SIO 210 Typical distributions (2 lectures) Fall 2011

Reading: DPO Chapter 4

Additional reading: Stewart Ch. 6, Tomczak Ch. 5

First problem set: due Oct. 7 (next Friday)

First lecture - upper ocean

- Mixed layer
- Thermocline/pycnocline
- Thermostads
- Ventilation along isopycnals

Second lecture - full water column

- Water masses
- Deeper water formation
- Time scales

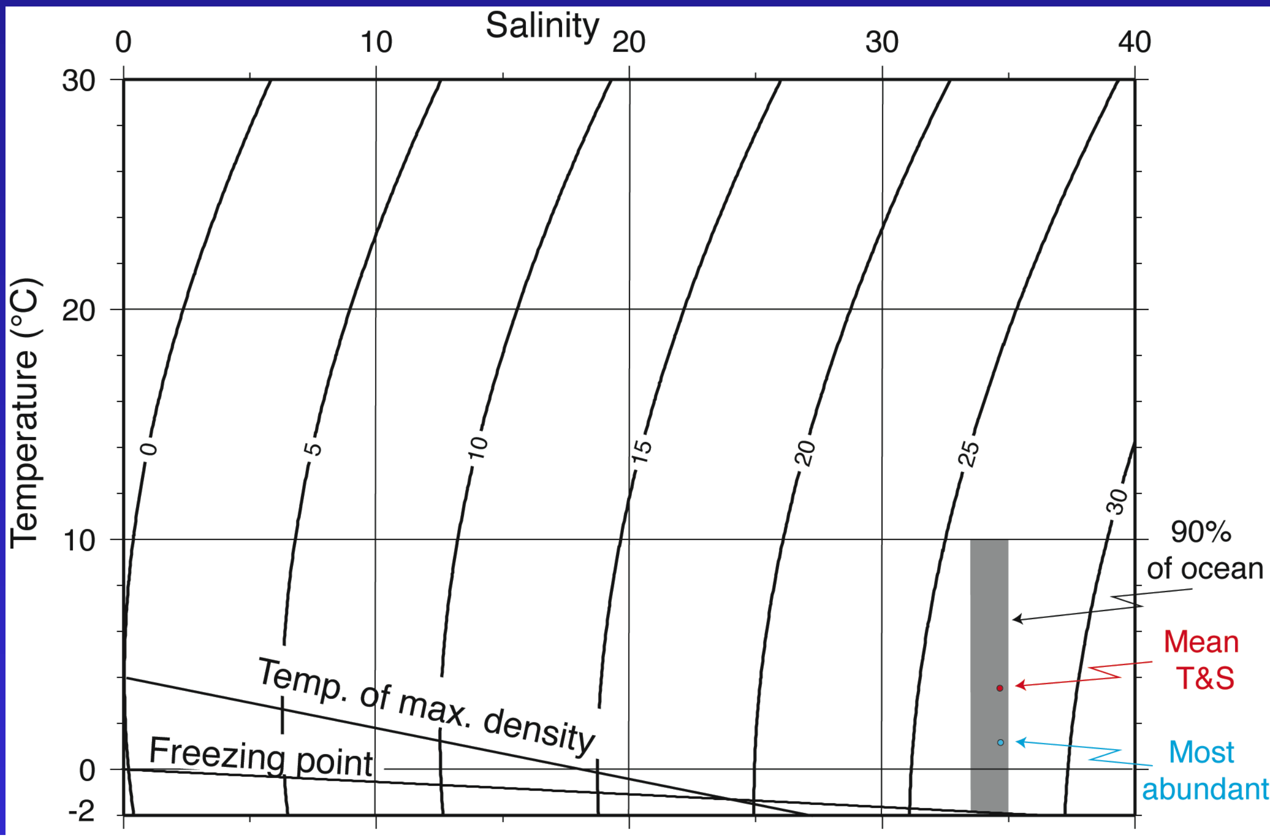
Course url: http://www-pord.ucsd.edu/~ltalley/sio210

Where does most of the volume of the ocean fit in temperature/salinity space?

75% of ocean is 0-6°C, 34-35 psu

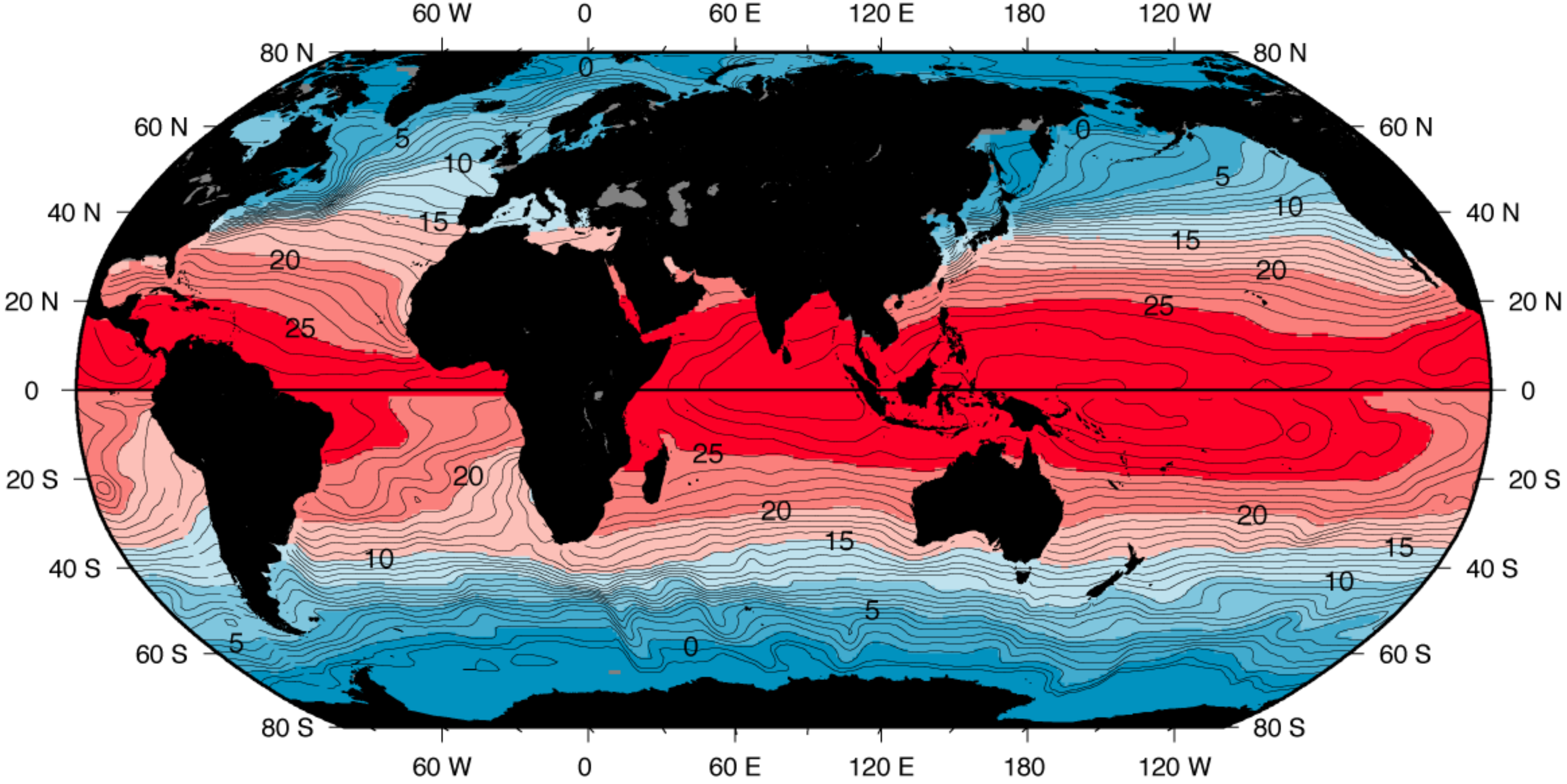
50% is 1.3-3.8°C, 34.6-34.7 psu (σ_θ=27.6 to 27.7 kg/m^3)

Mean temperature and salinity are 3.5°C and 34.6 psu



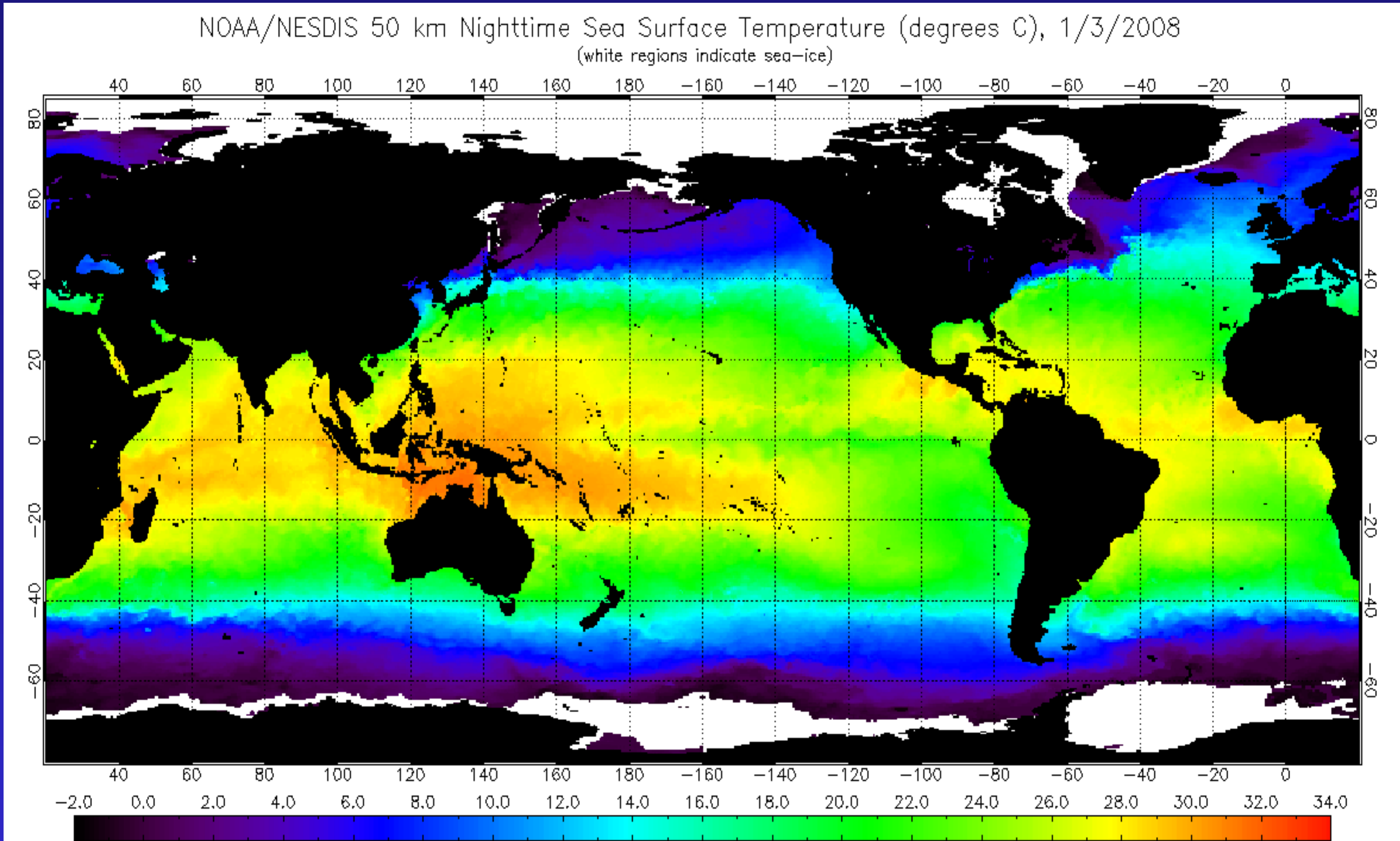
DPO Figure 3.1

Surface temperature: note where the 4°C isotherm occurs (most ocean volume is colder than this)



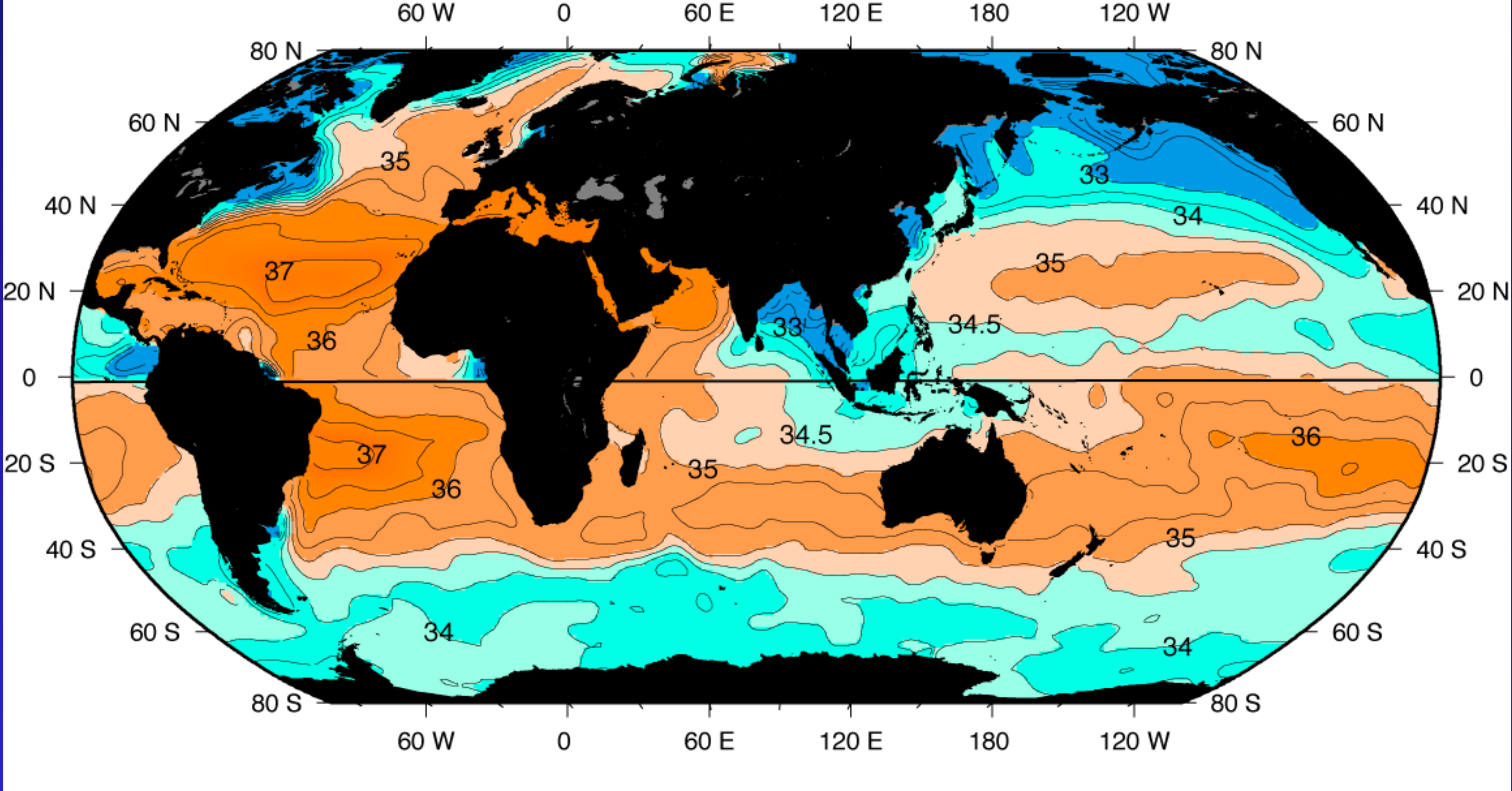
DPO Figure 4.1: Winter data from Levitus and Boyer (1994)

Surface temperature from satellite: much finer detail



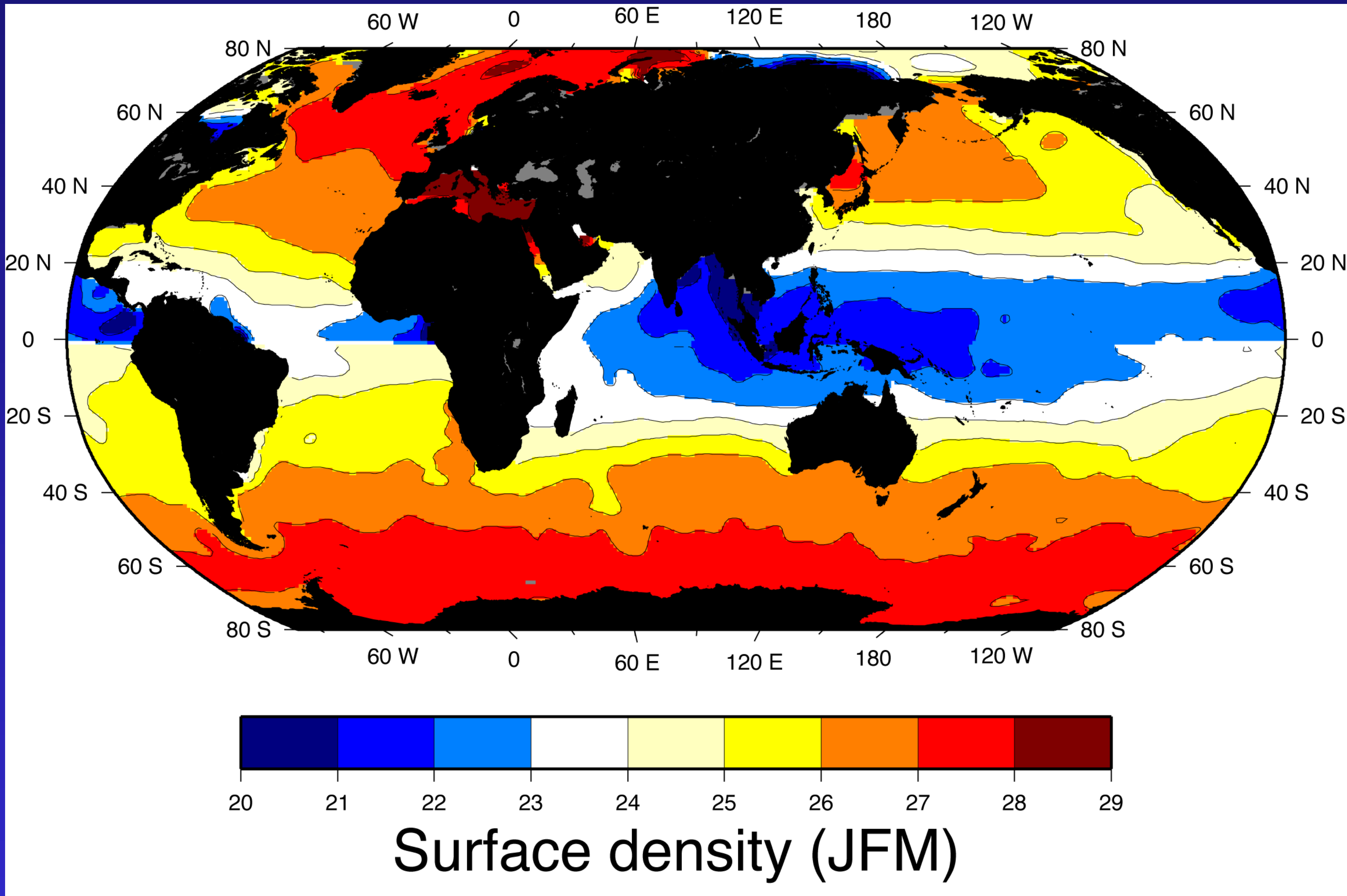
DPO Fig. 4.1b

Surface salinity



DPO Fig. 4.15

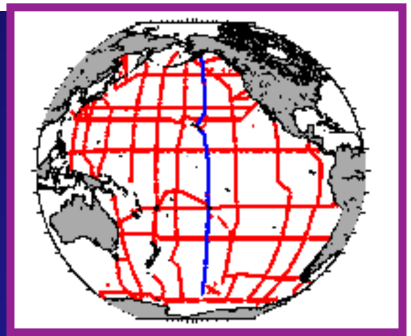
Surface density (winter)

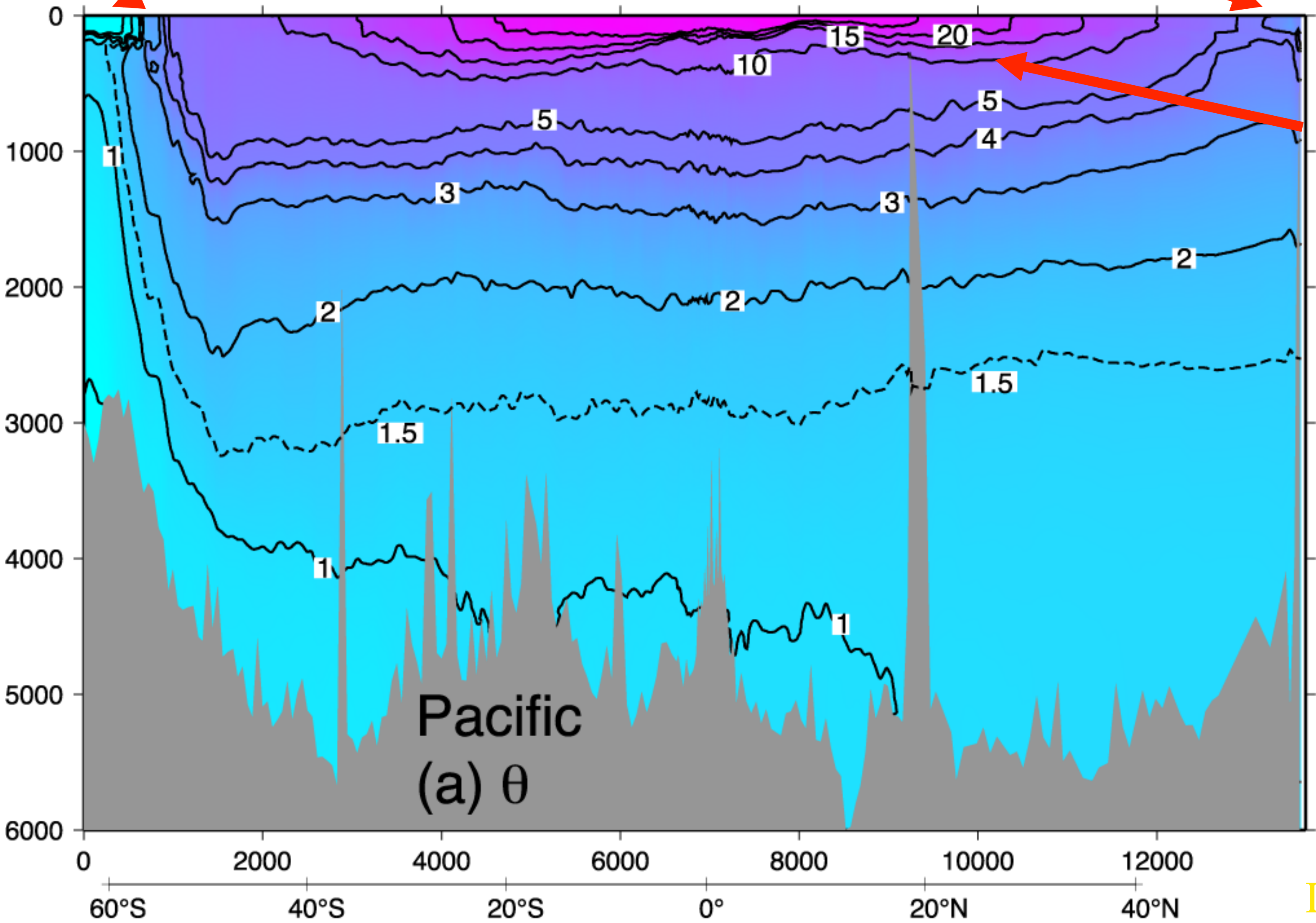


DPO Figure 4.19

Pacific potential temperature section

Inversions ("dichothermal layers")





thermocline

DPO Fig. 4.12a

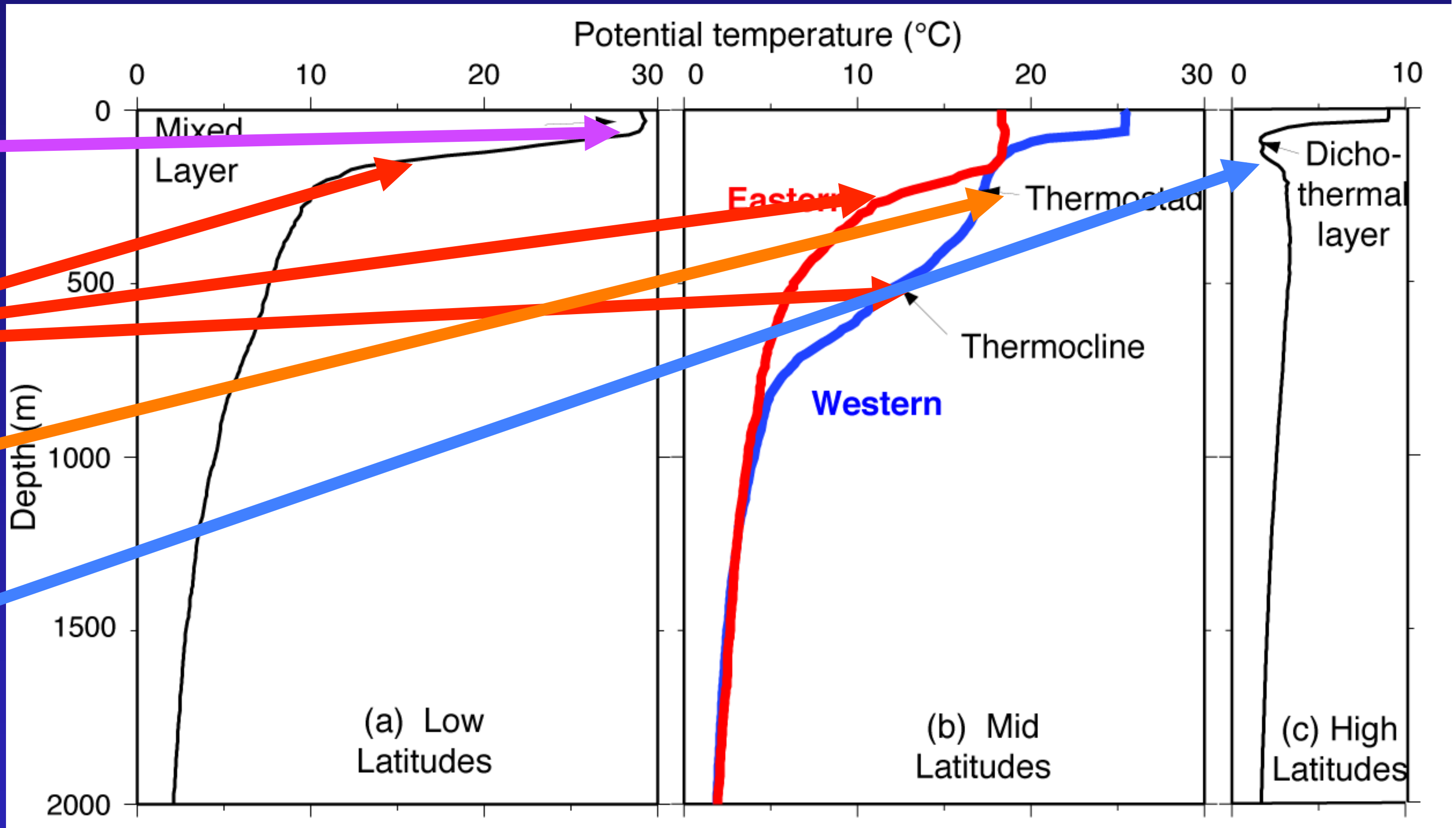
Temperature profiles: definitions

Mixed layer

Thermocline

Thermostad

Dichothermal layer (T minimum)



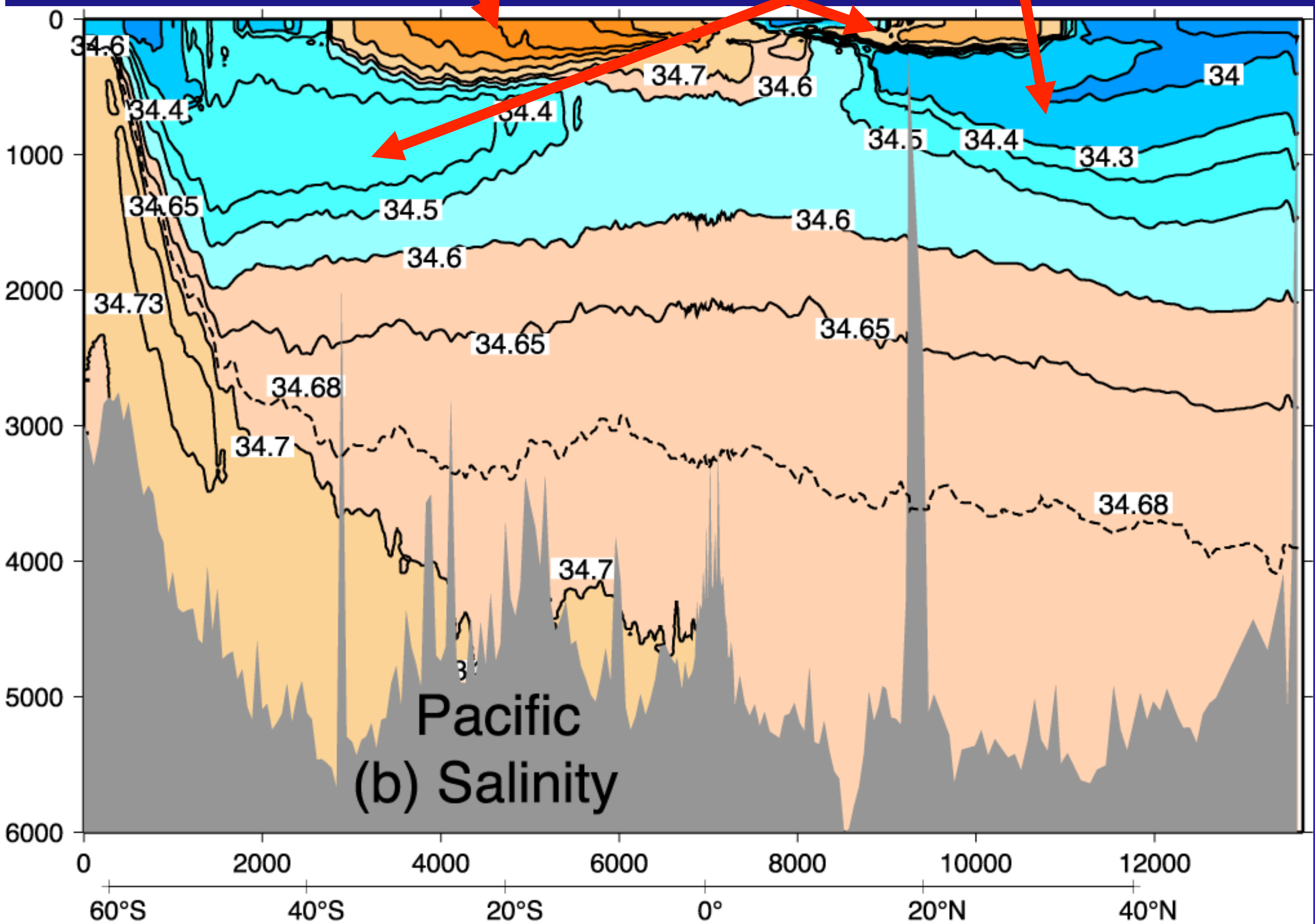
Typical North Pacific profiles

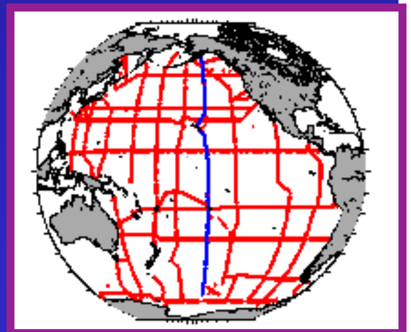
DPO Figure 4.2

Pacific salinity section

Salinity maximum layers

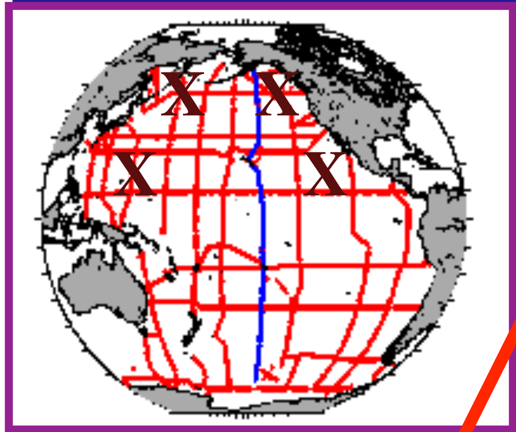
Salinity minimum layers - intermediate waters (Antarctic and North Pacific I.W.)

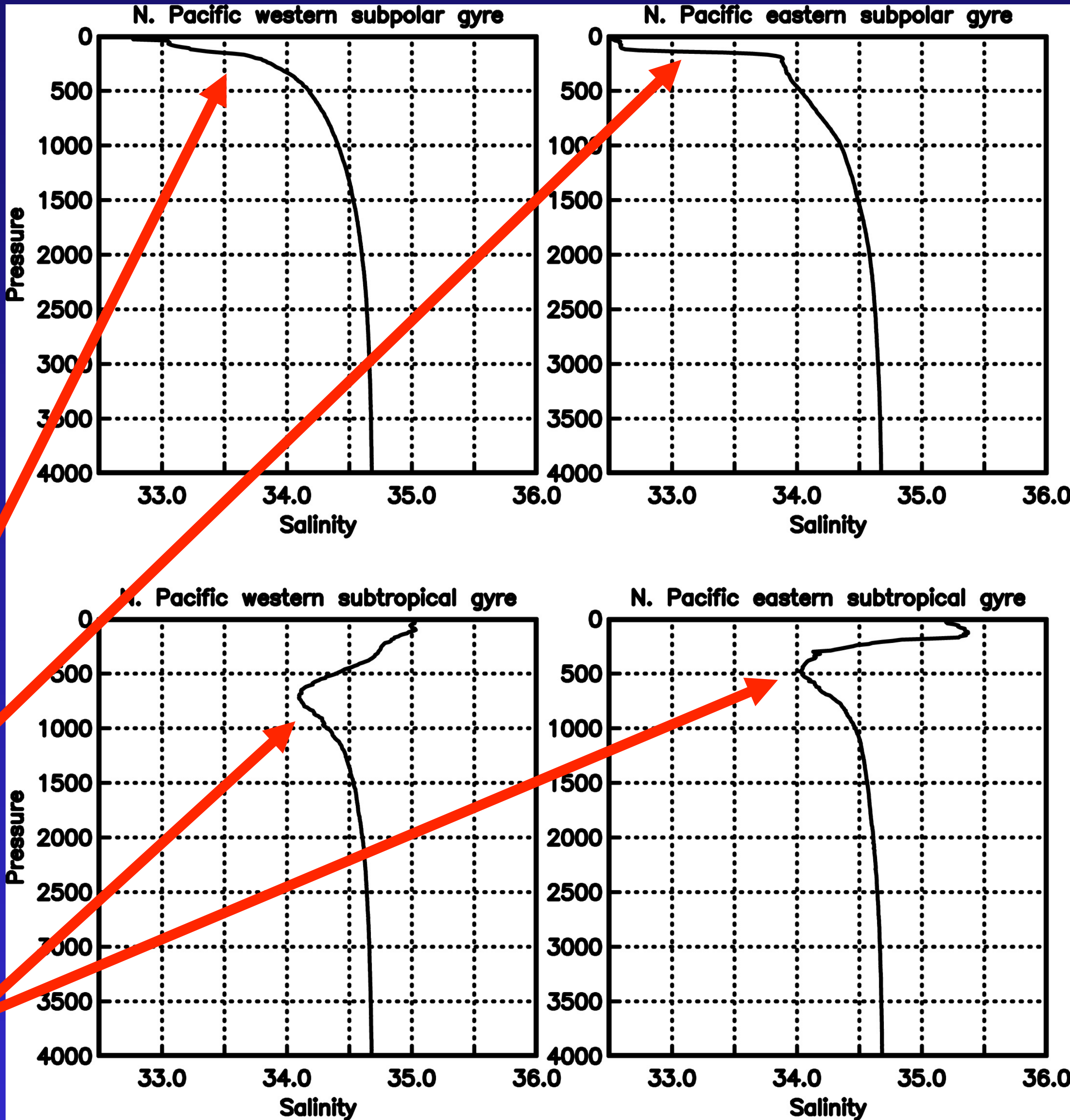




DPO Fig. 4.12b

Salinity: typical vertical profiles in the N. Pacific

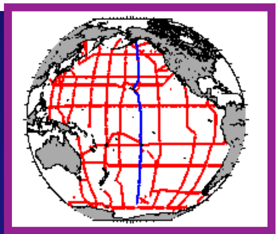


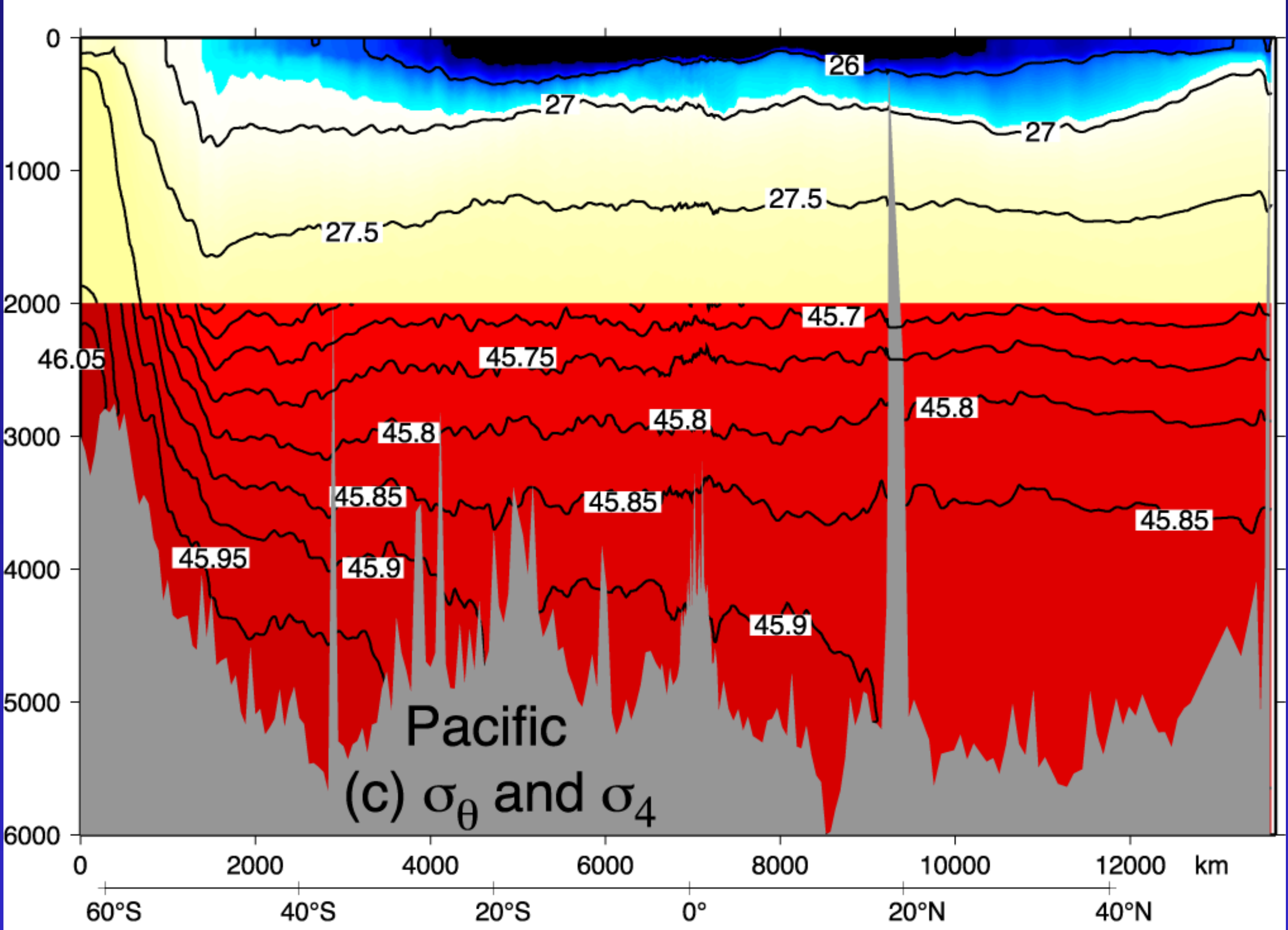


Halocline

Salinity minimum

Pacific section of potential densit(ies)





DPO Fig. 4.12

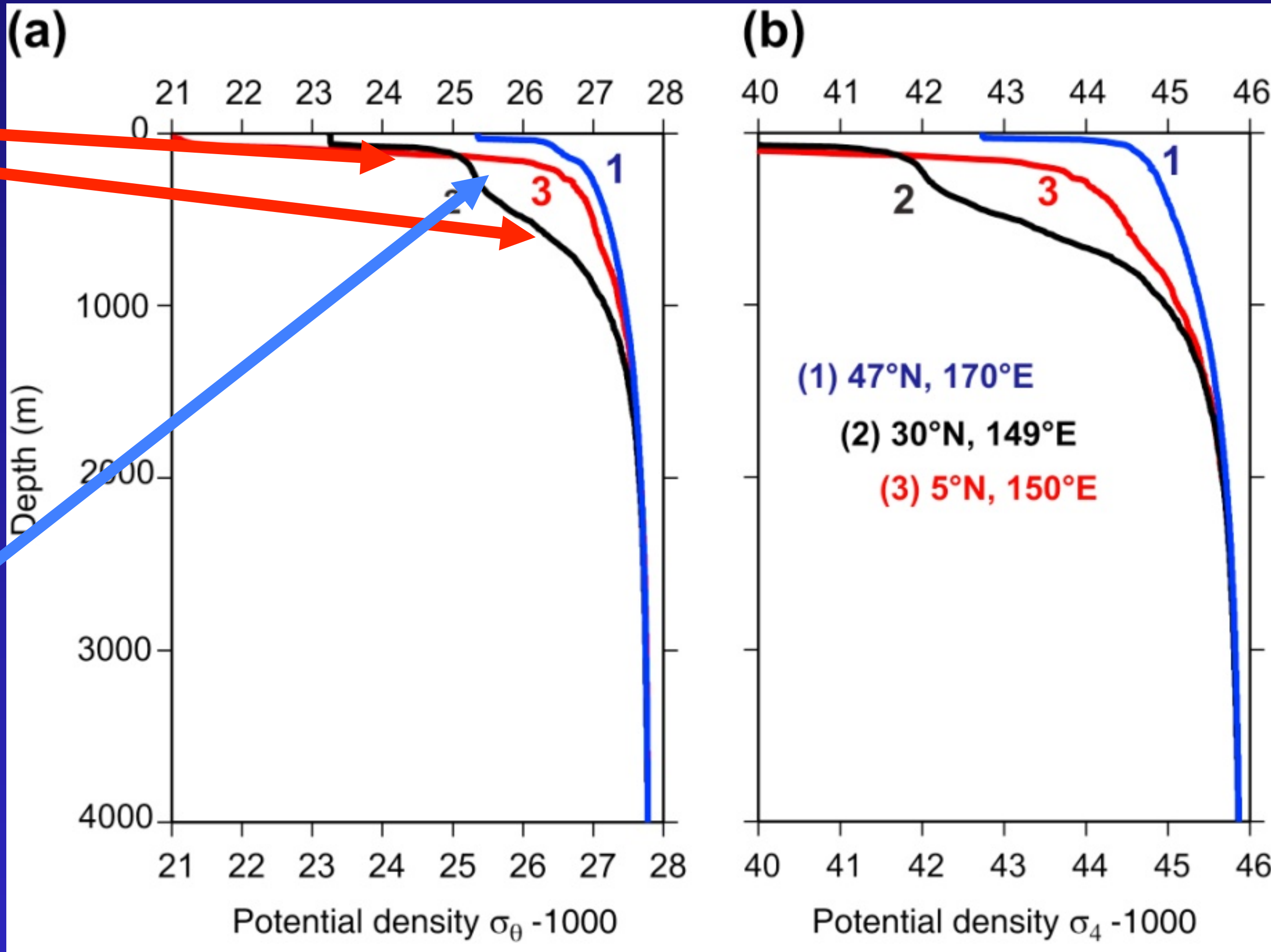
Typical potential density structure

Pycnocline:

Where density changes rapidly (large vertical gradient)

Pycnostad:

Where density changes slowly (small vertical gradient), generally refers to being embedded in the pycnocline, hencein the upper ocean.



DPO Figure 4.20

Summary of terminology for vertical structure

Mixed layer

Thermocline, halocline, pycnocline:
Vertical locations of high gradient
(large $\Delta T/\Delta z$, for thermocline, etc.)

Thermostad, halostad, pycnostad:
Vertical locations of low gradient, usually embedded in the …cline
(small $\Delta T/\Delta z$, for thermostad, etc.)

Vertical extrema sometimes have names:
salinity minima, temperature minima or maxima, etc. (e.g. dichothermal layer for very shallow temperature minimum usually in high latitudes

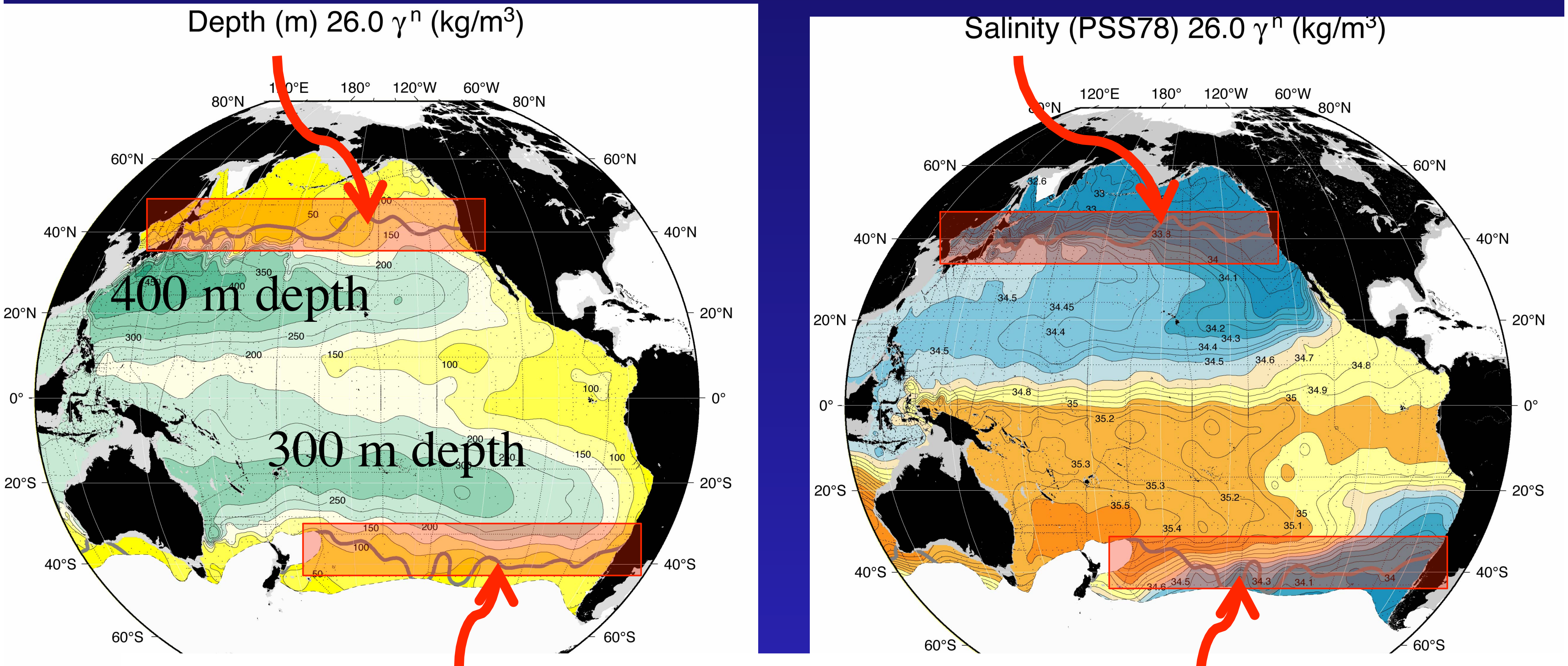
Concepts for studying ocean property distributions

1. Ventilation ("breathing"): properties of ocean waters are mostly set initially at the sea surface (heat, freshwater, gas exchange) and modified internally (mixing, biological processes, radioactive decay)

2. Flow and mixing along isentropic (isopycnal) surfaces is much easier than diapycnal flow and mixing, so water parcels tend to follow isopycnals as they enter the ocean interior

3. Water mass
   - Define the water mass based on properties (often a property extremum)
   - Define based on unique, identifiable formation process

1. And 2. Ventilation of the upper ocean



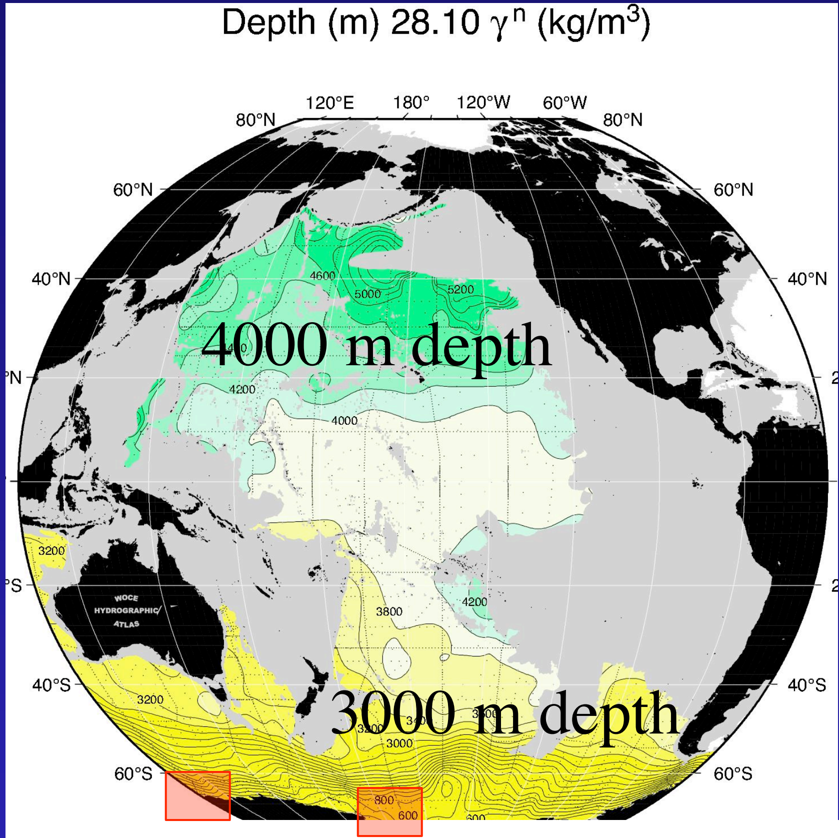
Surface outcrop: source of water for the this shallow isopycnal

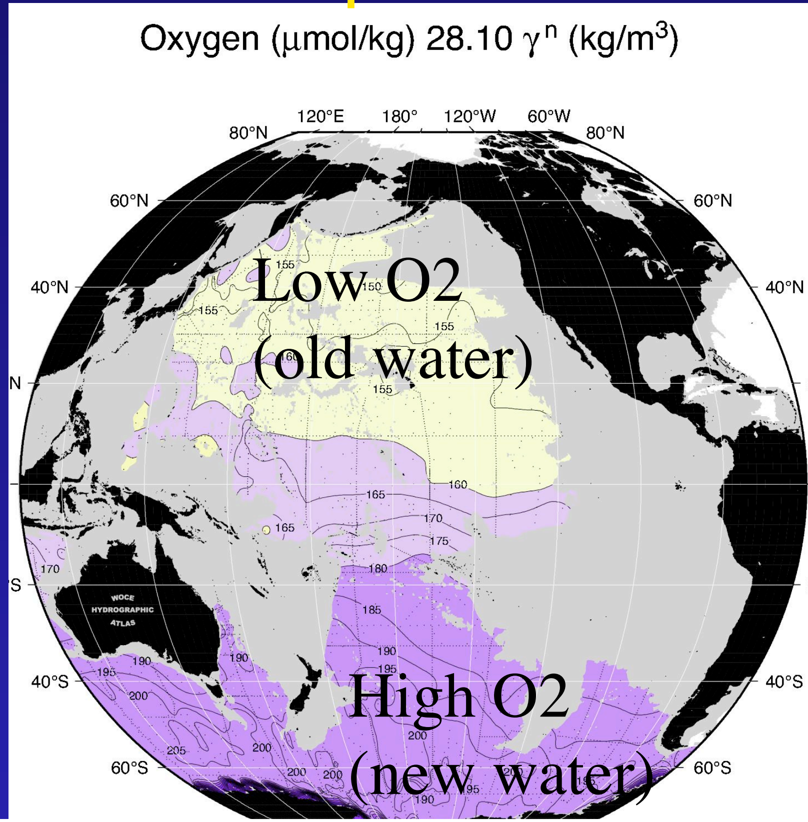
Water in ocean interior originates at surface outcrops. (There is no interior source of high density.)

The water mostly flows into the ocean interior along isopycnals (presuming only weak mixing).

WOCE Pacific Atlas (2007)

1. And 2. Ventilation of the deep ocean



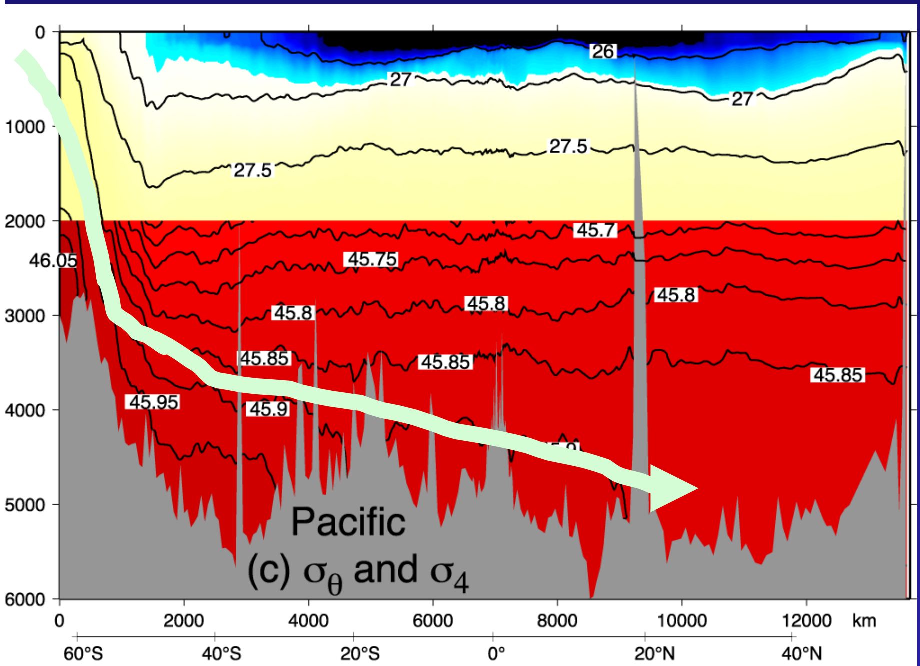


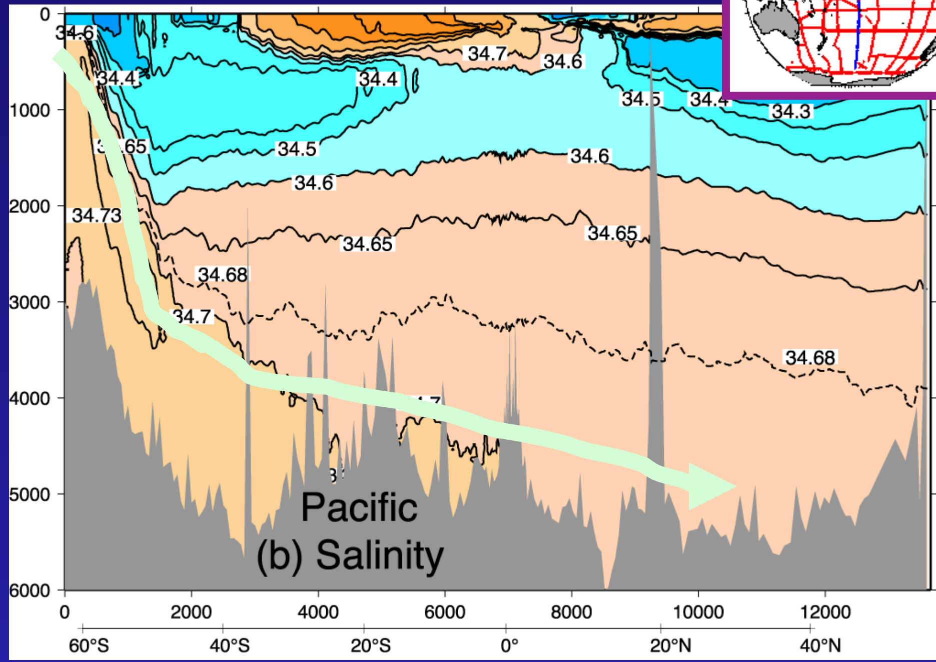
Very local high latitude sources of water for the this deep isopycnal

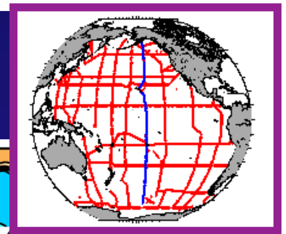
(Sources for this deep isopycnal include various sea ice formation regions along Antarctica, and dense water formation in the Nordic Seas, north of the N. Atlantic)

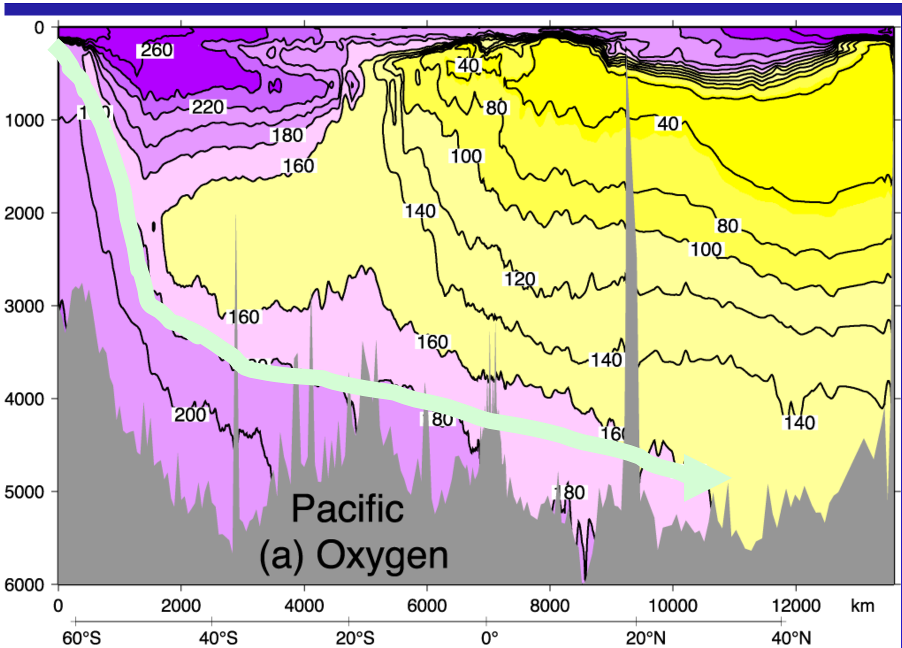
WOCE Pacific Atlas (2007)

2. Ventilation: isentropic processes









Flow along isopycnals if there is no mixing. Diapycnal flow requires diapycnal mixing, which is very weak (but crucially important at largest scales, even though flow and mixing are dominantly along-isopycnal).

3. Water masses and water types

(Tomczak and Godfrey, Ch. 5 definitions)

Water mass: “body of water with a common formation history”. Names are capitalized.

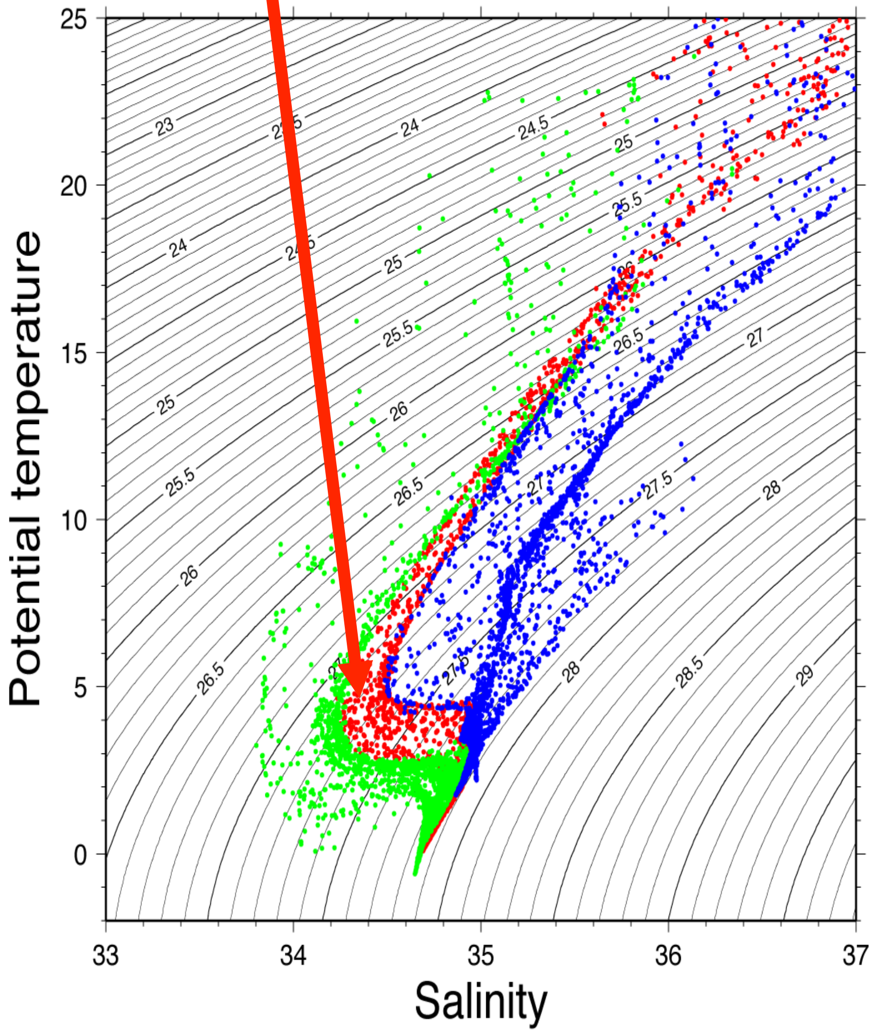
Water type: point on a temperature-salinity diagram (or more carefully, point in property-property-property-nthpropertthy space)

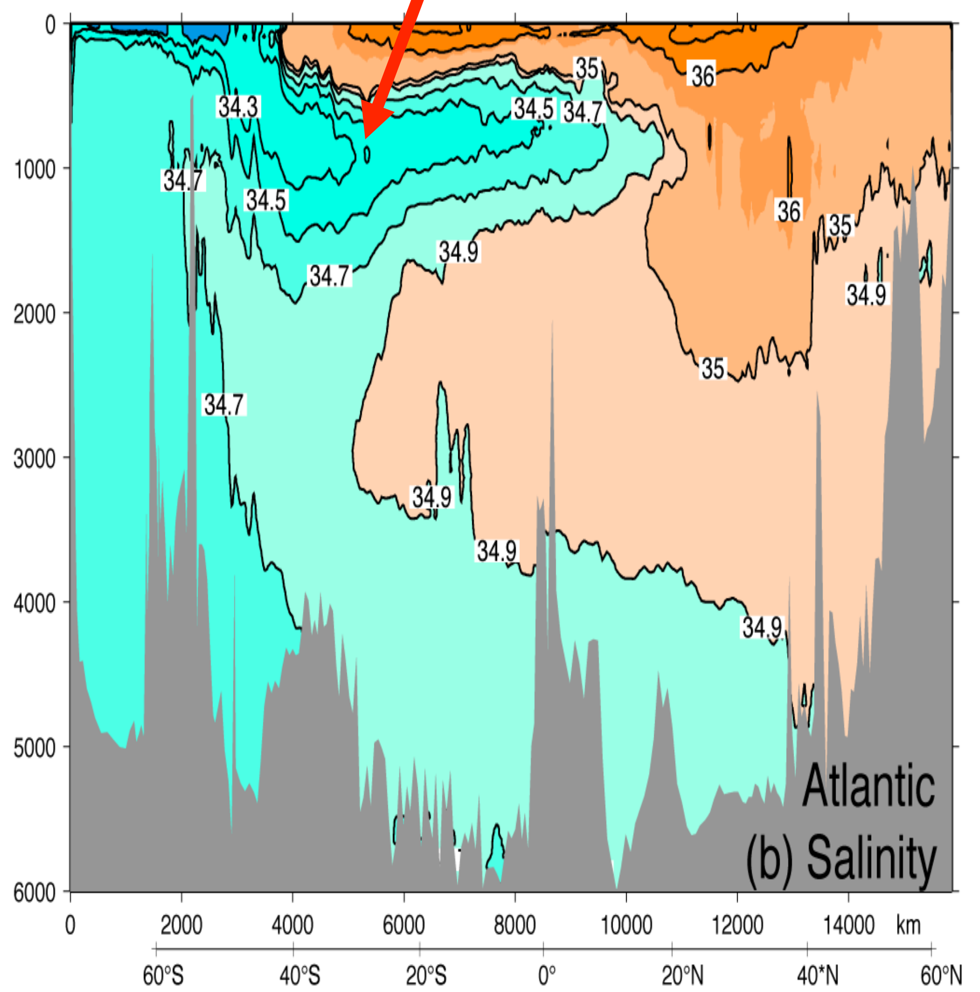
Source water type: water type at the source of a water mass

In practice, we just name the first, but are always aware that there are specific properties at the sources.

Water mass

Example: Antarctic Intermediate Water - (a) low salinity layer, (b) originating in surface mixed layers near Antarctic Circumpolar Current



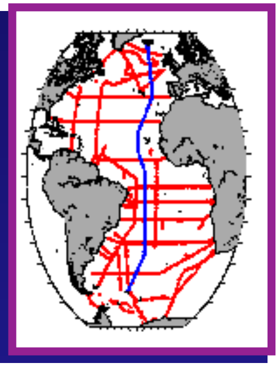


The approximately layered structure of the top-to-bottom ocean

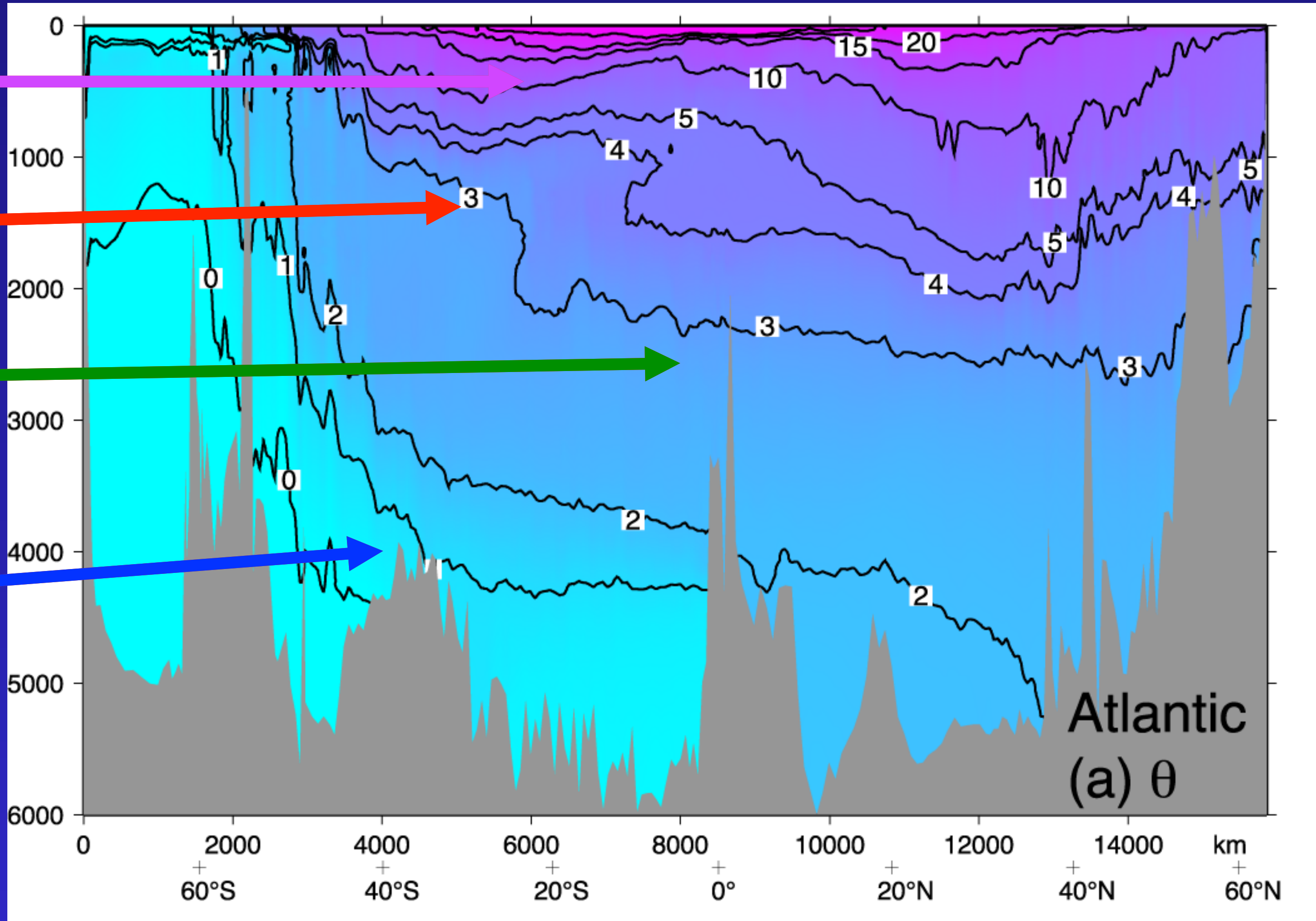
We can use four layers to describe the world's oceans.

1. Upper ocean (down through the permanent pycnocline)
2. Intermediate layer
3. Deep layer
4. Bottom layer

Atlantic vertical section: overall vertical structure

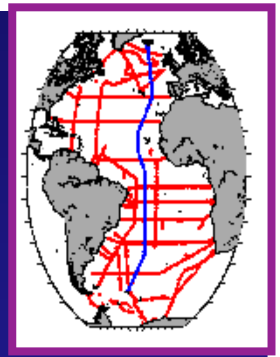


1. Upper
2. Intermediate
3. Deep
4. Abyssal



DPO Fig. 4.11

Atlantic vertical section: overall vertical structure



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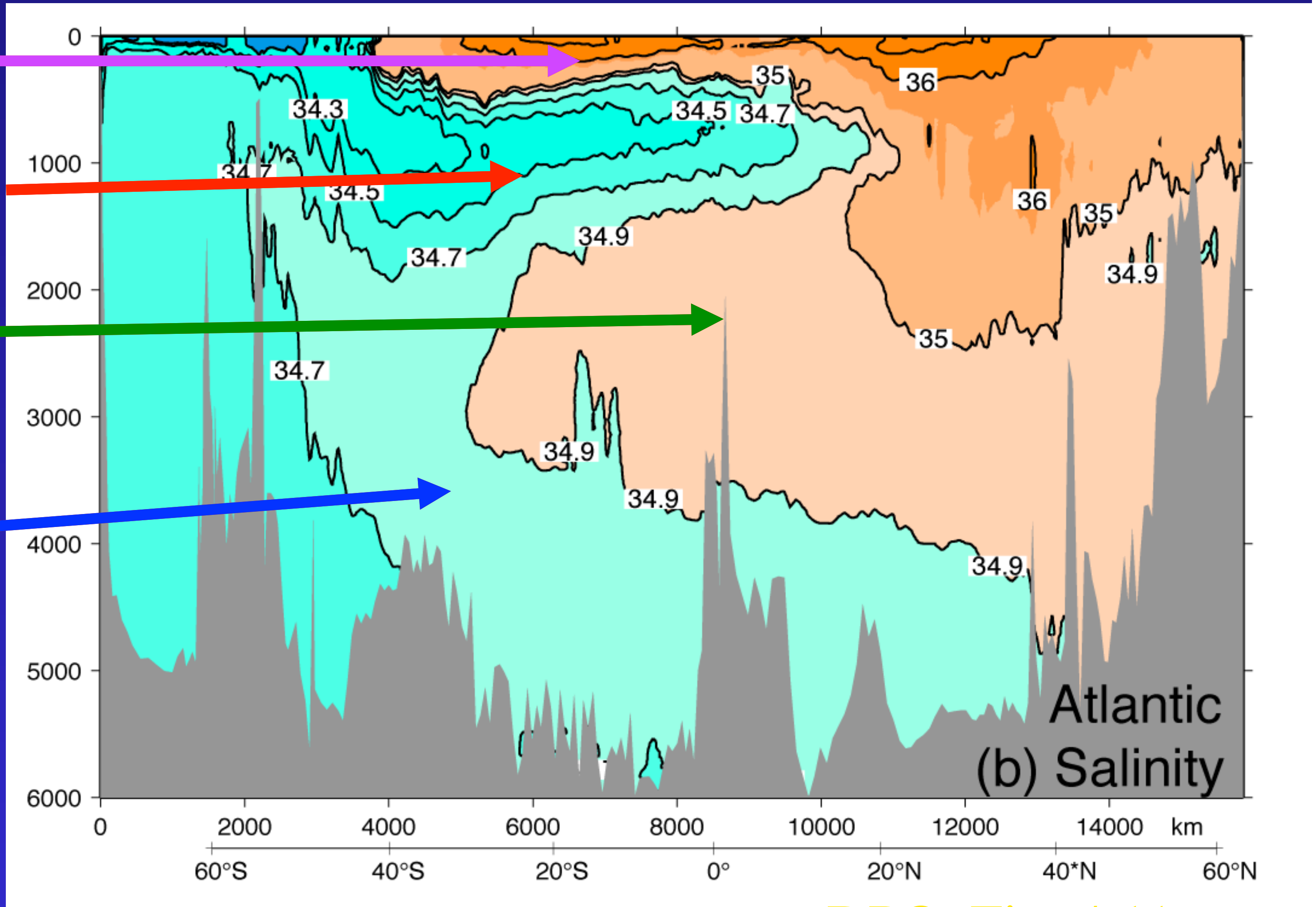
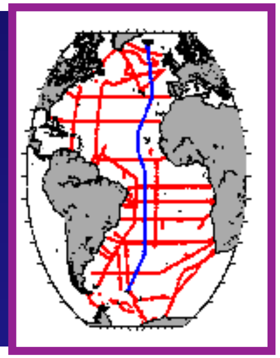
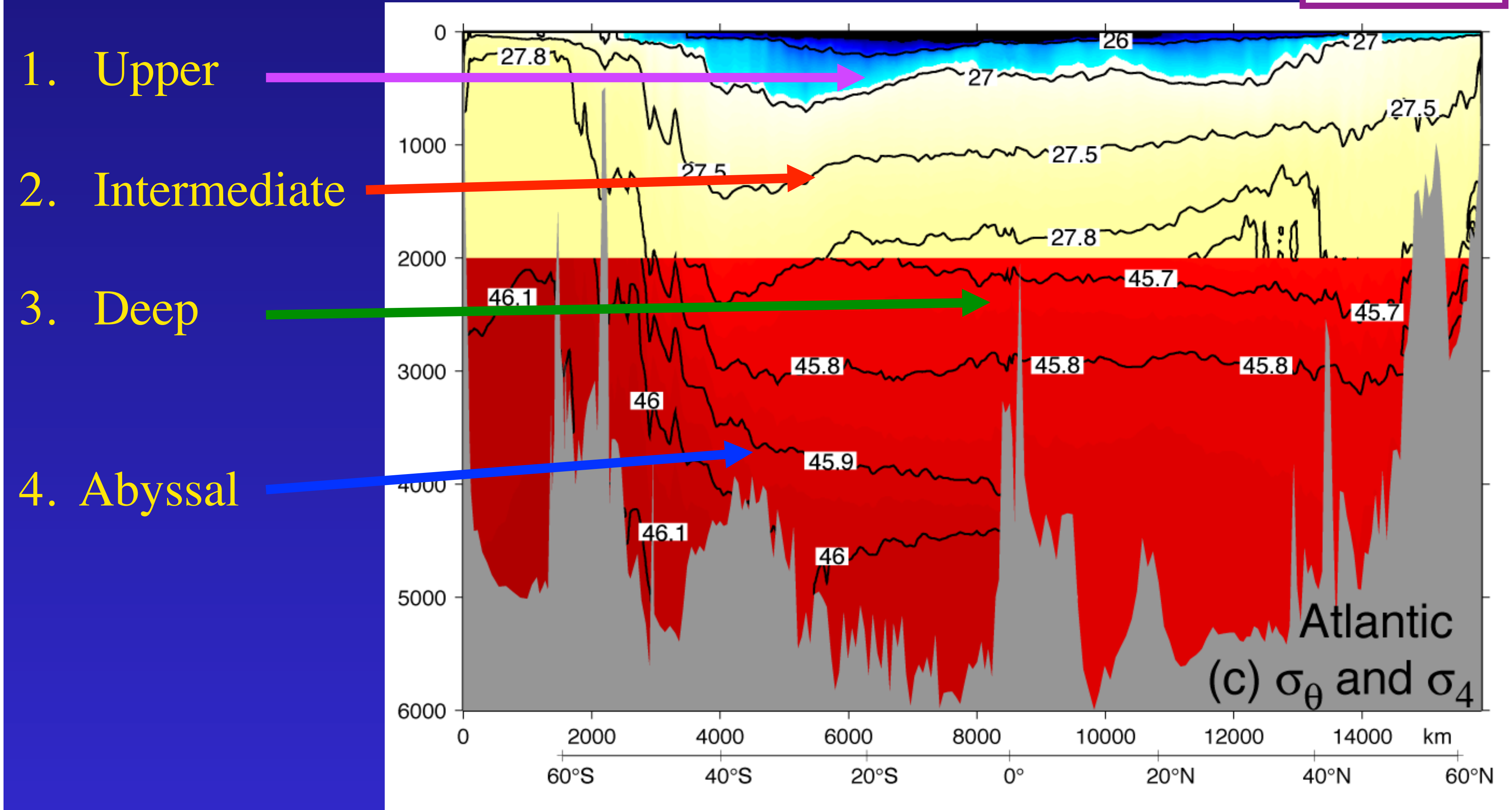


DPO Fig. 4.11

Atlantic vertical section: overall vertical structure





DPO Fig. 4.11

Upper ocean

Characterization: Surface mixed layer down through the main pycnocline.

Location: In the tropics and subtropics and into the subpolar regions (bounded by the Antarctic Circumpolar Current to the south, and the northern marginal seas to the north)

Formation mechanisms: late winter mixed layer properties are "subducted" into the ocean interior (slide down slightly inclined isopycnals from the mixed layer).

Mixed layer properties are set by air-sea fluxes, and depth by wind stirring or buoyancy-driven convection

Intermediate layer

Characterization: large-scale salinity maximum and minimum layers.

Location: just below the pycnocline in most of the ocean (especially tropics and subtropics), roughly 1000 to 2000 m depth.

Originate from very specific sources (“injection sites”) in the Labrador Sea, the Mediterranean Sea, the Red Sea, the Okhotsk Sea, and the Drake Passage region.

Formation mechanisms: Deep convection (reaching to about 1500 m); brine rejection; vigorous mixing where boundary currents meet; otherwise nearly-isopycnal spreading

Deep layer

Characterization: This is a thick layer below the intermediate layer and above the bottom waters, characterized by extrema of salinity, oxygen, nutrients.

Location: Roughly from 2000 to 4000 m depth.

The “North Atlantic Deep Water” originates through deep water formation processes north of the N. Atlantic (joined by Labrador Sea and Mediterranean Sea intermediate waters). It is relatively “new”.

The “Pacific Deep Water” originates through slow upwelling of bottom waters in the Pacific, and is the oldest water in the ocean. The “Indian Deep Water” is similar to the PDW.

The “Circumpolar Deep Water” is a mixture of these new (NADW) and old (PDW and IDW) waters, plus new deep waters formed in the Antarctic (Weddell Sea etc.).

Deep layer (continued)

Formation mechanisms and history: varied including

- deep convection (Nordic Seas, Labrador Sea)
- brine rejection (Antarctic contribution to deep water)
- upwelling (ocean-wide)
- vigorous mixing at specific sites (strait overflows)
- spreading along isopycnals with minimal mixing

Bottom layer

Characterization: Densest, coldest layer

Location: ocean bottom, usually connotes very dense water from the Antarctic.

Various names:

“Antarctic Bottom Water”

“Lower Circumpolar Deep Water”

Formation mechanism: brine rejection close to Antarctica

The approximately layered structure of the top-to-bottom ocean

1. Upper ocean (down through the permanent pycnocline)
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Mixed layers

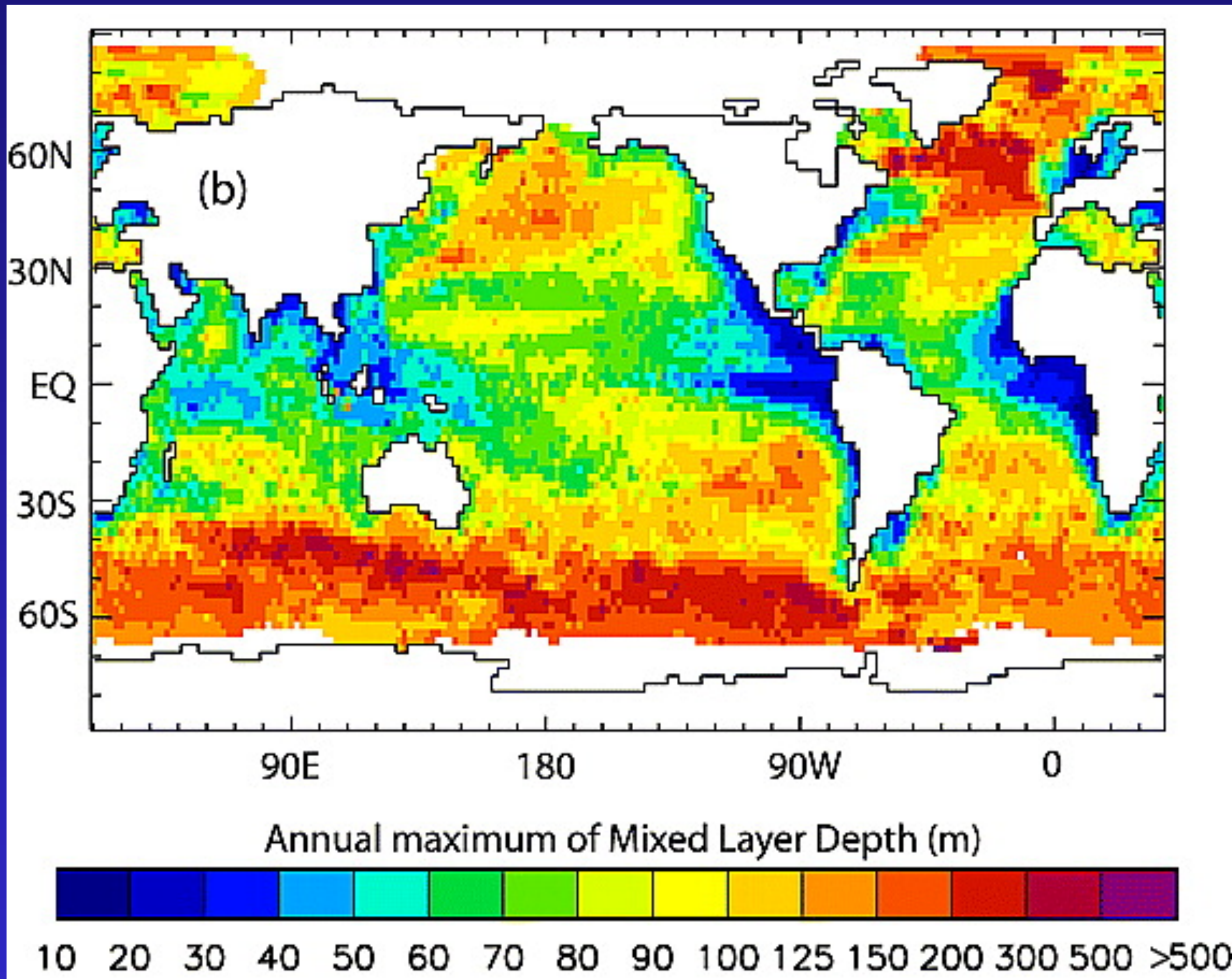
- Surface layer of the ocean is almost always vertically mixed to some degree
- In summer, calm, warm conditions, the mixed layer might be very thin (several meters)
- At the end of winter, after the full season of cooling and storms, mixed layers reach their maximum thickness

- Mixed layers are created by
  - Wind stirring (max. depth of such a mixed layer is around 100 m)
  - Cooling and evaporation (increasing the density of the surface water), which creates vertical convection. Max. depth of these mixed layers can range up to about 1000 m, but is mainly 200-300 m.

Maximum mixed layer depth (mainly late winter in each location)

Typically 20 to 200 m
Thicker (> 500) in some special locations,

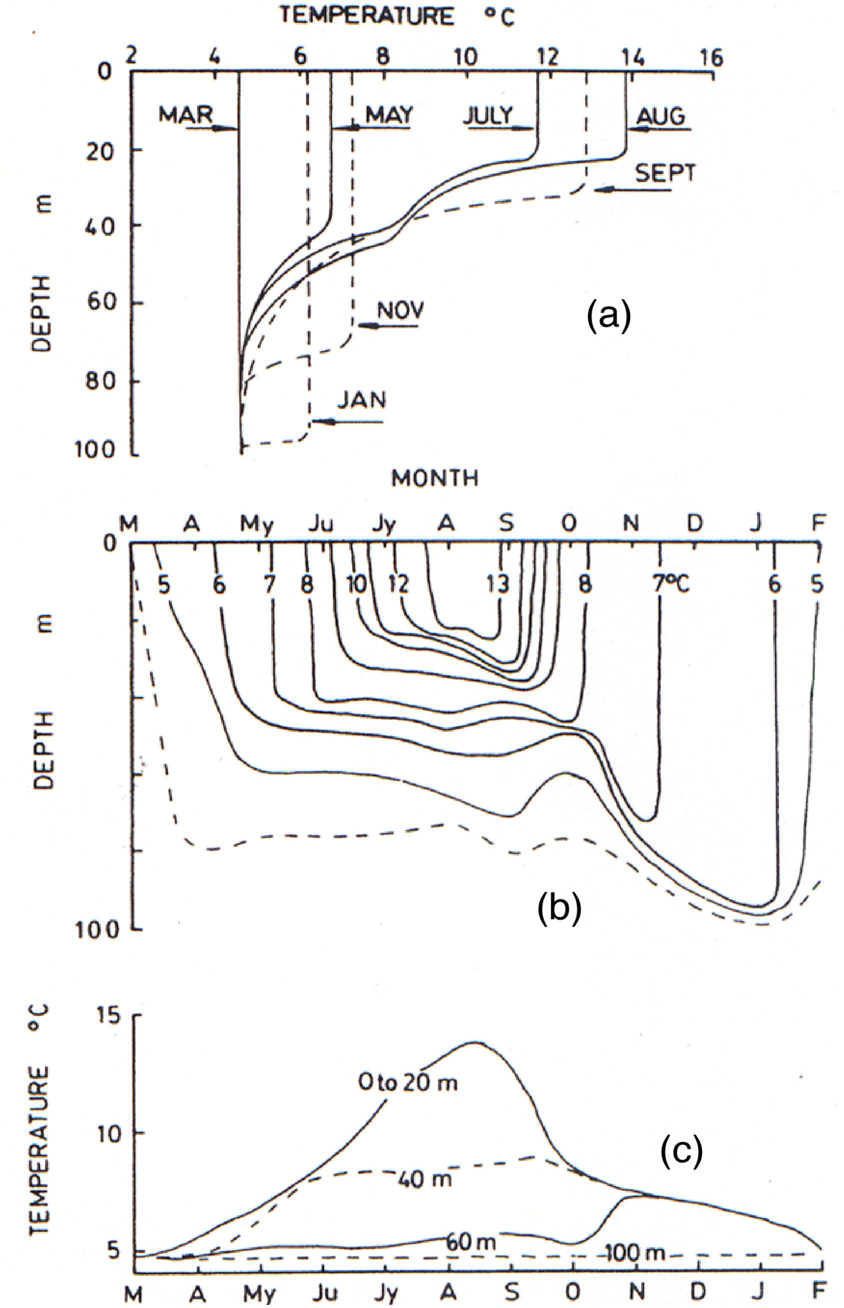
notably in
(1) band in the Southern Ocean and (2) northern North Atlantic



Using delta T = 0.2°C

deBoyerMontegut et al. (JGR, 2004)

Mixed layer development



Winter development of mixed layer:

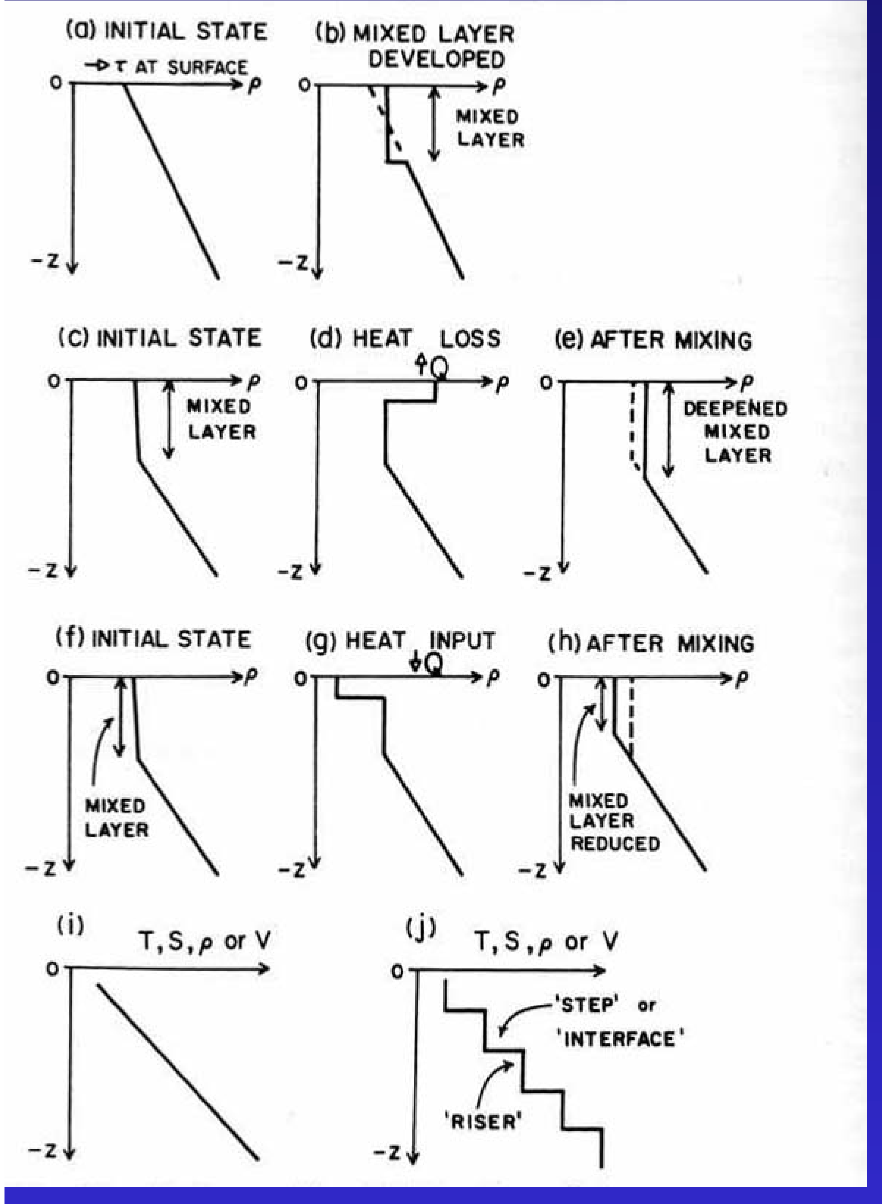
Wind stirring and cooling erode stratification, gradually deepening the mixed layer to maximum depth at the end of winter (Feb. to April depending on location)

Summer restratification:

Warming at the top adds stratified layer at surface, usually leaves remnant of winter mixed layer below.

DPO Figure 4.8

Mixed layer development



Winter development of mixed layer:

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DPO Figure 7.3

The approximately layered structure of the top-to-bottom ocean

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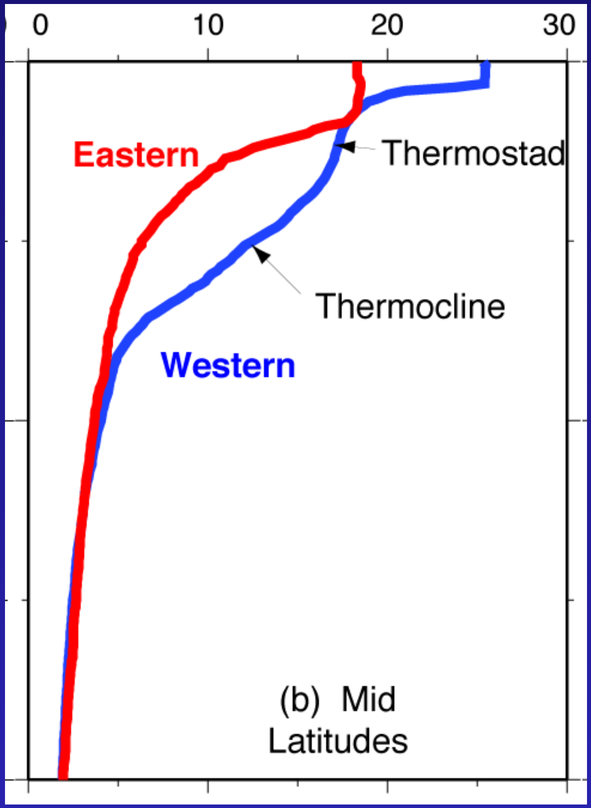
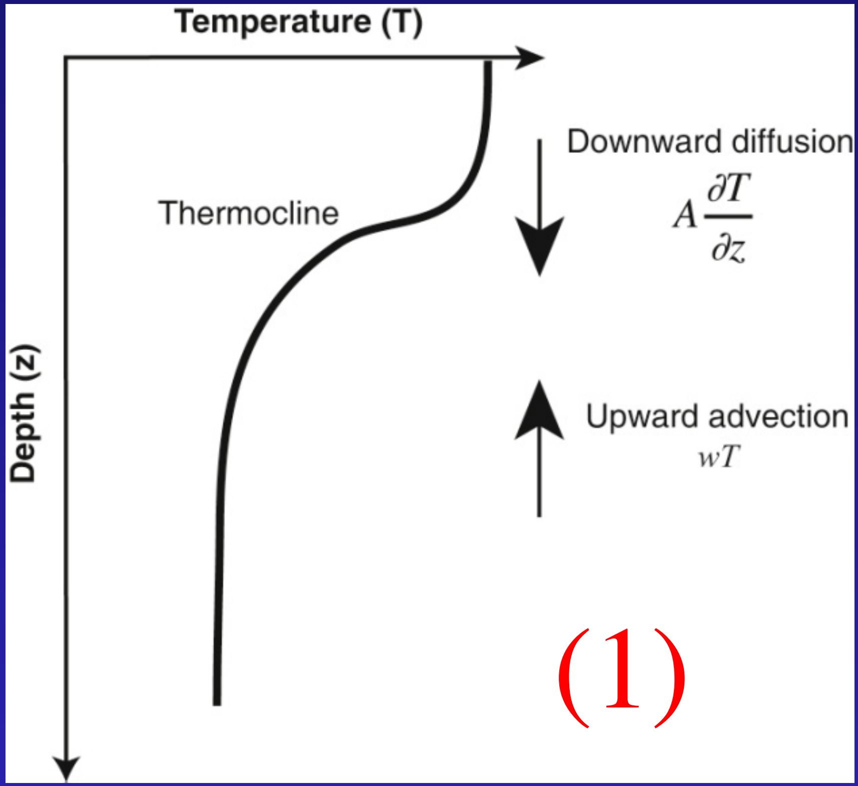
Thermocline (pycnocline)



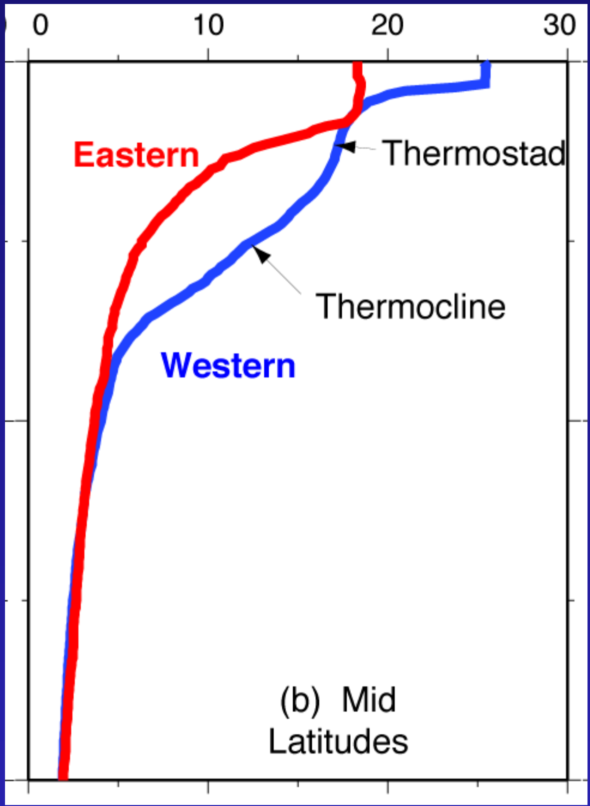


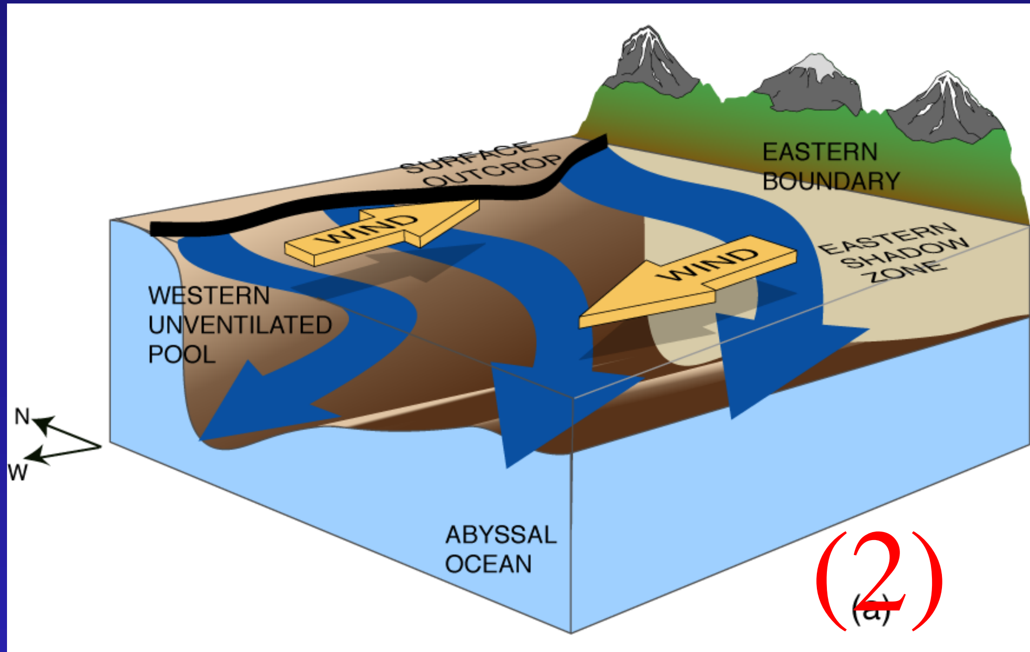
DPO Fig. 4.5

Two physical processes:

1. Vertical balance: mixing between warm, light surface waters and cold, dense deep waters, plus upwelling
2. Circulation of denser surface waters down into interior and thus beneath the lower density surface layers (subduction)

Thermocline (pycnocline)





DPO Fig. 7.15

Two physical processes:

1. Vertical balance: mixing between warm, light surface waters and cold, dense deep waters, plus upwelling
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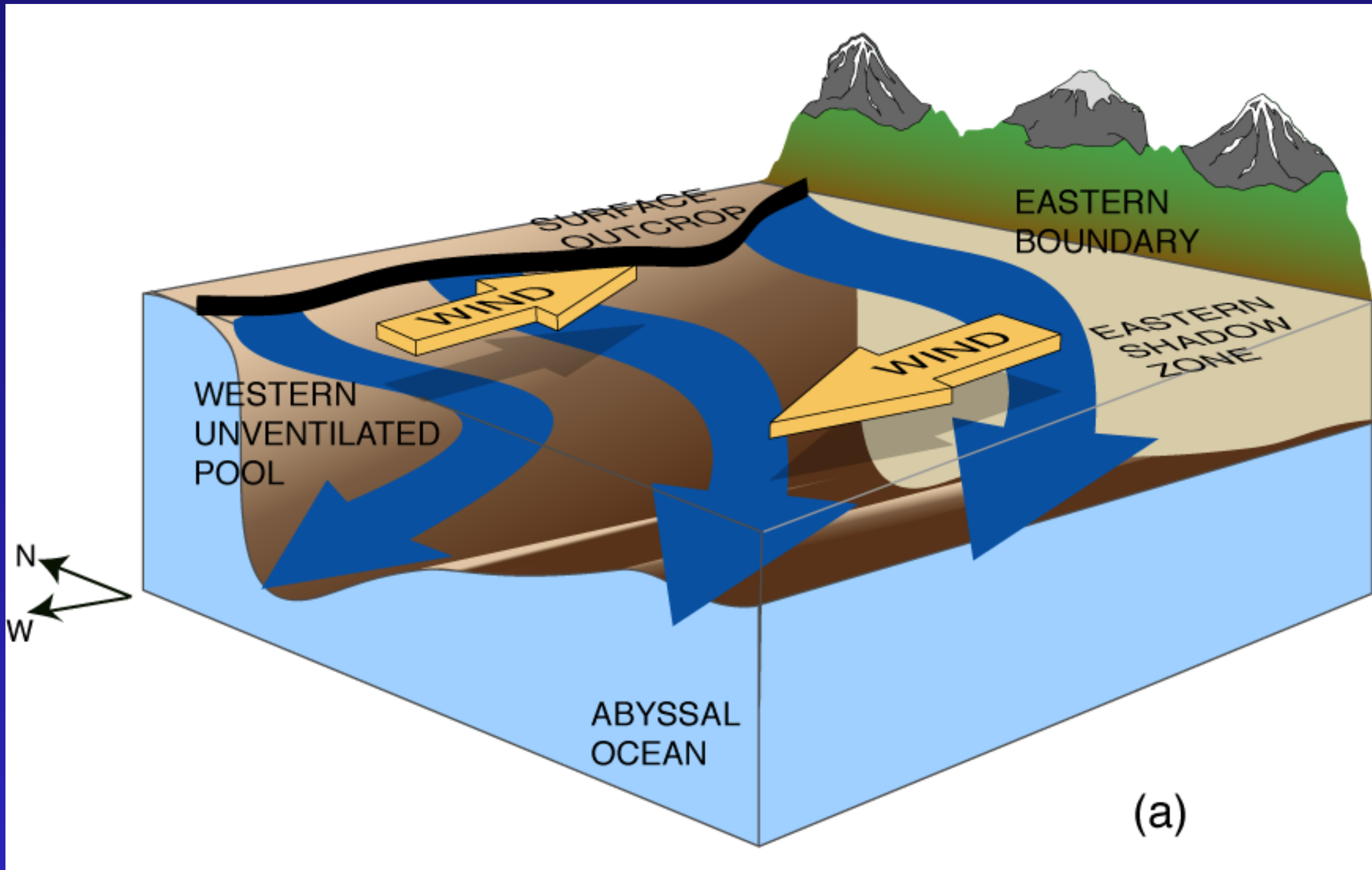
Ventilation through subduction

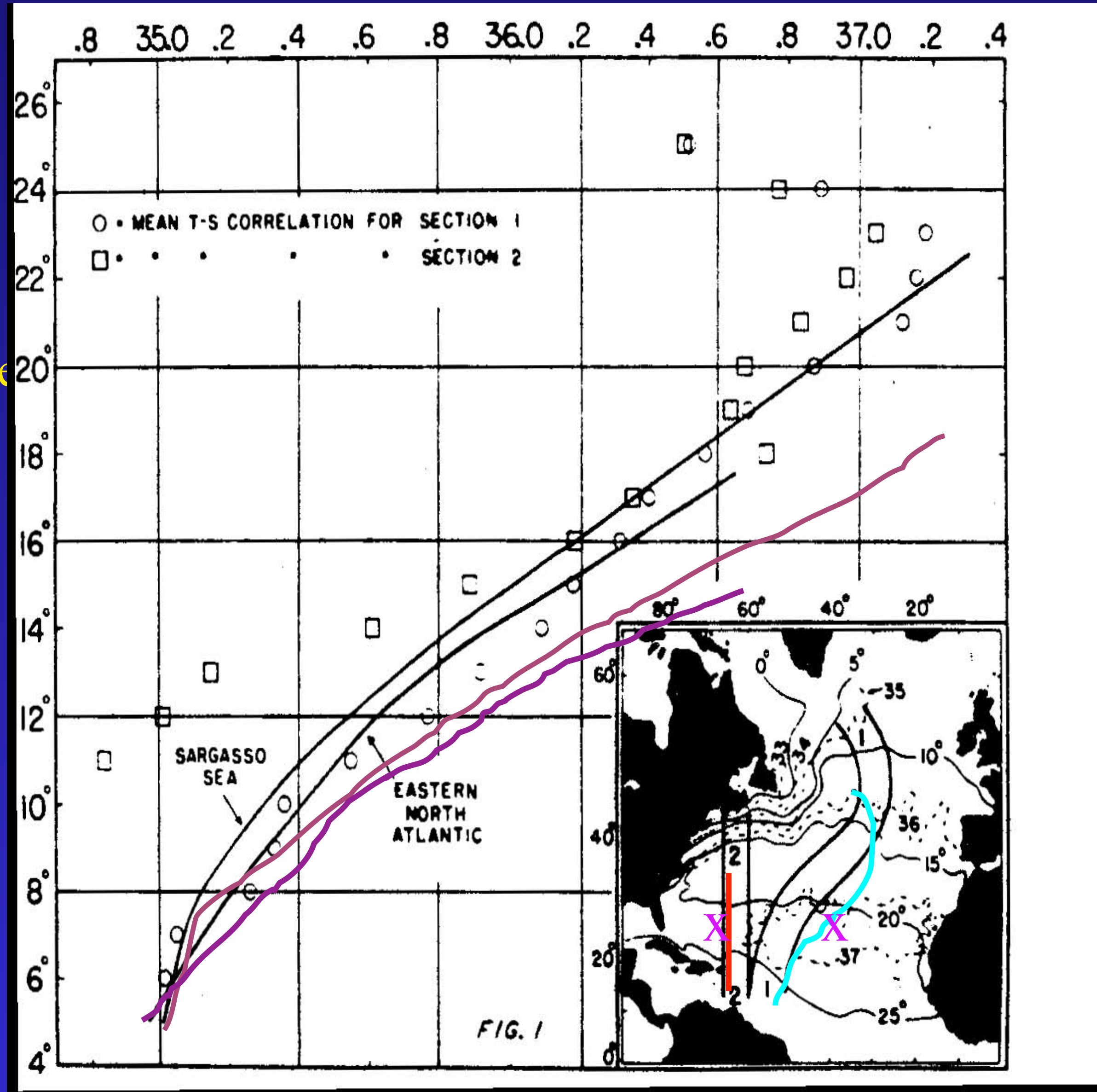


Subduction: flow from surface into interior along isopycnals.

DPO Figure 7.15

Creation of the thermocline through subduction

Iselin (1939): equivalence of surface properties on transect through N. Atlantic with properties on a vertical profile in the subtropical gyre --> hypothesized that properties are advected into the interior from the sea surface



Circles: section 1

Squares: section 2

Continuous plots: vertical profiles

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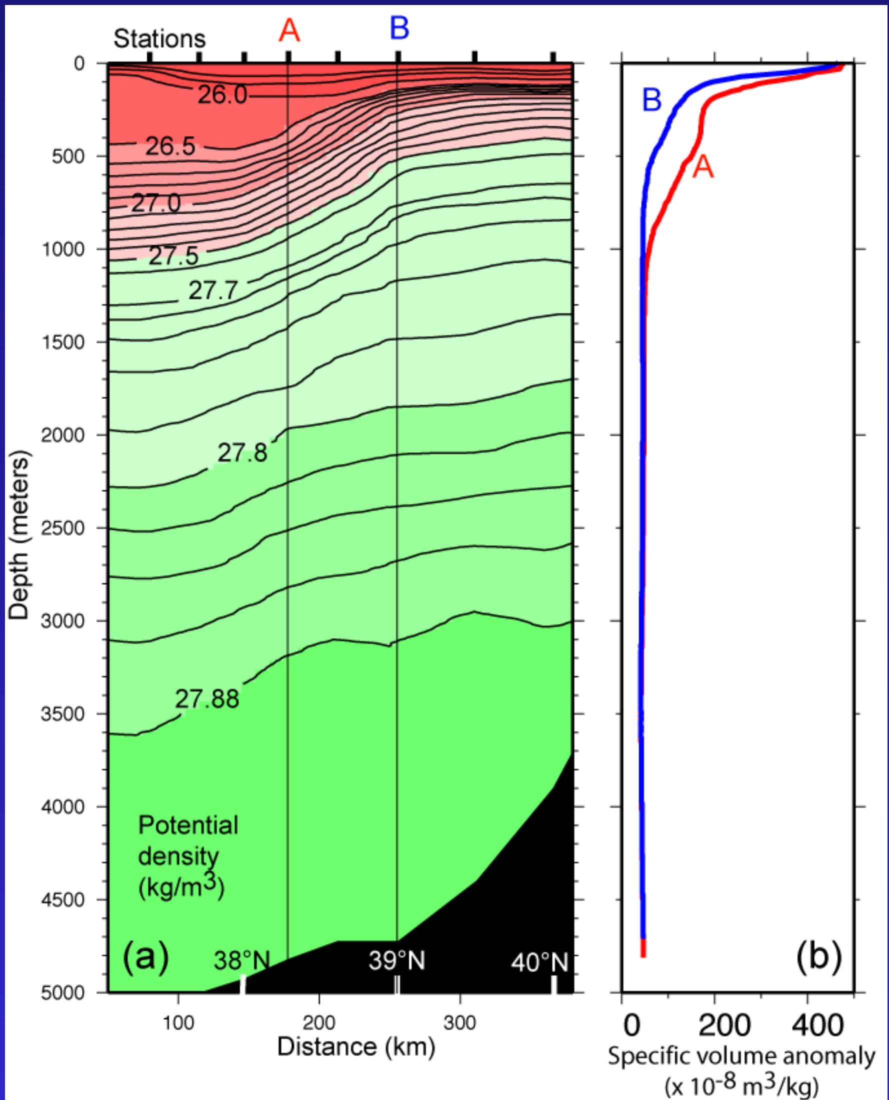
Thermostad development: Subtropical Mode Water (Eighteen Degree Water)



Section across Gulf Stream

- Thickening of isopycnals is the thermostad
- Forms at surface as a thick mixed layer near Gulf Stream in late winter.
- Circulates into the interior south of the Gulf Stream along isopycnals

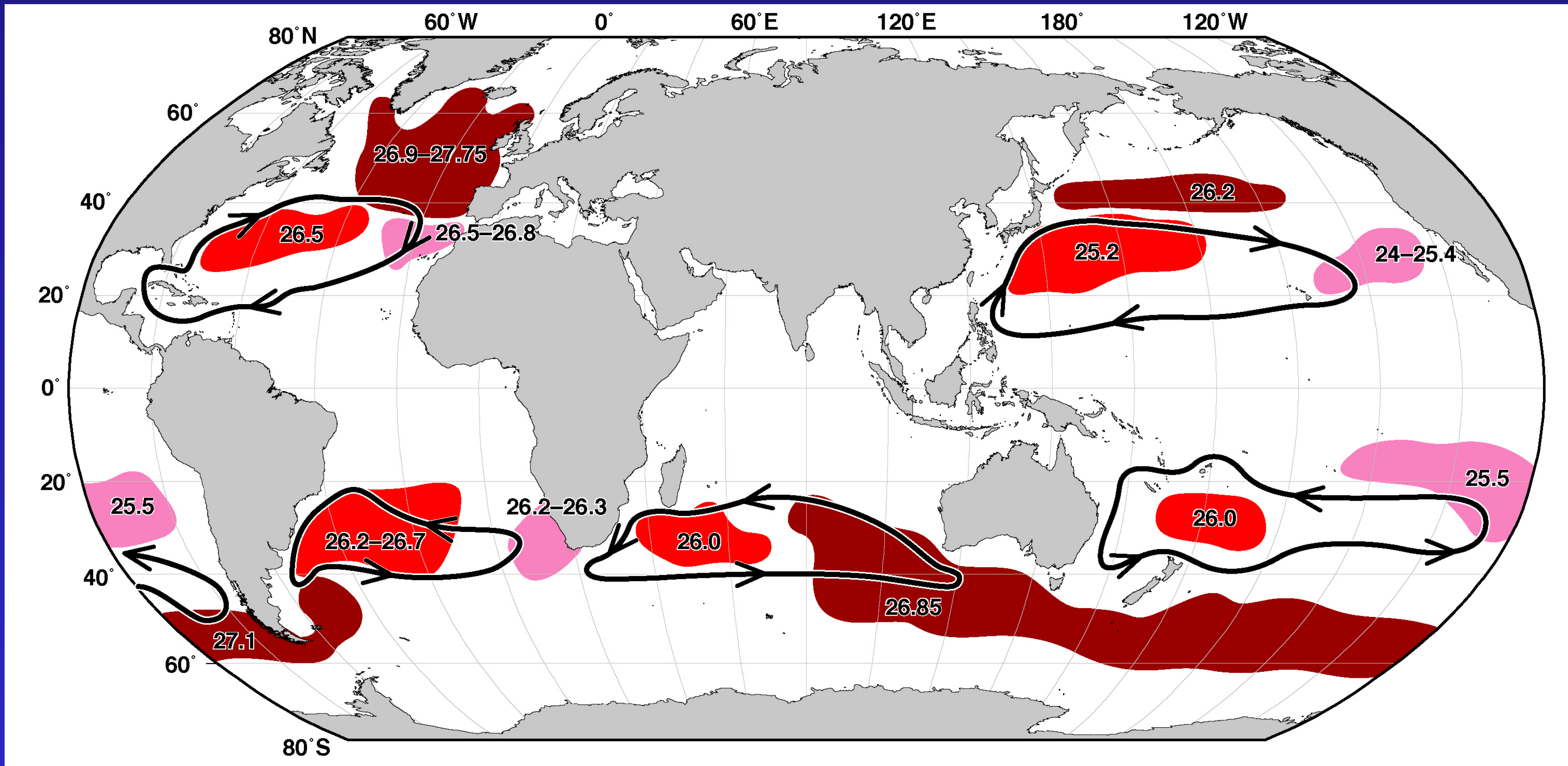
DPO Fig. 7.11

Mode water: definition, location and development

- Pycnostads/thermostads embedded in the pycnocline occur in identifiable regions
- They usually occur on the warm (low density) side of strong currents
- Example (previous slide): Gulf Stream has a pycnostad/thermostad at about 18°C on its south (warm) side.
- Because a pycnostad has a large volume of water in a given temperature-salinity interval, these waters were termed "Mode Waters", to indicate that the the mode of the distribution of volume in T/S space occurs in these particular T/S ranges.

Mode Waters

Location of thermostads - coordinated structures, derived from thick winter mixed layers that then spread into the interior along isopycnals

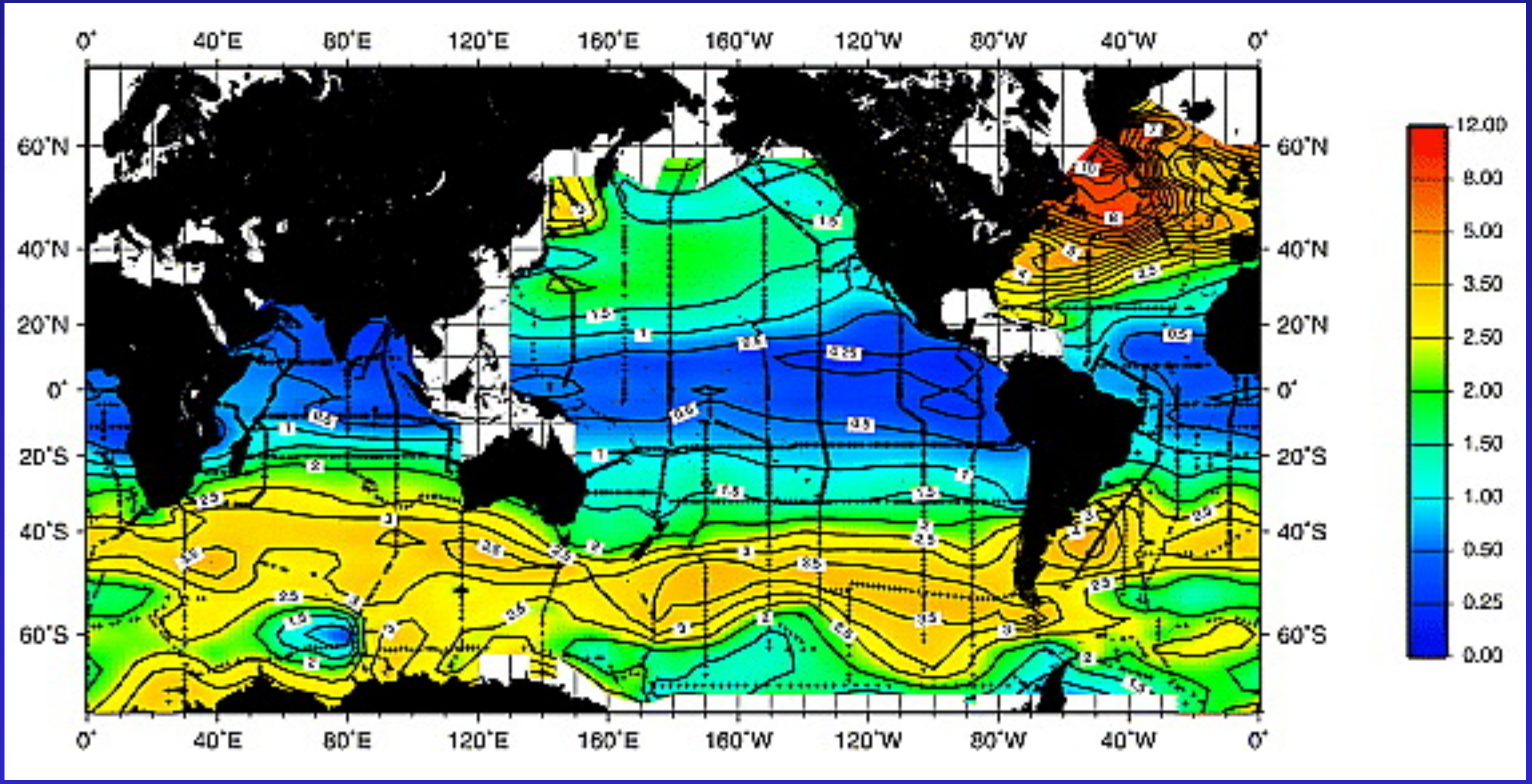


Hanawa and Talley (2001); DPO 14.12

Importance of mode waters for dissolved gas inventories

CFC water column inventories

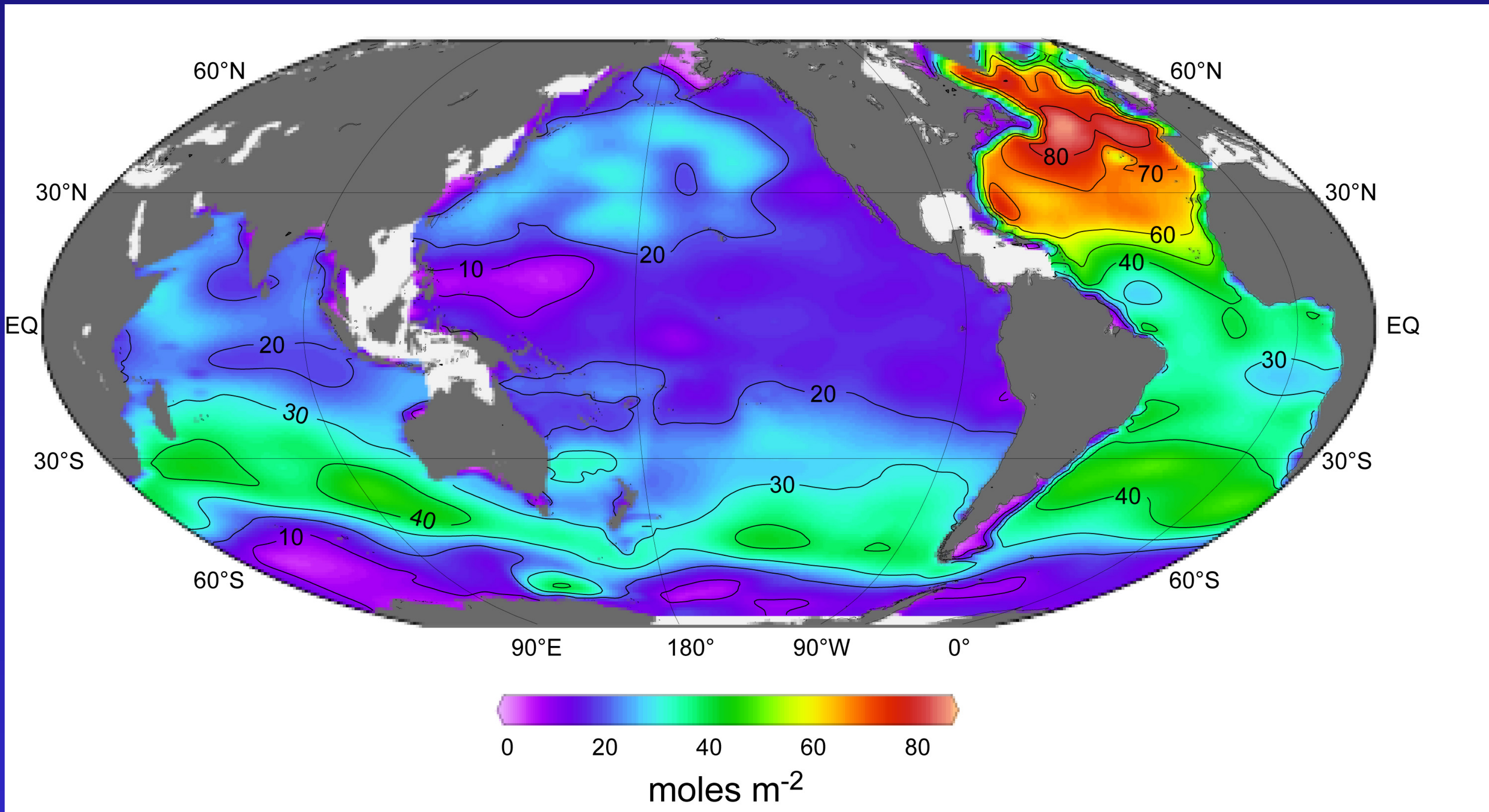
Note similarity with anthropogenic CO_2



Willey et al. (GRL 2004)

Importance of mode waters for dissolved gas inventories

Anthropogenic CO2



Sabine et al. (Science 2004)