Report on Findings from CICOES Project: North Pacific Momentum and Heat Flux Variability: A Bridge between Ocean and Atmosphere

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Background

Our project was based on the idea that most of the previous work on the climate variability of the North Pacific has focused on the patterns in sea surface temperature (SST) anomalies, but that approach is lacking from a mechanistic perspective. In particular, in this project we have documented the interactions between the ocean and atmosphere in terms of the fluxes of energy at the air-sea interface.

Our primary goal has been to address the following question: **How important are the surface energy fluxes in determining the distributions of long-term mean SST and SST variations in time (dSST/dt)?**

Towards addressing that goal, we considered these specific questions:

1. What are the long-term mean, trends, seasonal climatologies and leading modal patterns of variability in the net and component surface energy fluxes?
2. Are the leading modes of the surface energy fluxes different from the leading modes of SST and dSST/dt?
3. In the regions where the time variability in net surface energy fluxes explains a substantial fraction of dSST/dt, which of the four components of the net surface energy flux (latent, sensible, shortwave radiative, and longwave radiative energy flux) are most important and how do they vary seasonally?

Project Activities

A key element of our effort was the development of a new atlas of surface energy fluxes for the North Pacific, carried out by the part of the team at OSU. This also benefited from the efforts of undergraduate student researcher Tera Hackett, who was engaged with the group during a previous REU and continued during this project. The atlas, and associated post-processed fields and relationships, were developed and examined by the project team through a regular series of video meetings. The analysis was based on reanalysis output from the European Centre for Medium-Range Weather Forecasting product ERA5 and facilitated through the use of a shared Google drive. The group benefited from the diversity in the backgrounds and expertise of its individual members with OSU, the UW and NOAA/AFSC. Our results, as summarized directly below, are being described in a journal manuscript that is in preparation.

The spatial distribution of the long-term mean net surface energy fluxes is shown in Figure 1. Since the overall trends in SST are small, Figure 1 shows that the ocean is being cooled by the atmosphere in the regions of the Kuroshio extension, the western Bering Sea and coastal Gulf of Alaska, and is being warmed by the atmosphere in the central North Pacific and along the west coast of the United States and Baja California. Considering the individual components comprising the net heat fluxes (not shown), we found is generally the latent heat flux component that dominates in the regions of cooling, and the shortwave radiative heat flux that dominates in the regions of warming by the atmosphere (not shown), with the former (latter) most important in winter (summer). Oceanic processes, namely a combination of temperature advection and vertical mixing, therefore serve to compensate for the net surface heat fluxes in the long-term mean. While these and other basic results from our projects are consistent with what is known from previous studies, the surface heat fluxes over the North Pacific have not gained much scrutiny from the climate community, and these basic results represent a foundation for our other analyses. For this report, we include these figures to provide the reader with an orientation to our study domain and its fundamental patterns.

We expect substantial interest from the climate and oceanographic communities in our results detailing the variability in the net surface heat fluxes, and in particular how the associated spatial patterns and their time-dependencies compare with the leading modes of SST variability, the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO). Our project has established that the four individual components of the surface energy flux, and the net surface energy flux, have complex relationships with the leading modes of SST and dSST/dt. As a result, the surface energy fluxes are not well represented by the leading modes of North Pacific SST variability typically used on by climate and oceanographic researchers, i.e., the PDO and NPGO. An example is shown in Figure 2, which reveals that the 1st mode of variability in the net surface energy (heat) fluxes resembles the pattern associated with the PDO (which is the 1st mode of SST), but with its center of action in the middle latitudes shifted significantly westward. A comparable map for the 2nd modes of the net surface heat fluxes and of SST (i.e., the NPGO; not shown) features maxima that are more nearly co-located, implying differences in the dynamics and time scales in the air-sea interactions associated with the PDO versus the NPGO. These ideas are fleshed out through frequency decomposition and cross-covariance and correlation analyses at selected locations in the North Pacific (additional figures not shown, but are included in the manuscript in preparation).

Our manuscript in preparation will close with recommendations for new indices that better represent atmosphere-ocean heat exchanges in the North Pacific. These new indices will complement the existing PDO and NPGO indices. Further, by determining where, and on what time scales, the air-sea heat fluxes and the time rate of change of SST are not well correlated, we will quantitatively identify the regions where advection of heat, not surface fluxes, dominates North Pacific SST variability.

Accomplishments

<u>Manuscript in preparation:</u>

Wettstein, J., et al. Leading modes of air-sea energy fluxes and sea-surface temperature variability in the North Pacific. In preparation for Journal of Climate.

Student training:

1. Tera Hackett was an REU student with Wettstein before this project started, and this project builds on and continues her work. She attended the project meetings, continuing to build her understanding of climate research in the North Pacific. She will be a coauthor on the resulting manuscript.
2. Megan Duncan is a Master's student advised by Wettstein. She attended project meetings to broaden her understanding of North Pacific variability and is working on a related project.
3. Emily Hayden is a PhD student advised by O'Neill. She also attended project meetings and is studying air-sea fluxes in the Bering Sea in relation to recent SST warming and ice cover changes.
4. Yi-Wei (Michael) Chen is a Master's student advised by O'Neill. He attended project meetings and is studying storm-driven air-sea heat fluxes in the North Pacific in relation to recent marine heat waves.

Follow-Up Activities

This project has served to foster collaboration among researchers at OSU, the UW and NOAA/AFSC with complementary expertise in North Pacific climate (Wettstein, Bond), air-sea interactions on basin scales (O'Neill) and in the California Current System (Fewings), marine heat waves (Bond, Fewings, O'Neill), and climate-fisheries connections (Litzow). This team is in the process of completing a journal manuscript that is expected to gain a great deal of interest from the North Pacific climate and oceanography communities. Fruitful directions for future work, and an external proposal, are being discussed; for example the team is interested in determining whether the temporal variability in the net surface heat fluxes can help account for the variability found by Litzow et al. (2018, 2020) in the correspondence between the PDO and various metrics for Alaskan fisheries. We are also keen to quantify the relative contributions of oceanic advective and mixing processes in the regions where the net surface heat fluxes fail to explain the variability in SST. The results from our work also can and should be used to determine how well current climate models replicate the actual interactions between the atmosphere and ocean across the North Pacific, and hence the extent to which their projections of these interactions for future decades are realistic. The project's participants are planning a future proposal to be submitted to NSF, or if appropriate, a targeted RFP by NOAA or NASA.

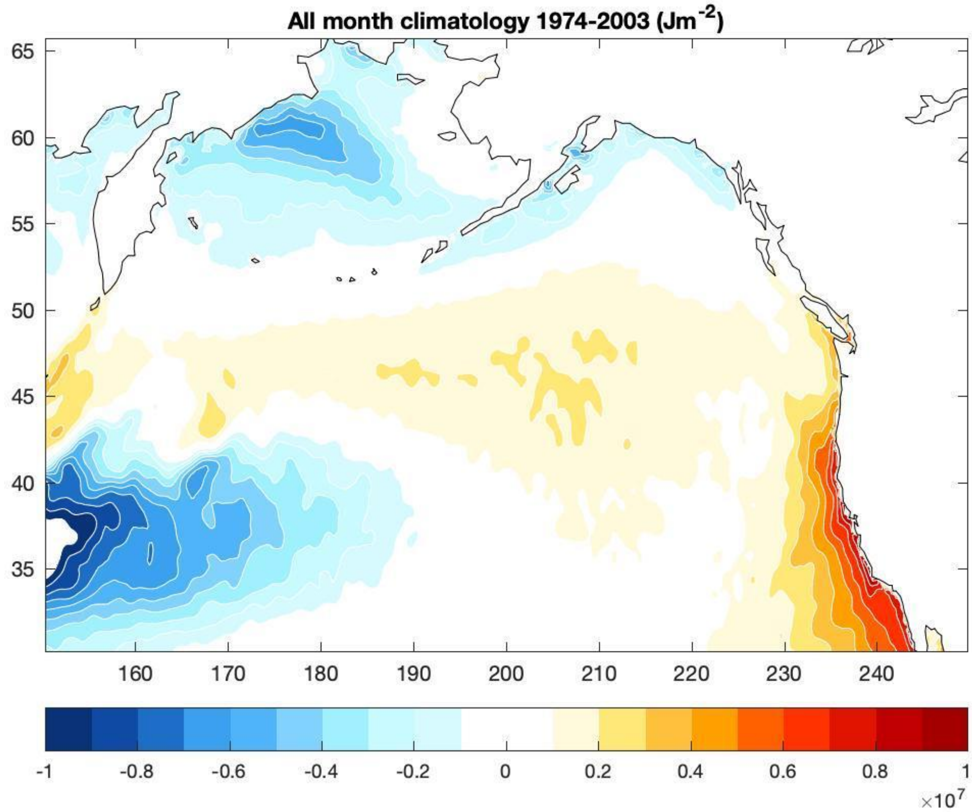

Figure 1 Time mean of the net surface energy flux (J m^{-2}) from atmosphere to ocean for the years of 1974-2003 based on ERA5 reanalysis output. The vertical axis is latitude in degrees north and the horizontal axis is longitude in degrees east. The time period was chosen to evenly straddle the regime shift in ~1990 that has been previously described in the literature (e.g., Litzow et al., 2018, 2020). Positive (negative) values imply heating (cooling) of the ocean by the atmosphere.

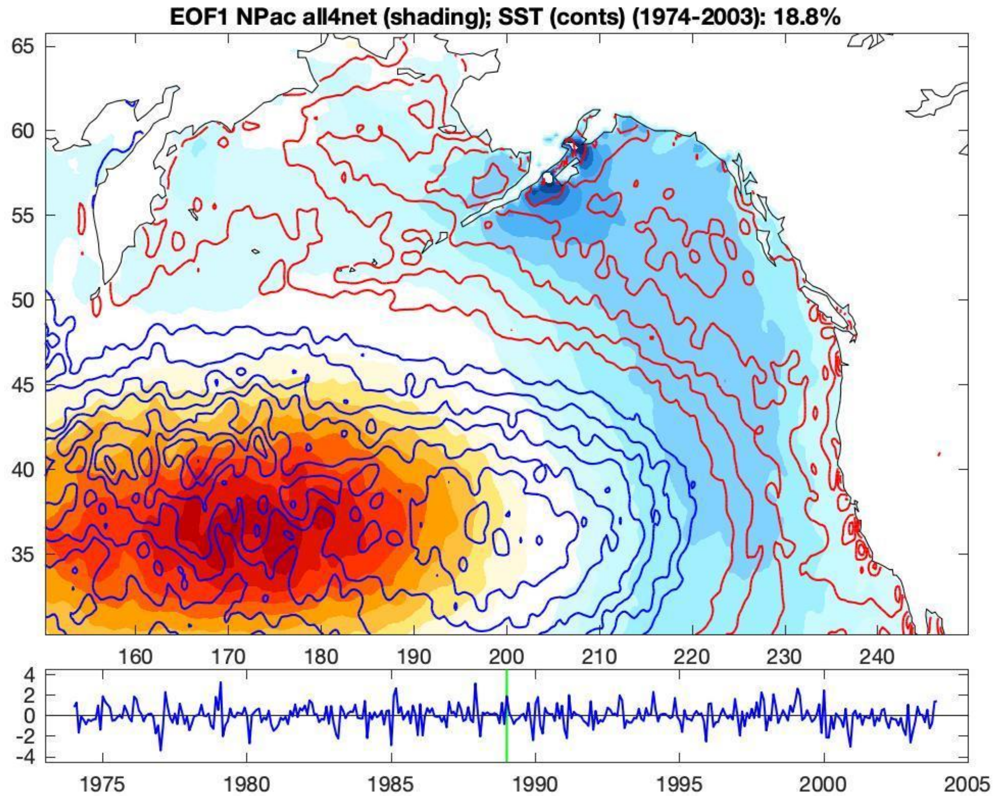

Figure 2 Leading modes (1st empirical orthogonal functions) of net surface heat fluxes (color fill) and dSST/dt (contours), with the latter representing essentially the PDO, based on ERA5 reanalysis output. In the upper plot, the vertical axis is latitude in degrees north and the horizontal axis is longitude in degrees east. The time series at the bottom is the principal component of the 1^{st} mode of the net surface heat fluxes (normalized units). The location of maximum variability in the surface heat flux mode is in the southwest part of the figure (red), whereas the maximum in variability in the rate of change of SST is located ~2500 km farther east (closed blue contour, centered about 37N, 200E).