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Contrasting physical and biological drivers of subsurface oxygen change in the northern California Current System

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Contents of this file

Text S1: Evaluating CTD vs bottle oxygen

We examine the oxygen observations performed for each individual cruise from which we use a subset of profiles. We evaluate the Seabird SBE43 sensor oxygen data by comparing them with all available, quality-controlled (quality flags 0, 2, or 6 as per waterproperties.ca) paired discrete water samples (Winkler titrated, Carpenter et al. 1965). To evaluate oxygen observations in the subsurface, we calculate the difference in oxygen (CTD minus bottle oxygen) for all subsurface (>50 m) pairs where density is between σ_θ25.8 and 27 kg m^{-3}.

Overall, the mean CTD and bottle oxygen difference across all cruises is -0.5 ± 1 μmol kg^{-1} (Figure S1d). When the CTD-bottle differences are averaged within cruises, 84% of these cruise-mean differences fall within this range. Agreement between bottle and CTD oxygen improves with time (Figure S1a, c). We discover a small tendency in early data towards lower CTD oxygen values (negative mean O2 difference values, Figure S1d, e); however, over time the total change in the mean oxygen difference per cruise is small: ~1 μmol kg^{-1} over the entire 20-year time series (Figure S1e), and the distribution is overall centred (Figure S1f).

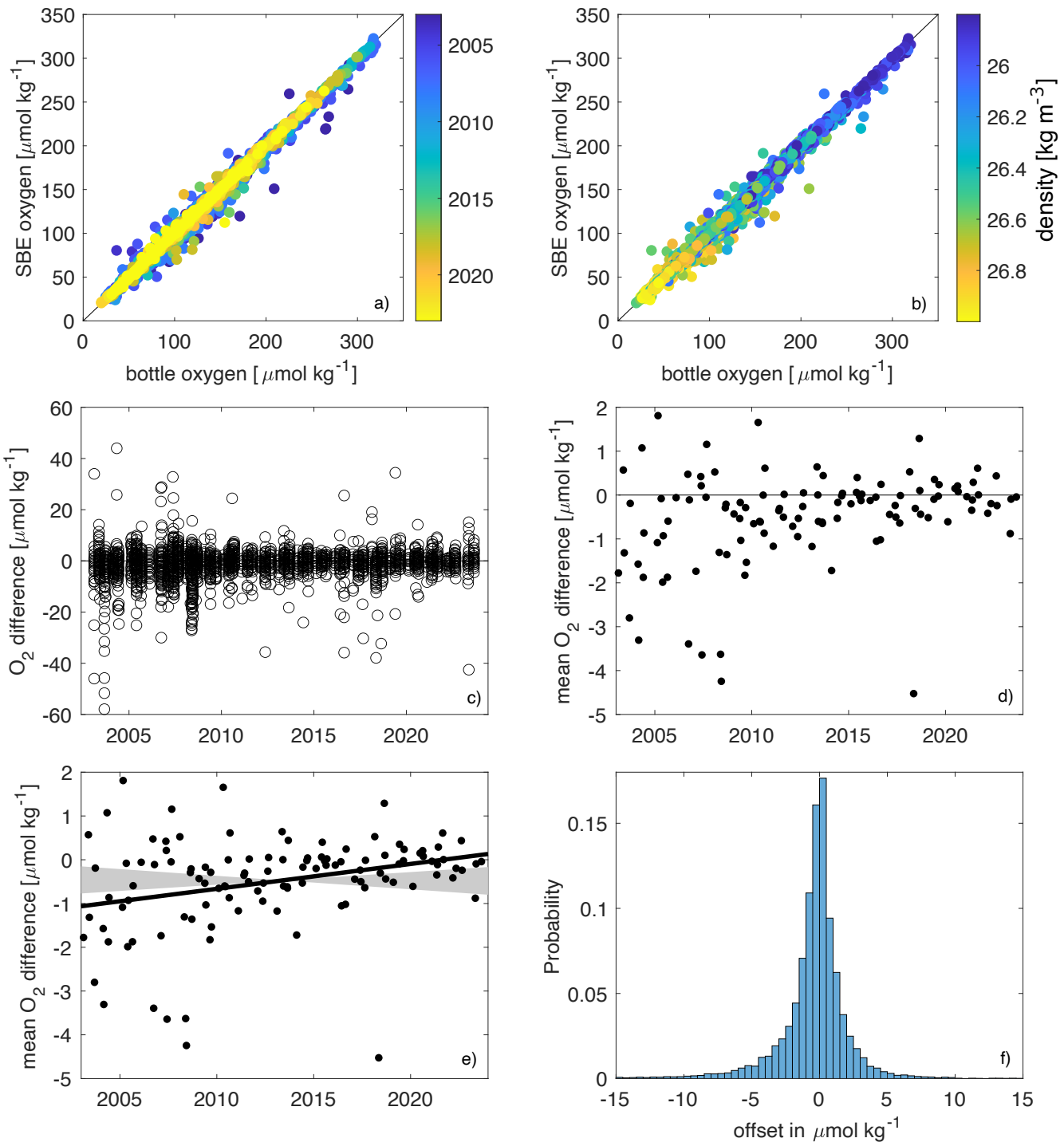

Figure S1 – Oxygen data quality evaluation for all full cruises from which we use data, where depth > 50 m and density σ_θ ≥ 25.8 and ≤ 27 kg m^{-3}. a) and b), CTD (Seabird, SBE34) vs bottle oxygen coloured by year of the cruise and density of the pair, respectively. c), CTD minus bottle oxygen for each pair over time. d), like c), but averaged for each cruise. e), like d), but with trend (see Text 2.3). f), probability distribution for each pair in c).

Text S2: Potential impact of the Juan de Fuca eddy

Within the study area, the Juan de Fuca eddy develops and persists during the upwelling season (e.g., Foreman et al., 2008). It is a centre of high surface productivity (Marchetti et al., 2004) and long retention times (MacFadyen et al., 2008), resulting in frequently hypoxic bottom waters (Crawford and Peña, 2013). In this supplementary text, we separate the shelf region of our study (Figure 1b) into regions inside and outside the eddy (Figure S2), based on the typical location of the eddy (Crawford and Pena, 2013).

We repeat all analyses from the main paper for the shelf under the eddy and shelf outside the eddy and find that seasonal patterns and trends are generally the same. However, the isopycnals in the eddy shoal higher (during LUW, Mann-Whitney test for all comparisons, significantly different for all three isopycnals), are slightly less spicy (during EUW and LUW, on 26.6) and have lower oxygen (during both EUW and LUW, for all three isopycnals) than the isopycnals outside the eddy (Figure S3). Spiciness and oxygen correlate more strongly (but still weakly) outside the eddy than within (Table S1), but the general seasonal pattern is as described in the main paper (Section 2).

The increase in spiciness we observe during EUW for the full shelf (26.3, Figure 4d) is observed outside the eddy, but not within (Figure S4c, d), while the increase in spiciness on both mid-depth isopycnals during LUW (Figure 4h) is present both outside and within the eddy (Figure S4g, h). We also observe the same decrease in oxygen during EUW both inside and outside the eddy (Figure 4b, Figure S4a, b). Significant shoaling of the mid-depth isopycnals is observed within the eddy, but not outside or on the full shelf (Figure S5a, S9b). During LUW, we do not observe a significant oxygen trend on the (full) shelf (Figure 4f). We do however observe a decrease in oxygen within the eddy in mid-depths (on 26.0, Figure S4f), and an unexpected significant increase in oxygen near the bottom outside the eddy (on 26.6, Figure S4e). We do not have enough data to resolve these differences, but suggest they be the target of future research.

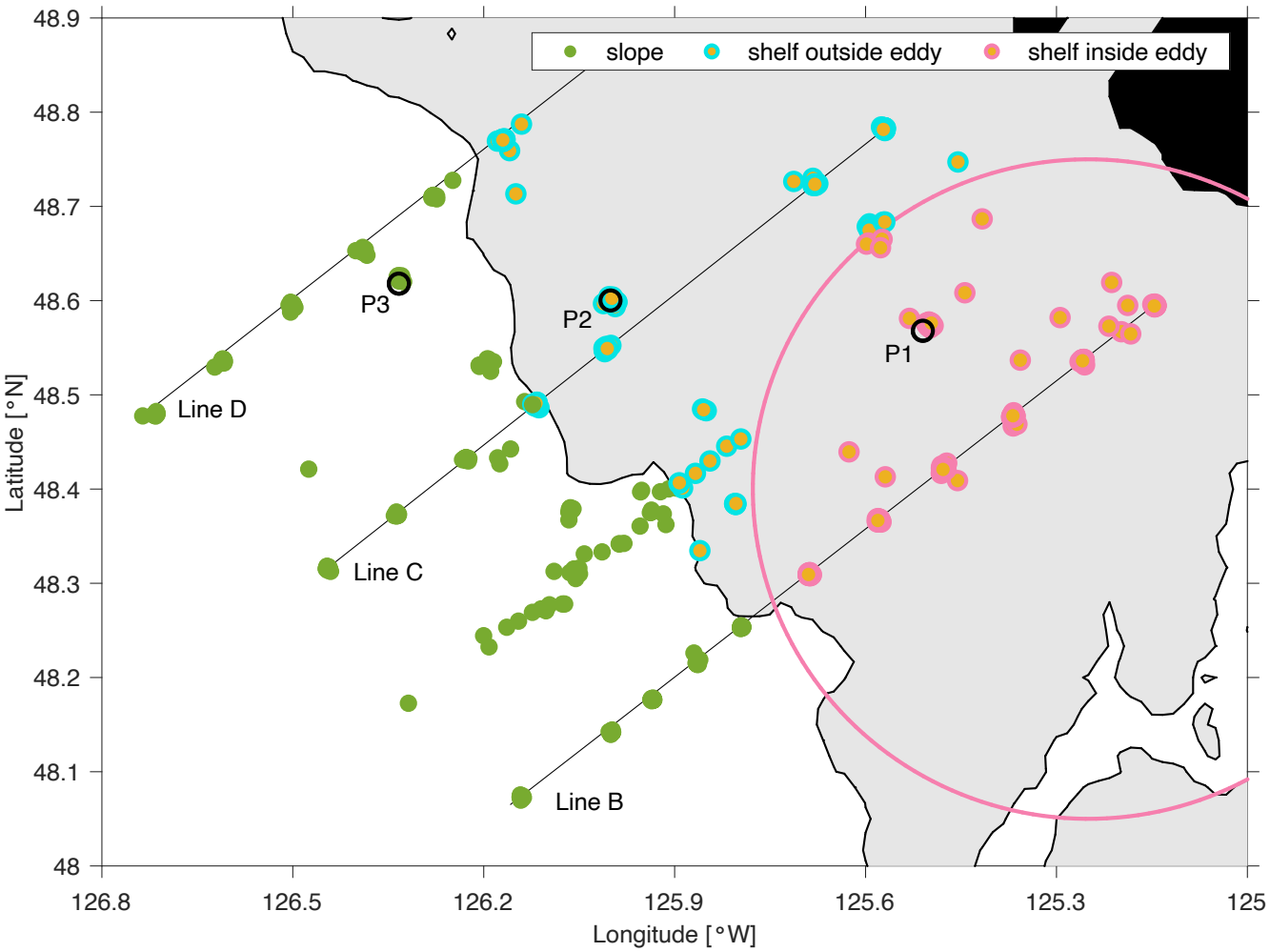

Figure S2: Spatial distribution of the study area, with the slope stations in green and shelf stations in yellow. The shelf stations in the zone where the eddy is typically found are outlined in pink, while those outside the eddy are outlined in cyan. The shelf (depth ≤ 200 m) is shown in light grey. The eddy outline is based on Crawford and Peña, 2013, and Franco et al., 2023. We also label Line P stations P1, P2, and P3, as well as La Perouse lines B, C, and D.

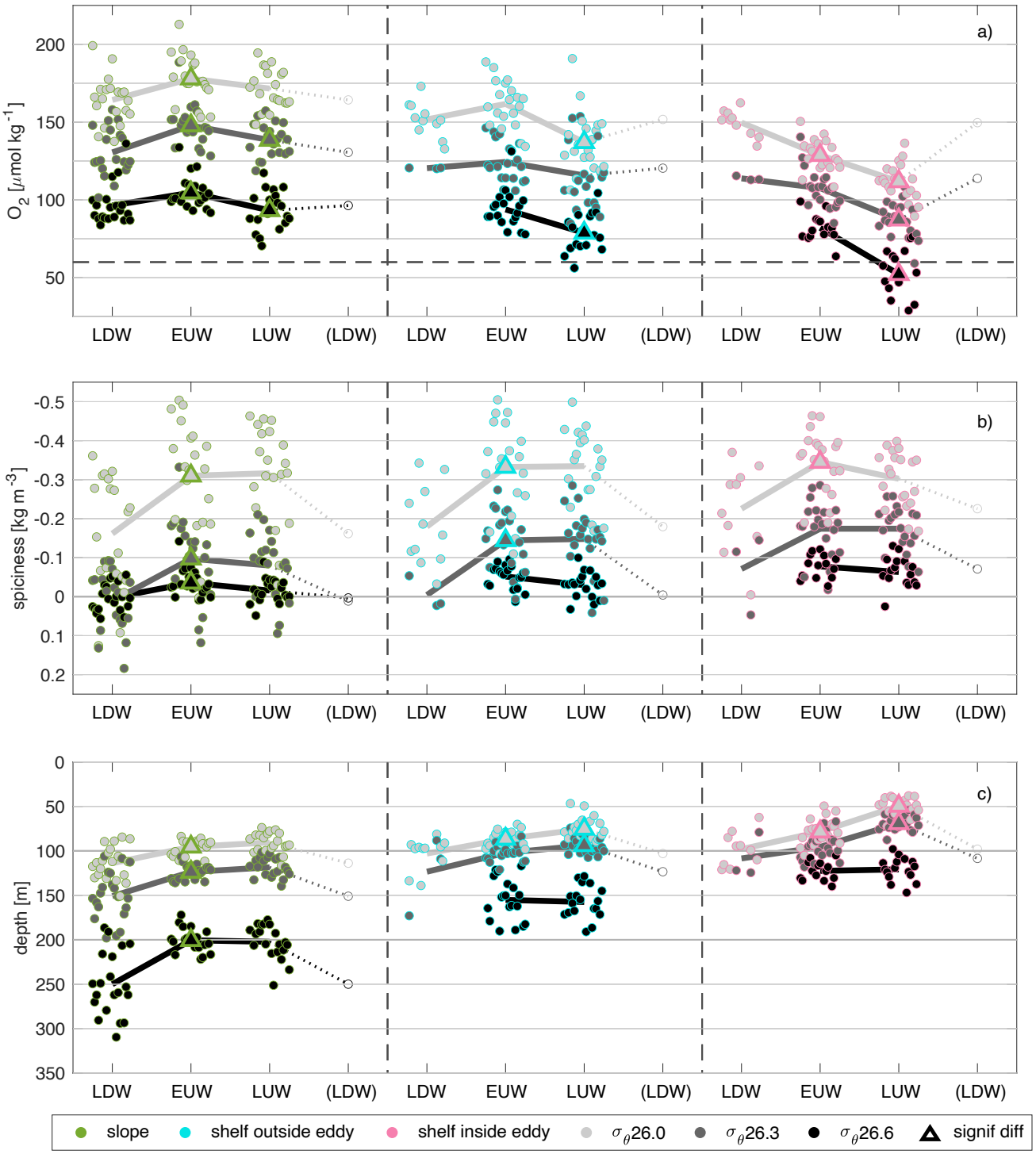

Figure S3: Seasonality of a) oxygen, b) spiciness (increasing downwards), and c) depth for the 26.0 (light grey), 26.3 (dark grey) and 26.6 (black) isopycnals, for each location (slope outlined in green, shelf outside the eddy in cyan and shelf inside the eddy in pink) for LDW, EUW, LUW. The binned values (by season) for each year are shown by the clustered dots (slightly offset for legibility). The seasonal mean is shown by the thick line (dashed to show full cycle and return to LDW). The mean is highlighted with a triangle where significantly different to the previous season (Mann-Whitney test).

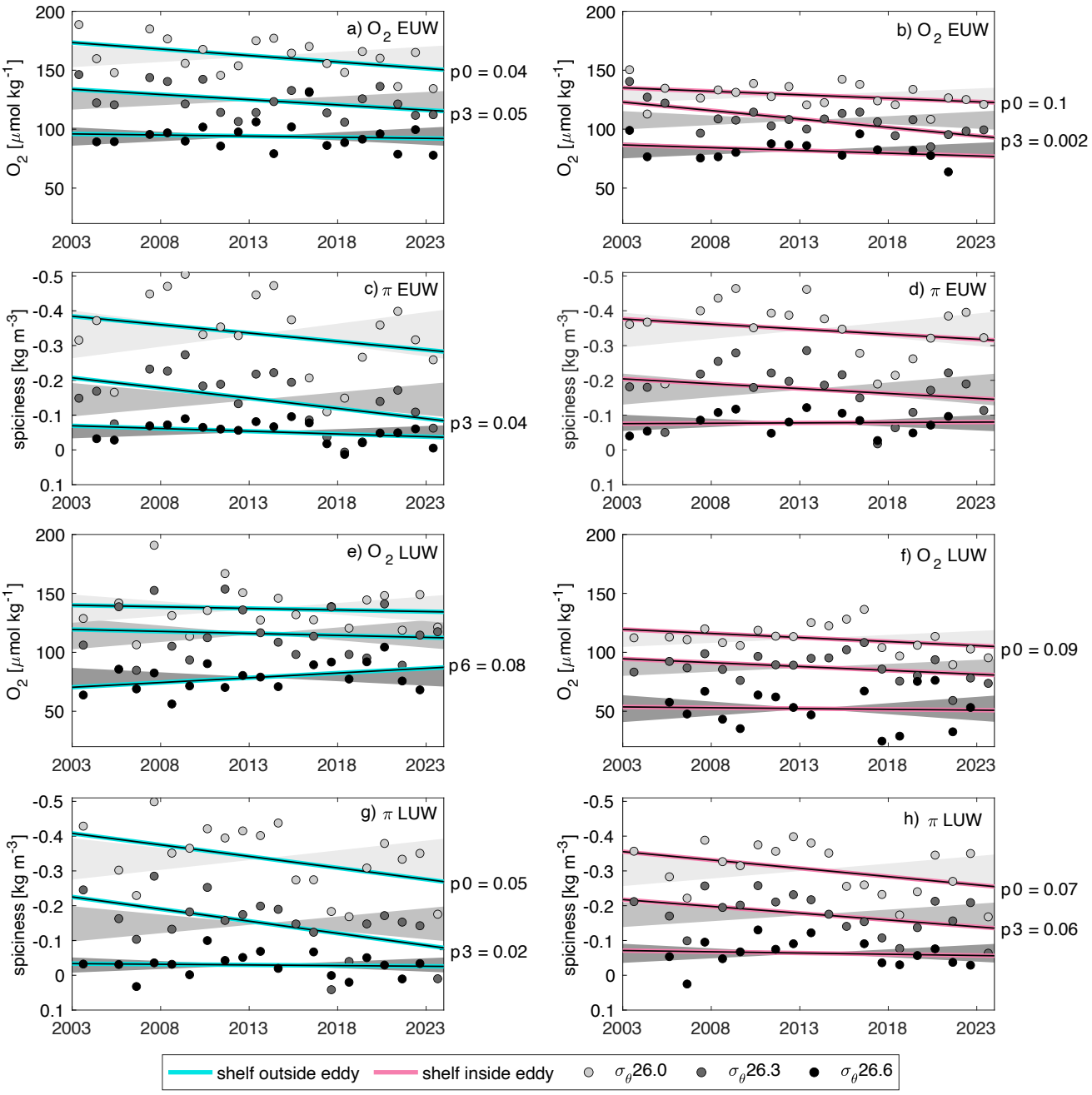

Figure S4: Time series of oxygen and spiciness (π) for EUW (spring, first and second row) and LUW (late summer, third and fourth row) seasons on the 26.0 (light grey), 26.3 (dark grey) and 26.6 (black) isopycnals. The 90% confidence interval from bootstrapping is shown in the bowtie-shape of the same colour. The linear trend is shown in cyan (shelf outside the eddy) or pink (shelf inside the eddy), and the p-value is given on the right where significant (p0 for the 26.0, p3 for the 26.3, and p6 for the 26.6 isopycnal).

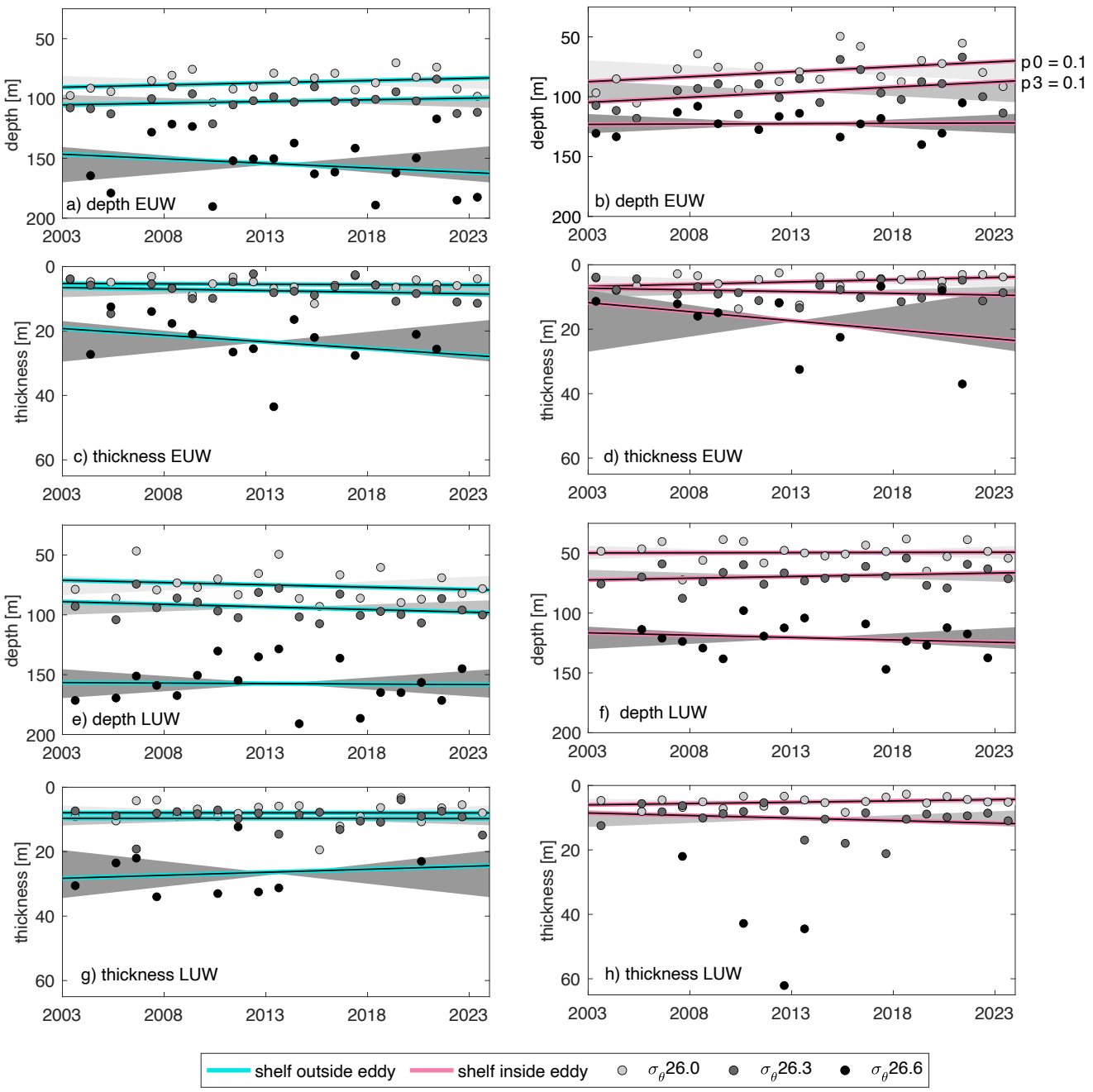

Figure S5: Time series of depth and isopycnal thickness for EUW (spring, first and second row) and LUW (late summer, third and fourth row) seasons on the 26.0 (light grey), 26.3 (dark grey) and 26.6 (black) isopycnals. The 90% confidence interval from bootstrapping is shown in the bowtie-shape of the same colour. The linear trend is shown in cyan (shelf outside the eddy) or pink (shelf inside the eddy), and the p-value is given on the right where significant (p0 for the 26.0, p3 for the 26.3 isopycnal).

Text S3 External effects on local density and spiciness

A brief examination of the time series associated with each source water mass (P26 and C93) shows opposing changes in spiciness since 2003 (Figure S6). At P26, both mid-depth isopycnals have become significantly spicier over the last two decades (26.0: 0.12 ± 0.07 kg m^{-3} and 26.3: 0.14 ± 0.07 kg m^{-3}), while at C93, 26.3 has become significantly mintier (-0.07 ± 0.03 kg m^{-3}). P26 is known to experience variable southern water influence (e.g., Pelland et al., 2016), while the California Current System is subject to varying inflow of subarctic water (e.g., Bograd et al., 2019). Although spiciness at P26 has increased, it is minty (-0.75 ± 0.1 kg m^{-3}) compared to the southern water (0.54 ± 0.08 kg m^{-3}).

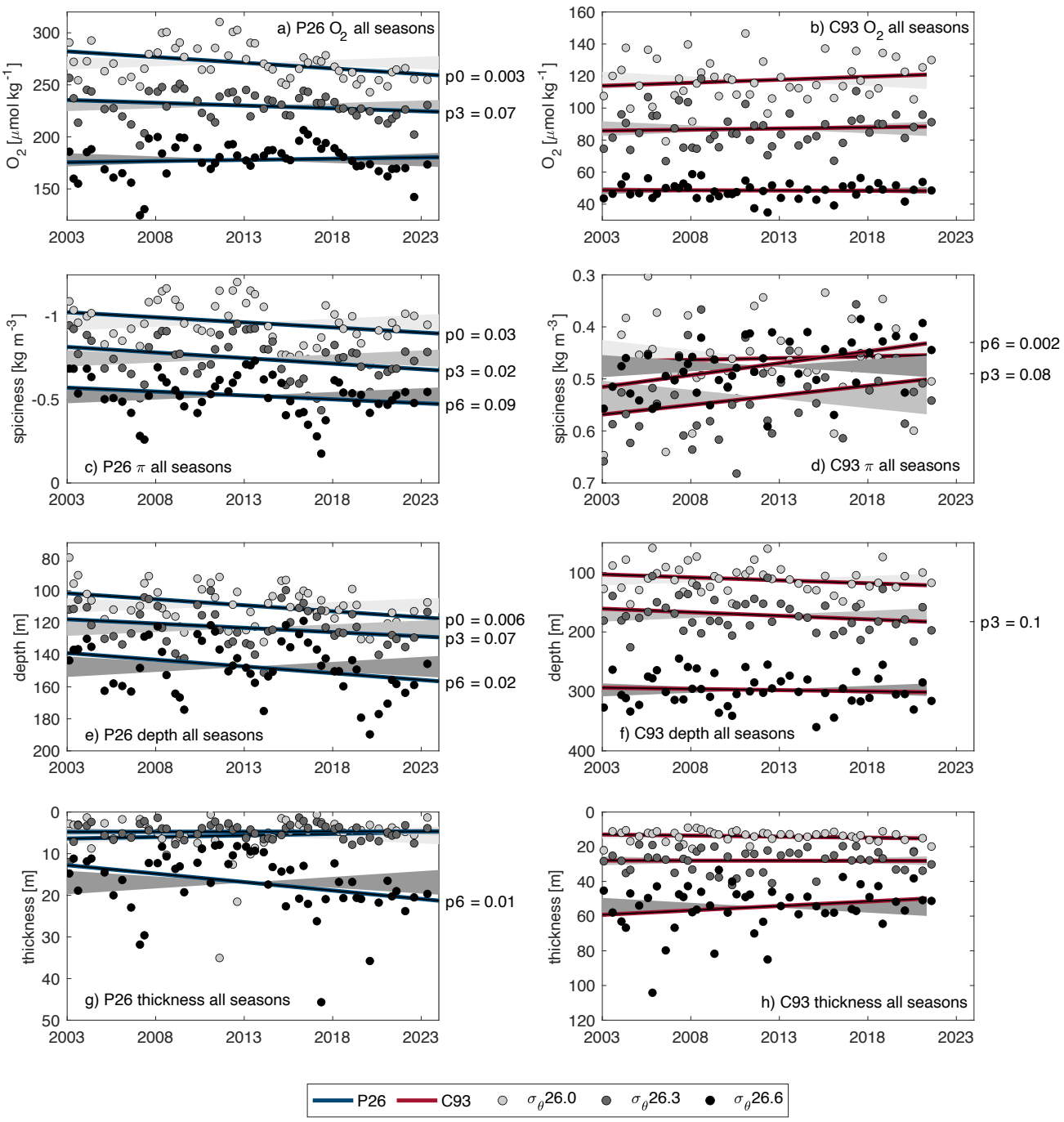

Figure S6: Time series (all seasons together) of oxygen, spiciness (π), depth, and isopycnal thickness on the 26.0 (light grey), 26.3 (dark grey) and 26.6 (black) isopycnals. The 90% confidence interval from bootstrapping is shown in the 'bow tie'-shape of the same colour. The linear trend is shown in blue (P26) or red (C93), and the p-value is given on the right where significant (p0 for the 26.0, p3 for the 26.3, and p6 for the 26.6 isopycnal).

Text S4 Subsampling of raw data

Slope and Shelf data

We obtain the raw data from https://www.waterproperties.ca/data/ (accessed April 2025), by setting the "Bounding Box or Lat/Lon" to 48°N to 48.54°N and 126.48°W to 125°W. We first download all .bot, .che, and .ctd profiles from 2003/01/01 to 2023/12/31. The .bot and .che files are only used for the oxygen evaluation in Supplementary Text S1, the analysis in the paper uses only .ctd files. Buoy files and data with bad quality flags are excluded from this analysis.

We subsample this dataset to within Lines B and D from the LaPerouse cruises (see also Figure S2 above), bounded by corners 49.00°N, -125.75°E; 48.65°N, -125.00°E; 48°N, -126.15°E; 48.48°N, -126.76°E.

We separate the data based on water depth; into SLOPE (> 200 m) and SHELF (> 75 m and < 200 m). Water depth is determined by bathymetry, which we obtain from the etopo1 dataset, https://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/data/ice_surface/grid_registered/binary/etopo1_ice_g_i2.zip.

Station P26

We obtain the raw data from https://www.waterproperties.ca/data/ (accessed April 2025), by setting "Station" to P26 and selecting all .ctd profiles from 2003/01/01 to 2023/12/31. Data with bad quality flags are excluded from this analysis.

CalCOFI Station C93.30

The raw data for CalCOFI Station C93.30 were taken from the CalCOFI archives: https://calcofi.org/downloads/database/CalCOFI_Database_194903-202105_csv_16October2023.zip (accessed April 2025). This file provides "cast" and "bottle" data which need to be combined for full profiles. From the combined dataset, we subsample Station 93.30.3 (DbSta_ID 9330300).

Supplementary Figures S7 – S10:

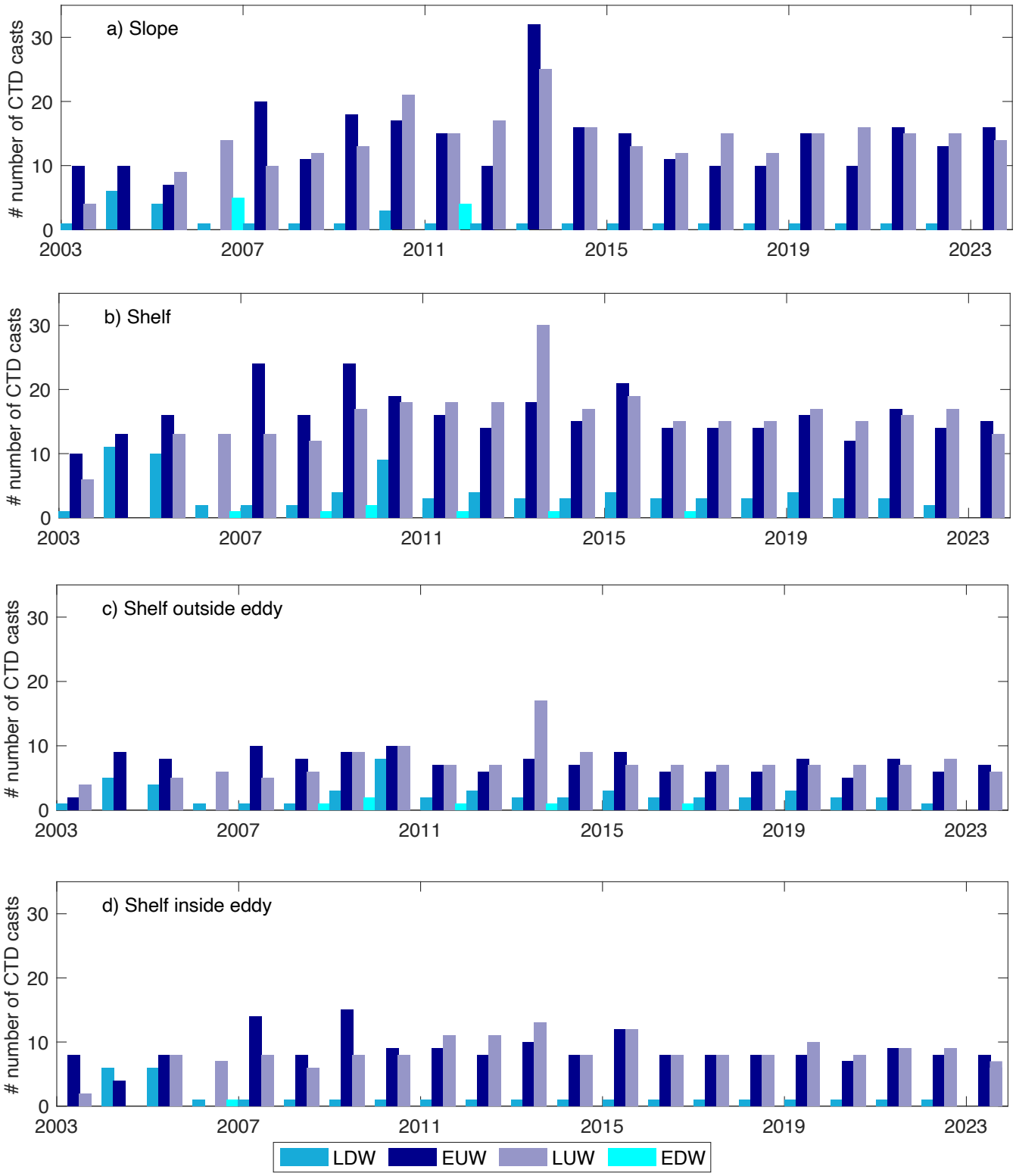

Figure S7: Number of observations (CTD casts) in our study region, available from early 2003 – early 2023. We show early downwelling (EDW), late downwelling (LDW), early upwelling (EUW)

and late upwelling (LUW) (Figure 1c), for a) the slope, b) the shelf, c) the shelf outside the eddy, and d) the shelf inside the eddy.

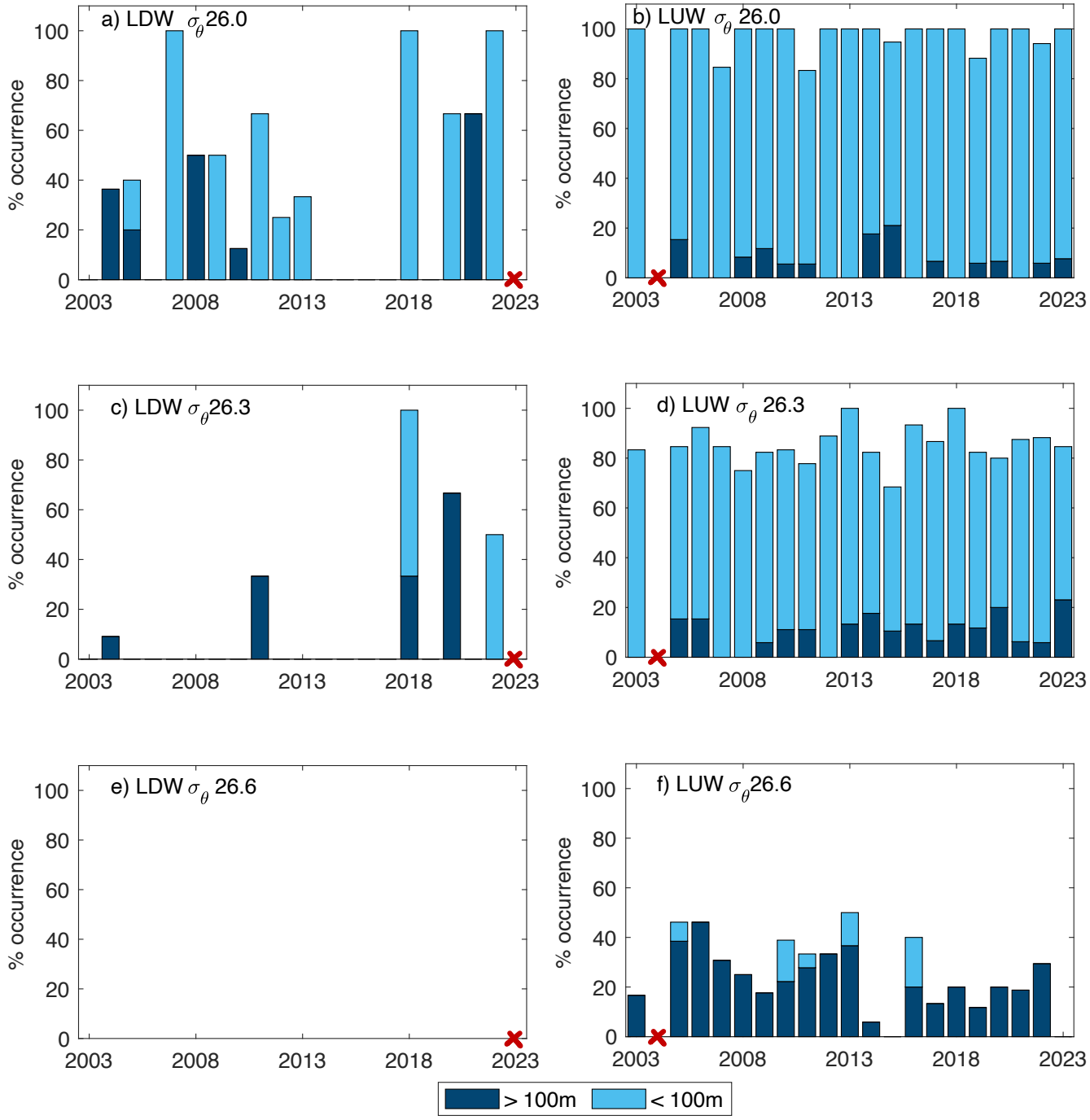

Figure S8: Occurrence of the isopycnals of interest on the shelf during late downwelling (LDW, left) and late upwelling (LUW, right) (see Figure 1c), expressed as percentage of profiles from 2003 until 2023. Light (dark) blue shows the isopycnal is observed above (below) 100 m depth. Panel e) indicates that the 26.6 isopycnal is completely absent from the shelf during downwelling. No cruise data are available for LUW of 2004 and LDW of 2024 (red x).

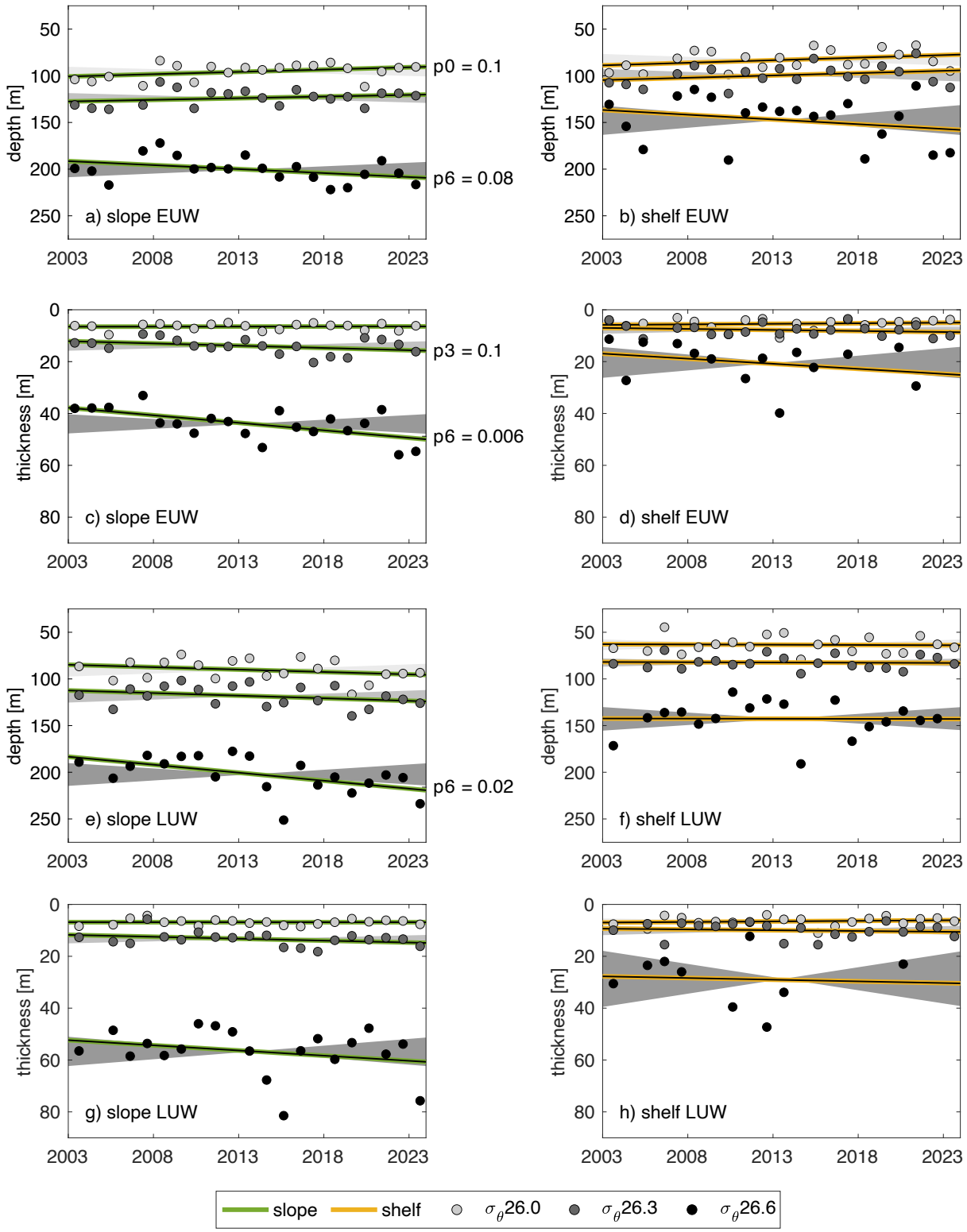

Figure S9: Time series of depth and isopycnal thickness for EUW (spring, first and second row, respectively) and LUW (summer, third and fourth row, respectively) seasons on the 26.0 (light grey), 26.3 (dark grey) and 26.6 (black) isopycnals. (Longer time series, 1984-2021 of the same properties, are shown in Maier et al., 2025). The 90% confidence interval from bootstrapping is shown in the 'bow tie'-shape of the same colour. The linear trend is shown in green (slope) or yellow (shelf), and the p-value is given on the right where significant (p0 for the 26.0, p3 for the 26.3, and p6 for the 26.6 isopycnal).

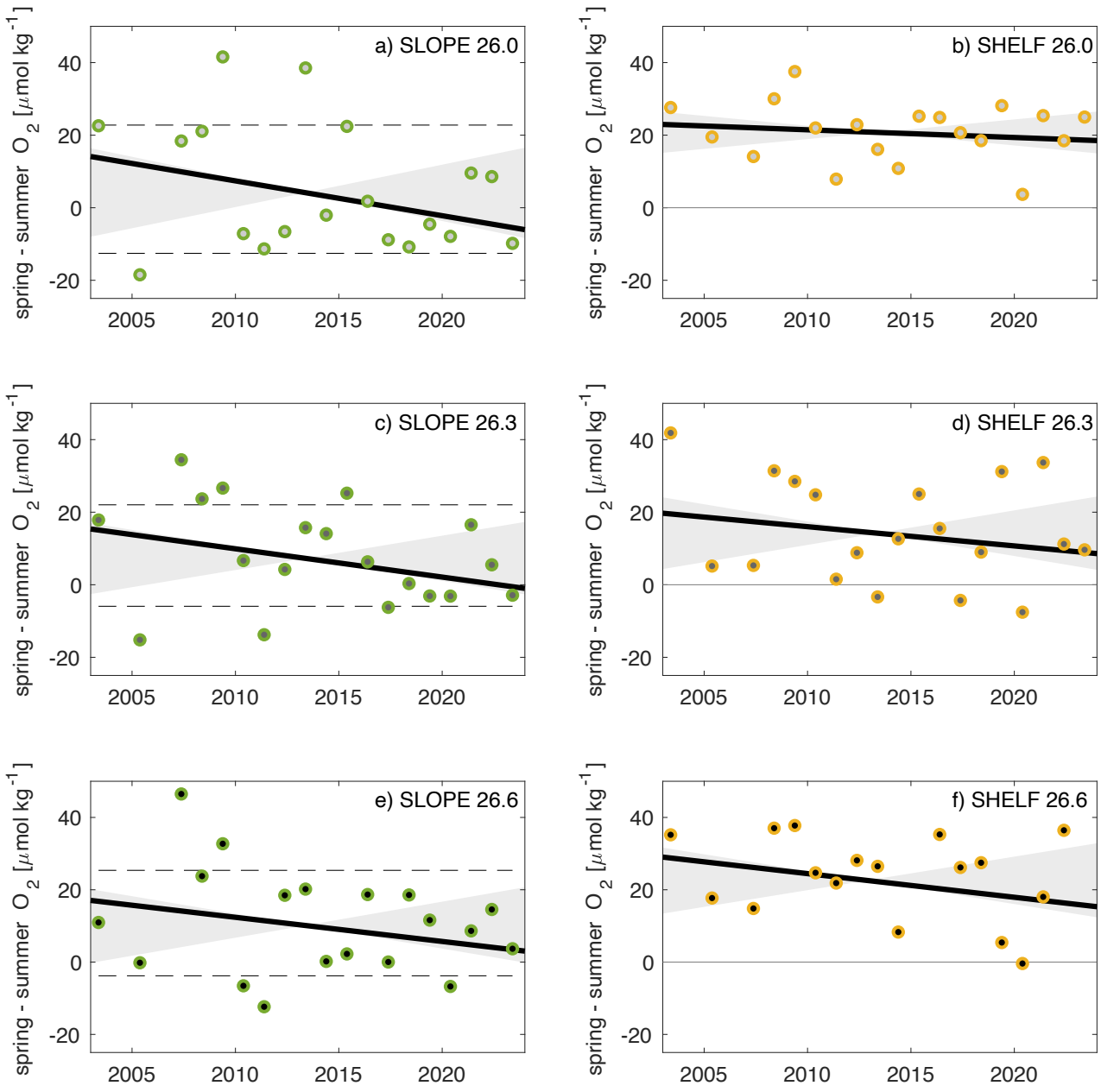

Figure S10: Subsurface summer oxygen consumption: the difference between oxygen observed during EUW and oxygen observed during LUW on the slope (outlined in green, left) and shelf (outlined in yellow, right) as a function of time for the three isopycnals 26.0 (light grey, a, b), 26.3 (grey, c, d) and 26.6 (black, e, f). The trend is shown in black, the 90% confidence interval from bootstrapping is shown in the 'bowtie'-shape in grey. Values closer to zero suggest oxygen values during LUW more closely resemble those observed during EUW. All p-values exceed 0.2.

Table S1 – Correlations between oxygen and spiciness on the three isopycnals of interest, σ_θ = 26.0, 26.3, and 26.6 kg m^{-3}. Correlations are given for the three seasons that contain sufficient data: late downwelling (LDW), early upwelling (EUW), and late upwelling (LUW). We provide the ordinary R^2 value and the significance (t-test). R^2 values greater than 0.5 that are statistically significant are highlighted in bold. For the source water, where subsurface seasonality is minimal or lacking, all four seasons are combined in the analysis.

		LDW		EUW		LUW		Yearly	
		R^2	significant	R^2	significant	R^2	significant	R^2	significant
slope	26.0	0.18	no	**0.76**	**yes**	0.13	no		
	26.3	0.17	no	**0.64**	**yes**	0.08	no		
	26.6	0.46	yes	**0.66**	**yes**	**0.66**	**yes**		
shelf	26.0	0.04	no	0.05	no	0.36	yes		
	26.3	0.56	no	0.06	no	0.04	no		
	26.6	NaN	NaN	0.03	no	0.24	yes		
shelf no eddy	26.0	0.22	no	0.09	no	0.31	yes		
	26.3	0.26	no	0.26	yes	0.03	no		
	26.6	NaN	NaN	0.26	yes	0.14	no		
shelf eddy	26.0	0.05	no	0.00	no	0.18	no		
	26.3	0.21	no	0.02	no	0.15	no		
	26.6	NaN	NaN	0.26	no	0.26	yes		
P26	26.0							**0.59**	**yes**
	26.3							0.19	yes
	26.6							0.03	no
C93	26.0							**0.59**	**yes**
	26.3							**0.76**	**yes**
	26.6							**0.54**	**yes**

Table S2 – Expected and observed changes between seasonal means. We report the mean (by season, over the 20-year record, on each isopycnal) and standard error ("SE") of observed spiciness (π) and the change between seasons (Δ) with uncertainty (propagated from standard error). We then calculate the expected change in oxygen based on the endmember (P26, C93.30) equations (slope of the relationship) from Figure 2. We report the mean and standard error of observed oxygen and the change between seasons with uncertainty (propagated from standard error). Finally, we report the difference between the oxygen change estimated from the spiciness change and the observed oxygen change.

Region / Isopycnal	Season	Observed Spiciness (π) [kg m^{-3}]				oxygen change from spiciness [μmol kg^{-1}]		Observed Oxygen [μmol kg^{-1}]				Observed - expected Oxygen [μmol kg^{-1}]	
		mean	standard error	seasonal difference	uncertainty	change	uncertainty	mean	standard error	seasonal difference	uncertainty	diff	uncertainty
On 26.0: $O_2 = -110*\pi + 170$ (from Figure 2a)													
Slope 26.0 LDW → EUW	LDW	-0.162	0.033	-0.15	0.046	16	5.0	164	3.4	14	4.9	-3	7.0
	EUW	-0.310	0.032					178	3.5				
Slope 26.0 EUW → LUW	EUW	-0.310	0.032	-0.01	0.042	1	4.7	178	3.5	-6	4.5	-7	6.5
	LUW	-0.316	0.028					172	2.8				
Shelf 26.0 LDW → EUW	LDW	-0.203	0.029	-0.14	0.037	15	4.0	152	2.7	-7	3.4	-22	5.3
	EUW	-0.338	0.022					145	2.1				
Shelf 26.0 EUW → LUW	EUW	-0.338	0.022	0.02	0.029	-1	3.2	145	2.1	-21	3.2	-19	4.5
	LUW	-0.319	0.018					124	2.5				
On 26.3: $O_2 = -110*\pi + 150$ (from Figure 2d)													
Slope 26.3 LDW → EUW	LDW	0.0113	0.018	-0.11	0.03	12	3.3	131	3.4	17	4.5	5	5.6
	EUW	-0.0971	0.024					148	3				
Slope 26.3 EUW → LUW	EUW	-0.0971	0.024	0.02	0.03	-2	3.3	148	3	-9	3.8	-7	5.1
	LUW	-0.0799	0.019					138	2.4				
Shelf 26.3 LDW → EUW	LDW	-0.0529	0.035	-0.1	0.039	12	4.3	117	1.4	0	2.7	-12	5.0
	EUW	-0.1580	0.017					117	2.2				
Shelf 26.3 EUW → LUW	EUW	-0.1580	0.017	0	0.023	0	2.5	117	2.2	-16	3.5	-16	4.3
	LUW	-0.1600	0.015					101	2.7				

On 26.6: $O_2 = -130*\pi + 110$ (from Figure 2g)													
Slope 26.6 LDW → EUW	LDW	0.00327	0.0079	-0.04	0.011	5	1.5	96	2.9	8	3.7	3	4.0
	EUW	-0.03560	0.008					105	2.4				
Slope 26.6 EUW → LUW	EUW	-0.03560	0.008	0.02	0.011	-3	1.4	105	2.4	-11	3.6	-9	3.9
	LUW	-0.01560	0.0068					93	2.7				
Shelf 26.6 LDW → EUW	LDW*	0.00327	0.0079	-0.06	0.011	8	1.4	96	2.9	-7	3.6	-15	3.8
	EUW	-0.05680	0.0071					90	2.1				
Shelf 26.6 EUW → LUW	EUW	-0.05680	0.0071	0.01	0.011	-2	1.4	90	2.1	-23	3.4	-21	3.7
	LUW	-0.04460	0.0081					67	2.7				

*we use slope LDW here, because the 26.6 isopycnal is not on the shelf during LDW, but upwells from the slope during EUW (Figure S8).

Table S3 – Trends in spiciness and oxygen for the three isopycnals of interest. Trends and errors are calculated following subsection 2.3. The rough expected oxygen change is calculated from the spiciness trend following Figure 2.

Region	Isopycnal	Season(s)	Spiciness (π) Trend ± error [kg m^{-3} / 20 yrs]	π p-value	Oxygen Trend ± error [μmol kg^{-1}/ 20 yrs]	O_2 p-value	Estimated O_2 change from π [μmol kg^{-1}/ 20 yrs]
C93	26.0	all	-0.01 ± 0.05	0.77	7 ± 5	0.29	1
C93	26.3	all	**-0.07 ± 0.03**	**0.09**	3 ± 4	0.64	8
C93	26.6	all	**-0.08 ± 0.02**	**0.00**	-1 ± 2	0.84	11
P26	26.0	all	**0.12 ± 0.07**	**0.04**	**-22 ± 9**	**0.00**	-14
P26	26.3	all	**0.14 ± 0.07**	**0.02**	**-11 ± 8**	**0.08**	-15
P26	26.6	all	**0.09 ± 0.07**	**0.10**	5 ± 12	0.55	-12
shelf	26.0	EUW	0.08 ± 0.07	0.26	**-13 ± 6**	**0.05**	-9
shelf	26.0	LUW	**0.11 ± 0.05**	**0.06**	-9 ± 7	0.29	-13
shelf	26.3	EUW	**0.09 ± 0.06**	**0.08**	**-21 ± 3**	**0.00**	-11
shelf	26.3	LUW	**0.11 ± 0.04**	**0.03**	-7 ± 6	0.46	-12
shelf	26.6	EUW	0.02 ± 0.03	0.34	-5 ± 4	0.47	-2
shelf	26.6	LUW	0.01 ± 0.02	0.70	9 ± 7	0.33	-1
slope	26.0	EUW	**0.24 ± 0.09**	**0.02**	**-26 ± 9**	**0.02**	-26
slope	26.0	LUW	**0.17 ± 0.08**	**0.08**	-6 ± 6	0.55	-18
slope	26.3	EUW	**0.20 ± 0.07**	**0.01**	**-17 ± 7**	**0.08**	-22
slope	26.3	LUW	**0.14 ± 0.05**	**0.03**	1 ± 5	0.94	-15
slope	26.6	EUW	0.04 ± 0.02	0.13	-7 ± 6	0.36	-4
slope	26.6	LUW	-0.01 ± 0.02	0.65	6 ± 8	0.51	1