NSF | NCAR OPERATED BY UCAR

CGD Laboratory

NASA Salinity project
80NSSC20K0890

2026 Ocean Salinity Science & Technology Meeting

# Comparisons of Salinity and Temperature budgets in the Upper Ocean:

## Insights from a high-resolution model

**Justin Small (NSF-NCAR),**
**Lucas Laurindo (UM), LuAnne Thompson (UW)**


*This material is based upon work supported by the NSF National Center for Atmospheric Research, a major facility sponsored by the U.S. National Science Foundation and managed by the University Corporation for Atmospheric Research. Any opinions, findings and conclusions or recommendations expressed in this material do not necessarily reflect the views of NSF.*

# Introduction

- Previous heat and salinity budgets from the high-resolution Community Earth System Model
  - Bryan and Bachman (2015, J.P.O.), Johnson et al. (2016) – salinity budget for subtropical salinity maximum: mean and eddy contribution
  - Small et al. (2020, J. Clim.) – Global heat budget for non-seasonal variability
  - Laurindo et al. (2024, GRL) - Global salinity budget for non-seasonal variability
  - These papers analyzed month-to-month variability and sensitivity to spatial scale

- This update:
  - A full comparison of salinity budgets with upper-ocean heat budgets
  - I gave a telecon presentation in  Feb. 2025 on month-to-month variability
  - This talk also includes interannual and decadal timescales
  - And salinity vs salt content results

# Background on heat vs salinity budgets

- For heat budget, SST anomalies are damped by air-sea fluxes,
  - Latent, sensible and upwelling longwave heat fluxes depend on SST
  - Typical values of 5-30 Wm-2 per deg. C (typically a negative feedback)
  - limiting the variance and persistence
  - Frankignoul and Hasselmann 1977, Barsugli and Battisti 1998, Bishop et al. 2017, Laurindo et al. 2022 , Siqueira et al. 2024
  - Total damping is due to this surface flux feedback plus entrainment and mixing processes.

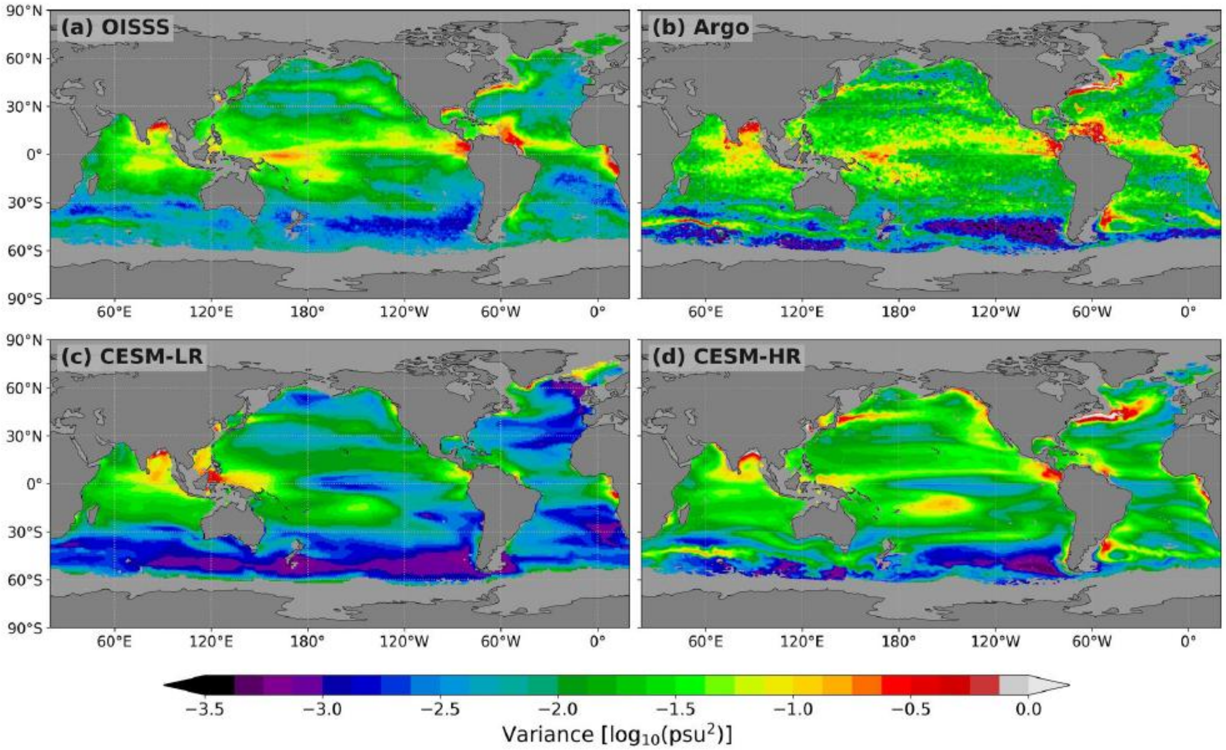
- For salinity budget, no feedback of SSS to air-sea fluxes
  - Anomalies can persist longer (Frankignoul et al. 1998, Mignot and Frankignoul 2003)
  - Damping is instead due to entrainment and mixing processes.
  - See Lisan Yu's talk

- Patrizio and Thompson (2022) argue that ocean processes damp the heat budget at time-scales> 4 years
  - Do ocean processes enhance or damp variability of *salinity* at longer timescales?

# Community Earth System Model (CESM)

- CESM is fully coupled 😎
  - Uses version 1.3 of CESM (Hurrell et al. 2013)
- Ocean model POP uses virtual salt flux 😟
  - Linear free surface allows for SSH variations (Smith and Gent 2010)
  - For the top cell, tendency of salt content given by d/dt(S(1+SSH/dz))
- CESM-HR is **H**igh-**R**esolution 😎
  - 1/10th deg. ocean and ice, 1/4deg. atmosphere and land.
  - Ocean mesoscale eddies are mostly resolved (but not submeso) (Small et al. 2014, Chang et al. 2020)
  - Synoptic atmosphere variability is well captured: tropical cyclone-permitting
- *CESM version 3 will have real freshwater flux* 😎
  - *MOM6 allows for real surface fluxes (Adcroft, Halberg, Griffies)*
  - *Similar to ECCO in this respect (Forget et al. 2015)*
  - *High-resolution version of CESM3 is in progress (Marques, Castruccio, Barr)*
  - *So we use CESM1.3 for the moment*

# Salinity variance from coupled model and observations




Above: variance of monthly non-seasonal sea-surface salinity (SSS) from observations and CESM1. Note log scale.
From Laurindo et al. (2024, GRL).

# Temperature and salinity budgets

TEMPERATURE->converted to heat

$$\rho_0 c_p \int_{-H}^{0} \frac{\partial T}{\partial t}\partial z = \rho_0 c_p \int_{-H}^{0} (-\nabla \cdot uT + HMIX)\partial z + Q - \rho_0 c_p \kappa \left(\frac{\partial T}{\partial z} - \Gamma\right)_{-H} - Q_{p,-H}$$

*Tendency* *Advection* *Hmix* *Sfc_Flux* *Vmix* *Pen. SW*

SALINITY

$$\int_{-H}^{0} \frac{\partial S}{\partial t}\partial z = \int_{-H}^{0} (-u \cdot \nabla S + HMIX)\partial z + S_{ref}(E - P) - \kappa \left(\frac{\partial S}{\partial z} - \Gamma\right)_{-H}$$

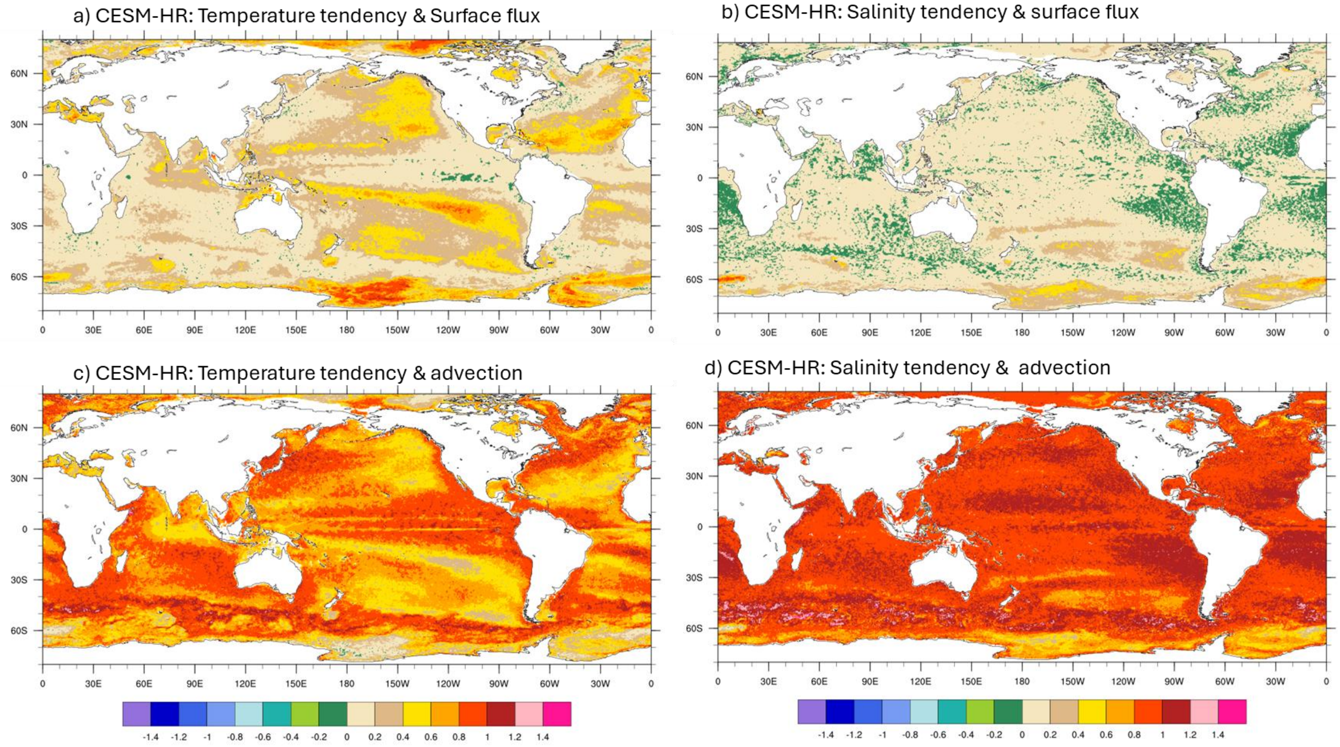
**+R**

*Tendency* *Advection* *Hmix* *Sfc_Flux* *Vmix*

- Here temperature and salinity budgets use the advective form for transport
  - Budgets are derived from daily 3D variables, mixing is a residual
- Missing terms:
  - HMIX is a generally small mixing term in CESM-HR
  - Q_p is penetrative shortwave
  - Qflux (sea-ice term) is in residual for salinity
- Heat and salt content budgets have also been analyzed, using the flux form for transport.
  - Budgets are ~closed (30 year segment) or mixing is a residual (100 year segment)

# Salinity vs temperature:

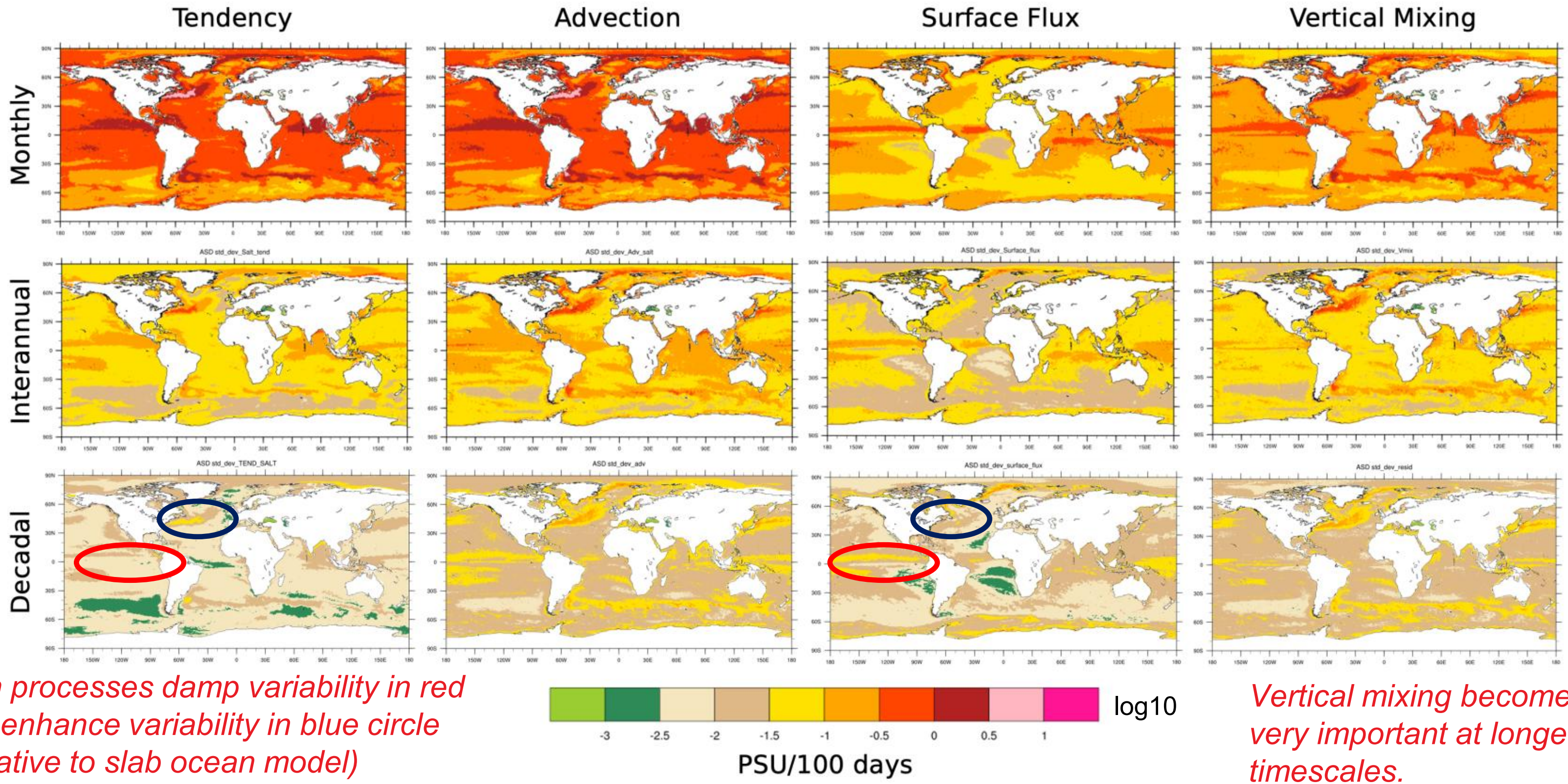
## surface fluxes have a smaller influence on the salinity budget than on the temperature budget




Budget regressions for temperature (left) and salinity (right). Monthly non-seasonal variability to 50m depth. The tendency is regressed onto surface fluxes (top) and advection (bottom).

# Timescale dependence (1) : salt content

## dominance of advection reduces for longer timescales



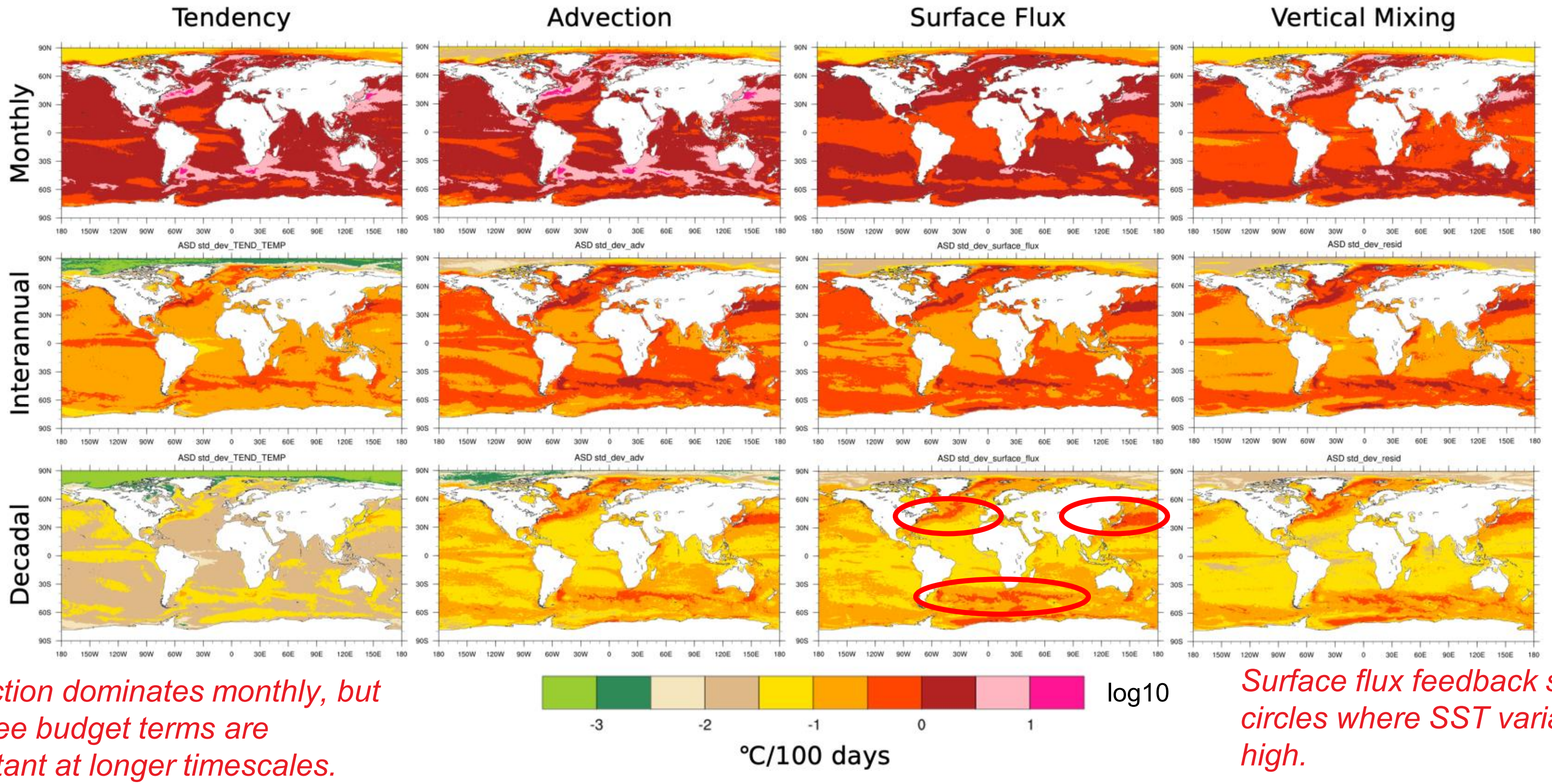

*Ocean processes damp variability in red circle: enhance variability in blue circle (all relative to slab ocean model)*

*Vertical mixing becomes very important at longer timescales.*

Standard deviation of salt content budget terms integrated to 50 m for monthly, interannual, and decadal timescales, from the MesaClip CESM climate simulations. The units are PSU/100 days, and the color bar is on a log scale .

# Timescale dependence (2) : Temperature

## surface flux playing important role at longer timescales

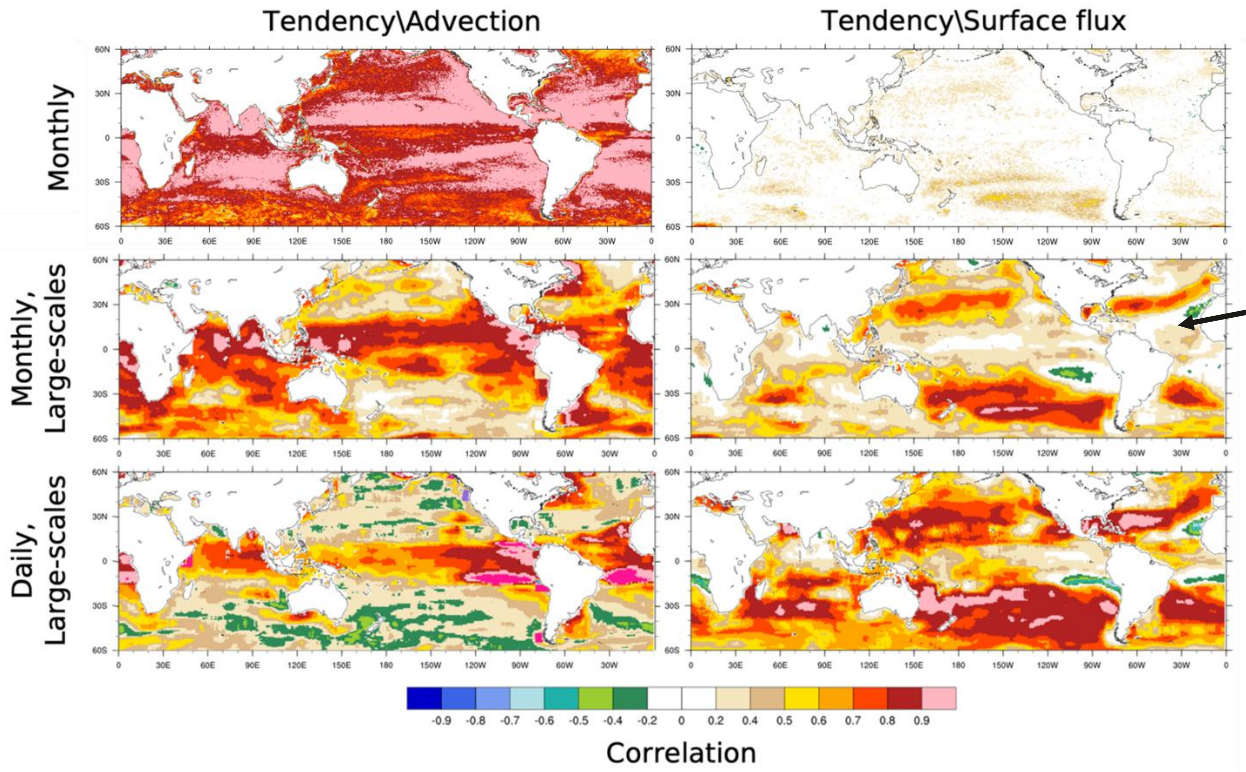



*Advection dominates monthly, but all three budget terms are important at longer timescales.*

*Surface flux feedback seen in red circles where SST variability is high.*

Standard deviation of temperature budget terms integrated to 50 m for monthly, interannual, and decadal timescales, from the MesaClip CESM climate simulations. The units are °C/100 days, and the color bar is on a log scale .

# Spatial-scale dependence:
## surface fluxes are more important at larger scales



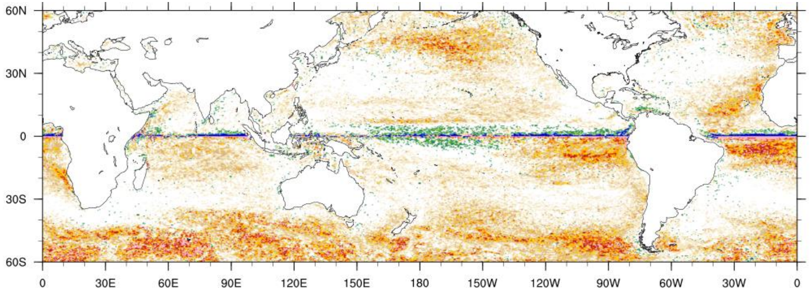

Similar to ECCO results, Vinogradova and Ponte 2013

Salinity. Correlation of tendency with advection (left) and surface flux (right).
Top: Monthly non-seasonal variability. Middle: large-scale monthly variability (>10deg. scale). Bottom: high-frequency (< 14 day), large scale.

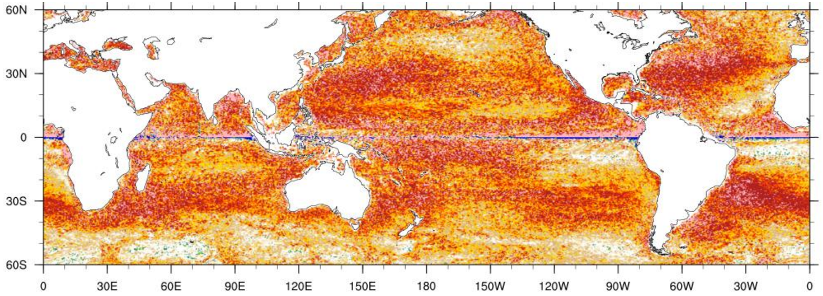
# Advection processes:

## Geostrophic advection important on monthly timescales: Ekman important for larger time and space scales

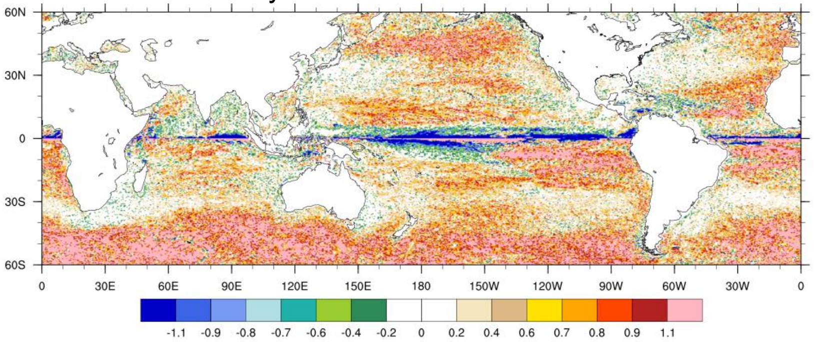
Monthly Salinity: Horizontal advection and Ekman



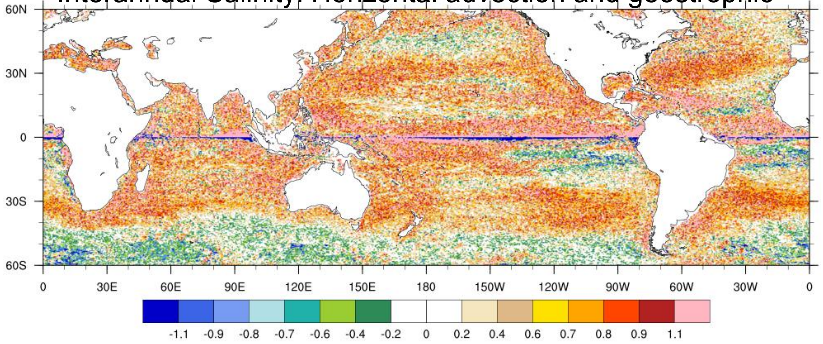

Monthly Salinity: Horizontal advection and geostrophic




Interannual Salinity: Horizontal advection and Ekman




Interannual Salinity: Horizontal advection and geostrophic

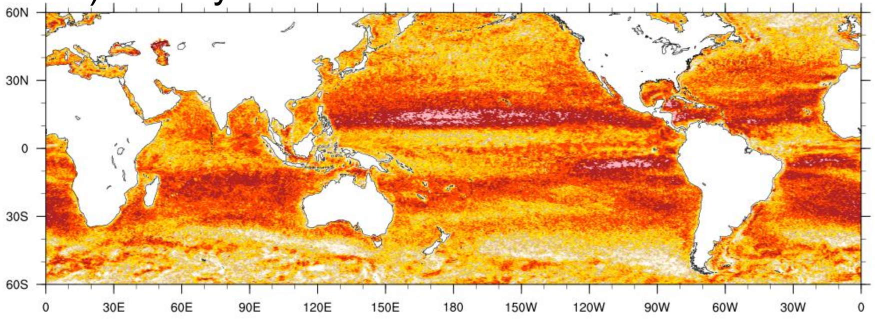



Salinity: decomposition of horizontal advection into Ekman and geostrophic (see Yu 2011, 2023). Plots show the regression of horizontal advection onto Ekman (left) and geostrophic (right). Monthly (top) and Interannual (bottom). Similar results using 3D advection. Ekman dominates in Southern Ocean, North Pacific etc., Geostrophy dominates in Tropics/subtropics and eddying regions.

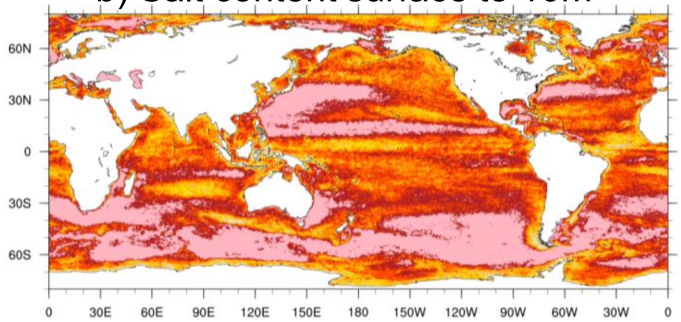
# Salinity (S) vs salt content (S(1+SSH/dz) in top cell):

## SSH is important even for 50m integrations

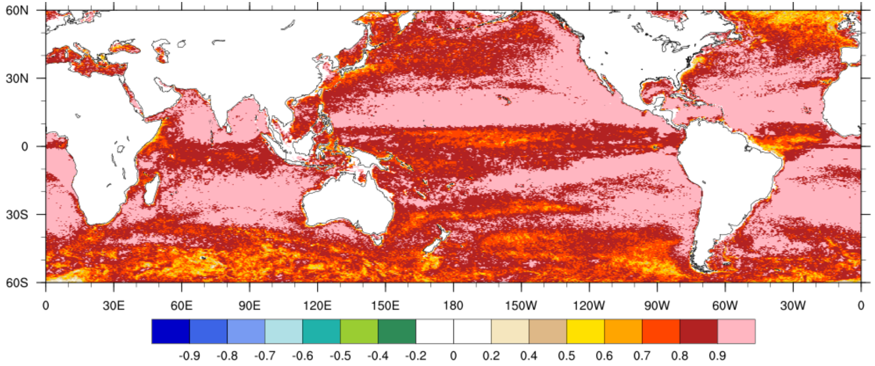
a) Salinity 0-10m



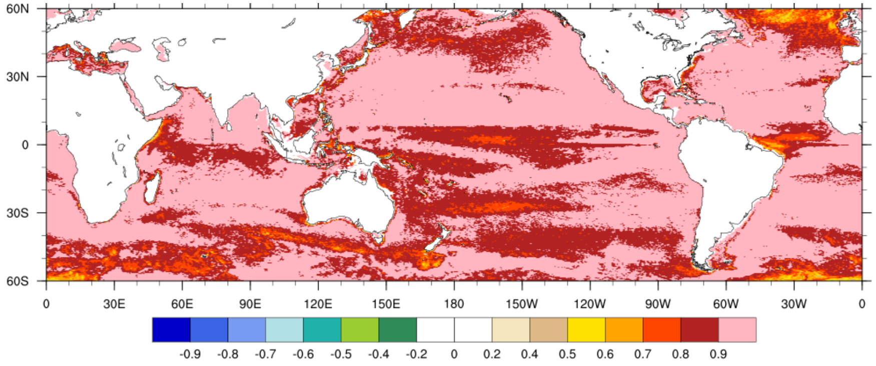

b) Salt content surface to 10m




c) Salinity 0-50m




d) Salt content surface to 50m




Correlations of advection with tendency. Sensitivity to depth of integration, and salinity vs salt content. Unfiltered monthly data. Left column: salinity budget, Right column: salt content budget.

# Summary

- Salinity vs temperature:
  - surface fluxes have a smaller influence on the salinity budget than temperature
  - Due to lack of surface flux feedback
- Spatial-scale dependence:
  - surface fluxes more important at larger scales
- Advection processes:
  - Geostrophic advection important on monthly timescales: Ekman important for larger time and space scales
- Salinity (S) vs salt content (S(1+SSH/dz) in top cell):
  - SSH is important even for 50m integrations
- Timescale dependence (1) : salt content
  - dominance of advection reduces for longer timescales
  - Vertical mixing becomes important
- Timescale dependence (2) : Temperature
  - surface flux playing important role at longer timescales
  - surface flux feedback

# Next Steps

- Completion of a paper on the budgets (this talk)
- Interpretation of budget analysis with stochastic model for mixed-layer salinity
  - Lucas Laurindo, Luanne Thompson and Justin Small
  - Following Laurindo et al. 2022 (JGR: stochastic model for temperature combined with CESM-HR results)

# Air-sea feedback (Frankignoul et al. 1998)

$$\alpha = \frac{1}{n}\sum_{i=1}^{n} \frac{\overline{SST'(t)Q'(t+i\delta t)}}{\overline{SST'(t)SST'(t+i\delta t)}} \qquad (1)$$

where we sum over the lag of Q (surface heat flux) relative to SST, with n=3 and δt=1 month (Hausmann et al. 2016).

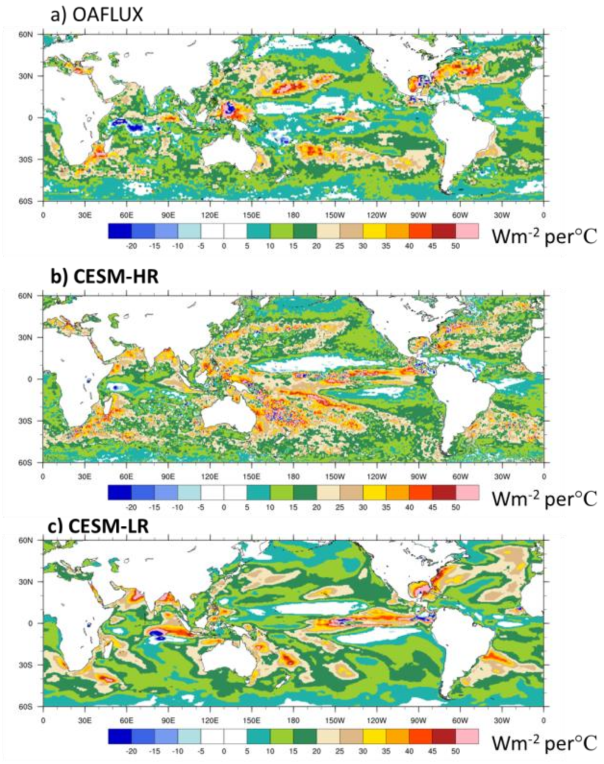



Fig. 1 The Air-Sea Feedback parameter, defined by (1) and using latent heat flux only. a) From OAFLUX, b) from CESM-HR, c) from CESM-LR.