Building and removing stratification in the Arctic Ocean

John Marshall
Massachusetts Institute of Technology

With help and advice from:

An Nguyen
Patrick Heimbach
Hajoon Song
Christopher Klingshirn

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Water mass transformation

Buoyancy gain
Pump

Buoyancy loss
Suck

‘heavy’ subduction

eddies

Briefly review aspects of circulation in the Arctic basin

Dynamics of the Beaufort Gyre

Example of light subduction
Figure 3. Schematic diagram of the three phases of open-ocean deep convection: (a) preconditioning, (b) deep convection, and (c) lateral exchange and spreading. Buoyancy flux through the sea surface is represented by curly arrows, and the underlying stratification/outrcrops is shown by continuous lines. The volume of fluid mixed by convection is shaded.
Dynamical ideas

• Extract buoyancy from surface of homogeneous, rotating ocean

Natural Rossby number

\[ R_o^* = \frac{l_{rot}}{H} = \frac{1}{H} \left( \frac{B}{f^3} \right)^{\frac{1}{2}} \]

Radius of deformation

\[ \frac{l_P}{H} = \sqrt{R_o^*} \]

Numbers

\[ f = 10^{-4} s^{-1} \]

Ocean - rotation important

\[ B \sim 10^{-7} m^2s^{-3} \quad H \sim 1km \]

\[ l_{rot} \sim 1km \quad R_o^* \sim 0.1 \rightarrow 1 \]

Atmosphere - rotation not important

on convective scale

\[ B \sim 10^{-2} m^2s^{-3} \quad H \sim 10km \]

\[ l_{rot} \sim 100km \quad R_o^* \sim 10 \rightarrow 50 \]
Interplay between convection and baroclinic instability

Convection → Baroclinic instability

Eddies flux buoyancy vertically to offset loss from the surface

Jack Whitehead

Upright convection

Baroclinic instability

cool

Vertical velocity \( W \)
Light subduction

Subtropical gyres!
Building Blocks

f-plane

Warm, pump

Cool, suck

β-plane gyres

Antarctic Circumpolar Current

Warm, pump

Warm, pump

Cool, suck
Review aspects of Arctic Circulation
Simulation of the Arctic Ocean using MITgcm

Ocean model
- 50 vertical levels, volume-conserving, C-grid
- Surface boundary conditions: JRA-25
- Initial conditions: WOA05

Sea ice model
- 2-category zero-layer thermodynamics [Hibler, 1980]
- Viscous plastic dynamics [Hibler, 1979]
- Initial conditions: Polar Science Center
- Snow simulation: [Zhang et al., 1998]

Regional Arctic solution
- 4.5, 9 and 18 km horizontal grid spacing.
- Boundary conditions from global solution.
- Bathymetry: IBCAO
- Time: 1992 – 2009 (18 years)

ECCO2 Project: collaboration between MIT and JPL
ECCO2

5-year climatology (1992-1997)

T at 200m
Blue circulation is sensitive to local atmospheric circulation

Anticyclonic circulation regime: JGR, 1997
Proshutinsky and Johnson
Wind stress

Mean wind stress $N/m^2$

Net freshwater flux in to the Arctic ($km^3/yr$)

<table>
<thead>
<tr>
<th></th>
<th>Nguyen et al. [2011]</th>
<th>Serreze et al. [2006]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precip.</td>
<td>2900</td>
<td>3300±680</td>
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<tr>
<td>Evaporation</td>
<td>-780</td>
<td>-1300±710</td>
</tr>
<tr>
<td>Runoff</td>
<td>2500</td>
<td>3200</td>
</tr>
<tr>
<td>Bering Strait</td>
<td>2160</td>
<td>2500</td>
</tr>
</tbody>
</table>

Balanced by ice and freshwater export
Section through the Beaufort Gyre

Pumping down of fresh water by the wind

Fresh water lens

T colored

S contoured

Halocline layer

Light subduction

Vast stores of available potential energy in the fresh water lens. Expect vigorous baroclinic instability.
Arctic is seething with baroclinic instability and geostrophic turbulence.
Dynamics of the Beaufort Gyre

What sets depth and stratification of the freshwater lens?

Downward buoyancy flux could be balanced by ‘small-scale’ mixing or ‘eddy fluxes’.

Note – cannot use ‘classic’ thermocline theory

\[ \beta = 0 \]
Laboratory experiment:

'f'-plane

warm pumped lenses

WARM

pump

eddies

T profile under disc


Fig. 5. Time-mean profile for the reference laboratory lens. The circles mark the actual mean temperatures measured at each thermocouple with the curve indicating the best fit exponential.
Theory

\[ Q = 2\pi r_o \overline{v'h'} \]

\[ \overline{v'h'} = cuh \]

\[ u = \frac{g'h}{fr_o} \]

\[ h \sim \sqrt{\frac{fW_{Ek}}{g'} r_o} \]

\[ u \sim \sqrt{\frac{g'W_{Ek}}{f}} \]

\[ \sqrt{\frac{fW_{Ek}}{g'} r_o} \]
Numbers for freshwater lens

e-folding scale

\[ h \approx \sqrt{\frac{f_{w}}{g'}} r \]

\[ h \approx \sqrt{\frac{1.4 \times 10^{-4} \text{s}^{-1} \times 10 \text{m/y}}{0.7 \times 10^{-2} \text{m s}^{-2}}} \times 500 \text{km} \]

\[ = 40 \text{ m} \]

\[ l_{rot} = \left( \frac{w g'}{f^3} \right)^{\frac{1}{2}} \approx 30 \text{ m} \]

\[ R^* = \frac{l_{rot}}{h} \approx 1 \]

\[ L_{\rho} = \sqrt{l_{rot} \times r} \]

\[ \approx 4 \text{ km} \]

In the correct ball-park
Average Profiles near 75N 145W Sept 2006 to Aug 2007

Salinity (psu)

e-folding scale of 70m

Data courtesy of Mary-Louise Timmermans

Ice-Tethered Profilers
John Toole

http://www.whoi.edu/itp/data/
Conclusions

Dynamical and water mass transformation processes in the Arctic basin are complex:

--- observations reveal extraordinary detail
--- models (GCMs) can capture only broad aspects

Geostrophic turbulence is ubiquitous
    ---- not just noise, surely there for a reason

Beaufort gyre is a beautiful example of ‘Light Subduction’
    Geostrophic eddies likely play a role in equilibrating the fresh water lens

Flow of Atlantic water at depth likely has very different dynamics
    See, e.g., Nost and Isachsen, JMR, 2003