

Title: Skillful Multiyear Prediction of Marine Habitat Shifts Jointly Constrained by Ocean Temperature and Dissolved Oxygen

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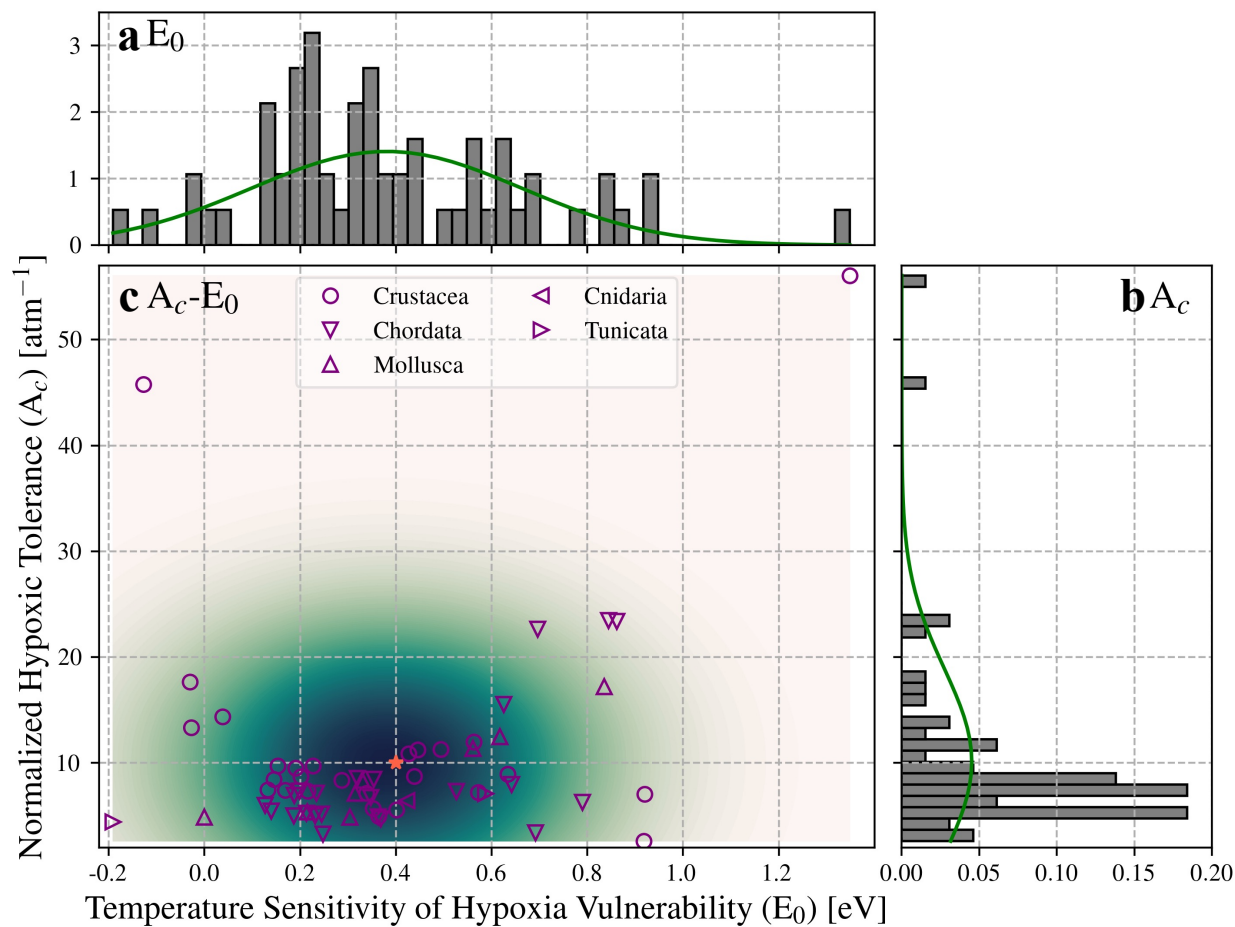
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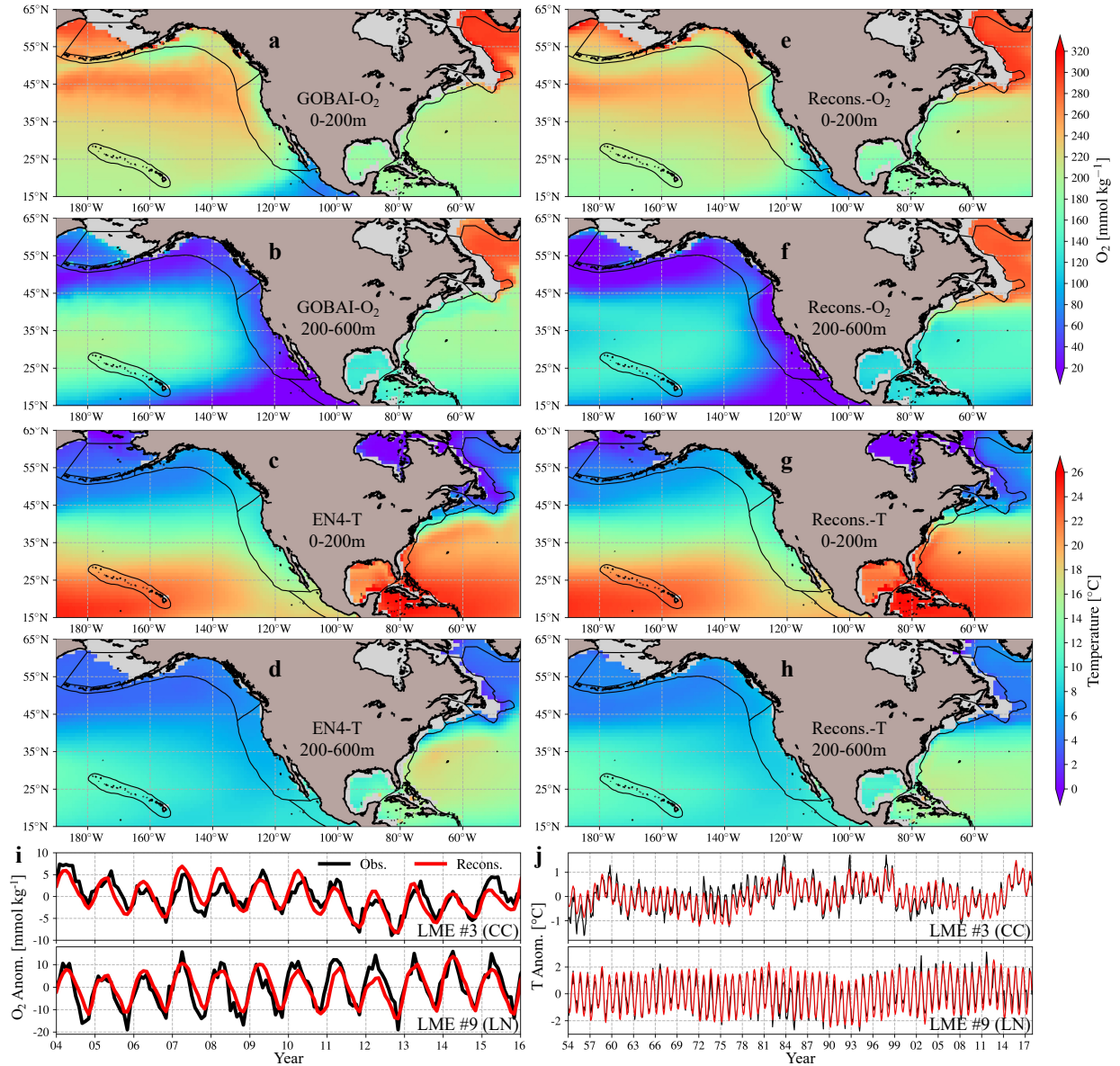
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21 **Supplementary Figures**

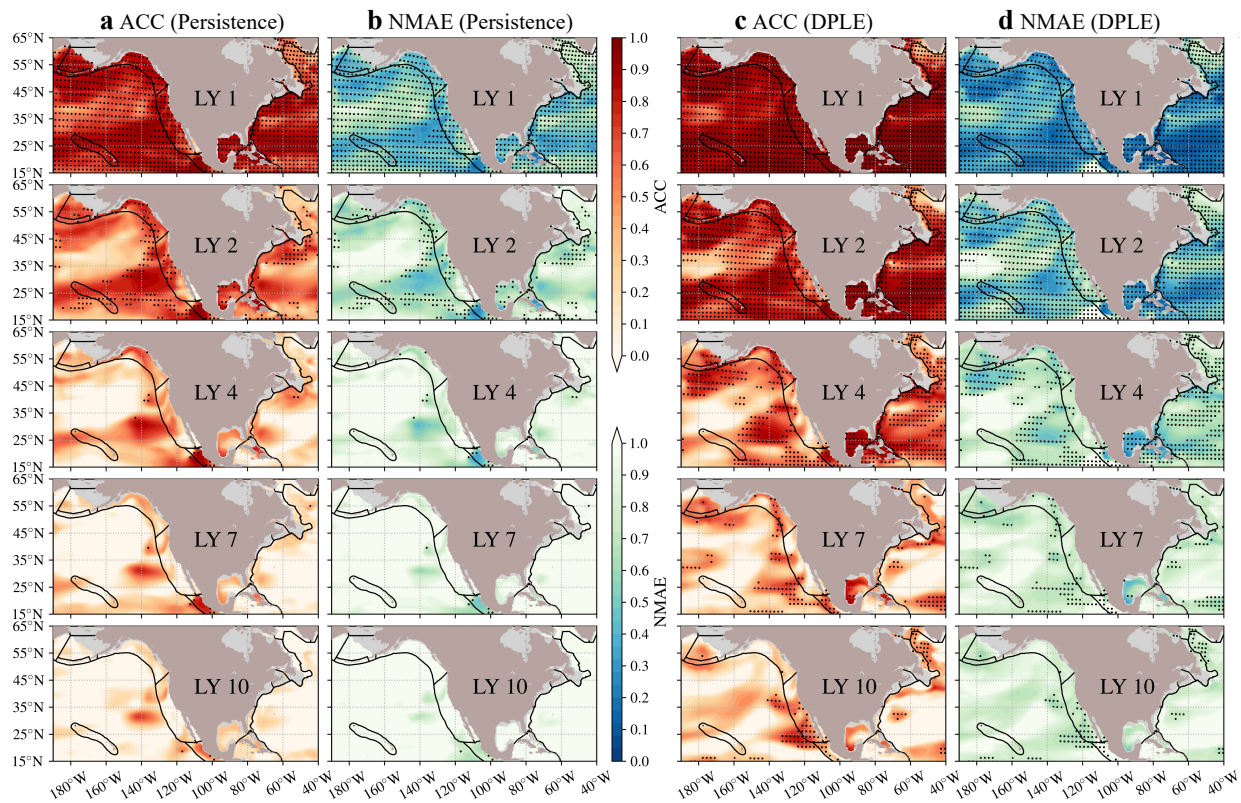


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23 **Supplementary Figure 1.** Metabolic traits distribution based on the database from *Deutsch et al.*
24 [2015]. **a-b** Histograms of the two metabolic traits - temperature sensitivity of hypoxia
25 vulnerability (E_0 ; **a**) and normalized hypoxic tolerance (A_c ; **b**), and their fitted probability density
26 functions (PDFs; green curves). **c** The A_c - E_0 trait space with purple hollow markers representing
27 observations sorted by Phylum and the fitted two-dimensional PDF distribution (represented by
28 color shading). The orange star represents the medium values of the two traits ($A_c=10 \text{ atm}^{-1}$,
29 $E_0=0.4 \text{ eV}$).

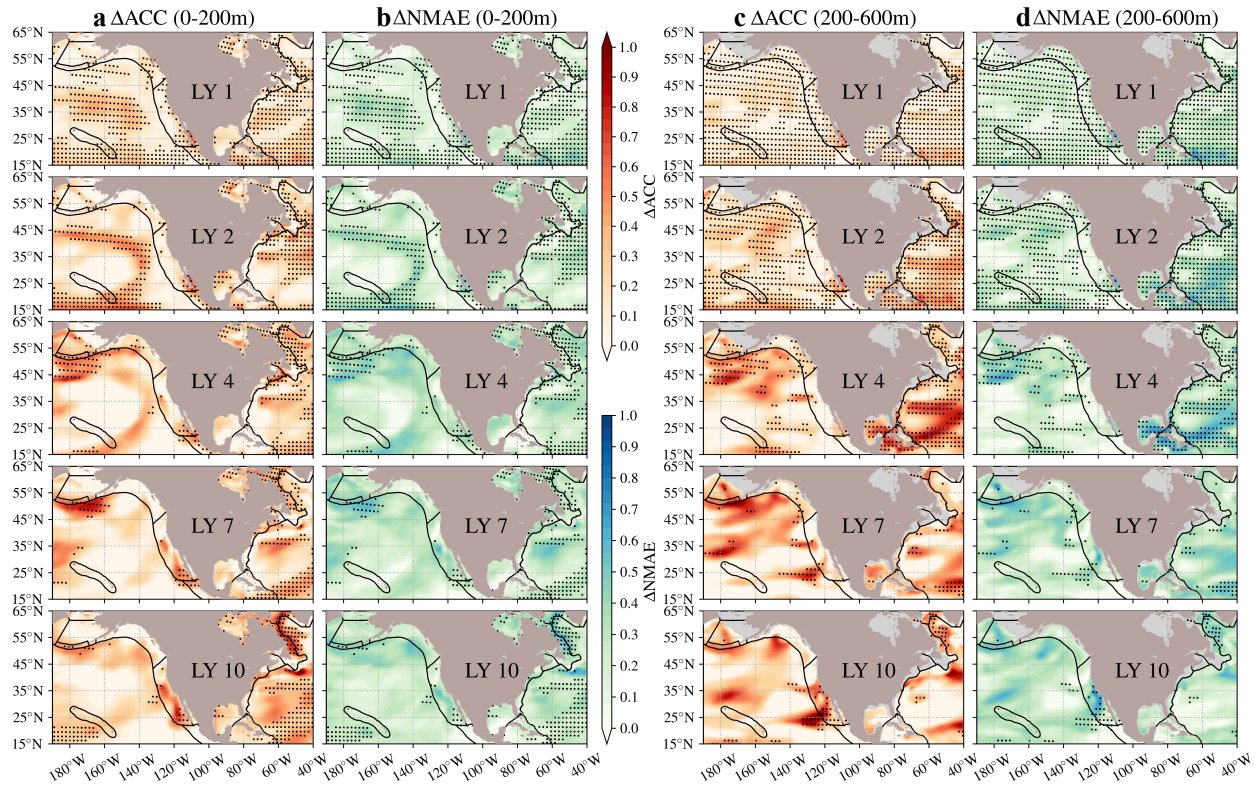


Supplementary Figure 2. The reconstruction model evaluation in dissolved oxygen (O_2) and temperature (T) compared against observation products of O_2 from the GOBAI-O₂ [2004-2015; Sharp *et al.*, 2022] and T from the EN4 version 4.2.1 [1954-2017; Good *et al.*, 2013]. **a-h** Climatological averages of O_2 (**a-b** and **e-f**) and T (**c-d** and **g-h**) at the upper-200 m (**a, c, e, and g**) and deeper 200-600 m (**b, d, f, and h**) layers between observation products (**a-d**) and the model reconstruction (**e-h**). Boundaries of the Large Marine Ecosystems (LMEs) are plotted as black solid lines in each panel. **i-j** Monthly-mean time series comparison of O_2 (**i**) and T (**j**) anomalies (with the climatological averages removed) in two observation-abundant LMEs – the California Current (CC; LME 03) and Labrador-Newfoundland (LN; LME 09), at the upper-200 m layer. The black line in each panel represents the observation product, and the red line represents the model reconstruction.

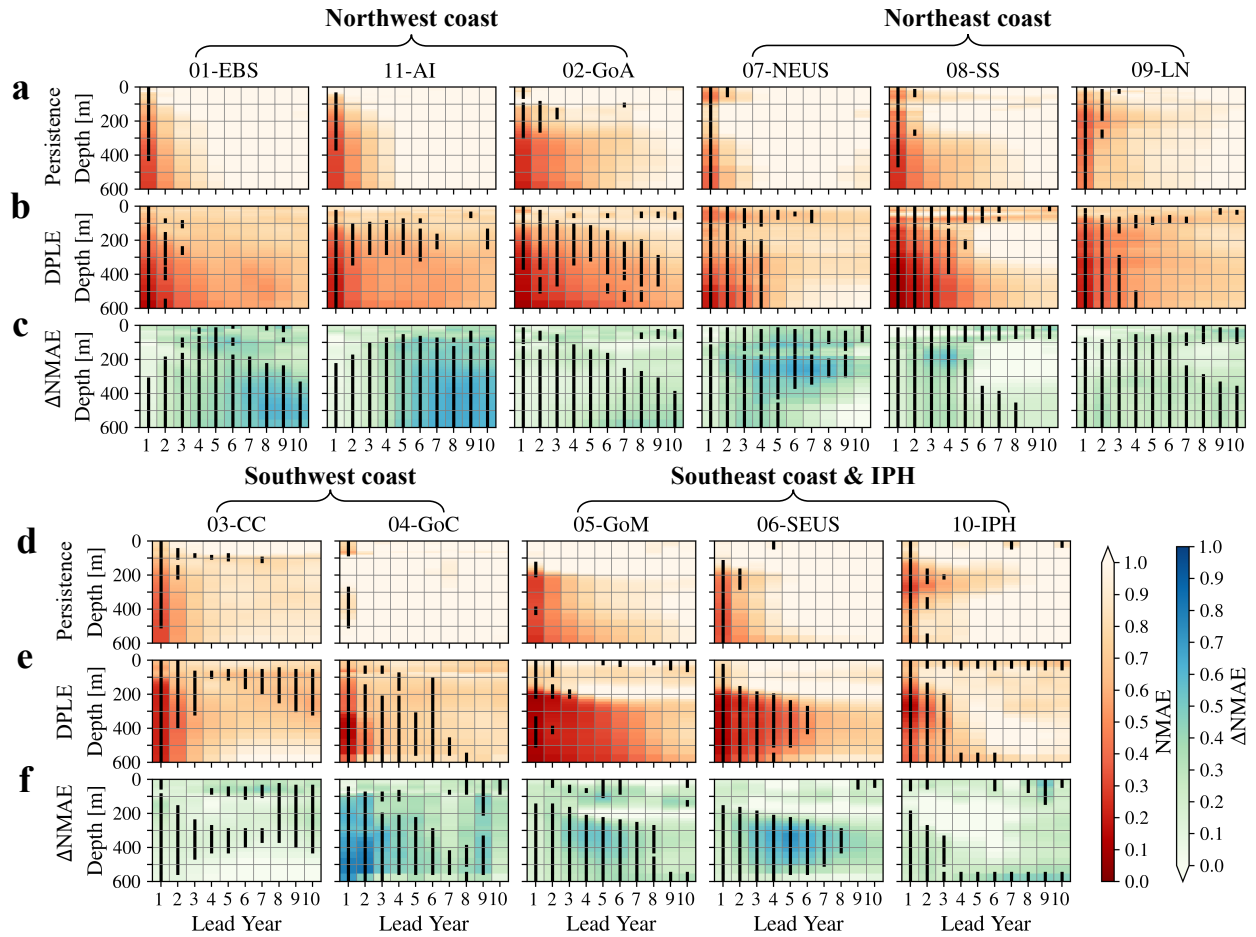
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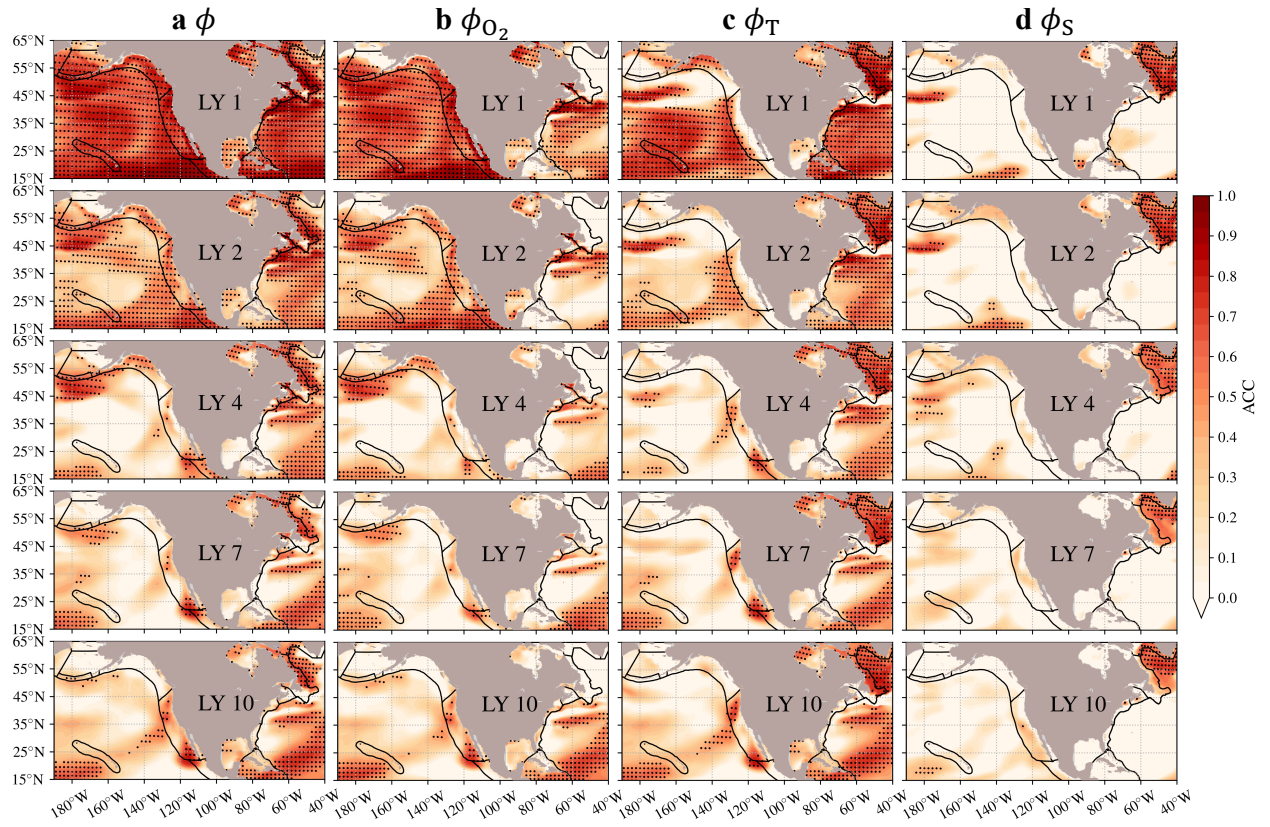
Supplementary Figure 3. Same as Figure 3, but for the deeper 200-600 m layer.



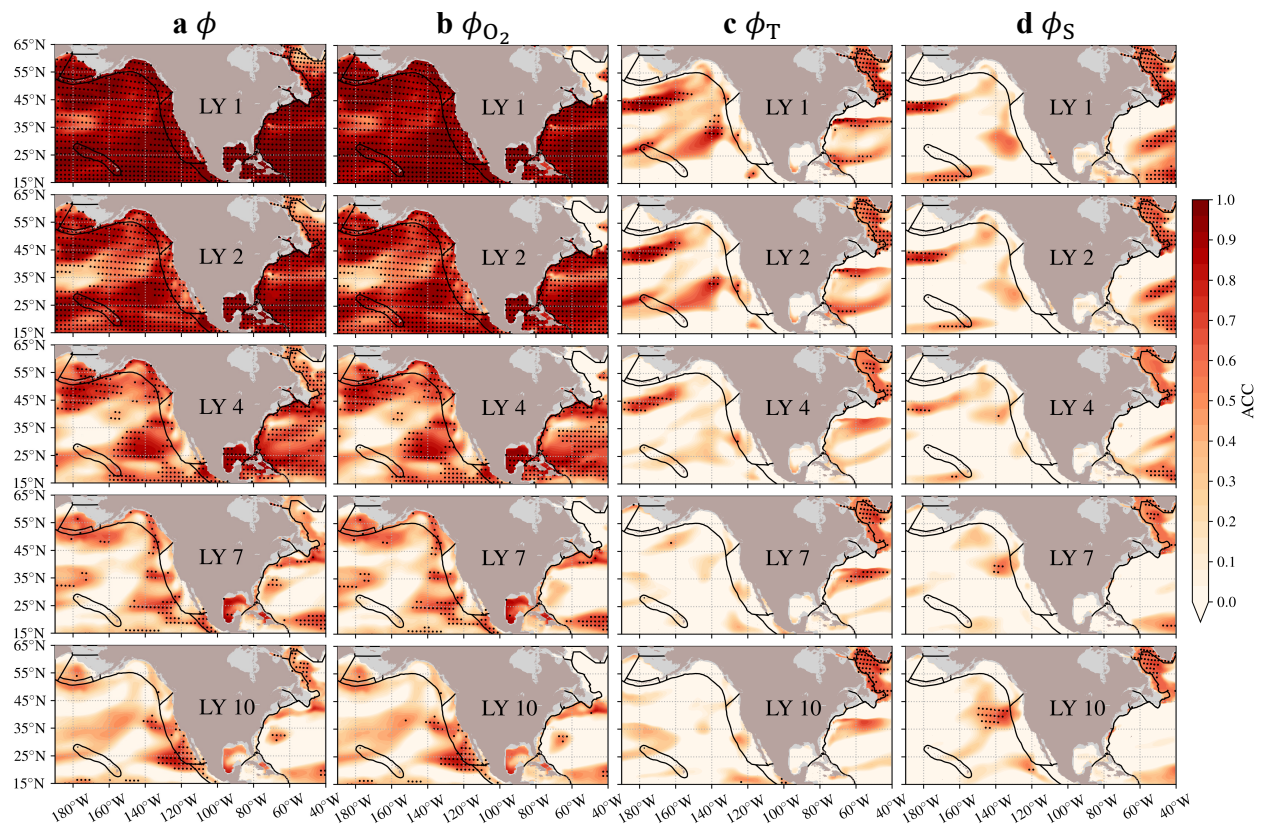
Supplementary Figure 4. Same as **Figure 3** and **Supplementary Figure 3**, but for the spatial skill improvement in Anomaly Correlation Coefficient (ACC) and Normalized Mean Absolute Error (NMAE) of the Decadal Prediction Large Ensemble (DPLE) forecast against the simple persistence forecast at lead year (LY) 1, 2, 4, 7, and 10. The ACC difference (ΔACC) is calculated as the DPLE ACC minus persistence ACC. The NMAE difference (ΔNMAE) is calculated in the opposite manner (persistence minus DPLE). The black dots in each panel indicate the DPLE ACC significantly increased ($\Delta\text{ACC} > 0$) from that of persistence at the 95% confidence level.



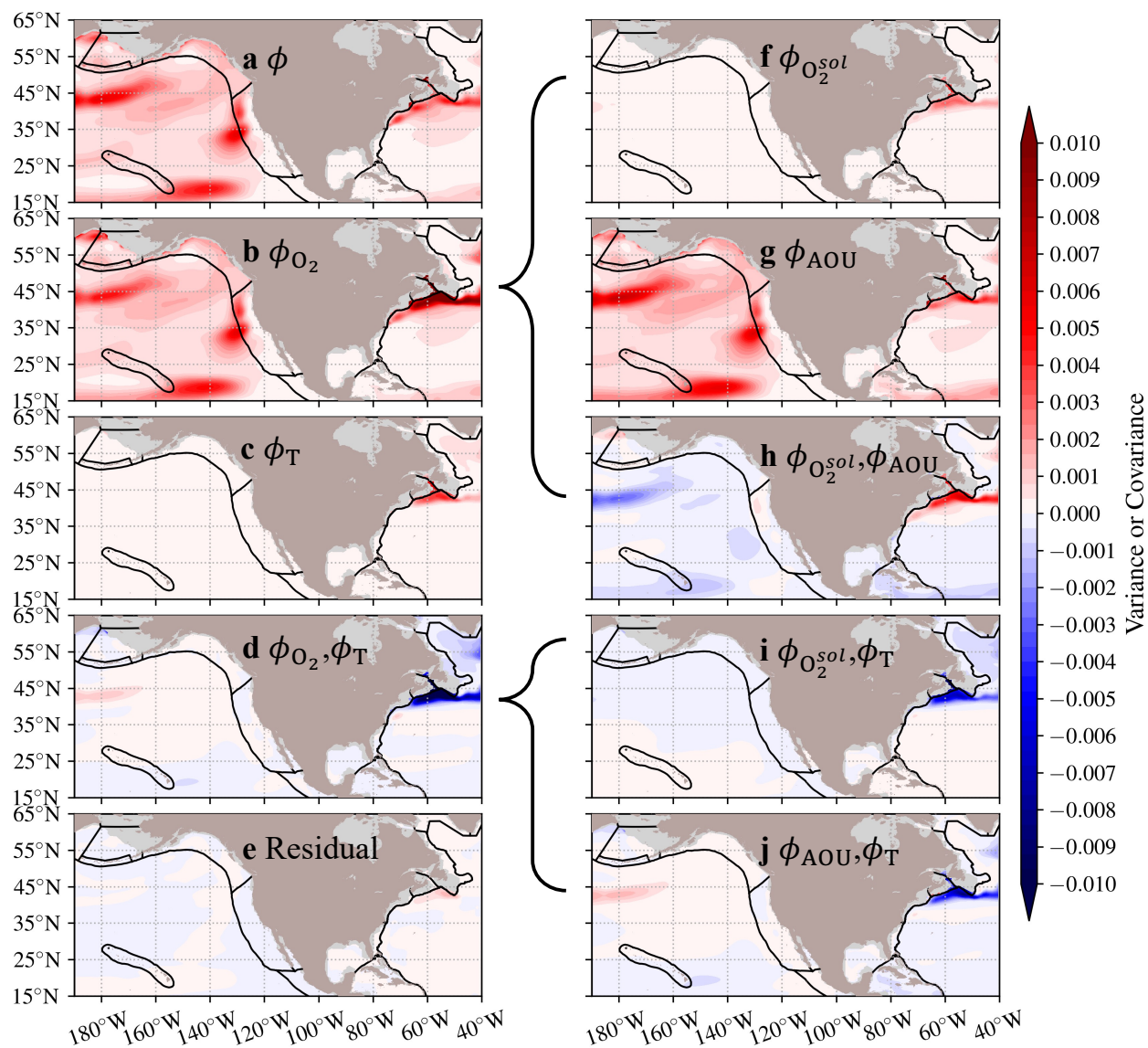
Supplementary Figure 5. Same as **Figure 4**, except the color shading in each panel represents the corresponding prediction skills of the Normalized Mean Absolute Error (NMAE; **a-b** and **d-e**) and the improved skills from the Decadal Prediction Large Ensemble (DPLE) forecast relative to persistence (Δ NMAE; persistence minus DPLE; **c** and **f**).



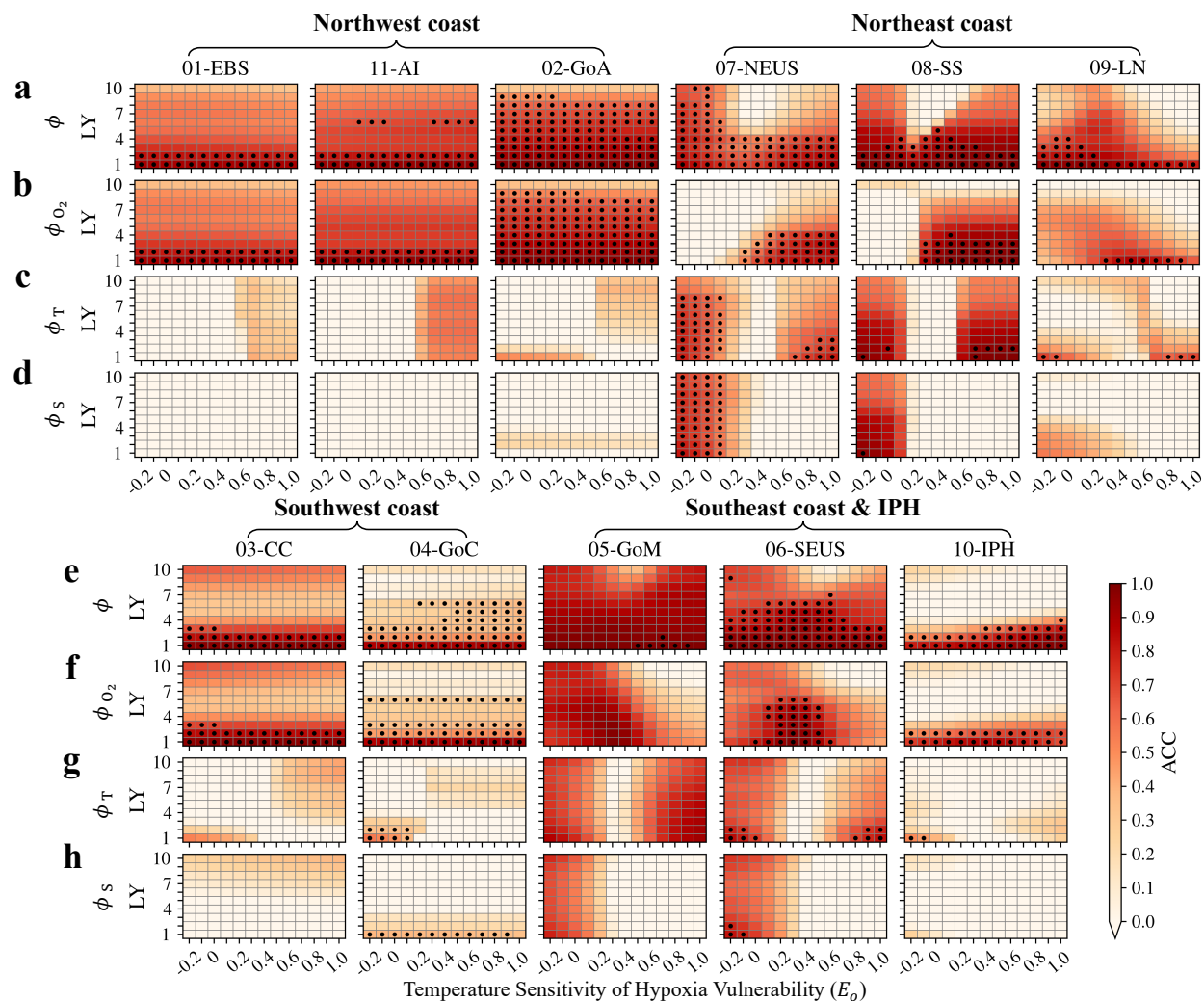
Supplementary Figure 6. Spatial comparison of the interannual-to-decadal prediction skills between the normalized Metabolic Index (ϕ ; **a**) and its oxygen (ϕ_{O_2} ; **b**), temperature (ϕ_T ; **c**), and salinity (ϕ_S ; **d**) components, at lead years of 1, 2, 4, 7 and 10. The prediction skills are assessed as the Anomaly Correlation Coefficient (ACC) using the decadal prediction system at the upper 200 m layer.



Supplementary Figure 7. Same as **Supplementary Figure 6**, but for the deeper 200-600 m layer.



Supplementary Figure 8. Same as **Figure 6**, but for the deeper 200-600 m layer.



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70 **Supplementary Figure 9.** Same as **Figure 7**, but for the deeper 200-600 m layer.