ATM 241, Spring 2020
Lecture 10
The Thermohaline Circulation

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Marshall & Plumb
Ch. 11

In this section…

Questions

- Where does deep oceanic convection occur?
- How does deep oceanic convection occur?
- How does the thermohaline circulation operate?
- How is the thermohaline circulation connected with the structure of the Atlantic and Pacific at depth?
- Where can the “youngest” and “oldest” ocean waters be found?
- What is the climatic relevance of the thermohaline circulation?

The Thermohaline Circulation

Thermo

(temperature)

-haline

(salinity)

Definition: The **thermohaline circulation** refers to a global circulation driven by convection at polar latitudes.

Sometimes referred to as **ocean conveyor belt**, the **great ocean conveyor**, or the **global conveyor belt**.

The Thermohaline Circulation

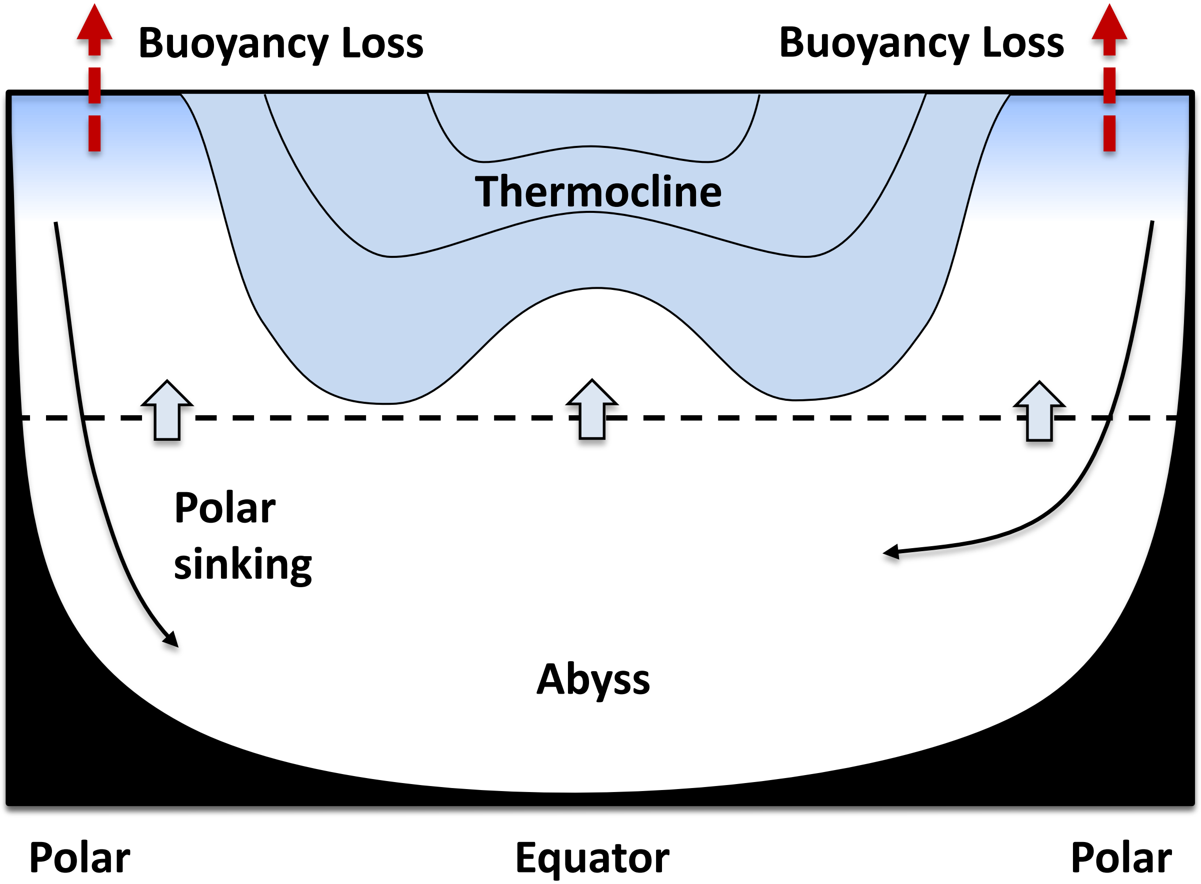


Figure: The deep ocean is ventilated by localized convection at polar latitudes induced by a loss of buoyancy (due to cooling and/or salt input). Compensating upwelling is thought to occur on a large-scale.

The Thermohaline Circulation

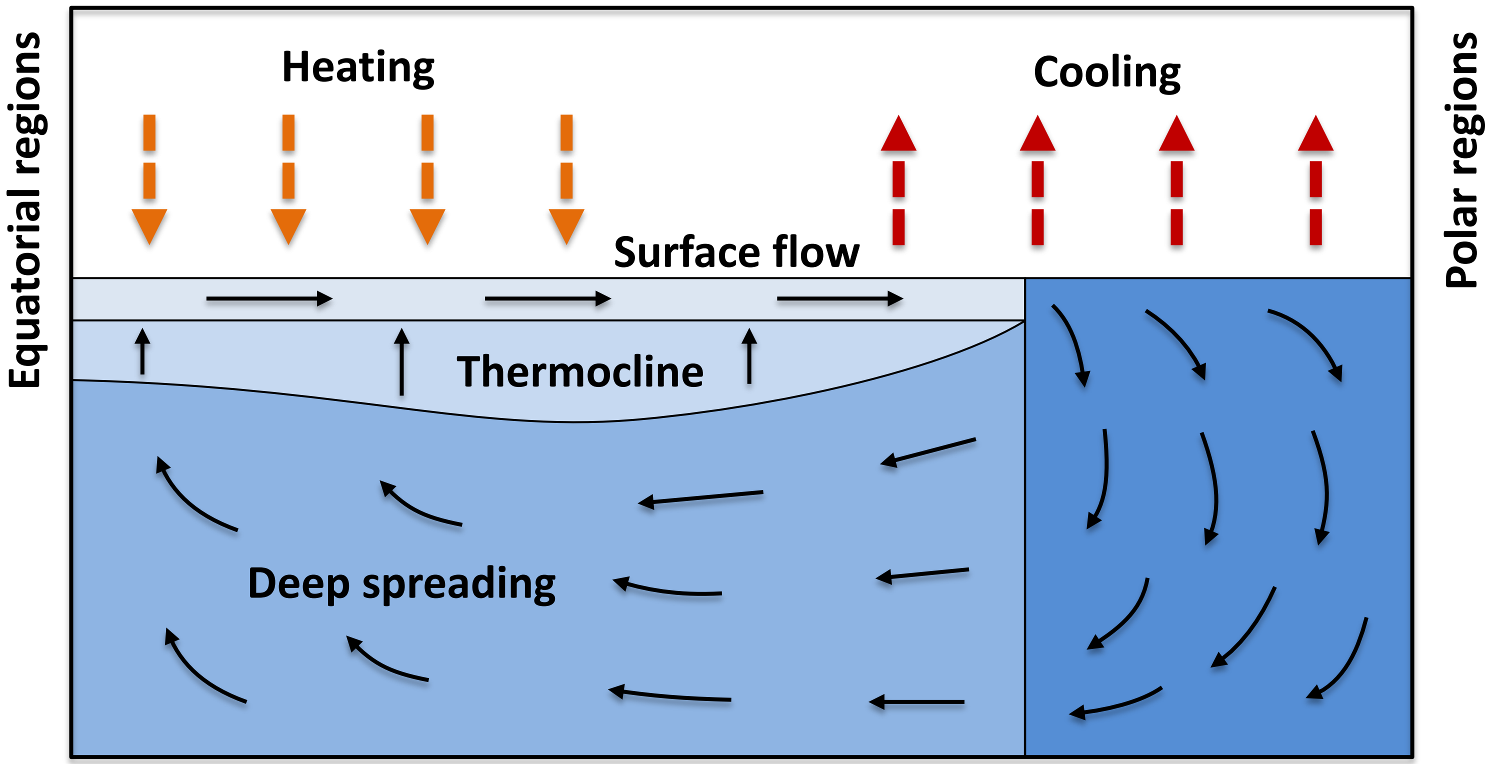
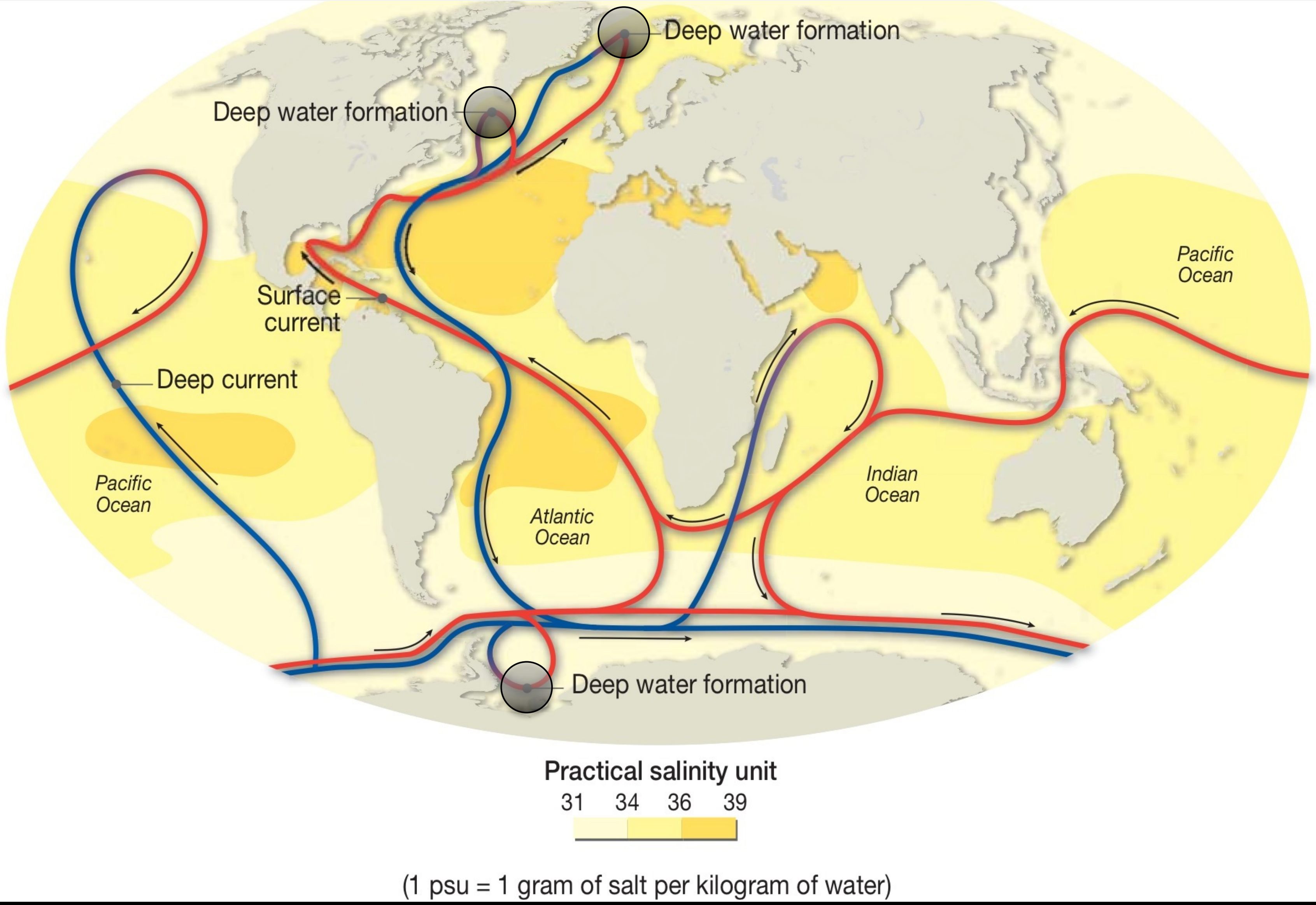


Figure: The deep ocean is ventilated by localized convection at polar latitudes induced by a loss of buoyancy (due to cooling and/or salt input). Compensating upwelling is thought to occur on a large-scale.

Thermohaline Circulation

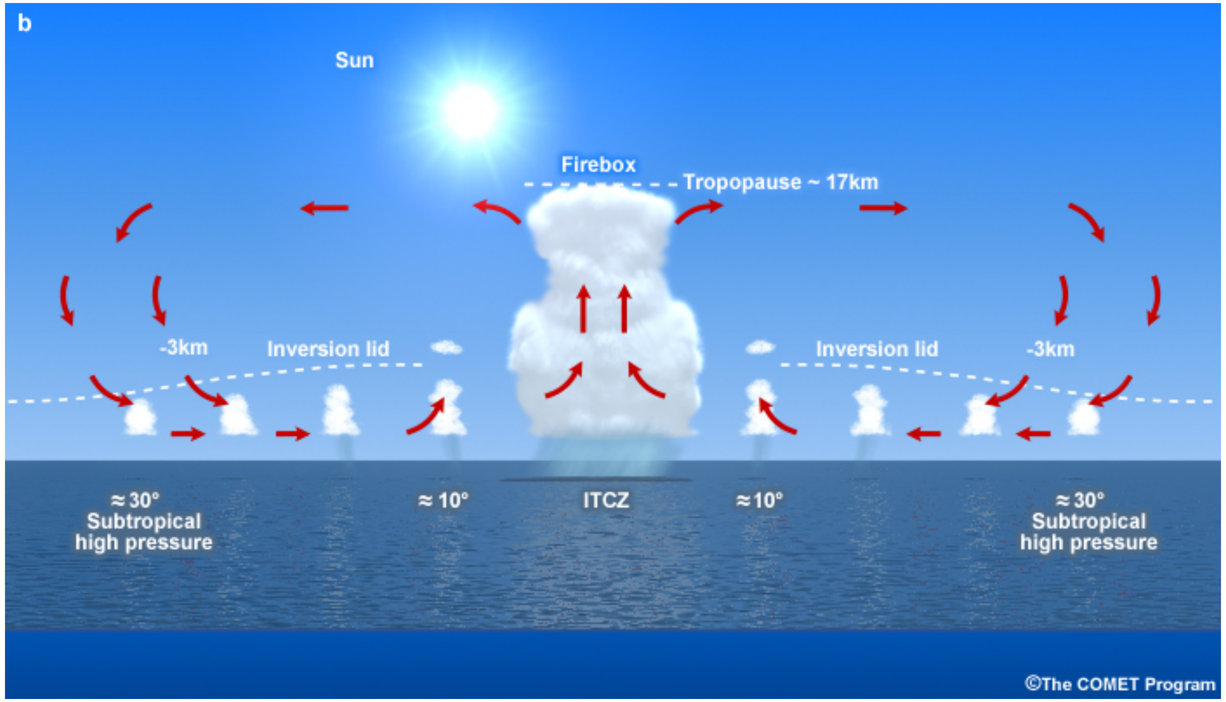


Source: NASA

Atmospheric Deep Convection

Recall that atmospheric convection is triggered by surface warming.

Atmospheric deep convection is confined to a few regions of strong updrafts driven by deep convection over the tropics, with subsidence in between.



Oceanic Convection

However, the ocean is typically heated from above, which actually stabilizes the mixed layer.

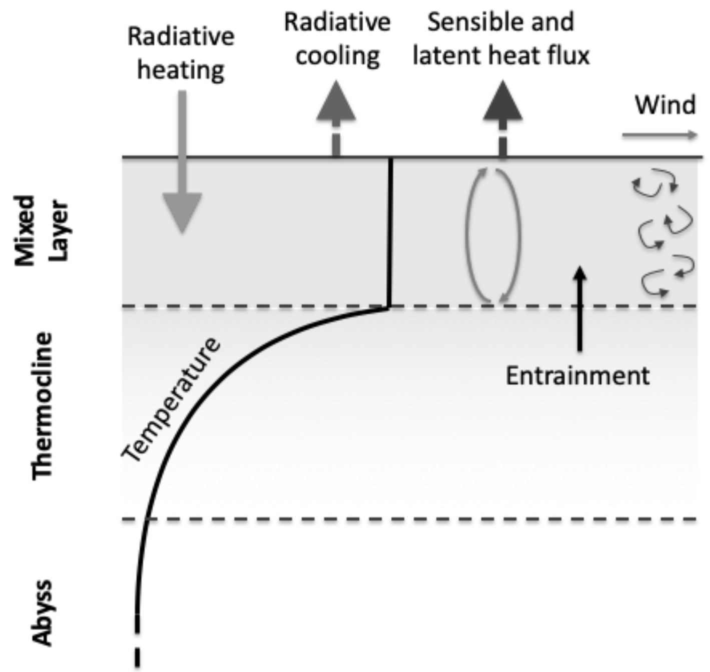
Convection will only be triggered if dense ocean water settles above less dense fluid.

Deep convection will thus occur in regions with the coldest air-ocean surface.

Surface density increases (buoyancy loss) must occur via two main processes:

1. **Direct cooling** (radiative, sensible or latent).

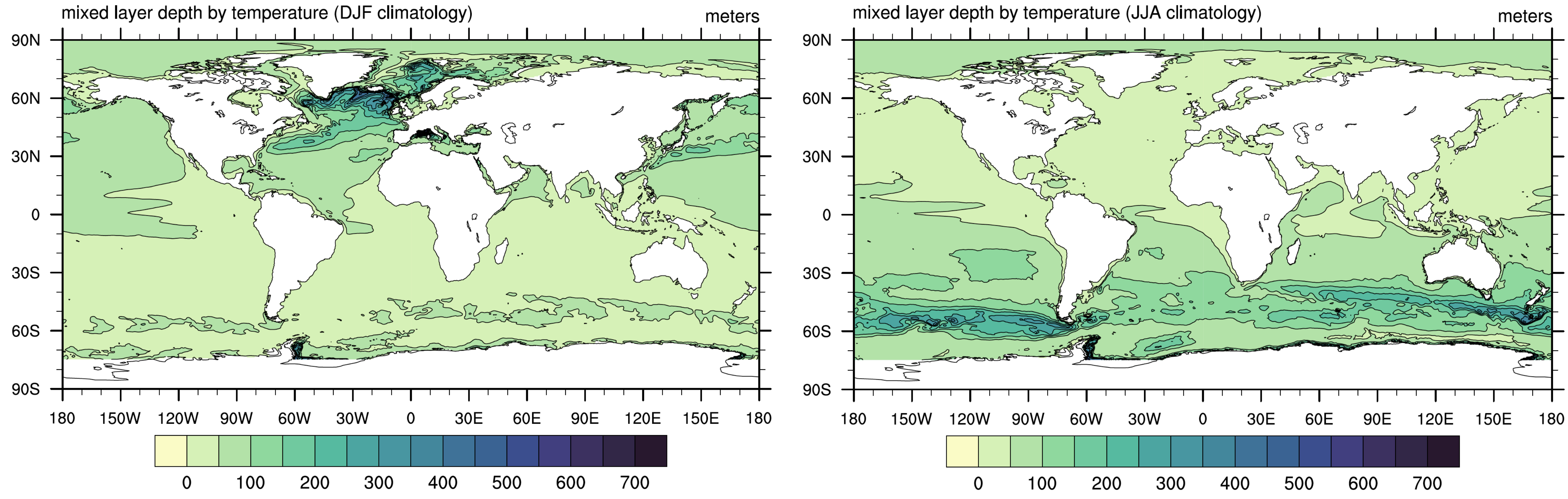
2. **Brine rejection** in ice formation, which increases the salinity of ocean water.



Mixed Layer Depth

Figure: Mixed layer depth (in meters) for DJF (left) and JJA (right).

The mixed layer is deepest in the wintertime of each hemisphere, when strong winds and surface friction drive turbulence to depth.



Oceanic Convection

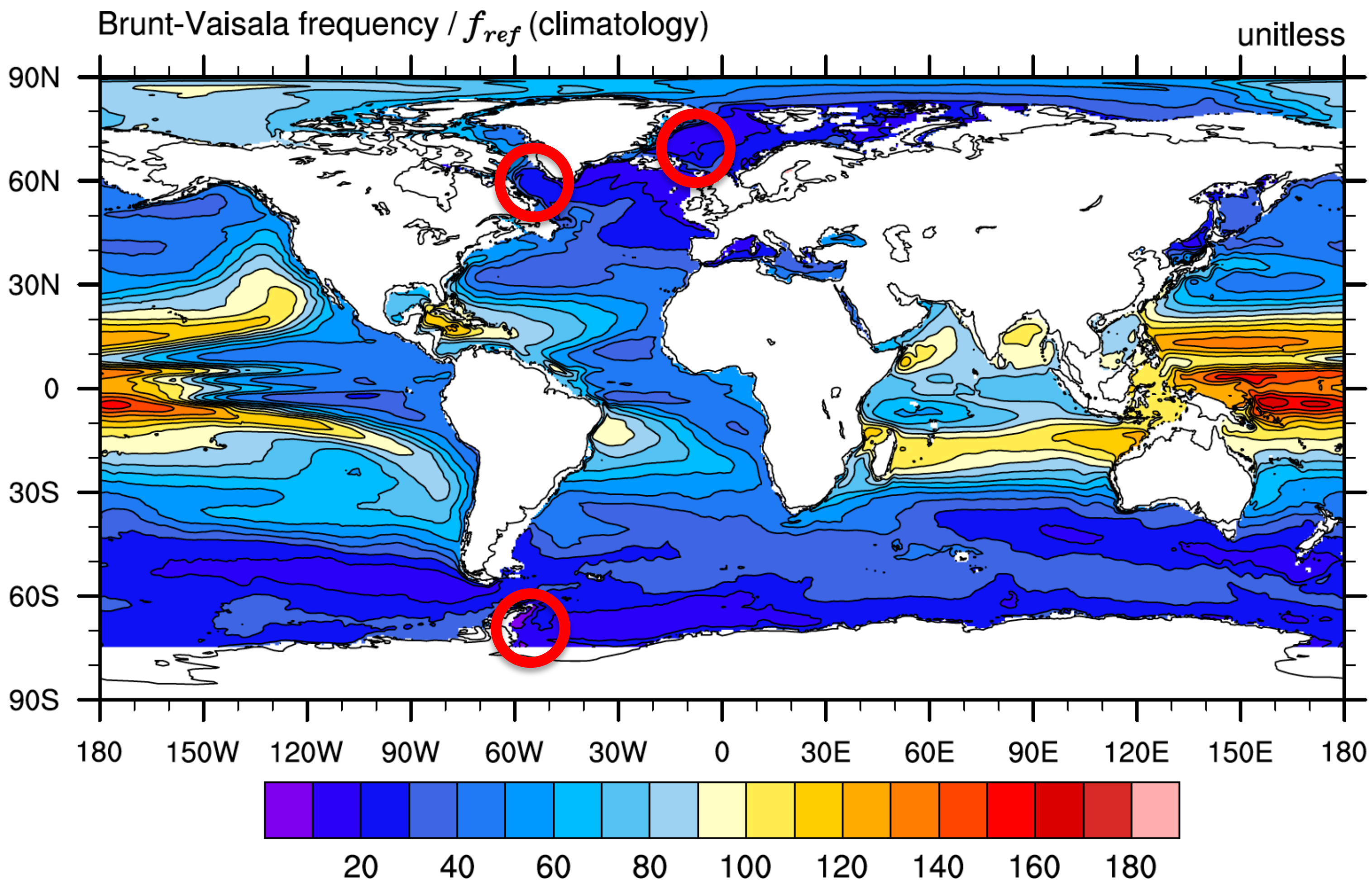


Figure: Annual-mean ocean stratification at 200m, as measured by N/f_{ref}, i.e. the buoyancy frequency (with $f_{ref} = 10^{-4}\ s^{-1}$). Sites of deep convection are highlighted.

Oceanic Convection

- The deepest mixed layers in the winter hemisphere (where one would expect deep convection to occur) can be found in the Labrador and Greenland Seas of the North Atlantic where they can reach in excess of 1km. Also in the Weddell Sea (southern Atlantic off the coast of Antarctica).

- **No deep mixed layers in the Pacific:** Waters here are relatively fresh and remain buoyant even when cooled.

- Observed tracer distributions and temperatures suggest surface waters can only reach the abyss at these points.

Oceanic Convection

Regions of deep oceanic convection have common features:

(1) Cold, dry winds blow over the water inducing both large sensible and latent heat fluxes and large moisture fluxes.

(2) Ocean stratification here is weak, perhaps by mixing from previous convection.

(3) Ekman suction draws ocean waters upward to the surface where they can be exposed to buoyancy loss.

Observations of Oceanic Convection

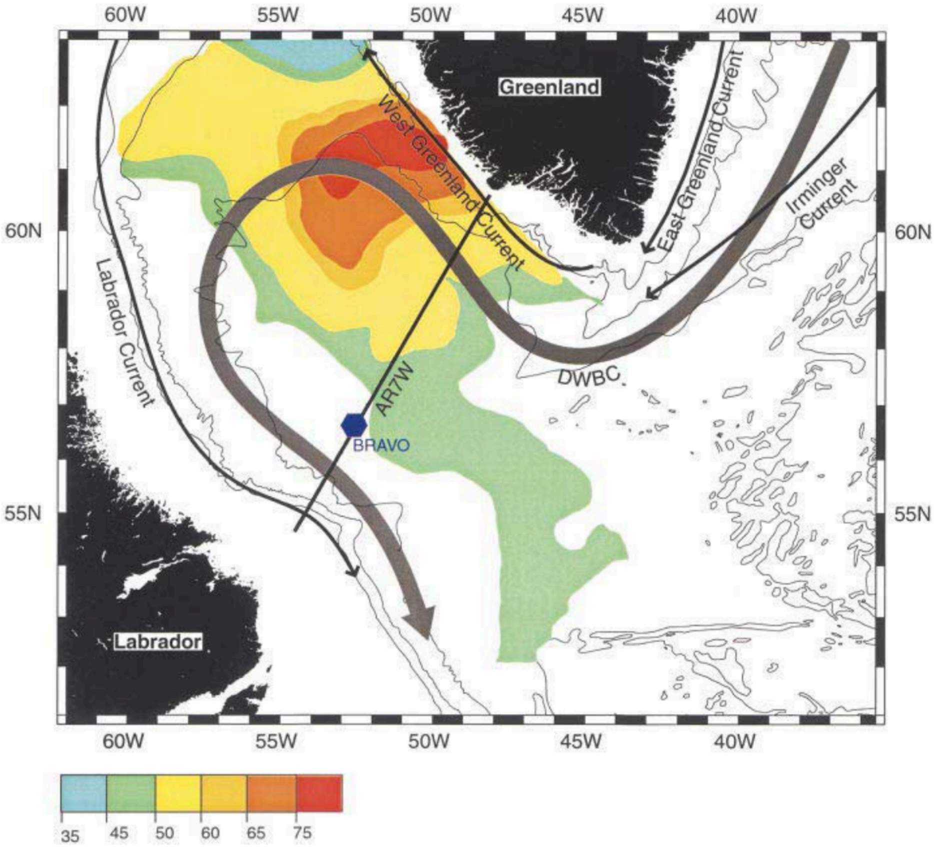


Figure: Prominent boundary currents of the Labrador Sea. Coloring denotes the standard deviation of the sea surface height anomaly (in mm). Figure 1 from Pickart, Torres and Clarke (2001).

Pickart, Torres and Clarke (2001) document changes in the Labrador Sea before and after the winter period when convection occurs. The cross-sections on the following slides show cross sections in October 1996 and March 1997 over the line marked AR7W in the Figure above.

Observations of Oceanic Convection

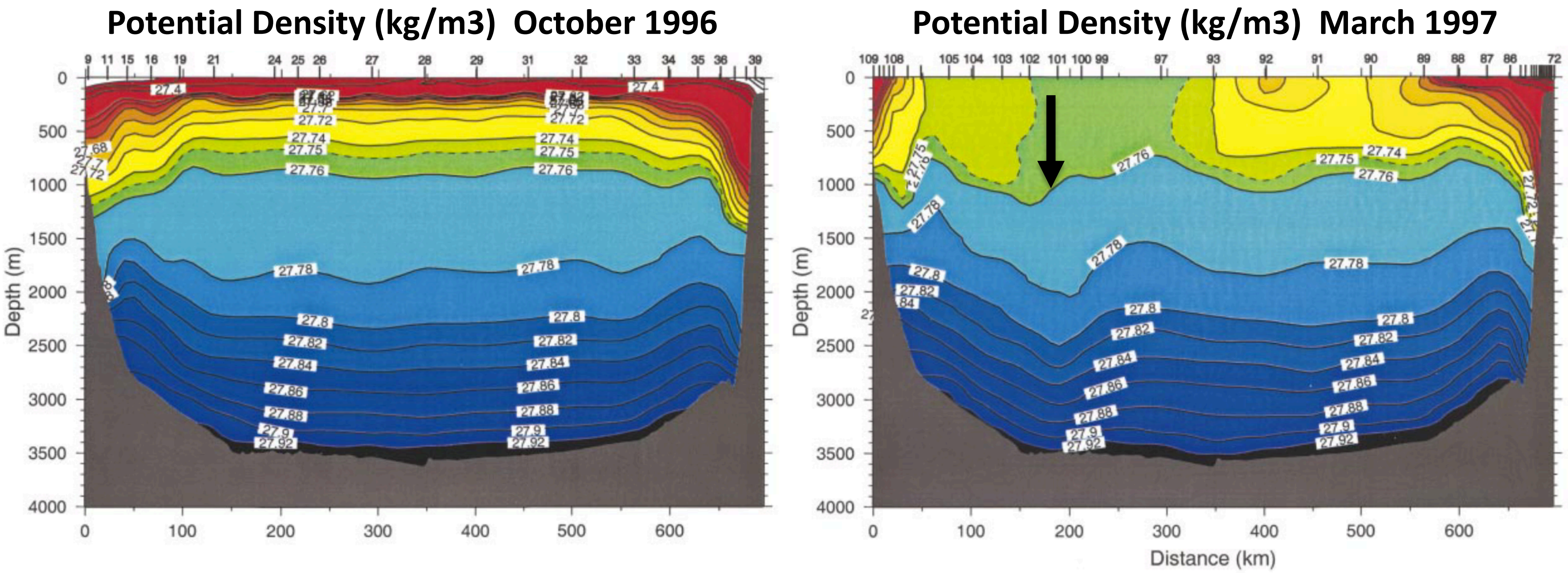


Figure: Observations of a convective event showing potential density. October shows a near-surface stratified layer overlaying a well-mixed intermediate-depth layer. By March next year convection triggered by cooling of the surface has punched through the stratified layer, mixing intermediate and surface fluid. From Pickart, Torres and Clarke (2001) Figure 8c.

Observations of Oceanic Convection

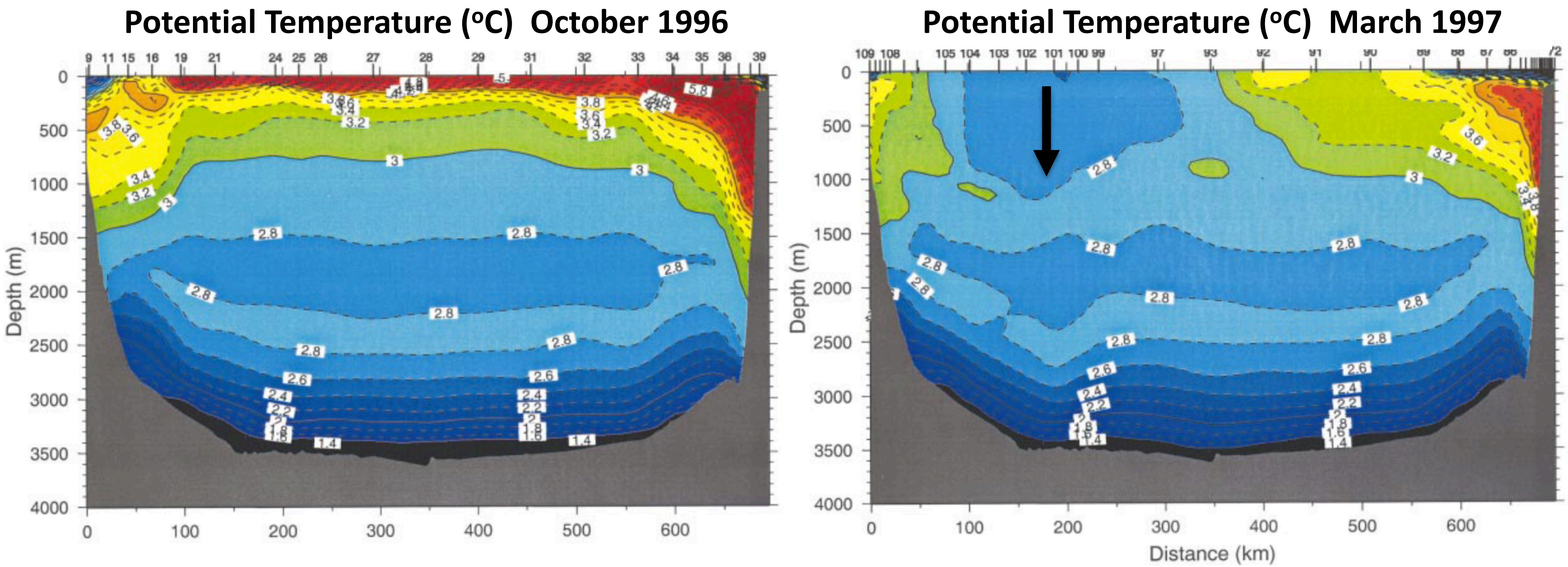


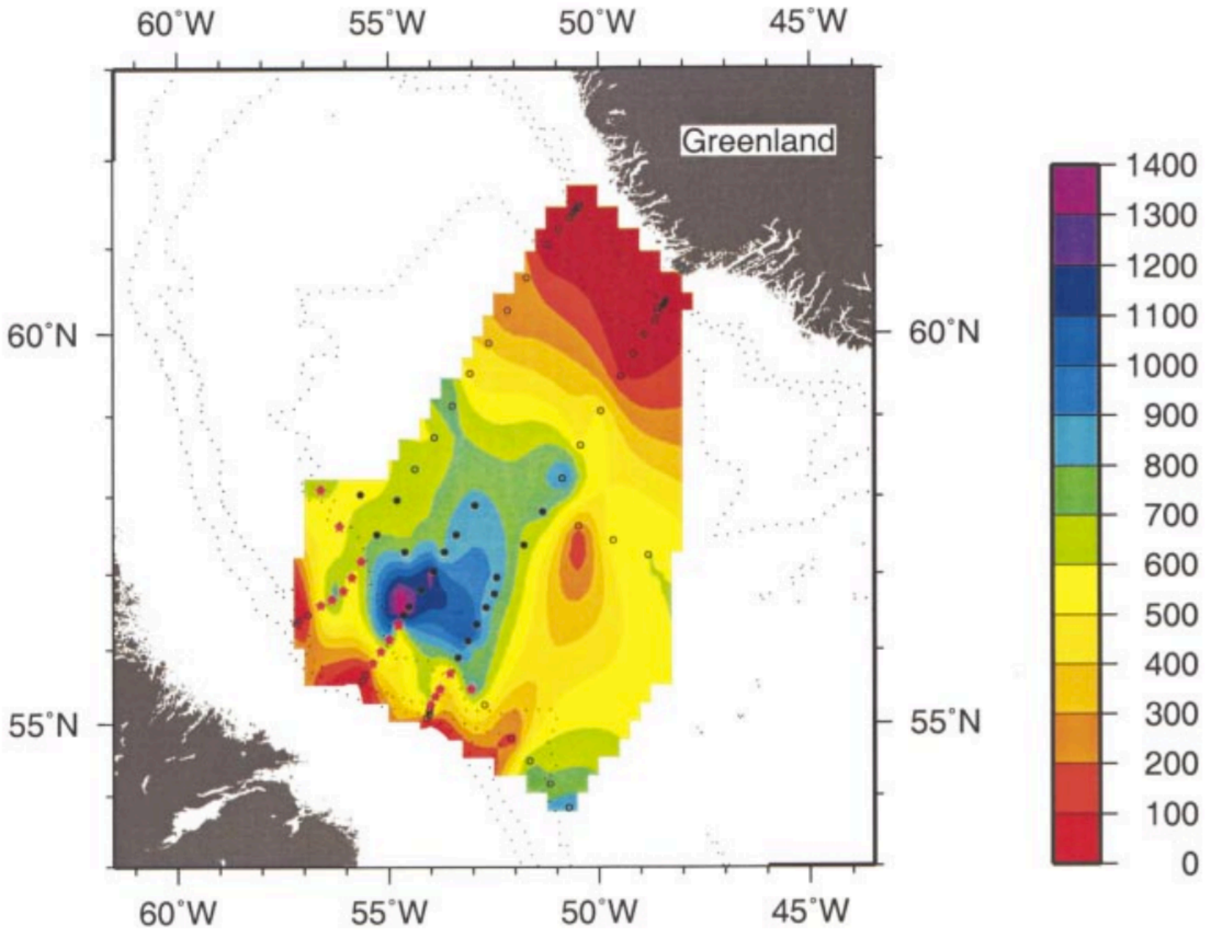
Figure: Observations of a convective event showing potential temperature. October shows a near-surface stratified layer overlaying a well-mixed intermediate-depth layer. By March next year convection triggered by cooling of the surface has punched through the stratified layer, mixing intermediate and surface fluid. From Pickart, Torres and Clarke (2001) Figure 8a.

Oceanic Convection

Figure: For the observations on the previous slide, showing the mixed layer depth observed over Feb-Mar 1997. From Pickart, Torres and Clarke (2001) Figure 12d.

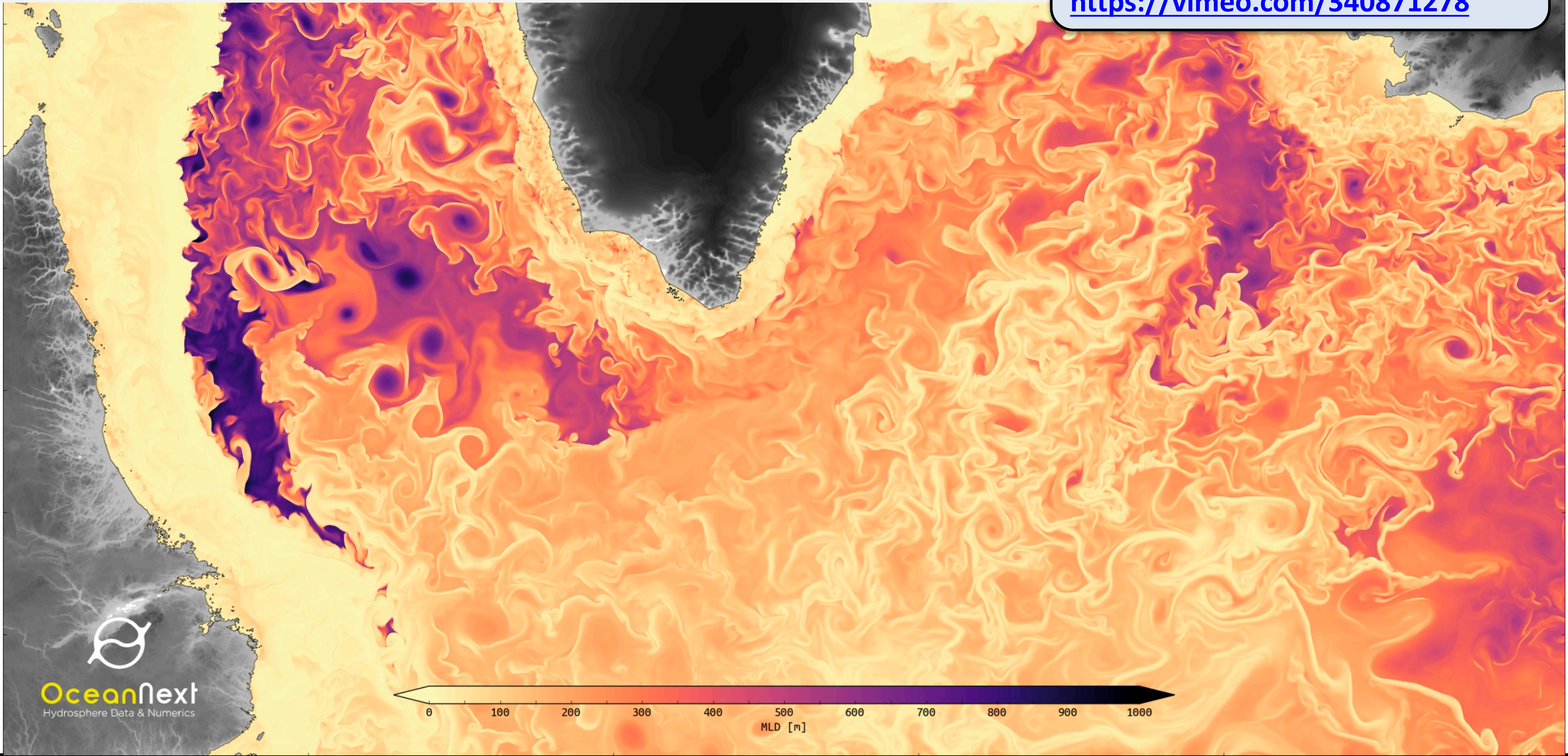
Convection has led to the formation of a particularly deep, localized mixed layer.

Mixed-layer Depth (meters)



Deep Water Formation

Labrador/Irminger seas’ mixed-layer depth in eNATL60 simulation
https://vimeo.com/340871278



Three Phases of Oceanic Convection

Phase 1: Loss of Buoyancy

Loss of buoyancy from surface layers of the ocean due to heat and moisture loss in addition to brine rejection leads to a weakening of the stratification over the winter.

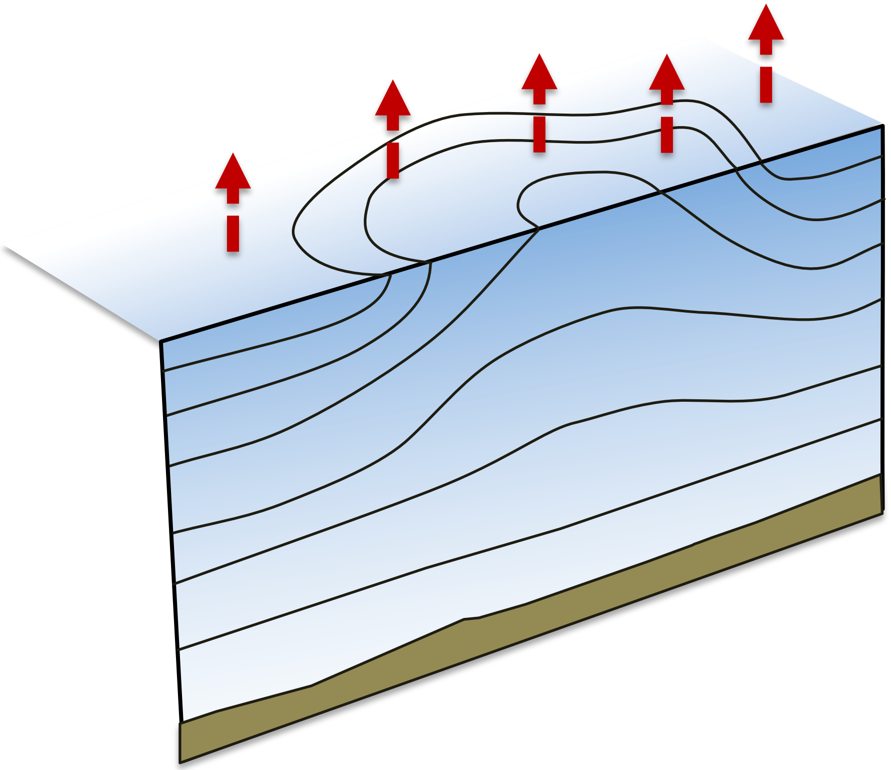


Figure reproduced from From Marshall and Schott (1999).

Three Phases of Oceanic Convection

Phase 2: Convection and Mixing

Once buoyancy loss has reached a critical threshold, convection and mixing is induced in the surface and intermediate ocean layers.

An overturning circulation forms bringing surface waters into the deep ocean and deep ocean waters to the surface.

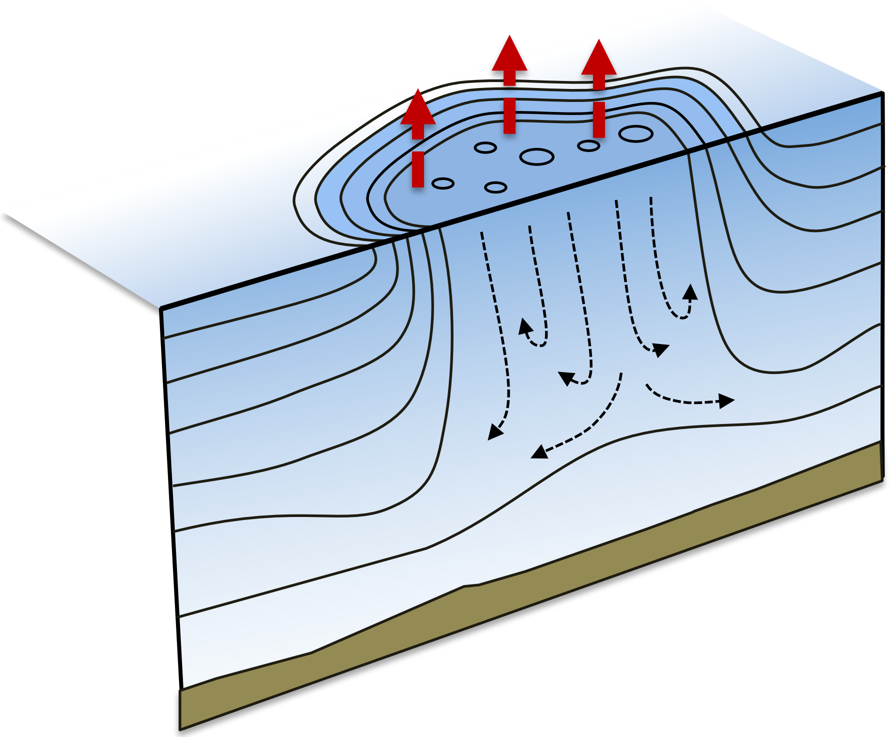


Figure reproduced from From Marshall and Schott (1999).

Three Phases of Oceanic Convection

Phase 3: Sinking and Spreading

Convection stops when mixing is sufficient to smooth out density anomalies in the convective layer. Denser waters on the interior of the convective cell settle to lower depths. Warming in the Spring then leads to a stabilized stratification.

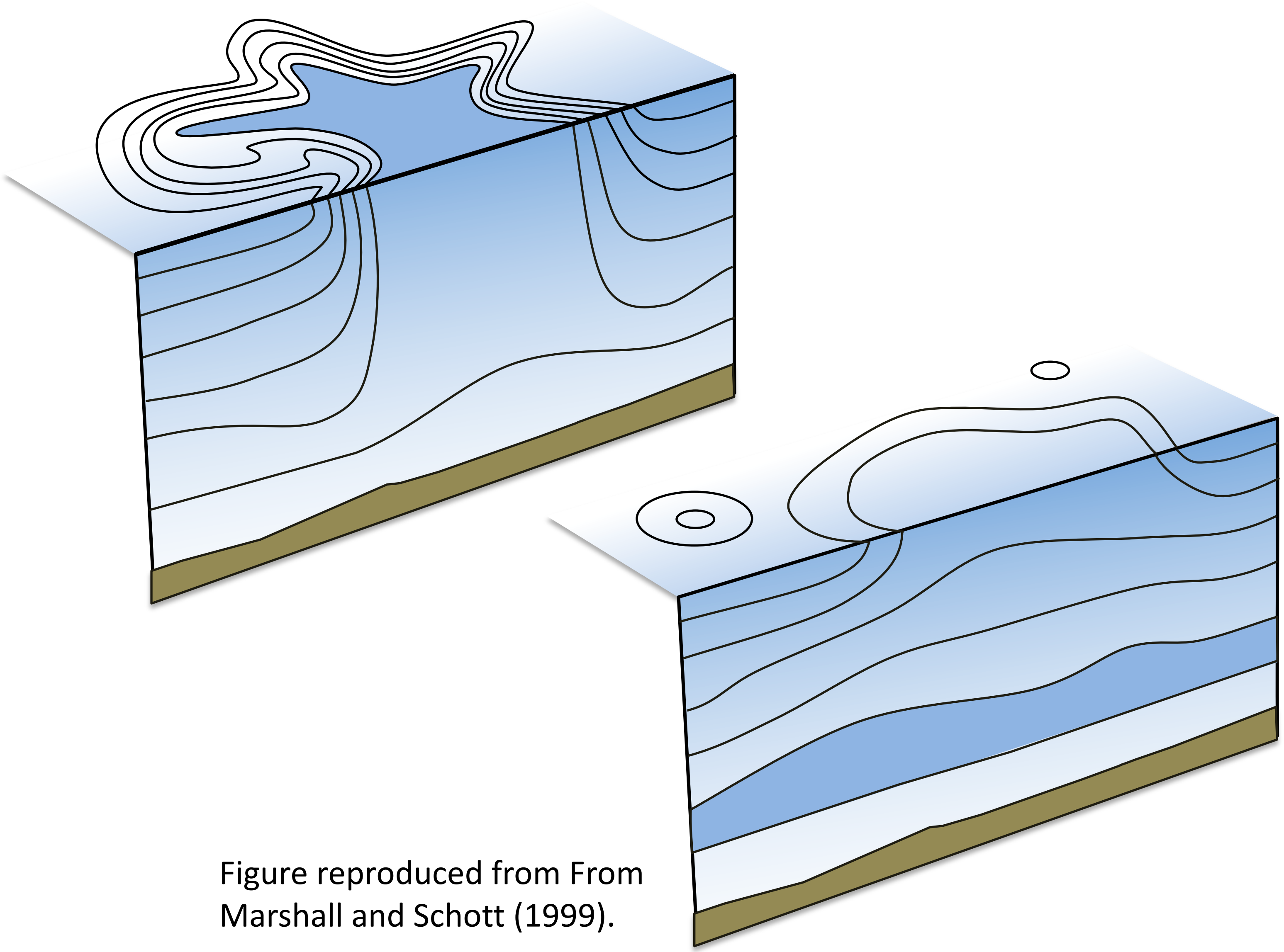


Figure reproduced from From Marshall and Schott (1999).

Observations

- The abyssal circulation in the ocean is typically far too slow to be observed directly. Instead inferences can be made about the origin of certain deep oceanic waters.

- Tracers are commonly used to identify the age and origin of these waters: Temperature and salinity can be used to identify a source region.

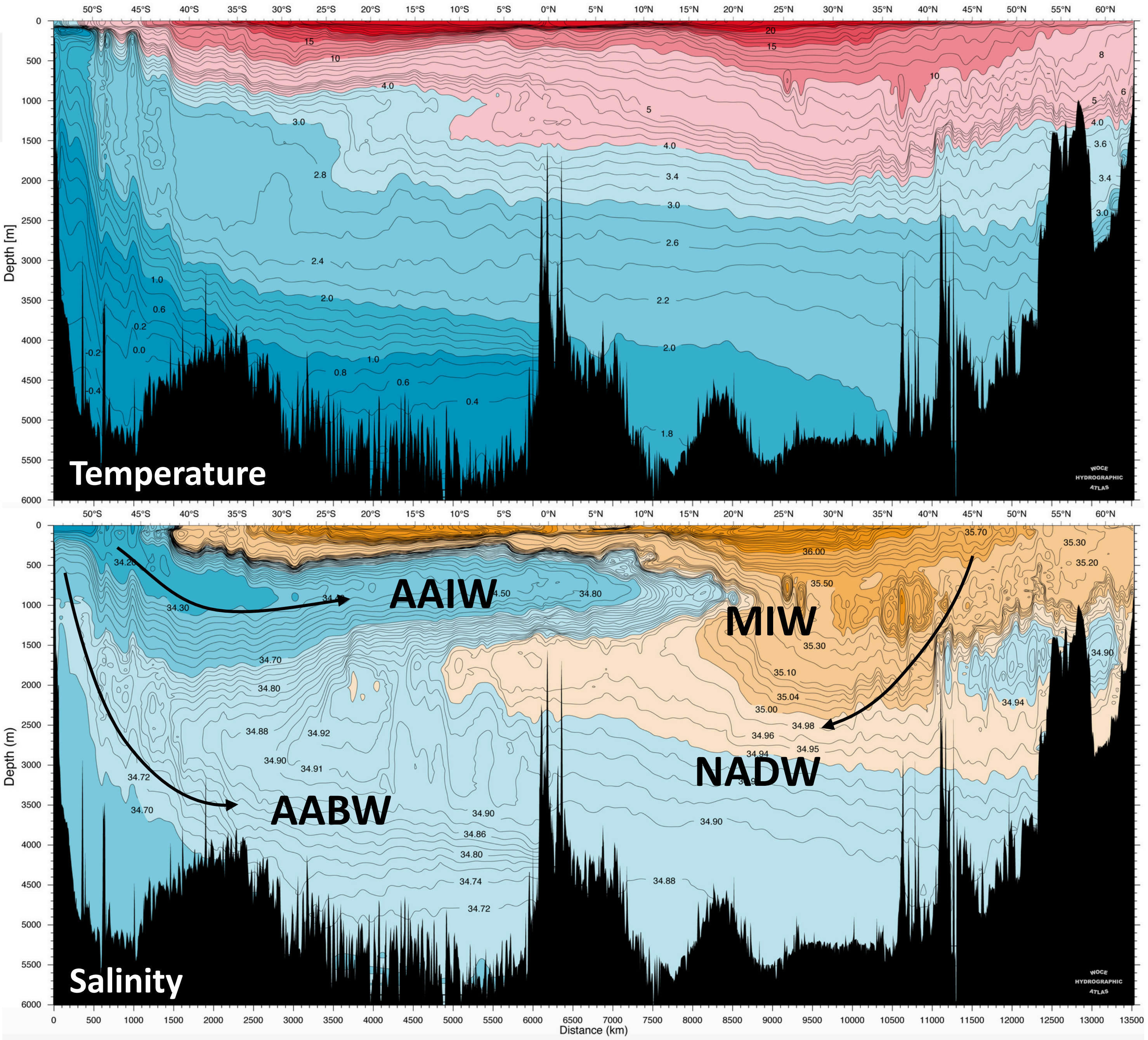
- Passive tracers such as CFCs and tritium (from atomic weapon tests of the 1960s) can be used to identify age. Oxygen is also a important tracer species, since its source is at the ocean surface and it is used over time in biological processes.

Observations

Figure: Temperatures and salinity from a mid-Atlantic cross section (WOCE Atlas transect A16, http://woceatlas.ucsd.edu/).

We observe that Atlantic waters at depth can be divided into four regimes:

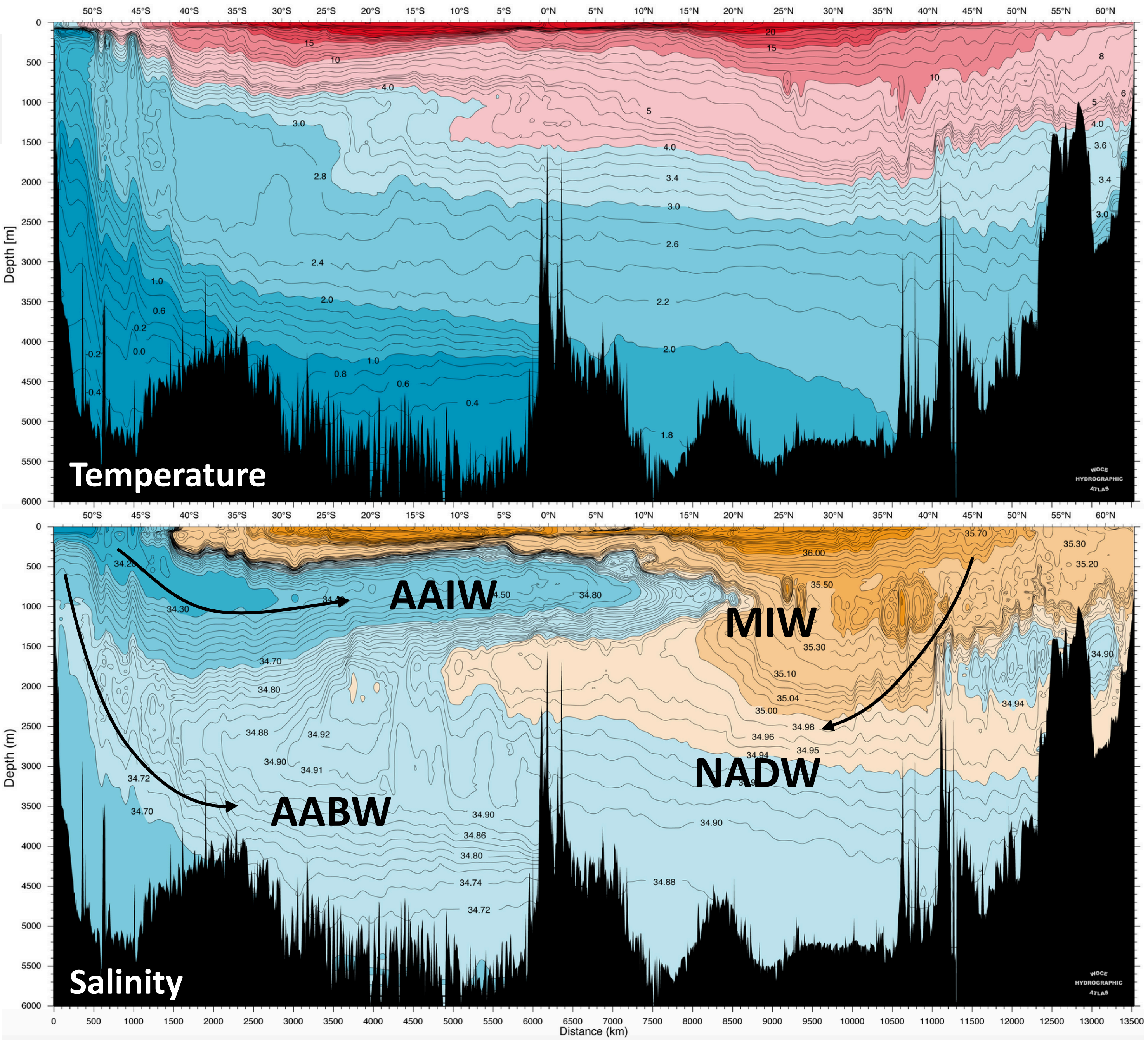
Antarctic Intermediate Water (AAIW)
Antarctic Bottom Water (AABW)
North Atlantic Deep Water (NADW)
Mediterranean Intermediate Water (MIW)



Observations

Figure: Temperatures and salinity from a mid-Atlantic cross section (WOCE Atlas transect A16, http://woceatlas.ucsd.edu/).

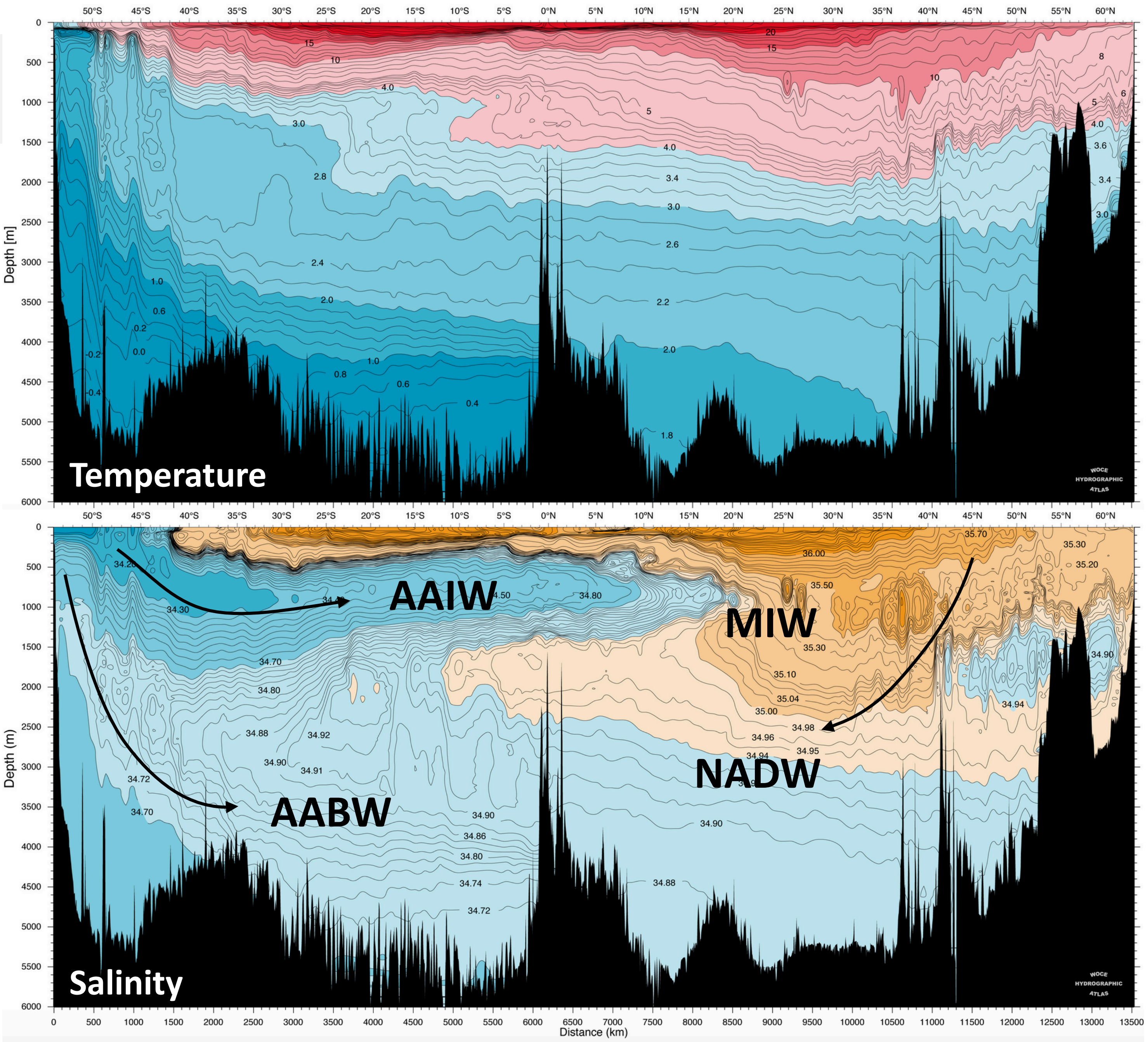
***(1) Antarctic Intermediate Water* (AAIW)** is low-salinity water (34.4 psu), slightly lower temperature than water above or below. This water is associated with the deep mixed layers of the Antarctic Circumpolar Current (ACC).



Observations

Figure: Temperatures and salinity from a mid-Atlantic cross section (WOCE Atlas transect A16, http://woceatlas.ucsd.edu/).

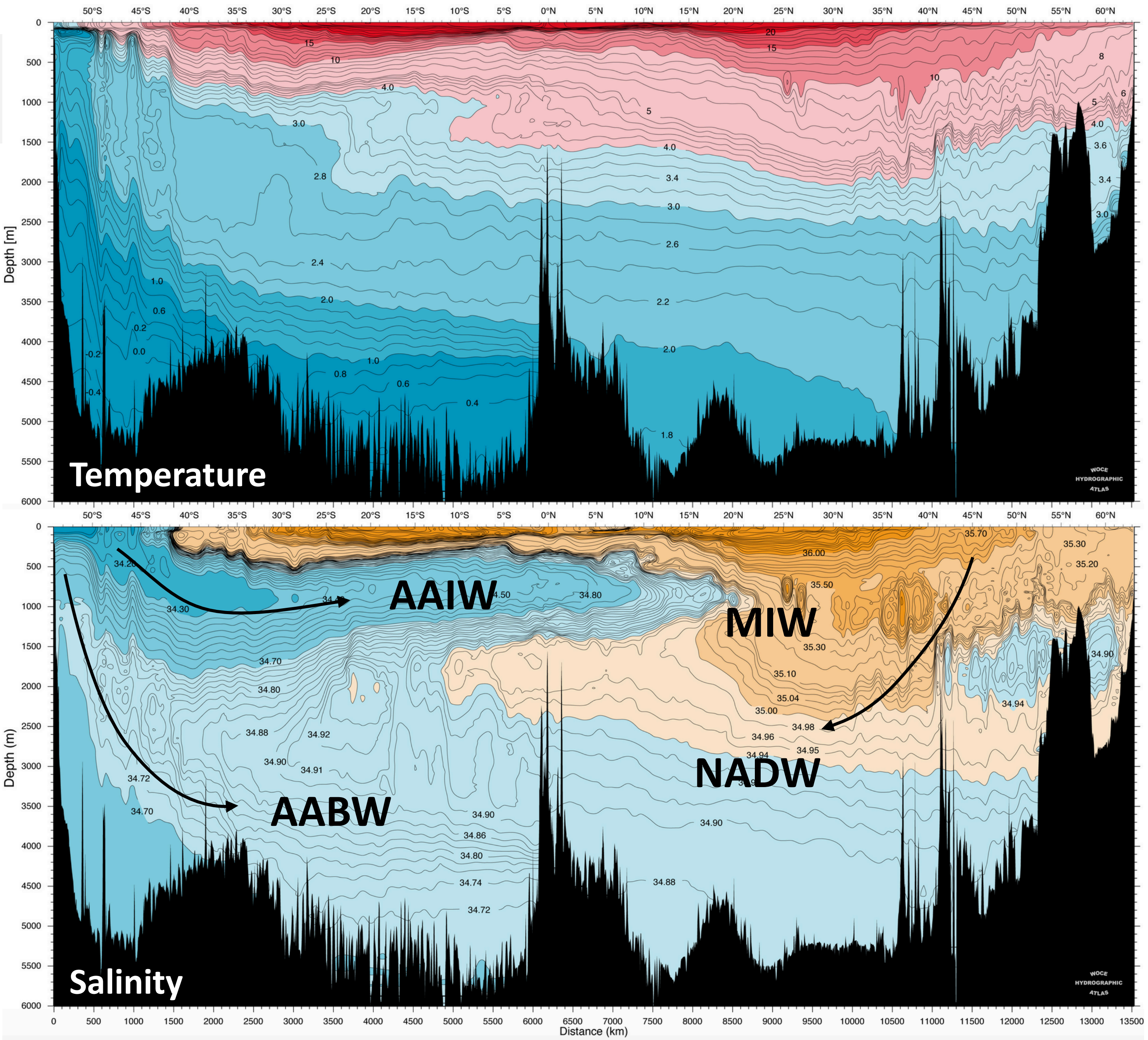
***(2) Antarctic Bottom Water* (AABW)** has lower salinity than NADW but is typically colder (and denser) than NADW.



Observations

Figure: Temperatures and salinity from a mid-Atlantic cross section (WOCE Atlas transect A16, http://woceatlas.ucsd.edu/).

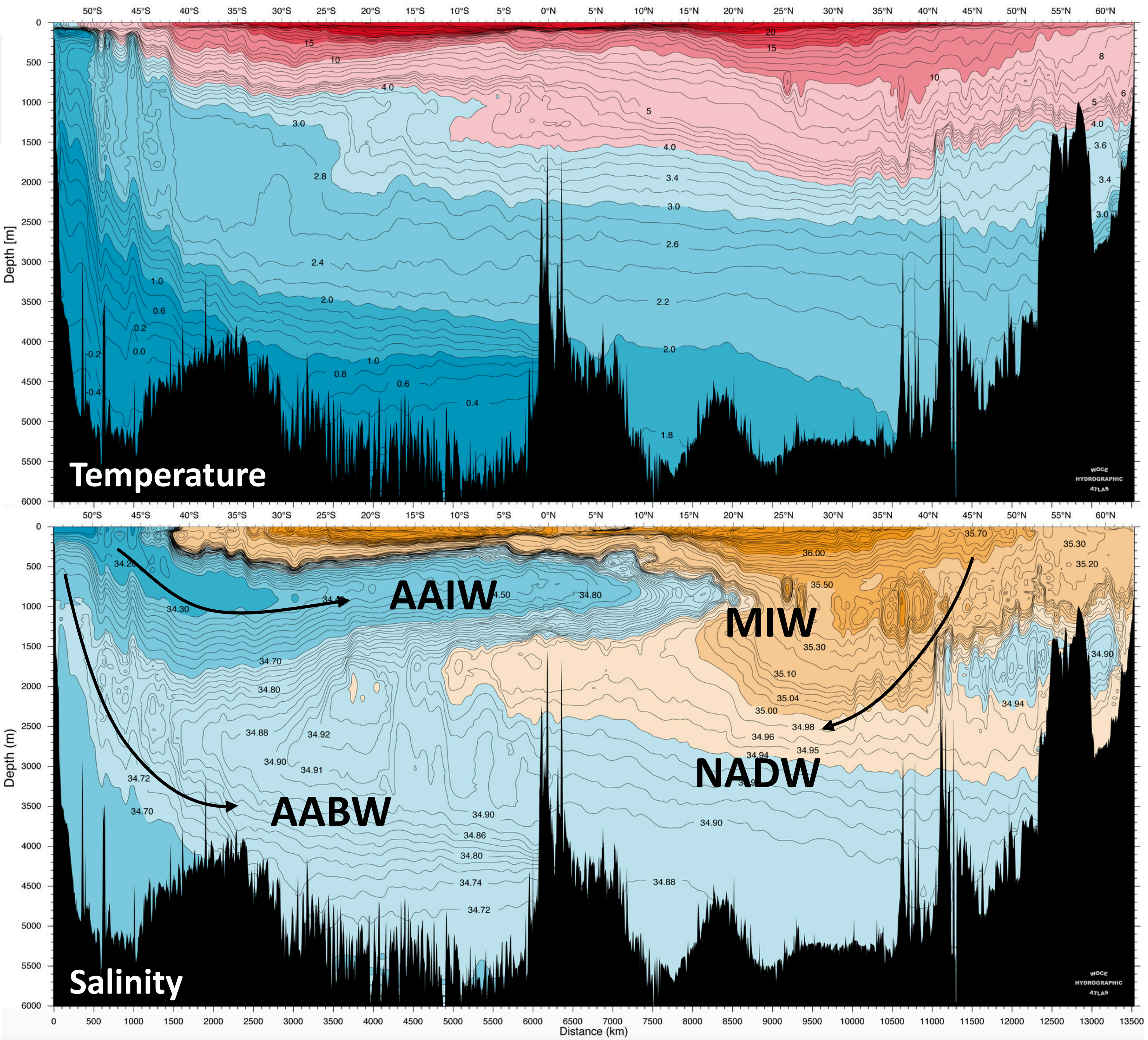
***(3) North Atlantic Deep Water* (NADW)** is high salinity water (34.9 psu) originating at high northern latitudes, but identifiable as far south as 40°S.



Observations

Figure: Temperatures and salinity from a mid-Atlantic cross section (WOCE Atlas transect A16, http://woceatlas.ucsd.edu/).

(4) Mediterranean Intermediate Water **(MIW)** forms by evaporation of relatively warm water in the Mediterranean Sea. This high salinity water then sinks to the bottom of the Sea. Salty MIW flows over the sill at Gibraltar and sinks into the Atlantic Ocean.

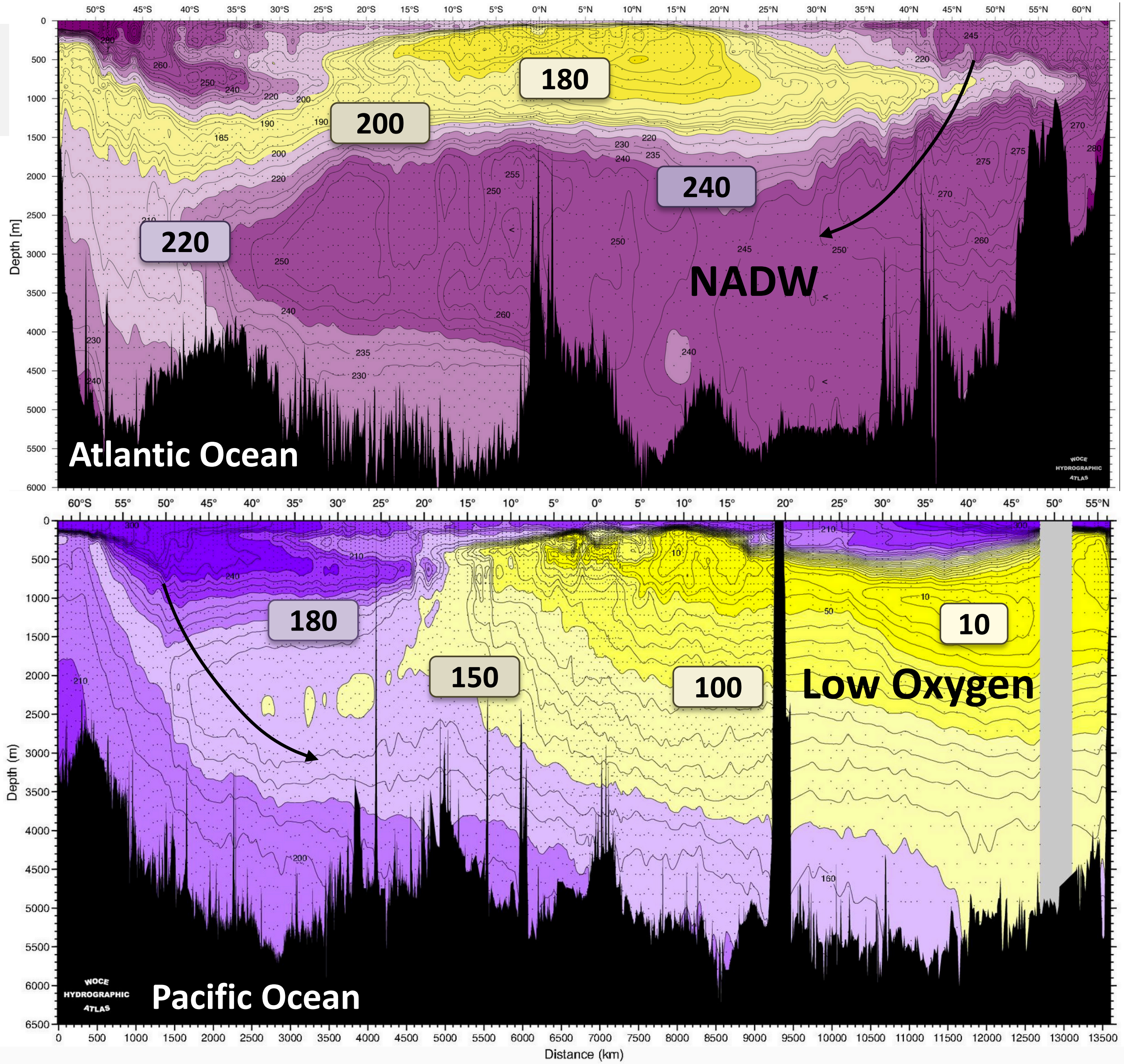


Observations

Figure: Zonal average dissolved oxygen content (μM/kg) across Atlantic and Pacific oceans (WOCE Atlas transects A16 and P16). Darker colors indicate higher oxygen content (“younger” water).

The Atlantic basin shows an increase in age from north to south, suggesting that deep ocean waters originate at high latitudes and are pumped to depth.

Pacific Ocean waters are relatively “old” by comparison, with youngest waters close to Antarctica.

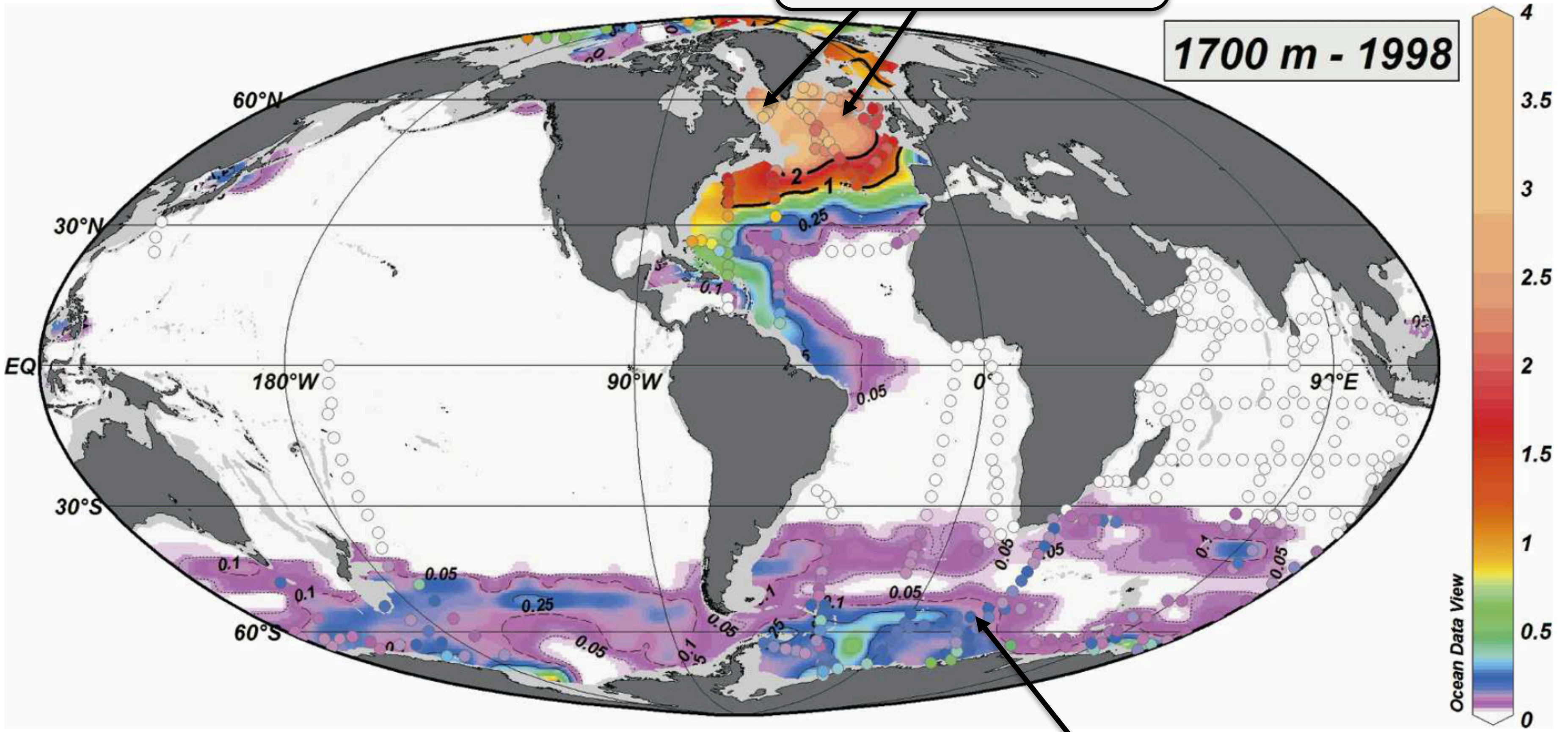


Observations

Figure: CFC-11 concentrations (pmol kg^{-1}) for year 1998 at 1700m depth simulated by a model (color-shaded field) and data for the period 1995–2000 (colored dots) (Source: Schlitzer 2006).

Note the southward western boundary currents at depth laying beneath the Gulf Stream (see Marshall and Plumb section 11.3).

Generation of North Atlantic Deep Water

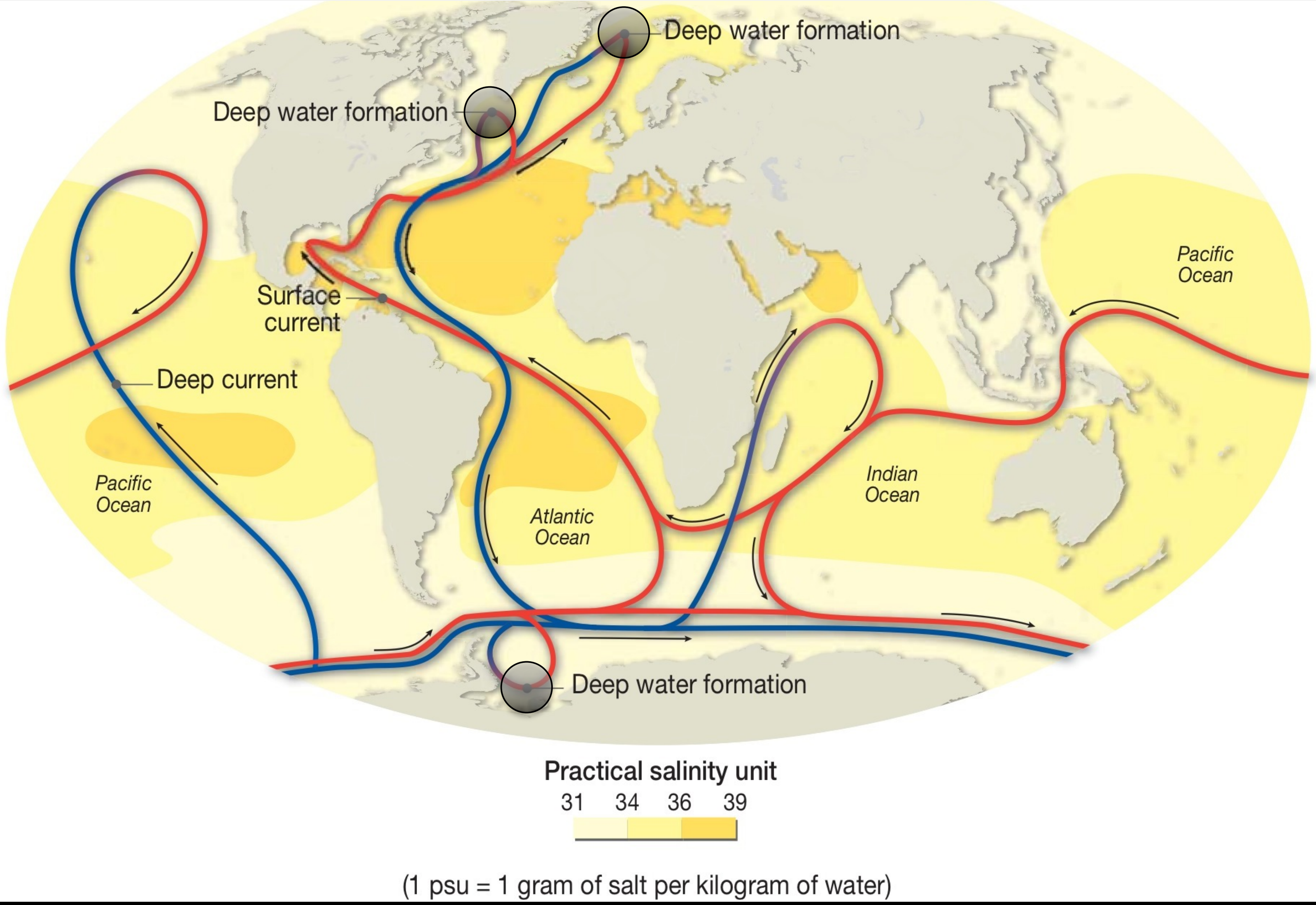


Deep mixing in the ACC generating Antarctic Intermediate Water

Thermohaline Circulation

- Dense water is formed at the surface in small, highly localized regions of the ocean in polar seas.
- Since every molecule of water that is carried to depth must be replaced by a molecule returning to the surface, there must exist some mechanism for upward transport of ocean waters.
- Observations do not suggest a single localized return branch, so one can infer that there is widespread compensating upwelling over the whole basin.
- The deep flow is sluggish with very long timescales: Ocean ventilation over the Atlantic basin has a timescale of approximately **700 years**. Horizontal flow will be on the order of 10^{-3} m/s with upwelling velocities (assumed distributed over the whole basin) of **4 meters per year**.

Thermohaline Circulation



Source: NASA

Climate Relevance

- The thermohaline circulation is important for **providing heat to the polar regions**, and hence is important for **regulating sea ice production** in these regions.
- The thermohaline circulation also **governs the rate at which deep ocean waters are exposed to the surface**, and hence determines the strength of atmosphere-ocean fluxes. In turn, this process affects the carbon dioxide concentration in the atmosphere.
- Influxes of low-density meltwater from deglaciation in North America are though to have led to a disruption in deep water formation in the North Atlantic and led to a climate period in Europe known as the Younger Dryas (a 1300 year period of cold climatic conditions).

ATM 241 Climate Dynamics
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Thank You!