North Pacific Decadal Predictability of Subsurface Temperature, Oxygen, and the Metabolic Index

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I. Motivation

- Global Earth System Models have demonstrated skill in predicting physical and biological variables important to fish and fisheries on seasonal to decadal time scales of significance to management [*Tommasi et al.*, 2016; *Park et al.*, 2019];
- Interannual variations in ocean temperature and oxygen concentration contribute to the habitat variability of valuable marine fish species, but it is difficult to disentangle few predictive studies incorporate this information in developing projections of impacts on living marine resources;
- A physiologically mechanistic Metabolic Index (Φ) was recently developed that explicitly combines the joint influence of oxygen concentration and temperature-dependent metabolic demands.

II. Data & Methods

North Pacific 12 Large Marine Ecoregions (LMEs)

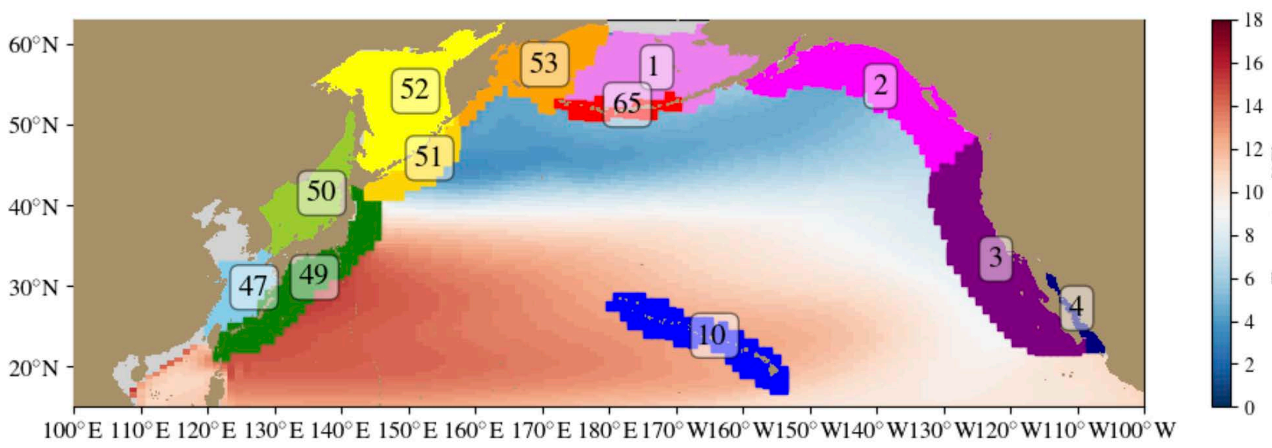

Figure 1. The 12 Large Marine Ecosystems over the North Pacific.

1 East Bering Sea (EBS)	**10** Pacific Hawaiian (PH)	**51** Kuril Islands (KI)
2 Gulf of Alaska (GoA)	**47** East China Sea (ECS)	**52** Sea of Okhotsk (SO)
3 California Current (CC)	**49** Philippine Sea (PS)	**53** West Bering Sea (WBS)
4 Gulf of California (GoC)	**50** Sea of Japan (SJ)	**65** Aleutian Islands (AI)

CESM-Decadal Prediction Large Ensemble (DPLE)

- The CESM-DPLE is a novel suite of initialized retrospective Earth System Model with embedded ocean biogeochemistry [*Yeager et al.*, 2018] (~1°×1°; 60 levels);
- It was initialized each year on Nov. 1st from 1954 to 2017 for a total of **64 initialization dates**, and each date has an ensemble of **40** forecast members. Each ensemble member spreads for **~10 years (122 months)**;
- Drift adjustment is performed with CESM-DPLE, followed the same procedures as in *Yeager et al.* [2018], in order to correct for model drift caused by full-field initialization.

The Forced Ocean-Sea Ice (FOSI) Reconstruction

- The FOSI reconstruction has the identical spatial resolutions as the CESM-DPLE. It's a non-assimilative hindcast simulation from 1948 to 2017, forced by a modified version of the Coordinated Ocean-Ice Reference Experiment (CORE) with interannual forcing [*Griffies et al.*, 2009; *Large & Yeager*, 2009].

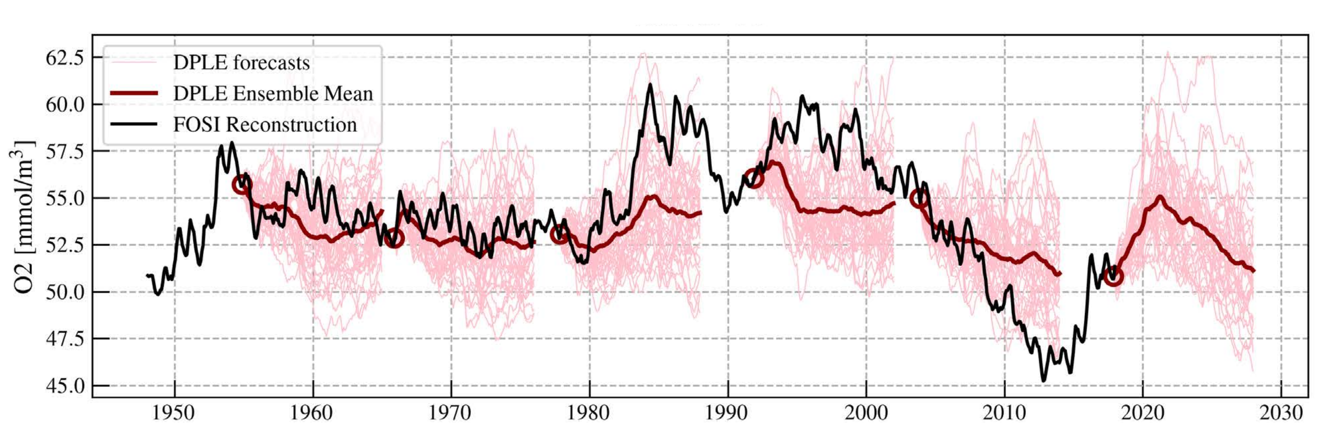

Figure 2. Experimental design of the decadal prediction system. The drift-corrected O_2 time series in the California Current LME of both the FOSI reconstruction (black line) and the CESM-DPLE forecasts (pink lines). The dark red lines represent ensemble mean. Only DPLE forecasts initialized in 1954, 1965, 1977, 1991, and 2017 are plotted for visual clarity.

The Metabolic Index Φ

- The Metabolic Index (Φ) is defined as the ratio of oxygen supply (S) to an organism's resting metabolic demand (D), which can be calibrated with physiological data of certain marine taxa [*Deutsch et al.*, 2015]:

$$\Phi = \frac{S}{D} = A_0 B^n \cdot pO_2 \cdot e^{\frac{E_0}{k_B T}}$$

where $A_0 = \frac{\alpha_S}{\alpha_D}$ is the ratio of rate coefficients for gas exchange (S) and minimum metabolic rate (D), and n is the difference between scaling exponents applied to biomass B for oxygen supply and demand, E_0 is the temperature sensitivity of hypoxia tolerance, and k_B is the Boltzmann constant [*Gillooly et al.*, 2001].

- The Metabolic Index is calculated using the medium values of metabolic traits database from *Deutsch et al.* [2015], the values of A_0 and E_0 are 7.35 and 0.34, respectively.

Prediction Skill Assessments

- Potential predictability is assessed by calculating the Anomaly Correlation Coefficient (ACC) and root mean square error (RMSE) between the CESM-DPLE ensemble mean forecast and the FOSI reconstruction, both of which are on annual time scale (annual averages over January-December).
- Statistical significance of ACC is tested at the 90% confidence level via a Student's t test, and statistical significance for the difference between two ACCs is also tested at the 90% confidence level following *Steiger* [1980].

III. Results & Discussions

Black crosses : significance level p < 0.1

Black crosses : significantly increased ACC at p < 0.1;
Gray crosses: not significantly increased ACC from persistence

A. Spatial Distribution of Decadal Potential Predictability of the Metabolic Index Φ, temperature, and oxygen at 200-600 m

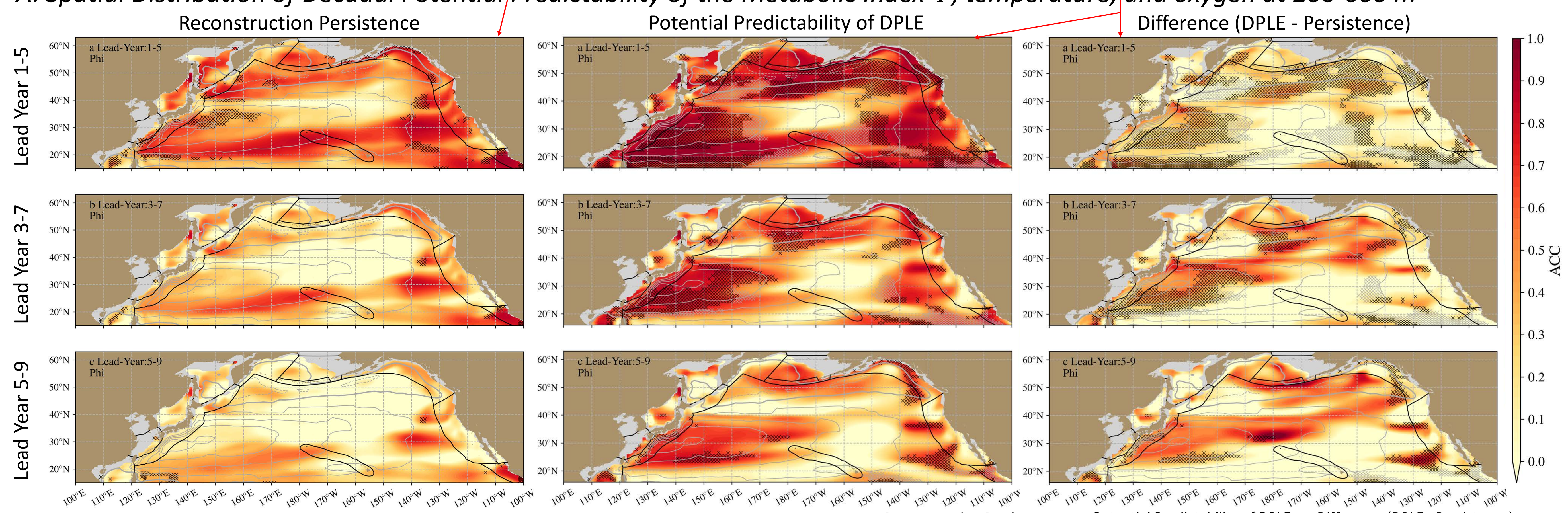

Figure 3. Potential predictability (ACC) of the persistence forecast (left column), the Metabolic Index (middle column), and their differences in prediction skills (right column). The background solid gray lines represent the barotropic stream function (BSF).

- The CESM-DPLE shows much higher potential predictability over the FOSI reconstruction persistence for all three variables over the decadal time scales. Generally, the longer the lead time, the higher the increased prediction skill;
- Spatial distributions of potential predictability of the Metabolic Index are very similar to those of the oxygen at the 200-600 m layer for both reconstruction persistence forecast and CESM-DPLE ensemble mean forecast: largely increased predictability over the Kuroshio Current region, EBS and the AI, and GoA; decreased predictability over the Kuroshio Extension and the mid of North Pacific;
- Subsurface temperature has very different spatial potential predictability of CESM-DPLE that are mainly located over the Northeast of North Pacific as a "dove" shape.

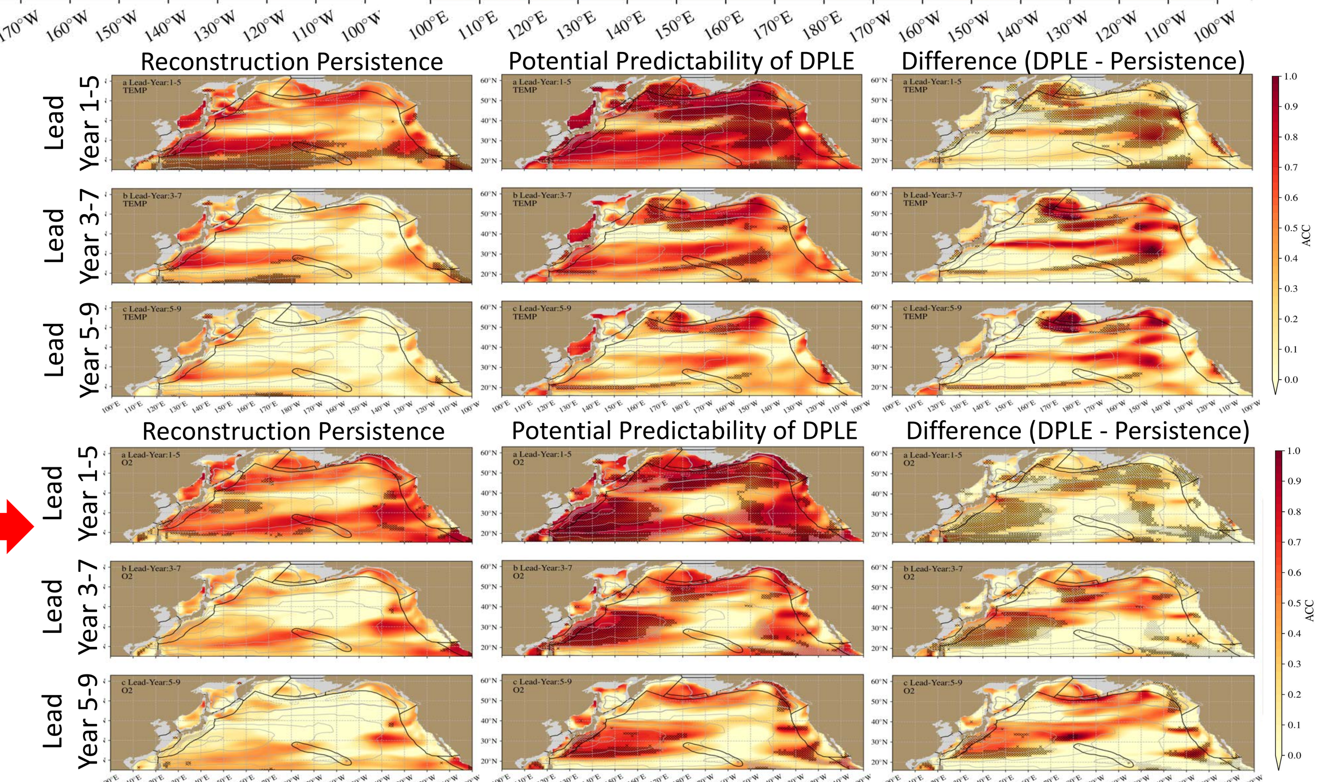

Figure 4. Same as **Figure 3**, but for temperature (upper 9 panels) and oxygen (lower 9 panels) at 200-600 m.

B. Decadal Potential Predictability in North Pacific LMEs

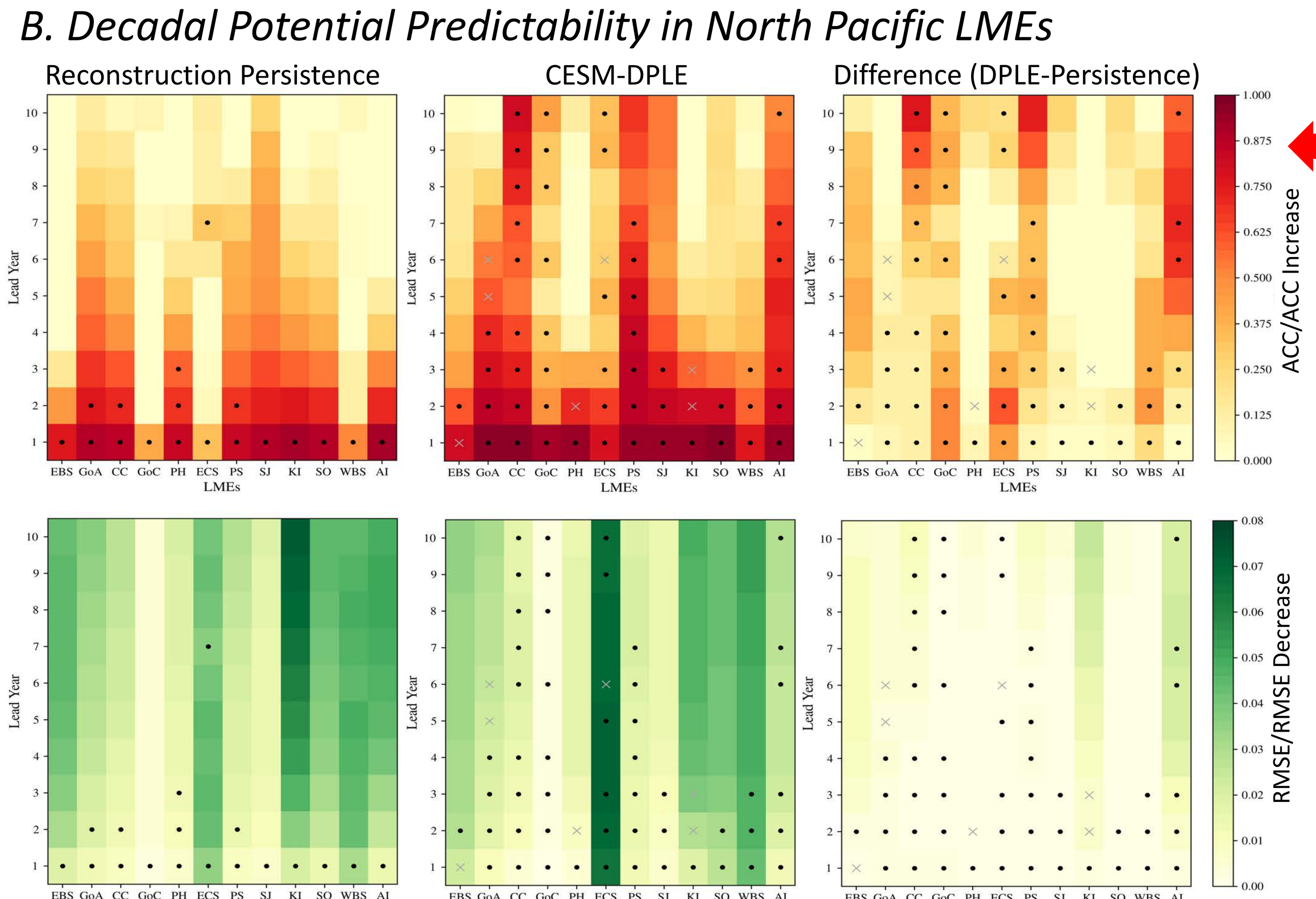

Figure 5. Potential predictability of the Metabolic Index in the 12 North Pacific LMEs at 200-600 m, for prediction skills in ACC (upper 3 panels) and RMSE (lower 3 panels).

- The CESM-DPLE shows very different potential predictability of the Metabolic Index in the 12 North Pacific LMEs: largely increased ACC (>0.25) in the AI (6-7 lead years), CC (7-10 lead years), GoC (1-3 lead years; 8-10 years), and ECS (1-3 lead years);
- The California Current (LME#03) has a decreased potential predictability when lead time increase from 1-year to 5-year, but it increases again when the lead time increase from 5-year to 10-year;
- The Metabolic Index in the California Current LME is decreasing during the recent time series, suggesting an increased habitat constraints for fisheries.

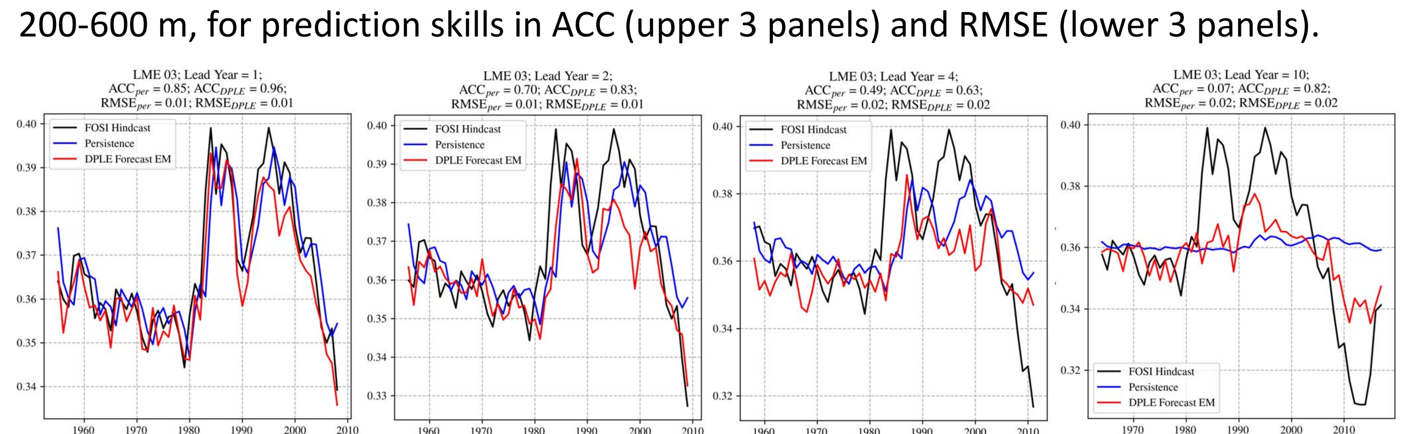

Figure 6. The time series of the Metabolic Index in the California Current (LME#03) at 200-600 m, for the reconstruction (black lines), reconstruction persistence forecast (blue lines), and the CESM-DPLE ensemble mean forecast (red lines), at the lead time of 1, 2, 4, 10 years (from left to right panels).

C. Relative Contribution to Predictability of Φ from T and O_2

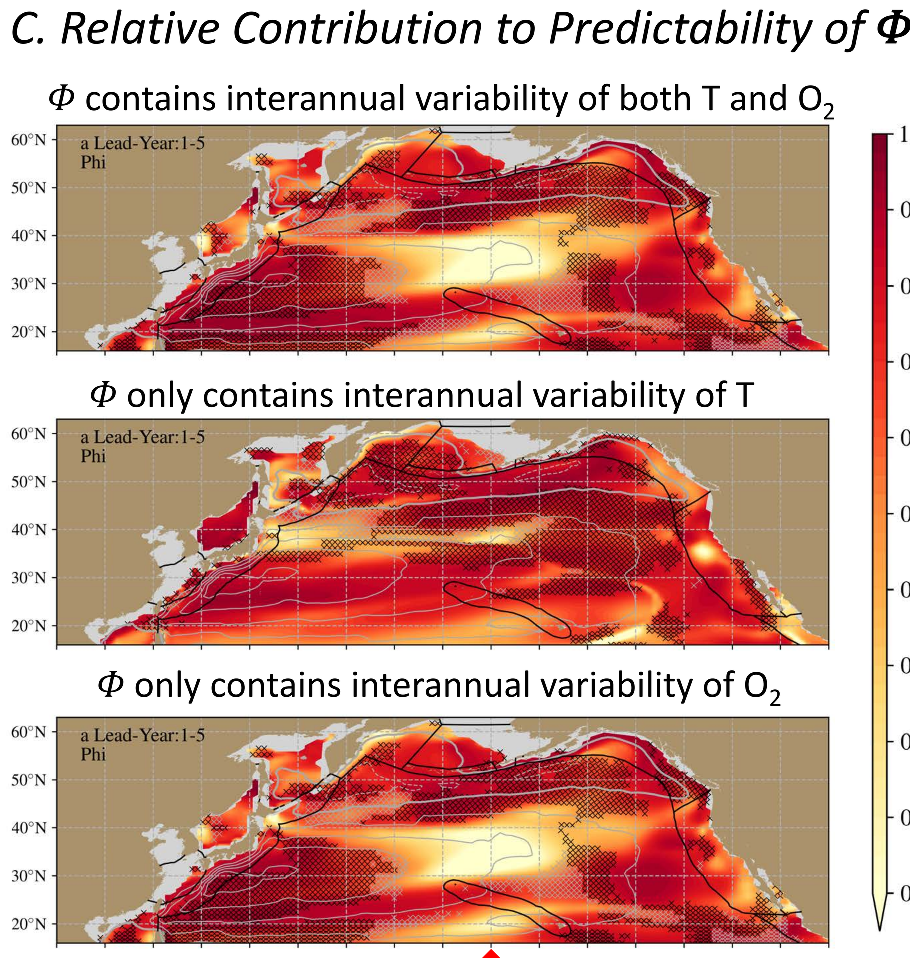

Figure 7. Potential predictability (ACC) of the Metabolic Index at the 200-600 m layer using CESM-DPLE when both interannual variabilities of T and O2 are included (upper), when only interannual variability of T is included (middle), and when only interannual variability of O_2 is included, all at the lead time 1-5 years.

- Potential predictability of the Metabolic Index at lead time of 1-5 years shows almost the identical spatial pattern when interannual variability of T is removed; but largely changed when interannual variability of O2 is removed.

IV. Conclusions

- The Metabolic Index is predictable on decadal time scales that enables quantifying habitat constraints arising from the metabolic dependence on temperature and requirements for oxygen, as well as temperature and oxygen at the 200-600m layer;
- The CESM-DPLE provides higher potential predictability in the three metrics at 200-600m over the simple, low-cost FOSI reconstruction persistence forecast, in the North Pacific with a lead time of 1-10 years;
- Spatial difference in potential predictability and its increase from persistence exists in the North Pacific as well as the 12 Large Marine Ecosystems;
- Interannual variability of oxygen is the dominant role against that of temperature in contributing the potential predictability of the Metabolic Index over the North Pacific.

References

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