Advances in Arctic Conceptual Modeling: A Beaufort Gyre Example

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Why use conceptual models when computers are powerful enough to represent more processes and simulate the real ocean more accurately?

- Well designed conceptual models (analytical or numerical) eliminate non-essential processes and focus on a system of reduced complexity
- A nondimensional framework identifies the key parameters, and parameter combinations, that control the behavior
- Nondimensional numbers can be interpreted as the competition between different processes
- Conceptual models require simplifying assumptions (geometry, dynamics) but they can be effectively combined with more comprehensive models or observations to test limits of the approximations

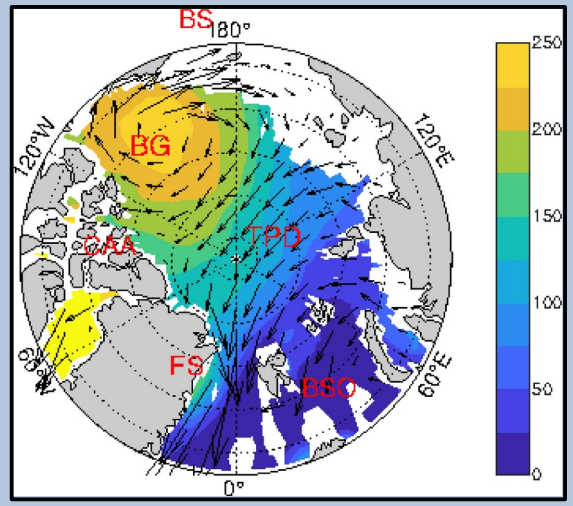
A Beaufort Gyre Example

The Beaufort Gyre is a dominant feature of the Arctic Ocean circulation and hydrography

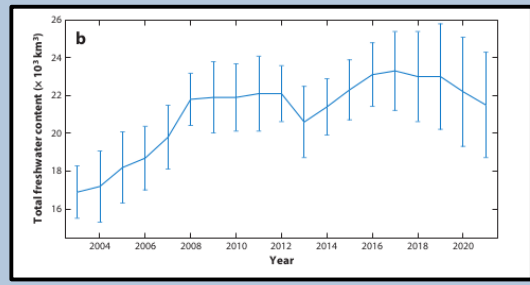
Stores approximately 20,000 km^3 of freshwater

Anticyclonic circulation of several Sv

Storage and release of freshwater impacts water masses and deep convection at lower latitudes, linked to Great Salinity Anomalies



Ice velocity and halocline thickness



Freshwater content
(Timmermans and Toole, 2023)

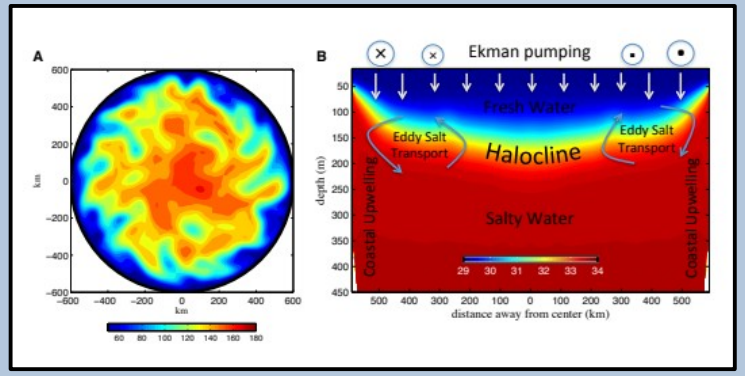
It was hypothesized that fluctuations in freshwater storage in the BG are driven by shifting the dominant pattern of wind stress curl in the Arctic Ocean – A balance between Ekman pumping and lateral eddy fluxes
(Proshutinsky and Johnson, 1997)

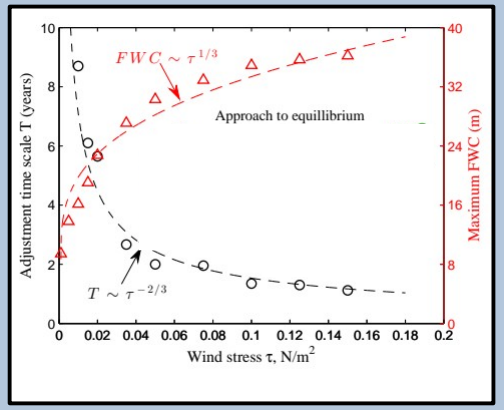
The dynamics of the Beaufort Gyre differ from those of mid-latitude wind-driven gyres
(beta is small, no western boundary)

More similarity with the mid-latitude atmosphere and Southern Ocean (Andrews and McIntyre, 1978, Marshall and Radko, 2003)

Numerous studies have considered an isolated region of anticyclonic stress curl, some using the Transformed Eulerian Mean approach

(e.g. Davis et al., 2014; Yang, 2009; Marshall, 2015; Manucharyan et al., 2015, 2016; others)





(Manucharyan and Spall, 2015)

Conceptual model balances Ekman pumping with lateral eddy thickness fluxes.
Eddy flux parameterization leads to a prediction of how BG depth, FWC, and spinup timescale depend on surface stress and stratification

Identified the role of eddies and gives a prediction of how FWC depends on surface stress, but it is a steady theory.

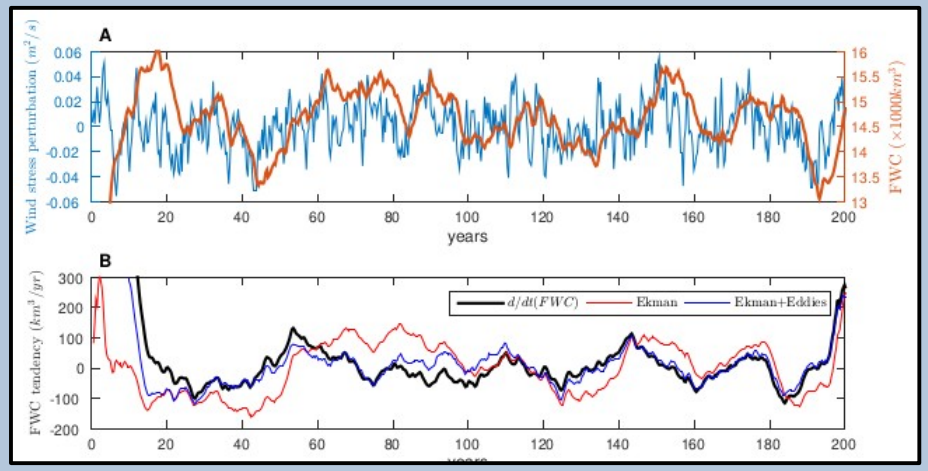
Manucharyan et al. (2016) added time-dependence:

$$h_t = \underbrace{\frac{1}{r}\left(nK_0 r h_r\right)_r}_{\text{Eddy diffusion}} + \underbrace{\frac{1}{r}\left(r\frac{-\tau}{\rho_0 f}\right)_r}_{\text{Ekman pumping}} .$$

Idealized model forced with red noise stress
Produces low frequency variability in FWC

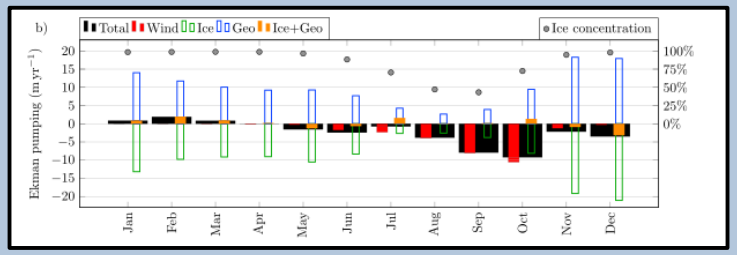
Ekman pumping alone can not explain the change in FWC

Ekman + eddy fluxes compares well with full PE model
Eddies are most important on interannual and longer time scales



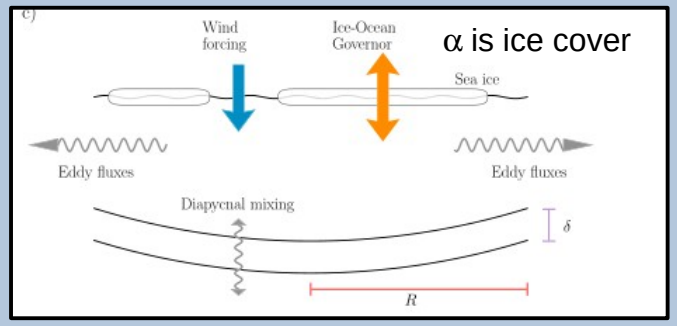
These initial models were forced with a specified surface stress

In reality the winds put stress onto the ice and the ice transmits stress into the ocean
They generally are not the same due to internal ice stresses and ocean currents (Meneghello et al., 2018a, b)



Observations indicate that the net ice-ocean stress is much less than expected by the ice motion alone

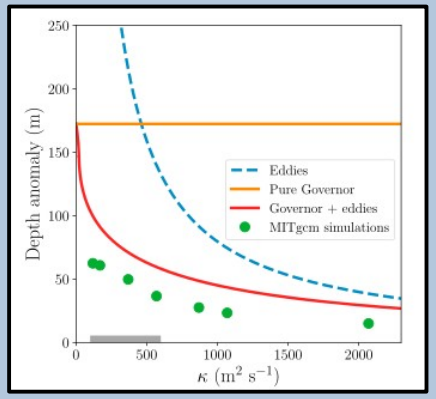
This is because the ocean currents are in the same direction as the ice motion



Modify the theory to account for ocean currents under the ice

$$h_{eq} = \frac{u_i f R}{g'} - \frac{f^3 R}{2\alpha g'^2 C_{Di}} \left(\kappa \mp \sqrt{\kappa \left(\kappa - \frac{4\alpha C_{Di} u_i g'}{f^2} \right) + \frac{4\alpha(1-\alpha) C_{Da} u_a^2 \rho_a C_{Di} g'^2}{f^4 \rho}} \right),$$

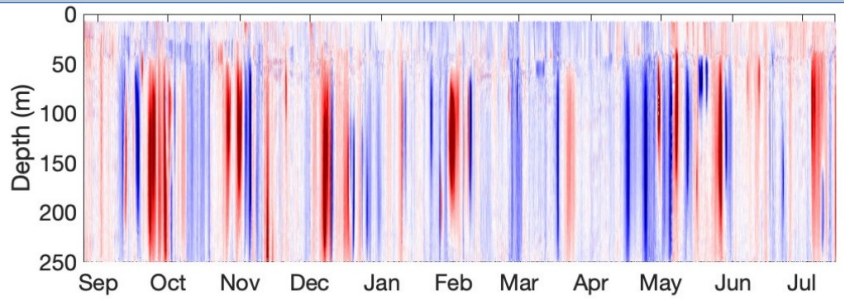
(Doddridge et al., 2019)



Numerical models find that including the ocean velocity and sea ice reduces the halocline thickness compared to equilibrium with eddies only or ice-ocean governor only

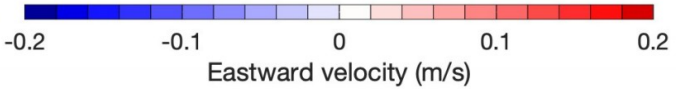
Observational evidence for large-scale meanders?

ITP data shows energy over a wide range of scales (Cole)



Total velocity

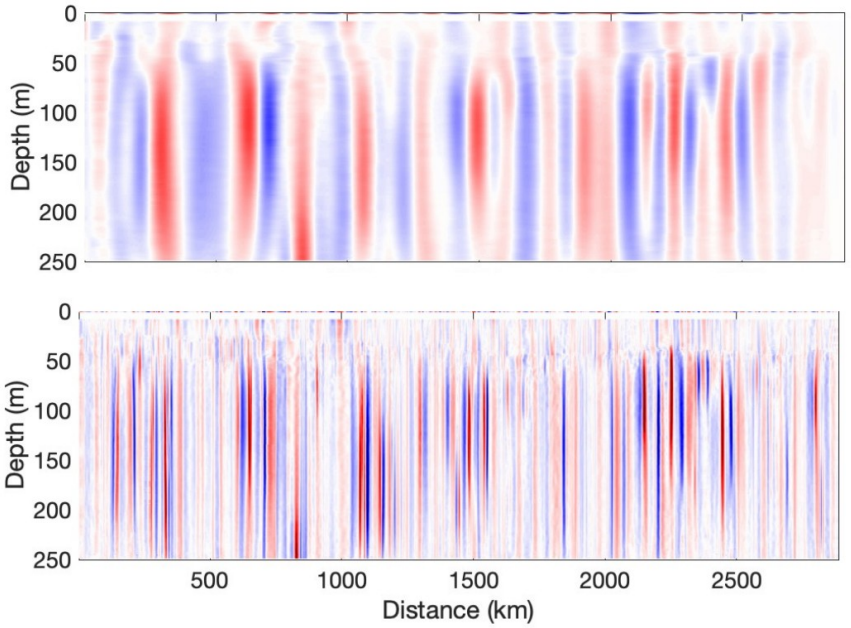
ITP-70



Large-scale eddies not evident from raw timeseries but do show up upon analysis

Small-scale eddies are very strong but absent from the simple two-layer models

Some are generated at the boundaries but some are likely generated in the interior

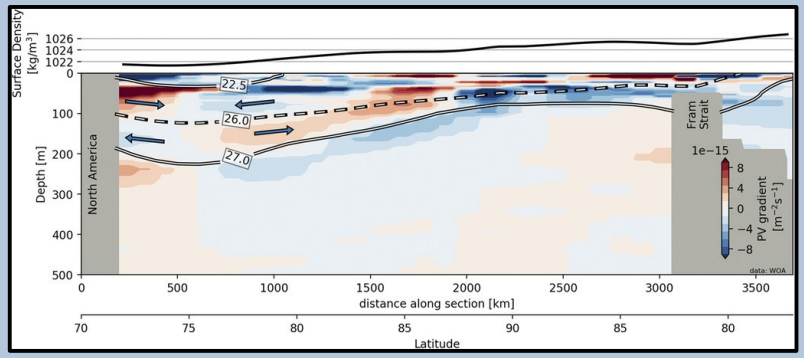


Large eddies
100-600 km
~12-70 days

Small eddies
10-100 km
~1-12 days

Observations indicate that PV gradients change sign within the halocline.

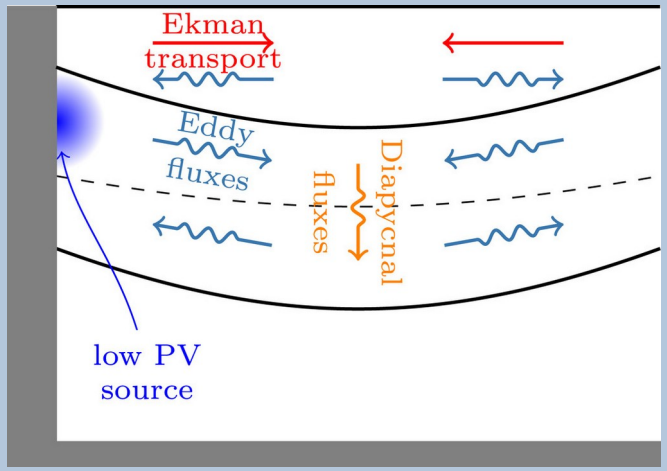
This is inconsistent with pure Ekman forcing



PV gradient

Suggests diapycnal mixing is important, e.g. boundary source of low PV water (Pacific Winter Water) and interior mixing

This is not represented in the simple two-layer theory

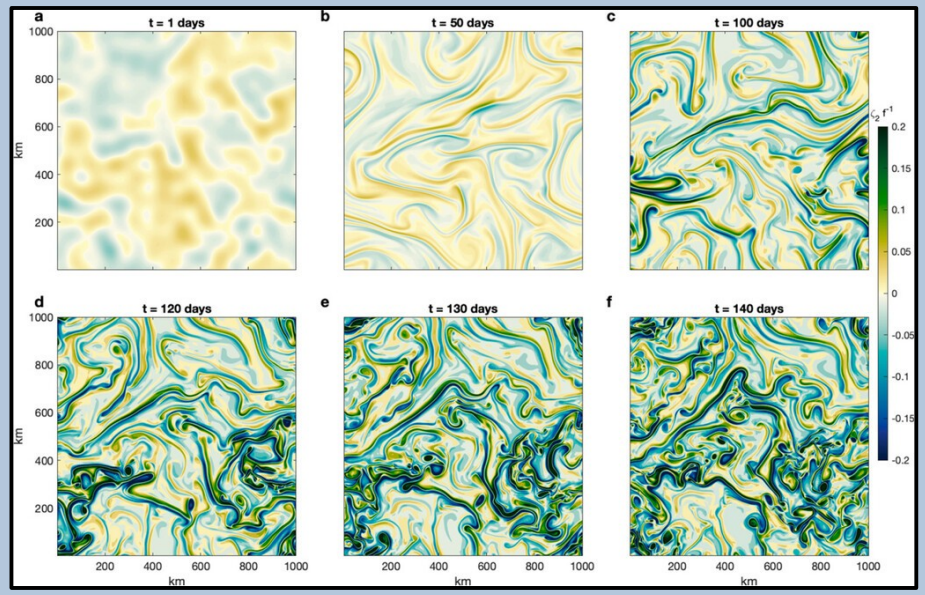


(Meneghello et al., 2020)

Addition of an interior PV gradient produces smaller eddies with a second baroclinic mode vertical structure

Small eddies arise from instability of fronts generated by stirring of the interior PV gradients by barotropic, large-scale eddies

Still an open question on what supports the along-isopycnal PV gradients in the interior of the Beaufort Gyre



3-layer QG model

(Manucharyan and Stewart, 2022)

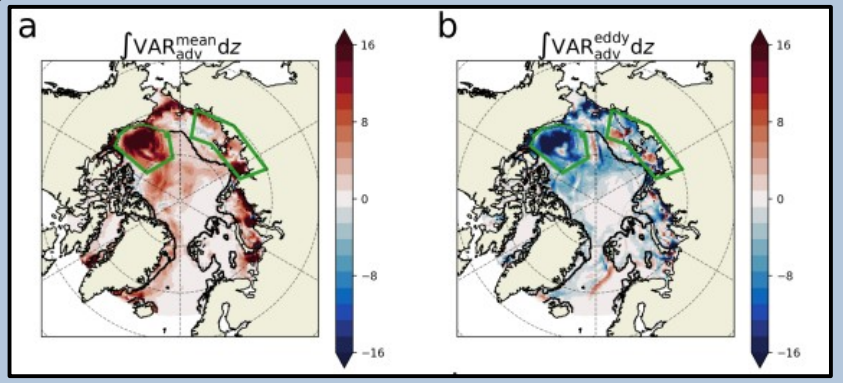
Predictions from the conceptual models can also be tested in more realistic models

Hochet et al. (submitted) evaluate contributions to salinity variance in the 1 degree ECCO v4r3 state estimate

The leading order balance in the Beaufort Gyre is between advection of mean salinity (Ekman pumping) and (GM parameterized) eddy fluxes

Additional terms (diffusion and surface fluxes) not included in the basic TEM theory contribute about 10% of the variance, small but not negligible

This confirms leading order balance and suggests additional processes that might be included in the theory



mean advection eddy advection

ECCO v4r3

Conceptual models provide a valuable contribution to understanding the oceanic general circulation

The Beaufort Gyre provides a nice example of how to combine process models with observations and more comprehensive GCMs. Theory provides a framework for analysis, observations/models can verify, and also identify elements missing from, the theory

The Arctic has some elements in common with mid-latitude regimes, where our dynamical understanding is more mature, but also differs in important ways:

- no western boundary
- ice-cover limits mixing
- strong feedbacks between ocean-ice-atmosphere (momentum, heat, freshwater fluxes)
- boundaries act as important water mass sources (boundary currents and convection)
- salinity dominates equation of state

<u>Areas ripe for further development of dynamical understanding:</u>

Penetration of Atlantic Water into the Arctic
The Trans Polar Drift
Double estuary
Variability in exchanges with lower latitudes