Physical oceanography
Lecture 4
Freshwater transports in the ocean: importance, techniques and results

ICTP: The General Circulation of the Atmosphere and Oceans: A Modern Perspective

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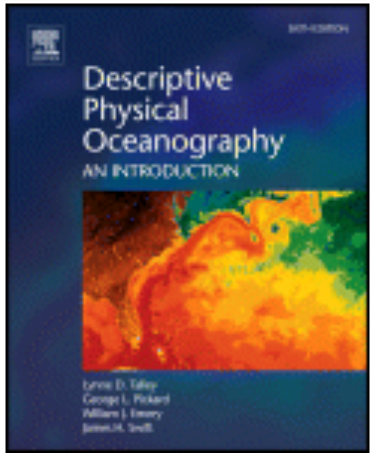
Descriptive Physical Oceanography: An Introduction (6th edition)
Talley, Pickard, Emery, Swift (2011) (Elsevier)
http://www-pord.ucsd.edu/~ltalley/DPO/ has links to all of the temporary web materials.

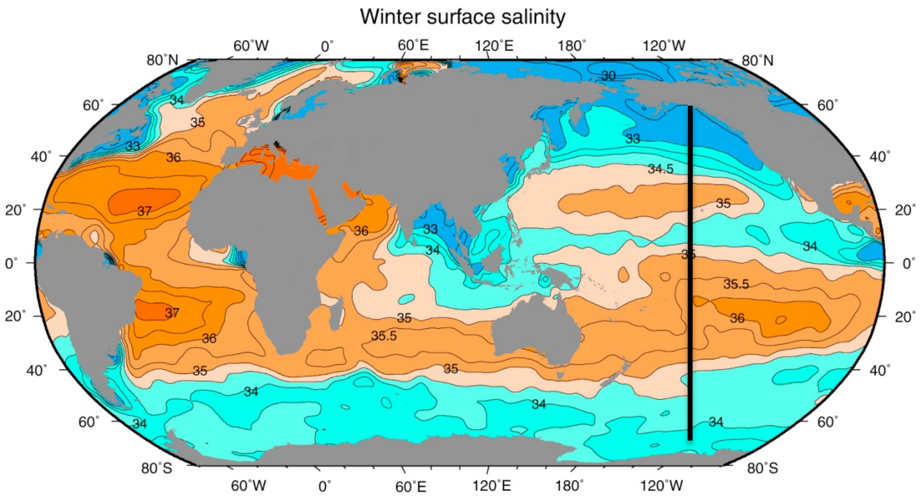
Updated information from the publisher this week:
Complimentary copies are available for professors who might adopt the book: requests are made through textbooks.elsevier.com

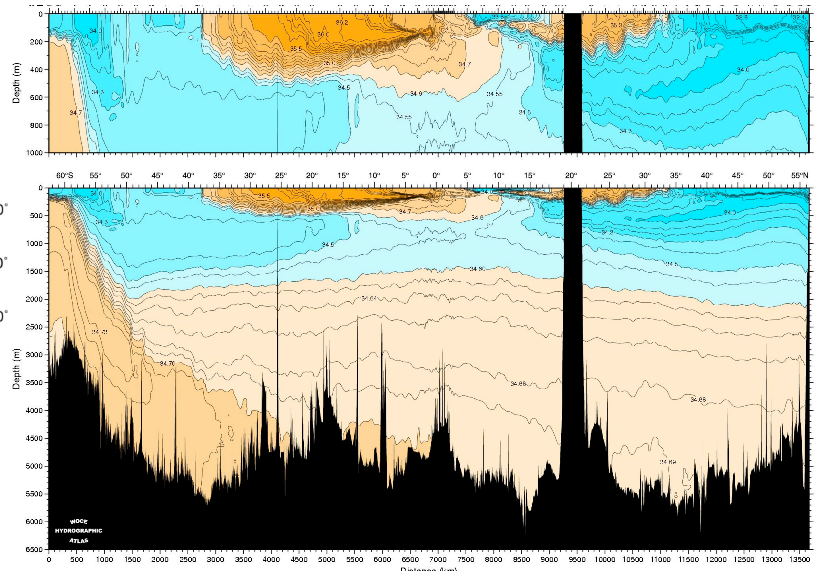


Freshwater transport

- E-P, projected climate change signal, salinity
- Necessity for freshwater transport balance between the mean ocean and atmosphere circulations
- Atmospheric water vapor transport
- Ocean freshwater transport calculations: calculation of an extremely small residual
- Observed freshwater transport by the ocean
- Relative importance of wind-driven, overturning and throughflows (Indonesian and Bering) circulations in transport freshwater

Freshwater transport: salinity, E-P, projected climate change signal





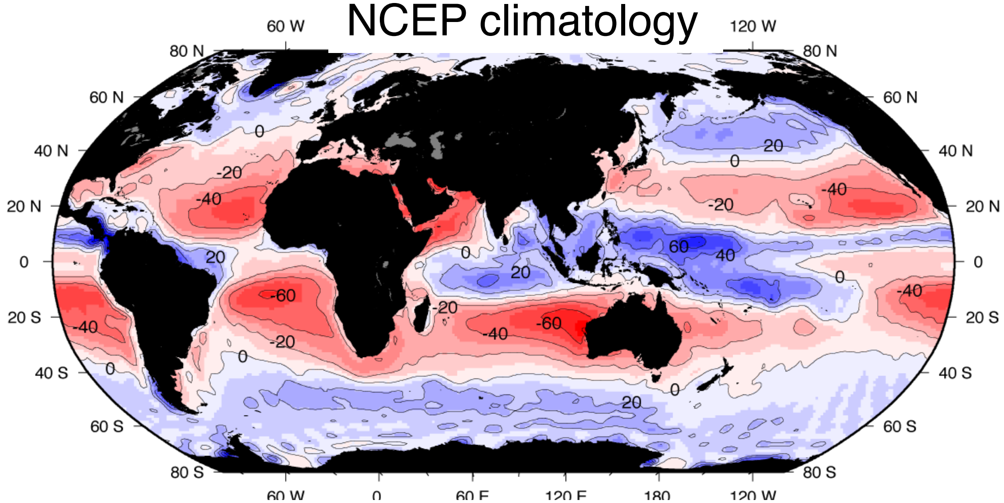
The salinity distribution dictates the Atlantic-Pacific asymmetry in deep water formation (on vs. off).

Why? Surface northern Pacific much fresher than surface northern Atlantic. Because saline water from Atlantic/Antarctic fills the deep Pacific, and cooling even to freezing point in upper ocean, and even production of brines in the Okhotsk/Bering Seas, cannot punch through the stratification in the North Pacific.

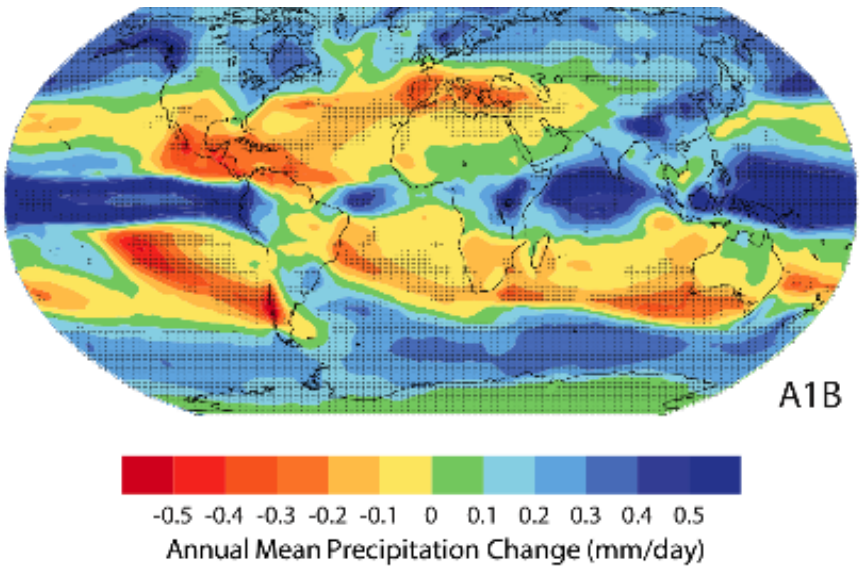
What maintains this distribution of salinity in the mean?

Freshwater transport: E-P, projected climate change signal, salinity

NCEP climatology



Predicted precipitation change (IPCC, 2007)



- Ocean salinity integrates changes in E-P, runoff and ice melt
- Changes in salinity are more observable than changes in E-P etc.

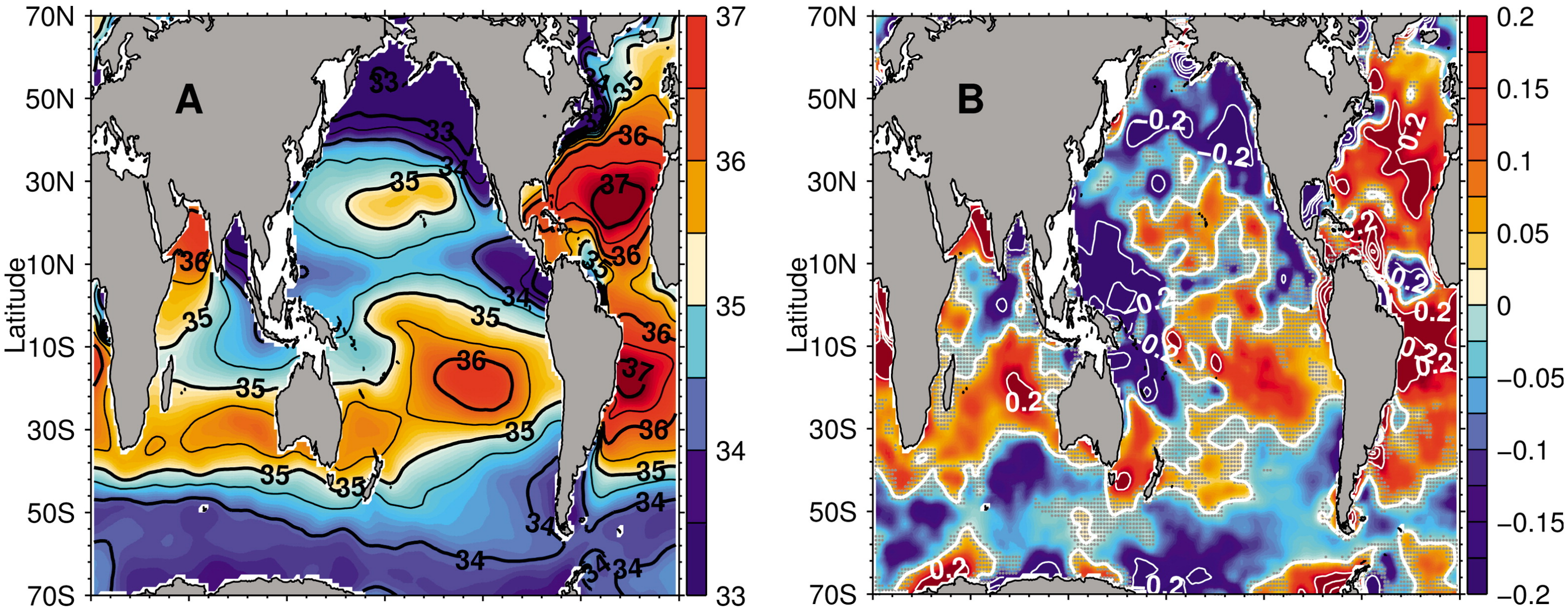
- A warmer world pumps more water vapor into the atmosphere (with the ocean an enormous holding tank for the water): increased hydrological cycle
- Impacts are recorded in ocean salinity, potential for (indirect) feedbacks on climate through changed ocean stratification

Dry areas become drier

Wet areas become wetter

Freshwater transport: E-P, projected climate change signal, salinity

- The most recent version of salinity trends over 50 years, with Argo floats as the end point: relatively clear but noisy relation to the mean salinity distribution; supporting earlier work by Boyer et al. (2005) and conclusions of IPCC (2007) based on much the same data without Argo profiles at the end of record.



Mean surface salinity

Salinity trend (50 years)

Durack and Wijffels, 2010
Hosoda et al., 2010

Freshwater transport: Atmosphere's water vapor transport

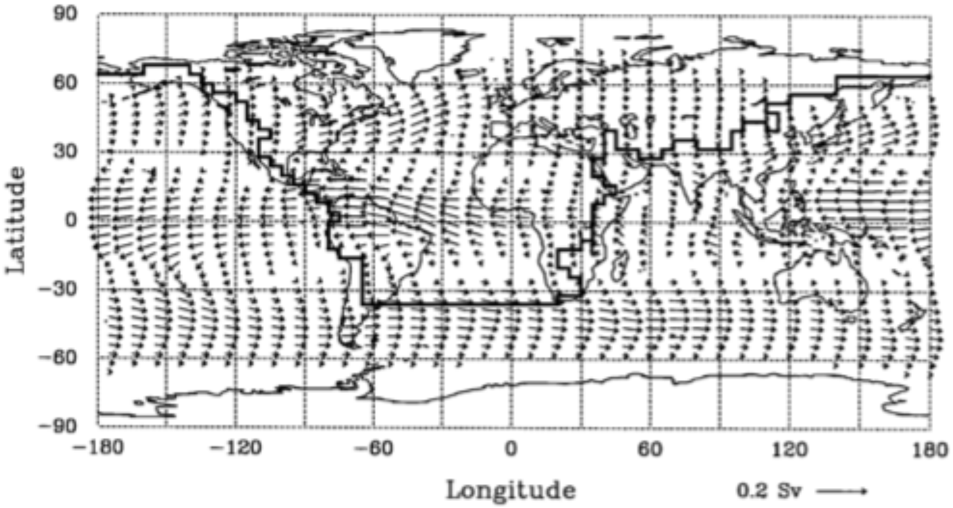


Fig. 2. Vertically integrated atmospheric water vapor transport, observations [*Oort*, 1983]; 10-year average; the thick line is the model drainage divide between Atlantic and Pacific/Indian Ocean; only every other grid box in longitudinal direction is drawn and values < 0.01 Sv are suppressed.

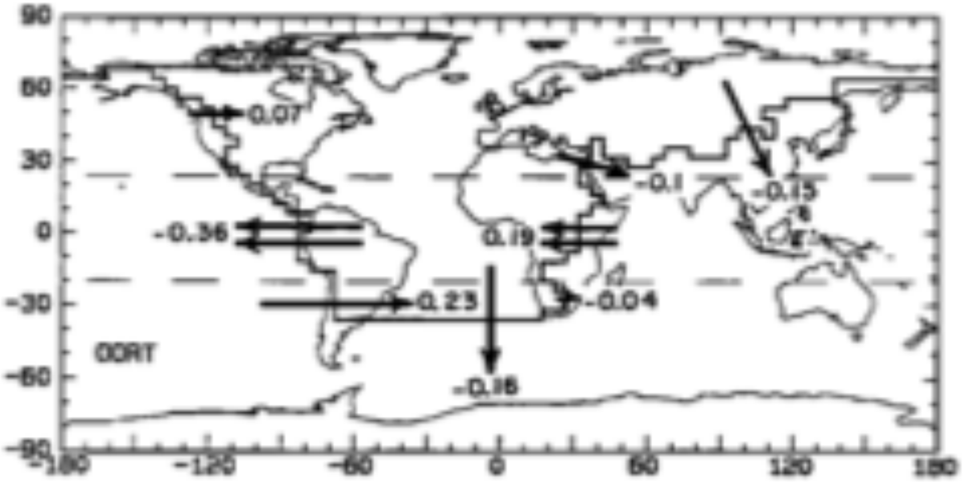


Fig. 5. Atmospheric water vapor transport across several parts of the drainage divide. Observations [*Oort*, 1983]. Negative values are Atlantic freshwater loss.

Water vapor transport in Sv, based on on Oort (1983)

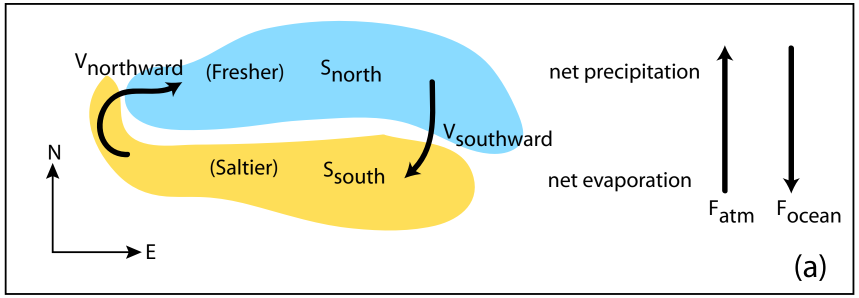
Net transport in tropics into Pacific from Atlantic/Indian Oceans

Meridional transport also implied in global pattern, not quantified in lower map.

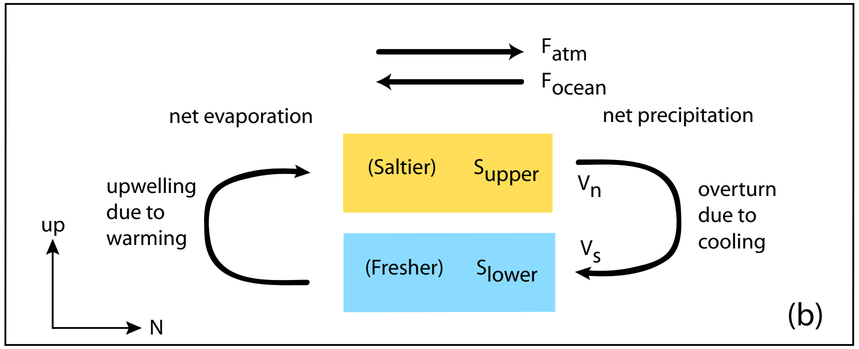
(Zaucker and Broecker, 1992)

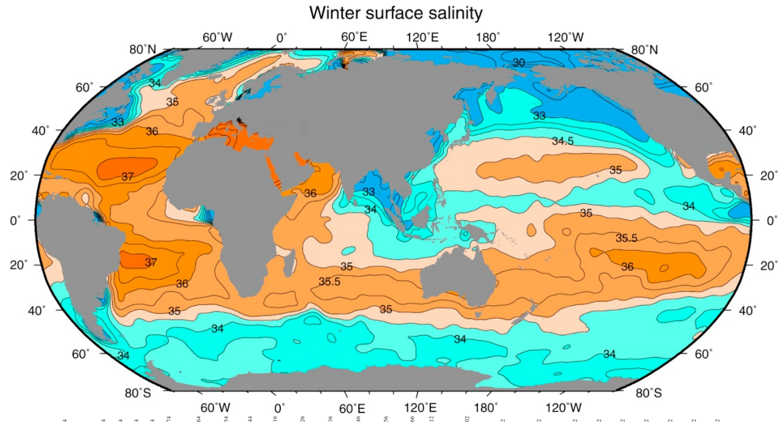
Note the size of the transports: order tenths of Sverdrups. Such small transports are impossible to measure directly in the ocean – within the uncertainty of any transport measurement

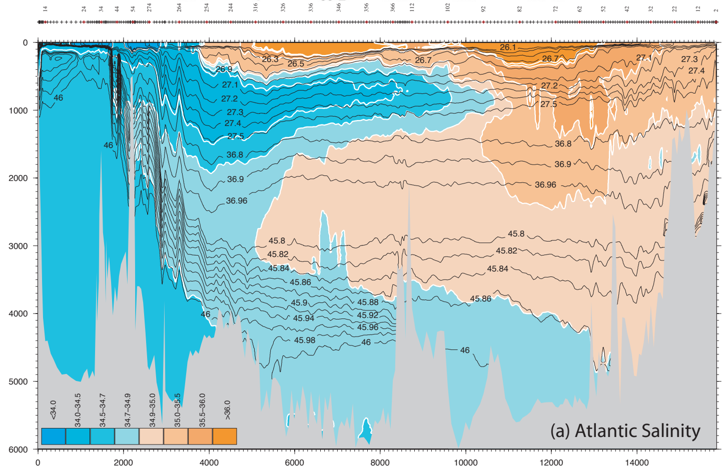
Freshwater transport: what is ocean freshwater transport?



$V_{southward} = -V_{northward}$ $F_{ocean} = -F_{atm}$







The atmosphere transports water vapor from evaporation to precipitation regions. This is set by the atmosphere alone.

For the large-scale mean state, the ocean MUST transport exactly the same amount of freshwater in the opposite direction, from fresh to salty regions BECAUSE there are no sources or sinks of salt.

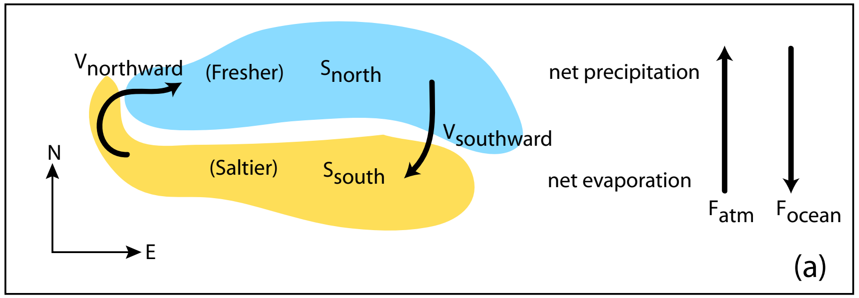
Freshwater transport: what is ocean freshwater transport?

$-F_{atm} = F_{ocean} = V(S_{south} – S_{north})/S_o = V\Delta S/S_o$

where S_o is an arbitrary reference salinity and V is the ocean's volume transport exchange between reservoirs.

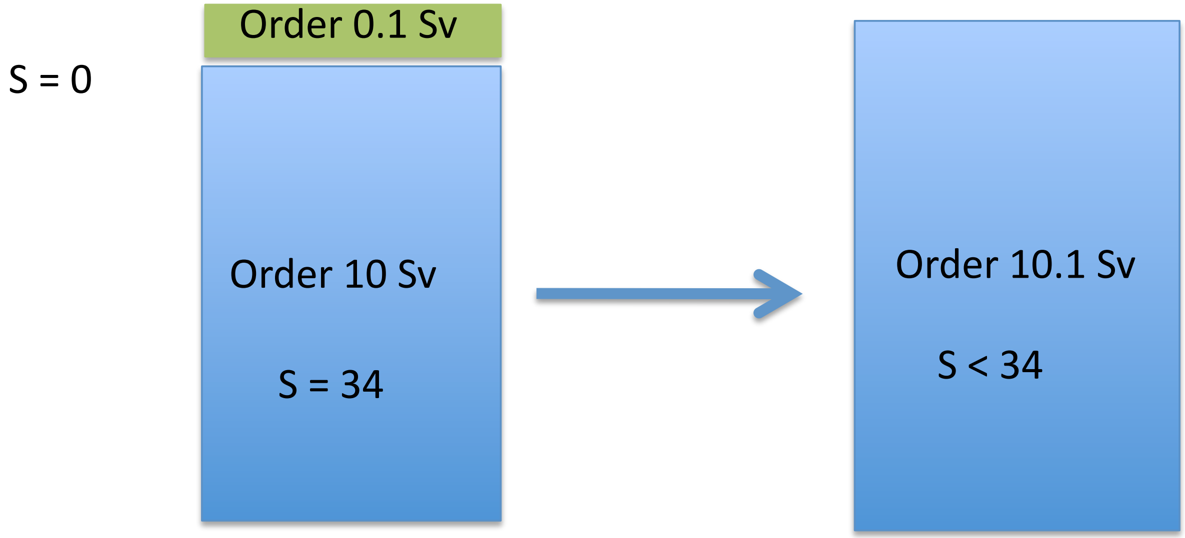
Therefore $\Delta S = FS_o / V$, so if F is set by the atmosphere and V is set externally by the flow, the salinity difference can be calculated. (Of course V can depend on ΔS, as in the Stommel thermohaline oscillator.)

- For larger atmospheric F transport, get larger ΔS
- For larger V ocean transport exchange, get smaller ΔS



$V_{southward} = -V_{northward}$ $F_{ocean} = -F_{atm}$

Freshwater transport basics



We can reasonably approximate the volume transport as unchanging, especially within error of measurements.

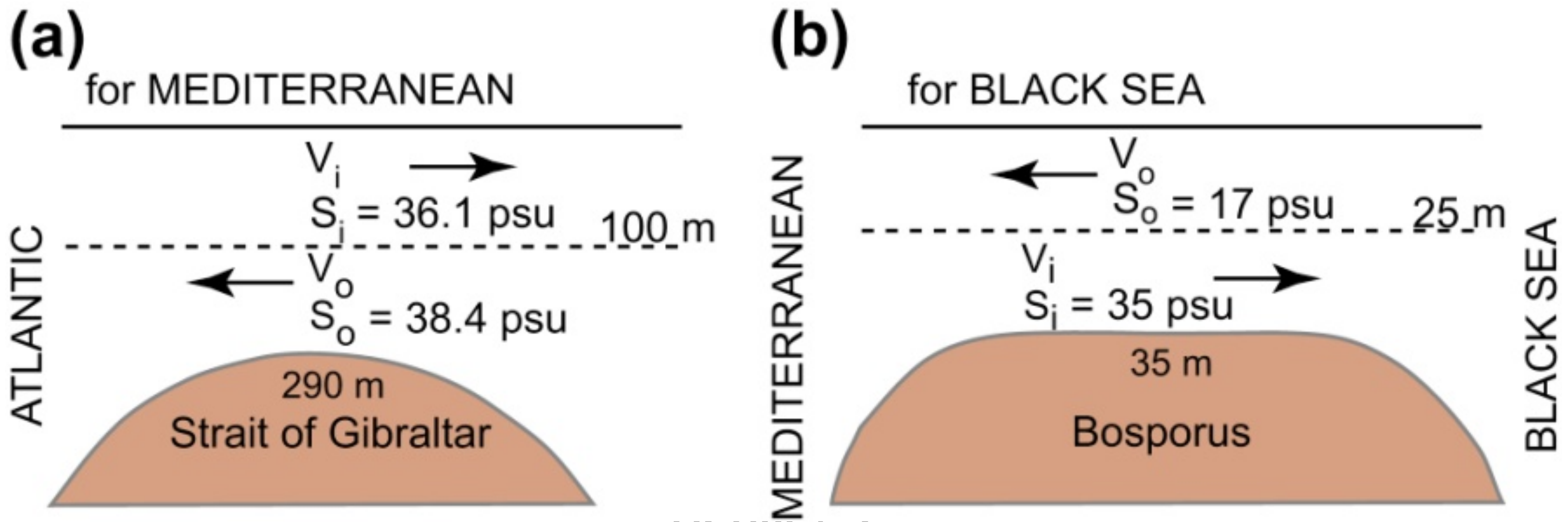


FIGURE 5.3

TALLEY

Conservation of freshwater

Mass: $F = \rho_o V_o - \rho_i V_i = (R + AP) - AE$

Salt: $\xi = V_o \rho_o S_o - V_i \rho_i S_i = 0$ (salt is conserved)

Salt divided by an arbitrary constant, about equal to mean salinity:

$$\xi / S_m = V_o \rho_o S_o / S_m - V_i \rho_i S_i / S_m = 0$$

Subtract $F - \xi / S_m = F - 0$

$F - \xi / S_m = \rho_i V_i (1 - S_i / S_m) - \rho_o V_o (1 - S_o / S_m)$

Assume $\rho_i V_i \sim \rho_o V_o = \rho V$ given error in observations, so

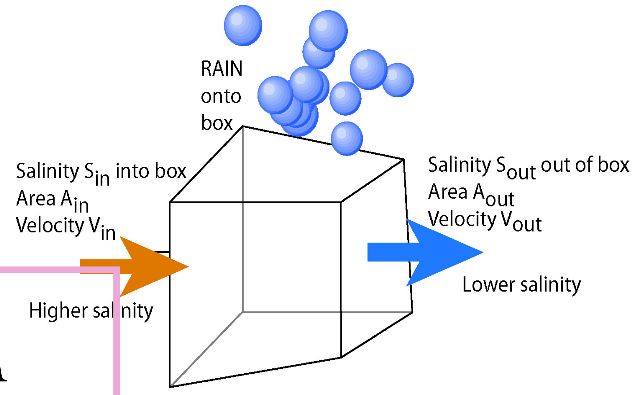
$F \sim \rho V (S_o / S_m - S_i / S_m)$

So the freshwater input calculated from the difference in salinity between inflow and outflow equals the net precipitation, evaporation, runoff

Freshwater transport: calculation of a small residual

Freshwater transport divergence and salt conservation are

$$\begin{cases} \delta = E - P - R = \oiint \rho v \, dA \\ 0 = \oiint \rho v s \, dA \end{cases}$$



$$\delta = E - P - R = \oiint \rho v \left(1 - \frac{s}{s_o} \right) dA$$

where E = Evaporation, P = Precipitation, R= Runoff

S = salinity S_o = arbitrary reference salinity

and Area integral is through the sides of a closed box

Chose reference salinity of 34.9 for my global calculation (the value doesn't matter, as long as it's the same for all components of calculation, all sections, all Ekman, etc.)

Freshwater transport: calculation of a small residual

Uncertainties with application to observations:

We can't possibly evaluate this balance: $$\delta = E - P - R = \iint \rho v dA$$

which is why we use this one instead (a residual), which should be valid for any arbitary non-0 S_{ref}:

$$\delta = E - P - R = \iint \rho v \left(1 - \frac{S}{S_{ref}}\right) dA$$

In practice, with observations, we assume mass conservation:

$$0 = \iint \rho v_A dA$$

This leads to an error δ' in the freshwater transport, which we can show is equal to:

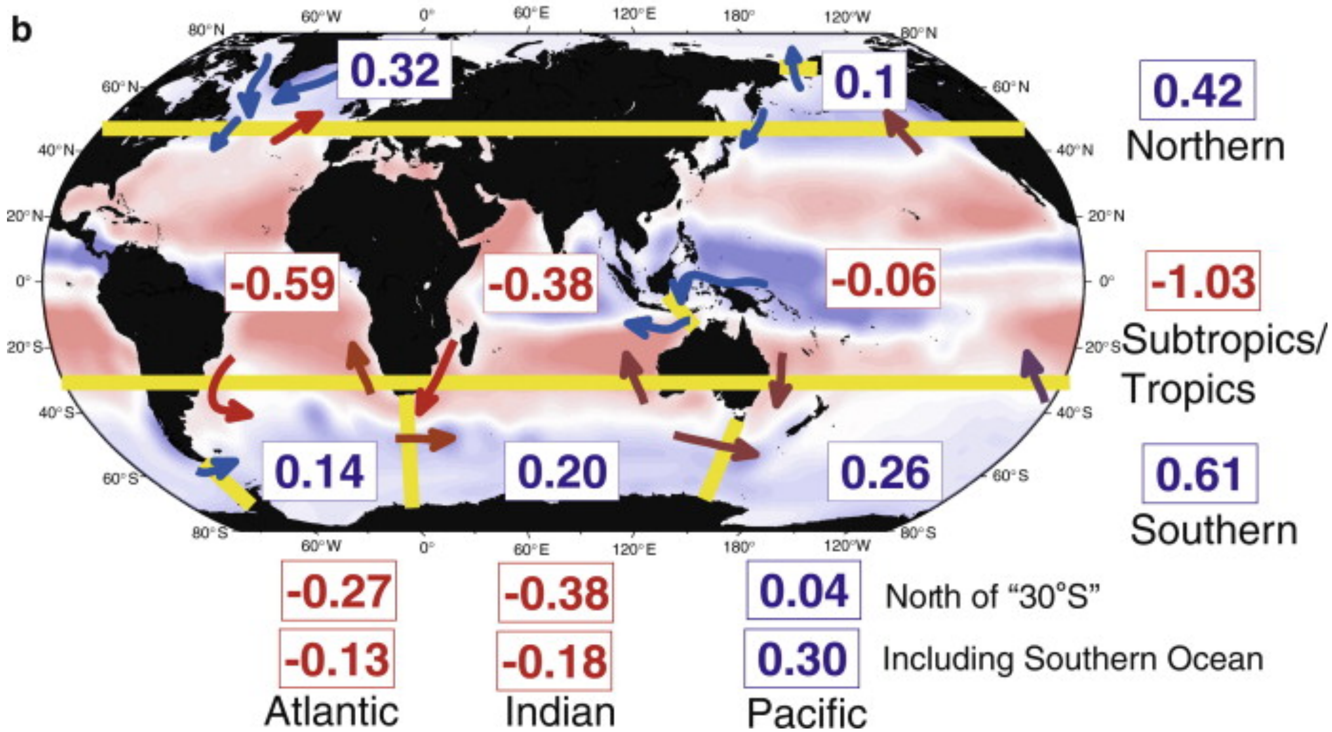
$$\delta' = -\delta \left(1 - \frac{\bar{S}}{S_{ref}}\right)$$

where δ is the FW transport and $\bar{S}$ is the mean salinity.

Calculating this uncertainty due to the assumption of mass conservation: for typical FW transports of 0.1 Sv, the error is order 0.001 Sv, so totally minscule. Uncertainties due to noise/unknowns in velocity are on the order of 10 to 100%, hence much more important.

Freshwater transport: Observed freshwater transport by the ocean

Net freshwater divergence (Sv) from ocean velocities and salinities along hydrographic sections (Talley, 2008)



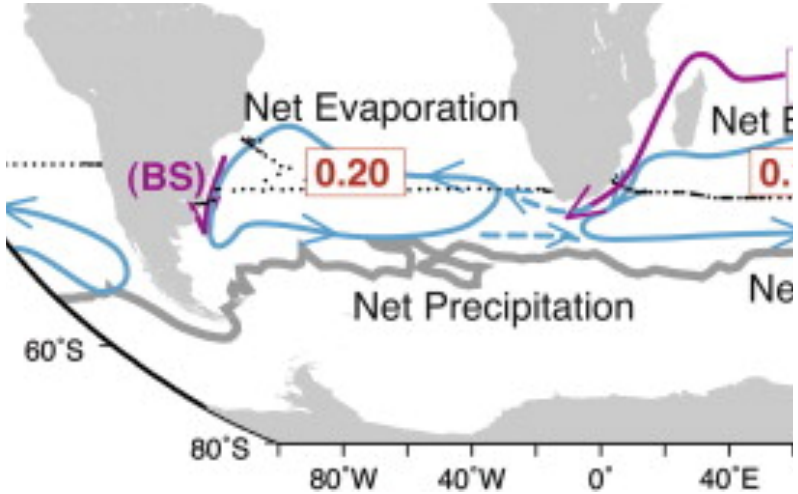
Meridional ocean transports of freshwater from high to low latitudes

"Zonal" ocean transports of freshwater from Pacific to Atlantic/Indian

Fun calculation: $F = V\Delta S/S_o$
For F = 0.3 Sv and ΔS= 35.2-34.6=0.6, then V = 17 Sv

Freshwater transport: Observed freshwater transport by the ocean

Decompose FW transports into
(1) upper ocean gyre
(2) throughflow (Indonesian Throughflow and Bering Strait)
(3) deeper overturning component



Example of how upper ocean freshwater transport works:
Western boundary current carries salty water southward from evaporation region and equatorward gyre flow carries fresher water back

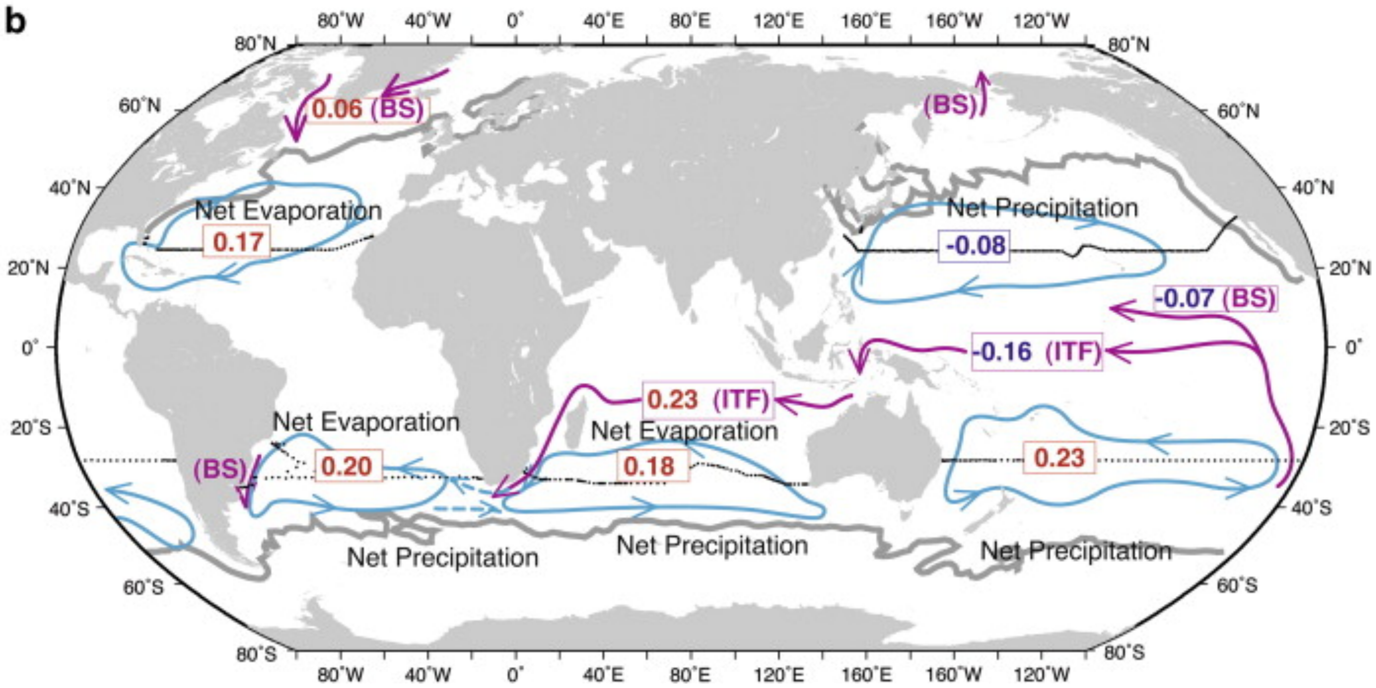
For the calculation: volume transports MUST balance, just as for heat transports – we are looking at the salinity difference between northward and southward flow. The very small (< 0.2 Sv) freshwater transports of course represent a volume imbalance, but they are well within the uncertainty of the volume transport calculation, which we approximate as being exactly balanced.

- For the gyres: mass balanced (gyre transport above maximum subduction density plus Ekman balanced by portion of western boundary current)

Talley (2008)

Freshwater transport: Observed freshwater transport by the ocean

Upper ocean and throughflow freshwater transports



Net Bering Strait impact: < 0.1 Sv

Net ITF: order 0.2 Sv for both Pacific and Indian

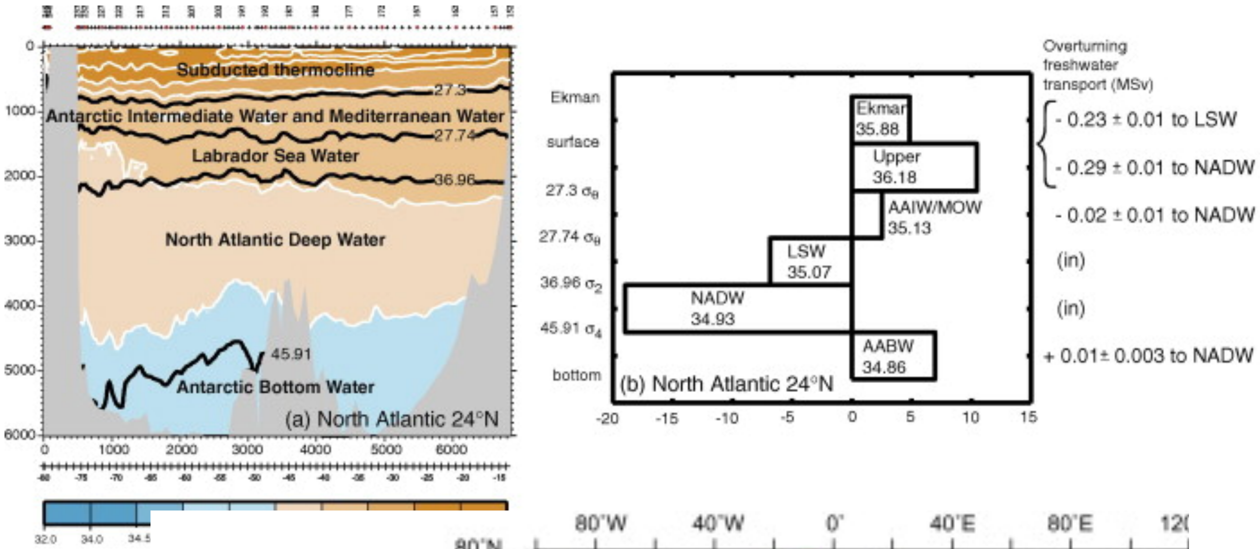
Net northward out of Southern Ocean is 0.61 Sv

- Order of 0.1 to 0.2 Sv for these (mostly) upper ocean components, which are affected directly by input fluxes from E-P-R

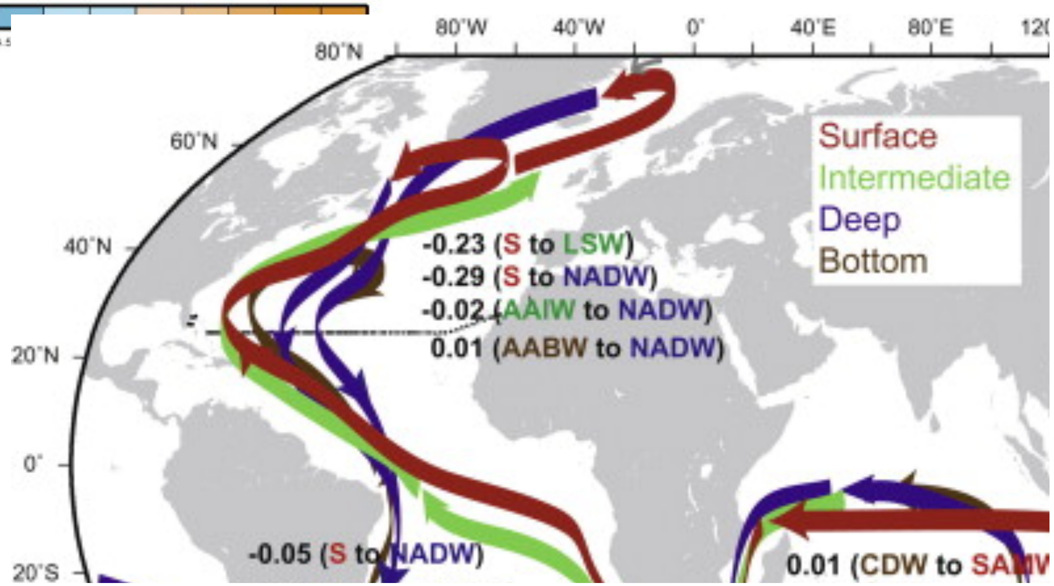
Talley (2008)

Freshwater transport: Observed freshwater transport by the ocean

Meridional overturning component of FW transport



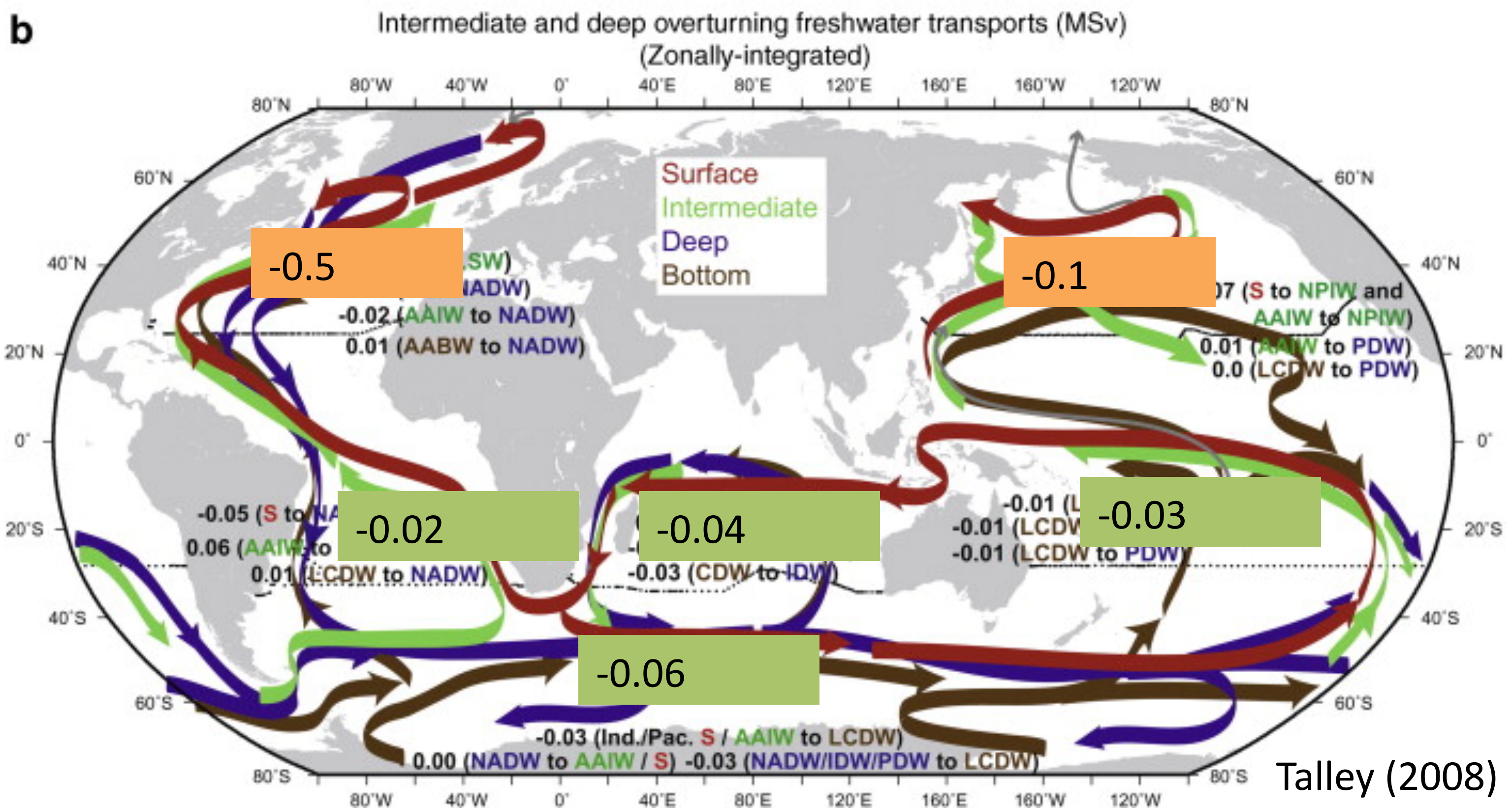
- Compute zonally-averaged overturning in isopycnal layers
- Example: North Atlantic at 24 °N



- •Schematic based on calculated transports through the sections
- •Freshwater transport values are directly calculated

Observed freshwater transport by the ocean

Intermediate and deep overturning components

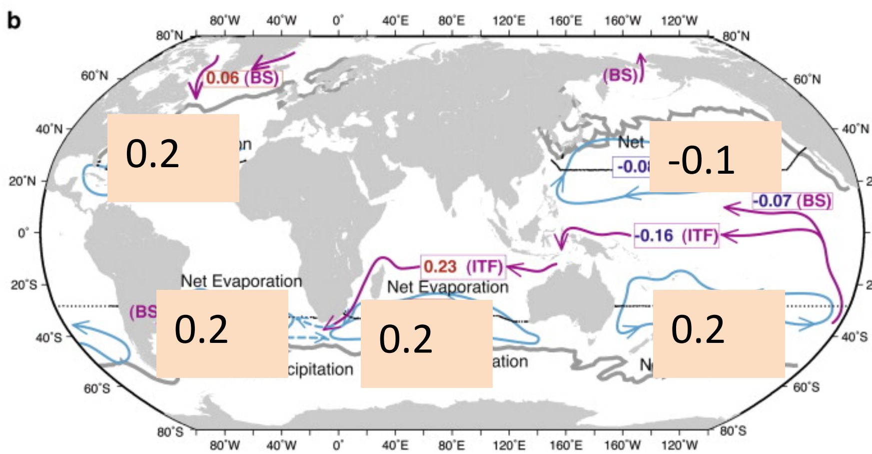


Talley (2008)

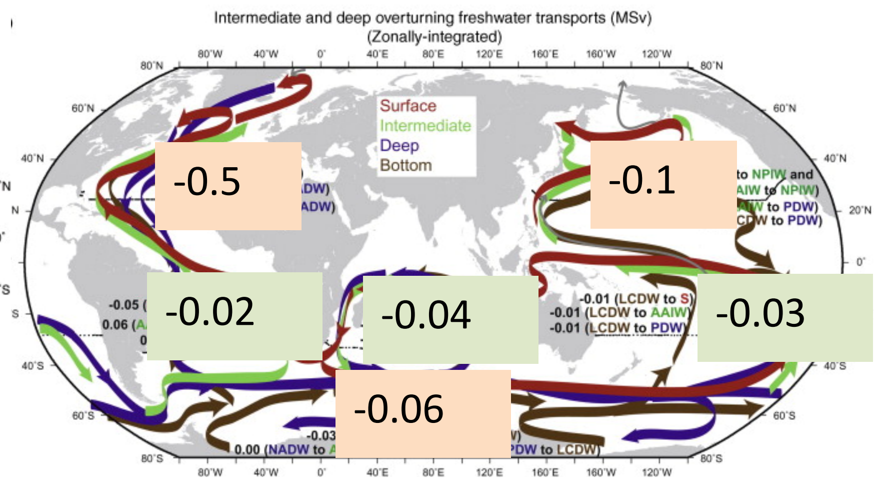
Northern hemisphere: NADW and NPIW formation dominate equatorward FW transport
Southern hemisphere: deep transformations (AABW formation, NADW/IDW/PDW) provide only a weak FW transport (also weak heat transport)

Observed freshwater transport by the ocean: NH-SH asymmetry

- Northern Hemisphere exports freshwater southward through NADW and NPIW formation (0.5 and 0.1 Sv)
- Southern Hemisphere exports freshwater northward through upper ocean gyres (0.6 Sv), (order of magnitude less through intermediate and deep water formation)
- Why: Drake Passage inhibits transport of salty, warm surface waters to Antarctica (Warren, 1980; Toggweiler and Samuels, 1995).
- Thus Antarctic surface waters are upwelled deep waters, already cold. They can only be freshened a small amount and still be able to sink to the bottom (freshening due to net E-P-R and small salt addition through brine rejection).
- Hence, surface freshwater input in the Antarctic just floats in surface layer, can't become dense enough to sink



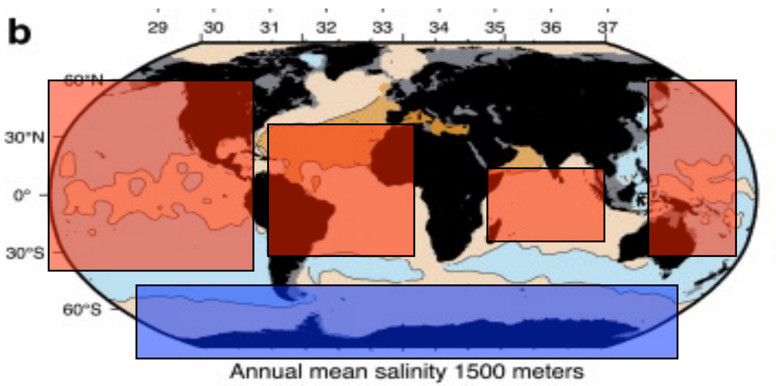
Upper ocean pathways



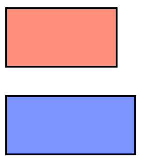
Intermediate and deep pathways

Observed freshwater transport by the ocean

- What about the smaller order freshwater transports (order 0.01 Sv)?
- Even though small, the signs are robust (accurately reflect the difference in salinity between the inflow and outflow waters)
- These small FW transports are critical for deep water salinity differences, which ultimately determine global distribution of deep water formation



Location of large volume transformation with small FW transports
(NADW not shown because it has large FW transport)



Observed freshwater transport by the ocean

- Interbasin differences in salinity also require ocean freshwater transports to balance them
- These are almost entirely upper ocean/thermocline processes - reflected in observed S changes (climate changes – Boyer et al., 2005) that are mostly in the upper ocean
- There is no single dominant process in any basin: multiple pathways must be evaluated/ monitored to interpret changes

Atlantic 35.0 psu
Net evaporation

Bering Strait	0.1 in
Agulhas upper	-0.05 out
AAIW	0.06 in
S.O.ST gyre	0.2 in

Indian 34.8 psu
Net evaporation

ITF/Agulhas	0.2 in
S.O. ST gyre	0.2 in

Pacific 34.5 psu Net precipitation

Bering Strait	-0.1 out
ITF/S.Pac.gyre	-0.2 out
S.O. ST gyre	0.2 in

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