Woods Hole Oceanographic Institution

FAMOS

Forum for Arctic Modeling and Observational Synthesis

Building and removing stratification in the Arctic Ocean

John Marshall
Massachusetts Institute of Technology

With help and advice from:

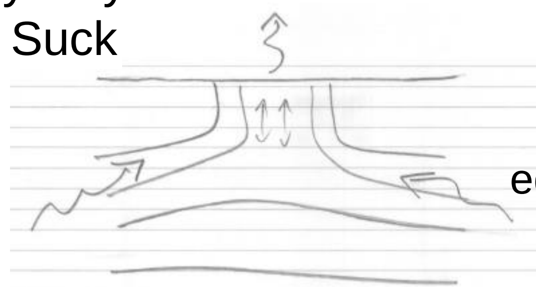
An Nguyen
Patrick Heimbach
Hajoon Song
Christopher Klingshirn

FAMOS School for young scientists
Tuesday, October 22nd, 2013

I

Water mass transformation

Buoyancy loss
Suck



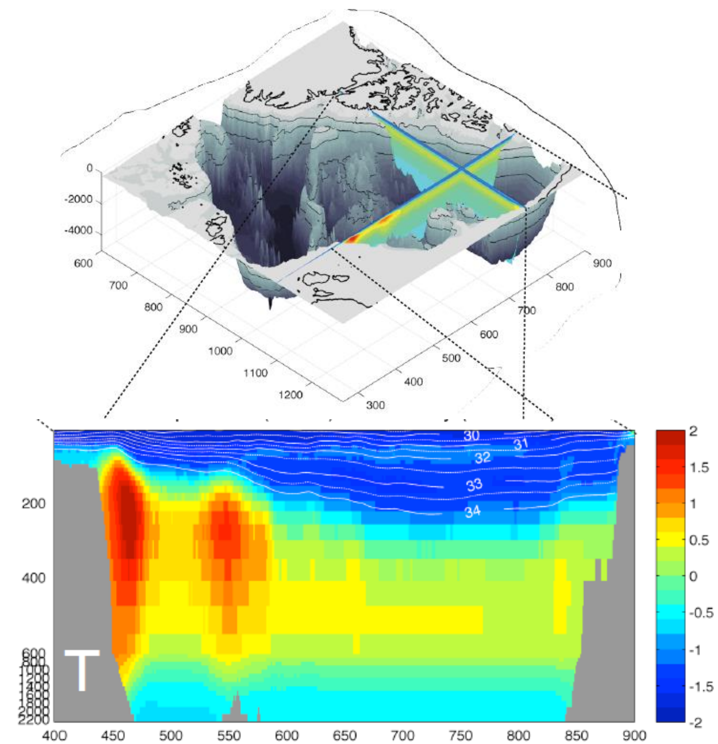
‘heavy’ subduction

Buoyancy gain
Pump

‘light’ subduction

II

Briefly review aspects of circulation in the Arctic basin



III

Dynamics of the Beaufort Gyre

Example of light subduction

Water mass transformation

'heavy' subduction

Greenland and
Labrador Sea

cool, suck

preconditioning

mixing

spreading

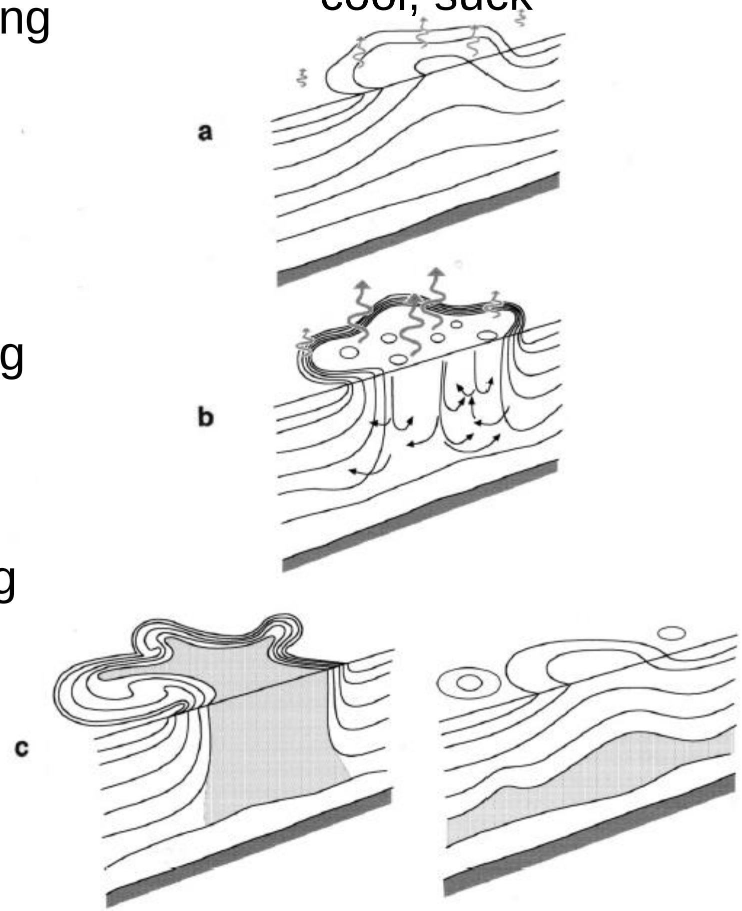
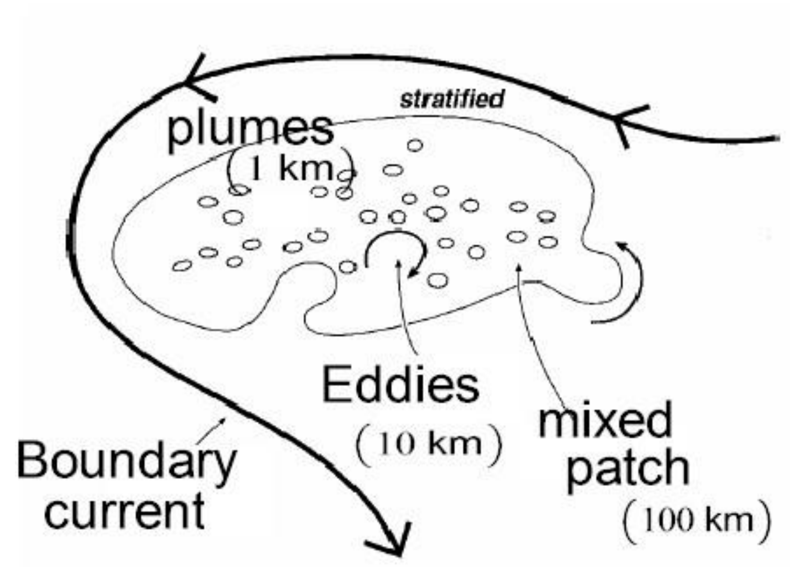
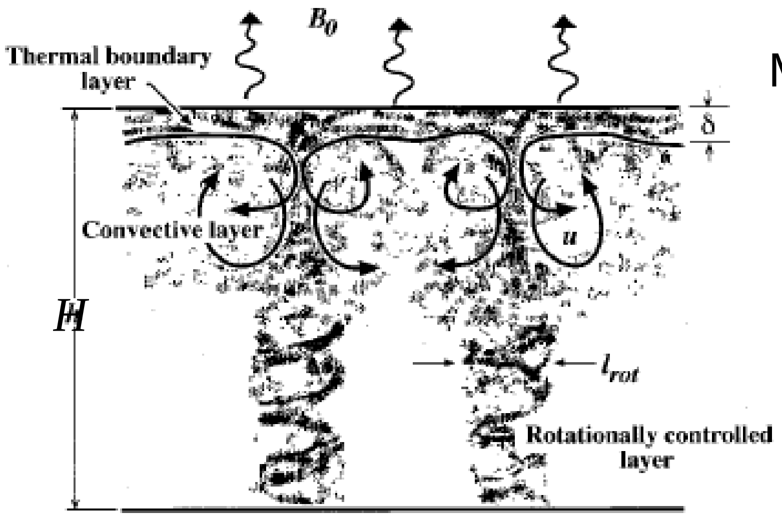


Figure 3. Schematic diagram of the three phases of open-ocean deep convection: (a) preconditioning, (b) deep convection, and (c) lateral exchange and spreading. Buoyancy flux through the sea surface is represented by curly arrows, and the underlying stratification/outcrops is shown by continuous lines.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



Dynamical ideas

- Extract buoyancy from surface of homogeneous, rotating ocean



Jones and Marshall, 1993

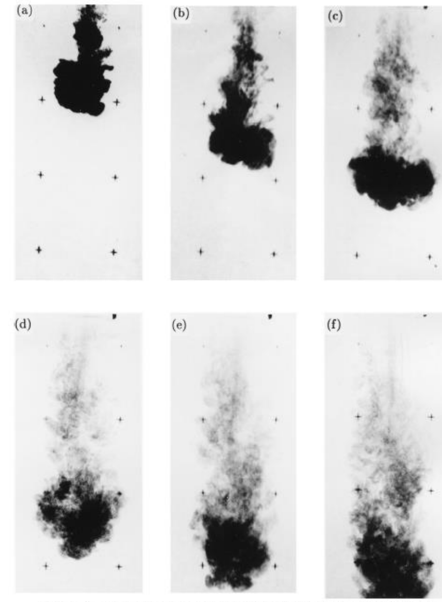


Figure 20. A sequence of photographs from a laboratory experiment carried out by *Helfrich* [1994]. The effects of rotation are evident in Figures 20d through 20f. The radius remains nearly constant, and the front falls to form a columnar structure, which ultimately undergoes geostrophic adjustment to form an anticyclonic conical eddy of dense fluid on the tank bottom.

Helfrich 1994

Natural Rossby number

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

Radius of deformation

$$\frac{l_\rho}{H} = \sqrt{R_o^*}$$

Numbers

$$f = 10^{-4} s^{-1}$$

Ocean - rotation important

$$B \sim 10^{-7} m^2 s^{-3} \qquad H \sim 1 km$$

$$l_{rot} \sim 1 km \qquad R_o^* \sim 0.1 \longrightarrow 1$$

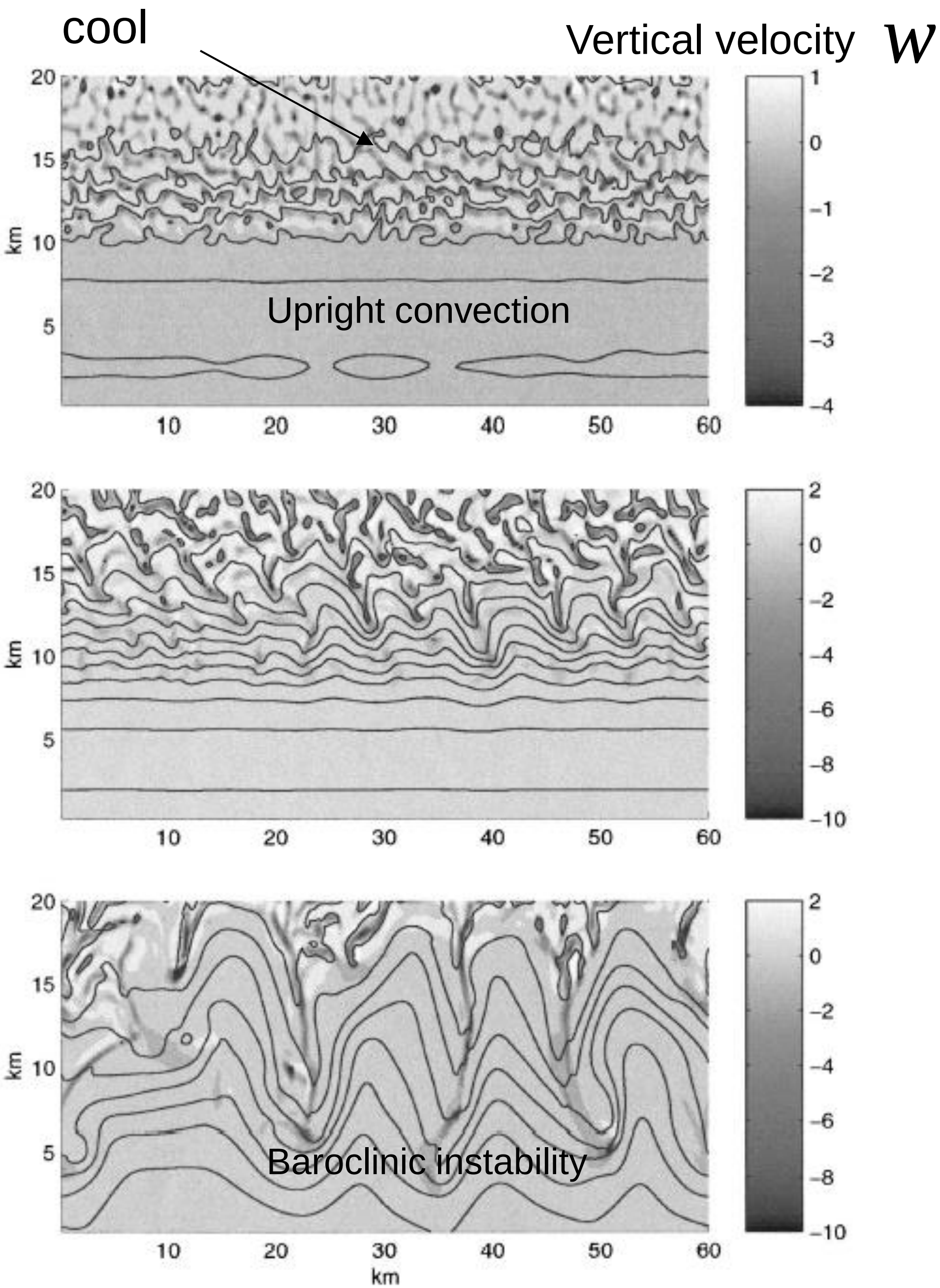
Atmosphere - rotation not important

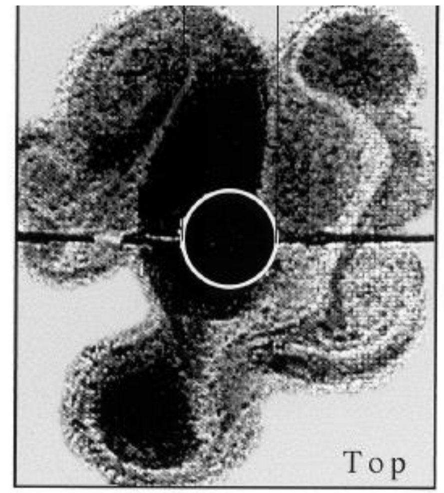
on convective scale

$$B \sim 10^{-2} m^2 s^{-3} \qquad H \sim 10 km$$

$$l_{rot} \sim 100 km \qquad R_o^* \sim 10 \longrightarrow 50$$

Interplay between convection and baroclinic instability





Jack Whitehead

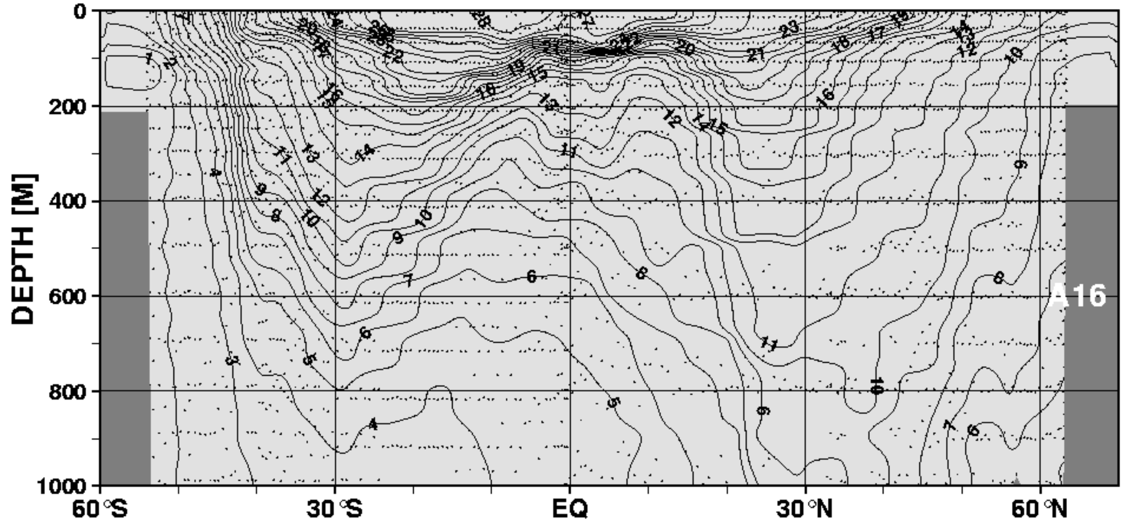
Convection → Baroclinic instability

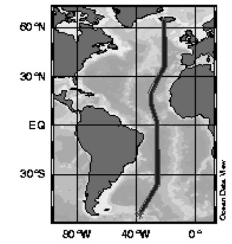
reminiscent of metrological flows

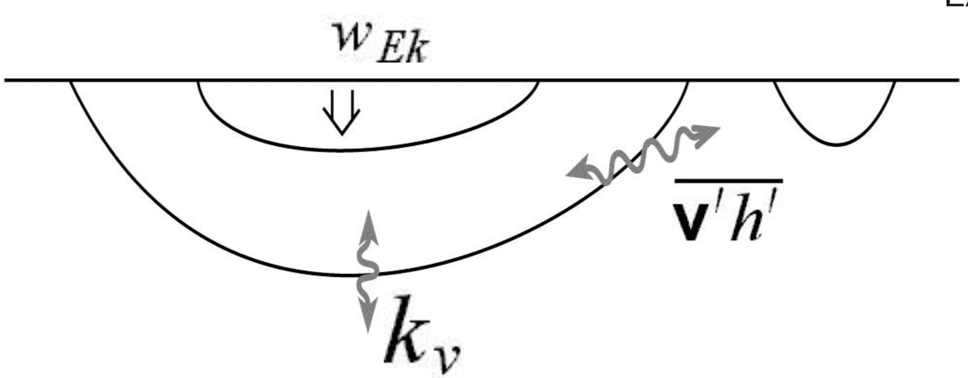
Eddies flux buoyancy vertically to offset loss from the surface

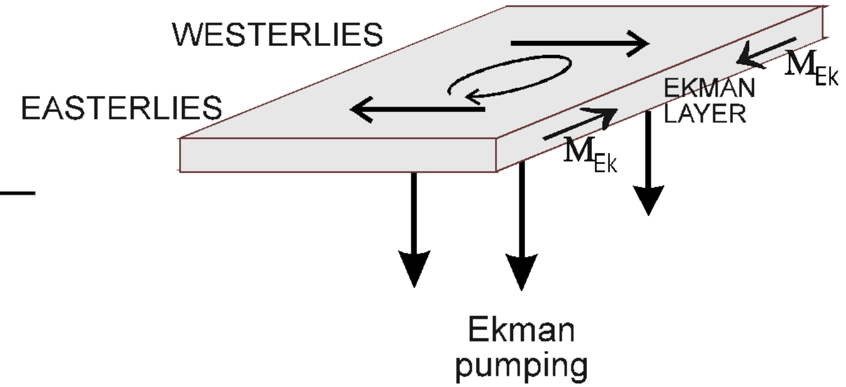
Light subduction

Subtropical gyres!



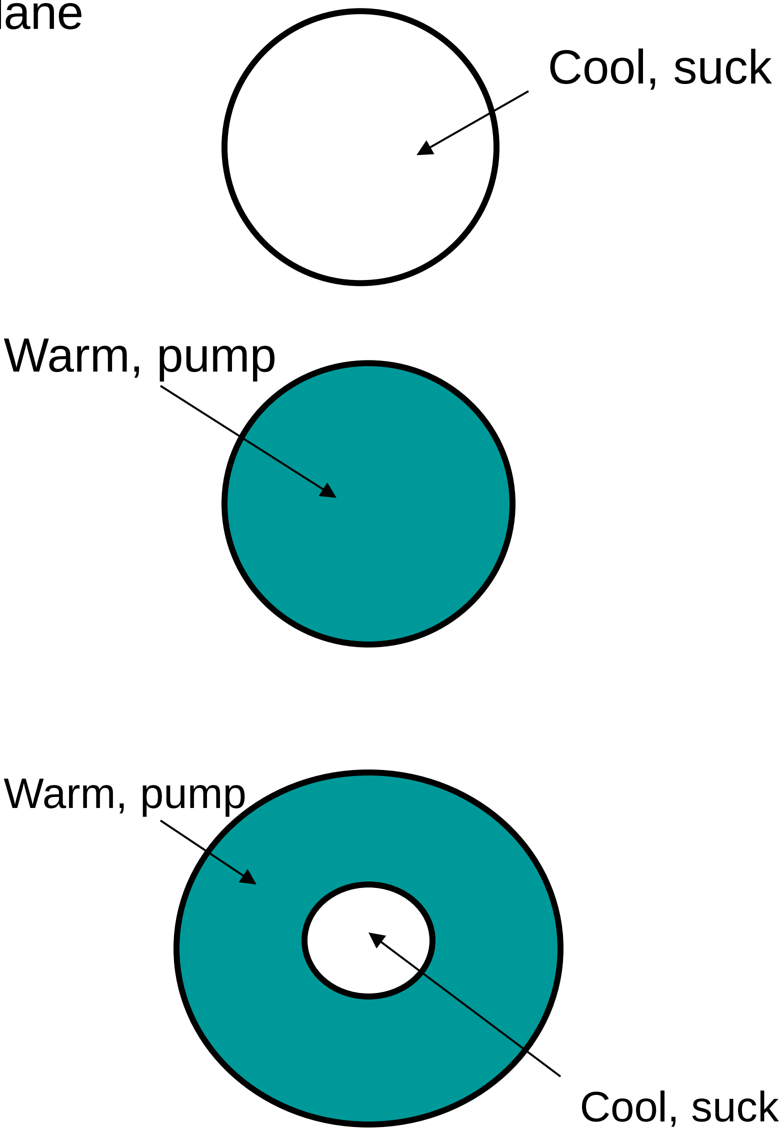




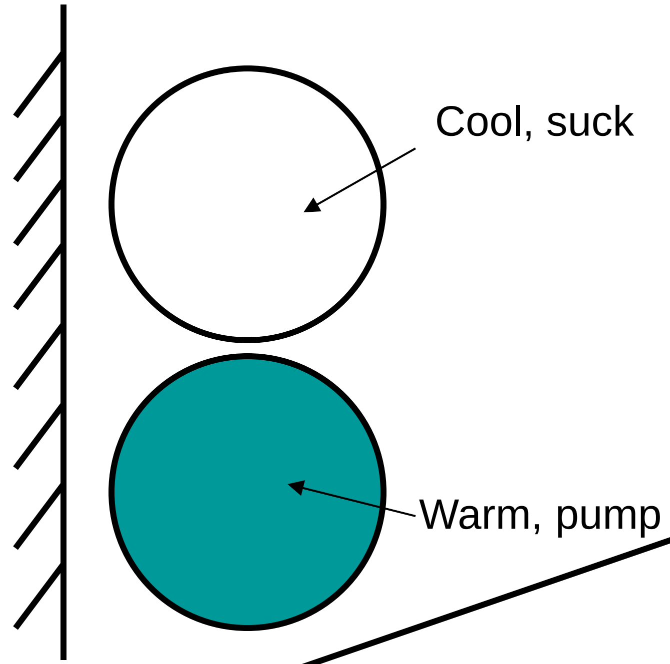


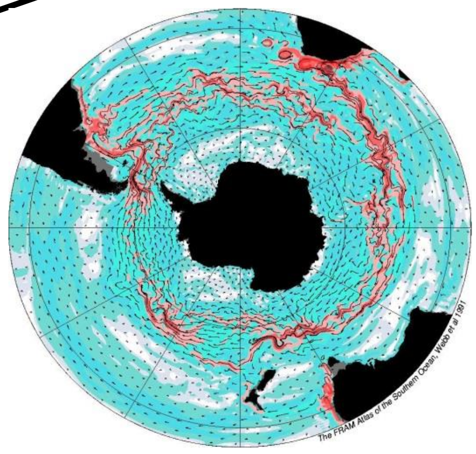
Building Blocks

f-plane



β -plane gyres

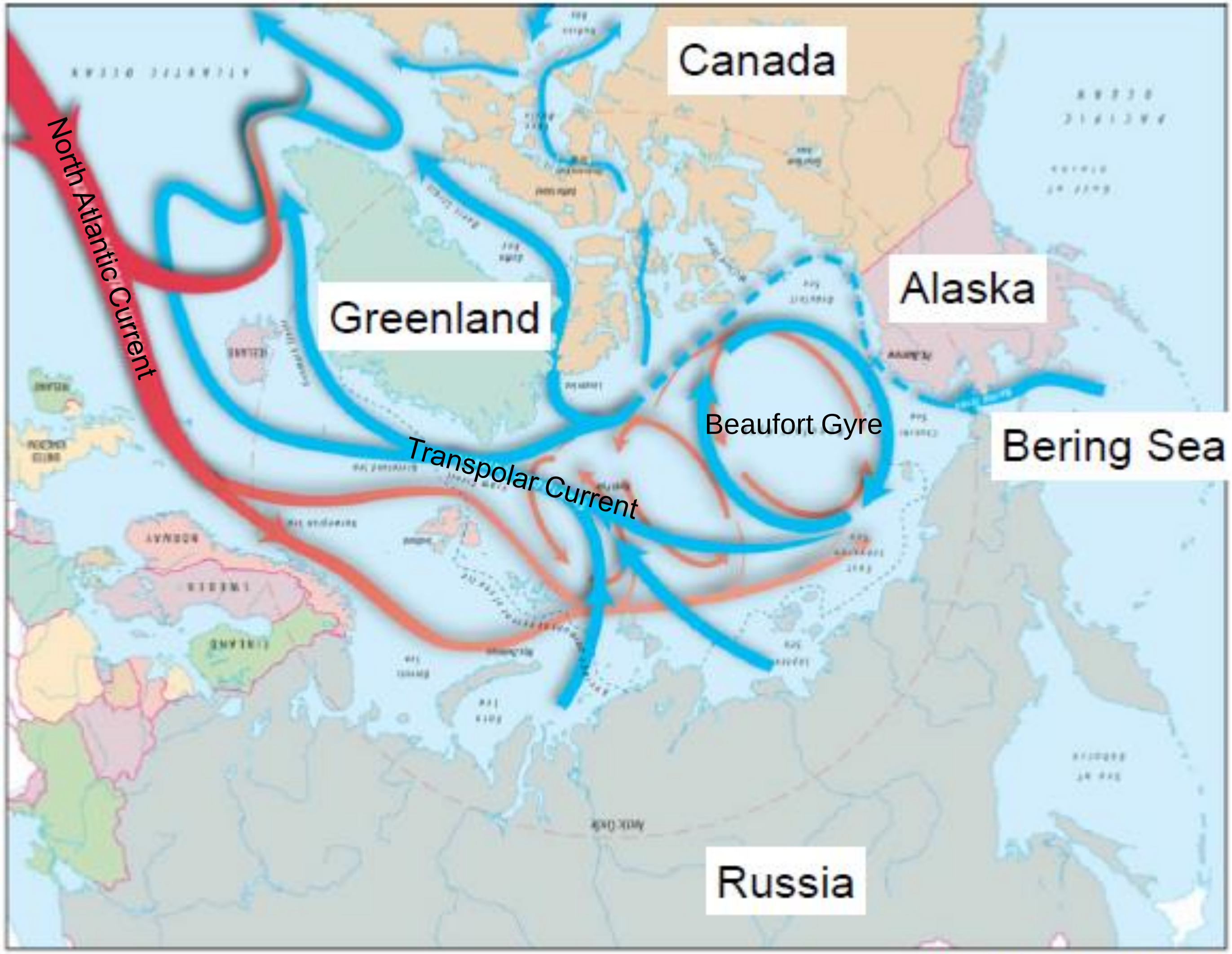




Antarctic Circumpolar Current

II

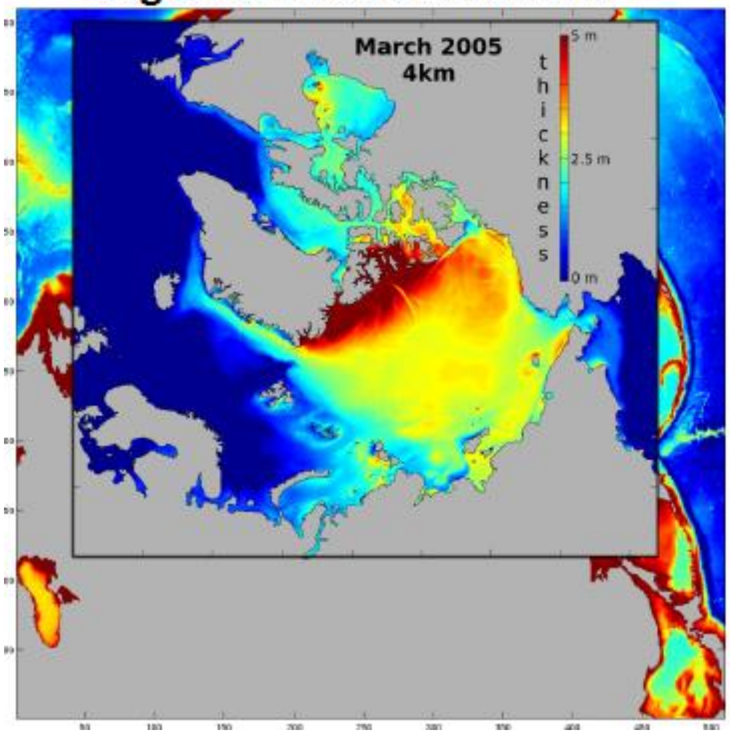
Review aspects of Arctic Circulation



Courtesy of Jack Cook, WHOI

Simulation of the Arctic Ocean using MITgcm

Regional Arctic solution:



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

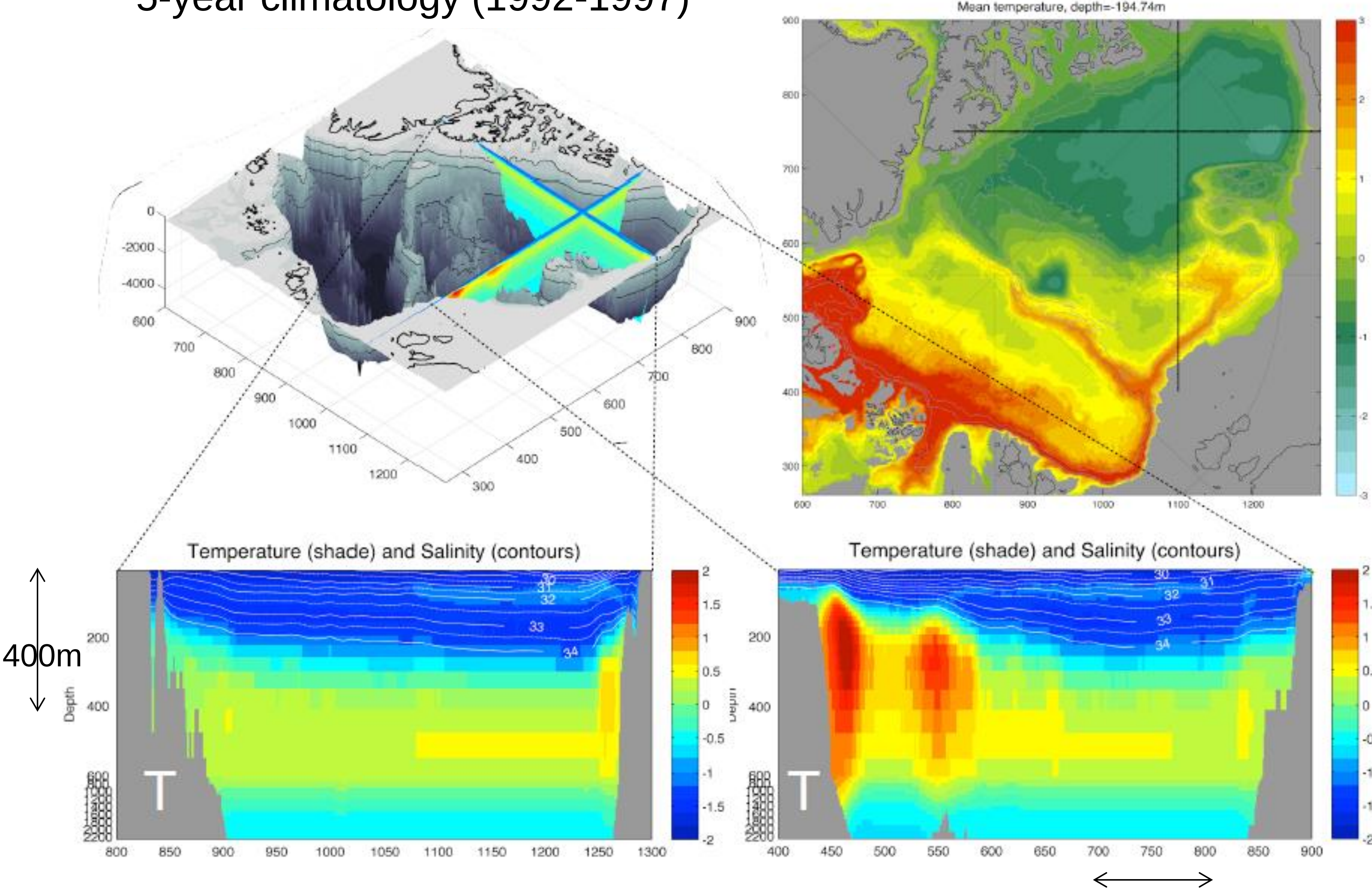
- 4.5, 9 and 18 km horizontal grid spacing.
- Boundary conditions from global solution.
- Bathymetry: IBCAO
- Time: 1992 – 2009 (18 years)

ECCO2 Project: collaboration between MIT and JPL

ECCO2

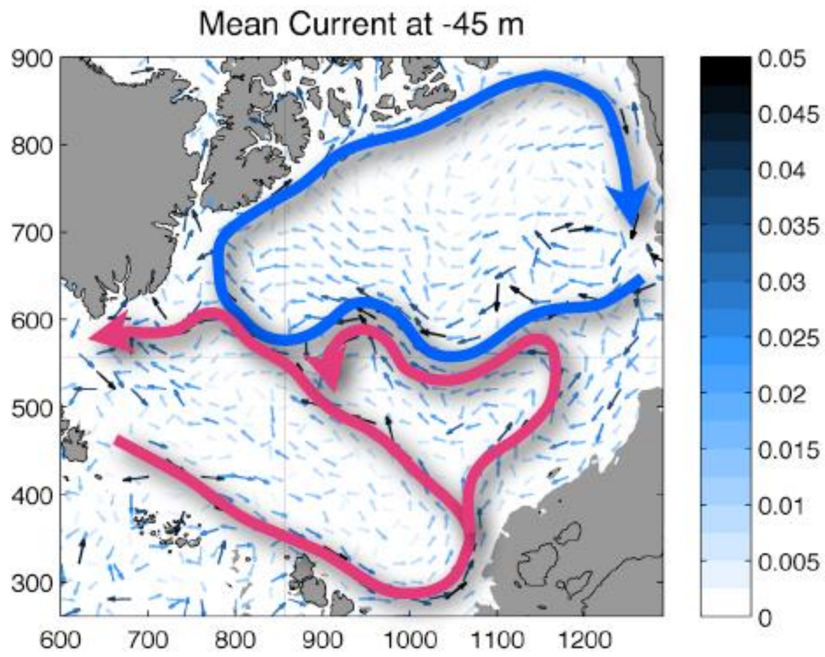
5-year climatology (1992-1997)

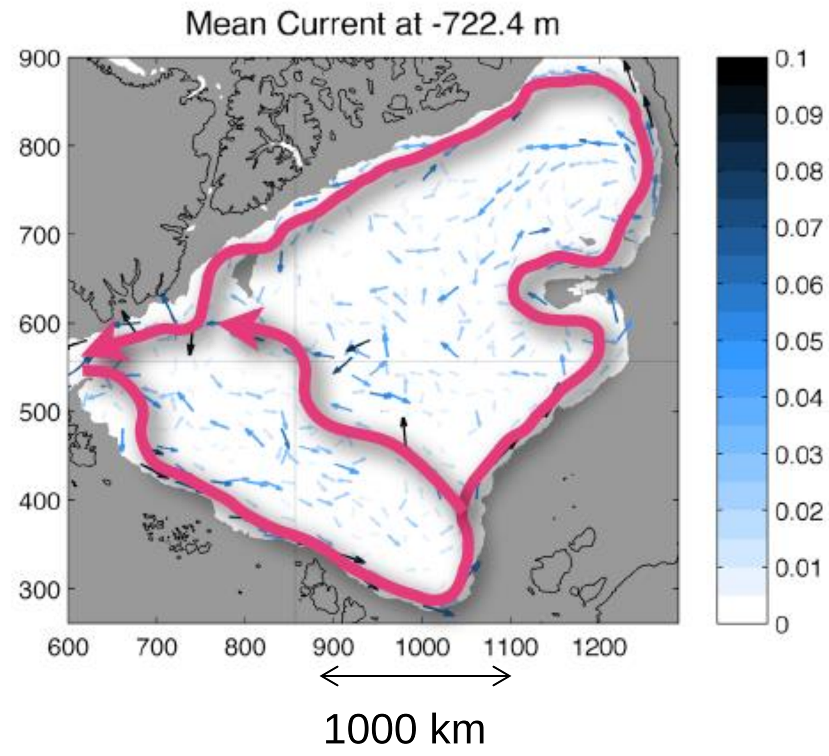
T at 200m



500km

1992-1997



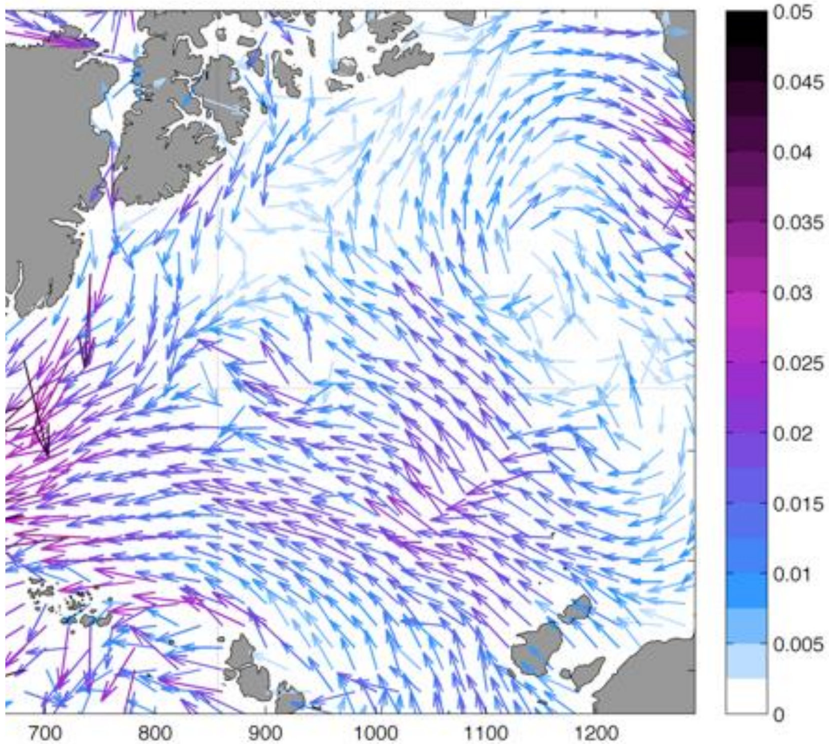


Blue circulation is sensitive to local atmospheric circulation

Anticyclonic circulation regime: JGR, 1997
Proshutinsky and Johnson

Wind stress

Mean wind stress N/m**2



Net freshwater flux in to the Arctic

(km³/yr)

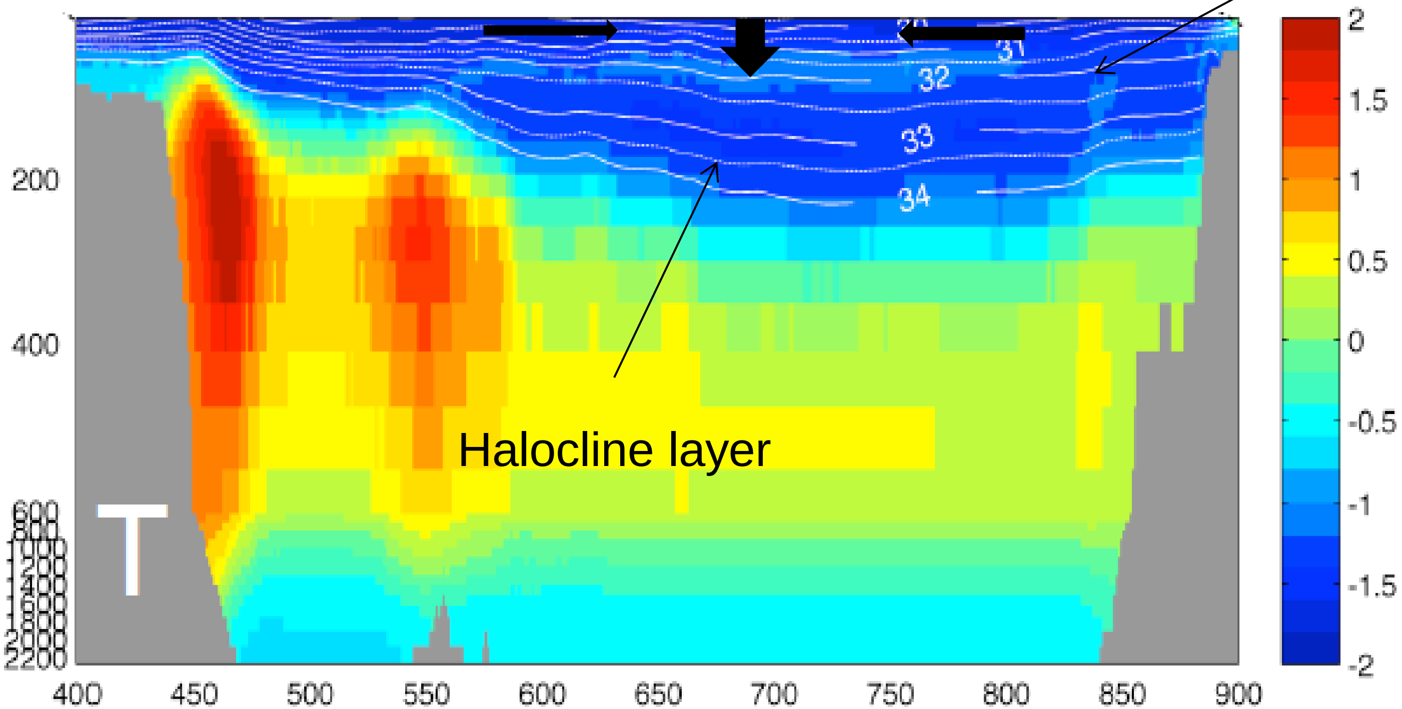
	Nguyen et al. [2011]	Serreze et al. [2006]
Precip.	2900	3300±680
Evaporation	-780	-1300±710
Runoff	2500	3200
Bering Strait	2160	2500

Balanced by ice and freshwater export

Section through the Beaufort Gyre

Pumping down of fresh water by the wind

Fresh water lens



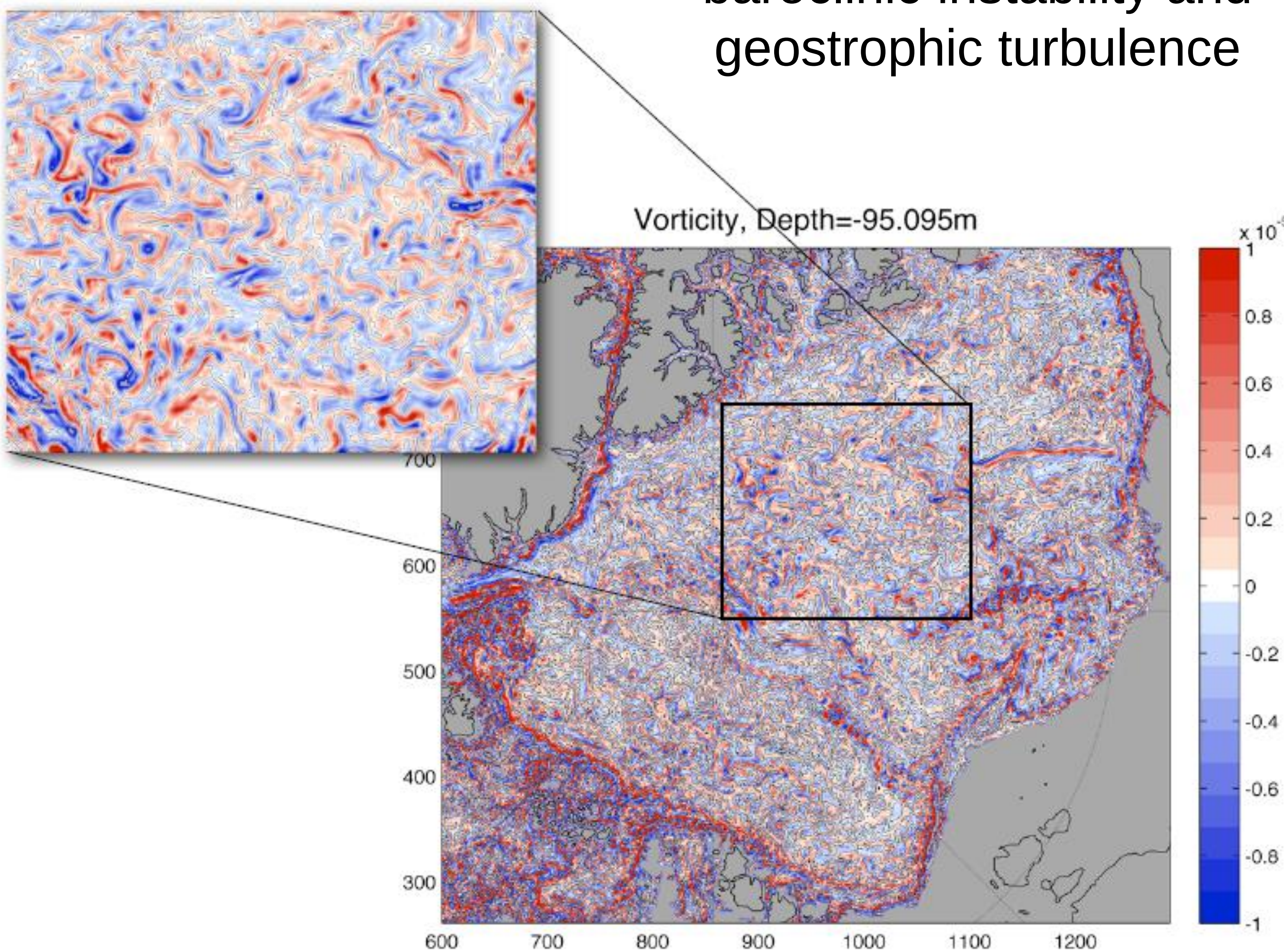
T colored

S contoured

Light subduction

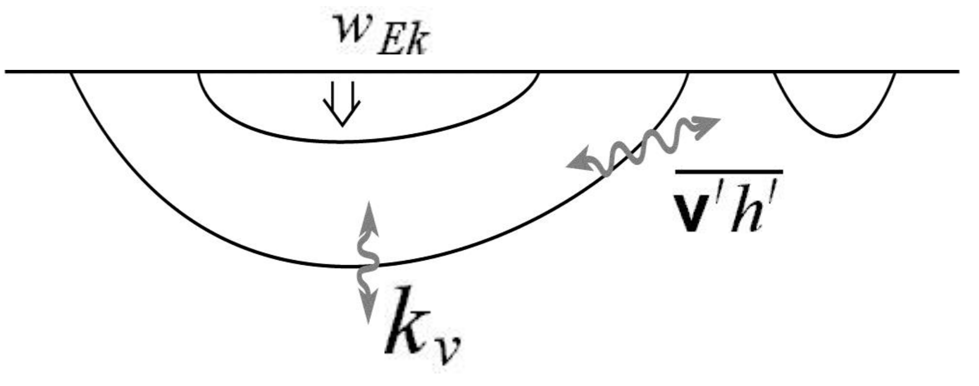
Vast stores of available potential energy in the fresh water lens. Expect vigorous baroclinic instability.

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

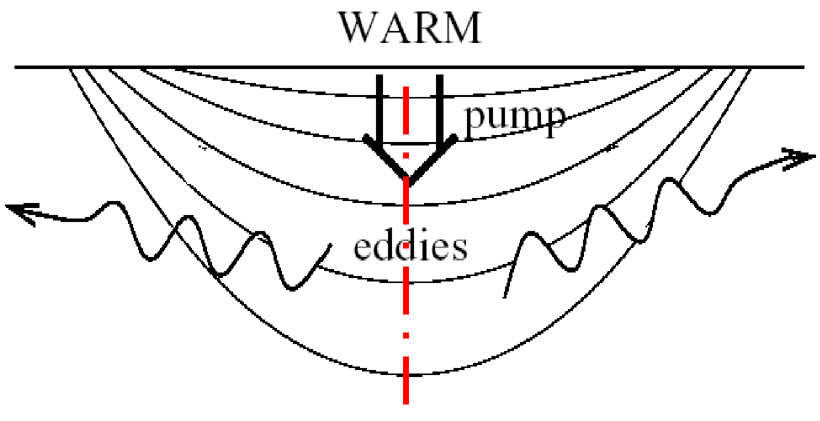
$$\beta = 0$$

Marshall et al. (2002)

Laboratory experiment:

warm pumped lenses

‘f’-plane



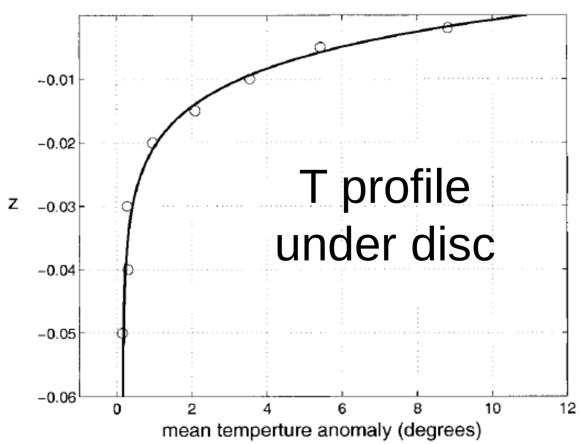
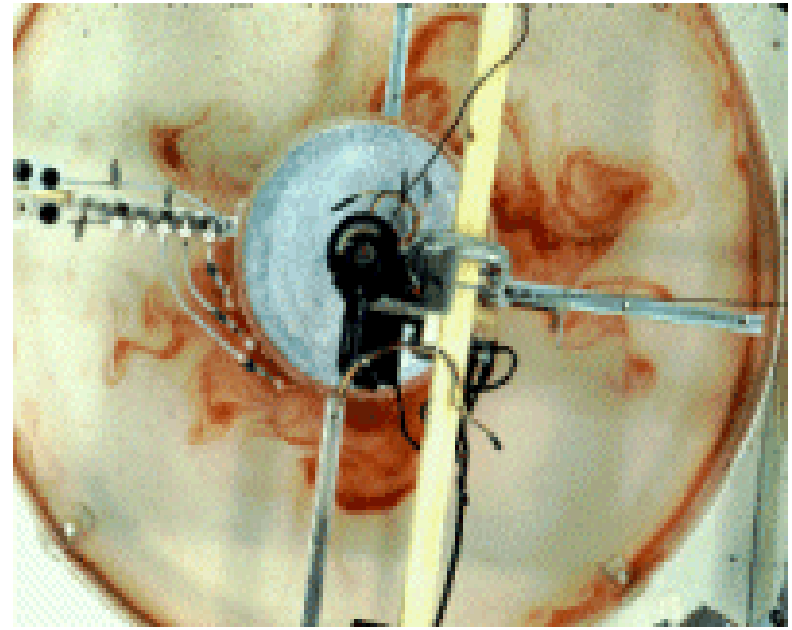
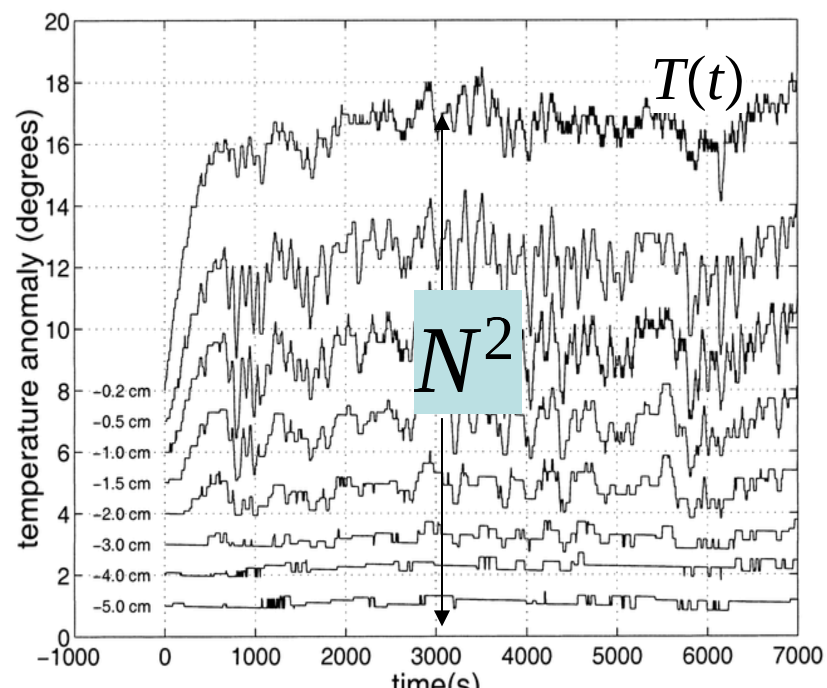


FIG. 5. Time-mean profile for the reference laboratory lens. The circles mark the actual mean temperatures measured at each thermocouple with the curve indicating the best fit exponential.





Theory

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

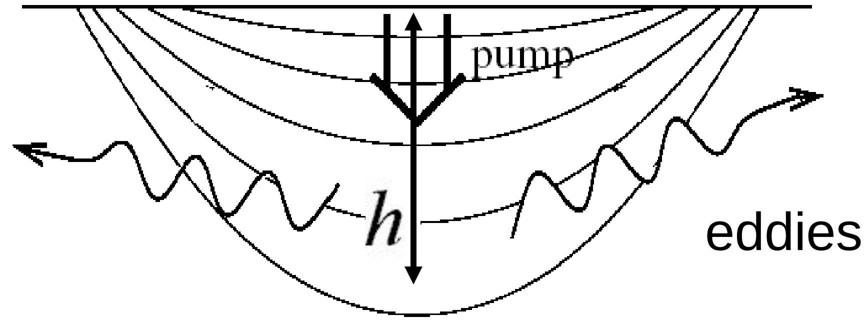
$$\overline{v'h'} = cuh$$

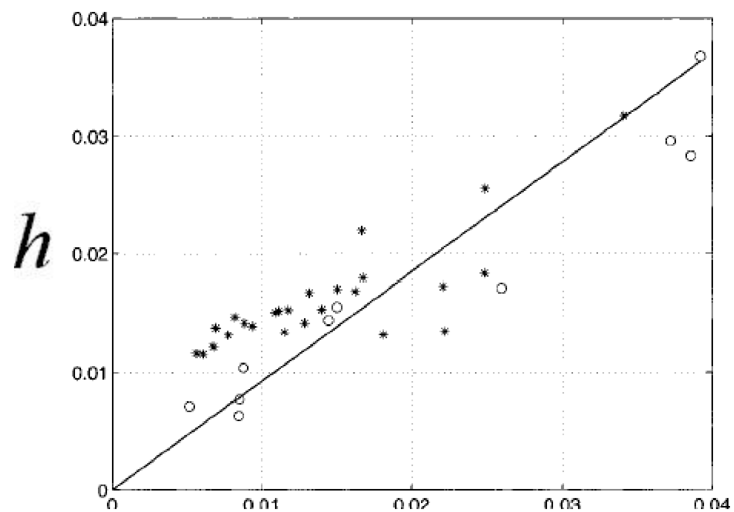
$$u = \frac{g'h}{fr_o}$$

$$h \sim \sqrt{\frac{f w_{Ek}}{g'}}\, r_o$$

$$u \sim \sqrt{\frac{g' w_{Ek}}{f}}$$

$$Q = \pi r_o^2 w_{Ek}$$





$$\sqrt{\frac{f w_{Ek}}{g'}}\, r_o$$

Numbers for freshwater lens

e-folding scale

$$h \simeq \sqrt{\frac{fw}{g'}}\, r$$

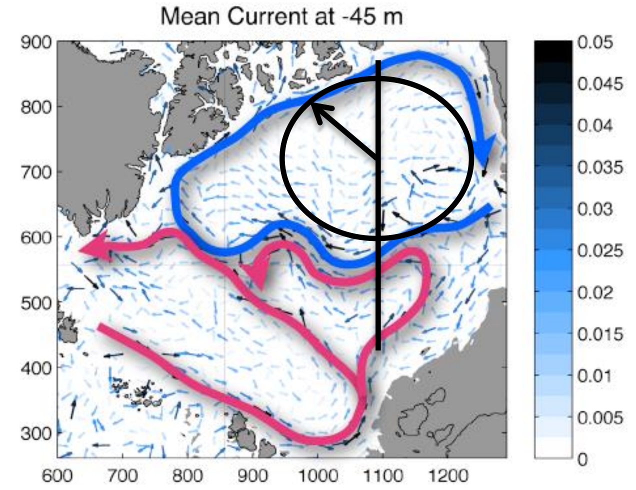
$$h \simeq \sqrt{\frac{1.4\times10^{-4}\,\mathrm{s}^{-1}\times10\,\mathrm{m/y}}{0.7\times10^{-2}\,\mathrm{m\,s}^{-2}}} \times 500\,\mathrm{km}$$

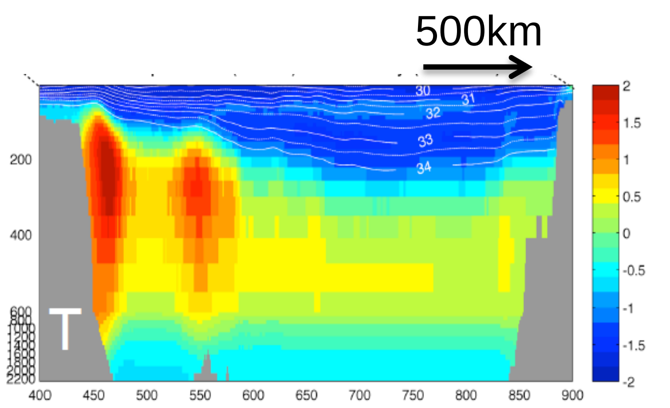
$$= 40\,\mathrm{m}$$

$$l_{rot} = \left(\frac{wg'}{f^3}\right)^{\frac{1}{2}} \simeq 30\,\mathrm{m}$$

$$R_o^* = \frac{l_{rot}}{h} \simeq 1$$

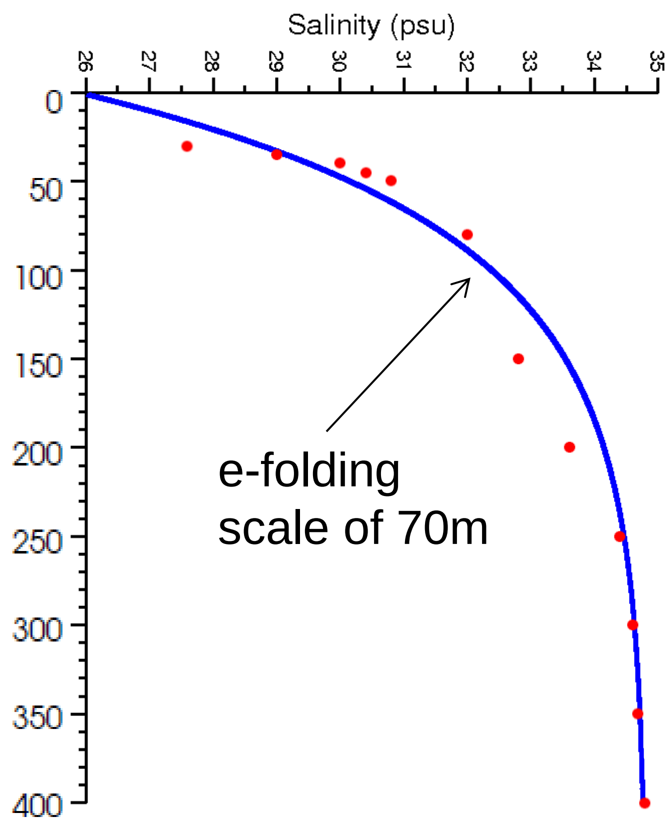
$$L_\rho = \sqrt{l_{rot}\times r} \simeq 4\,\mathrm{km}$$

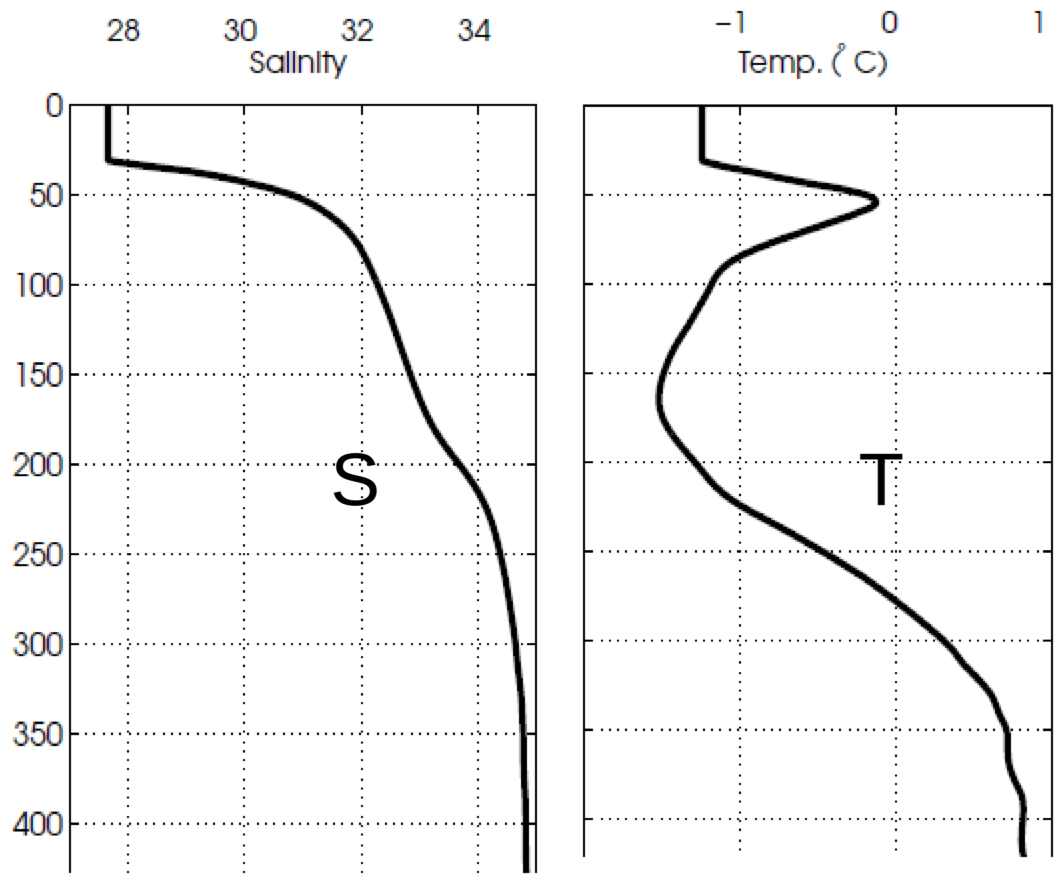




In the correct ball-park

Average Profiles near 75N 145W Sept 2006 to Aug 2007



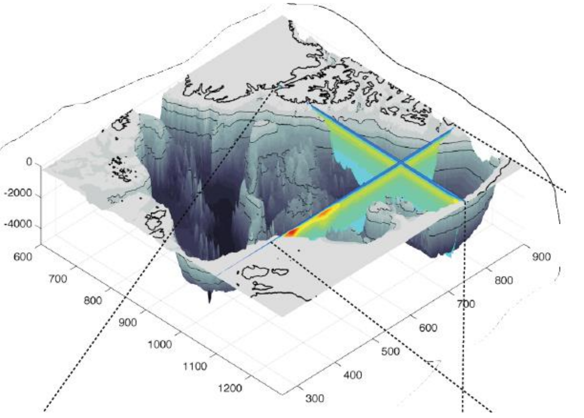


Data courtesy of
Mary-Louise Timmermans

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