Recent Changes in the North Pacific Basin: Physical Drivers & Biogeochemical Impacts

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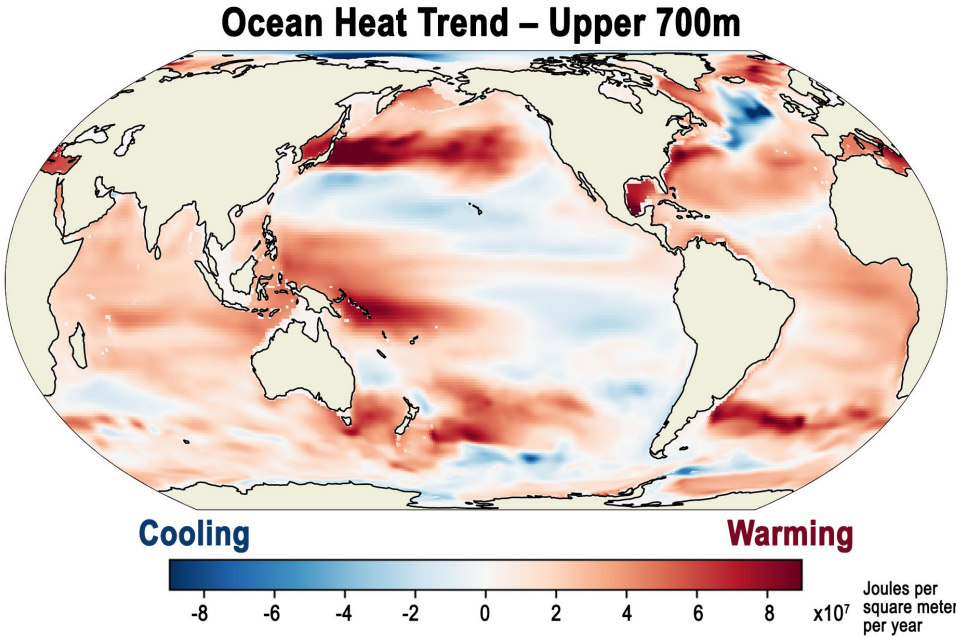
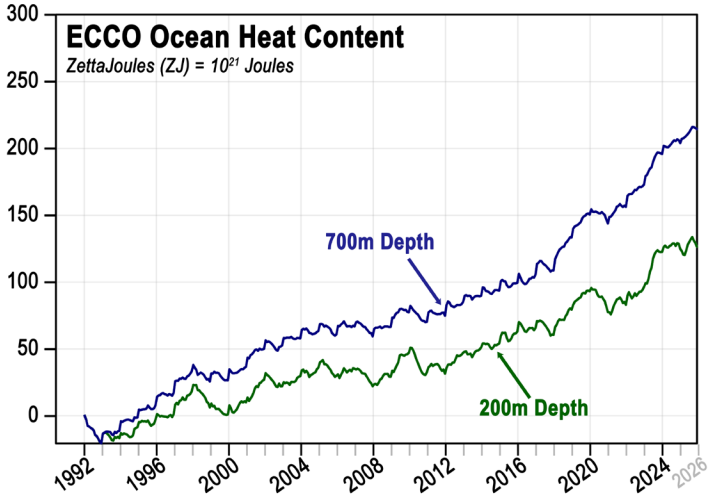
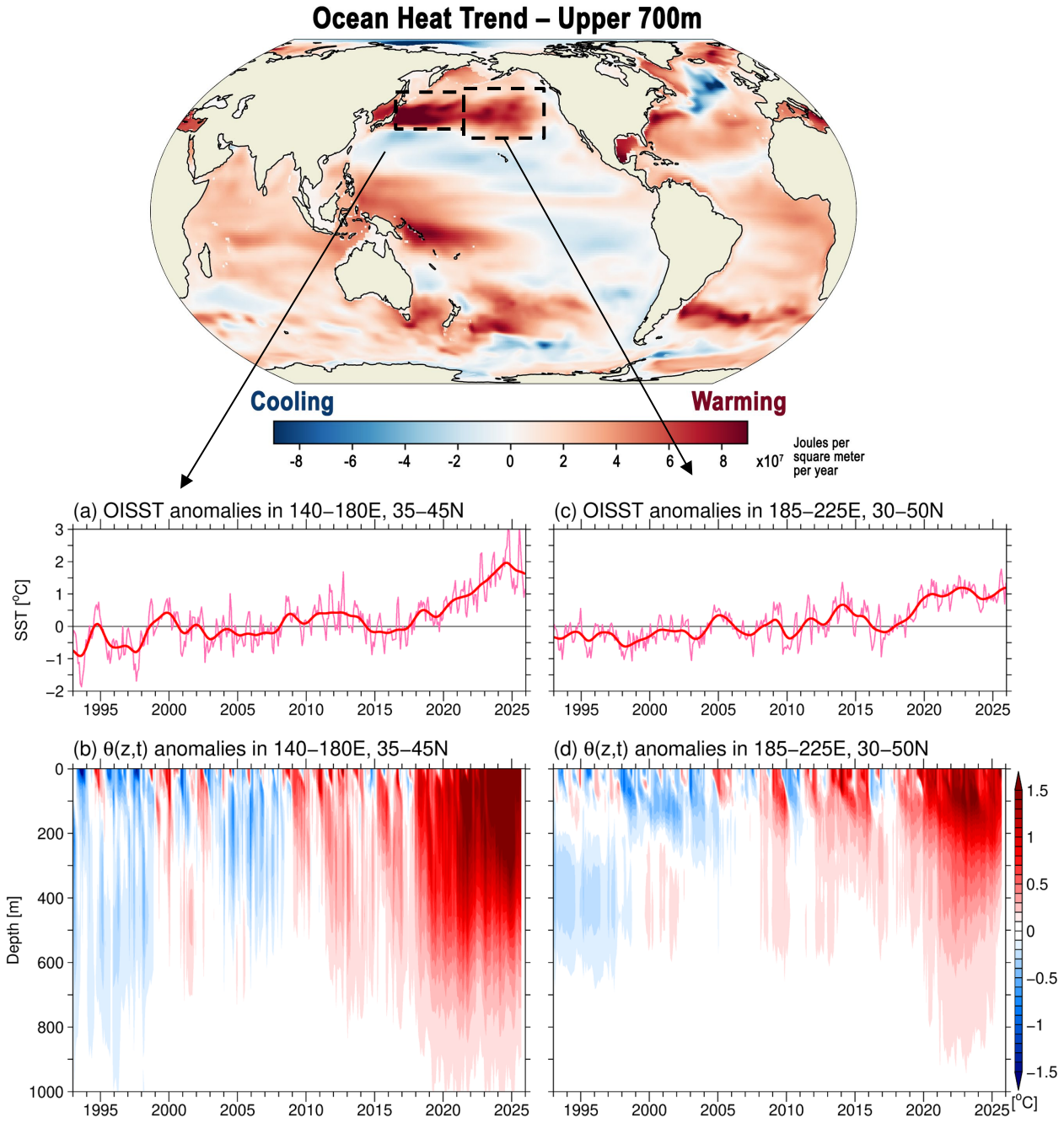




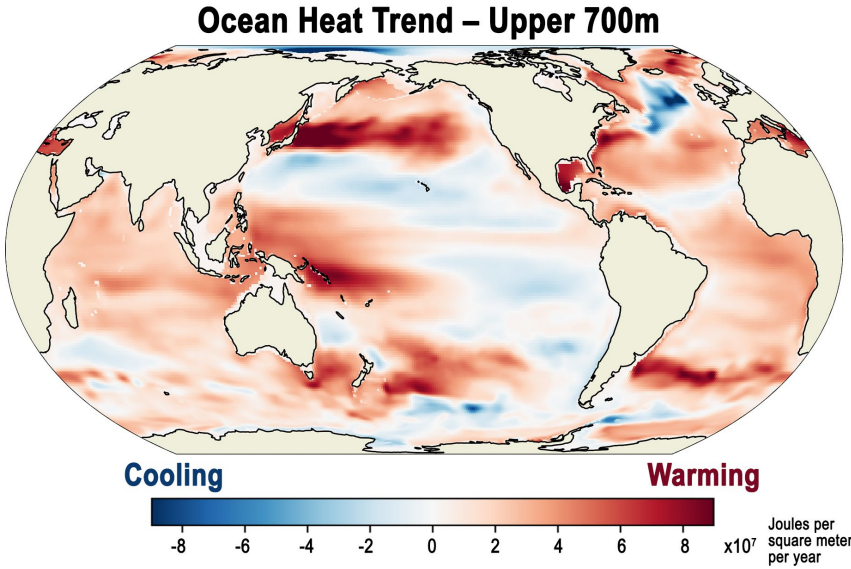
- Ocean heat content has increased *steadily* over the past 3.5 decades
- Hint of an acceleration after 2018
- Oceanic warming is spatially *nonuniform*!

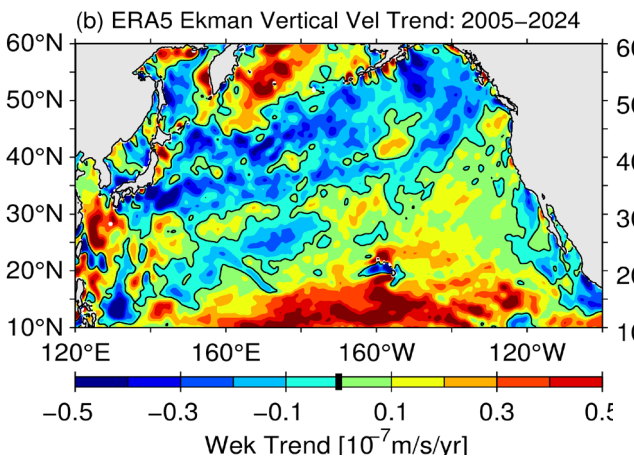
PICES Annual Meeting, Nanaimo, Canada, 26-30 October 2026

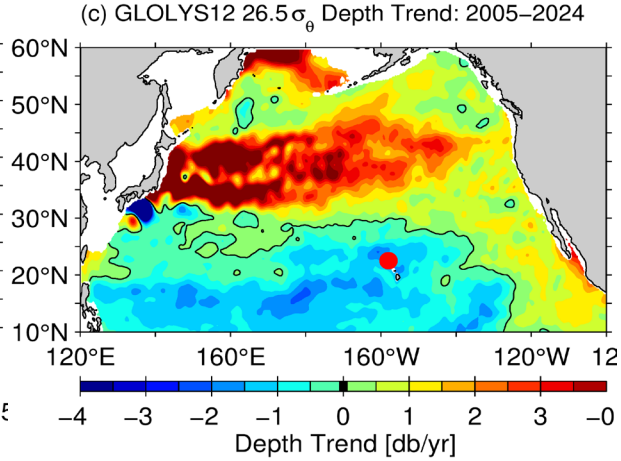


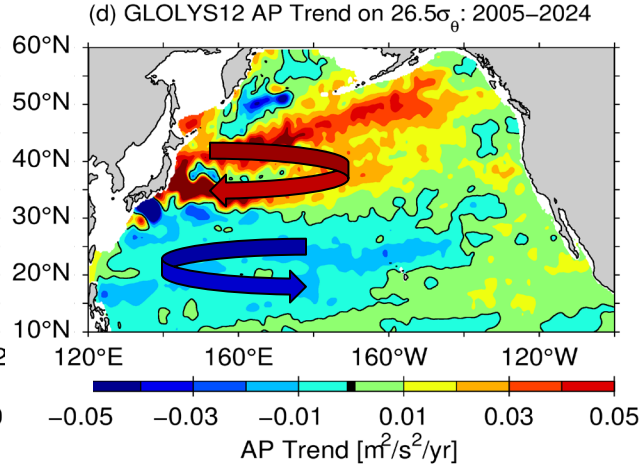
Anomalies are relative to 1993-2017 baseline

- Recent accelerated warming in NP occurs *coherently* across eastern & western basins north of 30°N
- The warm anomalies are not confined to ML, but extend beyond main thermocline
- Such anomalies in eastern NP basin behave differently from earlier “warm blobs”







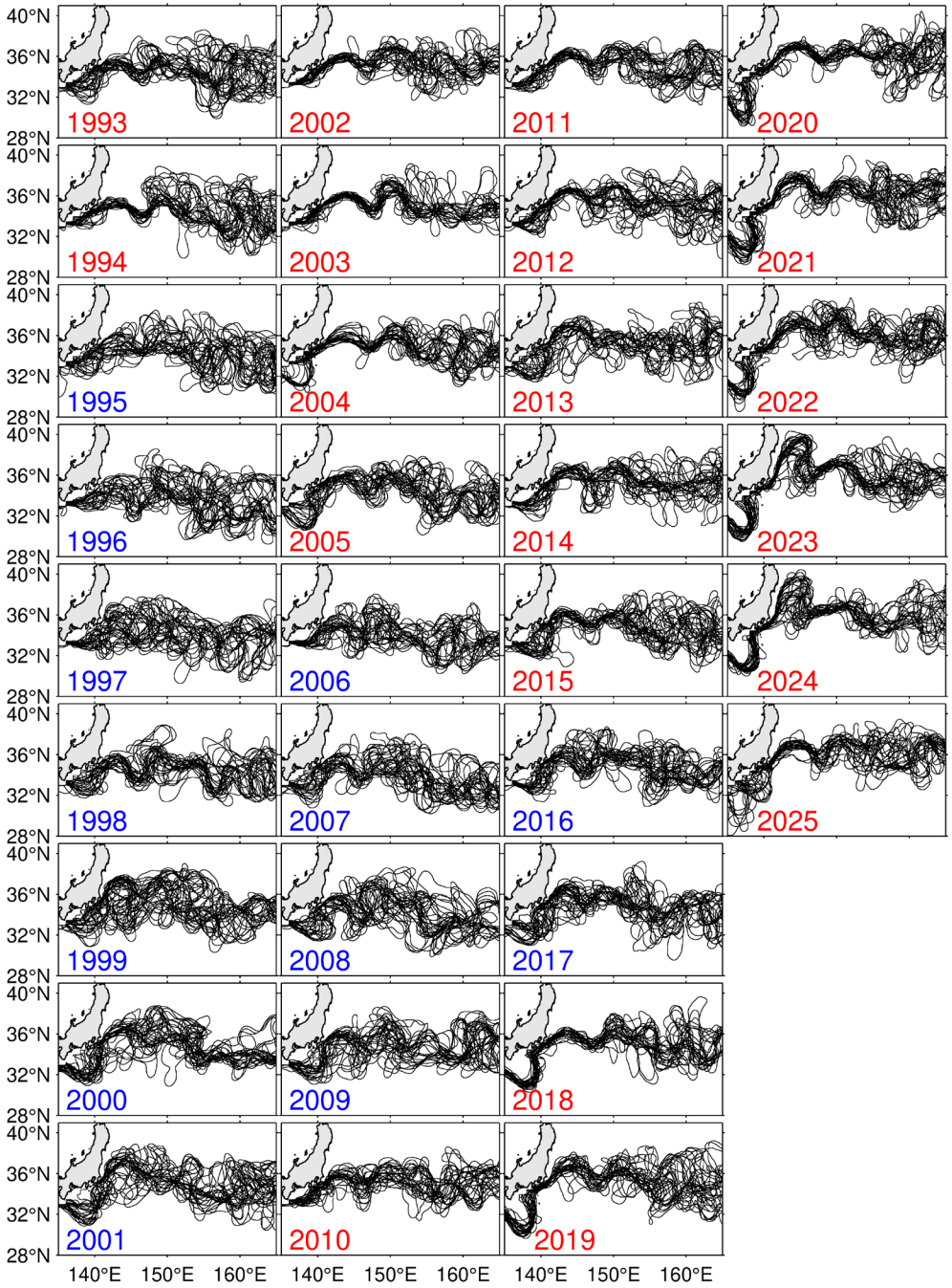


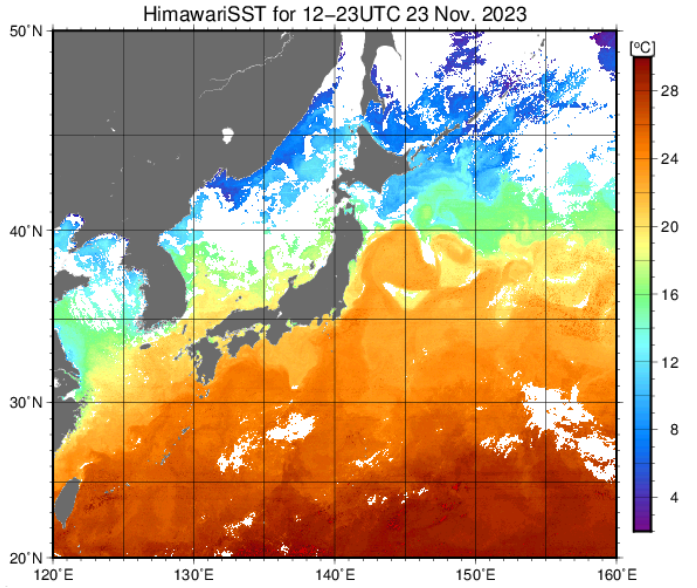
- Wind-driven Ekman pumping enhanced north of 30°N, & reduced south of 30°N

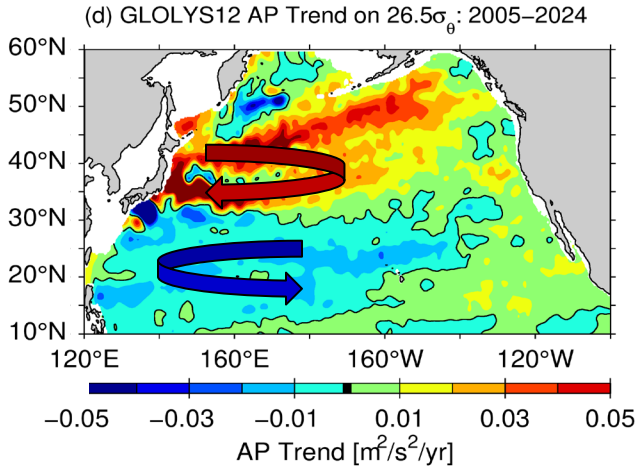
- Deepening of upper layer/ heat content north of 30°N, & shoaling south of 30°N

- Slowing down of subtropical gyre & poleward shift of Kuroshio Extension/NPC

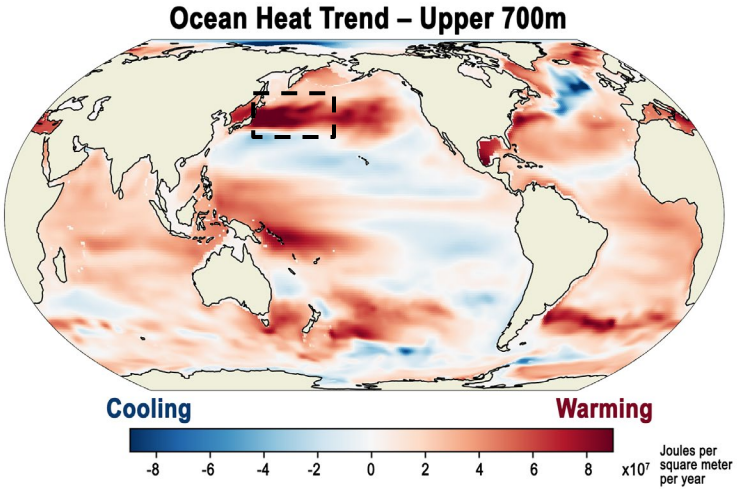
Annual maps of bi-weekly Kuroshio/KE jet paths







- Slowing down of subtropical gyre & poleward shift of Kuroshio Extension/NPC



A New Dynamic Regime in the Kuroshio/Kuroshio Extension and the North Pacific Climate System after 2018

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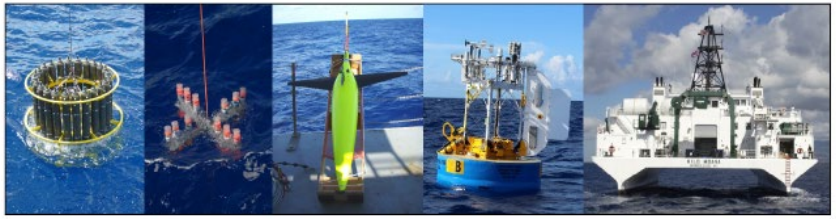
ABSTRACT: Over the four decades following the 1976/77 climate regime shift, the Kuroshio Extension (KE) in the North Pacific subtropical gyre exhibited quasi-decadal oscillations between stable and unstable dynamic states. These oscillations were facilitated by a delayed negative feedback loop involving wind-forced interior ocean adjustment, its modulation on the KE dynamic state, and the KE's feedback on atmospheric storm tracks and the wind stress field. However, this feedback loop ceased functioning after 2018, giving rise to a new dynamic regime. In this new regime, the Kuroshio south of Japan assumes a persistent large-meander (LM) path, while the stabilized KE jet migrates poleward. This study identifies three key processes responsible for the emergence of this regime: 1) a shift in the external forcing field, characterized by intensified wind forcing over the northern subtropical gyre and weakened forcing over the southern gyre; 2) nonlinear reinforcement between the Kuroshio LM and the poleward-migrated KE jet; and 3) altered storm-track and wind stress responses to the KE's new stable dynamic state. The establishment of this regime has played a critical role in the recent upper-ocean warming—manifested as frequent marine heat waves—along the 35°–45°N band of the western North Pacific. An upper-ocean temperature budget analysis reveals that this cumulative warming is primarily driven by lateral advection associated with the migrating KE jet, while the net surface heat flux forcing acts to dampen the advection-induced temperature anomalies.

KEYWORDS: Advection; Boundary currents; Atmosphere-ocean interaction; Climate; Ekman pumping; Pacific decadal oscillation

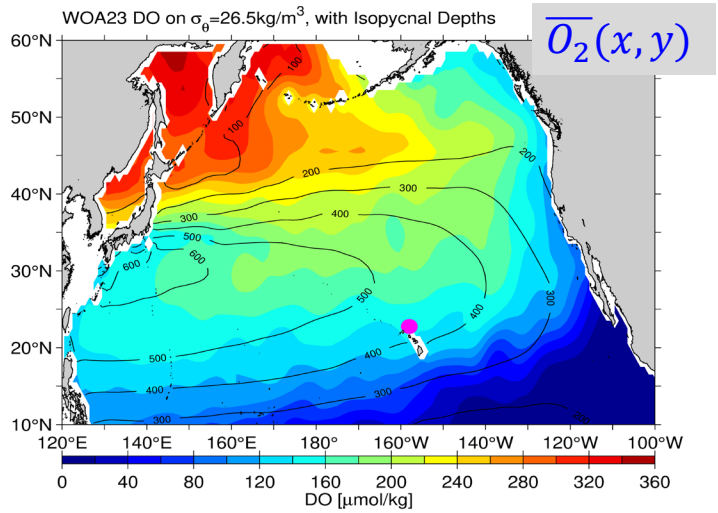
1. **Shift in external wind forcing**: intensified in the northern subtropical gyre & weakened in southern subtropical gyre
2. **Nonlinear reinforcement:** interaction between the Kuroshio Large Meander & poleward-shifted KE jet
3. **Altered storm-track & wind stress responses:** resulting in a new KE dynamic state

Qiu & Chen (2026, *J. Climate*)

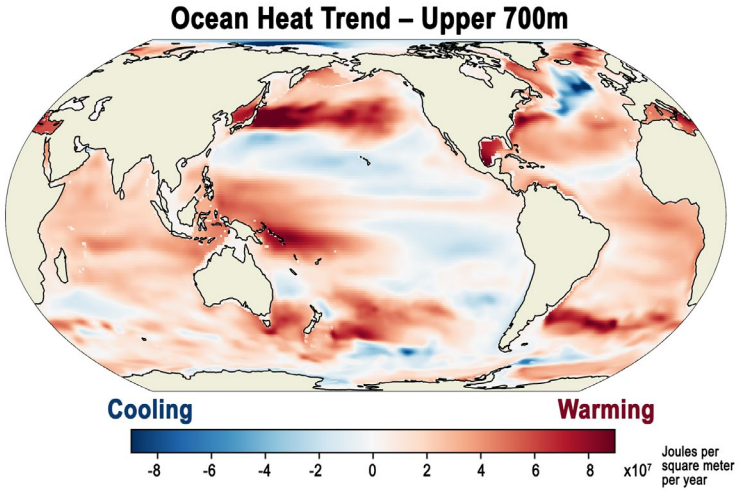
Hawaii Ocean Time-series (HOT)



https://hahana.soest.hawaii.edu/hot/



$\overline{O_2}(x, y)$

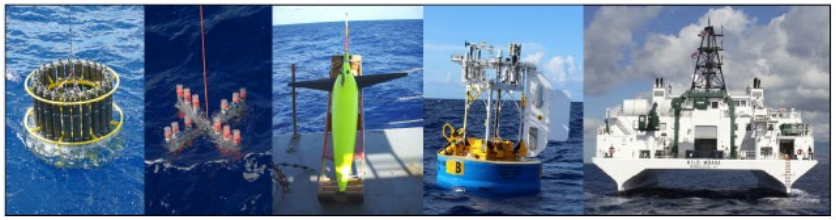


Questions:

1. Given the substantial thermal & circulation changes across the NP basin in recent changes, have there been corresponding significant changes in its marine BGC properties?

2. If so, what are the underlying mechanisms driving these changes?

Hawaii Ocean Time-series (HOT)



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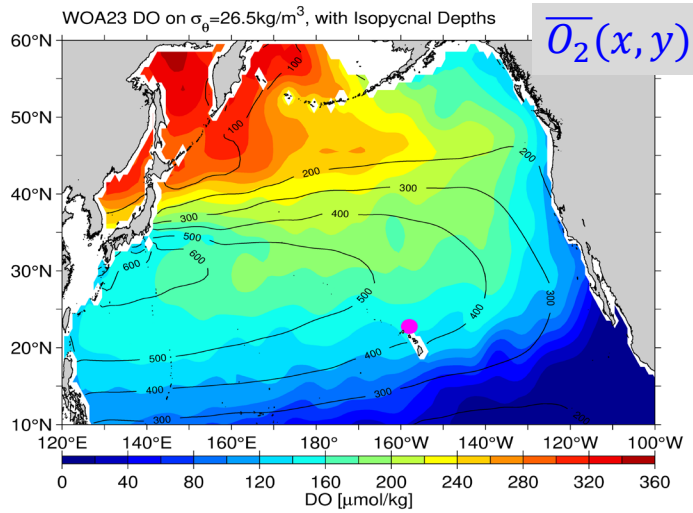
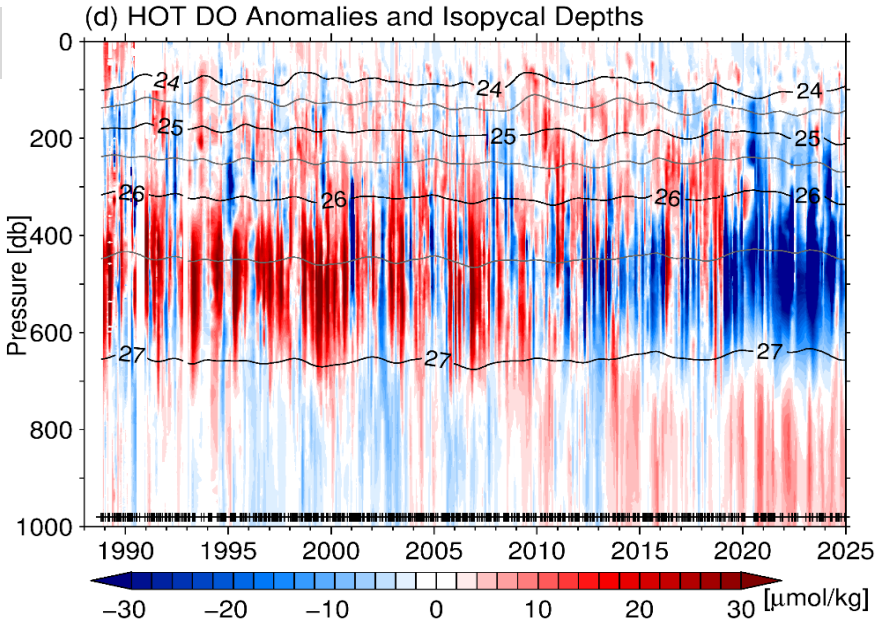
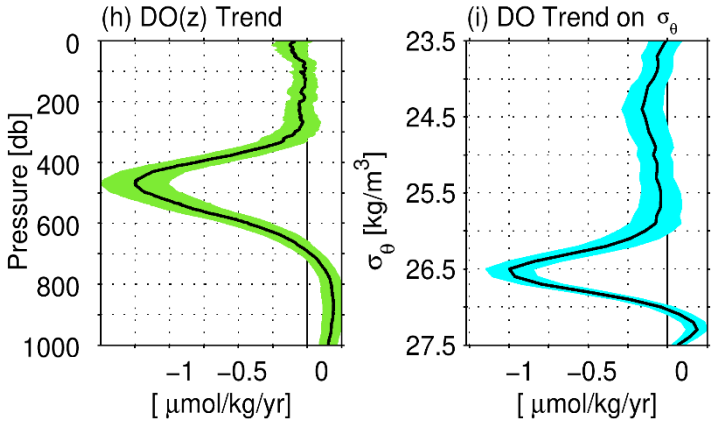


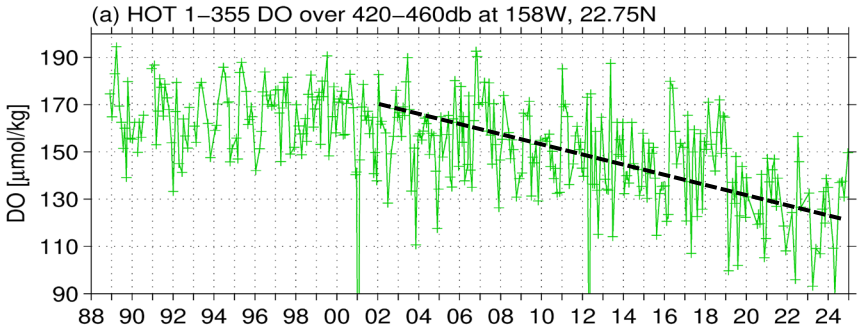
$\overline{O_2}(x,y)$



$O_2'(z,t)$

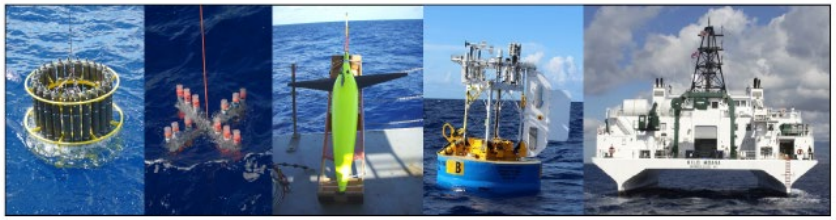
isobaric trend ~ isopycnal trend





~ 50% drop!!

Hawaii Ocean Time-series (HOT)



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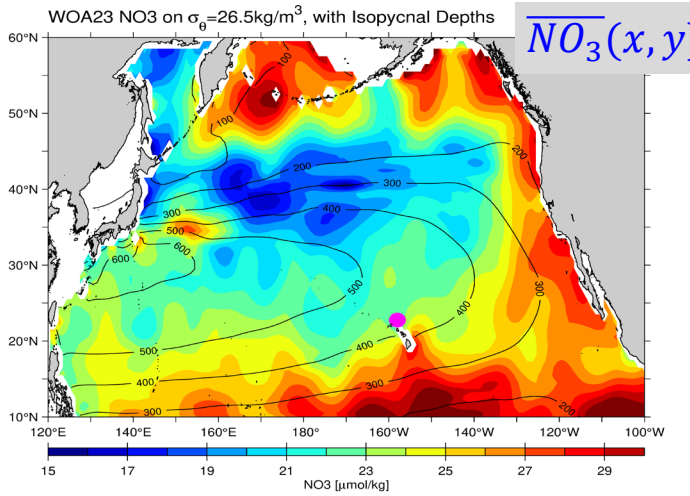
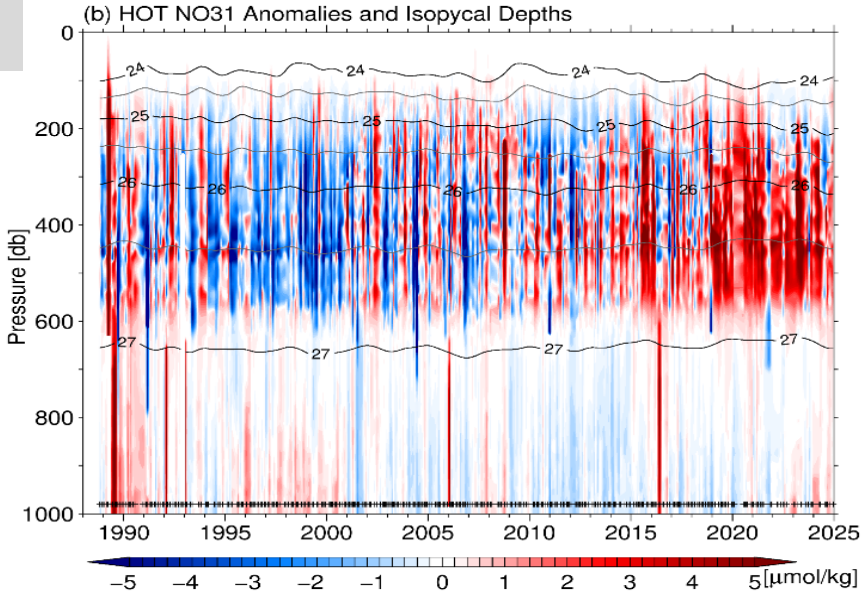
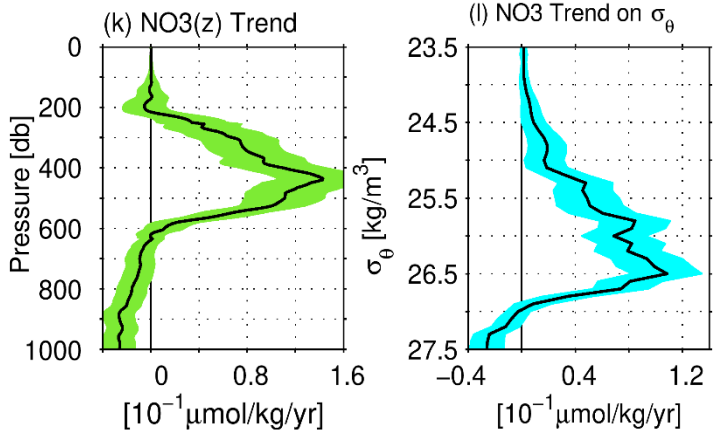


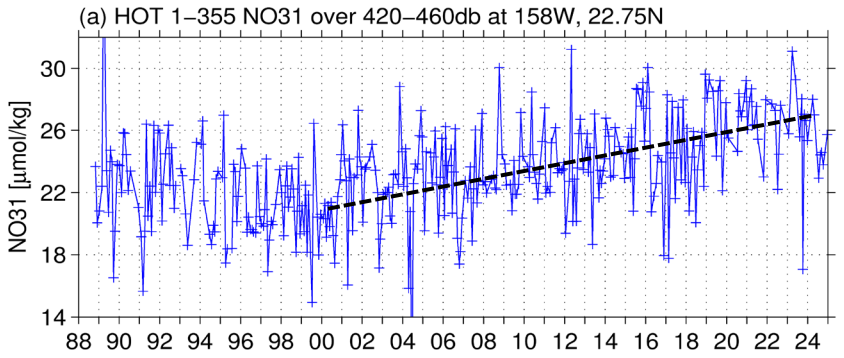
$\overline{NO_3}(x,y)$

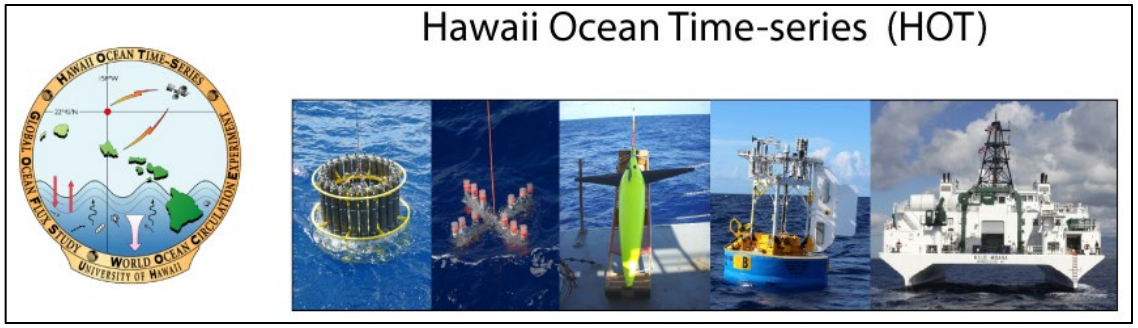


$NO_3'(z,t)$

isobaric trend ~ isopycnal trend







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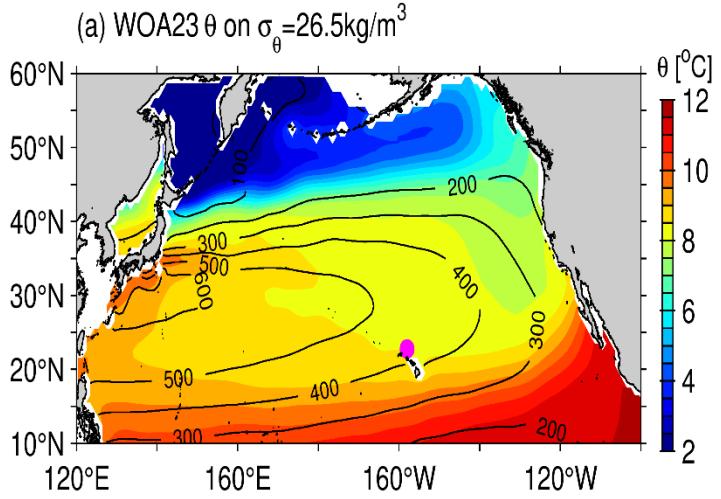
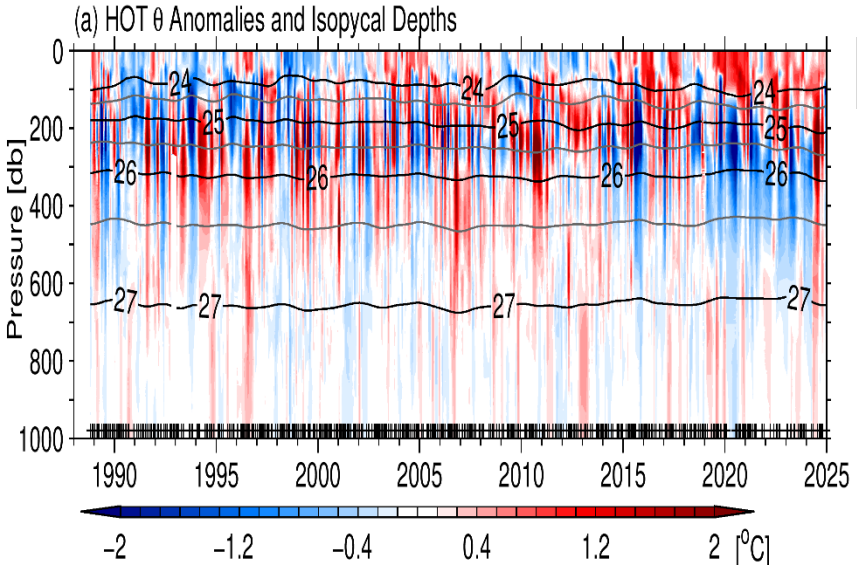
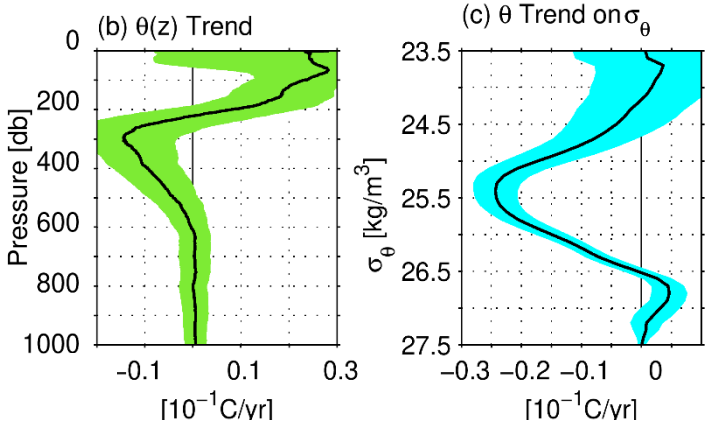




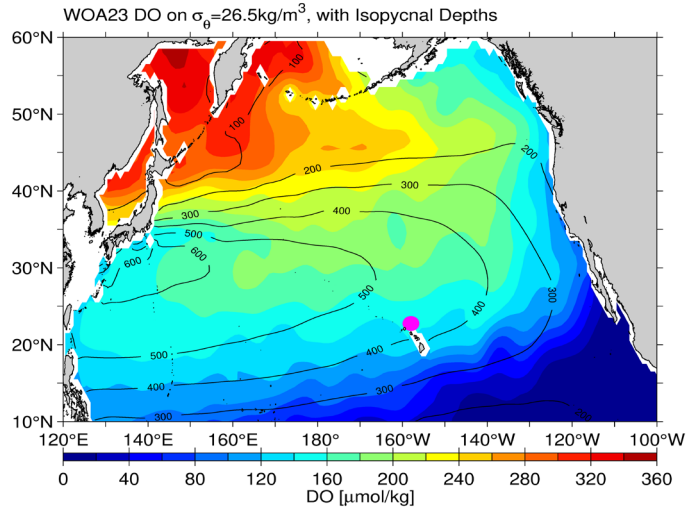
$\theta'(z,t)$

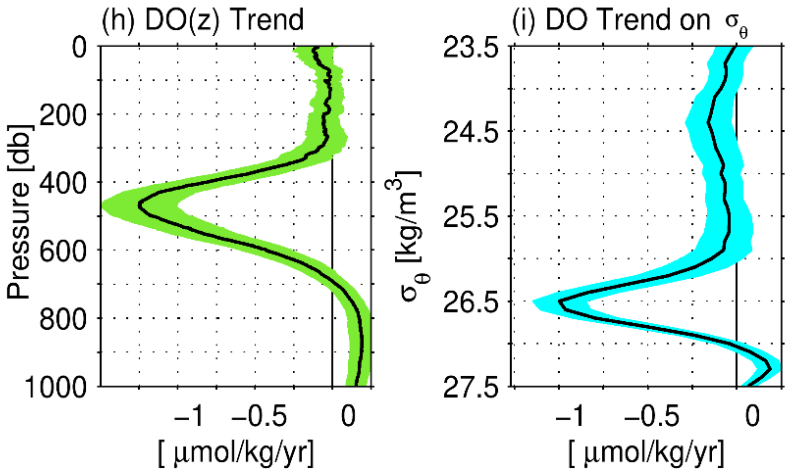
isobaric trend < isopycnal trend

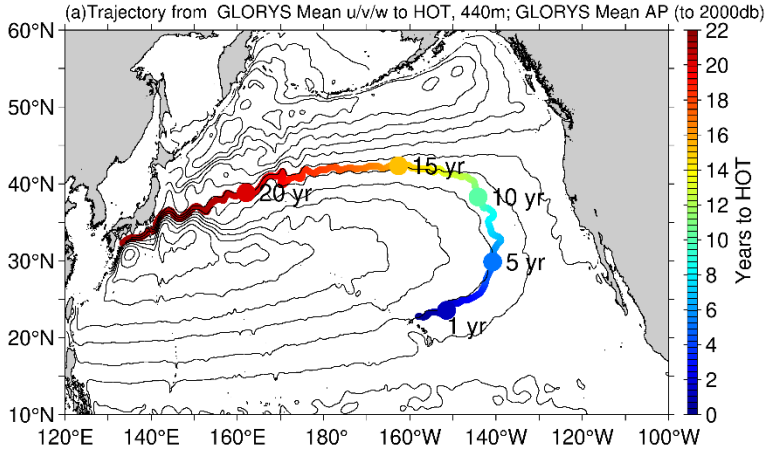


Maximum θ/*S* trends occur at a depth (~300 m) different from that of DO/NO_3 (~450 m)!

Hypothesis I : DO/NO_3 trends along the 26.5 σ_ϑ isopycnal at Stn. ALOHA are driven by water-mass variability in the northwestern Pacific outcrop region



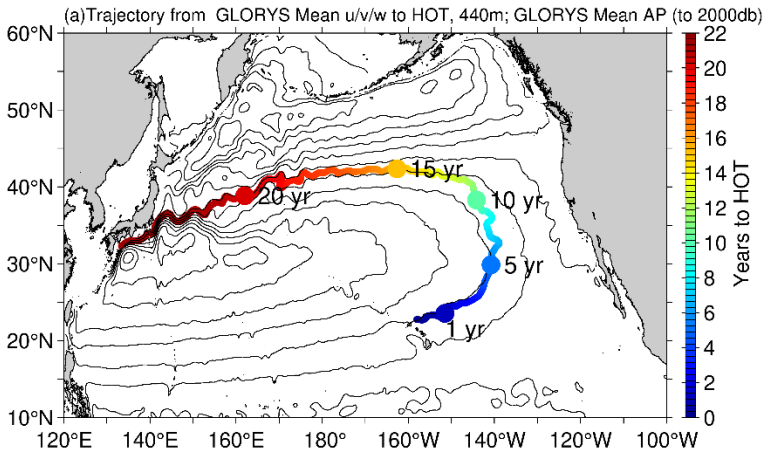




- **Con-1:** 26.5 σ_ϑ isopycnal outcrops in NW Subarctic Gyre & it does not subduct into the wind-driven subtropical gyre

- **Con-2:** It takes > 20 years for water subducted along 26.5 σ_ϑ to reach Stn. ALOHA

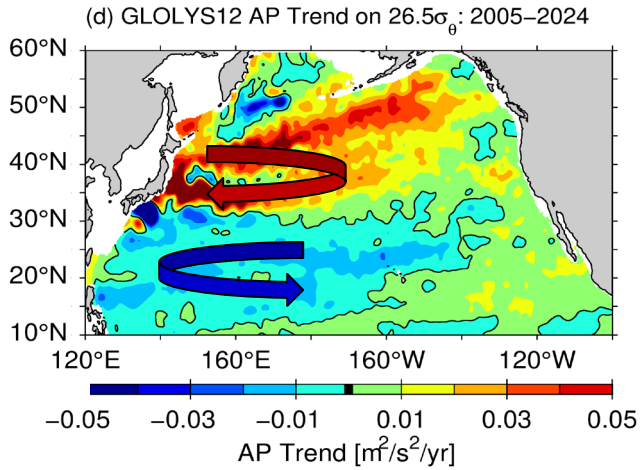
Hypothesis II : DO/NO_3 trends along the 26.5 σ_ϑ isopycnal at Stn. ALOHA are driven by long-term changes in wind-driven gyre circulation

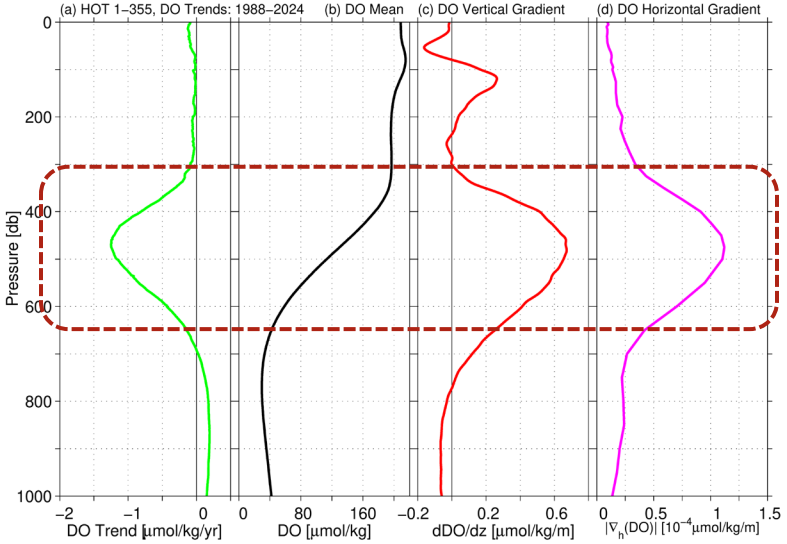


$$\frac{D_m O_2'}{Dt} = \boxed{-\boldsymbol{u}'} \cdot \nabla_3 \overline{O_2} - \varepsilon O_2'$$

- **Pro-1:** Significant velocity changes have occurred along the advective pathways leading to Stn. ALOHA on the 26.5 σ_ϑ isopycnal

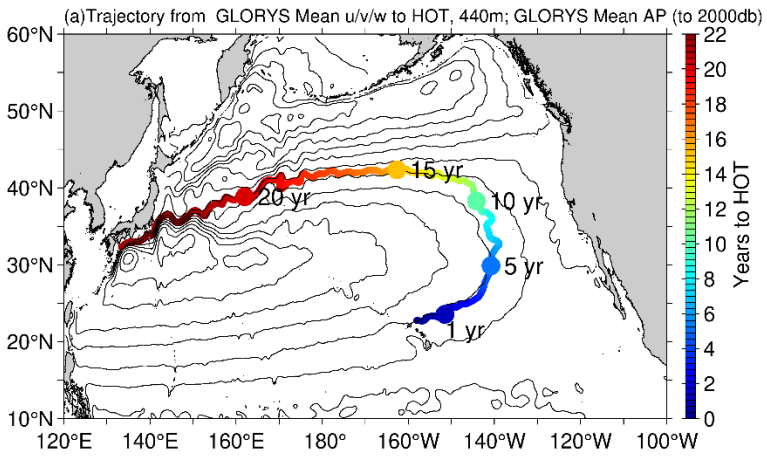
- **Pro-2:** The isopycals exhibiting the strongest trends coincide with where $\nabla_3 \overline{O_2}$ is largest





O_2'trend $\quad \overline{O_2}(z) \quad d\overline{O_2}/dz \quad |\nabla_h \overline{O_2}|$

To test Hypothesis II, we tracked water parcels terminating at Stn. ALOHA using a Lagrangian advection-decay model:



$$\frac{D_m O_2'}{Dt} = -\boldsymbol{u}' \cdot \nabla_3 \overline{O_2} - \varepsilon O_2'$$

- $\overline{O_2}$ & $\overline{NO_3}$: *WOA*23 climatology

  $\frac{D_m}{Dt}$: Lagrangian derivative following the *mean* velocity path with 3-D $\overline{\boldsymbol{u}}$ calculated from GLORYS12 reanalysis

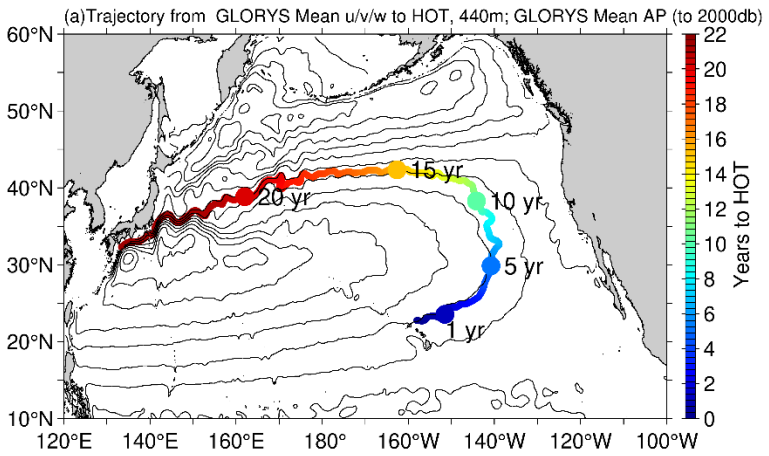
  $\boldsymbol{u}'$: Time-varying 3-D velocity field calculated from GLORYS12 reanalysis

  ε : Newtonian damping rate (= 1 /year), representing mixing & biological consumptions

- Because the 3-D velocity field is better constrained by global Argo *T/S* measurements after 2005, modeled & observed signals are compared over the 2010 – 2024 period

To test Hypothesis II, we tracked water parcels terminating at Stn. ALOHA using a Lagrangian advection-decay model:

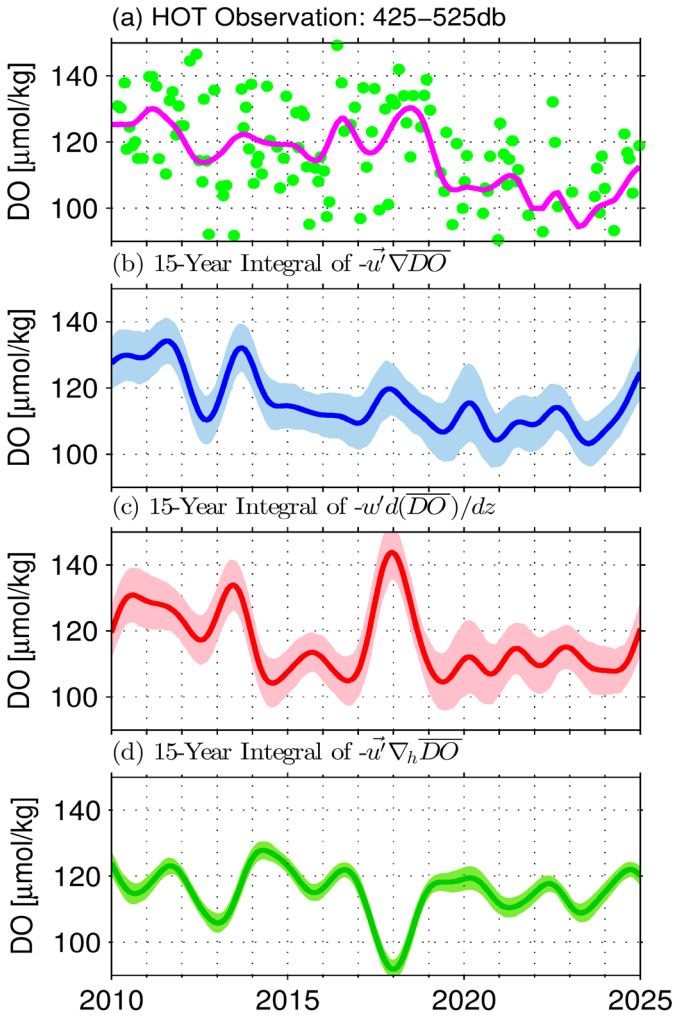
$$\frac{D_m O_2'}{Dt} = -\boldsymbol{u}' \cdot \nabla_3 \overline{O_2} - \varepsilon O_2'$$



- Modeled & observed O_2' variations compare well: $R = 0.66$; $P < 0.05$

- O_2' trend = – 1.36 µmol/kg/yr from model vs. – 1.61 µmol/kg/yr from HOT observations

- Anomalous vertical advection accounts for 81% of O_2' trend, while the remaining 19% is attributable to anomalous horizontal advection



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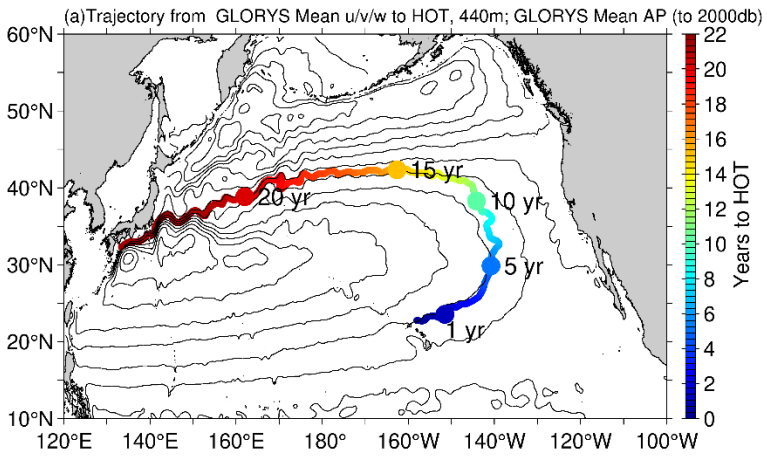
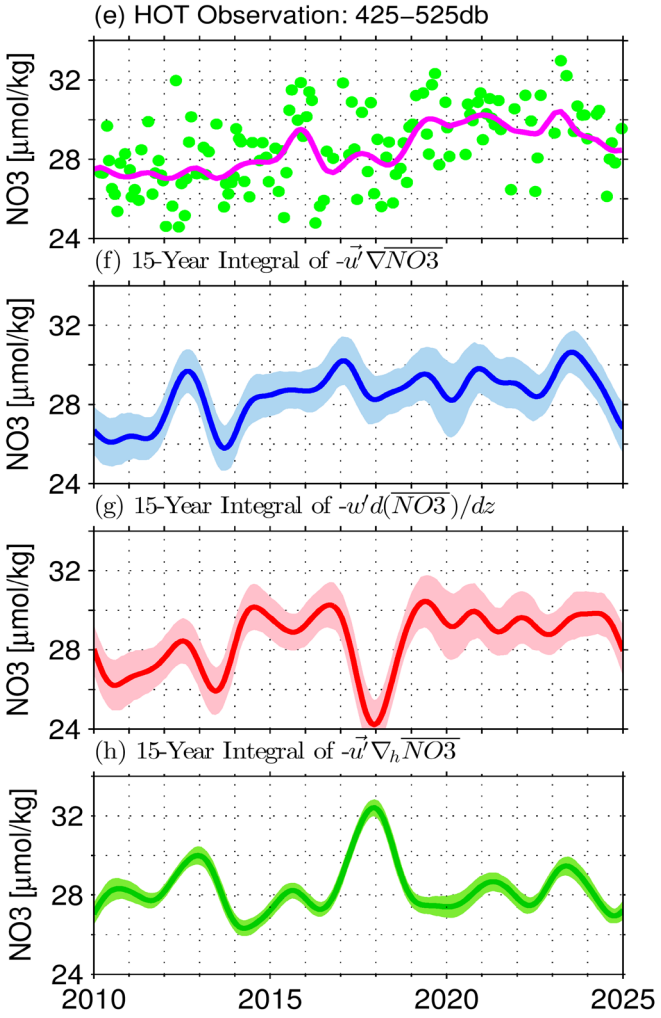
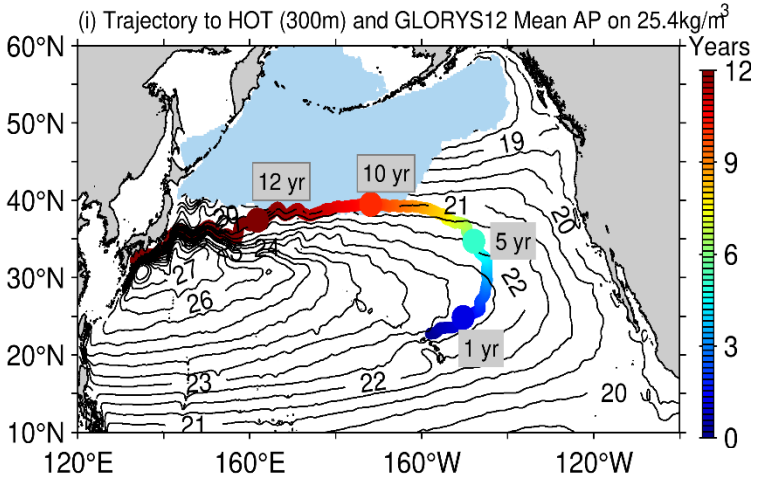


$$\frac{D_m NO_3'}{Dt} = -\boldsymbol{u}' \cdot \nabla_3 \overline{NO_3} - \varepsilon NO_3'$$

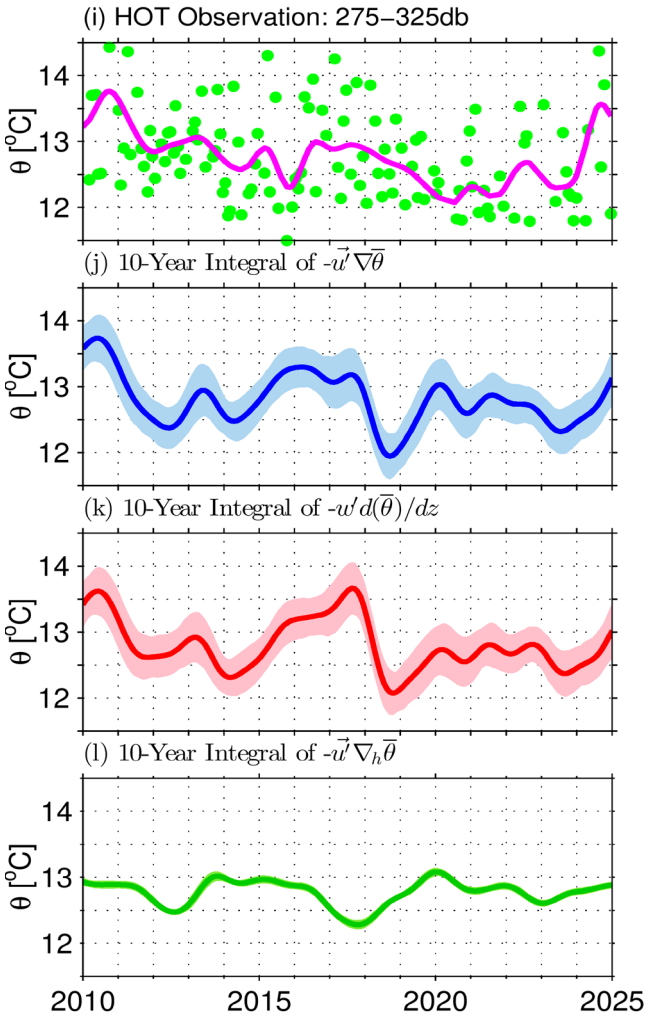


- Simulated & observed NO_3' variability compare well: $R = 0.61$, $P < 0.05$
- NO_3' trend = 0.178 µmol/kg/yr from model vs. 0.197 µmol/kg/yr from HOT observations
- Anomalous vertical advection accounts for 97% of the NO_3' trend; anomalous horizontal advection contributes marginally

Is advection-decay model with decay parameter ε too simple for marine biogeochemistry changes?



$$\frac{D_m\theta'}{Dt} = -\boldsymbol{u}' \cdot \nabla_3\bar{\theta} - \varepsilon\theta'$$



- The advection-decay model can simulate physical property trends equally well
- Similar to DO/NO_3, maximum trend in θ occurs at the depth where $\nabla_3\bar{\theta}$ is largest (i.e., thermocline)
- This implies physical & BGC property changes are both governed by the same anomalous advective processes

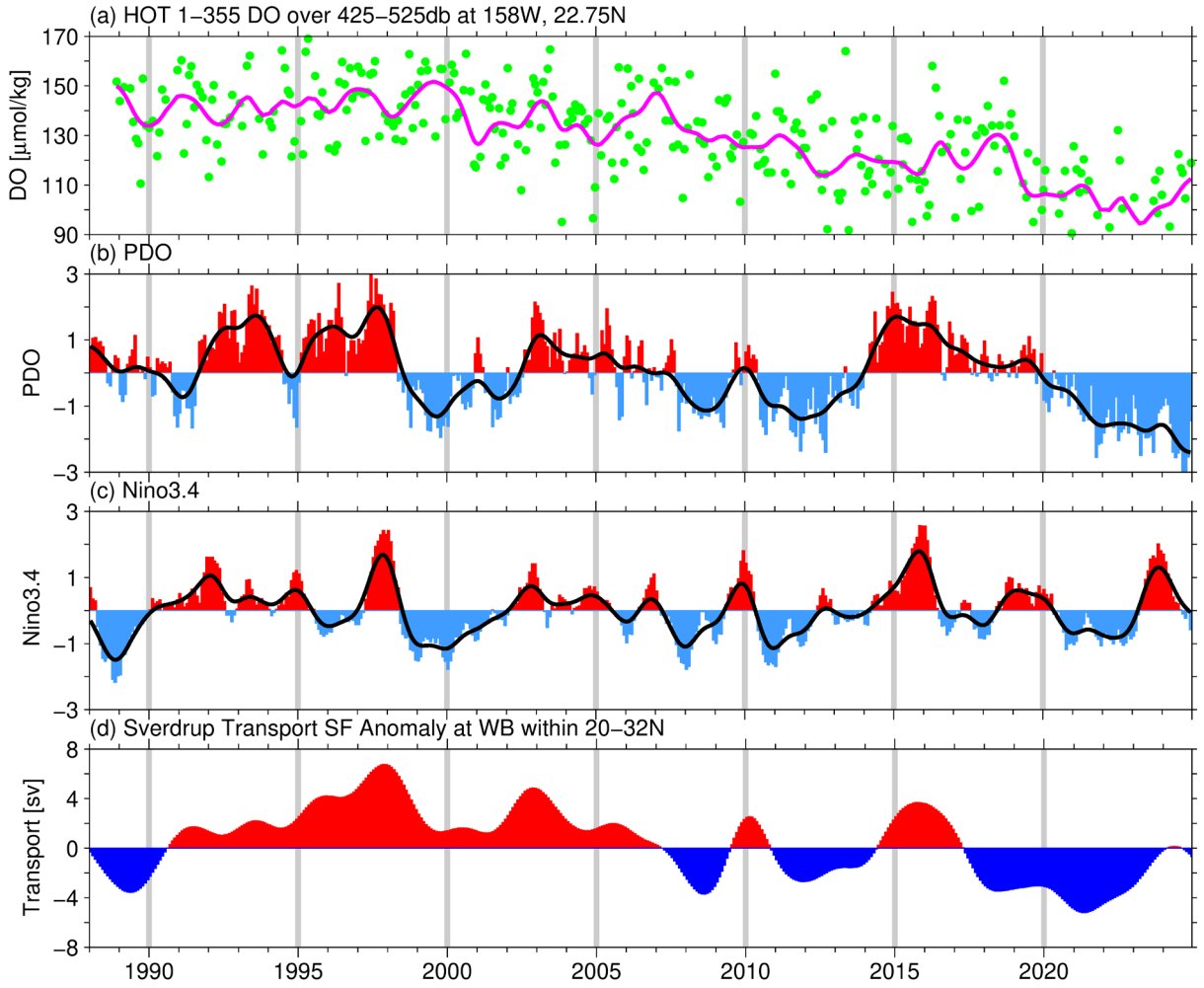
Concluding Remarks

- Significant changes have occurred in the wind-driven circulation of the North Pacific in recent decades: Strengthening in northern subtropical gyre & weakening in southern subtropical gyre

- Enhanced deoxygenation & eutrophication trends were observed at Station ALOHA, centered along 26.5 σ_θ isopycnal at depths of 400~500m

- Trends in physical properties, including freshening & cooling, were observed along *shallower* 25.5 σ_θ isopycnal surface at ~ 300m depth

- These DO, NO_3 & θ trends at Station ALOHA are largely induced by wind-diven circulation changes; depth differences between the background pycnocline and oxycline/nutricline shape contrasting hydrographic & BGC responses



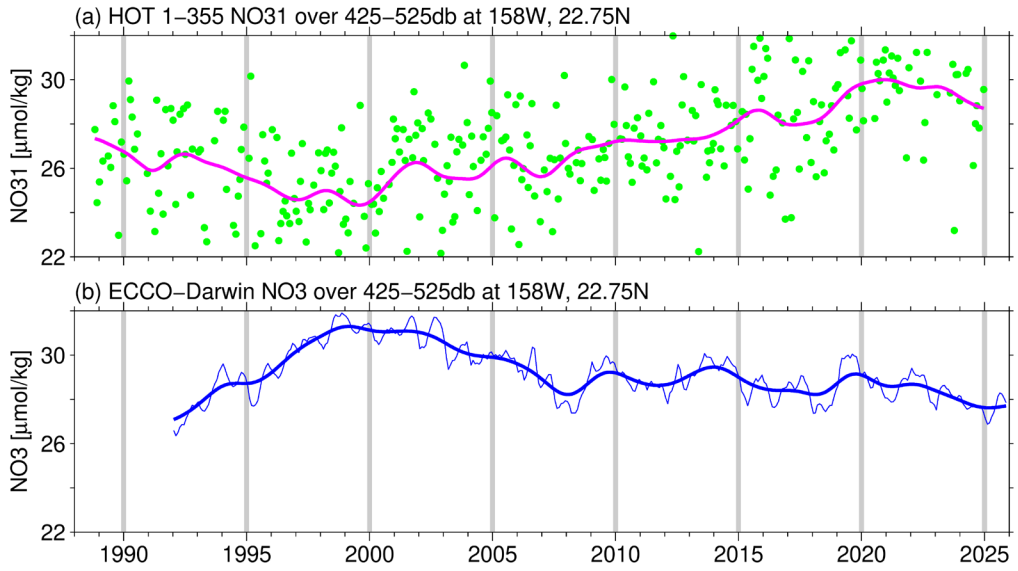
R = 0.48, no lag

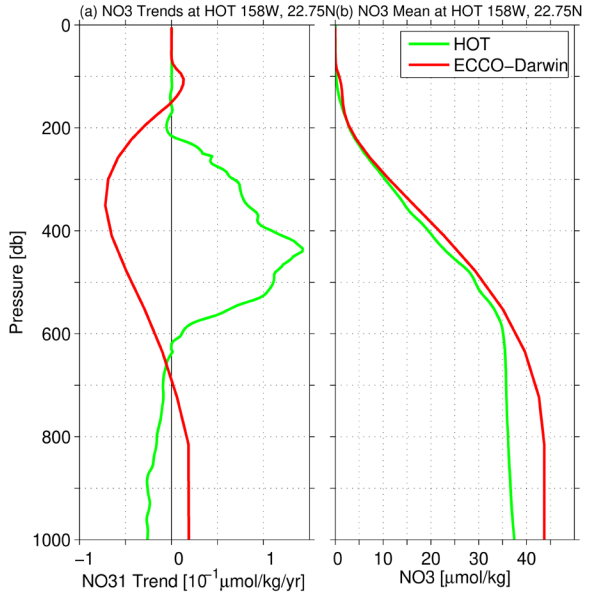
R < 0.2, with/ without lag

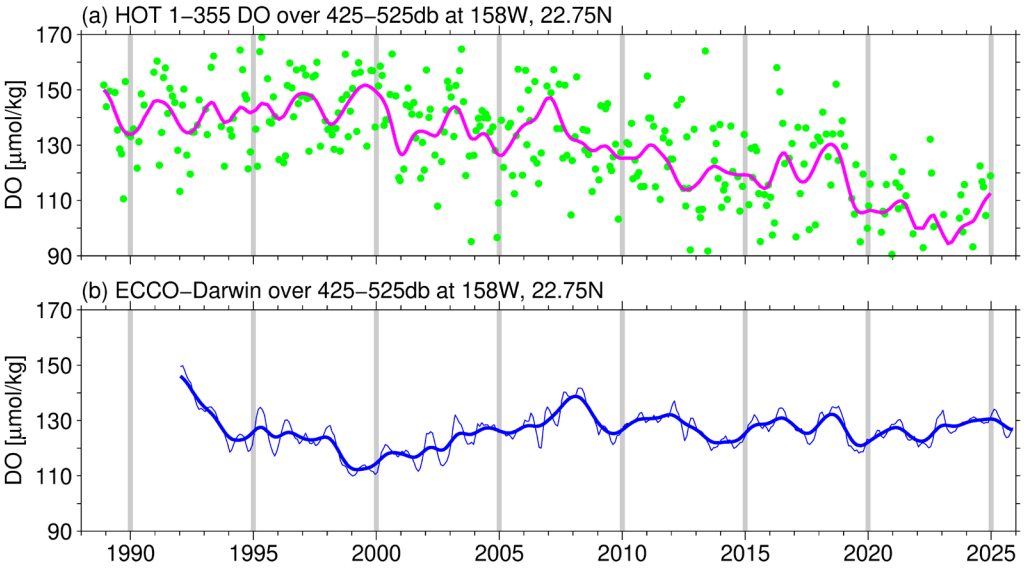
R = 0.70, 1-yr lag

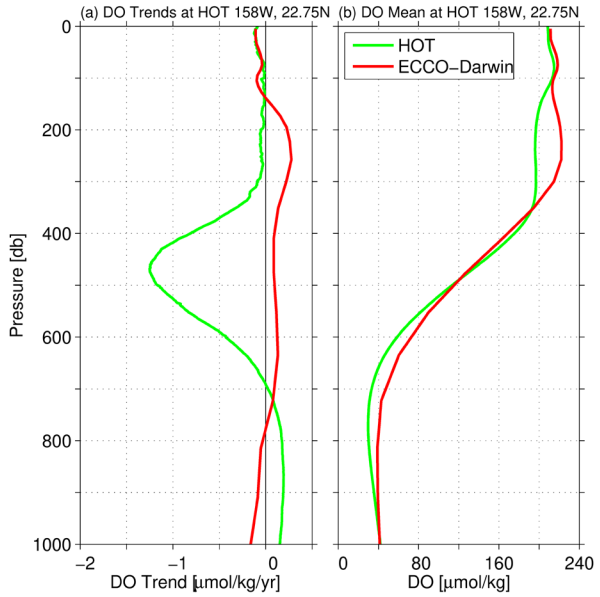
Figure R2: (a) Time series of DO (green dots) from individual HOT cruises within the 425–525 m depths. The pink line shows the low-pass filtered DO time series, obtained using a Gaussian filter with an 8-month half-power width. (b) PDO index. (c) Nino-3.4 index. (d) Time series of wind stress curl anomalies averaged over the southern portion (20°–32°N) of the NPSG based on the ERA5 reanalysis.

Comparisons between HOT & ECCO_DARWIN NO3/DO time series









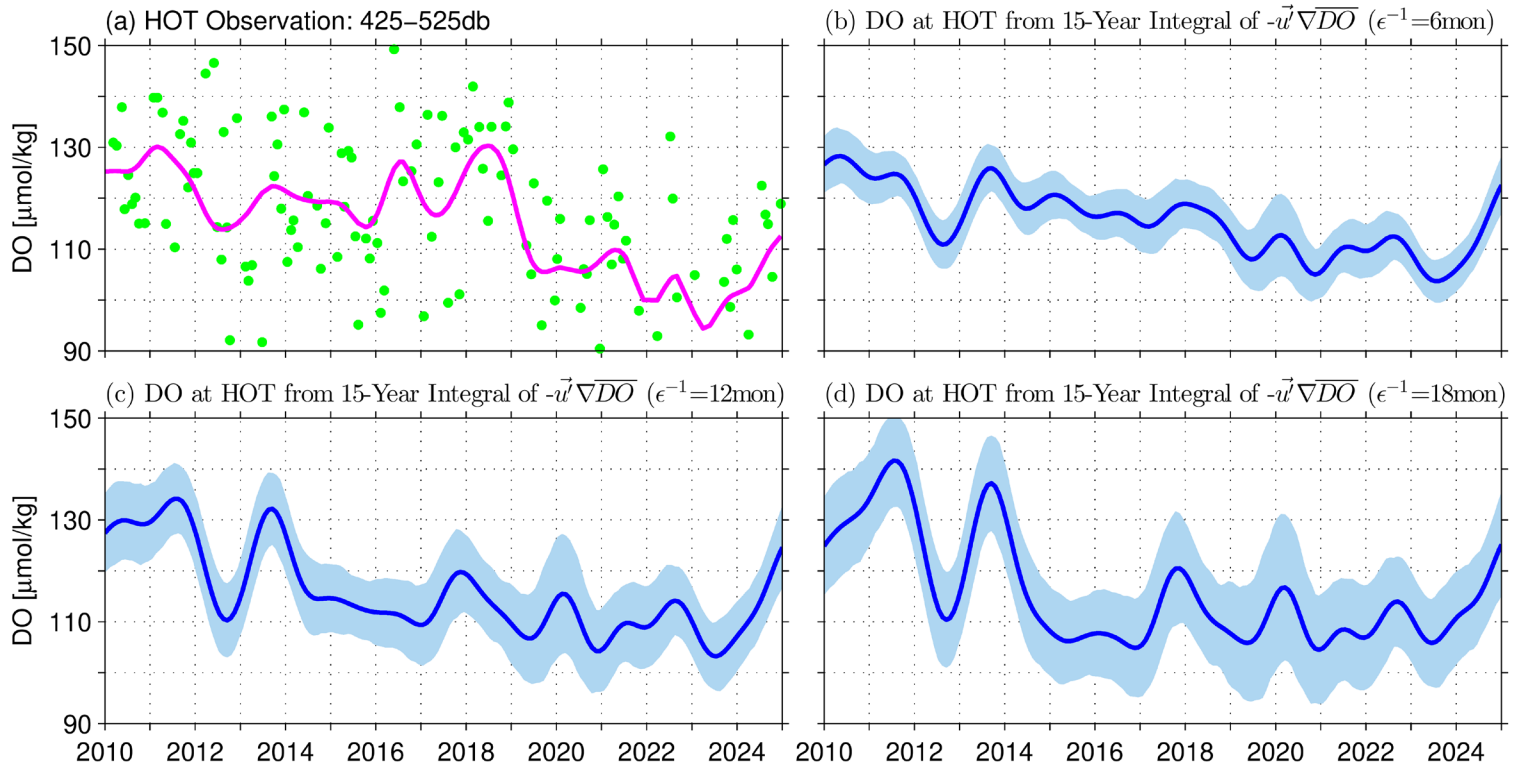


Figure S2: Sensitivity of modeled DO to the Newtonian damping coefficient, ε. (a) Time series of DO (green dots) from individual HOT cruises. Same as Fig. 4a. (b) Modeled DO time series using ε^{-1} = 0.5 yr in Eq. (1). (c) Same as (b), but using ε^{-1} = 1.0 yr, corresponding to the value used in Fig. 4b. (d) Same as in (b), but using ε^{-1} = 1.5 yr. The linear trends in (a)−(d) are −1.608, −1.115, −1.362, and −1.450 µmol/kg/yr, respectively.