How do variations in Northeastern Pacific circulation affect the delivery of subarctic and equatorial water to the Canadian shelf?

Motivation and background

The supply of intermediate waters from the interior Pacific to the Northeastern Pacific shelf is thought to be an important mechanism for modifying ocean conditions along the Canadian Pacific margin. However, the mechanisms which link interior waters to the continental slope and drive exchange with shelf waters are unclear. It is also not clear if the supply of interior water masses is consistent along the meridional extent of the Canadian Pacific or variable in space and time.

A recent analysis by Meier et al., 2025, showed that waters located on the 26.6 kg/m^3 isopycnal (100-200 m deep) at the southern Vancouver Island continental slope and shelf consist of a relatively consistent (on interannual timescales) mixture of subarctic water, arriving via the North Pacific Current (NPC), and equatorial water, arriving via the California Undercurrent (CUC). A recent analysis by Stevens et al., 2025 showed that the interannual and decadal variability of dissolved oxygen located on the 26.5 kg/m^3 (100-200 m deep) at the Queen Charlotte Sound shelf and slope seem to be related to variability in subarctic waters transported via the NPC but do not seem to be linked to variability in the transport of equatorial waters via the California Undercurrent. These shelf seas are relatively close geographically and therefore might be expected to display similar variability; However, they appear to have variability that is not coupled over interannual timescales.

As these areas are located in a dynamic region influenced by poleward CUC and eastward NPC transport, it is possible that variations in the NPC and CUC could result in the delivery of different Pacific water masses mixtures to different regions of the Canadian Pacific coastline. Is there a way to understand the varying expression of the prevailing ocean circulation and its impacts on water mass composition on the Canadian Pacific shelf? The isopycnal range of 26.0-26.6 kg/m^3 spans a large portion of the water column below 100 m on the shelf— my analysis focuses on spice as a measure of water mass composition in these isopycnal range.

California Undercurrent

Approach

Variations in the expression of the NEP circulation can be clearly observed in monthly temperature anomaly (T') fields at 400 m depth from the GLORYS 1/12° reanalysis product (see Figure 1). During some periods, there is a clear extension of the warmer equatorial CUC waters all the way up to Haida Gwaii. During other periods, this influence quickly diminishes north of Juan de Fuca Strait and colder subarctic waters are present over large portions of the Canadian Pacific shelf.

A PCA analysis (hereafter referred to interchangeably as PCA or EOF analysis) of T' from GLORYS monthly reanalysis fields from 1993-2024 provides a way to quantify of this mode of variability. The third EOF of this analysis (Figure 2a) accounts for 5% of the regional variability and represents warmer waters along the continental slope of the NE Pacific. Strong positive expressions of this EOF (Figure 2b) primarily represent warmer waters along the Canadian Pacific shelf, while negative expressions (Figure 2c) represent cooler waters along the shelf. The third PC of this analysis (Figure 2d) quantifies the time-varying expression of this mode of variability, which I can compare to spice along the Canadian Pacific on the 26.6 kg/m^3 isopycnal to understand the impact of CUC variability on the shelf region.

Results

Similar to Meier et al., 2025, I can use spice variability on the 26.6 kg/m^3 isopycnal at stations along the shelf to assess contributions of spicy equatorial water and minty subarctic water to the deeper waters that are present on the Canadian Pacific shelf. Station P4 is located in the CUC path on the southern VI continental slope with interannually consistent spiciness (Figure 3a), similar to spice observed at stations nearby by Meier et al. Stations CS01 and CS09 are located on the QCS slope and shelf, respectively. They are mintier than P4 on average and more variable on interannual time scales, suggesting that they are more strongly influenced by subarctic waters than areas on the Vancouver Island shelf. This finding is consistent with the linked oxygen variability observed between subarctic waters and QCS by Stevens et al., 2025. Station CS09 (shelf) is mintier than CS01 (slope), on average— Meier et al., 2025 suggest (for the VI shelf) that this is due to the influence of equatorward-flowing upwelling currents transporting mintier water from the north during summer.

The annual spice at CS09 and CS01 is correlated with PC3 (Figure 3c). This implies that spicer equatorial water is more prevalent in QCS during periods when PC3 is positive, when the influence of the CUC extends further poleward (e.g. Figure 2b). Conversely, when PC3 is negative, the influence of the CUC is reduced and QCS waters are mintier, suggesting an increased prevalence of subarctic waters (e.g. Figure 2c). This relationship is also observed on the 26.1 kg/m^3 isopycnal in the inshore waters of Fitzhugh Sound (the deepest isopycnal that is consistently present in this basin), indicating that variations in the poleward expression of the CUC impacts the supply of offshore water to marginal regions of the Canadian Pacific. Importantly, there is no significant correlation between PC3 and spice at Station P4 (Figure 3c), which suggests that variations in the poleward extension of this current does not play a significant role in water mass delivery to the Vancouver Island shelf.

North Pacific Current

Approach

Freeland (2006) derived two modes of variability related to the NPC: the "breathing mode", which quantified variations in the overall transport of water through the NPC, and the "bifurcation mode", which quantified redistribution in transport into either the Alaska Current or the California Current. This analysis used four years of Argo float data from the early 2000s to calculate differences in dynamic height between three stations in the North Pacific: station G, representing a local minimum in dynamic height in the Alaska gyre; station C, representing a local maximum in dynamic height in the California Current, and station B, representing the location where the dividing streamline hits the BC coast. He then performed a PCA analysis on the signals to extract the two modes of variability.

To assess if either mode plays a role in delivering subarctic waters to the Canadian Pacific shelf, I have recreated this analysis using GLORYS 1/12° monthly reanalysis fields from 1993-2024 (Figure 4). Quantitative comparisons of the eigenvectors from mine and Freeland's PCA analyses are consistent, and qualitative comparisons between the results of the two analyses suggest that they provide roughly consistent outputs. I can then compare the newly calculated breathing and bifurcation mode PCs to spice along the Canadian Pacific on the 26.0 kg/m^3 isopycnal to understand the impact of NPC variability on the shelf region.

Results

Waters at the 26.0 kg/m^3 isopycnal (Figure 5a) are generally mintier than those at deeper 26.6 kg/m^3 isopycnal (Figure 3a), with increased interannual variability. Similar to the 26.6 kg/m^3 isopycnal, waters on the 26.0 kg/m^3 isopycnal are generally spicier at station P4 indicating an increased influence of equatorial waters, and nearshore waters are generally mintier.

There are statistically significant anticorrelations between annual mean spice on the 26.0 kg/m^3 isopycnal and annual mean PCs of the breathing mode at all stations. These correlations suggest that, for VI and QCS, waters at around 100 m depth become mintier when NPC transport is stronger, and spicier when NPC is weaker. This observation is consistent with increased NPC transport delivering mintier subarctic waters to the shelf, while weaker NPC transport allows for greater influence of spicier equatorial waters. There are no significant correlations between the annual mean spice and the bifurcation mode at any of the stations analysed. This finding suggests that variations in the supply of water to either the Alaska Current or the California Current do not play a significant role in modifying the composition of the Canadian Pacific shelf.

Key takeaways

- Waters below 100 m on the Canadian Pacific shelf are a variable mix of subarctic and equatorial water masses, with differences in interannual variability between regions.
- A principal component (PC3) from a regional EOF of temperature anomaly at 400 m depth captures the poleward expansion of warmer equatorial waters. When PC3 is high, spicier (equatorial) water reaches further north.
- The breathing mode of the North Pacific Current (NPC), which reflects the overall strength of NPC transport, is anticorrelated with spice on the 26.0 kg/m^3 isopycnal—suggesting stronger transport enhances delivery of minty (subarctic) water to all areas of the BC shelf.
- The bifurcation mode of the NPC, which reflects shifts in transport between the Alaska and California Currents, does not appear to significantly affect shelf water properties along the Canadian margin.
- Spice variability at QCS reflects a varying supply of subarctic water via the NPC and an episodic influence of equatorial water, likely due to the intermittent poleward reach of the CUC.
- Spice variability at VI reflects a varying supply of subarctic water via the NPC and a consistent influence of equatorial water via the CUC.
- These results help explain why oxygen variability on the QCS shelf is linked to subarctic waters but is decoupled from variability further south.
- These results also provide insight into the results of Thomson and Krassovski (2010), who identified CUC influence north of VI. They employ long-term means

over decades which would include periods where the CUC influence extends poleward, though PC3 suggests this extension is not a consistent feature.

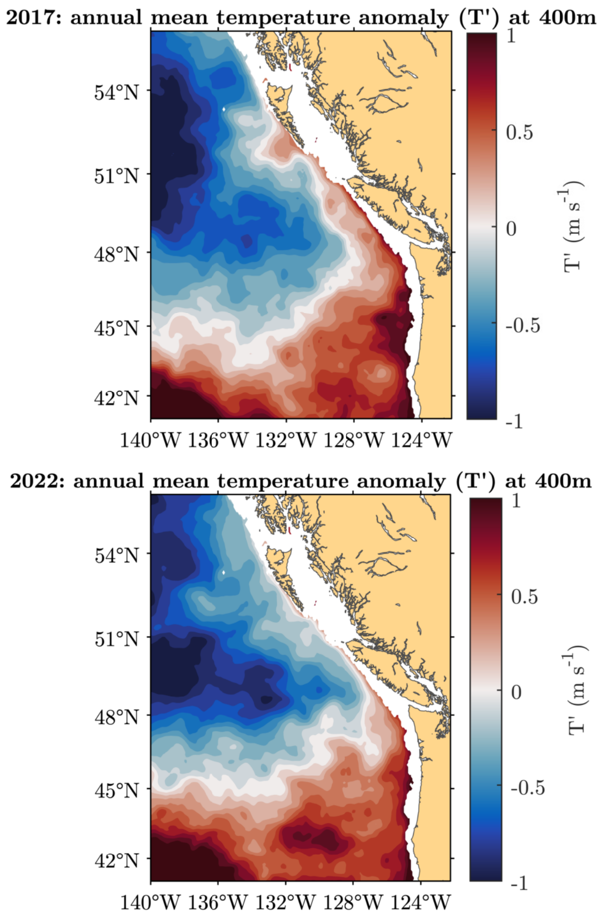

Figure 1: Annual mean temperature anomaly at 400 m depth from two representative years. Data from the GLORYS12V1 product with 1/12° horizontal resolution.

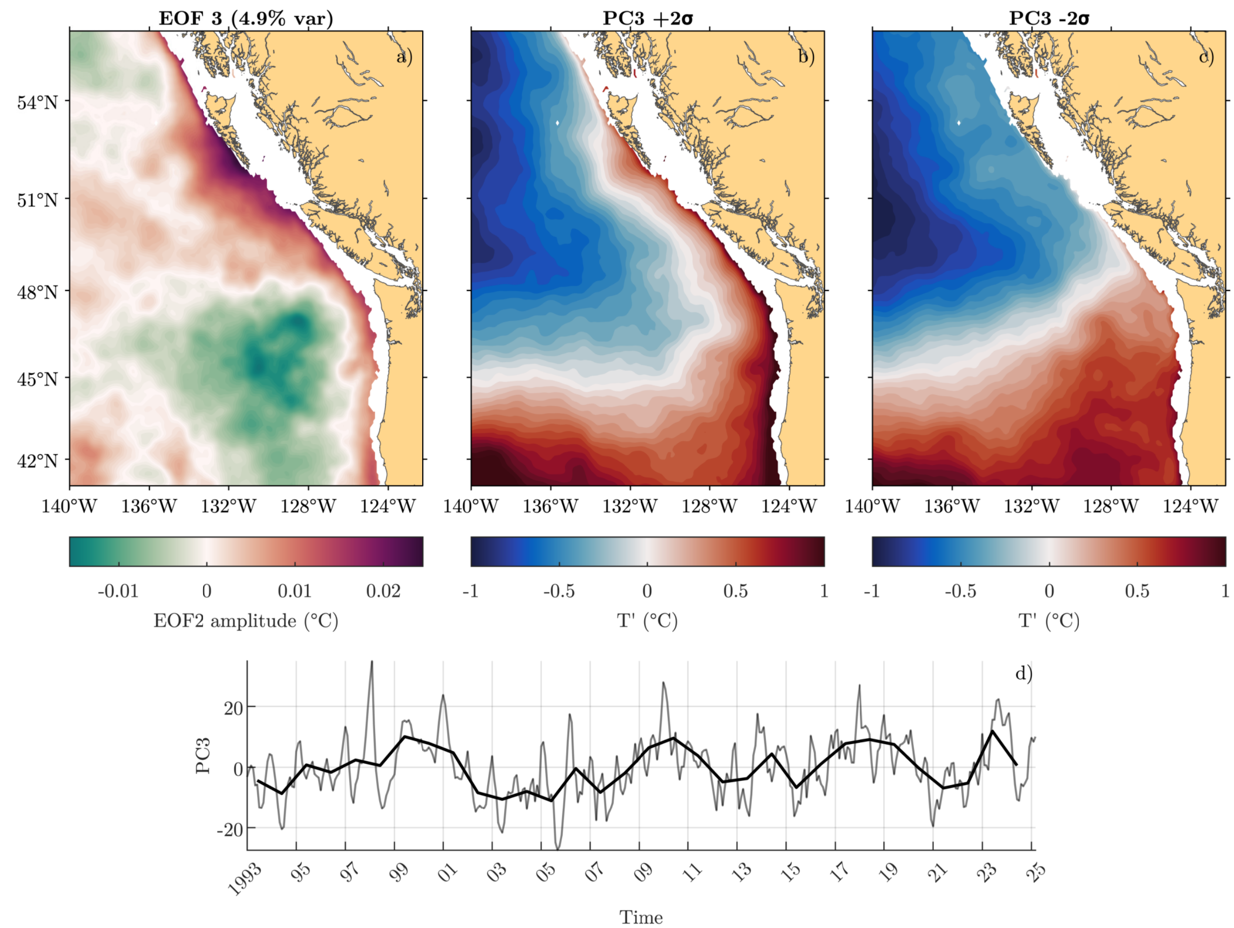

Figure 2: A PCA analysis of monthly T’ from GLORYS reanalysis fields from 1993-2024. a) The third EOF of the analysis, b) and c) strong positive/negative representations of EOF2, d) Monthly (thin black line) and annual mean (thick black line) PC3.

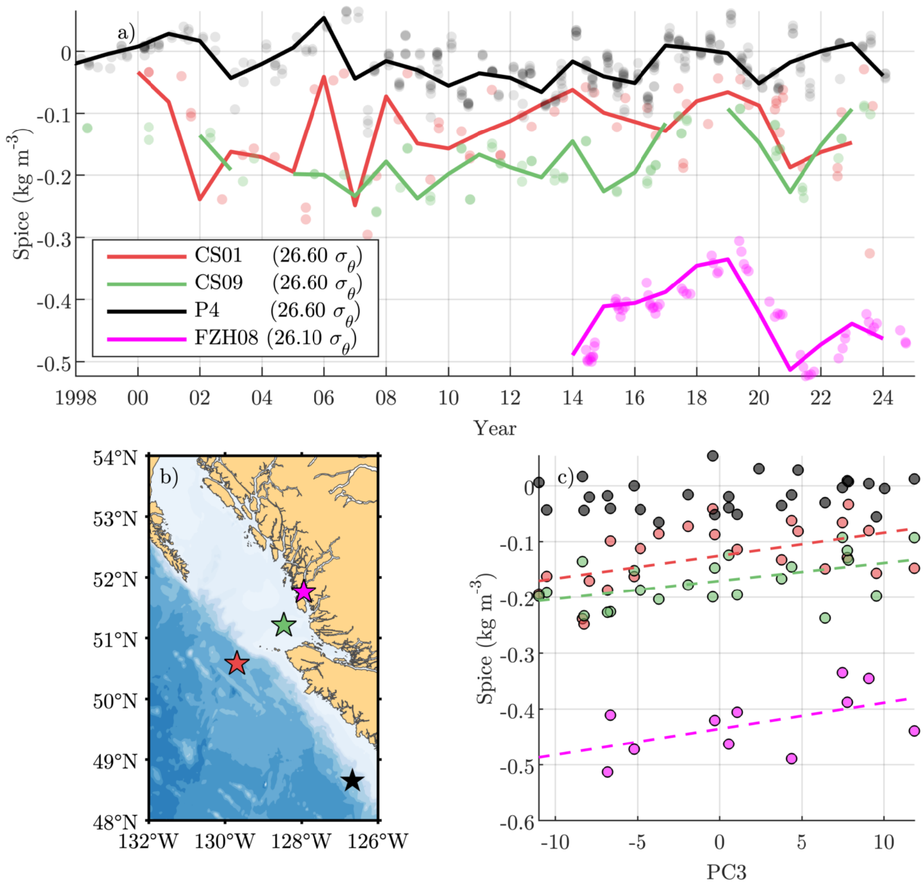

Figure 3: a) Time-series of spice at stations along the Canadian Pacific. Colored circles represent individual measurements while colored lines represent the annual mean spice. Colors in a) correspond to station locations (stars) in b). c) Spice vs. PC3 for each station with dashed lines where a statistically significant relationships are observed.

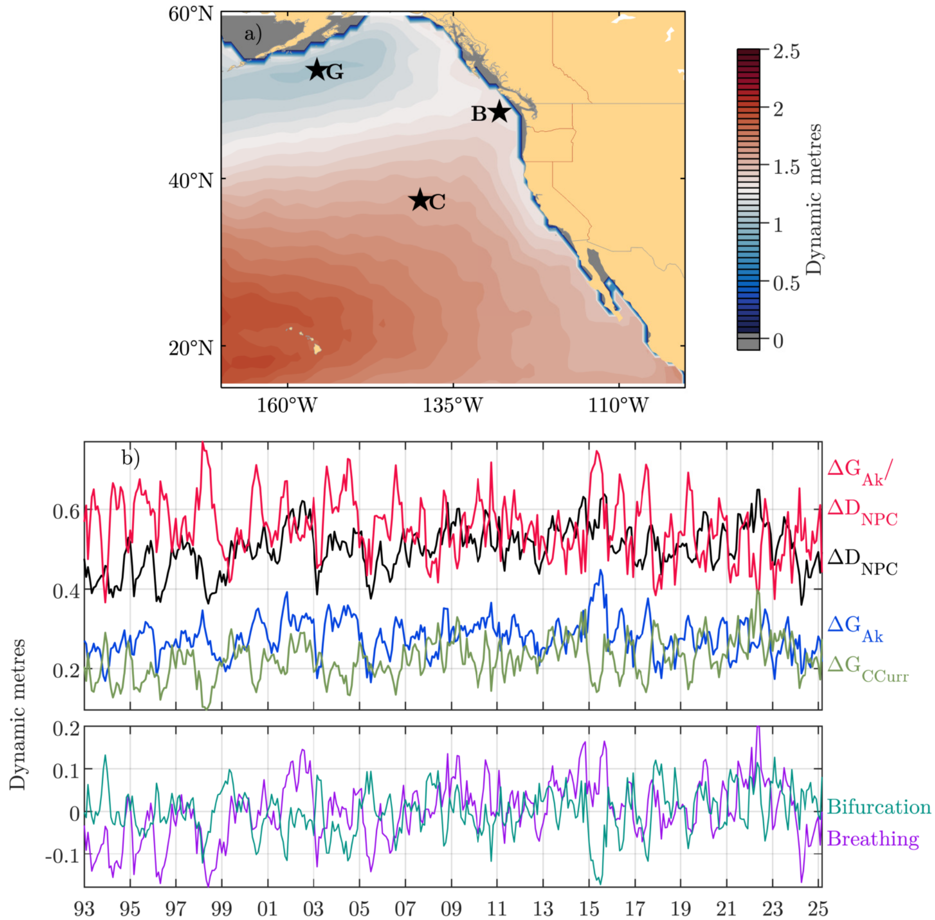

Figure 4: a) Dynamic height referenced to 1000 m from the GLORYS 1/12° reanalysis product with Alaska gyre (G), California Current (C), and bifurcation (B) stations marked. b) Differences in surface dynamic height between stations used to estimate transport across key current systems: ΔD_{NPC} = G – C (black) represents transport across the North Pacific Current; ΔD__GAk = G – B (red) represents transport into the Alaska Gyre; and ΔD__CCurr = B – C (green) represents transport into the California Current. c) Principal component time series of the first (breathing mode, purple) and second (bifurcation mode, cyan) EOFs derived from a PCA of these dynamic height differences.

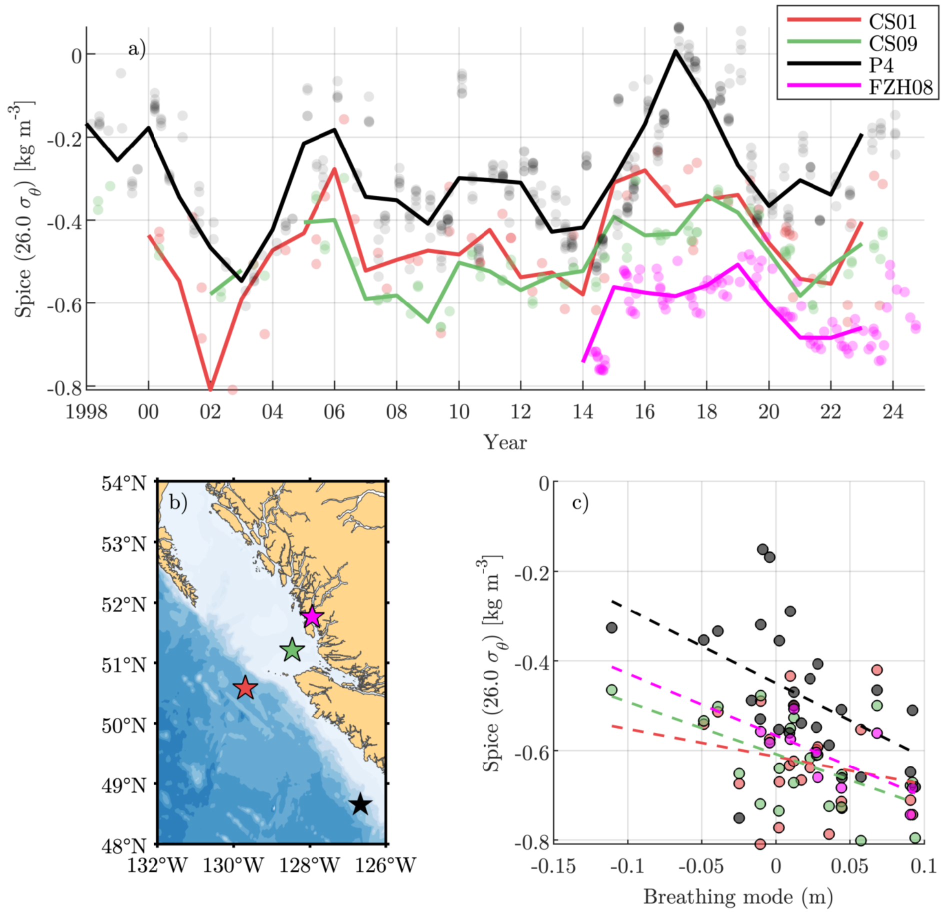

Figure 5: a) Spice on the 26.0 kg m^{-3} isopycnal at stations along the Canadian Pacific shelf. Light-colored circles represent individual observations, and bold lines show the annual mean at each station: CS01 (red), CS09 (green), P4 (black), and FZH08 (magenta). b) Locations of the four stations analyzed. c) Relationship between annual mean spice on the 26.0 kg m^{-3} isopycnal and the breathing mode index at each station. Dashed lines indicate linear regressions where a statistically significant relationship was found.