Seasonal Variation in the Effective Depth of Air-Sea Interaction

Jacob Cohen[1], LuAnne Thompson[1]
1. University of Washington School of Oceanography
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Email: jtcohen@uw.edu
Website: cohenjt.github.io

This presentation focuses on quantifying the relative roles of oceanic and atmospheric processes on driving air-sea interaction and upper ocean heat variability. The research was conducted by Jacob Cohen and LuAnne Thompson at the University of Washington.

What mechanisms control mid-latitude air-sea heat exchange and SST variability?

- Ocean heat transport convergence processes
- Atmospheric variability

So what?

- Important for understanding climate variability
- Potential to improve climate forecasting

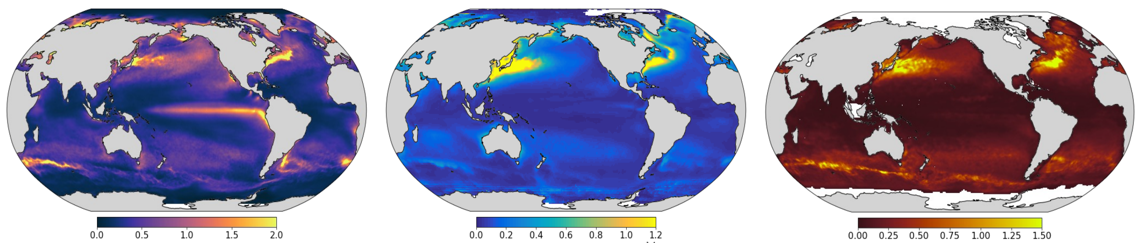
Do these mechanisms vary throughout the annual cycle?

- Strong seasonal winds
- Deep seasonal mixed layers

Our goal is to understand the relative roles of ocean heat transport convergence processes and atmospheric variability on driving air-sea heat exchange and SST variability. We also investigate the seasonality of these processes and how the relative roles change throughout the annual cycle. The focus of this work is on the midlatitudes, so we investigate the North Atlantic Ocean, the North Pacific Ocean, and the Southern Ocean with an emphasis on the western boundary currents (the Gulf Stream and the Kuroshio Current) and the Antarctic Circumpolar Current (ACC).

Observational data from 1993-2019

Variable	Spatial Resolution	Temporal Resolution	Source
Sea surface temperature (SST)	1/4°	Daily	OISST
Mixed-layer heat content (MLHC)	1/4°	Weekly	Lyman and Johnson
Turbulent heat flux (Q_{turb})	1°	Monthly	OAFLUX



SST variance [ºC^2]   Q variance [(W m^{-2})^2]   MLHC variance [(J m^{-2})^2]

Monthly 1º estimates of turbulent surface heat flux (Q; positive out of the ocean), sea surface temperature (SST) anomalies, and upper ocean heat content (HC) anomalies are derived from observational data products spanning the full available record of satellite observations from 1993 to 2019. The turbulent heat flux is calculated from the sum of latent and sensible heat flux products from the Woods Hole Oceanographic Institution's Objectively Analyzed air-sea Fluxes Project (OAFlux), which are derived from a synthesis of satellite observations and atmospheric reanalysis and are provided on monthly 1º grids. For SST, we use monthly averages of the NOAA Daily ¼º Optimum Interpolation Sea Surface Temperature (OISST), which integrates observations from satellites, ships, buoys, and Argo floats. To obtain an estimate of the MLHC, we use daily ¼º ocean heat content observations for 10 layers over the upper 2000 m of the global ocean from Lyman and Johnson. After resampling the data to a monthly timescale, we integrate the heat content to the monthly climatological mixed-layer depth from MIMOC. We then remove the linear trend and the monthly climatology from the Q, SST, and HC fields.

Atmosphere-ocean feedbacks describe the surface heat flux response to ocean temperature and heat anomalies.

$$\overbrace{\rho C_p H \frac{dT_o}{dt}}^{\text{Ocean heat content tendency}} = \overbrace{-\lambda_q(T_o - T_a)}^{Q_{turb}} \overbrace{- \lambda_r T_o}^{\text{Radiative cooling}} + \overbrace{N_o}^{\text{Ocean noise}}$$

$$\lambda_{SST}(\tau) = \frac{R_{SST-Q}(\tau)}{R_{SST-SST}(\tau)}$$

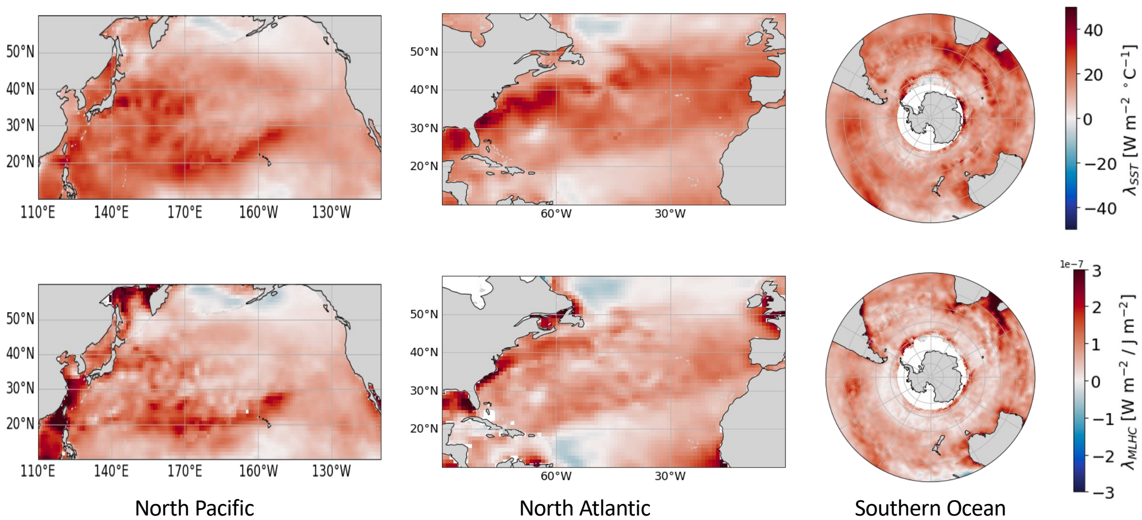
λ_q Turbulent flux feedback

λ_r Radiative flux feedback

$$\lambda_q >> \lambda_r$$

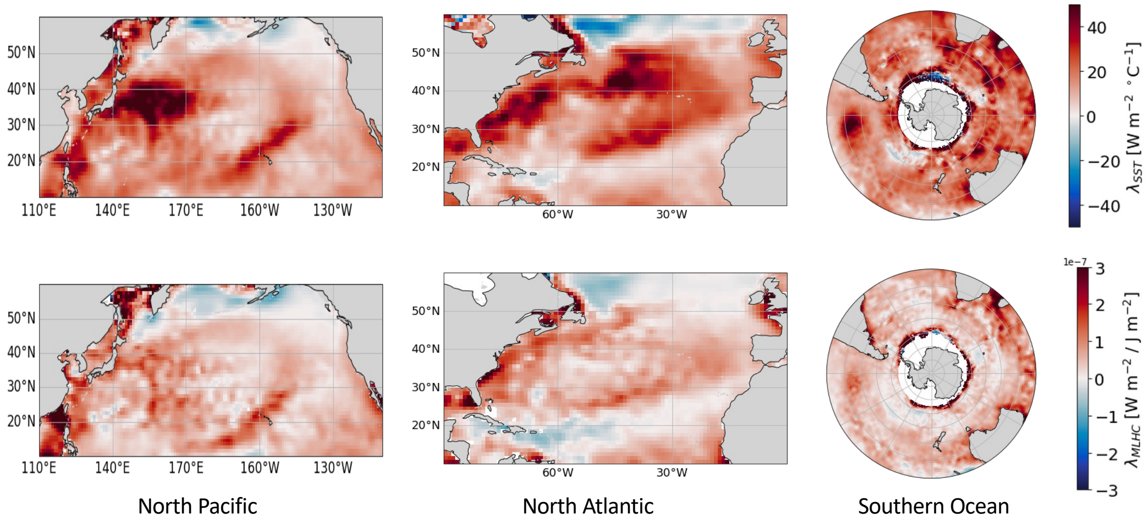
We calculate the turbulent flux feedback to sea surface temperature (SST) and to mixed-layer heat content (MLHC) to understand how the atmosphere interacts with the ocean heat budget. These feedbacks describe the atmospheric response to ocean temperature and heat anomalies. The equation on the right replaces the turbulent flux feedback term in the heat budget on the left and is the ratio of the covariance between SST and surface heat flux (Q) to the autocovariance of SST. The MLHC feedback is identical, replacing SST with MLHC. We calculate the feedback on an annual basis using all monthly data, and on a seasonal basis using data just from the winter (DJF) or summer (JJA) months.

Annual Case: SST and MLHC feedbacks are collocated and are high in regions of strong currents.



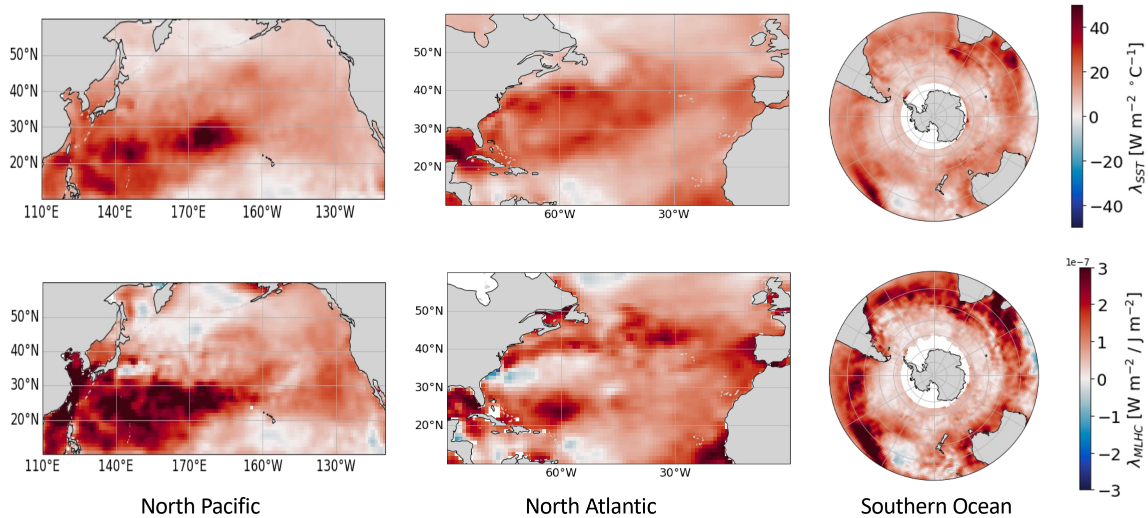
In the annual case, SST feedback (top) and MLHC feedback (bottom) are similarly high in the strong currents in each region. These feedbacks are mostly collocated and demonstrate that local surface heat flux damps both SST and MLHC anomalies.

Winter: SST feedback is higher than MLHC feedback



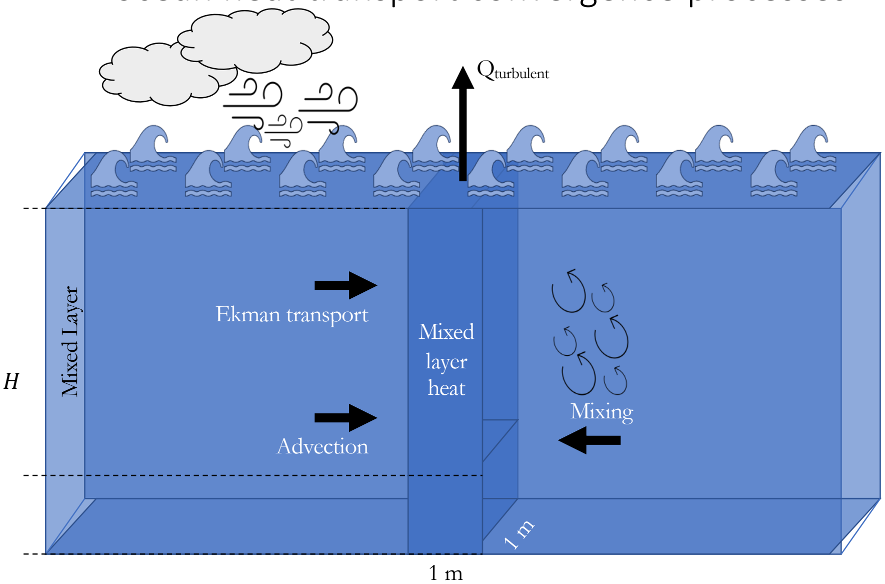
In the winter, SST feedback is higher than the annual average, while MLHC feedback is lower. Strong winds and currents, as well as the deep winter mixed-layer, contribute to these differences.

Summer: MLHC feedback is higher than SST feedback



In the summer, we tend to see the opposite. Here, the MLHC feedback is mostly higher than the annual case, while SST feedbacks are similar or lower. In some regions, however, we see an extremely low MLHC feedback. Some of these values occur because the shallowest ocean layer for which we have heat content data exceeds the summertime mixed layer depths, which are often shallower than 20 meters. As a result, the MLHC feedback we calculate represents significantly more of the ocean heat content than it should in theory. As a result, we should be cautious to interpret the summertime results in regions with mixed layers shallower than 40 meters.

H captures both mixed-layer heat and heat brought in from ocean heat transport convergence processes

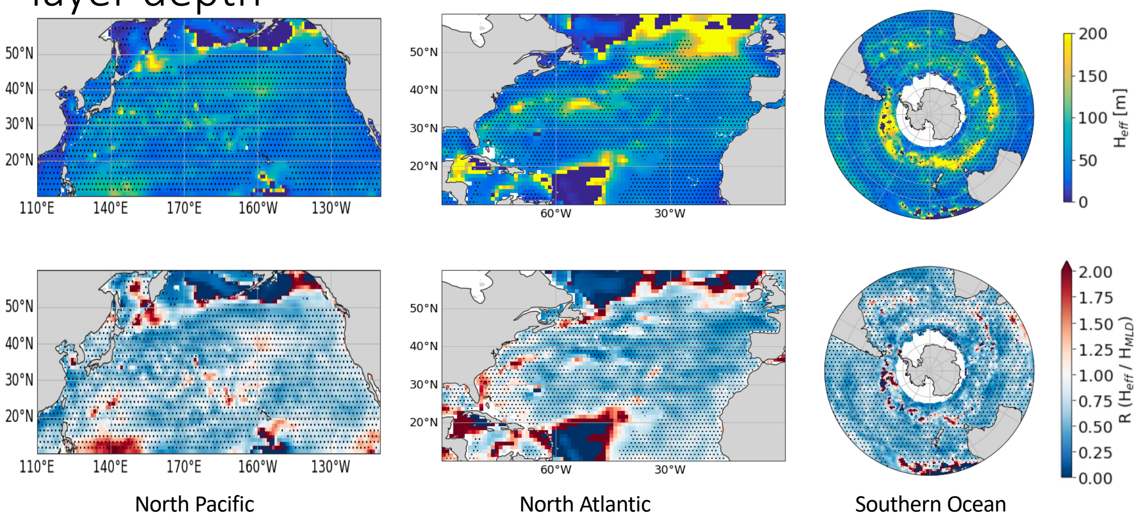


$$H = \frac{\lambda_{\mathrm{SST}}}{\lambda_{\mathrm{MLHC}}} \frac{1}{\rho_0 C_P}$$

$$R = \frac{H}{\mathrm{MLD_{max}}}$$

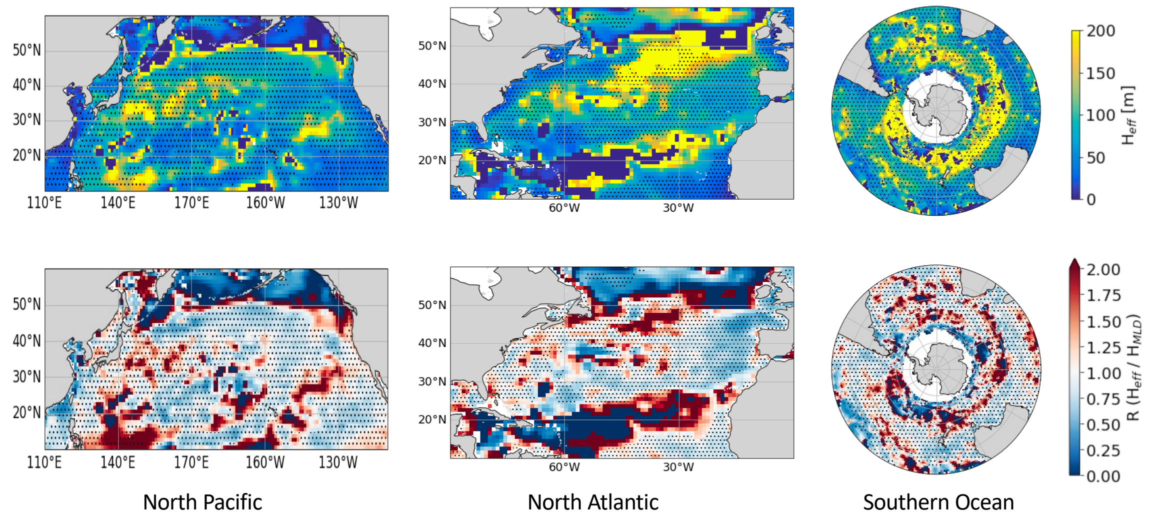
The effective depth of air-sea interaction (H) describes the volume of water that contributes to the surface heat flux through a 1m x 1m area of the ocean surface. This volume of water and the heat it contributes include water in the column below the surface as well as the water involved in ocean heat transport convergence processes such as advection, entrainment, and mixing. The effective depth is calculated as the ratio of the SST feedback to the MLHC feedback, scaled by the density and heat capacity of seawater. We interpret the effective depth by dividing it by the maximum climatological mixed layer depth to calculate the depth ratio (R). Where the effective depth of air-sea interaction exceeds the maximum mixed-layer depth (R>1), oceanic processes drive air-sea interaction more than atmospheric processes.

Annual Case: Strong currents exhibit effective depths of air-sea interaction exceeding the maximum mixed-layer depth



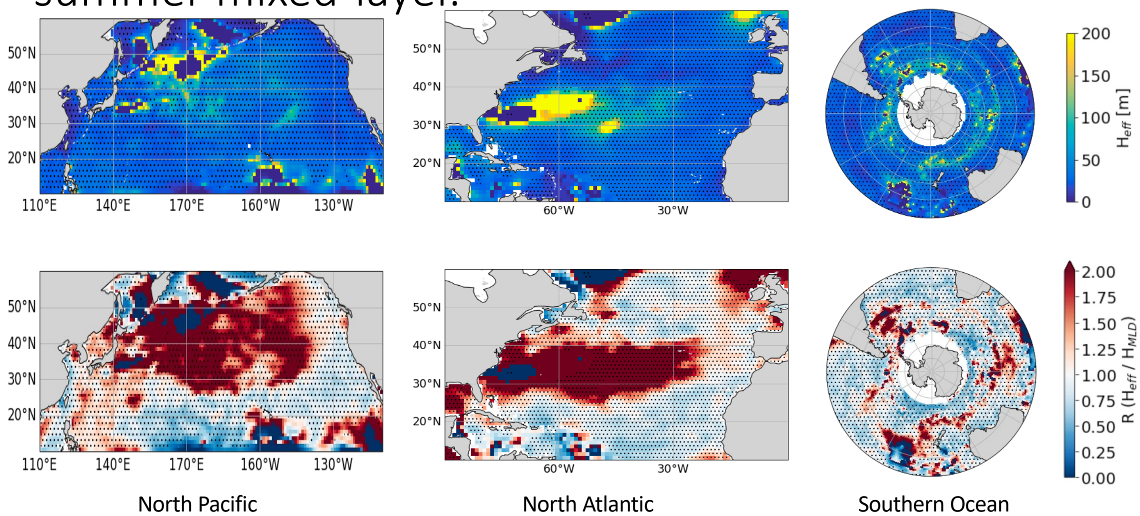
In the annual case, we see large effective depths (top) and depth ratios (bottom) in regions of strong western boundary currents and the ACC. This agrees with previous research demonstrating the importance of ocean dynamics and ocean heat transport convergence in renewing upper ocean heat anomalies and driving air-sea interaction. Stippled regions in all future plots indicate regions with statistically significant values.

Winter: Effective depths and ratios are larger than the annual average in many regions



In winter, both the effective depths and the depth ratios are larger than the annual case in the strong currents. This suggests that the relative role of ocean dynamics is more important in the winter.

Summer: Large ratios are caused by the heat content data averaged over depths deeper than the shallow summer mixed-layer.



In summer, we see mostly shallow effective depths, but very large depth ratios. As mentioned on the slide showing the summer feedback, this is due to the data being unable to capture the heat content of such shallow mixed layers. The regions in the North Pacific and the North Atlantic with ratios exceeding 2 all have summer mixed-layer depths of about 20 meters. As a result, we cannot draw any meaningful conclusions from the high ratios shown here.

Takeaways

- Atmospheric feedback to SST and MLHC is strong in western boundary currents and the ACC in the annual case and in the winter
- In the annual case and in the winter, **ocean processes have a relatively large role in driving air-sea interaction!**