Boring but important disclaimers:

- If you are not getting this from the GitHub repository or the associated Canvas page, you are probably getting the substandard version of these slides (e.g. CourseHero, Chegg etc.) Don't pay money for those, because you can get the most updated version for free at

  `https://github.com/julianmak/academic-notes`

  The repository principally contains the compiled products rather than the source for size reasons.
- Associated Python code (as Jupyter notebooks mostly) will be held on the same repository. The source data however might be big, so I am going to be naughty and possibly just refer you to where you might get the data if that is the case (e.g. JRA-55 data). I know I should make properly reproducible binders etc., but I didn't...
- I do not claim the compiled products and/or code are completely mistake free (e.g. I know I don't write Pythonic code). Use the material however you like, but use it at your own risk.
- As said on the repository, I have tried to honestly use as content that is self made, open source or explicitly open for fair use, and citations should be there. If however you are the copyright holder and you want the material taken down, please flag up the issue accordingly and I will happily try and swap out the relevant material.

OCES 2003 : Descriptive Physical Oceanography

(a.k.a. physical oceanography by drawing pictures)

Lecture 5: Sea water properties (temperature and salinity)

Tue 16th Feb

Outline

- thermodynamic vs. mechanical forcing of ocean
  $\rightarrow$ two lectures on former, four lectures on latter

- ultimately care about density ρ (sort of, see ρ_θ and γ later...)
  $\rightarrow$ temperature T and salinity S contributions
  $\rightarrow$ horizontal and vertical structures
  $\rightarrow$ sea surface temperature/salinity (SST, SSS)
  $\rightarrow$ links to forcing

Key terms: density, buoyancy, temperature, salinity, SST, SSS, thermo/halocline, watermass property

Recap: forces

- sea water moves around since there are forces acting on it

  $\rightarrow$ e.g. wind $\Rightarrow$ "pushing" water

  $\rightarrow$ e.g. uneven heating $\Rightarrow$ movement to redistribute heat

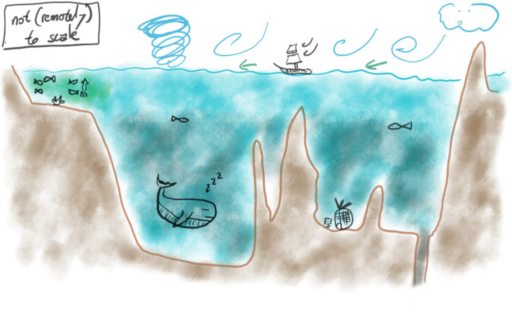


Figure: Schematic of ocean forcing.

to understand/predict circulation $\sim$ how forces act

Recap: equations of motion

Denoting $\boldsymbol{u} = (u, v)$ and $\boldsymbol{u}_3 = (u, v, w)$, to numerous approximations (!!!) (see OCES 3203) ocean dynamics is governed by

$$\rho_0 \left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + 2\boldsymbol{\Omega} \times \boldsymbol{u} \right) = -\nabla p + \boldsymbol{F_u} + \boldsymbol{D_u} \tag{1}$$

$$\frac{\partial p}{\partial z} = -\rho g \tag{2}$$

$$\nabla \cdot \boldsymbol{u}_3 = 0 \tag{3}$$

$$\left(\frac{\partial T}{\partial t} + \boldsymbol{u}_3 \cdot \nabla T \right) = F_T + D_T \tag{4}$$

$$\left(\frac{\partial S}{\partial t} + \boldsymbol{u}_3 \cdot \nabla S \right) = F_S + D_S \tag{5}$$

$$\rho = \rho(T, S, p) \tag{6}$$

Respectively, (1) momentum equation, (2) hydrostatic balance, (3) incompressibility, (4) temperature equation, (5) salinity equation, and (6) equation of state (EOS)

Buoyancy: motivating example

Q. which one is unstable?

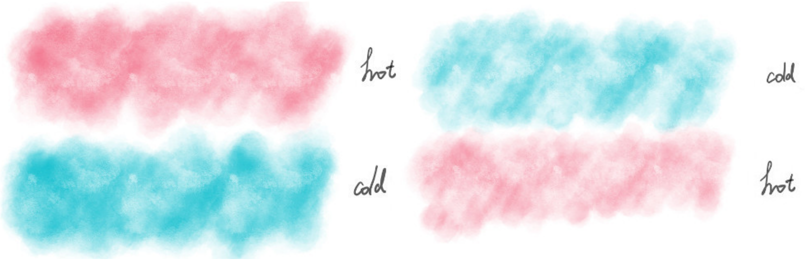


Figure: (Un)stable temperature configurations.

Buoyancy: motivating example

Q. which one is unstable?

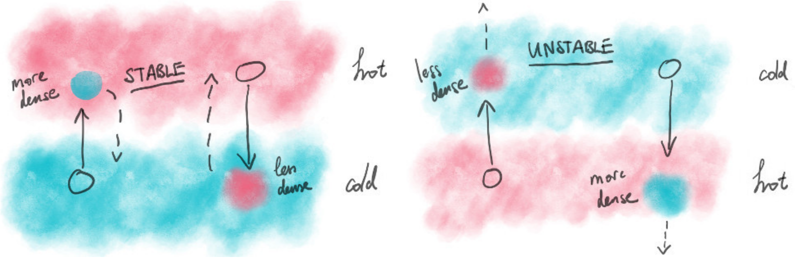


Figure: (Un)stable temperature configurations.

- density (!) ρ (units: $\mathrm{kg\ m^{-3}}$)
- buoyancy $b = -(\delta\rho/\rho_0)g$ (so units of...?)
  $\rightarrow$ how "floaty" something is (e.g. warm water, lighter density, **more** buoyant)

Buoyancy: motivating example

Q. which one is unstable?

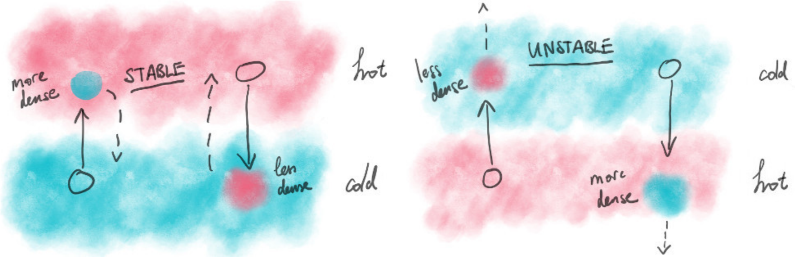


Figure: (Un)stable temperature configurations.

- density (!) ρ (units: kg m^{-3})
- buoyancy $b = -(\delta\rho/\rho_0)g$ (so units of...?)
  $\rightarrow$ how "floaty" something is (e.g. warm water, lighter density, **more** buoyant)

ultimately it's density/buoyancy we care about

Sea water properties

Q: What are the distinguishing features of sea water?

Main focus for here: what controls density of seawater?

Another hint: how is it **different** to air?

Sea water properties: temperature

Denote temperature (!) by T

(<u>other</u> temperatures/density next lecture)

- units of °C or K (0°C = 273.15 K)
- isotherm = lines/surfaces of constant temperature
- above around 4°C (!!!) warmer $\sim$ less dense, i.e.

$$\boxed{\rho \nearrow \text{ as } T \searrow}$$

  $\rightarrow$ water actually **most dense** around 4°C (EOS next lec.)

  $\rightarrow$ (otherwise consequence for ice?)

- measured by thermometer, sound speed etc.

Sea water properties: salinity

Denote salinity (!) by S

- given in g kg^{-1} or sometimes PSU (practical salinity unit)
  $\rightarrow$ dimensionless really, use of PSU **strongly discouraged**
- isohaline = lines/surfaces of constant salinity
- higher salinity = more things dissolved in water, so

$$\boxed{\rho \nearrow \text{ as } S \nearrow}$$

- chemical measure through chlorinity (e.g. titration)

$$S_A \approx 1.80655 \times \text{Chlorinity}$$

  $\rightarrow$ absolute salinity S_A
- usually now done through electrical conductivity (see lec. 19)
  $\rightarrow$ practical salinity S_P

Sea water properties: opacity

Sea water is dense and has things dissolved in it

- stops light going through (either diffusing or absorbing), opaque

  $\rightarrow$ light doesn't penetrate very deep, consequence for primary production

Figure: Picture of the sea. CC0 Public Domain, taken from `phys.org`

Sea water properties: opacity

One very important and interesting difference between atmosphere and ocean:

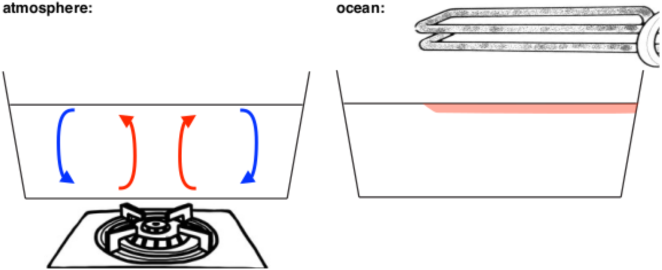
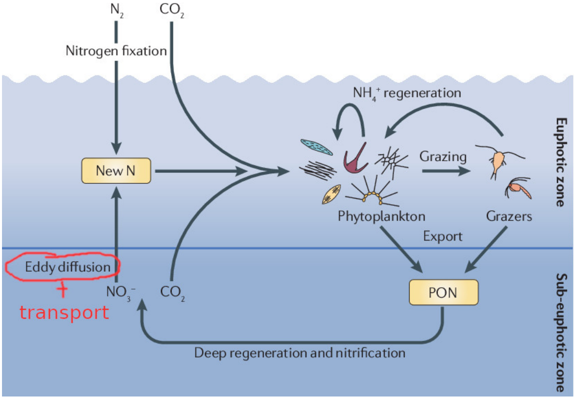


Figure: Schematic of principal sources of thermal forcing between atmosphere and ocean. Courtesy of David Marshall (Oxford).

- actually quite hard to drive up/down motion + deep circulation! (cf. Sandströrm's theorem)

  $\rightarrow$ but there is one, so why? (see Lec 11 - 18)

Sea water properties (sort of): other things



- things like nutrients, carbon, oxygen are dissolved in seawater
- negligible (?) impact for the physics, but important for biogeochemistry (some in Lec. 21 + 22) or tracking watermasses (see Lec. 14)

Warning!

There are different types of temperature...

- in-situ T vs . potential θ vs. conservative Θ
- subtle but !!!**VERY IMPORTANT**!!! differences

  $\rightarrow$ for dynamics usually we don't care about T

Warning!

There are different types of temperature...

- in-situ T vs . potential θ vs. conservative Θ
- subtle but !!!**VERY IMPORTANT**!!! differences

  $\rightarrow$ for dynamics usually we don't care about T

...and different types of salinity!

- practical S_P vs. absolute S_A

  $\rightarrow$ absolute salinity (sometimes S_A) part of **TEOS-10**

Warning!

There are different types of temperature...

- in-situ T vs . potential θ vs. conservative Θ
- subtle but !!!<u>**VERY IMPORTANT**</u>!!! differences

  $\rightarrow$ for dynamics usually we don't care about T

...and different types of salinity!

- practical S_P vs. absolute S_A

  $\rightarrow$ absolute salinity (sometimes S_A) part of **TEOS-10**

...and we have different densities $\rho/\rho_\theta/\gamma$ too!

- just be aware that subtleties <u>do exist</u> and <u>do matter</u>...

Observed TS profiles: horizontal (Lon, Lat) or (x, y)

- sun + radiation

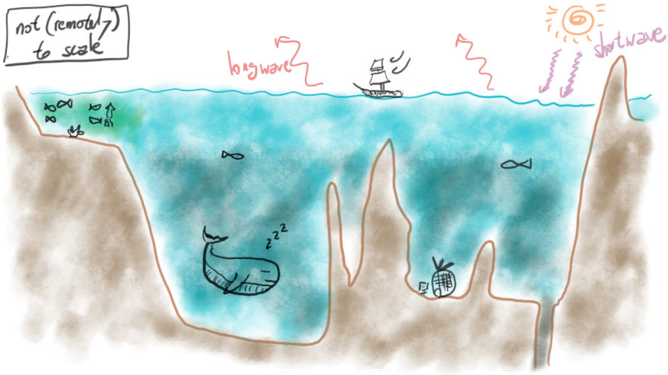


Figure: Schematic of temperature forcing at the ocean surface. Only showing shortwave and longwave radiation (latent heat + sensible heat can be gain or loss; not shown here).

Observed T profiles: horizontal (Lon, Lat) or (x, y)

Sea Surface Temperature (SST) **mostly**(!) by the sun

- shortwave radiation Q_{sw} here (units: $\mathrm{W\ m^{-2}}$)

  $\rightarrow$ not shown are longwave radiation (seen as a heat loss), latent + sensible heat (can be gain or loss) see homework? (look up any physical oceanography book under "heat budgets")

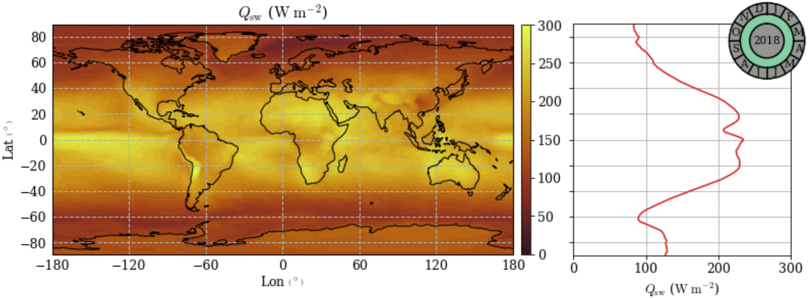


Figure: Year-averaged (left) and year and zonal averaged (right) shortwave radiation, from the JRA55 dataset (Kobayashi *et al.* 2015, *J. Meteor. Soc. Japan*). See `plot_jra55_sample.ipynb`

Observed T profiles: horizontal (Lon, Lat) or (x, y)

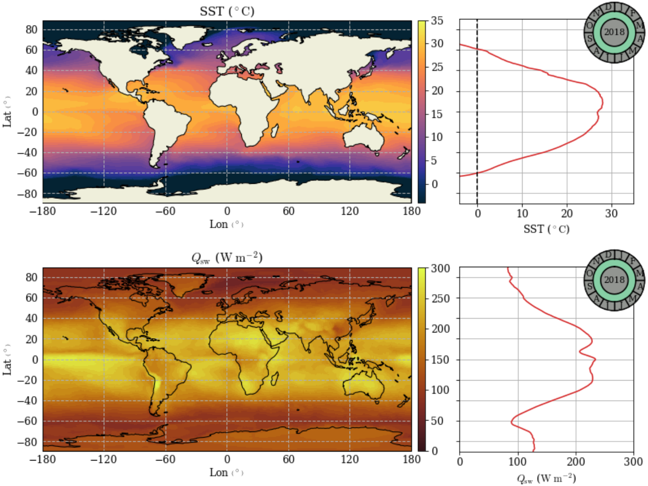


Figure: As previous figure but for SST (top) and shortwave radiation (bot).

- notice correlation between SST and Q_{sw}

Observed T profiles: horizontal (Lon, Lat) or (x, y)

- time-varying data with seasonal cycle (movie here)

Observed S profiles: horizontal (Lon, Lat) or (x, y)

- river runoff, evaporation, precipitation (see Lec. 5)

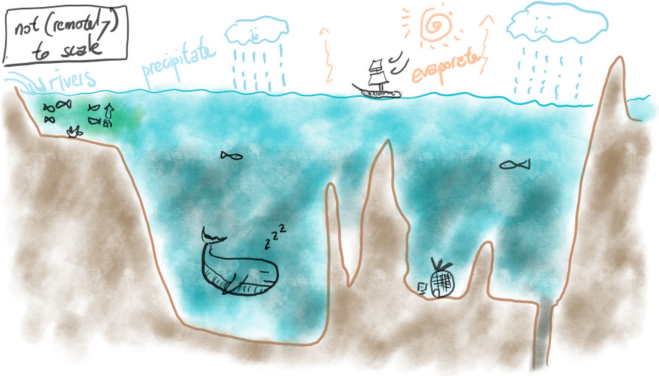


Figure: Schematic of ocean forcing.

Observed S profiles: horizontal (Lon, Lat) or (x, y)

Sea Surface Salinity (SSS) by

- **decrease** in salinity by precipitation (units: depends...)
- **increase** in salinity by evaporation (units: depends...)
- **decrease** in salinity by runoff (units: depends...)
  $\rightarrow$ river, ice melt

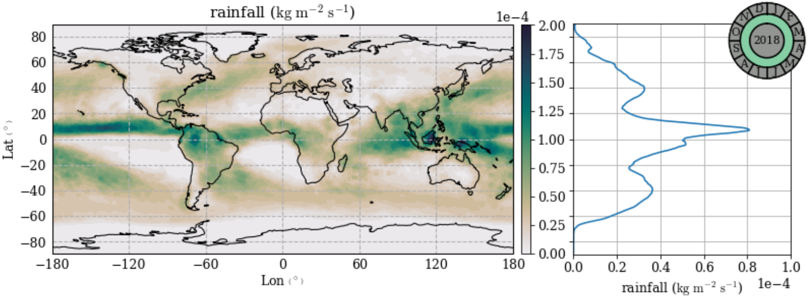


Figure: Year-averaged (left) and year and zonal averaged (right) rainfall (so **decrease** in salinity), from the JRA55 dataset (Kobayashi *et al.* 2015, *J. Meteor. Soc. Japan*). See `plot_jra55_sample.ipynb`

Observed S profiles: horizontal (Lon, Lat) or (x, y)

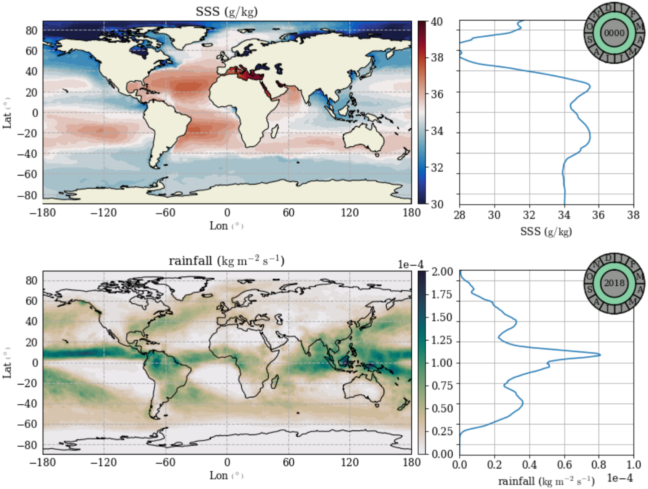


Figure: As previous figure but for SSS (top) and rainfall (bot). Notice how the Atlantic is **more salty** than the Pacific.

Q. why is SSS high when rainfall is also high?

Observed S profiles: horizontal (Lon, Lat) or (x, y)

- time-varying data with seasonal cycle (cheating here with SSS!)

Observed T profiles: sections e.g. (x, z) or (y, z)

- meridional section (i.e. (y, z)) of T

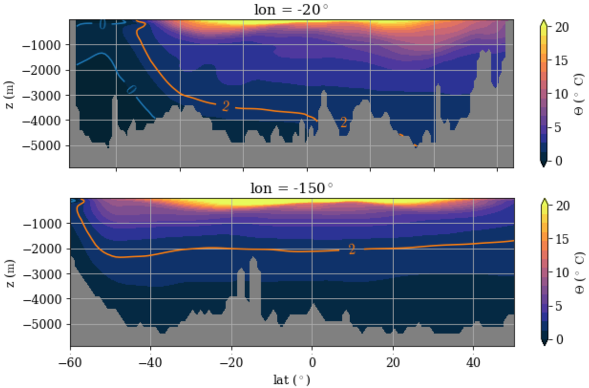


Figure: Meridional section of yearly-averaged conservative temperature in the Atlantic (top) and Pacific (bot), based on World Ocean Atlas 2013 data. Meridional range chosen to roughly correspond to Talley *et al.* (2011) Fig. 4.11 and 4.12. See `plot_WOA13_sample.ipynb`

- intrusion of bottom cold waters in Atlantic
- marked temperature contour is “higher” in Pacific

Observed S profiles: sections e.g. (x, z) or (y, z)

- meridional section (i.e. (y, z)) of S

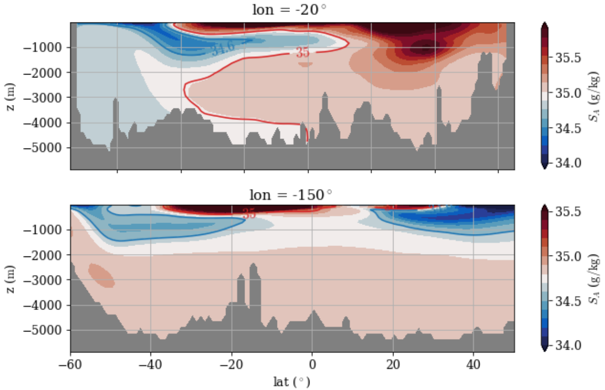


Figure: Meridional section of yearly-averaged absolute salinity in the Atlantic (top) and Pacific (bot), based on World Ocean Atlas 2013 data. Meridional range chosen to roughly correspond to Talley *et al.* (2011) Fig. 4.11 and 4.12. See `plot_WOA13_sample.ipynb`

- distinct salinity signature in salinity in Atlantic
- notice a fresh intermediate layer in Pacific

Observed T profiles: vertical usually (depth) or (z)

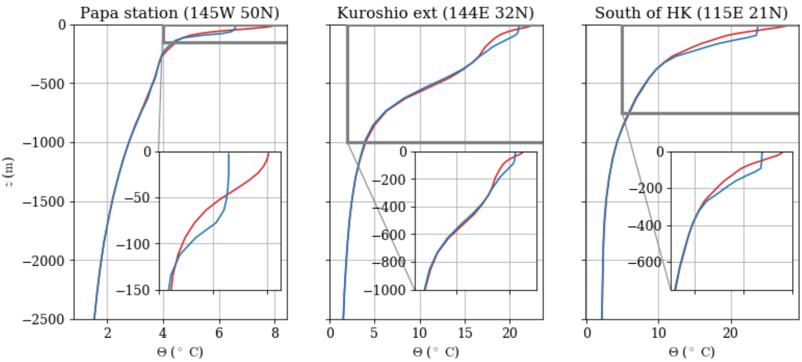


Figure: Vertical variation of Θ at some designated locations, based on WOA13 data. Red and blue line denote summer and winter climatology. See `plot_WOA13_sample.ipynb`

- notice a rapidly changing top part ("sharp", think **large gradient**) and slower varying ("smooth") bottom part

Observed T profiles: vertical usually (depth) or (z)

mixed layer (usually (!) $O(100\,\mathrm{m})$)

- very top bit where stratification is weak (see previous panel (c) in winter)

  $\rightarrow$ strong vertical mixing (see Lec. 17)

Observed T profiles: vertical usually (depth) or (z)

mixed layer (usually (!) $O(100\text{ m})$)

- very top bit where stratification is weak (see previous panel (c) in winter)

  $\rightarrow$ strong vertical mixing (see Lec. 17)

thermocline (usually $O(200 - 1000\text{ m})$)

- the transition region between the "sharp" and "smooth" part in **temperature**

  $\rightarrow$ hence the **thermo** part

  $\rightarrow$ it's gradients we care about, and thermocline is where temperature gradient is largest **below** the mixed layer

  $\rightarrow \rho \sim T$ (or Θ which is used here), so it indicates changes in density

Observed S profiles: vertical usually (depth) or (z)

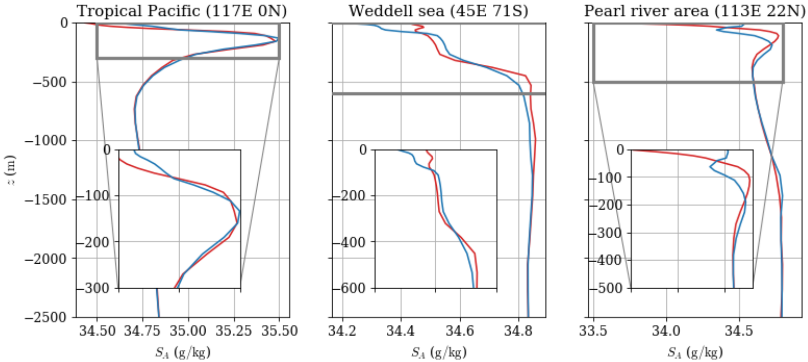


Figure: Vertical variation of S_A at some designated locations, based on WOA13 data. Red and blue line denote summer and winter climatology. See `plot_WOA13_sample.ipynb`

- similarly for salt, halocline

  $\rightarrow$ large evaporation, ice melt and river runoff here

Summary

- density ρ plays important role in ocean dynamics, with

$$\boxed{\rho = \rho(T, S, p)}$$

Summary

- density ρ plays important role in ocean dynamics, with

$$\boxed{\rho = \rho(T, S, p)}$$

- T largely follows atmospheric forcing at surface
  $\rightarrow$ thermocline (pycnocline next Lec.) in the vertical

Summary

- density ρ plays important role in ocean dynamics, with

$$\boxed{\rho = \rho(T, S, p)}$$

- T largely follows atmospheric forcing at surface
  $\rightarrow$ thermocline (pycnocline next Lec.) in the vertical
- S dependent on EmP and rivers (freshwater forcing)
  $\rightarrow$ halocline in high latitudes (ice) and near coasts (rivers)

Summary

- density ρ plays important role in ocean dynamics, with

$$\rho = \rho(T, S, p)$$

- T largely follows atmospheric forcing at surface
  $\rightarrow$ thermocline (pycnocline next Lec.) in the vertical
- S dependent on EmP and rivers (freshwater forcing)
  $\rightarrow$ halocline in high latitudes (ice) and near coasts (rivers)
- relatively distinct watermass properties geographically
  $\rightarrow$ because mixing relatively weak on large-scale (see lec. 10 + 17)

Summary

- density ρ plays important role in ocean dynamics, with

$$\rho = \rho(T, S, p)$$

- T largely follows atmospheric forcing at surface
  $\rightarrow$ thermocline (pycnocline next Lec.) in the vertical
- S dependent on EmP and rivers (freshwater forcing)
  $\rightarrow$ halocline in high latitudes (ice) and near coasts (rivers)
- relatively distinct watermass properties geographically
  $\rightarrow$ because mixing relatively weak on large-scale (see lec. 10 + 17)

!!! complication: different types of T and ρ relating to concept of work done related to pressure... (next lec)