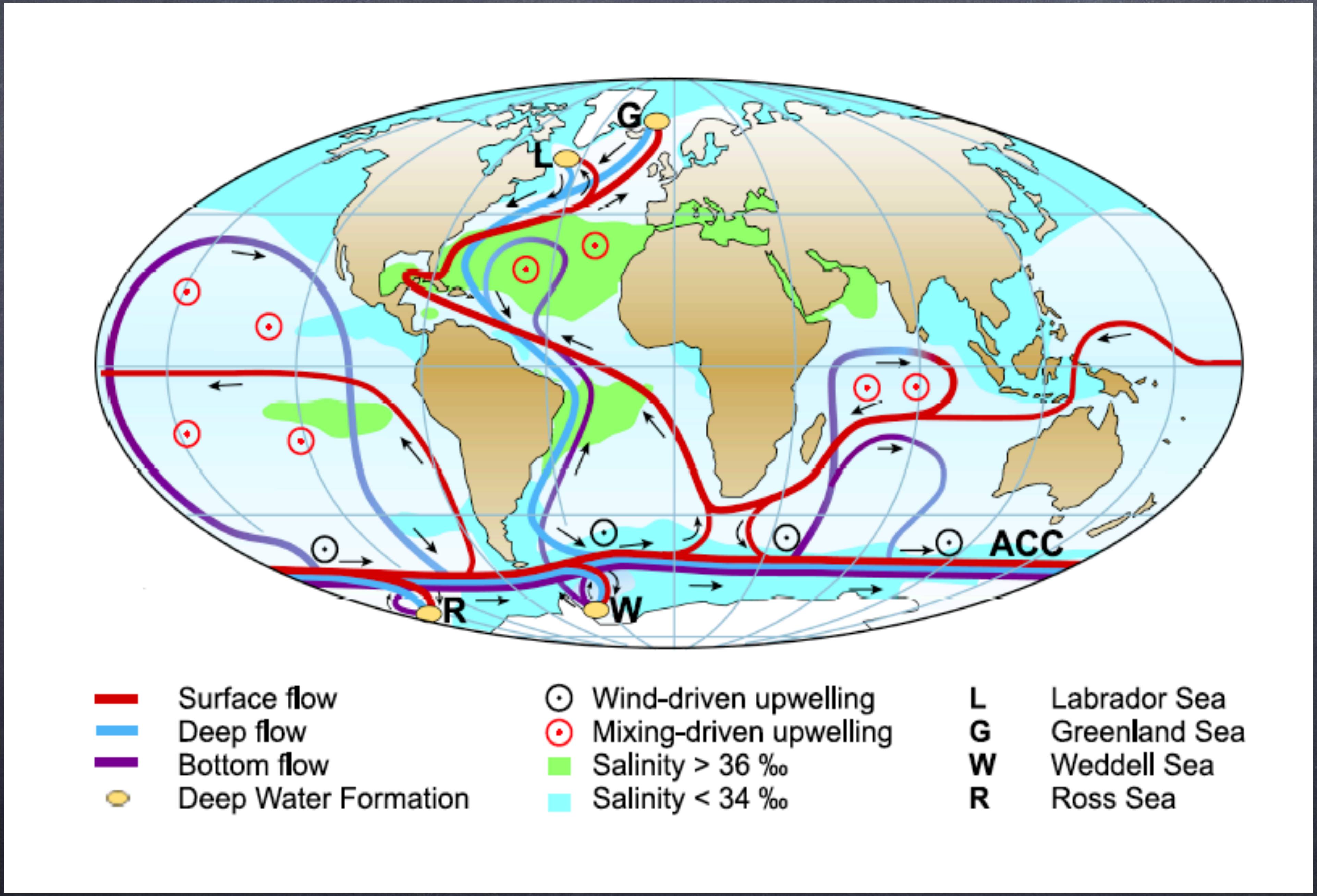
Abyssal circulation, convection and mixing

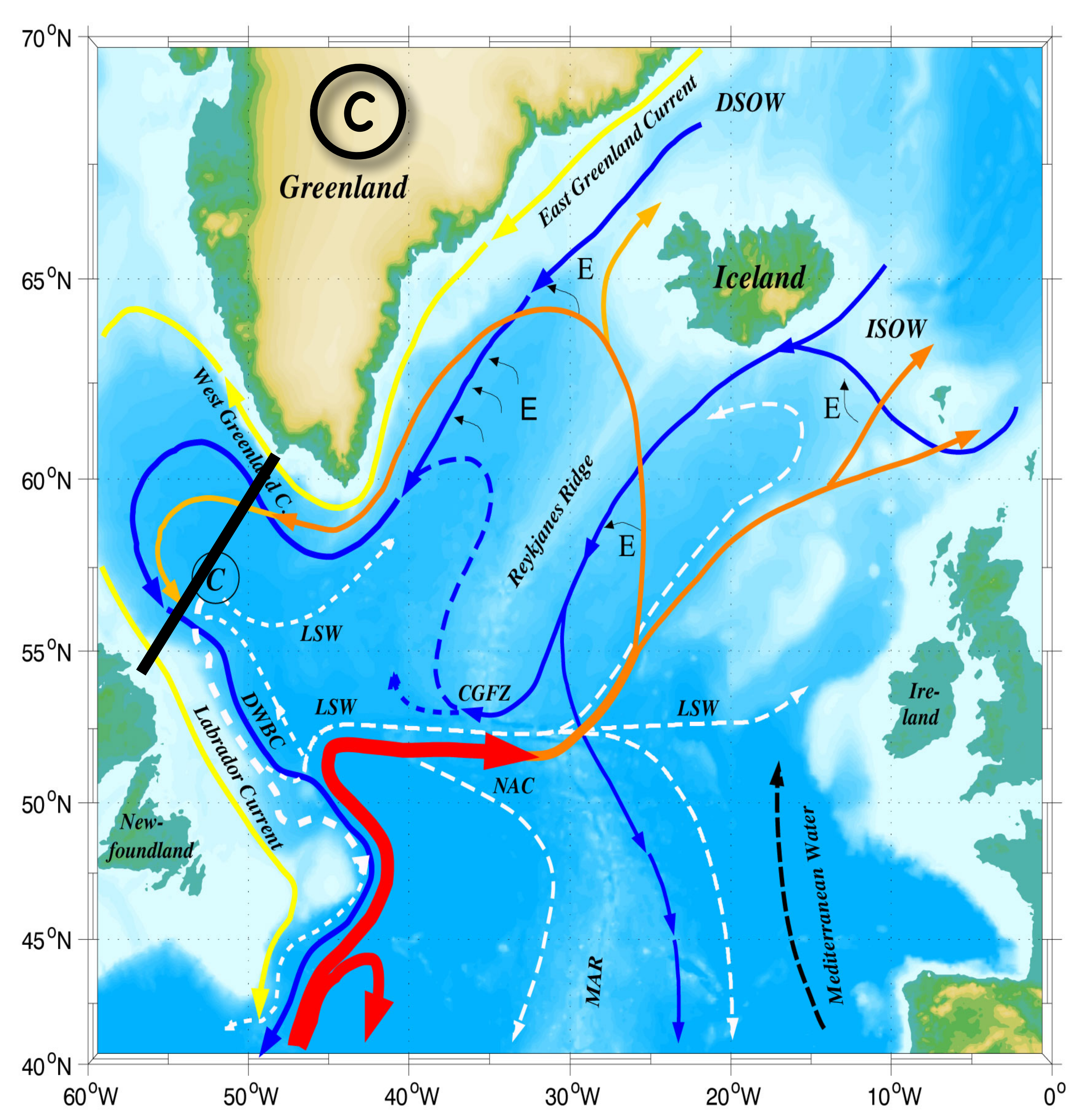
Lecture 21

Four main sites for deep and bottom water formation are in the coldest polar and sub-polar oceans.

Greenland Sea and Irminger Basin/Labrador Sea in the N. Atlantic, Weddell and Ross Seas in the Southern Ocean.



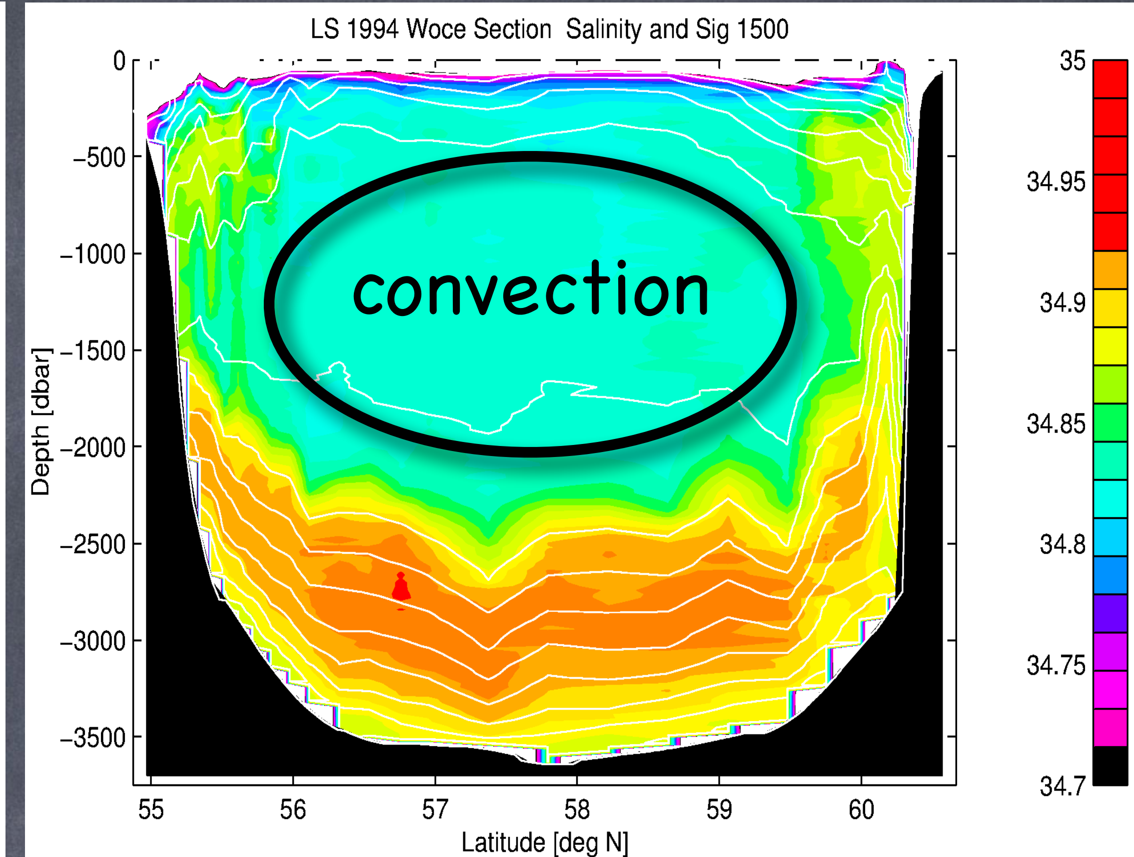
Kuhlbrodt et al. 2005

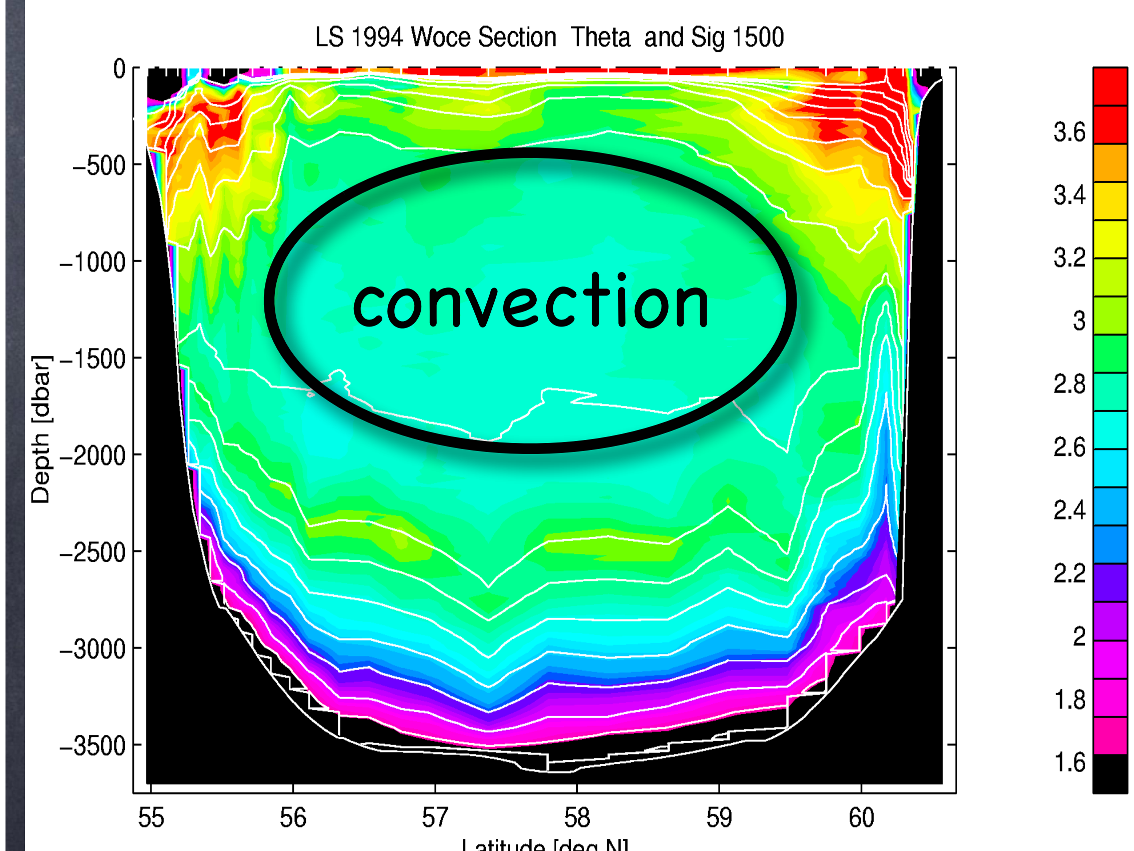


E: Entrainment   C: Convection   CGFZ: Charlie Gibbs Fracture Zone   MAR: Middle Atlantic Ridge

DWBC: Deep Western Boundary Current   NAC: North Atlantic Current

LSW: Labrador Sea Water   ISOW: Iceland Scotland Overflow Water   DSOW: Denmark Strait Overflow Water

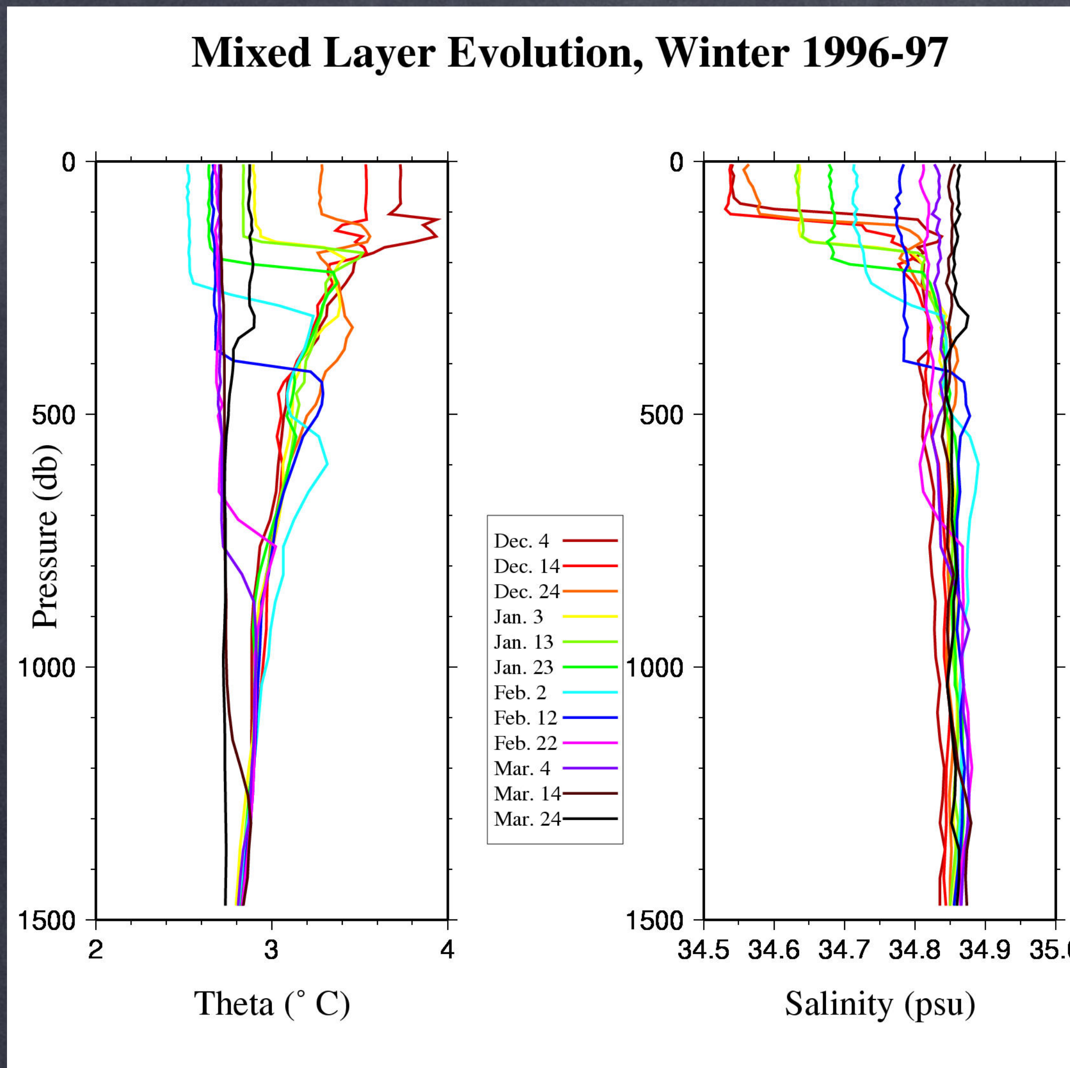




Deep Convection in the Labrador Sea

- Heat loss to atmosphere increases density of mixed layer, which gradually deepens.
- Deepest mixed layers occur near the ice edge - perhaps due to albedo effects? and/or brine rejection?
- Interior becomes weakly stratified and instabilities occur on small space and time scales
- Mixed layers up to 1500 m!

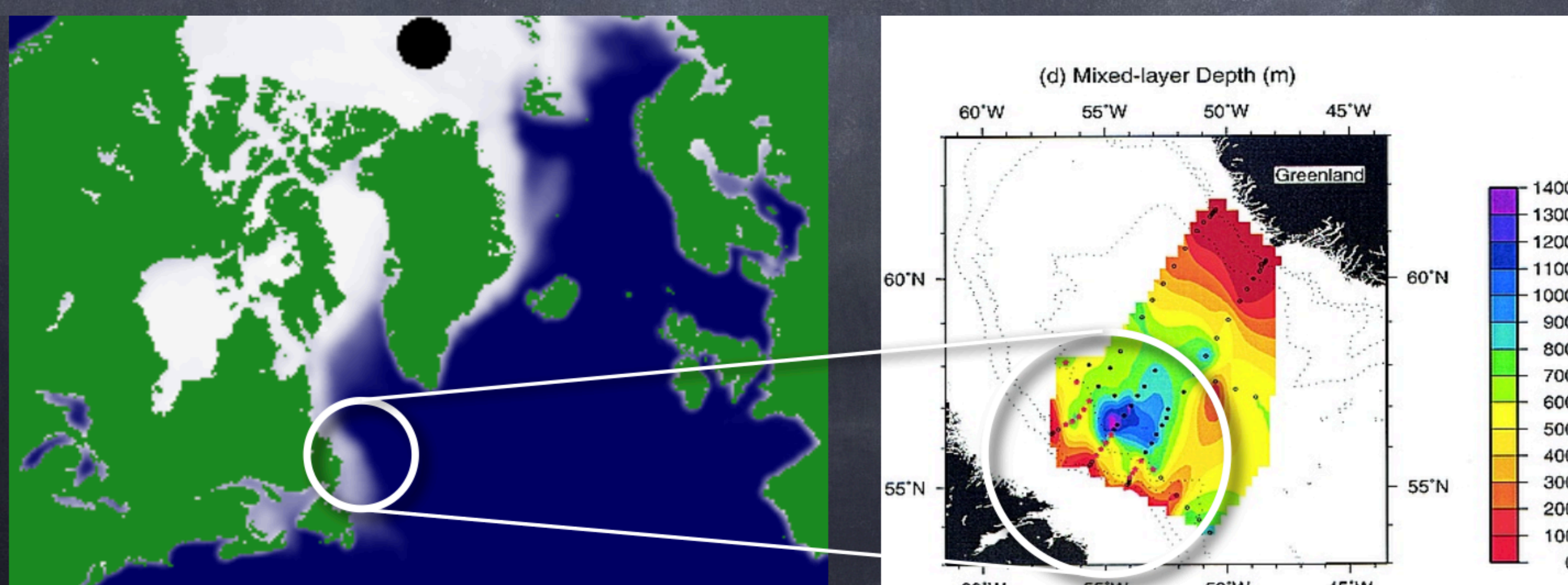
Deep Convection in the Labrador Sea



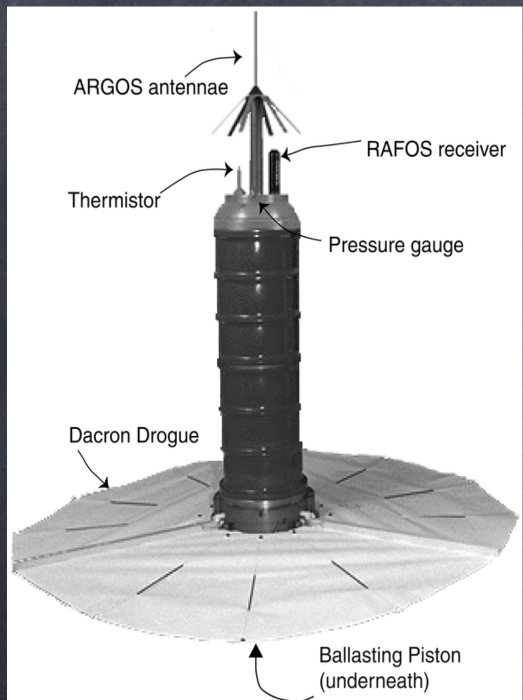
Change in temperature and salinity from December to March (from profiling float).

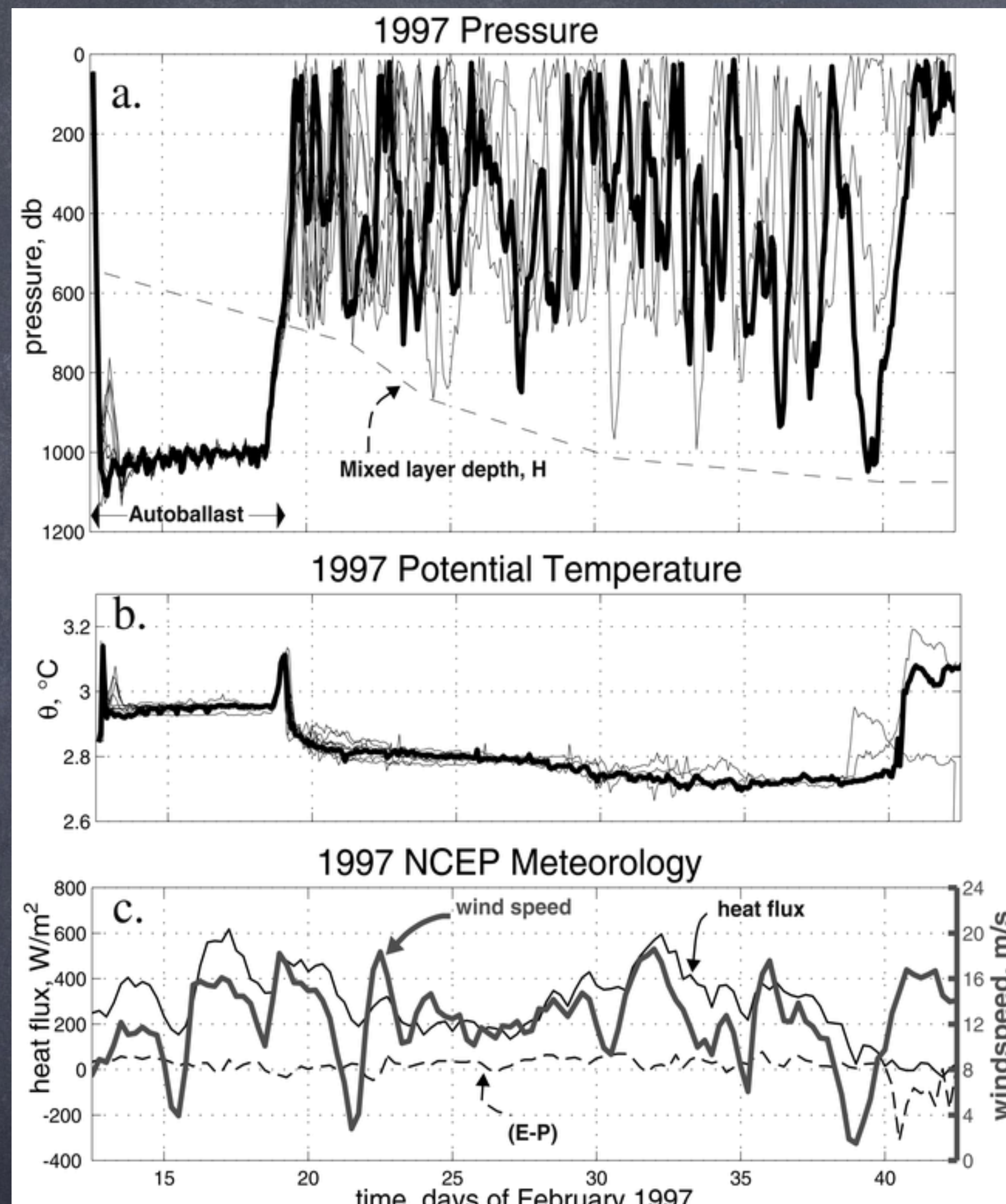
MLD in winter shows region of deep convection

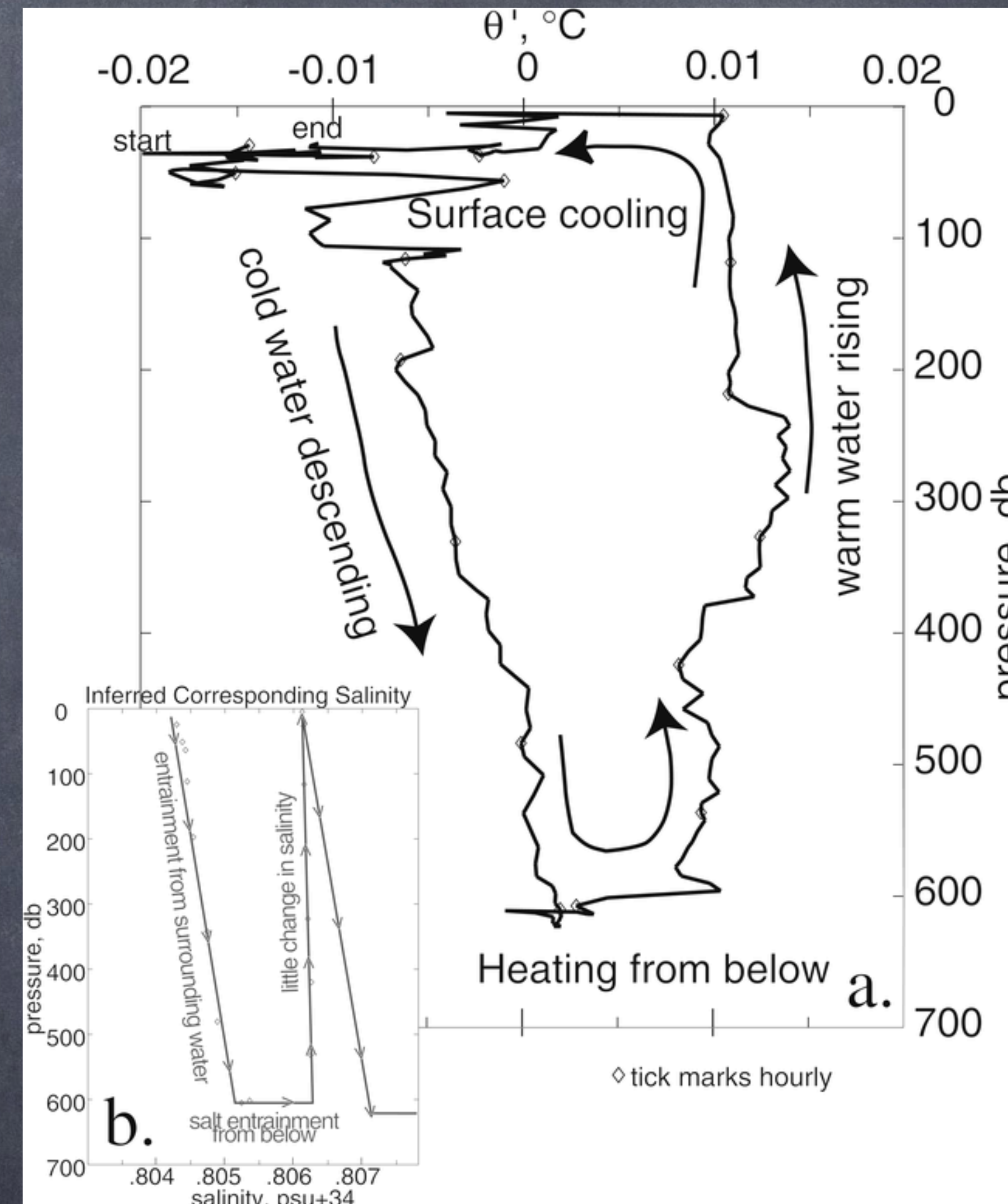
(Lavender & Davis, 1999; Lilly et al., 1999)



Deep Convection in the Labrador Sea



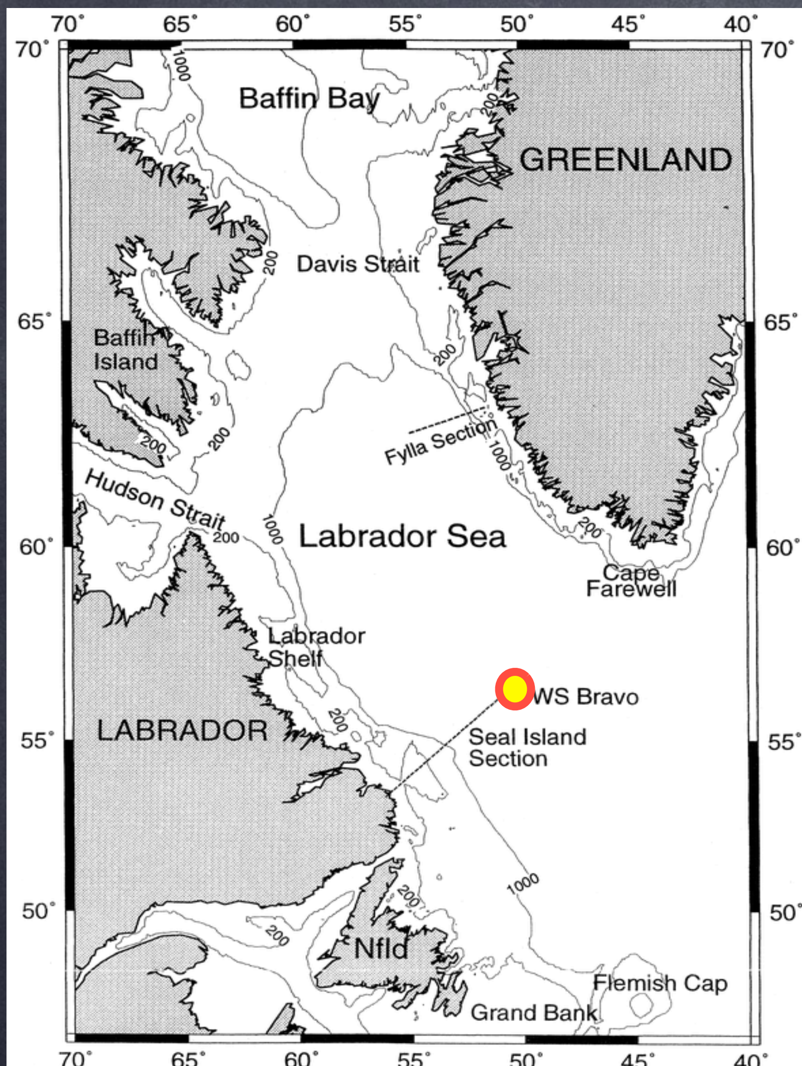


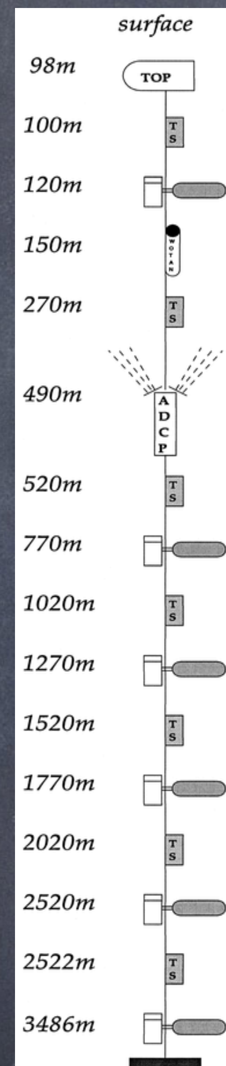


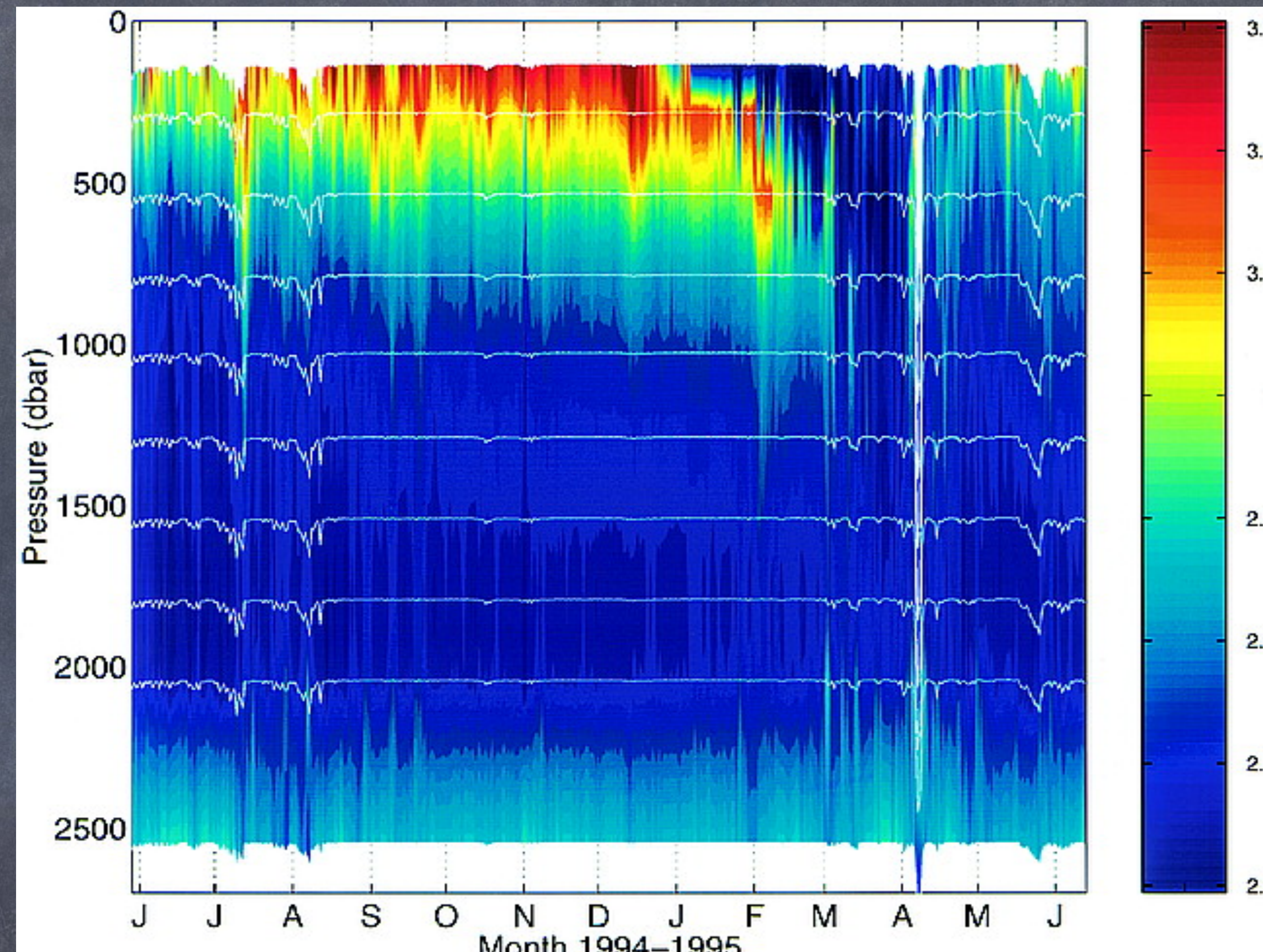
Lagrangian view of deep convection.
Note: water parcels move UP and DOWN - there is no mean vertical flow.

Steffen and D'Asaro

Deep Convection in the Labrador Sea







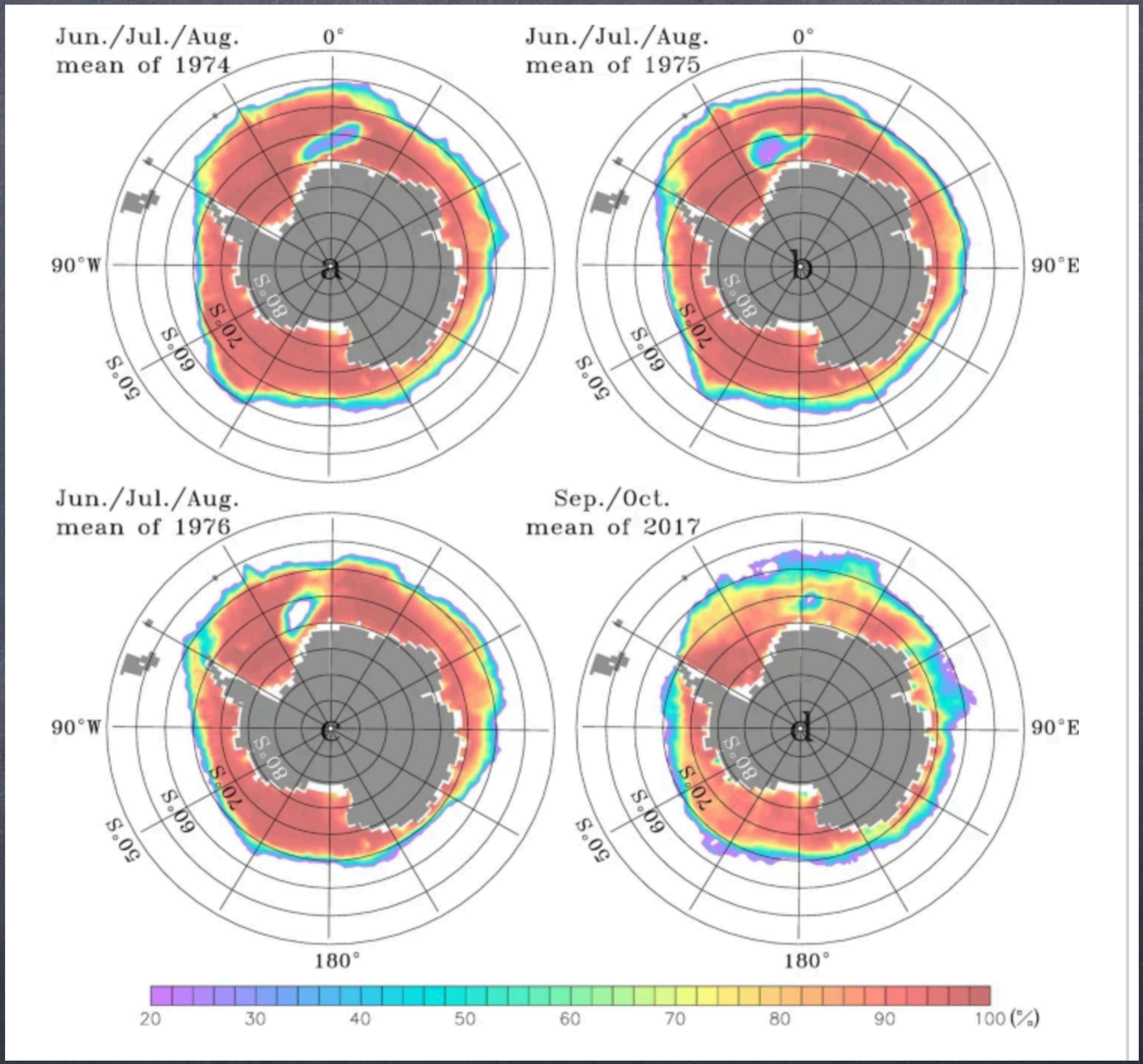
Time series of change in thermal stratification from a mooring.

Lilly et al. (1999)

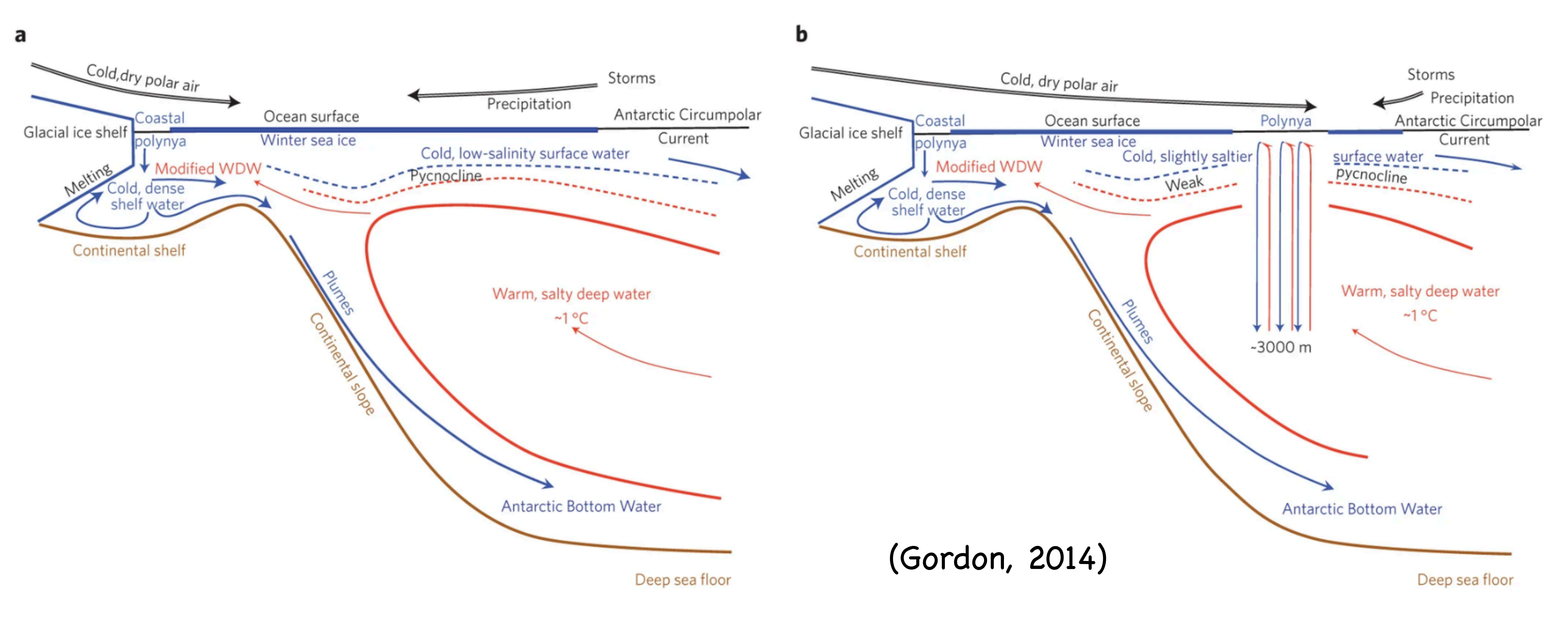
- Southern Ocean convection is common in polynyas - small areas of ice-free ocean (50-200 km) - where rapid cooling quickly destabilises the water column.

- Polynyas form close to ice shelves due to cold and dry katabatic winds, and sometimes in the open ocean when those winds extend north

rare open ocean polynyas



Deep Water formation in the Southern Ocean

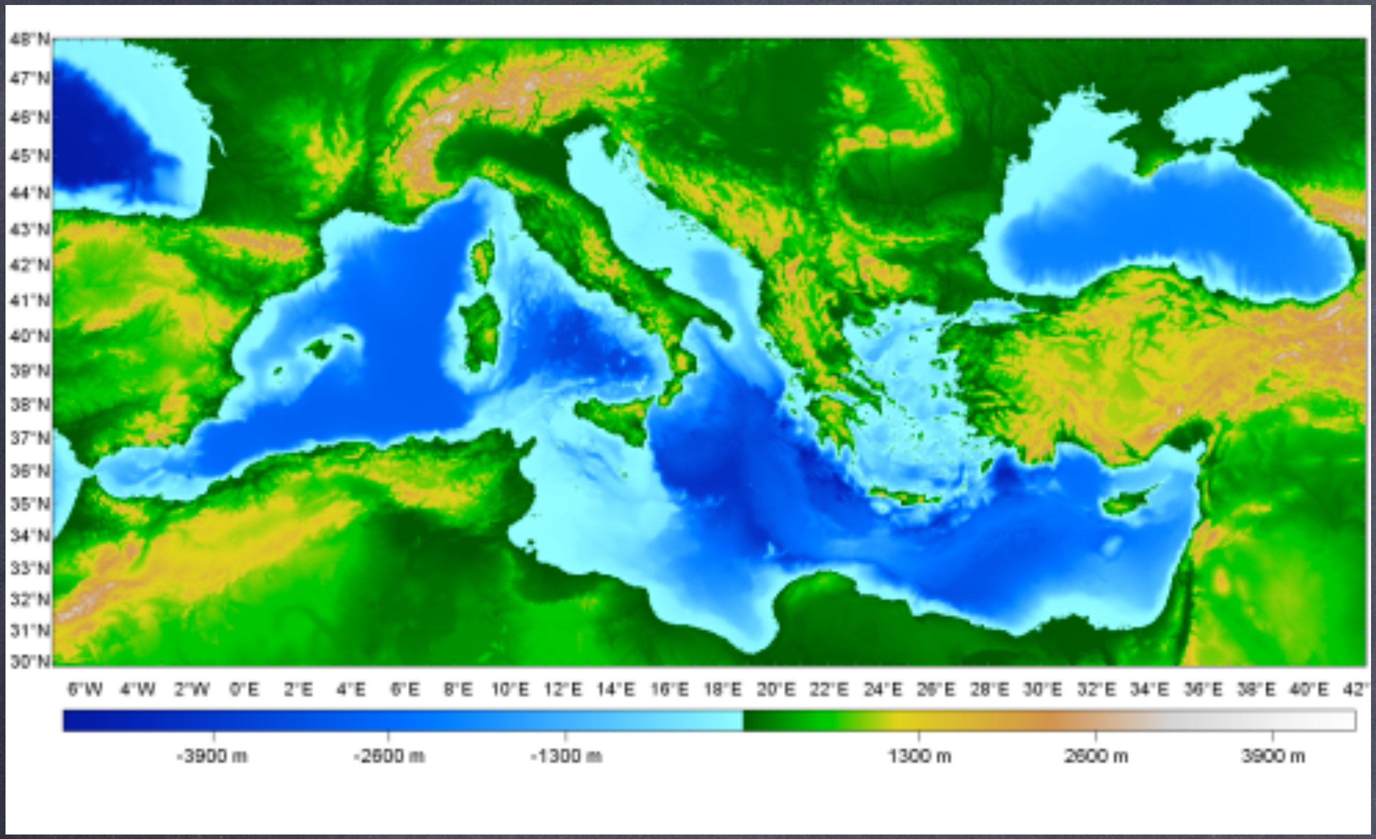


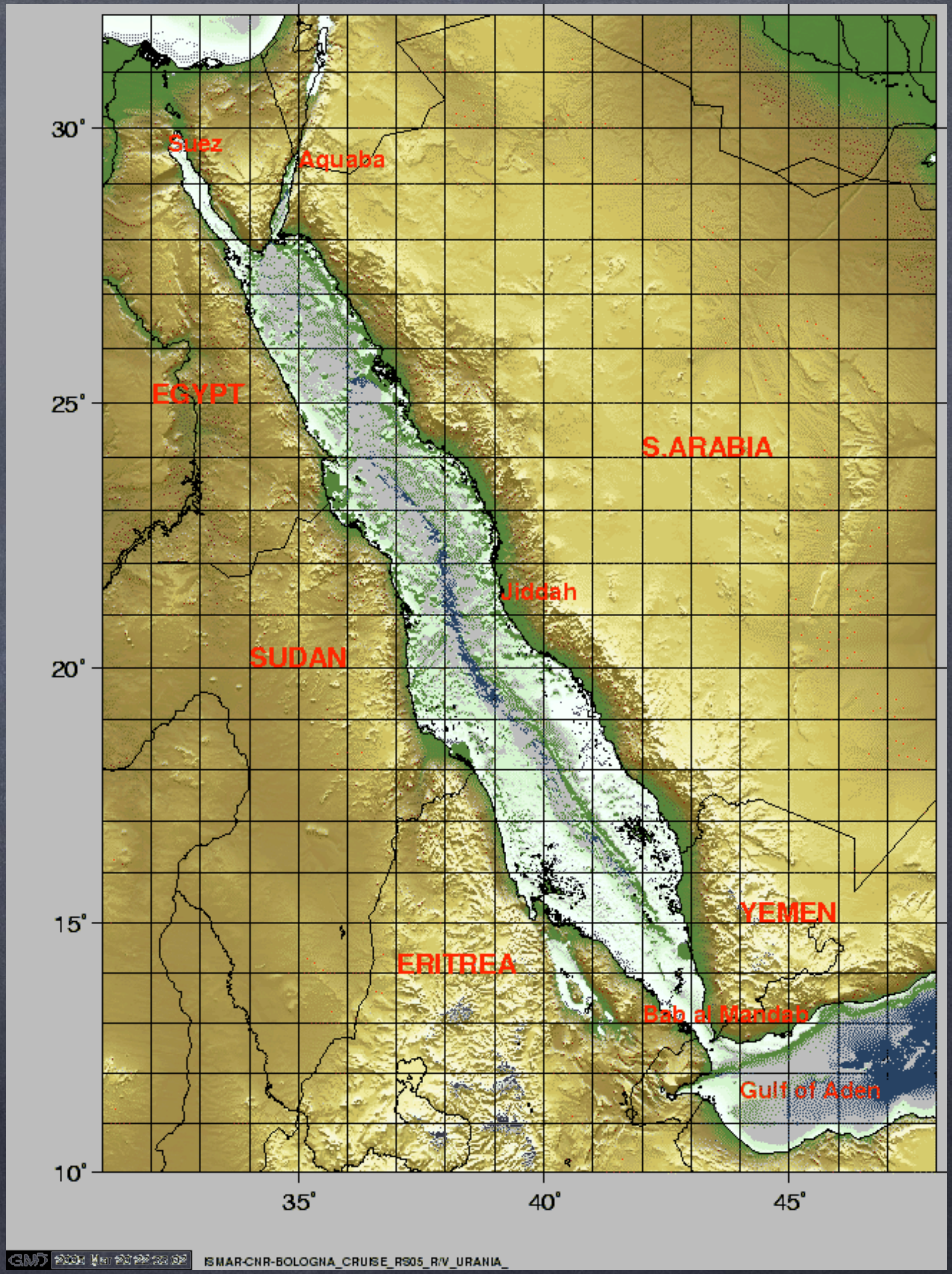
(Gordon, 2014)

(a) Cold fresh surface water over warm salty deep water. Open ocean convection is inhibited by storm belt precipitation and ice cover. Ventilation limited to continental shelf and slope. Brine rejection and cooling within coastal polynya and under glacial ice. Plumes of dense water descend the continental slope.

(b) Deep convection (3000 m!) can occur in polynya's formed in the storm belt when cold, dry polar air expands northward (negative Southern Annular Mode) and precipitation is reduced.

Evaporative Basins produce salty intermediate waters



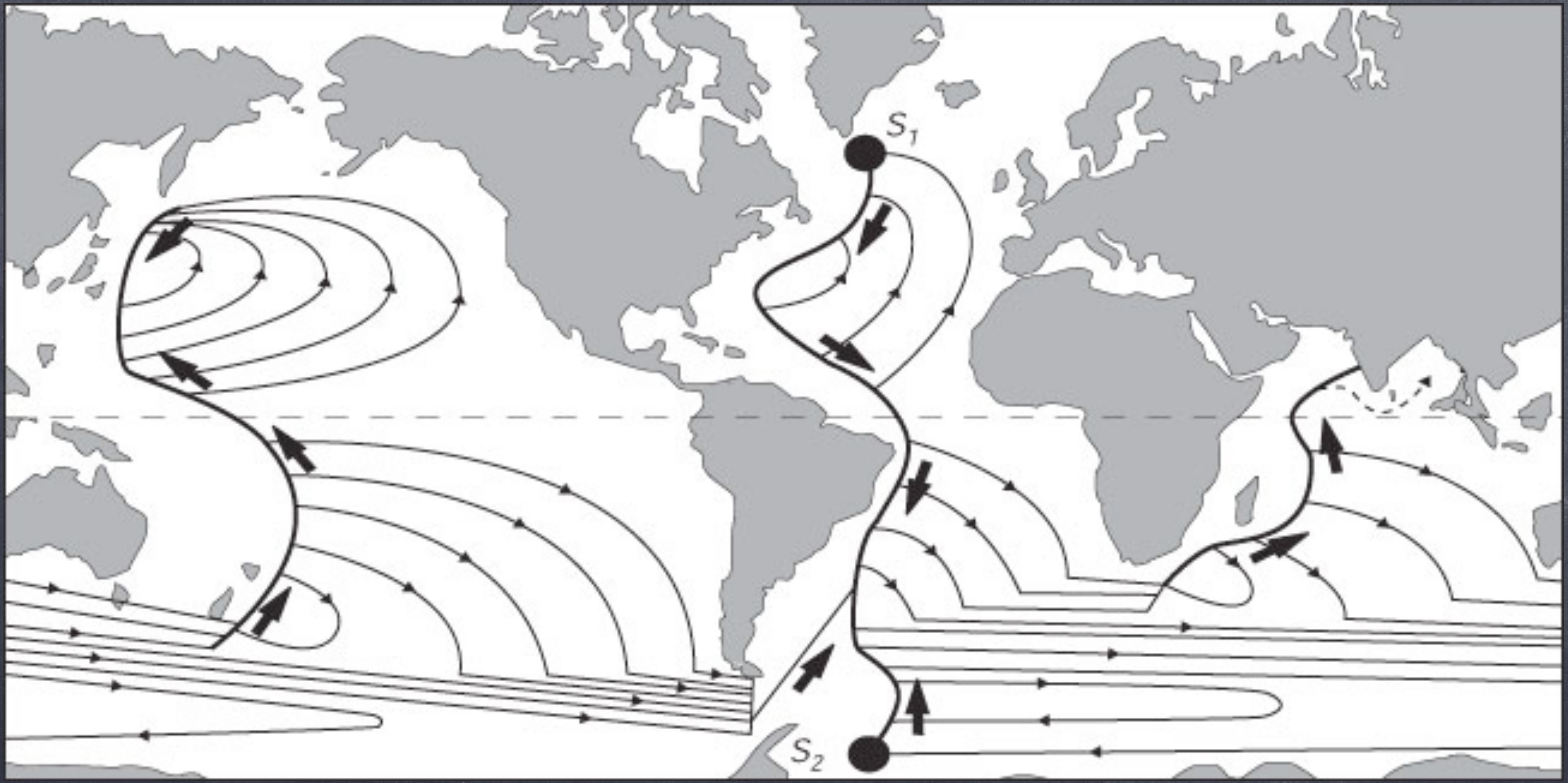


Med Sea Water, 39 psu

Although these waters are dense enough to sink to the bottom, rigorous mixing occurs with fresher waters as they overflow shallow sills into the open ocean. Both these waters end up spreading at about 600 - 1000 m depth with salinities 3-4 psu less than source.

Red Sea Water, 40 psu

Stommel-Arons theoretical abyssal circulation (1958-1960)

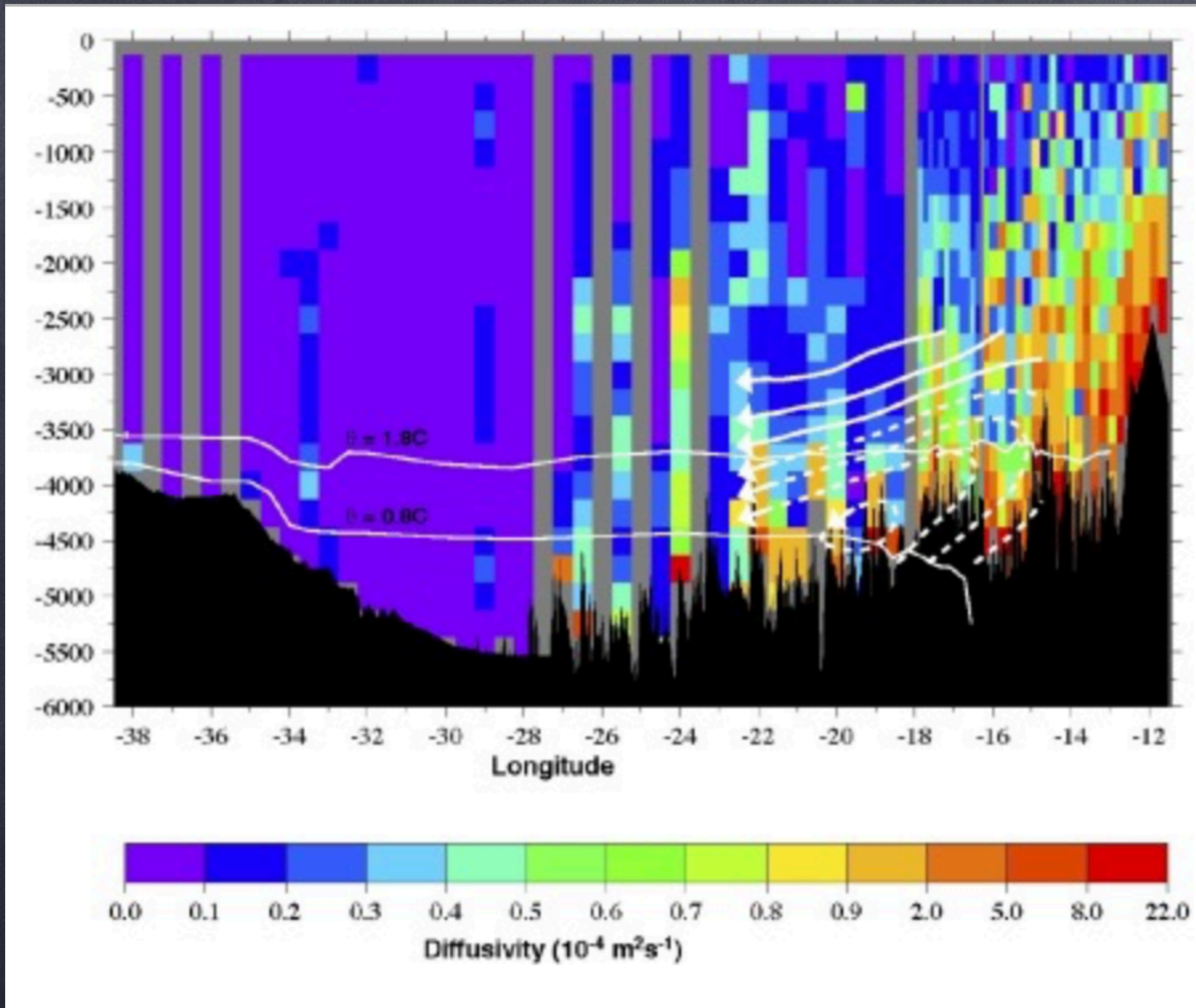


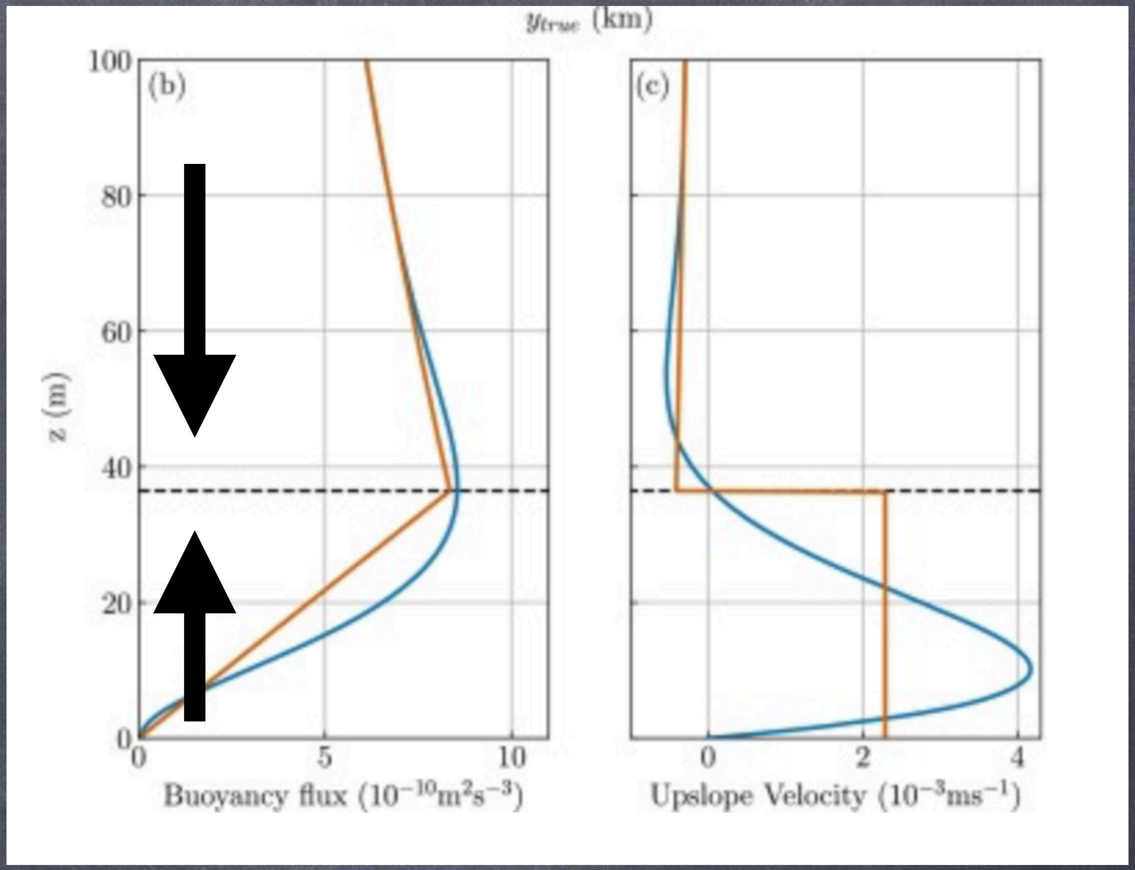
Driven by uniform upwelling. Single sources in North Atlantic and Southern Ocean. Analogy with Sverdrup Balance, but with upwelling somehow driven by turbulence.

John Swallow invented the neutrally buoyant float and observed the DWBC, proving Stommel's theory. Swallow floats also first revealed that eddies dominate in the open ocean, during the MODE experiment of the 1970s.

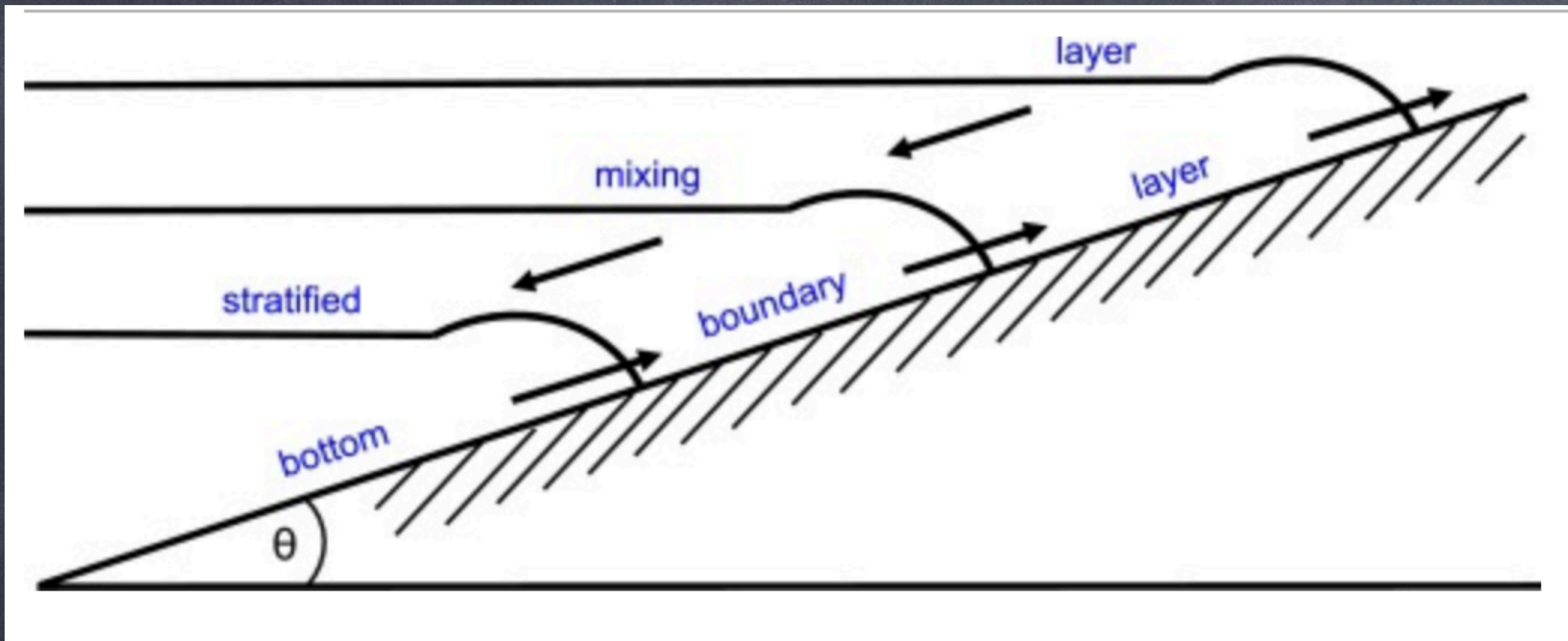
But where and how does upwelling happen?

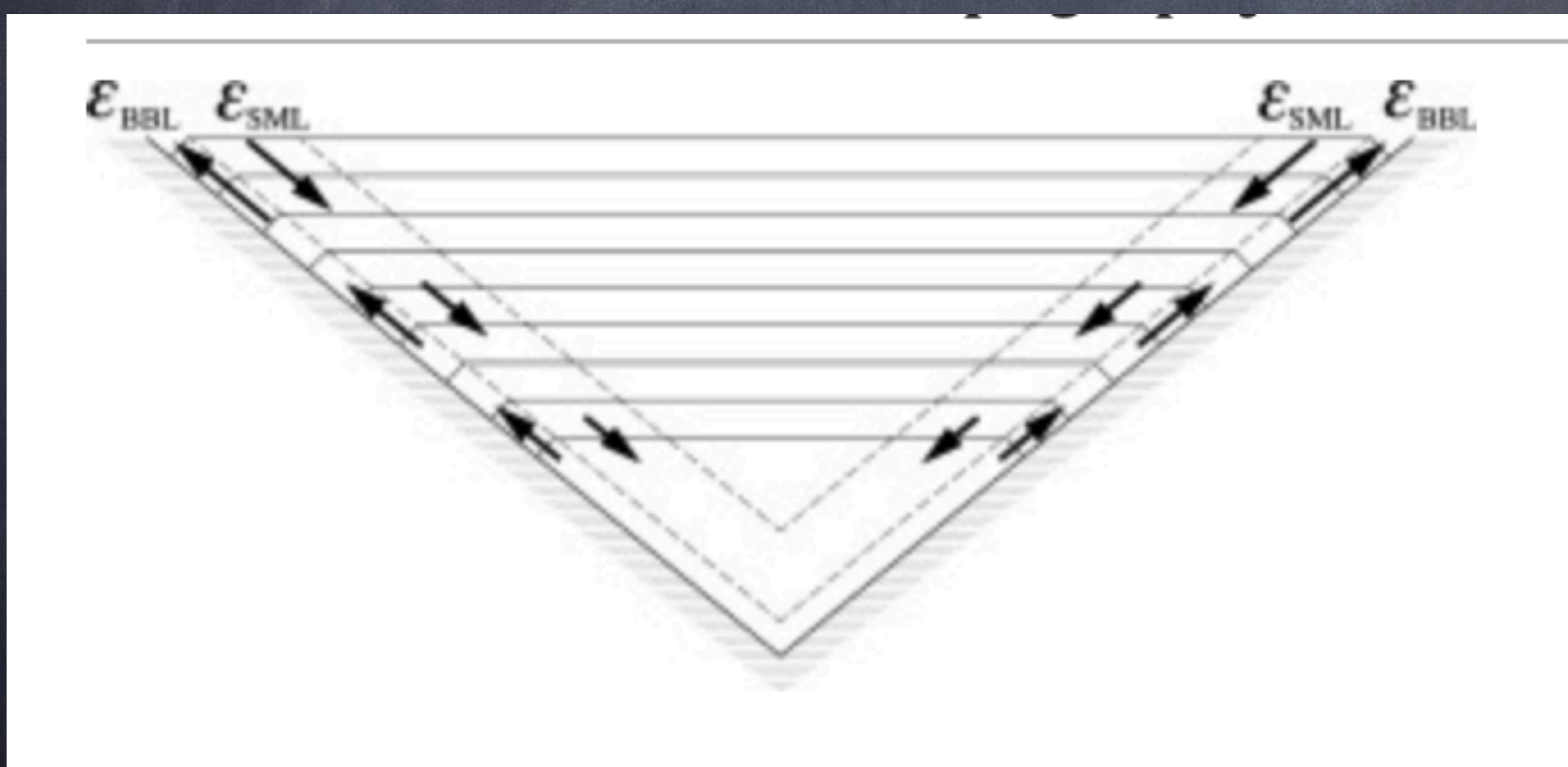
- Stommel-Aarons assumed uniform upwelling everywhere and Munk showed, thru a simple advective-diffusive balance, that this upwelling is $1x10^{-4}$ m^2 s^{-1} , or about 25-30 Sv of deep water formation globally.
- But, measurements of mixing in the open ocean are always 10-100x smaller
- In fact, open ocean mixing is measured to be bottom intensified, acting to move water DOWNWARD!





Elevated mixing over rough topography intensifies downward (Polzin et al, 1997). Resulting buoyancy flux is downward, except within bottom boundary layer, about 50 m (Ocean Mixing, 2022).

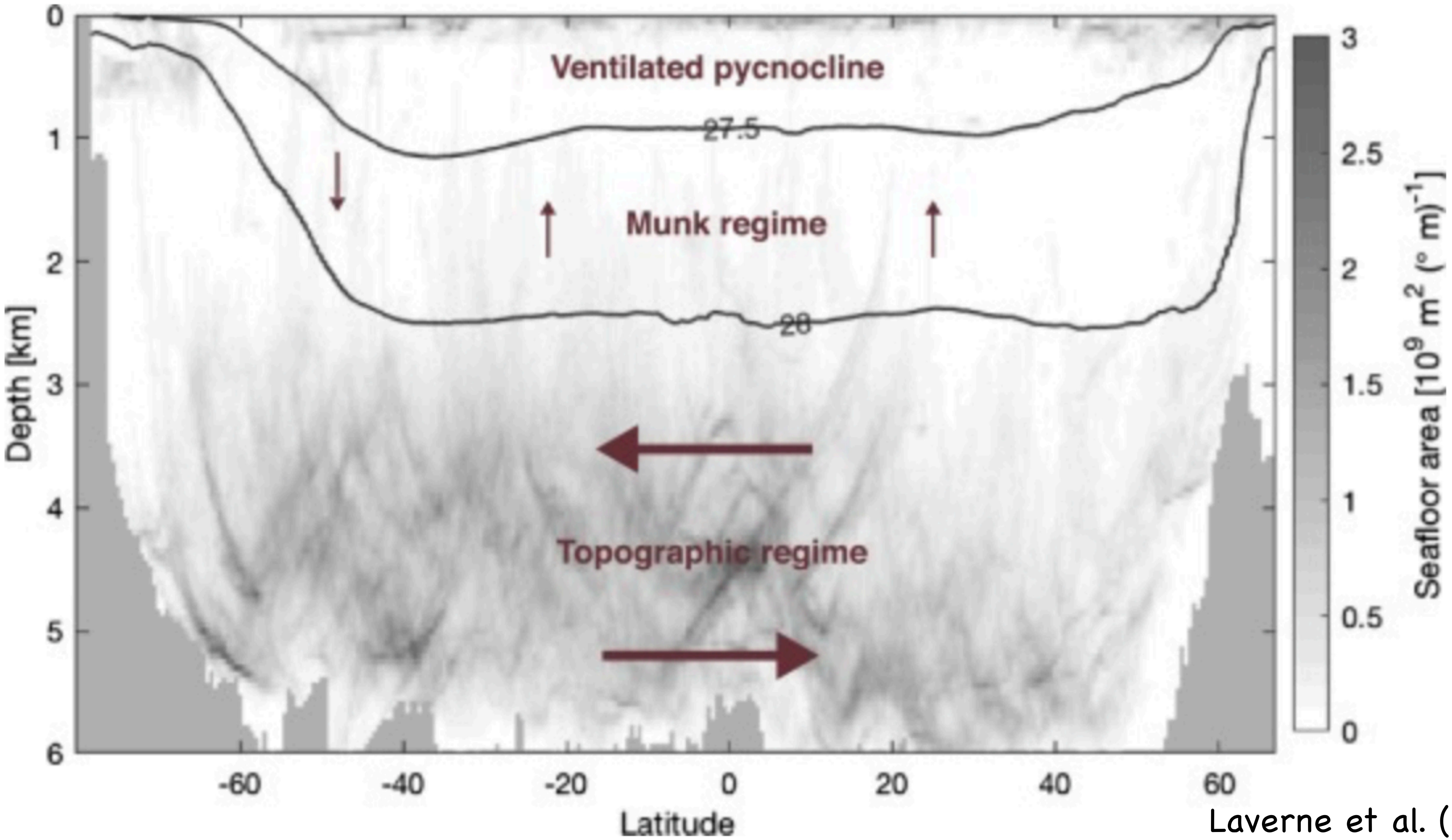




Upwelling is happening only in the bottom boundary layer

But, there is more boundary area as you go up in the ocean, so bbl upwelling will increase upward

(Ocean Mixing, 2022, Garabato and Meredith Eds.)



Laverne et al. (2022)
Ocean Mixing, Chapter 3

TOPO: Upwelling in BBL and downwelling above drives northward flow of bottom water and southward flow of deep water

MUNK: Small mixing driven by background 3-D turbulence

VENT: Adiabatic upwelling/ downwelling driven by surface mixing and fluxes

What exactly is Mixing?

- **3-D turbulence**: Gravitational and shear instabilities, on scales 1-100 m
  - Large in surface and bottom boundary layers, 10-100 $m^2\ s^{-1}$
  - Moderate in interior mostly due to breaking internal waves generated by tides, 1 $m^2\ s^{-1}$
  - Irreversible mixing of momentum and tracers
- **Geostrophic turbulence**: Barotropic and baroclinic instabilities, on scales of 1-300 km
  - Eddies stir momentum and properties horizontally, generating fronts, but not mixing
  - In boundary layers, where tracer surfaces are not aligned with density, eddies can irreversibly mix