NSF NCAR-Wyoming Supercomputer Center

NASA Salinity project 80NSSC20K0890

Comparisons of heat and salinity budgets in the upper ocean

Subtitle:
An update, and implications for hydrological cycle estimates.

R. Justin Small, NSF-NCAR,
Lucas Laurindo, Uni. Miami, LuAnne Thompson, UW

Thanks to Frank Bryan, Keith Lindsay, NSF-NCAR
Ivana Cerovecki, Scripps,
Dan Whitt, NASA Ames, Tony Lee, NASA JPL

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Background on heat vs salinity budgets

- For heat budget, SST small-scale anomalies are damped by air-sea fluxes,
  - limiting the variance and persistence
  - Frankignoul and Hasselmann 1977, Barsugli and Battisti 1998, Bishop et al. 2017, Laurindo et al. 2022

- For salinity budget, no feedback of SSS to air-sea fluxes
  - Anomalies can persist longer (Frankignoul et al. 1998)
  - Damping is due to entrainment and mixing processes.

Background on salinity budgets and the hydrological cycle (1)

Fifty-Year Trends in Global Ocean Salinities and Their Relationship to Broad-Scale Warming

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J. Clim. 2010, and Science, 2012.

Large, robust, and spatially coherent multidecadal linear trends in salinity to 2000-dbar depth are found. Salinity increases at the sea surface are found in evaporation-dominated regions and freshening in precipitation-dominated regions, with the spatial pattern of change strongly resembling that of the mean salinity field, consistent with an amplification of the global hydrological cycle. Subsurface salinity changes on pressure

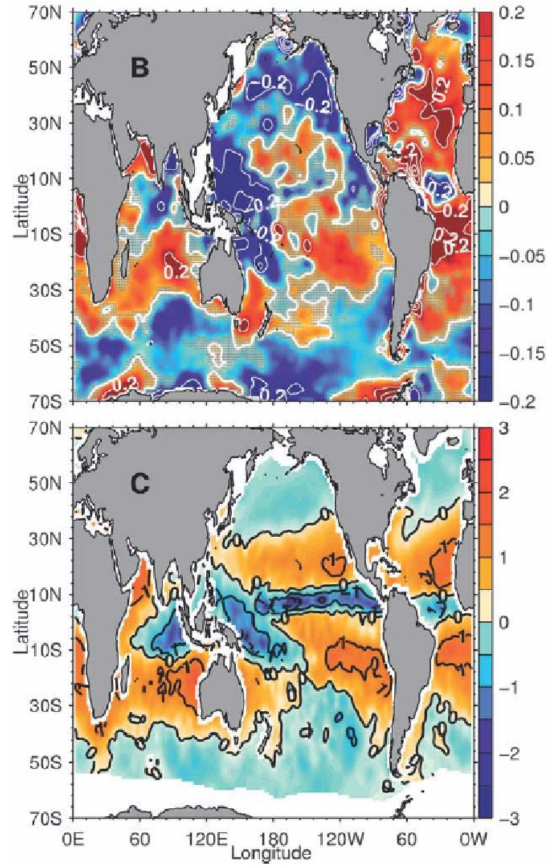

FIG. 5. (a) The 1950–2000 climatological-mean surface salinity. Contours every 0.5 pss are plotted in black. (b) The 50-yr linear surface salinity trend [pss (50 yr)$^{-1}$]. Contours every 0.2 are plotted in white. Regions where the resolved linear trend is not significant at the 99% confidence level are stippled in gray. (c) Ocean–atmosphere freshwater flux (m^3 yr^{-1}) averaged over 1980–93 (Josey et al. 1998). Contours are every 1 m^3 yr^{-1} in black.

See also:

1 DECEMBER 2020 CHENG ET AL. 10357

Improved Estimates of Changes in Upper Ocean Salinity and the Hydrological Cycle

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Background on salinity budgets and the hydrological cycle (2)

Clarifying the link between surface salinity and freshwater fluxes on monthly to interannual time scales

Nadya T. Vinogradova[1] and Rui M. Ponte[1]

J. Geophys. Res. 2013, see also Ponte and Vinogradova 2016

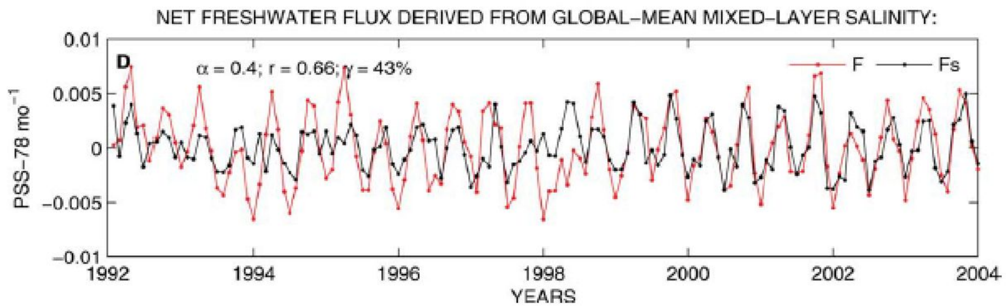

Figure 6. (a) Global-mean budget of the mixed-layer salinity showing total changes in salinity averaged over the global ocean ($\overline{\mathcal{S}'}$) and its tendency due to surface fluxes ($\overline{\mathcal{F}}$) and ocean fluxes ($\overline{\mathcal{O}}$). (b) Tendencies in global-mean mixed-layer salinity due to advection ($\mathcal{A}$), mixing ($\mathcal{M}$), and the entrainment of salt ($\mathcal{E}$). (c) Mean annual cycle of the global-average budget terms. (d) Salinity-derived values of $\overline{\mathcal{F}_S}$ inferred using linear model (black) and the observed (ECCO) values of the flux $\overline{\mathcal{F}}$ (red) with the mean annual cycle removed.

6. Conclusions

[39] Based on the analyses of a 13 year ECCO state estimate, changes in surface salinity reflect a complicated balance between atmospheric and oceanic processes across a range of time scales from months to years, with both $\mathcal{F}$ and $\mathcal{O}$ contributing to variability in $\mathcal{S}'$. Depending on region, all components of $\mathcal{O}$ (mixing, advection, entrainment) can give rise to variability in $\mathcal{S}'$, although advective fluxes are typically the largest (Figures 3a, 3d, and 3g). Given the non-negligible variability in $\mathcal{O}$, a one-to-one correspondence between local $\mathcal{S}'$ and $\mathcal{F}$ cannot be expected on monthly to interannual time scales. Because of the general poor correlation between $\mathcal{O}$ and $\mathcal{F}$, inferring $\mathcal{F}$ from $\mathcal{S}'$ values using simple linear regression models did not lead to much success: typically only a small part of the variability in $\mathcal{F}$ could be recovered at scales of ~100 km and larger, except in a few small regions (e.g., subtropical South Pacific gyre) and only at annual and shorter time scales.

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Approach

- Salinity, salt content, and heat content budgets
  - Salt content budget (depends on SSH) shows some interesting differences with salinity budgets (next slide)
- Eulerian Method
  - Grid point regressions***
- Scales of variability
  - distinguish different spatial scales
  - To help reconcile data taken at a single point, and data from a larger volume.
- Focus on non-seasonal monthly variability
  - Long-term mean, seasonal cycle and trend removed.
  - Regressions of tracer tendency on budget terms.
  - Values near 1 imply the budget term dominates the tendency.
- High-frequency (sub-monthly) variability

***Care needs to be taken with the salinity transport term as individual components of transport convergence are ill-defined in regular form (e.g. zonal, meridional or vertical) – see Tony Lee et al. 2004, JPO. But full 3D transport convergence is well-defined . Grid point advection is well defined.

Salt content budget and salinity budget in high-resolution CESM-HR

- Salt content budget

$$\frac{\partial S(1+\zeta)}{\partial t} = (-\nabla \cdot uS + HMIX) + \frac{\partial}{\partial z}\left\{\kappa\left(\frac{\partial S}{\partial z} - \Gamma\right)\right\}$$

$$\zeta = \frac{SSH}{dz}\ for\ first\ layer$$

$$\zeta = 0\ for\ other\ layers$$

Integrate to a depth H

$$\int_{-H}^{0} \frac{\partial S(1+\zeta)}{\partial t}\partial z = \int_{-H}^{0}(-\nabla \cdot uS + HMIX)\partial z + S_{ref}(E-P) - \kappa\left(\frac{\partial S}{\partial z} - \Gamma\right)_{-H}$$

  - HMIX is a biharmonic function in CESM-HR-POP
  - Note, in POP surface freshwater flux is contained as a virtual salt flux (unlike ECCO, MOM6 where it is real volume flux)

- Salinity budget

rewrite flux transport as advection noting the equations at right, as a consequence of which the ζ term drops out (see Piecuch 2017 for this method)

$$\frac{\partial S}{\partial t} = (-u \cdot \nabla S + HMIX) + \frac{\partial}{\partial z}\left\{\kappa\left(\frac{\partial S}{\partial z} - \Gamma\right)\right\}$$

$$\nabla \cdot uS = u \cdot \nabla S + S\nabla \cdot u$$

$$-\nabla \cdot u = \frac{\partial SSH}{\partial t}$$

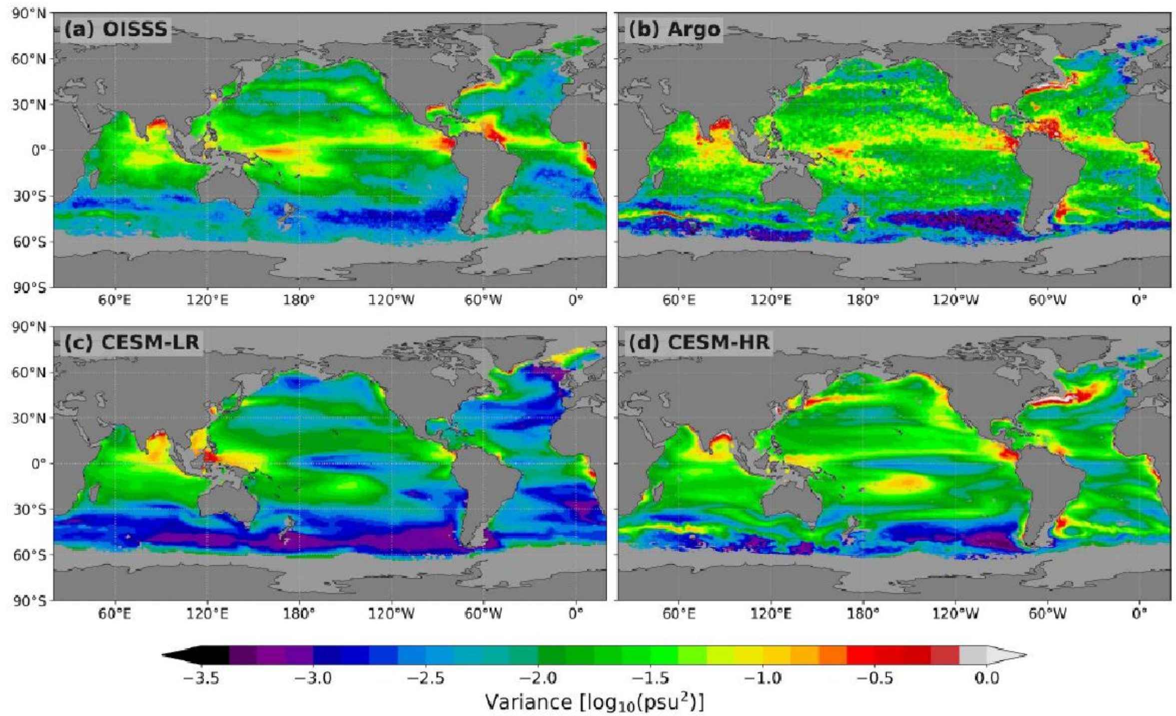
Integrate to a depth H

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

  - Note that here the ζ term has been removed from the tendency, and the flux form of transport replaced with the advective form

Model: Community Earth System Model (at high-resolution: CESM-HR)

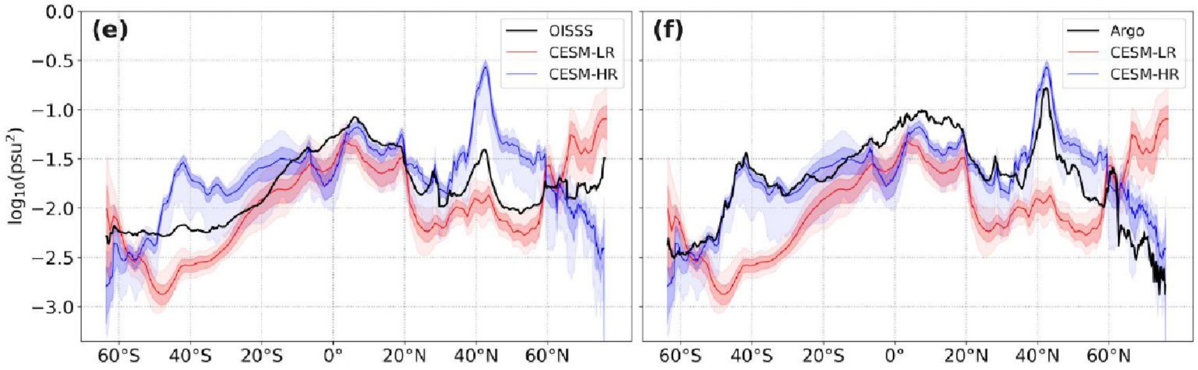
CESM-HR is a fully coupled model with 1/10th deg. ocean and ice, 1/4deg. atmosphere and land.



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

Model: Community Earth System Model (at high-resolution: CESM-HR)

CESM-HR is a fully coupled model with 1/10th deg. ocean and ice, 1/4deg. atmosphere and land.

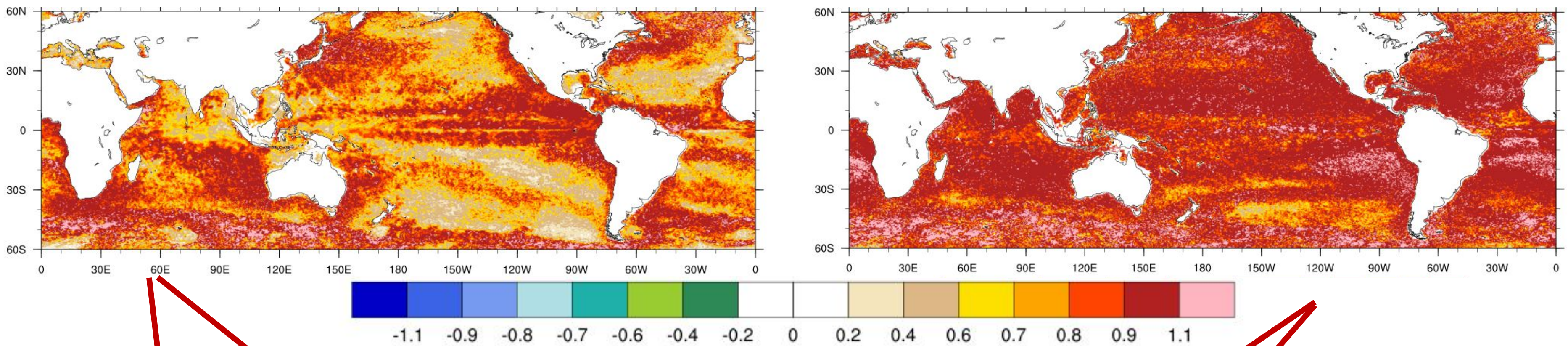


Above: zonal-mean variance of monthly sea-surface salinity (SSS) from observations and CESM.
Note log scale.
From Laurindo et al. (2024, GRL).

Comparison of heat and salinity budget regressions monthly, non-seasonal, to 50m depth: grid-point analysis (1)

CESM-HR: Tendency & Ocean heat flux convergence

CESM-HR: Tendency & salinity advection



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

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

Result: salinity budget is much more dominated by (3D) advection, or flux convergence, than the heat budget.

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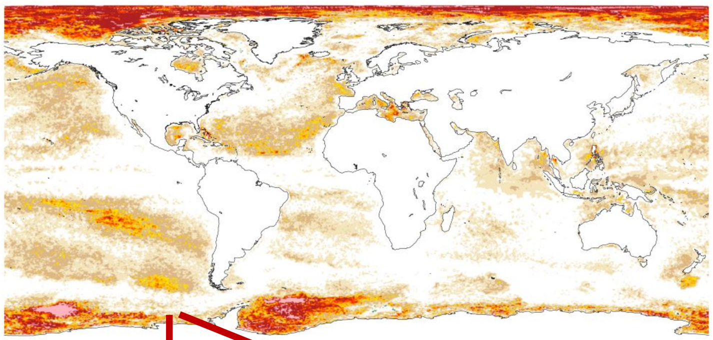
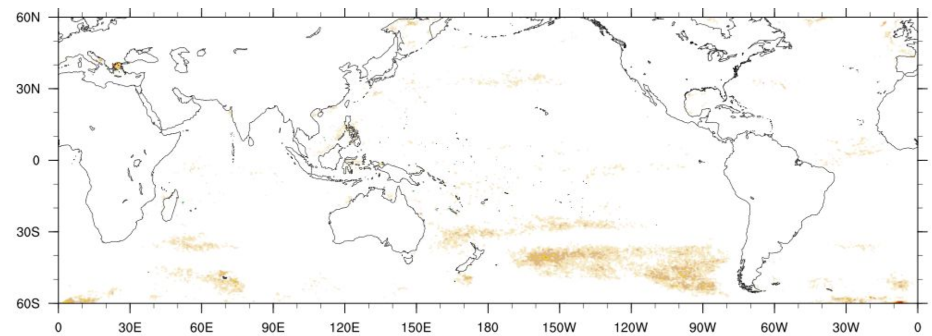
Small, R. J., F. O. Bryan, S. P. Bishop, S. Larson and R. A. Tomas, 2020. What drives upper ocean temperature variability in coupled climate models and observations? J. Climate, 33, 577-596. https://journals-ametsoc-org.cuucar.idm.oclc.org/doi/full/10.1175/JCLI-D-19-0295.1

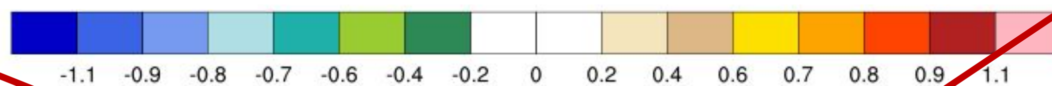
Comparison of heat and salinity budget regressions monthly, non-seasonal, to 50m depth: grid-point analysis (2)

CESM-HR: Tendency & Surface heat flux



CESM-HR: Tendency & surface freshwater flux





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

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

Result: influence of surface flux in salinity budget is much weaker than in the heat budget.

So, this seems to refute any suggestion to estimate hydrological cycle from salinity tendency… (but read on)

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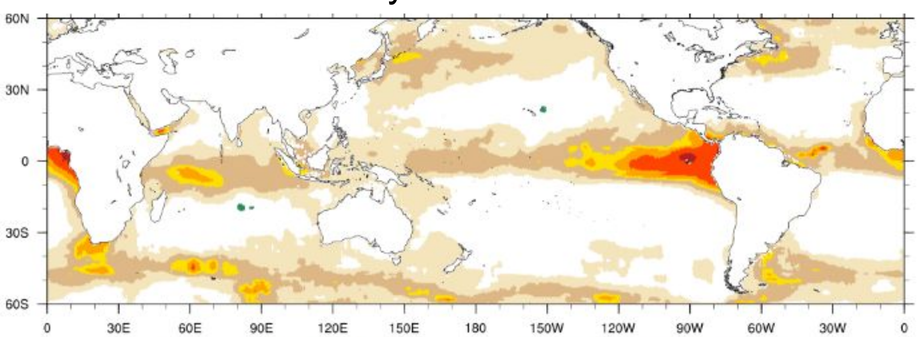
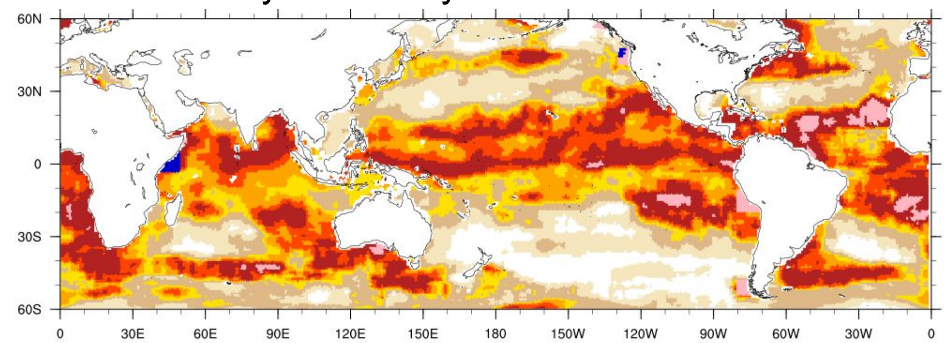
Small, R. J., F. O. Bryan, S. P. Bishop, S. Larson and R. A. Tomas, 2020. What drives upper ocean temperature variability in coupled climate models and observations? J. Climate, 33, 577-596. https://journals-ametsoc-org.cuucar.idm.oclc.org/doi/full/10.1175/JCLI-D-19-0295.1

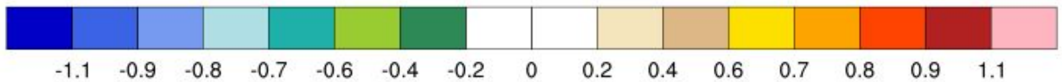
Sensitivity to spatial scale: heat and salinity budgets monthly, non-seasonal, to 50m depth, smoothed over 10deg. box. (1)

Heat: Tendency and 3D advection



Salinity: Tendency and 3D advection





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

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

Results: on large spatial scales, advection plays a lesser role than for grid-point analysis.

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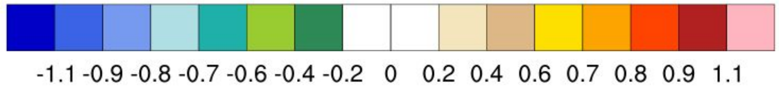
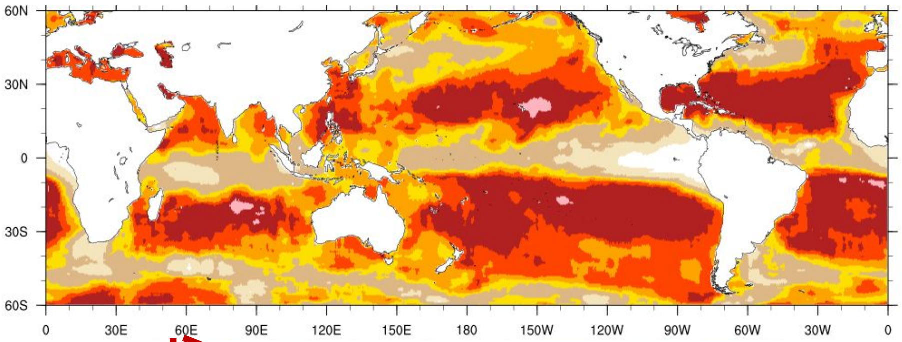
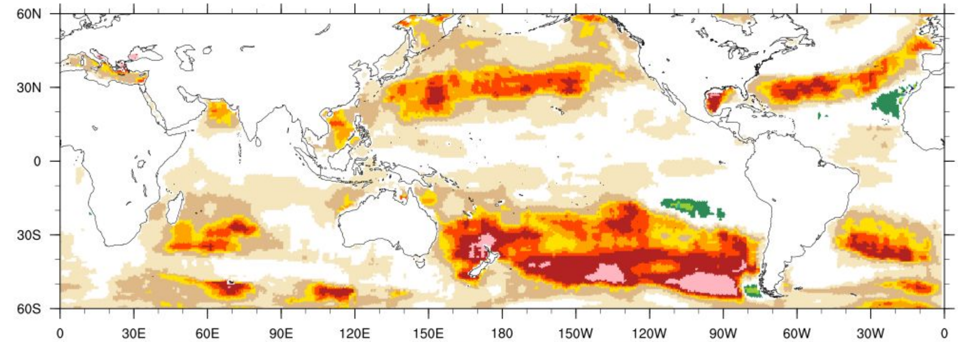


Sensitivity to spatial scale: heat and salinity budgets monthly, non-seasonal, to 50m depth, smoothed over 10deg. box. (2)

Heat: Tendency and surface flux &mixing



Salinity: Tendency and surface flux



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

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

Results: on large spatial scales, surface fluxes play an important role, moreso for heat budget.

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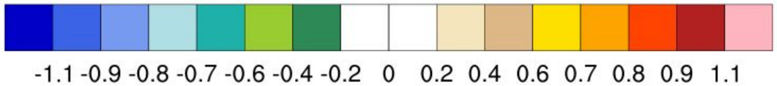
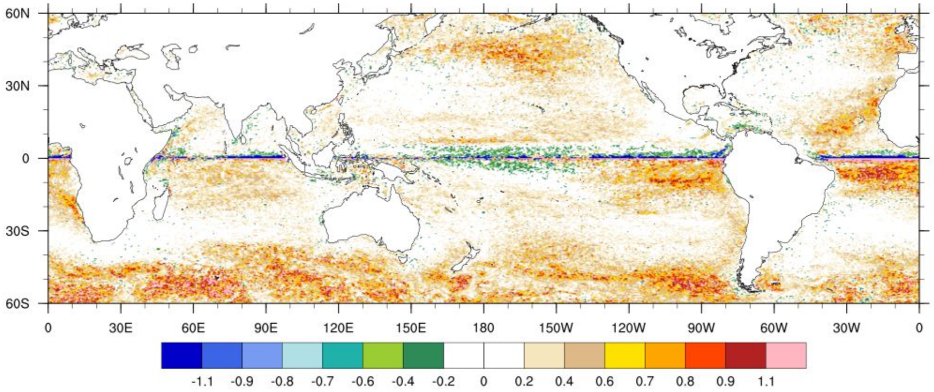
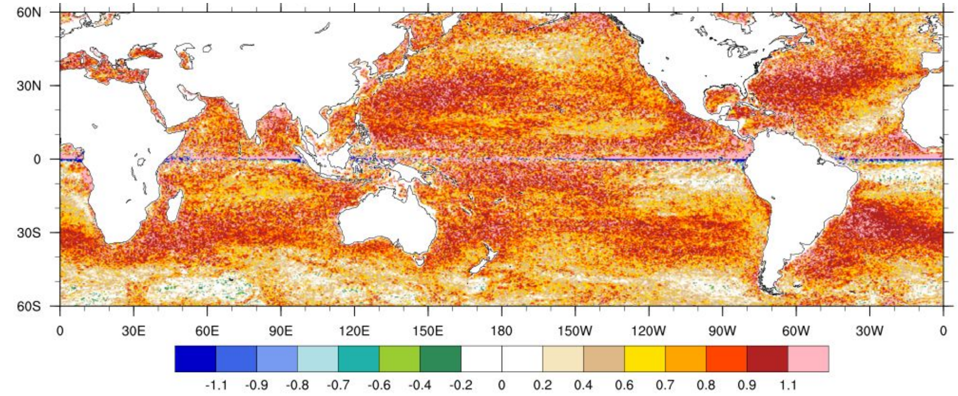


Salinity: The role of Ekman vs geostrophic advection

Horizontal advection and Ekman



Horizontal advection and geostrophic



Decomposition of advection into Ekman and geostrophic (see Yu 2011, 2023)

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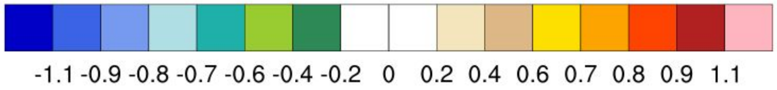
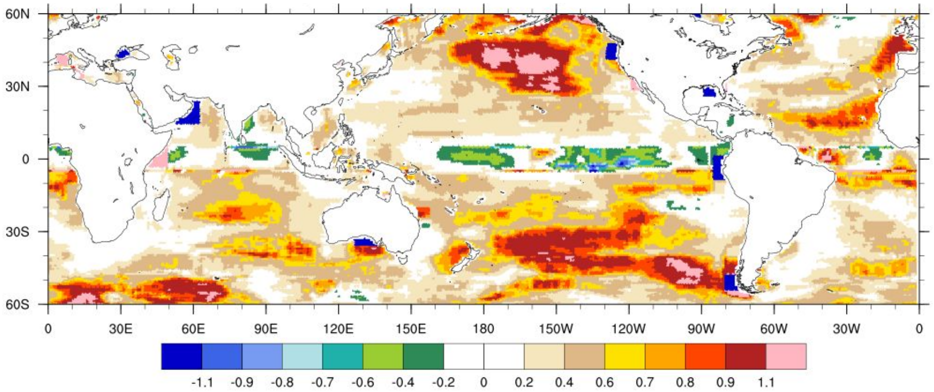
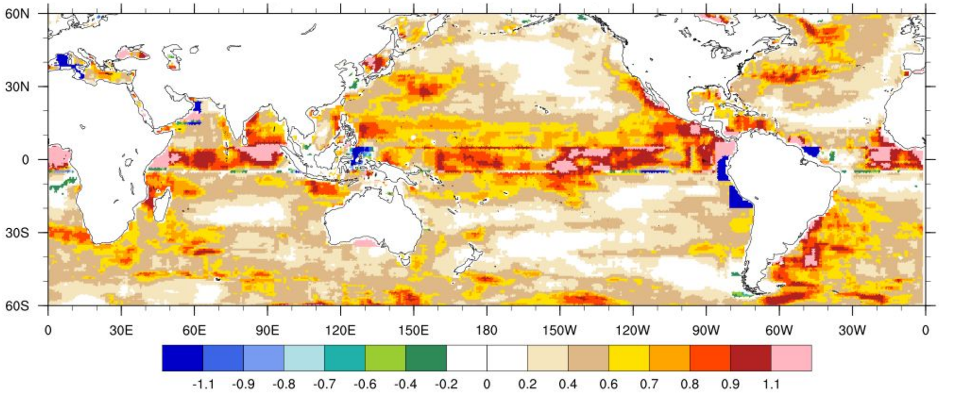


Salinity: The role of Ekman vs geostrophic advection: large-spatial scales

Smoothed Horizontal advection and Smoothed Ekman



Smoothed Horizontal advection and Smoothed Geostroph

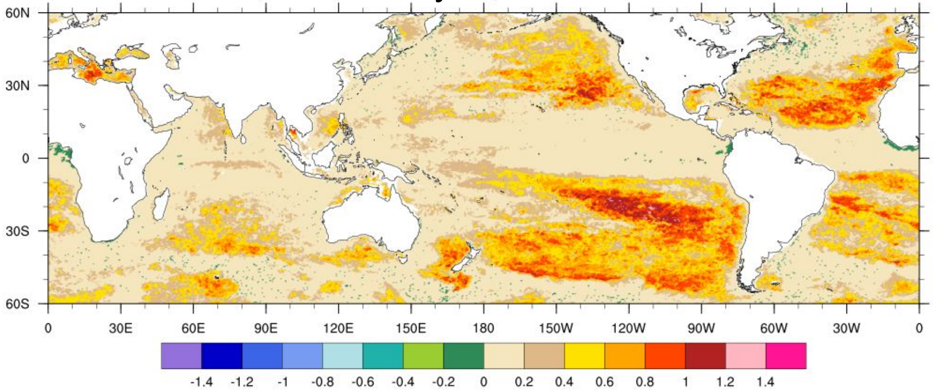


Ekman plays a bigger role for large spatial scales ***

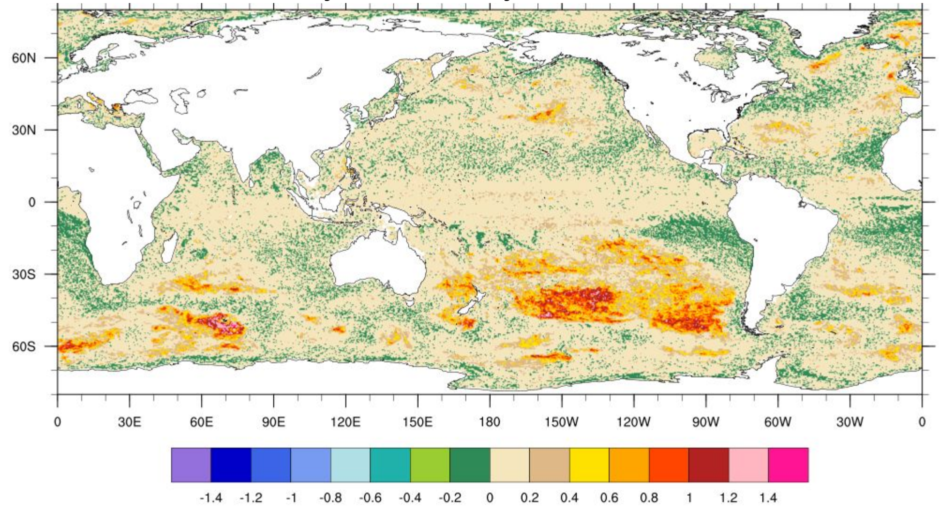
*** Caution – Lee et al (2004) argue against using spatial averages of horizontal advection terms

High-frequency variability (< 2 weeks)

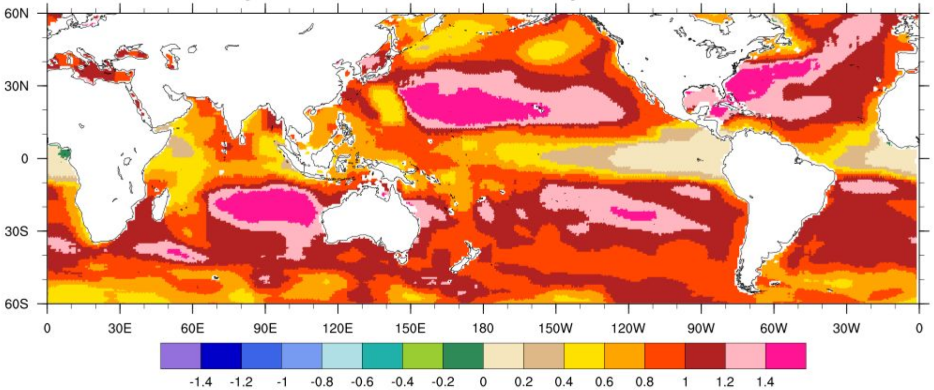
Heat: Tendency and surface flux



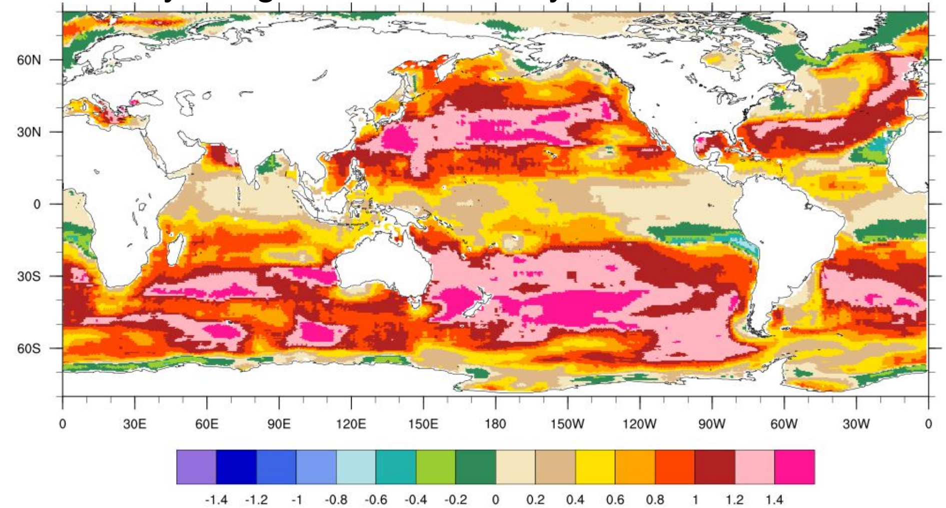
Salinity: Tendency and surface flux



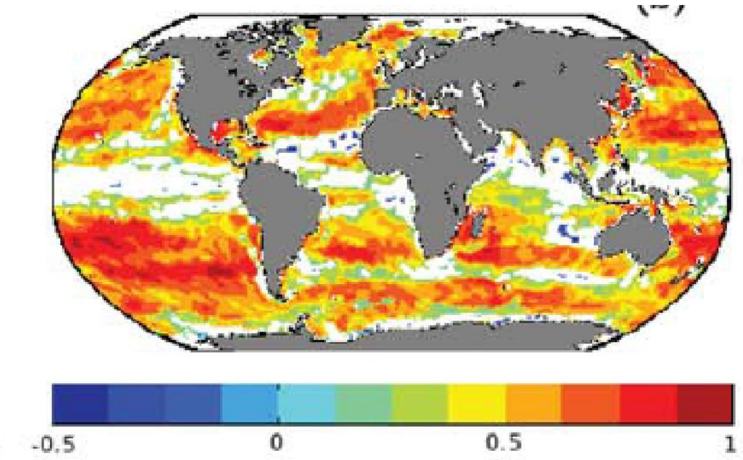
Heat: Large-scale Tendency and surface flux



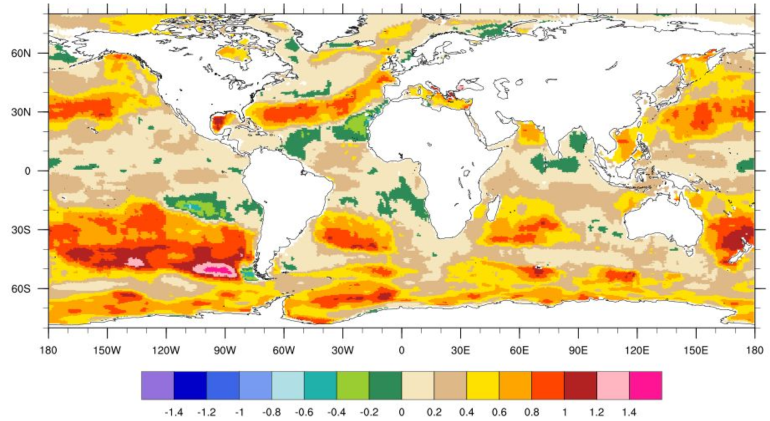
Salinity: Large-scale Tendency and surface flux



Reconciling with previous results: estimation of E minus P from salinity tendency



Left: ECCO: From Vinogradova and Ponte 2013. Correlation between salinity tendency and surface forcing, sub-12 month timescales.



Left: CESM-HR: regression of salinity tendency on surface flux, monthly data, non-seasonal. *Spatially smoothed data.*

This slides compares CESM-HR results with (Vinogradova and Ponte 2013, Fig. 4b) – reasonably good match

Summary

- Salinity budget (non-seasonal) dominated by advection on the grid-scale
  - More than heat budget

- Seasonal cycle shows more impact of surface flux

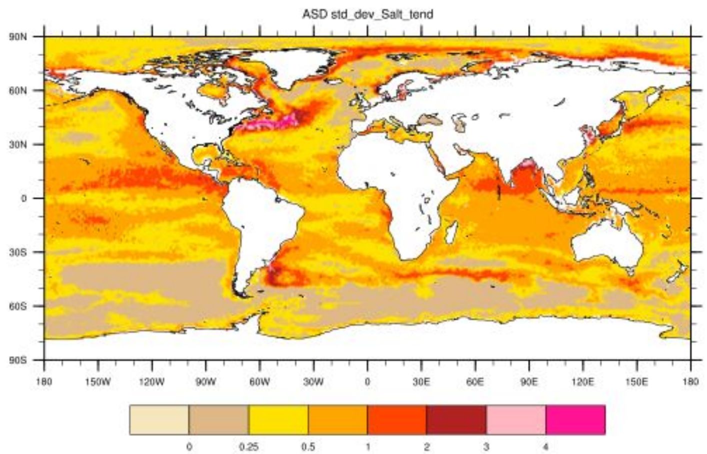
- On larger-spatial scales, surface flux plays an important role

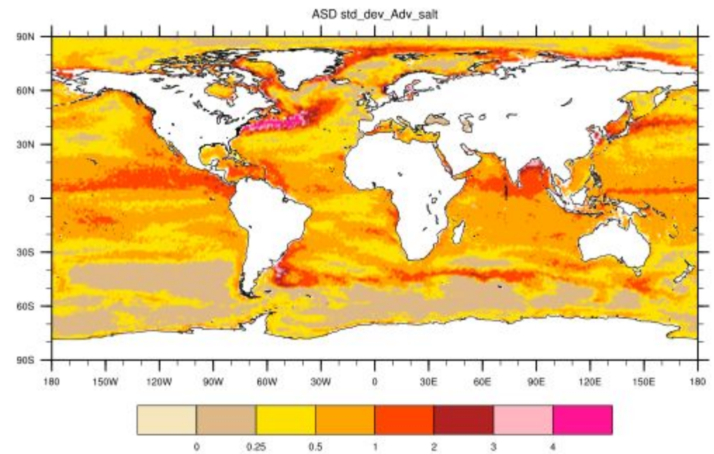
- Large-scale salinity-tendency can be used to estimate selected regional E minus P, as suggested by Vinogradova and Ponte 2013
  - Required: what timescale?
  - Some important regions not well estimated, including deep Tropics.

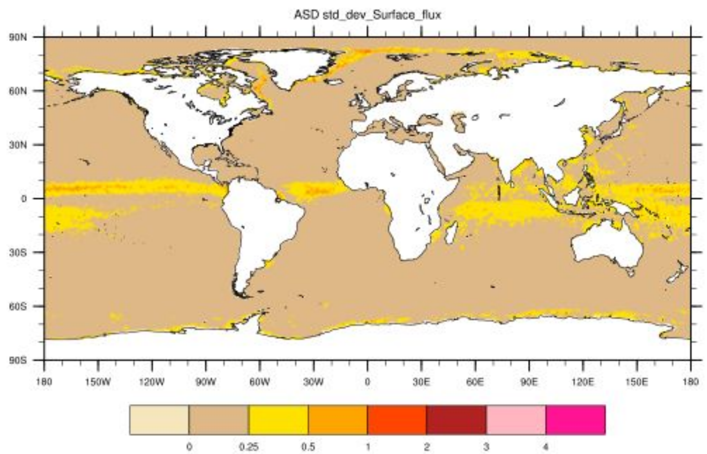
Next Steps

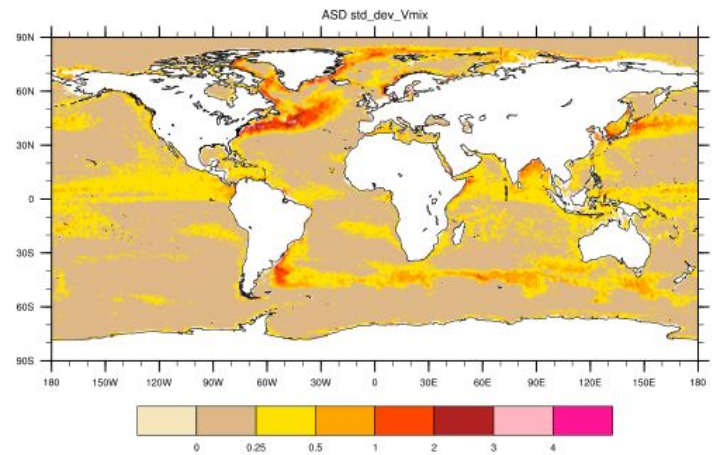
- Interpretation of budget analysis with stochastic model for mixed-layer salinity
  - Lucas Laurindo, Luanne Thompson and Justin Small
- Add more ECCO budget analysis – expand on Vinogradova et al. work to include different spatial scales
  - Justin Small and Ivana Cerovecki
- Time-scale dependence including high-frequency, and interannual->decadal
  - Justin Small and Dan Whitt

Standard Deviations (salinity, grid-point)

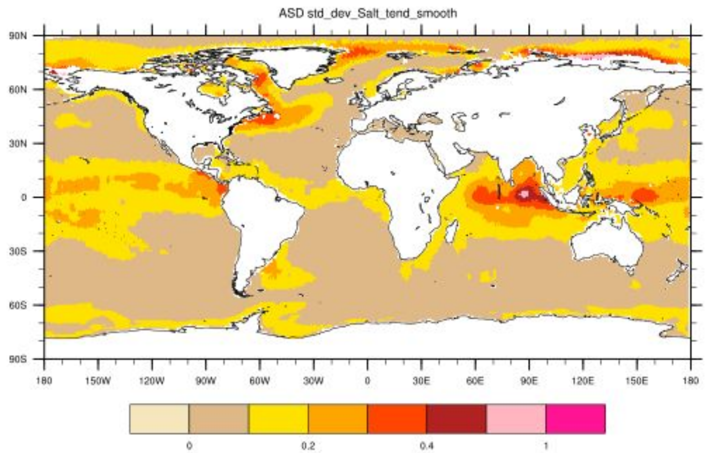


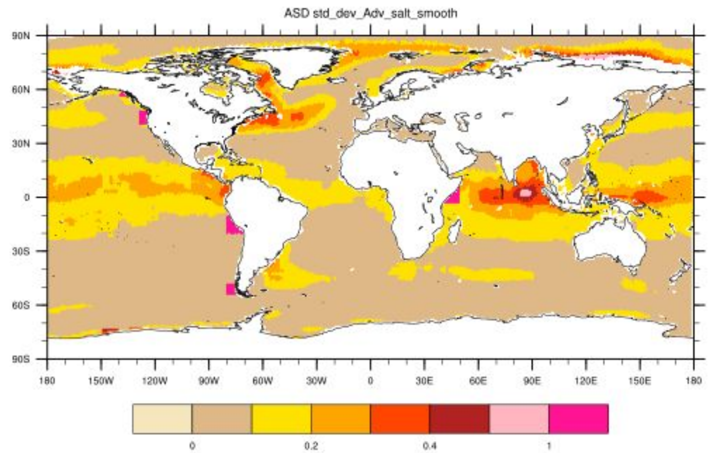


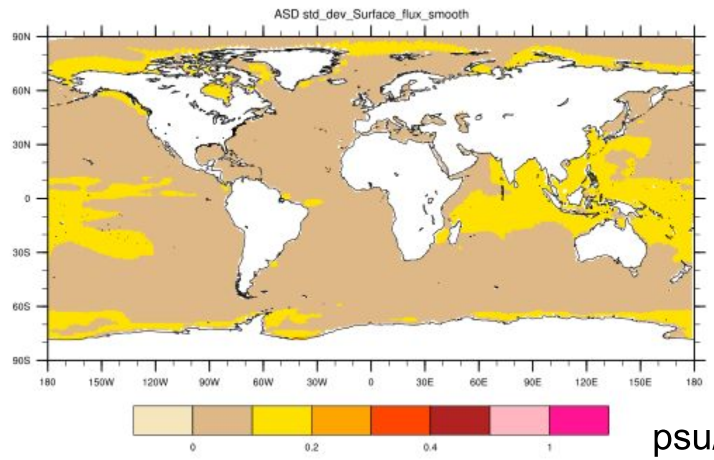




Standard deviations (salinity, smoothed)

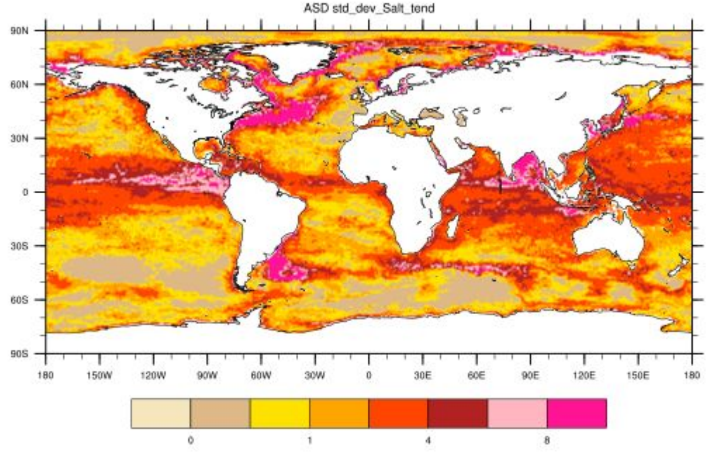


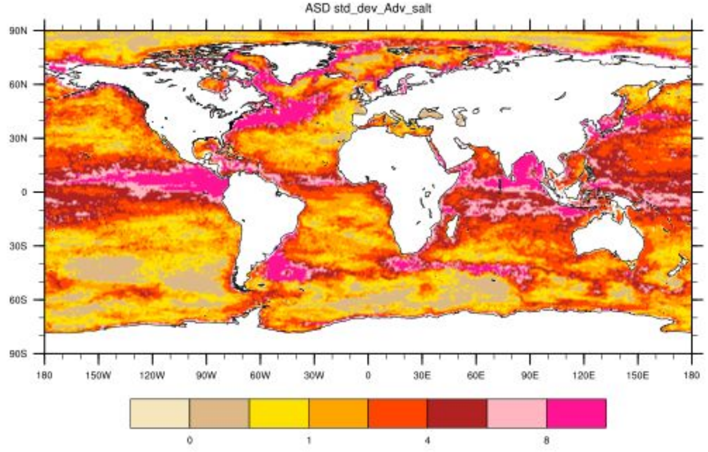


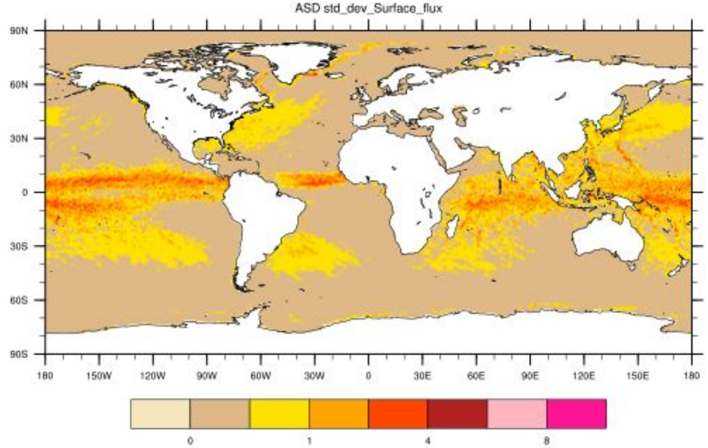


psu/ 100 days

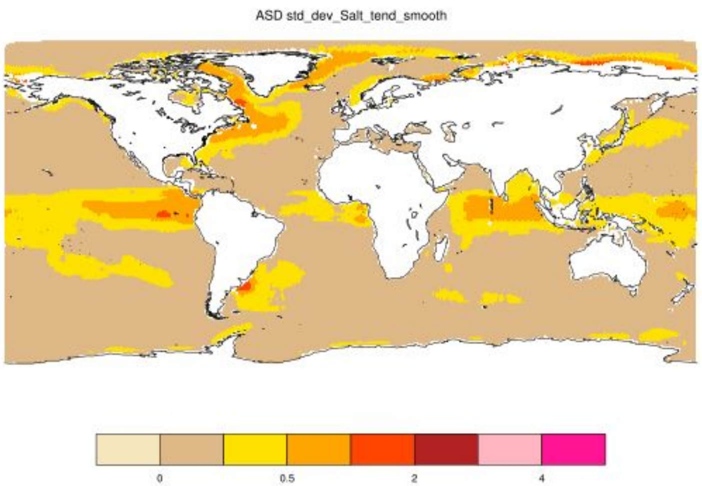
Standard deviations, salinity, high-frequency, grid-point

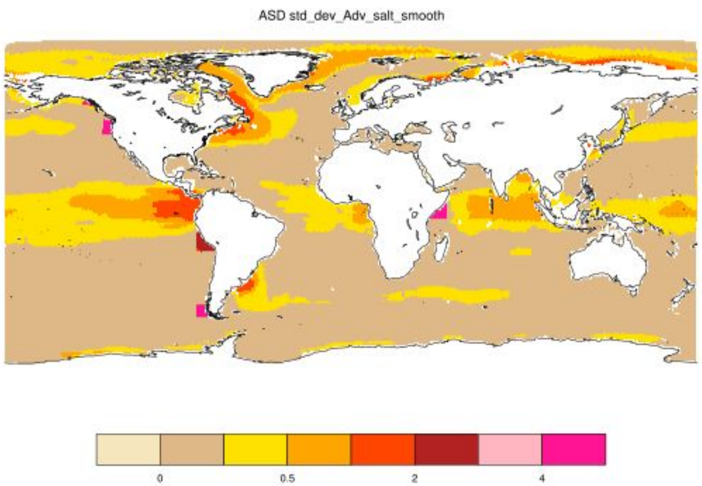


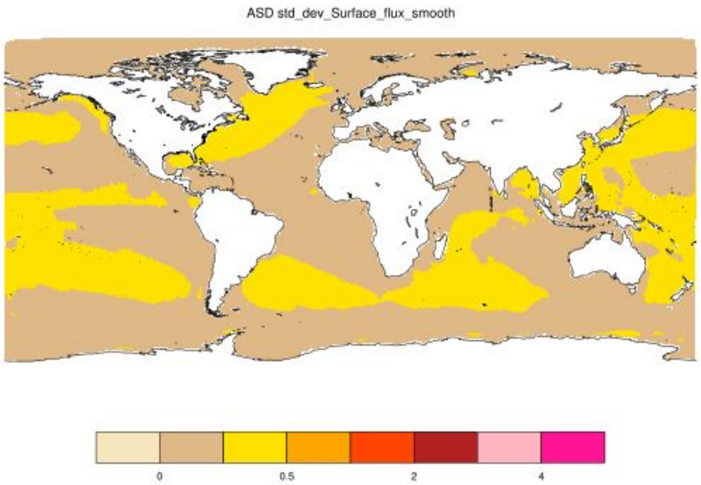




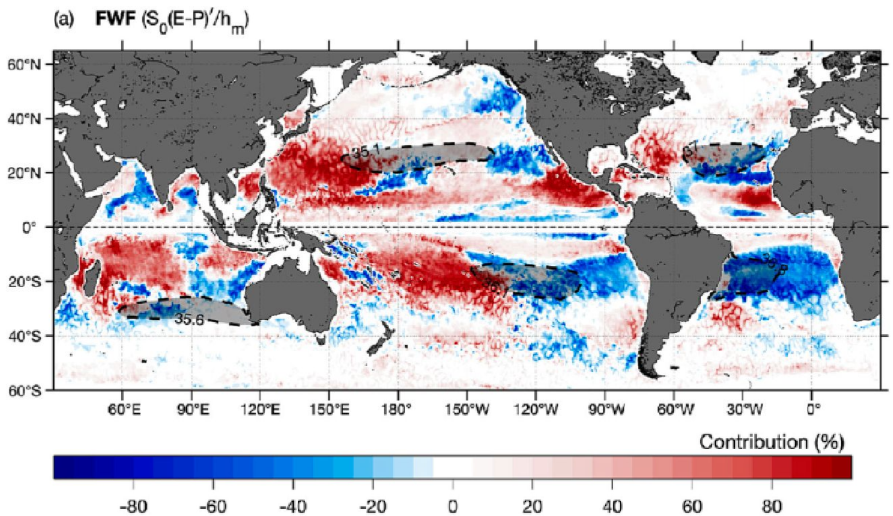
Standard deviations, salinity, high-frequency, smoothed



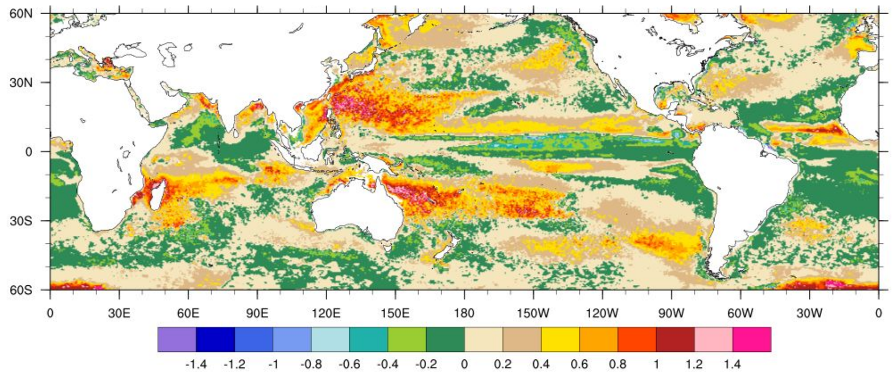




Reconciling with previous results (1)
role of surface flux in salinity seasonal cycle



Left: Yu (2023, Prog. Oceanogr.)
Contribution of surface flux to salinity tendency variance. From OAFLUX/GPCP.



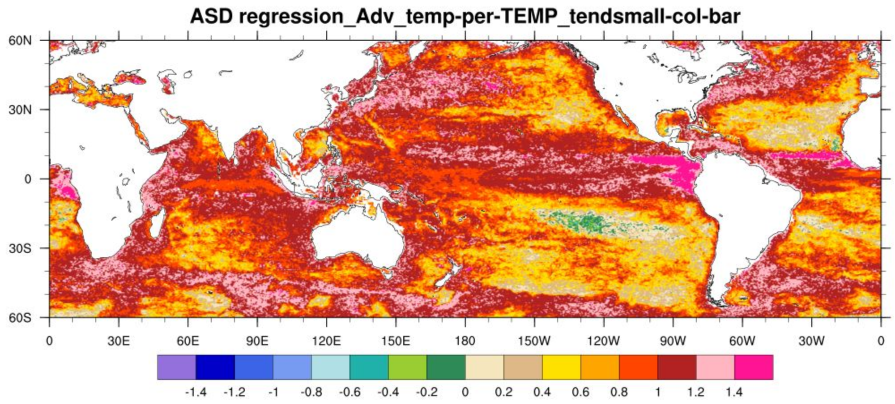
Left: CESM-HR. Seasonal cycle, regression of salinity tendency on surface flux. *Grid-point regressions.*

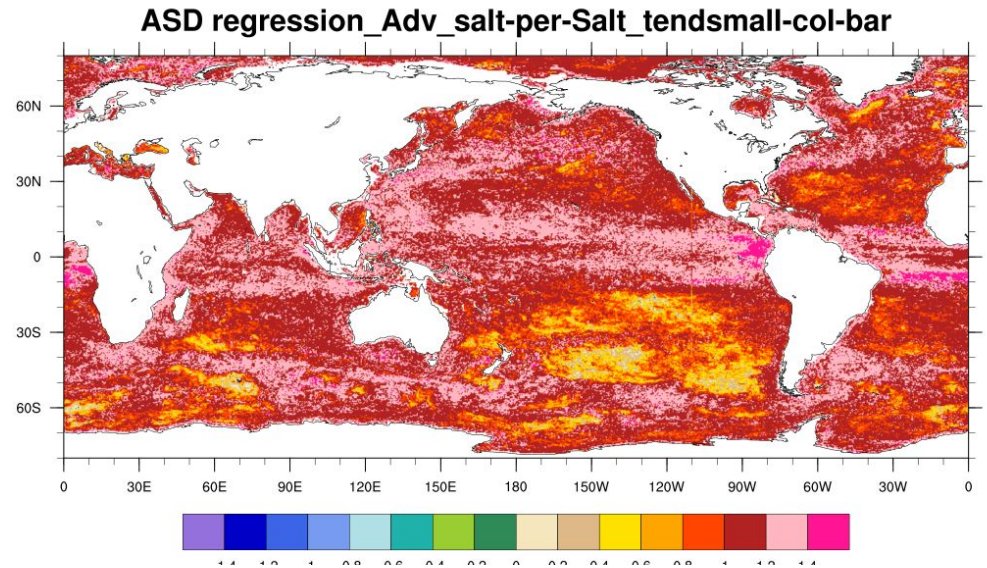
This slide compares CESM-HR results for seasonal cycle with Yu 2023.
Yu 2023 considered all variability – seasonal and non-seasonal

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

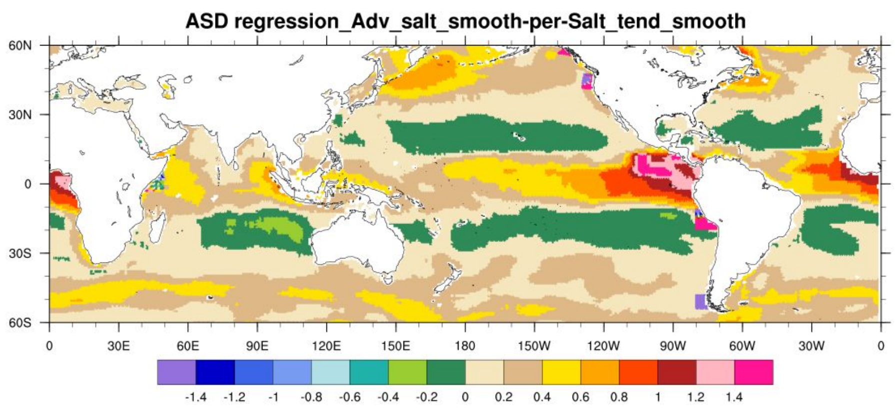
$$\int_{-H}^{0} \frac{\partial S}{\partial t} \partial z = \int_{-H}^{0} (-u \cdot \nabla S + HMIX)\partial z + S_{ref}(E - P) - \kappa \left(\frac{\partial S}{\partial z} - \Gamma\right)_{-H}$$

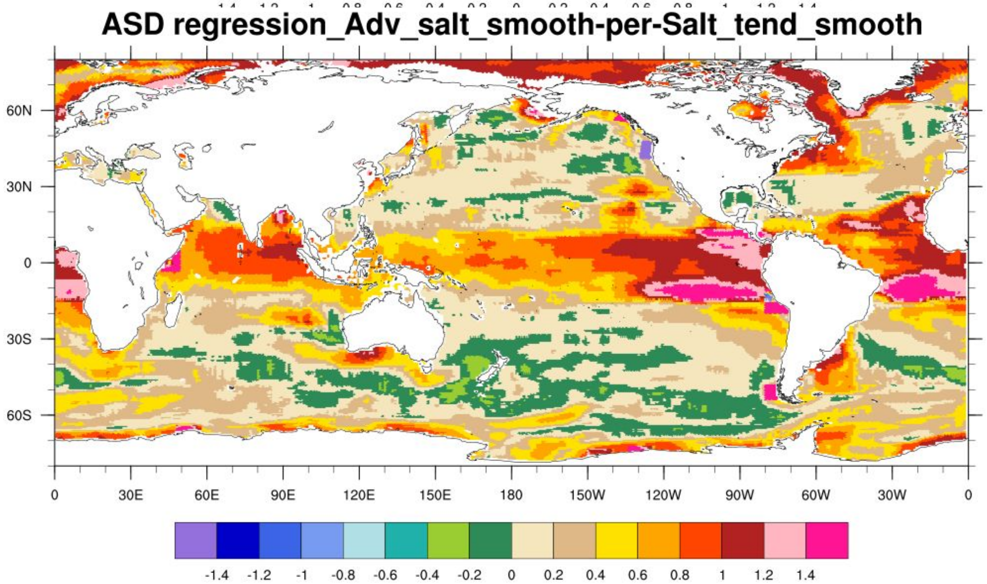
High-frequency variability (< 2 weeks)



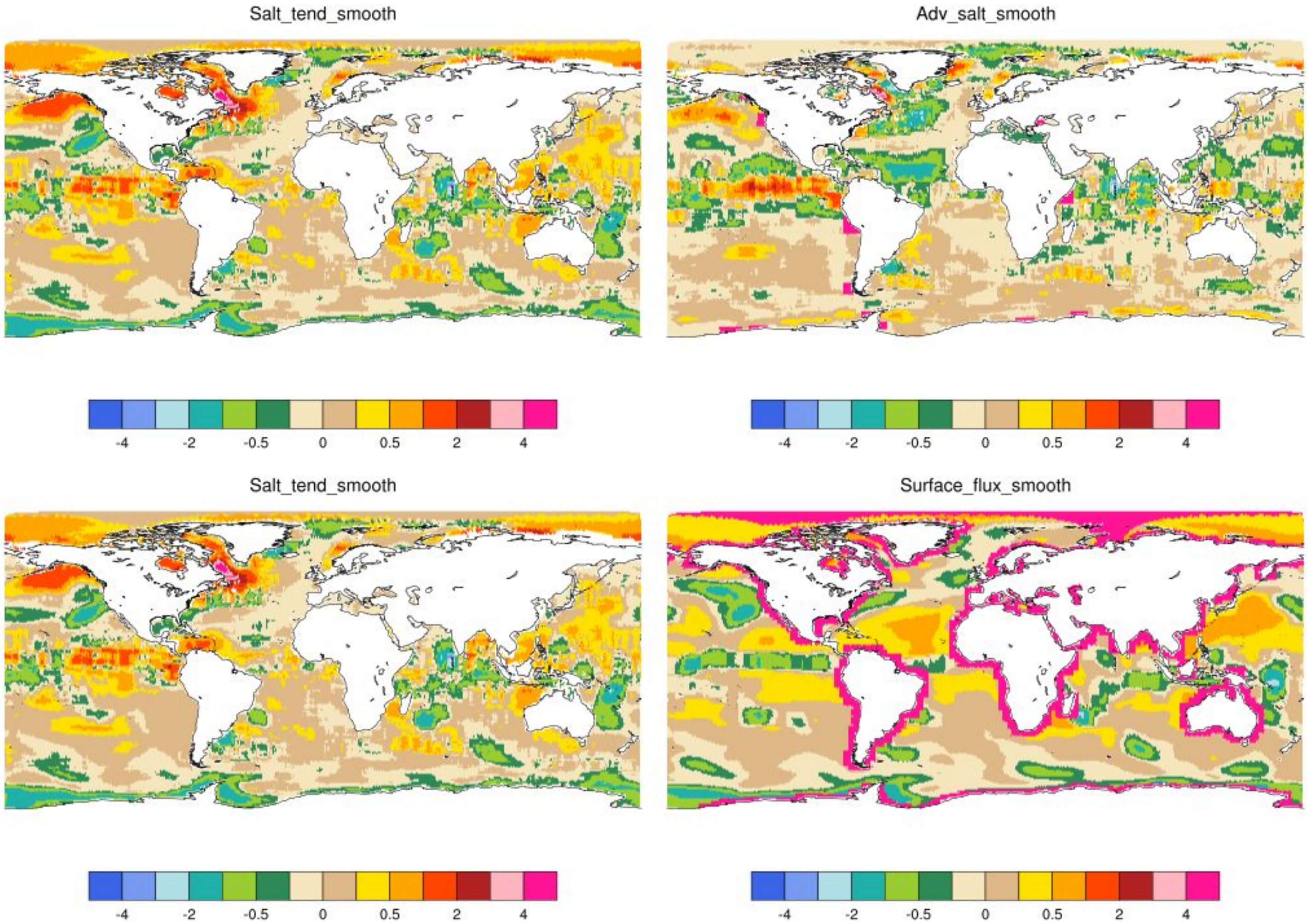


TEMP





Snapshot, daily salinity budget, smoothed



Introduction/Recap

- Last April Justin presented on:
  - monthly salt content budgets, focused on high-resolution CESM.
  - Included long-term mean, seasonal cycle, non-seasonal variability
- Last October, Lucas presented on:
  - salinity variance in models and observations,
  - highlighting role of advection.
- This update:
  - some comparisons of salinity budget with upper-ocean heat budgets
  - Revisit of seasonal cycle
  - Revisit of whether salinity (tendency) can give information on hydrological cycle – E minus P
  - High-frequency analysis