DISENTANGLING CLIMATE SIGNALS IN COASTAL WATERS
A 25-YEAR TIME SERIES PERSPECTIVE ON PUGET SOUND

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1 BACKGROUND

During the analysis period of 1999-2024, the Pacific Northwest experienced a series of notable climate events including the 2015 El-Niño, the expansive marine heat wave known as "the Blob", a triple-dip La Niña between 2020-2023, the 2021 Northwest Heat Dome, and historically-low snowpack during the winters of 2000-2001 and 2023-2024. Puget Sound's highly variable climate often results in large, persistent deviations from long-term temperature trends with the present trend nearly five times higher than historical warming rates (~0.1 °F/decade, UW Climate Impacts Group, Office of the Washington State Climatologist).

In this period of rapid change, long-term regional monitoring data provides key insights into the response of coastal marine systems to transient phenomena that can be used to advance understanding of how climate change is imprinted at local scales. This work aims to characterize the specific nature of interdecadal trends within the Puget Sound ecosystem through a data-driven joint analysis of drivers of variability and their integrated effects on the spatial signature of long-term trends.

2 METHODS

Anomaly Definition
Anomalies are calculated relative to bootstrapped monthly medians for each parameter, which are estimated from a baseline period of 1999-2023 for each station and depth (0.5m vertical resolution).

Emipirical Orthogonal Function Analysis
EOFs are calculated from detrended temperature and salinity anomaly records from station-depths that span at least 18 of the 25 years within the analysis period. Mode truncation is performed via a Monte-Carlo "Rule N" significance (p<0.05) testing procedure with assumed red noise.

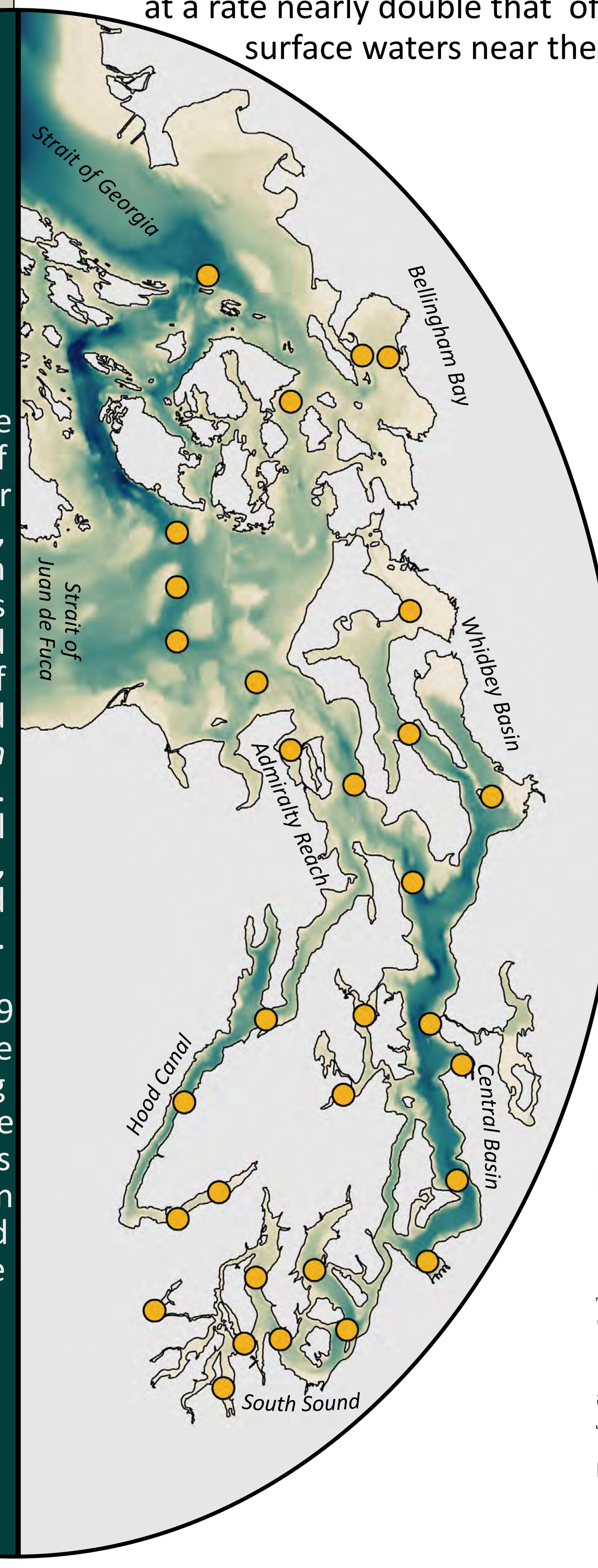
Trend Analysis
Temperature and salinity anomalies were evaluated for trends using the Mann-Kendall test (alpha = 0.05) and Sen's slopes to quantify long-term rate-of-change. Confidence intervals for Sen's slope were estimated following Hollander & Wolfe (1973).

Local Climate Indices
Local air temperature anomalies were calculated using observations from 6 stations within Puget Sound lowlands made available via the NCEI global hourly-integrated surface database. Total river discharge was estimated using USGS and Environment Canada gauge data for the Fraser, Skagit, Snohomish, Elwha, Cedar, Duwamish, Nisqually, Nooksack, Puyallup, Skokomish, and Stillaguamish Rivers.

DEPARTMENT OF ECOLOGY
State of Washington

The Marine Monitoring Unit at the Washington State Department of Ecology collects vertical water column profile data on a year-round, monthly basis at 31 stations within greater Puget Sound. C.T.D. packages deployed from surface vessels and float planes provide measurements of temperature, salinity, dissolved oxygen, turbidity, transmissivity, *in situ* flourescence, and chlorophyll a. Bottle samples are used for chemical analyses of nutrient species, particulates, total alkalinity, and dissolved inorganic carbon.

Using data collected between 1999 and 2024, we investigate the relative roles of local vs. large-scale forcing in driving observed temperature and salinity anomalies as well as explore the connection between spatial signatures and underlying physical estuarine processes.



3 LOCAL VS. LARGE-SCALE FORCING

An EOF analysis is used to investigate interannual patterns and the spatial coherence of temperature and salinity anomalies measured between 1999-2024. Correlation analyses were used to quantify linear relationships between leading principal components (PCs) and forcing indices that describe processes occuring on scales ranging from local to global.

Table 1 Pearson's correlation coefficients for leading principal components of Puget Sound temperature and salinity with indices of regional and large-scale climate variation. Significance at the 90%, 95%, and 99% level are indicated by *, **, and ***, respectively.

	Annual		Winter		Spring		Summer		Fall	
	PC_1 T	PC_1 S	PC_1 T	PC_1 S	PC_1 T	PC_1 S	PC_1 T	PC_1 S	PC_1 T	PC_1 S
PC_1 T	1.00		1.00		1.00		1.00		1.00	
PC_1 S	-0.16***	1.00	-0.08	1.00	0.02	1.00	-0.17	1.00	-0.32***	1.00
ONI	0.55***	0.26***	0.42***	0.19*	0.64***	0.19*	0.56***	0.27**	0.53***	0.53***
PDO	0.55***	-0.26***	0.41***	-0.21*	0.58***	-0.43***	0.71***	-0.23**	0.43***	-0.01
NPI	-0.34***	0.27***	-0.20*	0.38***	-0.55***	0.42***	-0.33***	0.23**	-0.01	-0.14
UPI	-0.18***	0.30***	-0.26**	0.14	-0.36***	0.31***	-0.18	0.45***	0.19	0.33***
$ATEMP_i$	0.72***	-0.13**	0.47***	-0.09	0.83***	-0.33***	0.82***	-0.07	0.57***	-0.04
Q_i	-0.22***	-0.75***	0.26**	-0.72***	-0.53***	-0.80***	-0.65***	-0.73***	0.16	-0.77***

Consistent with prior work (Moore et al 2008), results indicate that the highest correlations for PC1T and PC1S are a 1 mo lagged response to local air temperatures and river flow, respectively. ONI and PDO are positively correlated with temperature anomalies (5 mo and 0 mo lag). PC1 correlations exhibit a distinct seasonality such that large-scale marine forcing plays a larger role in contributing to cool season (fall/winter) temperature variation within Puget Sound than in warmer months.

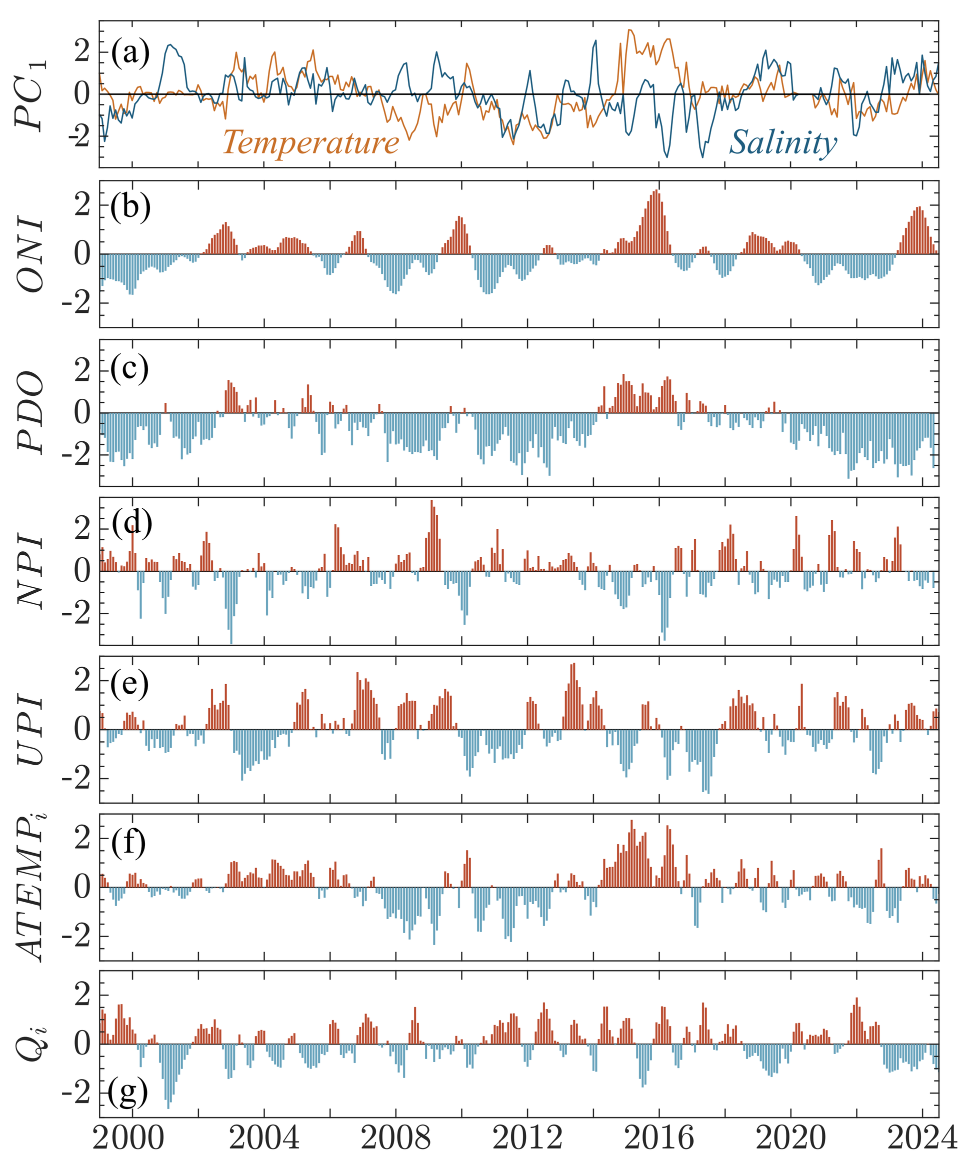


Figure 1 Monthly values of (a) PC1 for Puget Sound water temperature and salinity and the indices for (b) El Niño-Southern Oscillation, (c) Pacific Decadal Oscillation, (d) North Pacific Index, (e) Coastal Upwelling peristence (Deppe et al 2018), (f) Puget Sound lowland air temperature, and (g) total freshwater discharge. Subscript i indicates that value represents 3-month integrals of monthly anomalies. $ATEMP$, Q, UPI, and NPI have been normalized by their standard deviations.

4 SPATIALLY HETEROGENEOUS WARMING RATES

To complement the EOF analysis described in §3, warming trends within the upper 100m of Puget Sound between 1999-2024 were calculated on monthly data gridded to 5m vertical bins using a Theil-Sen estimator.

Results shown in Figure 2 exhibit a high degree of spatial heterogeneity and generally increase with landward distance from Admiralty Reach. Notably, average warming rates between 60-100m depth have a different spatial signature than surface waters with a regional maxima in Central Basin, which is warming at a rate nearly double that of adjacent Pacific surface waters near the estuary mouth.

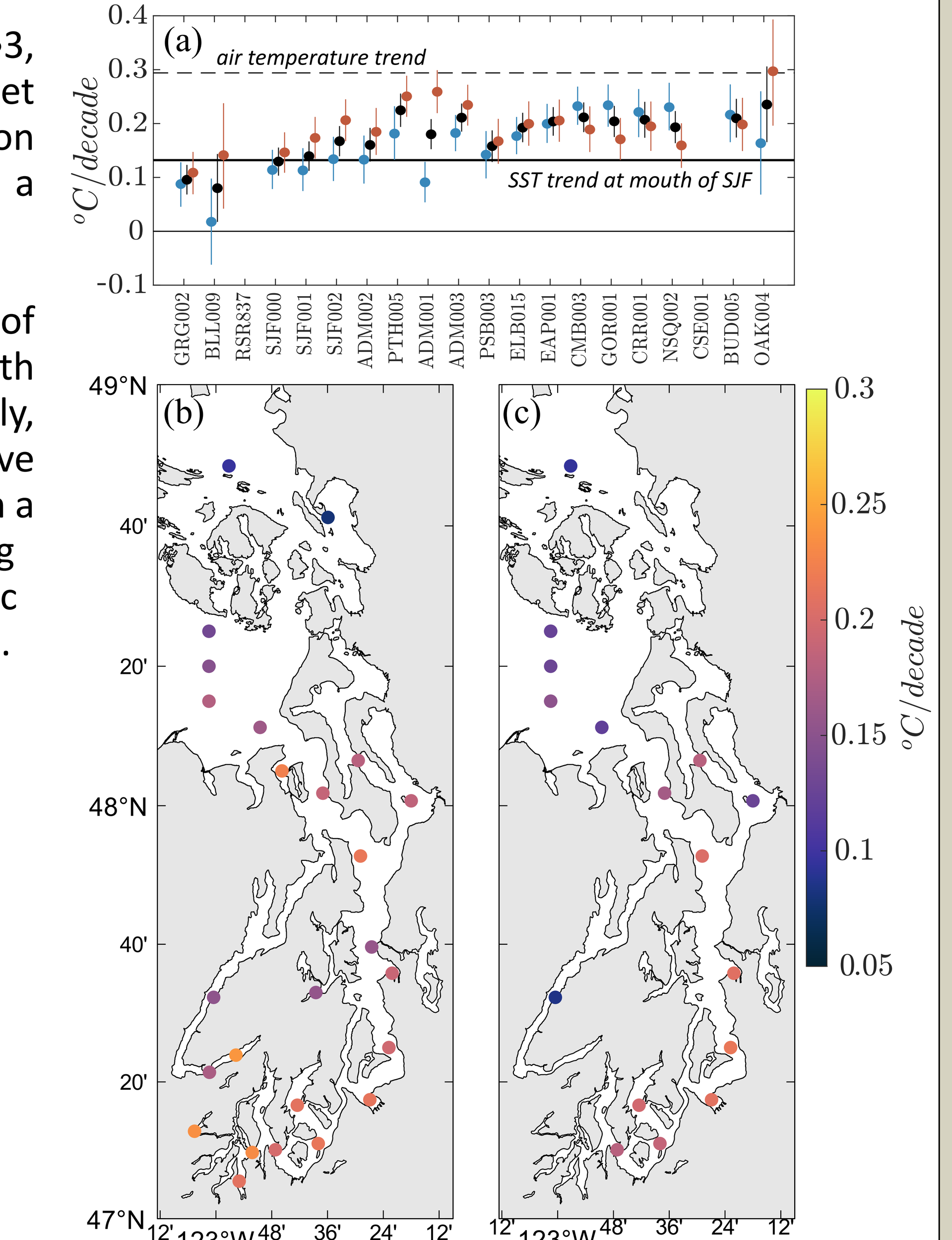


Figure 2 (a) Depth-averaged temperature trends across WA Ecology's monitoring network shown with 95% confidence intervals for full dataset (black), April-September (red), and October-March (blue). Estimates of regional warming rates in air temperature (Office of the Washington State Climatologist) and Pacific surface waters adjacent to SJF (estimated using NOAA OI SST v2) are also shown. Spatial maps of depth-averaged warming trends in Puget Sound for (b) 5-60m and (c) 60-100m.

5 ESTUARINE RESIDENCE TIME & CLIMATE SENSITIVITY

To assess the impact of spatially-variable residence times within Puget Sound on observed temperature trends, we compare the leading order spatial EOF mode to decadal averages of residual temperature anomalies (Figure 3). Results indicate that Central Basin and South Sound exhibit a high degree of sensitivity, such that waters landward of Admiralty Reach exhibit stronger temperature changes in response to discrete climate events.

Time-integrals of measured air temperature anomalies, based on integration windows that maximize correlation with observed subbasin water temperatures, mirror this observed tendency. The optimal integration windows (6 months, Central Basin; 4 months, Strait) are consistent with recent box model estimates of residence times within Puget Sound (MacCready et al 2021).

These results suggest that longer residence times combined with strong refluxing that occurs near sills act to promote enhanced climate sensitivity within Puget Sound principally through elevated exposure to local air temperature trends.

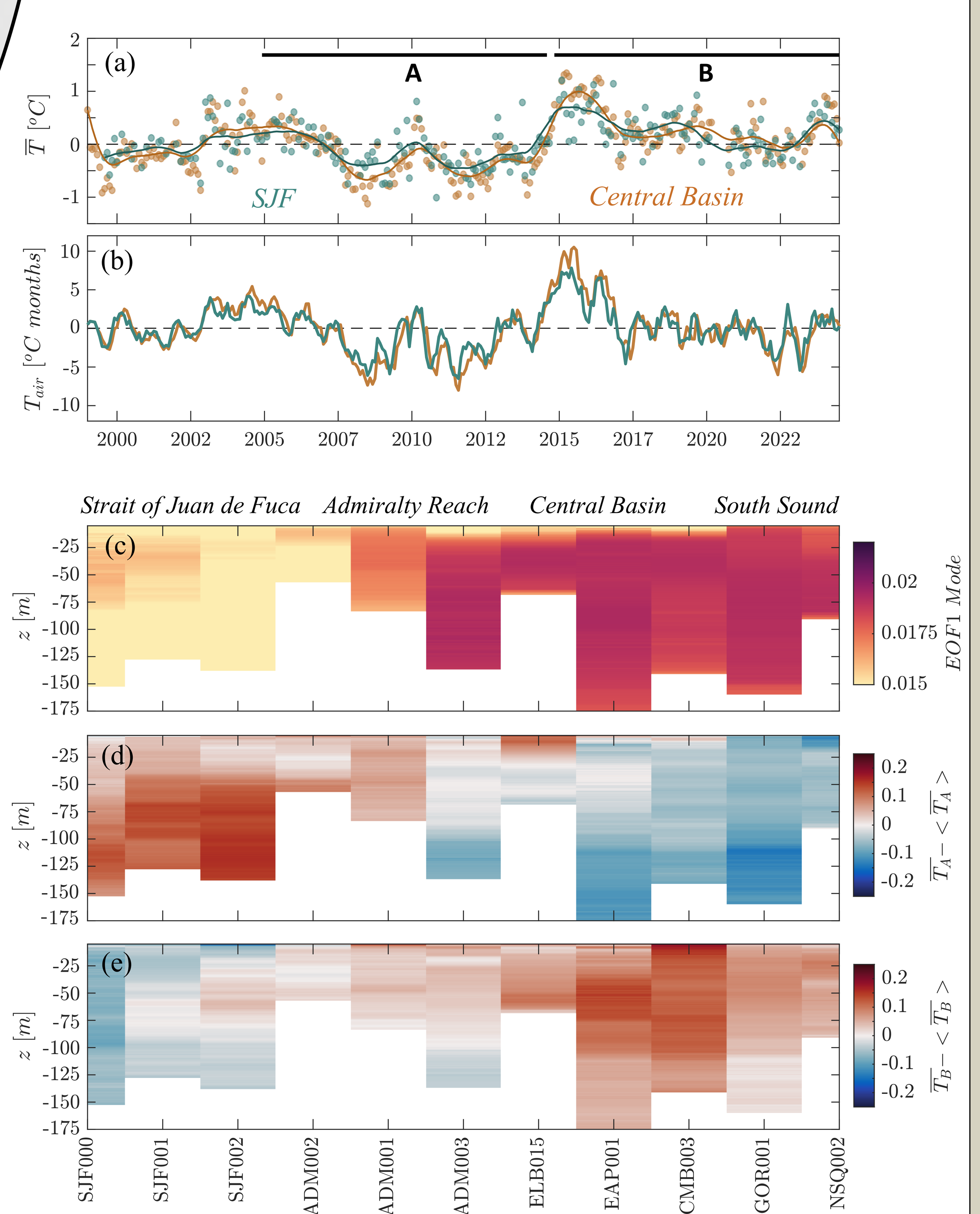


Figure 3 (a) Time series of depth-averaged temperature anomalies measured in Central Basin (orange) and the Strait of Juan de Fuca (green). (b) Time series of conditionally-integrated Puget Sound lowland air temperature anomalies that maximize correlation with observed water temperatures. (c) Leading EOF spatial mode. (d) Residual temperature anomaly field for 2004-2014. (e) Residual temperature anomaly field for 2014-2024.

6 CONCLUSIONS & FUTURE WORK

This work highlights the importance of resolving regional physical processes that control how climate change is imprinted in geographically-diverse nearshore environments. A joint analysis of interdecadal trends and principal components suggest that estuarine residence time plays a leading-order role in modulating the sensitivity of Puget Sound subbasins to climate warming through regulating exposure to local atmospheric trends.

Projected hydrologic changes and heat wave intensification underscores the need for future investigations of how changes in subtidal gravitational circulation will affect the response of estuaries to discrete climate events. High residence times within fjord-like systems have the potential to amplify climate impacts locally (Jackson et al 2018); monitoring strategies are needed to resolve shifts in physical dynamics that regulate deep-water renewal and vertical exchange within these environments.

Marine Water Column Data is made publicly avaiable through the Washington State Department of Ecology Environmental Information Management System

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