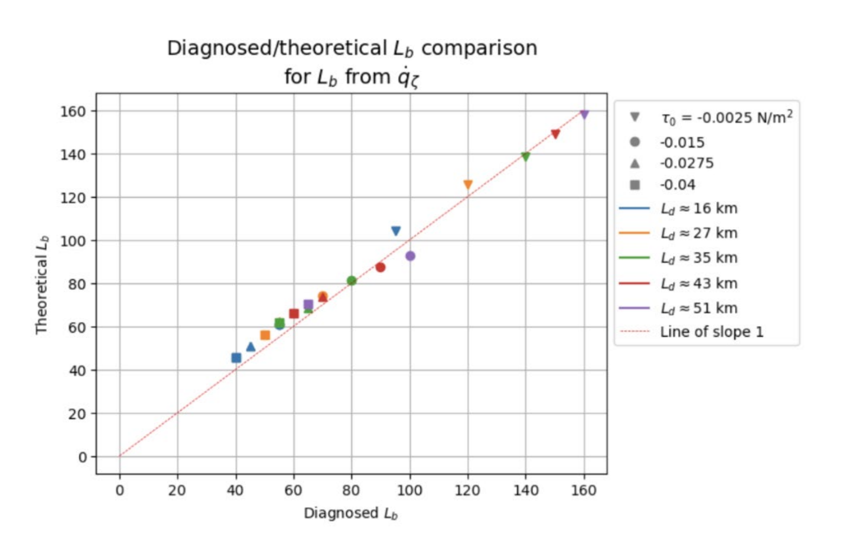
$$L_b = \alpha\sqrt{\frac{A|U_\theta^{max}|}{f|U_{Ek}^{max}|}}.$$

Steady state: layer 1 Ekman pumping opposed by layer 2 Ekman suction
+ geostrophy

$$|U_\theta^{max}| = \gamma\left[\frac{f|T_{Ek}^{max}|}{C_D(H_1+H_2-h_b))} + L_D^2\frac{f}{h_b}\sqrt{\frac{|T_{Ek}^{max}|}{k}}\right].$$

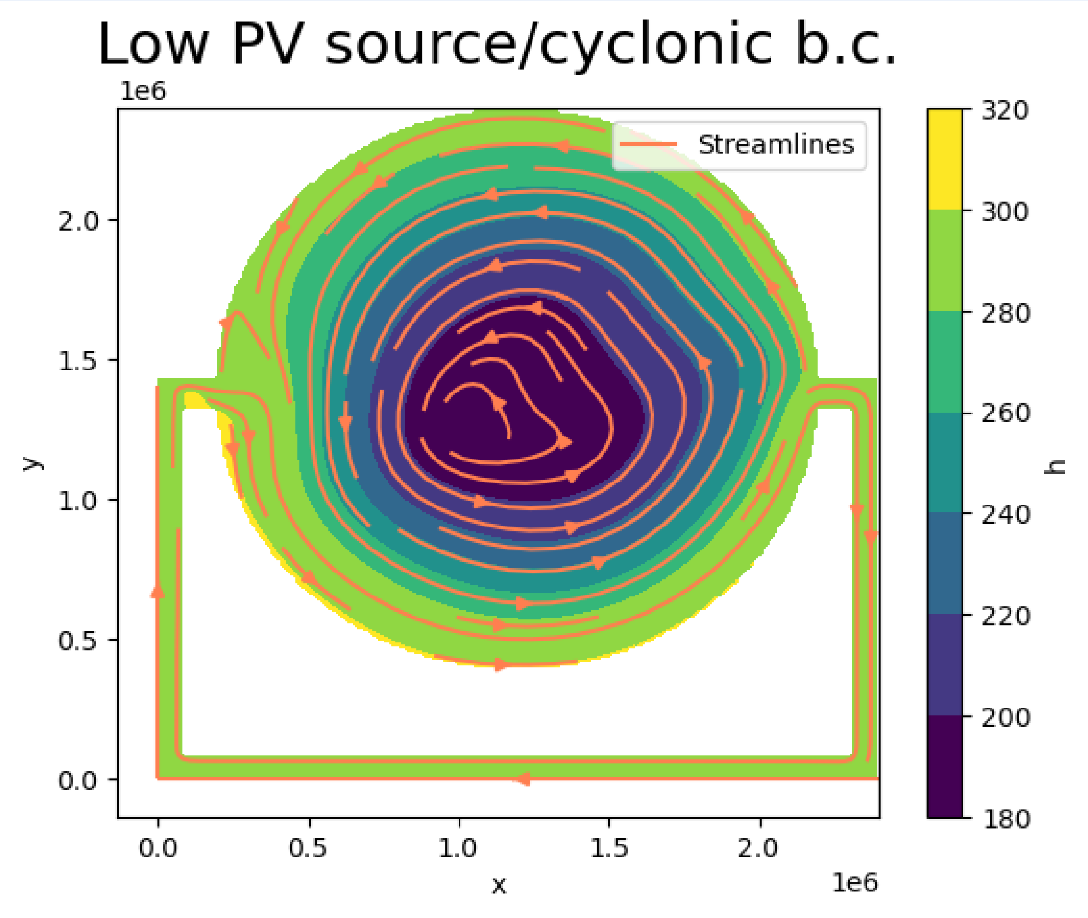
For γ = 1.2, α = 2, scalings from theory match model output very well

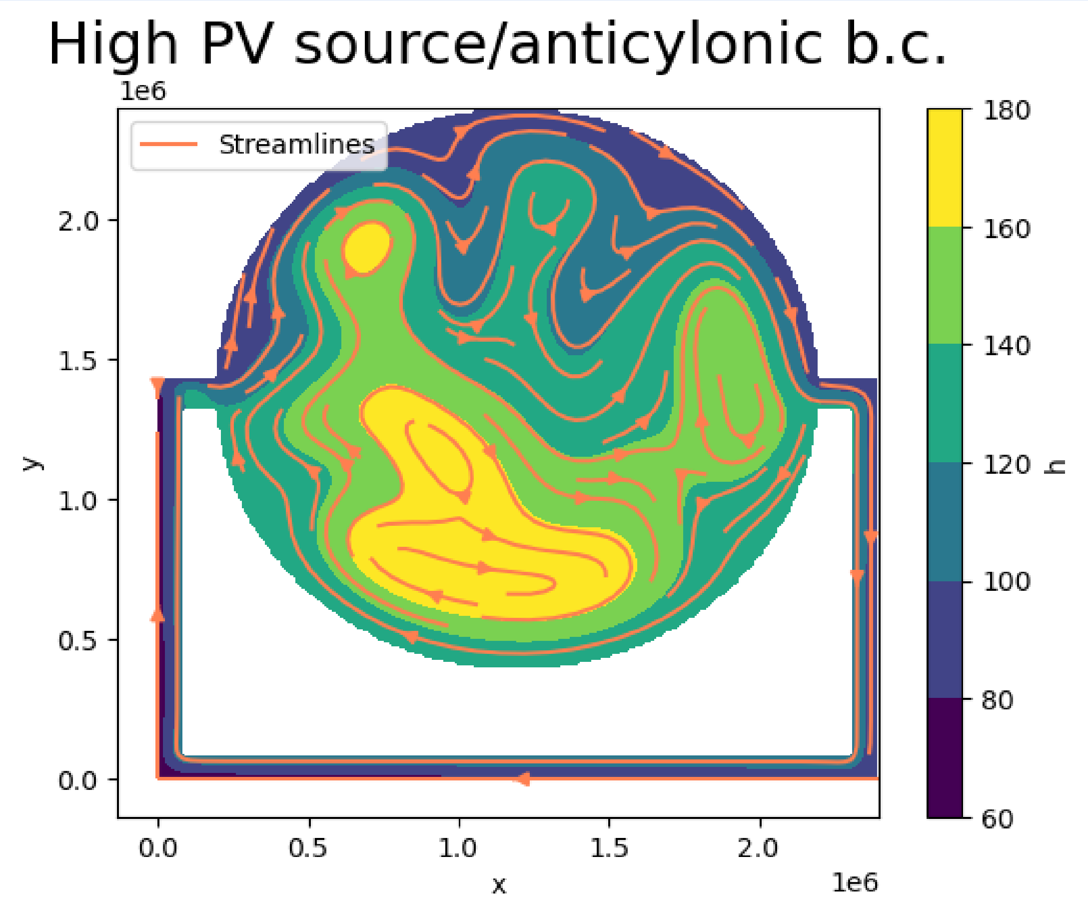




Symmetric straits, no surface stress –multiple equilibria depending on PV of strait

Layer 1 thickness after 50 years of integration – 1 Sv volume flux through strait





Takeaways for today

Ekman-eddy flux balance as described by Manucharyan and Spall (2016) applies to the interior of a bounded gyre.

First order momentum balance between Ekman & friction at the boundary produces a reliable scaling for the model.

Straits alone can also control basin-scale steady-state.

Next steps

- Compare timescales of straits-only equilibration to previous work on boundary current stability (e.g. Spall 2003, Straneo 2006)
- Straits plus surface stress (we find that strong surface stress overrides influence of straits)
- Cyclonic surface stress in addition to anticyclonic
- Time dependence of forcing/FWC adjustment (for unbounded gyre, see Manucharyan et al. 2016)