Week 2 : Large-scale ocean properties
Tally's book chapter 4

Review: salinity

- What’s the definition of salinity?
  - Mass of salt (g) dissolved in a unit mass of seawater (kg).
- What are the experimental methods to measure salinity?
  - Temperature and Conductivity (as in CTD instrument)
- What’s the meaning of the law of equal proportions?
  - Concentrations of dissolved constituents vary in equal proportion to salinity.

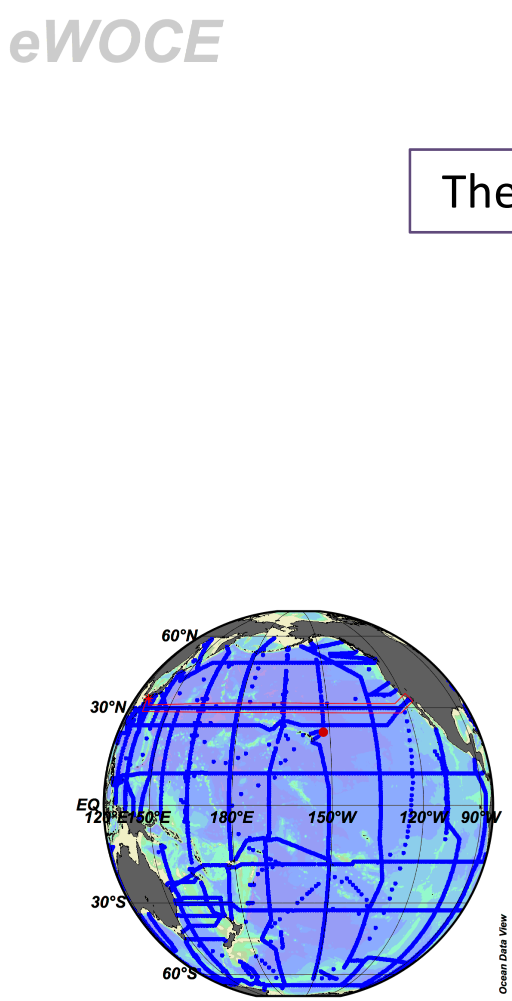
Review question: temperature/pressure

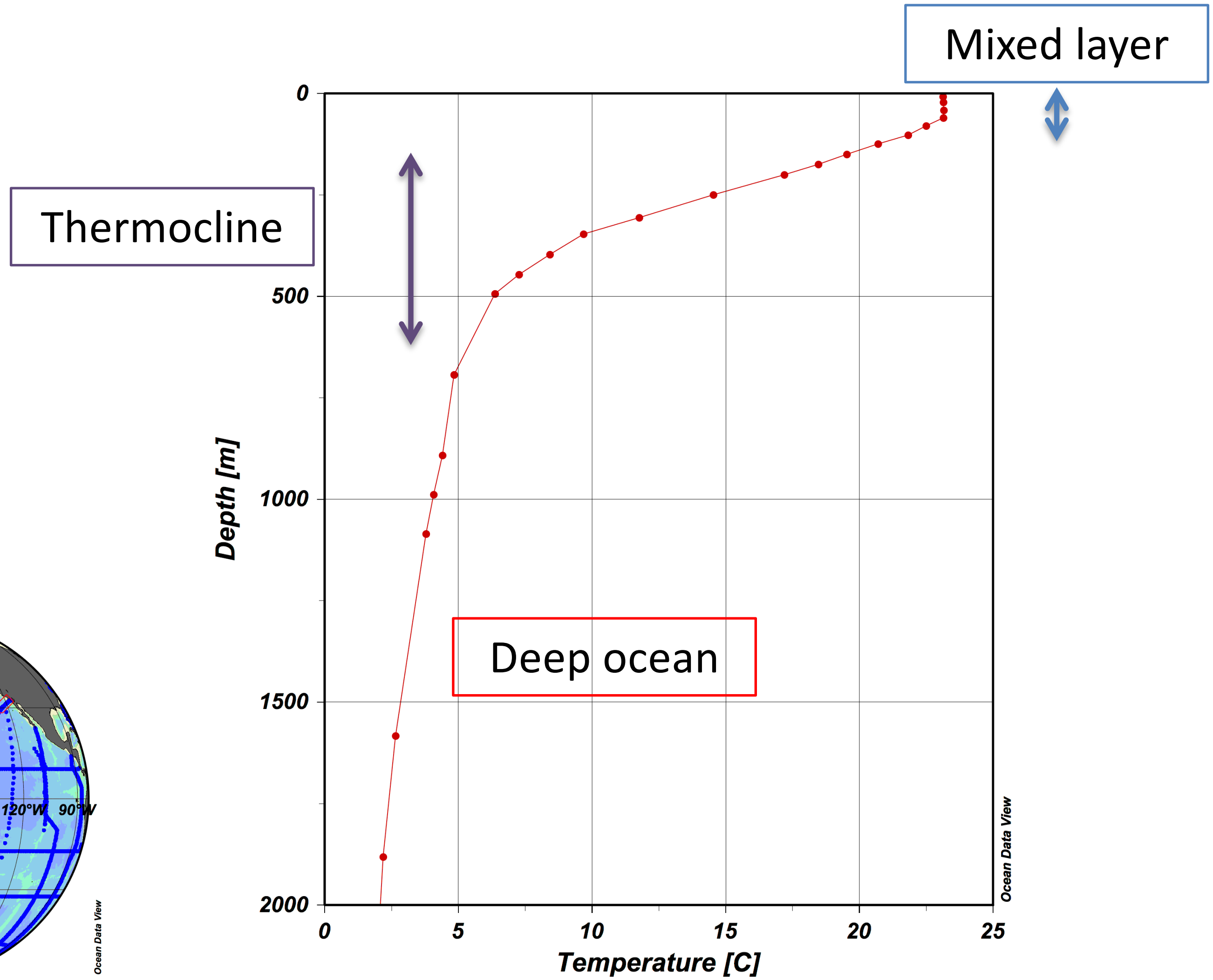
- What's the difference between temperature and potential temperature?
  - Potential temperature (θ) accounts for the compressibility of the seawater, and it measures the temperature of water if it were adiabatically raised to the surface.
- What are names of the three major regions in the (vertical) water column?
  - Mixed layer, thermocline, and deep ocean

Term project

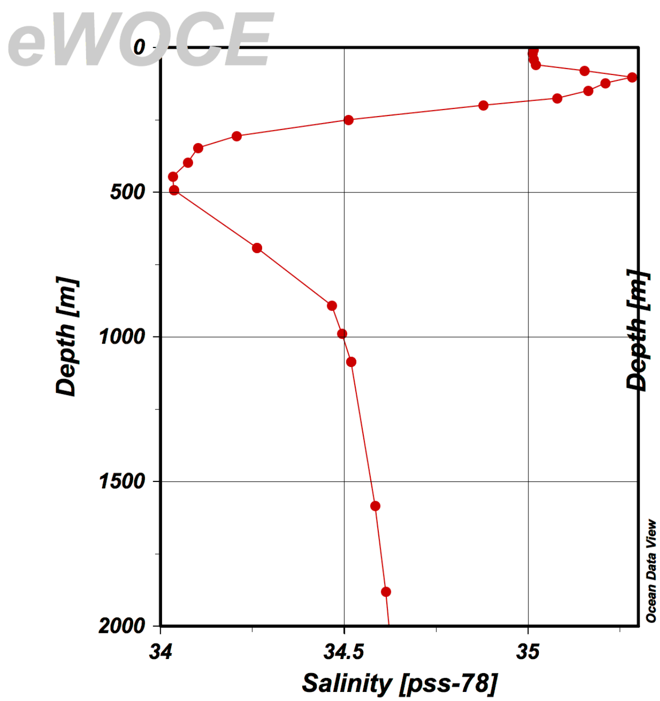
- Due Sept. 13th (Thu): Topic, objectives and questions
- **Example1: Atlantic meridional overturning circulation**
  - Objective: This term paper will summarize the recent progress and current knowledge gaps in our understanding about the Atlantic Meridional Overturning Circulation (AMOC).
  - Scientific questions: What is AMOC? Why is it important? How do we measure the magnitude of AMOC? What are the recent changes in AMOC? What do we know about its past change from paleoclimate proxies? What are the climate model projections of AMOC in this and coming centuries?
- **Example 2: Topic: Sea level rise**
  - Objective: This project will summarize the current status of knowledge about the sea level change?
  - Questions: What earth processes control the sea level? Why is it important? What are the timescales associated with different mechanisms? What are the effects of climate warming on the sea level? What are the relative importance between the melting polar ice caps and thermal expansion?
- Email Daoxun (sdxmonkey@gatech.edu): the topic, objective(s) and questions that define the goals of your term paper.
- What's next: draft an outline with bibliography

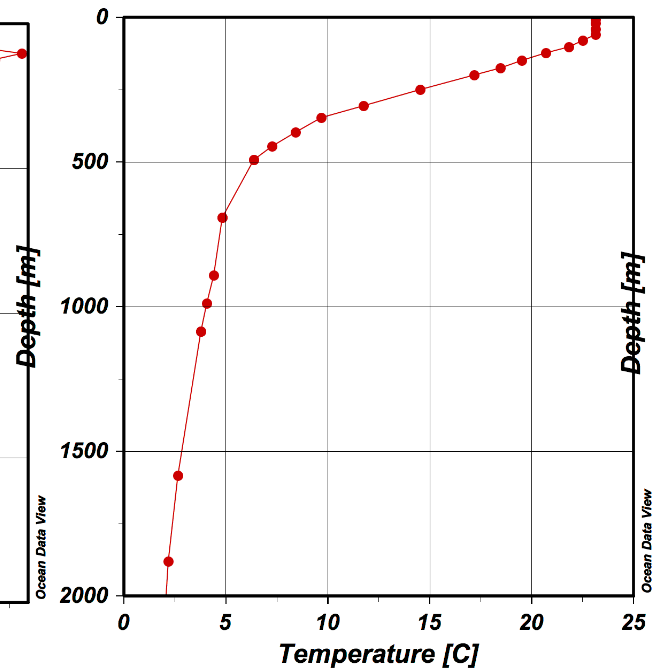
Three zones

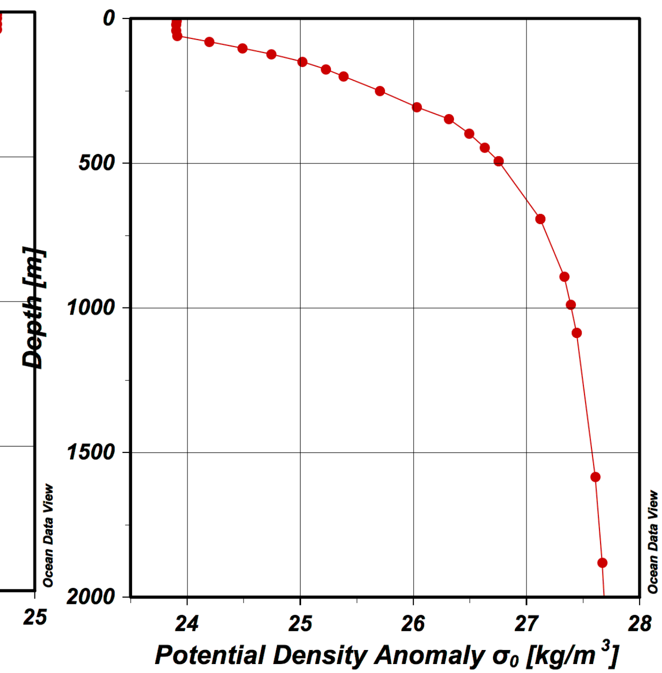

eWOCE
60°N
30°N
EQ
120°E
150°E
180°E
150°W
120°W
90°W
30°S
60°S
Ocean Data View

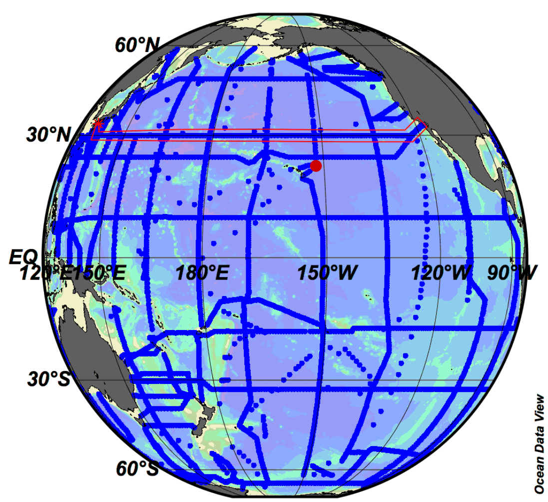

Mixed layer
Thermocline
Deep ocean
Depth [m]
0
500
1000
1500
2000
0
5
10
15
20
25
Temperature [C]
Ocean Data View

Halocline, Thermocline, Pycnocline









Potential density

Adiabatic compression has 2 effects on density:

(1) Changes temperature (increases it)

(2) Mechanically compresses so that molecules are closer together (density increases)

We are usually **NOT** interested in this purely compressional effect on density. We wish to trace water as it moves into the ocean. Assuming its movement is adiabatic (no sources of density, no mixing), then it follows surfaces that we should be able to define. This is actually very subtle because density depends on both temperature and salinity.

Potential density

Sigma-t: This outdated (DO NOT USE THIS) density parameter is based on temperature and a pressure of 0 dbar

$$\sigma_t = \sigma(S, T, 0)$$

Potential density: reference the density σ (S, T, p) to a specific pressure, such as at the sea surface, or at 1000 dbar, or 4000 dbar, etc.

$$\sigma_\theta = \sigma_0 = \sigma(S, \theta, 0)$$

$$\sigma_1 = \sigma(S, \theta_1, 1000)$$

.....

$$\sigma_4 = \sigma(S, \theta_4, 4000)$$

How to calculate potential density

Potential density: reference the density σ (S, T, p) to a specific pressure, such as at the sea surface, or at 1000 dbar, or 4000 dbar, etc.

First compute the potential temperature AT THE CHOSEN REFERENCE PRESSURE

Second compute density using that potential temperature and the observed salinity at that reference pressure.

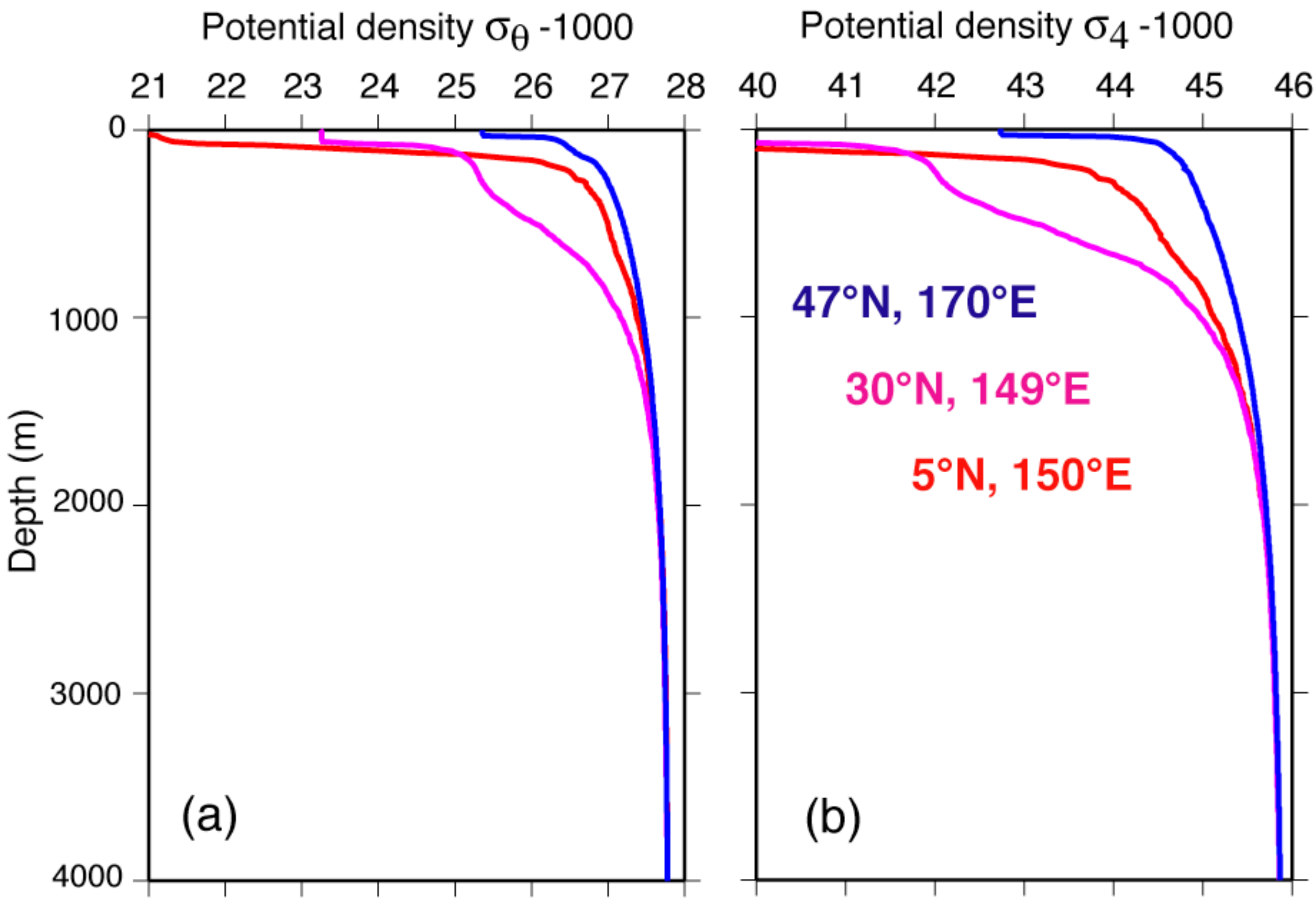
$$\sigma_\theta = \sigma_0 = \sigma(S, \theta, 0)$$

$$\sigma_1 = \sigma(S, \theta_1, 1000)$$

.....

$$\sigma_4 = \sigma(S, \theta_4, 4000)$$

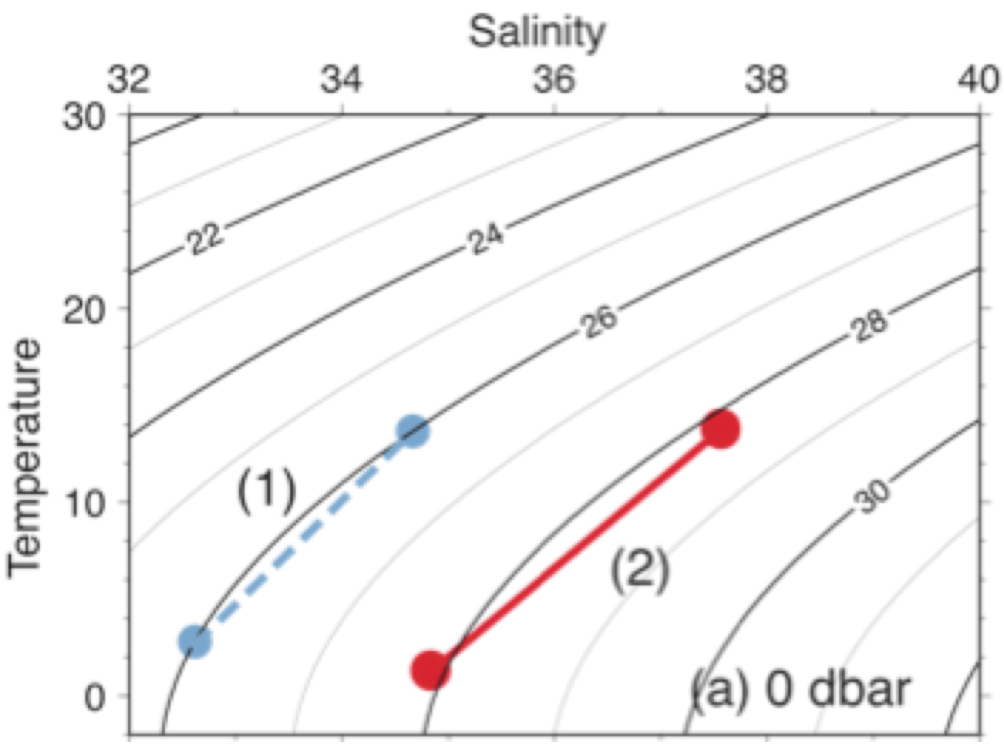
Potential density profiles (σ_θ & σ_4)



DPO Figure 4.17

The T-S diagram

- Plot salinity on x-axis and (potential) temperature on the y-axis.
- The line of constant density forms a contour line.



Assume you have two water mass with distinct (T,S) properties and you **mix** the two types of waters. The product of mixing is expected stay on the straight line in the T-S diagram.
→ Conservative tracer

Conservative or non-conservative?

- **Non-conservative properties** are not conserved following the circulation in the interior (subsurface) ocean
  - Nutrients, oxygen, carbon (biological sources/sinks)
  - Temperature
  - Density

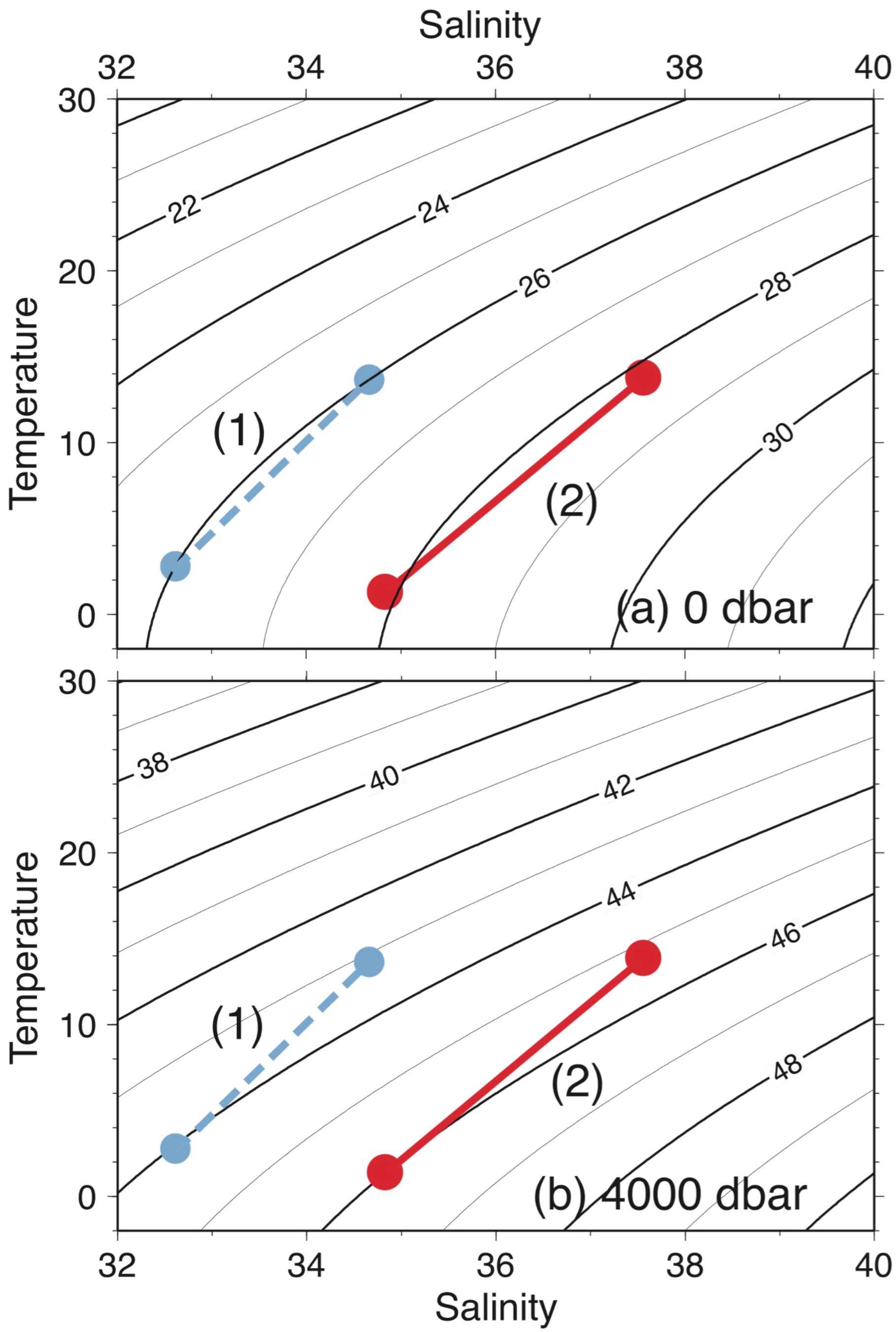
- **Conservative properties**
  - Salinity
  - Potential temperature
  - Potential density

An important nonlinearity for the EOS

- Cold water is more compressible than warm water (thermobaricity)

- At cold temperature, density is more sensitive to salinity variation.

- Density contour in T-S space has curvature. (see next slide). This curvature becomes flatter at higher pressure.



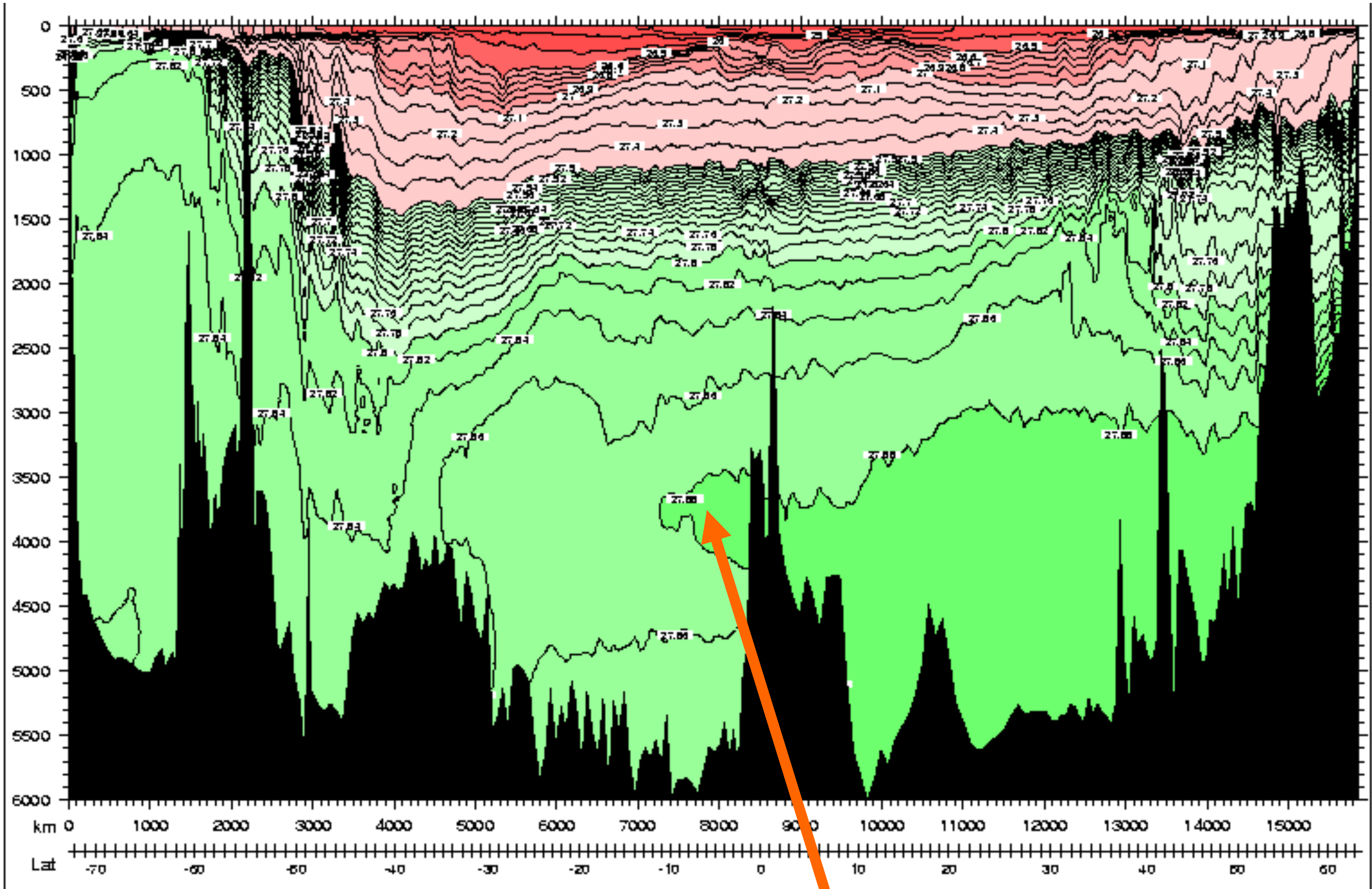
Potential density relative to 0 dbar and 4000 dbar

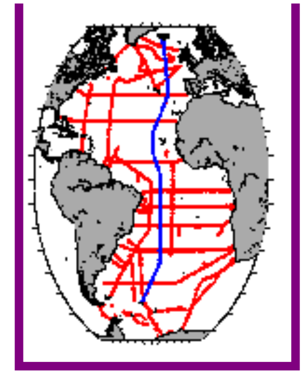
Cabbeling: Mixture of 2 different (compensating T,S) waters with the same density can lead to a different density

Thermobaricity: The density contours are flatter at 4000dbar. The combination of (S,T) having equal density at surface (0 dbar) will have different density at depth.

DPO Figure 3.5

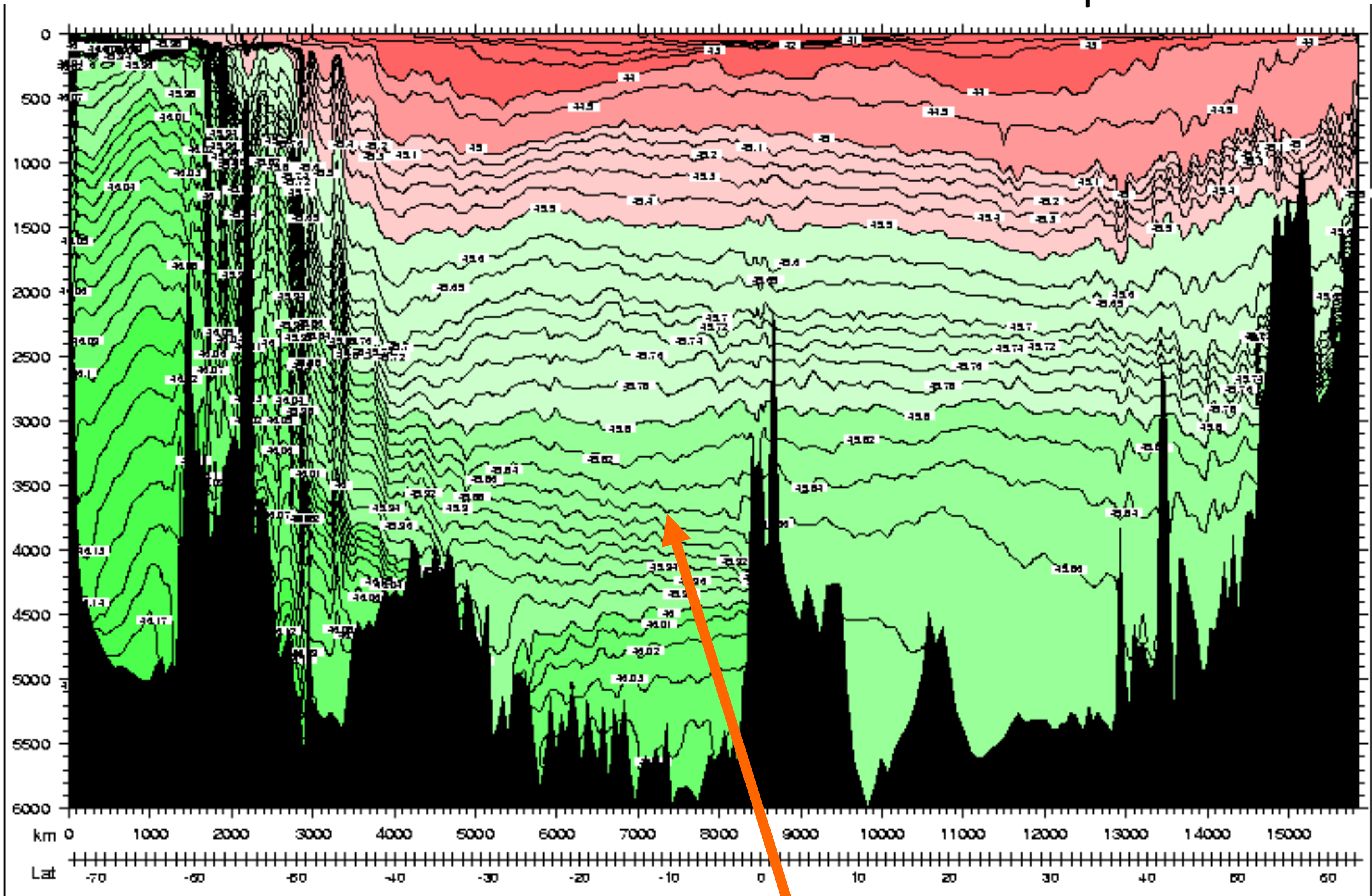
Atlantic section of potential density referenced to 0 dbar (σ_θ)

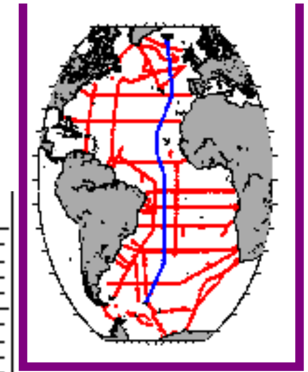




Note deep potential density inversion - need to use deeper reference pressures to show vertical stability

Atlantic section of potential density referenced to 4000 dbar: σ_4





Potential density σ_θ inversion vanishes with use of deeper reference (σ_4): in fact, extremely stable!!

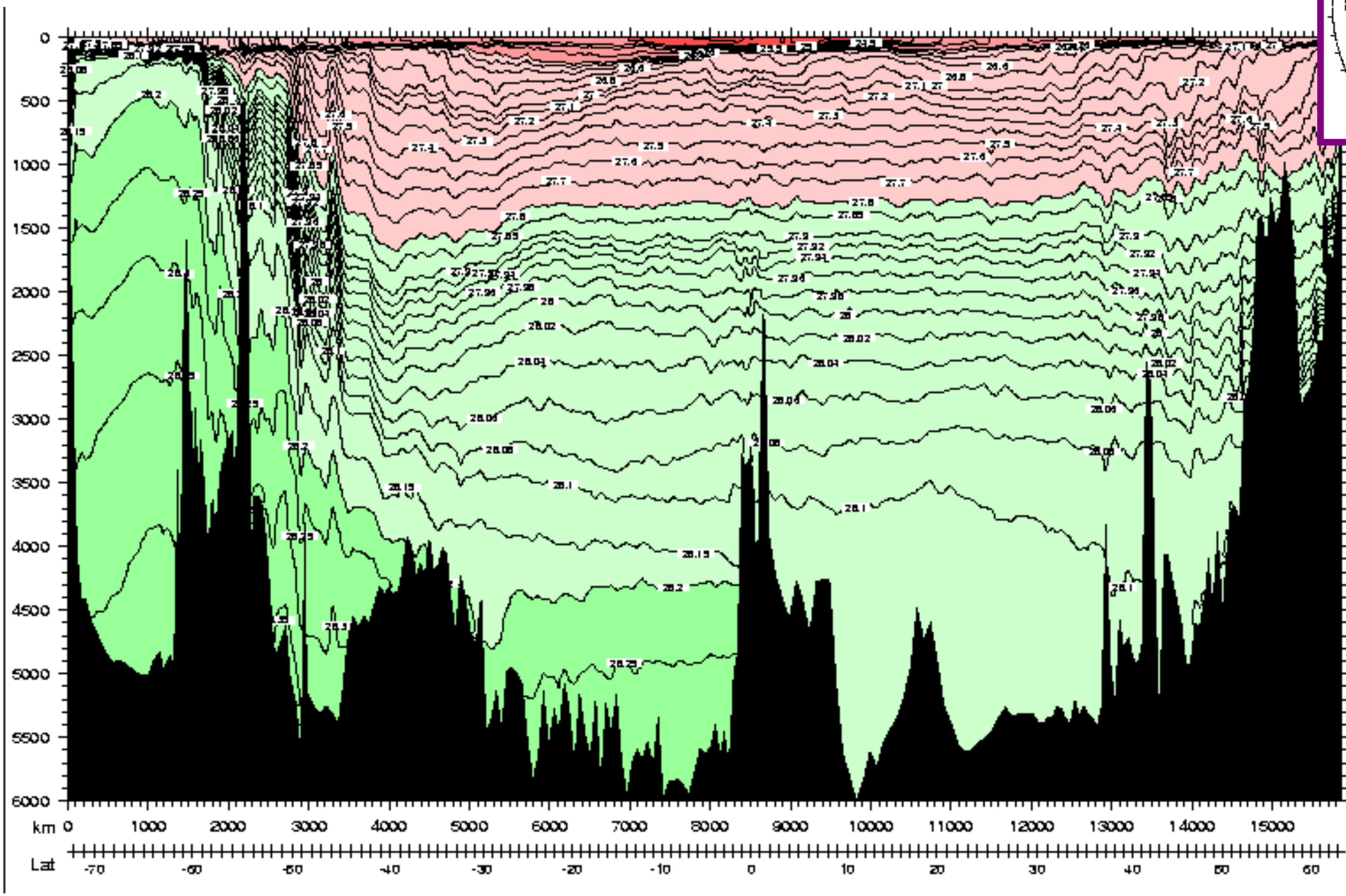
Neutral density γ^n

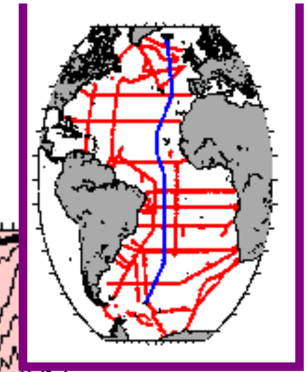
- To follow a water parcel as it travels down and up through the ocean:
- Must change reference pressure as it changes its depth, in practical terms every 1000 dbar

- Neutral density provides a continuous representation of this changing reference pressure. **(Jackett and McDougall, 1997)**

Isopycnal = Surfaces of constant potential density (σ_θ, σ_1, σ_2, …)
Isoneutral = Surfaces of constant neutral density (γ_n)

Atlantic section of "neutral density": γ^n





Isopycnal analysis: track water parcels through the ocean

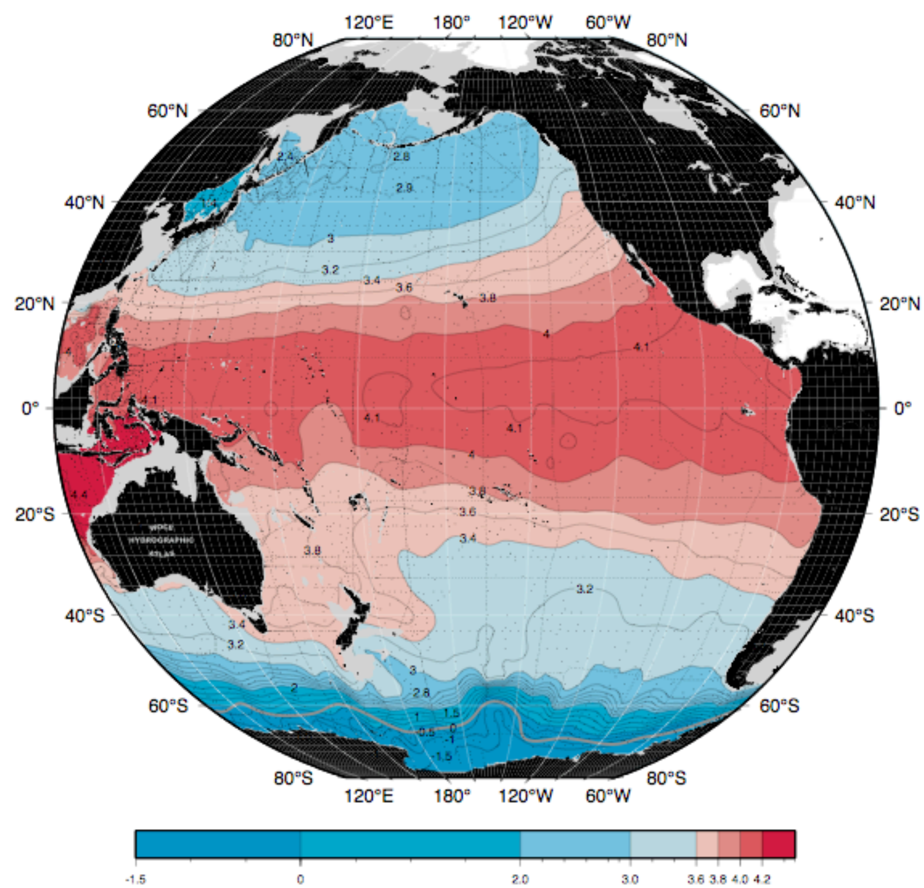
- Seawater move mostly adiabatically (isentropically). Mixing with parcels of the same density is much easier than with parcels of different density because of ocean stratification

- Use isopycnal (surface of constant potential density) surfaces to evaluate the transport of tracer properties (S, chemical tracers…)

Deep isopycnal surface in the Pacific Ocean

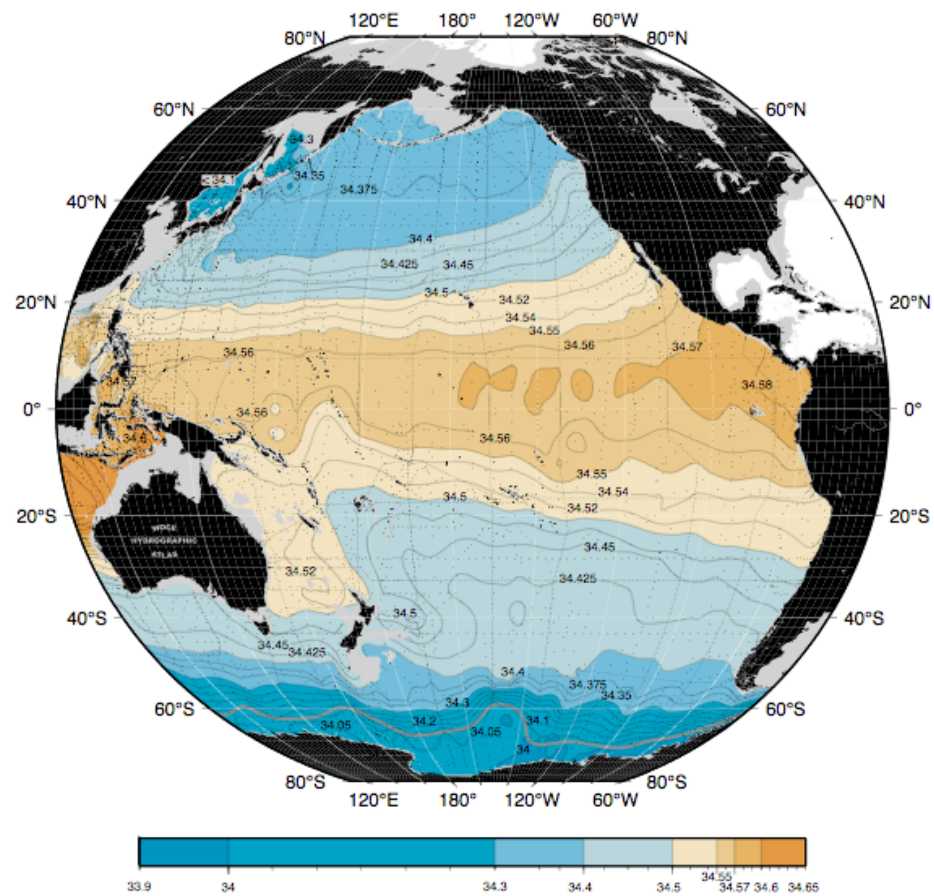
Potential temp.

Potential temperature (°C) 27.6 γ^n (kg/m^3)



Salinity

Salinity (PSS78) 27.6 γ^n (kg/m^3)

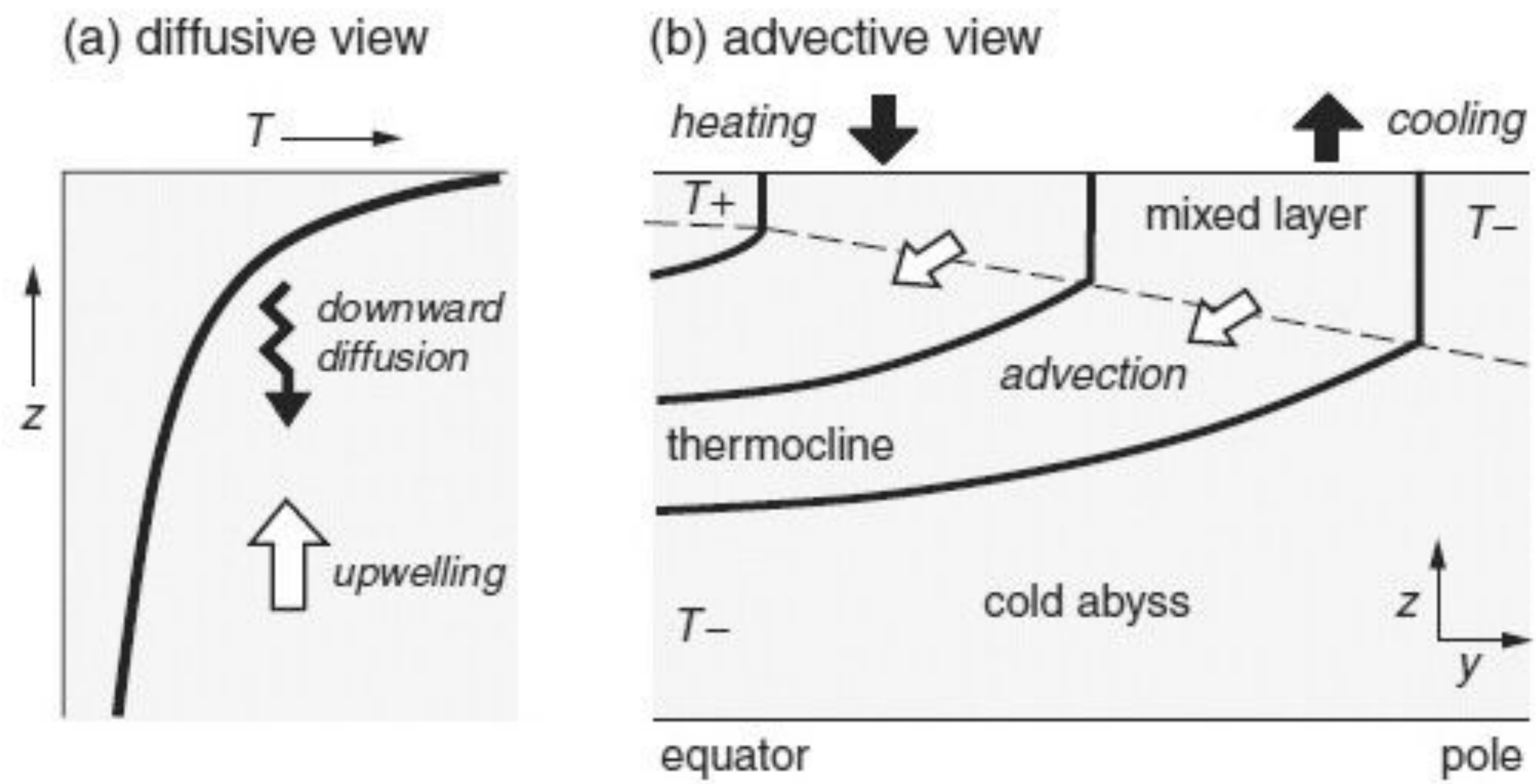


WHP Pacific Atlas (Talley, 2007)

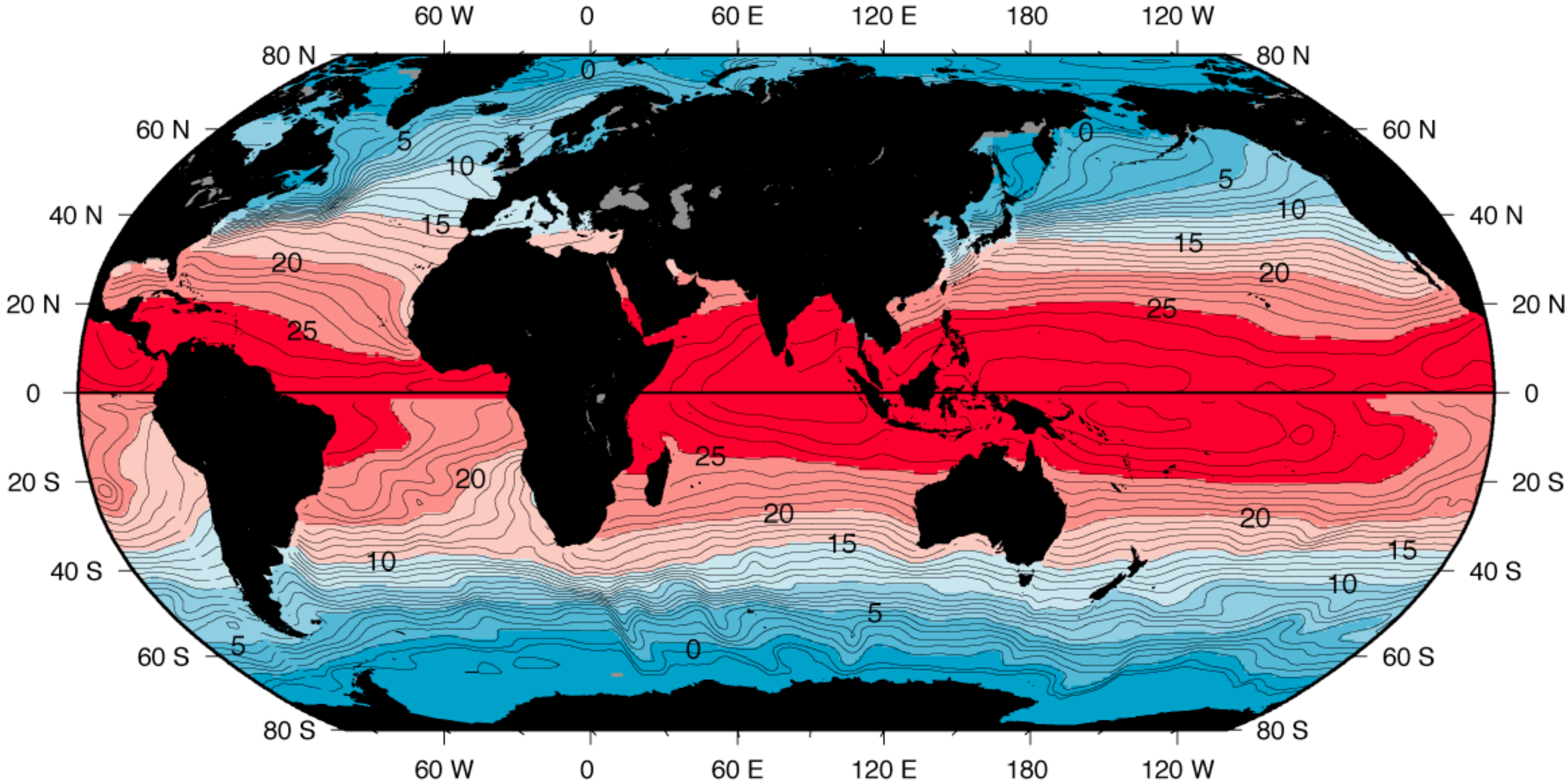
Ocean stratification and water masses

- Ocean is stratified → potential density increases with depth.
- The potential density can become a vertical coordinate. The advantage of using density coordinate is that the sea water tends to mix with waters that have the same density. The oceans can be viewed as stratified layers of density surfaces that has distinct physical and chemical properties, often originating from different formation regions → such body of waters are called "water mass(es)".

What controls the stratification?

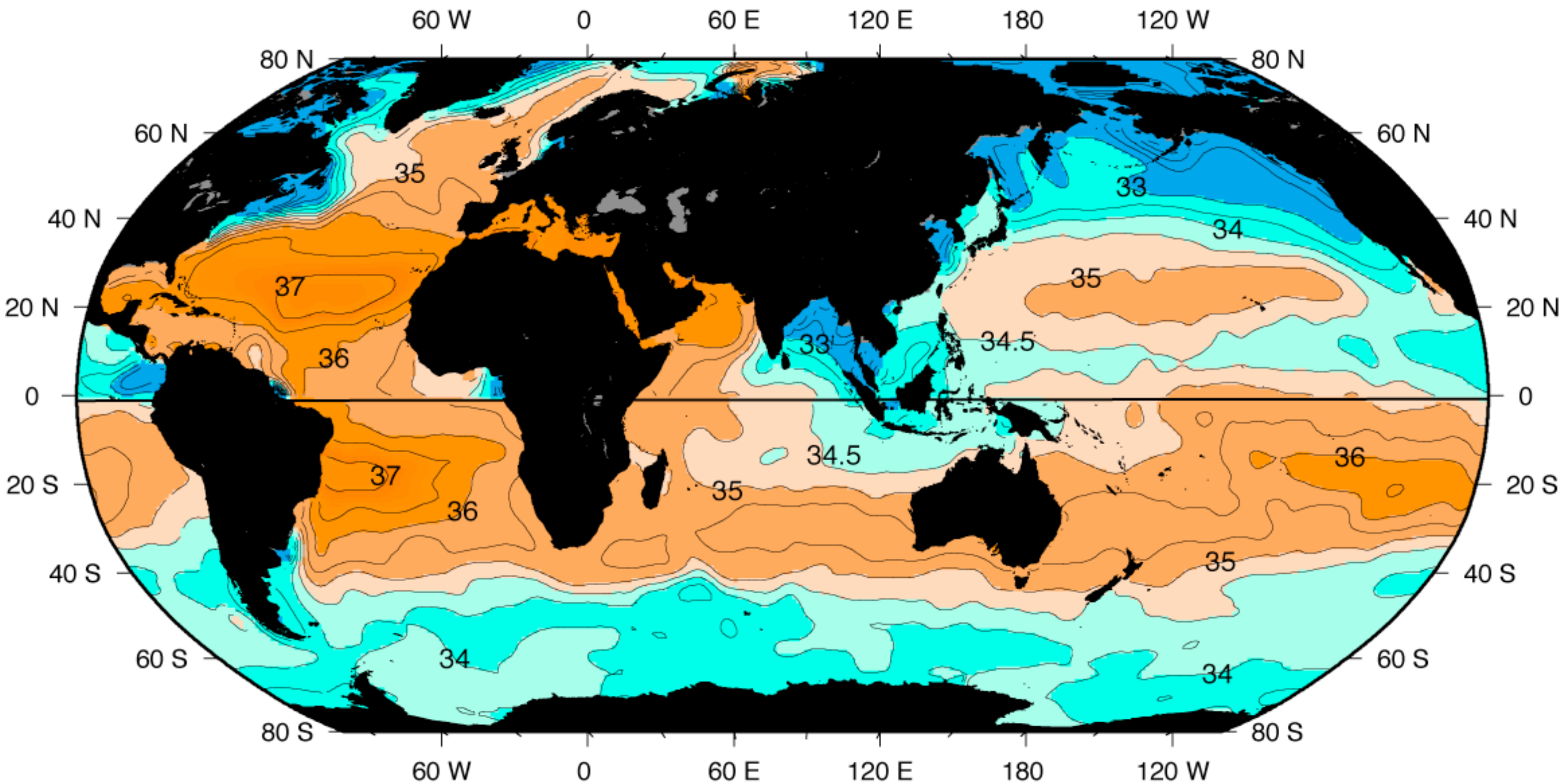


Surface temperature: note where the 4°C isotherm occurs (most ocean volume is colder than this)



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

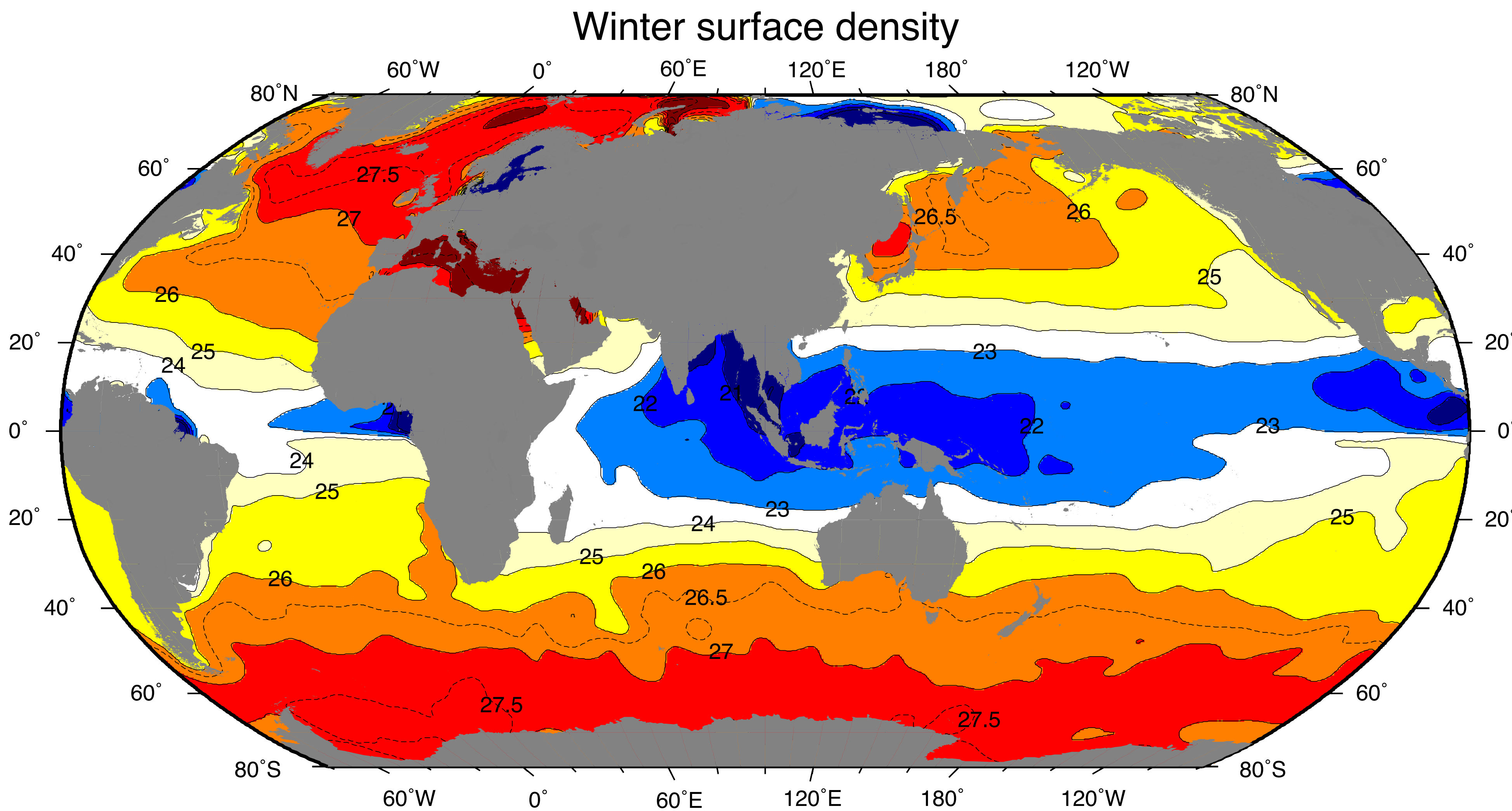
Surface salinity



Surface salinity (psu) in winter (January, February, and March north of the equator; July, August, and September south of the equator) based on averaged (climatological) data from Levitus et al. (1994b).

DPO Fig. 4.15

Surface density (winter)



Surface density σ_θ (kg m^{-3}) in winter (January, February, and March north of the equator; July, August, and September south of the equator) based on averaged (climatological) data from Levitus and Boyer (1994) and Levitus et al. (1994b).

DPO Figure 4.19

Review question

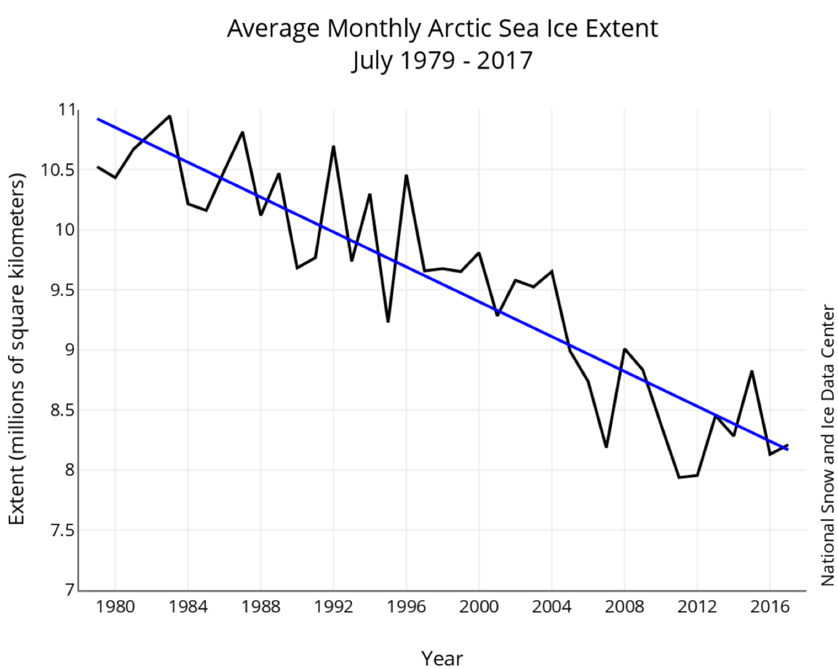
- How much pressure increase do you expect for a 1m depth increase?
- What controls the density of the seawater?
- What is the temperature of the densest water with S=0 and S=35 at the surface pressure?

Review questions

- What happens to the melting point of ice under high pressure?
- What causes the ”brine rejection”?
- What are the impacts of brine rejection on the deep circulation?

Measuring seaice thickness from space

- Summertime Arctic seaice has been declining, documented by the satellite imagery since late 1970s



- But, knowing the seaice extent is not enough to determine the mass balance.
- Thickness change is crucial for the calculation of total ice loss.
- Before 2000s, some observations exist from the Navy's submarine data.
- After 2003, satellite radar altimetry provides seaice thickness estimates (ERS-1, ICEsat, CryoSat-2)

Measuring seaice thickness from space

- Kwok (2010) J. Glaciology

Radar altimeter can measure the height of the sea surface, and freeboard ice height. Isostatic calculation will give the total thickness of the seaice.

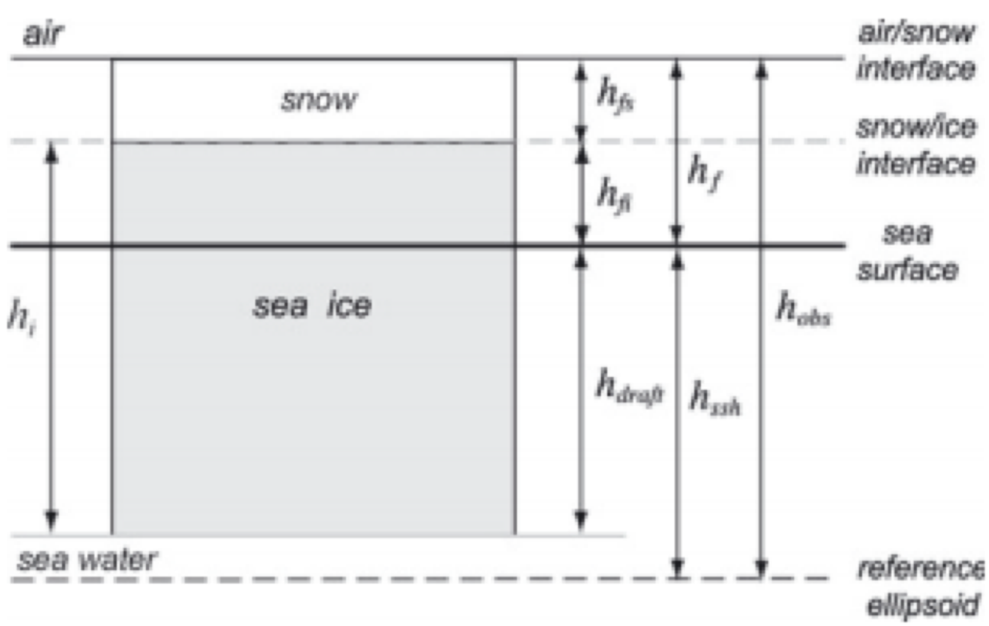
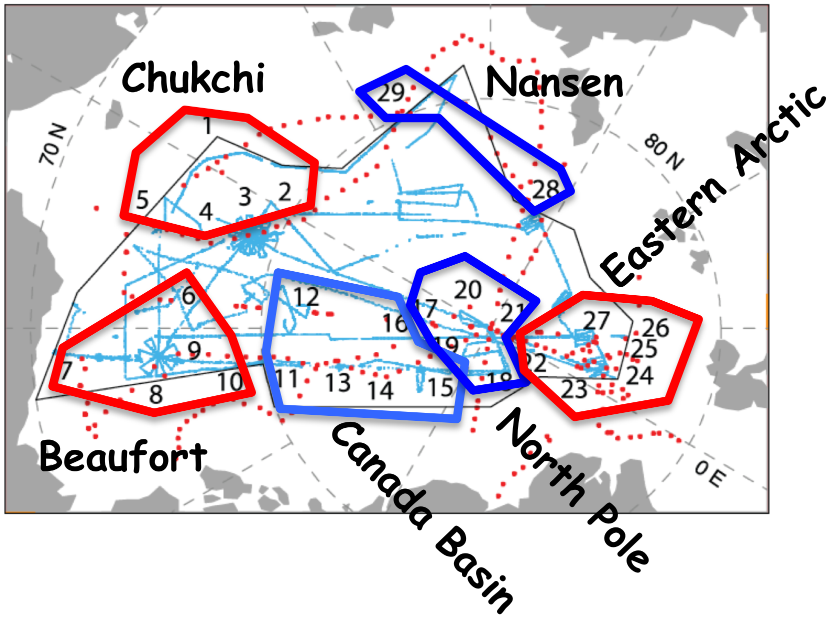
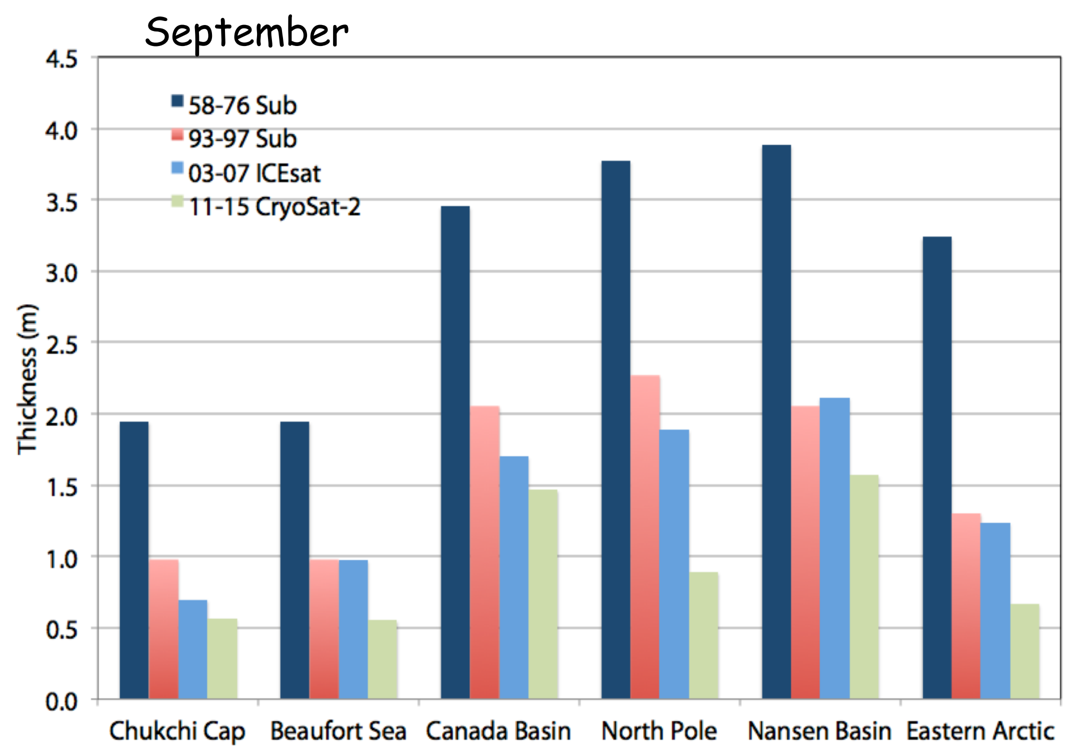


Fig. 1. Geometric relationships between snow depth, sea-ice freeboard, draft and thickness.

A major source of uncertainty is the thickness of the snow layer on top of the seaice.

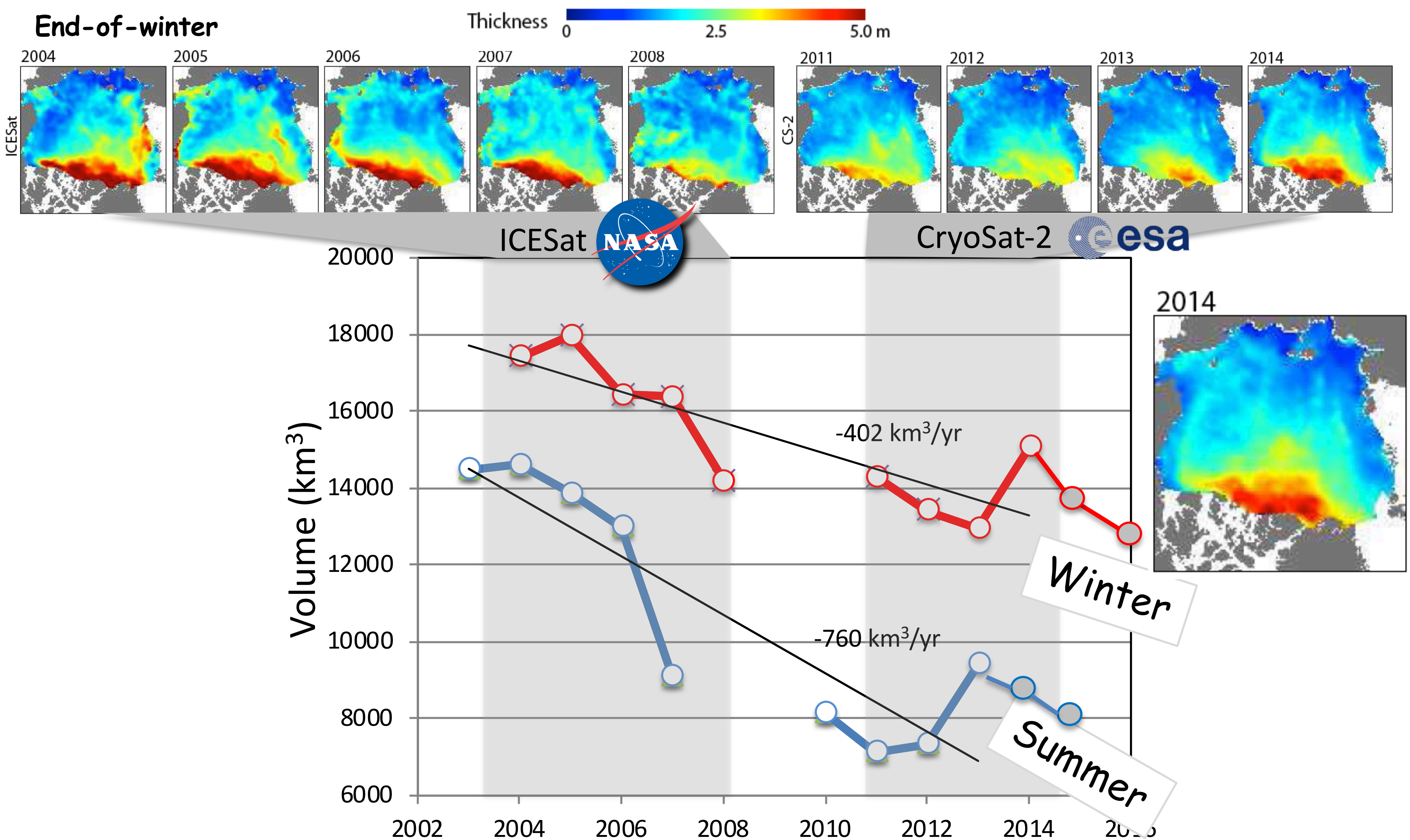
Thinning of Arctic seaice





R. Kwok, 2017

Decline of Arctic sea ice volume



Kwok and Cunningham (2015)

Review questions

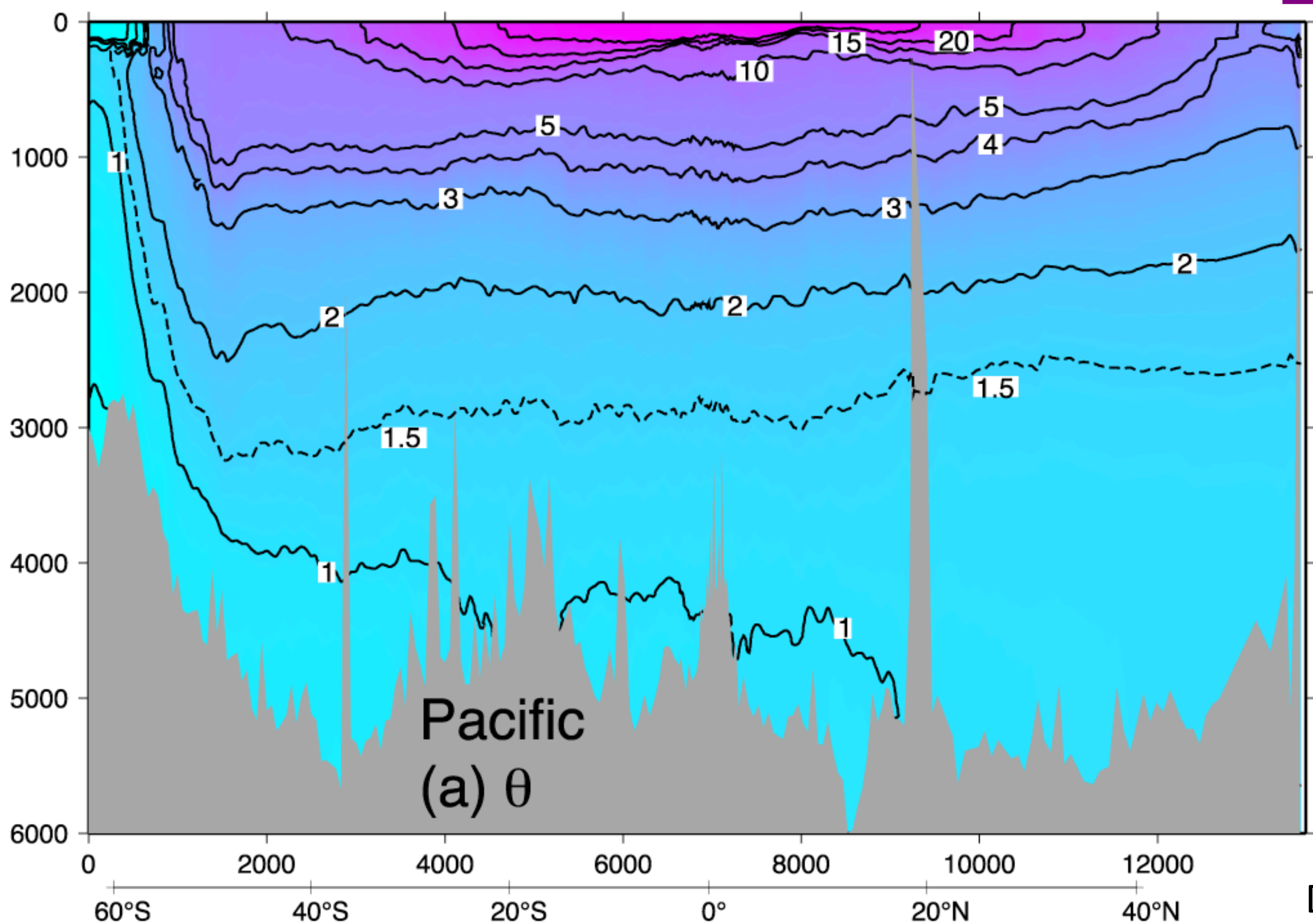
- What is the Thermodynamic Equation Of State (TEOS) of seawater?

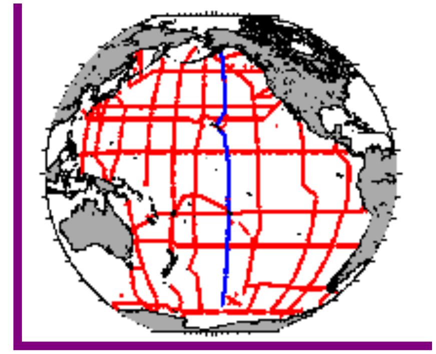
- What is the meaning of nonlinearity in the equation of state?

Review questions

- Imagine density contours in the T-S diagram. What are the effects of nonlinearity?
- Cold water is more compressible than warm water. What is the term used to explain this effect?
- What are the 3 major regions of the water column based on its temperature profile?

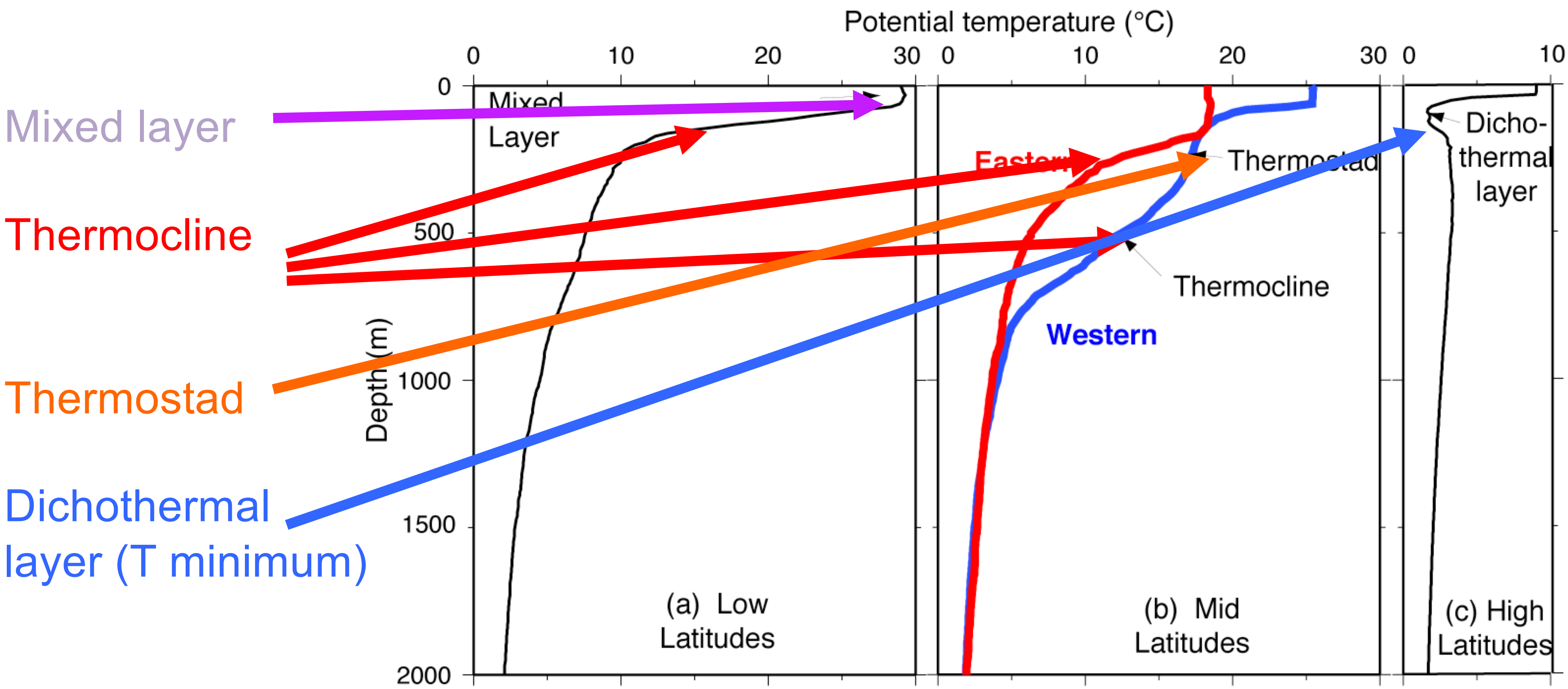
Pacific potential temperature section





DPO Fig. 4.12a

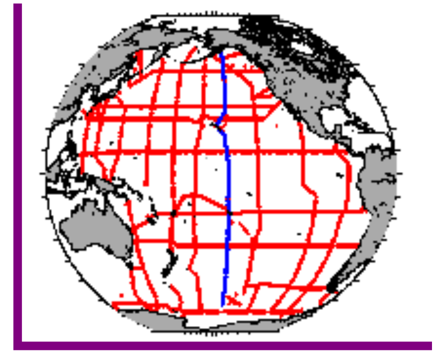
1. Definitions: vertical structures (temperature)



Typical North Pacific profiles

DPO Figure 4.2

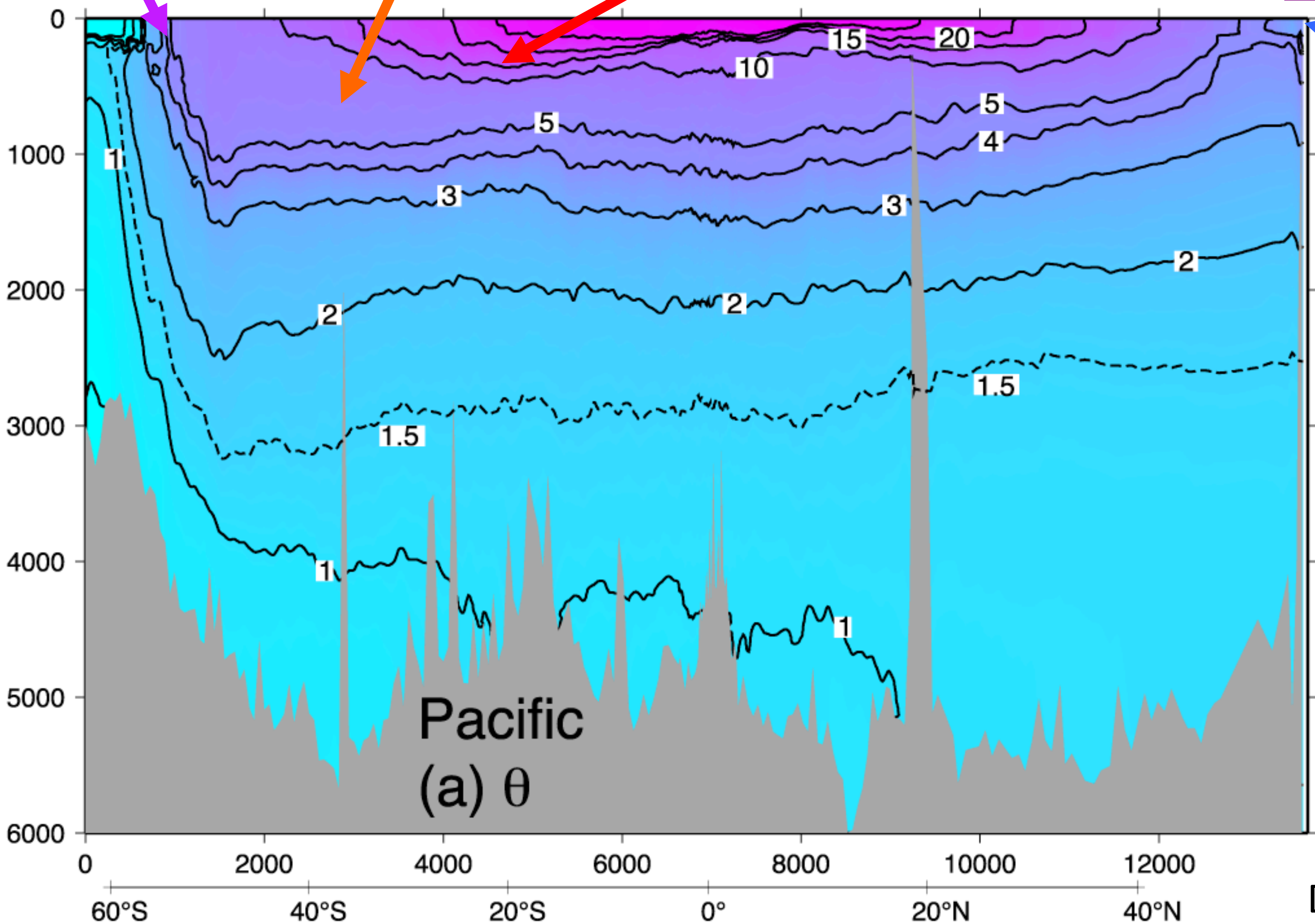
Pacific potential temperature section



Mixed layer

Thermostad

Thermocline



Dichothermal layer (T minimum)

DPO Fig. 4.12a

Water masses

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

A water mass has

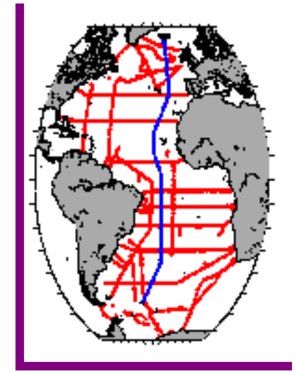
an identifiable property (usually an extremum of some sort)

an identifiable formation process

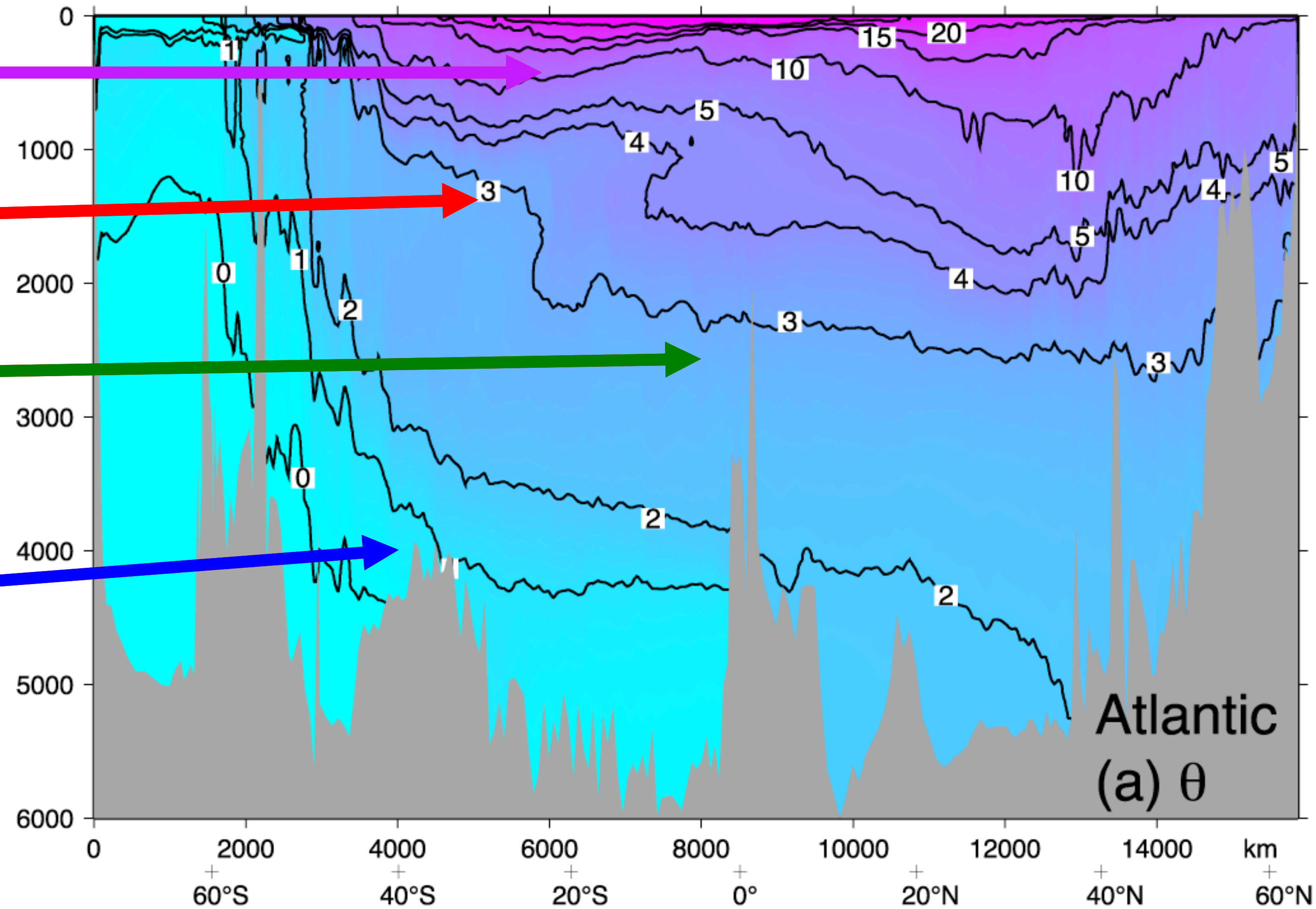
Water type: point on a temperature-salinity diagram (this can include additional properties such as nutrients)

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

Atlantic vertical section: overall vertical structure

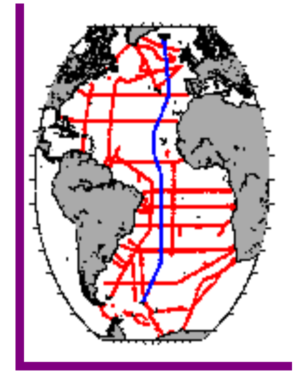


1. Upper
2. Intermediate
3. Deep
4. Abyssal

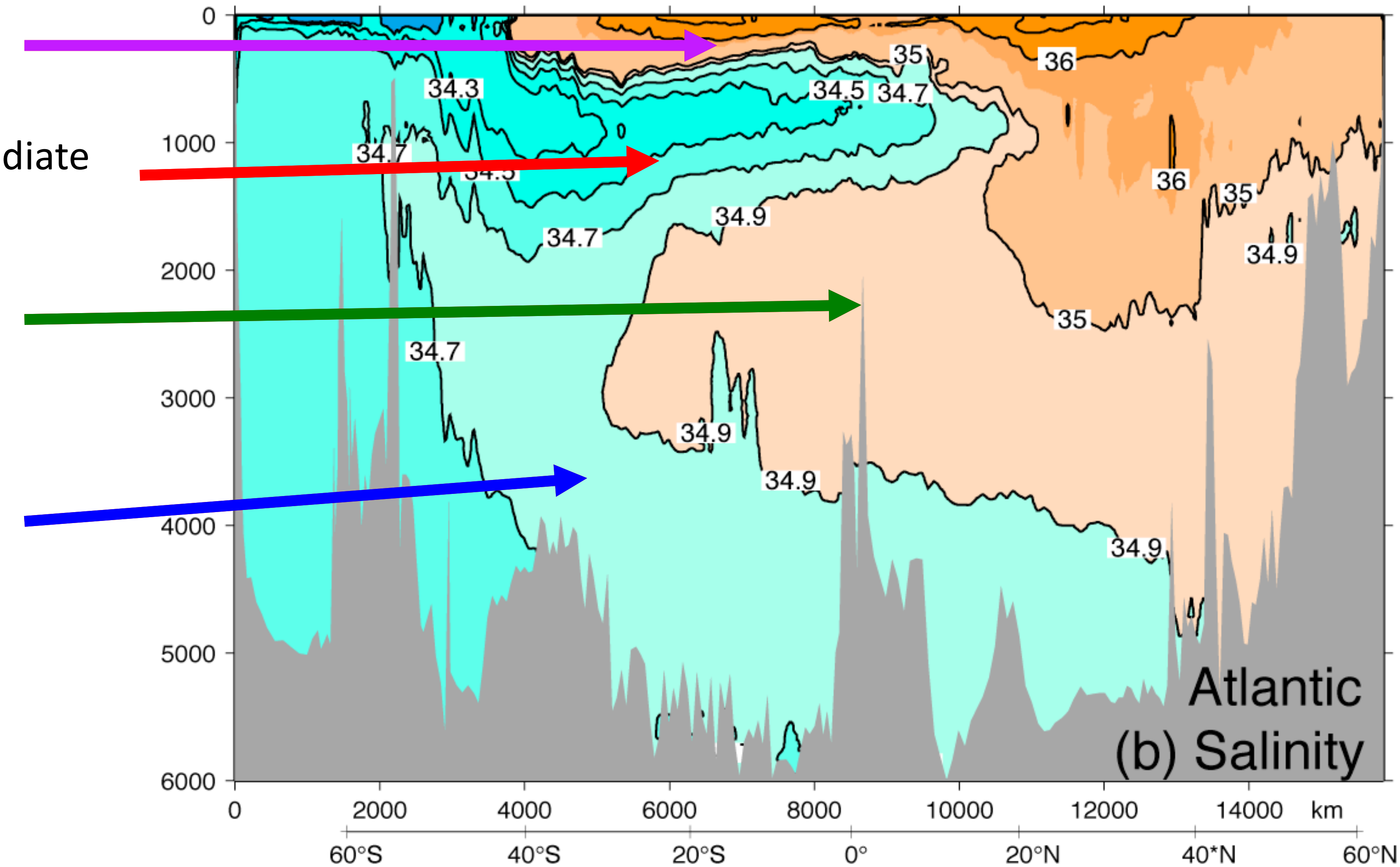


DPO Fig. 4.11

Atlantic vertical section: overall vertical structure



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



DPO Fig. 4.11

Upper ocean

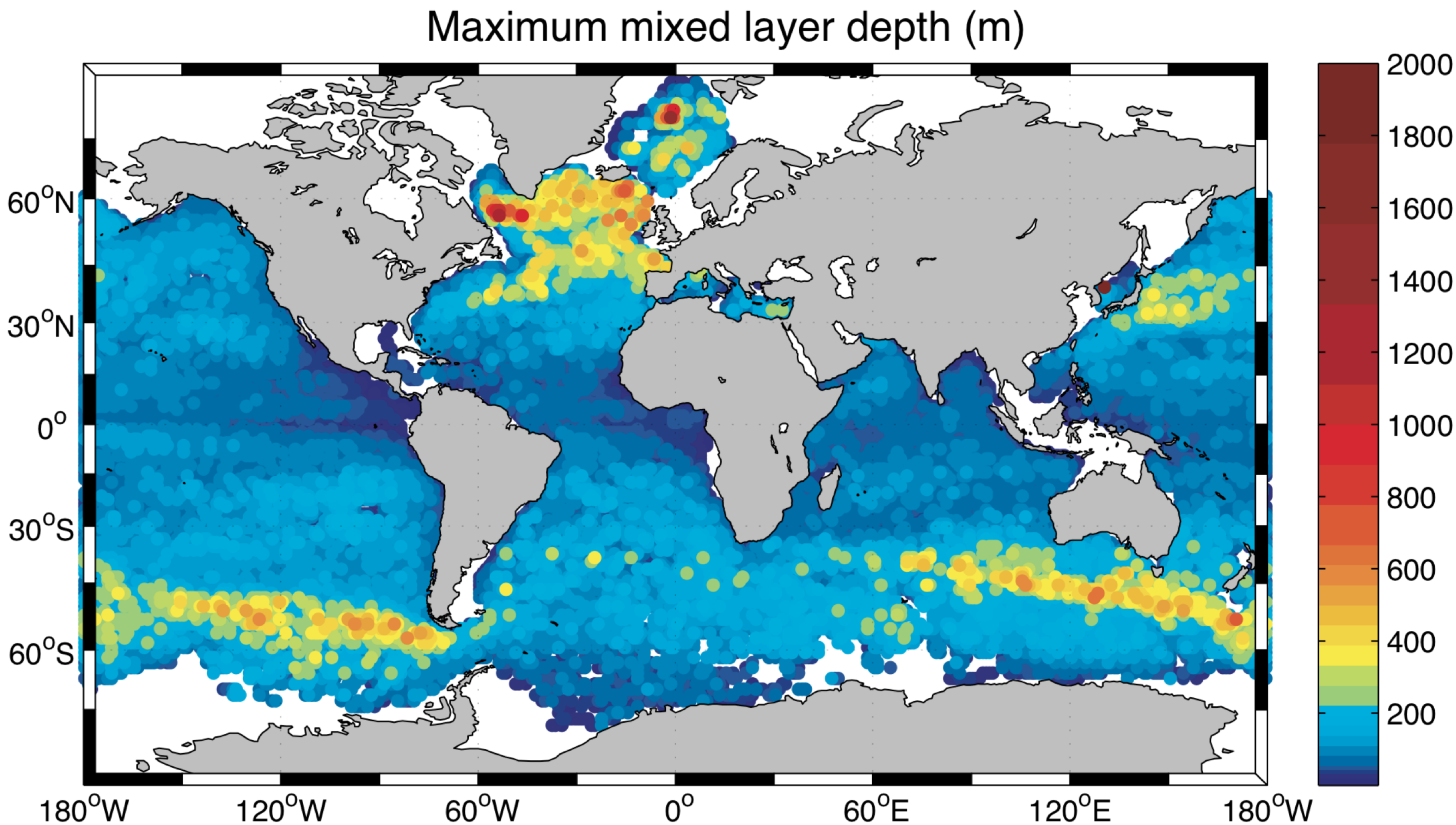
Characterization: Surface mixed layer down through the main pycnocline.

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). “Central Water”

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

Mixed layer depth

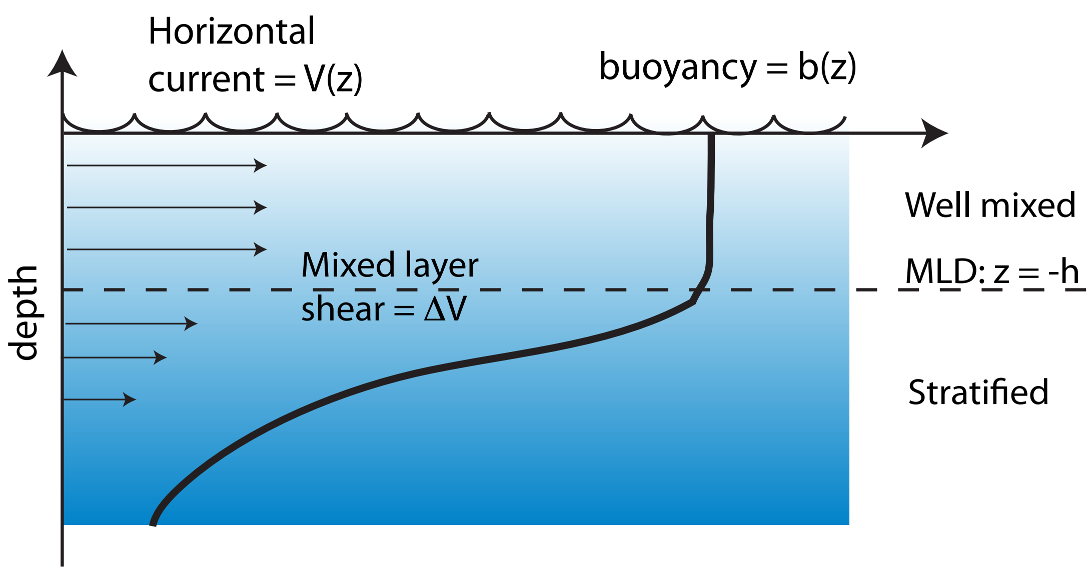


Typically 20 to 200 m (late winter)
Thicker (> 500) in some special locations, notably in
(1) band in the Southern Ocean and (2) northern North Atlantic

DPO Fig. 4.4c from Holte et al

What drives the turbulence in the mixed layer?

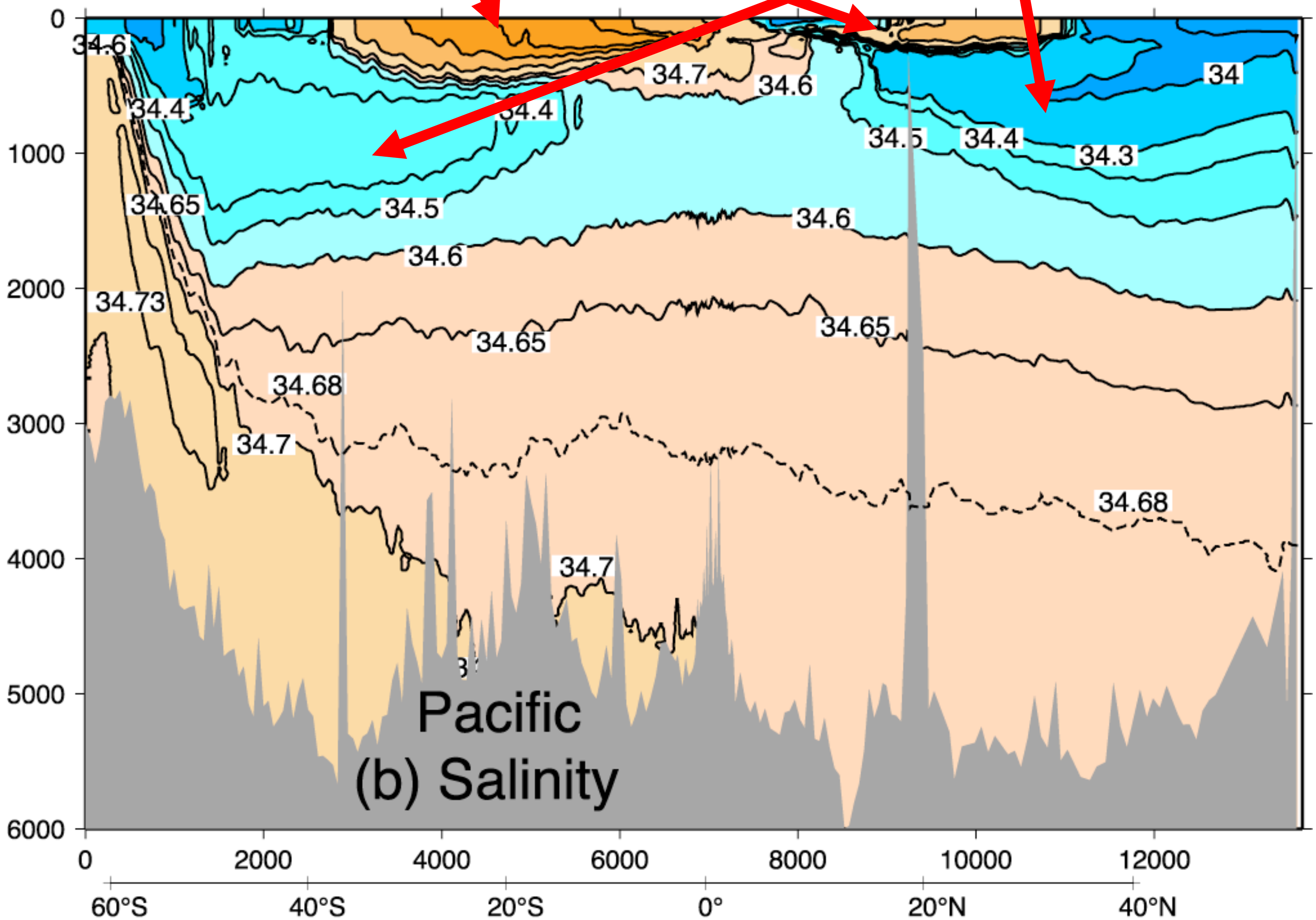
- Heat loss and convection (buoyancy effect)
- Atmospheric wind (mechanical effect)

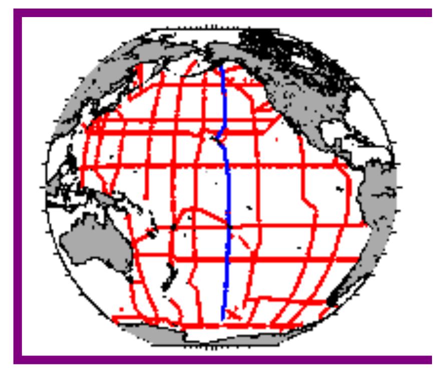


Pacific salinity vertical section

Salinity maximum layers

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



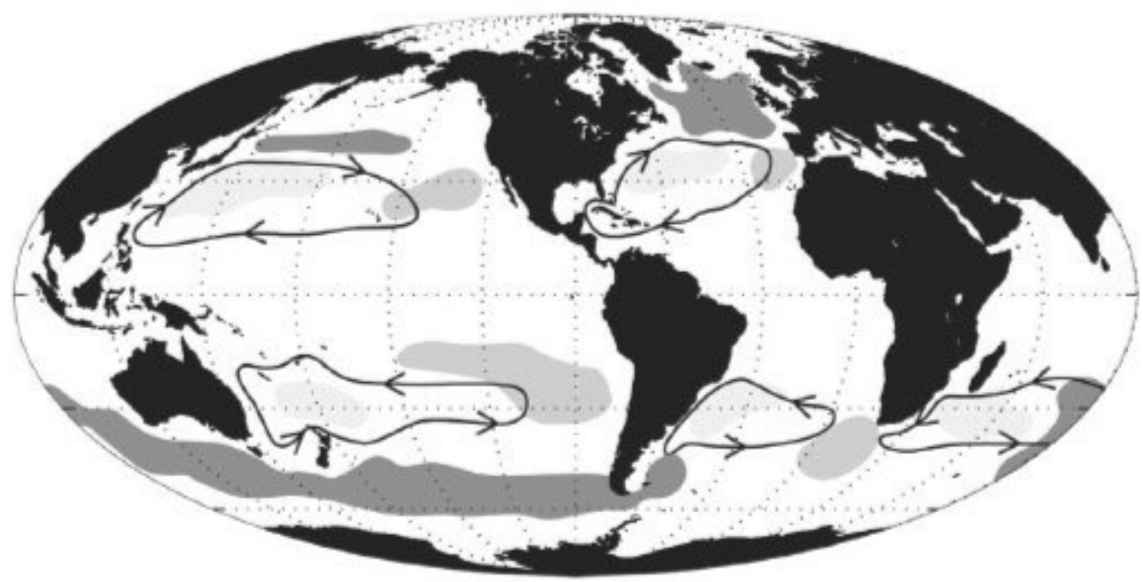


DPO Fig. 4.12b

Subtropical Mode Waters (STMW)

- "The 18-degree Water" in the North Atlantic
- Major thermocline water mass
  - Exists in all major basins forming "pycnostad"
  - Subtropical origin, relatively high S and T
  - Depth range: 200 – 600m

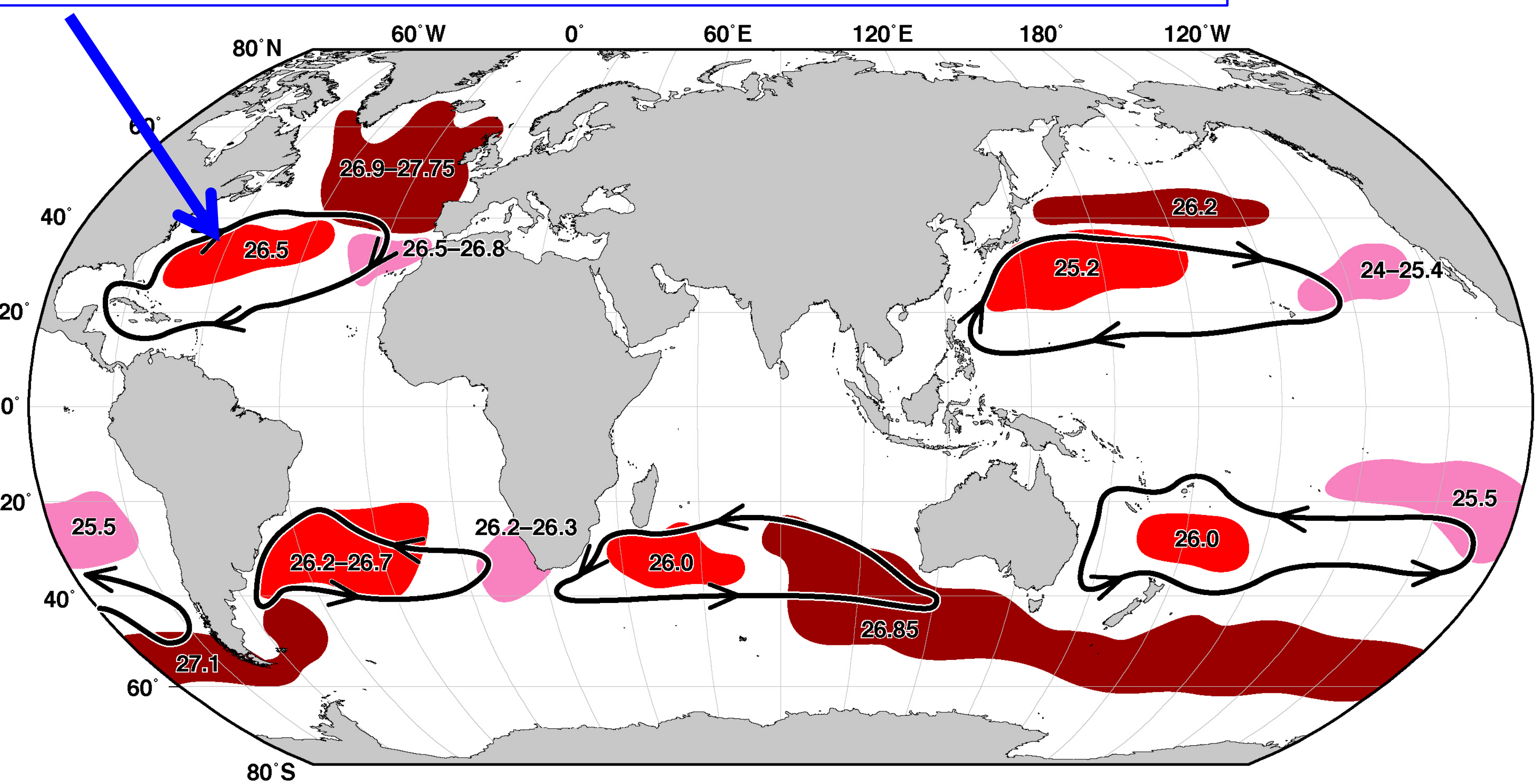
(a) subtropical mode waters



Global Mode Waters

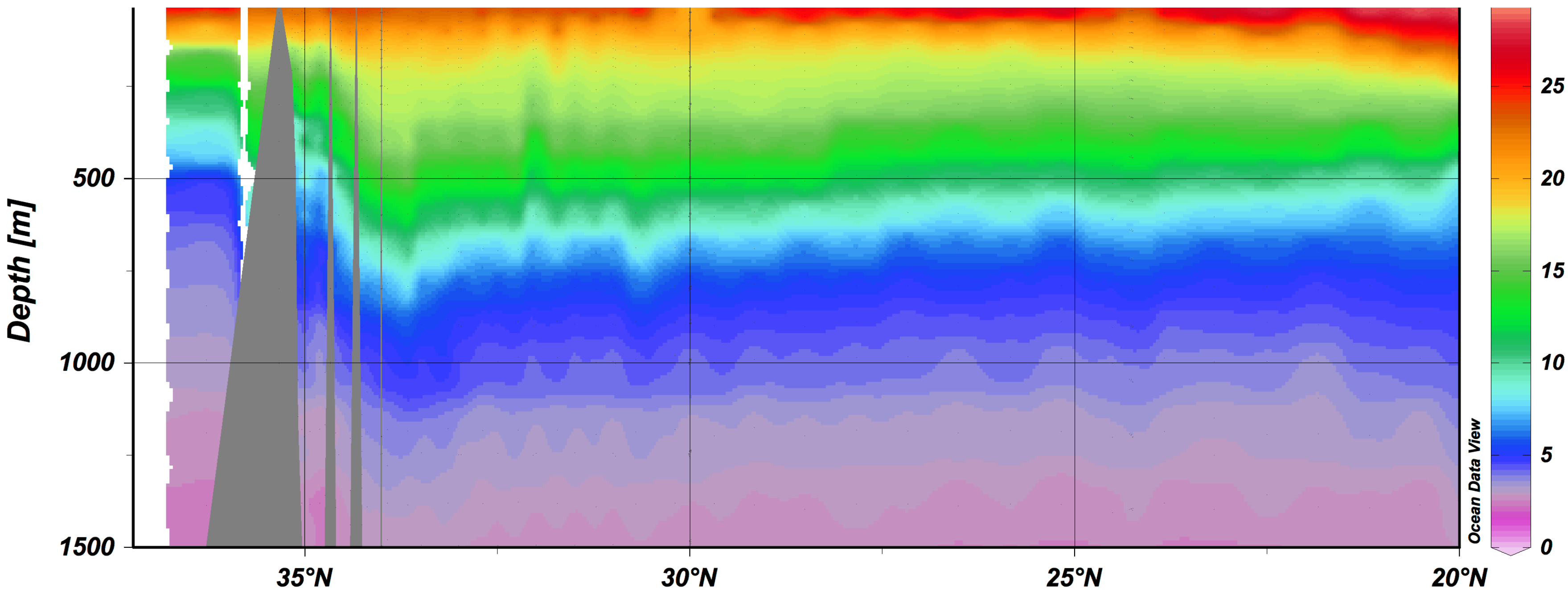
Location of especially strong, permanent thermostads/pycnostads - derived from thick winter mixed layers that then spread into the interior along isopycnals (subduct)

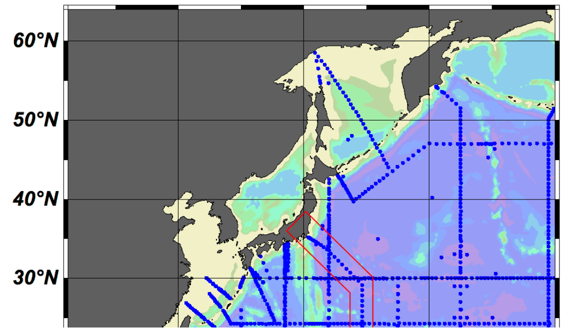
Gulf Stream's Eighteen Degree Water (Subtropical Mode Water of the North Atlantic) from previous slide



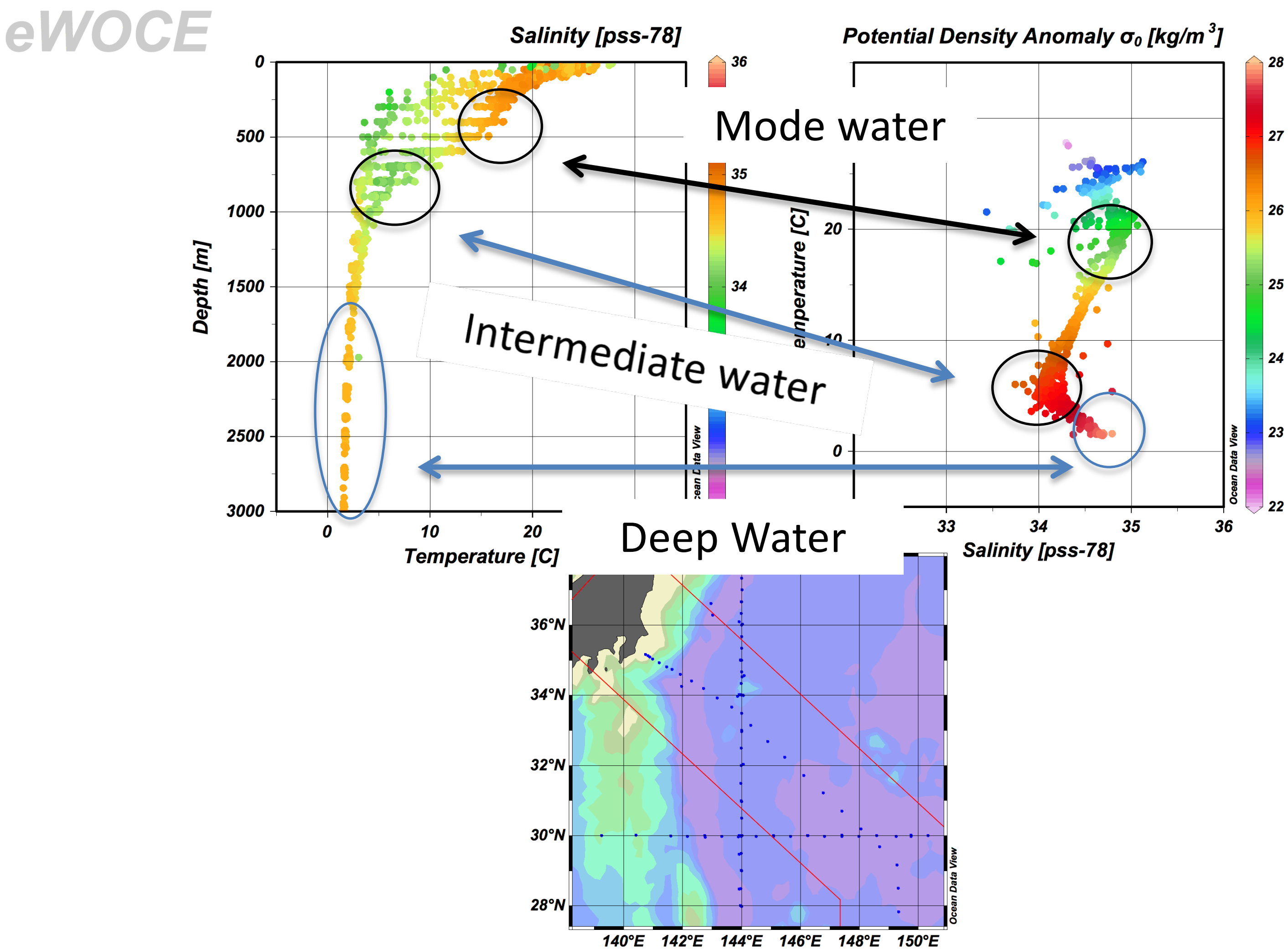
Hanawa and Talley (2001); DPO 14.12

An example: Kuroshio





Mode Water in the North Pacific

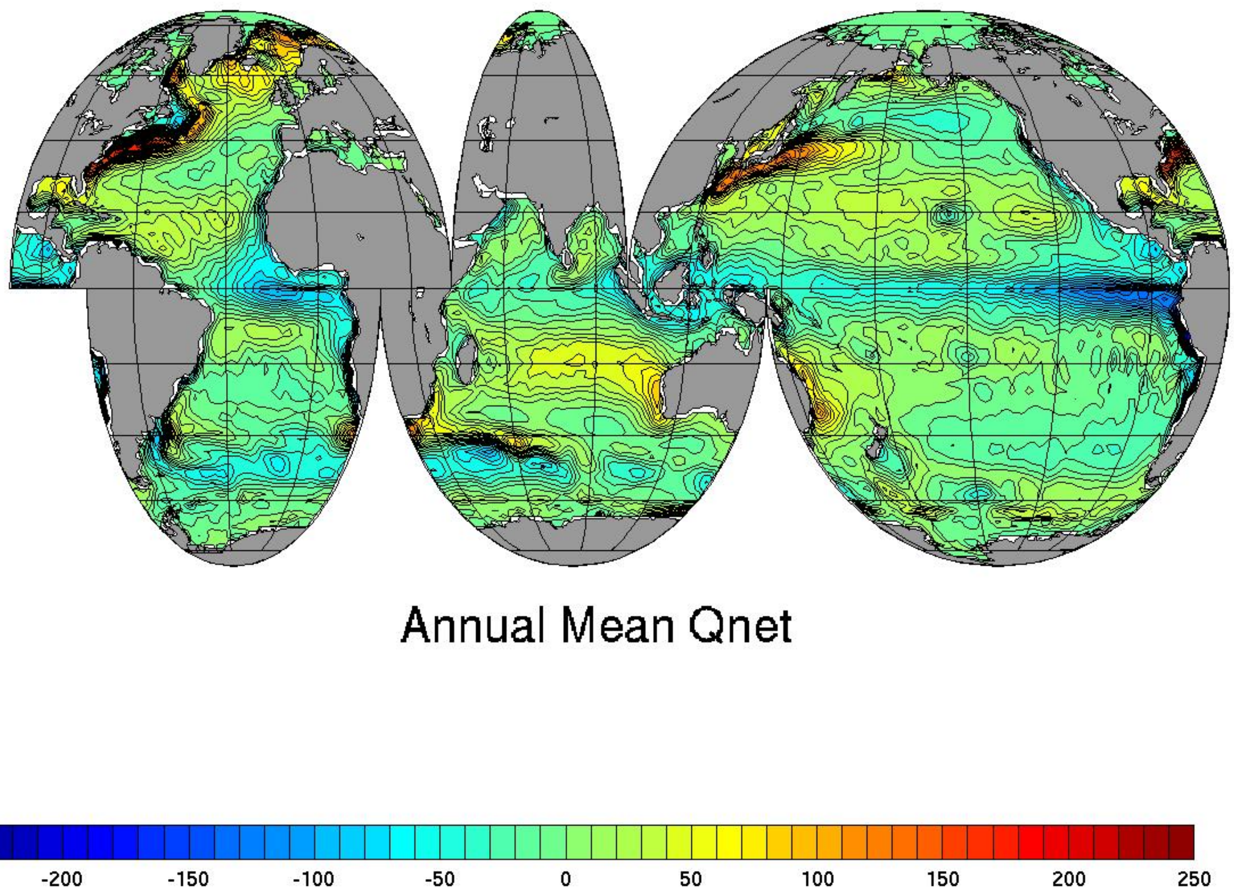


What regulates the mode water formation?

- Winter-time cooling
- Heat flux components: Q [W/m^2]
  - Q_{SW}: Short-wave radiation
  - Q_{LW}: Long-wave radiation
  - Q_{SH}: Sensible heat flux
  - Q_{LH}: Latent heat flux

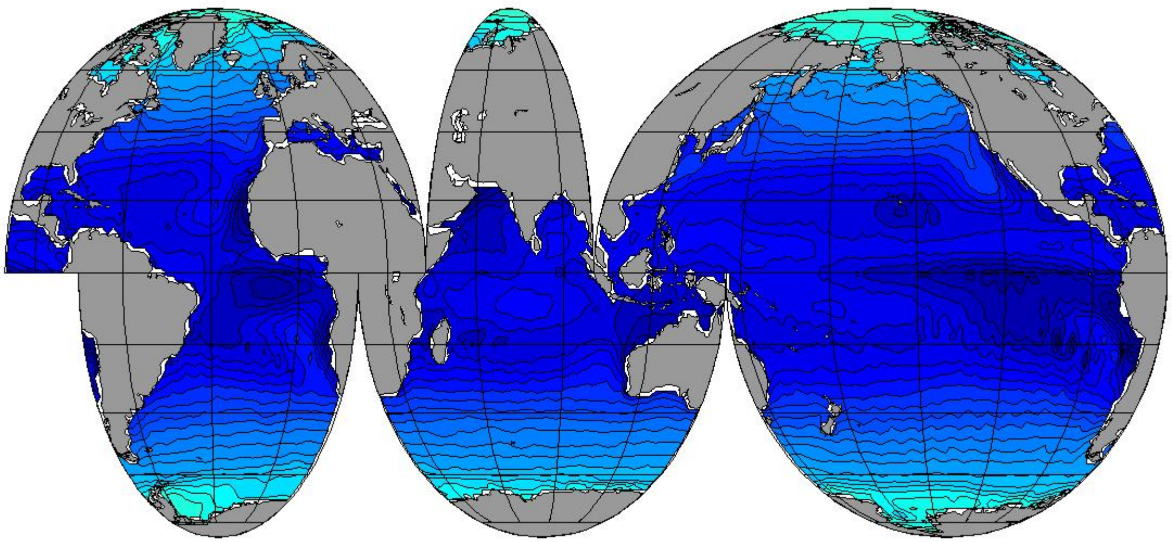
Net air-to-sea heat flux

- Sum of the four components
  - NCEP Reanalysis climatology 1968-1996
  - Upward positive (positive into the atmosphere)

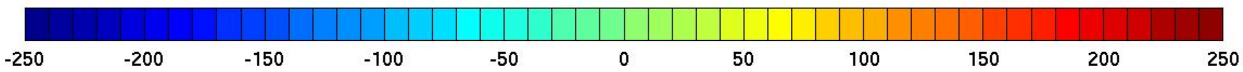


Shortwave radiation

- NCEP-Reanalysis
  - Climatology 1968-1996
  - Upward positive (positive into the atmosphere)

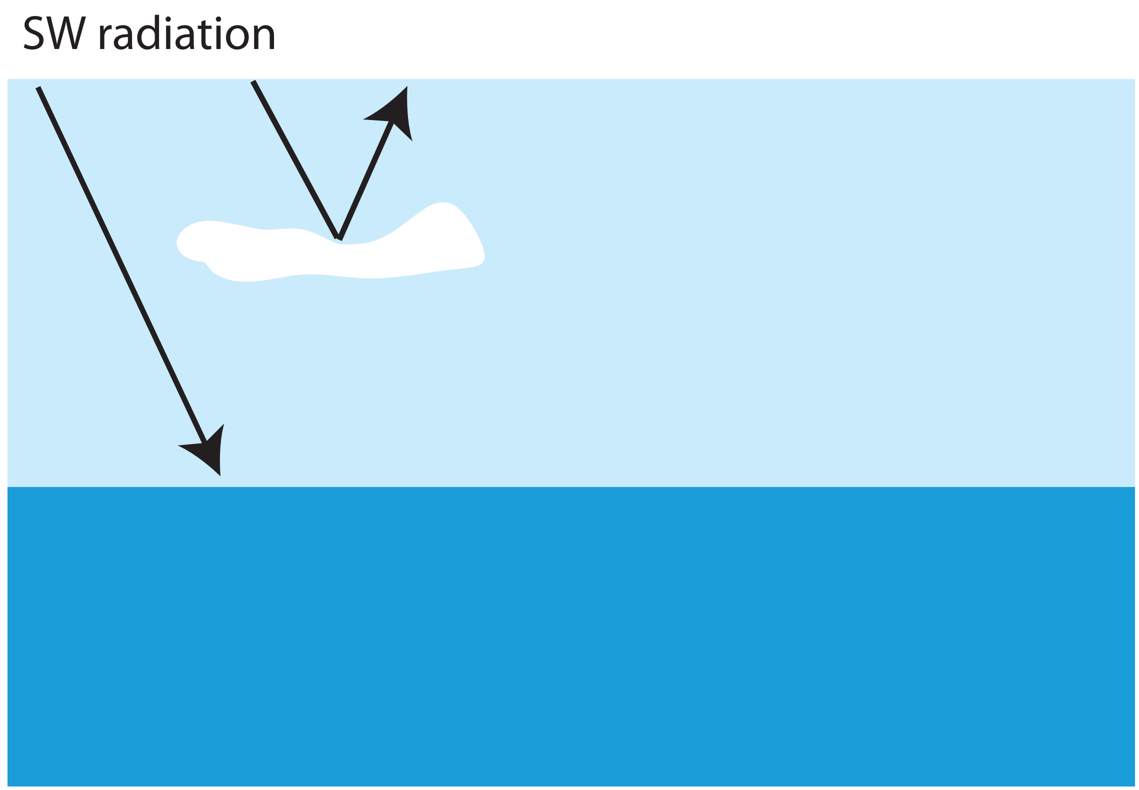


Annual Mean Qsw



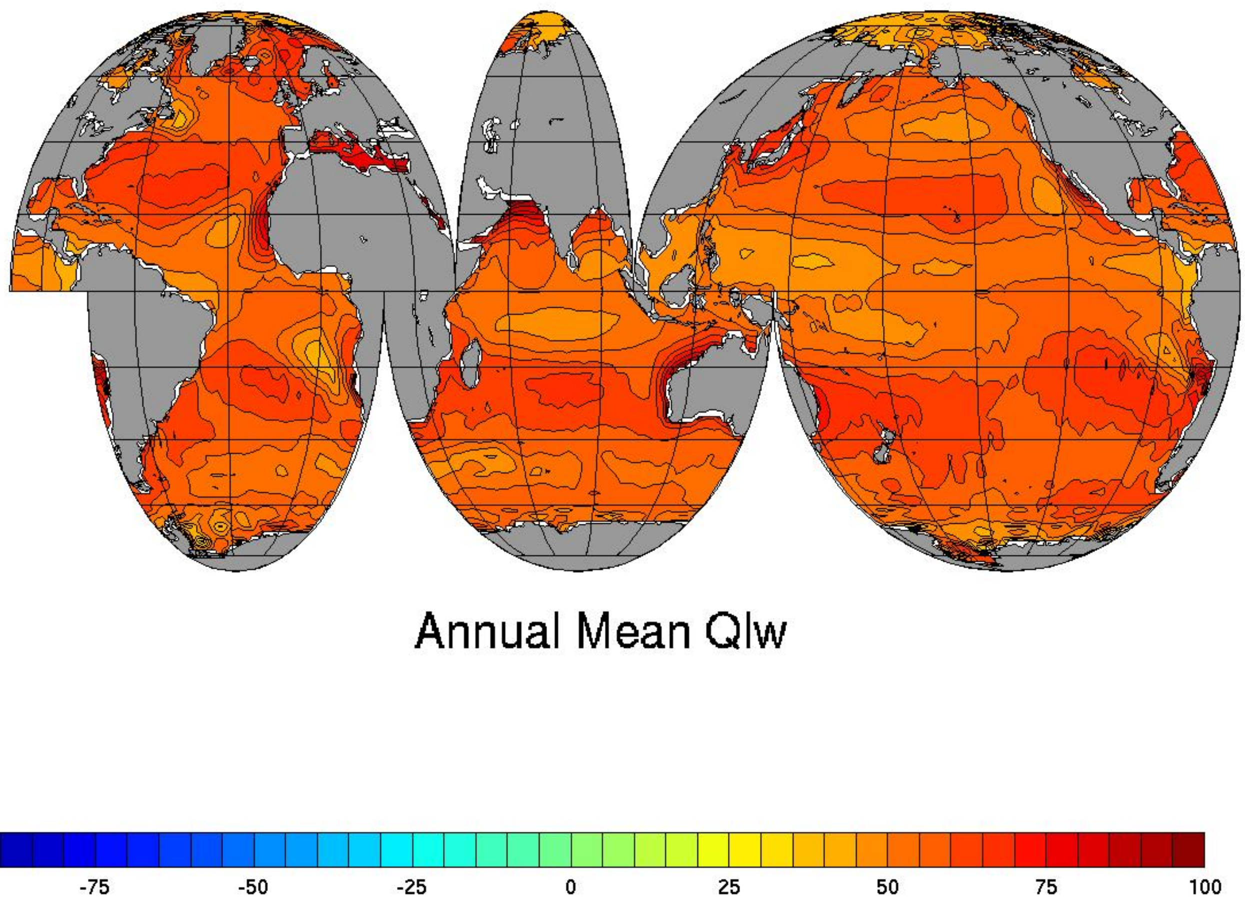
Factors controlling SW radiation

- Latitude
- Cloudines (albedo)



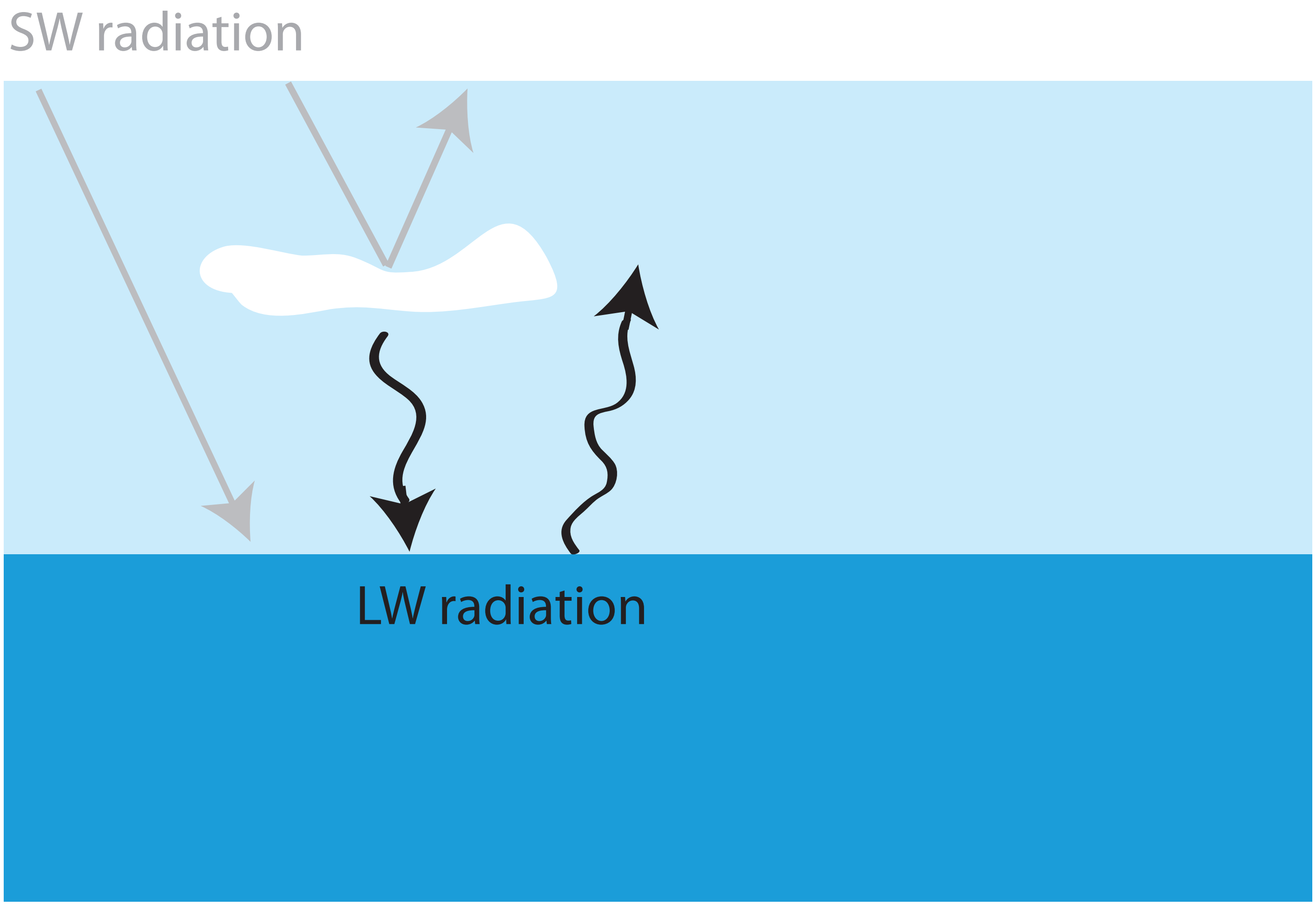
Longwave radiation

- NCEP-Reanalysis
  - Climatology 1968-1996
  - Upward positive (positive into the atmosphere)



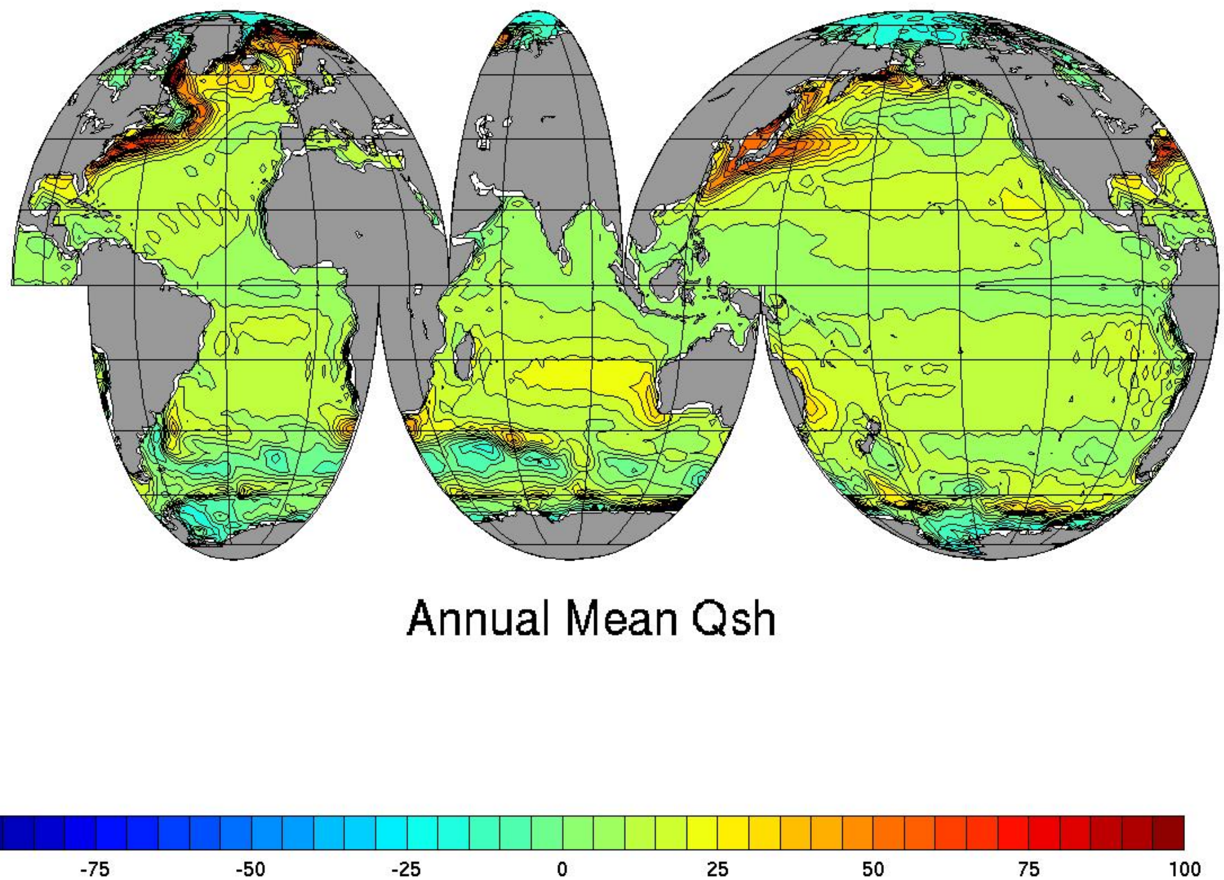
Longwave radiation

- SST, cloud and water vapor



Sensible heat flux

- NCEP-Reanalysis
  - Climatology 1968-1996
  - Upward positive (positive into the atmosphere)

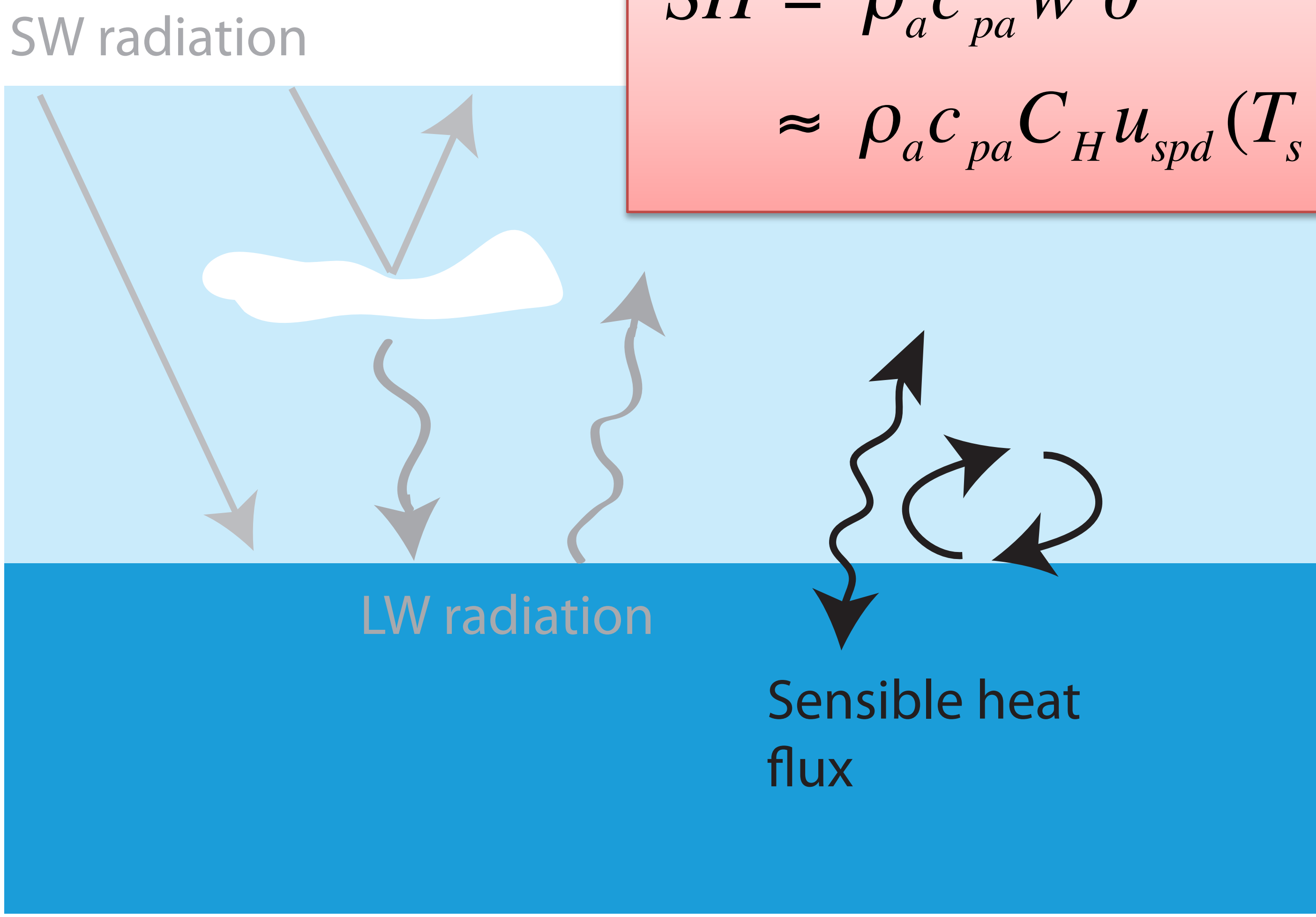


Annual Mean Qsh

Sensible heat flux

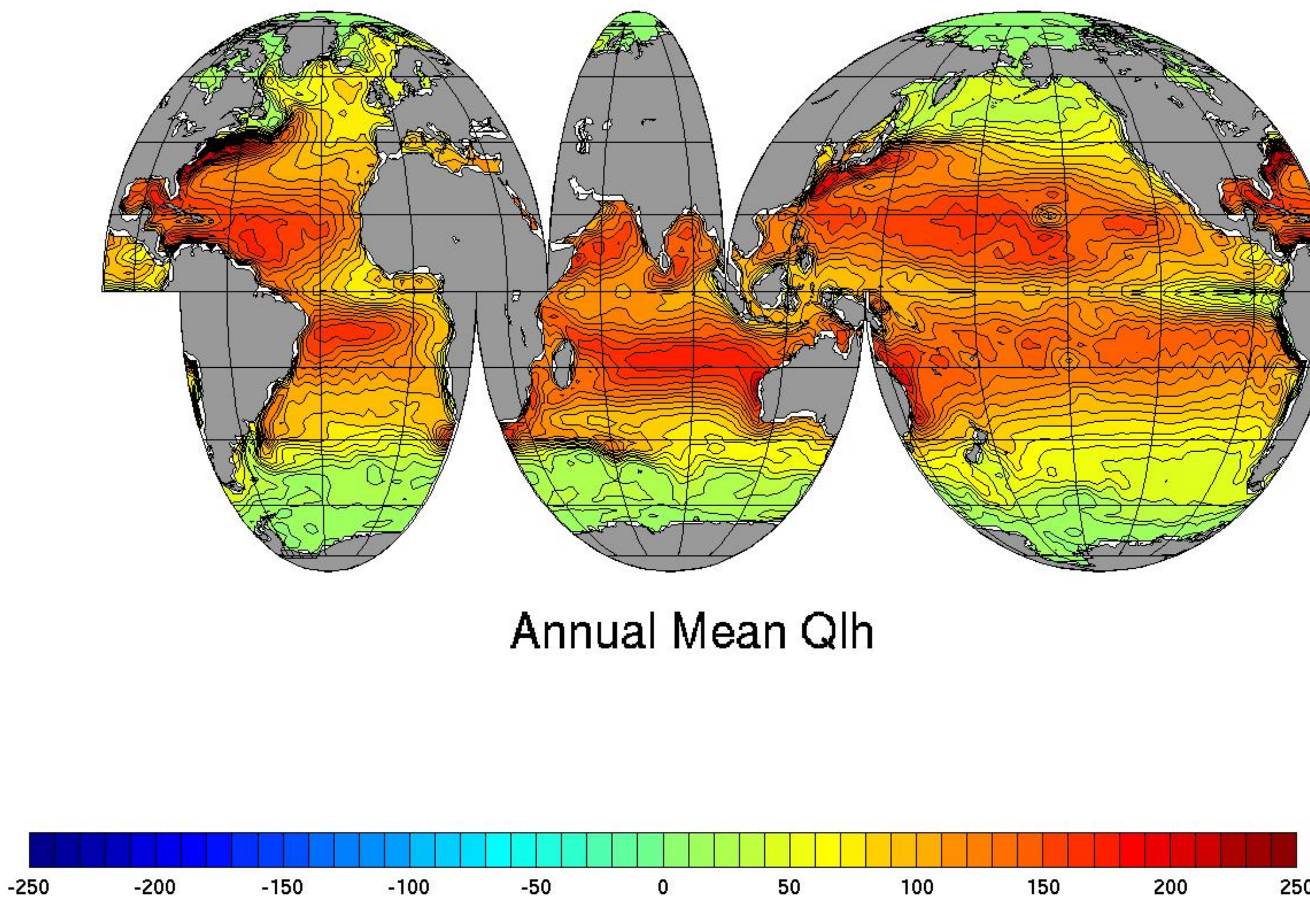
- Surface wind speed and air-sea temperature difference

$$SH = \rho_a c_{pa} \overline{w'\theta'}$$
$$\approx \rho_a c_{pa} C_H u_{spd} (T_s - T_a)$$



Latent heat flux

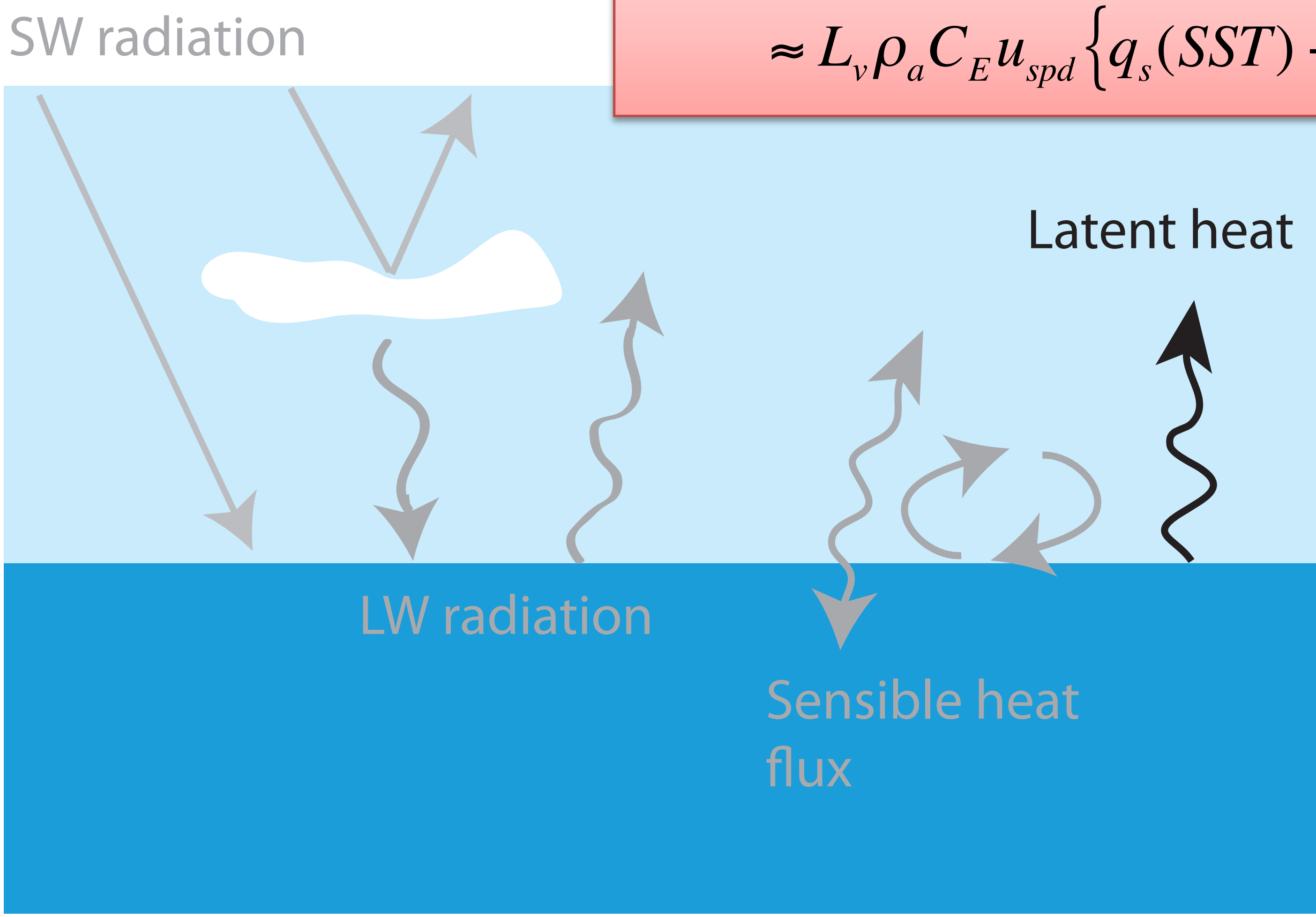
- NCEP-Reanalysis
  - Climatology 1968-1996
  - Upward positive (positive into the atmosphere)



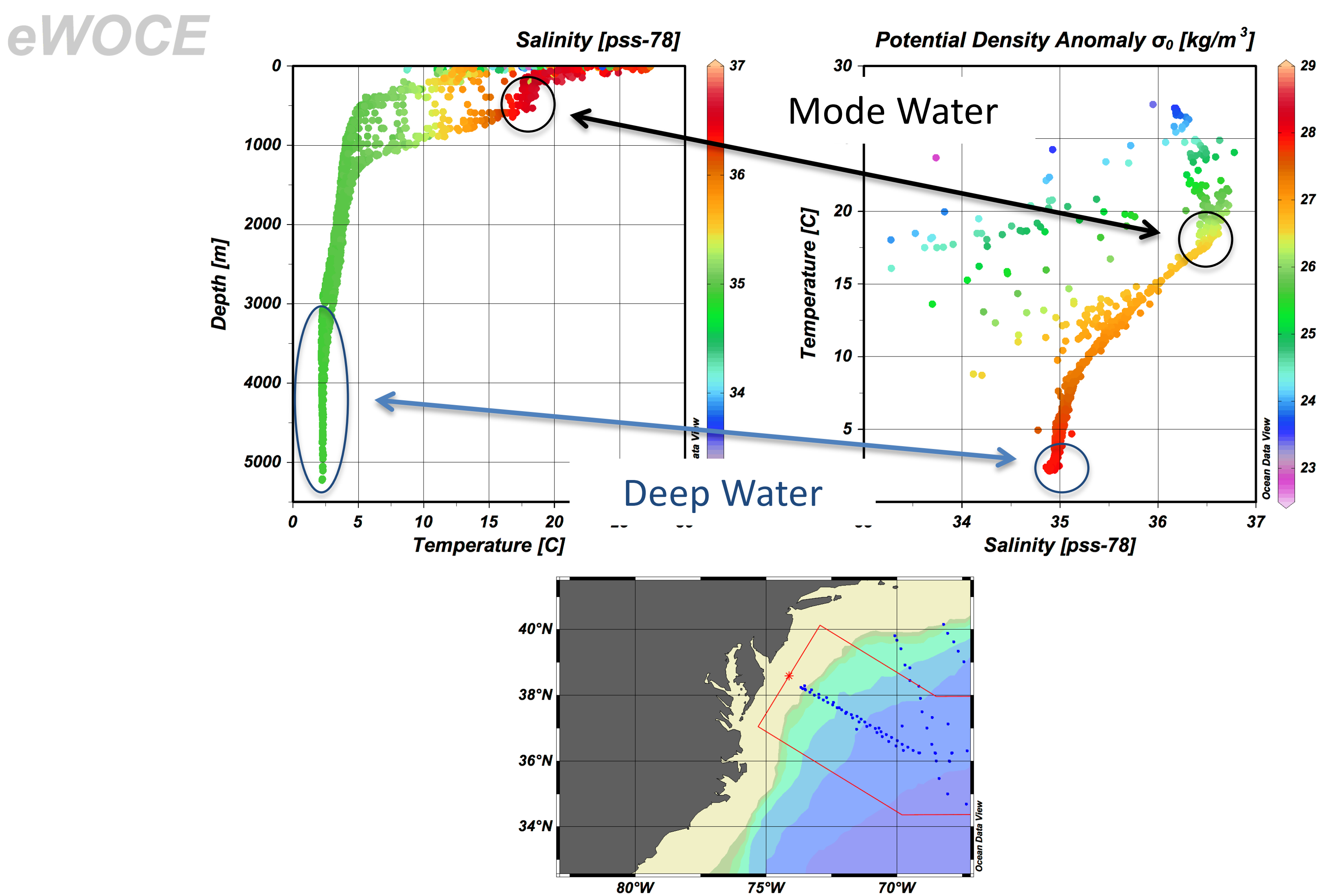
Latent heat flux

- Rate of evaporation

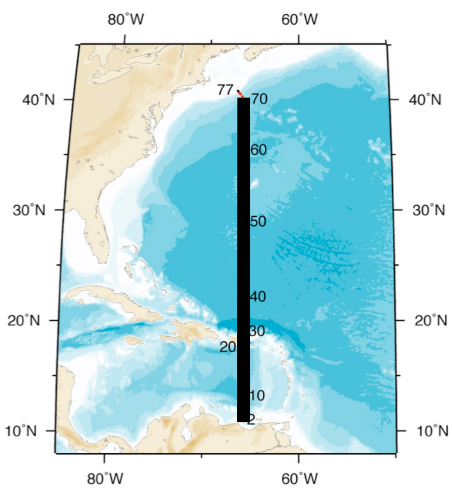
$$LH = L_v E = L_v \rho_a \overline{w'q'}$$
$$\approx L_v \rho_a C_E u_{spd} \left\{ q_s(SST) - q_a \right\}$$



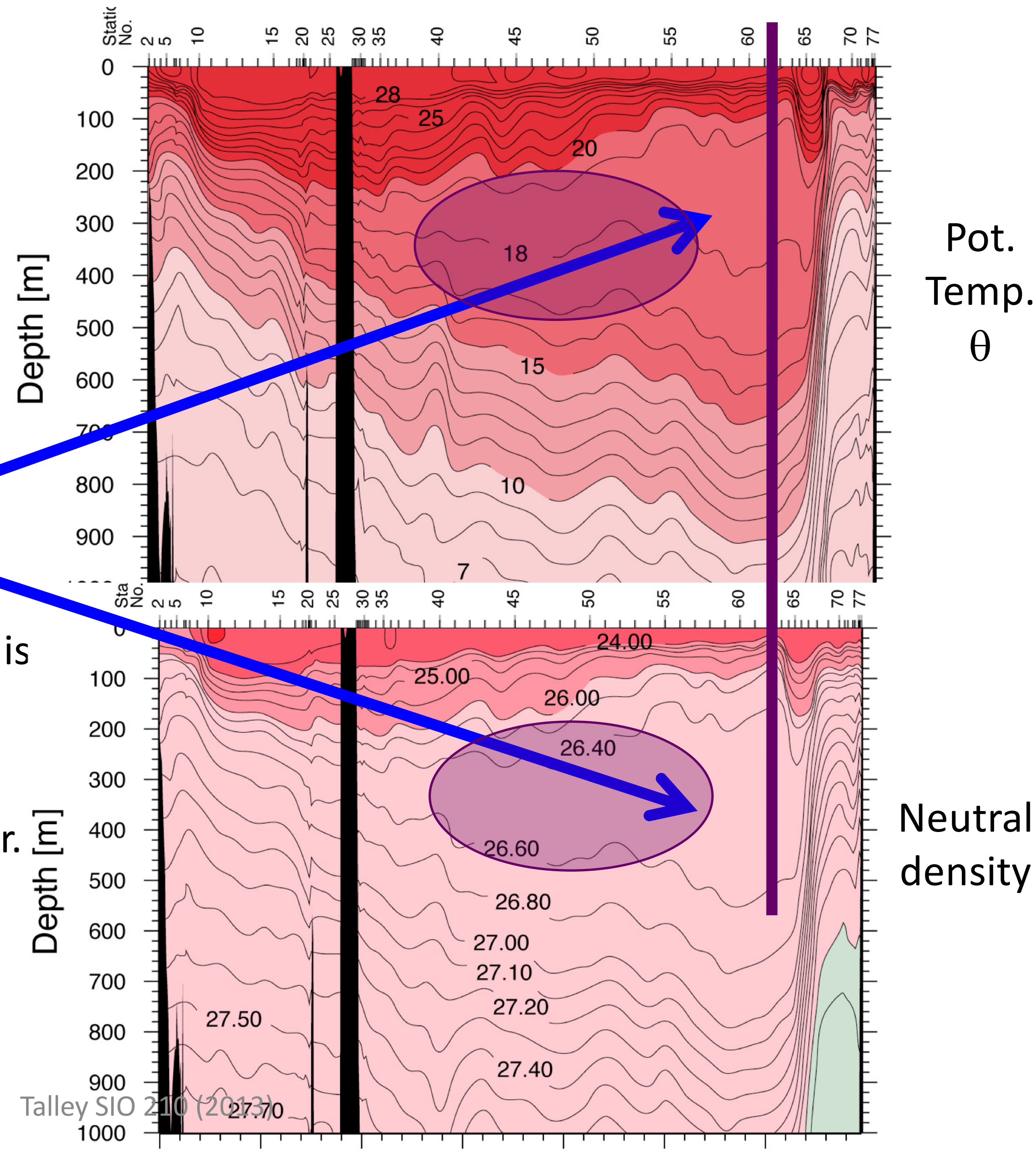
TS structure of the Gulf Stream



Thermostad : Subtropical Mode Water (Eighteen Degree Water)



WHP Atlas
Atlantic



Section across Gulf Stream

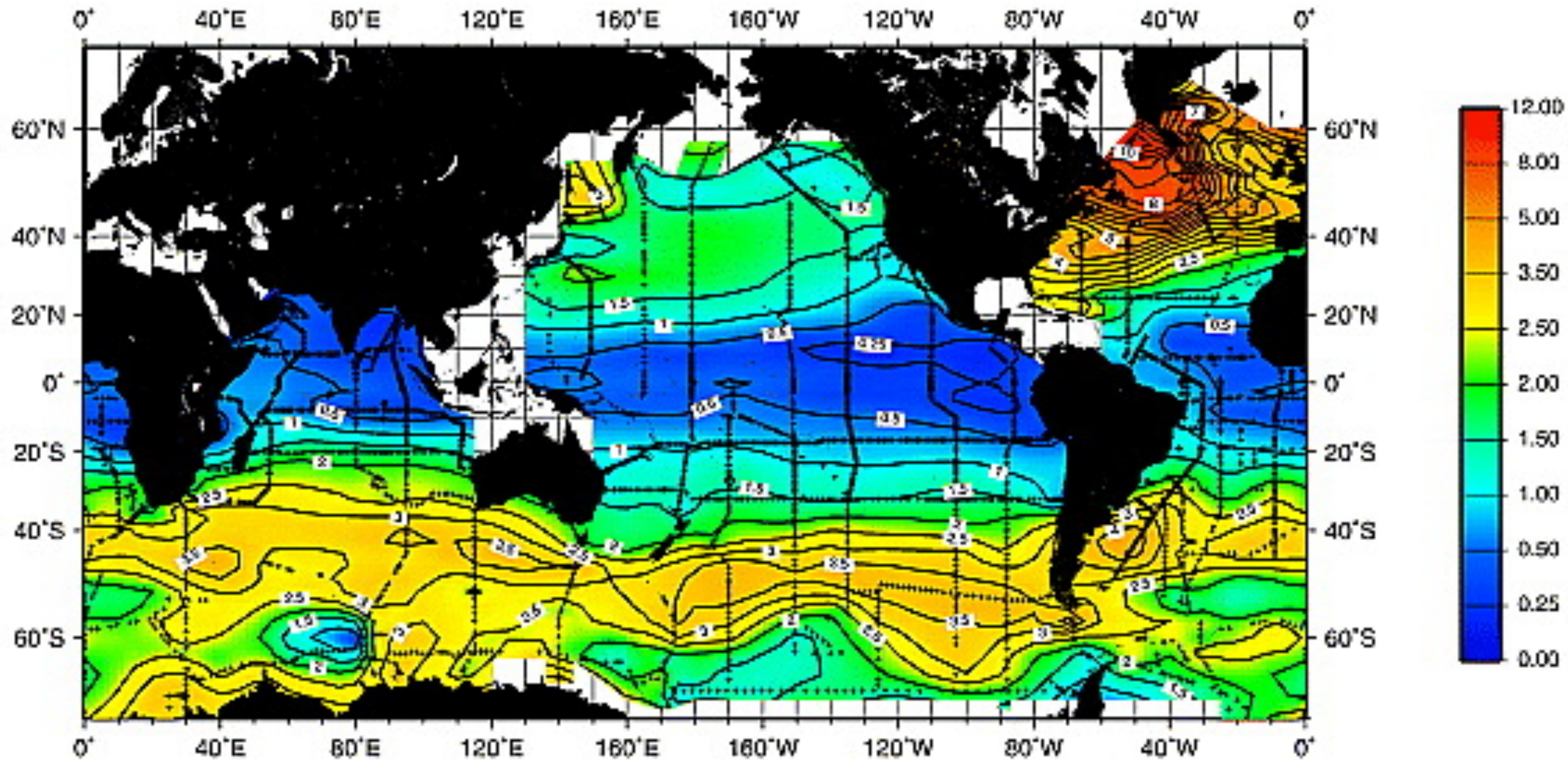
- Thickening of isotherms/isopycnals is the thermostad/pycnostad
- Forms at surface as a thick mixed layer near Gulf Stream in late winter.
- Circulates into the interior south of the Gulf Stream along isopycnals

Mode Water in the Upper Ocean

- 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.

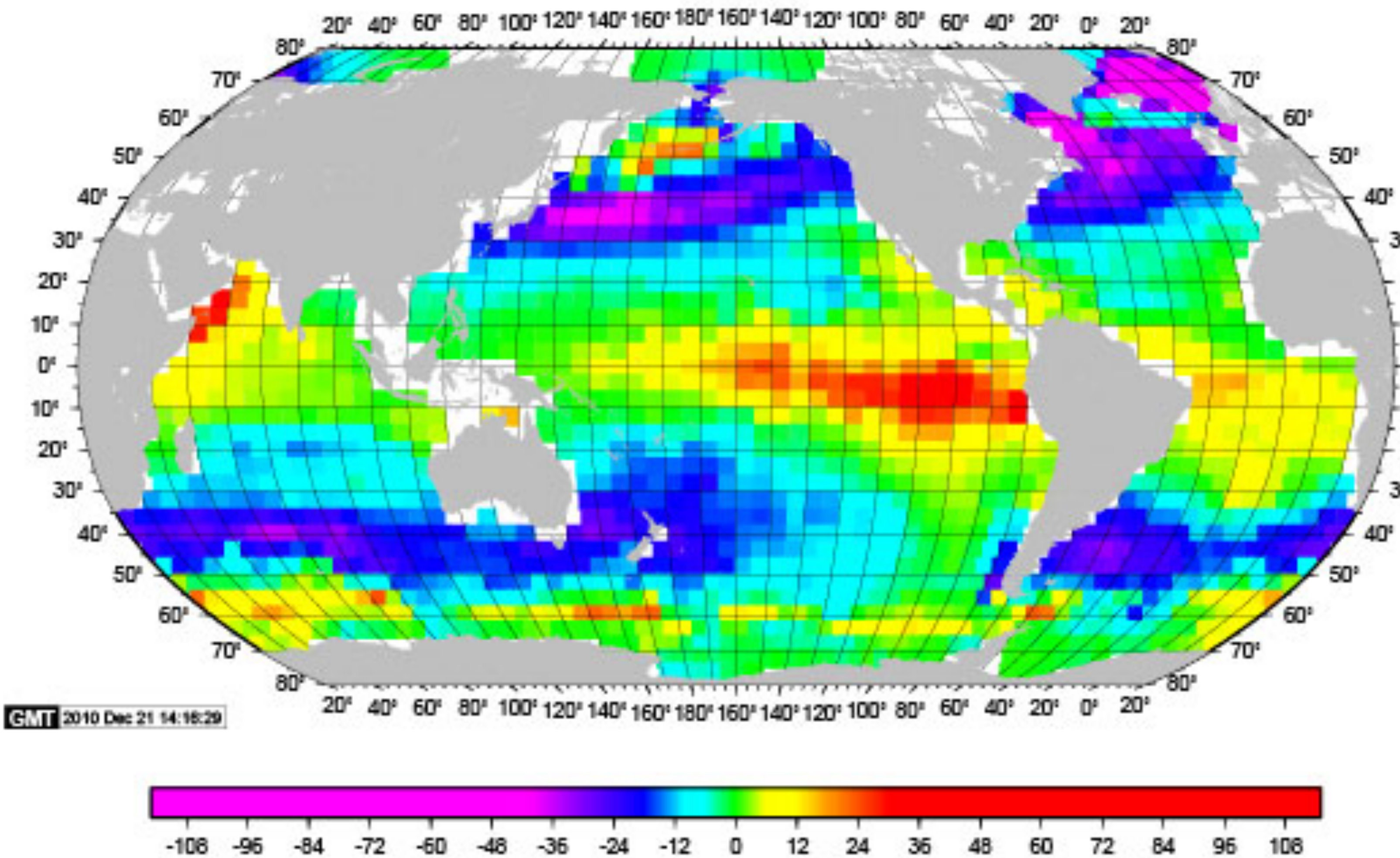
Importance of mode waters for dissolved gas inventories

Chlorofluorocarbon (CFC) water column inventory
(conservative anthropogenic tracer)

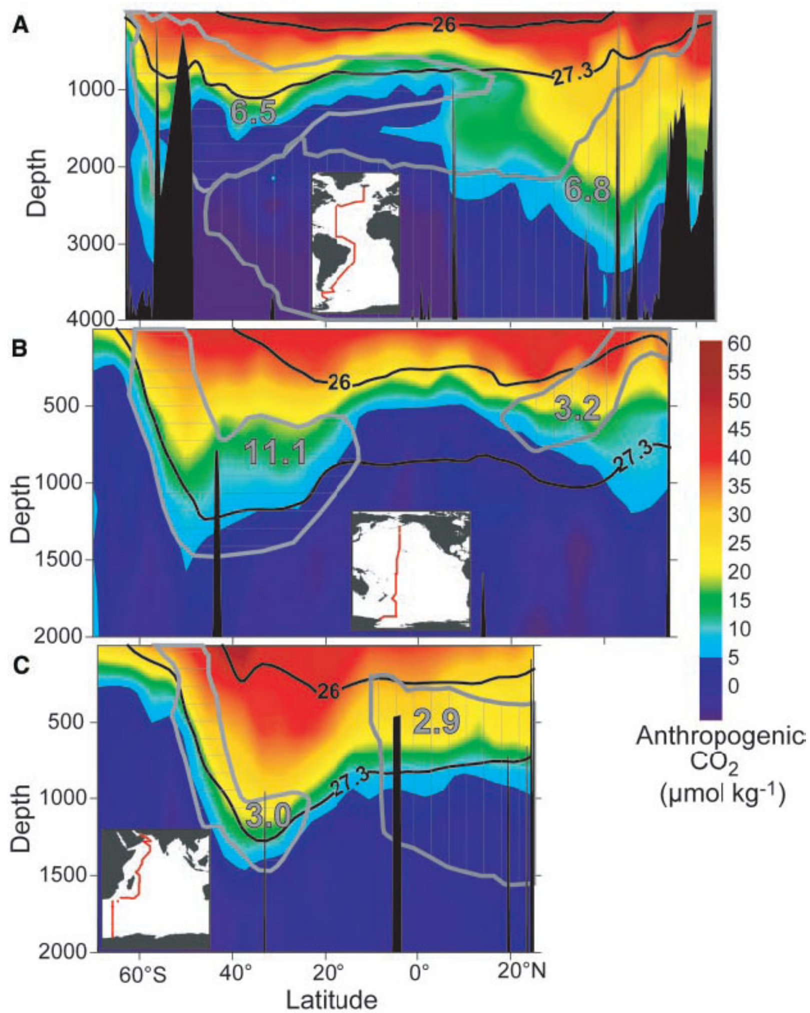


Willey et al. (GRL 2004)

Sea-to-air CO_2 flux



Distribution of fossil fuel CO_2



- Ocean absorbs about 1/4 - 1/3 of anthropogenic carbon emission each year.
- What part of the oceans is the carbon going to?

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.

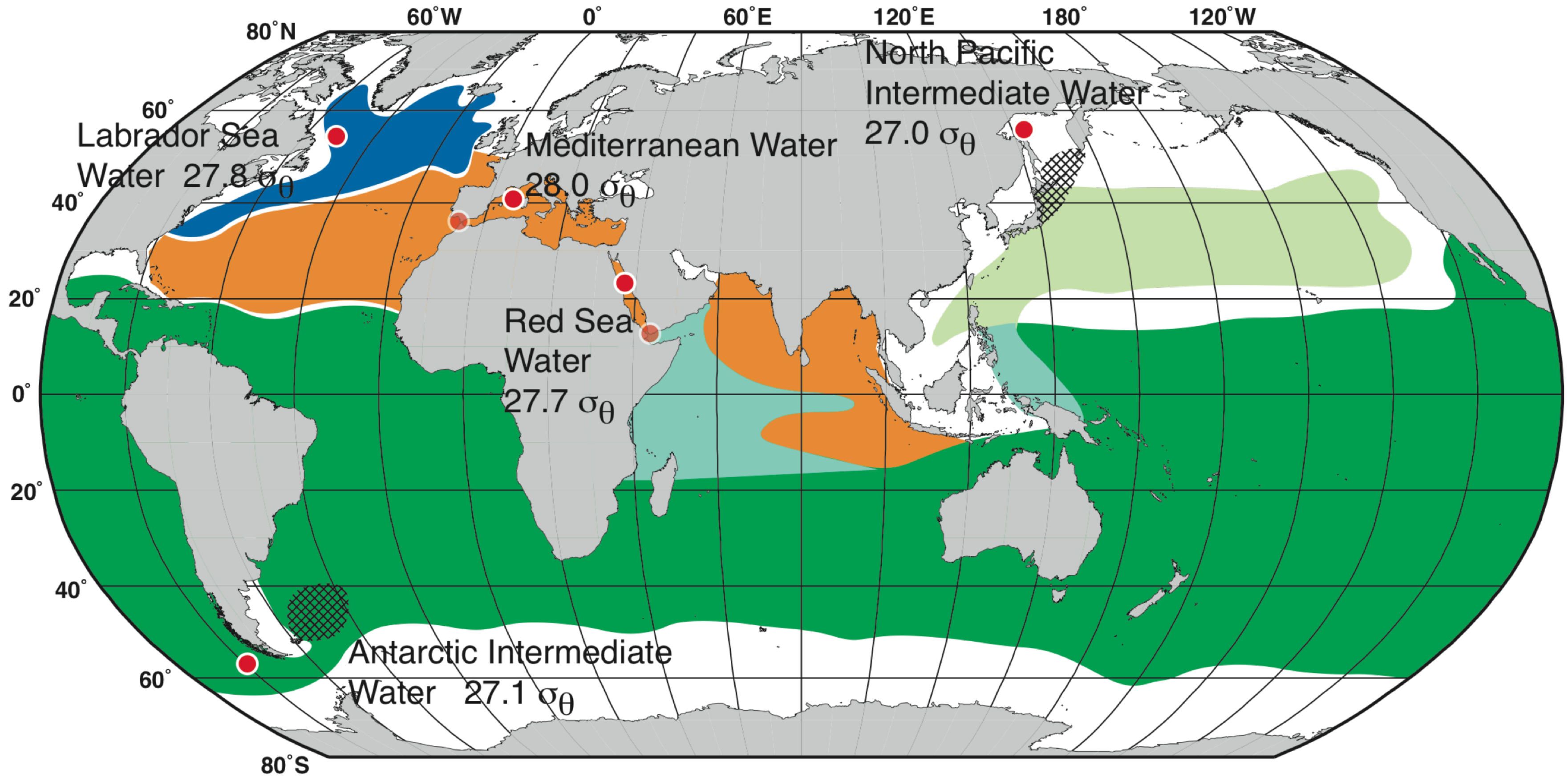
Originate from very specific sources (“injection sites”) in the Labrador Sea (“Labrador Sea Water”), the Mediterranean Sea (“Mediterranean Water”), the Red Sea (“Red Sea Water”), the Okhotsk Sea (“North Pacific Intermediate Water”), and the Drake Passage region (“Antarctic Intermediate Water”).

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

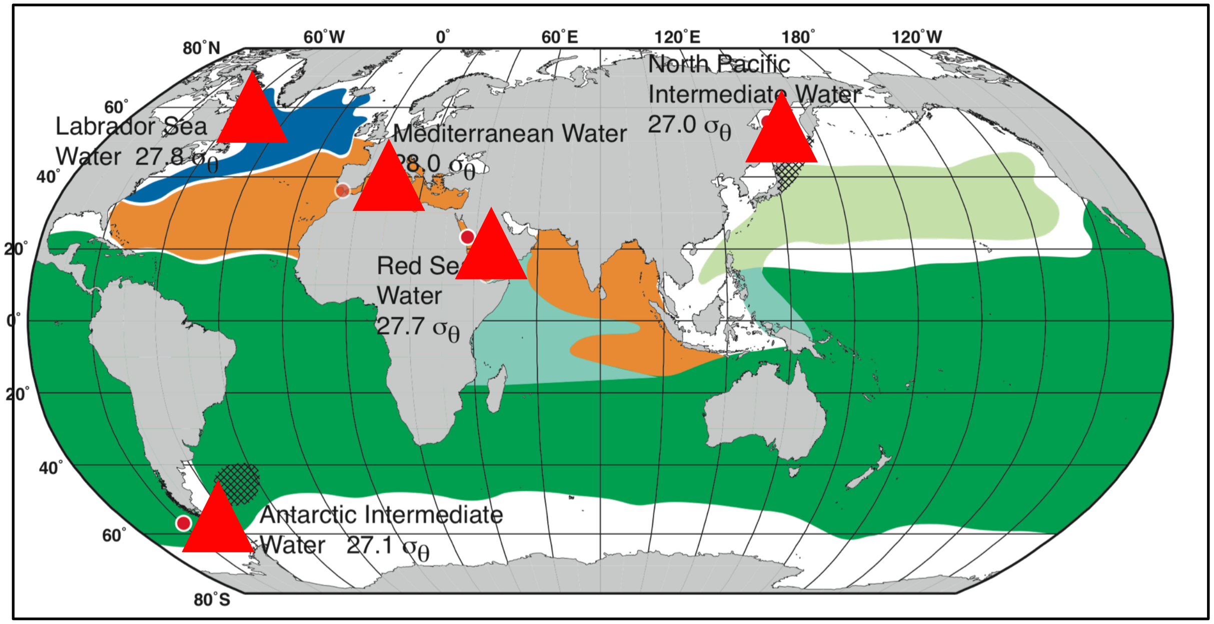
Intermediate water masses (salinity minimum)

- Low salinity intermediate layers (salinity minimum layers)

- High salinity intermediate layers (salinity maximum layers)



DPO Fig. 14.13



Intermediate water production sites ▲

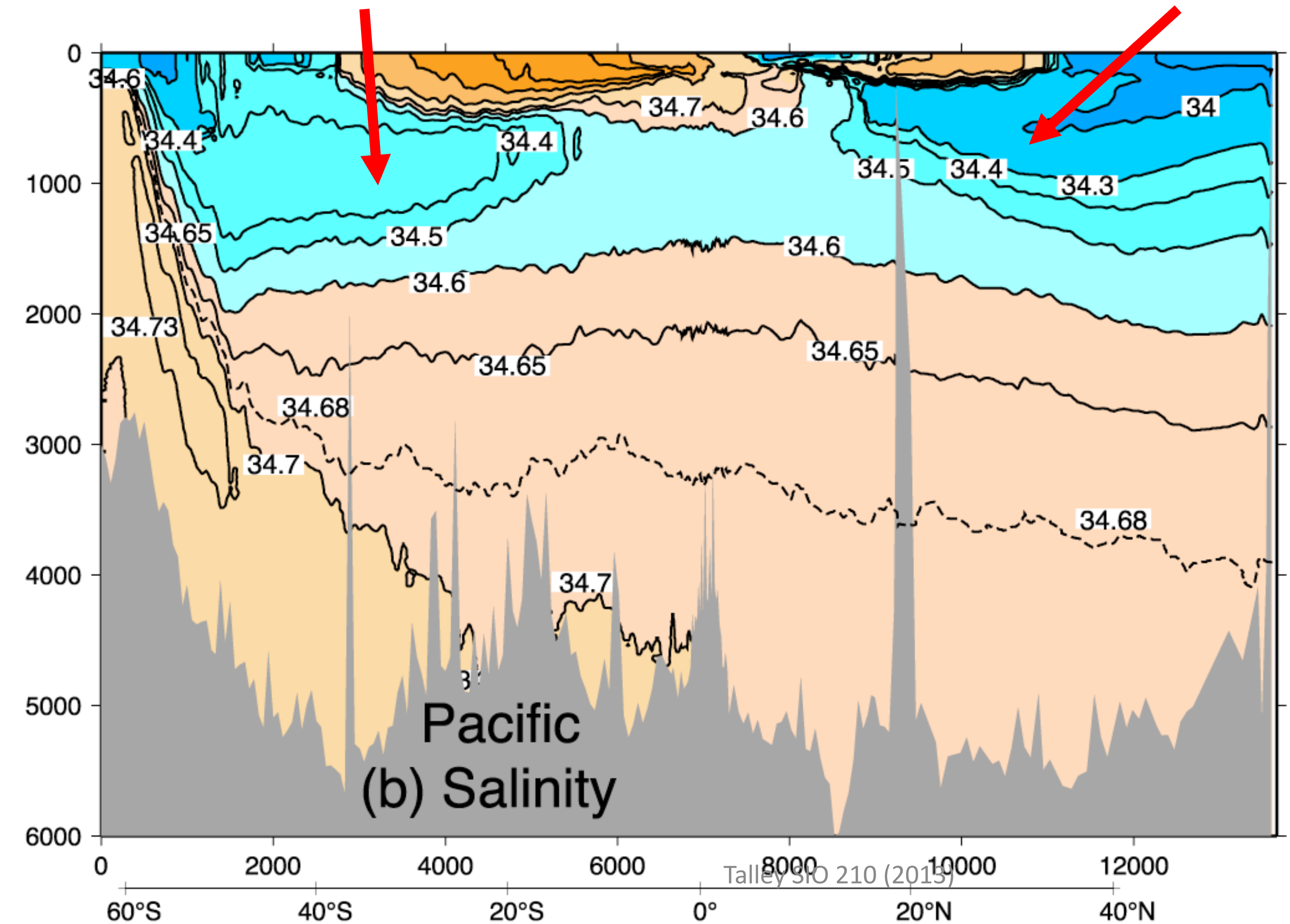
DPO Fig. 14.13

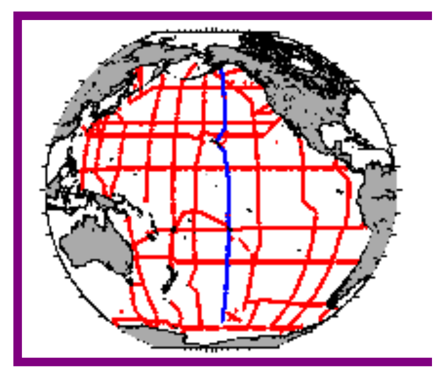
- Labrador Sea Water: salinity minimum, deep convection in Labrador Sea
- Mediterranean Overflow Water: salinity maximum, evaporation and cooling in Mediterranean Sea, overflow
- Antarctic Intermediate Water: salinity minimum, medium convection in Drake Passage region
- Red Sea Overflow Water: salinity maximum, evaporation in Red Sea, overflow
- North Pacific Intermediate Water (Okhotsk Sea): salinity minimum, brine rejection in the Okhotsk Sea

Pacific intermediate waters

Intermediate depth (500-2000 m), vertical salinity minima

Antarctic Intermediate Water (AAIW) North Pacific Intermediate Water (NPIW)





Talley SIO 210 (2013)

DPO Fig. 4.12

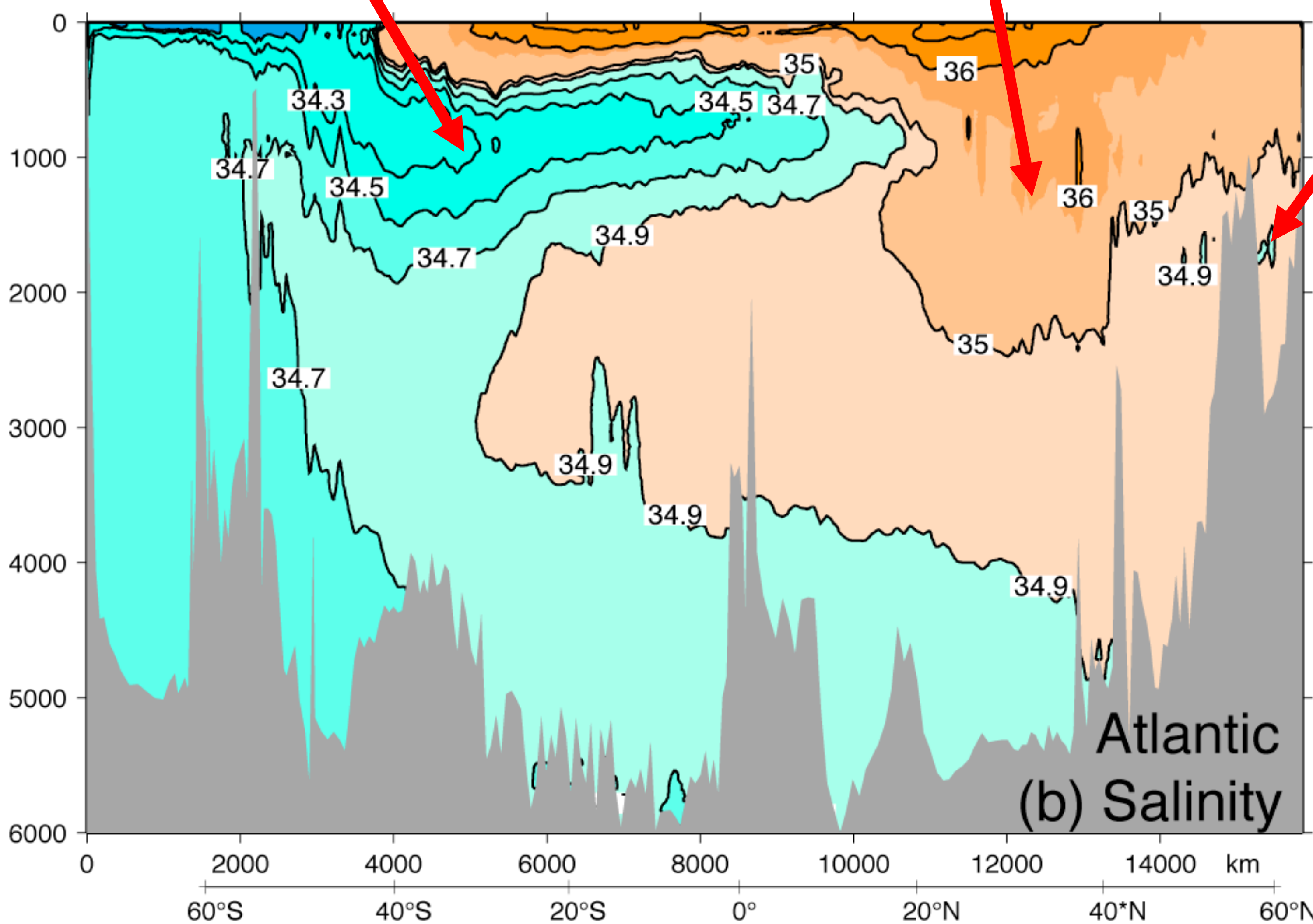
Atlantic intermediate waters

Intermediate depth (500-2000 m), vertical salinity minima AND maximum

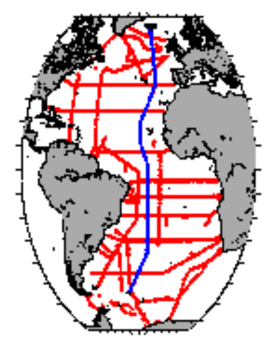
Antarctic Intermediate Water (AAIW)

Mediterranean Water (MW)

Labrador Sea Water (LSW)



Talley SIO 210 (2013)



DPO Fig. 4.11

Review question

- What water mass contains “thermostad”?
  1. Mixed layer
  2. Mode waters
  3. Intermediate waters
  4. Deep waters
  5. Bottom waters

Review question

- What is the most important formation mechanism for the mode waters?
  1. Deep convection in the polar ocean
  2. Brine rejection following seaice formation
  3. Winter-time heat loss and convection at mid-latitudes
  4. Summer-time mixing due to the wind-driven turbulence

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**

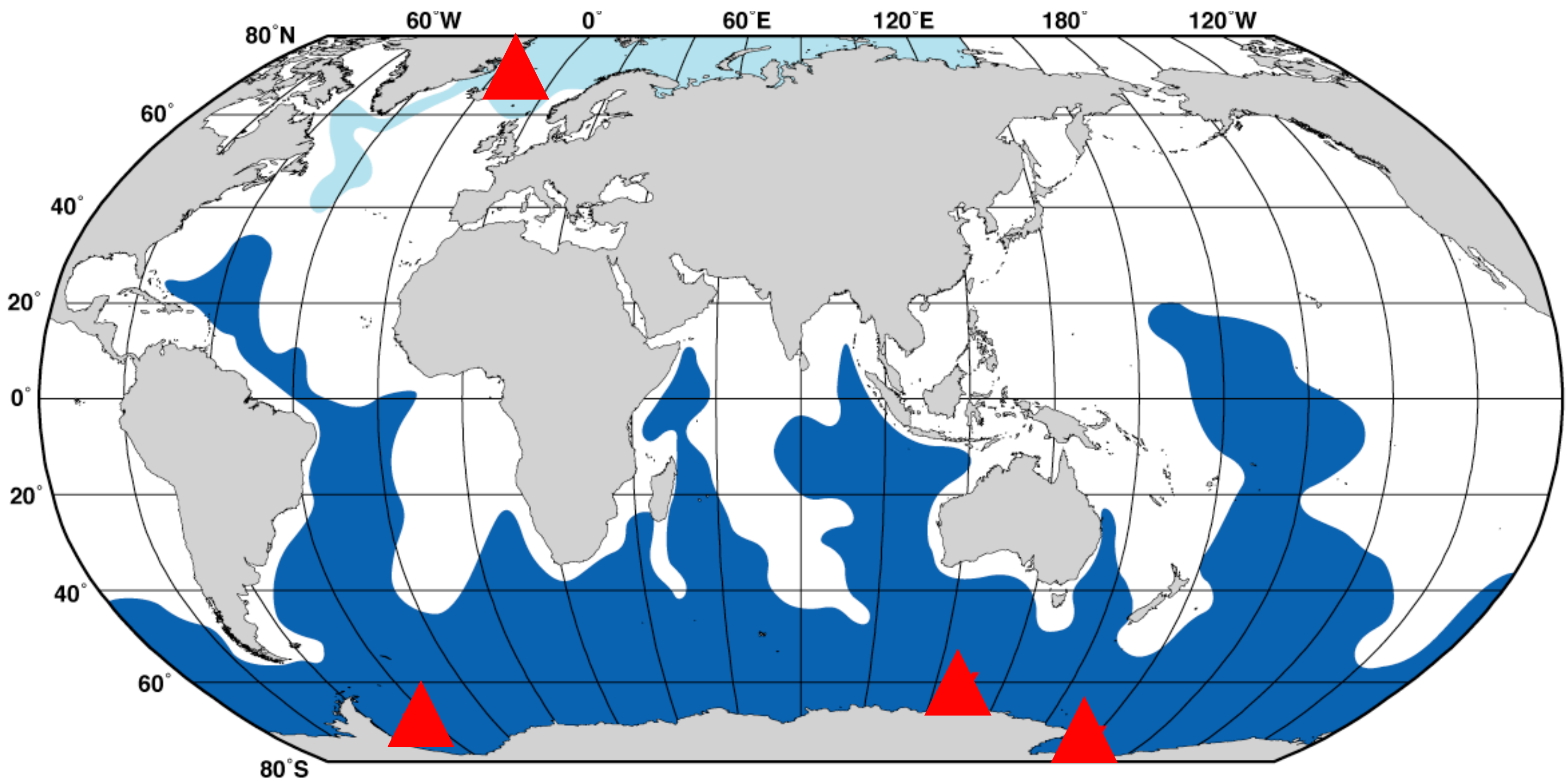
Location: ocean bottom, usually connotes very dense water from the Antarctic.

In the Antarctic region, **"Antarctic Bottom Water"**

Elsewhere, **"Lower Circumpolar Deep Water"**

Formation mechanism: **brine rejection close to Antarctica: coastal polynya**

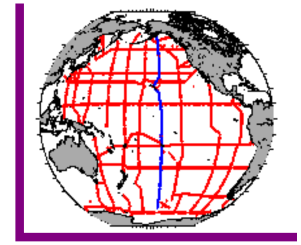
Ventilation of the deep ocean

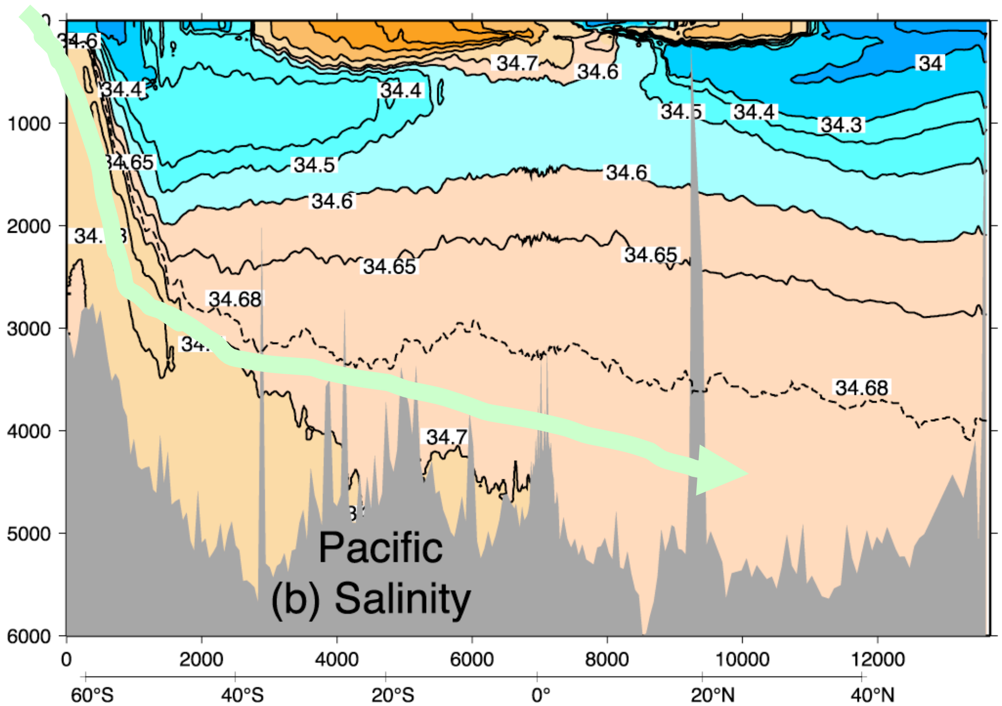


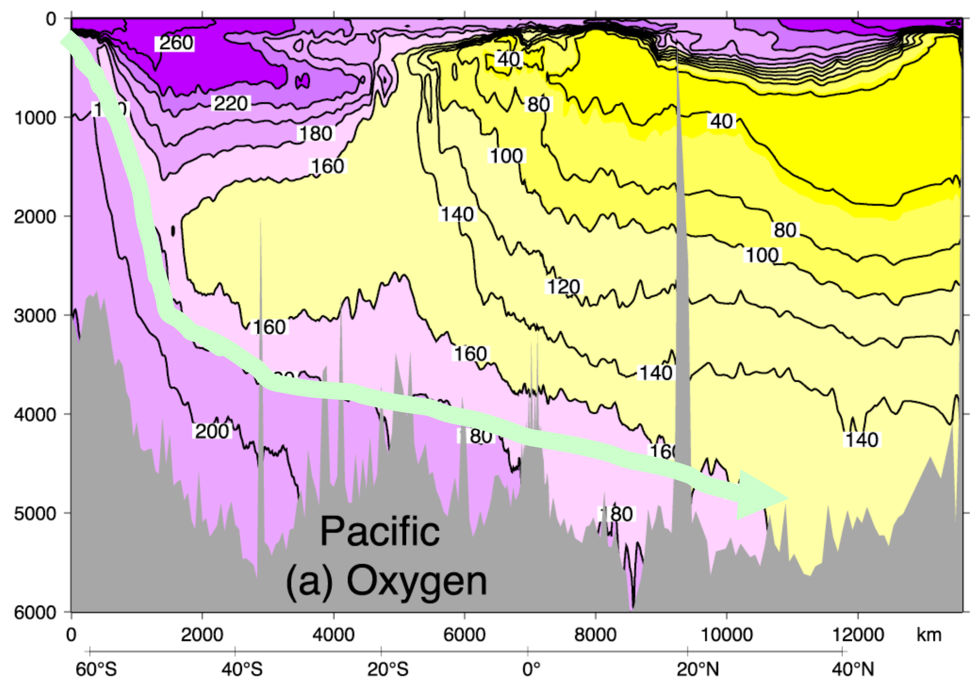
- Localized deep convection or brine rejection at high latitudes, with subsequent local turbulent mixing and then flow mostly along isopycnals

DPO Fig. 14.14a

Deep Ventilation



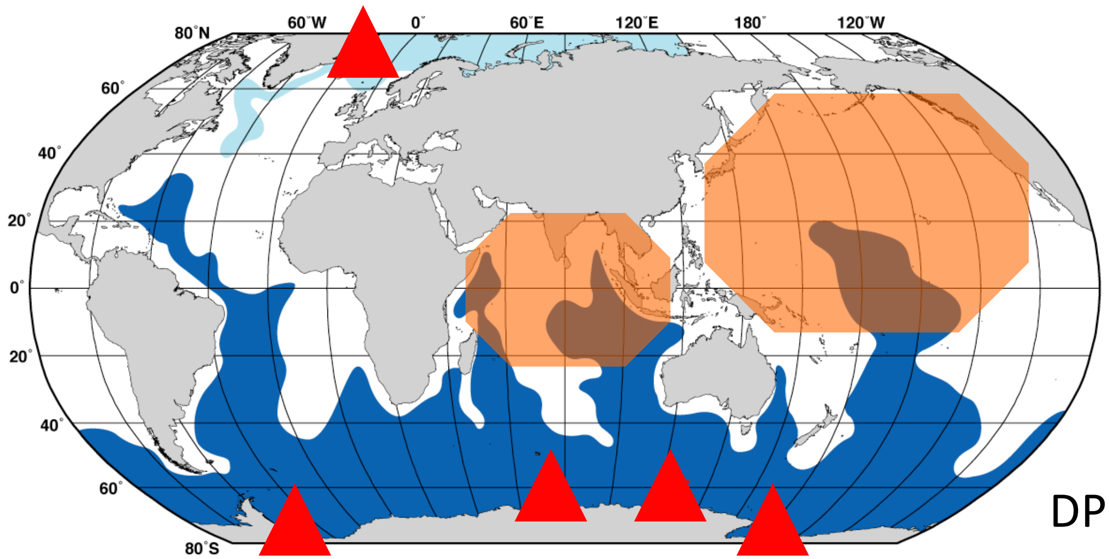




Flow and mixing is mostly along **isopycnals** (constant potential density surfaces)

Ocean circulation is mainly **adiabatic** --- movement/mixing of water is primarily oriented along isopycnals

Deep and bottom water



Deep and bottom water production sites

DPO Fig. 14.14a

- North Atlantic Deep Water: high salinity, high oxygen; mixture of NSOW, LSW and MOW; formed at sea surface through deep convection

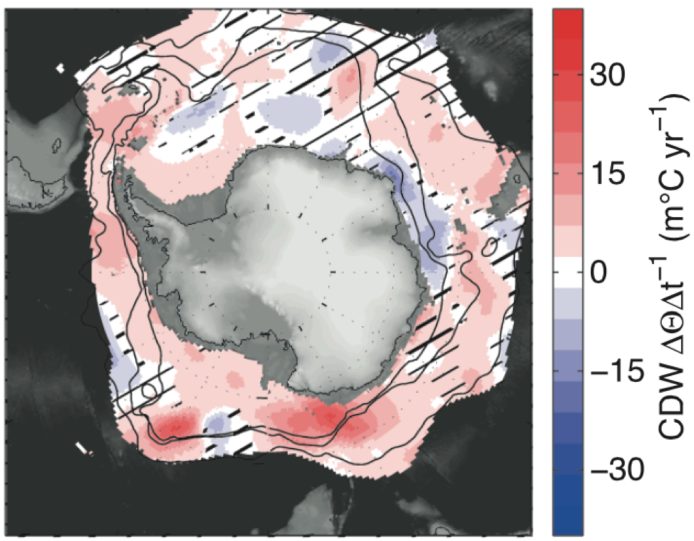
- Antarctic Bottom Water: very cold, high oxygen; formed near sea surface along coast of Antarctica through sea ice formation-brine rejection

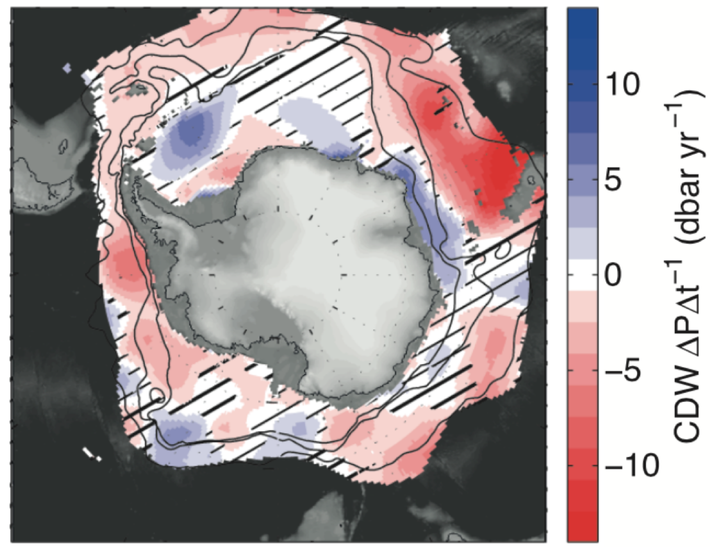
- Indian and Pacific Deep Waters: low oxygen, high nutrients; slow upwelling and slow deep mixing of inflowing NADW and AABW

Subsurface changes: Circumpolar Deep Water

- Gille 2002, 2008; Schmidtko et al., 2014

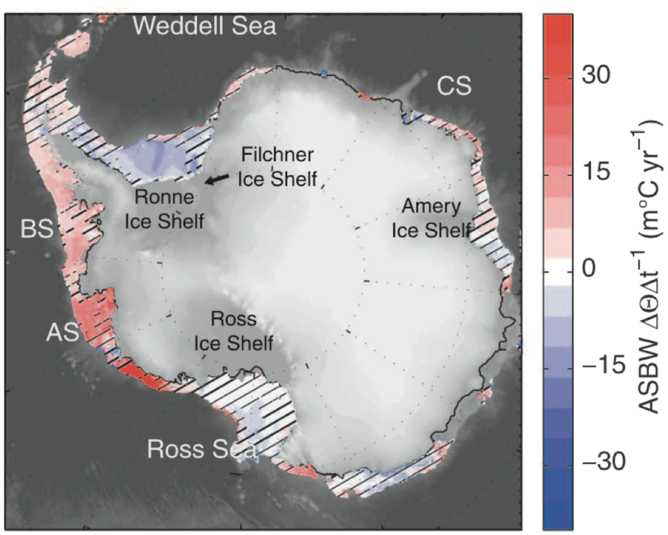
Trend at CDW core





Core of CDW = Tmax layer

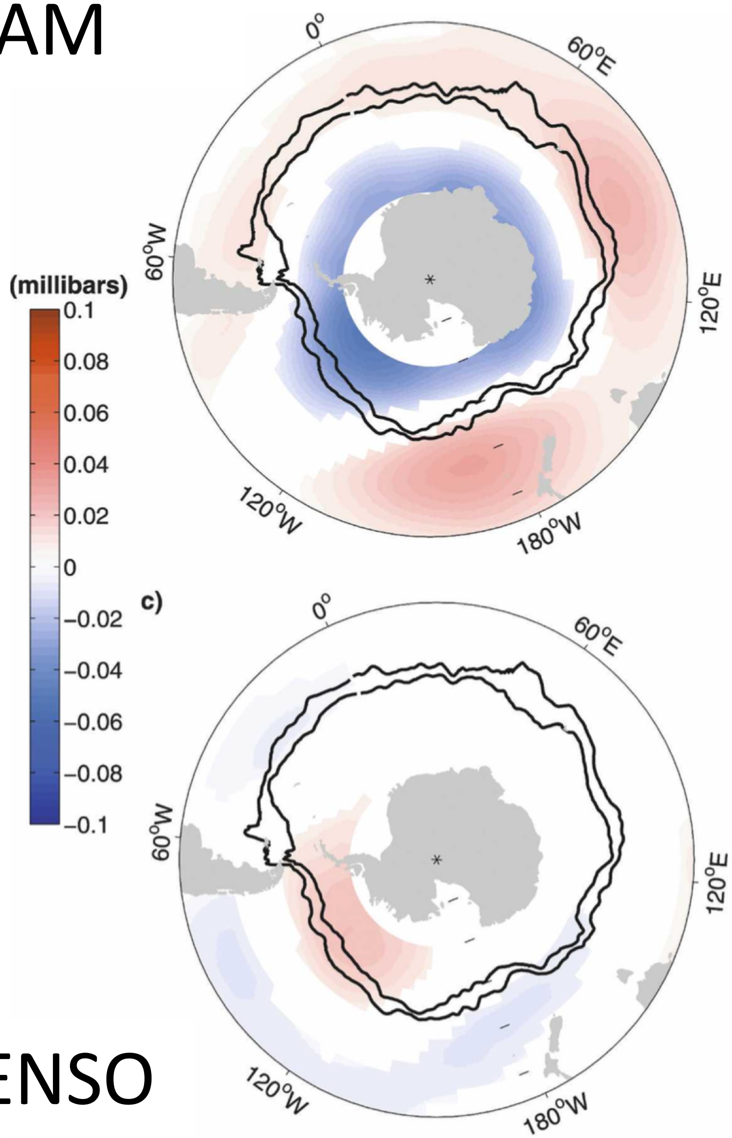
Trend at shelf bottom



- Since 1970s CDW is generally warming up and shoaling
- Trend is not zonally uniform
- Shelf warming promotes basal melting in the AS/BS sector

Recent changes in the Antarctic climate

SAM

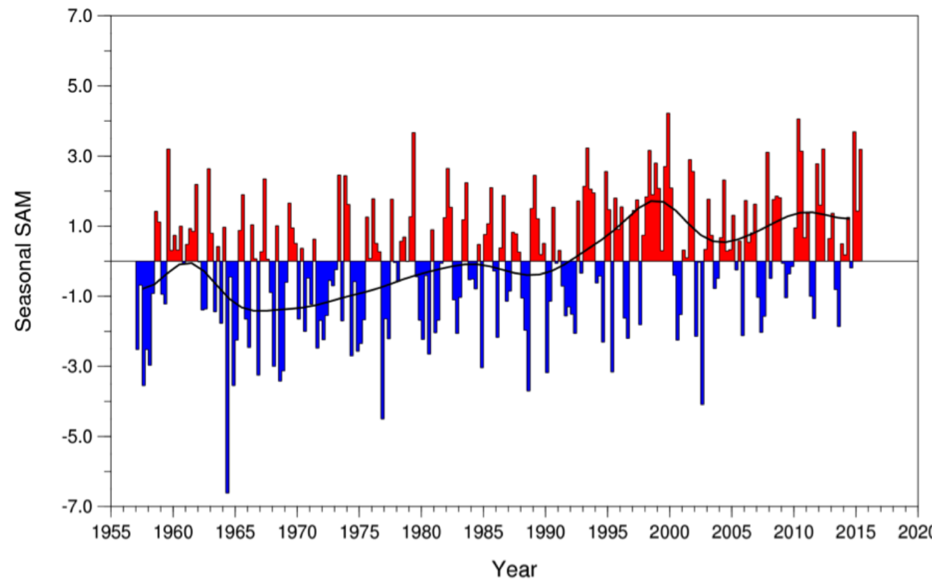


ENSO

Sallee et al., 2008

Positive trend in SAM = **intensified, poleward-shifted zonal wind**

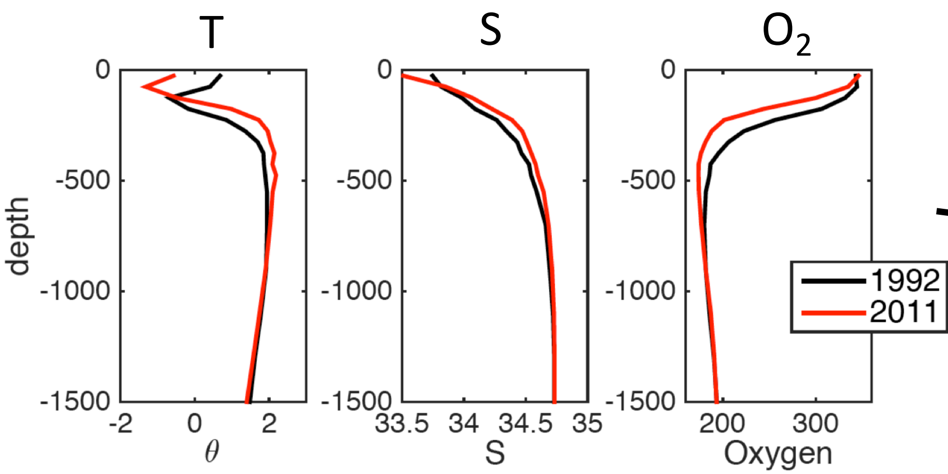
SAM index

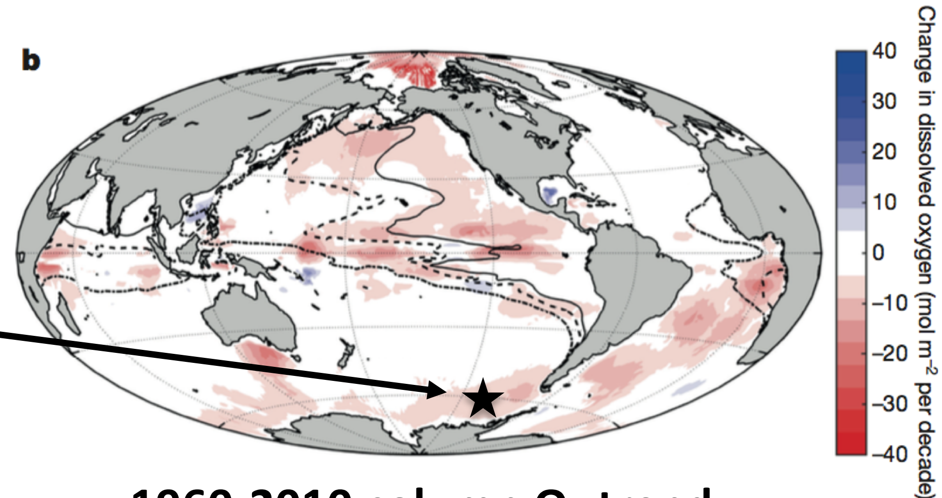


Marshall et al., 2016

Deoxygenation

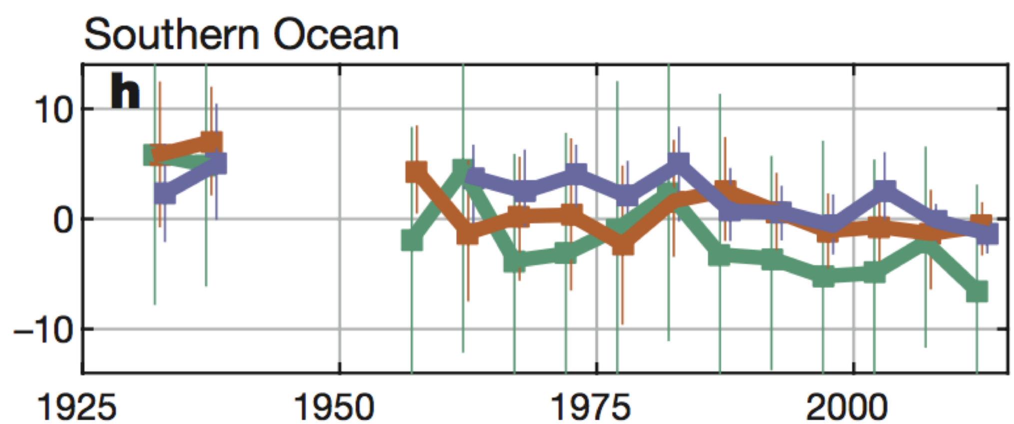
- Large scale obs analysis (Schmidtko et al., 2017; Ito et al., 2017)
- Vertical profiles (S4P, 1992 & 2011)





1960-2010 column O_2 trend

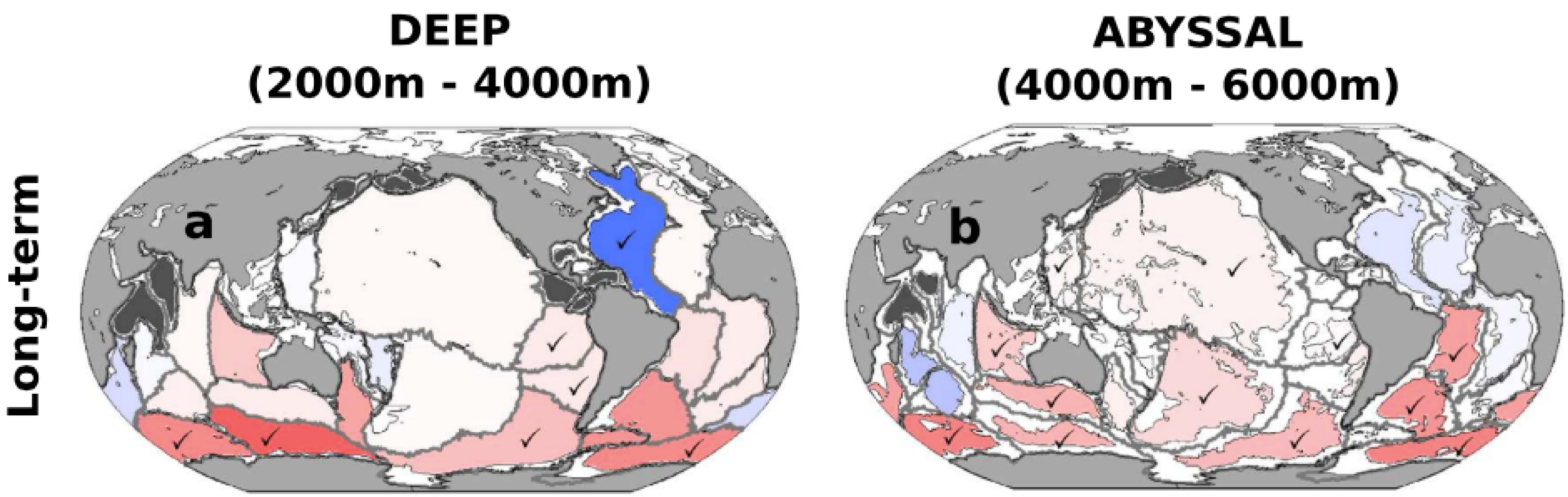
CDW is getting shallower, warmer and less oxygenated



Green (300m); Red (1000m); Blue (3000m)

Subsurface changes: Deep Waters

- Purkey and Johnson, 2013; Desbruyeres et al., 2013



- Freshening of AABW and glacial melt (Rignot et al., 2008; Jacobs and Giulivi 2010; Swift and Orsi 2012)
- Weakening of the lower limb MOC (Purkey and Johnson 2012; Kouketsu et al., 2011) → **consistent with deep O_2 loss**
- *Sea Surface Temperature in the Antarctic region has been neutral or even cooling during this time, but there is a widespread warming in the subsurface*

Summary: deep waters

- Deep water forms only in the North Atlantic and the Southern Ocean
  - Deep nutrient and carbon has a large inter-basin gradient
  - Deep water accumulates respired nutrients and carbon
  - Deep North Pacific has the highest nutrient and lowest oxygen concentration