

Temperature and Salinity

EPS131, Introduction to Physical Oceanography and Climate

Dept of Earth and Planetary Sciences, Harvard University

Eli Tziperman

Energy balance and the greenhouse effect

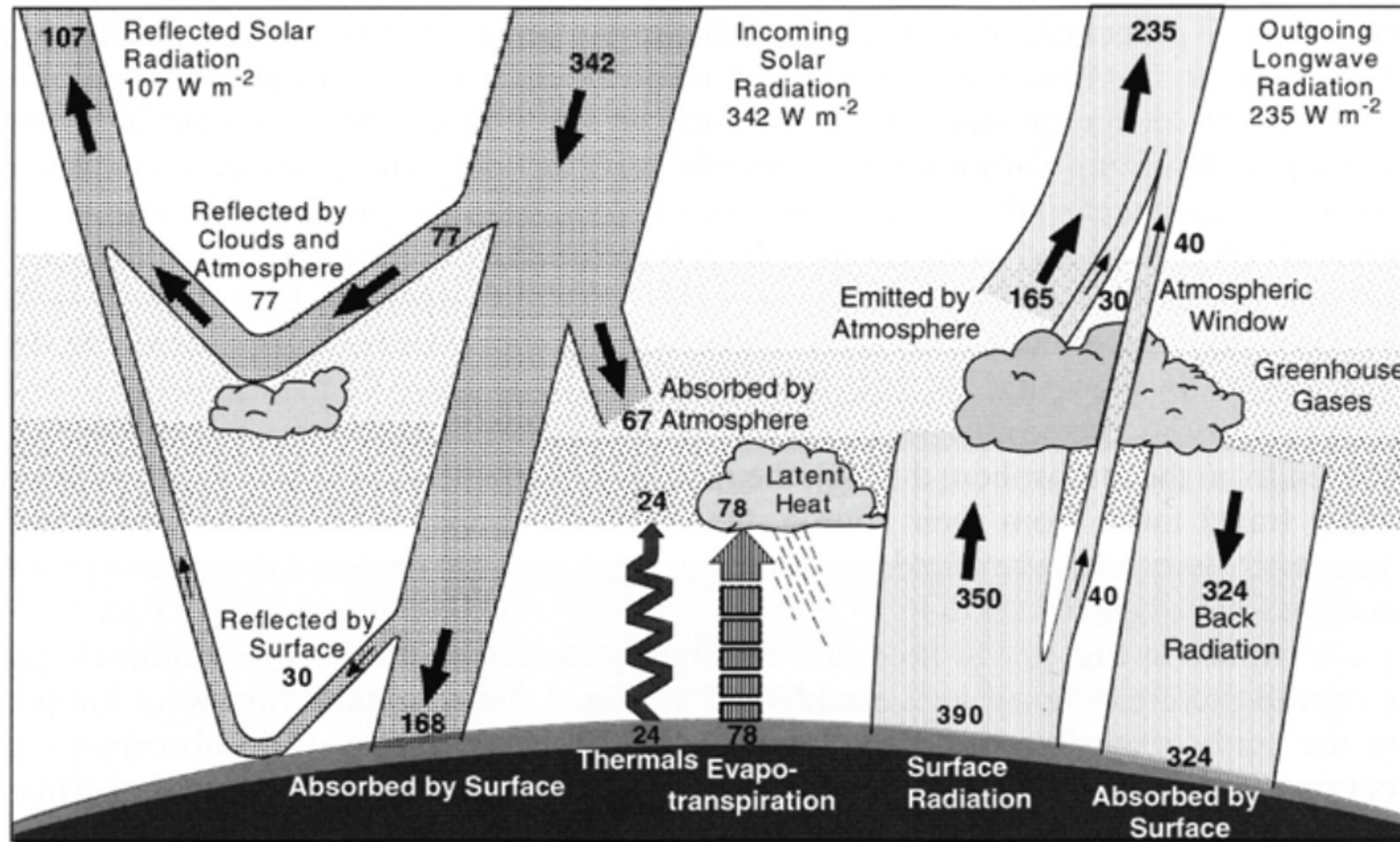
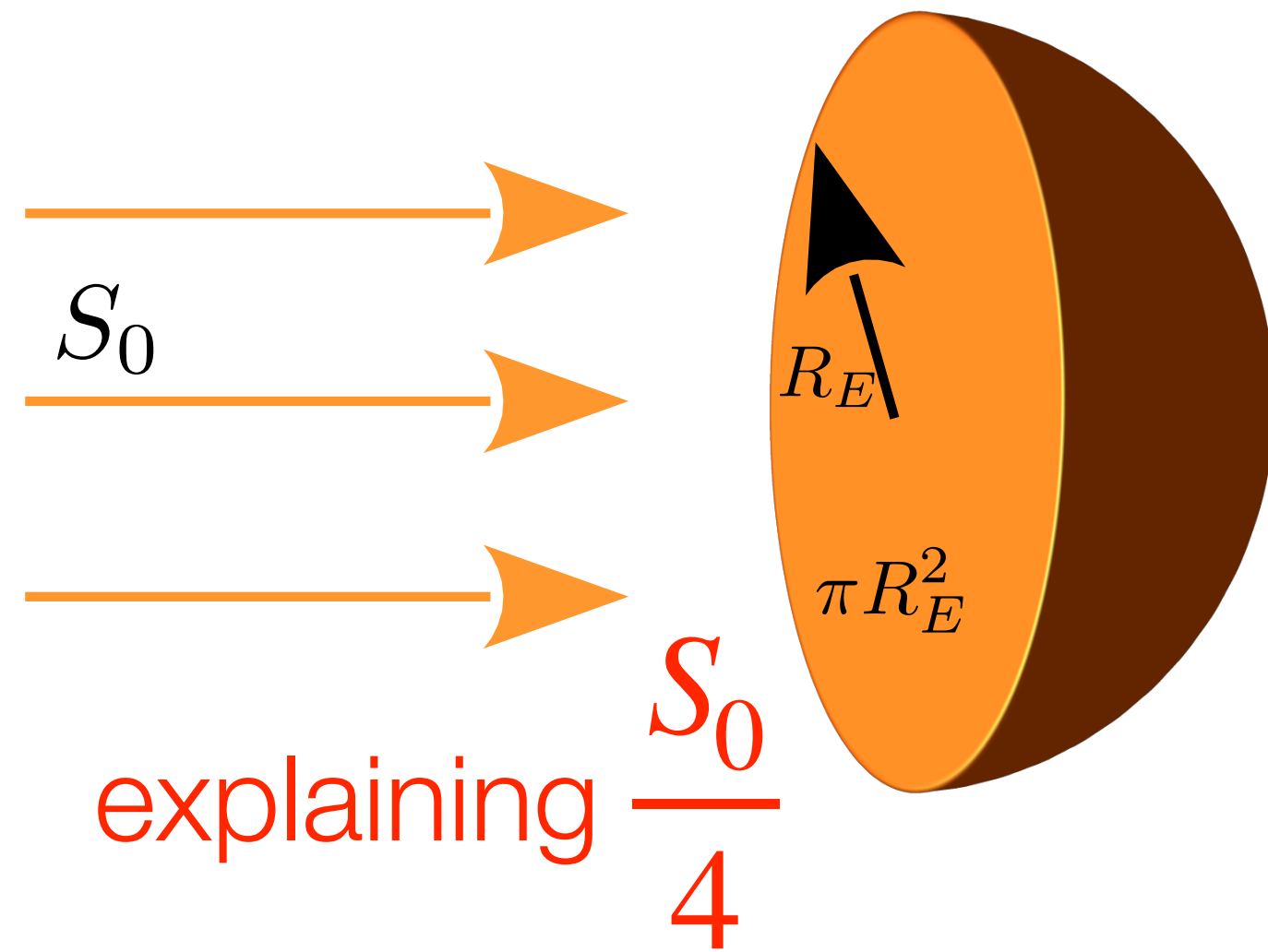


FIGURE 9.4. Earth's energy balance (from Trenberth, K.E., and D.P. Stepaniak, 2004: The flow of energy through the Earth's climate system. *Q.J.R.Meteorol.Soc.*, **130**, 2677-2701).

energy balance and greenhouse effect showing main fluxes

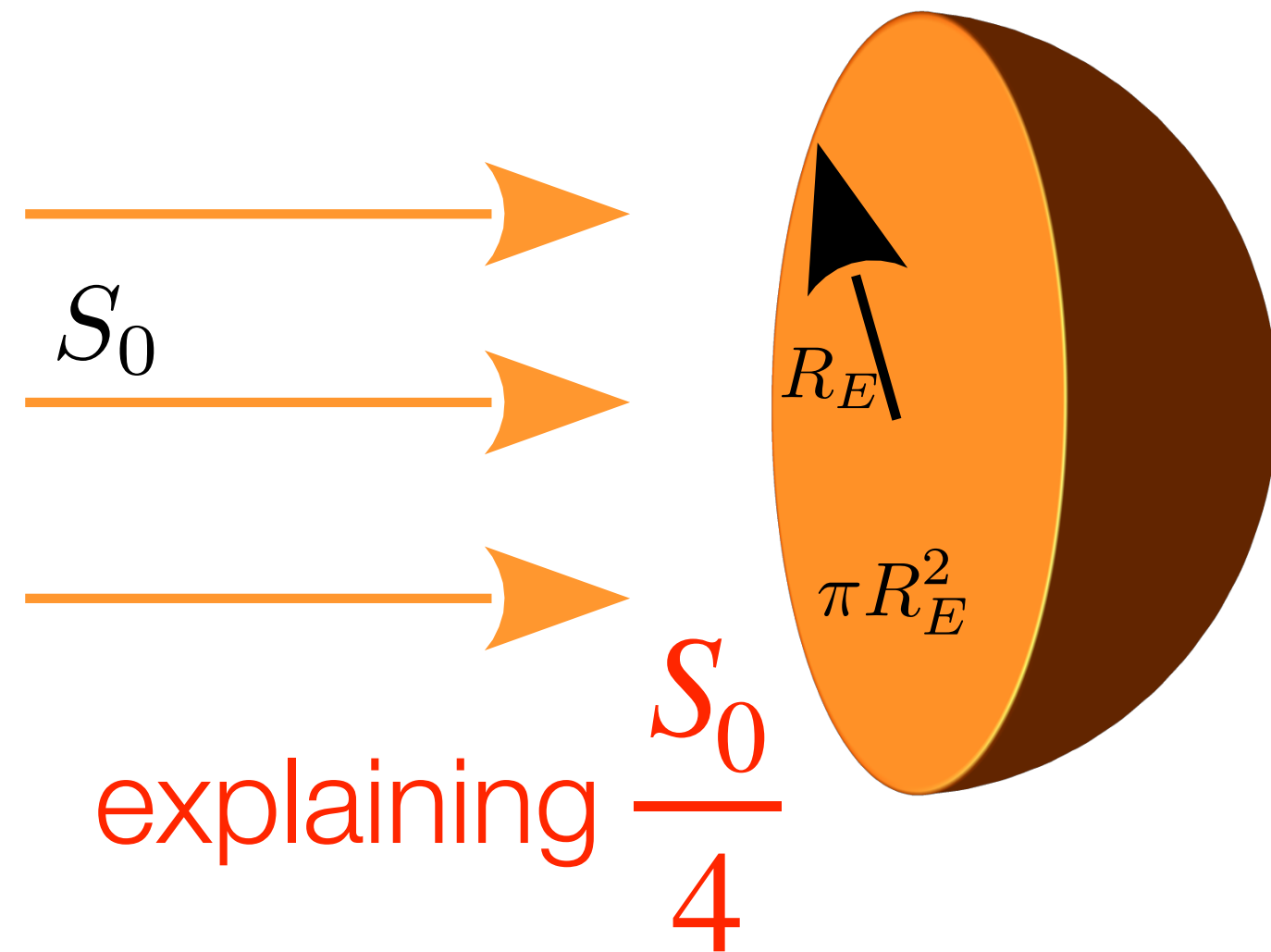
Energy balance and the greenhouse effect



$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}.$$

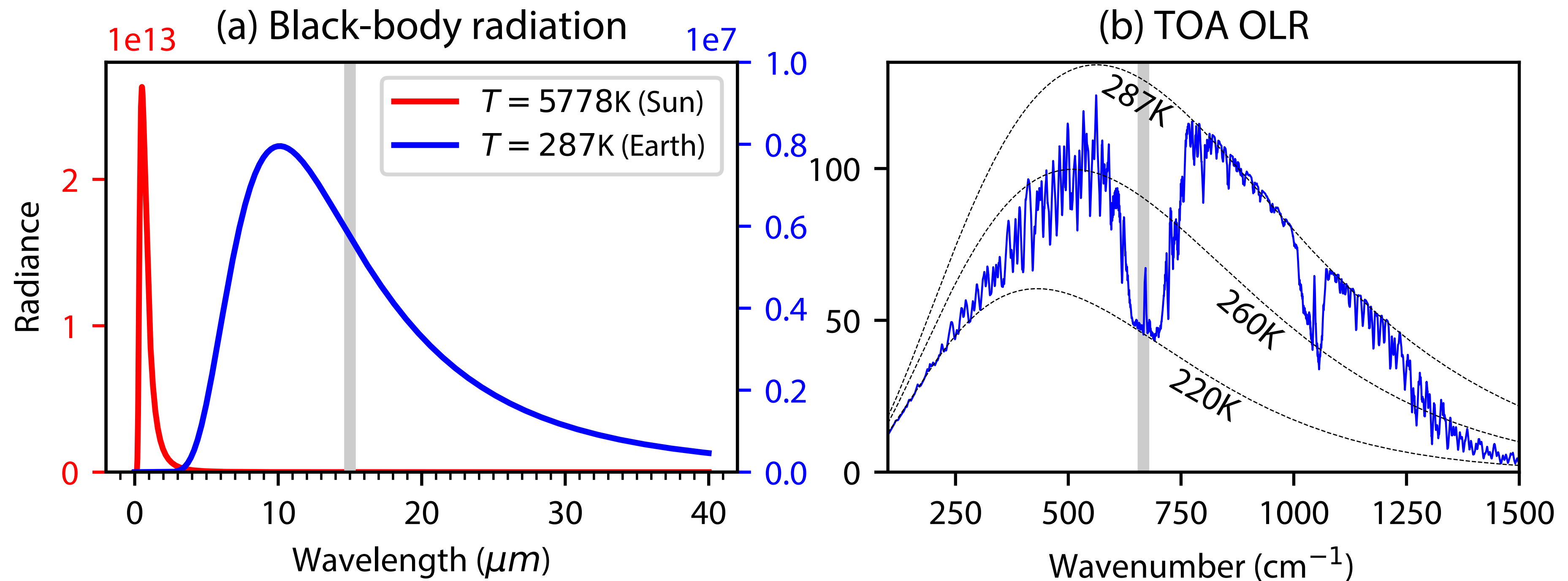
Planck's radiation law

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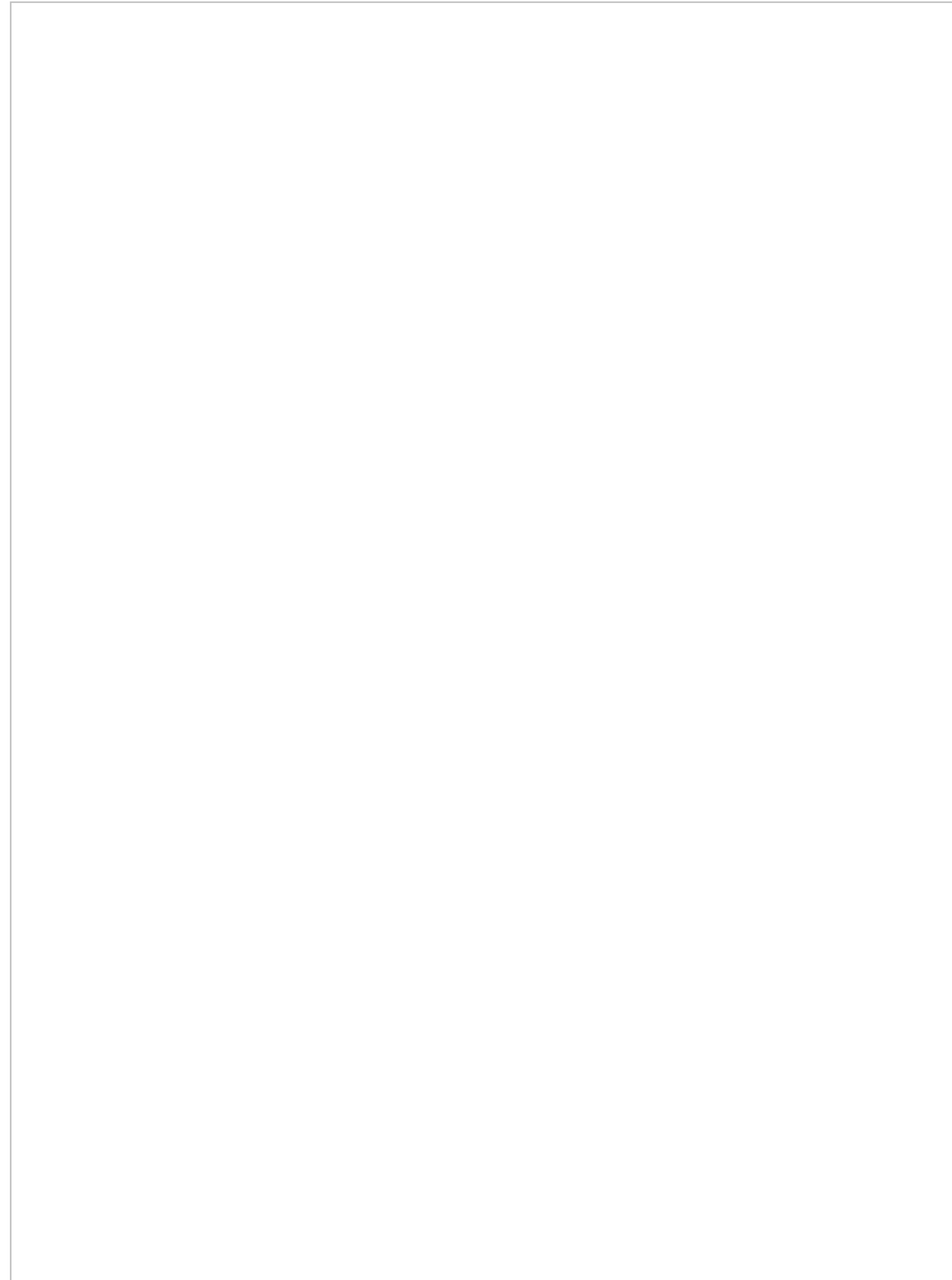
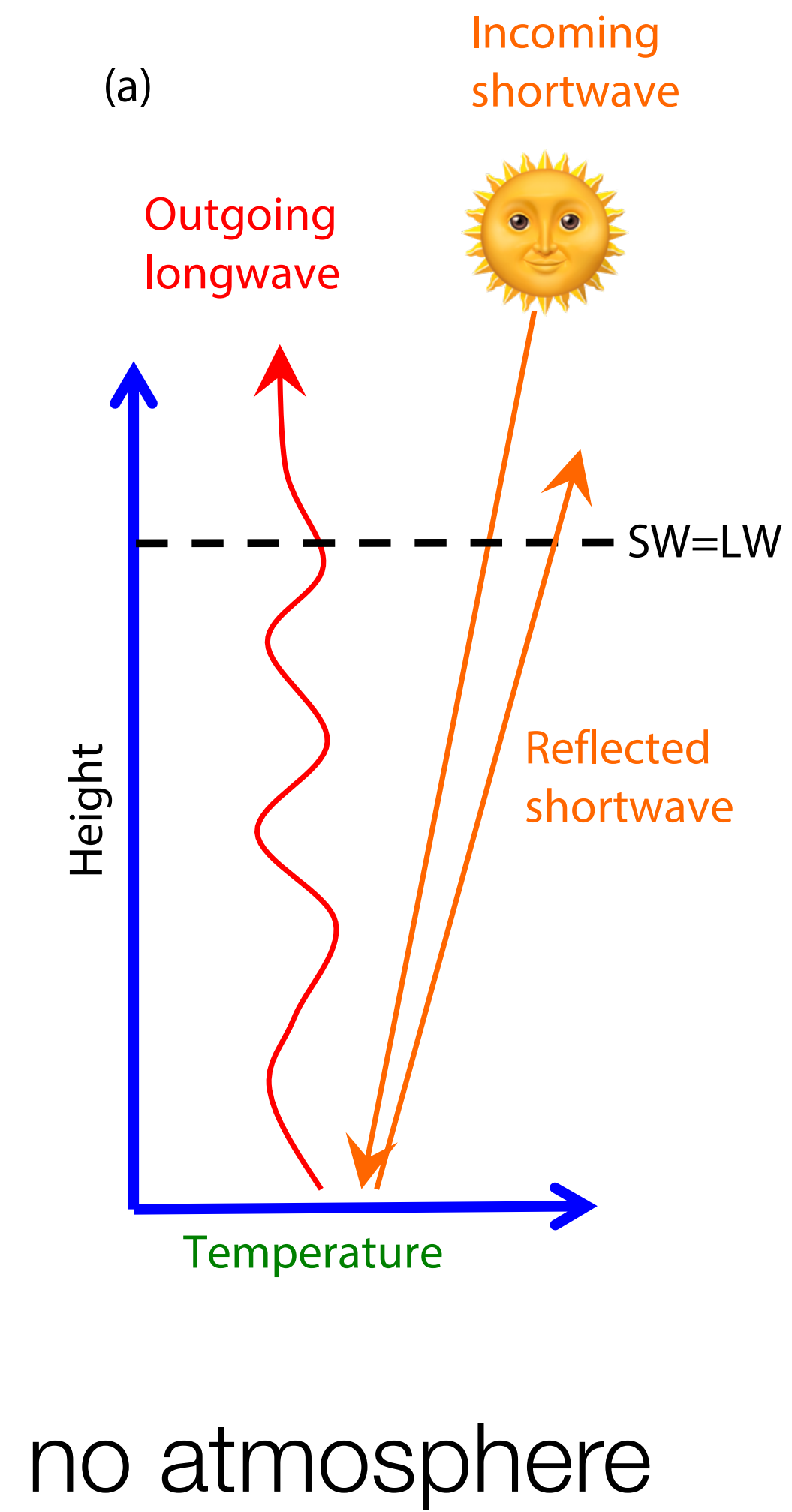
longwave (LW) vs
shortwave (SH) and
the CO_2 absorption
window

notes

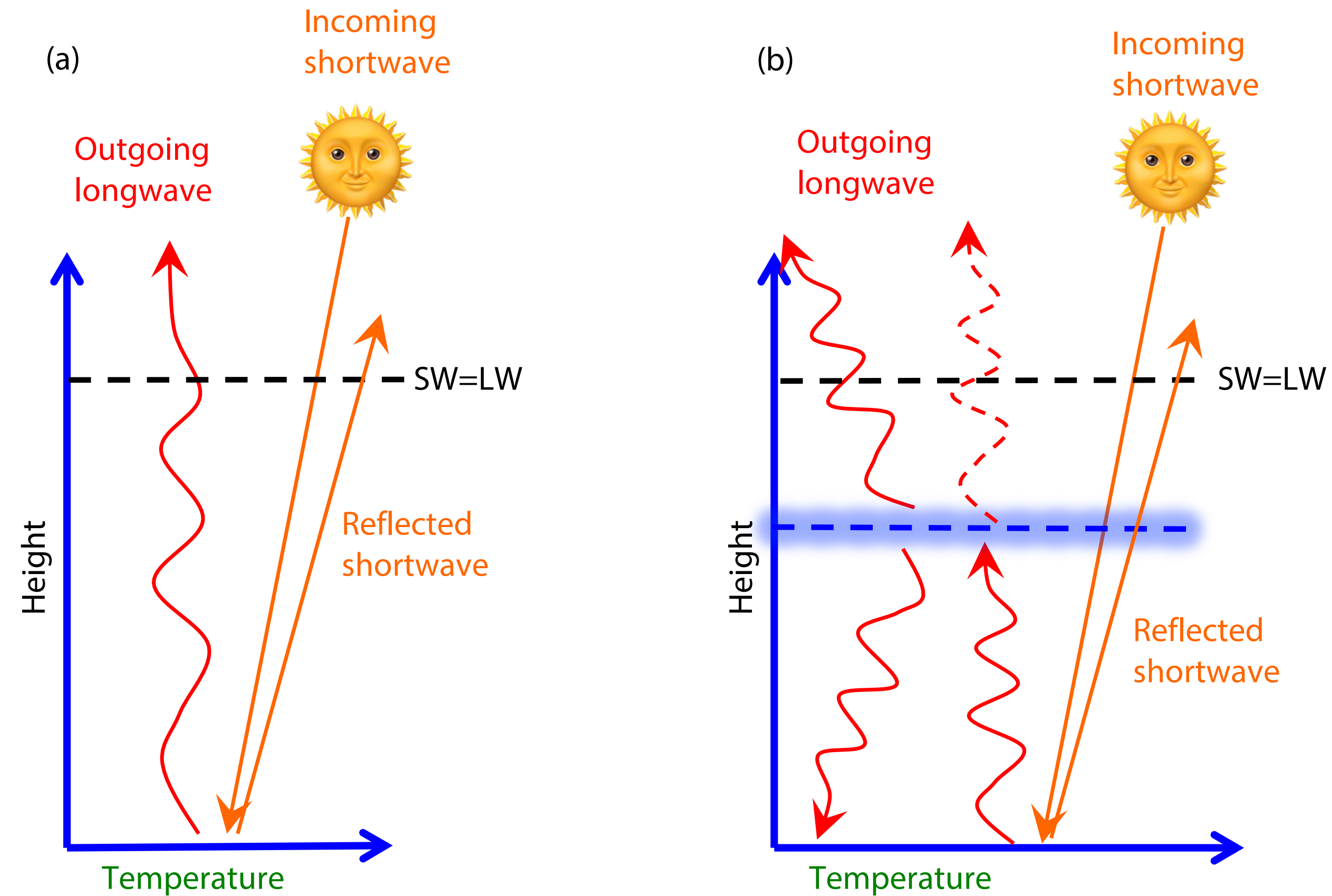
section 1, greenhouse

see following two slides

Energy balance and the greenhouse effect



Energy balance and the greenhouse effect



no atmosphere

with atmospheric (natural) greenhouse effect

mini-quiz surface temperature

Given:

$$\frac{S_0}{4}(1 - \alpha) + \epsilon\sigma\theta^4 = \sigma T^4$$
$$\epsilon\sigma T^4 = 2\epsilon\sigma\theta^4.$$

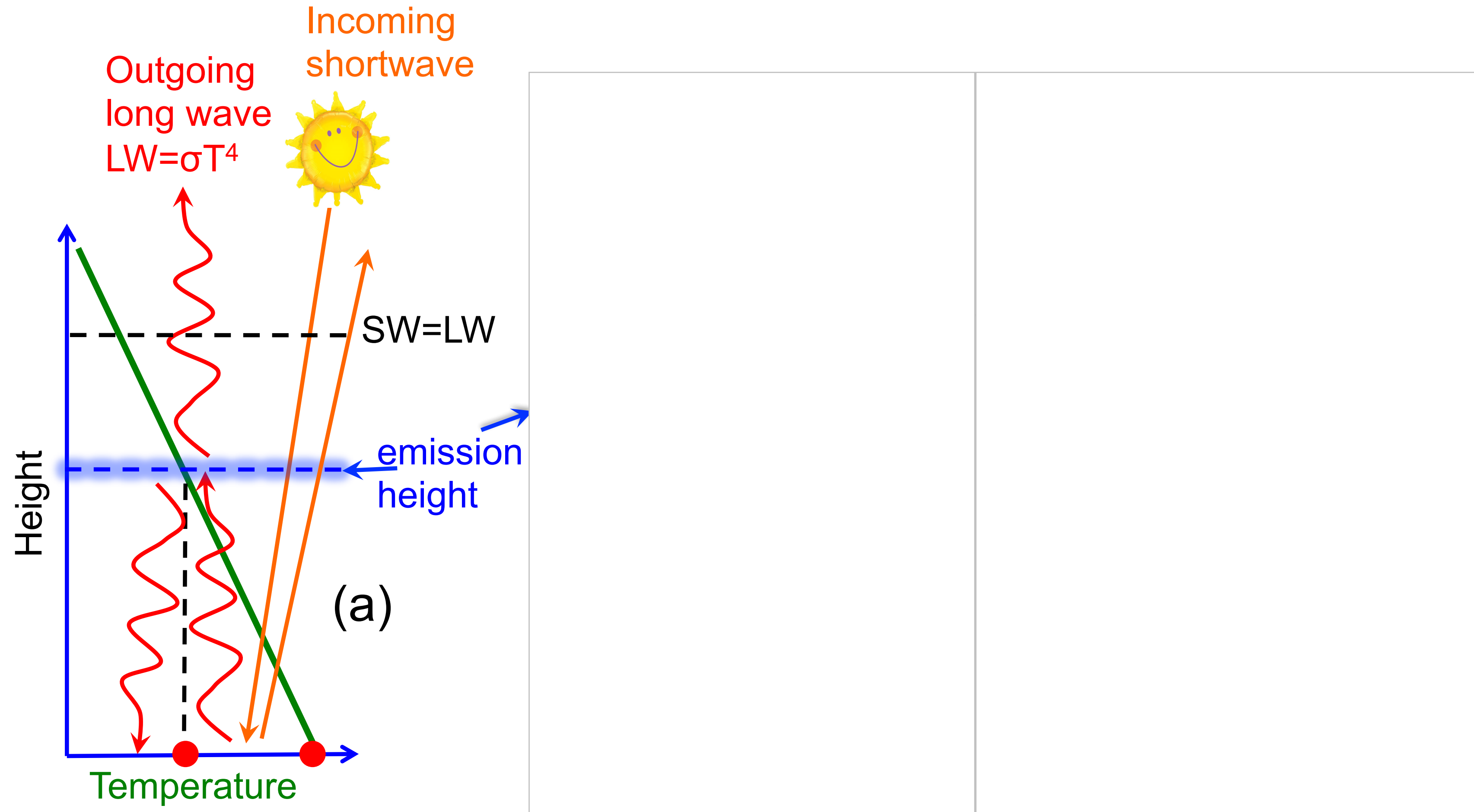
where,

- $S_0 = 1388$ watts/m²: top of the atmosphere insolation at the equator.
- $\sigma = 5.66961 \times 10^{-8}$ W m⁻²K⁻⁴ Stefan-Boltzmann coefficient
- T globally averaged temperature of Earth
- $\alpha = 0.25$ albedo
- $\epsilon = 0.75$ the emissivity of the atmosphere

Calculate the global-mean surface temperature T

The Anthropogenic Greenhouse Effect

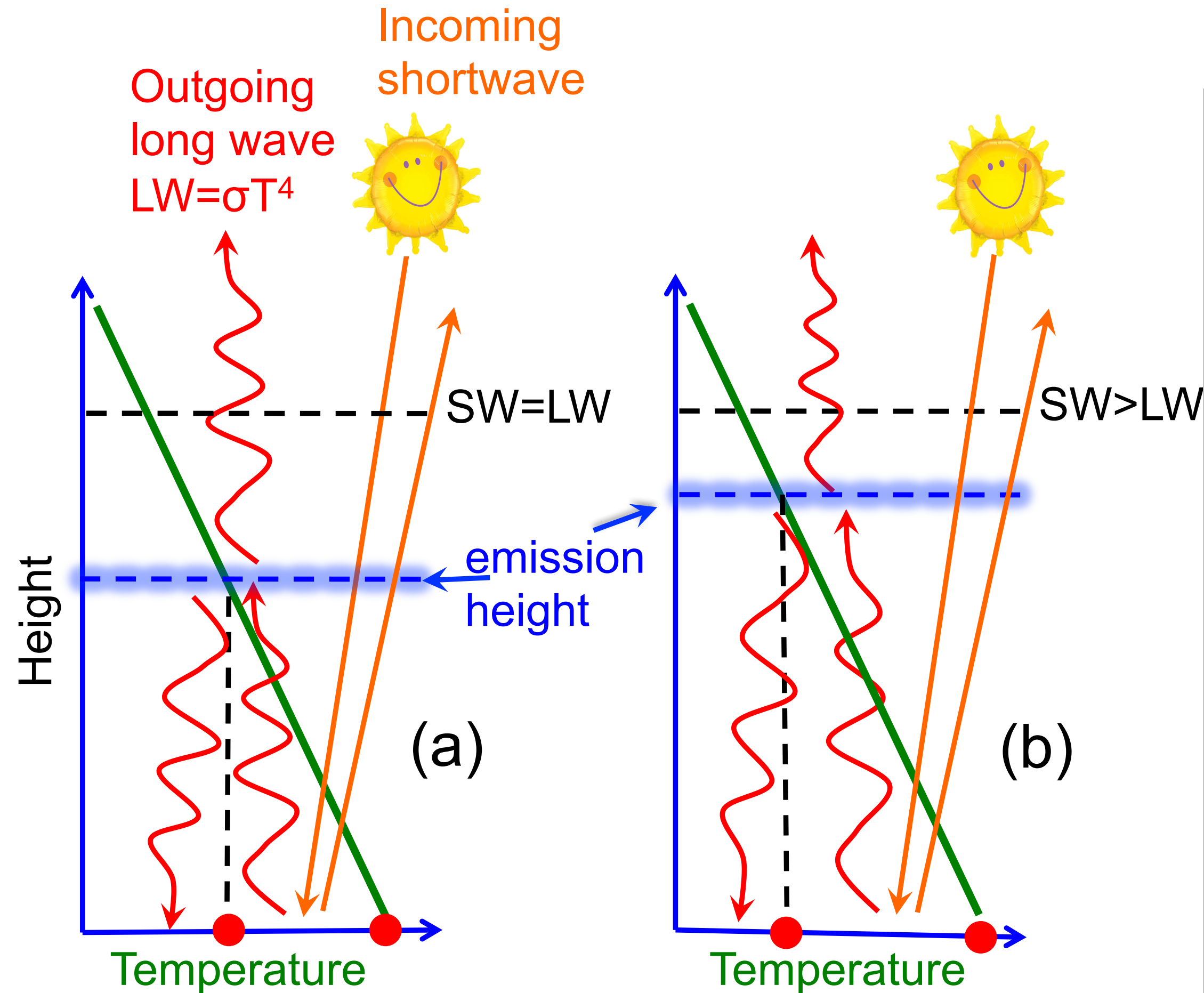
add a continuous atmospheric temperature profile



- Level of last absorption: where most of the radiation emitted upward escapes to space without being absorbed again
- Increasing greenhouse gas \Rightarrow raising the emission level/level of last absorption \Rightarrow Earth radiates from a colder temperature \Rightarrow Energy balance is broken: $LW < SW \Rightarrow$ Temperature must adjust

The Anthropogenic Greenhouse Effect

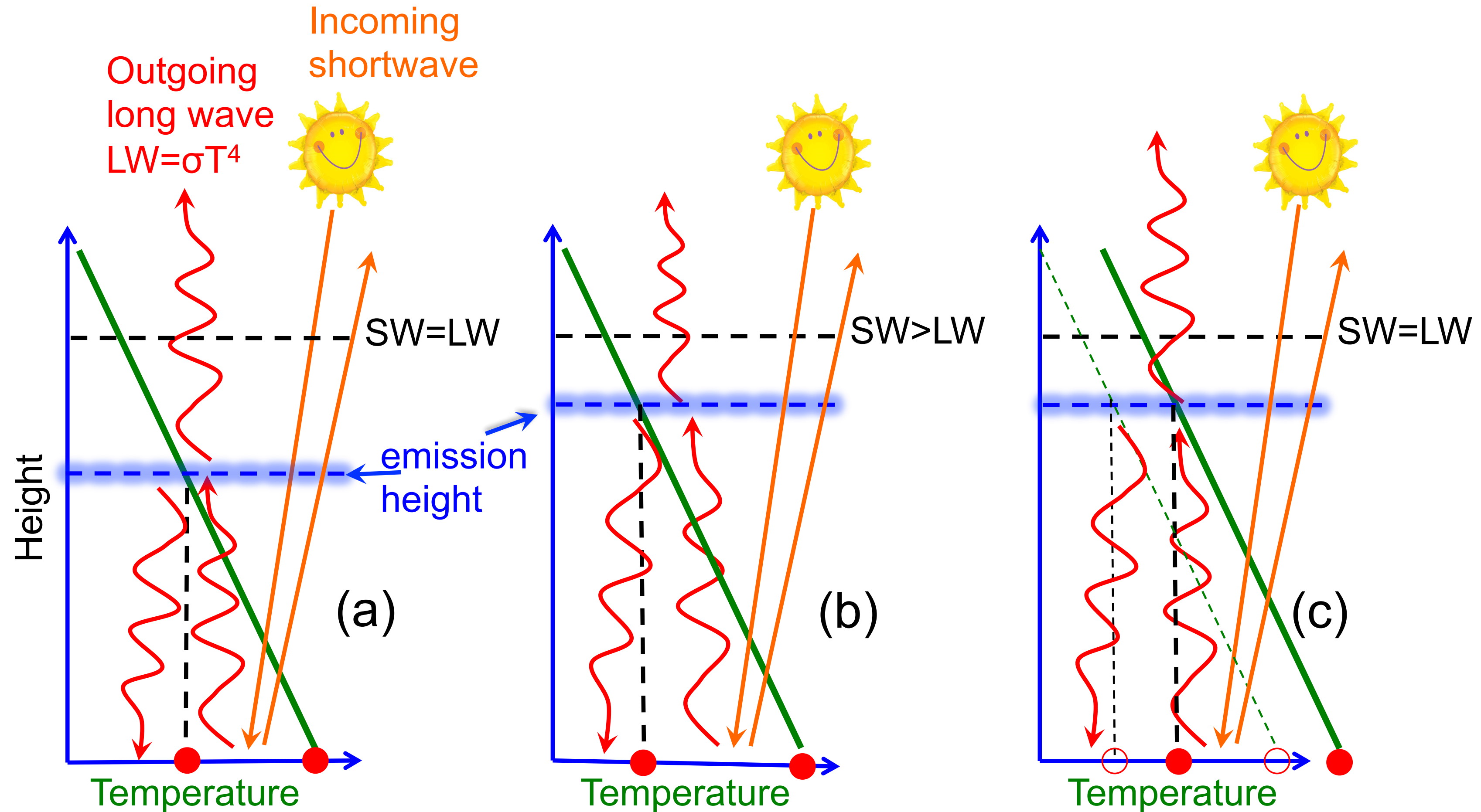
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The Anthropogenic Greenhouse Effect

add a continuous atmospheric temperature profile



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mini-quiz emission level

Calculate the the increase in emission height Δh that compensates for a doubling in CO_2 , where a doubling leads to a $\Delta F = 4 \text{ W/m}^2$ increase in radiative forcing.

Hint: [see notes] First calculate the relevant ΔT and then use a lapse rate of 6.5 K/km to calculate Δh .

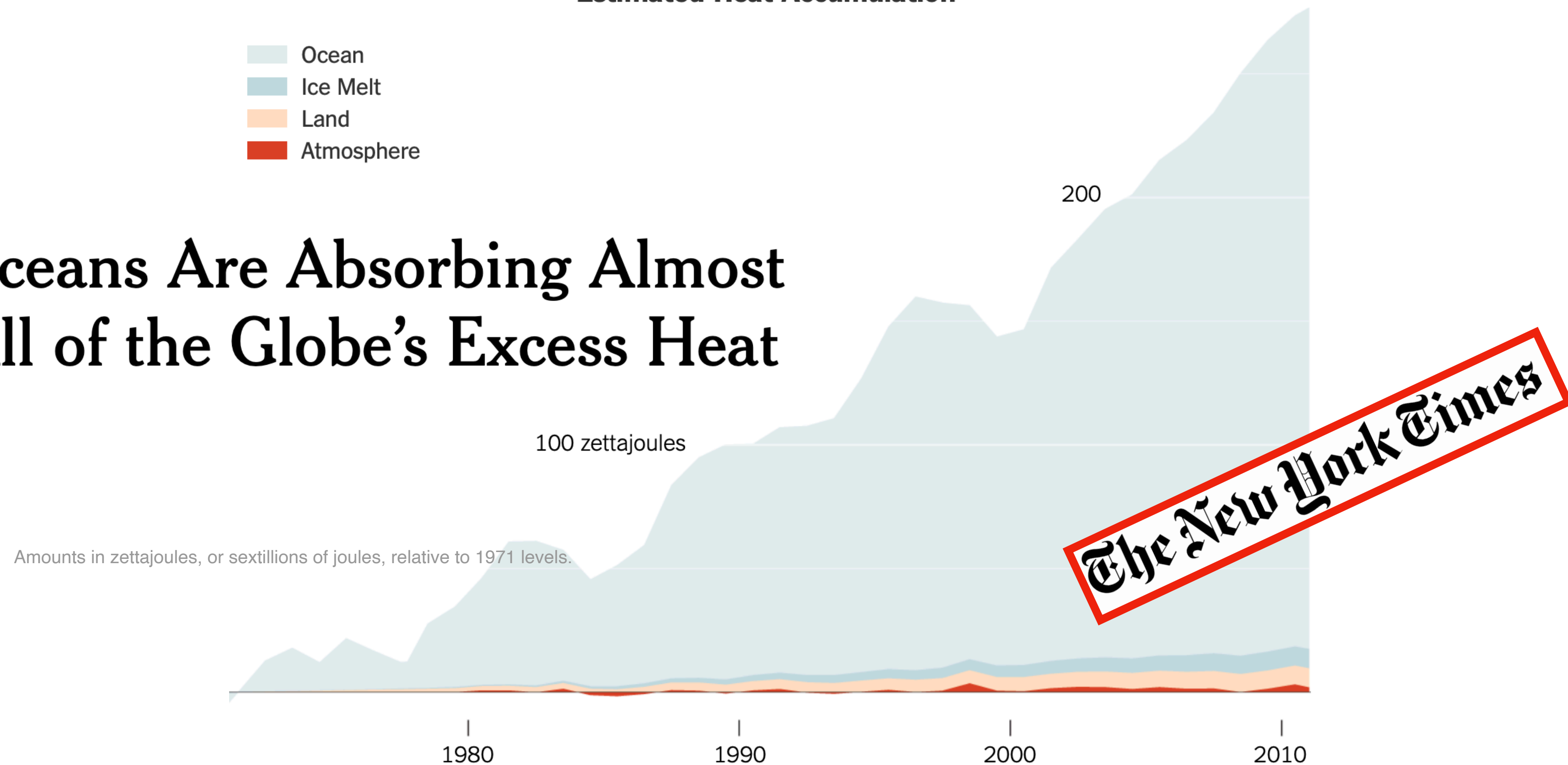
Role of the ocean in delaying warming due to anthropogenic climate change

The ocean is absorbing all that heat, what would have happened otherwise?

Estimated Heat Accumulation

- Ocean
- Ice Melt
- Land
- Atmosphere

Oceans Are Absorbing Almost All of the Globe's Excess Heat



Heat Accumulates in the Oceans: “Since 1955, more than 90 percent of the excess heat retained by the Earth as a result of increased greenhouse gases has been absorbed by the oceans, leaving ocean scientists ... at the National Oceanic and Atmospheric Administration feeling that **90 percent of the climate change story is being ignored.**”

The warming you might have expected by now

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$$\Delta T \propto \Delta F \propto \log(\text{CO}_2/280)$$

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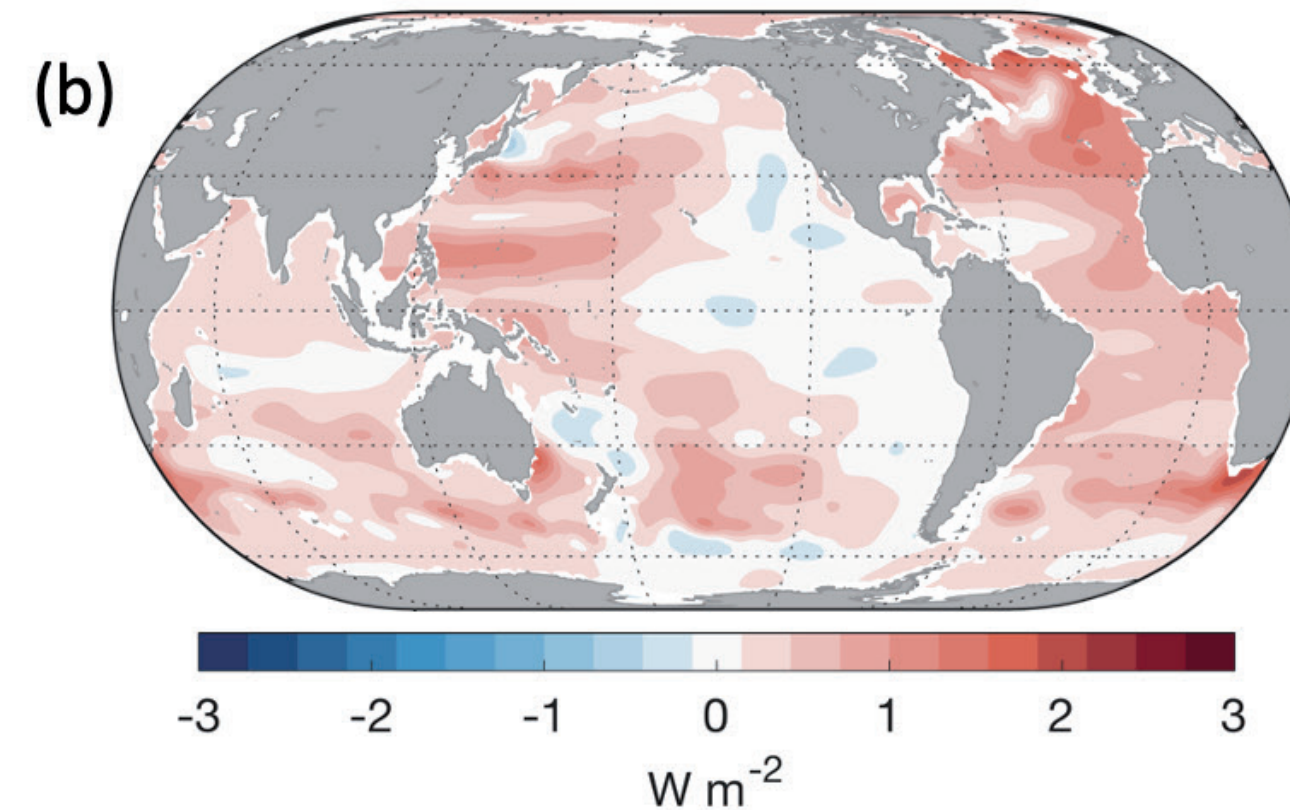
➔ Significantly more than as has been observed (1.5 °C)!

What's going on?

Ocean warming

Observed OHC Trends

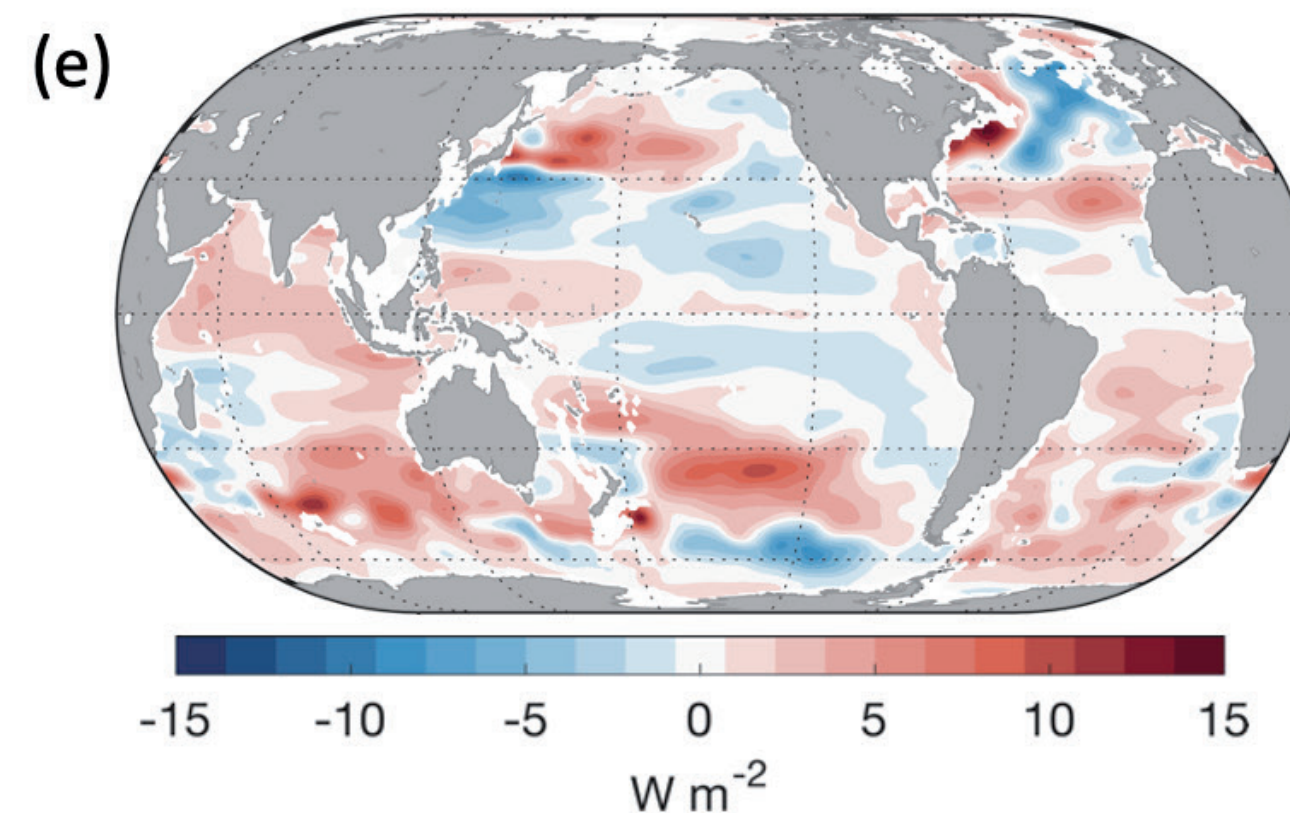
0-700m depth (1971→2014)



upper ocean warming
rate (W/m^2) 0–700 m

(IPCC AR6, 2022)

0-2000m depth (2005→2014)



warming rate (W/m^2)
further into deeper
ocean, 0–2000 m

Figure 9.6 | Ocean heat content (OHC) and its changes with time. (b–g) Maps of OHC across different time periods, in different layers. Maps show the observed (Ishii et al., 2017) trends of OHC for (b) 0–700 m for the period 1971–2014, and (e) 0–2000 m for the period 2005–2017.

Transient climate sensitivity

The heat budgets of the upper ocean and the deep ocean:

$$C_{\text{surface}} \frac{d\Delta T_{\text{surface}}}{dt} = \Delta F_{2\times} - \lambda_{LW} \Delta T_{\text{surface}} - \gamma (\Delta T_{\text{surface}} - \Delta T_{\text{deep}})$$

Radiative forcing Outgoing LW Radiation transport into the deep ocean

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$$C_{\text{deep}} \frac{d\Delta T_{\text{deep}}}{dt} = \gamma (\Delta T_{\text{surface}} - \Delta T_{\text{deep}}). \quad (3.3)$$

where

$$C_{\text{surface}} \approx \rho_w c_p 50 \text{ m} \quad C_{\text{deep}} = \rho_w c_p H, \quad \text{and } H \text{ is the ocean depth}$$

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Steady shows the “equilibrium climate sensitivity”

$$\Delta T_{2\times} = \frac{\Delta F_{2\times}}{\lambda_{LW}}$$

but it takes a long time to get there, due to the large heat capacity of the ocean.

Transient climate sensitivity: role of ocean depth

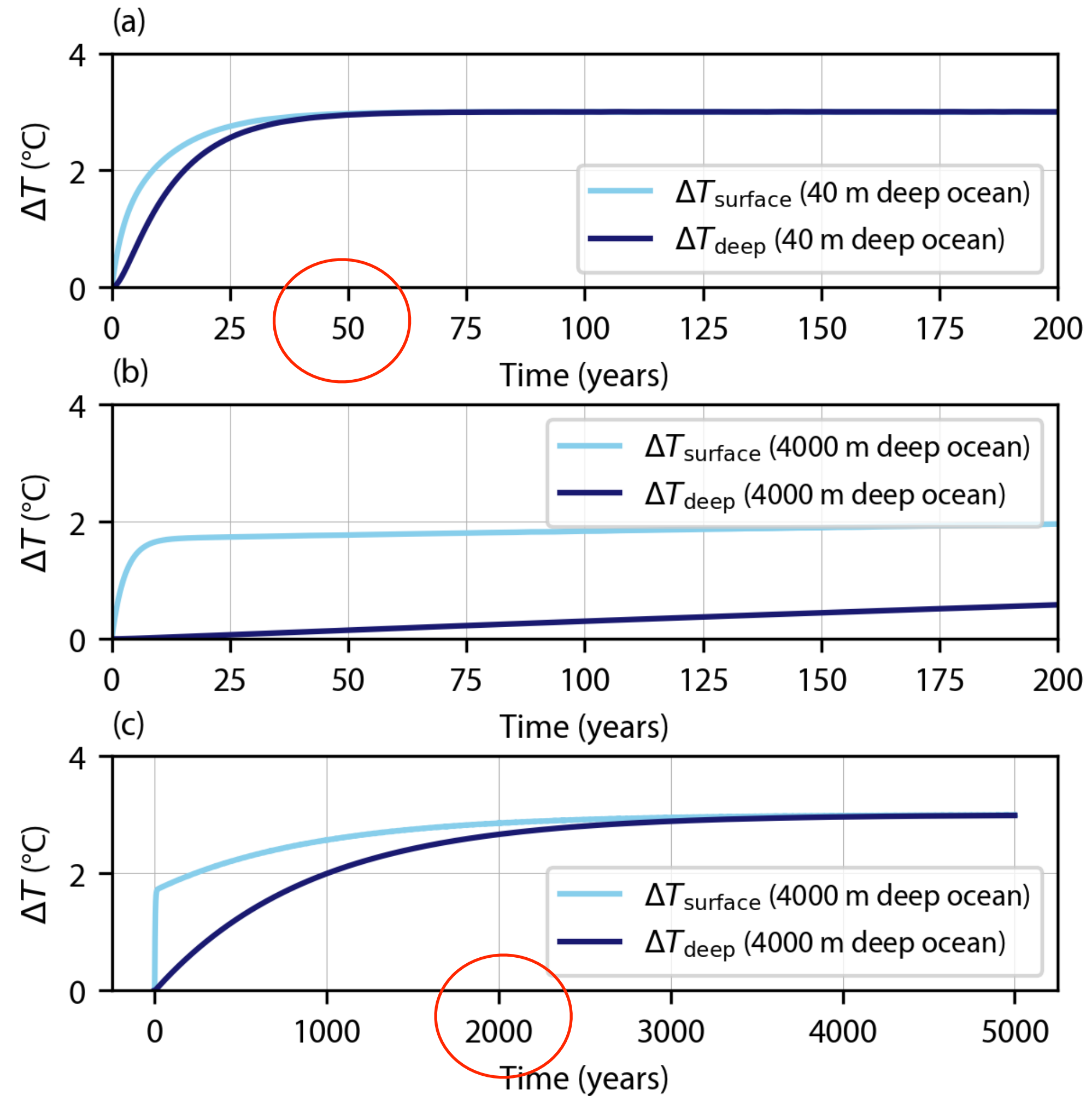


Figure 3.3: Transient climate sensitivity.

The temperature anomalies of the upper ocean and of the deep ocean, as a function of time in a scenario of instantaneous CO_2 doubling. (a) Artificial case assuming the subsurface ocean is only 40 m deep. (b) A more realistic scenario, assuming an ocean depth of 4000 m, showing the first 200 yr of adjustment to an abrupt doubling of CO_2 . (c) Same scenario as in (b), and showing the full period of adjustment.

A calculation of the expected sea level rise due to ocean warming



<https://gis2.harvard.edu/services/project-consultation/project-resume/sea-level-change-global-warming>

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<https://www.vanityfair.com/news/2006/05/warming200605>

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warming



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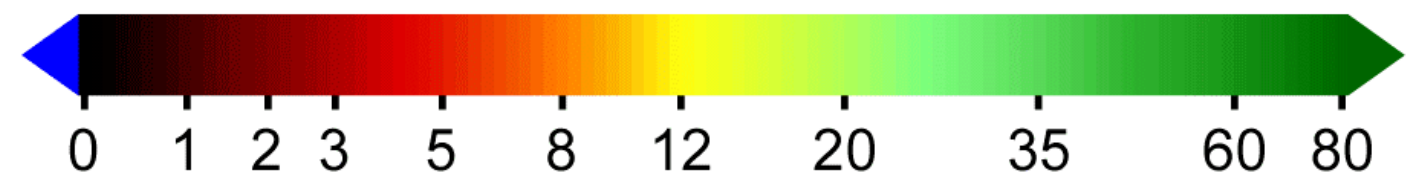
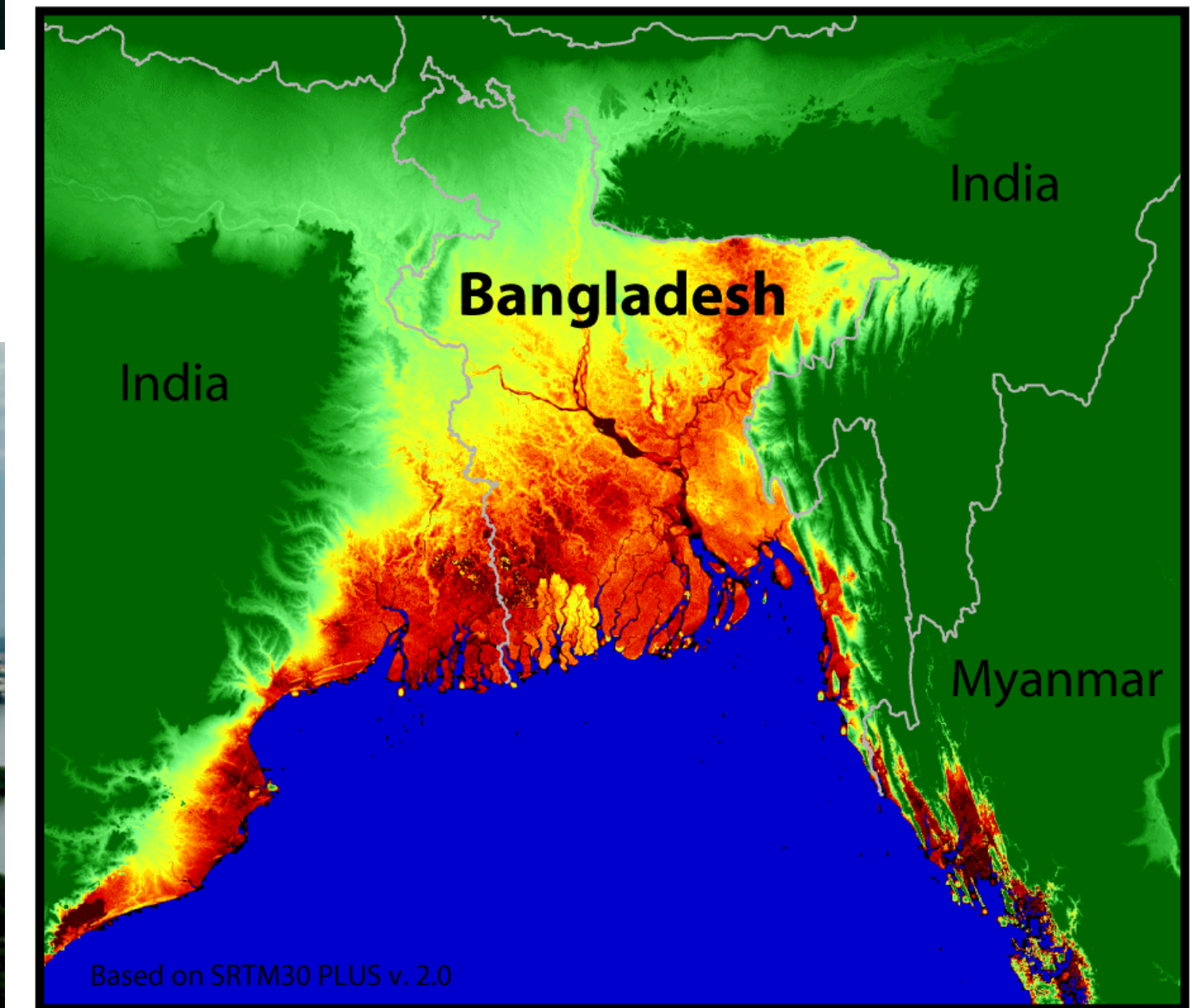
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warming



<https://www.vanityfair.com/news/2006/05/warming200605>

Sea Level Risks - Bangladesh



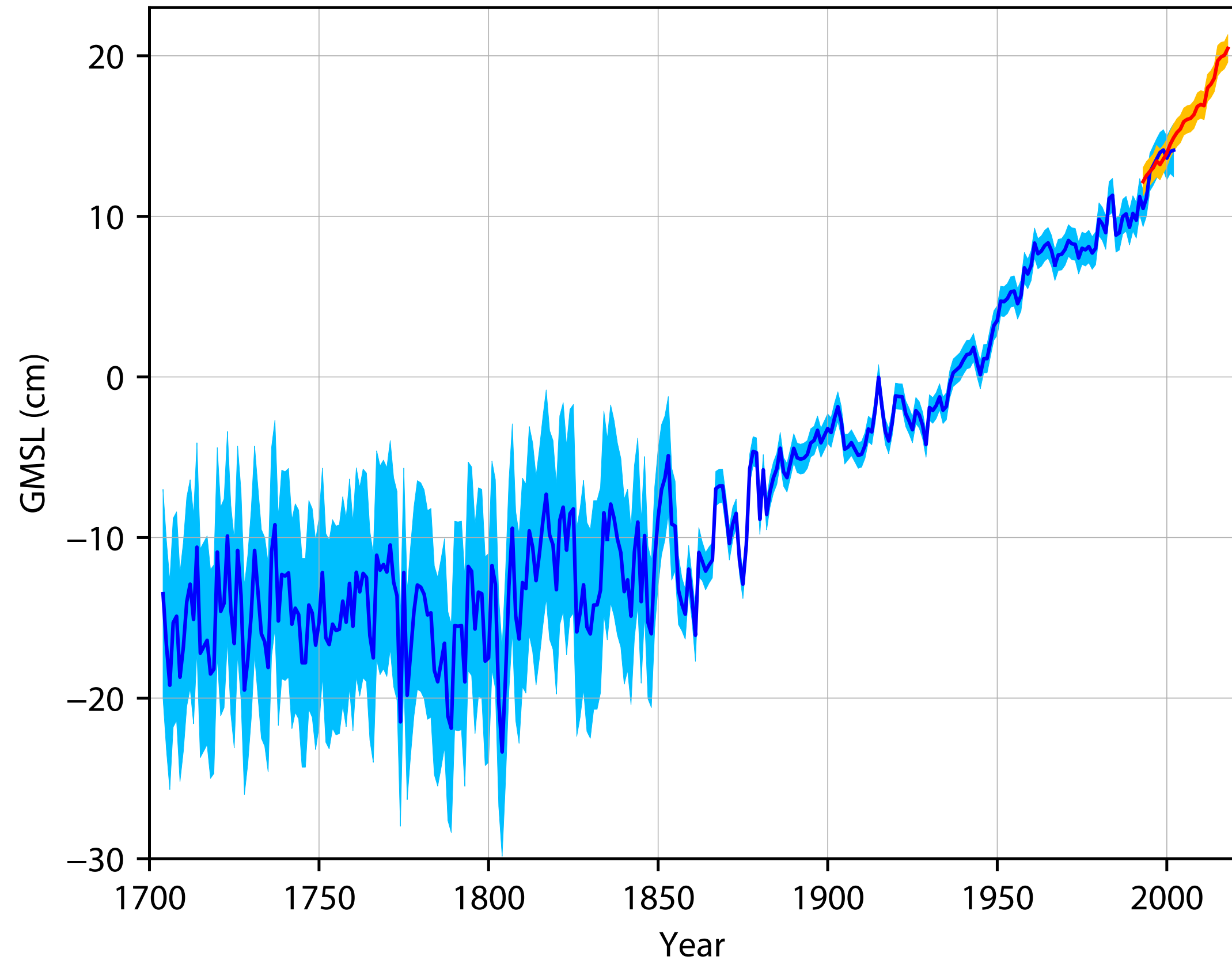
Height Above Sea Level (m)

https://de.wikipedia.org/wiki/Datei:Bangladesh_Sea_Level_Risks.png



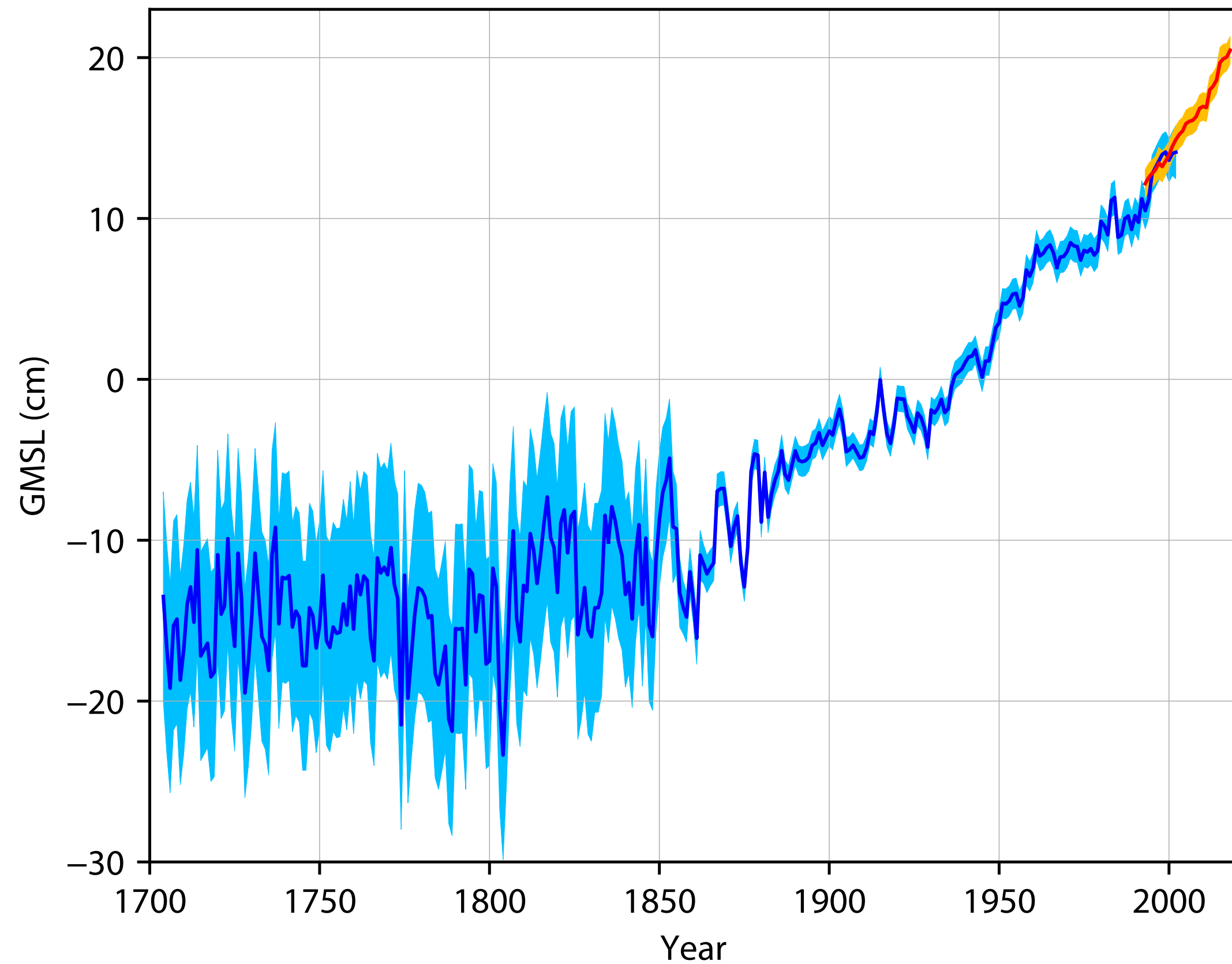
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Sea level rise due to ocean warming



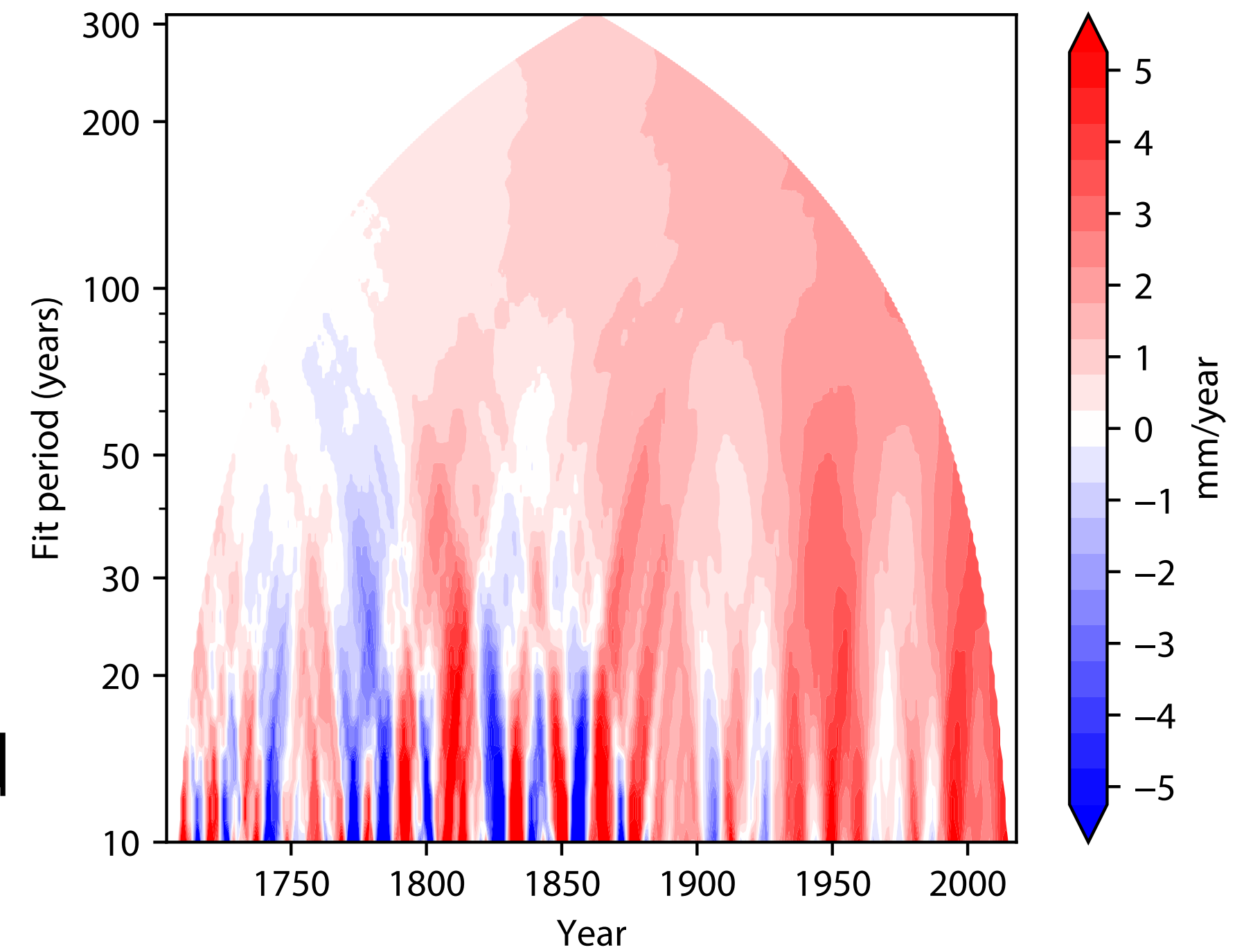
last 300 years

Sea level rise due to ocean warming

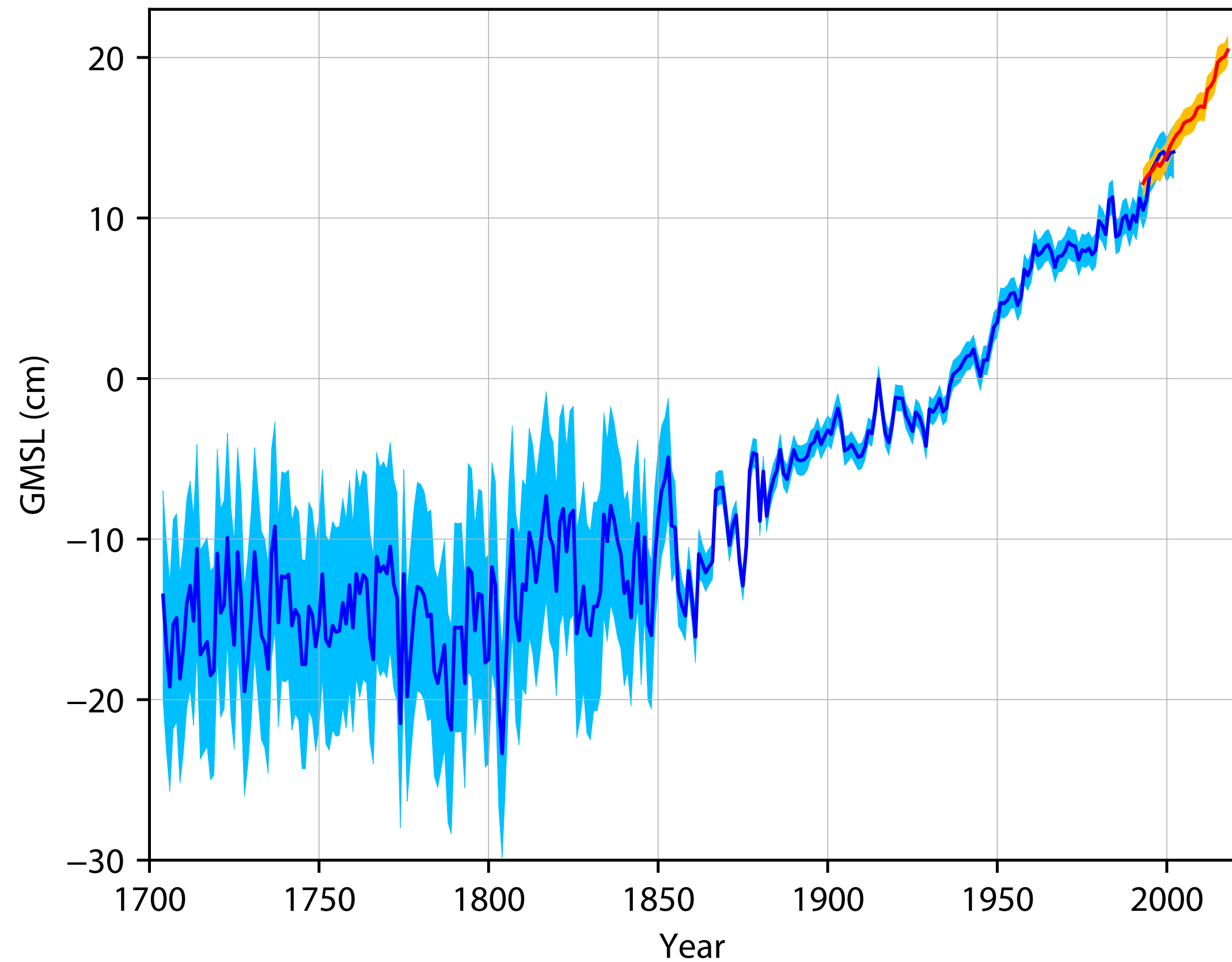


last 300 years

sea level **trends**
as a function of
averaging period
and time

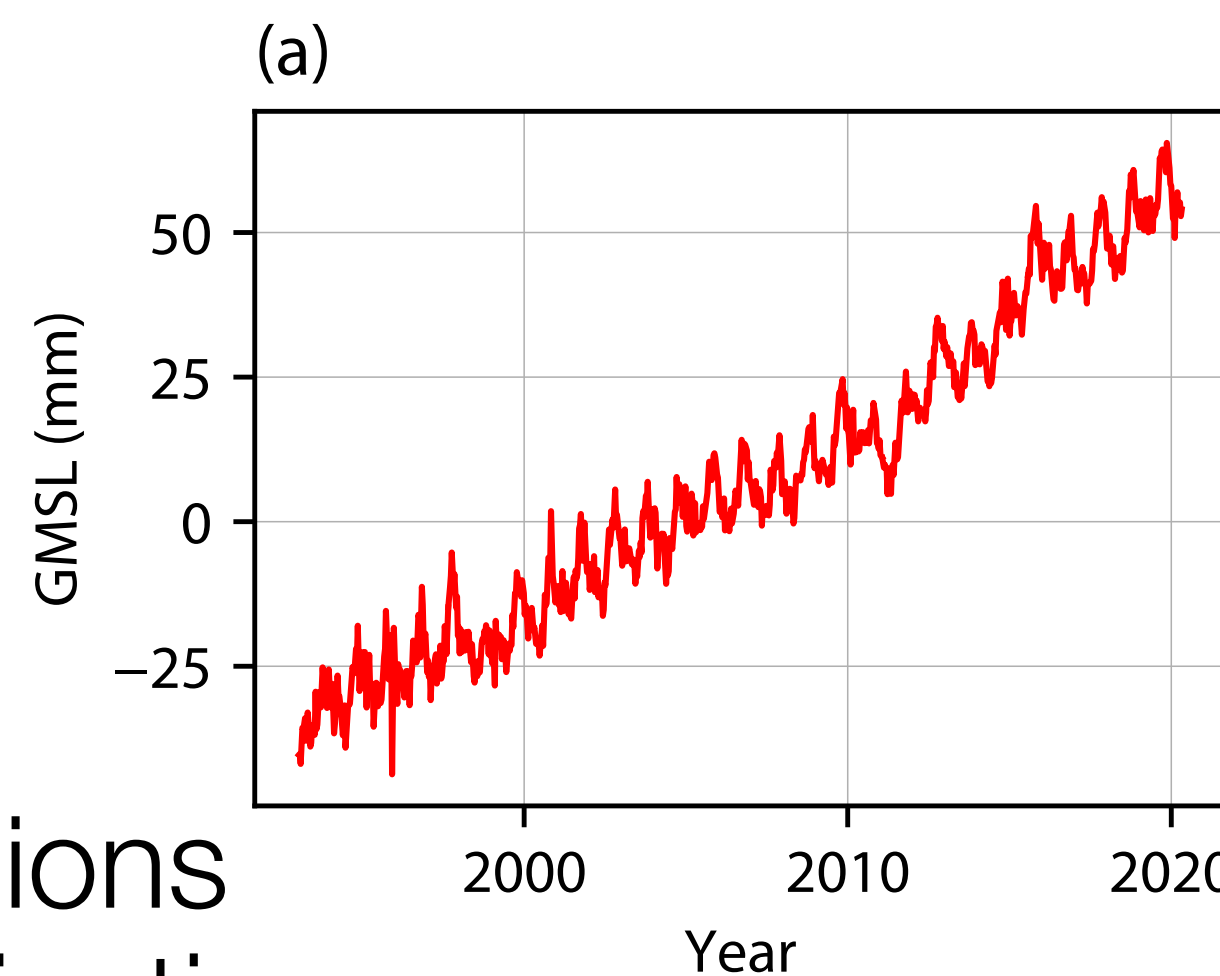
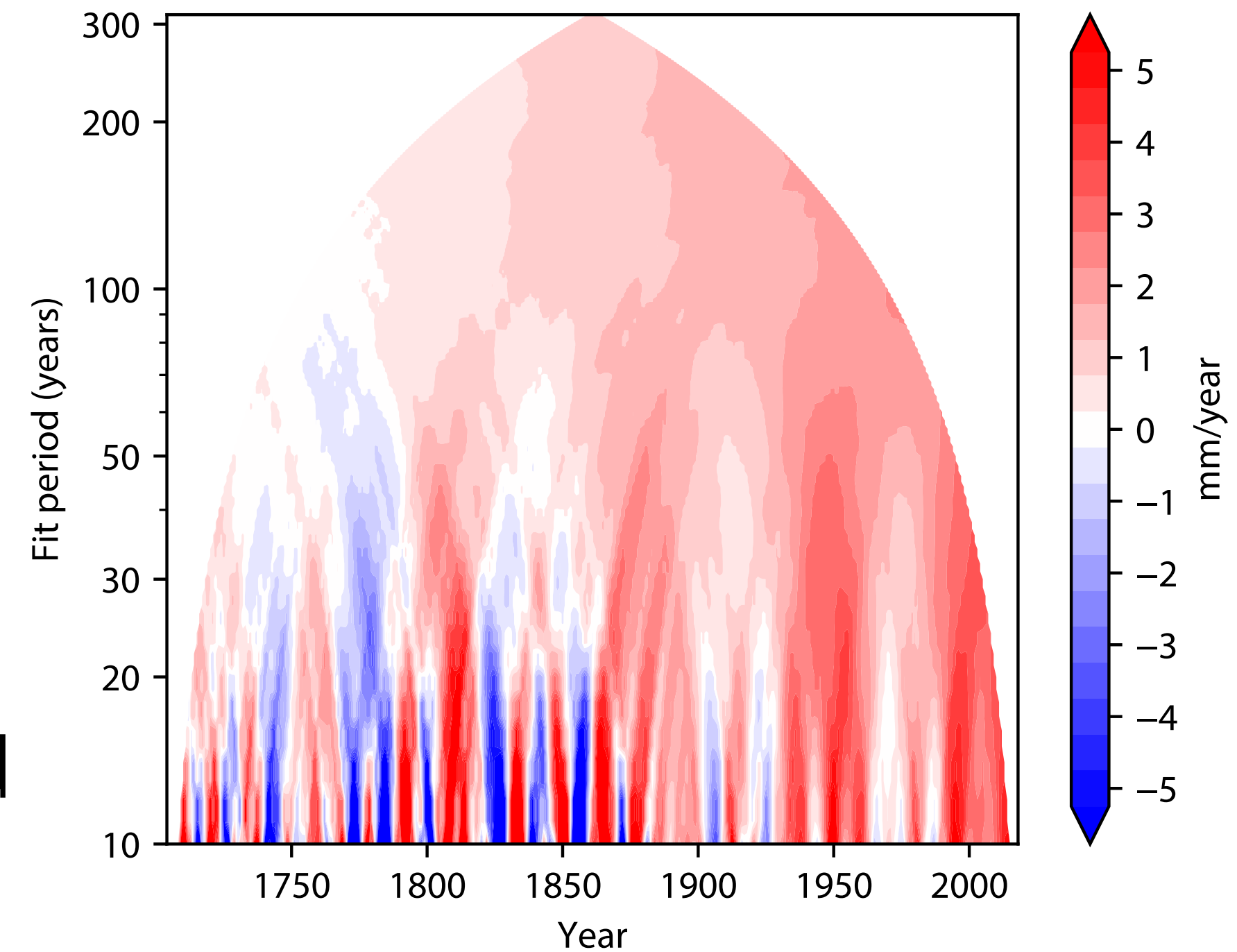


Sea level rise due to ocean warming

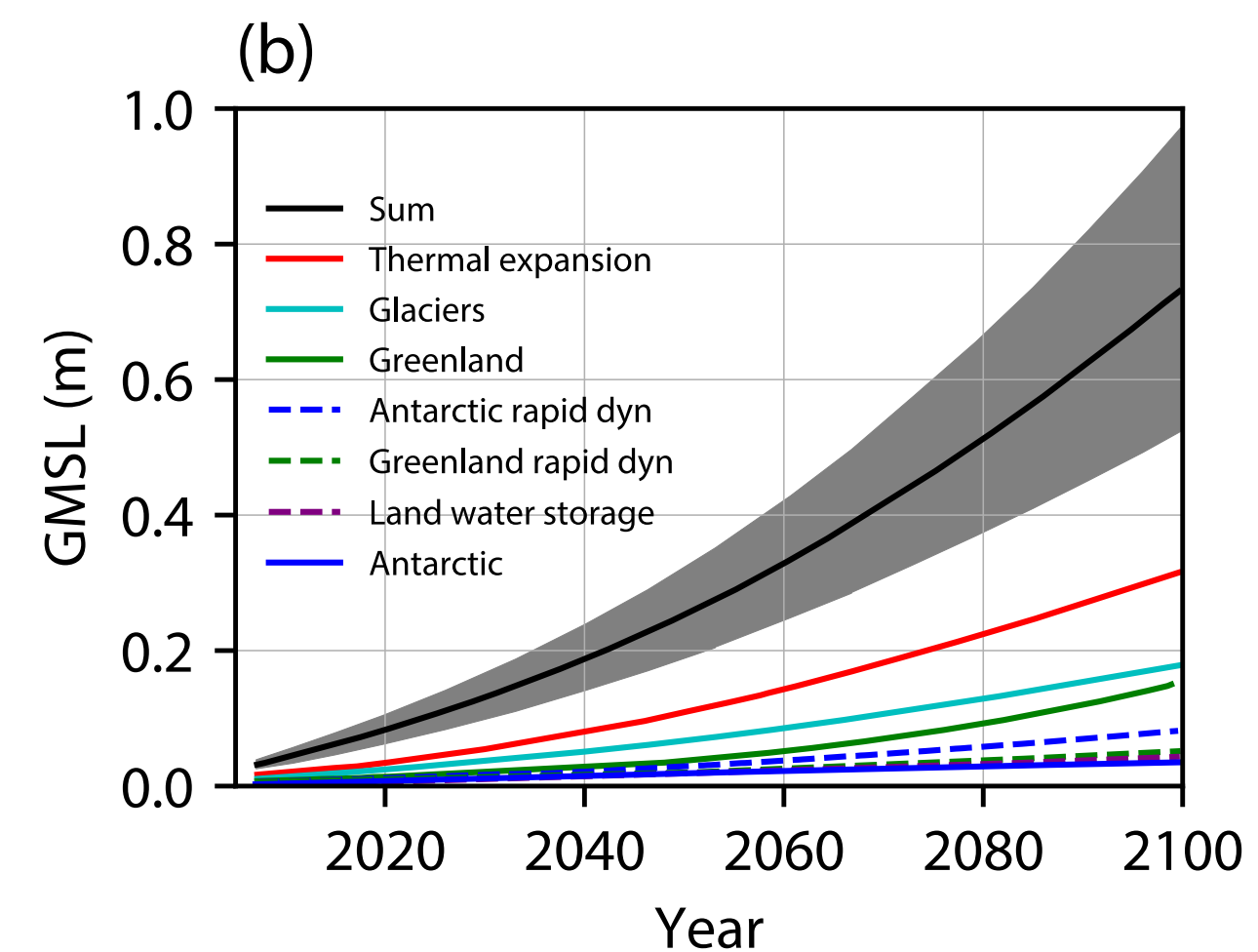


last 300 years

sea level *trends* as a function of averaging period and time



(a) satellite observations and (b) RCP8.5 projections



Notes

section 2, sea level

mini-quiz sea level

Calculate the increase in sea level Δd if:

$$d_0 = 500 \text{ m,}$$

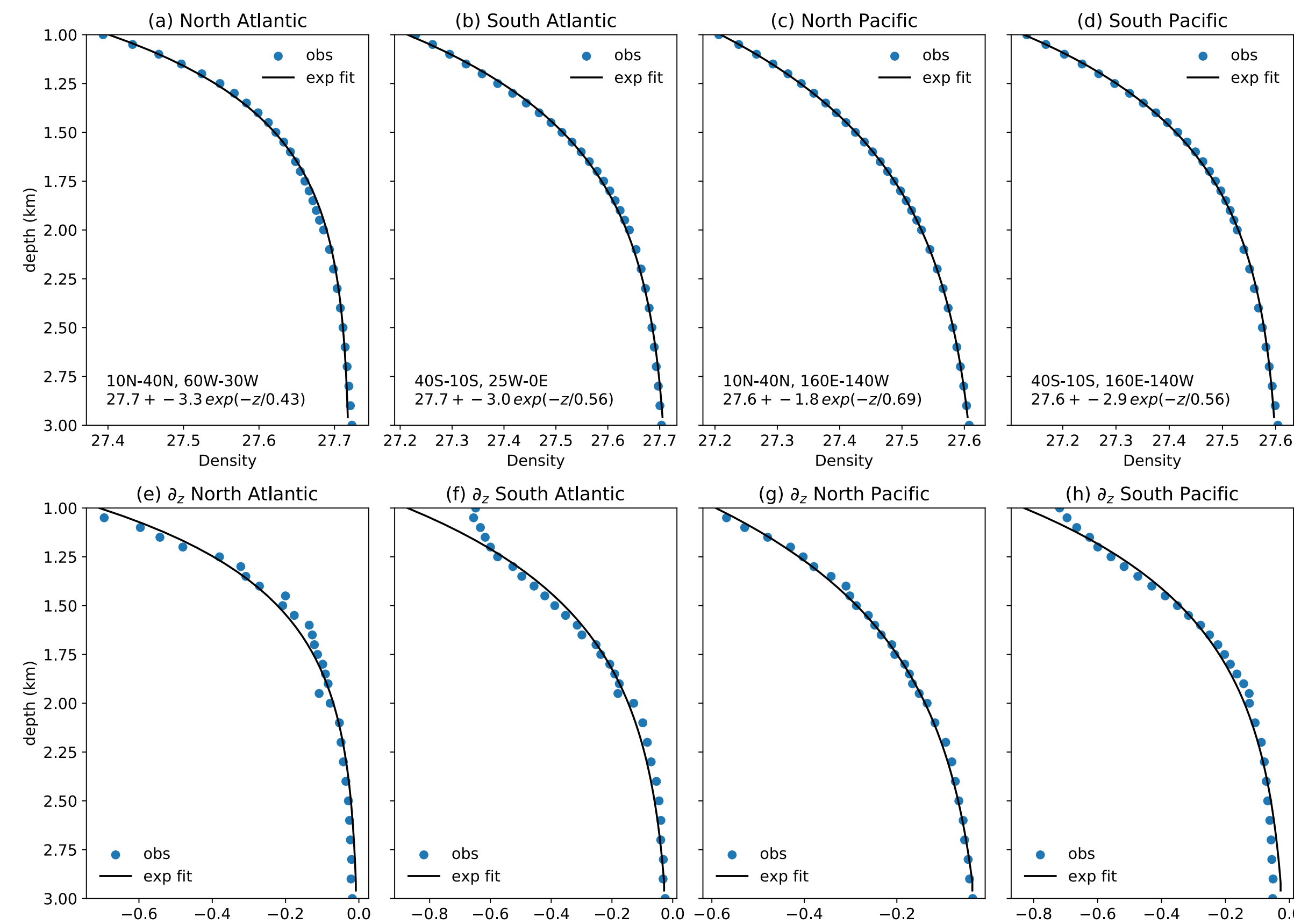
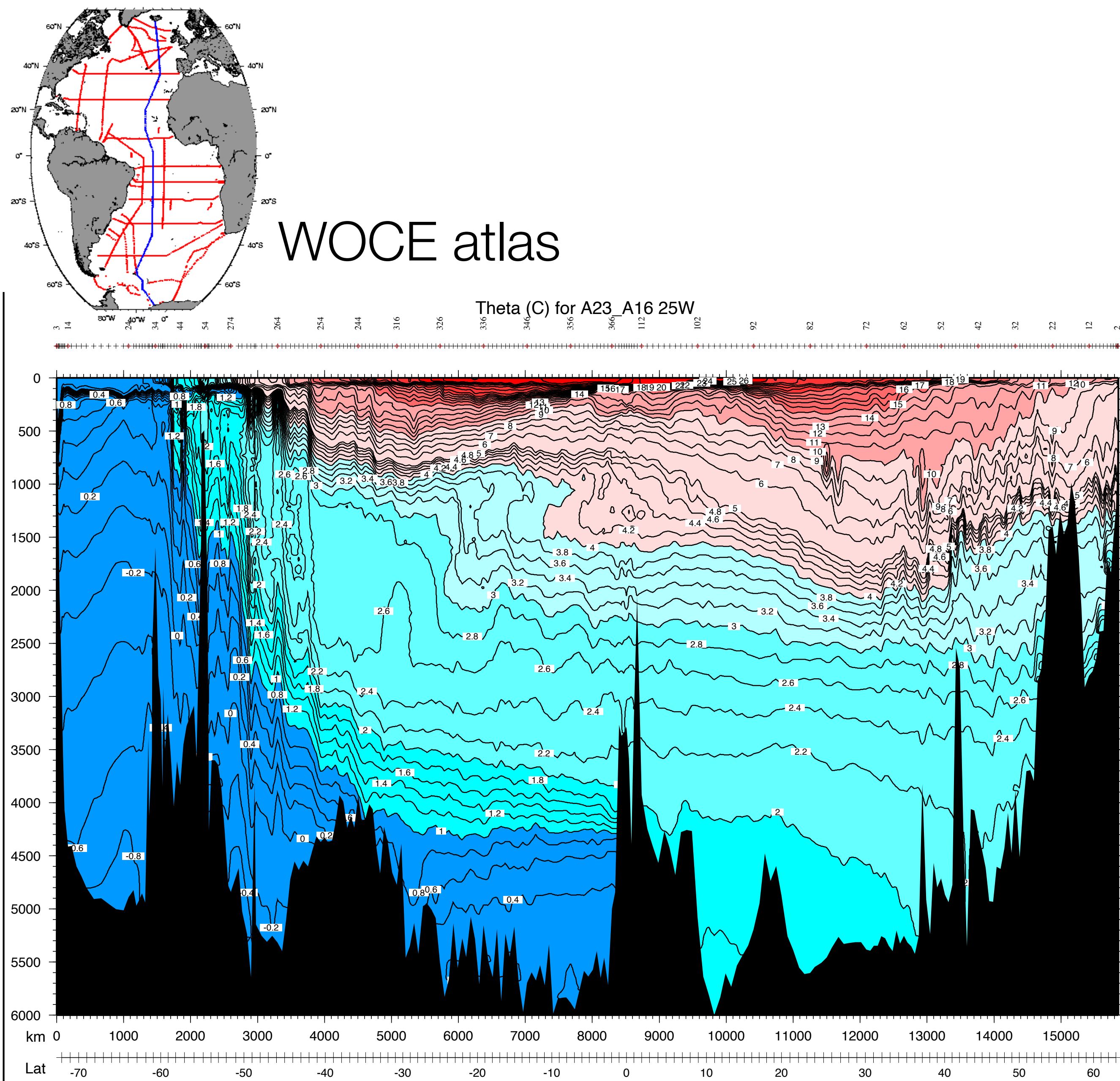
$$\Delta T = 3^\circ,$$

$$T_0 = 16^\circ,$$

$$\rho(16^\circ\text{C}, 35 \text{ ppt}) = 1025.75 \text{ kg/m}^3,$$

$$\rho(19^\circ\text{C}, 35 \text{ ppt}) = 1025.022 \text{ kg/m}^3$$

On the deep exponential stratification: abyssal recipes



Miller, Yang, Tziperman 2020
after Munk 1966

On the deep exponential stratification: abyssal recipes

notes

section 3, abyssal recipes

mini-quiz abyssal recipes

Starting from:

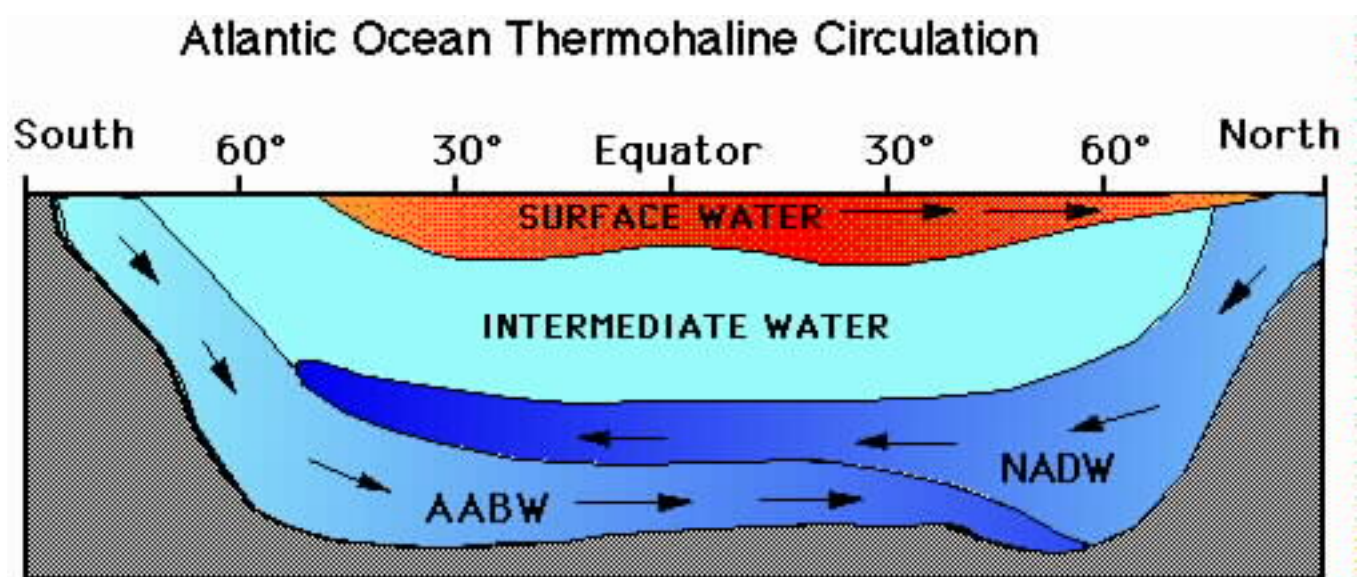
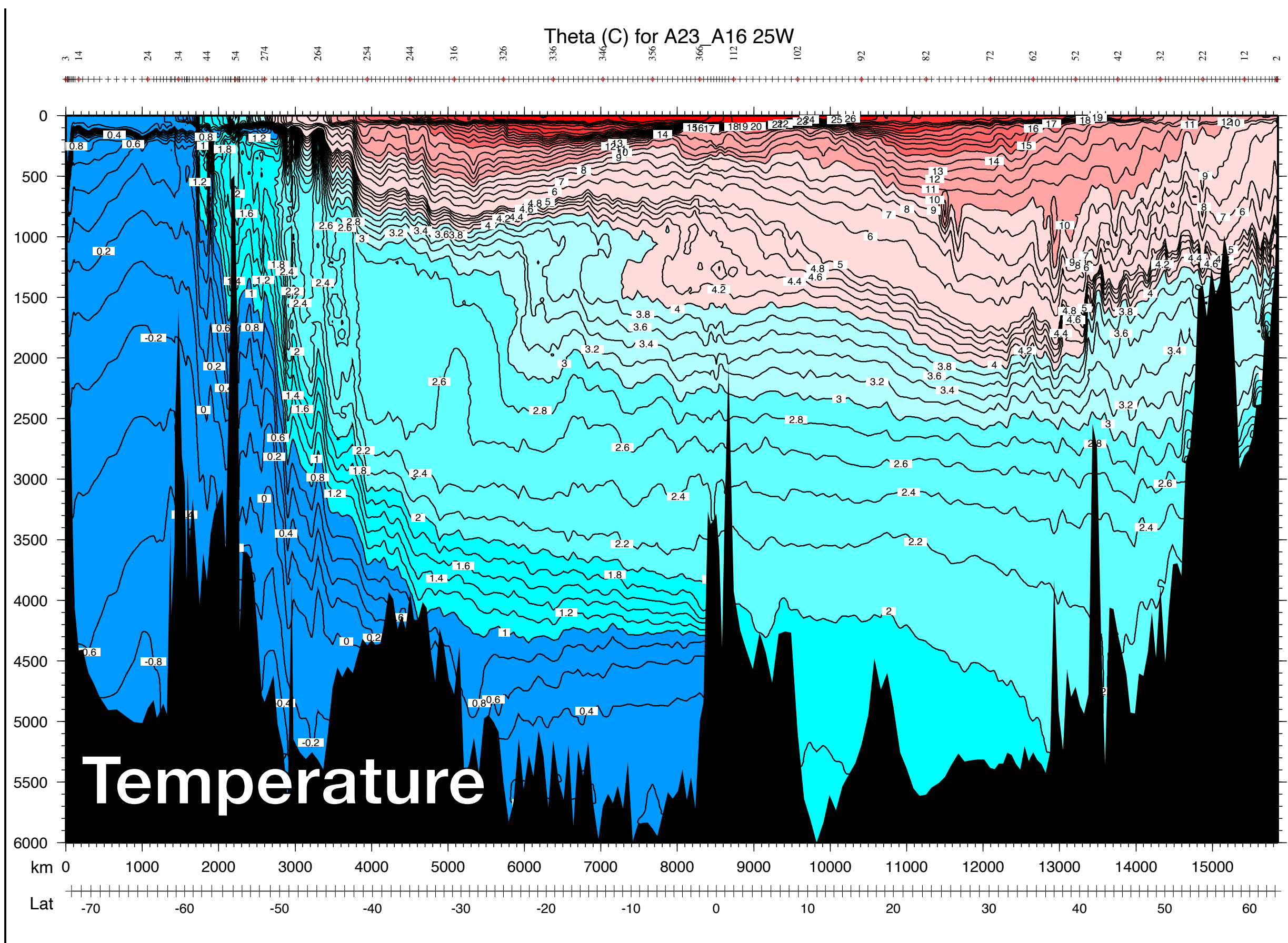
$$w \frac{\partial T}{\partial z} = \kappa \frac{\partial^2 T}{\partial z^2}$$

assume the solution is exponential,

$$T = T_0 + ae^{bz}$$

substitute it into the equation to find $T(z)$ and in particular the exponential decay scale.

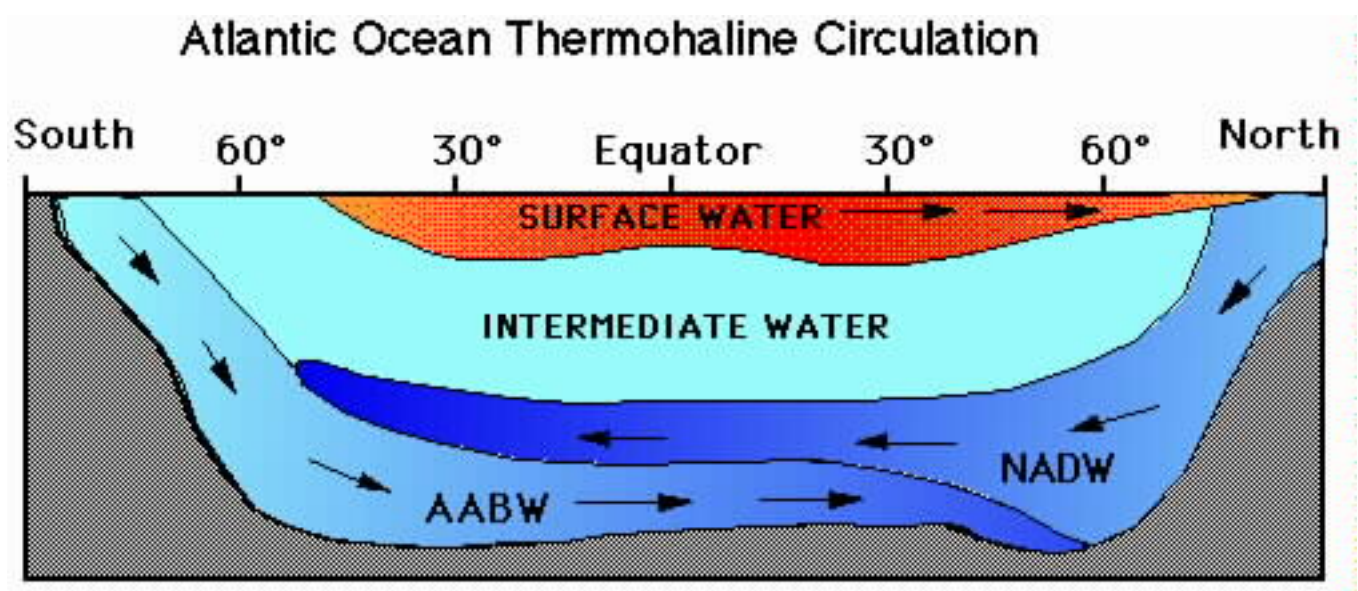
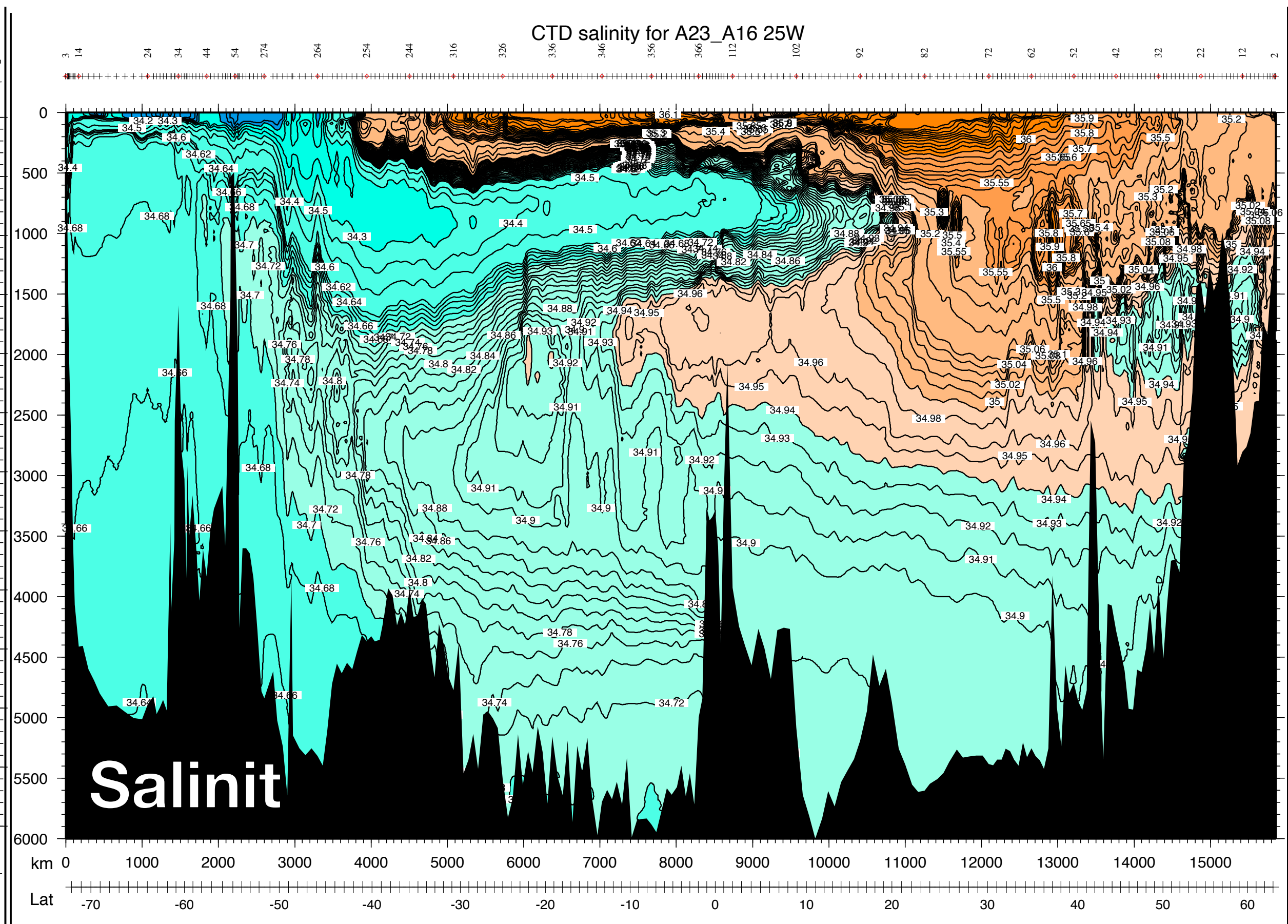
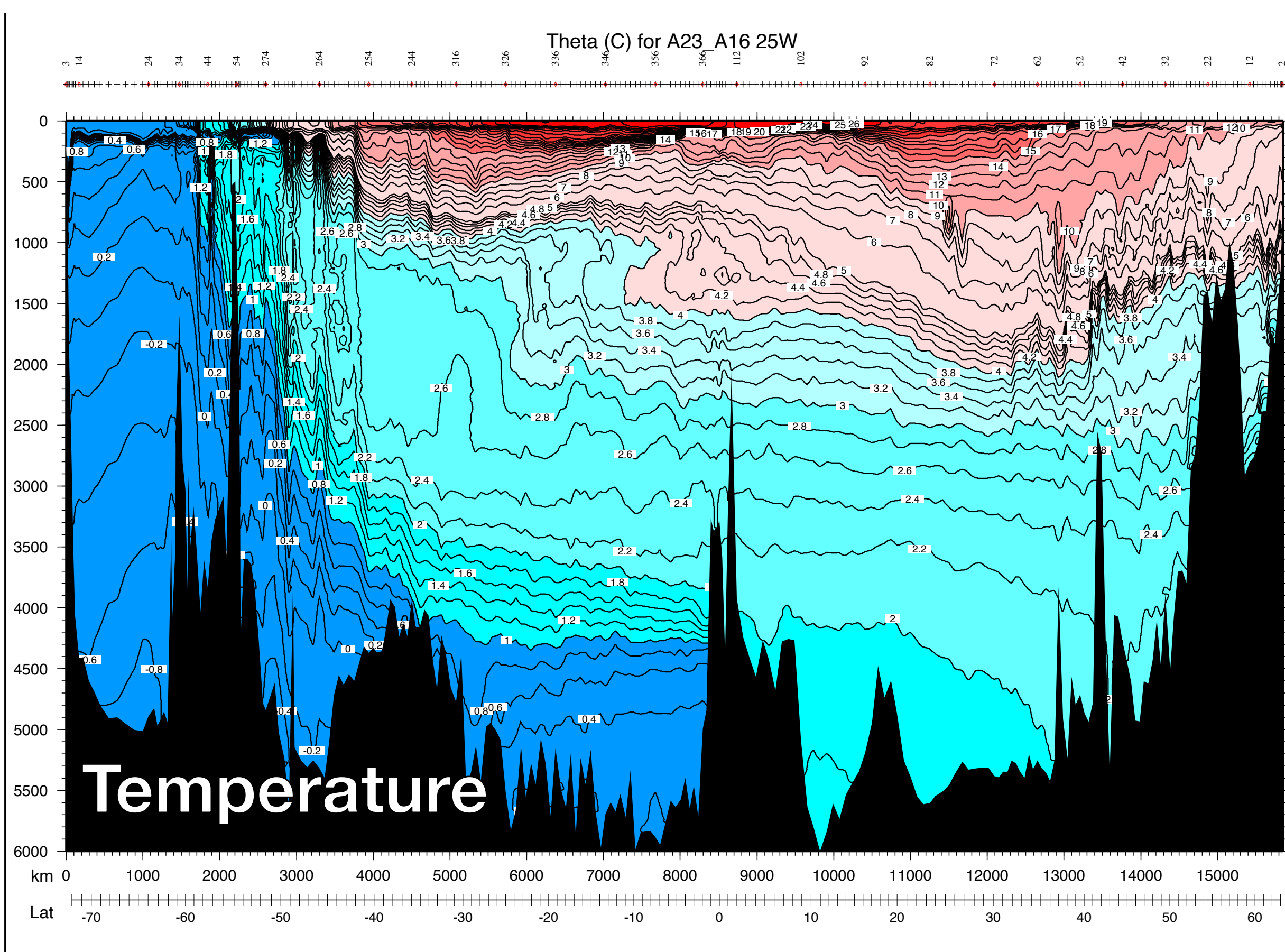
Evaporation–Precipitation and ocean salinity changes



WOCE atlas

Increased nutrients & dissolved CO₂  <https://mail.tku.edu.tw/086138/EnvFutures/WebPages/Global%20warming/Thermohaline%20Circulation.htm>
Warm, low nutrients, & oxygenated 

Evaporation–Precipitation and ocean salinity changes



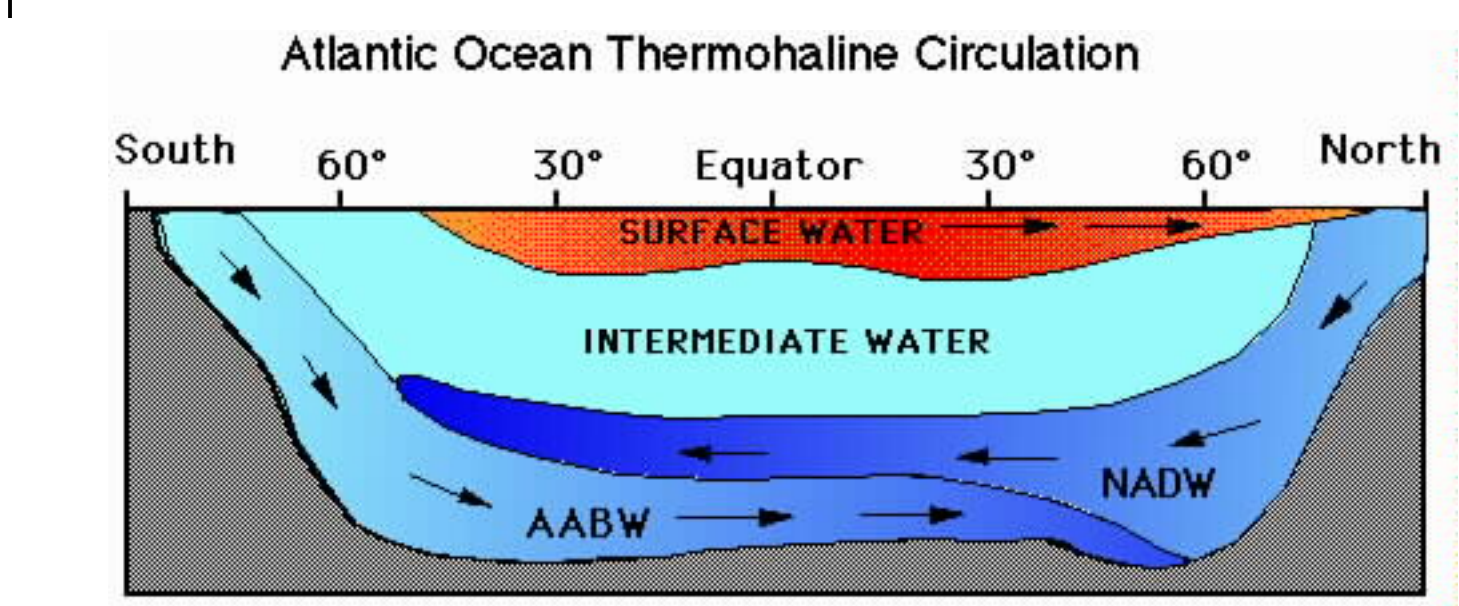
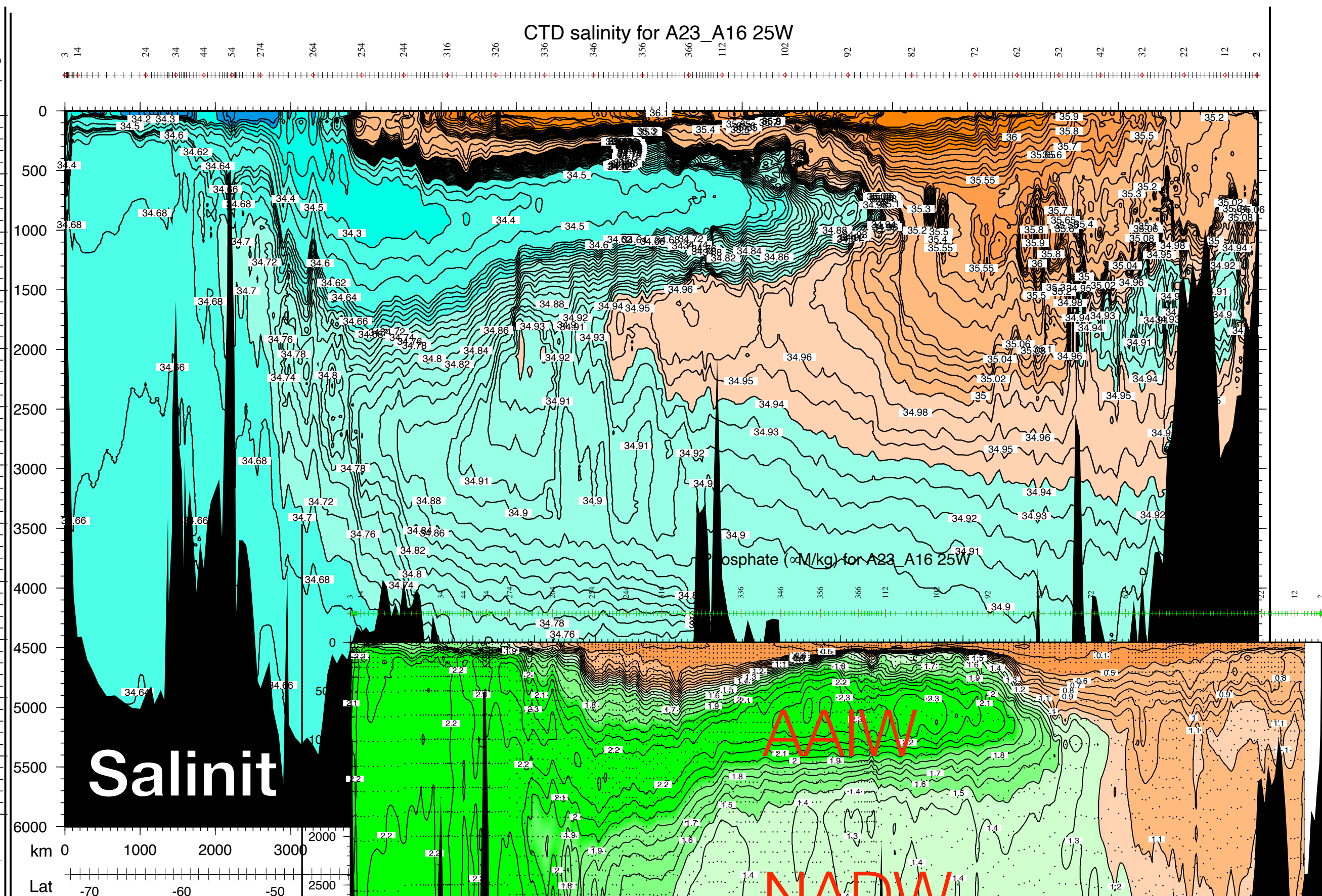
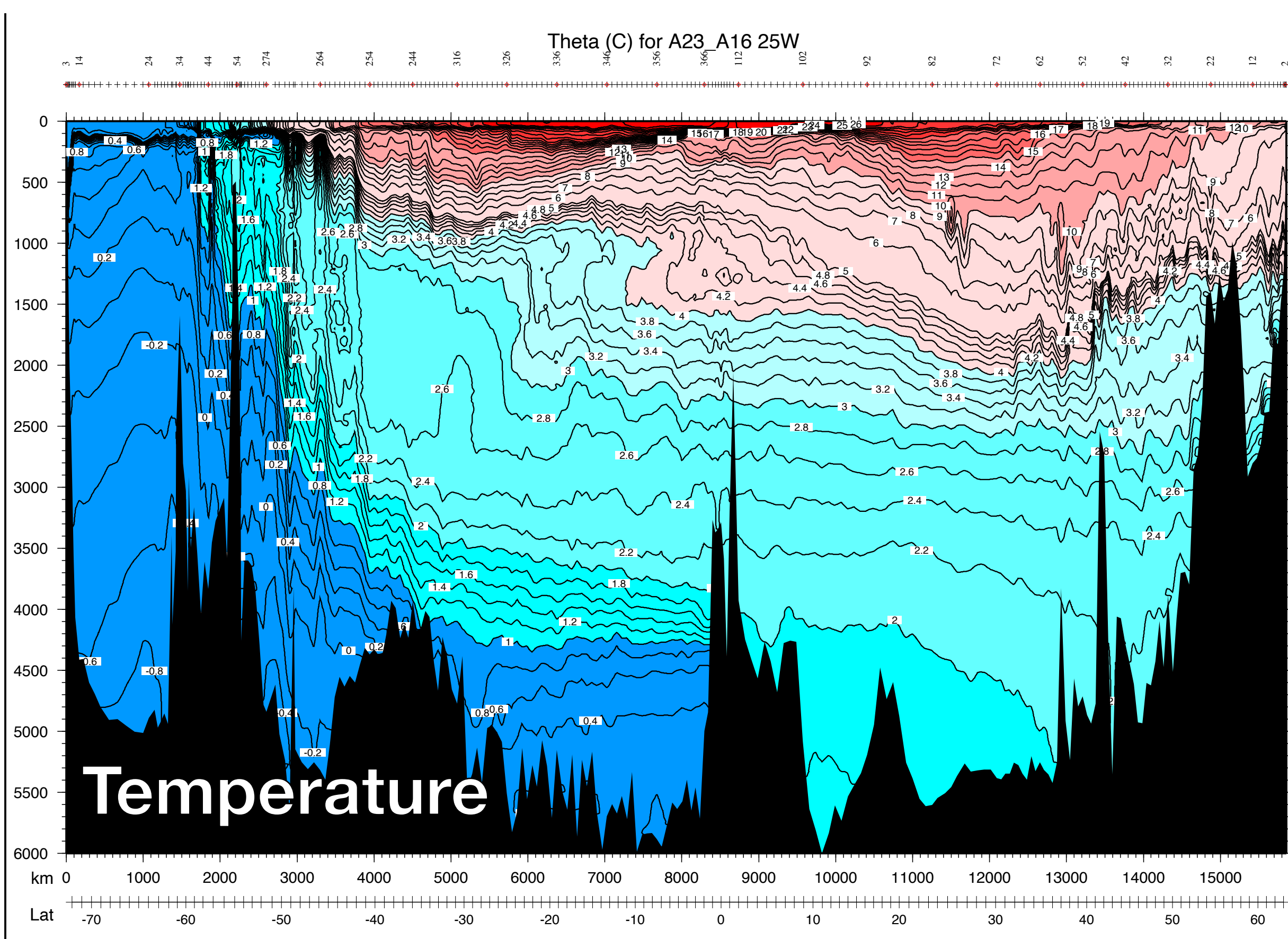
WOCE atlas

Increased nutrients & dissolved CO₂ █

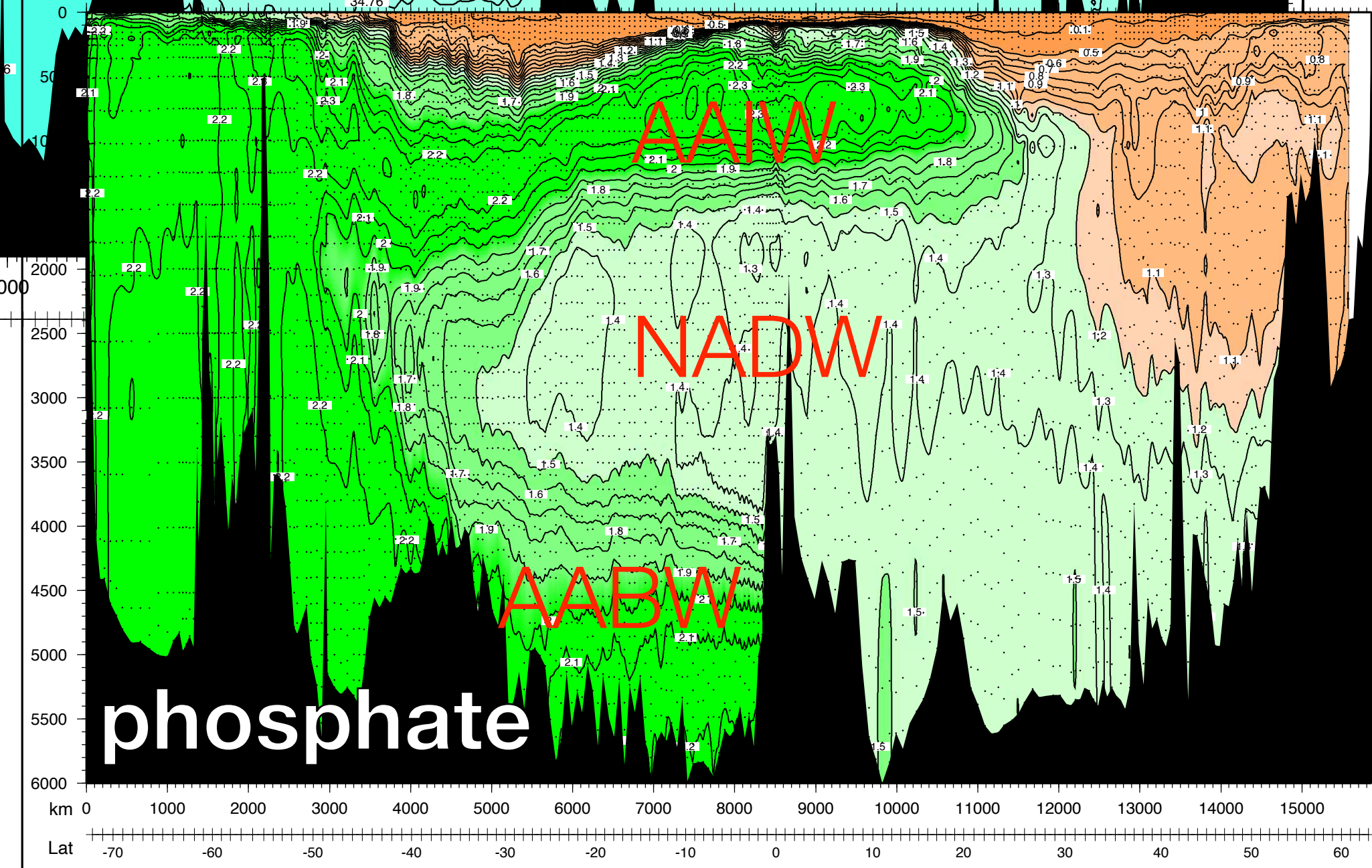
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Evaporation–Precipitation and ocean salinity changes



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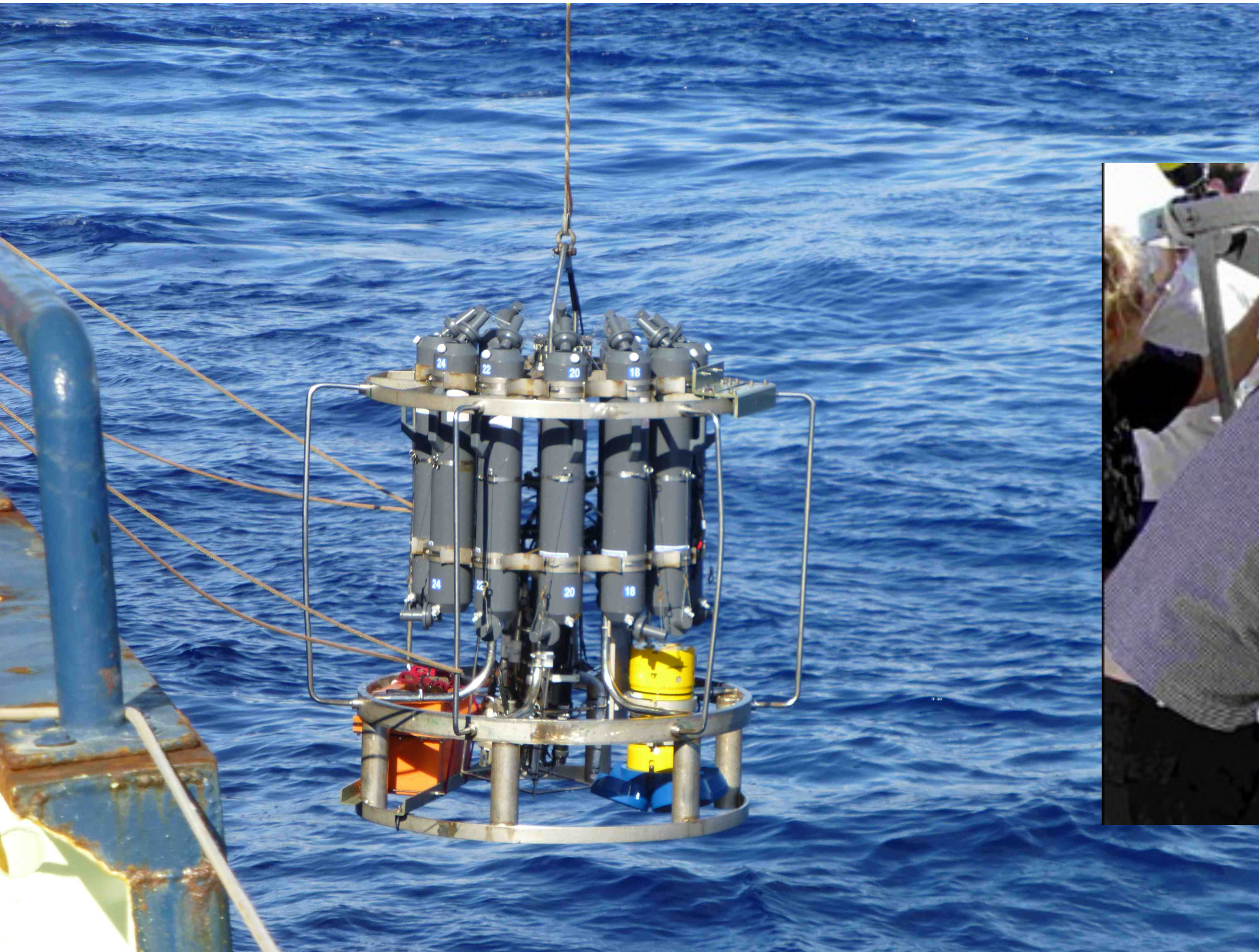


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Evaporation–Precipitation and ocean salinity changes



<https://earthobservatory.nasa.gov/blogs/fromthefield/tag/spurs-2/page/4/>

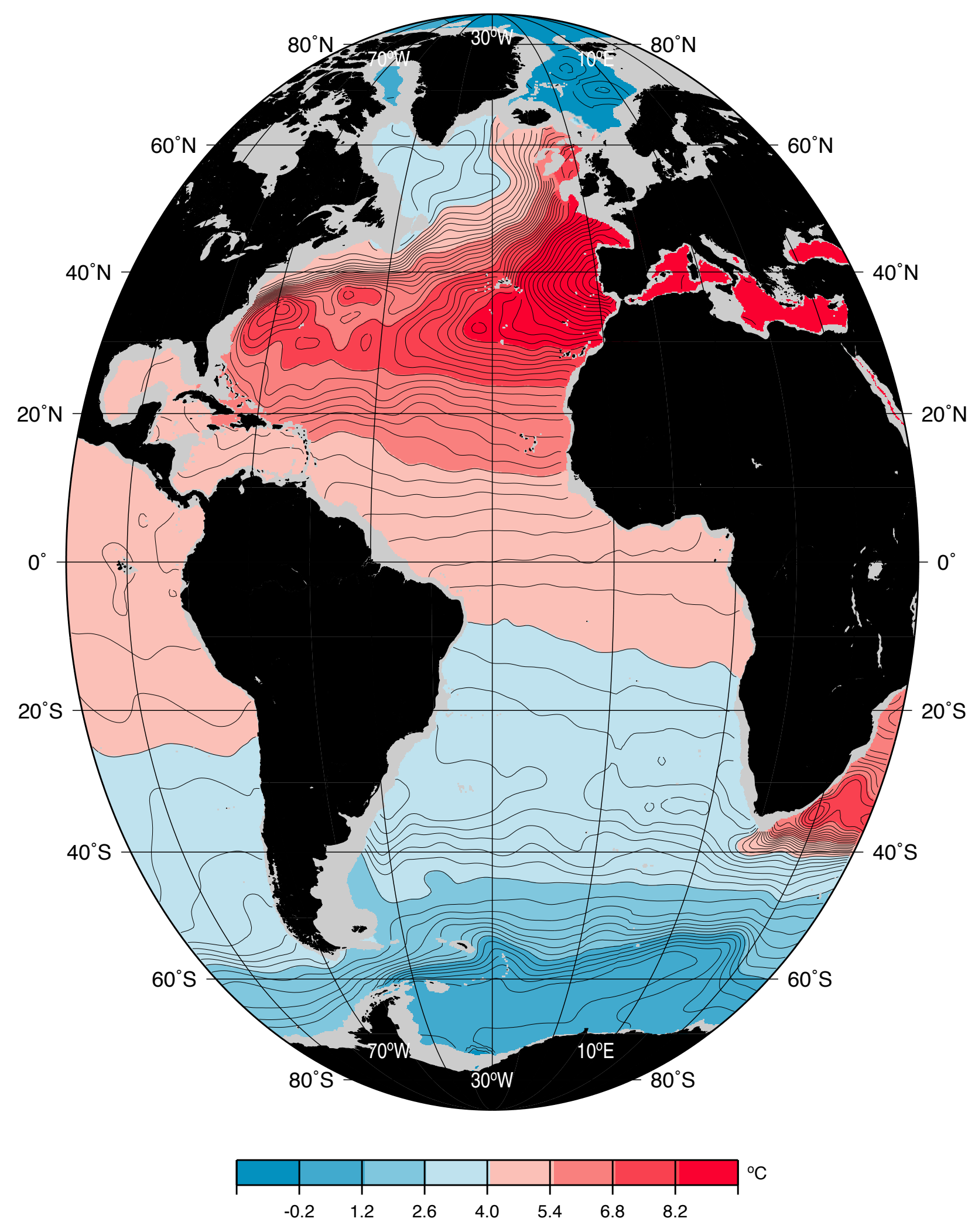


<https://www.wm.edu/news/stories/2009/study-shows-vims-professors-on-cutting-edge-001.php>

measuring salinity: conductivity, temperature, depth (CTD) and sampling bottles

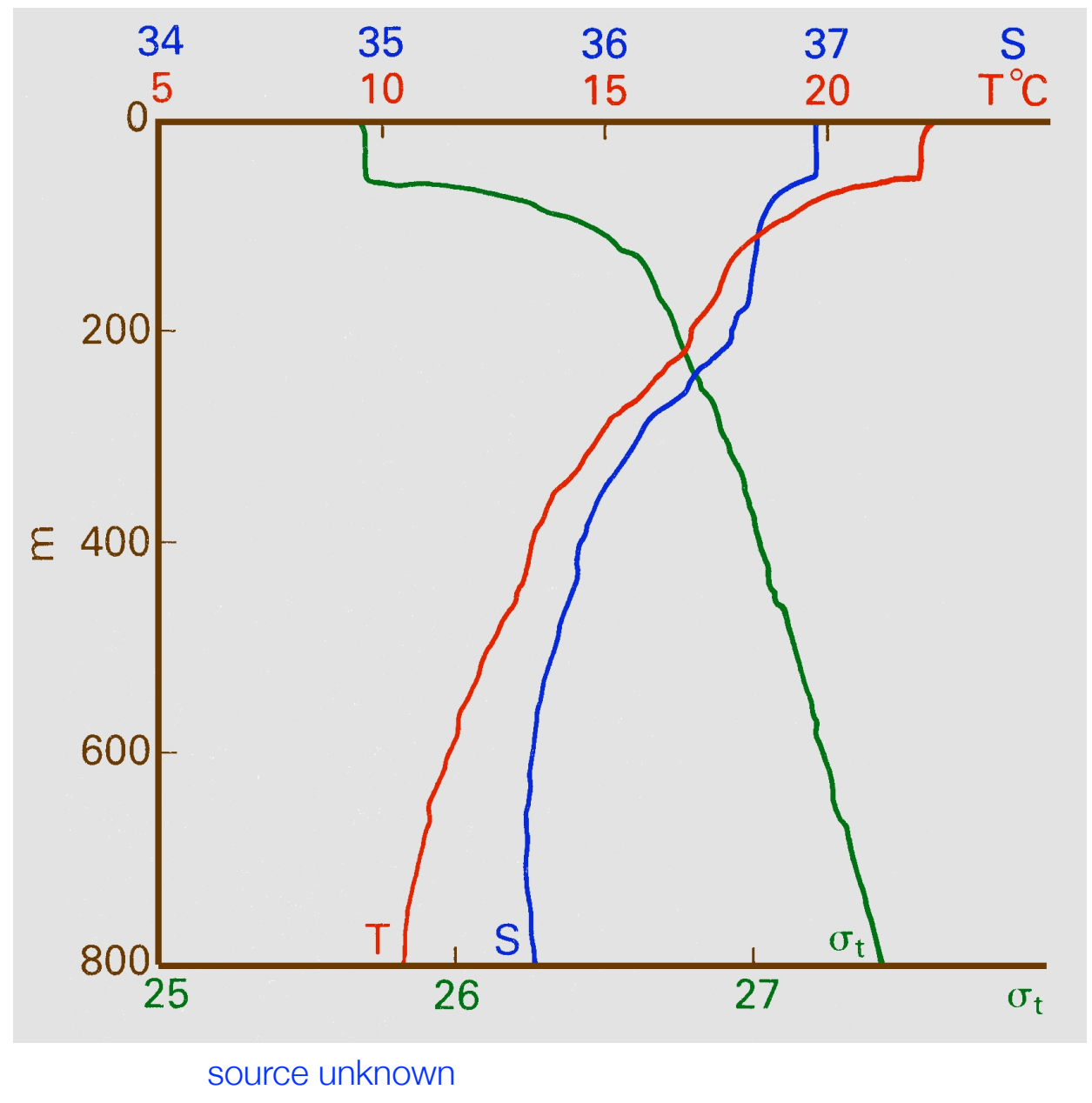
Evaporation–Precipitation and ocean salinity changes

Potential Temperature at 1000 m Depth

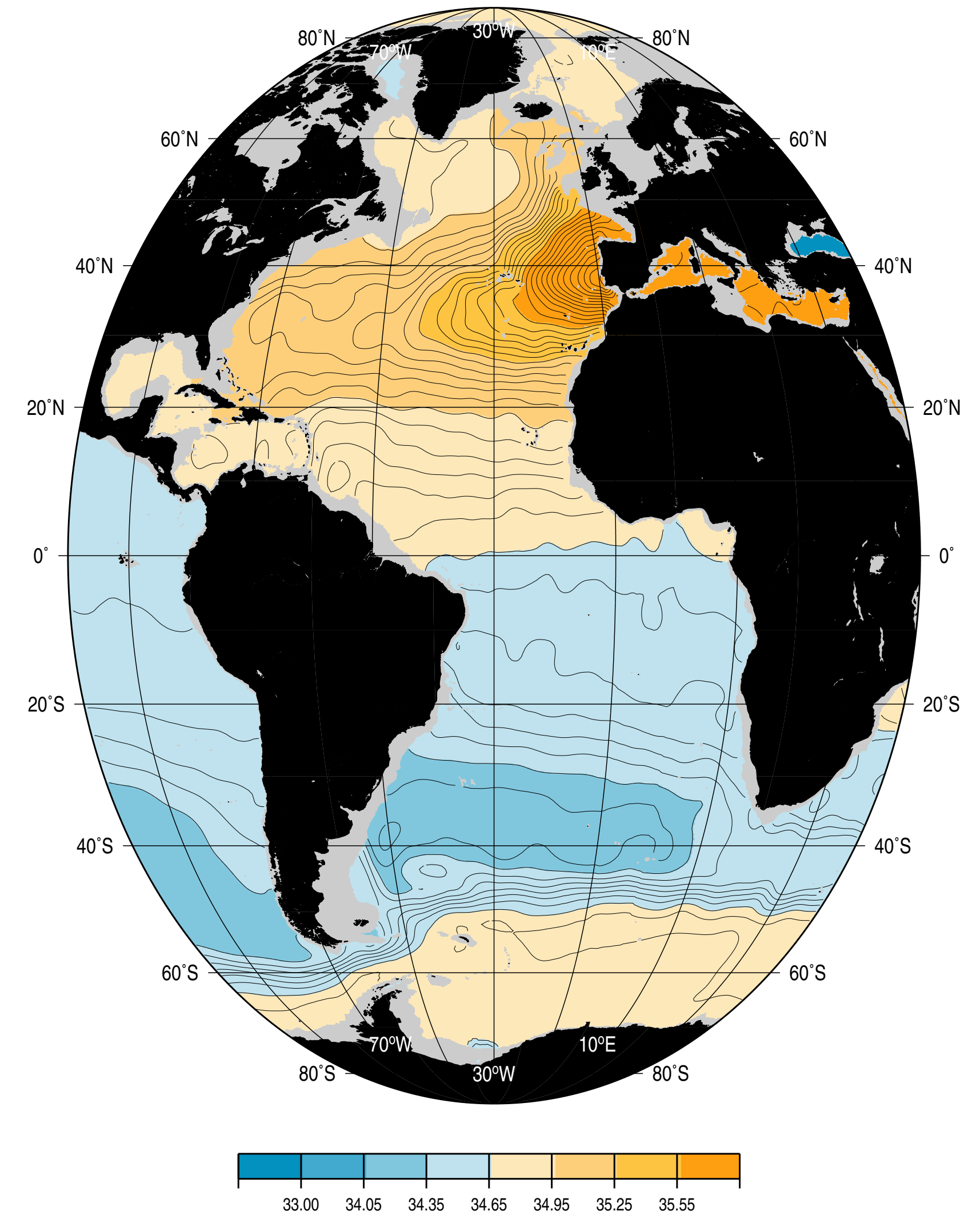


WOCE atlas

http://whp-atlas.ucsd.edu/atlantic/maps/stddep_sort/stddep_1000.htm



Salinity at 1000 m Depth



The mediterranean outflow high salinity, high temperature “tongue”

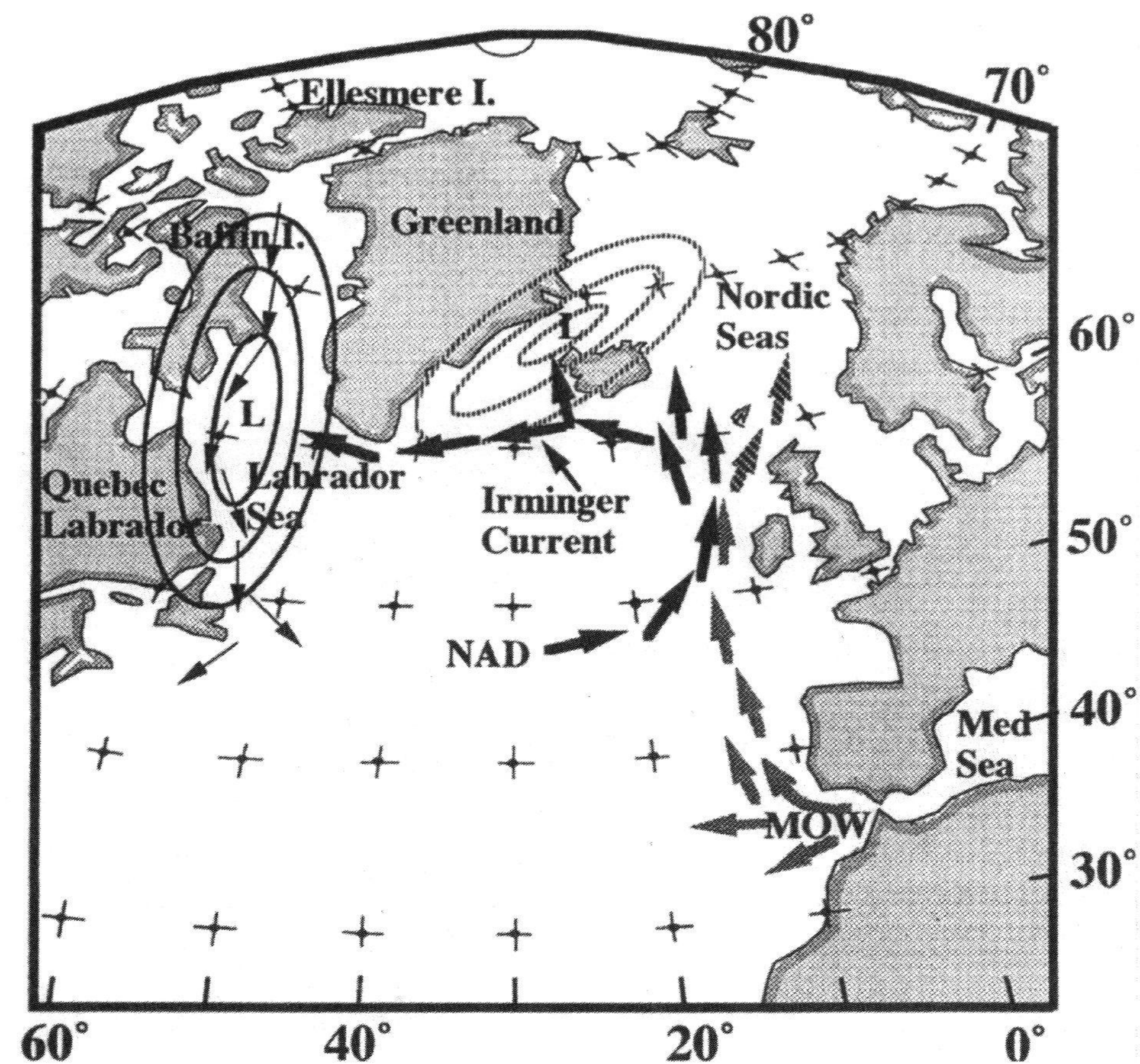
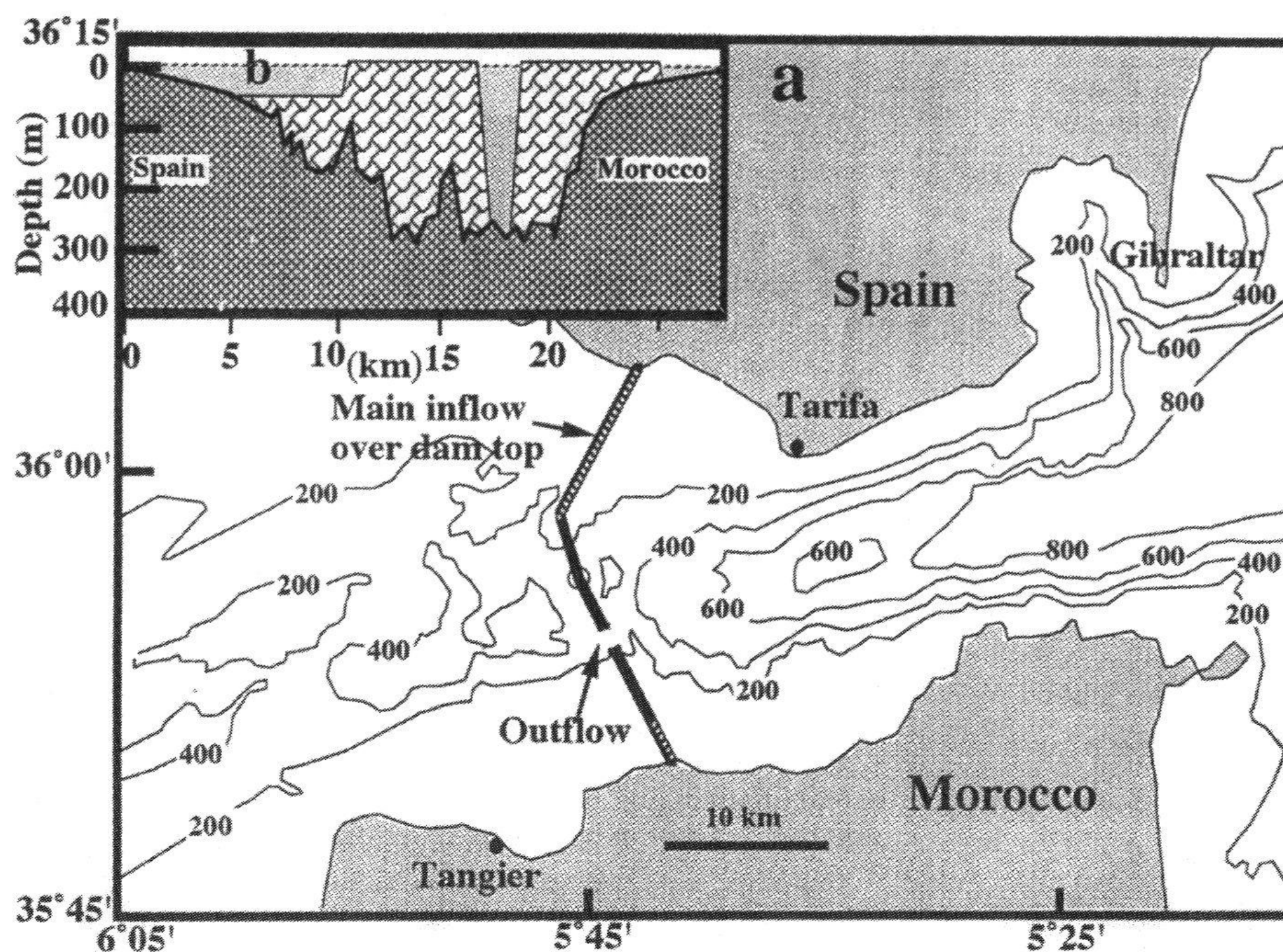
Evaporation–Precipitation and ocean salinity changes

EOS

Climate Control Requires a Dam at the Strait of Gibraltar

PAGES 277, 280–281

R. G. Johnson



Cooling the North Atlantic by shutting down AMOC using a dam at the Strait of Gibraltar 🤔

Evaporation–Precipitation and ocean salinity changes



<https://www.youtube.com/watch?v=IAupJzH31tc>
Brinicle, Underwater Icicle "Finger of Death"

Evaporation–Precipitation and ocean salinity changes

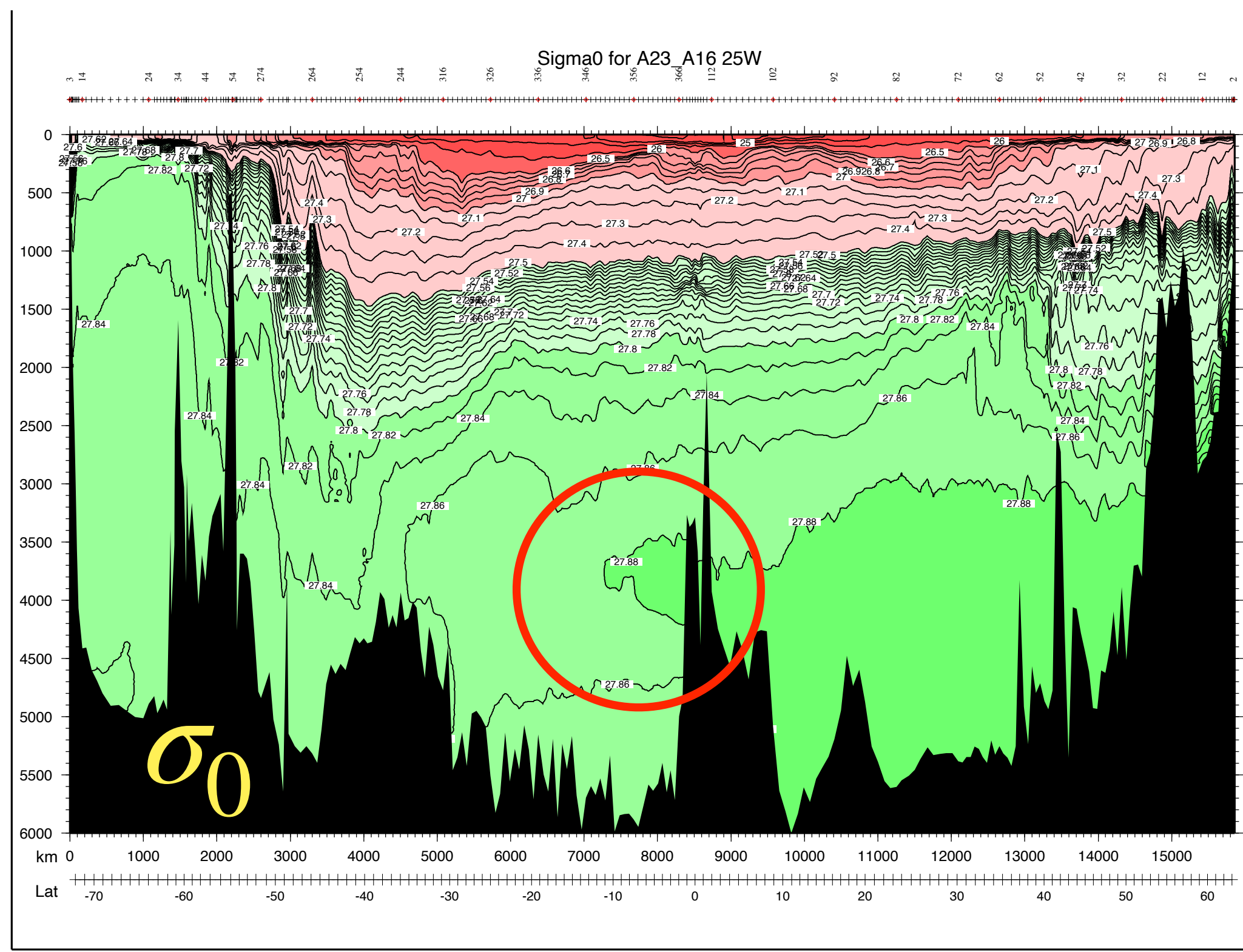


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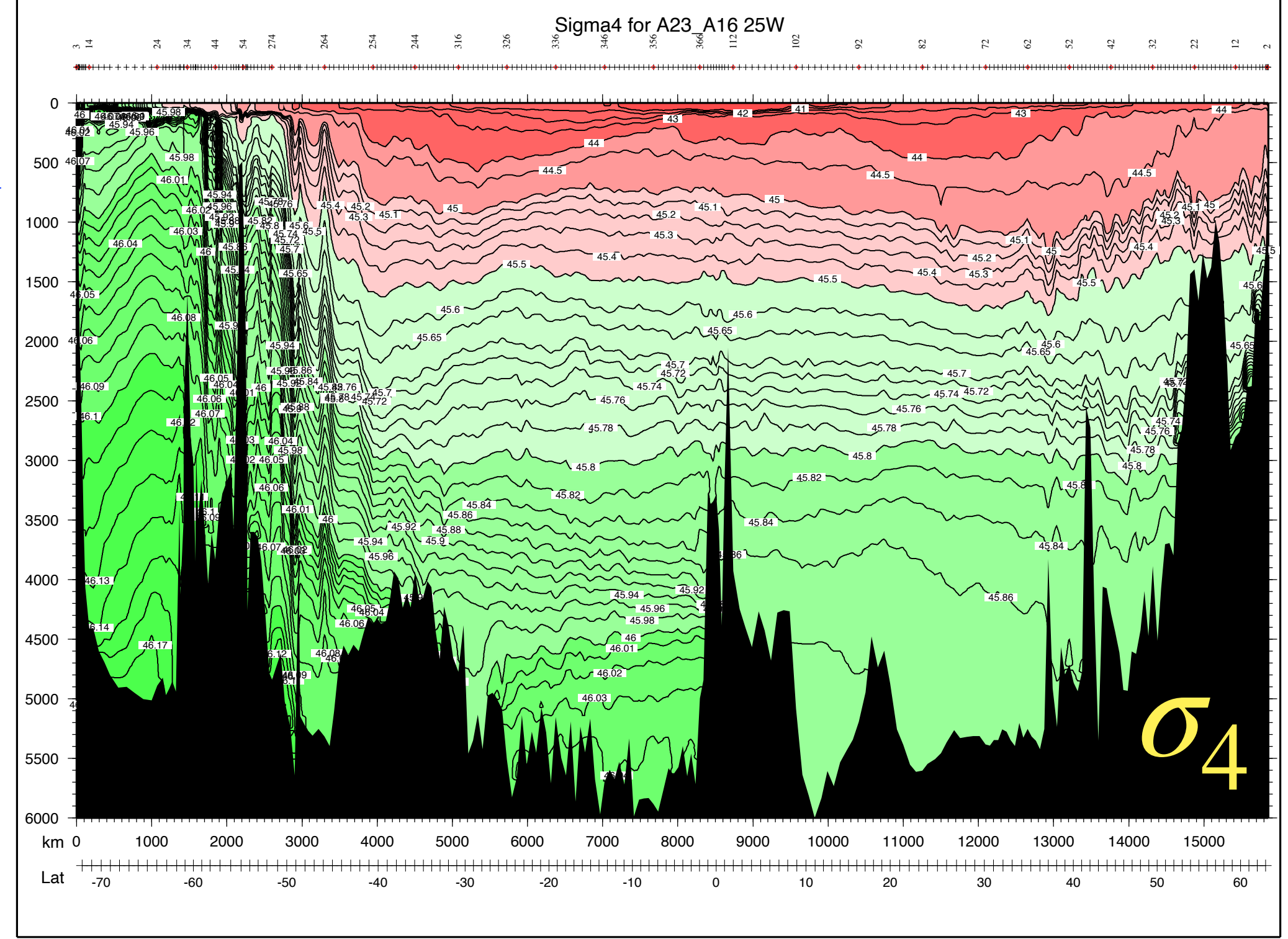
section 4, salinity

Density, potential density, and the equation of state

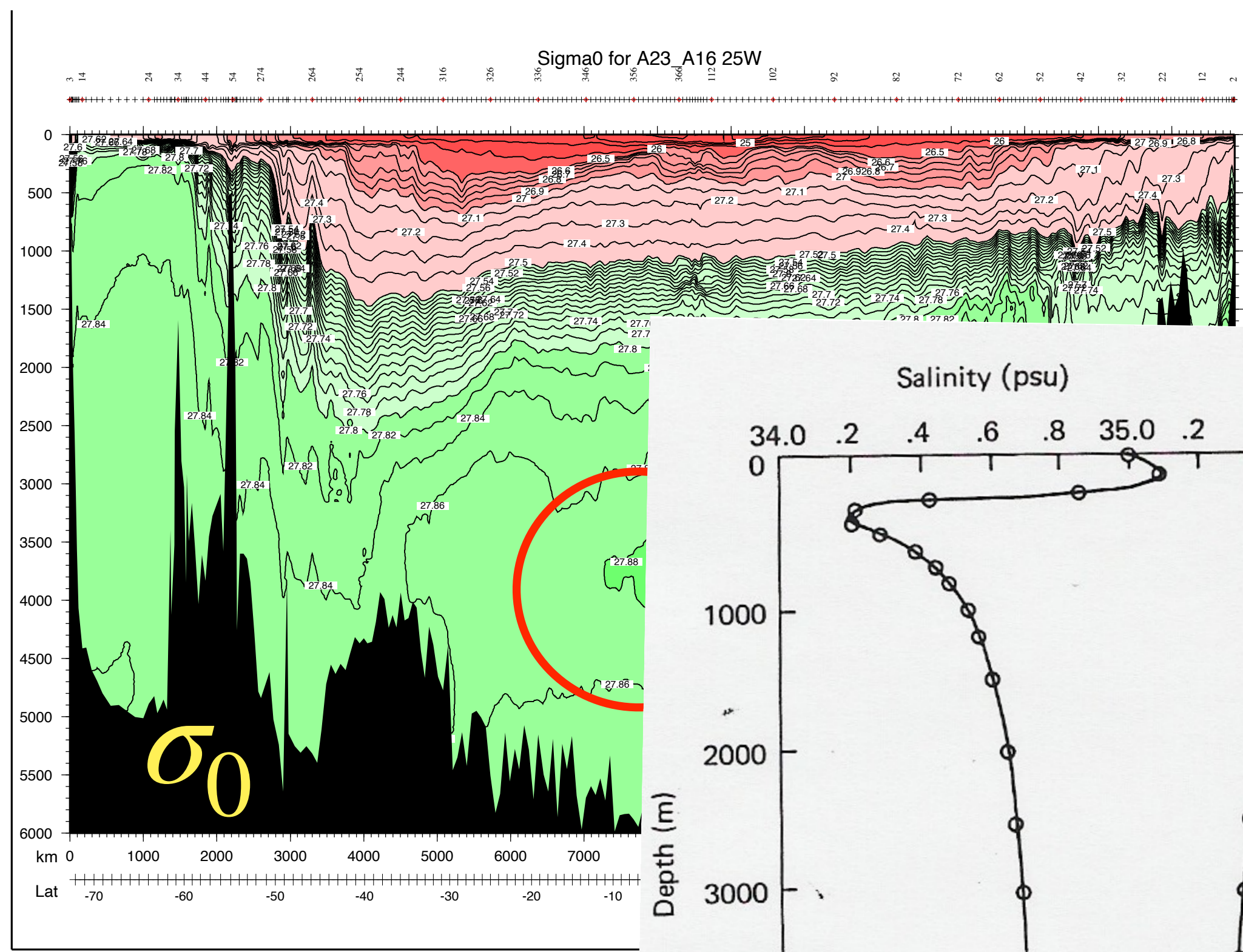


WOCE atlas

<http://whp-atlas.ucsd.edu/atlantic/sections.htm>



Density, potential density, and the equation of state



WOCE atlas

<http://whp-atlas.ucsd.edu/atlantic/sections.htm>

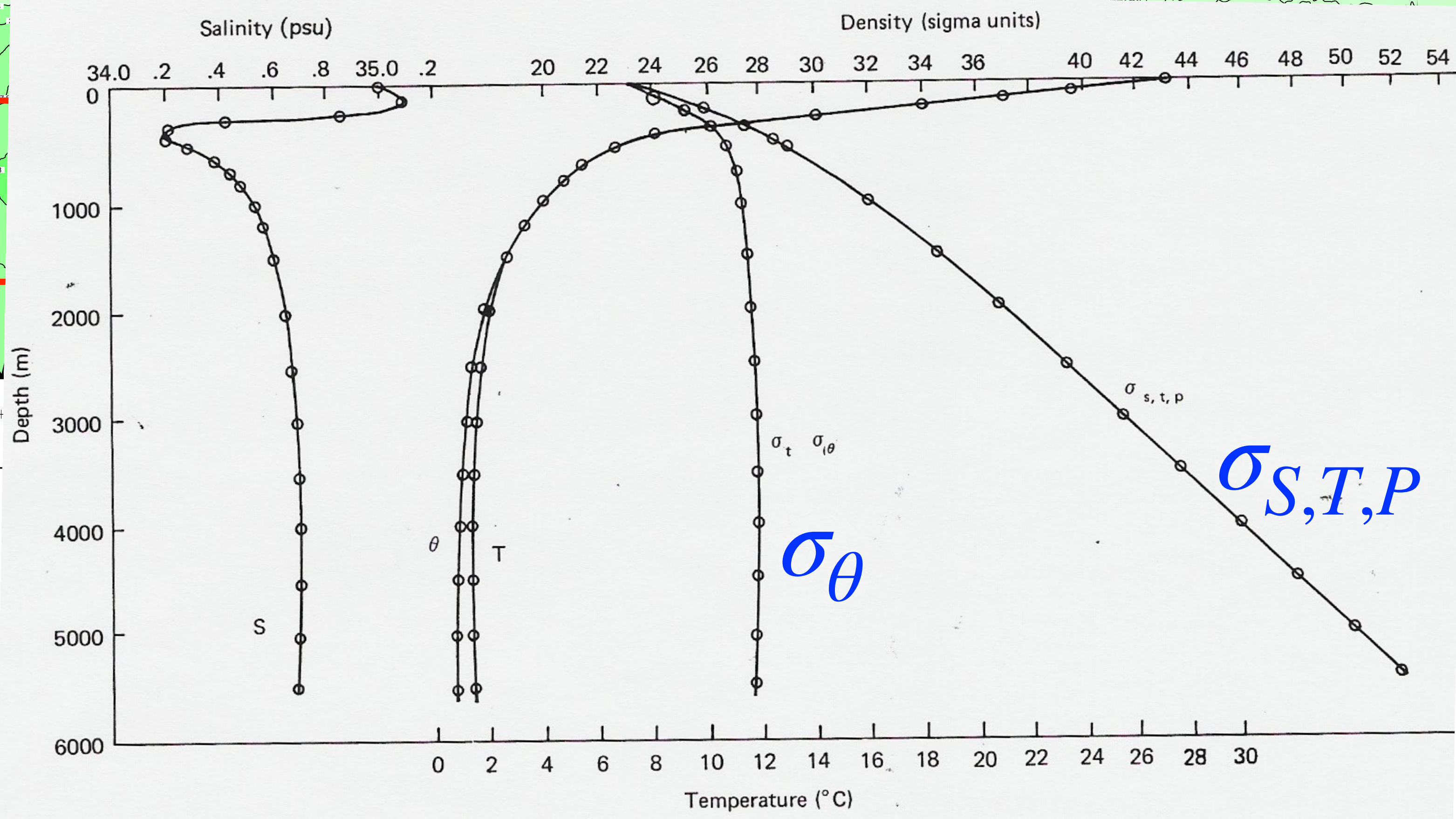
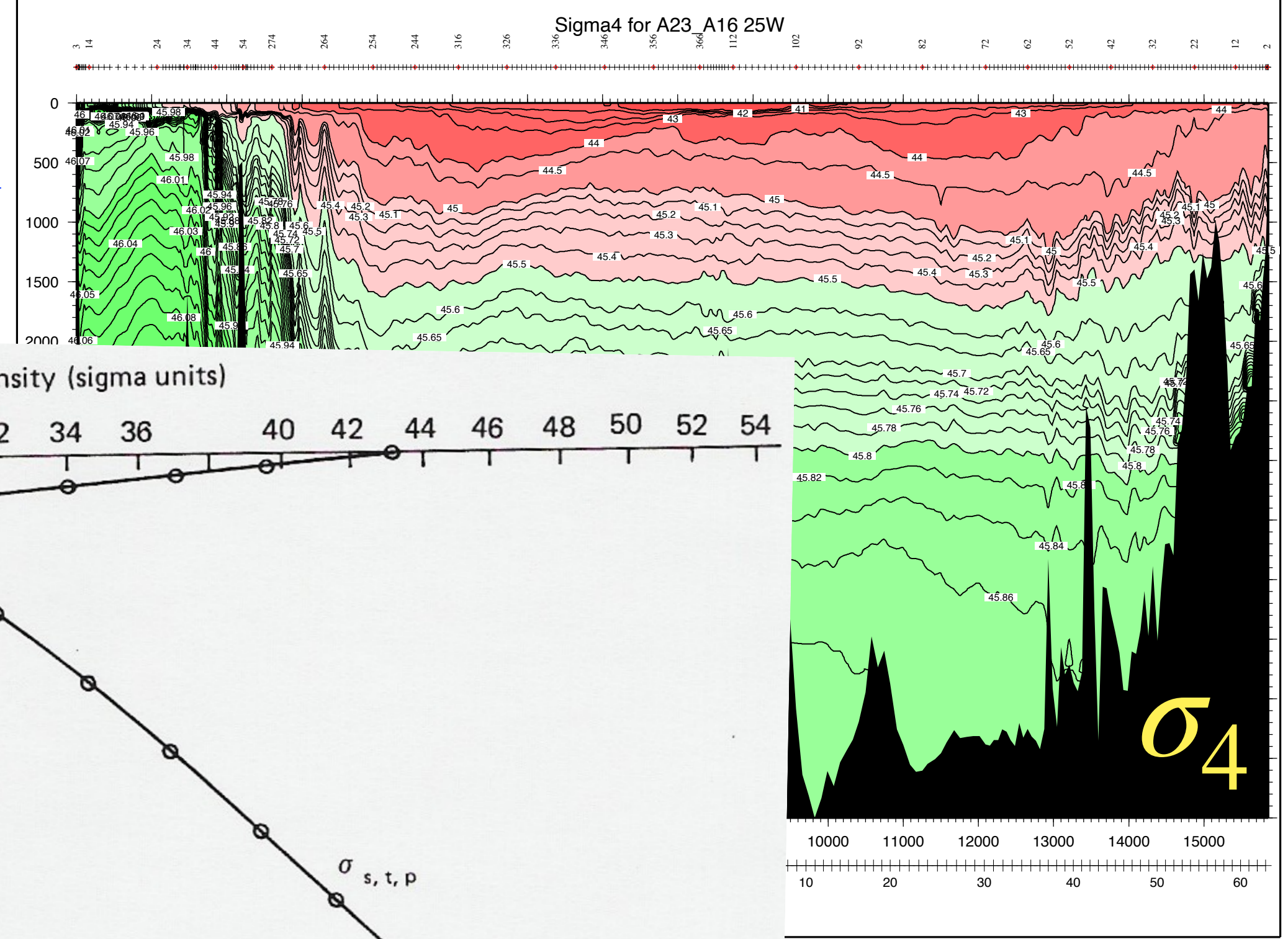
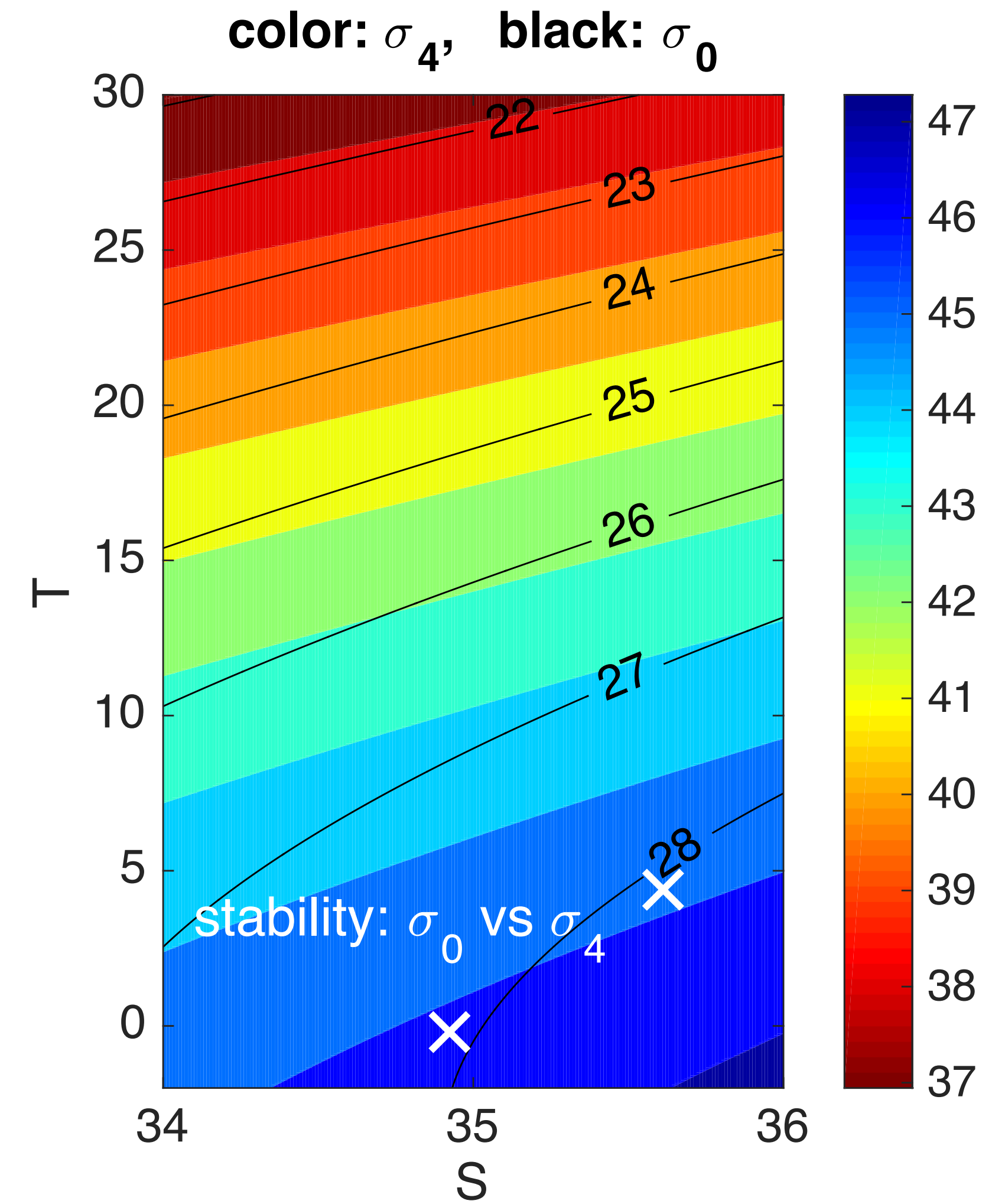
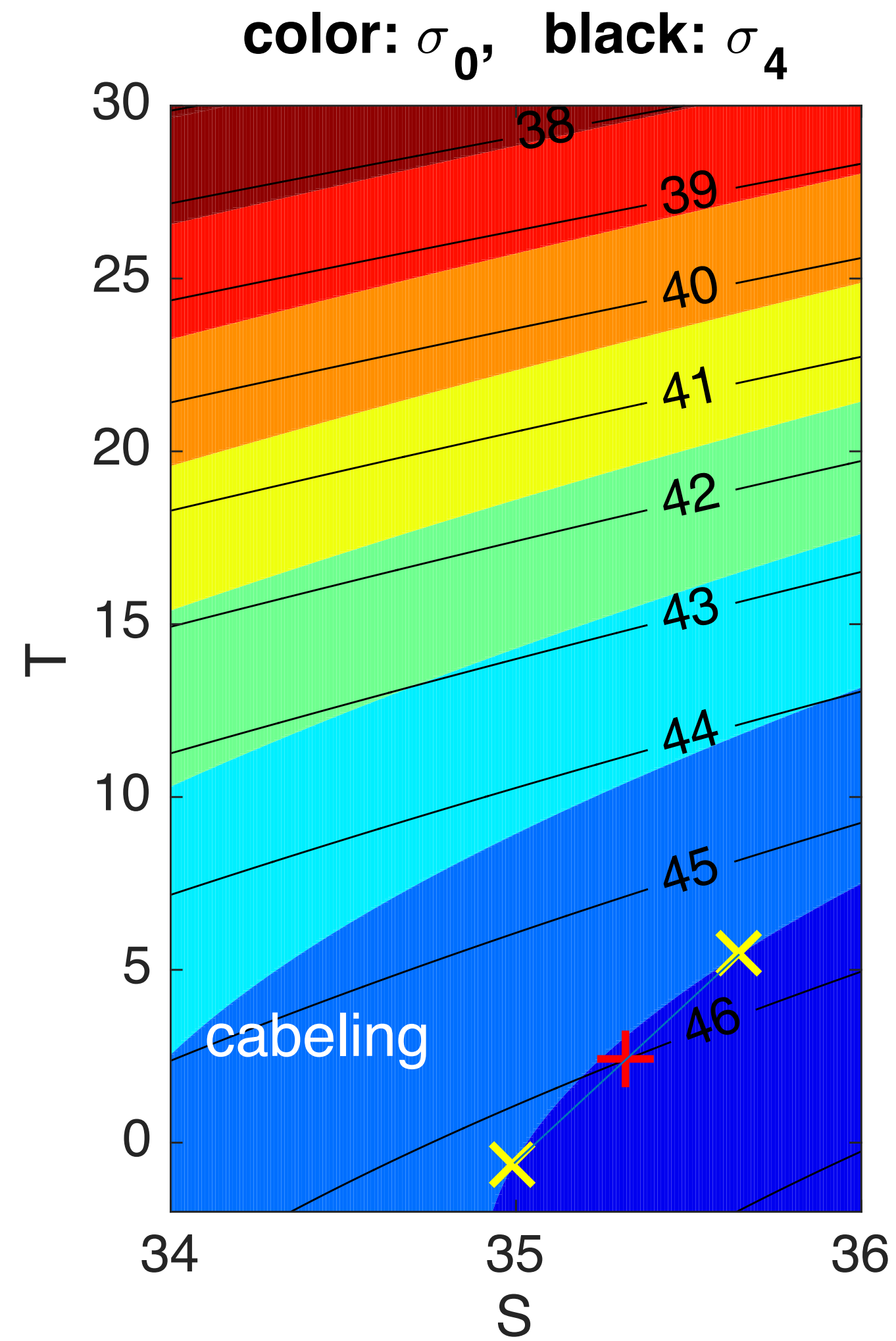
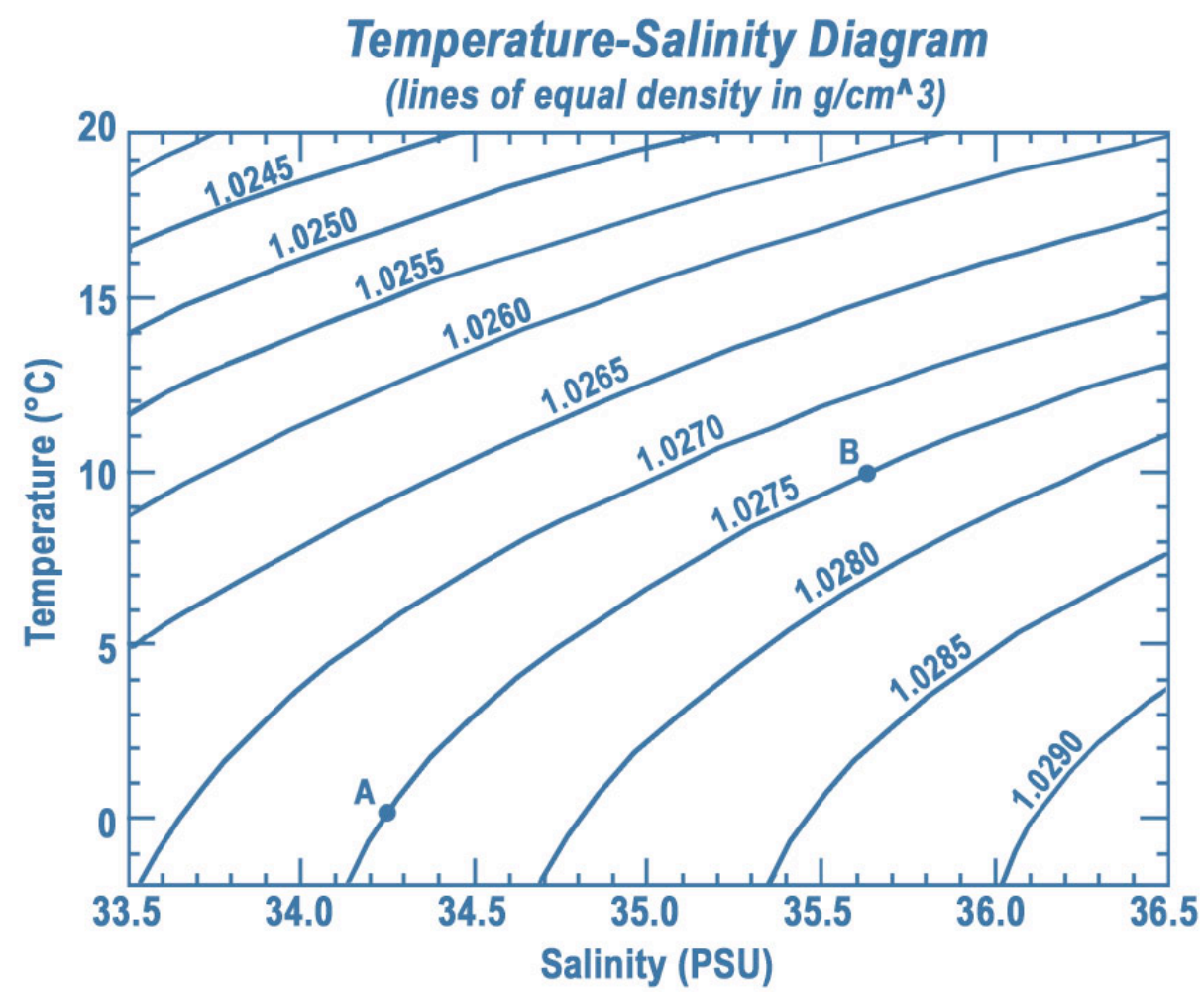


Figure 2.4 Salinity, potential temperature, in situ temperature, σ_θ , σ_t , and $\sigma_{S,T,P}$ -for a station in the North Pacific at 17° N and 162° W. (See Table for numerical values.)

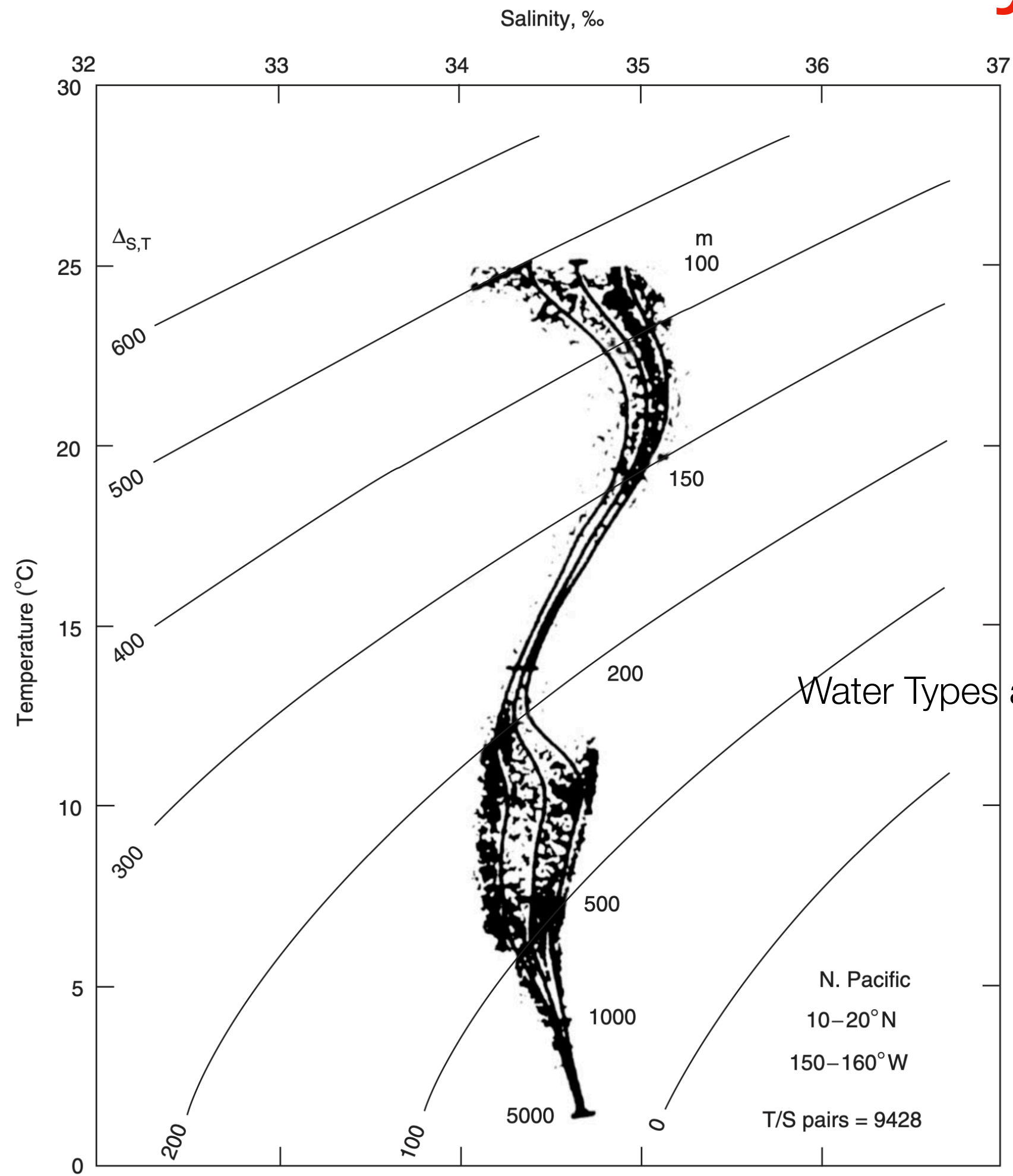
Notes

section 6, equation of state
(use following slides)

Density and the equation of state

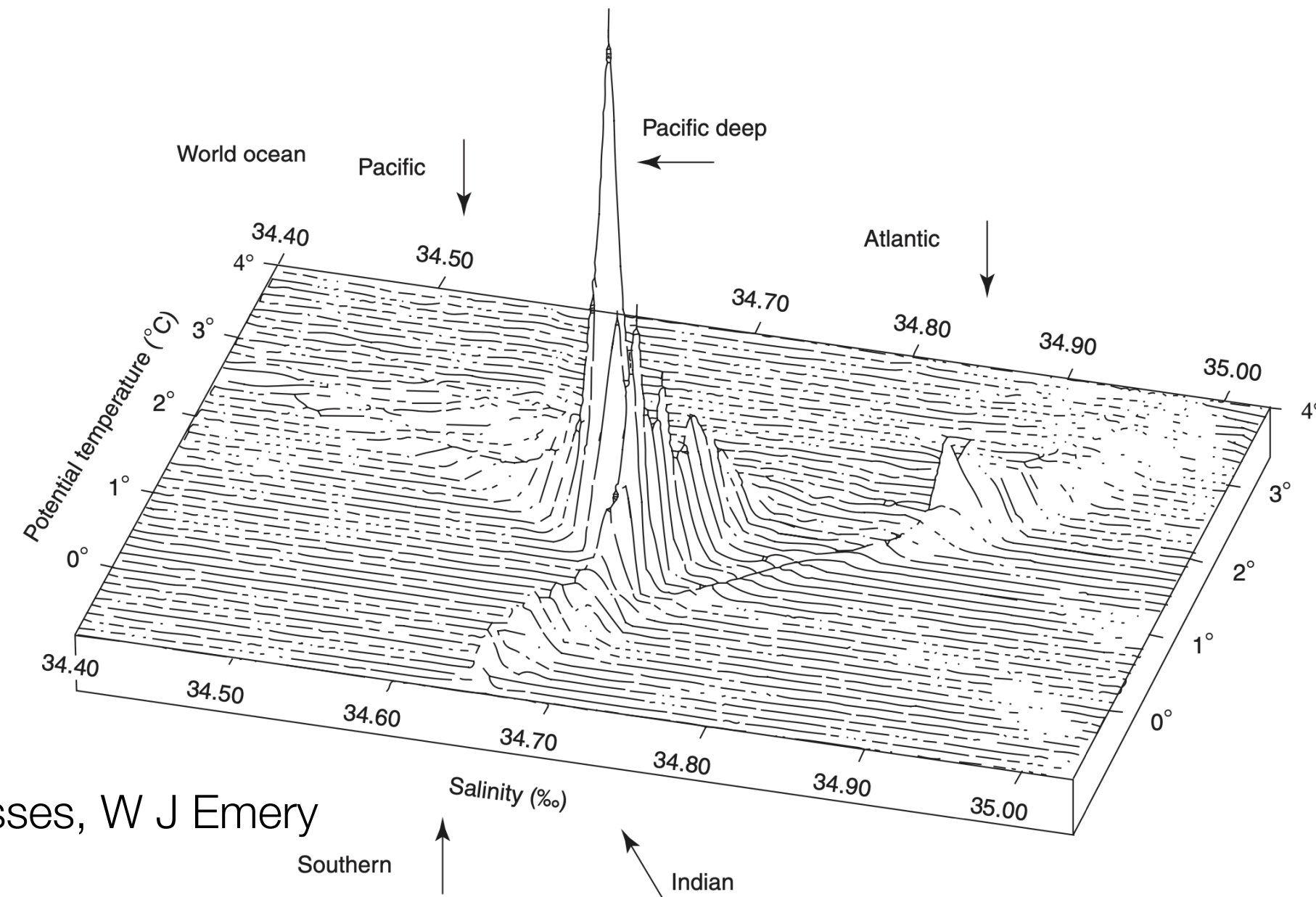


Density and the equation of state



Water Types and Water Masses, W J Emery

Tropical upper
 Tropical Sal. Max.
 N. Pacific central
 N. Pacific Intermediate and AAIW (mixing)
 Deep



226

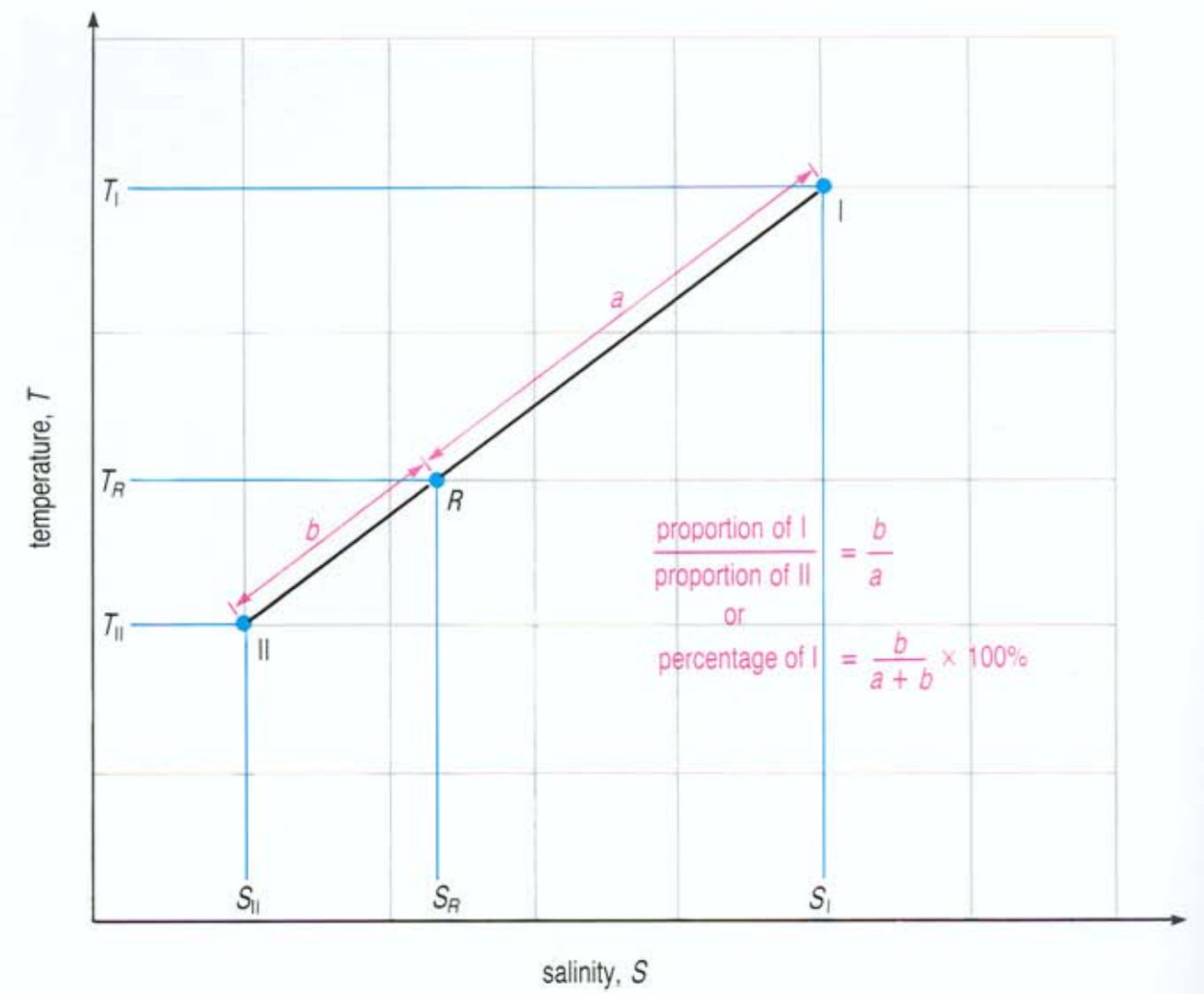
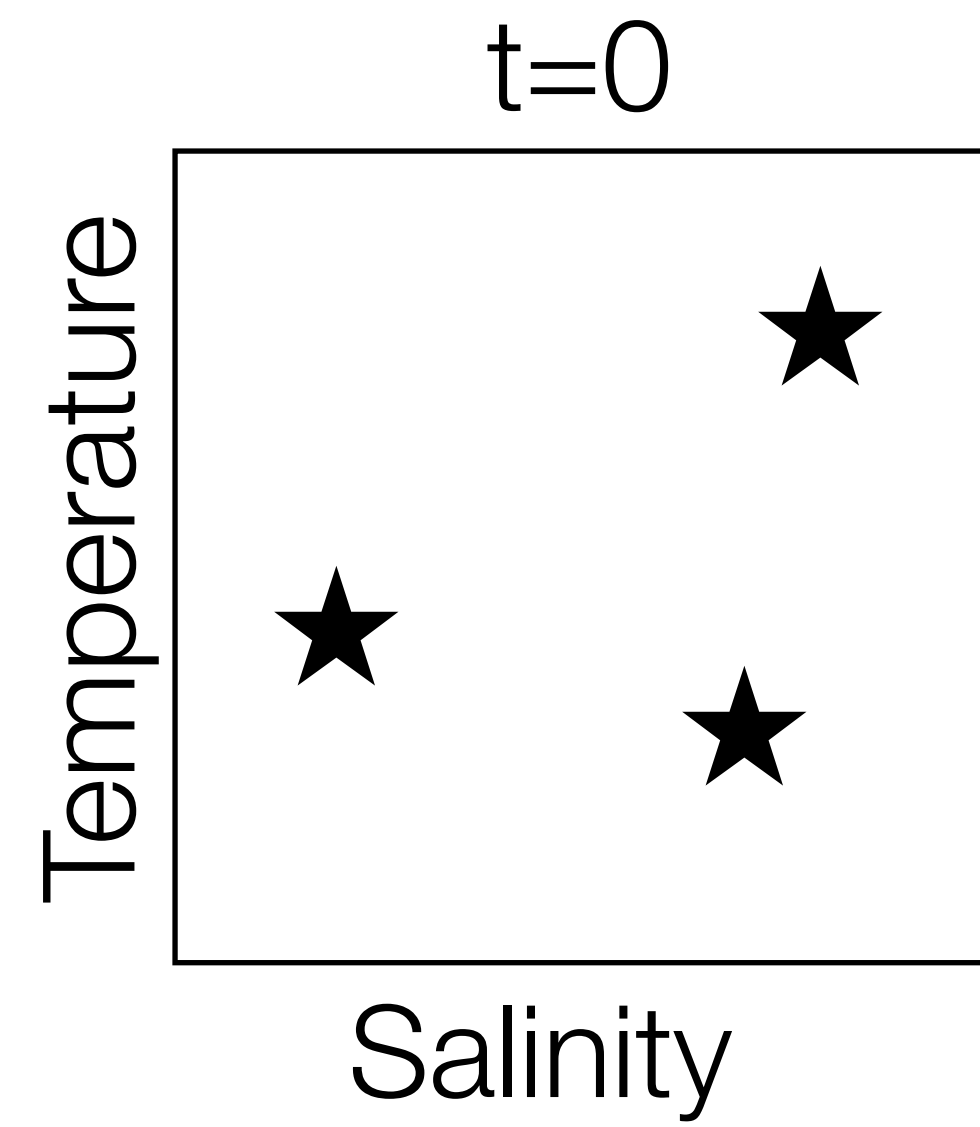
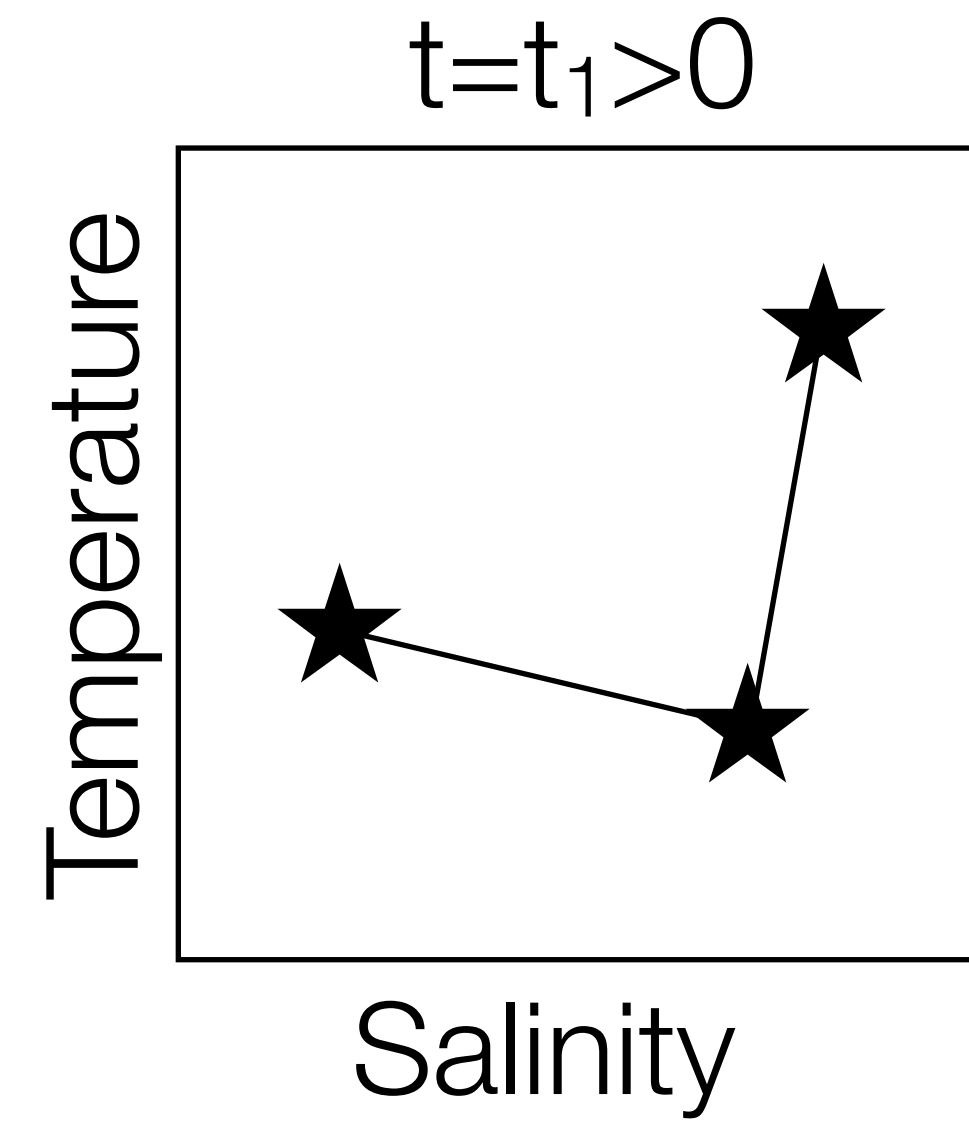
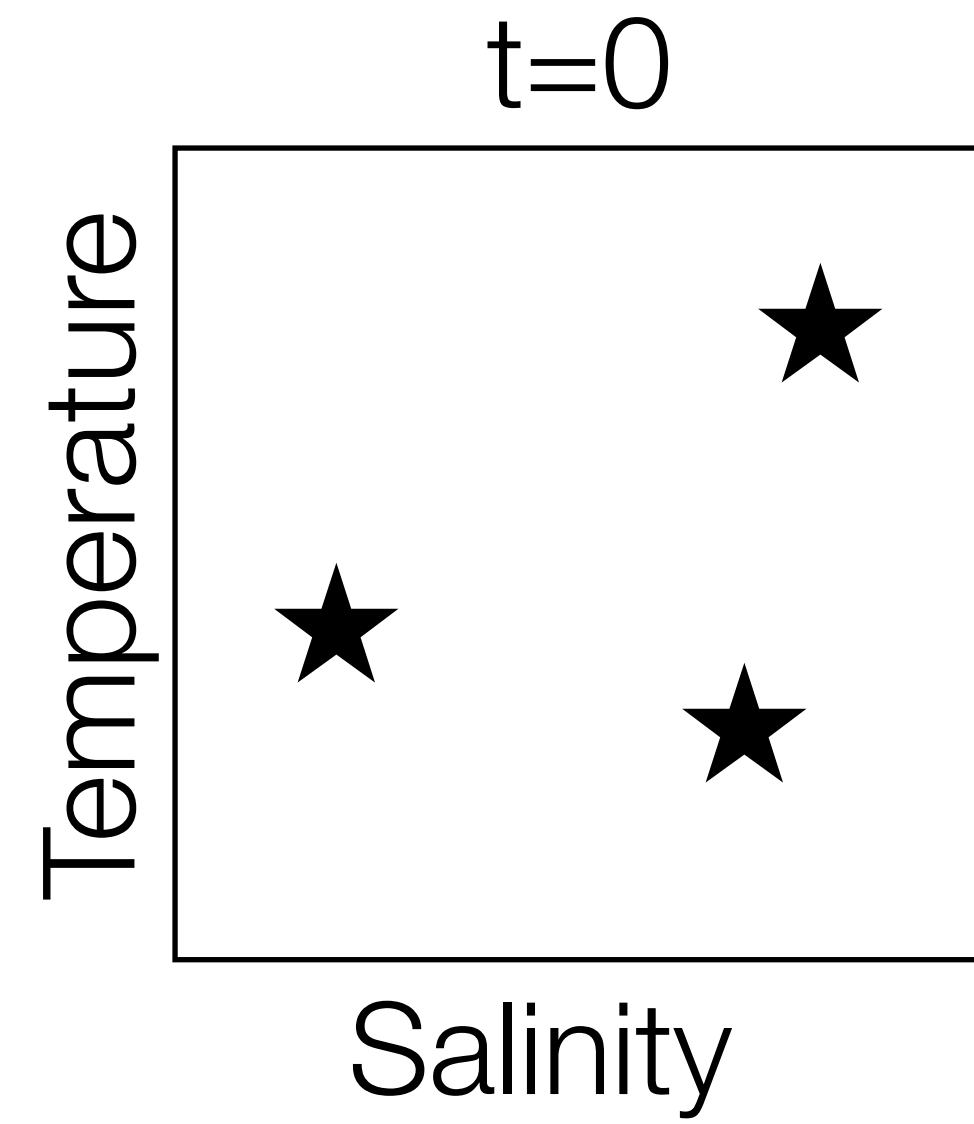


Figure 6.29 A temperature-salinity diagram showing the effect of mixing water type I having T_I and S_I with water type II having T_{II} and S_{II} . The resulting mixture R (having T_R and S_R) will be represented by a point on the line between I and II, the position of which will be determined by the relative proportions of the two water types in the mixture.

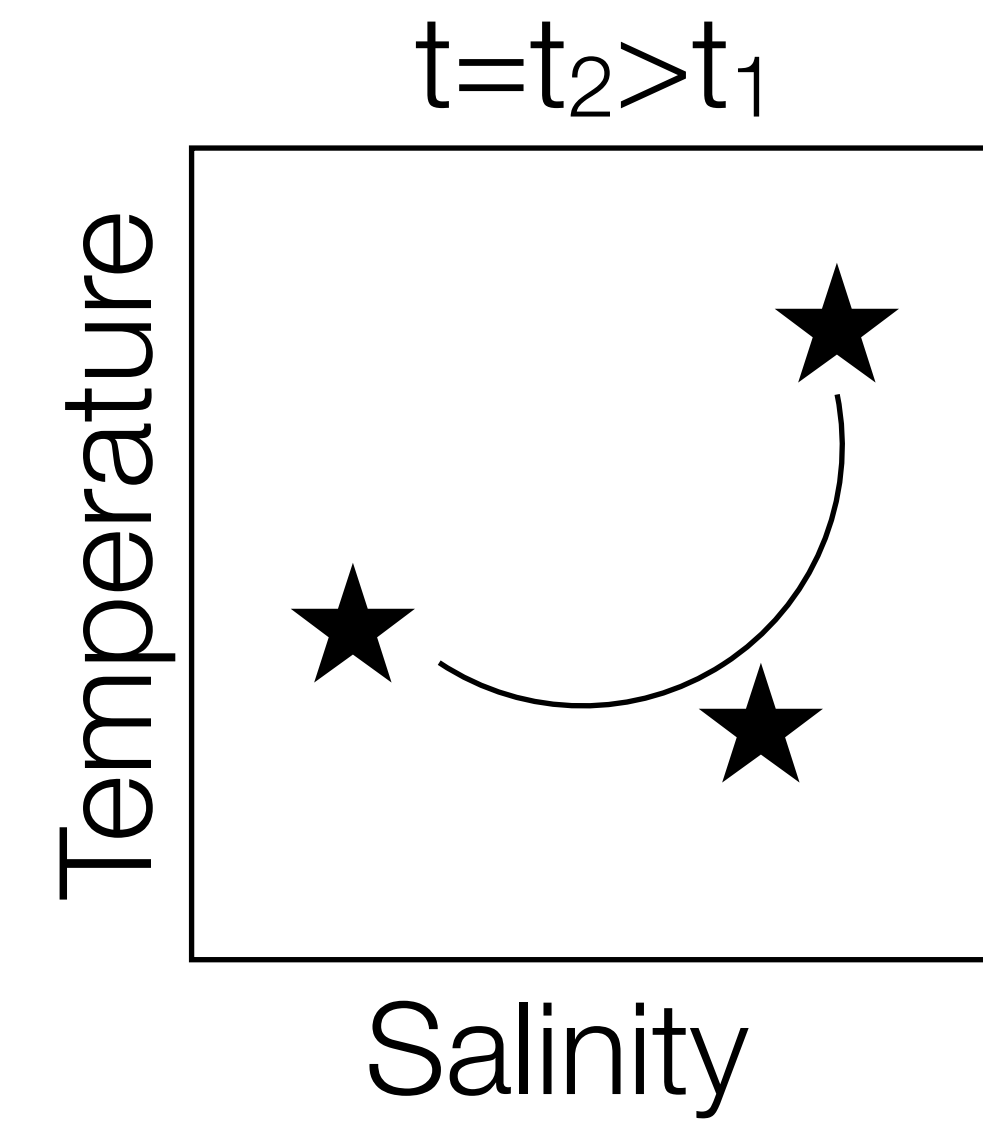
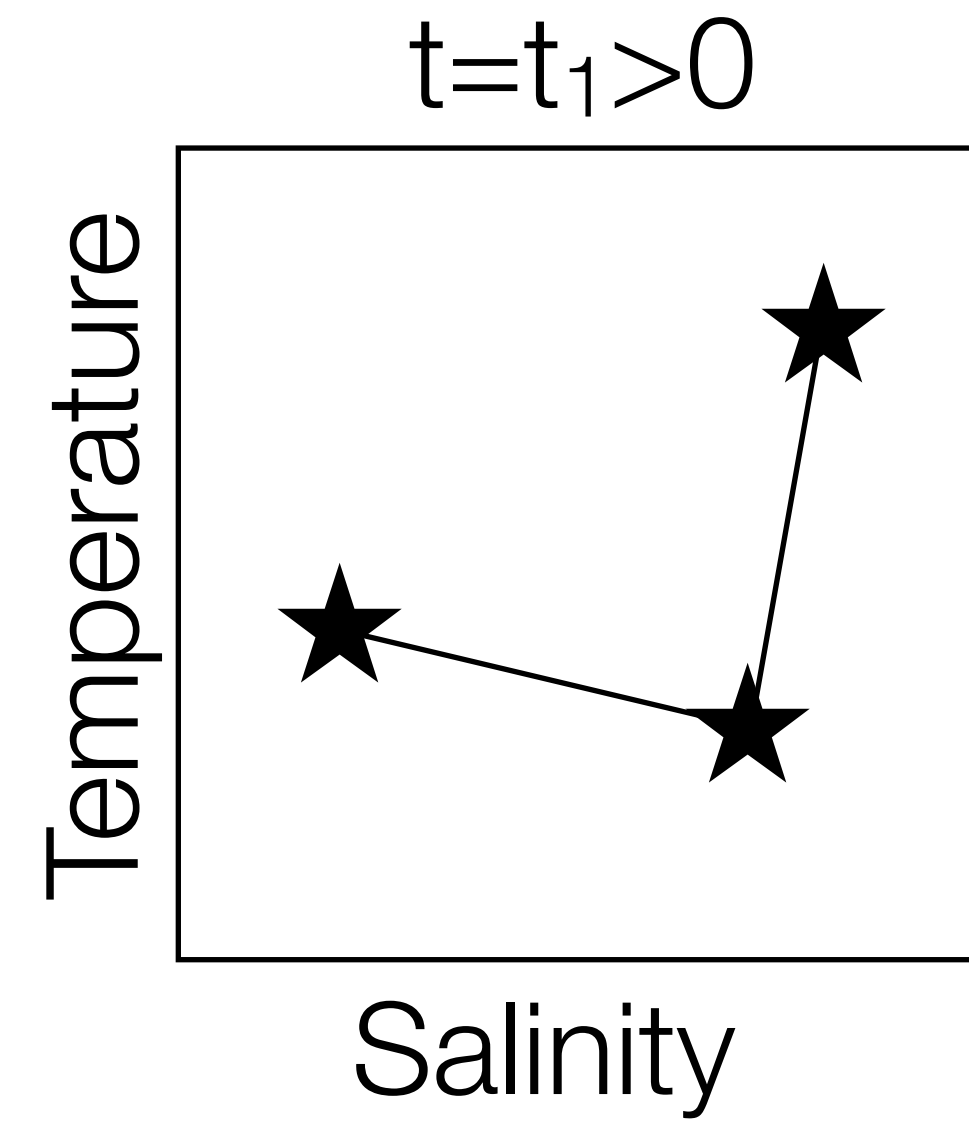
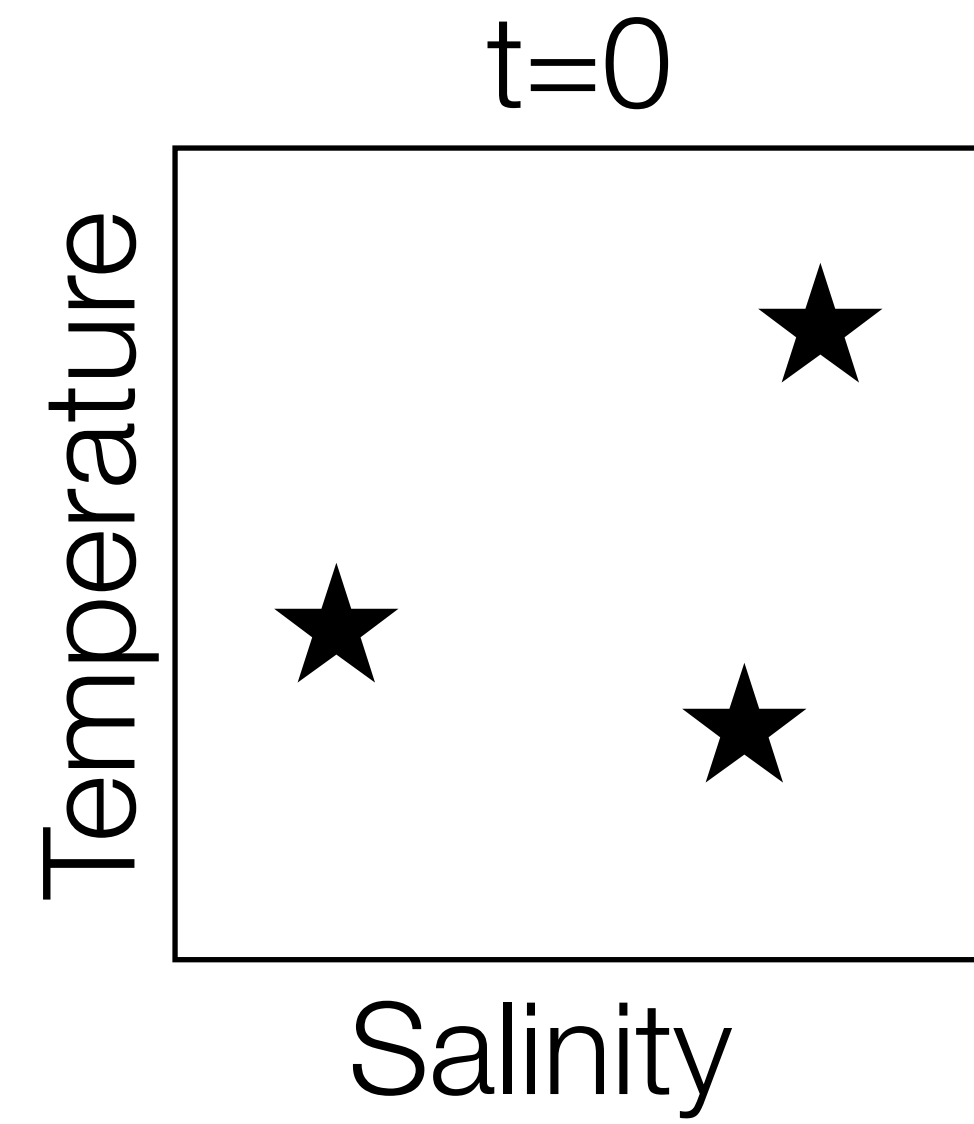
Mixing of three water masses



Mixing of three water masses



Mixing of three water masses



Mixing of three water masses

