

Physics and Chemistry of the Oceans

EAS4305/6305

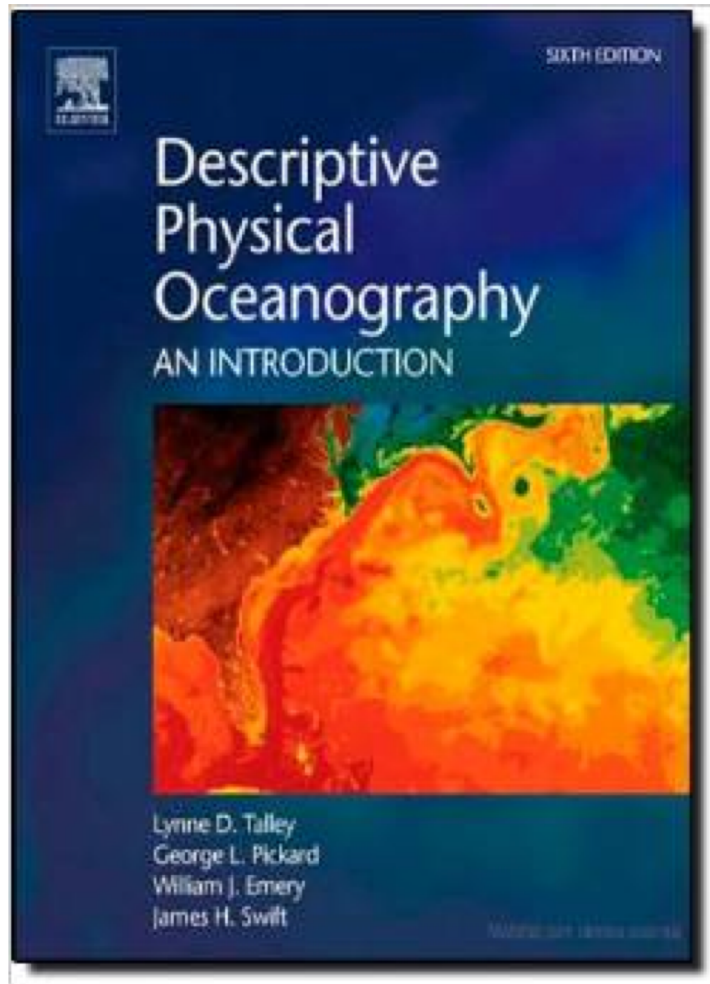
Fall 2018

Logistics

- Class: Tuesday and Thursday 12:00-13:15
- My office: EST 1st floor, 1102
- Email: taka.ito@eas.gatech.edu
- Course materials will be uploaded on <http://shadow.eas.gatech.edu/~Ito/webdata/teaching.html>
- Grader: Daoxun Sun (sdxmonkey@gatech.edu)
- Informal TA: Filippos Tagklis (ftagklis@gatech.edu)

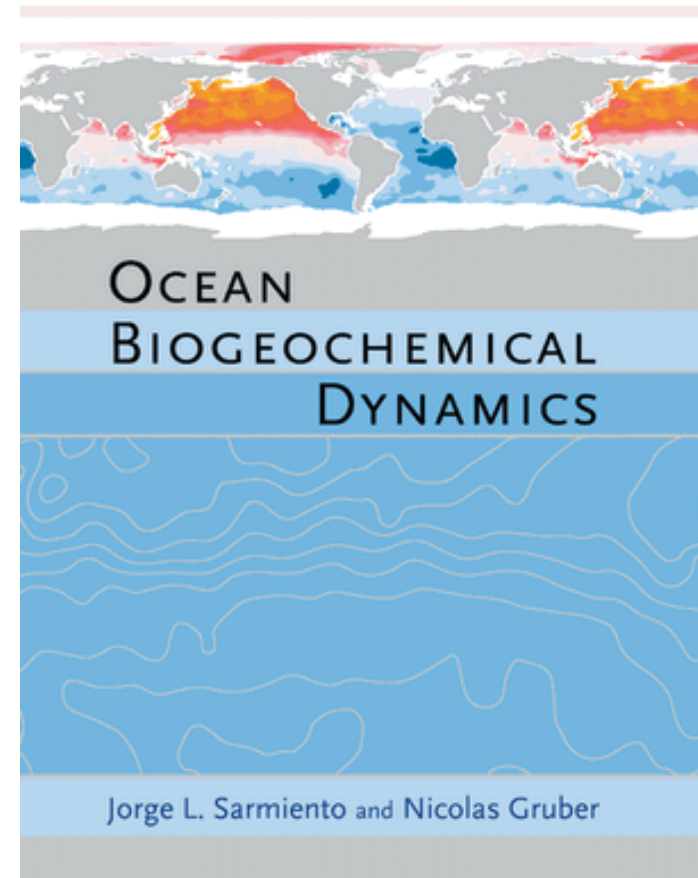
Textbooks

Main



Talley et al., (2011) Available both in print and electronic copy ~ \$60

Secondary on chemistry-related topics



Sarmiento and Gruber (2006) Available both in print and electronic copy ~ \$90

Expectations

- Come to class
 - Covers basic concepts
- Read textbook
 - About one chapter/week
- Do homework
 - Problem solving
 - Computer exercises

Evaluation

- 40% homework
 - Weekly assignment
 - Graduate student may get extra questions
- 20% midterm
 - In-class exam (80 min)
 - Sample questions distributed in advance
- 30% term paper
- 10% attendance/participation

Schedules

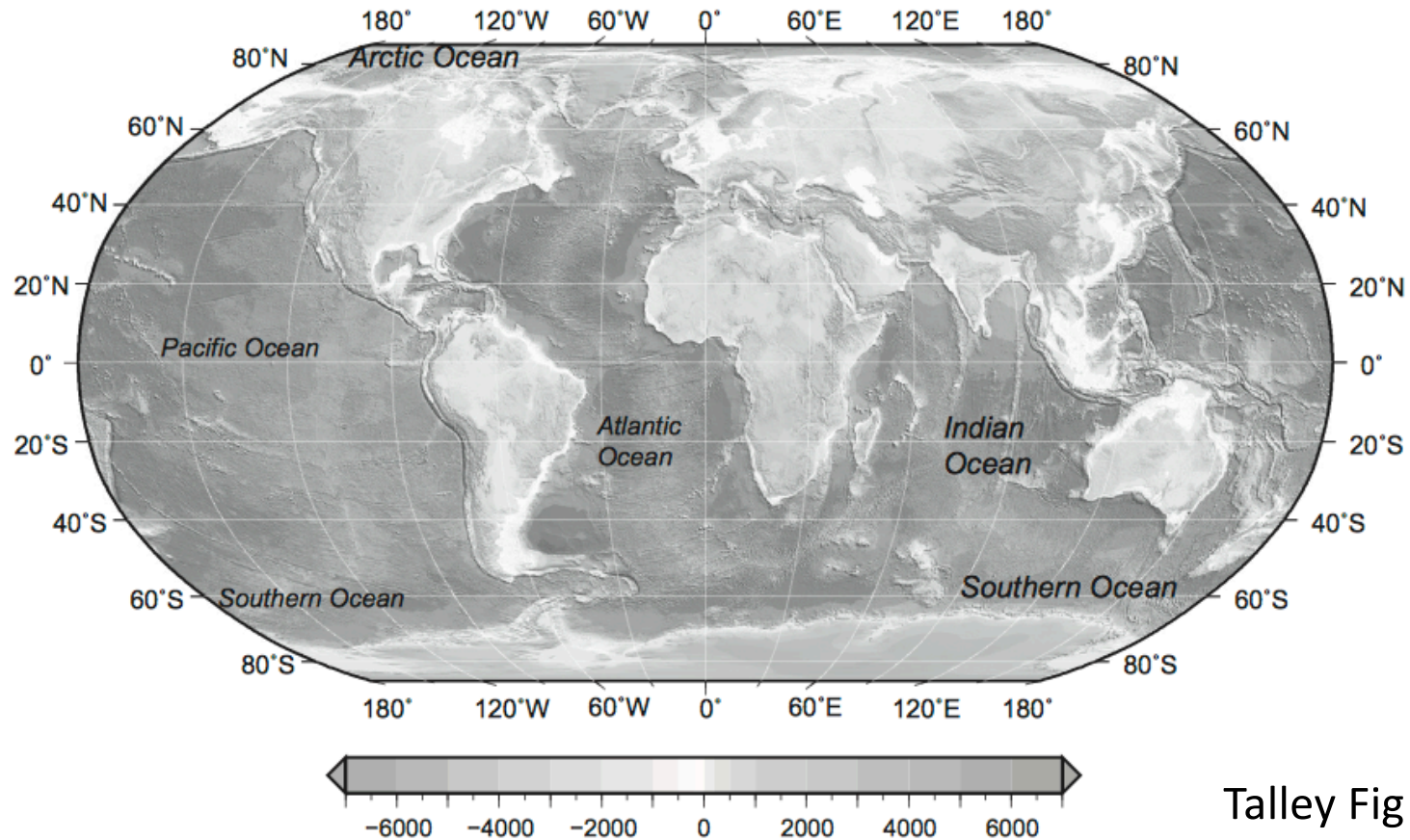
- **Part 1.** Thermodynamics and fluid mechanics (week 1 through 10 and midterm exam; October 25th)
- **Part 2.** Biogeochemical processes (week 11 through 16)

Term paper

- A review
 - Choose a topic, read reference papers, synthesize your findings
 - You could ask your academic advisor/mentor about potential topics
 - Examples: thermohaline circulation; ice-ocean interaction; global warming impacts; decadal ocean variability; phytoplankton bloom; oxygen minimum zones; ocean acidification; sediment-water interaction; ocean eddies

Week 1: Ocean bathymetry and
properties of seawater
Talley's book chapter 1-3

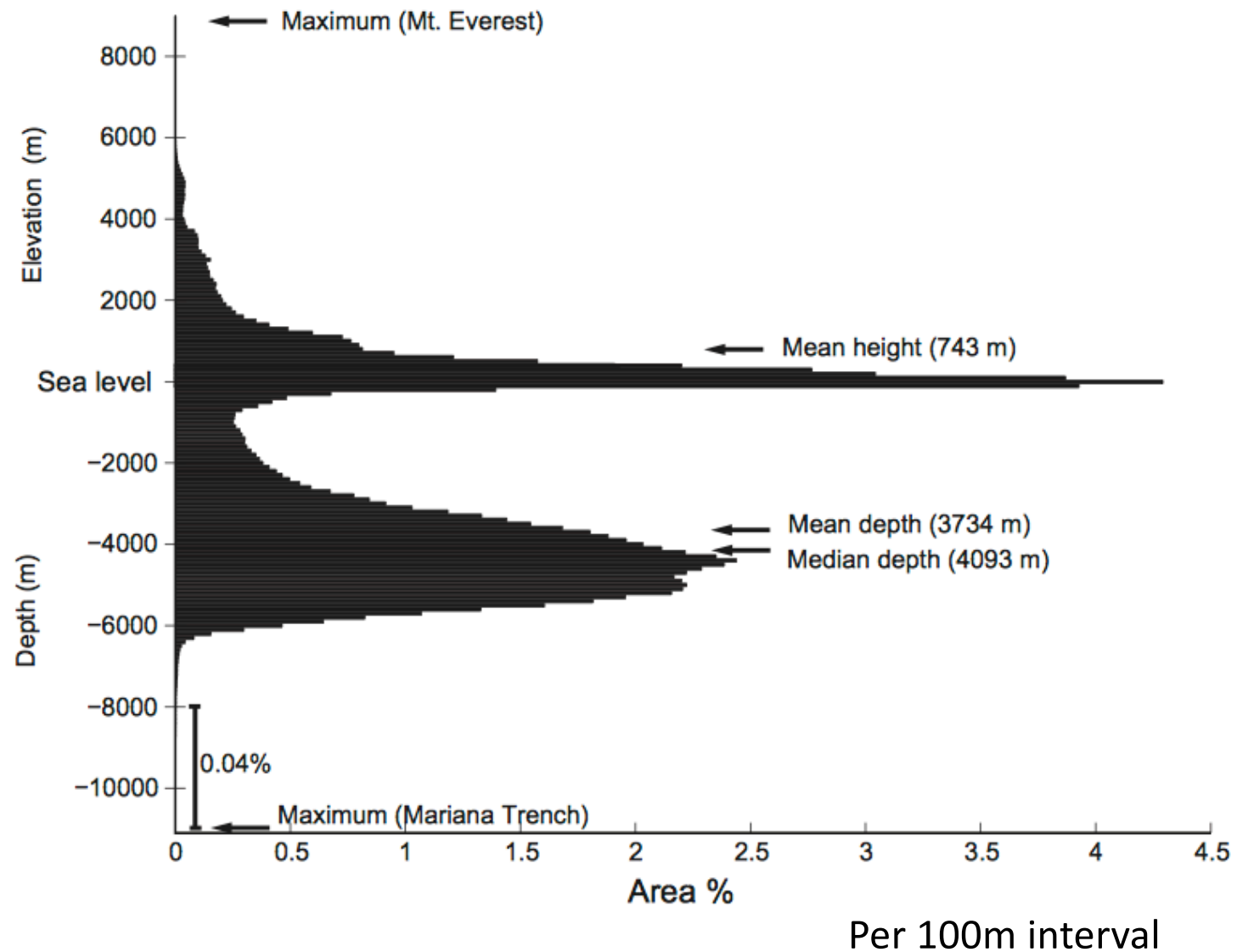
Ocean basins



Talley Fig 2.1

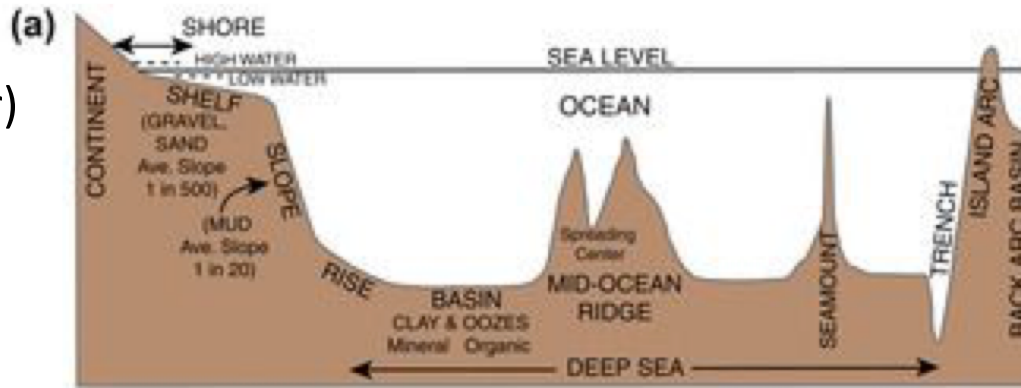
- 70% of the surface of the Earth is covered by the oceans.
- Major ocean basins are connected through narrow pathways, the Southern Ocean and the Arctic Ocean.

Mean and median depth of the oceans

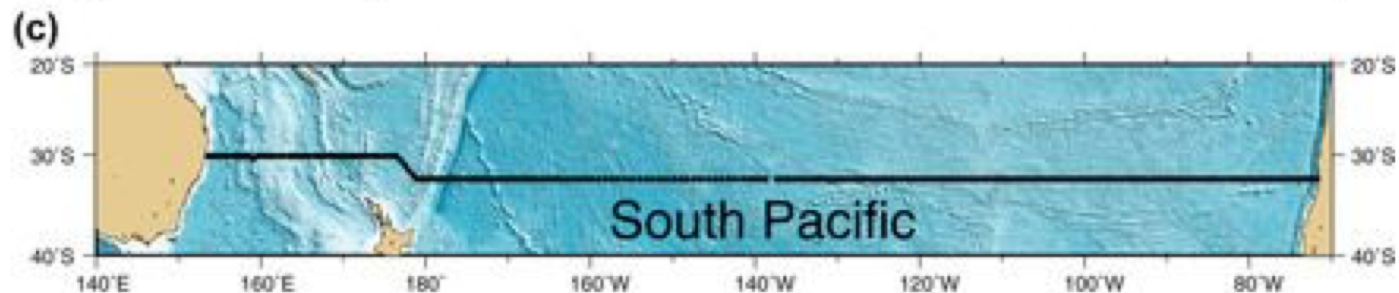
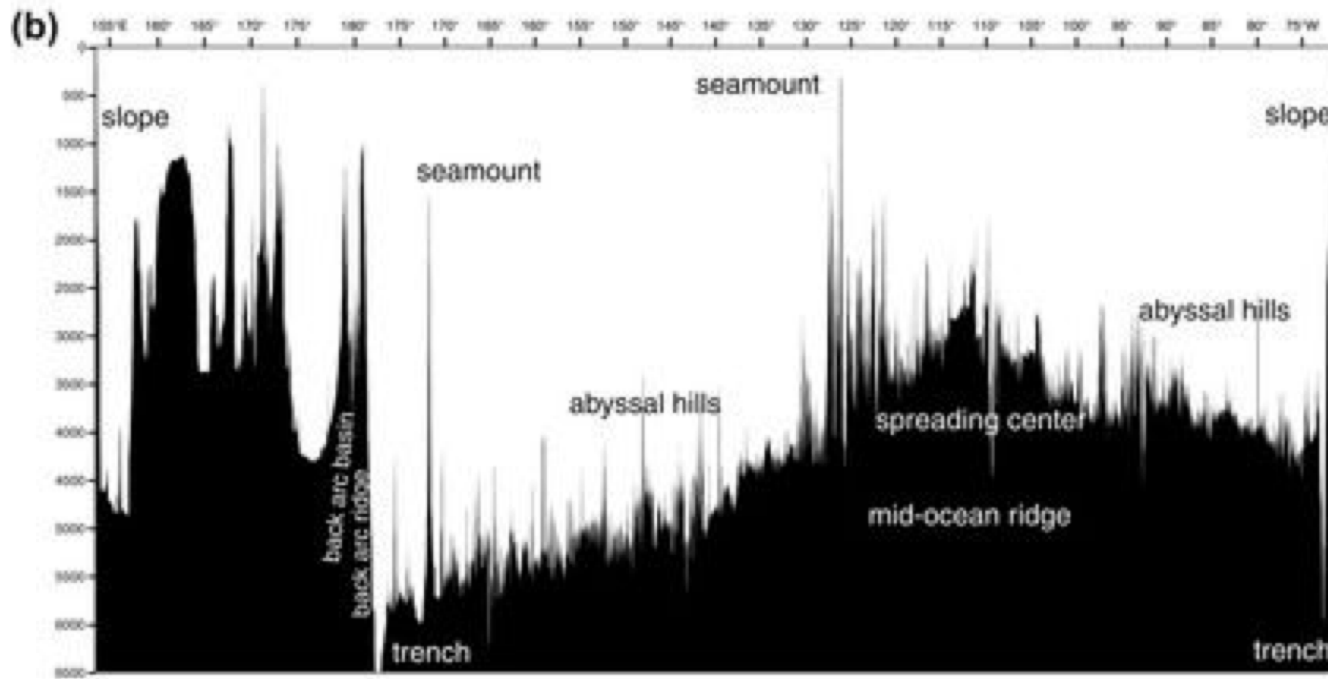


Transect of the ocean bathymetry (=shape of seafloor)

Shelf is a continuation of the continent



Open (pelagic) ocean has average depth of ~ 4,000m



Physical properties of the seawater

- 1. Pressure
- 2. Depth
- 3. Temperature
- 4. Salinity

1. Pressure

- Pressure = weight of overlying water + air
- Units = Force / area

What is “force”?

Newton's law: $\mathbf{F} = m\mathbf{a}$ where \mathbf{F} and \mathbf{a} are 3-D vector force and acceleration, and m is mass.

Units of force: mass x length / (time)²

cgs: 1 dyne = 1 gm cm / sec²

mks: 1 Newton = 1 kg m / sec²

1. Pressure

What are the units of “pressure”?

Units of pressure: dyne/cm² and N/m²

SI: 1 Pascal = 1 N/m²

Conventional: 1 bar = 10⁶ dynes/cm² = 10⁵ N/m²

approximately the atmospheric pressure at sea level

1 atmosphere = 1000 millibar = 1 bar

1 decibar = 0.1 bar

Decibar or “**dbar**” is the most common pressure unit used in oceanography because it is so close to 1 m, given the density of seawater: approximately the pressure for 1 meter of seawater. (Don't use the abbreviation “db” because dB is used for decibels – sound intensity.)

2. Relating pressure and depth

“Hydrostatic balance”

From Newton’s law, use the force balance in the vertical direction (per unit area)

P: vertical force = pressure

$\int \rho dz$: mass = density integrated over the vertical extent of the fluid

-g: vertical acceleration = gravity (positive upward)

Newton’s law: $P = -\int \rho g dz$

Differential form

$$\frac{\partial P}{\partial z} = -\rho g$$

where ρ is the density of seawater, $\rho \sim 1025 \text{ kg/m}^3$,

Gravitational constant, $g \sim 9.8 \text{ m/s}^2$

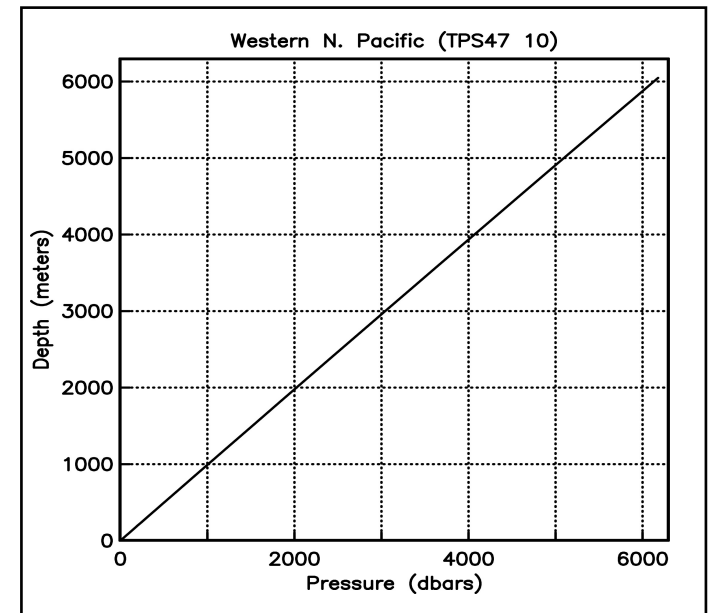
2. Relating pressure and depth

We can then solve for the change in pressure for a given change in depth.

For:

$\Delta z = 1$ meter, density $\rho \sim 1025 \text{ kg/m}^3$, and $g = 9.8 \text{ m/s}^2$, we get

$$\Delta p = -\rho g \Delta z = (1025 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(1 \text{ m}) = 10045 \text{ kg/(m s}^2) = 0.10045 \text{ bar} = 1.0045 \text{ dbar}$$

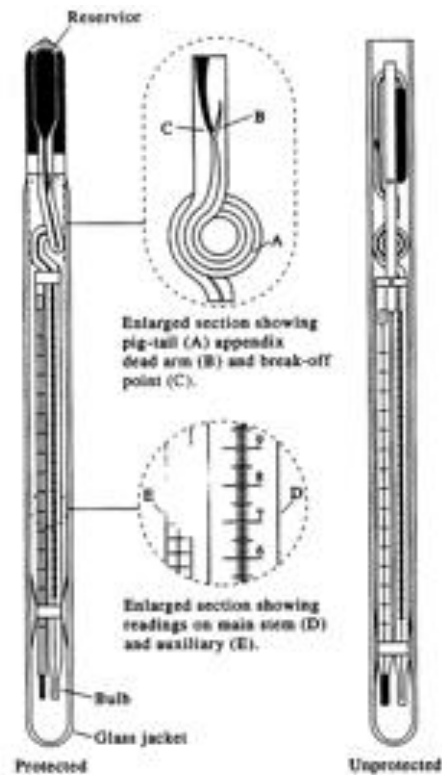


3. Temperature

- Temperature units: Kelvin and Celsius
- Kelvin is absolute temperature, with 0 K at the point of zero entropy (no motion of molecules)
- Celsius 0°C at melting point at standard atmosphere (and no salt, etc)
- $T_K = T_C + 273.16^\circ$
- Ocean temperature range: freezing point to about 30° or 31°C
- (Freezing point is $< 0^\circ\text{C}$ because of salt content)

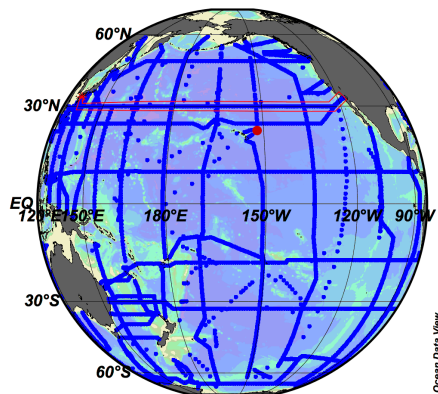
Observing pressure & temperature

- Reverse thermometer pair (old)
- Quartz transducer (electrical)
- Thermistor (electrical)

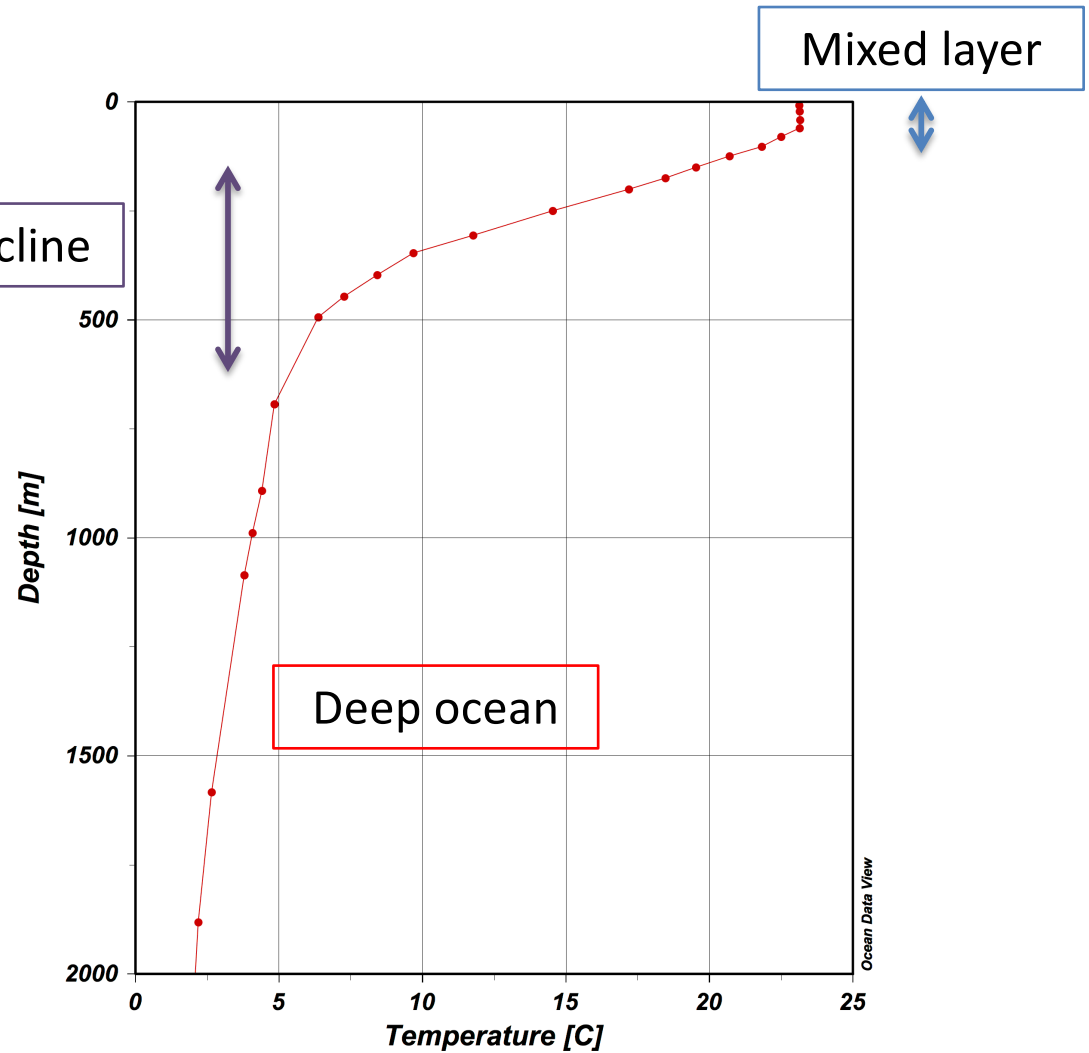


Temperature “profile”

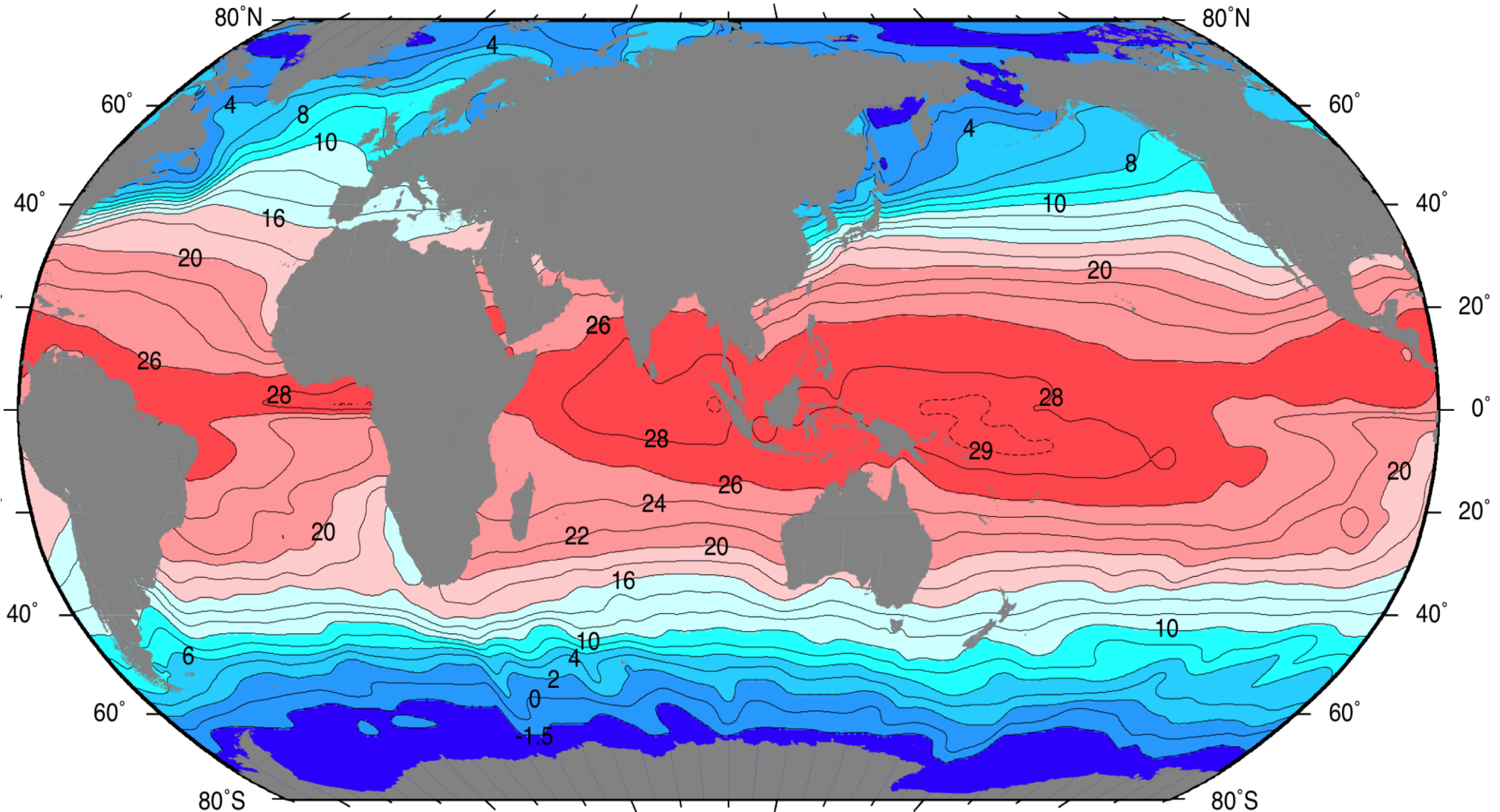
eWOCE



Thermocline



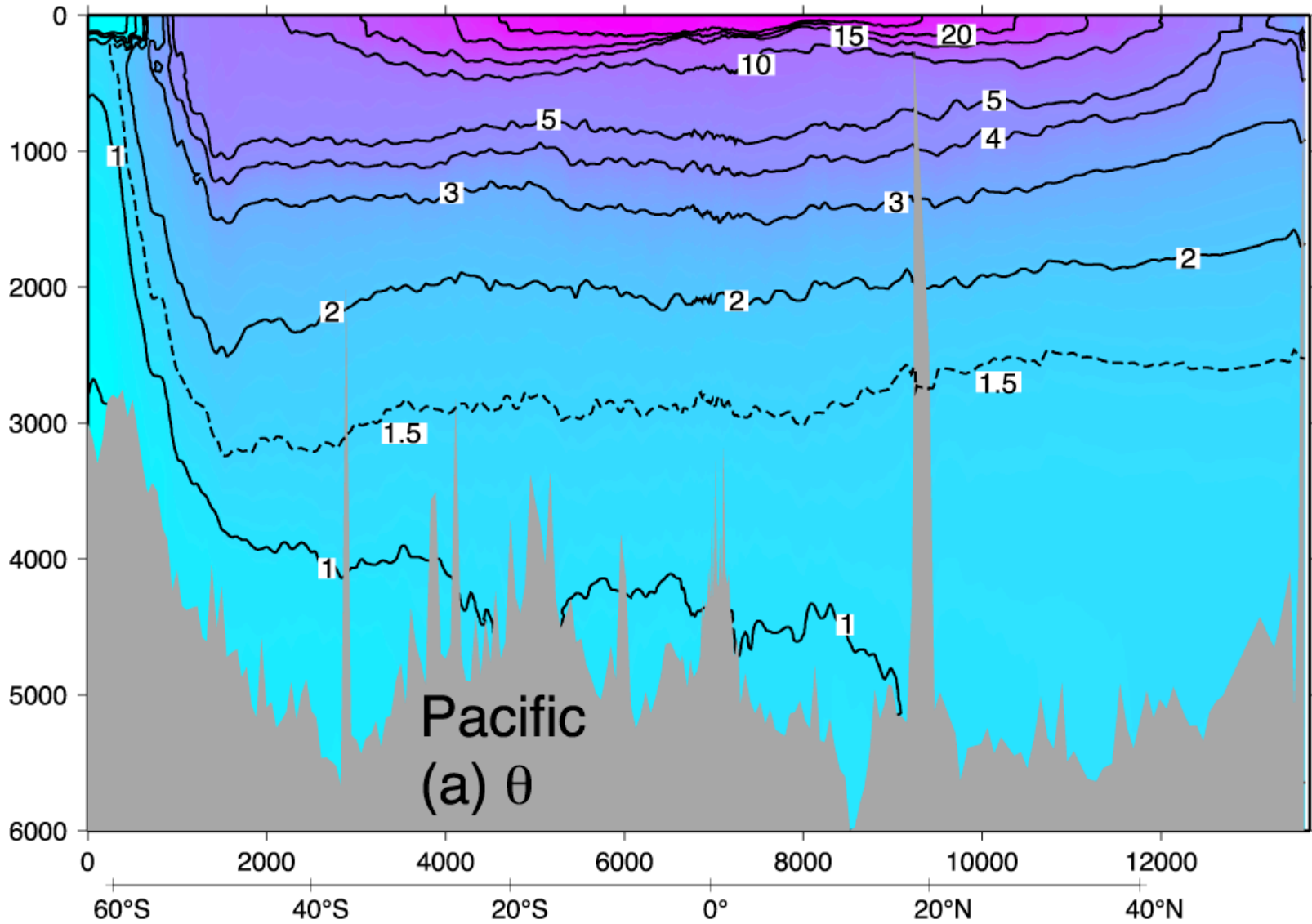
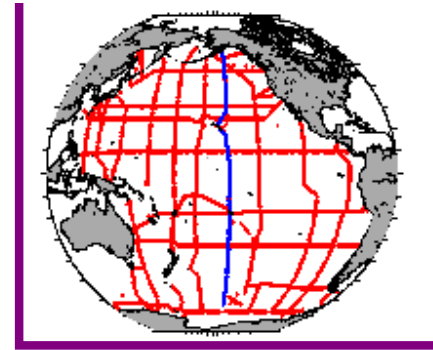
Surface temperature (°C)



Note total range and general distribution of temperature

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

Pacific potential temperature section ("potential" defined on later slides)



Note total range and general distribution of temperature

Potential temperature

Water (including seawater) is compressible.

If we compress a volume of water adiabatically (no exchange of heat or salt), then its temperature increases. (“adiabatic compression”)

When we think of vertical motion in the ocean, we are not interested in the adiabatic compression effect on temperature. We prefer to track something that is conserved following the parcel.

Define “potential temperature” as the temperature a parcel of water has if moved adiabatically (without heat exchanges or mixing) to the sea surface.

Use the Greek letter θ to denote potential temperature.

Potential temperature is always lower than measured temperature except at the sea surface (where they are the same by definition)

Potential temperature expressions

The change in temperature with pressure that is due solely to pressure is called the “adiabatic lapse rate”:

$$\Gamma(S, T, p) = \partial T / \partial p \quad (> 0)$$

In the atmosphere, the adiabatic lapse rate is equivalent to 6.5°C per 1000 m altitude.

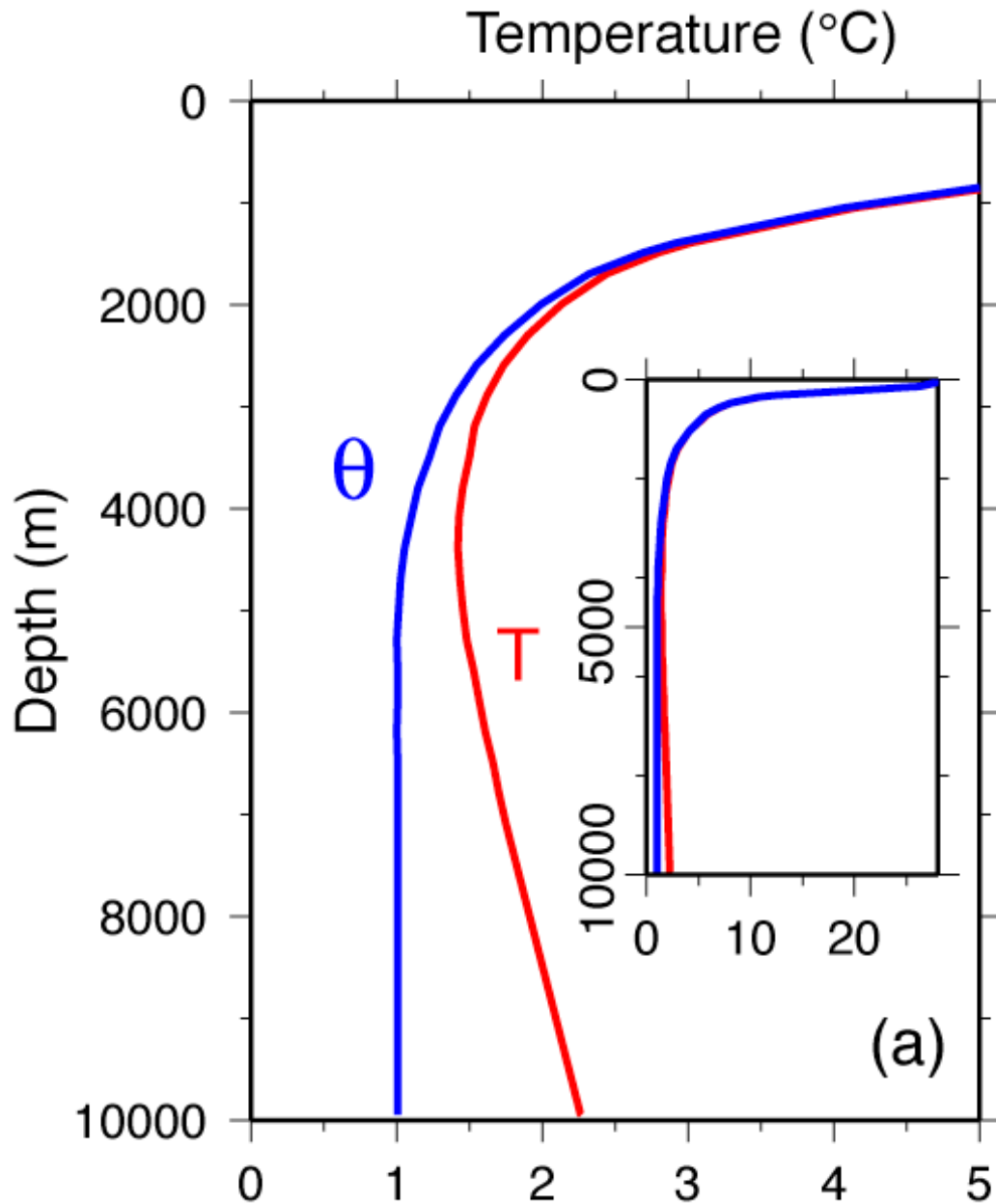
In the ocean, the adiabatic lapse rate is about 0.1°C per 1000 m depth (1000 dbar pressure).

Potential temperature is defined as

$$\theta(S, T, p) = T + \int_p^{p^{ref}} \Gamma(S, T, p') dp'$$

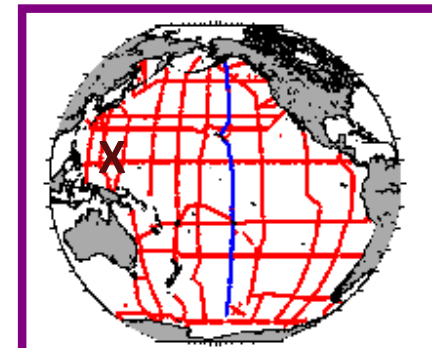
Again: potential temperature is always lower than measured temperature except at the sea surface (where they are the same by definition) ($p_{ref} = 0$ dbar, p is > 0 dbar)

Pressure effect on temperature:
Mariana Trench (the most extreme example because of its depth)



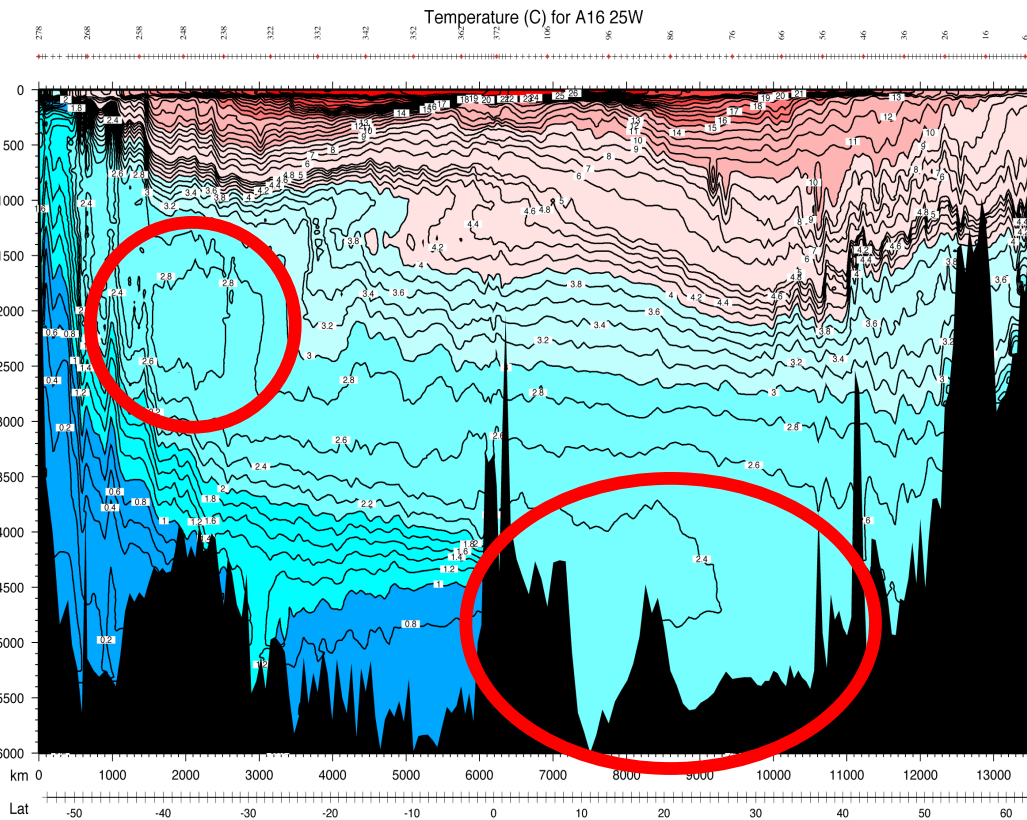
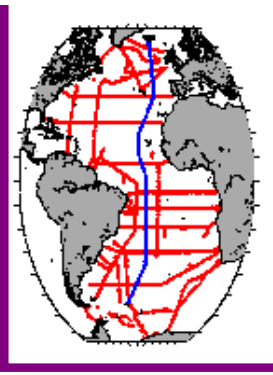
Note the measured temperature has a minimum around 4000 dbar and increases below that.

Potential temperature is almost exactly uniform below 5000 m: the water column is “adiabatic”.(This is because all of the water in this trench spilled into it over a sill that was at about 5000 m depth.)

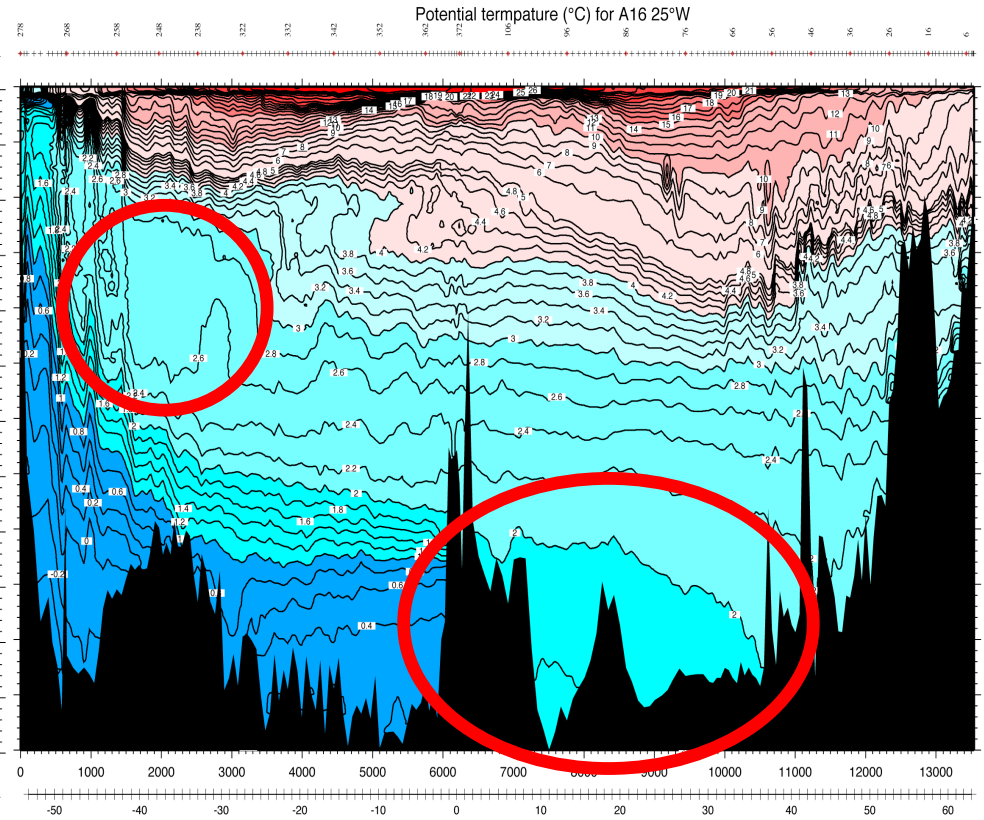


DPO Figure 4.9

Atlantic temperature and potential temperature sections for contrast

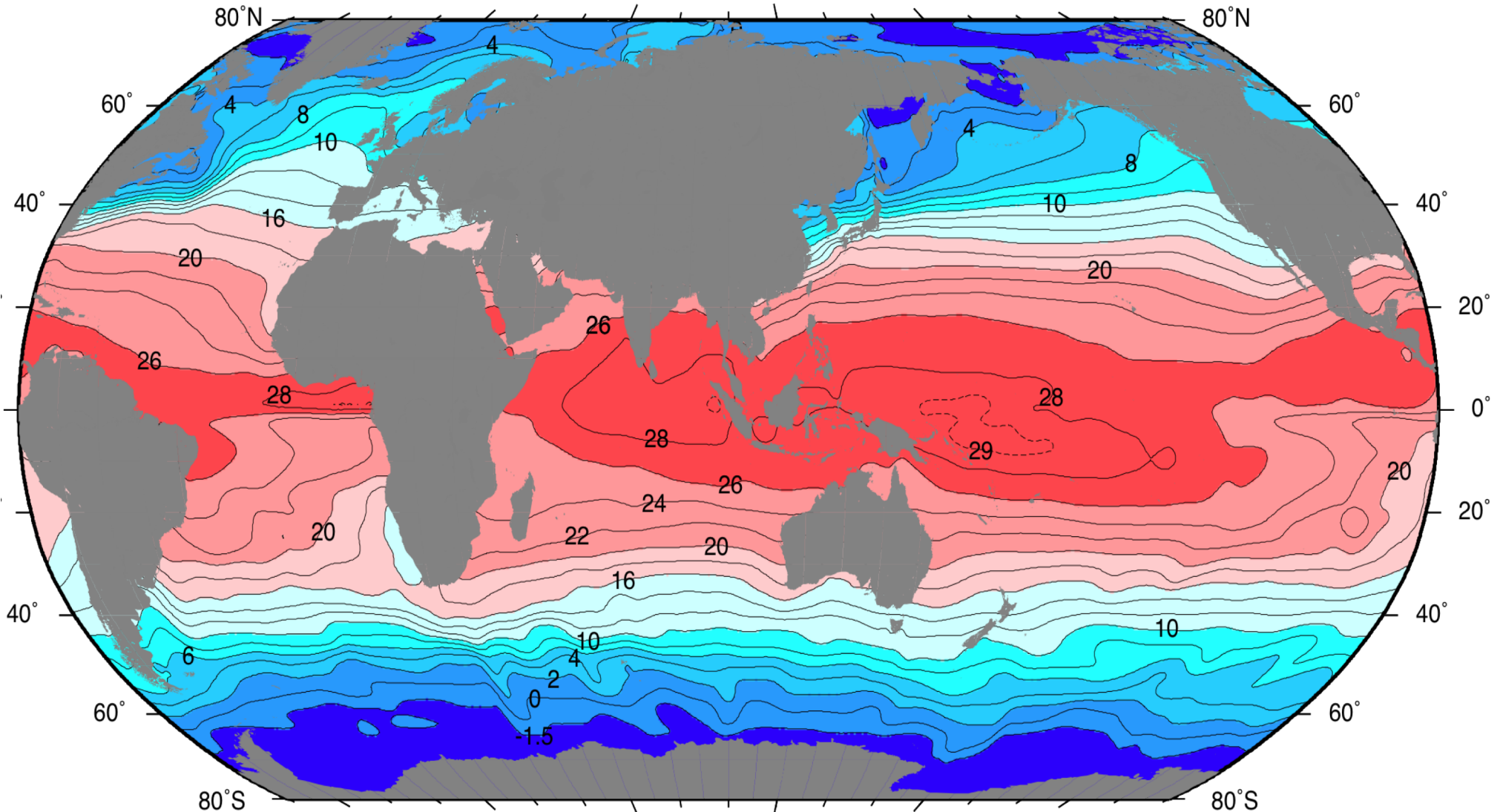


Temperature



Potential temperature

Surface temperature (°C)



Note total range and general distribution of temperature

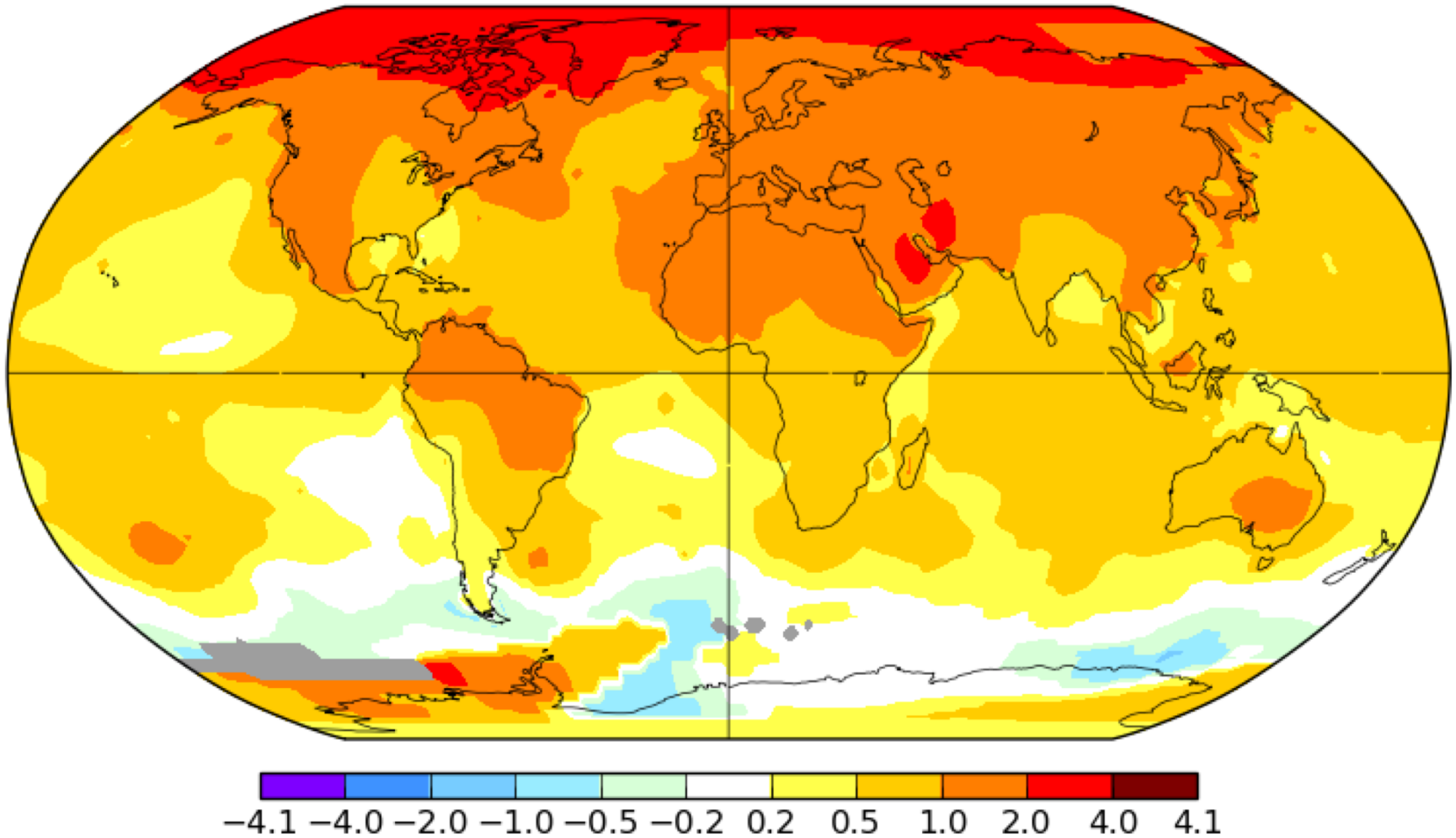
DPO Figure 4.1: Winter data from Levitus and Boyer (1994)

Recent changes in surface temperature

Annual J-D

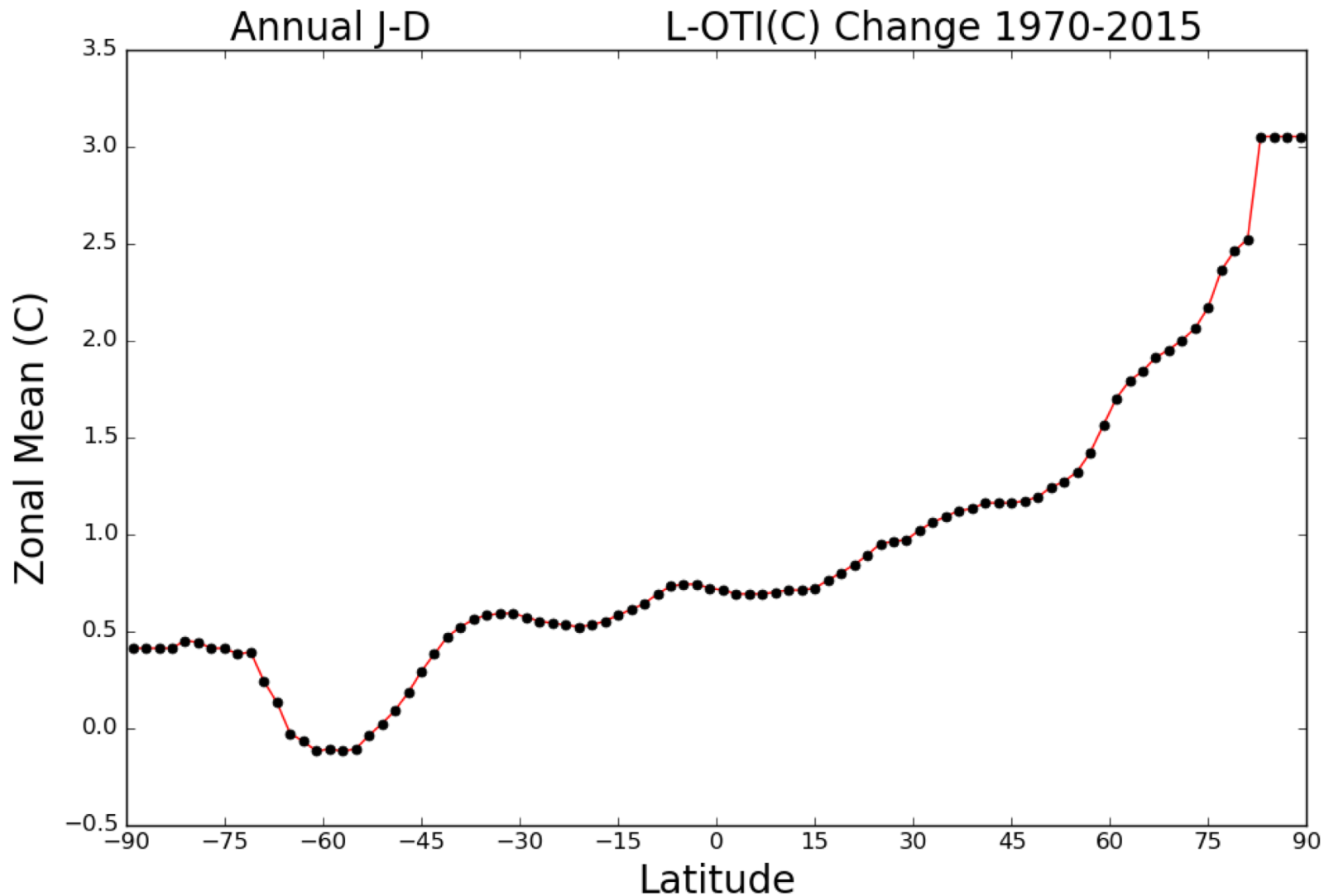
L-OTI(°C) Change 1970-2015

0.77

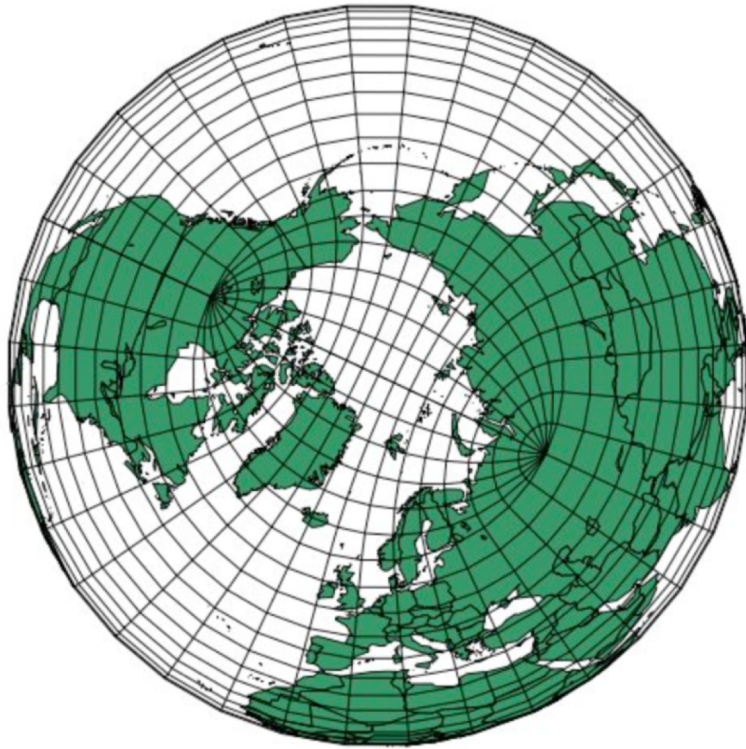


<https://data.giss.nasa.gov/gistemp/maps/>

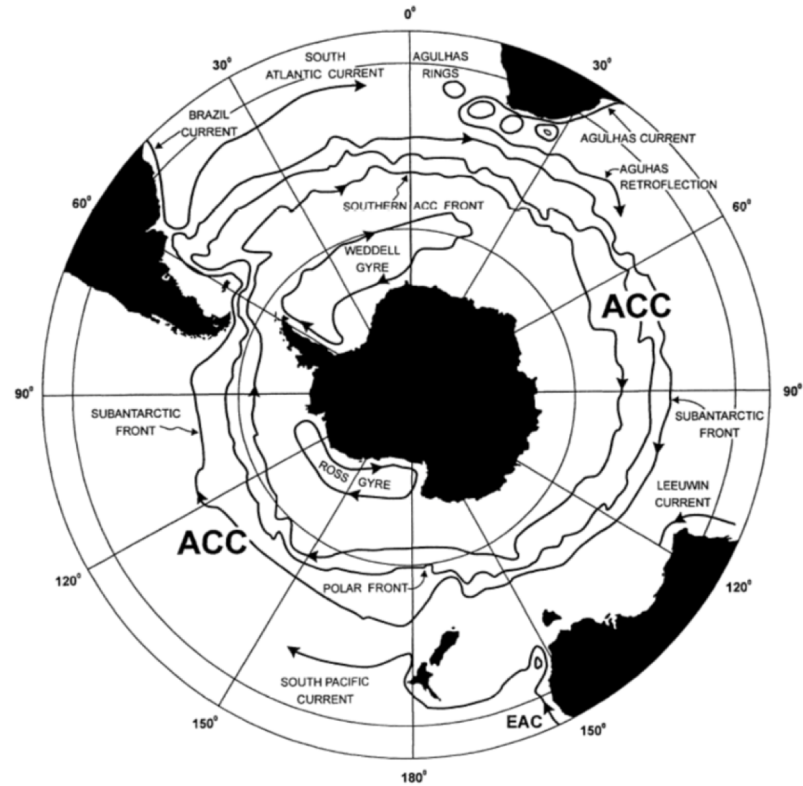
Zonal mean temperature trend



Zonal mean = average across the constant latitude circles



North Pole:
Ocean + sea-ice
Surrounded by **land**

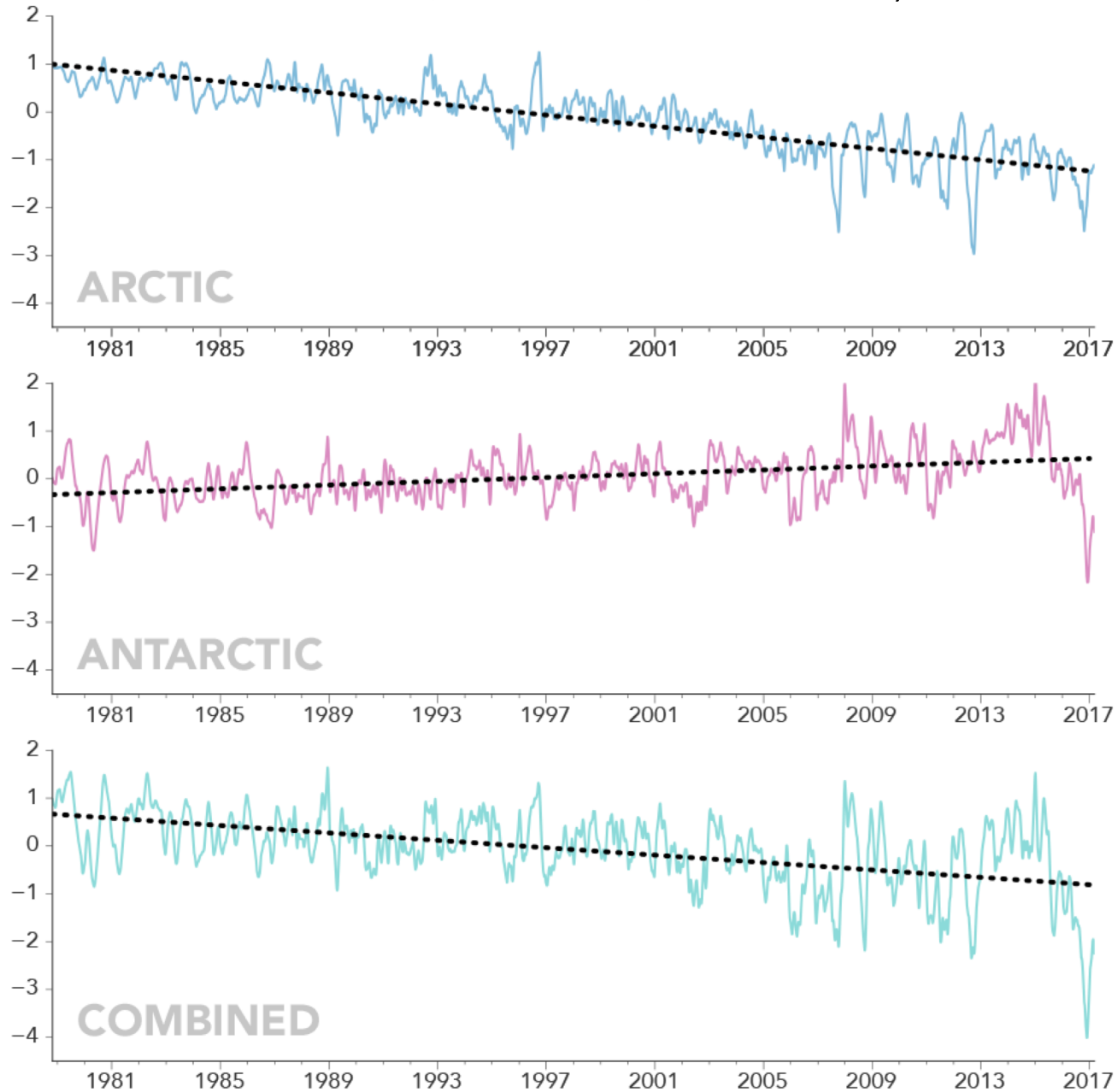


South Pole:
Land mass + Land ice
Surrounded by **oceans**

Sea ice area

Deviation in Sea Ice Extent (x 1 million km²)

J. Steven, NASA Earth Observatory



4. Salinity

- “Salinity” in the oldest sense is the mass of matter (expressed in grams) dissolved in a kilogram of seawater = **Absolute salinity**
- Units are parts per thousand (o/oo) or “psu” (practical salinity units), or unitless (preferred UNESCO standard, since salinity is mass/mass, but this has now changed again, in 2010)
- The concept of salinity is useful because all of the constituents of sea salt are present in almost equal proportion everywhere in the ocean.
- This is an empirical “**Law of equal proportions**”
- (There are really small variations that are of great interest to marine chemists, and which can have a small effect on seawater density, but we mostly ignore them; note that the new definition of salinity in TEOS-10* takes these small variations into account.)

*TEOS-10 is “Thermodynamic Equation of State 2010”

4. Salinity

•“Salinity” in the oldest sense is the mass of matter (expressed in grams) dissolved in a kilogram of seawater = **Absolute salinity**

- Amount of salt per unit mass of seawater

$$S = \frac{\text{mass of salt [g]}}{1\text{kg of seawater}}$$

- S in a typical seawater is about 35.

Salinity measurement

- Typical ocean salinity is 34 to 36 (i.e. 34 to 36 gm seasalt/kg seawater)

- Measurements:

Oldest: evaporate the seawater and weigh the salts

Old: titration method to determine the amount of chlorine, bromine and iodine (prior to 1957)

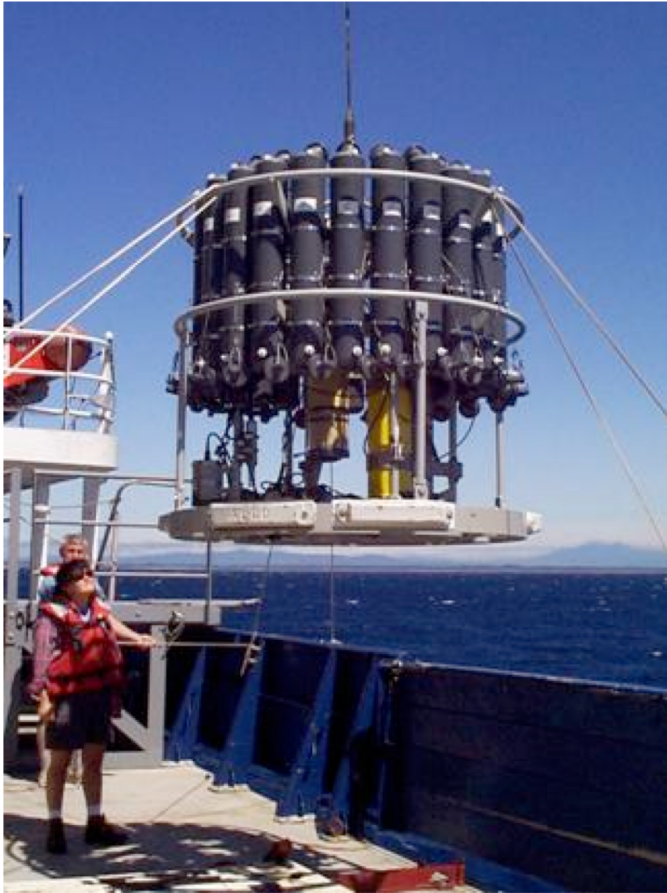
Modern: Use **seawater conductivity**, which depends mainly on temperature and, much less, on salinity, along with accurate temperature measurement, to compute salinity.

Modern conductivity measurements:

- (1) in the lab relative to a **reference standard**

- (2) profiling instrument (which **MUST** be calibrated to (1))

Salinity instruments



Bottles for collecting water samples



Autosalinometer for running salinity analyses relative to standard seawater



CTD (conductivity, temperature, pressure) for measuring conductivity in a profile (on the fly)

TEOS-10: Thermodynamic Equation of State 2010

There are really small variations* that are of great interest to marine chemists, and which can have a small effect on seawater density, but we mostly ignore them; note that the new definition of salinity in TEOS-10* takes these small variations into account.

These variations comes from the spatial variation in silicate, nitrate and alkalinity.

“Absolute salinity” (TEOS-10)

Absolute salinity = reference salinity + correction for other stuff

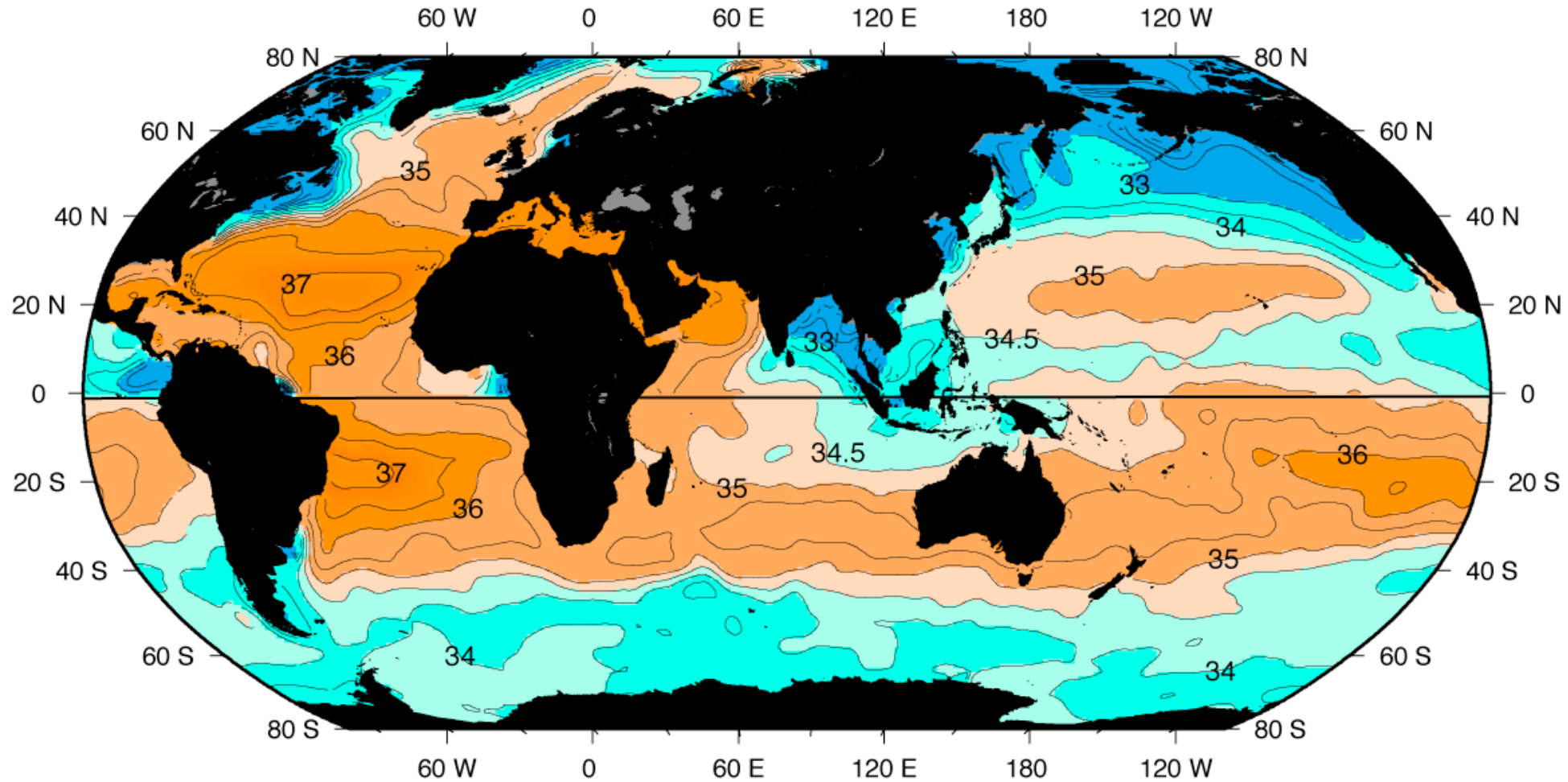
$$S_A = S_R + \delta S_A$$

Reference salinity $S_R = 35.16504/35$ * Practical salinity = 1.0047*psu

Reference salinity has been corrected for new knowledge (since 1978) about sea water stoichiometry as well as new published atomic weights.

The correction δS_A is for dissolved matter that doesn't contribute to conductivity variations: silicate, nitrate, phosphate, etc.

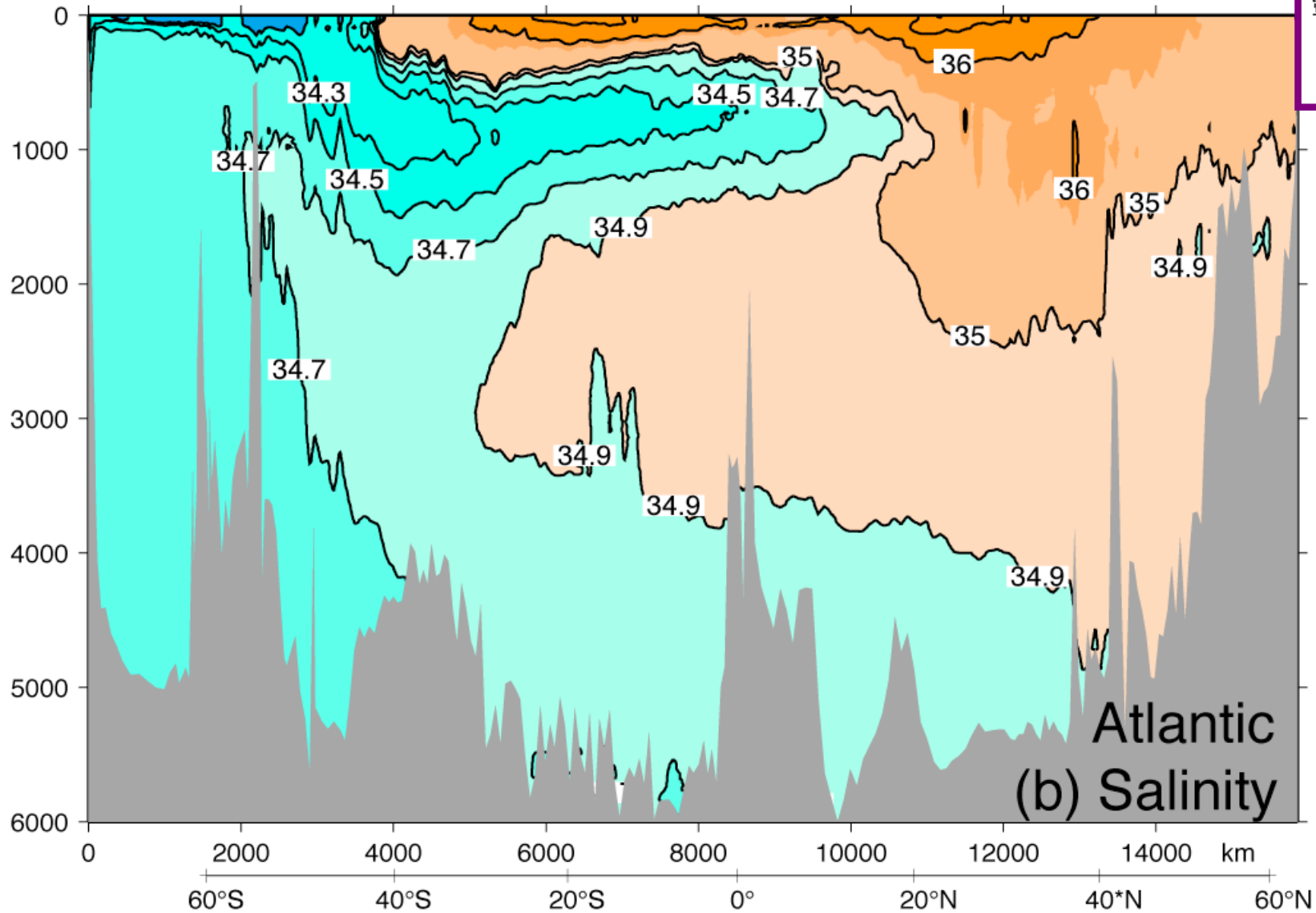
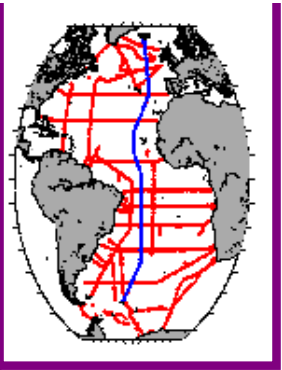
Surface salinity



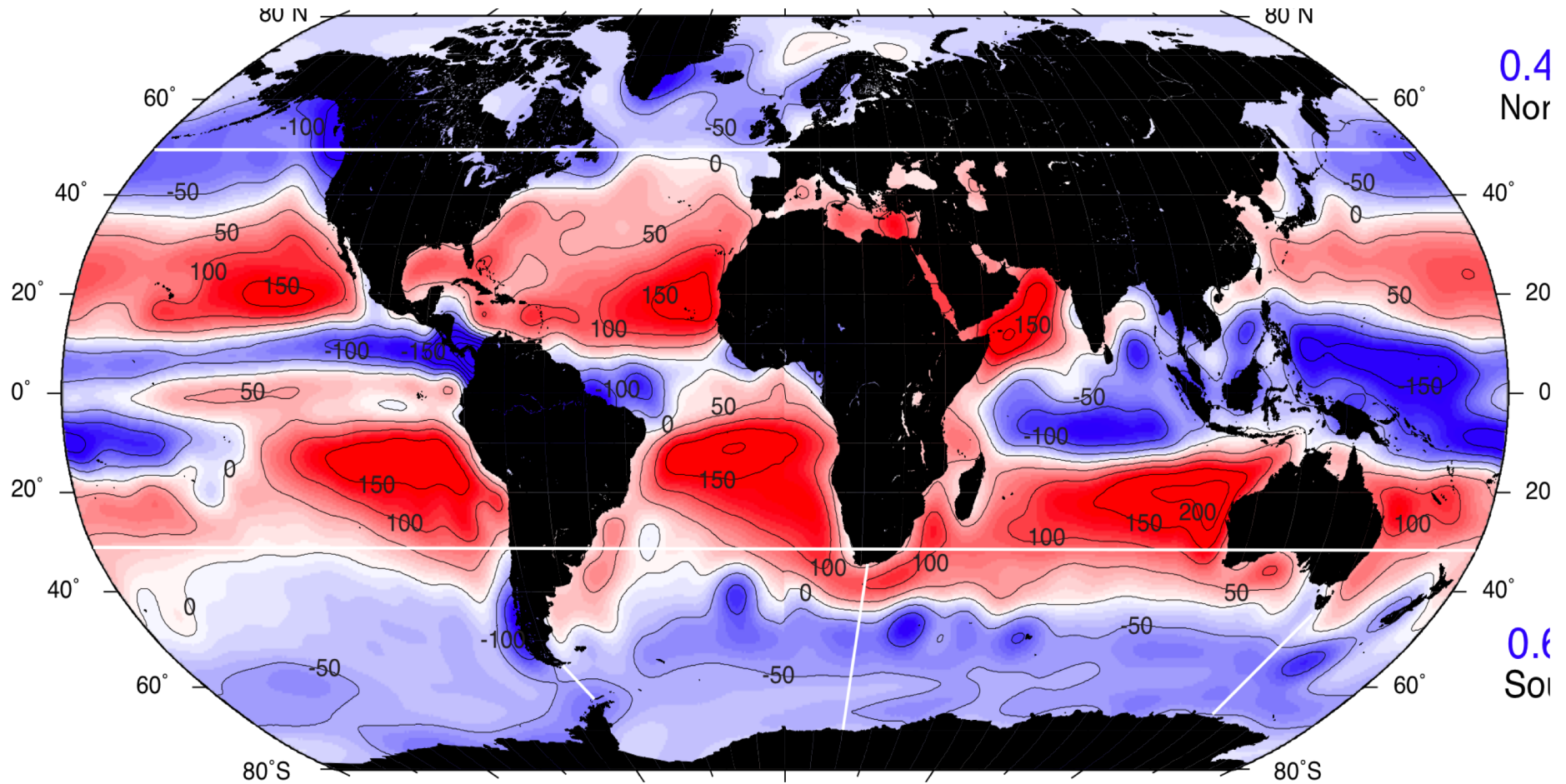
Note range of values and general distribution

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).

Atlantic salinity section



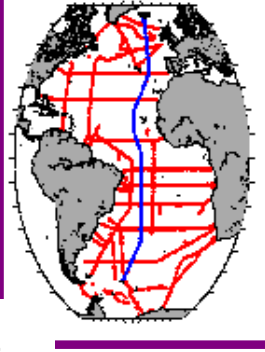
What sets salinity? Precipitation + runoff minus evaporation (cm/yr)



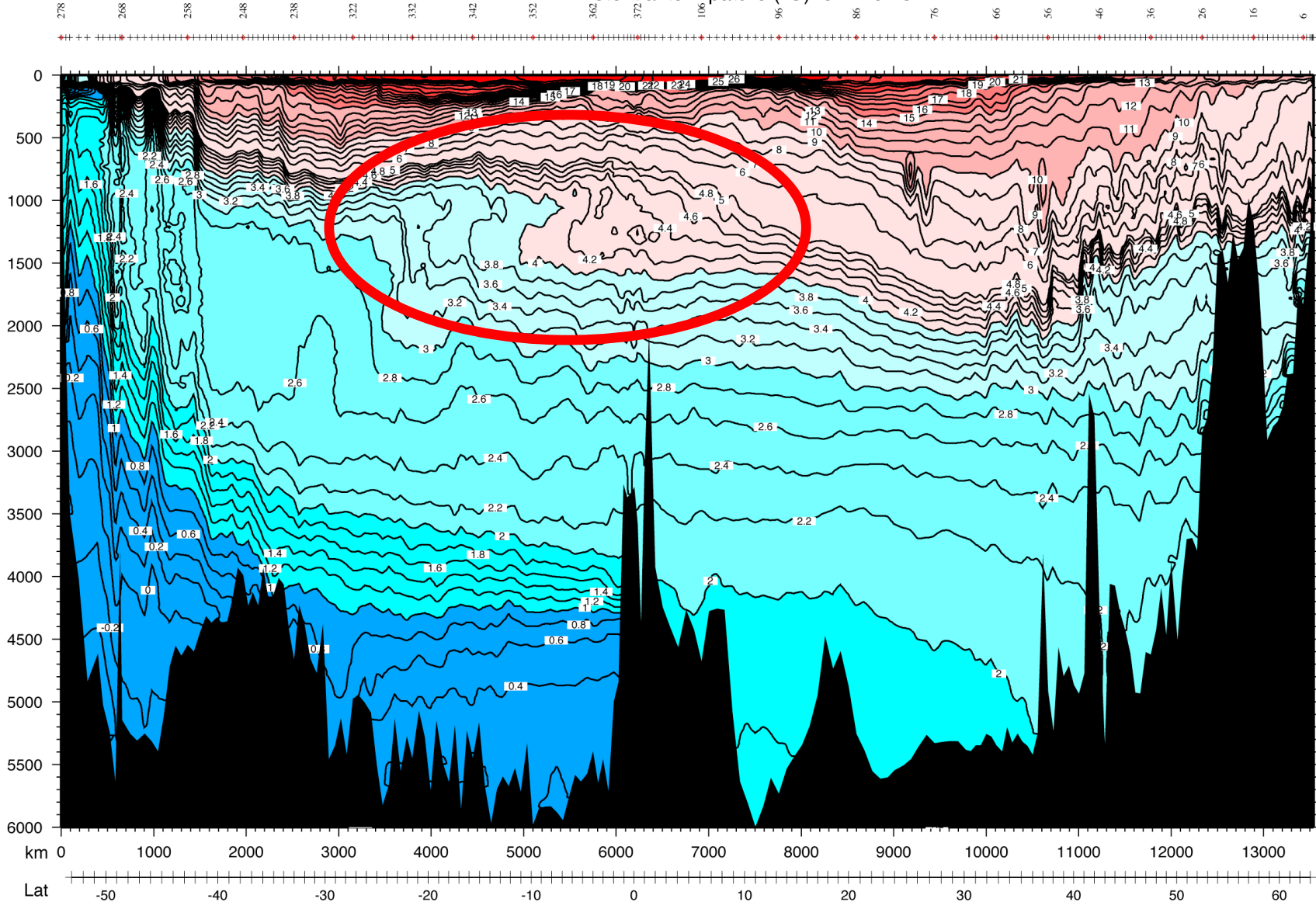
Salinity is set by freshwater inputs and exports since the total amount of salt in the ocean is constant, except on the longest geological timescales

Return to Atlantic potential temperature

what about this inversion – why is it vertically stable?



Potential temperature (°C) for A16 25°W



Density of seawater

Seawater density depends on S, T, and p

$$\rho = \rho(S, T, p) \quad \text{units are mass/volume (kg/m}^3\text{)}$$

Specific volume

$$\alpha = 1/\rho \quad \text{units are volume/mass (m}^3\text{/kg)}$$

Pure water has a maximum density (at 4°C, atmospheric pressure) of

$$\rho(0,4^\circ\text{C},1\text{bar}) = 1000 \text{ kg/m}^3 = 1 \text{ g/cm}^3$$

Seawater density ρ ranges from about 1022 kg/m³ at the sea surface to 1050 kg/m³ at bottom of ocean, mainly due to compression

Equation of state (EOS)

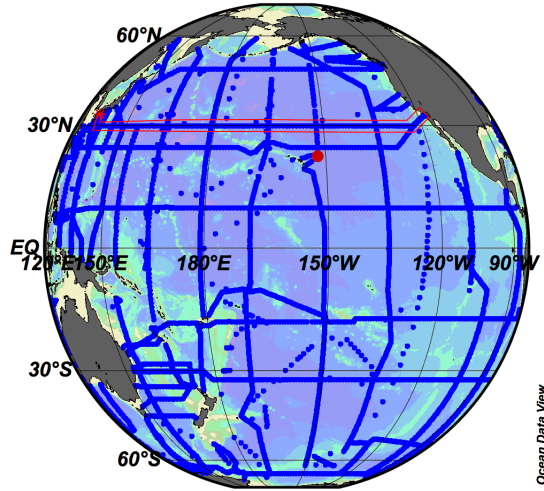
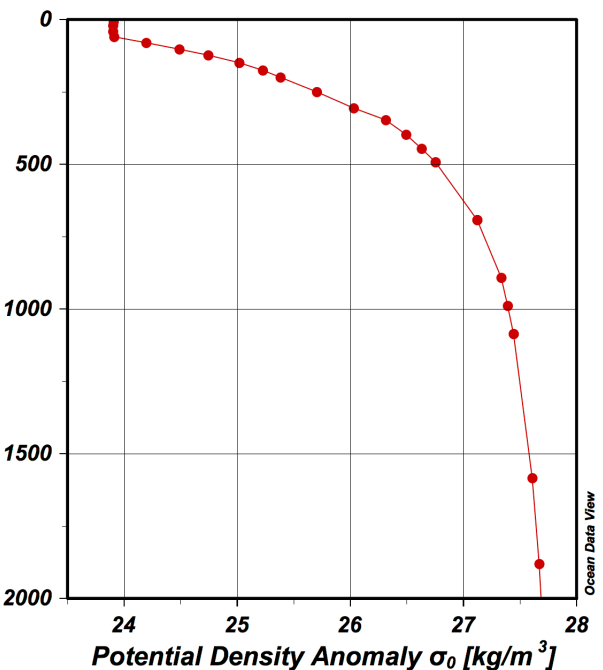
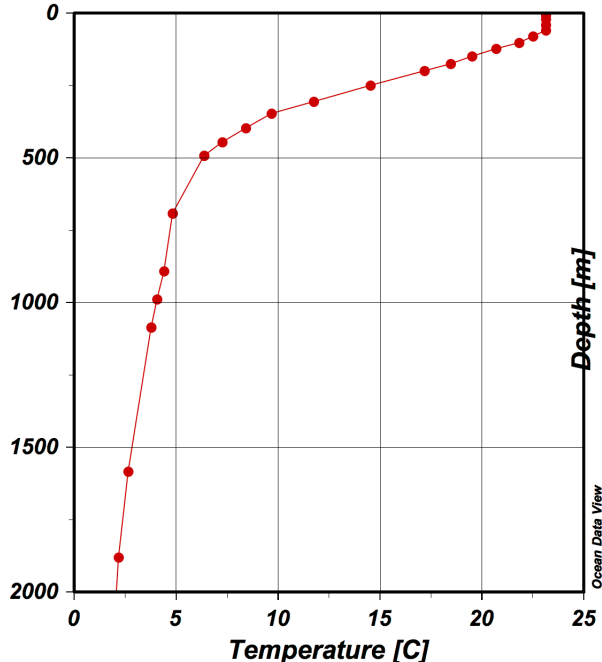
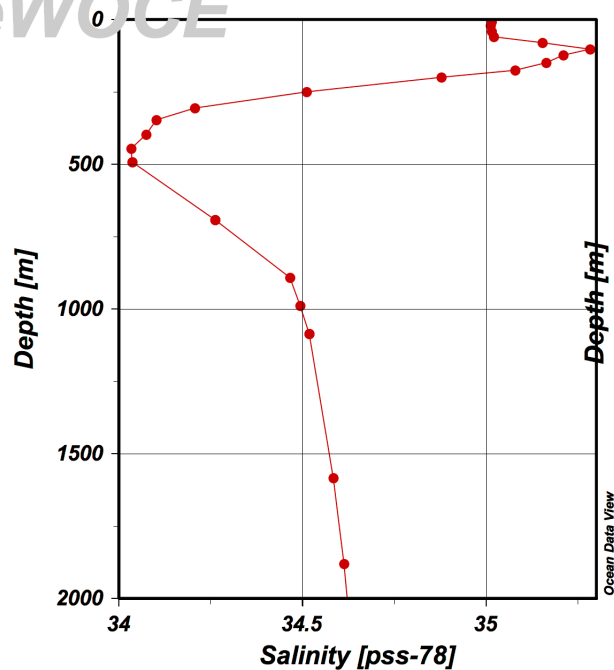
- Common way to express density is as (“sigma”)

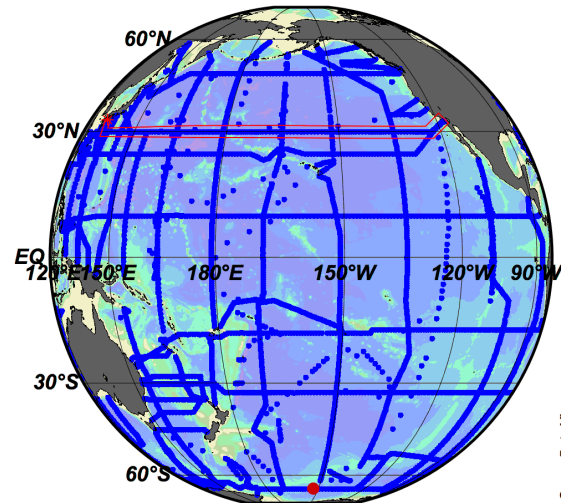
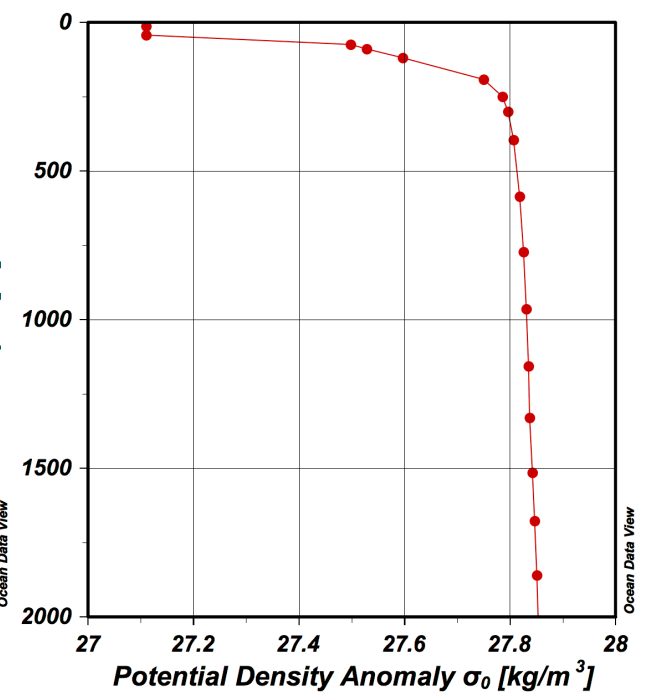
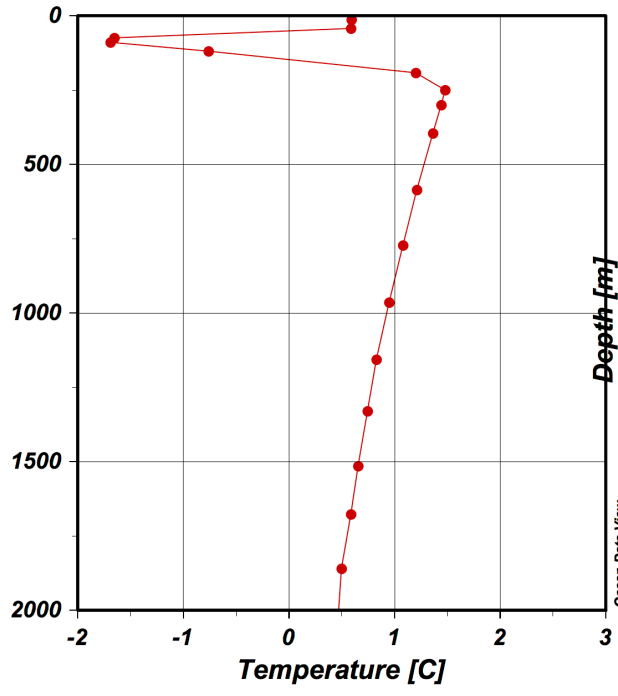
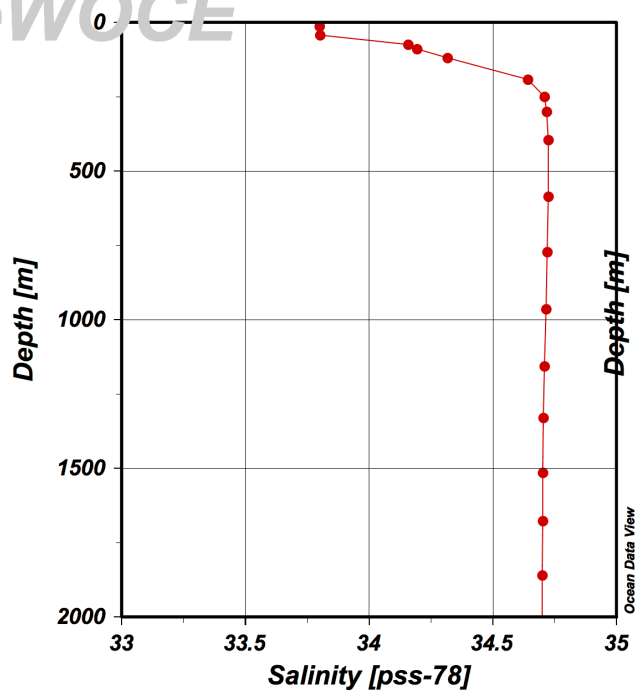
$$\sigma (S, T, p) = \rho(S, T, p) - 1000 \text{ kg/m}^3$$

- The EOS is **nonlinear**
- This means it contains products of T, S, and p with themselves and with each other (i.e. terms like T^2 , T^3 , T^4 , S^2 , TS , etc.)
- You will calculate density of seawater in HW#2.

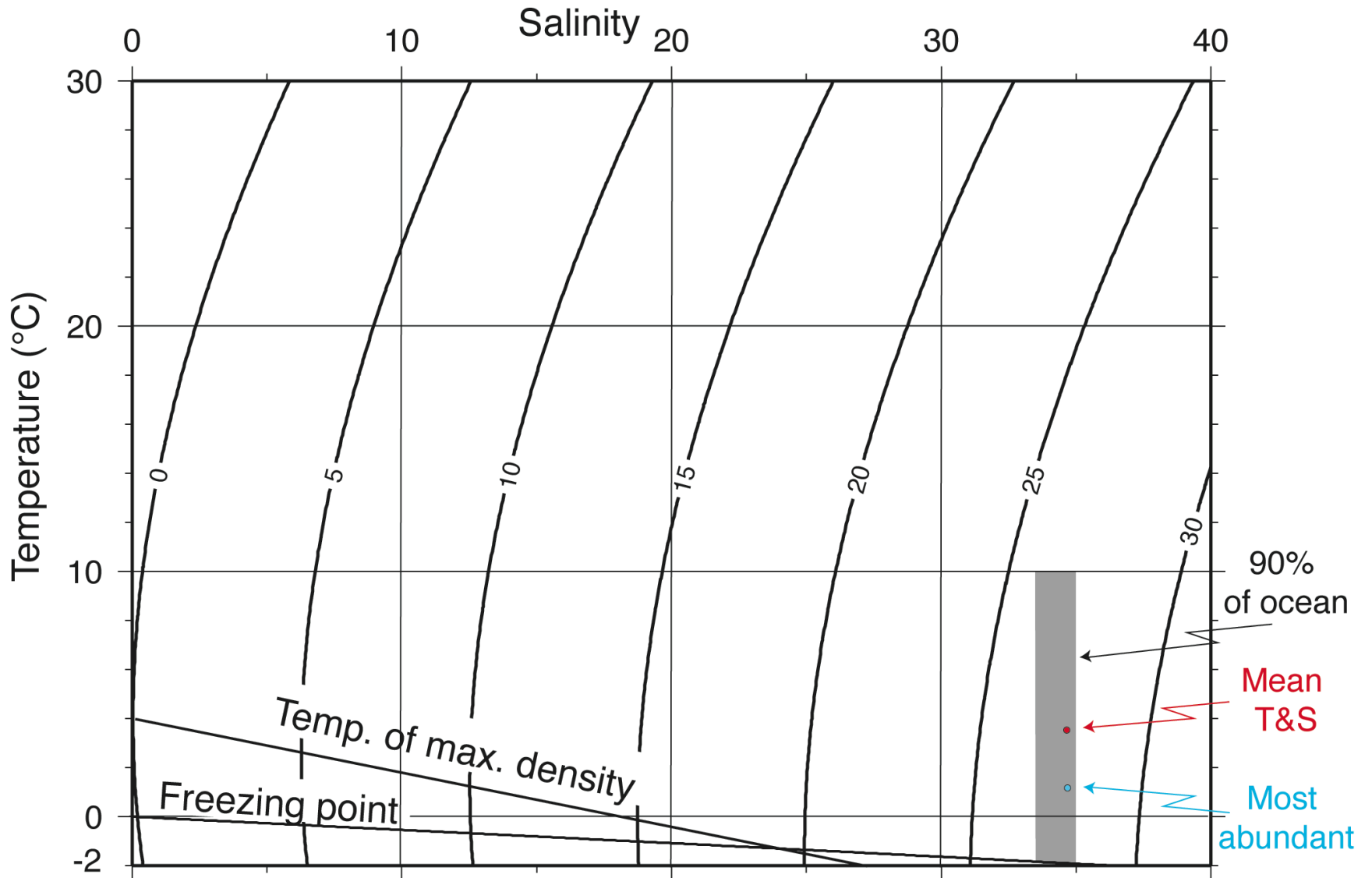
Salinity, temperature and density

eWOCE





Seawater density, freezing point



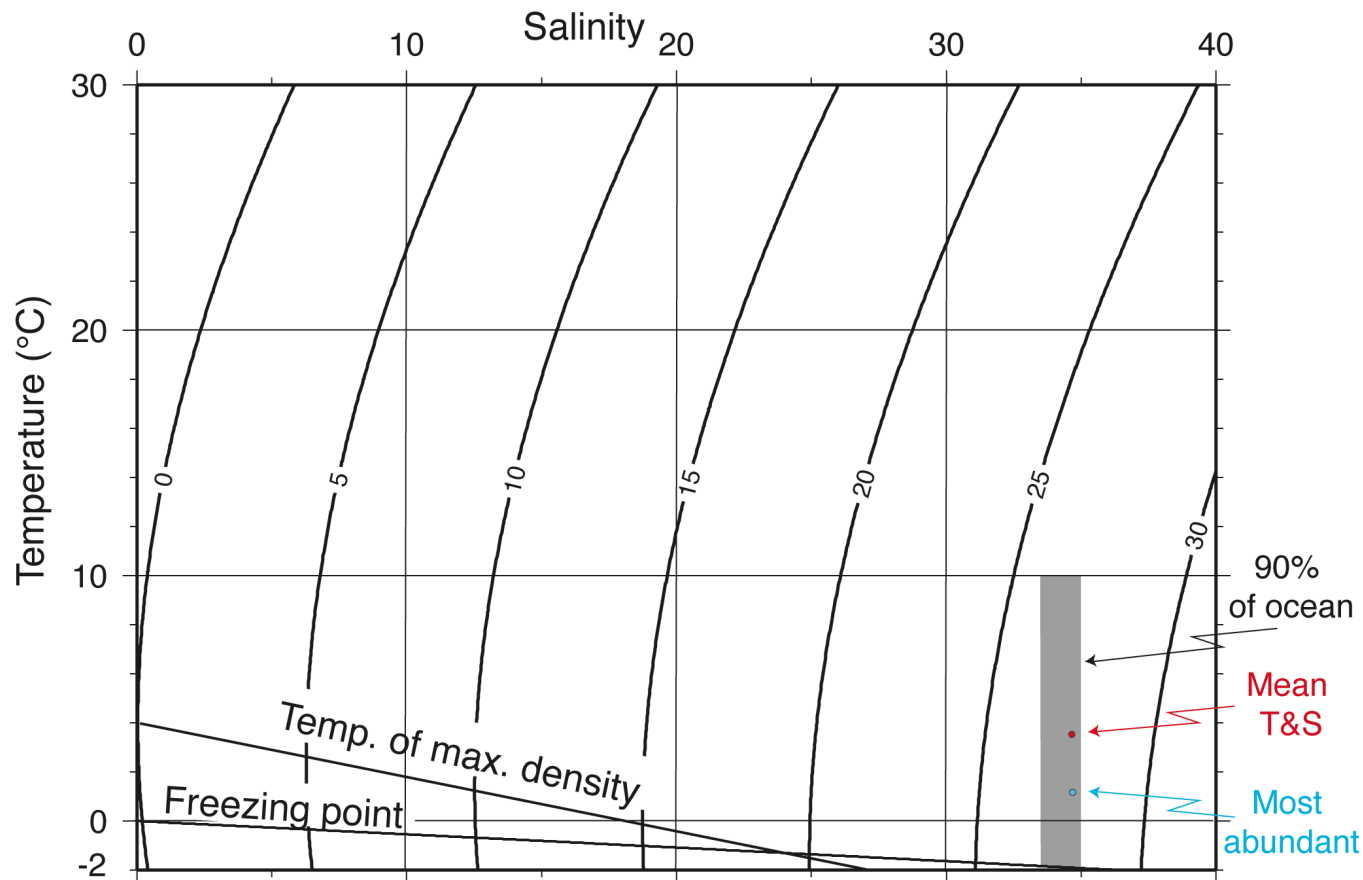
DPO Figure 3.1

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 ($\sigma_\theta=27.6$ to 27.7 kg/m³)

Mean temperature and salinity are 3.5°C and 34.6 psu



DPO Figure 3.1

freezing point and sea ice

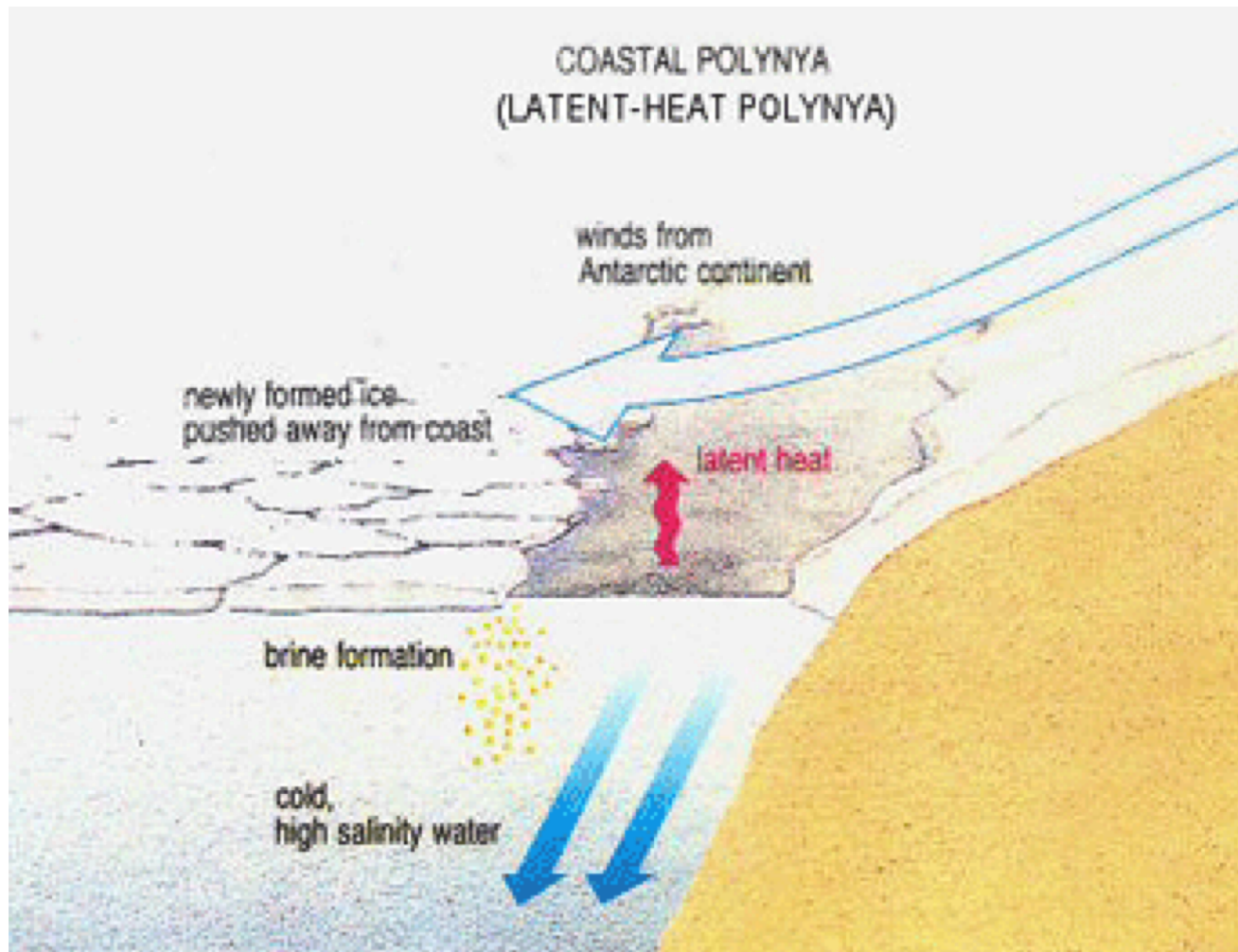
- Freezing point temperature decreases with increasing salinity
- Temperature of maximum density decreases with increasing salinity
- They cross at ~ 25 psu.
- Most seawater has maximum density at the freezing point
- Deep water is generally colder than 4°C . Density of deep water is controlled by salinity more than temperature.



Brine rejection

- Brine rejection: as sea ice forms, it excludes salt from the ice crystal lattice.
- The salt drips out the bottom, and the sea ice is much fresher (usually $\sim 3-4$ psu) than the seawater (around 30-32 psu)
- The rejected brine mixes into the seawater below. If there is enough of it mixing into a thin enough layer, it can measurably increase the salinity of the seawater, and hence its density
- This is the principle mechanism for forming the densest waters of the world ocean.

Polynya, seaice production, dense water formation



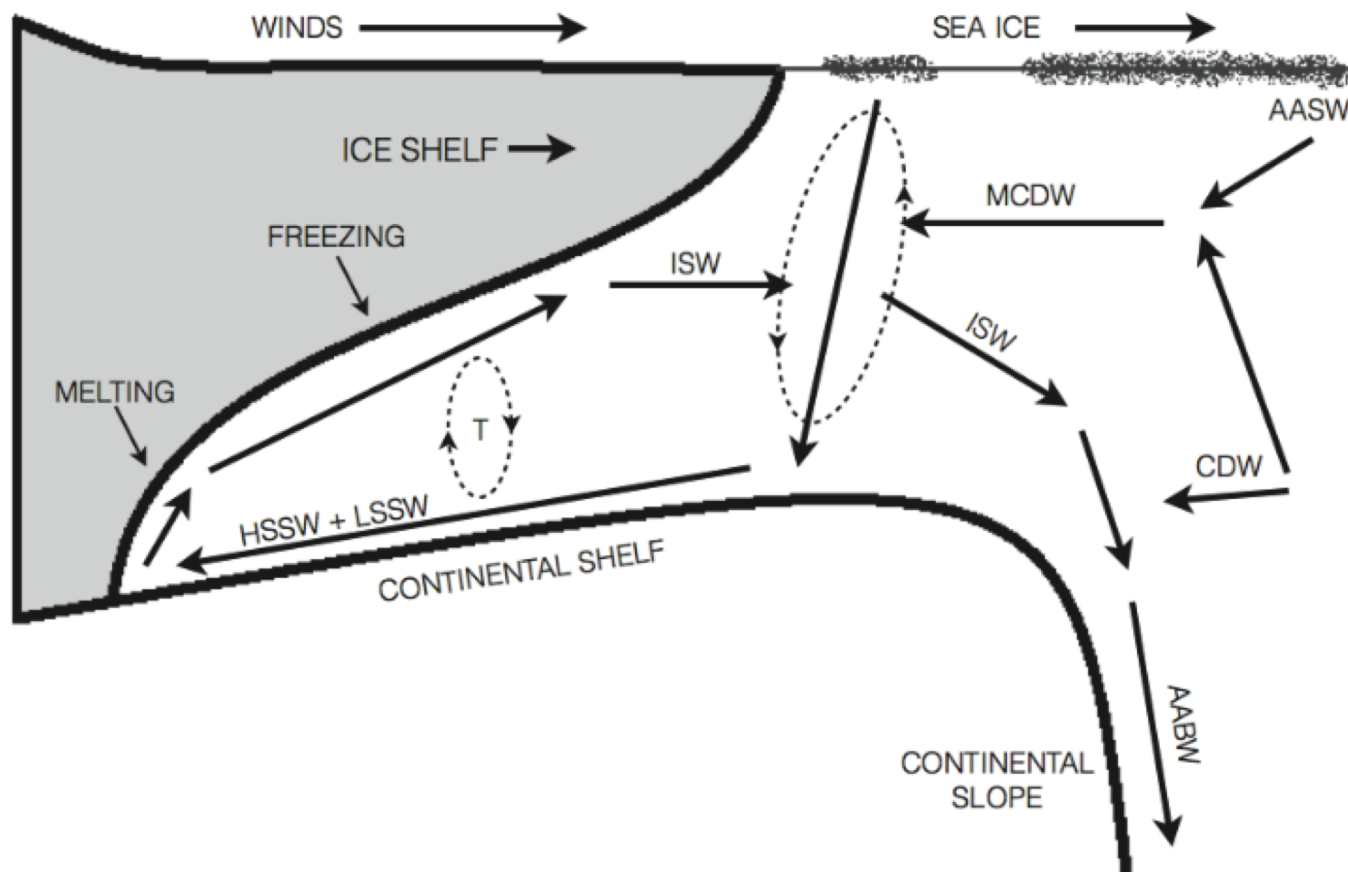


Fig. 1. Schematic representation of the circulation under the Ross Sea Ice Shelf. AASW: Antarctic surface water, CDW: circumpolar deep water, MCDW: modified circumpolar water, LSSW: low salinity shelf water, HSSW: high salinity shelf water, ISW: ice shelf water, AABW: Antarctic bottom water. T refers to tidal mixing.

Continue to week 2