Supplementary methods and results for warm low oxygen episode sequences

Companion to Persistence and intervening states of warm low oxygen episodes at eight southeastern United States estuarine stations

REPRODUCIBLE DEFINITIONS AND SOURCE HANDLING

This supplement documents the observational support, source interpretation, and secondary results of the eight-station analysis. The primary environmental tables derive from the frozen release and its computational reconstruction. Additional common-year and outcome-year influence diagnostics were specified after the primary results were available and are identified separately as post hoc. NIW denotes North Inlet–Winyah Bay and GTM denotes Guana Tolomato Matanzas. Short codes are NIW-CB, NIW-DC, NIW-OL, NIW-TA, GTM-FM, GTM-PC, GTM-PI, and GTM-SS; the main manuscript gives their full names and source identifiers.

Source population and retained observations

The final source cohort contains the original 48 annual station files for 2018–2023. The reference temperature distribution uses the whole annual window, whereas occupancy and episode analyses use only eligible May–September seasons. Feasibility files from other years and Sapelo Island preserve the screening history but do not enlarge the primary estimand. The R1 reviewer archive includes these 48 unmodified CSVs, 12 annual NIW/GTM metadata documents, and a manifest specifying filename, size, SHA256, source DOI, and access date. Hashes establish identity to the preserved snapshot; the DOI and source attribution identify its reported official provenance. The DOI remains stable while the provider archive can change. The access date is 30 September 2026.

The source grid is fixed EST (UTC−05:00), without daylight-saving adjustment. Temperature and dissolved oxygen must be observed simultaneously at the same sensor. Numerical flag 0 and Historical = 1 are required. Parameter comments are retained separately from the numerical flag: CDA and CAB do not themselves invalidate an observation. The operational ledger distinguishes effects on temperature, oxygen, both variables, and optional conservative scenarios. Original measurements and source timestamps were never overwritten by the analysis.

A depth-sensor calibration error is distinct from displacement of the water-quality sensor. Primary masks address documented physical exposure or displacement and explicit failures that can compromise temperature or oxygen; depth/level-only calibration offsets are not transferred automatically to those variables. Possible wiper loss or fouling with accepted parameters is assessed separately. The combined ledger has 87 rows, including intervals already missing in the base data and intervals used only in the conservative sensitivity. Its row count is not a count of unique excluded readings. Overlapping exclusions are applied as masks without multiplying time.

Table S1 summarizes nominal sensor positions and location qualifications. Full annual deployment and metadata records accompany the computational materials. Coordinates are reference locations from the latest metadata compilation, not evidence of unchanged submeter position in every year. NIW annual coordinates vary slightly by reported precision without a documented permanent relocation. Temporary physical departures from the nominal geometry are addressed by the exclusion ledger.

Table S1. Nominal station locations and sensor geometry

Station	Waterbody	Latitude, longitude (decimal degrees)	Installation
NIW-CB	North Inlet	33.33391, -79.19290	Fixed piling; nominally 0.30 m above bed
NIW-DC	North Inlet	33.36014, -79.16746	Fixed piling; nominally 0.30 m above bed
NIW-OL	North Inlet	33.34934, -79.18888	Fixed piling; nominally 0.30 m above bed
NIW-TA	Winyah Bay	33.29912, -79.25596	Fixed piling; nominally 0.30 m above bed
GTM-FM	Matanzas estuary	29.73704, -81.24595	Fixed piling and tube; nominally within 1 m of bed
GTM-PC	Pellicer Creek, Matanzas system	29.66707, -81.25740	Fixed piling and tube; nominally within 1 m of bed
GTM-PI	Tolomato River	30.05086, -81.36746	Fixed piling and tube; nominally within 1 m of bed
GTM-SS	San Sebastian–Matanzas confluence	29.86885, -81.30743	Fixed piling and tube; nominally within 1 m of bed

Reference coordinates from the metadata compilation: NIW values use the latest 2024 site table, which is provisional; GTM decimal coordinates are in 2023–2024 metadata. They identify the sites, not a reconstruction of exact historical position. Water-level variation means sensor depth below the surface is not constant. All stations used a 15-min interval, fixed EST, EXO2 sondes, and optical oxygen sensor model 599100-01 during the analyzed record. Temperature/conductivity and antifouling hardware were not identical throughout.

Coverage and the thermal reference

Each May–September season contains 14,688 expected 15-min positions. The primary season criterion is ≥90% jointly valid observations overall and ≥80% in each month; the strict criterion is ≥95% and ≥90%, respectively. At least three primary eligible seasons are required per station, including after the optional conservative mask. Table S2 gives all 48 candidates, preserving exclusions independently of environmental outcomes. Across eligible seasons, 3,626 grid positions were missing or invalid, occurring in 114 runs totaling 906.5 scheduled hours without paired valid observations; the longest missing run comprised 501 positions or 125.25 scheduled hours.

The fixed P90 is calculated from temperature-valid observations across the full annual 2018–2023 window, irrespective of oxygen availability. The quantile uses linear interpolation at rank $(n - 1) \times 0.90$ in the ordered valid readings. Every month pooled over reference years must retain ≥75% expected temperature coverage. All eight primary station references met this rule; the minimum pooled-month coverage was 83.33%. The primary reference counts and thresholds appear in Table S3. Leave-one-year-out thresholds are recalculated excluding the assessed year and then applied to that year only. This does not create six whole-record analyses, each using a single alternative threshold.

Table S2. Coverage and eligibility for all candidate station-seasons

Station	Year	Valid pairs	Season coverage (%)	Lowest month coverage (%)	Primary	Strict	Selection
NIW-CB	2018	14664	99.84	99.29	Yes	Yes	Included
NIW-CB	2019	13147	89.51	46.74	No	No	Season and month
NIW-CB	2020	14682	99.96	99.93	Yes	Yes	Included
NIW-CB	2021	14669	99.87	99.66	Yes	Yes	Included
NIW-CB	2022	14235	96.92	89.72	Yes	No	Included
NIW-CB	2023	11257	76.64	30.78	No	No	Season and month
NIW-DC	2018	13006	88.55	53.02	No	No	Season and month
NIW-DC	2019	11733	79.88	66.08	No	No	Season and month
NIW-DC	2020	14386	97.94	89.95	Yes	No	Included

Station	Year	Valid pairs	Season coverage (%)	Lowest month coverage (%)	Primary	Strict	Selection
NIW-DC	2021	14581	99.27	96.28	Yes	Yes	Included
NIW-DC	2022	14686	99.99	99.97	Yes	Yes	Included
NIW-DC	2023	14227	96.86	84.85	Yes	No	Included
NIW-OL	2018	13368	91.01	54.20	No	No	Month
NIW-OL	2019	14685	99.98	99.90	Yes	Yes	Included
NIW-OL	2020	14685	99.98	99.97	Yes	Yes	Included
NIW-OL	2021	10955	74.58	0.00	No	No	Season and month
NIW-OL	2022	14682	99.96	99.90	Yes	Yes	Included
NIW-OL	2023	14232	96.90	85.08	Yes	No	Included
NIW-TA	2018	8565	58.31	0.00	No	No	Season and month
NIW-TA	2019	14658	99.80	99.55	Yes	Yes	Included
NIW-TA	2020	14132	96.21	83.13	Yes	No	Included
NIW-TA	2021	14687	99.99	99.97	Yes	Yes	Included
NIW-TA	2022	14685	99.98	99.93	Yes	Yes	Included
NIW-TA	2023	14664	99.84	99.23	Yes	Yes	Included
GTM-FM	2018	14687	99.99	99.97	Yes	Yes	Included
GTM-FM	2019	12925	88.00	58.50	No	No	Season and month
GTM-FM	2020	14688	100.00	100.00	Yes	Yes	Included
GTM-FM	2021	14688	100.00	100.00	Yes	Yes	Included
GTM-FM	2022	14688	100.00	100.00	Yes	Yes	Included
GTM-FM	2023	14682	99.96	99.93	Yes	Yes	Included
GTM-PC	2018	14688	100.00	100.00	Yes	Yes	Included
GTM-PC	2019	14688	100.00	100.00	Yes	Yes	Included
GTM-PC	2020	14408	98.09	90.28	Yes	Yes	Included
GTM-PC	2021	14688	100.00	100.00	Yes	Yes	Included
GTM-PC	2022	10797	73.51	37.00	No	No	Season and month
GTM-PC	2023	14255	97.05	84.97	Yes	No	Included
GTM-PI	2018	14687	99.99	99.97	Yes	Yes	Included
GTM-PI	2019	11811	80.41	50.00	No	No	Season and month
GTM-PI	2020	14687	99.99	99.97	Yes	Yes	Included
GTM-PI	2021	13000	88.51	41.39	No	No	Season and month
GTM-PI	2022	14688	100.00	100.00	Yes	Yes	Included
GTM-PI	2023	14248	97.00	84.79	Yes	No	Included
GTM-SS	2018	14684	99.97	99.93	Yes	Yes	Included
GTM-SS	2019	13958	95.03	75.50	No	No	Month
GTM-SS	2020	14684	99.97	99.86	Yes	Yes	Included
GTM-SS	2021	14688	100.00	100.00	Yes	Yes	Included
GTM-SS	2022	14688	100.00	100.00	Yes	Yes	Included
GTM-SS	2023	13533	92.14	62.67	No	No	Month

Expected observations per season: 14,688. Selection reasons identify the threshold(s) missed for primary eligibility. Strict denotes ≥95% season and ≥90% every month. Coverage uses jointly valid temperature and oxygen after manual masks. All eight stations meet the primary minimum of three eligible seasons.

Table S3. Annual temperature reference support

Station	Valid temperature readings	Fixed P90 (°C)	Lowest pooled-month coverage (%)
NIW-CB	204,009	29.1	88.53
NIW-DC	205,887	29.5	92.21
NIW-OL	205,408	29.5	84.62
NIW-TA	199,406	29.1	83.33
GTM-FM	205,318	29.5	89.01
GTM-PC	206,075	30.7	91.62
GTM-PI	206,627	30.5	89.05
GTM-SS	201,611	29.7	83.33

Reference window: January–December 2018–2023. Temperature validity is independent of simultaneous oxygen availability. Required minimum pooled-month coverage: 75%.

States and numerical invariants

At a valid paired timestamp, W denotes temperature above the fixed P90, L denotes oxygen below 2 mg/L, and C denotes their intersection. The states partition all valid observations: neither, warm only, low oxygen only, and compound. The temperature threshold is strict above and the oxygen threshold strict below. Thus, a reading at P90 is not warm and a reading at 2 mg/L is not low oxygen. A zero oxygen concentration is valid when authenticated and accepted by source quality control, although none of the primary compound readings had oxygen exactly zero.

Nominal state hours are reading counts × 0.25 h. The first-to-last span of N consecutive readings is (N − 1) × 0.25 h. These two quantities serve different purposes. For example, the longest primary run comprises 25 compound readings: 6.25 nominal occupancy hours, a 6-h first-to-last span, and adjacent non-compound readings that bracket its threshold crossings. A singleton has 0.25 nominal hours and zero span. The analysis does not assume a continuously constant state between readings.

No run crosses an invalid grid position or an excluded observation window. Immediately flanking valid non-compound readings establish complete bounds. All 417 primary runs were complete, but this is a property of detected runs; it does not exclude unobserved events during gaps. Primary classified compound readings all had flag 0 for both variables and retained the source CDA comment in dissolved oxygen.

Interepisode composition uses the first non-compound reading after the previous run, inclusive, through the first compound reading of the next run, exclusive. State counts × 0.25 h exactly equal the elapsed time between those anchors. Of 410 station-wise adjacent-run pairs, 396 were within a season, 384 were fully observed, and 12 crossed within-season missingness. A further 14 crossed separate seasonal windows and were unavailable. Neither absence nor persistence was imputed for unavailable pairs.

Across the 384 eligible intervals, the state-specific totals were 8,444.75 warm-only, 664 low-only, and 8,245.75 neither nominal hours, summing to 17,354.5 h. Time-weighted state composition and the fraction of intervals with no neither reading have different denominators. The longest uninterrupted neither run additionally distinguishes continuity from total neither occupancy. Complete interval records preserve all three representations.

For recurrence, the entire inclusive grid from the exit anchor to the 24-h or 72-h horizon must be valid within the same analytical window. An observed early re-entry does not rescue an otherwise incomplete horizon. Primary eligible denominators were 407 for 24 h and 396 for 72 h, with 10 and 21 censored exits, respectively.

COMPLETE SEASONAL AND SENSITIVITY SUMMARIES

Table S4 gives all 35 eligible seasons. V, L, and C denote valid paired, low-oxygen, and compound nominal hours; W/V is the warm fraction of valid readings. NA denotes a zero low-oxygen denominator, whereas 0 denotes an observed zero numerator. All state-specific counts and hours are retained in the accompanying machine-readable table.

Table S4. All primary station-season occupancy estimates

Station	Year	V (h)	L (h)	C (h)	C/L (%)	C/V (%)	L/V (%)	W/V (%)
NIW-CB	2018	3,666	45.5	9.75	21.4	0.266	1.241	28.6
NIW-CB	2020	3,670.5	69.25	36.25	52.3	0.988	1.887	21.8
NIW-CB	2021	3,667.25	42	16.75	39.9	0.457	1.145	18.2
NIW-CB	2022	3,558.75	57.75	17.5	30.3	0.492	1.623	18.6
NIW-DC	2020	3,596.5	2	1.5	75.0	0.042	0.056	21.9
NIW-DC	2021	3,645.25	0	0	NA	0.000	0.000	17.2
NIW-DC	2022	3,671.5	3	0	0.0	0.000	0.082	17.9
NIW-DC	2023	3,556.75	4.25	2.25	52.9	0.063	0.119	30.3
NIW-OL	2019	3,671.25	173	63.5	36.7	1.730	4.712	30.2
NIW-OL	2020	3,671.25	150.5	38.5	25.6	1.049	4.099	21.5
NIW-OL	2022	3,670.5	233.25	21	9.0	0.572	6.355	20.1
NIW-OL	2023	3,558	255	76	29.8	2.136	7.167	28.5
NIW-TA	2019	3,664.5	44.25	6	13.6	0.164	1.208	28.2
NIW-TA	2020	3,533	3.25	0	0.0	0.000	0.092	20.8
NIW-TA	2021	3,671.75	55.25	13.25	24.0	0.361	1.505	21.2
NIW-TA	2022	3,671.25	66.25	5.25	7.9	0.143	1.805	21.0
NIW-TA	2023	3,666	117.5	27.75	23.6	0.757	3.205	27.7
GTM-FM	2018	3,671.75	0	0	NA	0.000	0.000	21.5
GTM-FM	2020	3,672	2.5	0	0.0	0.000	0.068	30.0
GTM-FM	2021	3,672	0	0	NA	0.000	0.000	11.2
GTM-FM	2022	3,672	0.75	0	0.0	0.000	0.020	30.9
GTM-FM	2023	3,670.5	0	0	NA	0.000	0.000	27.0
GTM-PC	2018	3,672	0	0	NA	0.000	0.000	13.9
GTM-PC	2019	3,672	15.75	7	44.4	0.191	0.429	31.5
GTM-PC	2020	3,602	4.25	2.25	52.9	0.062	0.118	27.4
GTM-PC	2021	3,672	1.25	1.25	100.0	0.034	0.034	13.3
GTM-PC	2023	3,563.75	17.75	12.5	70.4	0.351	0.498	24.1
GTM-PI	2018	3,671.75	0	0	NA	0.000	0.000	26.8
GTM-PI	2020	3,671.75	0	0	NA	0.000	0.000	26.5
GTM-PI	2022	3,672	17.25	4	23.2	0.109	0.470	27.0
GTM-PI	2023	3,562	57.25	49.5	86.5	1.390	1.607	28.8
GTM-SS	2018	3,671	0	0	NA	0.000	0.000	23.5
GTM-SS	2020	3,671	0	0	NA	0.000	0.000	31.4
GTM-SS	2021	3,672	0.5	0	0.0	0.000	0.014	11.5
GTM-SS	2022	3,672	0.25	0.25	100.0	0.007	0.007	31.1

V, L, C, and W follow Table 2. NA means no observed low-oxygen reading, so C/L is undefined. Observed zeros remain zero. Units are nominal reading-hours, not a continuous-duration reconstruction.

Table S5 compares primary and selected prespecified sensitivity profiles for all eight stations. It retains counts, denominator changes, and undefined or unavailable results. These are descriptive profiles for each scenario, not independent tests. The full source table includes every thermal-margin and oxygen-threshold alternative, including broader oxygen conditions below 3 and 4 mg/L. Figure S2 provides all occupancy alternatives on a common display. The 2021–2023 subset is a within-primary-cohort temporal sensitivity; it is not required to furnish three new eligible years at each site.

Table S5. Persistence and sequence profiles under selected prespecified alternatives

Station	Scenario	Yrs	C (h)	C/L (%)	n	Median span (h)	C hours in span >3 h (%)	No neither / intervals	Recur / eligible 24 h
NIW-CB	Primary	4	80.25	37.4	88	0.25	0.0	32/79	57/83
NIW-CB	Strict	3	62.75	40.0	63	0.5	0.0	19/55	40/58
NIW-CB	Conservative	4	80.25	37.4	88	0.25	0.0	32/79	57/83
NIW-CB	P85	4	129.5	60.4	125	0.5	0.0	50/112	84/121
NIW-CB	P95	4	7.25	3.4	6	0.5	0.0	1/2	2/5
NIW-CB	Leave year out	4	70	32.6	84	0.25	0.0	31/75	54/79
NIW-CB	2021–2023	2	34.25	34.3	46	0.25	0.0	21/42	30/42
NIW-DC	Primary	4	3.75	40.5	7	0	0.0	1/4	2/7
NIW-DC	Strict	2	0	0.0	0	NA	NA	NA	NA
NIW-DC	Conservative	4	3.75	40.5	7	0	0.0	1/4	2/7
NIW-DC	P85	4	6	64.9	12	0	0.0	4/9	4/12
NIW-DC	P95	4	1.5	16.2	4	0	0.0	1/1	1/4
NIW-DC	Leave year out	4	3.75	40.5	7	0	0.0	1/4	2/7
NIW-DC	2021–2023	3	2.25	31.0	4	0.25	0.0	1/2	1/4
NIW-OL	Primary	4	199	24.5	121	0.75	48.9	44/112	77/116
NIW-OL	Strict	3	123	22.1	79	0.75	41.9	28/74	51/77
NIW-OL	Conservative	4	199	24.5	121	0.75	48.9	44/112	77/116
NIW-OL	P85	4	449.25	55.3	210	1.38	57.5	96/201	173/205
NIW-OL	P95	4	32.5	4.0	21	0.75	50.0	4/16	13/21
NIW-OL	Leave year out	4	186.25	22.9	117	0.75	48.3	43/108	73/112
NIW-OL	2021–2023	2	97	19.9	61	0.5	54.4	18/55	34/57
NIW-TA	Primary	5	52.25	18.2	73	0.25	13.9	35/68	47/73
NIW-TA	Strict	4	52.25	18.4	73	0.25	13.9	35/68	47/73
NIW-TA	Conservative	5	52.25	18.2	73	0.25	13.9	35/68	47/73
NIW-TA	P85	5	116.75	40.8	122	0.25	36.6	80/117	95/122
NIW-TA	P95	5	12.5	4.4	21	0	0.0	8/18	11/21
NIW-TA	Leave year out	5	53.5	18.7	74	0.25	13.6	37/69	48/74
NIW-TA	2021–2023	3	46.25	19.4	64	0.25	15.7	33/61	43/64
GTM-FM	Primary	5	0	0.0	0	NA	NA	NA	NA
GTM-FM	Strict	5	0	0.0	0	NA	NA	NA	NA
GTM-FM	Conservative	5	0	0.0	0	NA	NA	NA	NA

Station	Scenario	Yrs	C (h)	C/L (%)	n	Median span (h)	C hours in span >3 h (%)	No neither / intervals	Recur / eligible 24 h
GTM-FM	P85	5	0	0.0	0	NA	NA	NA	NA
GTM-FM	P95	5	0	0.0	0	NA	NA	NA	NA
GTM-FM	Leave year out	5	0	0.0	0	NA	NA	NA	NA
GTM-FM	2021–2023	3	0	0.0	0	NA	NA	NA	NA
GTM-PC	Primary	5	23	59.0	34	0	0.0	16/30	16/34
GTM-PC	Strict	4	10.5	49.4	20	0	0.0	6/17	6/20
GTM-PC	Conservative	5	23	59.0	34	0	0.0	16/30	16/34
GTM-PC	P85	5	27	69.2	44	0	0.0	28/40	22/44
GTM-PC	P95	5	12.25	31.4	16	0	0.0	5/12	9/16
GTM-PC	Leave year out	5	23	59.0	34	0	0.0	16/30	16/34
GTM-PC	2021–2023	2	13.75	72.4	17	0	0.0	11/15	10/17
GTM-PI	Primary	4	53.5	71.8	93	0.25	0.0	79/91	82/93
GTM-PI	Strict	3	4	23.2	7	0.25	0.0	2/6	3/7
GTM-PI	Conservative	<3	—	—	—	—	—	—	—
GTM-PI	P85	4	61.75	82.9	106	0.25	0.0	94/104	93/106
GTM-PI	P95	4	40.5	54.4	68	0.25	0.0	59/66	62/68
GTM-PI	Leave year out	4	53.5	71.8	93	0.25	0.0	79/91	82/93
GTM-PI	2021–2023	2	53.5	71.8	93	0.25	0.0	79/91	82/93
GTM-SS	Primary	4	0.25	33.3	1	0	0.0	NA	0/1
GTM-SS	Strict	4	0.25	33.3	1	0	0.0	NA	0/1
GTM-SS	Conservative	3	0.25	100.0	1	0	0.0	NA	0/1
GTM-SS	P85	4	0.5	66.7	2	0	0.0	NA	0/2
GTM-SS	P95	4	0	0.0	0	NA	NA	NA	NA
GTM-SS	Leave year out	4	0.25	33.3	1	0	0.0	NA	0/1
GTM-SS	2021–2023	2	0.25	33.3	1	0	0.0	NA	0/1

Yrs denotes eligible seasons; n denotes runs. Conservative Pine Island has insufficient multiyear support (<3 seasons); its dashes are not zeros. NA denotes an absent denominator or run distribution. The full all-variant CSV additionally includes oxygen <1.9, <2.1, <3, and <4 mg/L, thermal offsets ±0.2 °C, and all authenticated seasons. Different scenarios change thresholds or observation support; rows are not independent replicates. The 2021–2023 subset retains eligible seasons from the primary cohort. Data: independent_station_profiles_all_variants.csv.

The minimum-span sensitivity retains 259/417 episodes and 372.5/412 nominal hours at ≥0.25 h; the ≥0.5-h version retains 187/417 episodes and 336.5/412 h. These summaries describe retention of episodes and occupancy. They do not establish that recurrence is invariant after deleting brief episodes because recurrence under that altered episode definition was not the estimand of this retention calculation.

Exploratory resampling

Table S6 reports 2.5th and 97.5th percentile limits from 2,000 synchronized resamples of six calendar years. Station eligibility is preserved within each resampled year. No artificial runs are formed across concatenated resampled years because the bootstrap operates on station-year numerators and denominators. The procedure conditions on the fixed primary thermal thresholds and does not propagate baseline estimation or instrument uncertainty. Undefined draws remain absent. In particular,

a bootstrap limit of zero at a station with no observed compound reading is not evidence that its underlying event probability is known to be zero.

Table S6. Exploratory conditional year-bootstrap intervals

Station	Ratio	2.5th percentile (%)	97.5th percentile (%)	Valid draws	Undefined draws
NIW-CB	C/L	24.874	49.446	1997	3
NIW-CB	C/V	0.320	0.855	1997	3
NIW-DC	C/L	0.000	75.000	1972	28
NIW-DC	C/V	0.000	0.058	1998	2
NIW-OL	C/L	13.047	34.205	1994	6
NIW-OL	C/V	0.731	1.998	1994	6
NIW-TA	C/L	9.004	23.513	2000	0
NIW-TA	C/V	0.087	0.559	2000	0
GTM-FM	C/L	0.000	0.000	1815	185
GTM-FM	C/V	0.000	0.000	2000	0
GTM-PC	C/L	45.455	75.581	1998	2
GTM-PC	C/V	0.026	0.249	2000	0
GTM-PI	C/L	23.188	86.463	1850	150
GTM-PI	C/V	0.000	1.062	1999	1
GTM-SS	C/L	0.000	100.000	1815	185
GTM-SS	C/V	0.000	0.005	1997	3

Each row uses 2,000 synchronized calendar-year resamples and conditions on the fixed P90. These intervals do not propagate threshold uncertainty, sensor error, or spatial population sampling. Undefined draws were not set to zero.

Secondary daily comparison

The daily comparison contains 5,304 station-days with ≥90% joint valid readings and all four 6-h quadrants represented. None had both daily mean temperature above the primary P90 and daily mean oxygen below 2 mg/L. There were 256 days with at least one simultaneous compound reading and 609 days whose separate temperature maximum and oxygen minimum exceeded the corresponding criteria. Separate daily extrema need not be simultaneous; the resulting set relationship is expected from the definitions and is not a novelty claim. The comparison does not replace the point-level state sequences.

COMPUTATIONAL TRACEABILITY

The release was frozen at 2026-09-30 22:42:30 UTC and the first environmental estimate at 22:42:51 UTC. The protocol was internally specified before estimation and was not publicly preregistered. Protocol SHA256 is 25e4c24123e28d57f5fe9f68e2225b991439b7d2078acfd2bb7d71ebe2592c92. Ledger SHA256 is 7bee139744b1c103fefaf47789c9aa335d7b63e27344d8584f87a8c4f538c6b5. Configuration SHA256 is f5cc96cd7cb32d0665748afeff1aa5379b28db3be1789b479f4236574c81dc51. Source and code manifests preserve the remaining hashes. This internal time ordering is not public preregistration and does not establish the absence of prior exploratory inspection. The later paired-station comparison, interval partition, and R1 source-evidence selection remain explicitly post hoc.

The primary implementation passed 32 tests, including a synthetic integration test. A separately written reconstruction read the original 48 annual files and the ledger without importing the pipeline or using its thresholds or classified outputs as input. It calculated percentiles from ordered values and identified episodes with a sequential state machine. Five reconstruction-specific synthetic tests passed. The final comparison contained 49 passing groups, including the 514,080 primary grid positions, 35

seasonal occupancy rows, 417 episodes, interval and recurrence outputs, all prespecified scenario outputs, and 32,000 bootstrap quantities. The bootstrap comparison reuses the production resampling schedule and checks conditional summation, not an independent randomization design. Sixty-two provenance checks also passed. The synthetic tests verify specified behavior on artificial inputs, not the validity of the measured ecology. The separate implementation shares the original source data and exclusion ledger within the same AI-assisted workflow. Its agreement is a computational cross-check, not independent scientific validation or review by external human experts.

The historical comparison required repairs to the comparison script for omitted prelocked scenarios and year-field data types; these did not alter the frozen scientific analysis. The four historical source-audit examples, omitted from the reduced reviewer archive, were recovered for R1. Their original selection and trace files are preserved in provenance/recovered_historical_audit/historical. They contain 89 original rows for the longest run, a threshold-adjacent run, the run nearest an invalid timestamp, and a seeded random example (20260930). Original values, flags, timestamps and event membership were checked against the included CSVs and primary grids. The nearest invalid timestamp is 3.75 h from the selected run and does not truncate it. The original selection script is retained. Separately, provenance/episode_audit_R1 contains seven new post hoc examples (seed 20261004), including the Figure 5 examples and the longest runs in the 2020/2022 focal comparison; these do not replace the historical selection.

The post hoc protocols, year-support calculations, exact-timestamp reconstruction, crossed threshold comparison, and interval partition have separate scripts, validation reports, and output tables under revision_v2. They preserve the original release and do not convert the earlier specification into a preregistration of the later questions. The temporal-support script passed 465 computational checks, and two separate executions produced identical versions of all 17 result CSVs. The interval-component script separately checked eligibility, unique interval keys, state partitions, and interval-hour closure. These checks concern computational agreement and support, not external human scientific approval.

The R1 source trace contains 292 rows from six original annual CSVs, covering each selected run and four hours on either side. Each row preserves the original timestamp, source filename and SHA256, original CSV line number, Temp, DO_mgl, Historical, F_Record, F_Temp, F_DO_mgl, threshold values, applied primary exclusion reason, final classification, and immediate neighboring values and flags. Sensitivity-only ledger entries are reported separately. Source timestamps that are absent remain explicitly absent, with no invented measurement or line number. All available classifications match the reference grids. A further all_417_episode_grid_audit.csv verifies the count, first-to-last span, nominal occupancy, and non-compound boundaries of every primary episode; this grid-level check is distinct from the seven source-value examples. Additional recovery joins preserve 89 historical-example rows, 578 Figure 5 context rows and 748 focal common-year episode/context rows (1,276 unique station–timestamp pairs). All were checked against original fields and primary grids, including membership of all 103 primary and 13 P95 focal episodes. P95 joins retain primary state labels and separately identify P95 membership; they are not full P95 state grids.

The complete raw-to-result R1 execution and numerical comparison are documented in verification_R1. The original frozen scientific code, source data, ledger, and reference outputs are preserved. Windows path separators are canonicalized by a separate launcher for the Linux-authored documentary manifests. In the software comparison, flag-frequency categories are sorted canonically because equal-frequency ties can change row order between pandas 2.2.3 and 3.0.1; every category and count is compared unchanged. This adaptation changes no exclusion, threshold, event rule, or scientific quantity. Reproduction of primary results and post hoc tables tests computational agreement, while uncertainty about environmental mechanisms and generalization remains.

The main manuscript and supplement use the following machine-readable result families. Their filenames describe the computational artifacts and do not imply an online repository deposition.

Table S7. Reproducibility file guide

Result family	Machine-readable files
Eligibility and reference	cohort_selection.csv; coverage_monthly.csv; reference_temperature_coverage.csv; reference_pooled_month_coverage.csv; thermal_thresholds.csv
Occupancy and missingness	occupancy_station_year.csv; occupancy_pooled_observed.csv; missing_runs.csv; states_[station].csv.gz
Episodes and intervals	events.csv; persistence_station_year.csv; between_events.csv; recurrence.csv; recurrence_station_year.csv
Alternative definitions	sensitivity_occupancy_station_year.csv; sensitivity_persistence_station_year.csv; sensitivity_minimum_span.csv; independent_station_profiles_all_variants.csv
Resampling and daily comparison	bootstrap_exploratory.csv; bootstrap_shared_year_schedule.csv; bootstrap_draws.csv; daily_secondary.csv
Computational reconstruction	independent_reconstruction.py; comparison_checks.json; independent_provenance_checks.json; source_event_selection.csv; source_event_traces.csv
Figures	figures/source_data/fig1a_support.csv through figS4_annual_compound_burden.csv; figure_manifest.json; make_figures.py

Result filenames are relative to the analysis output directories in the accompanying package. Figure source tables include panel-level values and denominators. These files permit verification without treating text rounding as an analytical change.

POST HOC SUPPORT AND INTERVAL DIAGNOSTICS

These analyses were specified on 1 October 2026 after the primary results were available. They retain the release v1 state assignments, fixed station P90, eligible May–September seasons, and gap rules. Their protocols and code are archived separately from the pre-estimation specification. The common-year comparison addresses unequal calendar-year support, whereas exact-timestamp matching addresses the smaller difference in valid observations within common years.

Table S8 shows the Oyster Landing–Clambank Landing annual and common-pooled values, with the separate occupancy calculation on exact shared valid timestamps. A secondary matched-grid reconstruction also redetected compound fragments, without bridging any position invalid at either station. It retained all 51 Oyster Landing and 52 Clambank Landing native episodes, all complete, with no lost compound reading, new fragment, or truncated boundary. Oyster Landing retained five >3-h episodes and 18.25 assigned occupancy hours; Clambank Landing retained none. This is an observed-support diagnostic, not a correction for nonrandom missingness. The sites share only 2020 and 2022; they are not requalified under a new three-season rule. The numerically close compound-hour rates do not establish equality or statistical equivalence. Long-run occupancy and the median span answer different questions: the >3-h contribution differs even though the 2020 median span was lower at Oyster Landing.

Table S8. Post hoc common-year and exact-timestamp support for Oyster Landing and Clambank Landing

Station	Support	V (h)	C (h)	C h per 1,000 V h	Runs	C hours in span >3 h (%)	No neither / intervals
NIW-OL	2020	3,671.25	38.5	10.49	32	29.2	18/30
NIW-CB	2020	3,670.5	36.25	9.88	27	0.0	7/25
NIW-OL	2022	3,670.5	21	5.72	19	33.3	2/17
NIW-CB	2022	3,558.75	17.5	4.92	25	0.0	13/24
NIW-OL	2020, 2022	7,341.75	59.5	8.1	51	30.7	20/47
NIW-CB	2020, 2022	7,229.25	53.75	7.44	52	0.0	20/49
NIW-OL	Matched timestamps	7,227.25	59.5	8.23	—	—	—
NIW-CB	Matched timestamps	7,227.25	53.75	7.44	—	—	—

Annual and common-pooled profiles retain native station-valid support. The last two rows use only timestamps valid at both stations in 2020 and 2022; 458 otherwise valid Oyster Landing readings and eight Clambank Landing readings are outside that intersection. The matched rows summarize occupancy only and do not redefine episodes or eligible intervals. Dashes indicate deliberately unreported metrics for that occupancy diagnostic. Pairwise and three-station summaries for Thousand Acre are retained in the accompanying post hoc CSV files. All comparisons use the unchanged primary thresholds; they are not inferential tests.

Table S9 retains every station-level deletion of an eligible outcome year. The thermal thresholds remain fixed. This is distinct from the reference-year sensitivity in Table S5, which recalculates the thermal percentile before applying it to an omitted reference year. The files pair_common_year_metrics.csv and pair_common_year_contrasts.csv additionally preserve all three focal station pairs, individual common years, and each common-year deletion. Three-station summaries retain 2020 and 2022. Neither deletion ranges nor repeated points are independent confirmation of a site effect. In particular, the Oyster Landing–Clambank Landing illustration has two common primary years and only one under stricter coverage; its >3-h contrast vanishes at P95 on the common-year support. It is insufficient evidence of a persistent station effect.

Table S9. Post hoc deletion of each outcome year with fixed thermal thresholds

Station	Omitted year	Retained V (h)	Retained C (h)	C h per 1,000 V h	C hours in span >3 h (%)	No neither / intervals
NIW-CB	2018	10,896.5	70.5	6.47	0.0	28/67
NIW-CB	2020	10,892	44	4.04	0.0	25/54
NIW-CB	2021	10,895.25	63.5	5.83	0.0	24/61
NIW-CB	2022	11,003.75	62.75	5.7	0.0	19/55
NIW-DC	2020	10,873.5	2.25	0.21	0.0	1/2
NIW-DC	2021	10,824.75	3.75	0.35	0.0	1/4
NIW-DC	2022	10,798.5	3.75	0.35	0.0	1/4
NIW-DC	2023	10,913.25	1.5	0.14	0.0	0/2
NIW-OL	2019	10,899.75	135.5	12.43	47.2	36/85
NIW-OL	2020	10,899.75	160.5	14.73	53.6	26/82
NIW-OL	2022	10,900.5	178	16.33	50.7	42/95
NIW-OL	2023	11,013	123	11.17	41.9	28/74
NIW-TA	2019	14,542	46.25	3.18	15.7	33/61
NIW-TA	2020	14,673.5	52.25	3.56	13.9	35/68
NIW-TA	2021	14,534.75	39	2.68	0.0	32/60
NIW-TA	2022	14,535.25	47	3.23	15.4	33/59
NIW-TA	2023	14,540.5	24.5	1.68	29.6	7/24
GTM-FM	2018	14,686.5	0	0	NA	NA
GTM-FM	2020	14,686.25	0	0	NA	NA
GTM-FM	2021	14,686.25	0	0	NA	NA
GTM-FM	2022	14,686.25	0	0	NA	NA
GTM-FM	2023	14,687.75	0	0	NA	NA
GTM-PC	2018	14,509.75	23	1.59	0.0	16/30
GTM-PC	2019	14,509.75	16	1.1	0.0	13/21
GTM-PC	2020	14,579.75	20.75	1.42	0.0	14/24
GTM-PC	2021	14,509.75	21.75	1.5	0.0	15/28
GTM-PC	2023	14,618	10.5	0.72	0.0	6/17

Station	Omitted year	Retained V (h)	Retained C (h)	C h per 1,000 V h	C hours in span >3 h (%)	No neither / intervals
GTM-PI	2018	10,905.75	53.5	4.91	0.0	79/91
GTM-PI	2020	10,905.75	53.5	4.91	0.0	79/91
GTM-PI	2022	10,905.5	49.5	4.54	0.0	77/85
GTM-PI	2023	11,015.5	4	0.36	0.0	2/6
GTM-SS	2018	11,015	0.25	0.02	0.0	NA
GTM-SS	2020	11,015	0.25	0.02	0.0	NA
GTM-SS	2021	11,014	0.25	0.02	0.0	NA
GTM-SS	2022	11,014	0	0	NA	NA

Each row removes that year's outcomes from the station's full primary eligible cohort. No thermal reference is recalculated and no run or interval is connected across years. This differs from the prespecified leave-one-reference-year-out P90 sensitivity in Table S5. NA preserves absent compound or interval denominators. The CSV files also contain every pair-common-year deletion and synchronized network deletion. At network level, removing 2023 gives 75/202 intervals without neither; removing another calendar year gives 54.6–57.3%. These are influence summaries, not confidence intervals.

Table S10 gives the post hoc partition of intervals by the condition present between compound runs. The 183 entirely warm-only primary intervals had median length 2.25 h, the 22 entirely low-oxygen-only intervals 0.875 h, the two mixed single-condition intervals 8.25 h, and the 177 intervals containing neither 24.25 h. The first three classes sum to 207/384 intervals but only 1,237/17,354.5 h. A high count fraction can therefore coexist with a small share of total interval time. State-specific hours within the fourth class remain in the original composition analysis.

Table S10. Post hoc partition of fully observed interepisode intervals

Scenario	Observed state class	Class / all intervals	Intervals (%)	Median length (h)	Total class length (h)
Primary	Warm only throughout	183/384	47.7	2.25	1,191.5
Primary	Low oxygen only throughout	22/384	5.7	0.875	29
Primary	Both single states without neither	2/384	0.5	8.25	16.5
Primary	Contains neither	177/384	46.1	24.25	16,117.5
Strict coverage	Warm only throughout	70/220	31.8	1	547.5
Strict coverage	Low oxygen only throughout	18/220	8.2	0.75	21.5
Strict coverage	Both single states without neither	2/220	0.9	8.25	16.5
Strict coverage	Contains neither	130/220	59.1	24.25	12,029.25
Conservative	Warm only throughout	104/293	35.5	0.75	716
Conservative	Low oxygen only throughout	22/293	7.5	0.875	29
Conservative	Both single states without neither	2/293	0.7	8.25	16.5
Conservative	Contains neither	165/293	56.3	24.25	14,525.25

The four classes partition the eligible interval count in each scenario. "Both single states" means warm-only and low-oxygen-only readings occur in the same interval, with no neither reading; it does not mean compound readings occur between adjacent compound runs. Percentages in the fourth column weight intervals equally. Summed lengths of the first three classes are 1,237/17,354.5 h (7.1%) for primary, 585.5/12,614.75 h (4.6%) for strict coverage, and 761.5/15,286.75 h (5.0%) for conservative screening. Those time shares do not include single-condition portions of intervals in the fourth class. All thresholds, state assignments, and eligible intervals remain those of release v1.

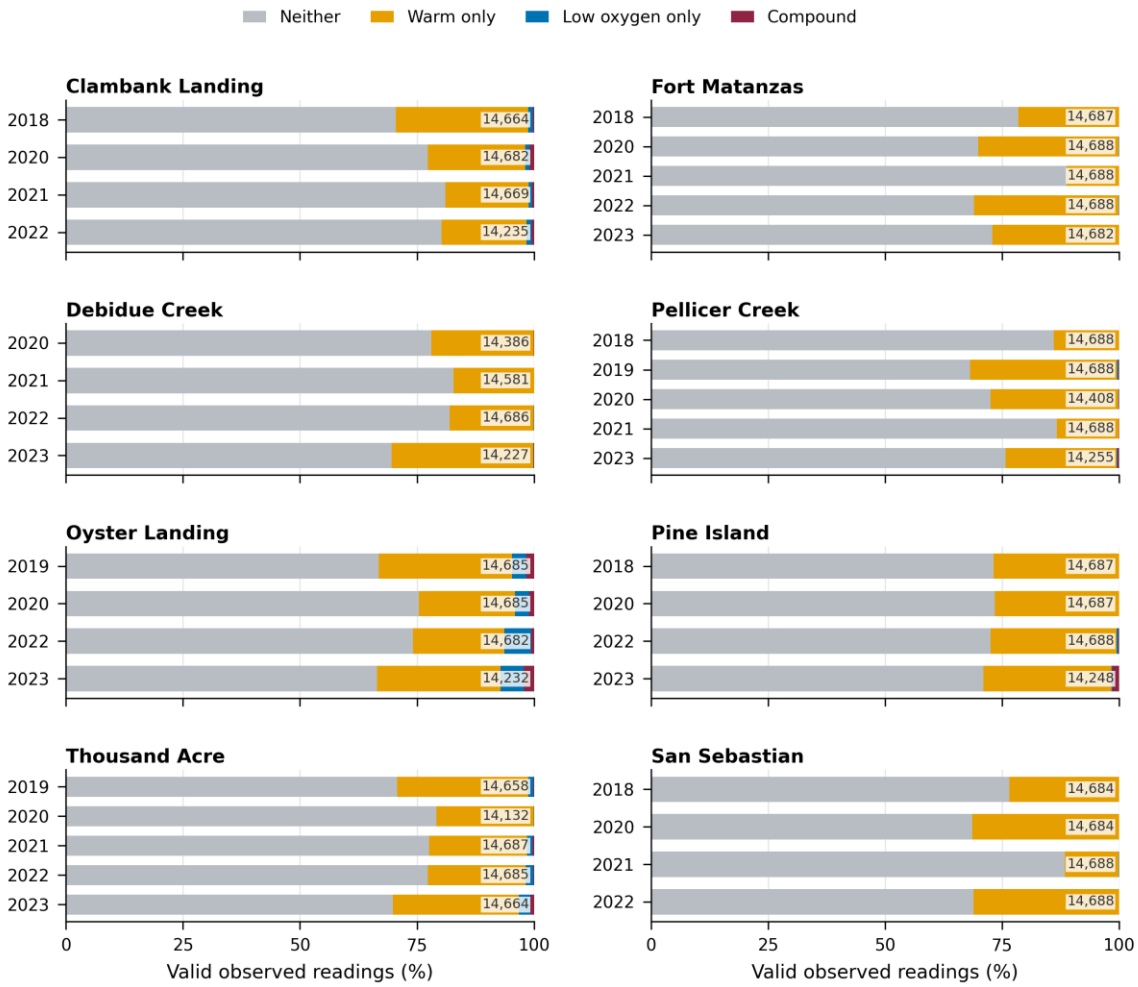
Table S11 crosses four original threshold alternatives with the same eligible 2020 and 2022 seasons. Under P95, Oyster Landing had eight episodes and 10.75 compound hours and Clambank Landing five episodes and 5 h; neither had a >3-h run. Oyster Landing had no compound reading in 2022 under

P95. At oxygen <1.9 mg/L, the >3-h contribution also disappeared at Oyster Landing in 2022, despite a positive pooled contribution. These results separate the primary P90 comparison from any claim of invariance across definitions. The P95 result concerns a smaller, differently classified set of episodes.

Table S11. Post hoc threshold alternatives on the common 2020 and 2022 support

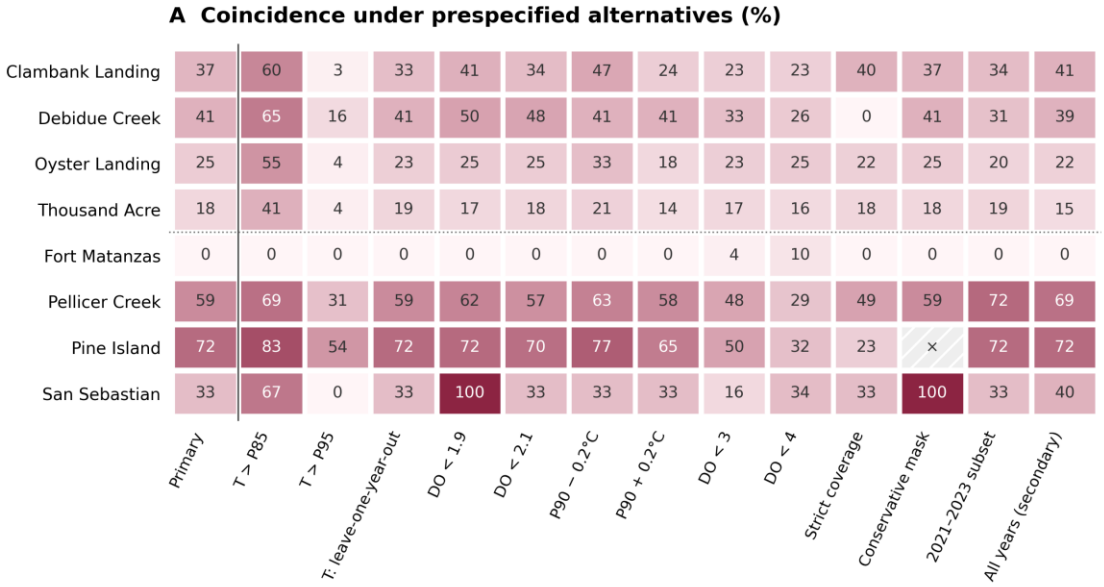
Definition	Years	Station	T cutoff (°C)	C (h)	Runs	C hours in span >3 h (%)	C h per 1,000 V h
Primary P90	2020	NIW-OL	29.5	38.5	32	29.2	10.49
Primary P90	2020	NIW-CB	29.1	36.25	27	0.0	9.88
Primary P90	2022	NIW-OL	29.5	21	19	33.3	5.72
Primary P90	2022	NIW-CB	29.1	17.5	25	0.0	4.92
Primary P90	2020, 2022	NIW-OL	29.5	59.5	51	30.7	8.1
Primary P90	2020, 2022	NIW-CB	29.1	53.75	52	0.0	7.44
P85	2020	NIW-OL	28.8	90.75	54	45.7	24.72
P85	2020	NIW-CB	28.5	50.75	37	0.0	13.83
P85	2022	NIW-OL	28.8	78.25	39	49.2	21.32
P85	2022	NIW-CB	28.5	29.25	38	0.0	8.22
P85	2020, 2022	NIW-OL	28.8	169	93	47.3	23.02
P85	2020, 2022	NIW-CB	28.5	80	75	0.0	11.07
P95	2020	NIW-OL	30.6	10.75	8	0.0	2.93
P95	2020	NIW-CB	30	4.75	4	0.0	1.29
P95	2022	NIW-OL	30.6	0	0	NA	0
P95	2022	NIW-CB	30	0.25	1	0.0	0.07
P95	2020, 2022	NIW-OL	30.6	10.75	8	0.0	1.46
P95	2020, 2022	NIW-CB	30	5	5	0.0	0.69
DO <1.9	2020	NIW-OL	29.5	25.75	28	28.2	7.01
DO <1.9	2020	NIW-CB	29.1	27.75	25	0.0	7.56
DO <1.9	2022	NIW-OL	29.5	12.75	13	0.0	3.47
DO <1.9	2022	NIW-CB	29.1	11	17	0.0	3.09
DO <1.9	2020, 2022	NIW-OL	29.5	38.5	41	18.8	5.24
DO <1.9	2020, 2022	NIW-CB	29.1	38.75	42	0.0	5.36
DO <2.1	2020	NIW-OL	29.5	53	36	23.1	14.44
DO <2.1	2020	NIW-CB	29.1	45.75	32	0.0	12.46
DO <2.1	2022	NIW-OL	29.5	30.75	30	27.6	8.38
DO <2.1	2022	NIW-CB	29.1	25.25	28	0.0	7.1
DO <2.1	2020, 2022	NIW-OL	29.5	83.75	66	24.8	11.41
DO <2.1	2020, 2022	NIW-CB	29.1	71	60	0.0	9.82

Temperature must exceed the listed cutoff. Oxygen must be <2 mg/L except in the two scenario labels specifying a different oxygen cutoff. Every definition uses the original valid observations and eligible 2020 and 2022 seasons, with no recalculation of the reference percentiles. NA in P95 Oyster Landing 2022 means no compound readings, not zero persistence. P95 has no >3-h run at either station over these years. The <1.9 mg/L alternative retains a pooled contrast but none in 2022. These crossed comparisons were specified after release v1 and after the primary common-year result; they are not part of the pre-estimation specification.



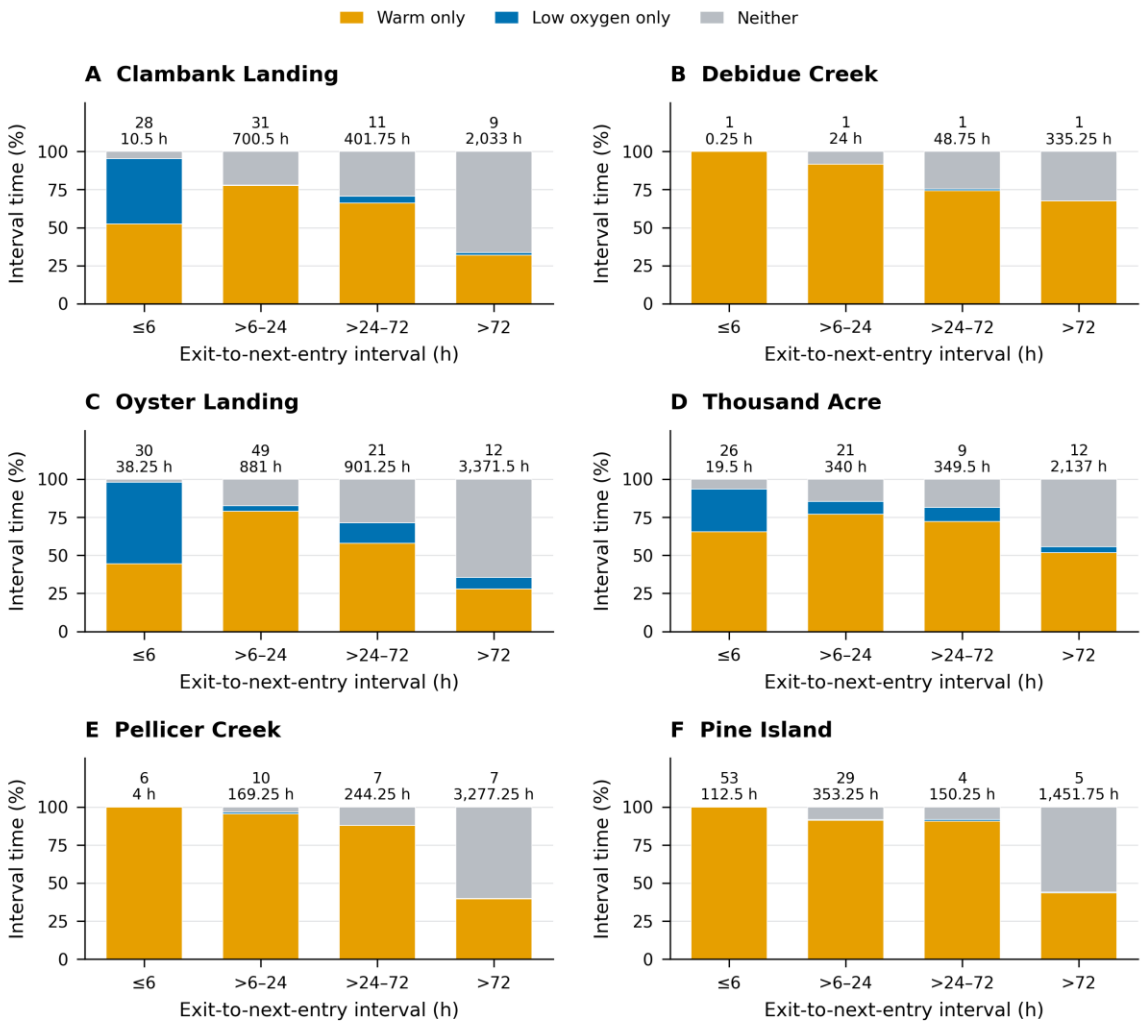
All 35 eligible station-seasons; labels give valid paired-reading denominators. Low oxygen and compound shares can be too small to resolve at this scale; exact counts are retained in source data and Figure S5.

Figure S1. Four-state occupancy in all eligible station-seasons. Horizontal compositions show each state's share of joint valid readings within each eligible season. Labels give the valid-reading denominator. State hours are nominal occupancy estimates from a regular grid, not continuously observed exposure. The shared 0–100% scale is useful for full composition but visually compresses rare low-oxygen and compound states; their exact counts are retained in the source data, absolute low-oxygen totals in Figure S5, and compound seasonal detail in Figure S4. Data: figS1_full_state_occupancy.csv.



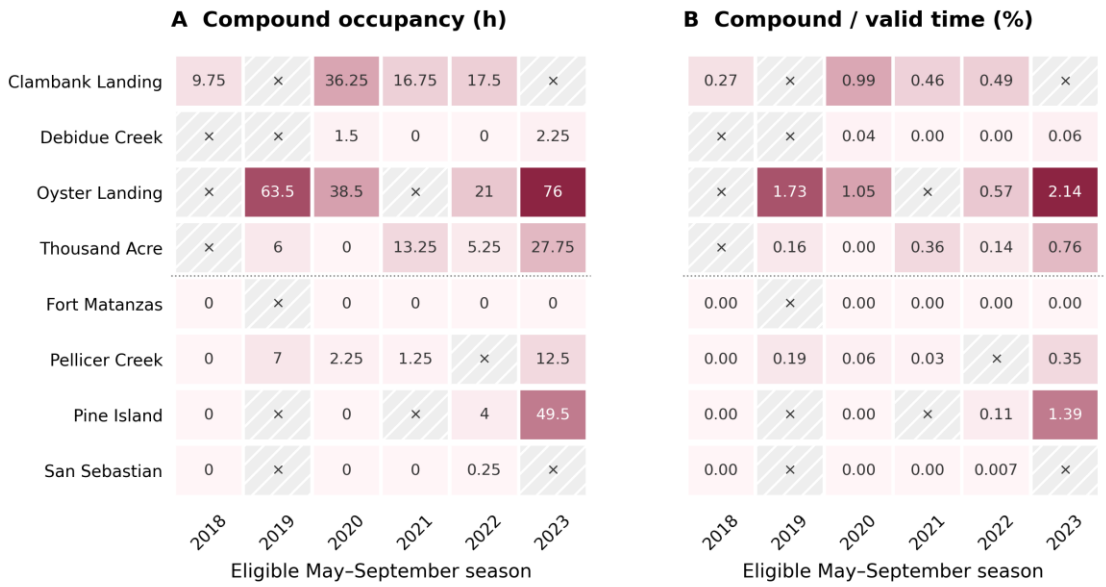
Cell values = compound / low-oxygen readings × 100; NA = zero low-oxygen denominator.
× = insufficient cohort support (Pine Island under the conservative mask: only 2 eligible seasons).
Broader DO cutoffs change the state definition; T/DO offsets are classification perturbations, not error intervals.

Figure S2. Coincidence fractions under prespecified occupancy alternatives. Cells display the pooled within-station compound/low-oxygen fraction, as a rounded percentage, for the primary specification and each occupancy alternative: thermal P85/P95, leave-one-year-out P90, DO < 1.9/2.1 mg/L, P90 shifted by −/+0.2°C, broader DO < 3/4 mg/L conditions, stricter coverage, conservative optional-deployment exclusions, the 2021–2023 subset, and all authenticated seasons as a secondary observed-support comparison. The source data retain each alternative's compound, low-oxygen, and valid-reading denominator and number of seasons. A crossed cell denotes insufficient eligible cohort support: Pine Island has only two eligible seasons under the conservative mask and is therefore absent under the predefined minimum-three-season rule. This is not a zero coincidence estimate and does not attribute any primary event to sensor artifacts. NA denotes an undefined fraction with zero low-oxygen readings. Different DO thresholds change the state definition; small classification-margin perturbations are not probabilistic uncertainty bounds. Data: figS2_sensitivity_matrix.csv.



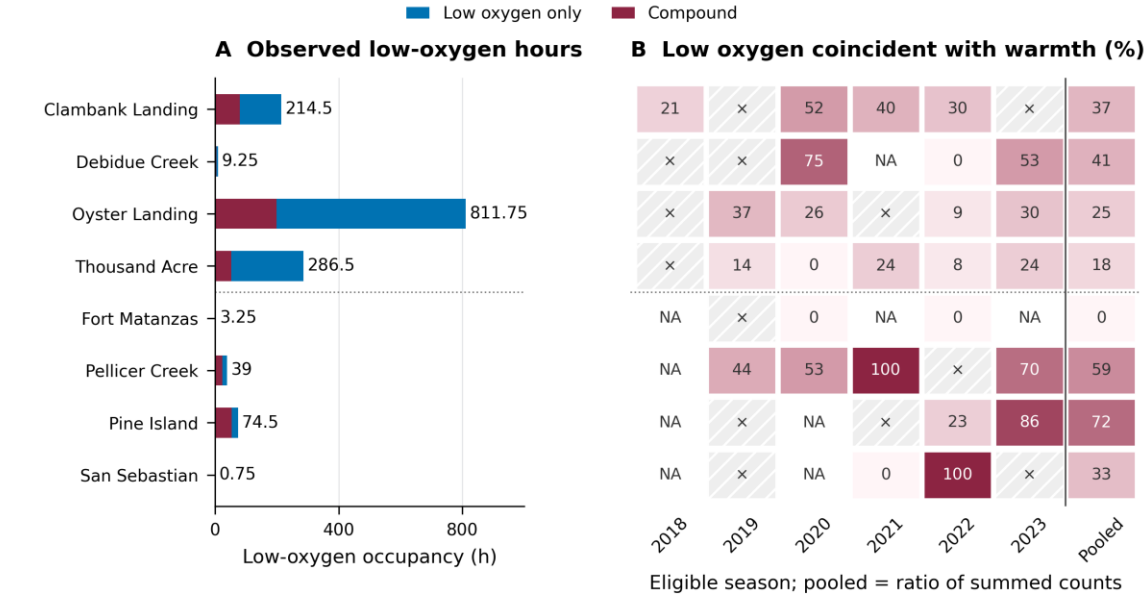
State hours are summed within each station and interval-length bin; labels show interval count and nominal hours.
Only fully observed interepisode intervals are included. Fort Matanzas and San Sebastian have no eligible interval.
The pool of observed intervals does not represent all time outside compound conditions.

Figure S3. Station-specific interepisode state composition. State composition of the fully observed interepisode intervals in Figure 4, shown separately for the six stations with at least one eligible interval. Within each interval-length bin, colored shares are sums of state-specific reading-hours divided by total observed interval hours. Above-bar labels give interval count and exact nominal hours, including 0.25-h support. Fractions are time-weighted and do not give the proportion of intervals lacking a neither-state reading. Fort Matanzas and San Sebastian have no eligible interval. Data: figS3_station_interval_composition.csv.



Zero is retained; × = excluded season. Separate color scales are used in A and B; percentages in B are rounded.
Pine Island: 49.5 of 53.5 nominal compound hours occur in 2023; 2018 and 2020 have zero compound readings.
The conservative-mask omission in Figure S2 is a support failure, not proof that these readings are artifacts.

Figure S4. Seasonal concentration of compound occupancy. (A) Nominal compound occupancy hours in every eligible season, preserving observed zeros and marking excluded seasons with a crossed cell. (B) Corresponding fractions of valid observed time, with rounded numerical percentages. Color intensity is scaled separately within each panel. Pine Island's 53.5 pooled nominal compound hours include 49.5 h in 2023, 4 h in 2022, and zero in its eligible 2018 and 2020 seasons; all other station profiles are shown on the same basis. The source data include valid-reading denominators. Yearly heterogeneity should be considered alongside pooled fractions and recurrence estimates. Data: figS4_annual_compound_burden.csv.



Low oxygen: DO < 2 mg/L; warm: T > local annual-reference P90. Occupancy = readings × 0.25 h.
× = excluded season; NA = no low-oxygen readings (undefined ratio); 0 = observed zero coincidence.
Rows retain protocol order. Fractions with small absolute denominators require particular caution.

Figure S5. Absolute low-oxygen occupancy and its coincidence with locally high temperature. (A) Nominal observed hours under DO < 2 mg/L, partitioned into low oxygen only (blue) and compound warmth–low oxygen (dark red). Labels give total low-oxygen occupancy, calculated as valid classified readings multiplied by 0.25 h. These totals accompany rather than substitute for the denominators of the fractions. (B) The compound fraction of low-oxygen readings in each eligible season and after pooling within station by summing numerators and denominators. Values are percentages rounded to the nearest whole percentage point. Crossed cells indicate excluded seasons; NA means no low-oxygen readings, so the ratio is undefined; zero means observed low oxygen without coincident warmth. Small denominators, especially at Fort Matanzas, Debidue Creek and San Sebastian, limit interpretation of the ratios. Pooled fractions are not averages across estuaries. Data: fig2a_low_oxygen_hours.csv and fig2b_seasonal_coincidence.csv.