The role of sea surface salinity in extreme El Niño events

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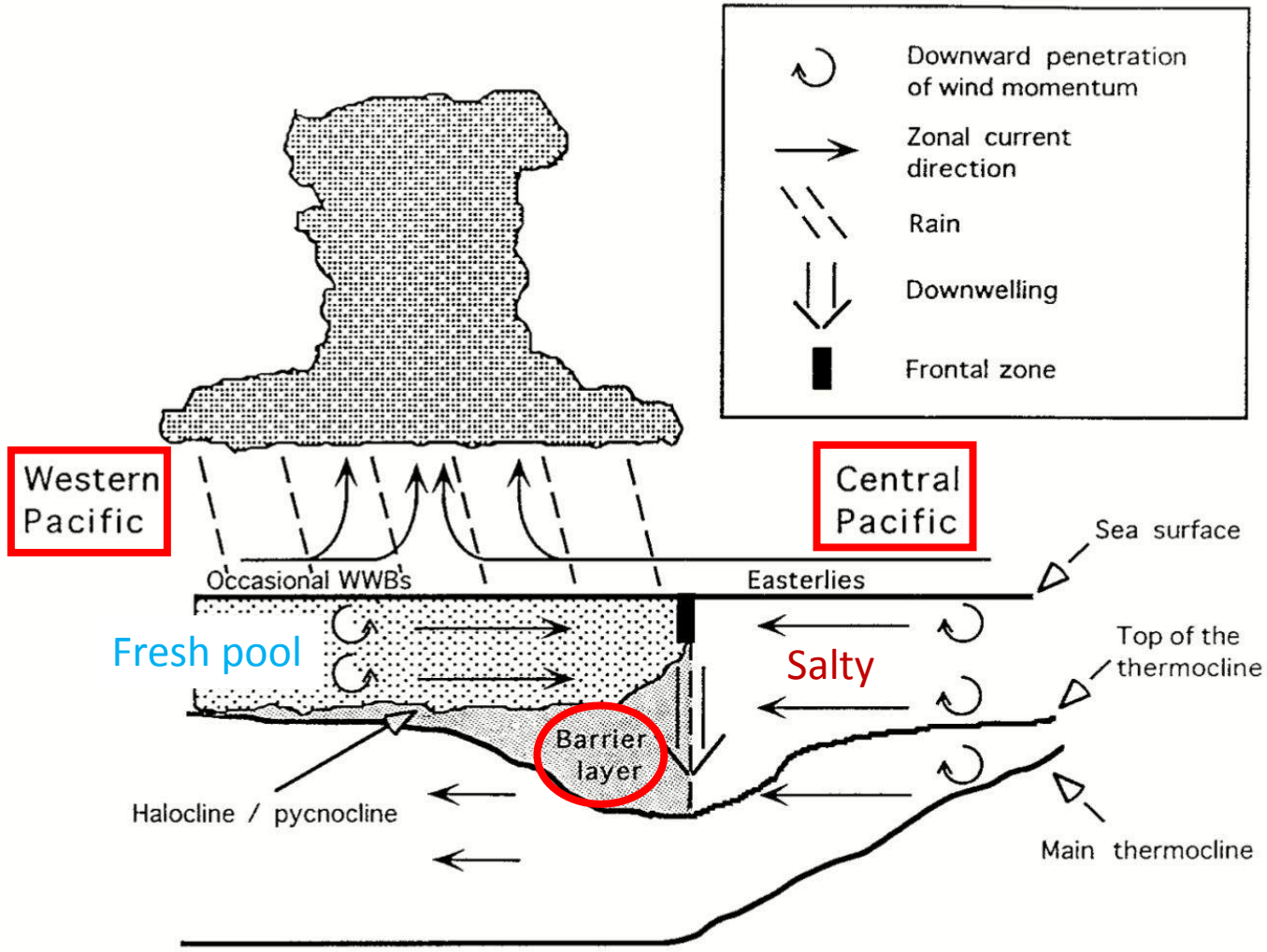
West Pacific salinity stratification can influence El Niño strength

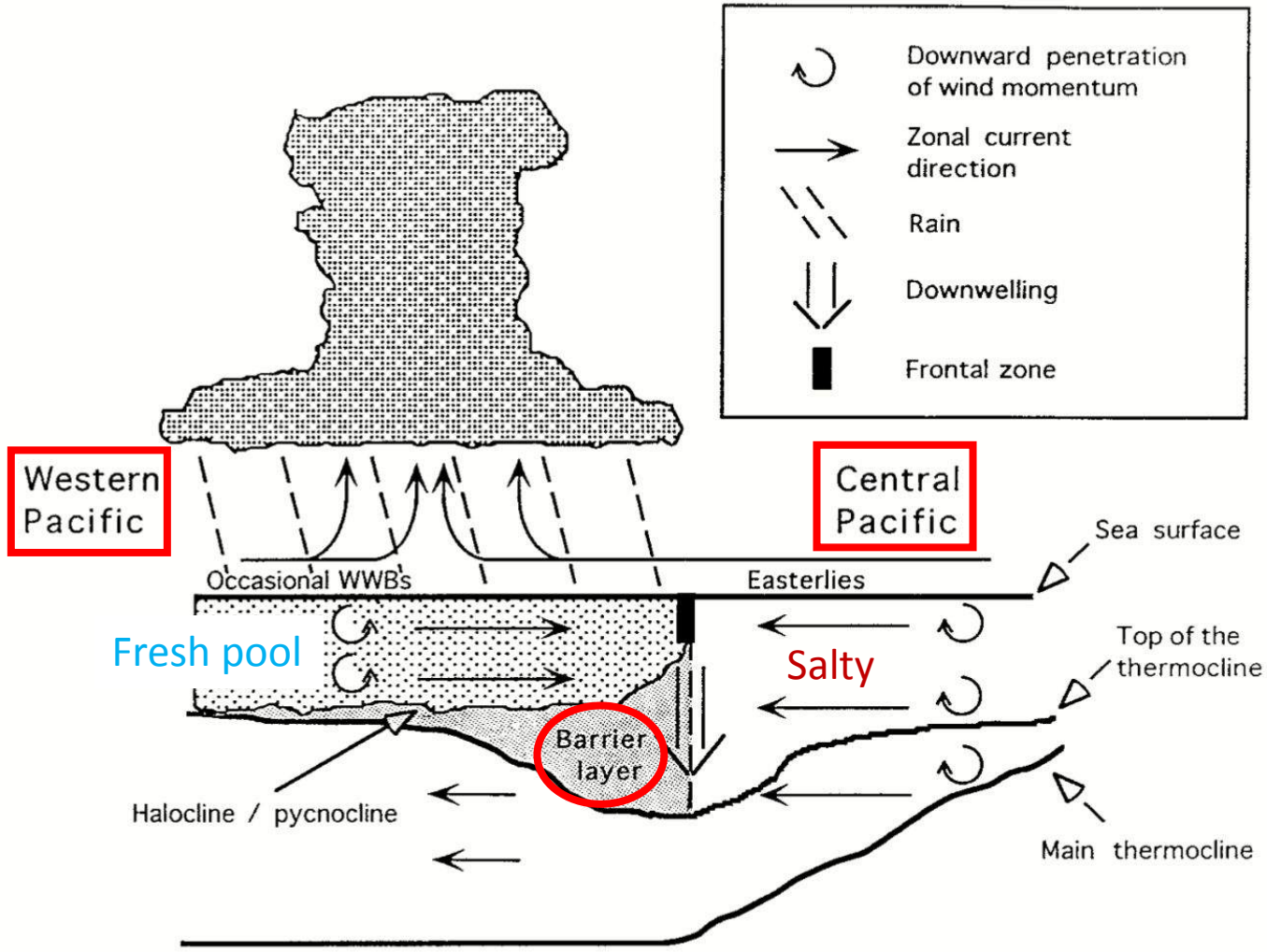
- **Barrier layer** influences mixed layer depth, heat & momentum at surface
- **Impacts El Niño** via interacting with westerly wind bursts, SST, mixing
- **Variability** linked to atmosphere and ocean (*P-E*, advection, etc.)



Vialard & Delecluse (1998)

Guiding questions

- How does SSS variability influence salinity stratification in the west Equatorial Pacific?
  - Surface subsurface
  - Local vs. remote
  - Timescales
- How does salinity stratification impact ENSO?



Vialard & Delecluse (1998)

Methods: SSS nudging to reduce variability

To investigate the role of sea surface salinity (SSS) variability in ENSO, we conduct two experiments:

Control: Freely-varying SSS (**CTL**)	Seasonal SSS only (**fixSSS**)
• Initial conditions: radiative forcing and land use of the year 1990 • Runs freely for 700 years, first 100 years discarded as spin-up	• Same as CTL, except **global SSS is prescribed to a monthly-varying climatology** from CTL years 101-200 (nudged every 5 days) • Initial condition: CTL's year 101

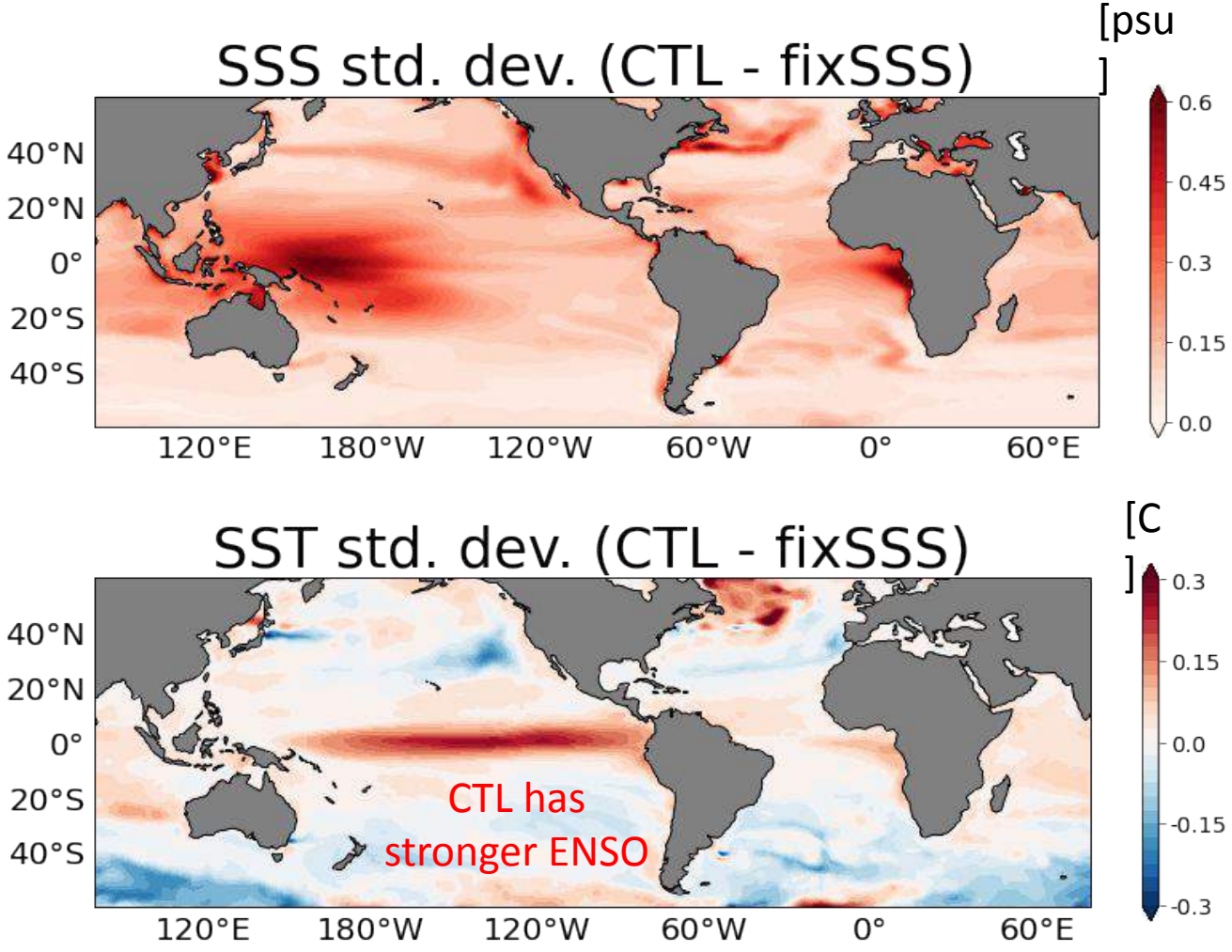
Same climatology,
but CTL has more SSS variability

Model: Forecast-oriented Low Ocean Resolution model (**GFDL CM2.5-FLOR**)

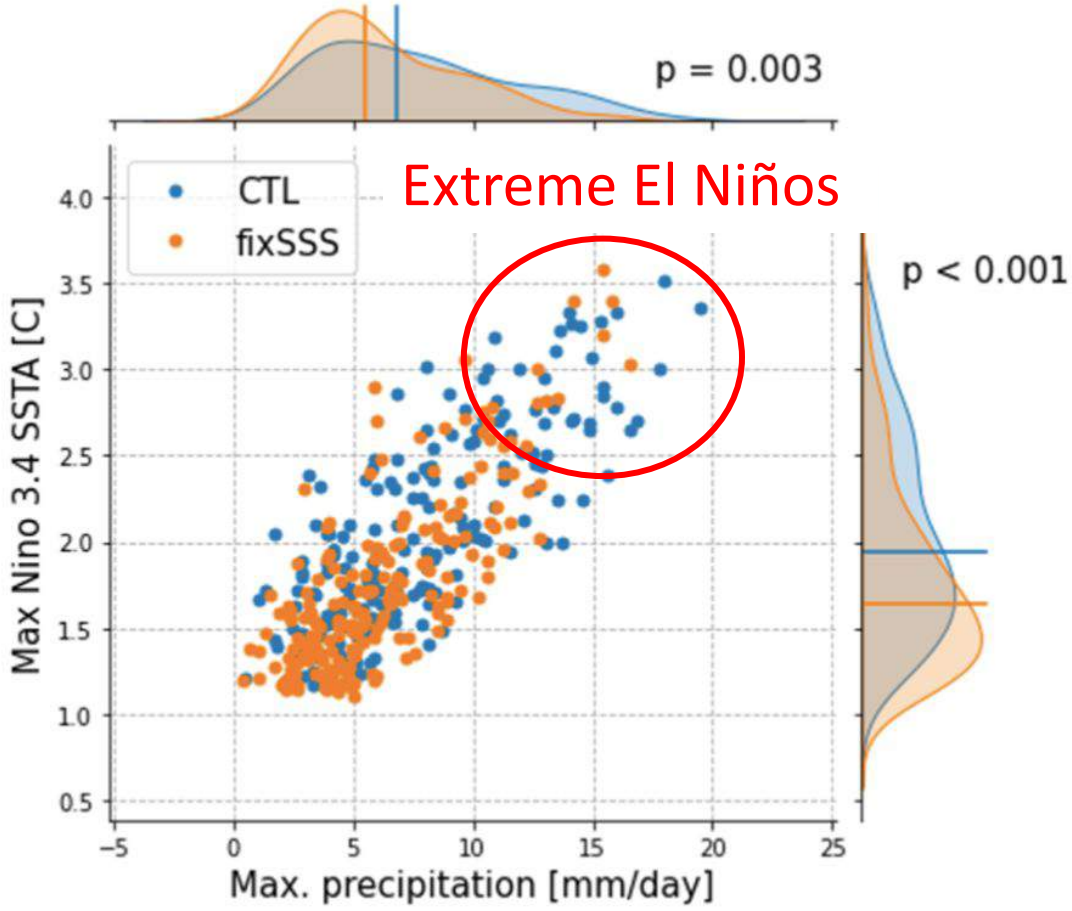
- Fully-coupled atmosphere and ocean
- Fully interactive salinity (P-E, advection)
- High-resolution atmosphere (50 km horizontal)
- Coarse-resolution ocean (10m depth near surface, 1° horizontal, 1/3° latitude near Equator)

When sub-seasonal/interannual SSS variability is included (CTL):

More SST variance in Eq. Pacific (stronger ENSO)



3x more frequent **extreme El Niño** (2x for extreme La Niña)



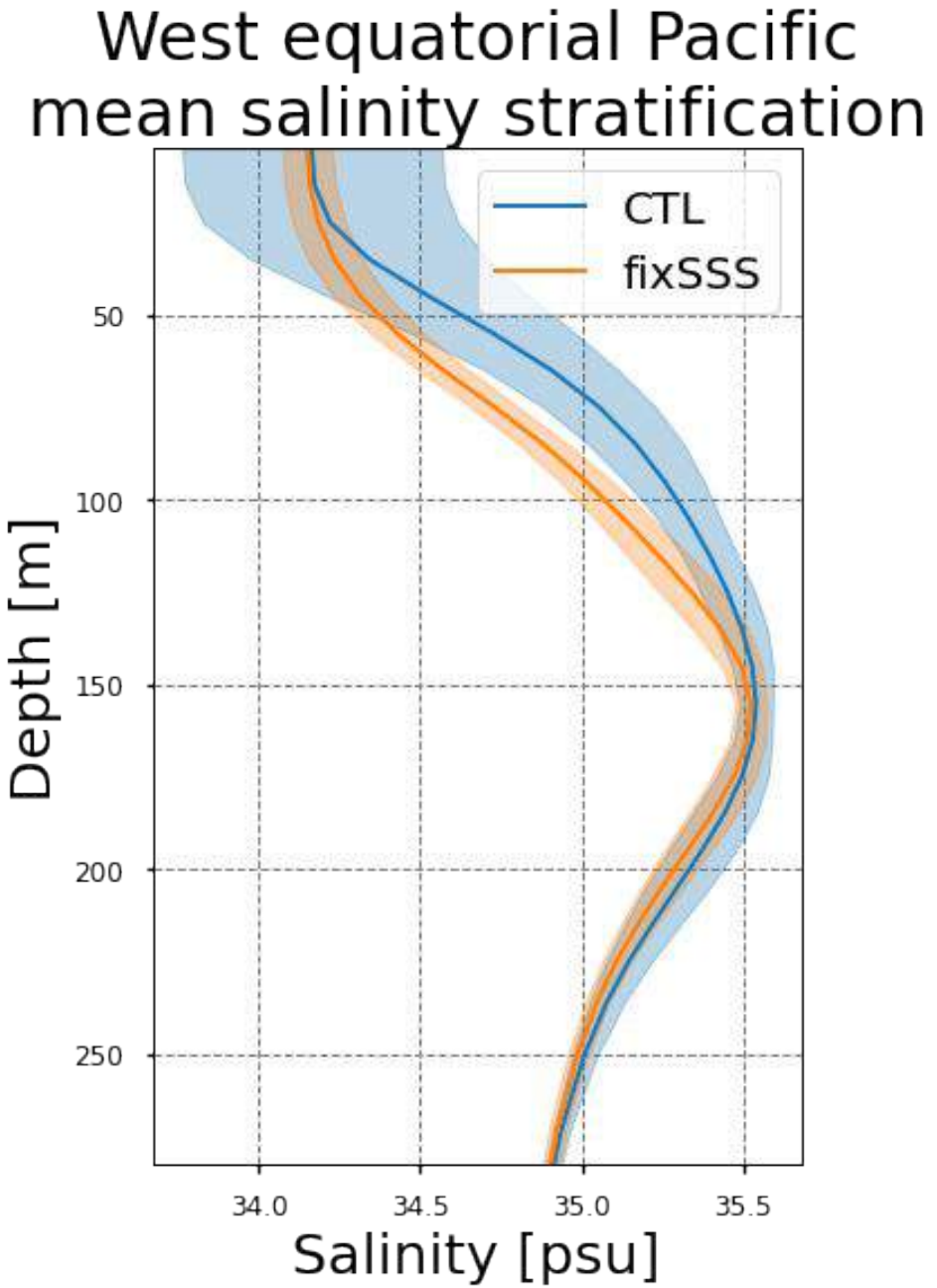
(East Equatorial Pacific)

Changing surface variance changes subsurface mean salinity

- West Equatorial Pacific (WEqP) salinity stratification is weakened, largely due to fresher subsurface.

⇒ SSS variability important for maintaining salty subsurface in WEqP

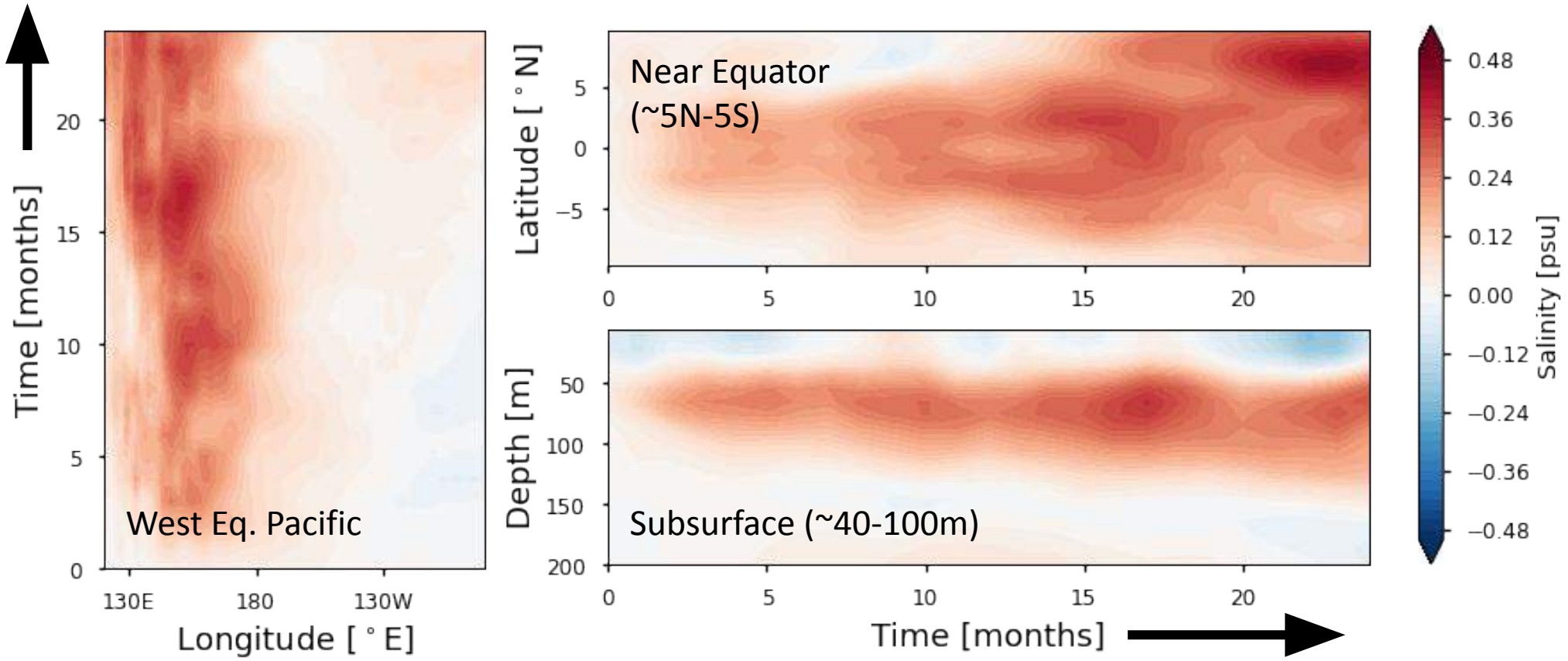
- Temperature climatology does not change significantly.



Shading: year-to-year std. dev.

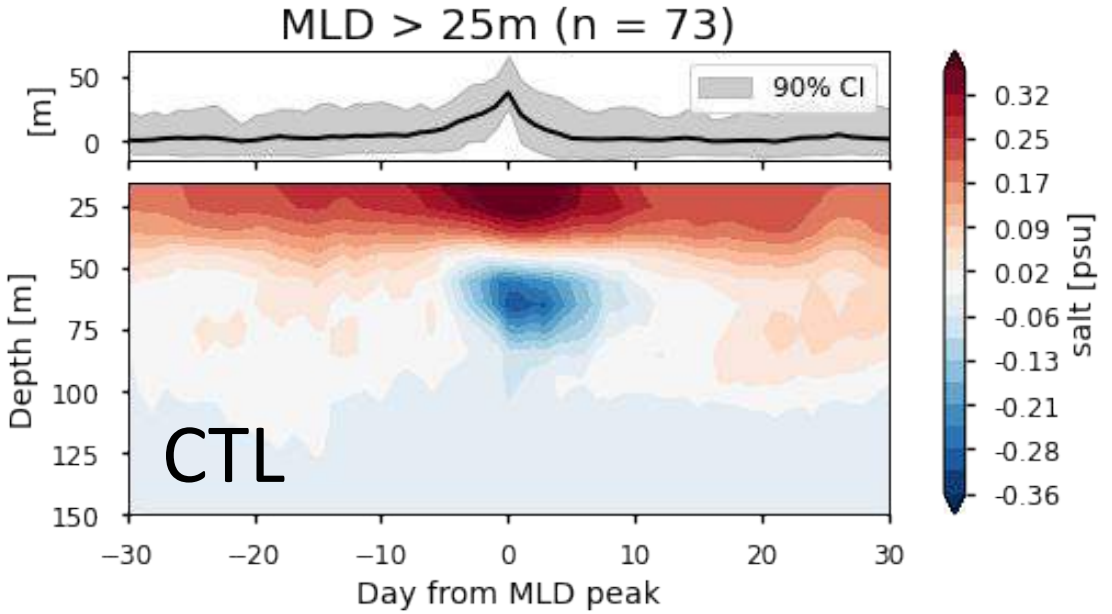
Hovmoller plots indicate **local** salinification at depth on the scale of **weeks** in west Eq. Pacific

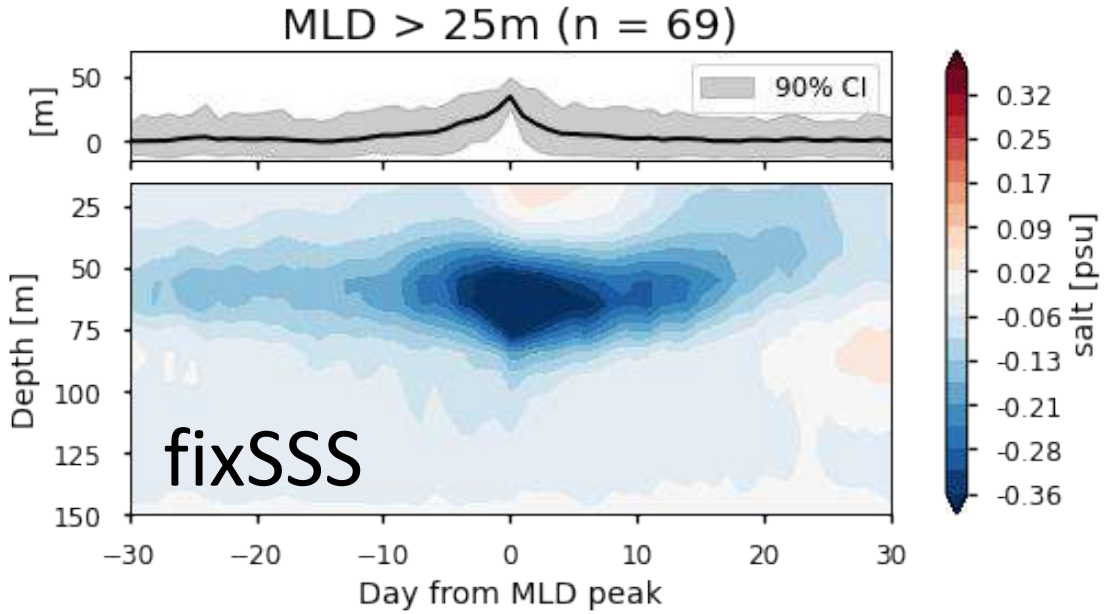
20-member ensemble: CTL minus fixSSS



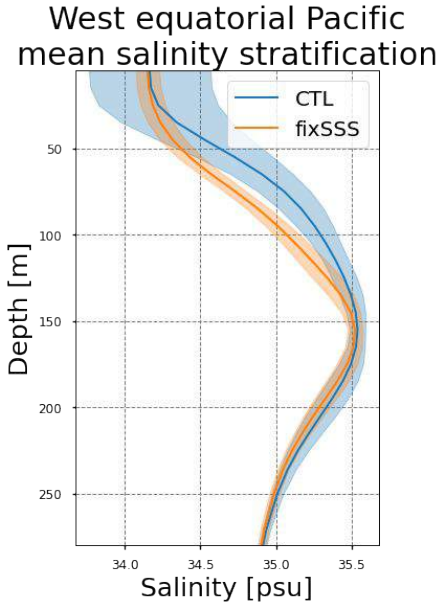
Subsurface salty anomaly starts almost immediately; no obvious connection to the surface

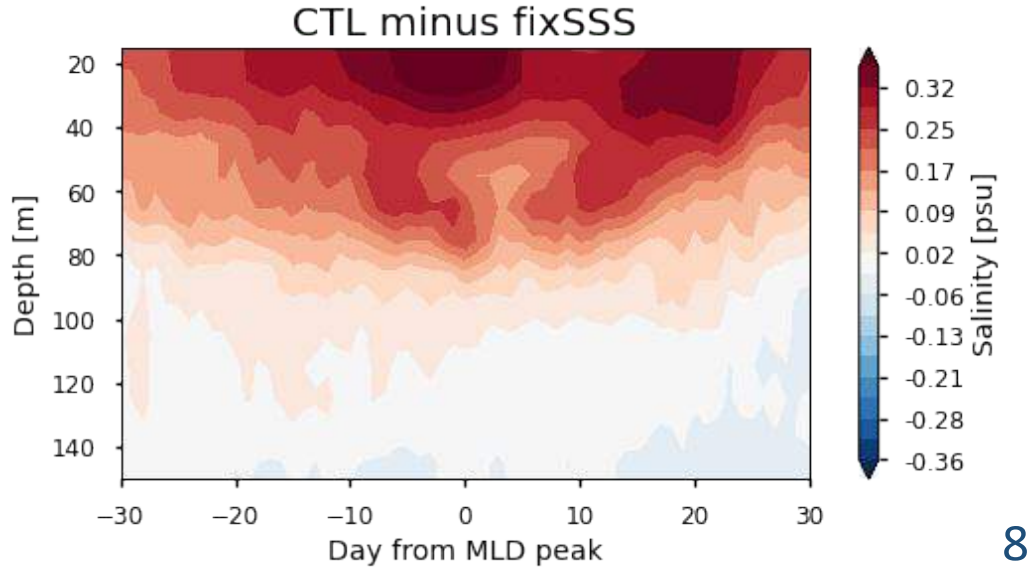
CTL has saltier SSS mixing into subsurface than fixSSS





Mixing from surface always causes subsurface freshening (due to background stratification),
but the SSS is saltier in CTL than fixSSS, therefore causing <u>less freshening</u> at depth (<u>salty anomaly</u>).

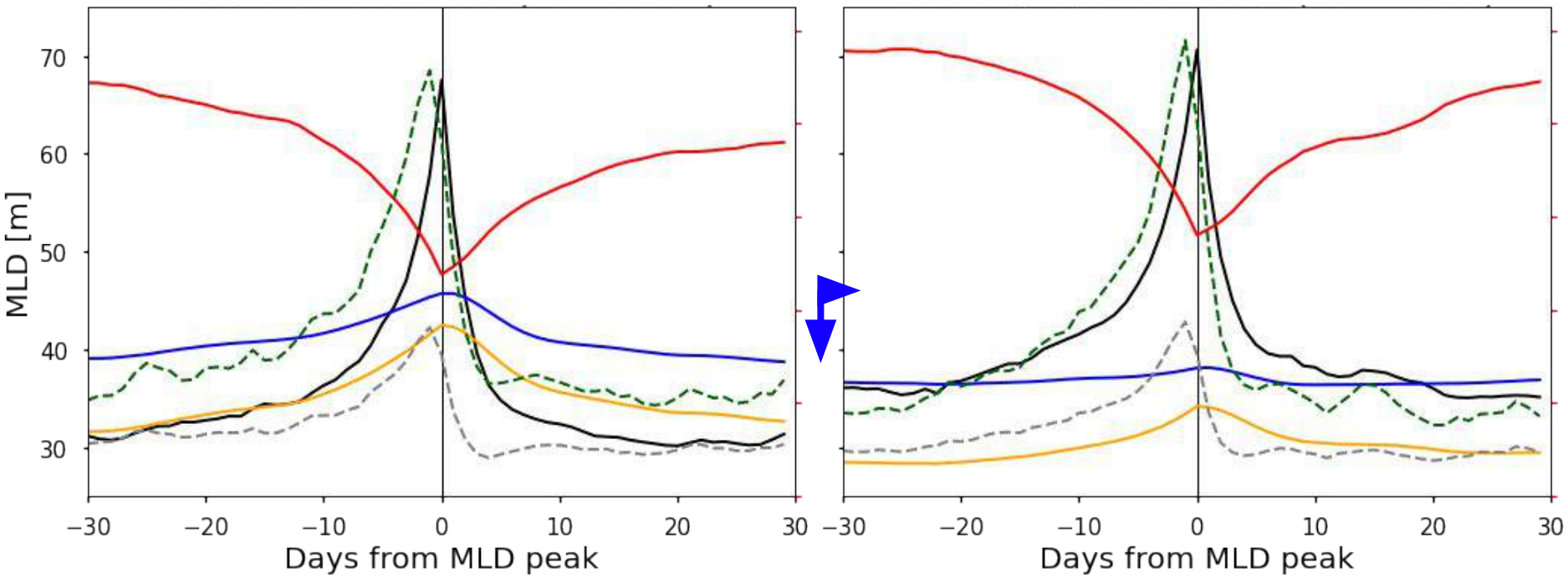


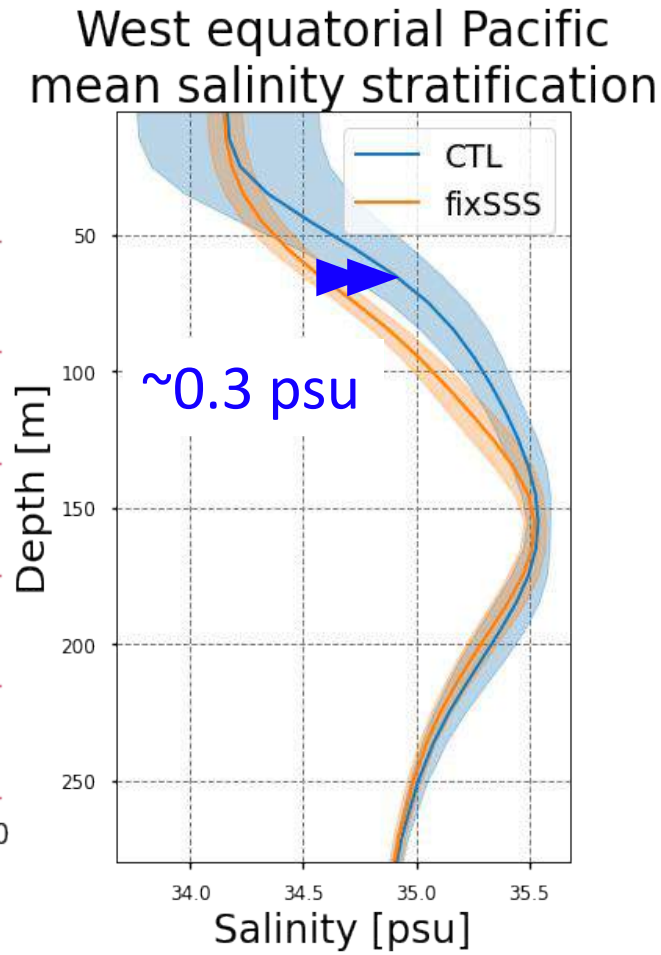


High winds (evap. cooling) => mixed layer deepening => subsurface salinity difference of similar magnitude to mean

CTL

fixSSS





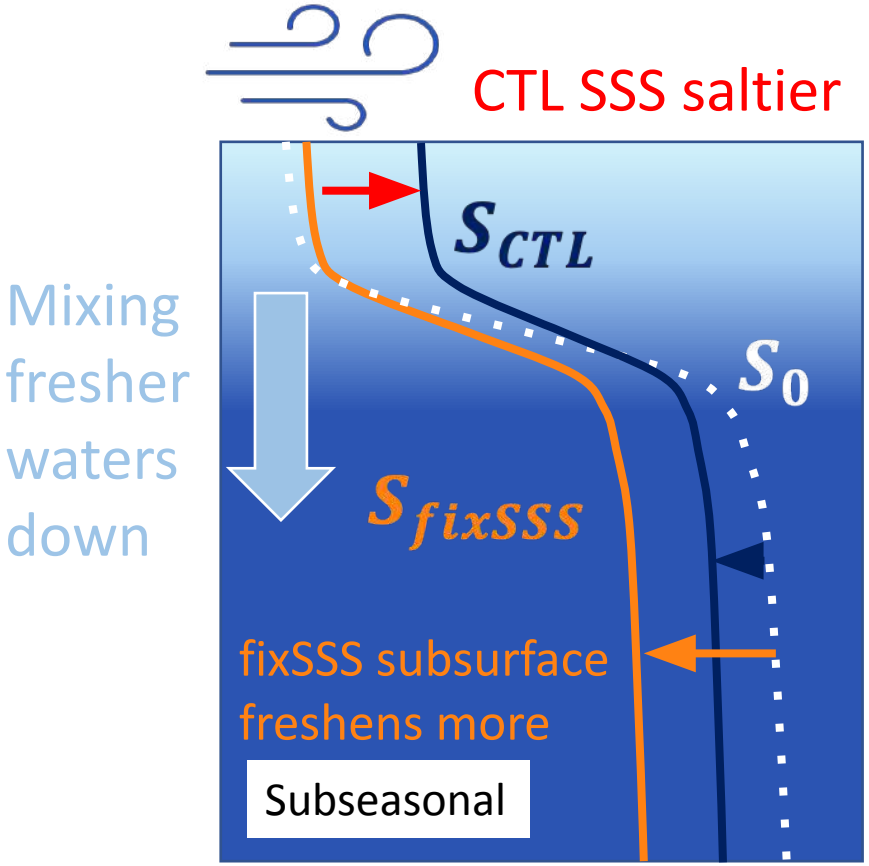
Solid lines (ocean):
MLD SST SSS
Surface density

Dashed lines (atmosphere):
Evaporation
Wind speed

- Wind speed, evaporation similar
- SSS **~0.3 psu** saltier in CTL than fixSSS

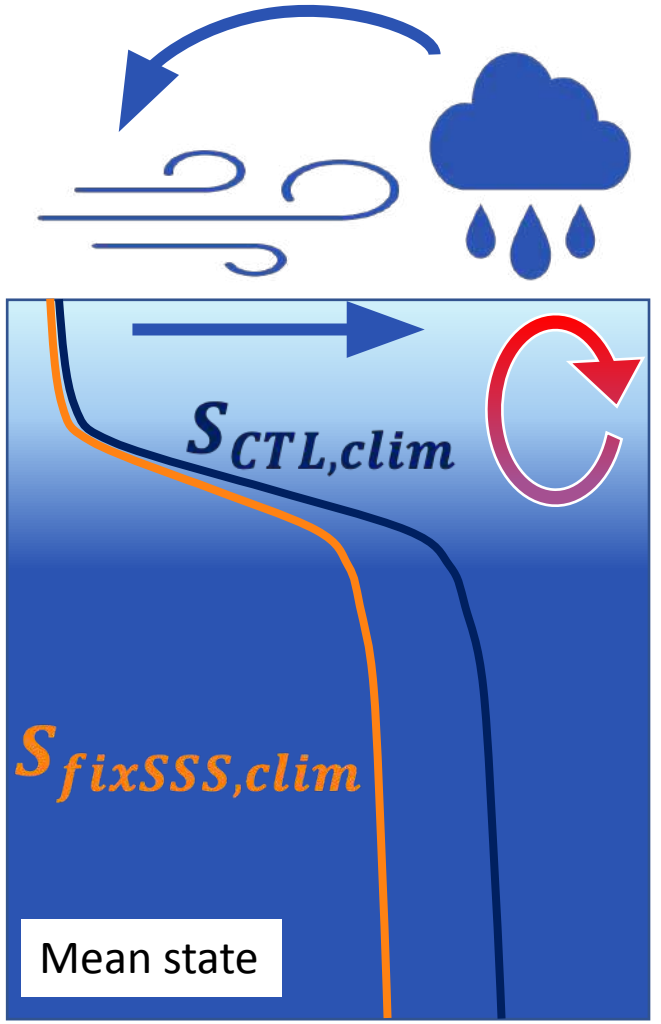
Hypothesis: Model with higher SSS variability preferentially mixes saltier waters into the subsurface => stronger salinity stratification, El Niño

If SSS saltier, subsurface freshens less during mixing events, maintains more stratification



Depth □

Mean state-enhanced El Niño



Higher climatological *S* stratification

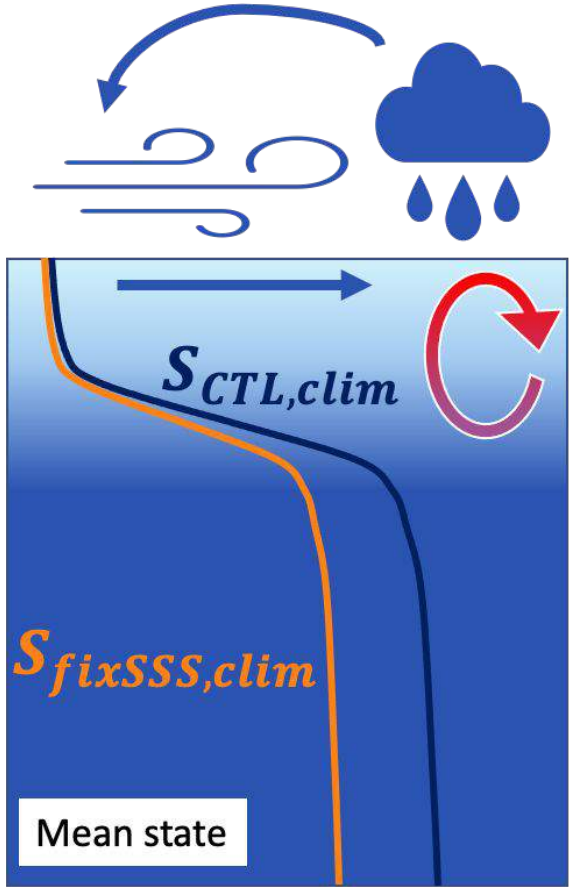
□

Traps more heat, momentum at surface

Takeaways

- In the west Equatorial Pacific, higher SSS variability can strengthen mean salinity stratification
  - Subduction of saltier waters, “less freshening” of subsurface, on short timescales
- Stronger mean-state salinity stratification associated with stronger ENSO

- <u>Implications:</u>
  - Models may need to simulate high-frequency salinity variability accurately to correct mean-state biases
  - Future changes in SSS variability □ mean state stratification □ ENSO?



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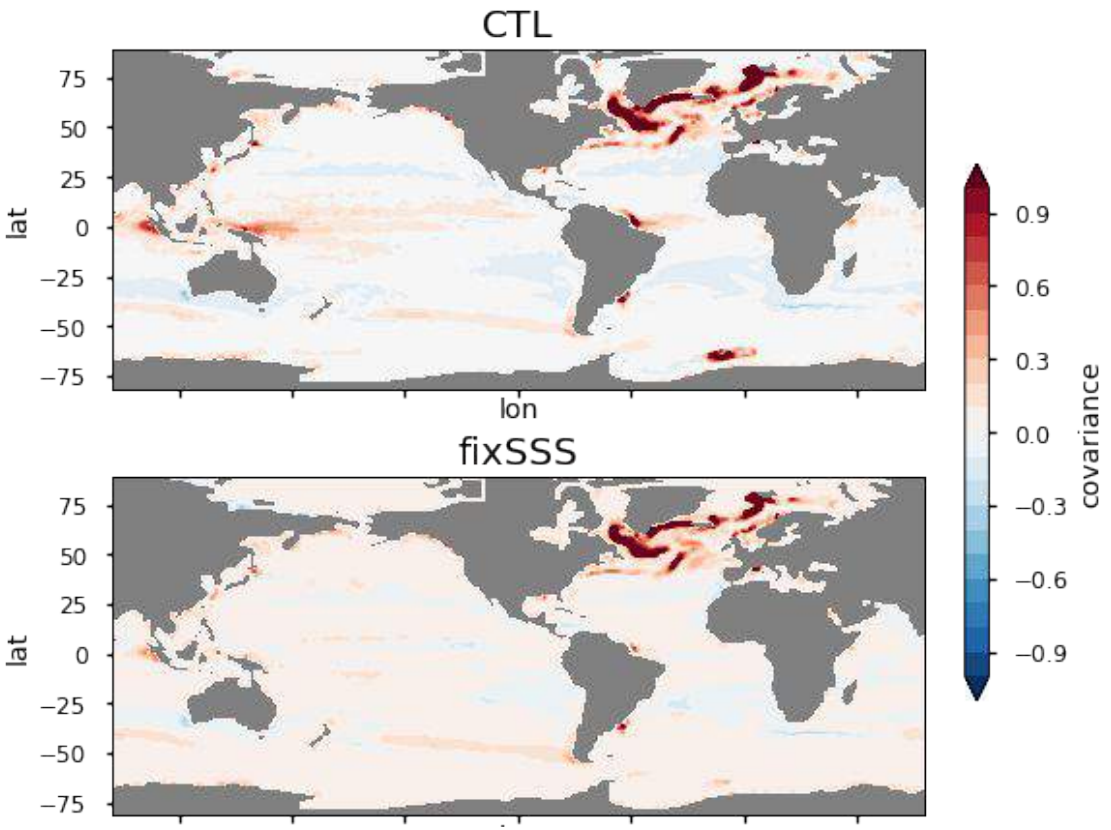
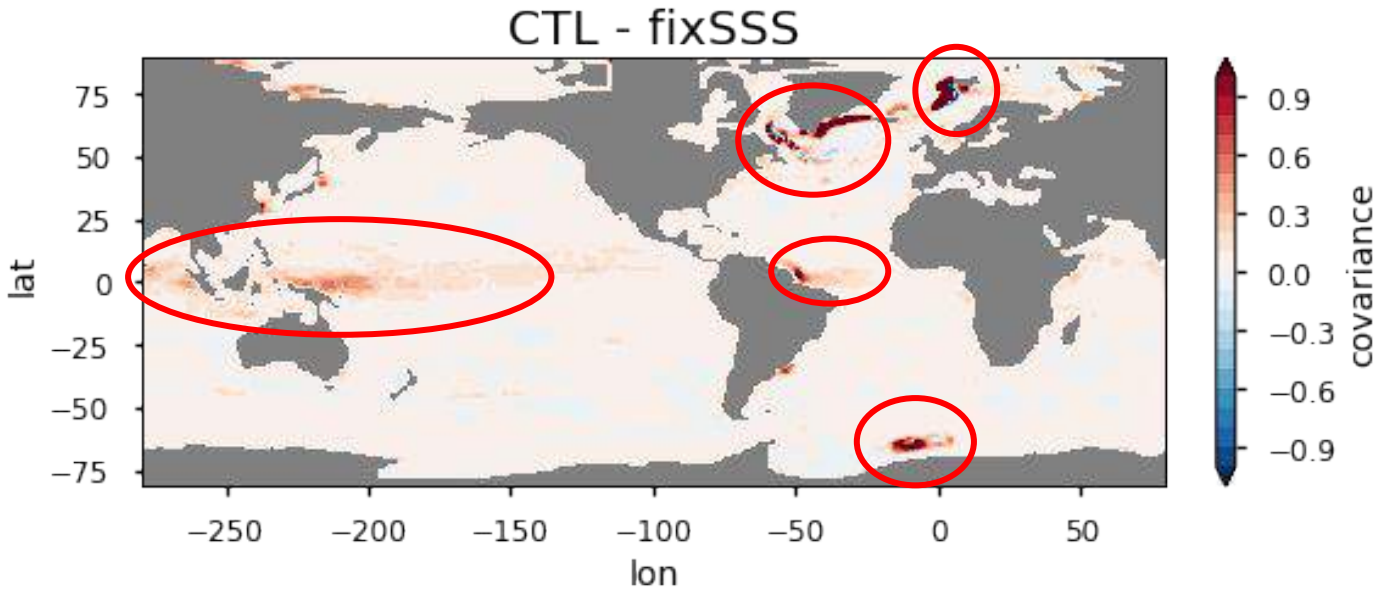
Extra slides

Other regions with high-frequency MLD and SSS covariance





- West equatorial Pacific
- East Indian Ocean
- River outflow (e.g. Amazon)
- East & south of Greenland
- Weddell Sea

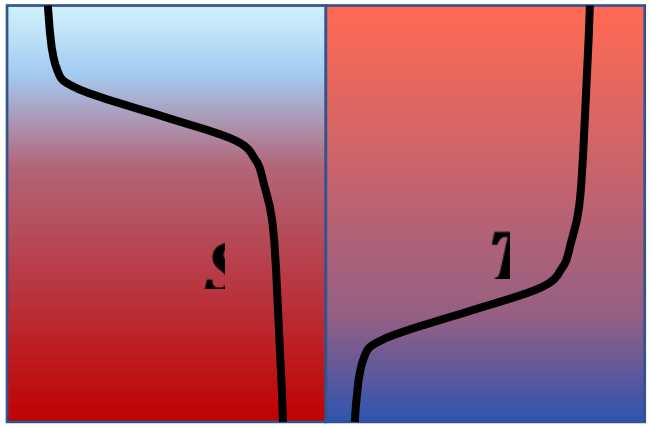
Do these regions have a similar salinity climatology change?

Barrier layer sustains warm SST & winds enhances El Niño

For the same KE input:

Mixed layer

With barrier layer



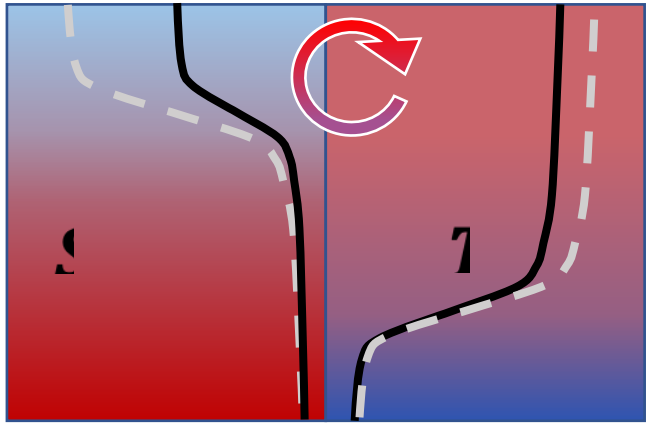
Evap. Cool.

Warm entrainment

Shallow MLD for longer

Warm SST, winds sustained

Mixed layer



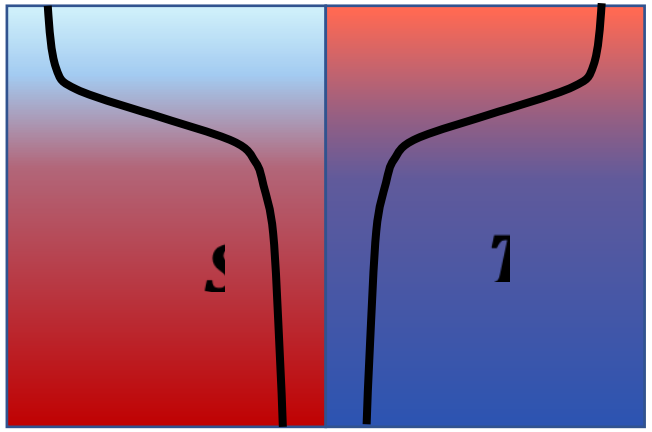
Momentum trapped at surface

Stronger El Niño

Evap. Cool.

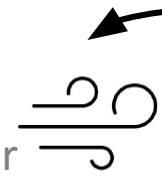
Mixed layer

No barrier layer



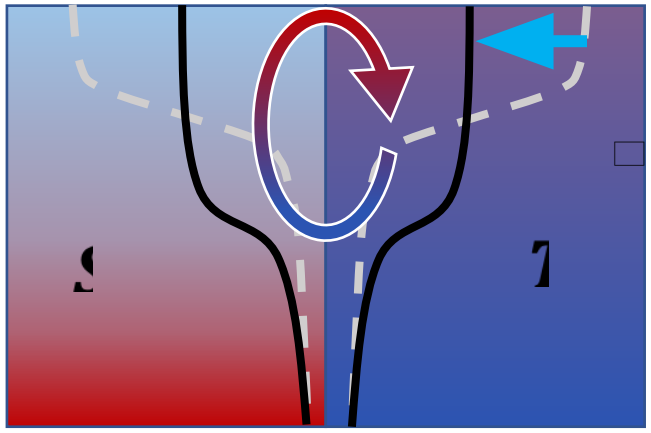
Cool entrainment

MLD deepens faster



Cooler SST, winds weaken

Mixed layer

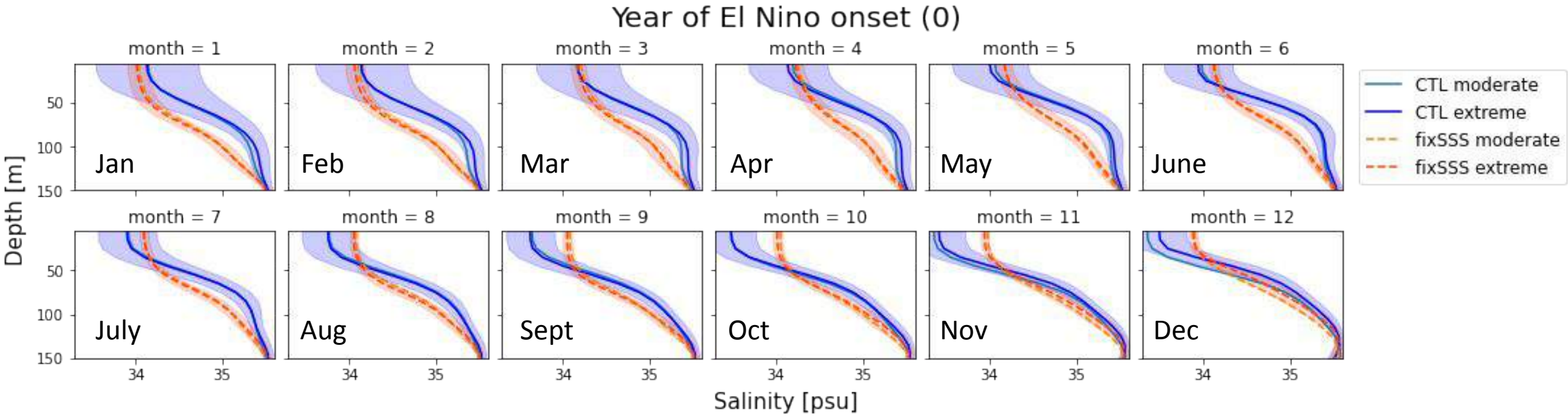


Less momentum at surface

Weaker El Niño

SSS variability appears to impact **mean state** more than difference between **extreme/moderate** El Niño

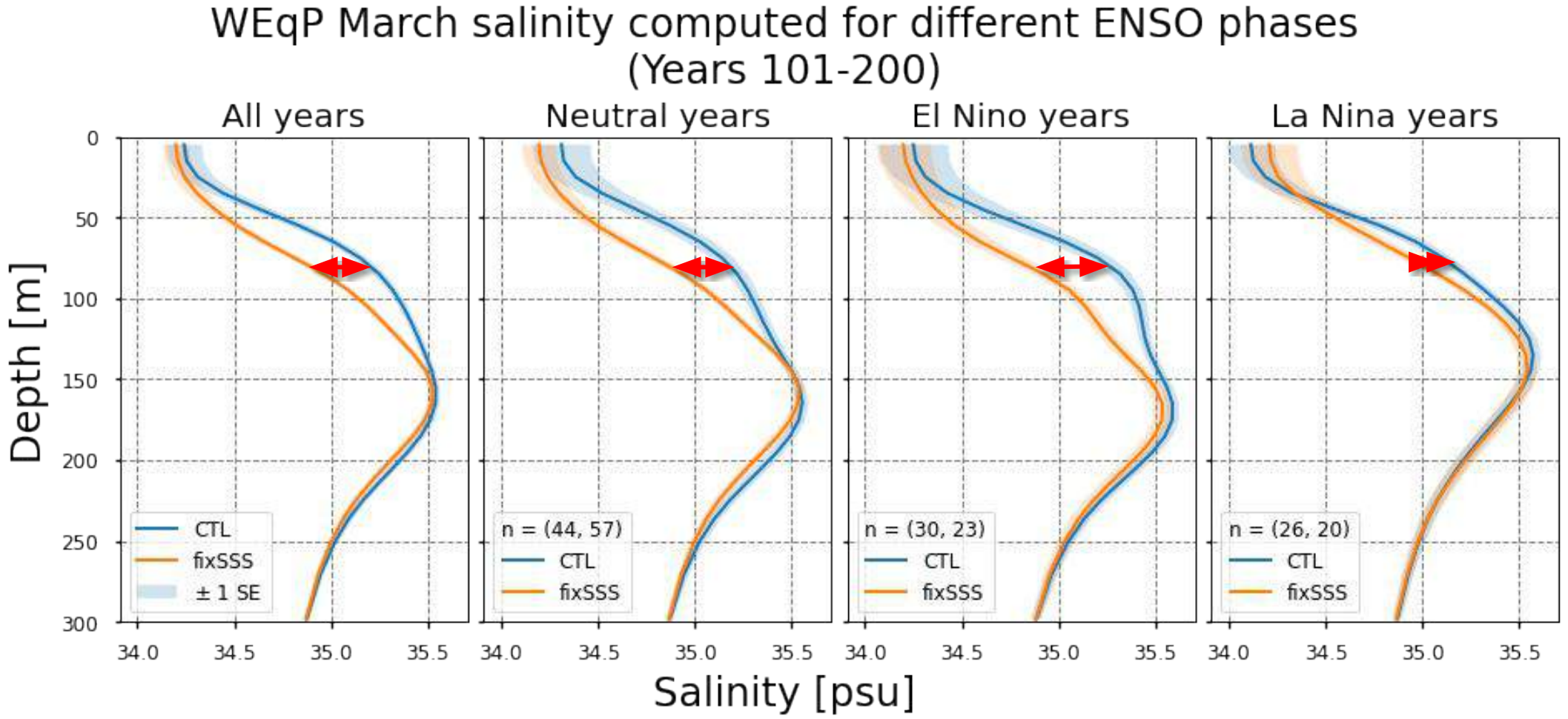
West equatorial Pacific salinity stratification



Extreme vs. moderate difference barely visible.

Shading: 1 standard deviation (across events) for extreme El Niño in CTL and fixSSS

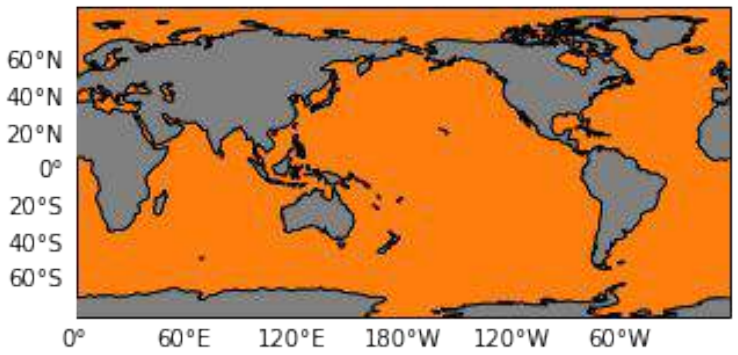
The salinity mean state difference is not explained by ENSO difference



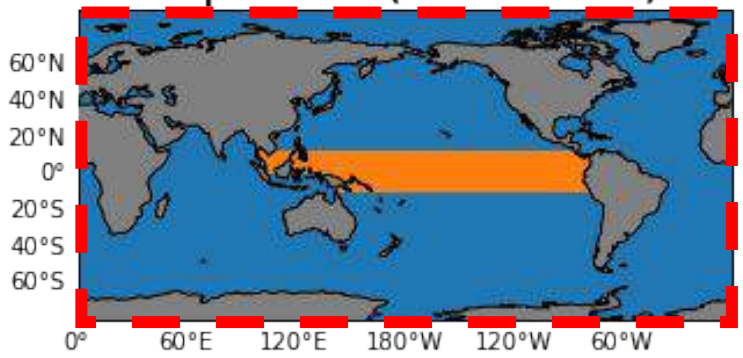
CTL ENSO > fixSSS ENSO. However, the west Equatorial Pacific salinity stratification is stronger in CTL than fixSSS during all phases of ENSO.

Local processes: Targeted SSS nudging shows **Equatorial Pacific** crucial for salinity climatology change

Global (fixSSS)

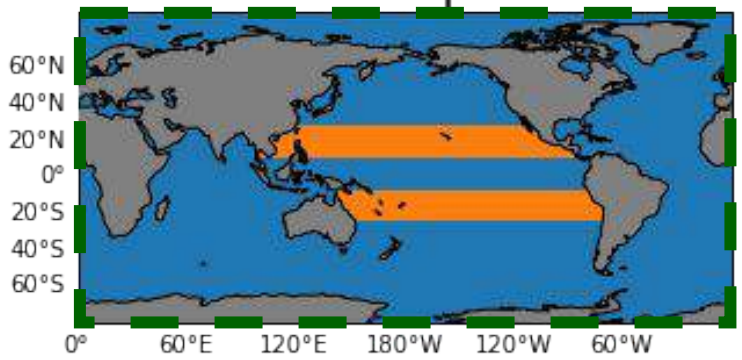


Equator (10N-10S)



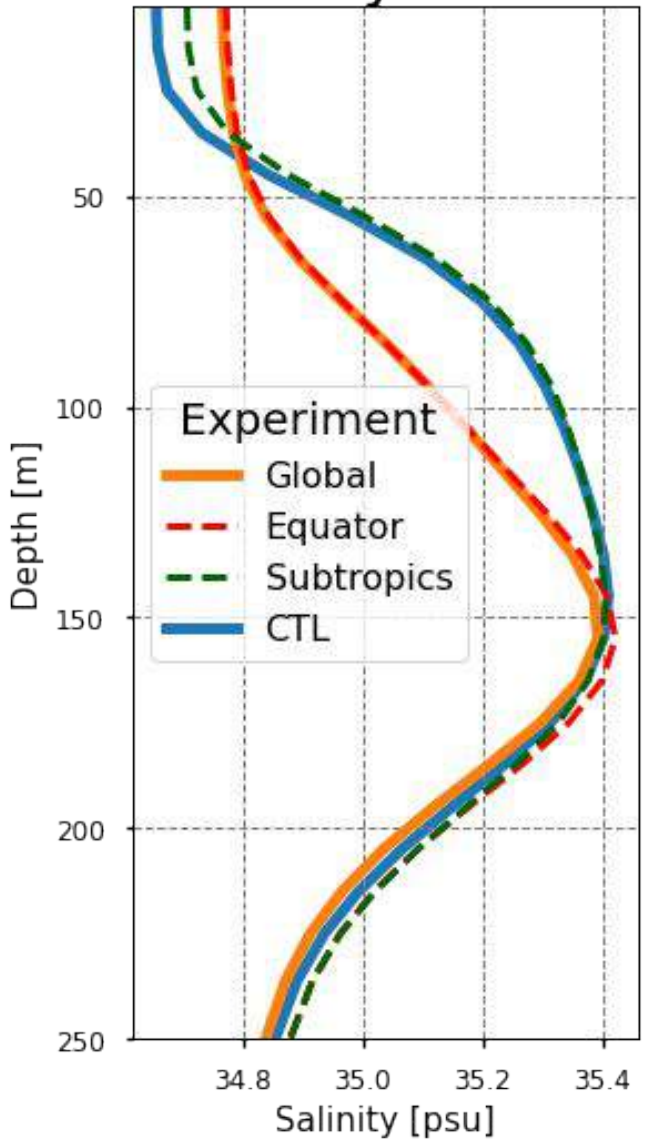
Nudging SSS to climatology between 10N – 10S weakens stratification (like fixSSS)

Subtropics



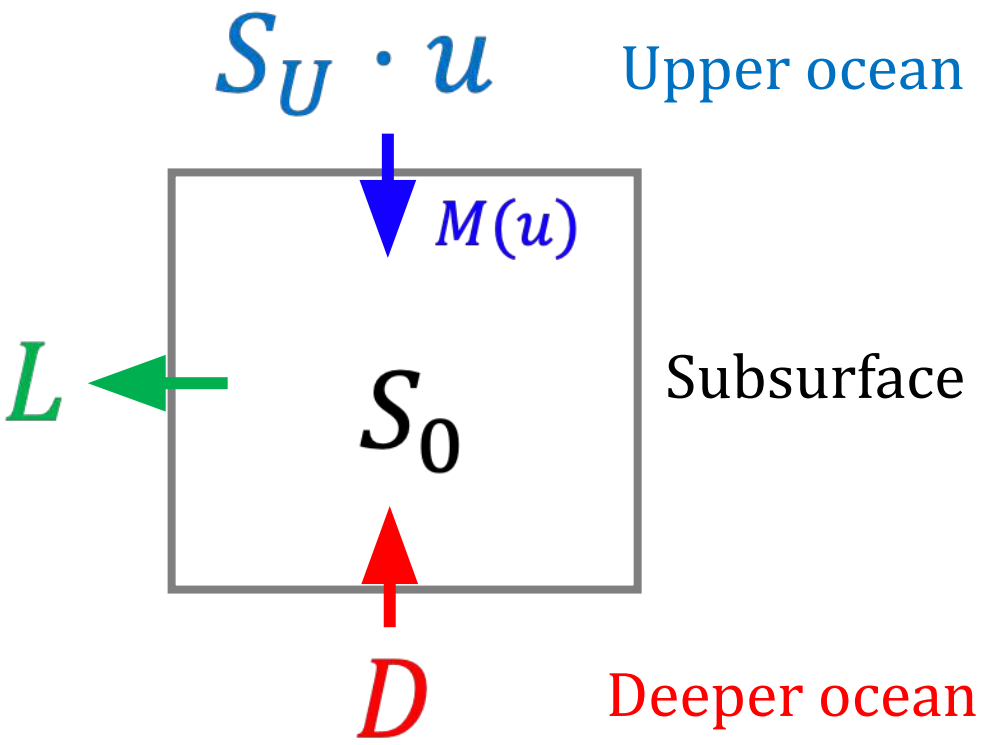
Strong stratification maintained (like CTL)

West Equatorial Pacific mean salinity stratification



Box model framework for SSS variations □ subsurface climatology change

$$M(u) = \begin{cases} 0, & u < 0 \\ u, & u \geq 0 \end{cases}$$ Heaviside function for deep mixed layer



$\zeta' = \zeta_{fixSSS} - \zeta_{CTL}$ (fixSSS minus CTL)

If there is a difference in surface salinity between CTL and fixSSS (S'_U) associated with downward mixing, what is the resulting difference in the subsurface salinity (S'_0)?

Assume fixSSS and CTL have equal mean D, L, u.

CTL: $0 = M(u)(S_{U,CTL} - S_{0,CTL}) + D + L$

fixSSS: $0 = M(u)(S_{U,fixSSS} - S_{0,fixSSS}) + D + L$

Subtract:

$$0 = M(u)(S'_U - S'_0)$$

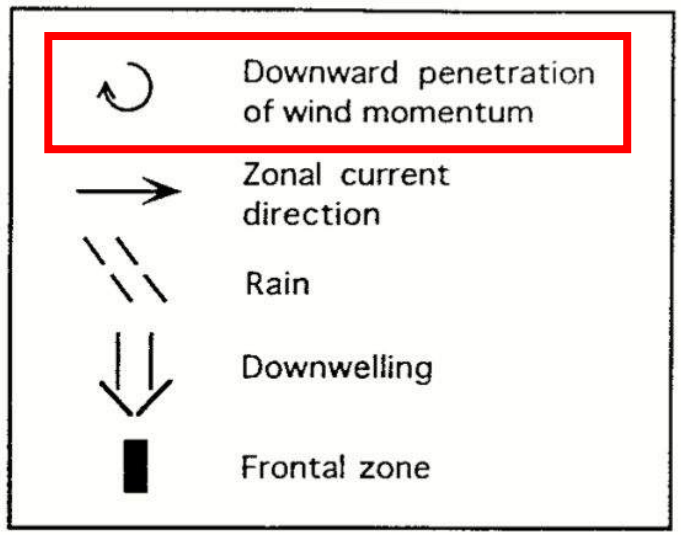
$$\therefore \boxed{S'_U = S'_0}$$

Assuming all else equal, the surface difference (during episodes of downward mixing) is **directly proportional** to the subsurface difference.

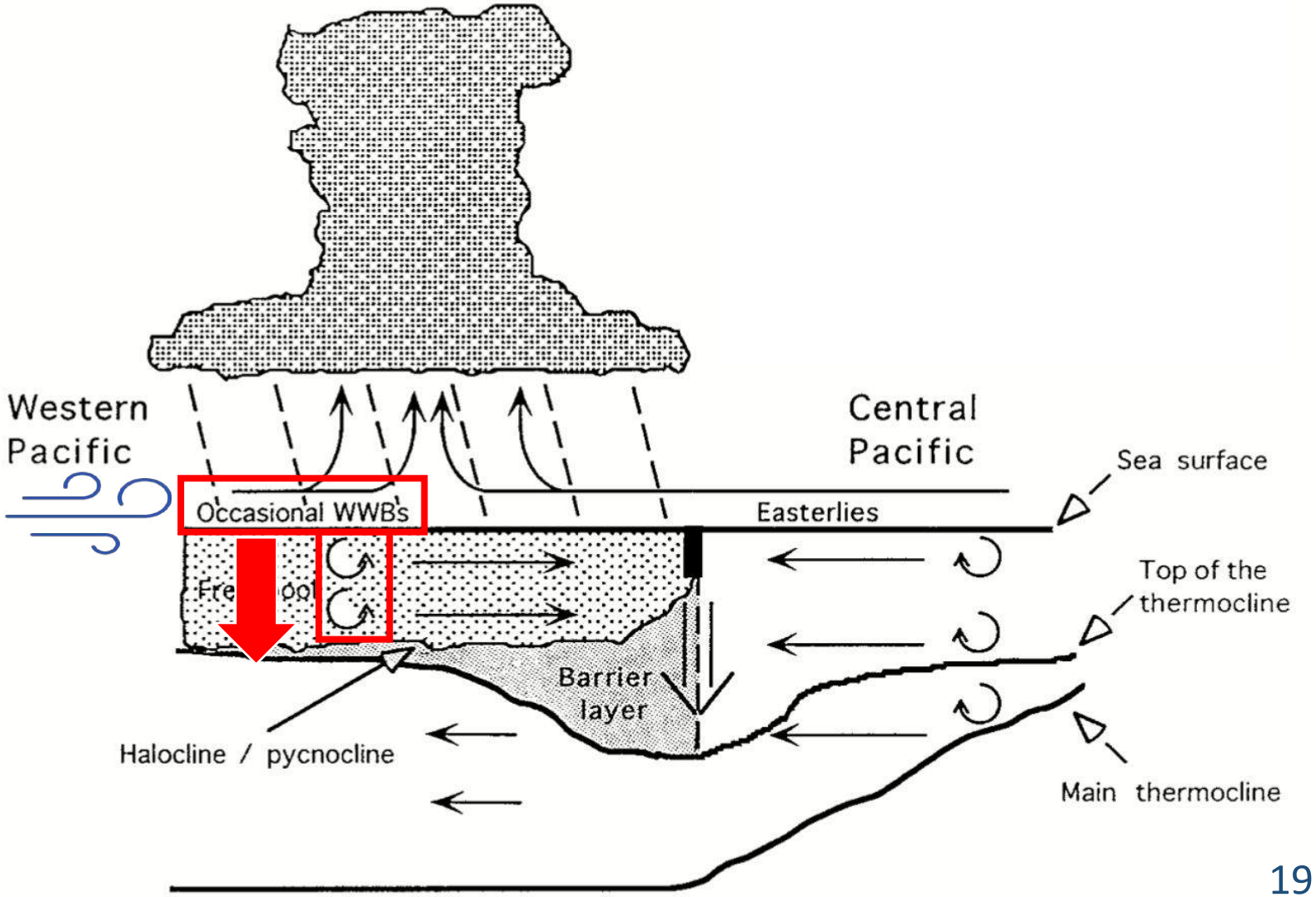
$$\sigma(S_U)' * H(u) = S'_0$$

$$= \boxed{\sim 0.3 \text{ psu}}$$

West Pacific climatological barrier layer does not only depend on the mean state



To evaluate mean-state biases, must also consider the variability



Vialard & Delecluse 1998

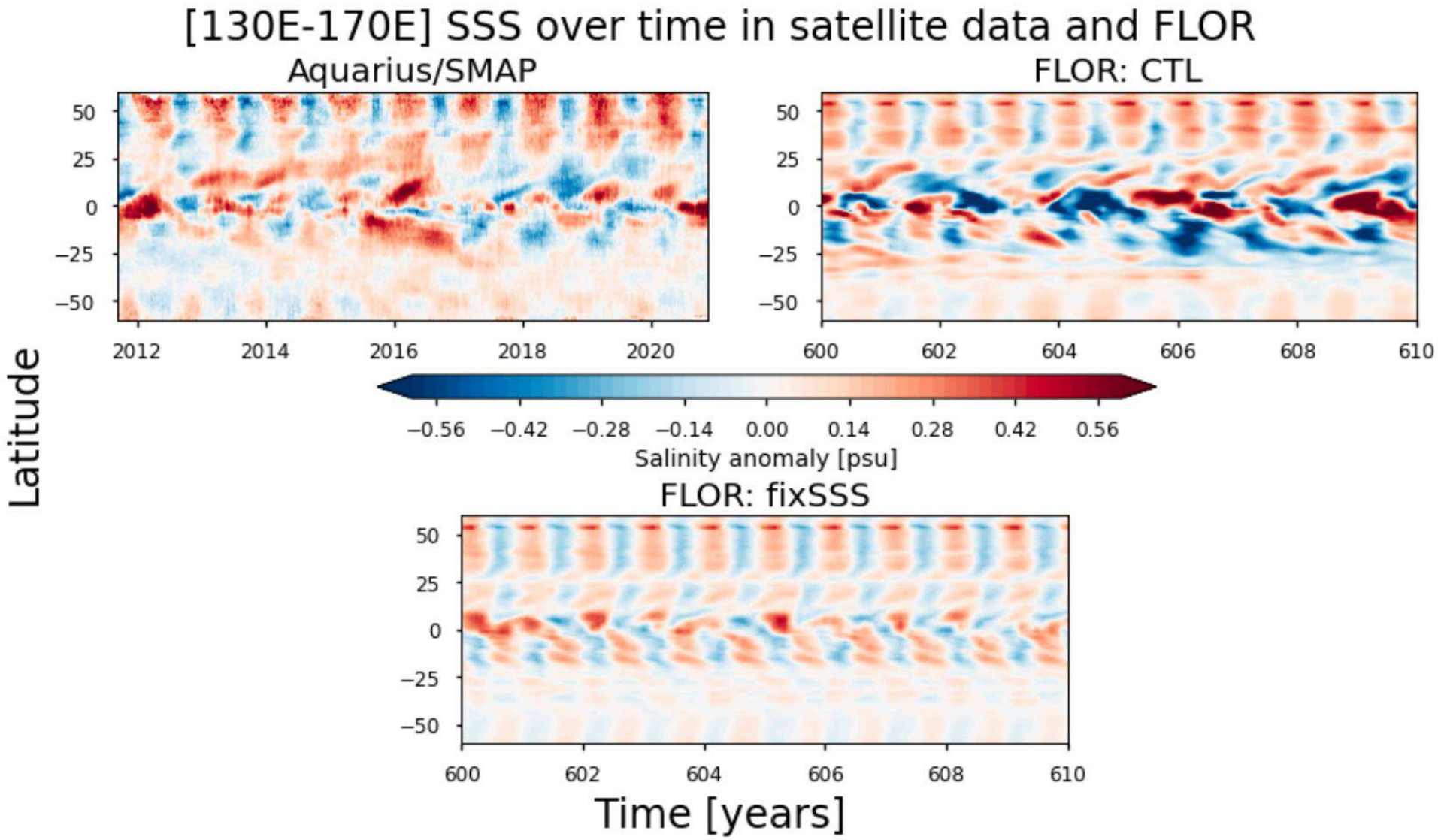
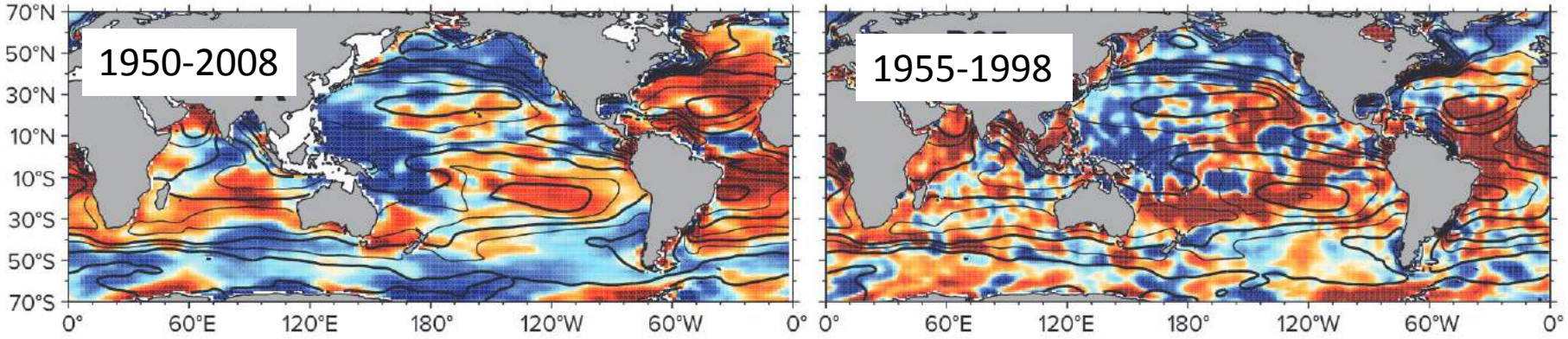


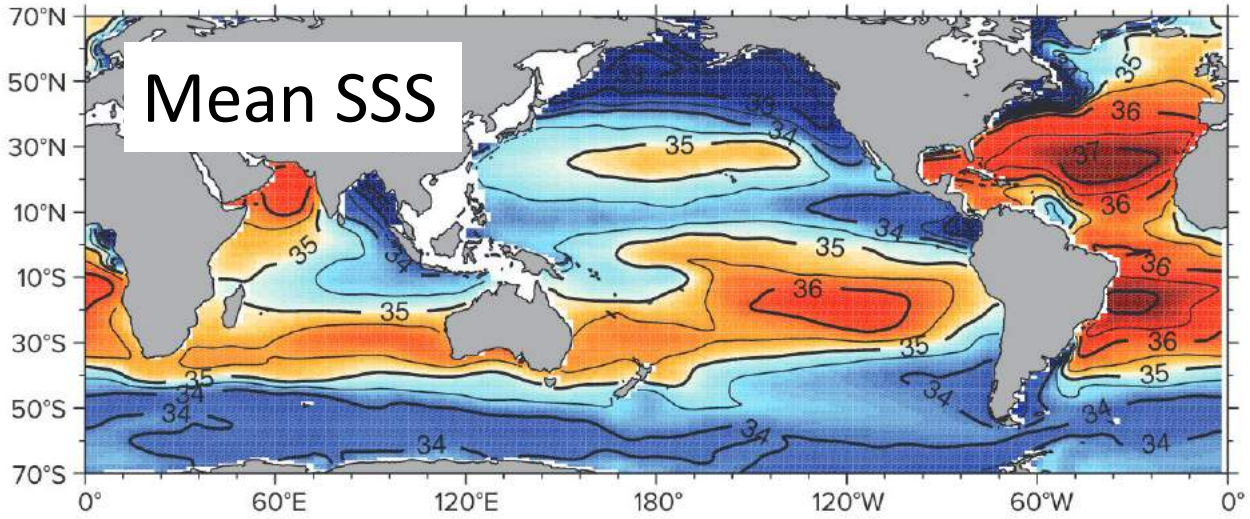
Figure 5.12: **FLOR vs. satellite SSS Hovmöller plots.** Latitude vs. time plots from Aquarius/SMAP **(upper left)**, the CTL experiment **(upper right)**, and the fixSSS experiment **(lower center)**. Hovmöller plots are averaged across (130°E-170°E). Satellite years are Common Era years, FLOR years are model years. See Methods section 4.2 for details on the satellite dataset.

Durack and Wijffels (2010)



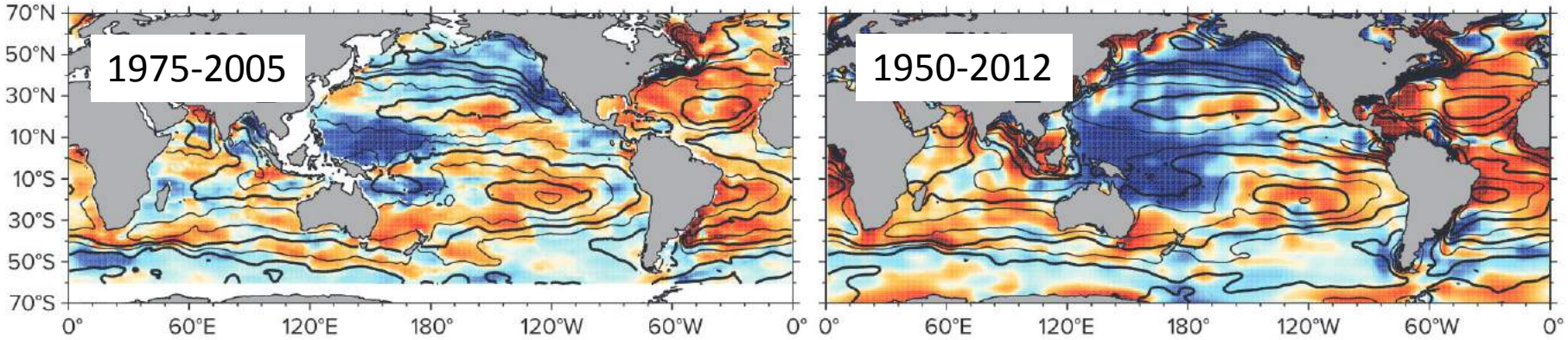
Boyer et al. (2005)

(No Argo)



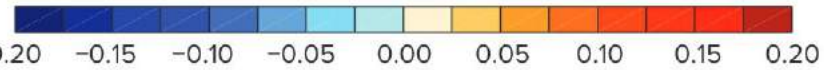
West Eq. Pacific SSS has already freshened

Hosoda et al. (2009)



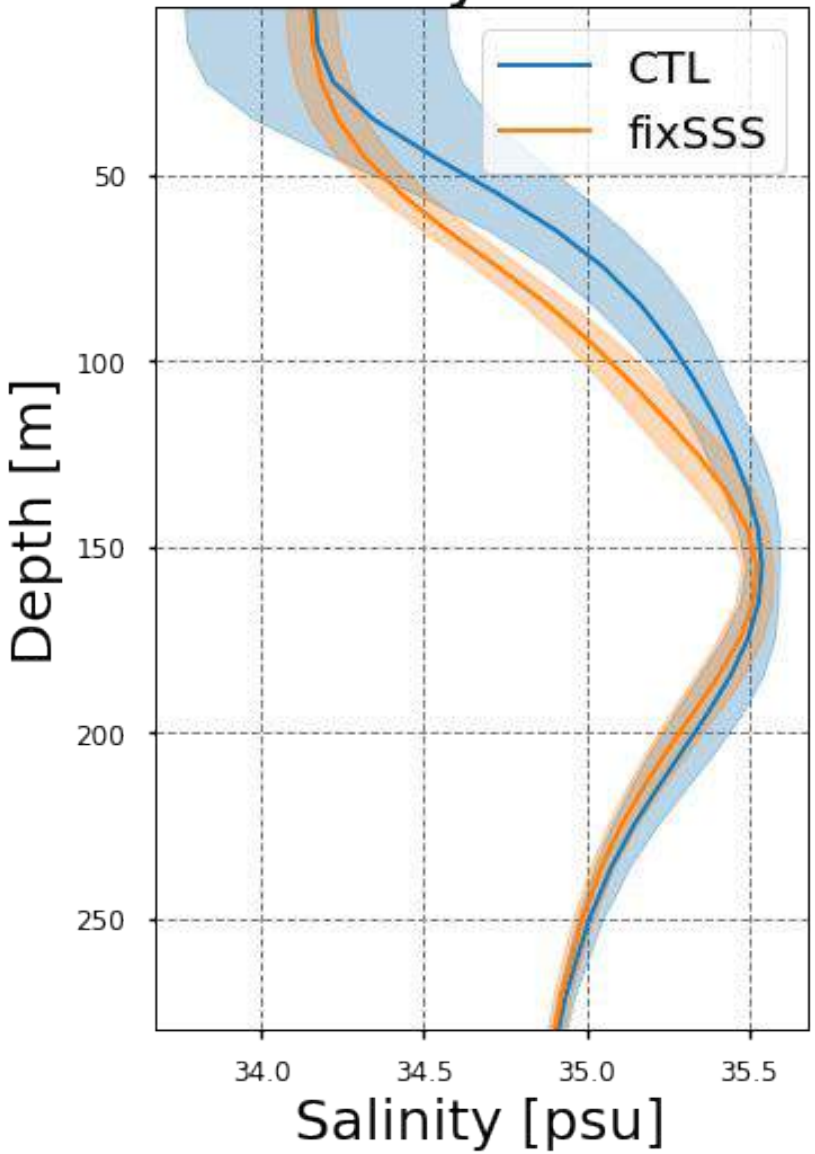
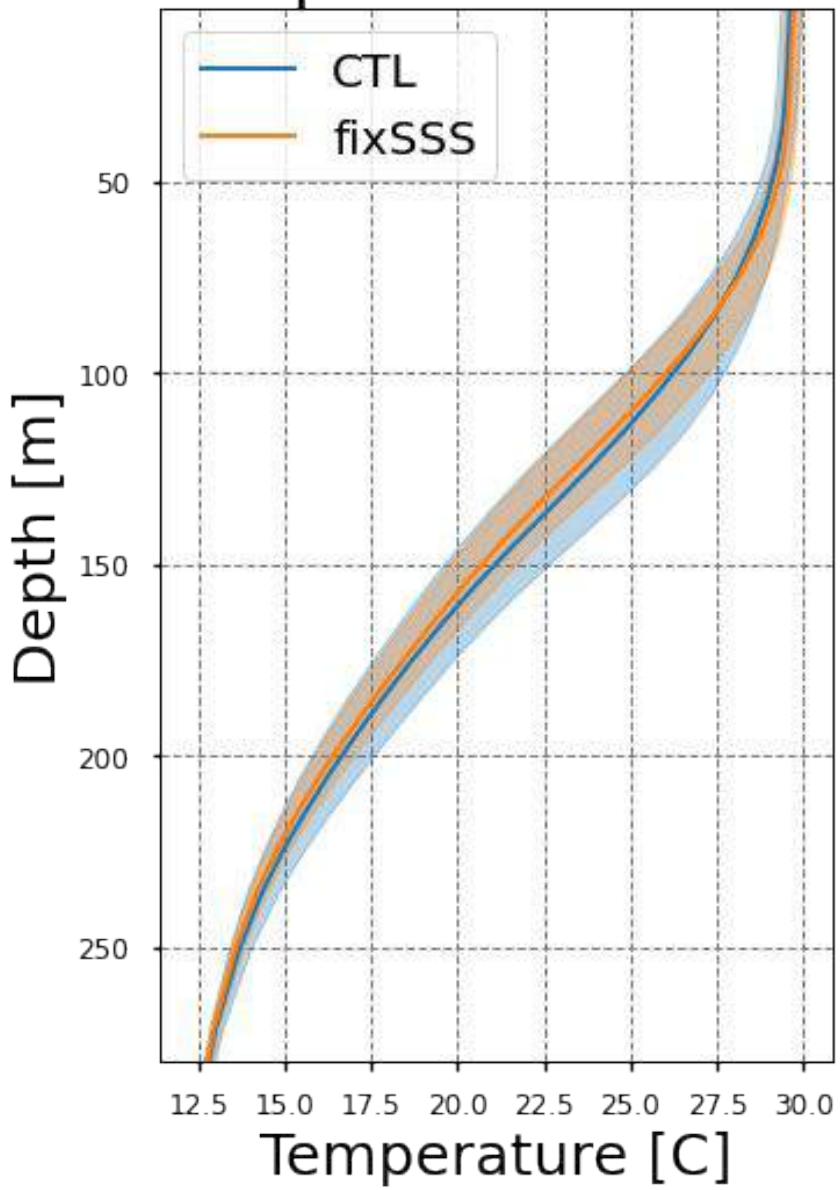
Good et al. (2014)

(Durack 2015)



Contours: climatological SSS

West equatorial Pacific
mean salinity stratification



West equatorial Pacific
mean temperature stratification