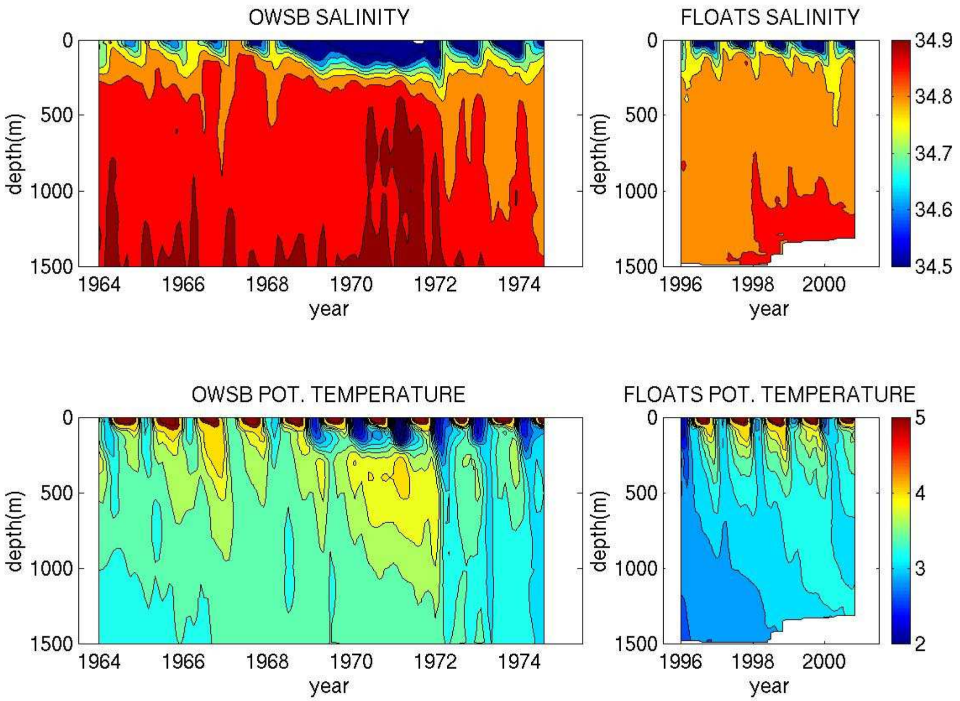
On the distinction between convection and sinking and its implication for overturning variability

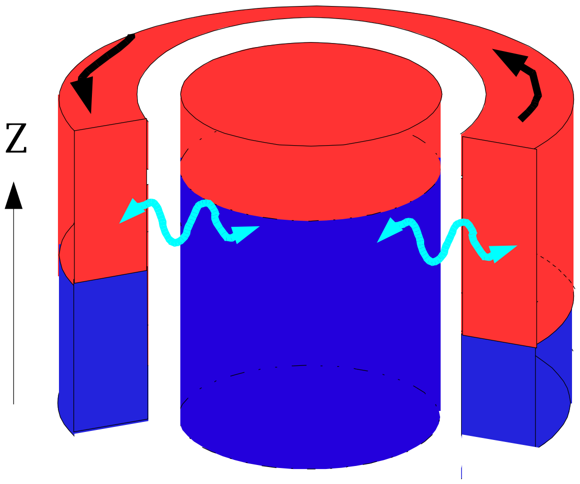
Fiamma Straneo


OWSB SALINITY

FLOATS SALINITY

OWSB POT. TEMPERATURE

FLOATS POT. TEMPERATURE

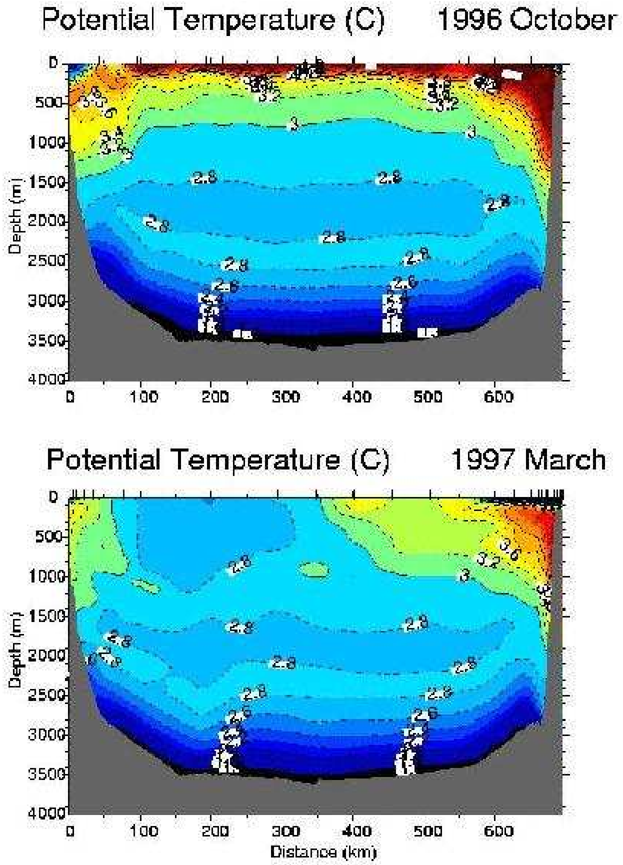


WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

What is convection and where does it occur

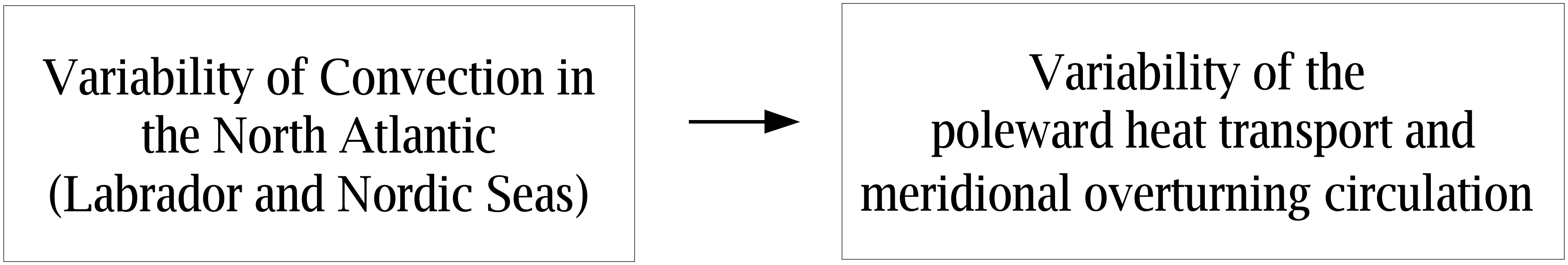
Deep/intermediate open-ocean convection occurs in a handful of locations (e.g. Labrador Sea, Nordic Seas, Northwest Mediterranean, Weddell Sea)

- large exchange of heat from the mid-depth ocean to atmosphere
- vertical mixing of nutrients, properties, tracers
- formation of deep and intermediate water masses
- **associated with the thermohaline circulation, meridional overturning circulation and poleward heat transport**



Pickart et al. 2002

Convection and Climate Variability



Variability of Convection in the North Atlantic (Labrador and Nordic Seas)

→

Variability of the poleward heat transport and meridional overturning circulation

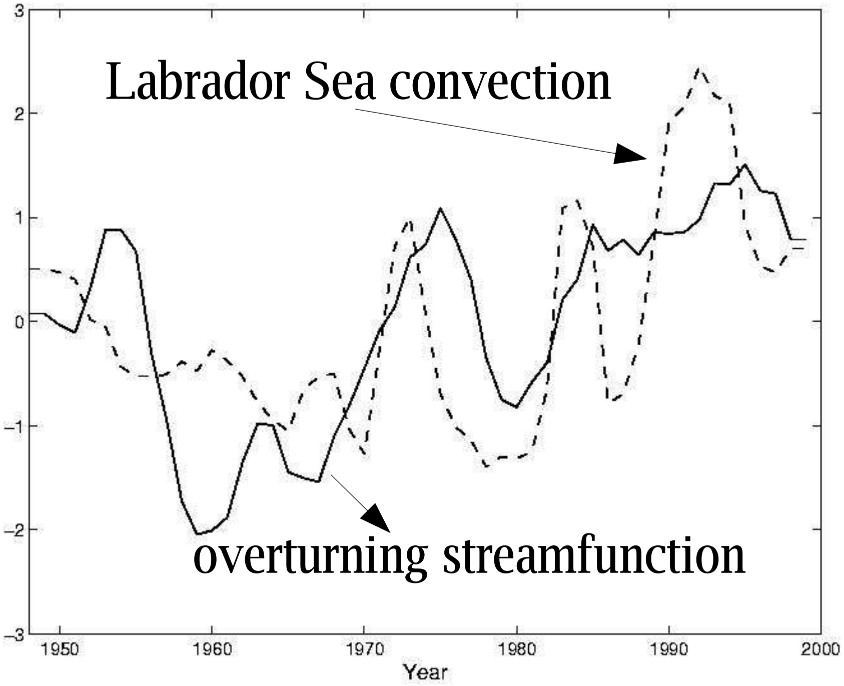
Convection and Climate Variability

Variability of Convection in
the North Atlantic
(Labrador and Nordic Seas)

→

Variability of the
poleward heat transport
meridional overturning circulation

On decadal to multi-decadal timescales Labrador Sea Convection leads the overturning streamfunction by a few years



Ensemble Mean of 4 BCM runs,
ocean only, forced with NCEP
Reanalysis 1950-2000
(high pass filtered (100yr cut-off)
and 3 year running mean).
Bentsen et al. 2004

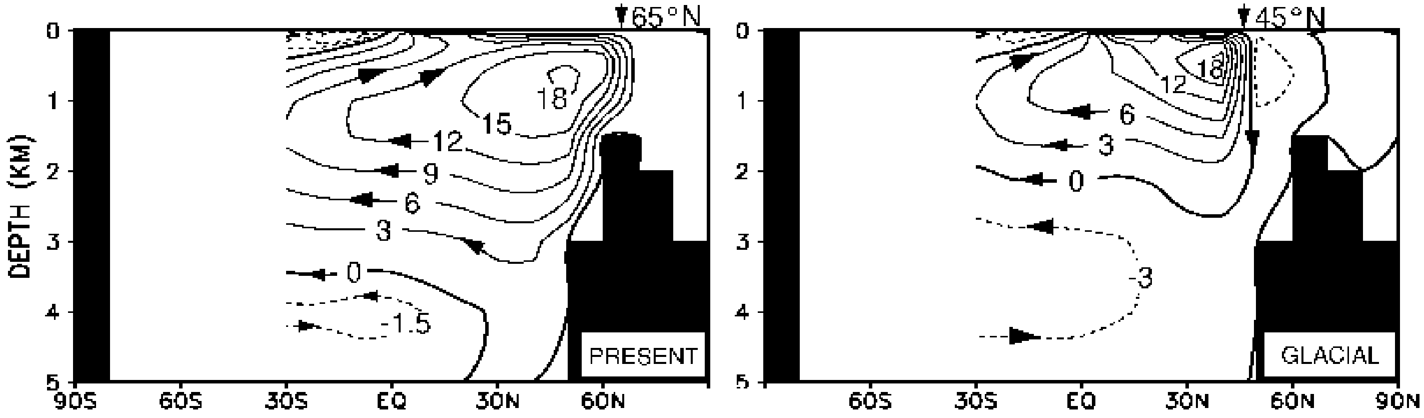
Convection and Climate Variability

Variability of Convection in the North Atlantic (Labrador and Nordic Seas)

→

Variability of the poleward heat transport meridional overturning circulation

Past climate scenarios are associated with changes in the extent and location of convection



Meridional overturning streamfunction for the Atlantic during modern times versus during the Last Glacial Maximum – from a global ocean-atmosphere coupled model, *Ganopolski et al. 1998*

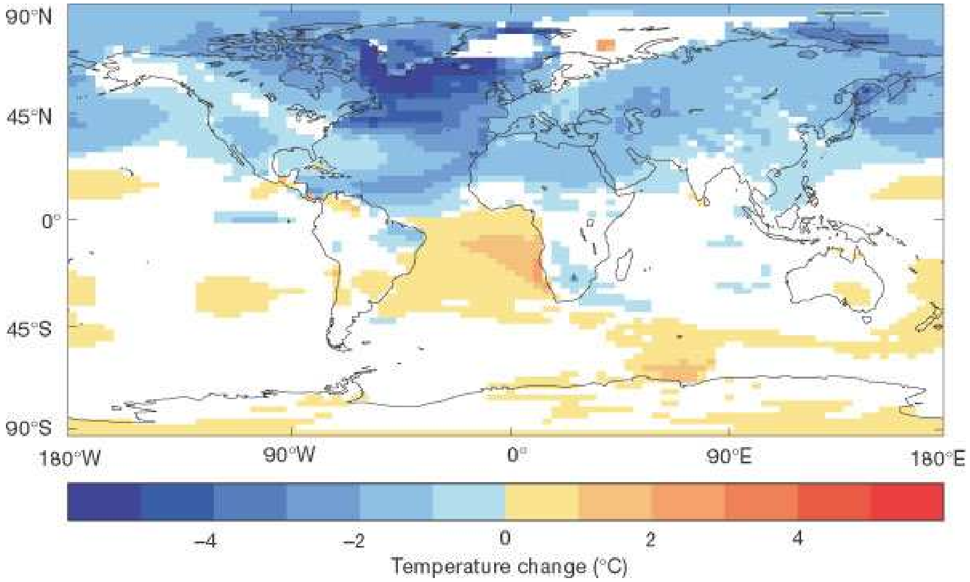
Convection and Climate Variability

Variability of Convection in
the North Atlantic
(Labrador and Nordic Seas)

→

Variability of the
poleward heat transport
meridional overturning circulation

Change in convective activity in the North Atlantic is projected to play a role in future climate scenarios.



Change in global mean temperature following the shutdown of the MOC due to an anomalous freshwater input

HADCM-3 Model
(Vellinga and Wood, 2002)

Convection and Climate Variability

"There is a huge gap in our conceptual understanding linking changes in convective activity, in the North Atlantic or elsewhere, to the thermohaline circulation and the northward heat transport."

(from *Abrupt Climate Change*, National Research Council, 2001, pp230)

Problem

We lack a dynamical understanding of how the variability of convection impacts "climate-related fields"

For example, Mauritzen and Hakkinen (1999) find that a 8-9 Sv decrease in formation of Labrador Sea Water leads to a decrease in the Meridional Overturning Circulation of only 5-6 Sv.

Why ?

The Good News:

We now understand much better how a convective basin works, so that we can begin to answer these questions.

Outline

Focus: Clarify the connection between convection (and its variability) and thermohaline circulation related quantities.

Step 1. Present a new paradigm for convective basins

Step 2. Develop a simplified model based on this paradigm and test it against observations

Step 3. Investigate the dynamical connection between convection, poleward heat transport and overturning circulation

Step 4. What are the Implications for the large-scale oceanic variability

Outline

Focus: Clarify the connection between convection (and its variability) and thermohaline circulation related quantities.

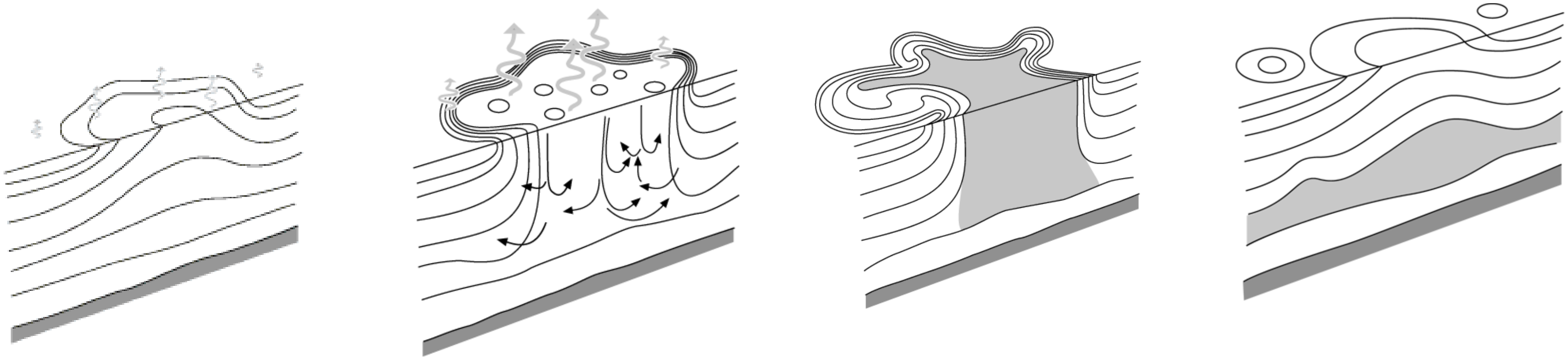
Step 1. Present a new paradigm for convective basins

Step 2. Develop a simplified model based on this paradigm and test it against observations

Step 3. Investigate the dynamical connection between convection, poleward heat transport and overturning circulation

Step 4. What are the Implications for the large-scale oceanic variability

The Old Paradigm



Jones and Marshall, 1993

Preconditioning

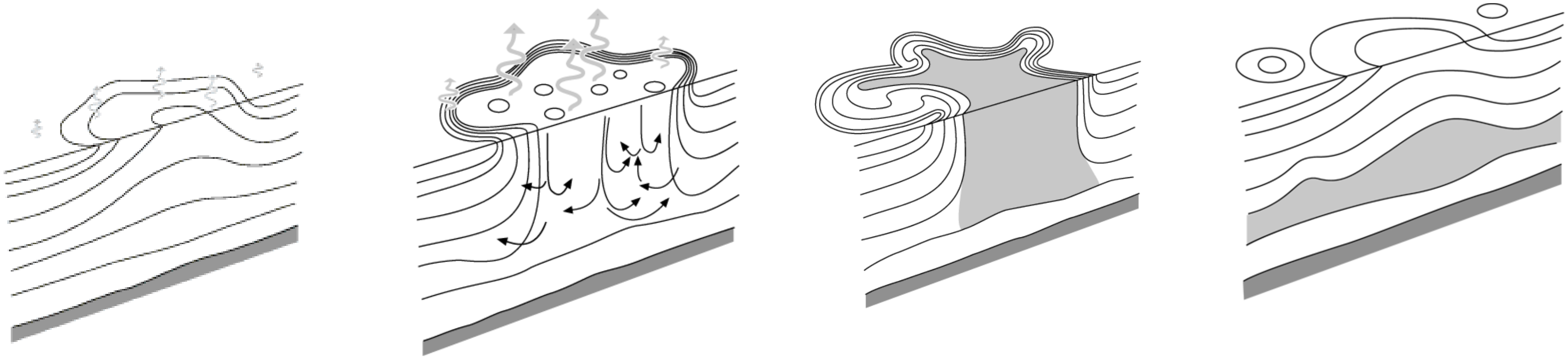
Violent Mixing

Collapse

Restratification
Export

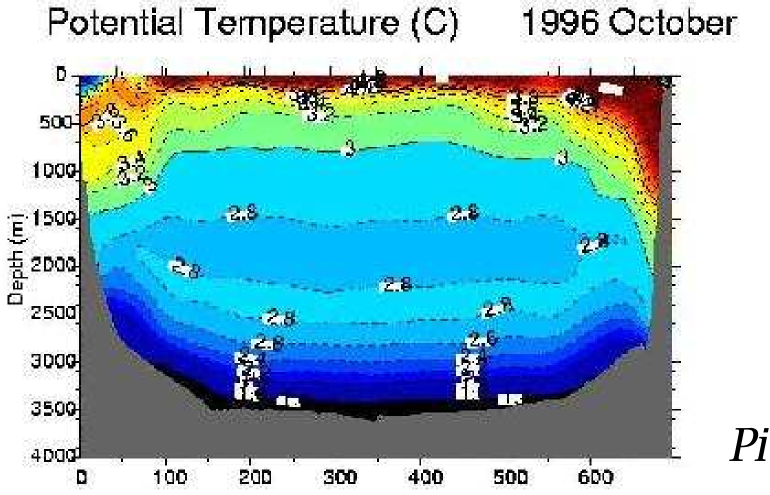
The Old Paradigm

Jones and Marshall, 1993



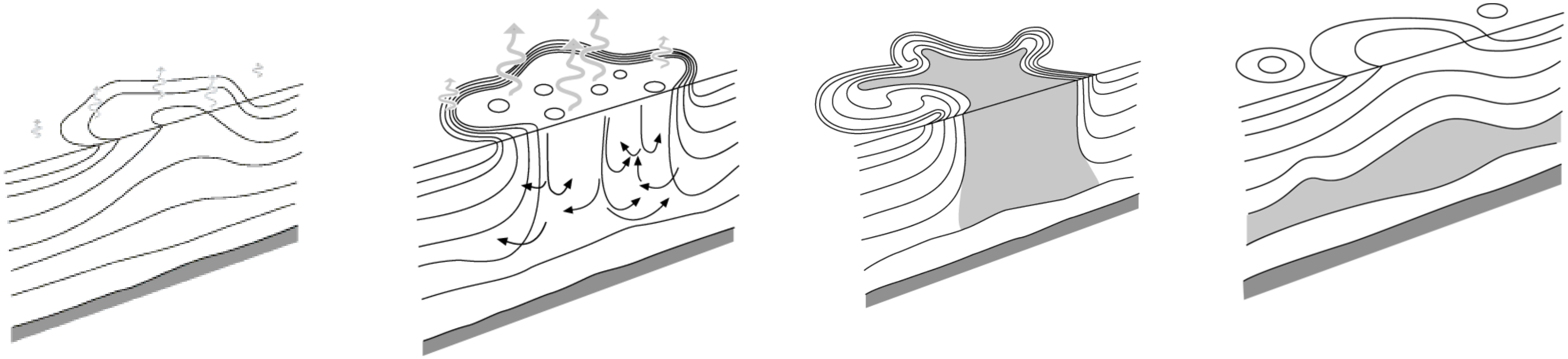
Problems with the old paradigm

i. preconditioning (wind?, not in large basins)


Potential Temperature (C) 1996 October

Pickart et al., 2002

The Old Paradigm

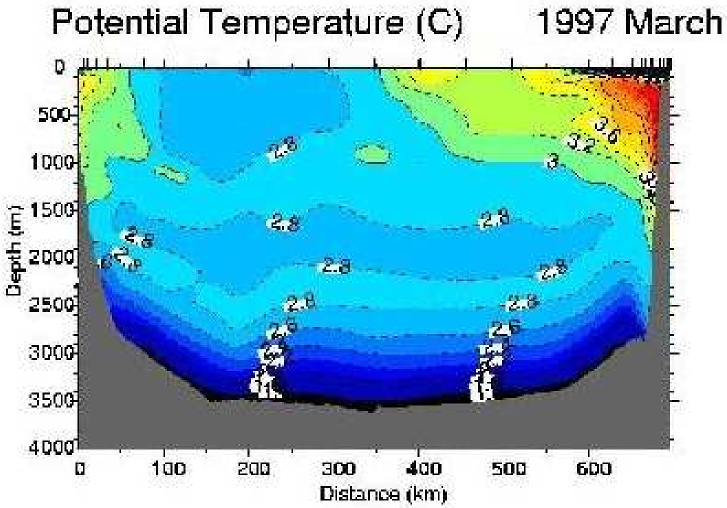


Jones and Marshall, 1993

Problems with the old paradigm

i. preconditioning (wind?, not in large basins)

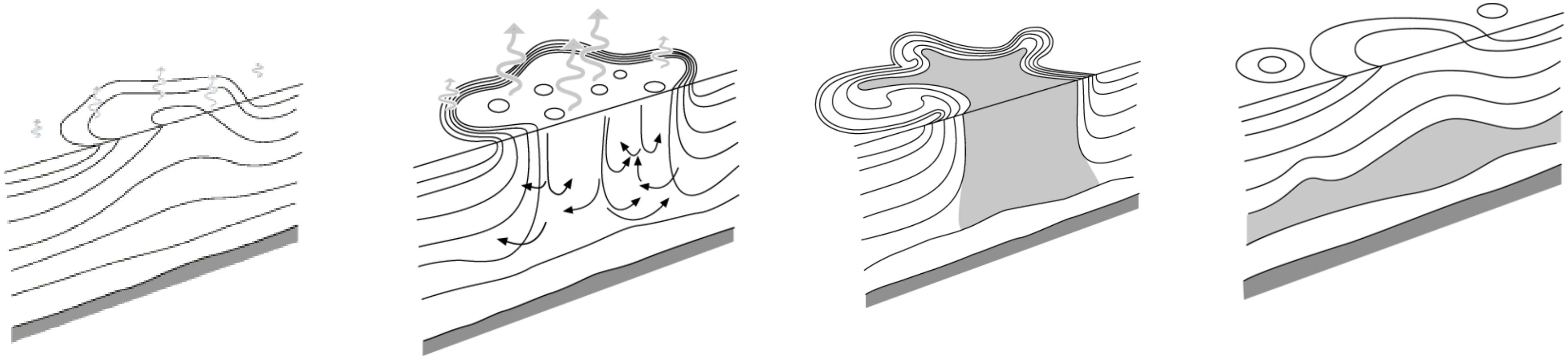
ii. strong rim current is not observed
(collapse by baroclinic instability?)



Pickart et al., 2002

The Old Paradigm

Jones and Marshall, 1993



Problems with the old paradigm

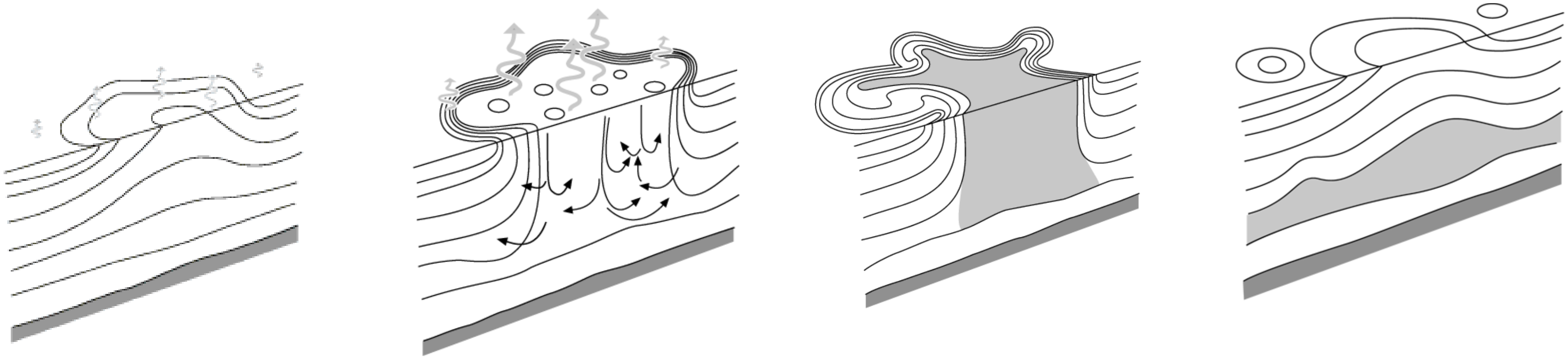
i. preconditioning (wind?, not in large basins)

ii. strong rim current is not observed

iii. dense water export in cyclonic eddies is not observed
    (e.g. eddies observed at the Bravo Mooring in the central Labrador Sea, Lilly et al. 2003)

The Old Paradigm

Jones and Marshall, 1993



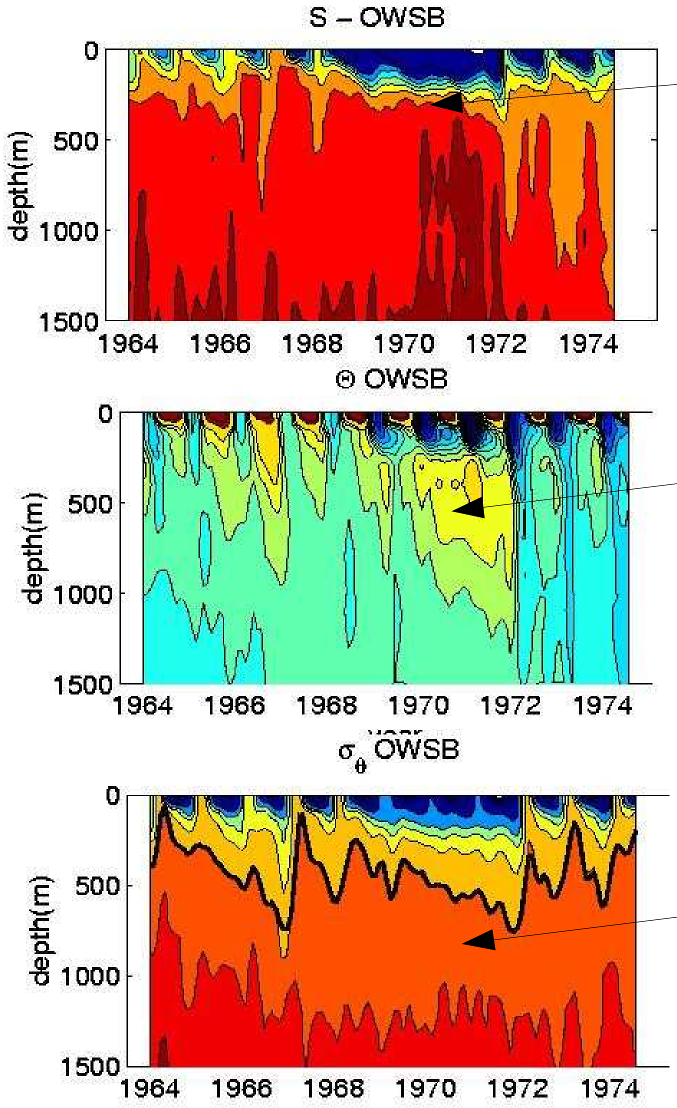
Problems with the old paradigm
i. preconditioning (wind?, not in large basins)
ii. strong rim current is not observed
iii. dense water export in cyclonic eddies is not observed
iv. restratification occurs even when convection does not occur

Restratification during the GSA

Salinity

Temperature

Density



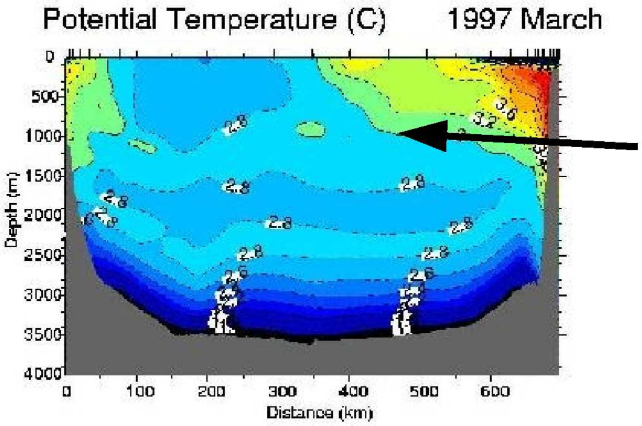
no convection for
3 years

persistent warming
and salinity increase

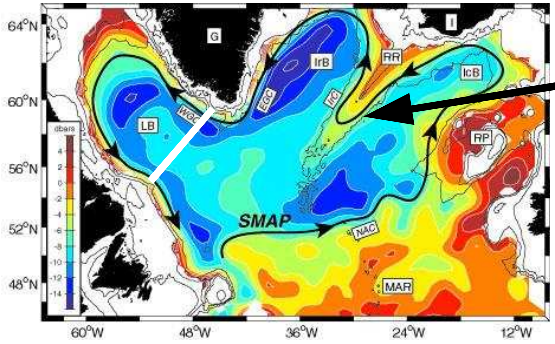
dense water
continuously
exported

A New Paradigm for a Convective Basin

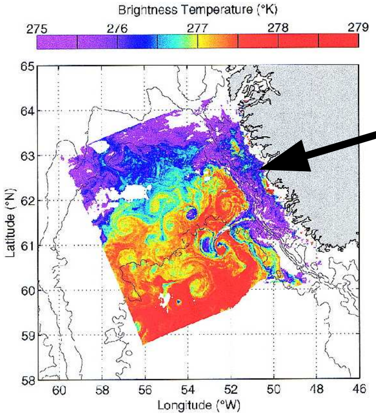
Pickart et al., 2002



Lavender et al., 2000



Prater, 2002



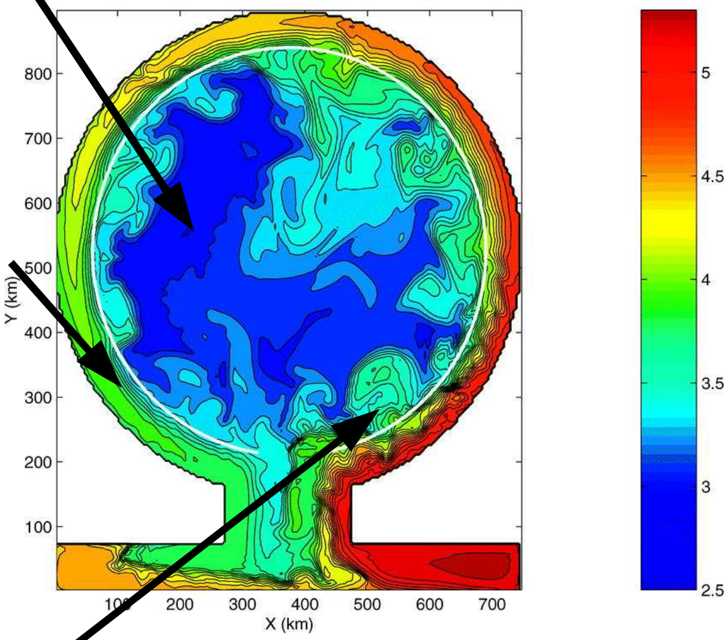
Lilly et al. 1999 and 2003, Lazier et al. 2002

Convection occurs in mostly quiescent interior regions

surrounded by a boundary current which is the principal pathway for the import of light fluid and export of dense fluid from the basin

the exchange between the two regions is regulated by boundary current instabilities - eddy fluxes

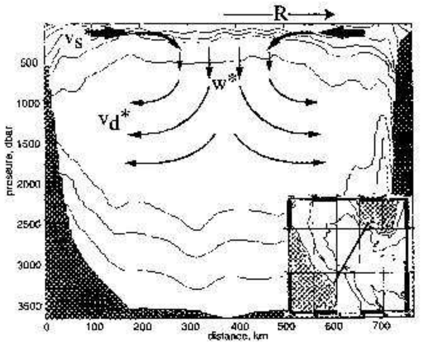
Spall, 2004



Visbeck et al. 1996,
Jones and Marshall 1996,
Khatiwala et al. 2002,
Katsman et al. 2004,
Chanut and Barnier, 2004

A New Paradigm for a Convective Basin

There is **no net sinking** (net vertical mass flux)
in open-ocean convection regions



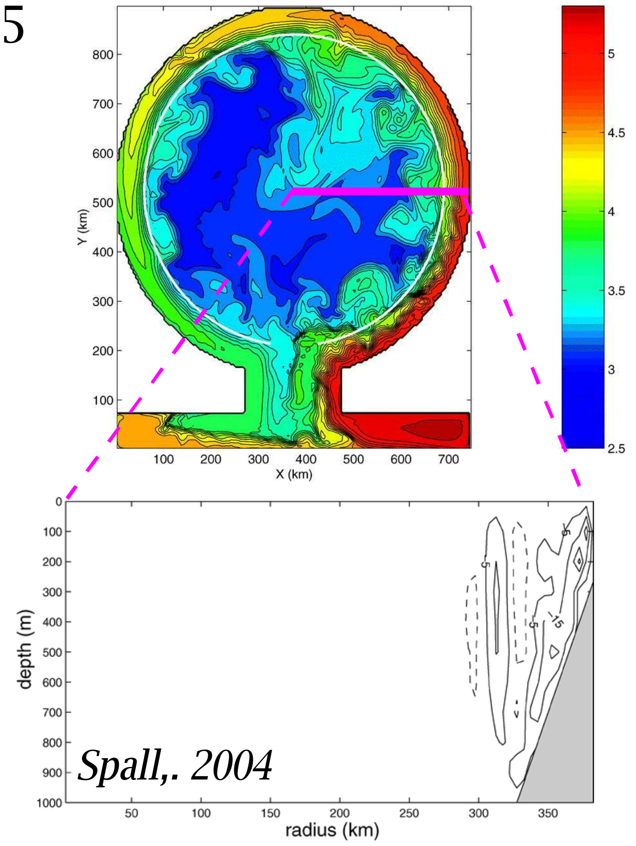
Khatiwala et al. 2002

During convection (1-2 weeks)
downward mass flux within plumes is balanced by
upwelling between them.

theory - Spall and Pickart, 2001; Send and Marshall, 1995
observations - e.g. Schott and Leaman, 1991
non-hydrostatic simuations – Send and Marshall 1995;

Post Convection:
the amount of sinking due to the eddy fluxes is small
theory – Spall and Pickart (2001)
non-hydrostatic simulations – Spall (2004)

But significant sinking can occur at the topographic boundaries.



Spall,. 2004

Outline

Focus: Clarify the connection between convection (and its variability) and thermohaline circulation related quantities.

Step 1. Present a new paradigm for convective basins

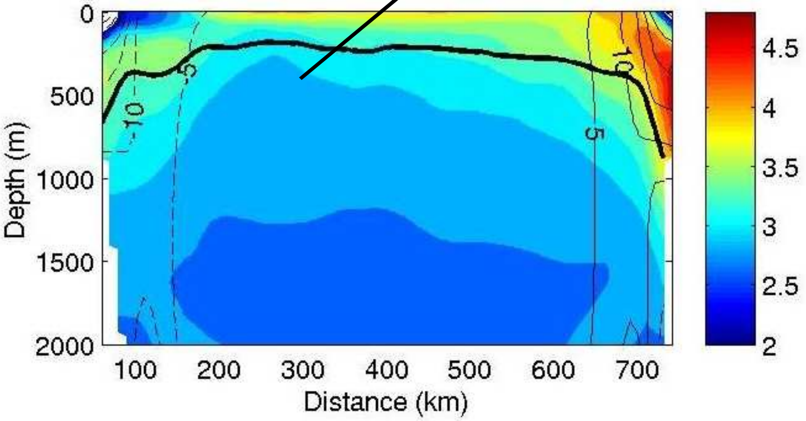
Step 2. Develop a simplified model based on this paradigm and test it against observations

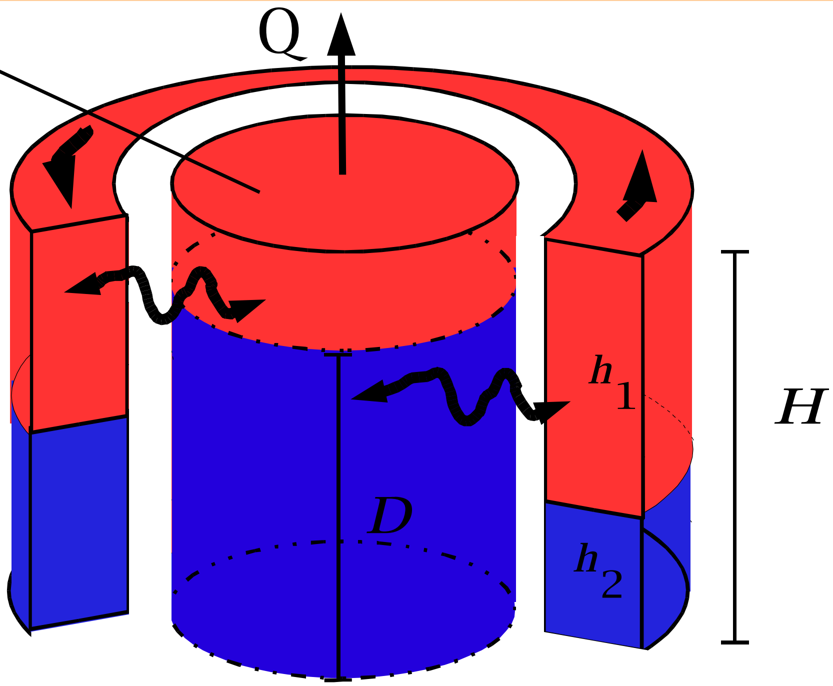
Step 3. Investigate the dynamical connection between convection, poleward heat transport and overturning circulation

Step 4. What are the Implications for the large-scale oceanic variability

A Two Layer Model for the Labrador Sea

Interior
- no mean flow, no sinking
- buoyancy loss converts **light** fluid into **dense** fluid



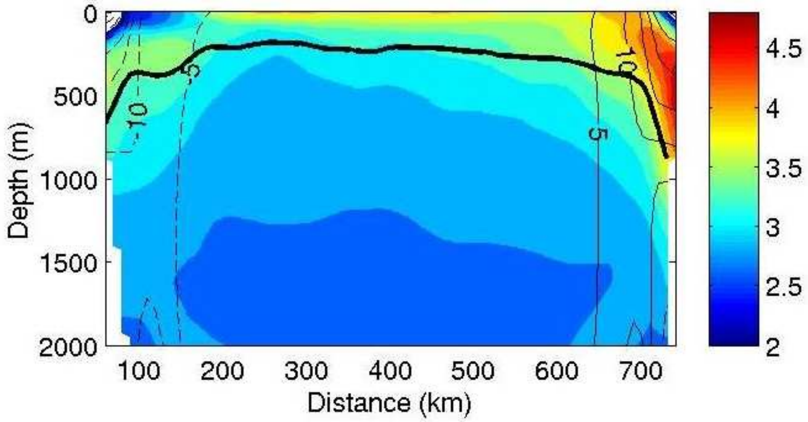


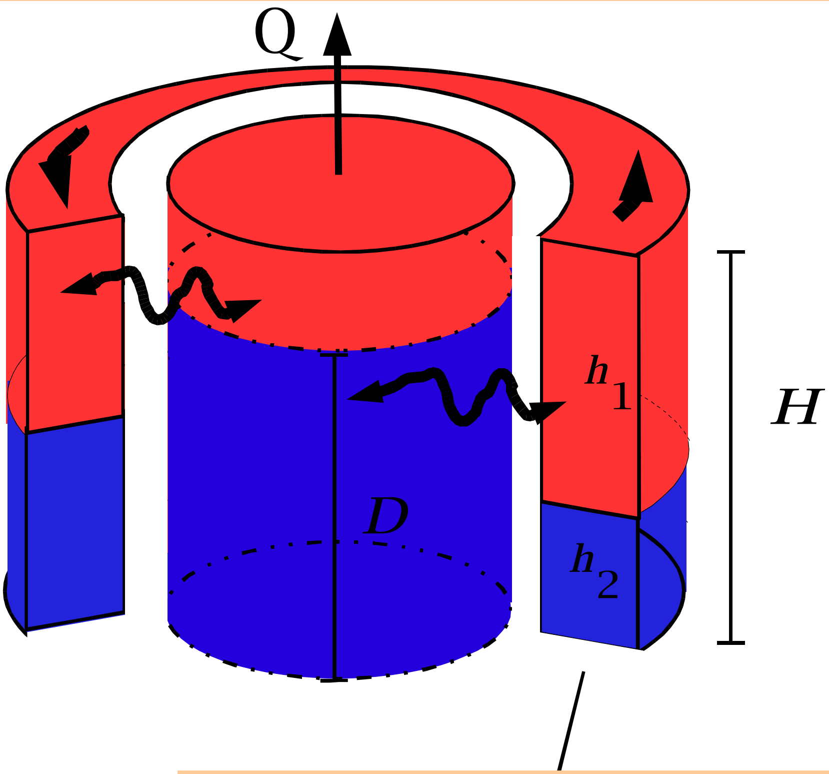
$$\frac{\partial}{\partial t}\int_{V}\rho\, dV+\int_{P}\int_{H}^{0}u'\rho'\, dl\, dz=\frac{\rho_{0}}{g}\int_{A}Q_{b}\, dS$$

A Two Layer Model for the Labrador Sea

Interior

- no mean flow, no sinking
- buoyancy loss converts **light** fluid into **dense** fluid





$$V_{bcl} = V_1 - V_2 = \frac{2g'}{fL}(D - h_2) \qquad g' = \frac{\Delta\rho}{\rho_0} g$$

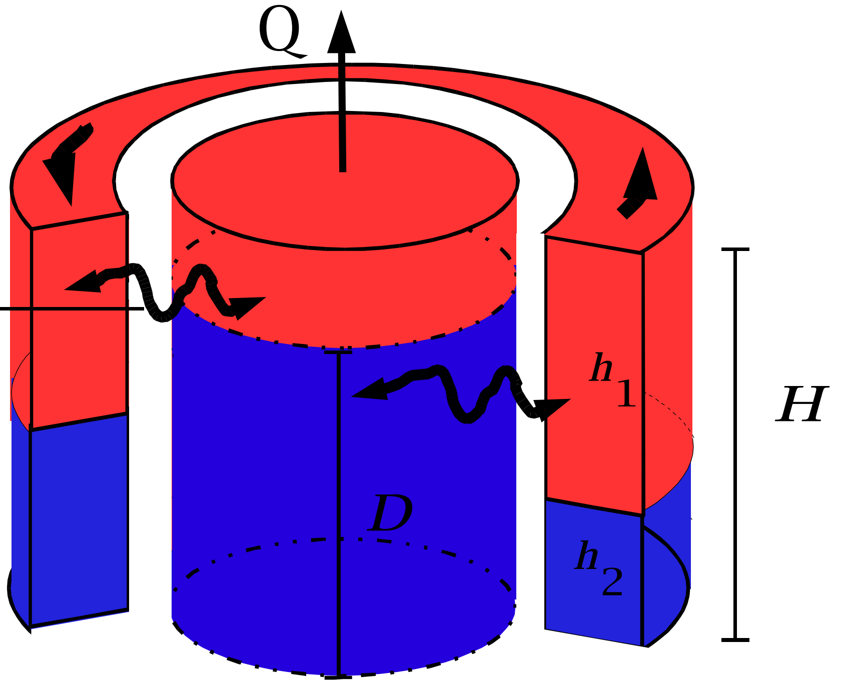
$$L\,\Delta\rho \frac{\partial h_2}{\partial t} + L\,\Delta\rho \frac{\partial (V_2 h_2)}{\partial l} = -\int_H^0 u'\rho'\,dz$$

Boundary Current

- wind and buoyancy driven
- geostrophic
- no convection
- mass conservation
- buoyancy conservation

A Two Layer Model for the Labrador Sea

Interior
- no mean flow, no sinking
- buoyancy loss converts light fluid into dense fluid



Eddy fluxes

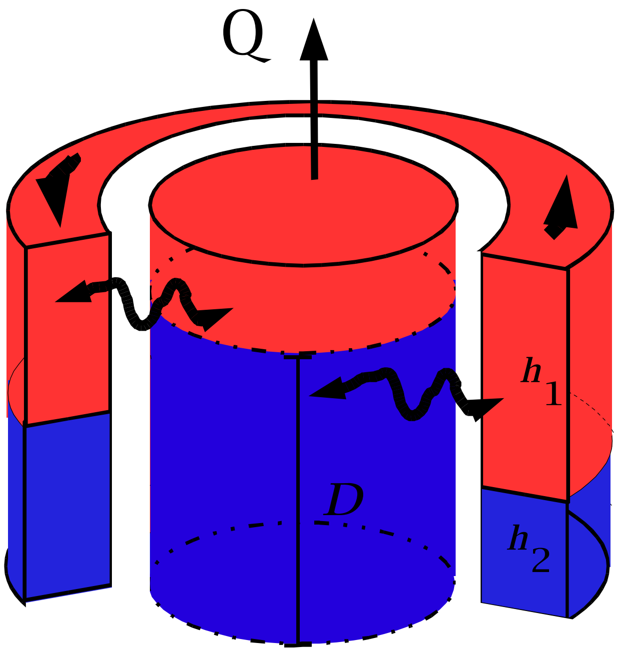
- proportional to the isopycnal gradient between interior and boundary current

$$u'\rho' = c\,\Delta\rho\,V_{bcl} = \frac{2cg'}{fL^2}(D - h_2)$$

Boundary Current

- wind and buoyancy driven
- geostrophic
- no convection
- mass conservation
- buoyancy conservation

Steady State



Interior

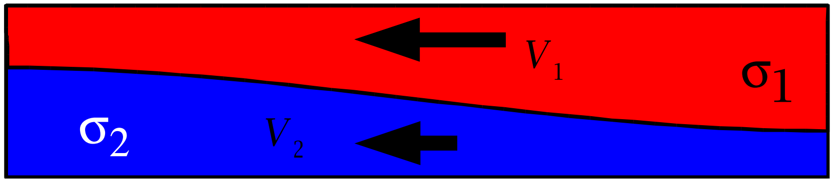
buoyancy loss: conversion of ρ_1 => ρ_2 (increase dense water reservoir)

eddy fluxes: flatten the interior/boundary current gradient (=> net import of ρ_1 and export of ρ_2)

Boundary Current

net loss of ρ_1 and gain of ρ_2

change in the density and hence velocity structure of the flow



A New Paradigm for a Convective Basin

Poleward Heat (Buoyancy) Transport

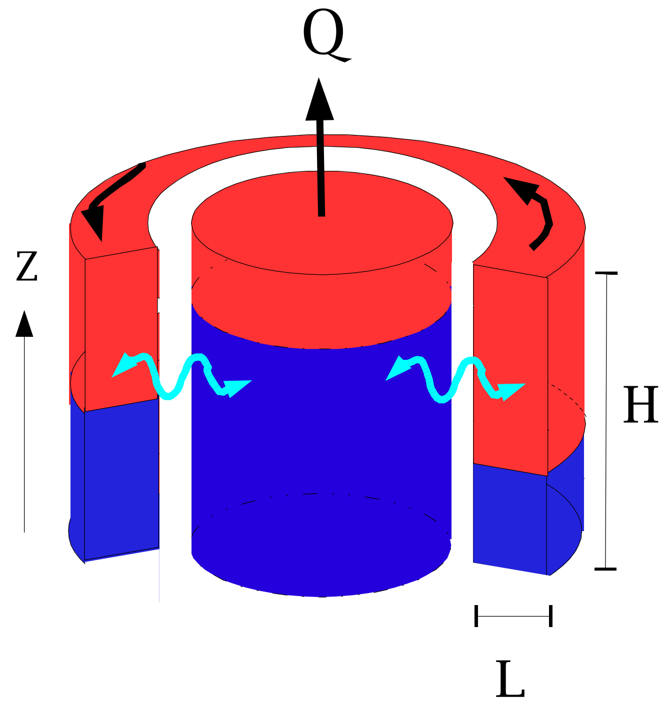
$$PHT = c_p \rho_0 L \left[\int_H^0 \theta(z) V(z) dz \right]_{inflow}^{outflow}$$

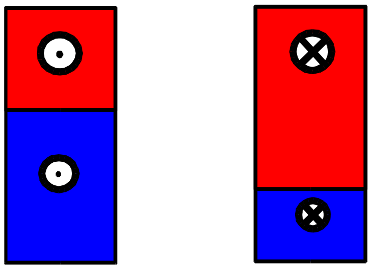
$$PBT = -g \alpha PHT = g' L [V_2 h_2]_{inflow}^{outflow}$$

$$= Q A = g' w_F$$

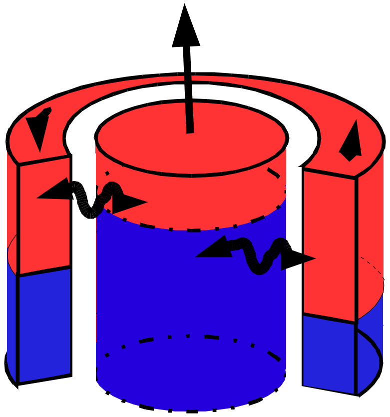
steady state

dense water formed





Steady State



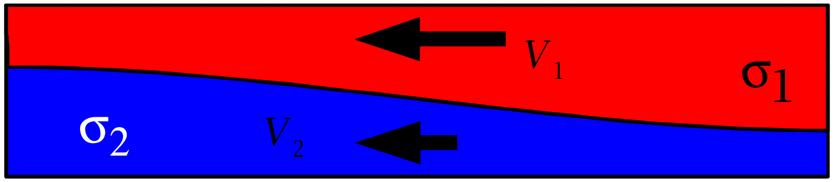
$$W_F = L[V_2 h_2]_{inflow}^{outflow} = W_H + W_D$$

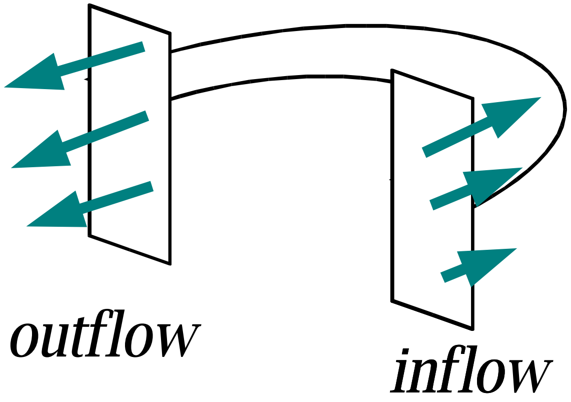
$$W_H = L V_2^{outflow} \Delta h$$

$$W_D = L h_2^{inflow} \Delta V_2$$

horizontal transport

sinking (depth) overturning



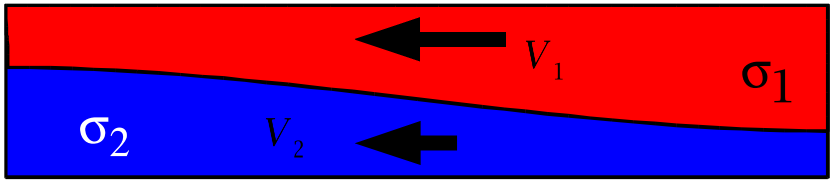


Why Does the Sinking Occur?

Eddy fluxes decrease the interior/boundary current gradient

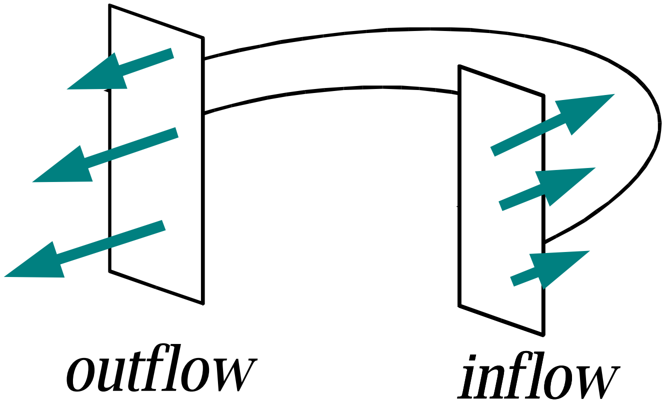
=> $V_{bcl} = V_1 - V_2$ has to decrease

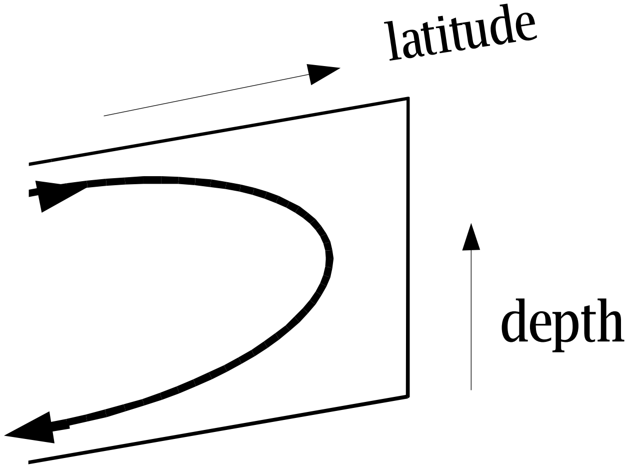
=> V_2 has to increase



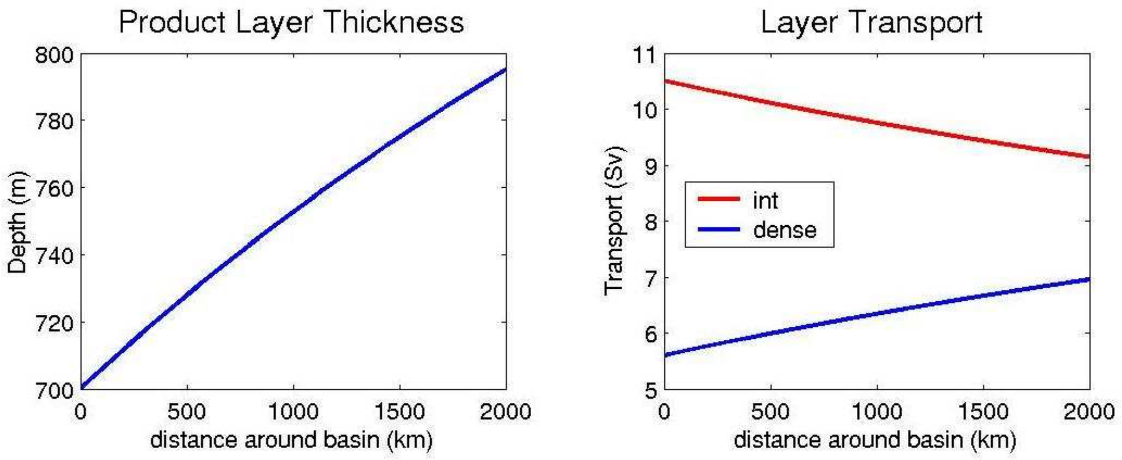
Sinking => Overturning

$$\Psi(z) = \int dx \int_z^0 V(x,z')\,dz'$$





Steady State Solution --- Labrador Sea Case



Labrador Sea Values:

R=250 km, L=100 km

H=1500m, h_2(in) = 700m,

V^W = 0.1 cm/s, c = 0.03,

Q = 30 W/m^2, Δρ = 0.05 kg/m^3

Model Predictions:

i. Mean LSW thickness 1250

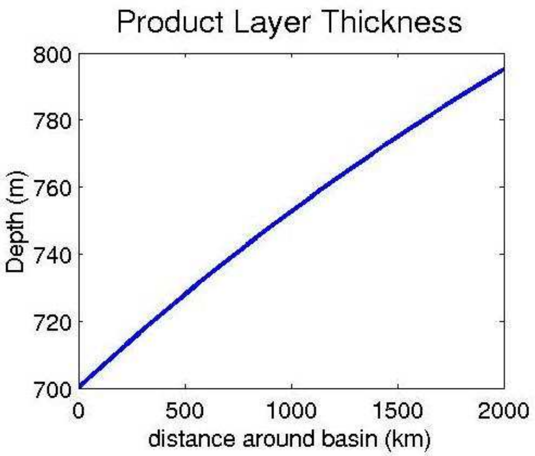
ii. BC thickness change = 100m

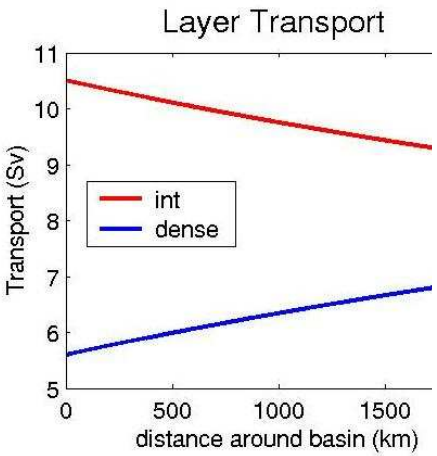
iii. dense water formed W_F = 2 Sv

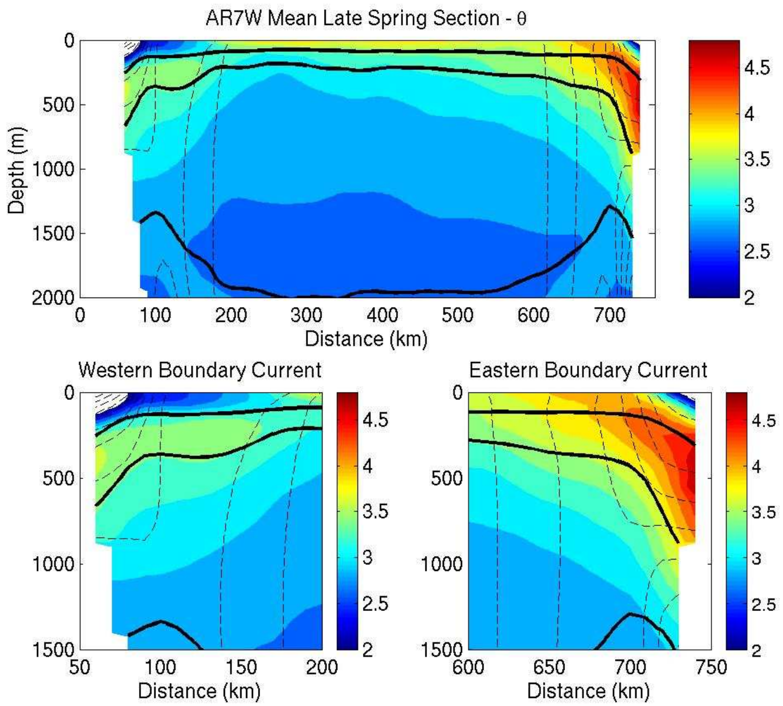
iv. Overturning = W_D = 0.8 Sv

Overturning circulation carries only 40% of the poleward heat transport.

Steady State Solution --- Model/Data Comparison







Model Predictions:

i. Mean LSW thickness 1250

ii. BC thickness change = 100m

iii. DWF --- $W_B = W_F = 2$ Sv

iv. Overturning = $W_D = 0.8$ Sv

Data:

i. Mean LSW thickness = 1200m

ii. BC thickness change 80m.

iii. 1.2 Sv to 7 Sv *(Rhein et al. 2002)*

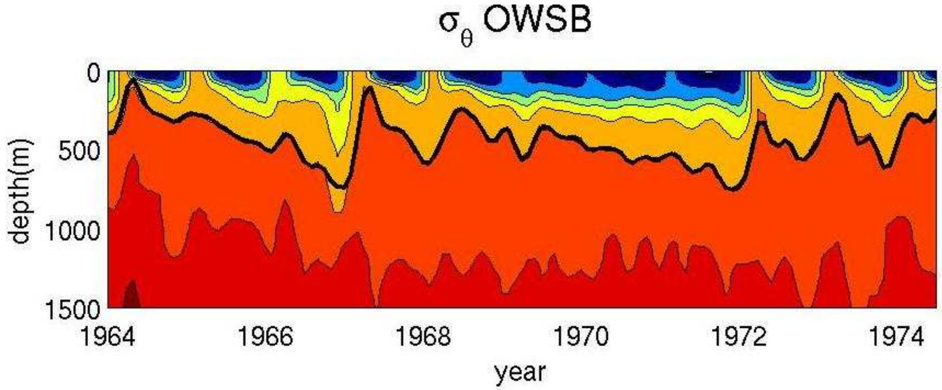
iv. 0.9 Sv from data

(Pickart & Spall, 2004)

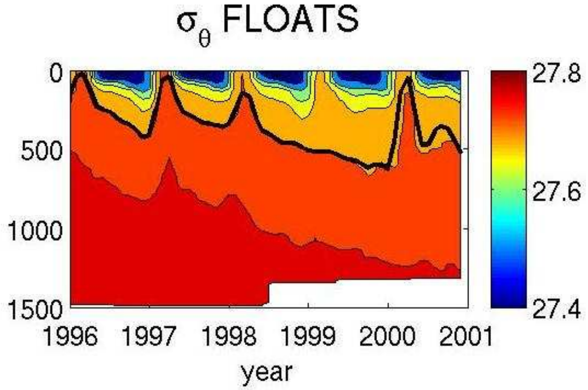
Overturning circulation carries only 40% of the poleward heat transport.

The Data

Ocean Weather Station Bravo
1964-1974



PALACE Float
1996-2000

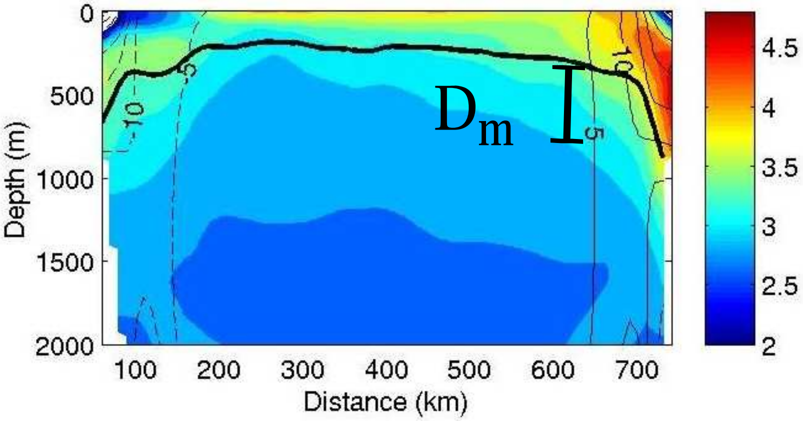


Lazier 1980, Straneo 2004

Interannual Restratification --- Model/Data Comparison

Theory - eddy fluxes are proportional to the boundary current/interior thickness gradient

$$u'\rho' = \frac{2cg'}{fL^2} D_m$$



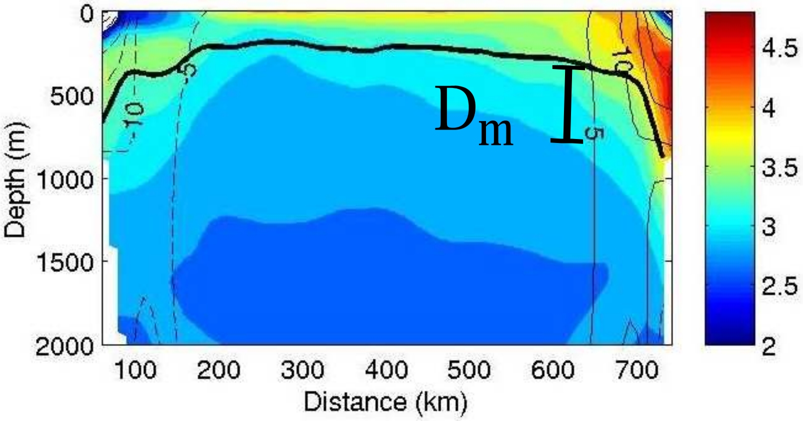
Prediction - if changes around boundary current are small

$$\frac{\Delta D_m}{\Delta t} \propto D_m^2(t=0)$$

Interannual Restratification -- Model/Data Comparison

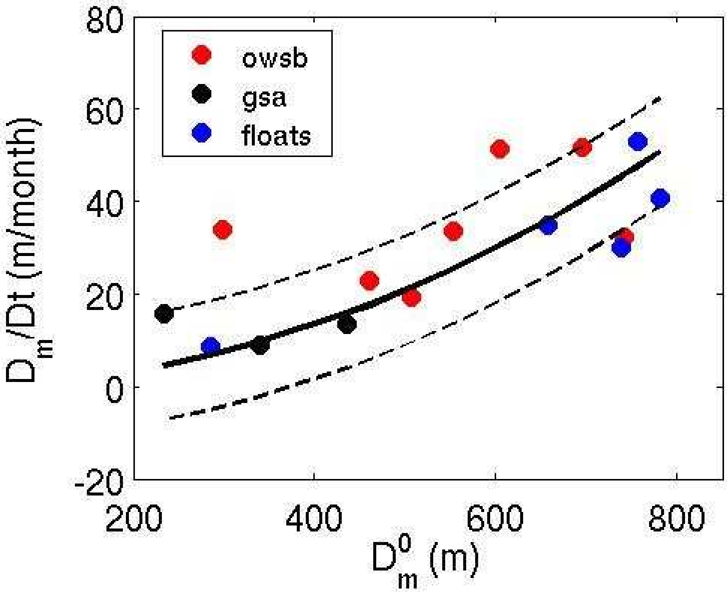
Theory - eddy fluxes are proportional to the boundary current/interior thickness gradient

$$u'\rho' = \frac{2cg'}{fL^2} D_m$$

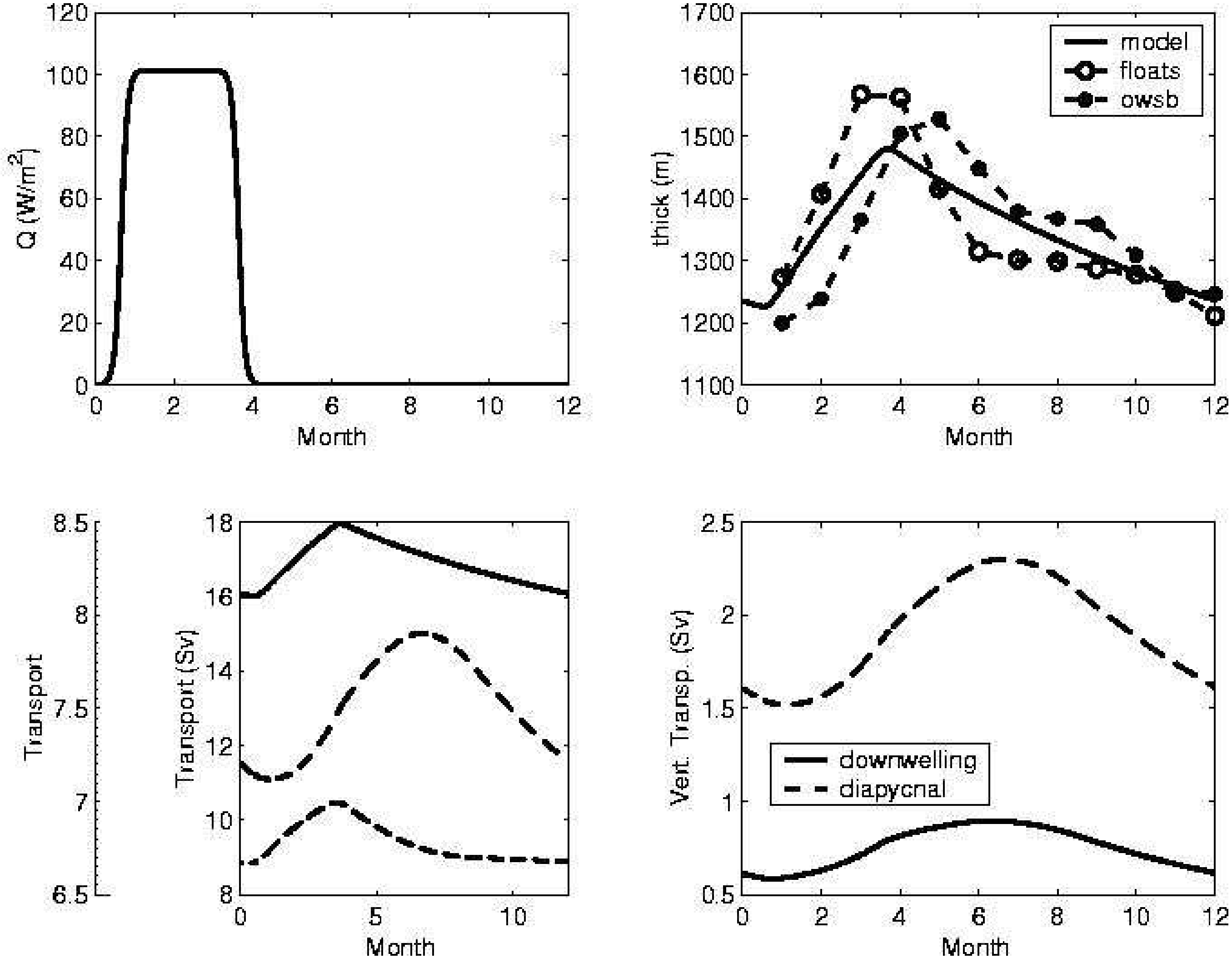


Prediction - if changes around boundary current are small

$$\frac{\Delta D_m}{\Delta t} \propto D_m^2(t=0)$$



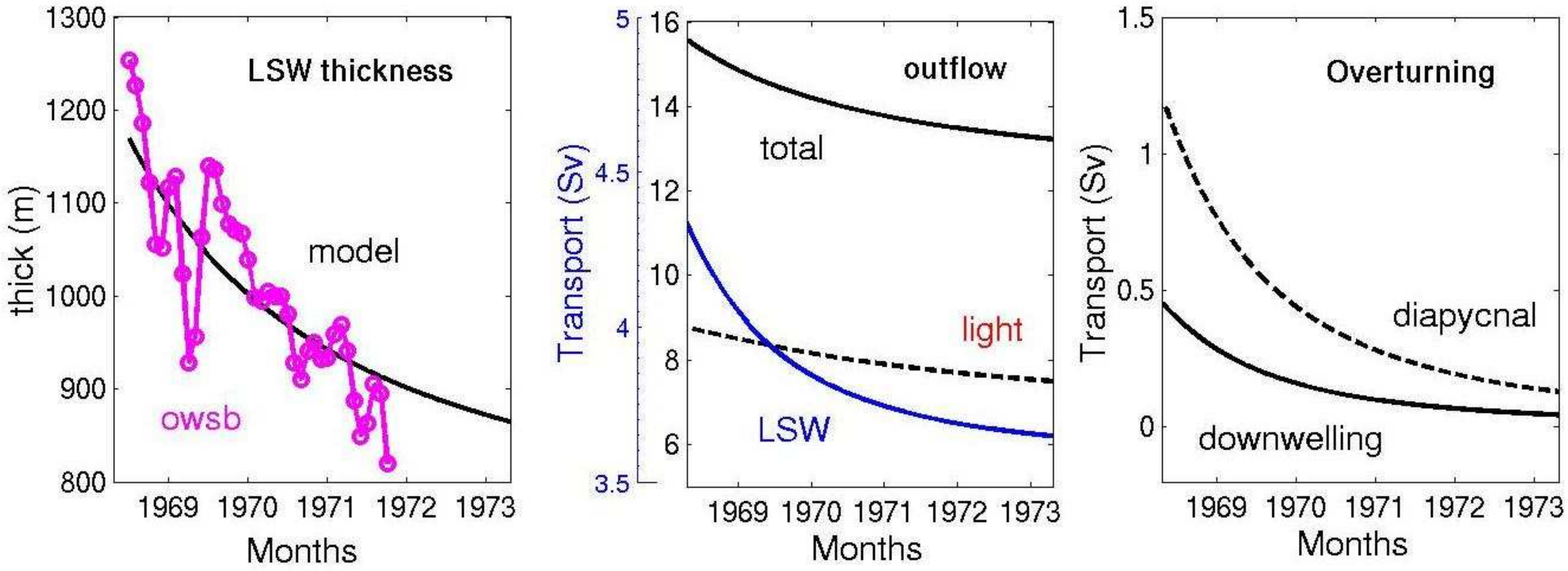
Model/Data Comparison **Seasonal Cycle**



Model-Data Comparison **Shutdown of Convection**

GSA anomaly shutdown 1968-1972

Theory - with no convection eddy fluxes will gradually drain LSW out of the basin



$$D_m(t) = D_m^0 \left(1 + \frac{t}{T_f}\right)^{-1}$$

Summary: New Paradigm/ New Model

1. New Paradigm for convective basins: convection maintains a reservoir of dense water in the interior, eddy fluxes continuously work to remove this reservoir

2. Poleward buoyancy transport is achieved both by a horizontal term and a sinking term.

3. Sinking occurs in the boundary current and arises from a need to conserve mass, while remaining in geostrophic balance.

4. The model is consistent with observations from the Labrador Sea

Outline

Focus: Clarify the connection between convection (and its variability) and thermohaline circulation related quantities.

Step 1. Present a new paradigm for convective basins

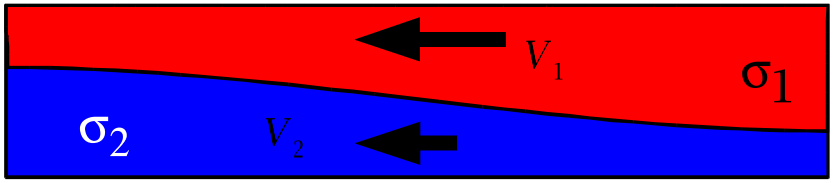
Step 2. Develop a simplified model based on this paradigm and test it against observations

Step 3. Investigate the dynamical connection between convection, poleward heat transport and overturning circulation

Step 4. What are the Implications for the large-scale oceanic variability

Model Analysis

What fraction of the PBT is carried by the overturning cell ?

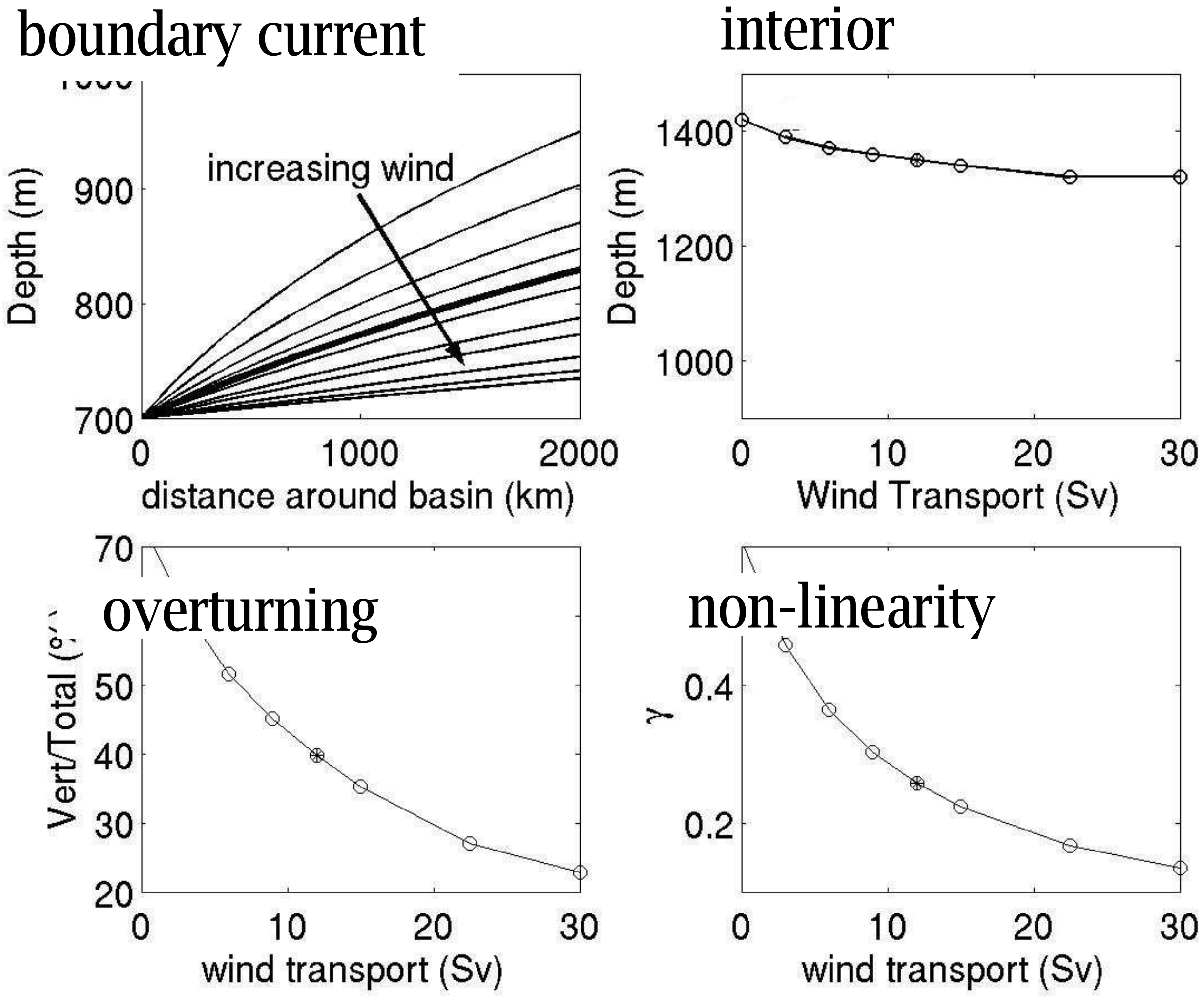


Inflow is both:
- wind-driven (barotropic)
- buoyancy-driven

Numerical solutions show how this is subject to change, and is not an intrinsic property of the basin.

Steady State Solution --- Different Wind-Driven Transports

Q and DWF
constant


boundary current

interior

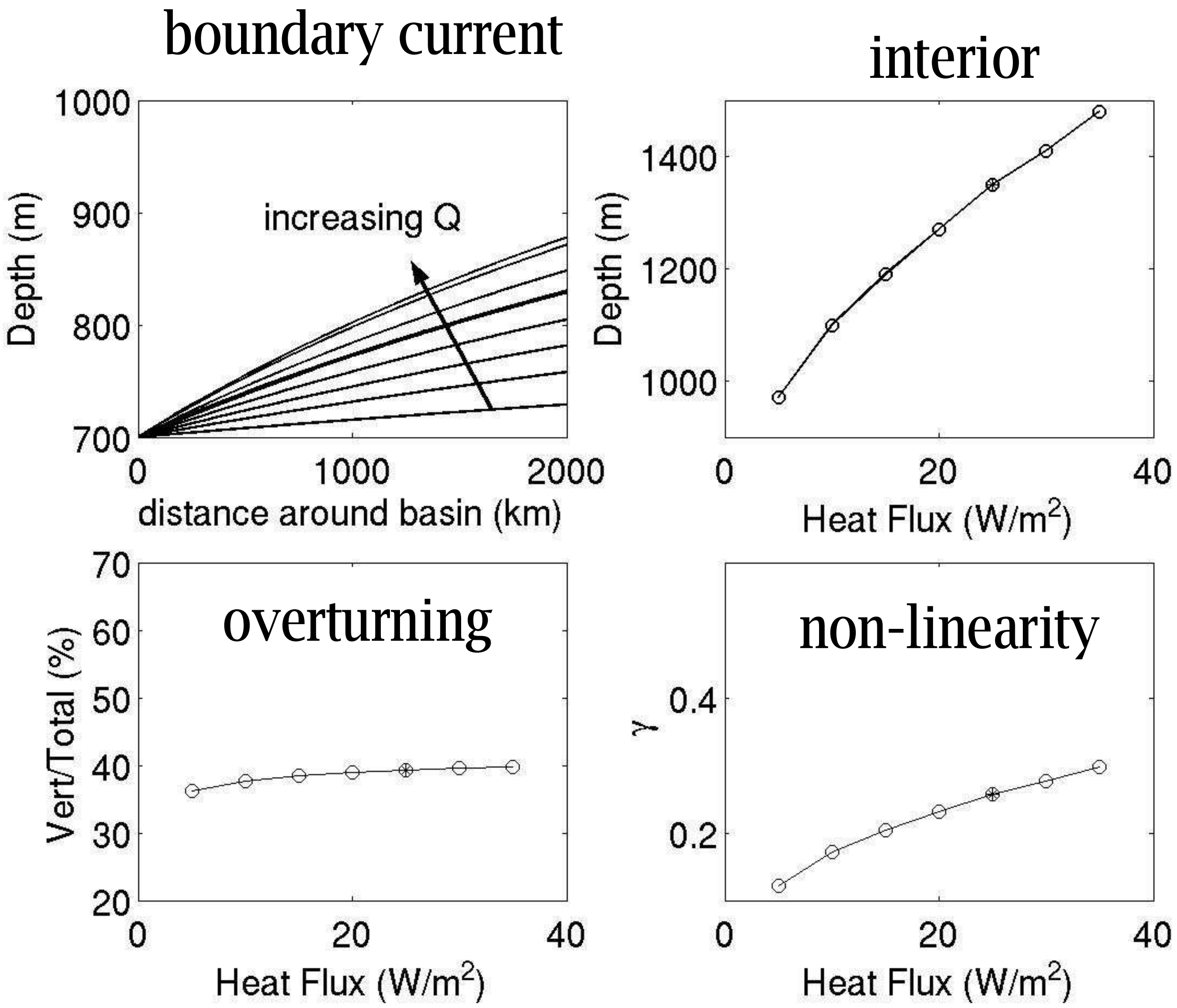
overturning

non-linearity

The fraction of PBT due to the overturning changes with varying wind-driven transport.

Steady State Solution --- Different Buoyancy Losses

Changing Q


boundary current

interior

overturning

non-linearity

Changes in the mean forcing alter the boundary current solution, and hence the vertical to horizontal heat transport partition.

Steady State Model Analysis

What fraction of the PBT is carried by the overturning cell ?

measure of non-linearity

$$\gamma = \frac{V^{0}_{bcl}}{V^{0}_{adv}} \frac{cP}{L} = \beta\,\epsilon = \frac{fluid \quad fluxed\ by\ eddies}{fluid \quad advected \quad around} = 0.4 \times 0.6 = 0.24$$

Labrador Sea

For small γ, ratio of overturning to horizontal transport:

$$\frac{W_D}{W_H} \approx \frac{V_{bcl}}{V_W}$$

=> transport by overturning increases with:
- decreasing wind
- increasing DWF
- increasing eddy efficiency

Summary: Overturning and Convection

1. Convective regions result in a poleward heat transport which is partitioned between a horizontal and overturning circulation.

2. The overturning is tied to the change in the baroclinic structure of the boundary current around the basin. In general the greater the boundary current modification, the larger the fraction transported by the overturning.

3. In the Labrador Sea - 60% of the poleward heat transport is due to the horizontal circulation, the remaining to the overturning.

Implications for MOC/THC Variability

1. Dense water formation does not imply sinking
(e.g. forming 2 Sv. of LSW results only in 0.4 Sv of overturning)
not co-located => not necessarily co-varying.

2. Some sinking has to occur in the boundary current but it may only be a fraction of the net DWF.

3. Fraction of sinking is not fixed but can vary as a result of wind (for example) even if the net amount of dense water formed remains the same (coupling of overturning and wind-driven circulation)

4. Variability of DWF and MOC are not necessarily directly related.

5. Basins with a sill (e.g. Nordic Seas) are almost entirely overturning systems, while the Labrador Sea is mostly a horizontal transport system.

What is Missing?

MANY THINGS..............

1. A surface layer in the model - e.g. to reproduce freshwater anomalies, that can prevent the convection at times

2. Watermass transformation within the boundary current

3. The feedback from the subpolar gyre and beyond for long timescales

4. A more sophisticated eddy parameterization, for example dependent on wind or velocity.