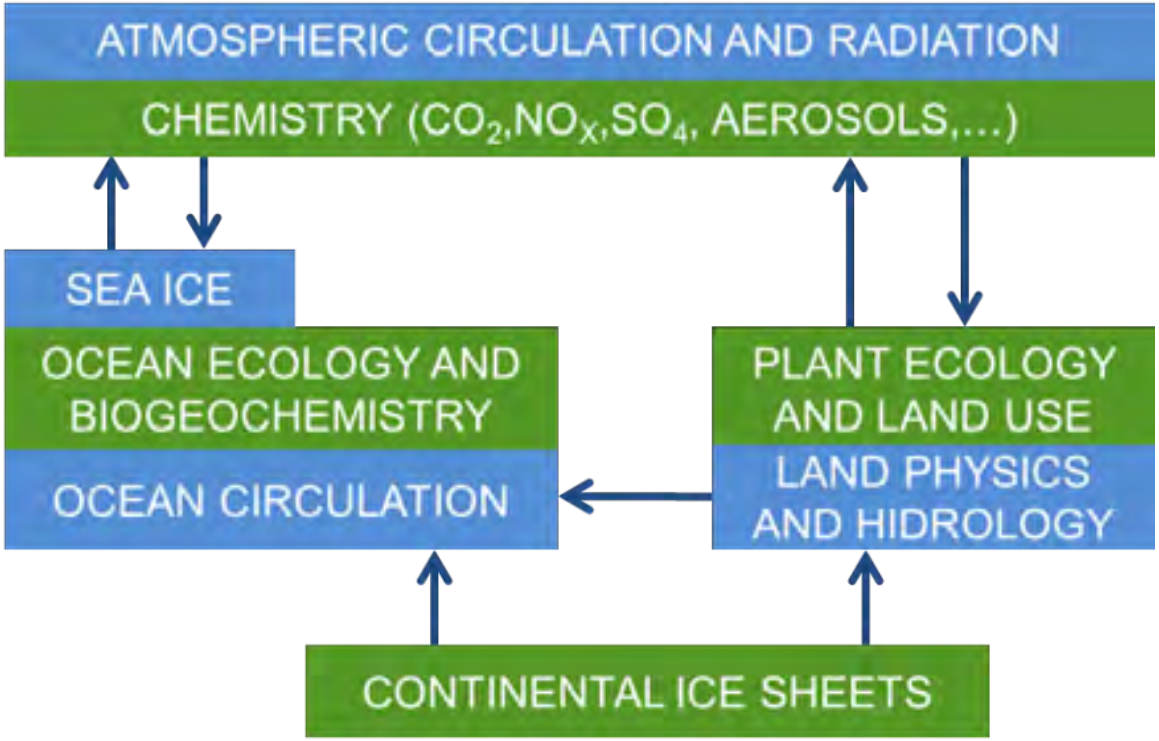
Earth system models and marine ecosystems in the context of climate variability and change

Matthew C. Long

Climate and Global Dynamics Laboratory
National Center for Atmospheric Research

Earth system models: a tool for actionable predication?

Self-contained, comprehensive climate-system representation



www.climateurope.eu

CMIP6 Scientific focus

WCRP Grand Science Challenges

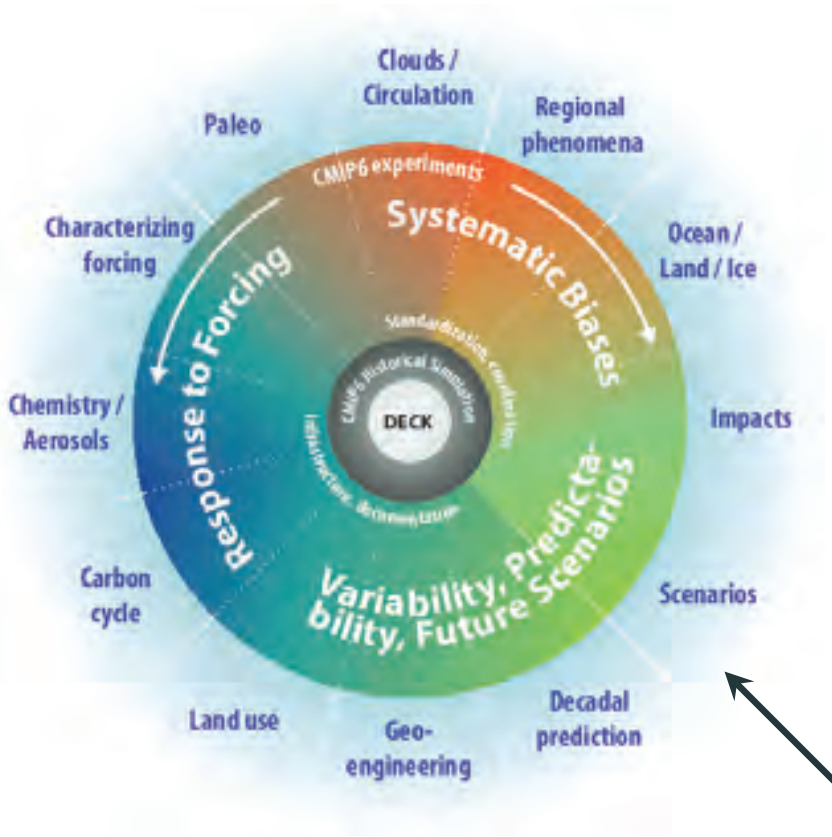
- Melting Ice and Global Consequences
- Clouds, Circulation and Climate Sensitivity
- Carbon Feedbacks in the Climate System
- Understanding and Predictng Weather and Climate Extremes
- Water for the Food Baskets of the World
- Regional Sea-Level Change and Coastal Impacts
- Near-term Climate Prediction

Motivating science questions

1. How does the Earth System respond to forcing?
2. What are the origins and consequences of systematic model biases?
3. How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios?

Eyring et al. 2016

CMIP6 Overview: Continuous and distributed organization



DECK := Diagnostic, Evaluation and Characterization of Klima

Eyring et al. 2016

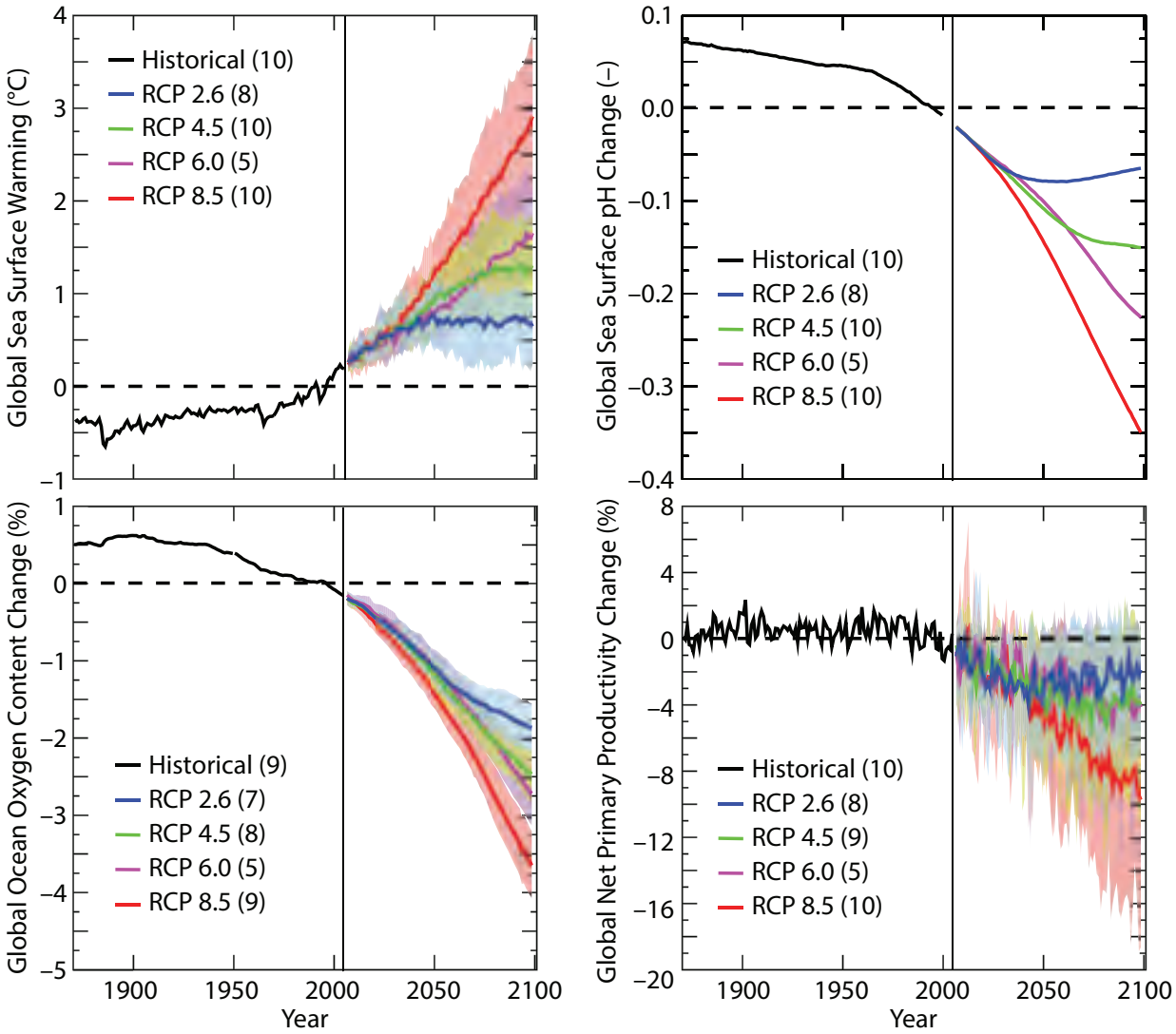
Requirements for entry

- DECK experiments
  1. AMIP historical (1979–2014)
  2. Pre-industrial control
  3. 1%/yr CO_2 increase
  4. Abrupt $4\times CO_2$
- CMIP6 historical simulation
  5. 1850–2014 under CMIP6 forcings

CMIP-Endorsed model intercomparison projects

Warming up, turning sour, losing breath*

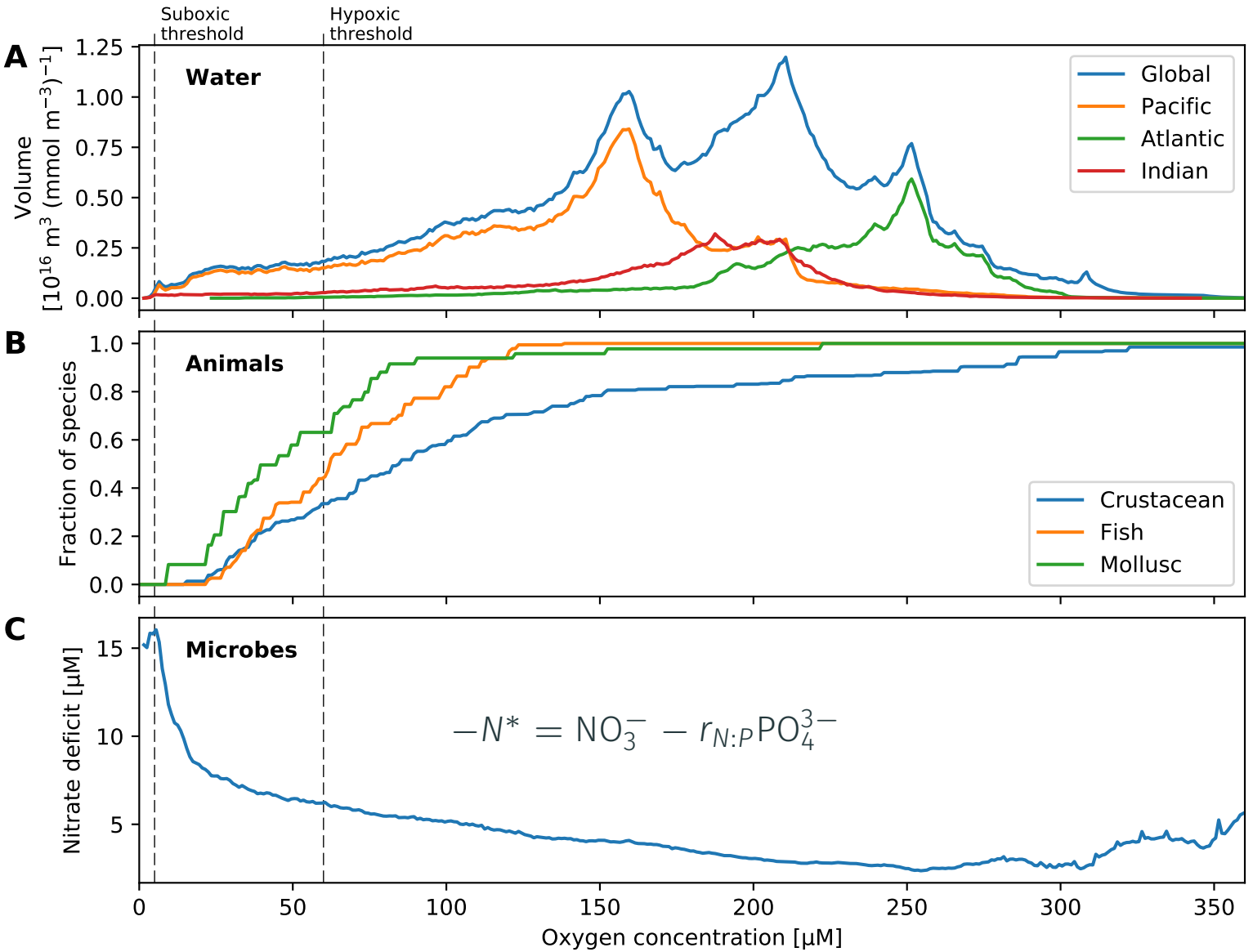
CMIP5 multi-model global-mean projections



Doney, Bopp, & Long, 2014

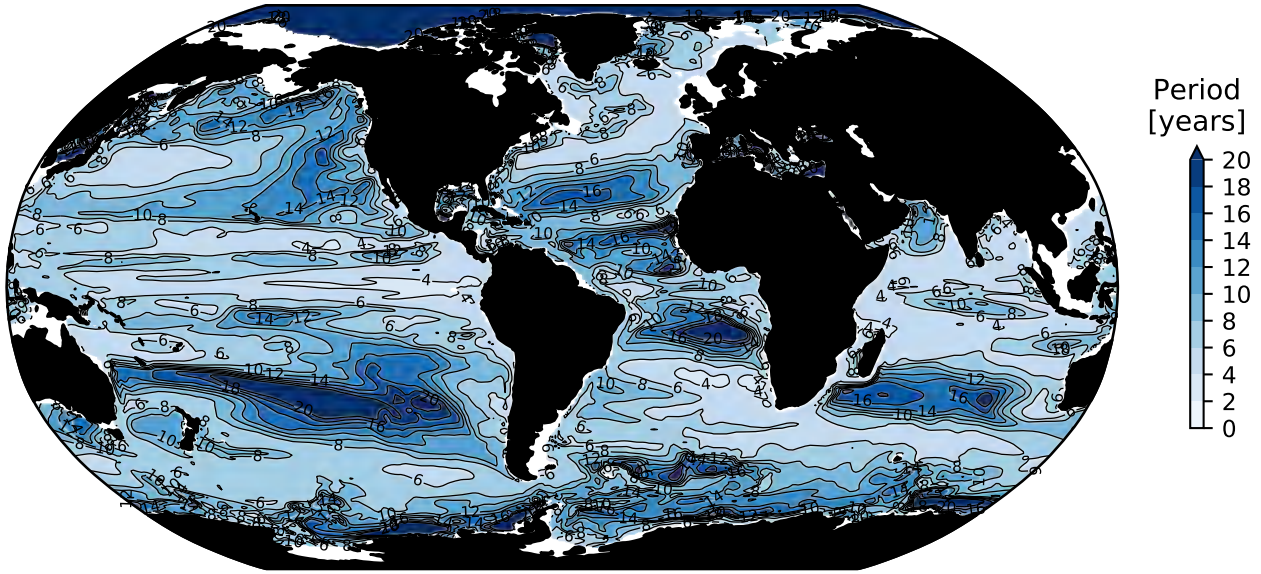
* *Gruber, 2011*

Oxygen is a fundamental environmental constraint



Timescales of natural variability in thermocline O_2

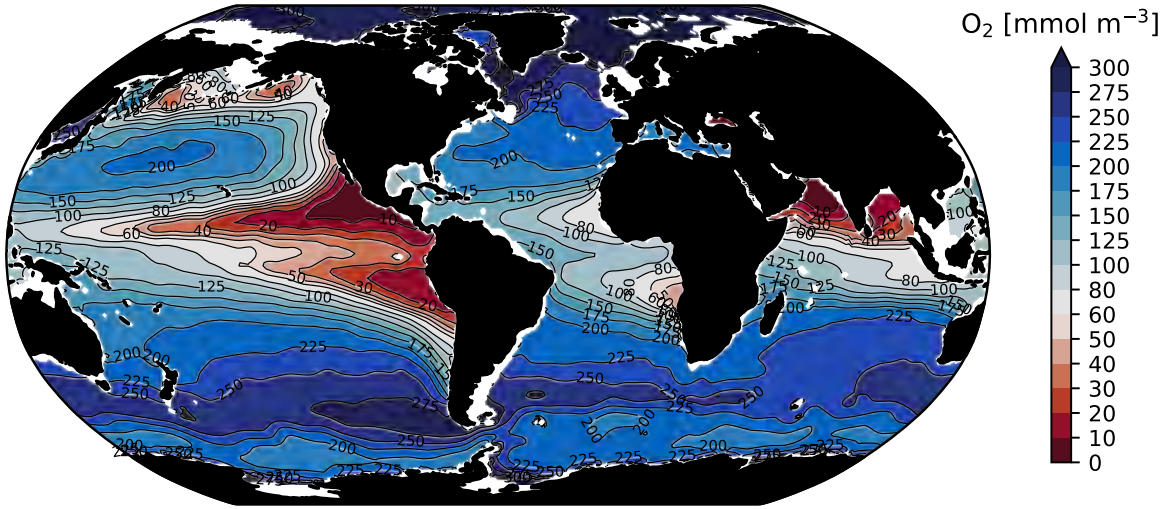
Variance-weighted mean period in CESM 1850-control



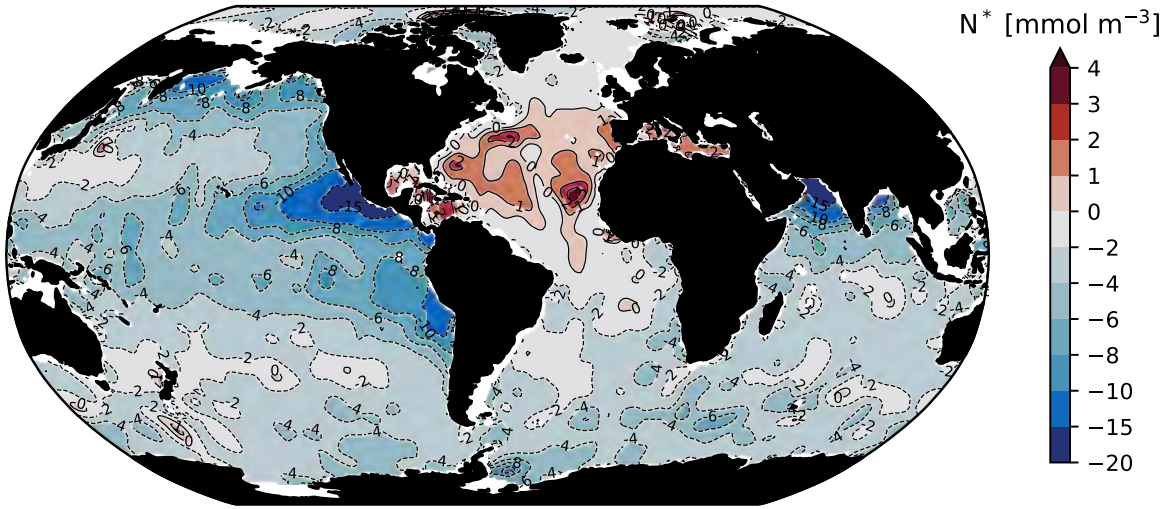
$$T_x = \sum_k V(f_k, x) / \sum_k f_k V(f_k, x)$$

Observed signature of denitrification: Nitrate deficit at low O_2

Thermocline oxygen (annual mean)



Thermocline nitrate deficit (N^*)



$$N^* = r_{N:P}PO_4^{3-} - NO_3^-$$

$$r_{N:P} = 16$$

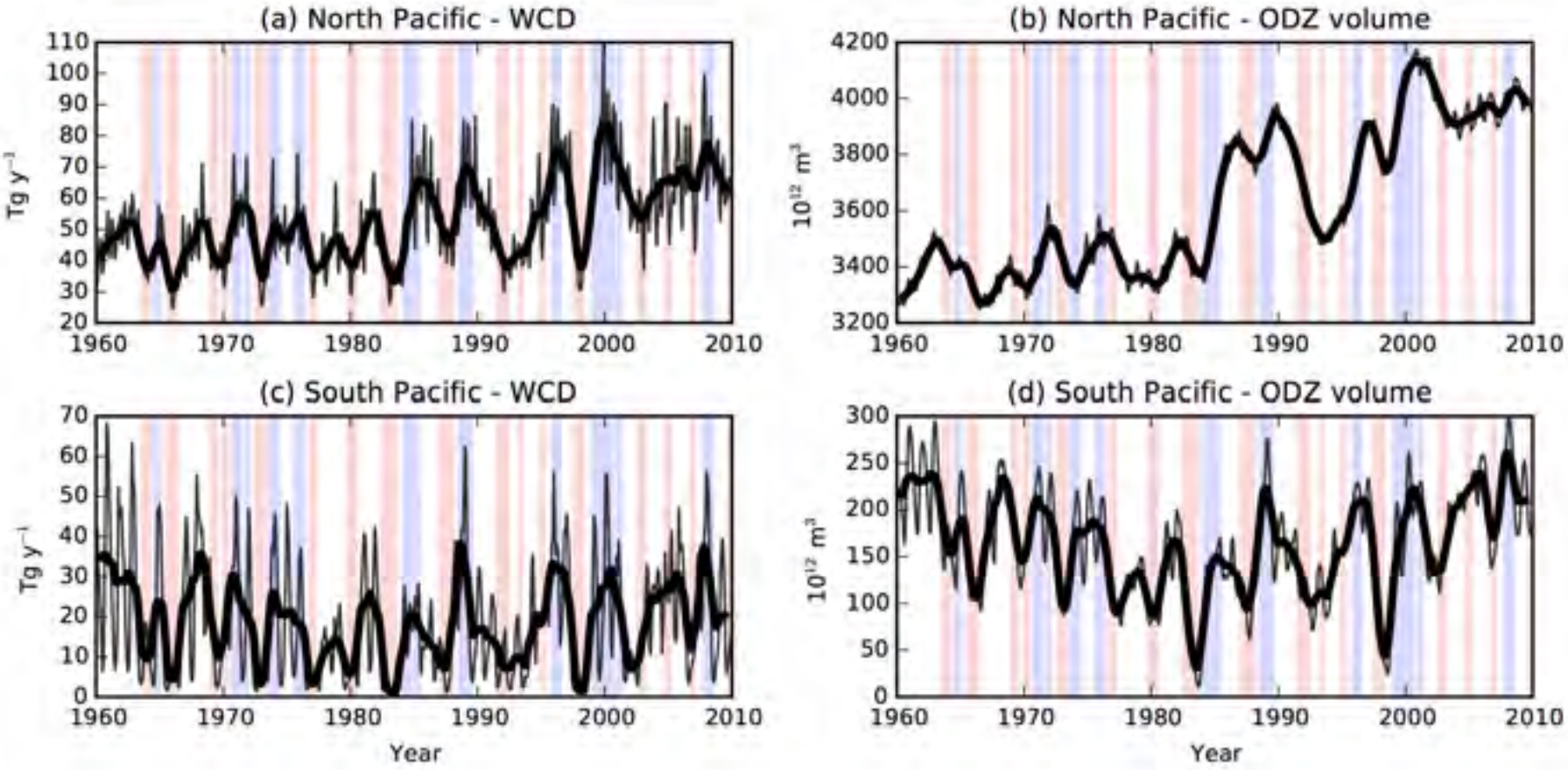
World Ocean Atlas, 2013

Dynamic regulation of biogeochemical transformations

CESM ocean-ice hindcast simulation

Water column denitrification (WCD)

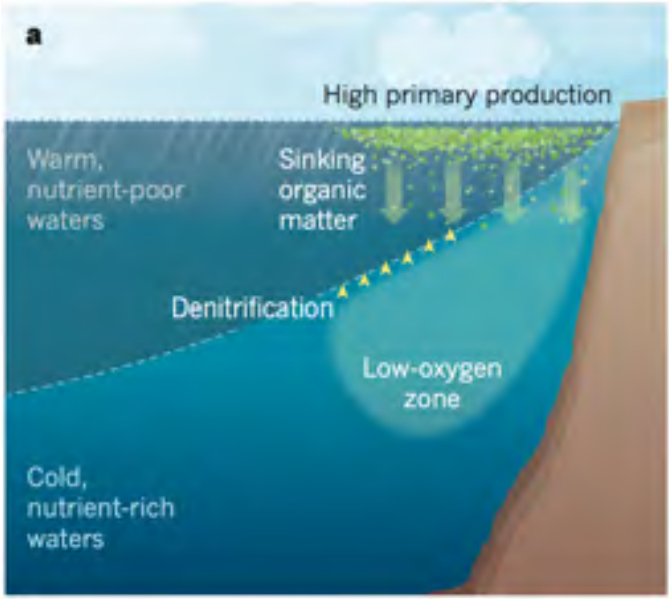
O_2 deficient zone (ODZ) volume



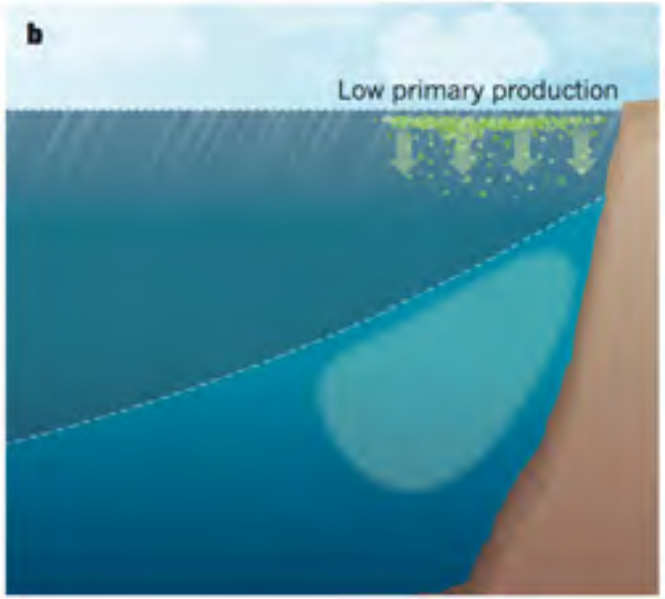
Yang et al., 2017

Denitrification is highly dynamic, responsive to climate forcing

La Niña

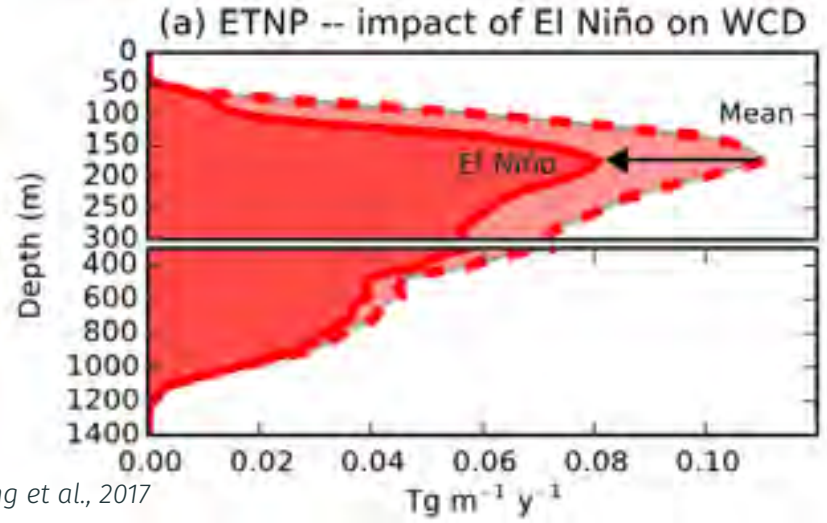


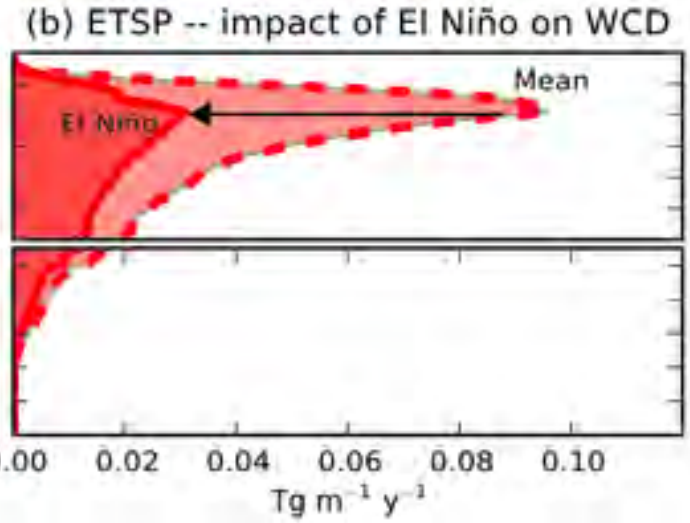
El Niño



Fennel, 2017

Water column denitrification (WCD)

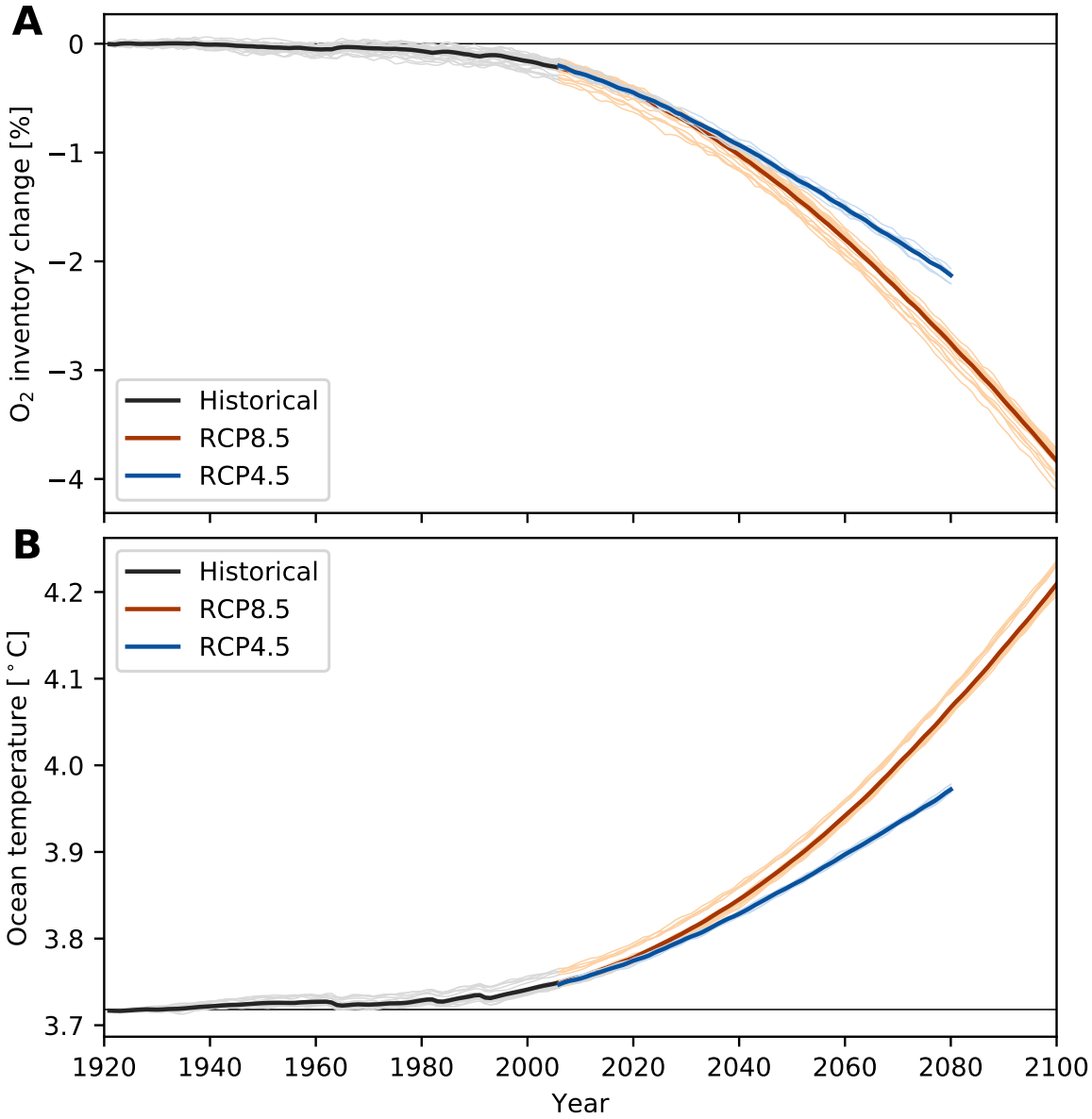




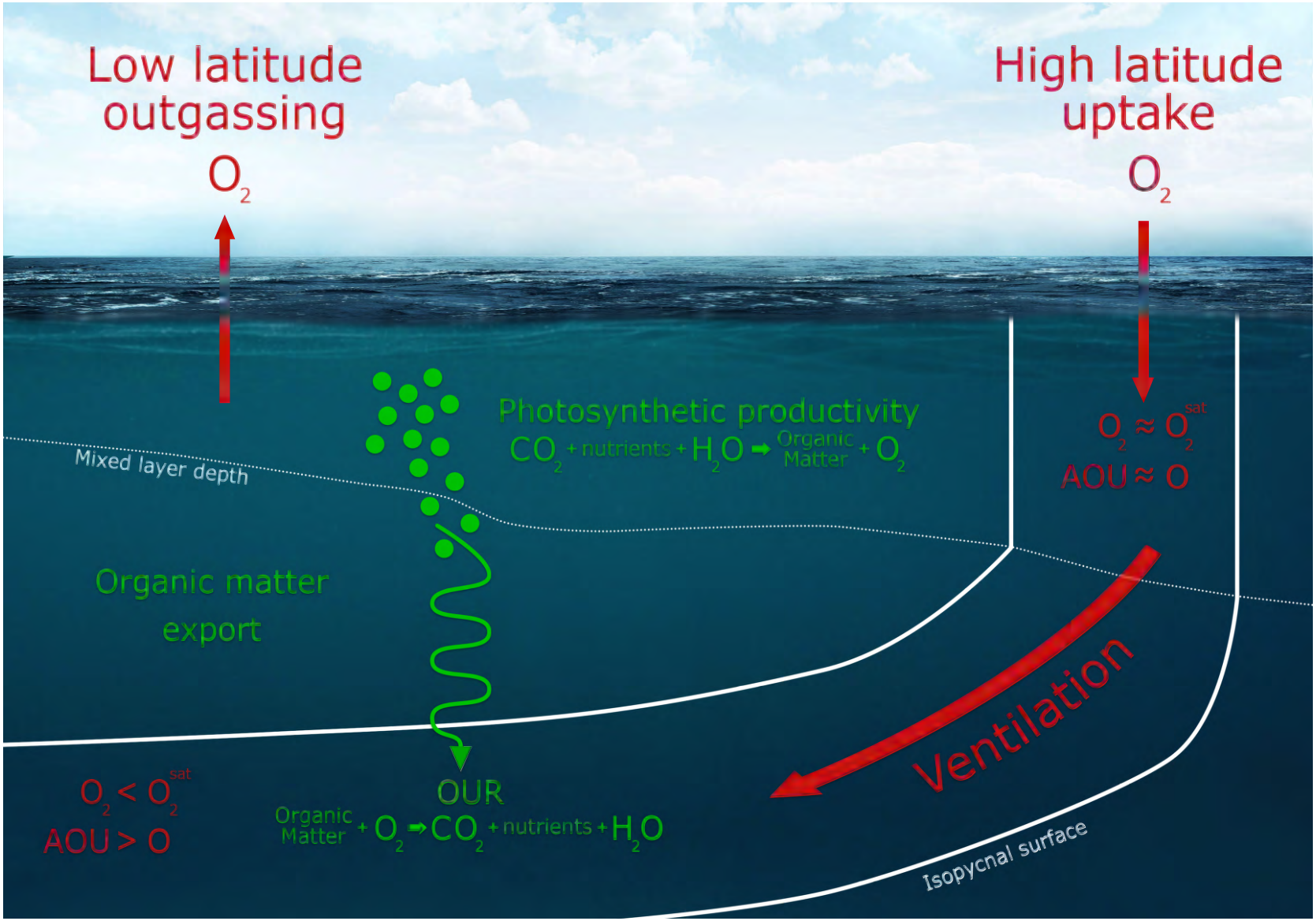
Yang et al., 2017

Oxygen decline projected to accelerate

CESM simulated change in global O_2 and heat



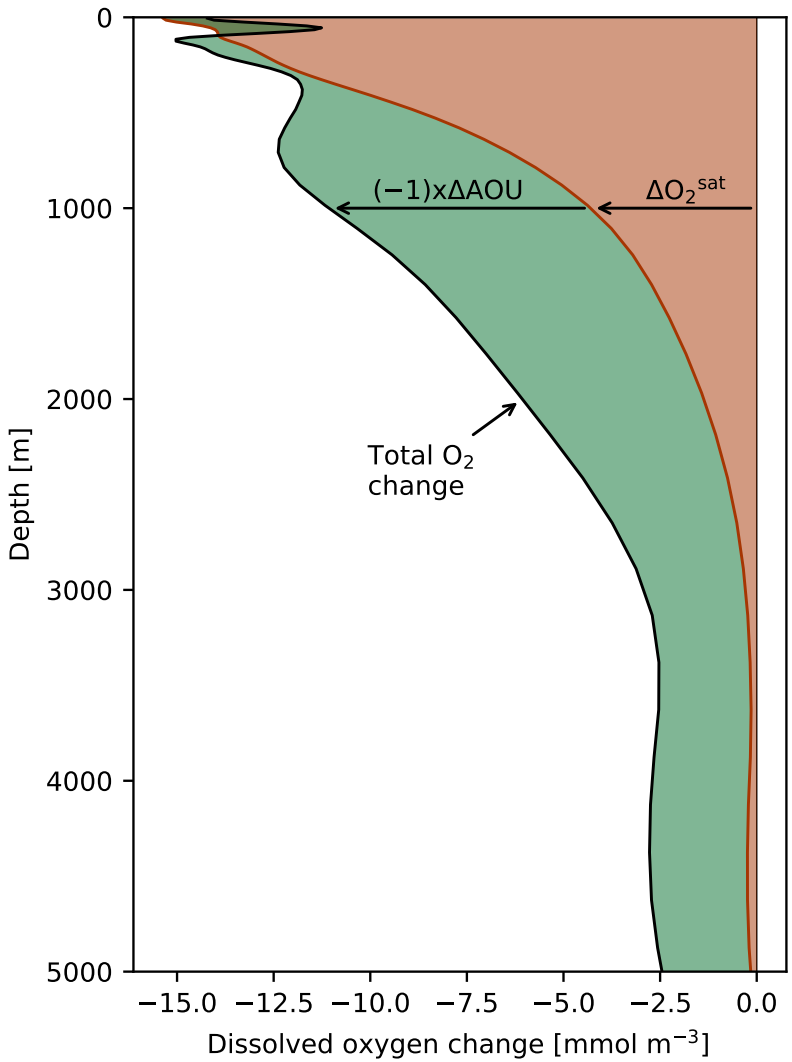
Physical & biological controls on interior oxygen



Graphic credit: M. Long and R. Johnson (NCAR)

CESM projection: global-mean drivers of deoxygenation

O_2 change at 2100

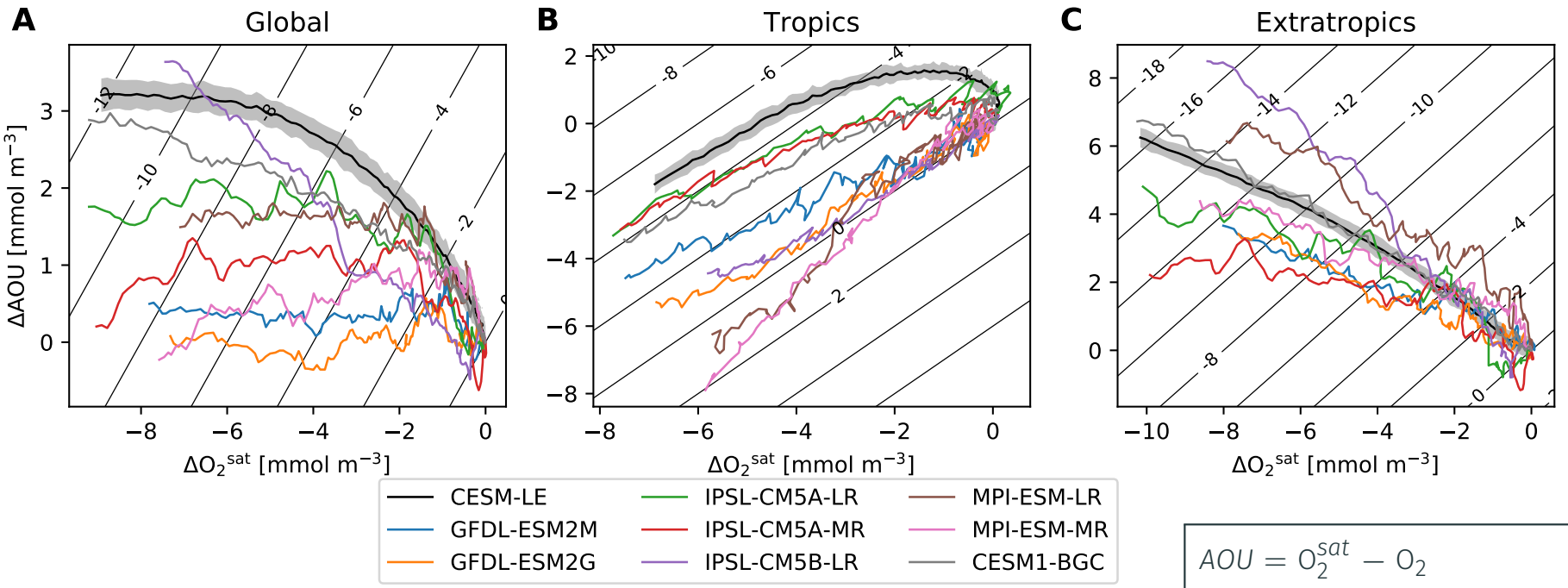


$$\Delta O_2 = \Delta O_2^{sat} - \Delta AOU$$

- Warming declines with depth;
- Surface *AOU* reduction: closer to equilibrium;
- Deep deoxygenation is *AOU*-dominated.

CMIP5 projection: global and regional drivers of deoxygenation

AOU v. O_2^{sat} phase space: Simulated $\langle O_2 \rangle$ change ($z > -1$ km)

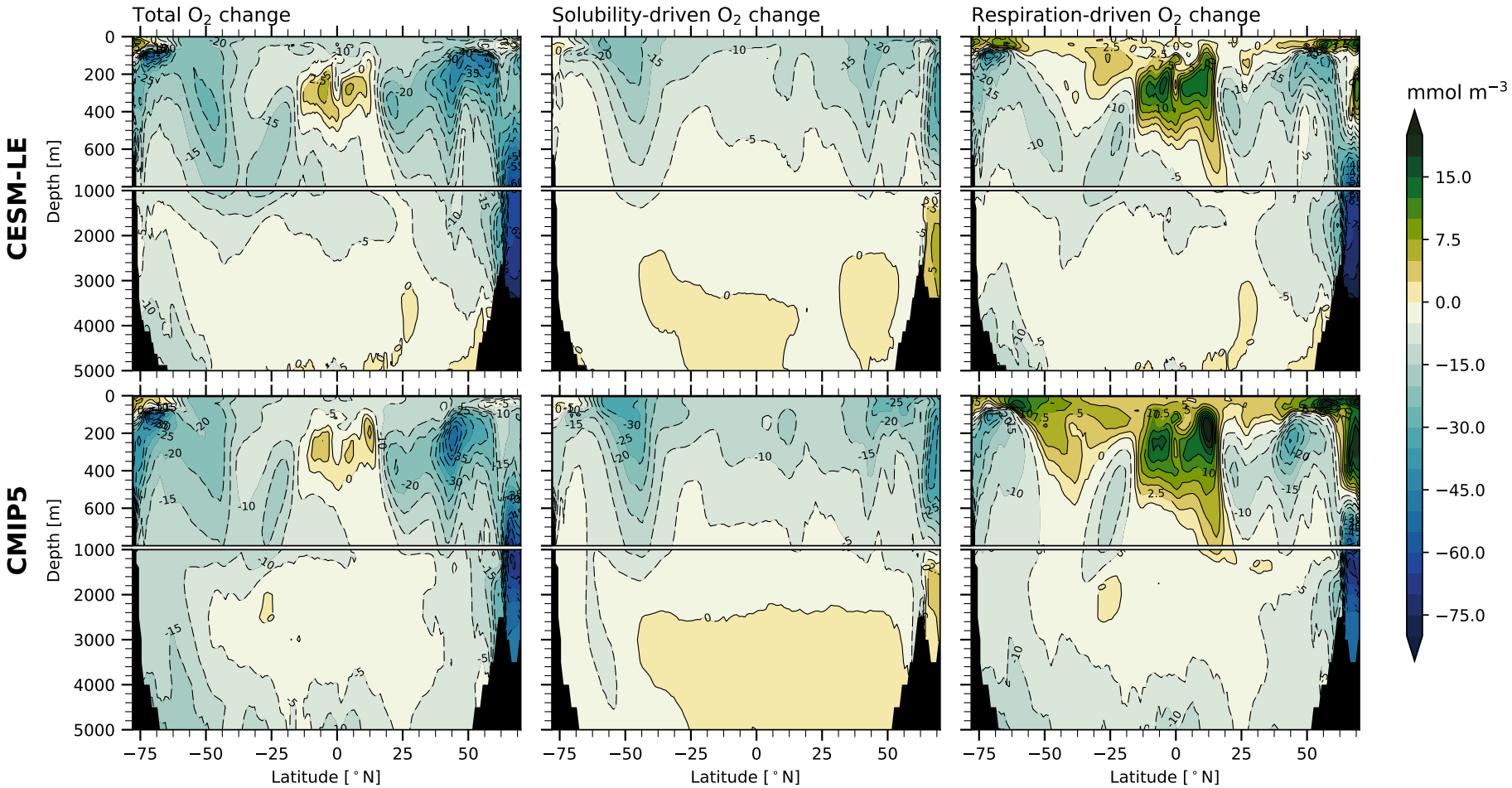


$$AOU = O_2^{sat} - O_2$$
$$= f(\text{Age}, O_2\text{-utilization})$$

- Tropics: warming compensated by reduced *AOU*;
- Extra-tropics: reinforcing *AOU* and solubility change;
- Cancelation between tropical & extra-tropical ΔAOU :
  global O_2 decline dominated by solubility effect.

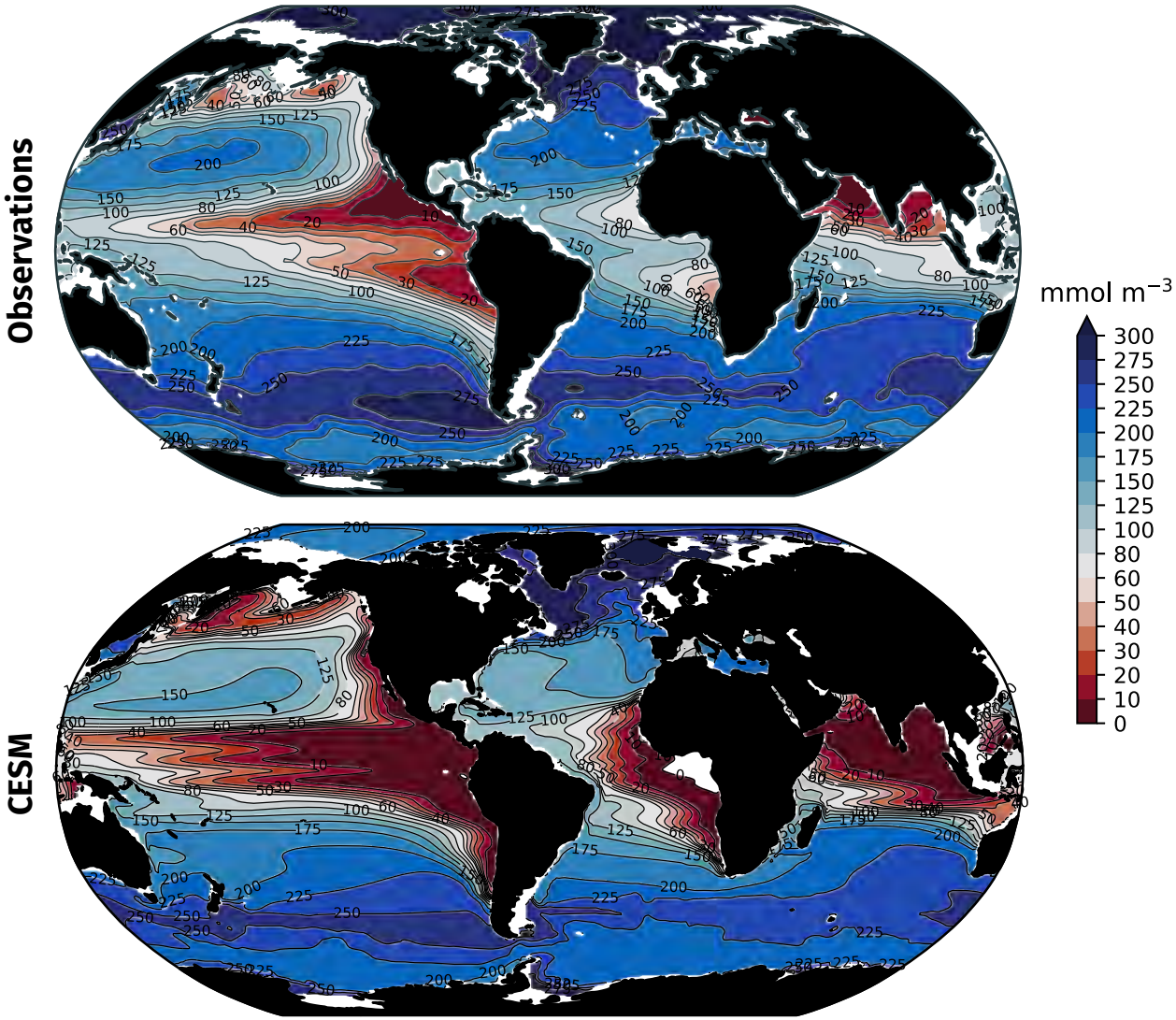
Reinforcing drivers at high-latitudes; compensation in tropics

Simulated change in zonal-mean O_2



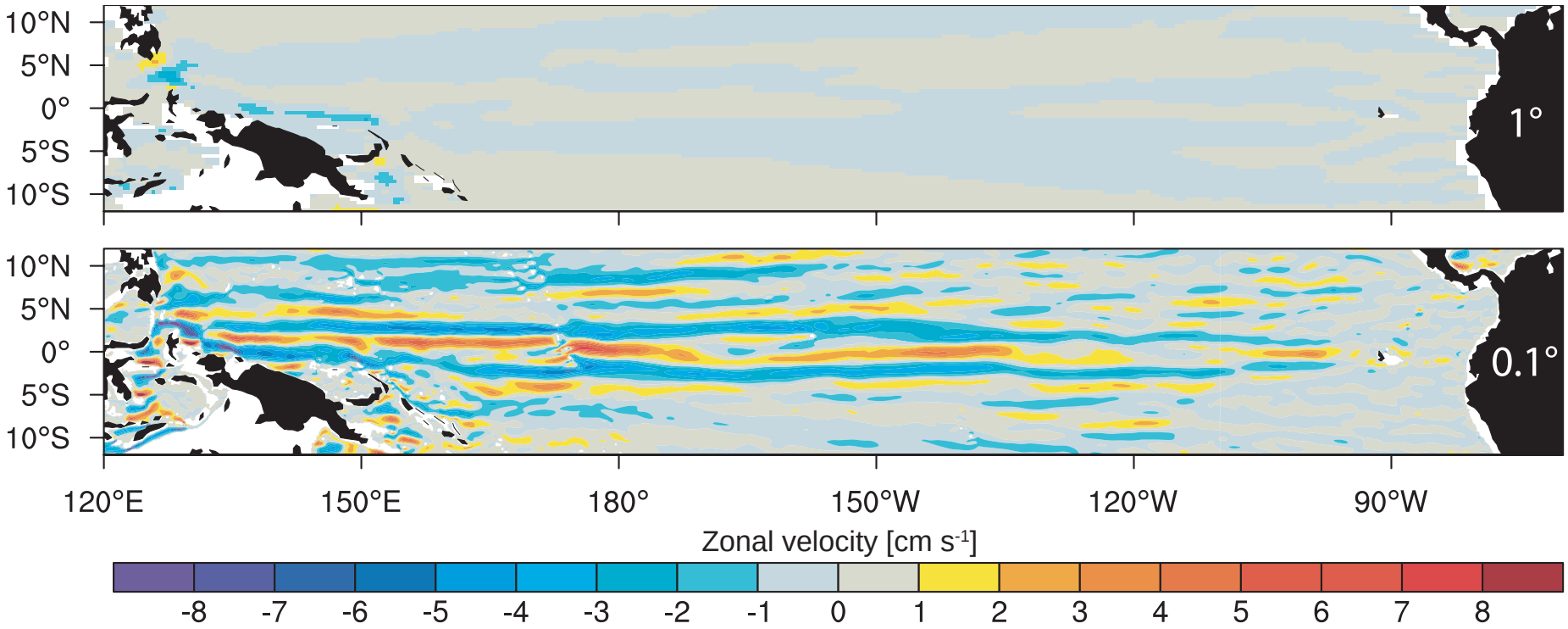
A persistent bias in Earth system models: Extensive OMZs

Thermocline (400–600 m) O_2 distributions



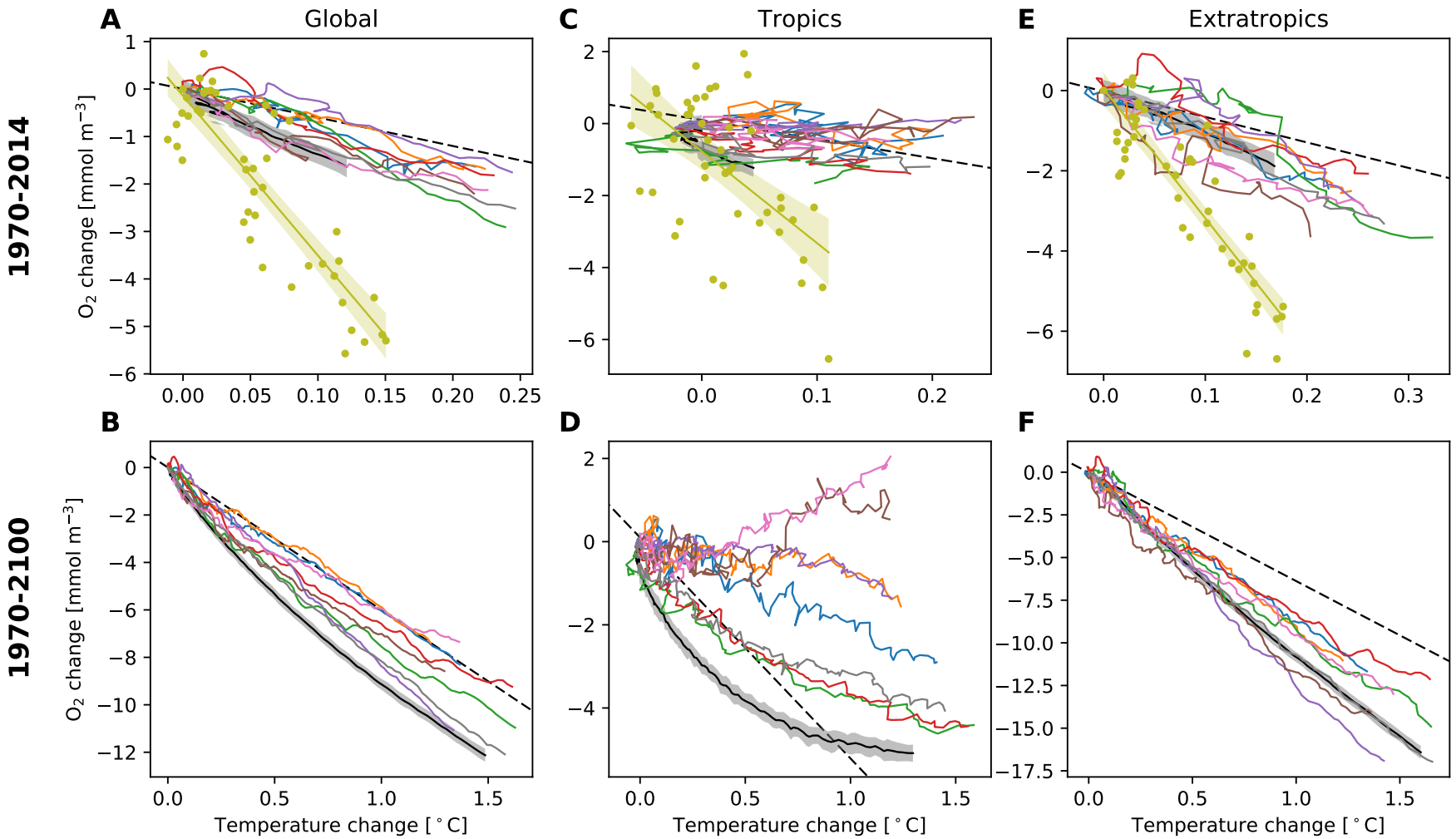
Model resolution determines ventilation dynamics

Simulated zonal velocity at 1000 m



Oxygen declines related to ocean heat content anomaly

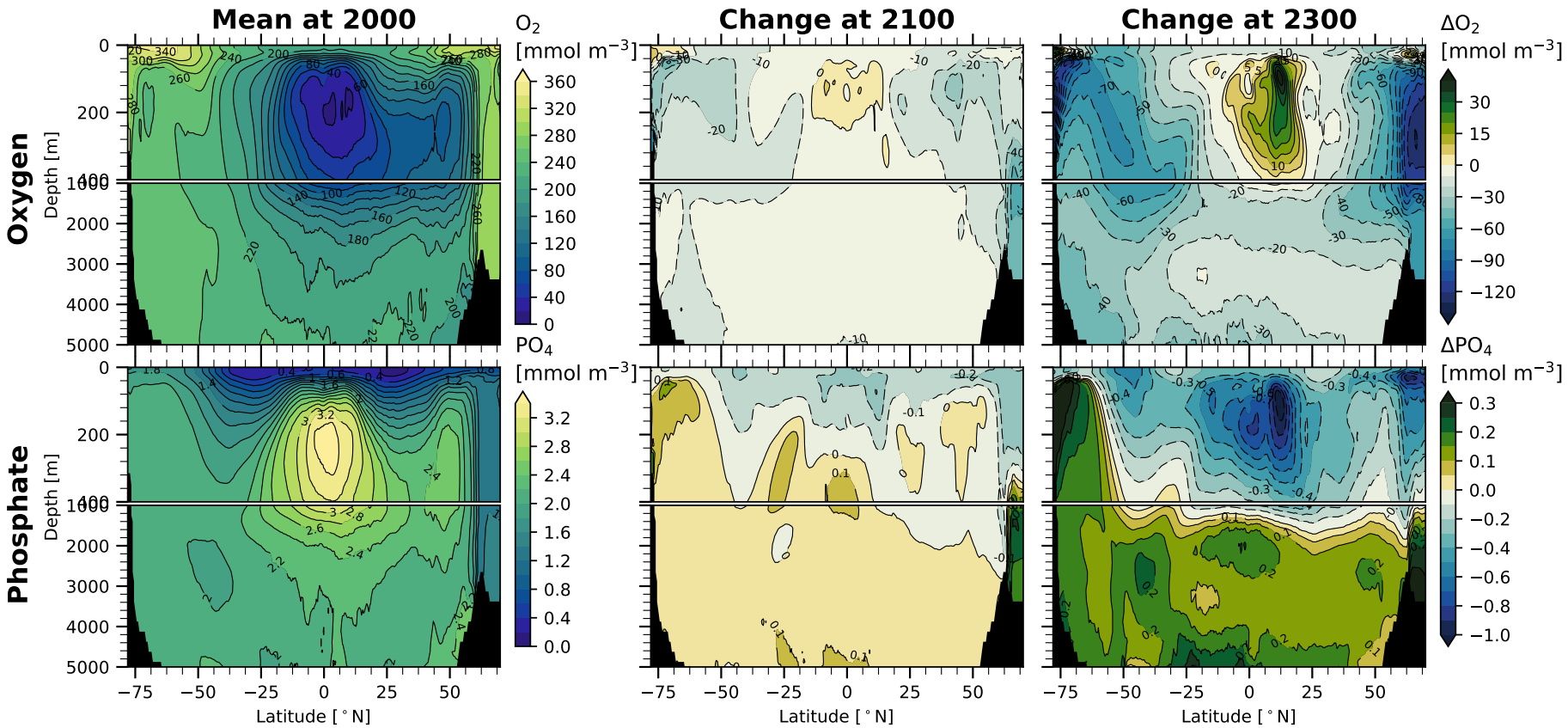
O_2^{sat} v. heat: Simulated $\langle O_2 \rangle$ change ($z > -1$ km)



Obs: Ito et al., 2017

Deep future looks to be dark: Southern Ocean nutrient trapping

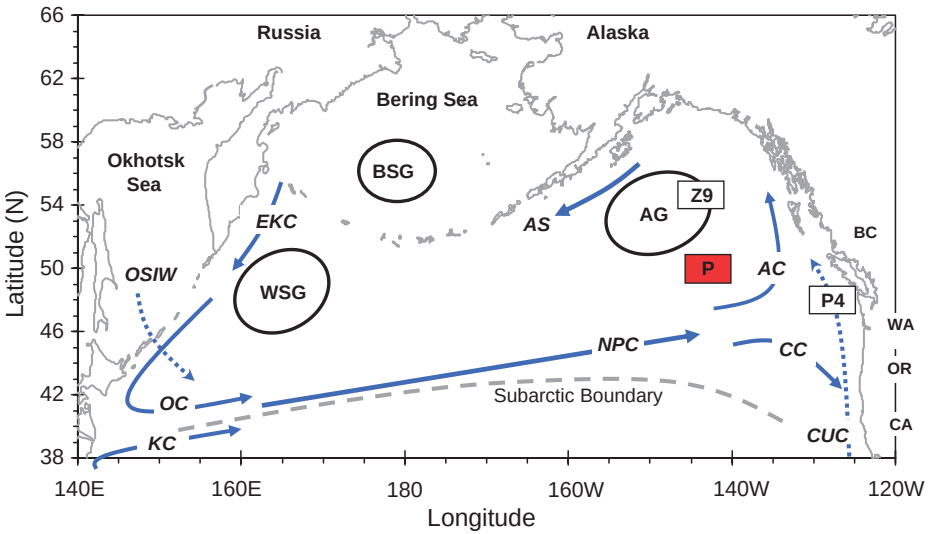
Global zonal-mean properties



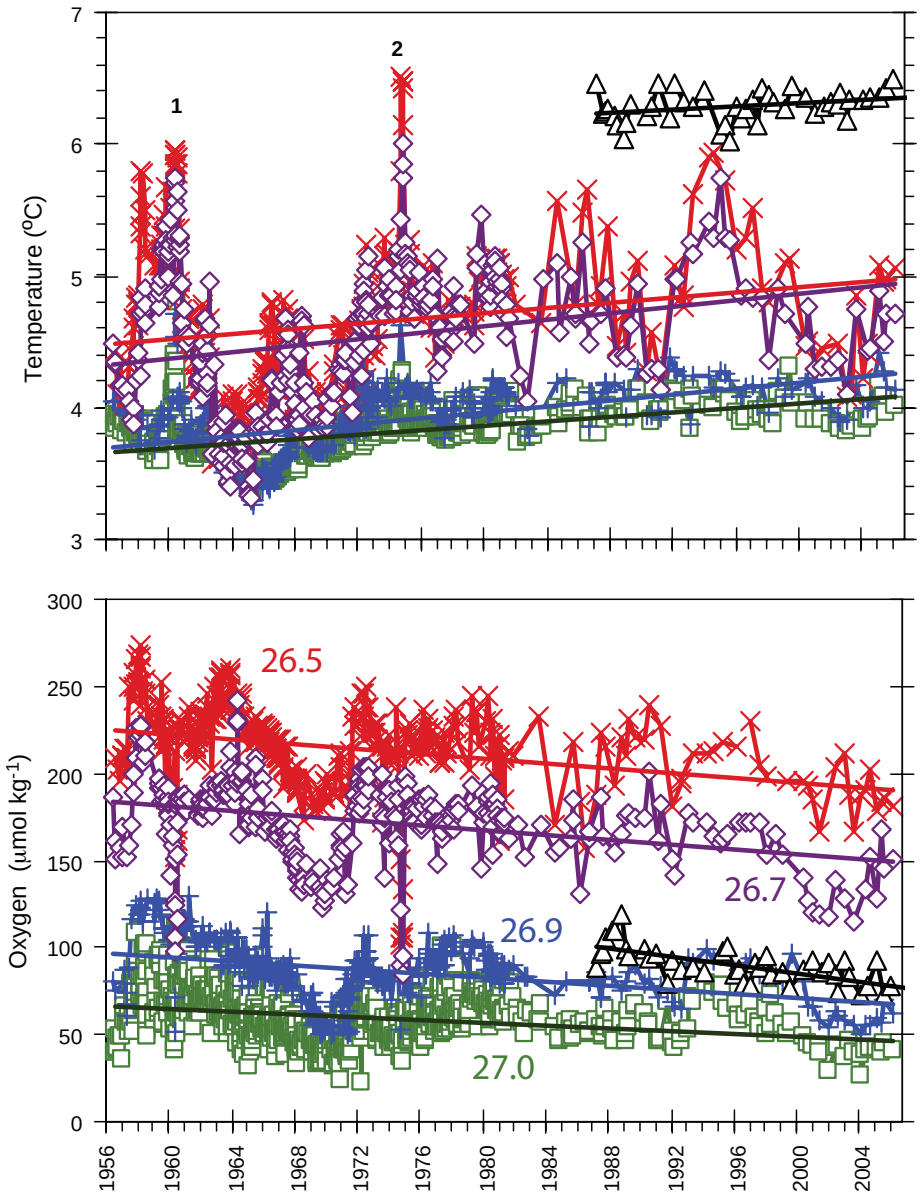
Are observed trends in interior O_2 forced?

Subarctic North Pacific

Ocean Station P: isopycnal surfaces

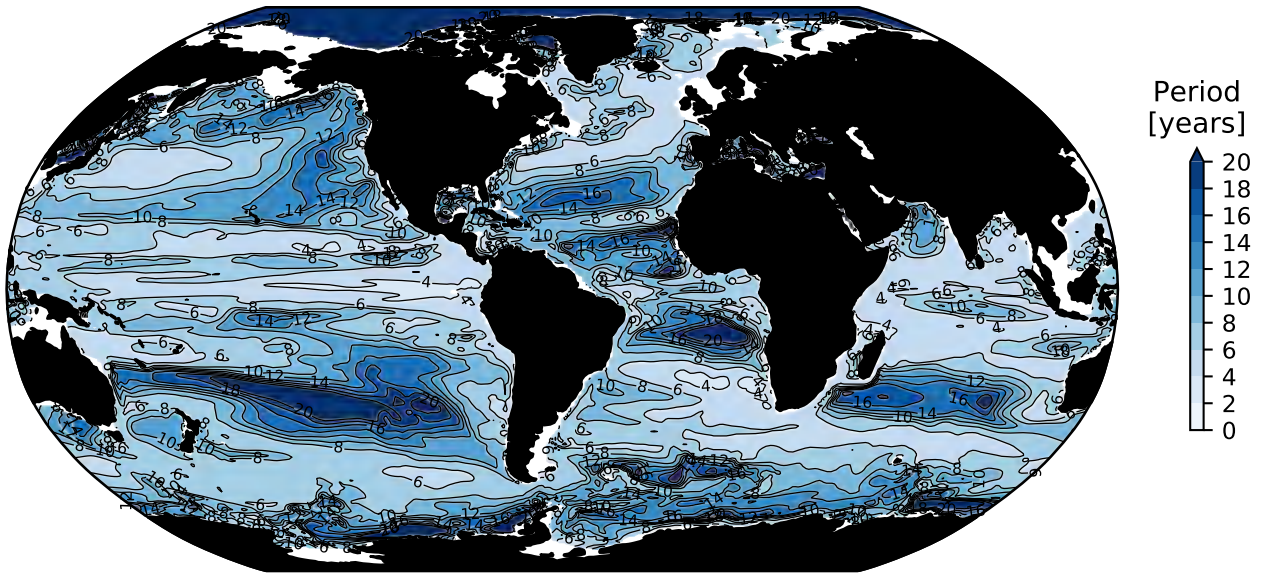


Whitney et al. 2007



Timescales of natural variability in thermocline O_2

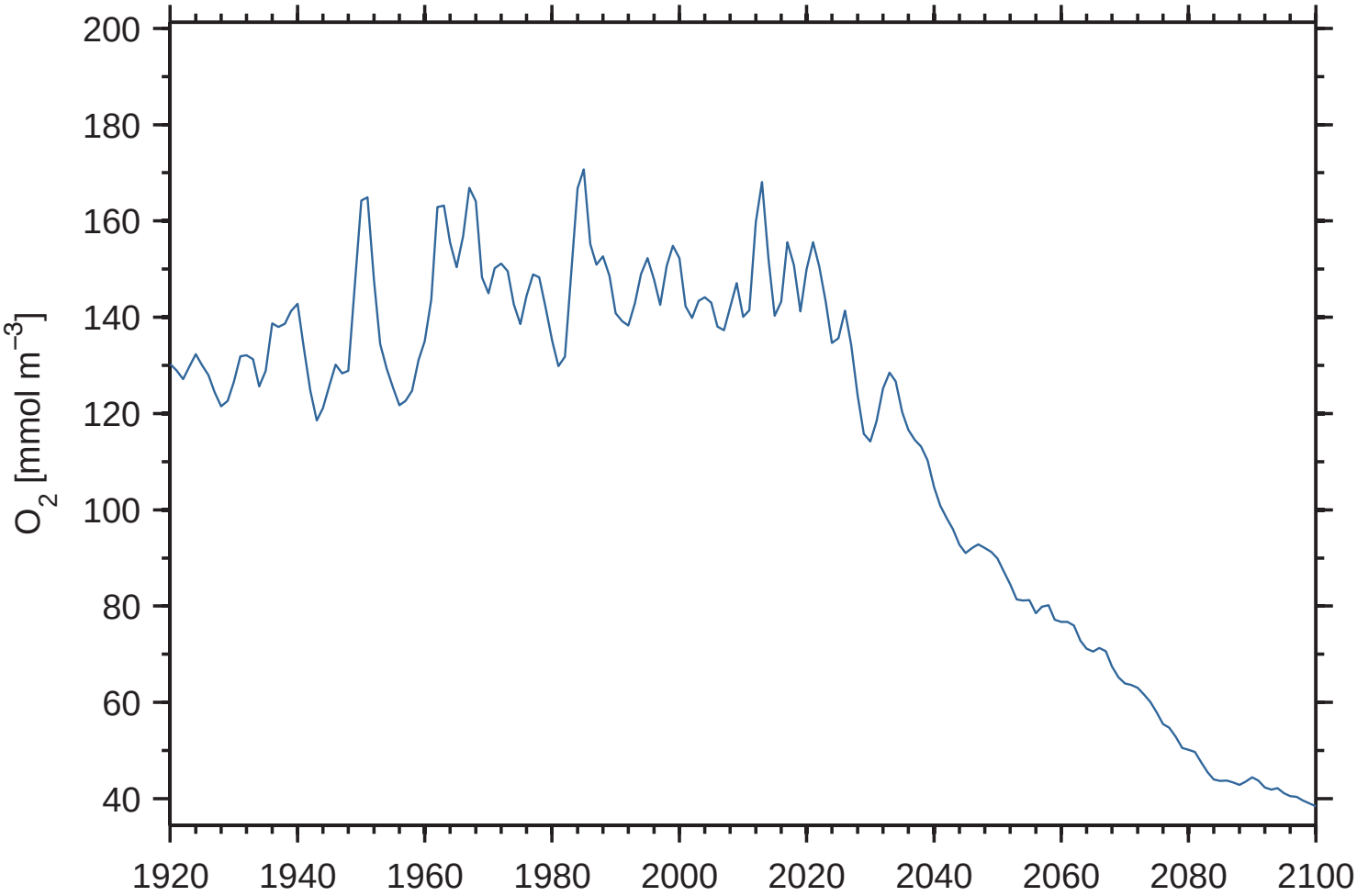
Variance-weighted mean period in CESM 1850-control



$$T_X = \sum_k V(f_k, x) / \sum_k f_k V(f_k, x)$$

Natural variability can reinforce or oppose trends

CESM-LE simulation of dissolved oxygen at Station P ($\sigma_\theta = 26.5$)



Long et al. 2016

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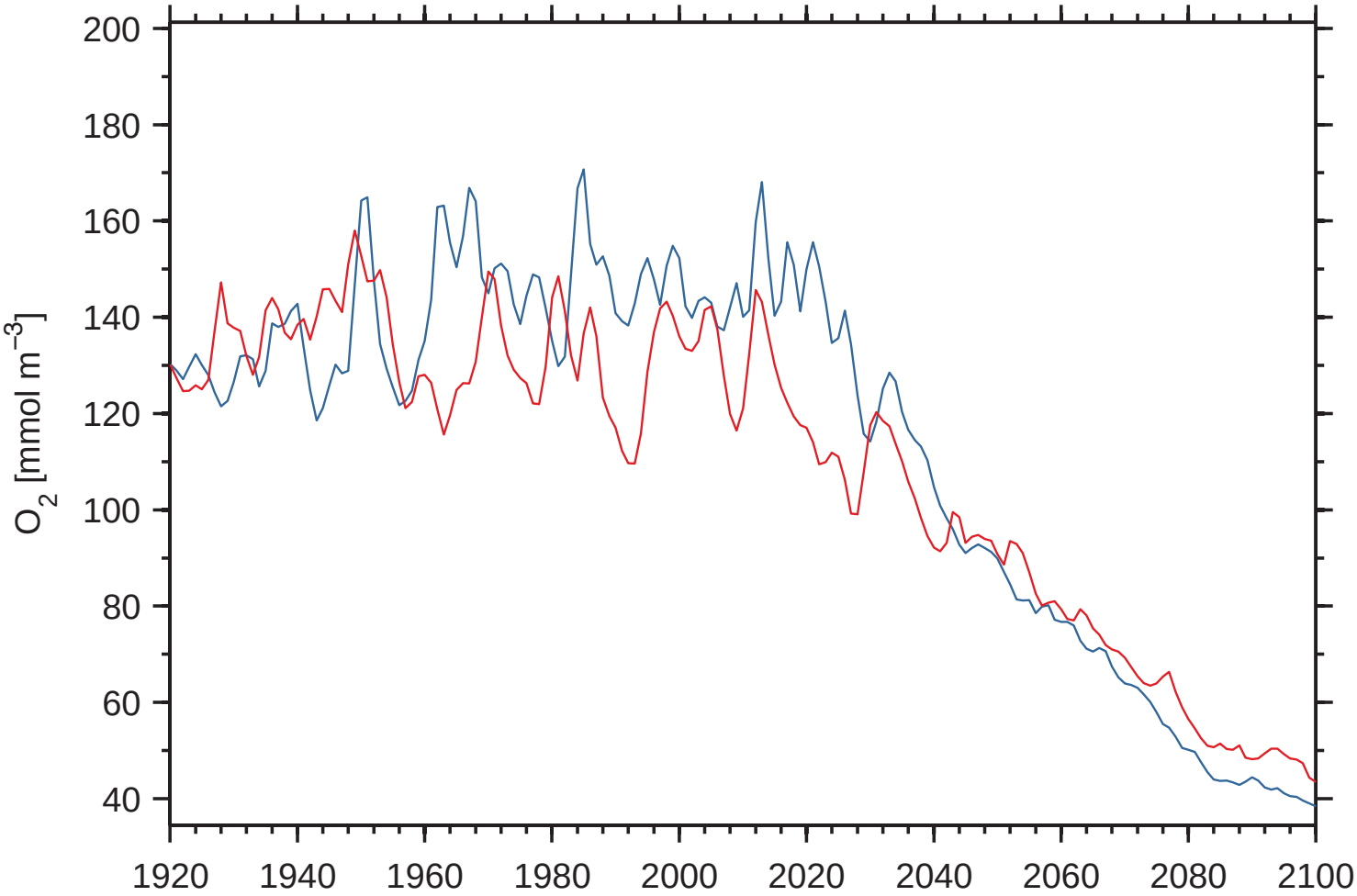

Long et al. 2016

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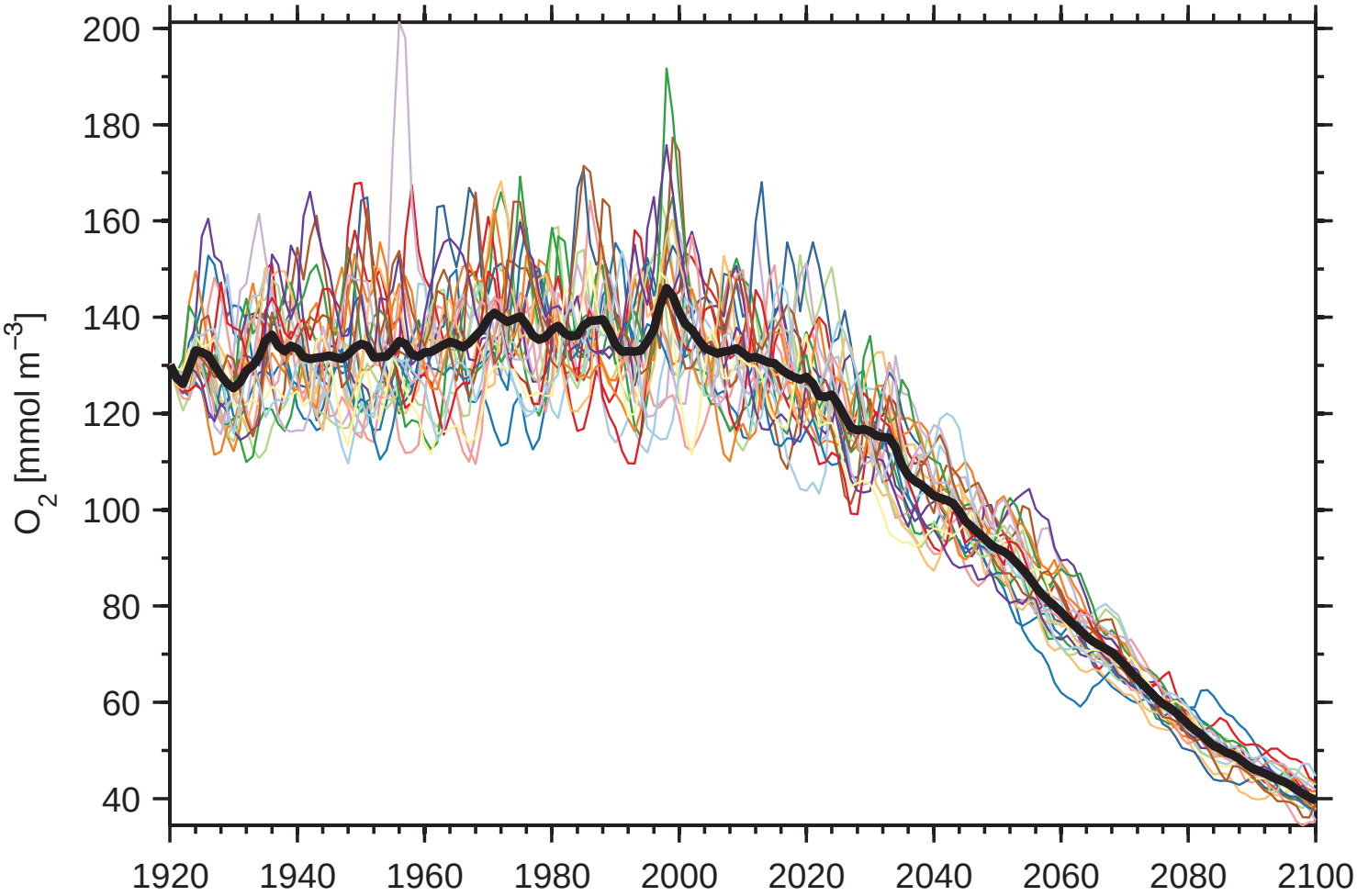
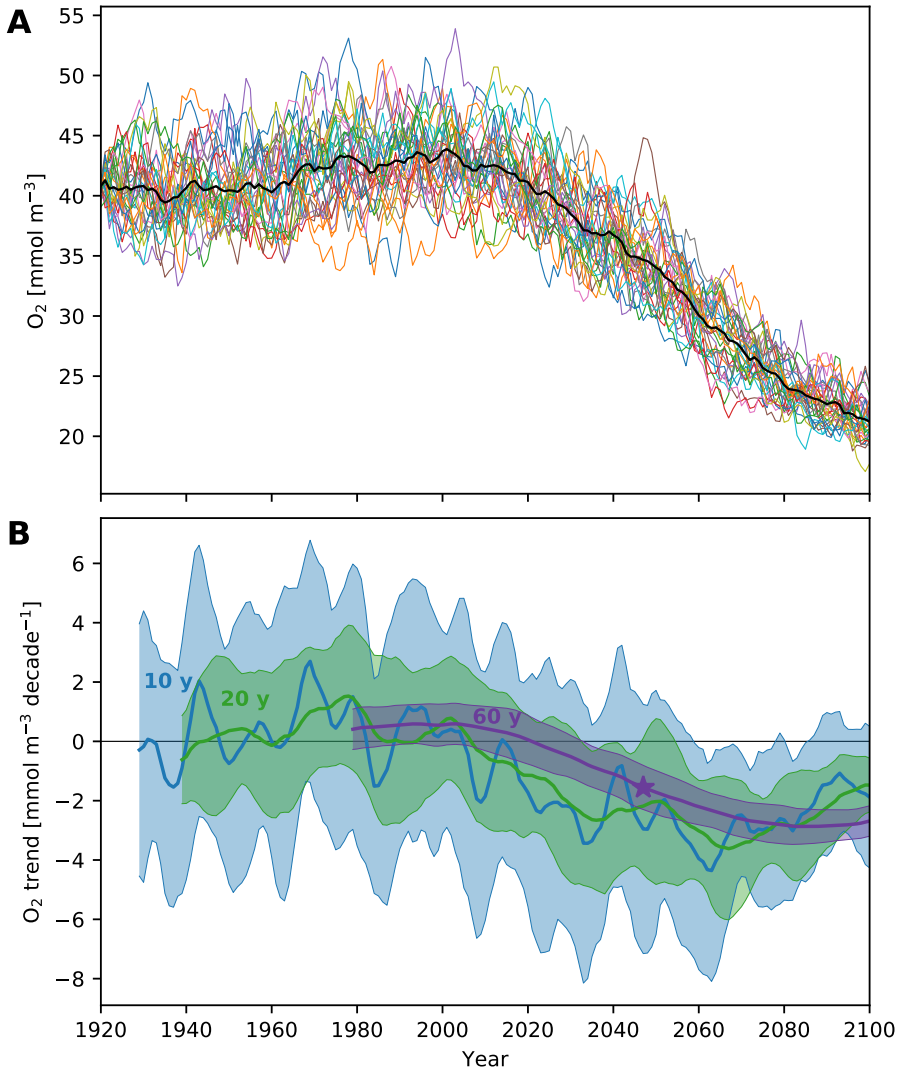


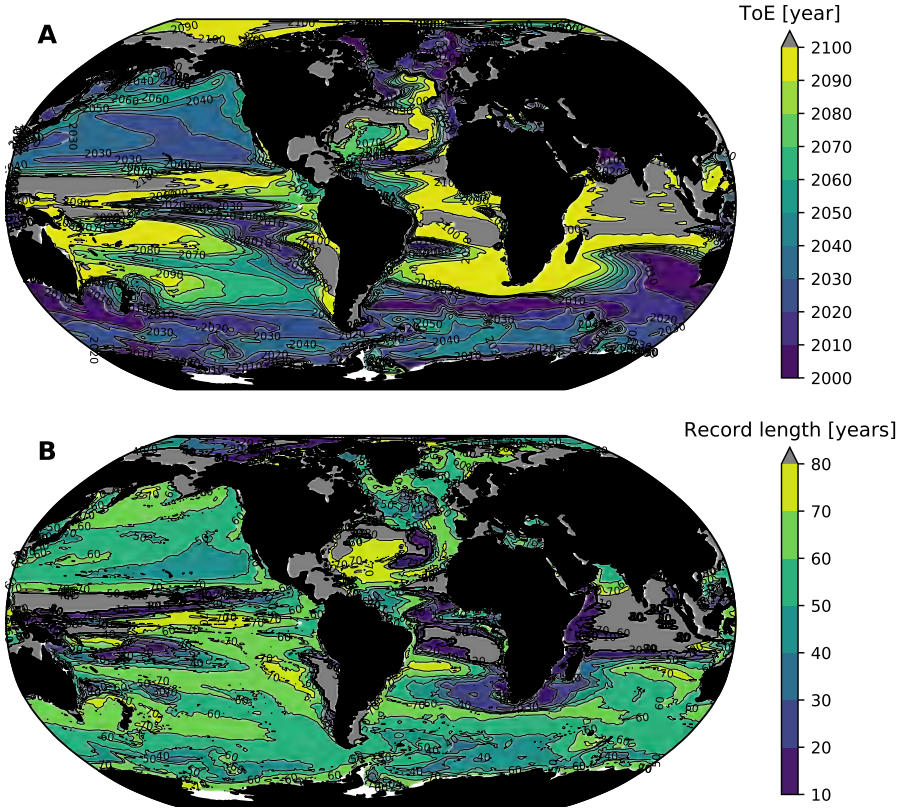
Long et al. 2016

Natural variability challenges detection and attribution

Thermocline O_2, California Current

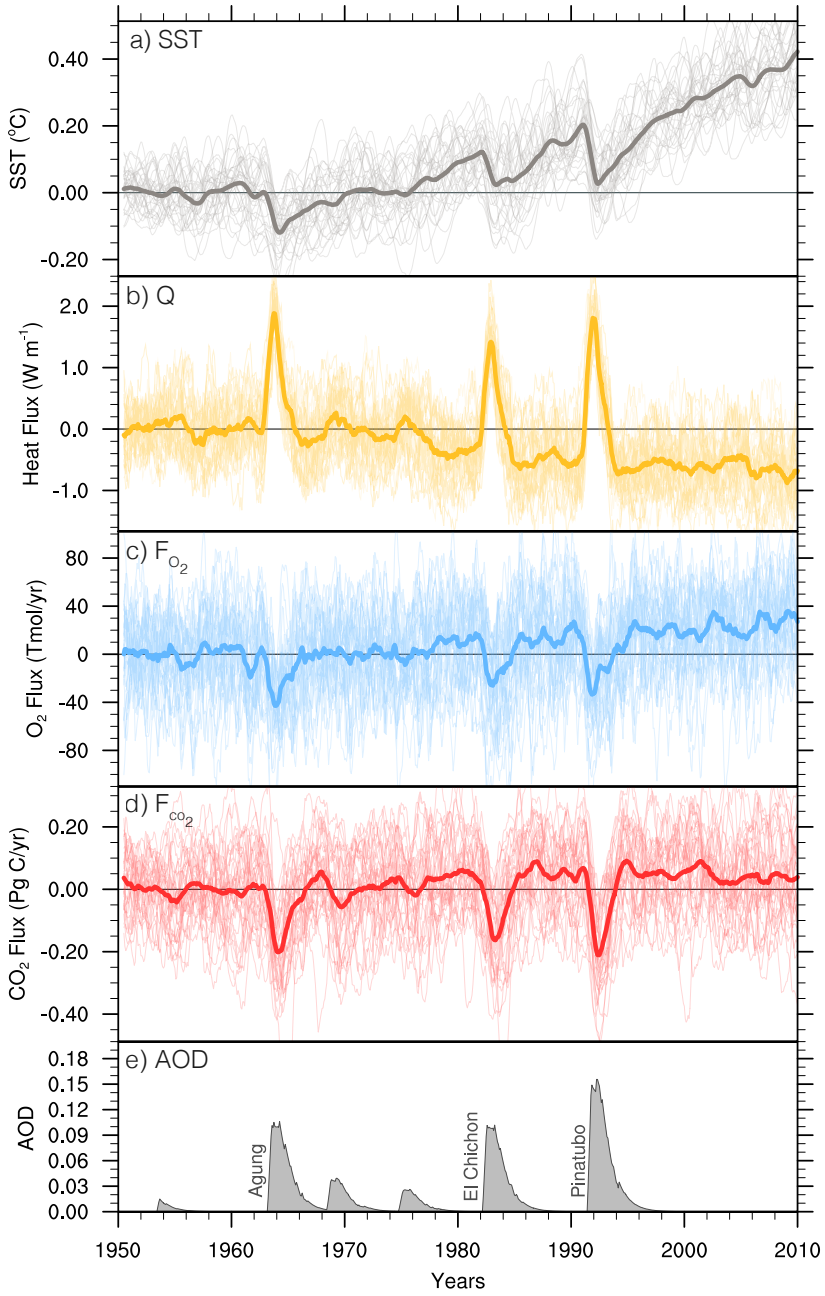


Time of emergence



Imprint of volcanic eruptions on ocean biogeochemistry

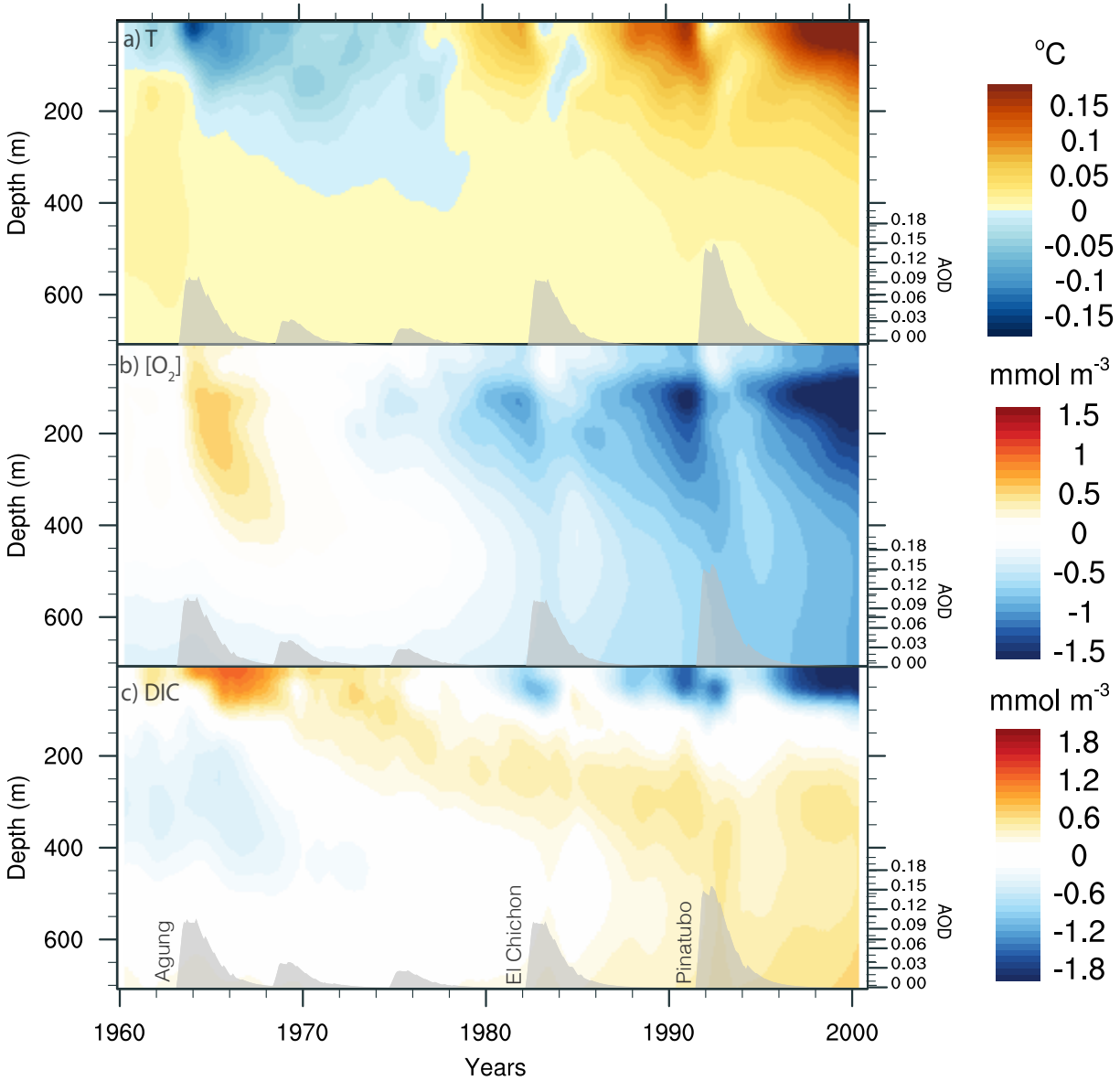
Global-mean timeseries
CESM Large Ensemble



Eddebbar et al., in prep

Imprint of volcanic eruptions on ocean biogeochemistry

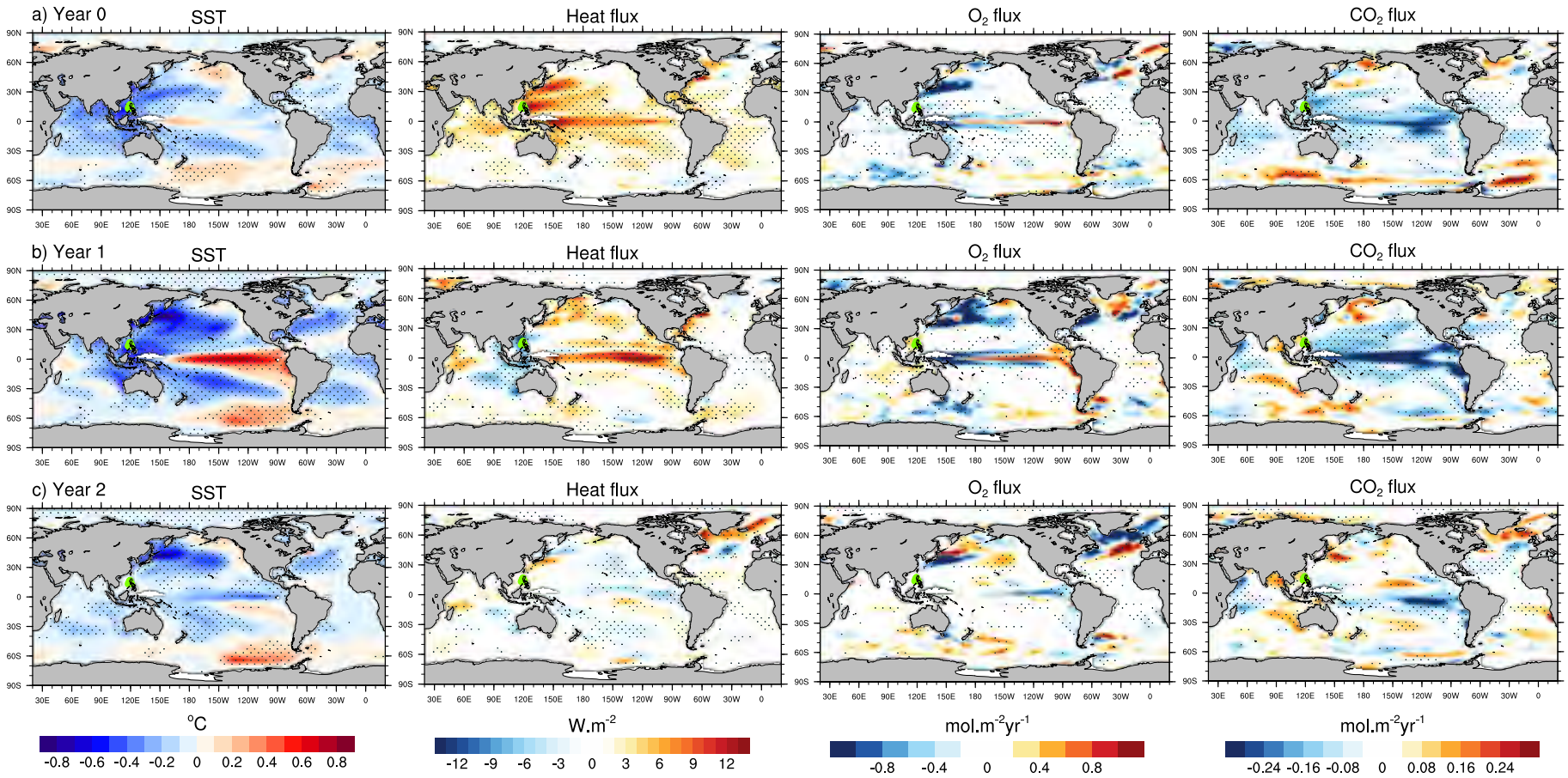
Global-mean ocean properties (CESM-LE)



Eddebbar et al., in prep

Imprint of volcanic eruptions on ocean biogeochemistry

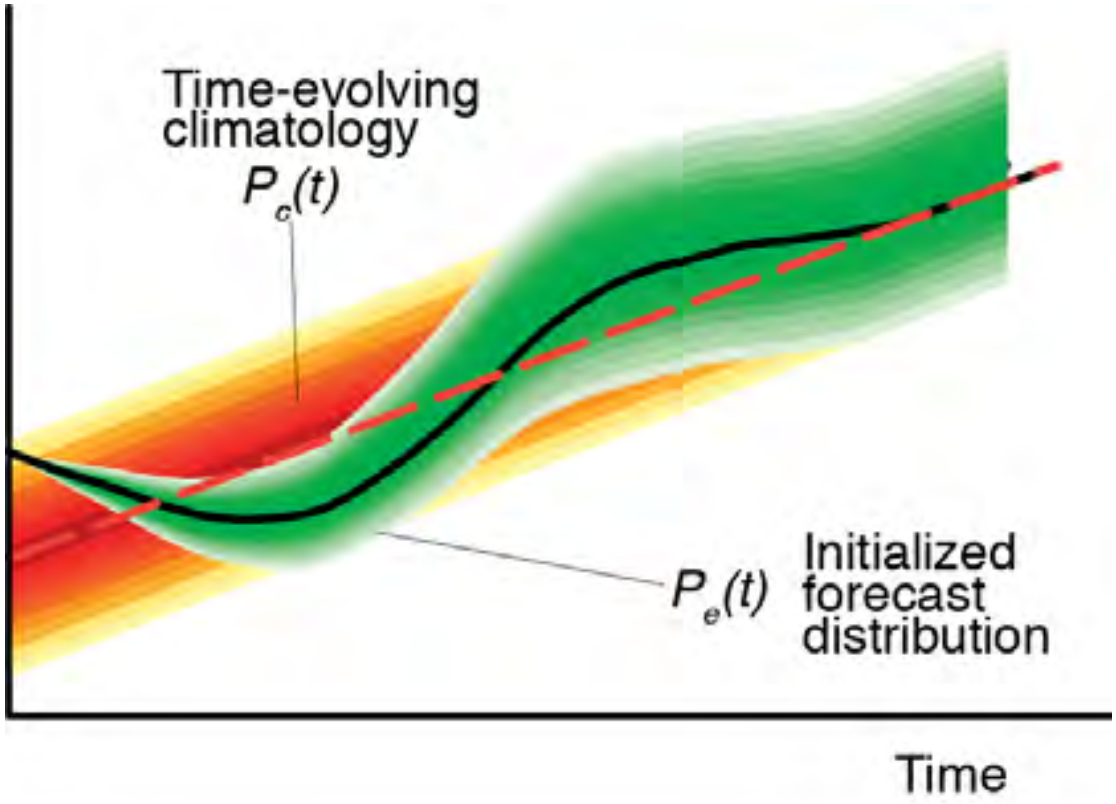
Response to Pinatubo (CESM-LE)



Eddebbar et al., in prep

Initial-Value Decadal Predictability

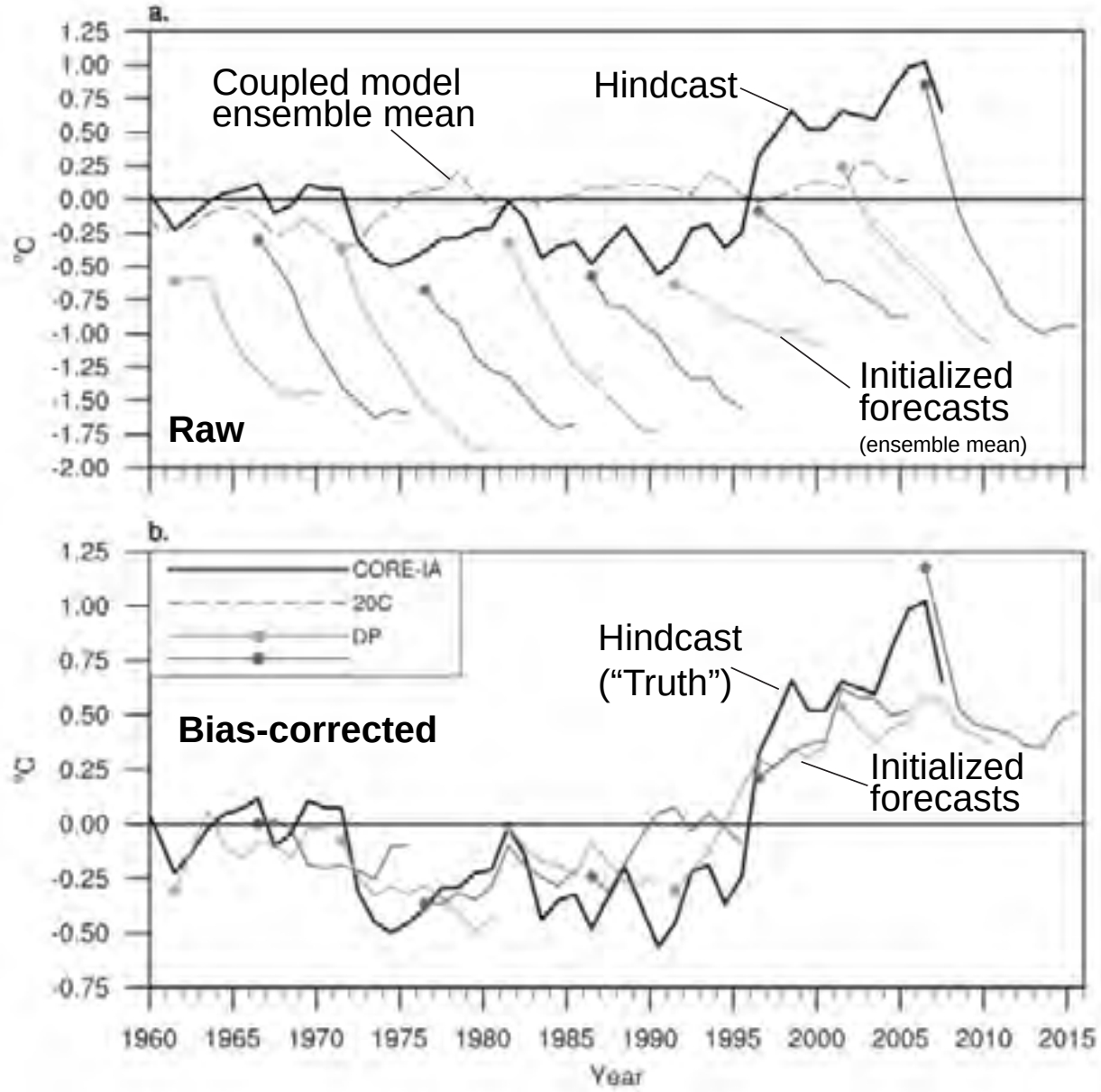
Time-evolving distributions under changing external forcing



Branstator & Teng et al. 2010

Skillful forecasts of upper ocean heat content on decadal timescale

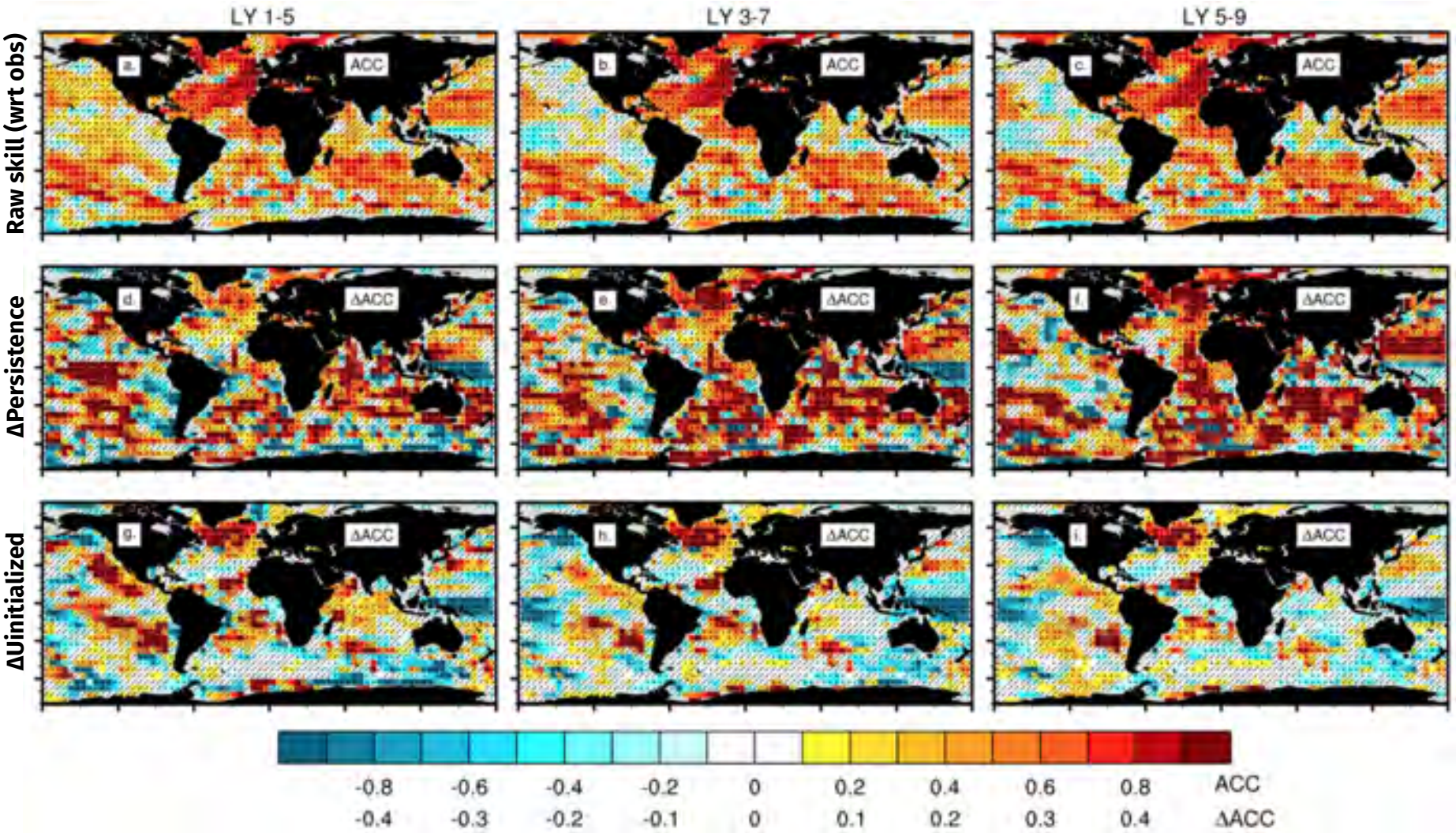
Heat content anomaly, N. Atlantic Subpolar gyre ($z > -275$ m)



Yeager et al. 2012

Predictability of annual upper ocean heat content ($z > -295$m)

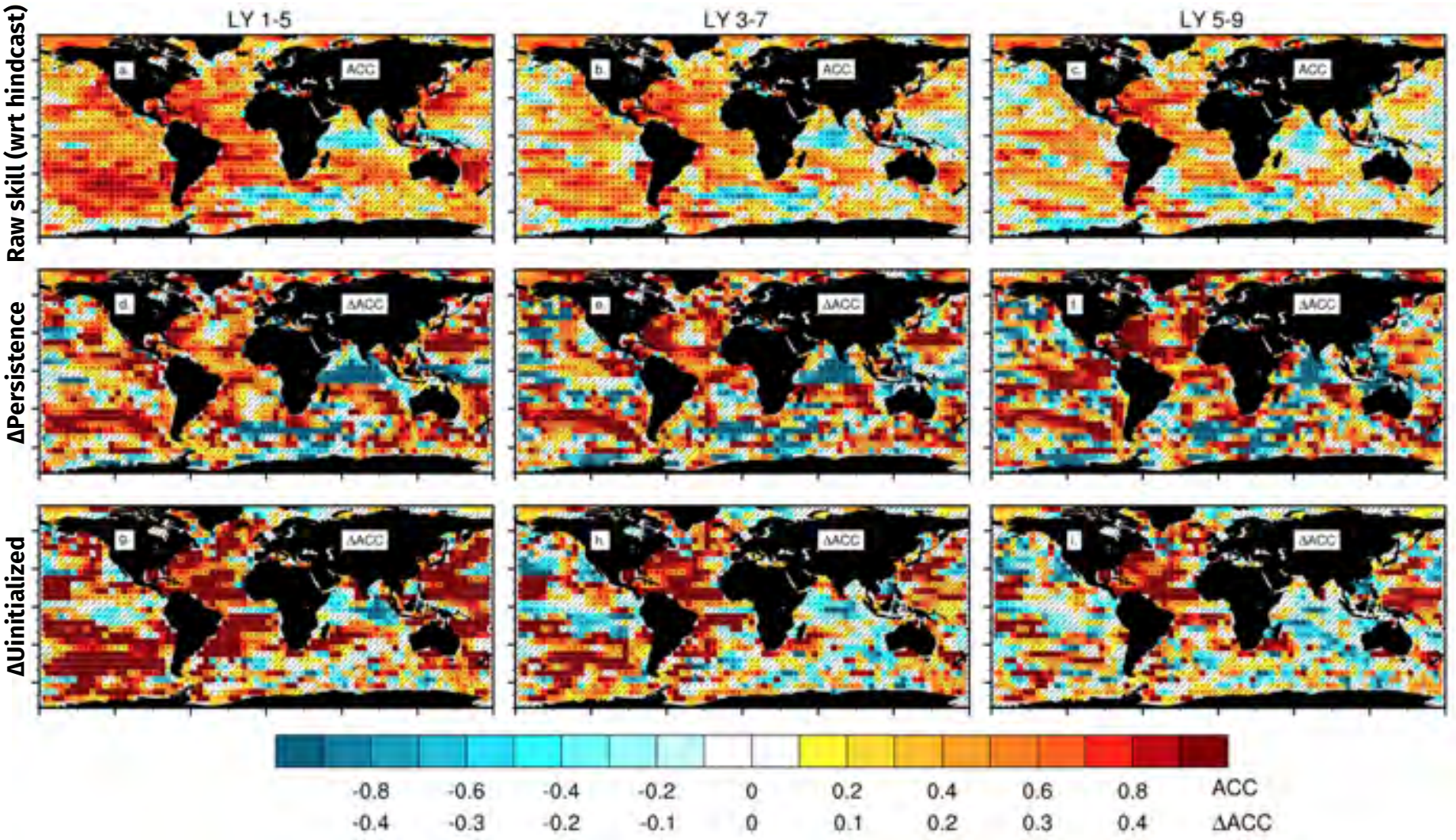
Anomaly correlation coefficient: upper ocean heat content



Yeager et al., 2018

Predictability of annual net primary productivity

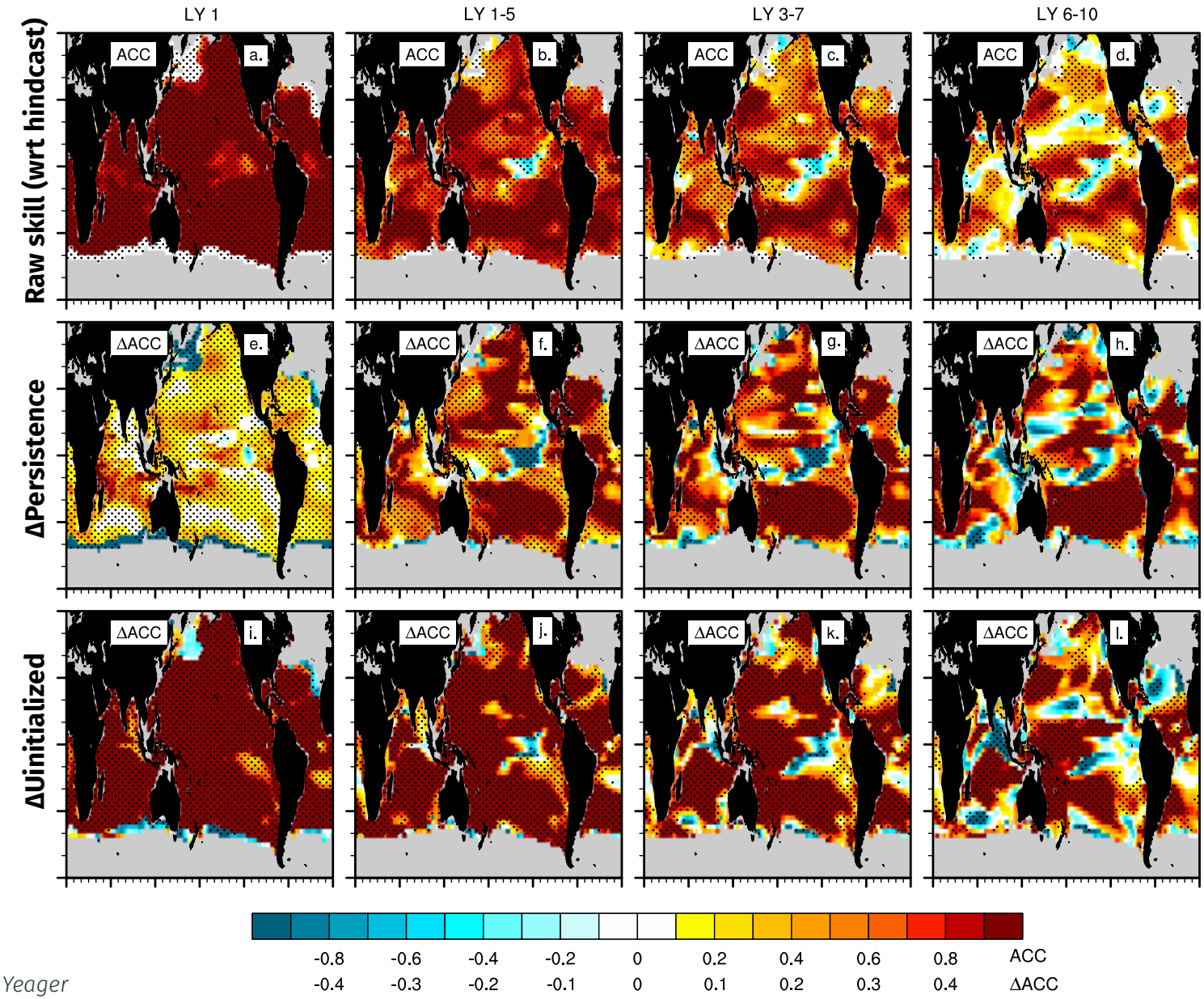
Anomaly correlation coefficient: NPP



Yeager et al., 2018

Thermocline oxygen concentrations look to be highly predictable

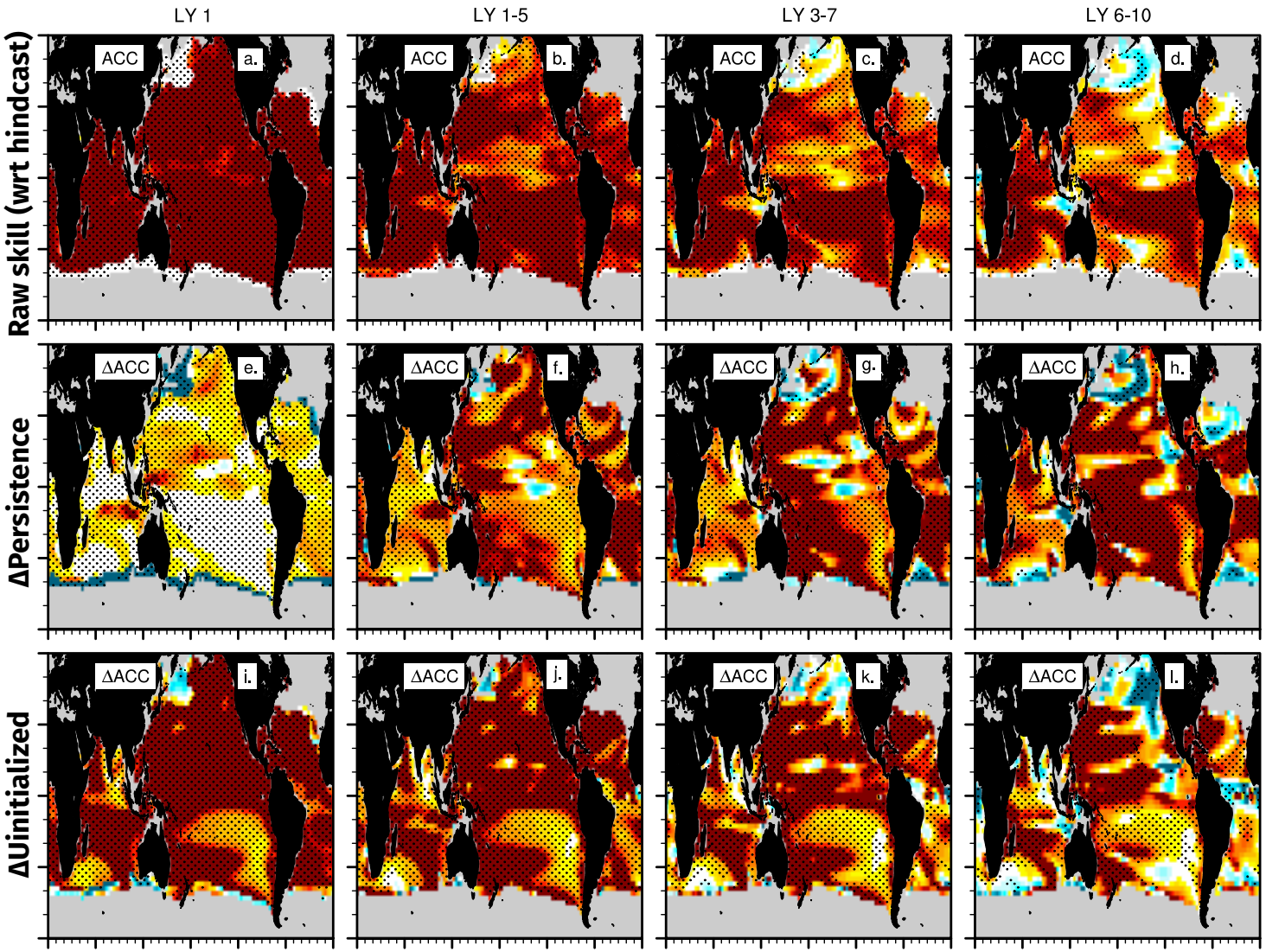
Anomaly correlation coefficient: O_2 on $\sigma_\theta = 26.5$



courtesy of S. Yeager

Thermocline oxygen concentrations look to be highly predictable

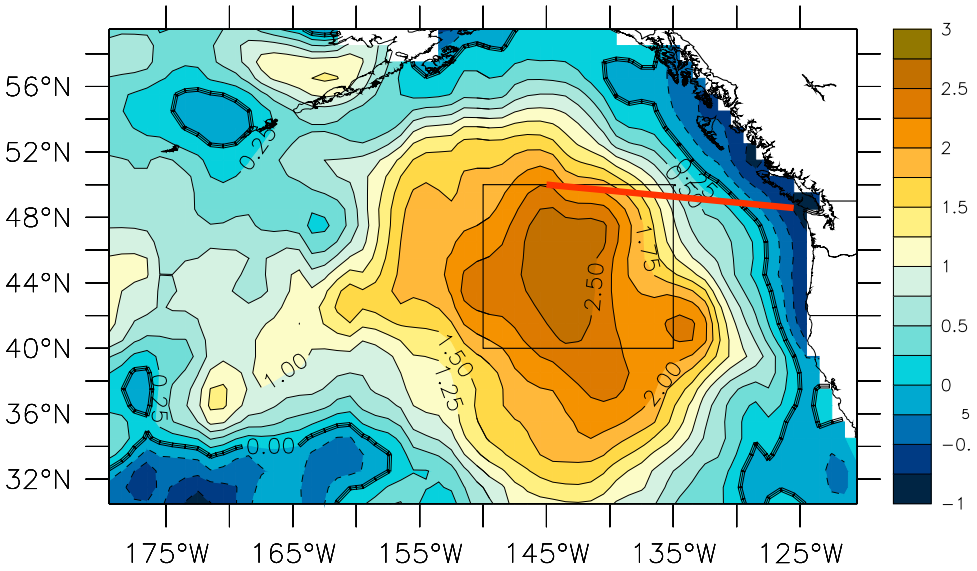
Anomaly correlation coefficient: Salinity on $\sigma_\theta = 26.5$

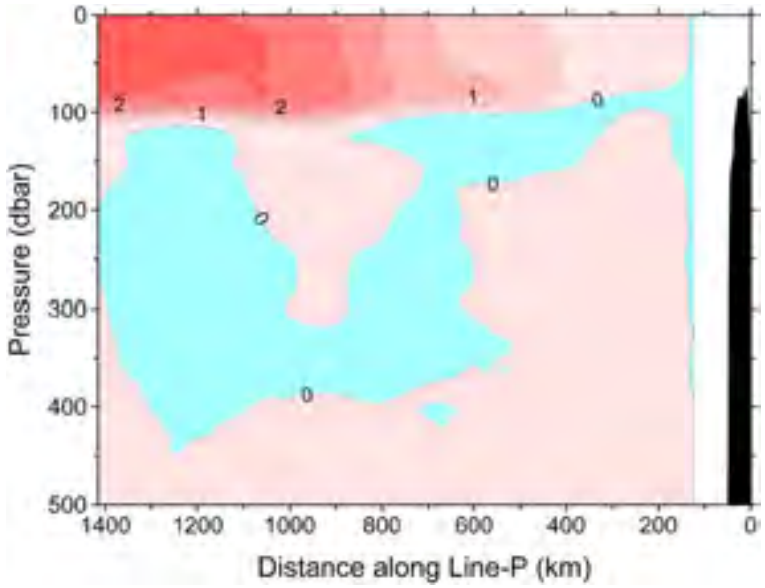


courtesy of S. Yeager

Prediction of extremes: The Blob

NE Pacific temperature anomalies, February 2014

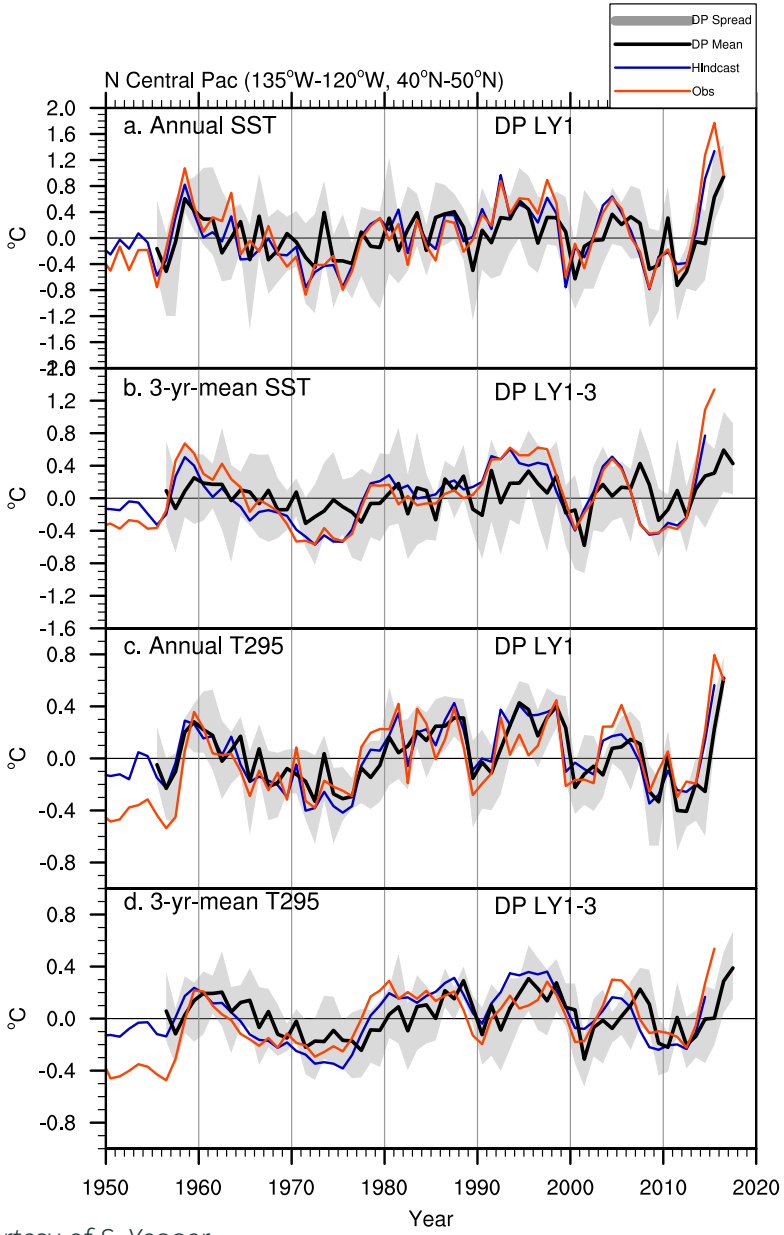




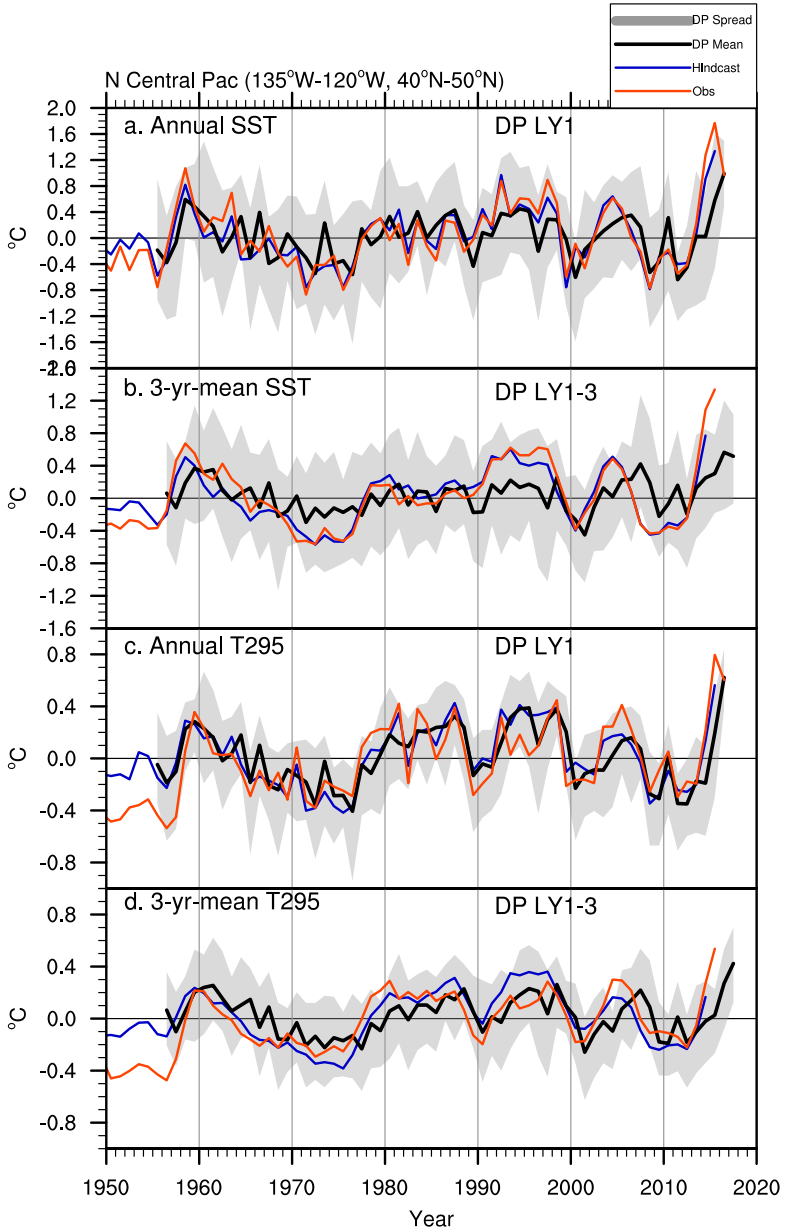
Bond et al., 2015

Prediction of extremes: The Blob (east)

10-member forecast ensemble



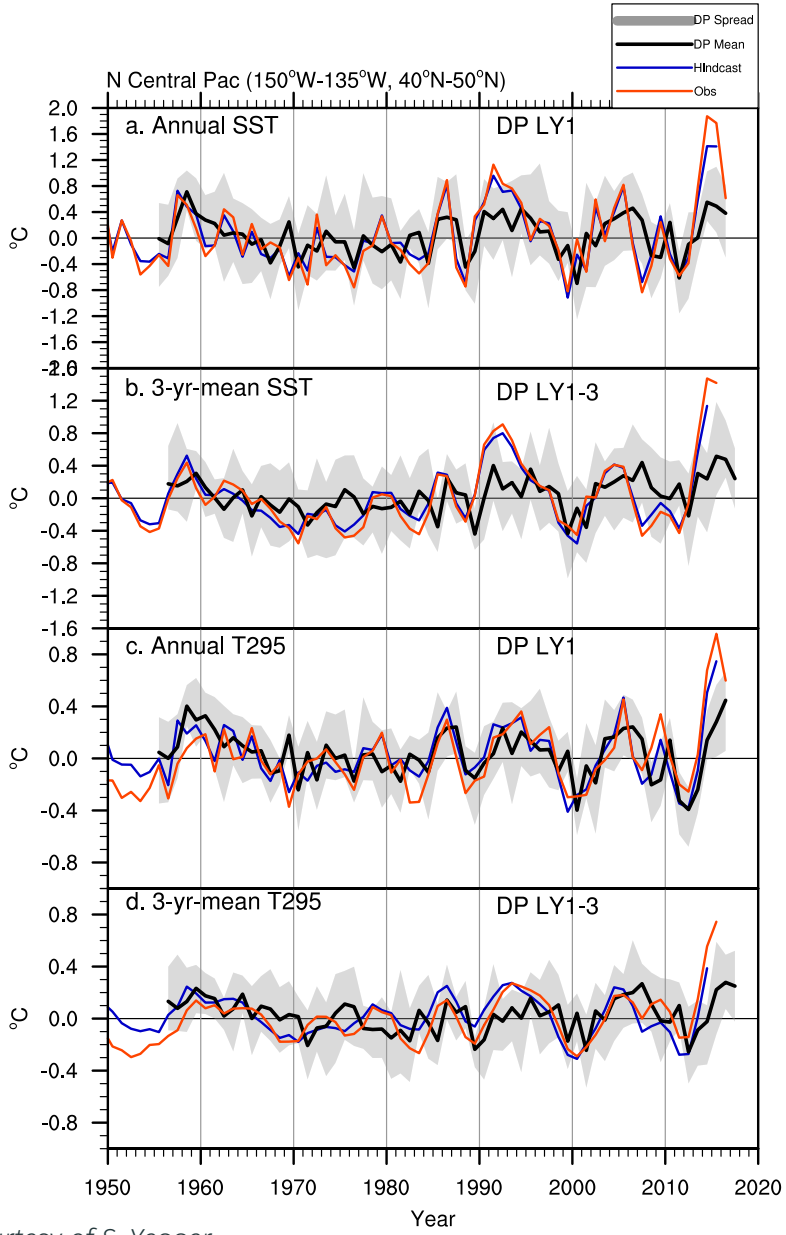
40-member forcast ensemble



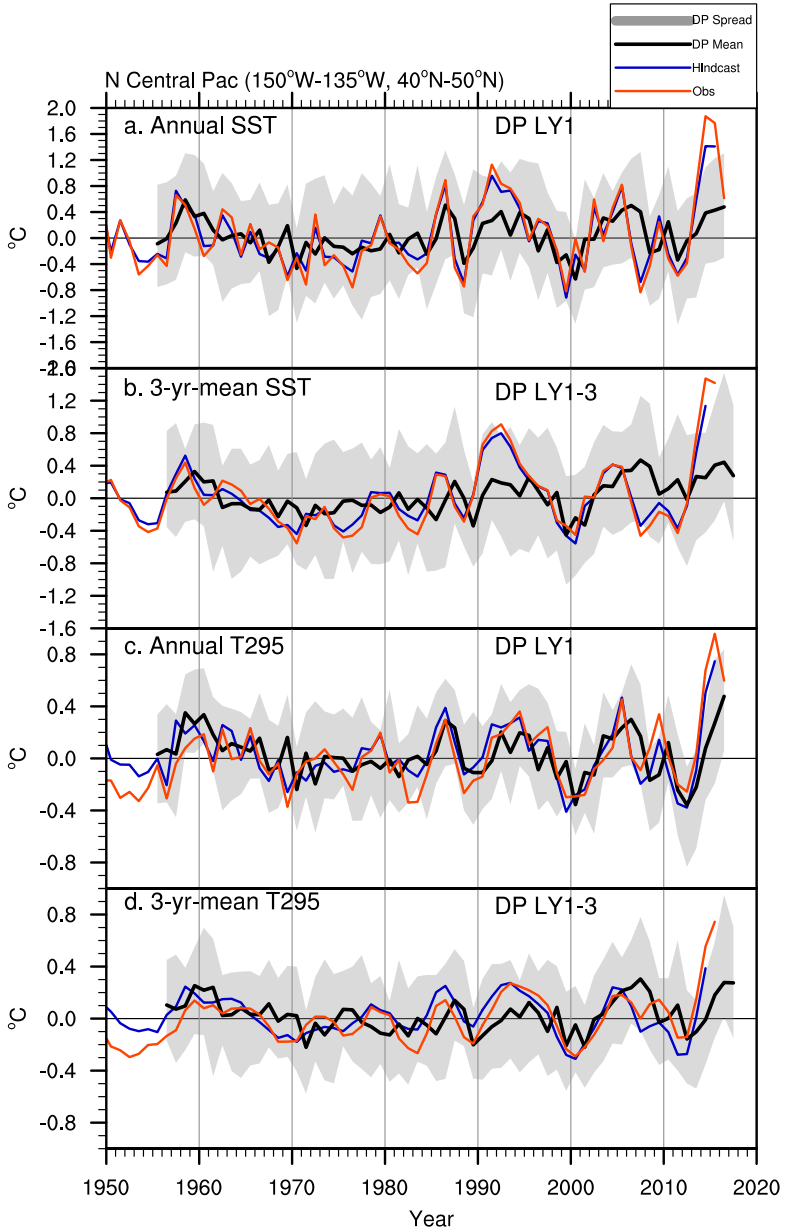
courtesy of S. Yeager

Prediction of extremes: The Blob (west)

10-member forecast ensemble



40-member forcast ensemble



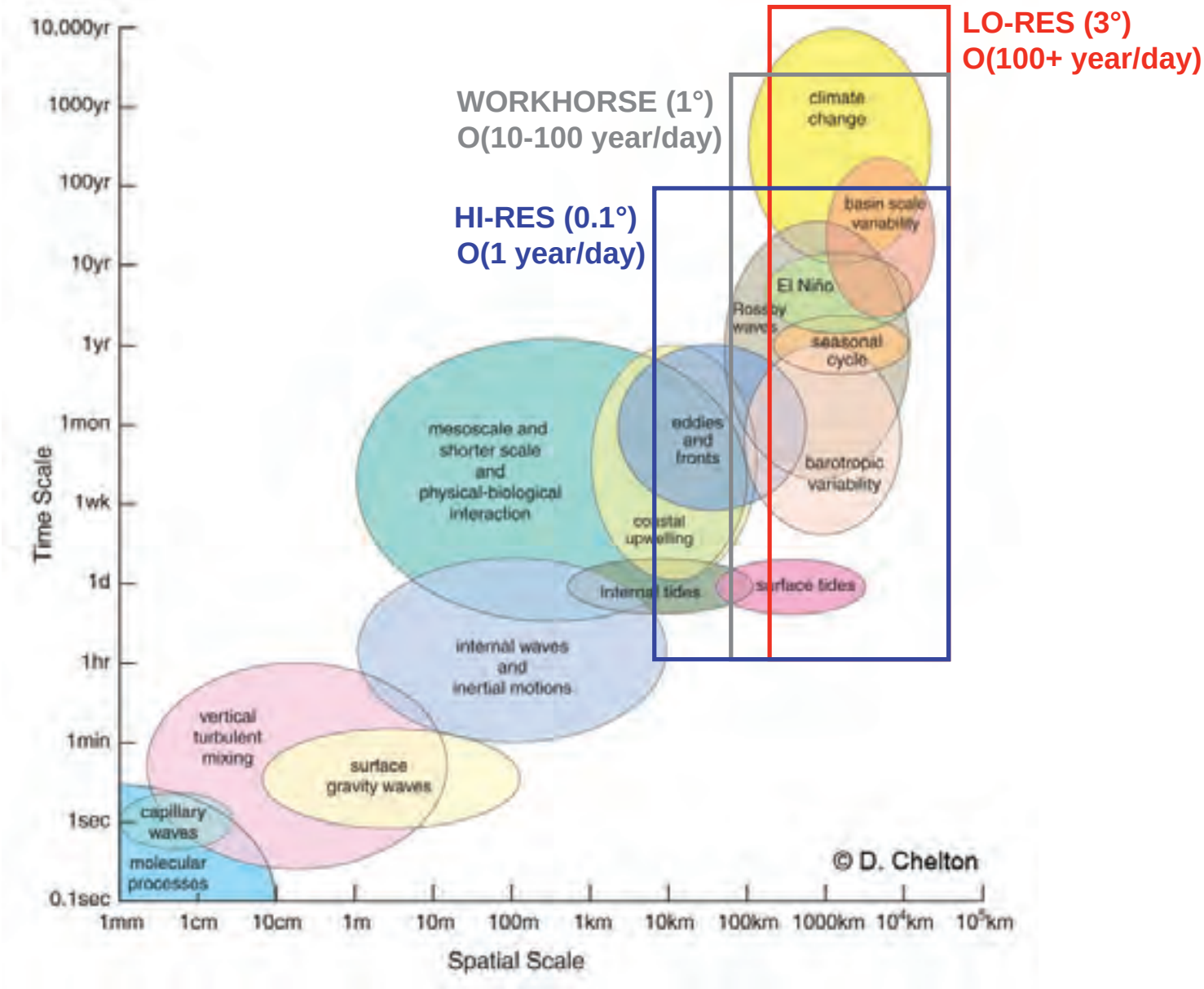
courtesy of S. Yeager

Summary and outlook

- ESMs provide a powerful tool for understanding ecosystem dynamics in the context of climate variability and change.
- Emerging capabilities for initialized prediction offer the potential to provide actionable information.
- Model skill remains a challenge: how to move forward?

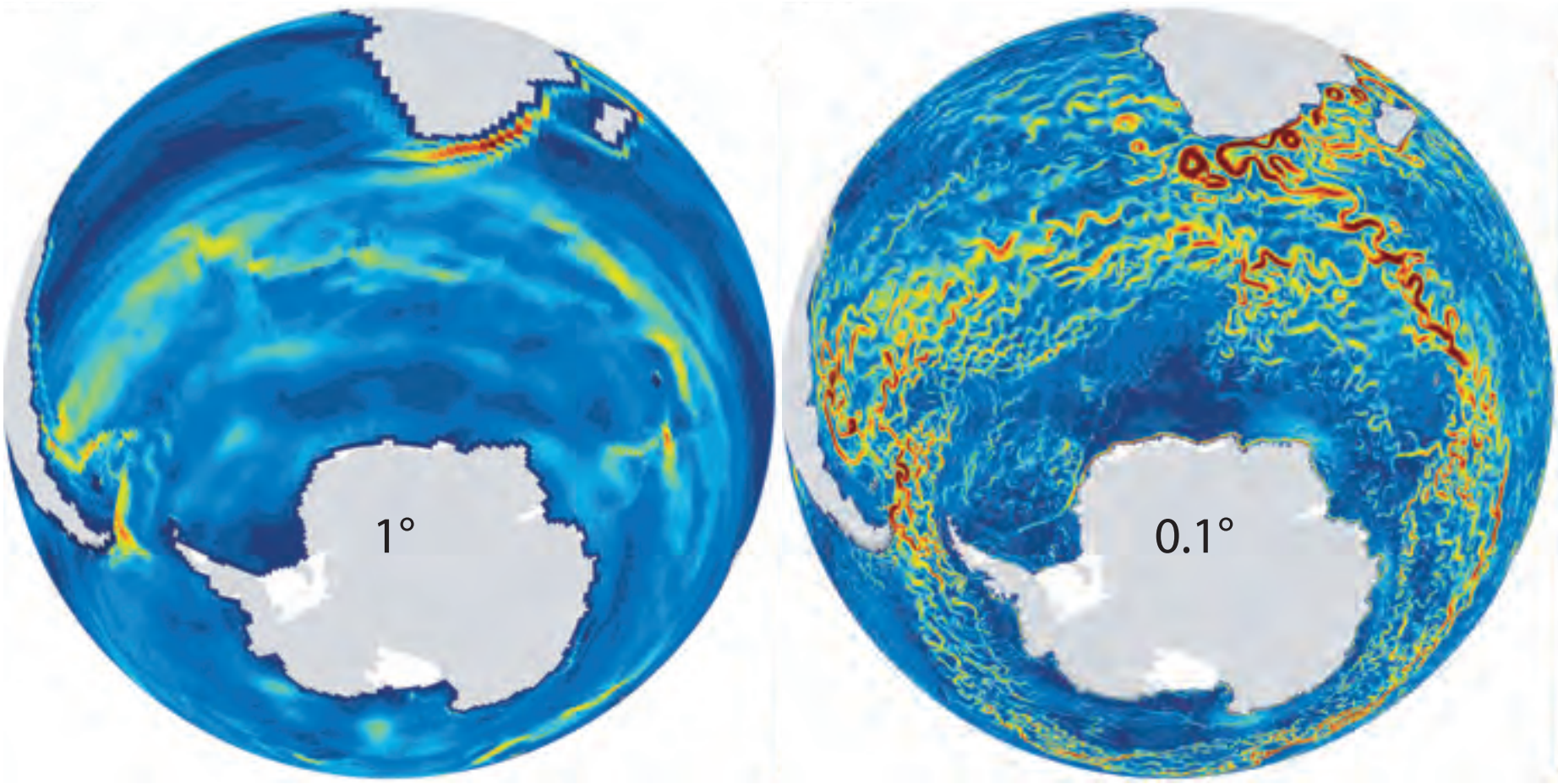
Earth system models: horizontal resolution

Approximate time & space scales of ocean variability



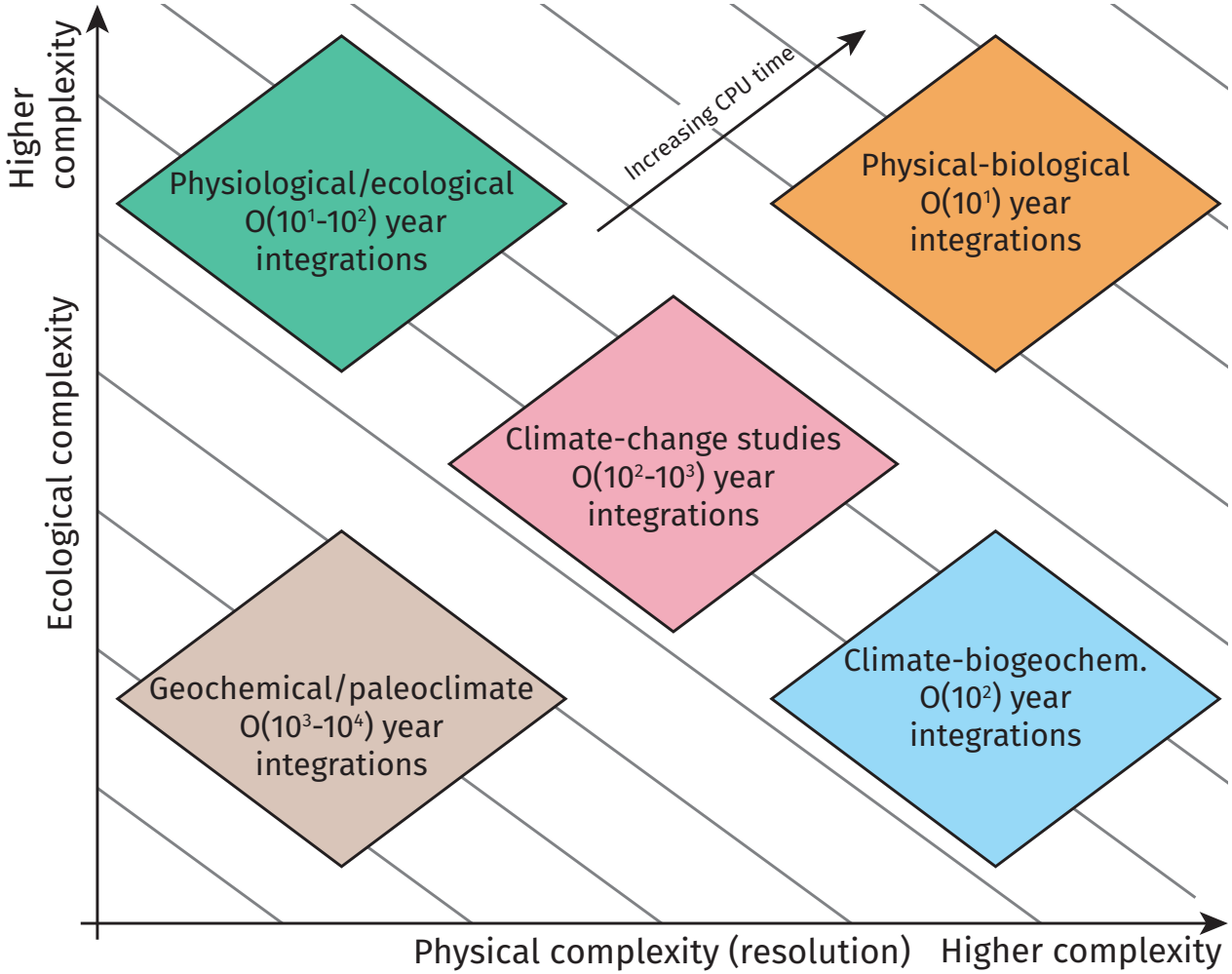
Earth system models: horizontal resolution

Surface kinetic energy



Model complexity is constrained by computational cost

Schematic computational landscape: Ecological v. physical complexity

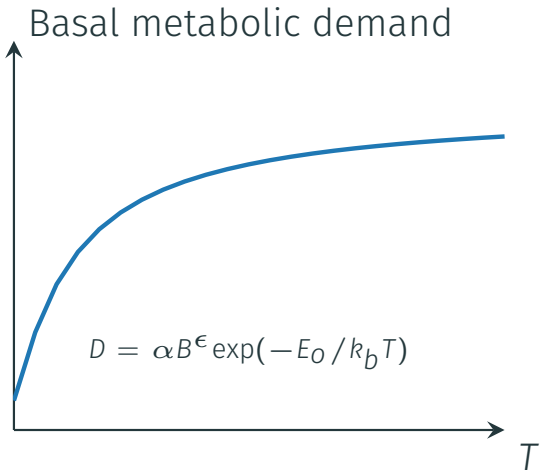


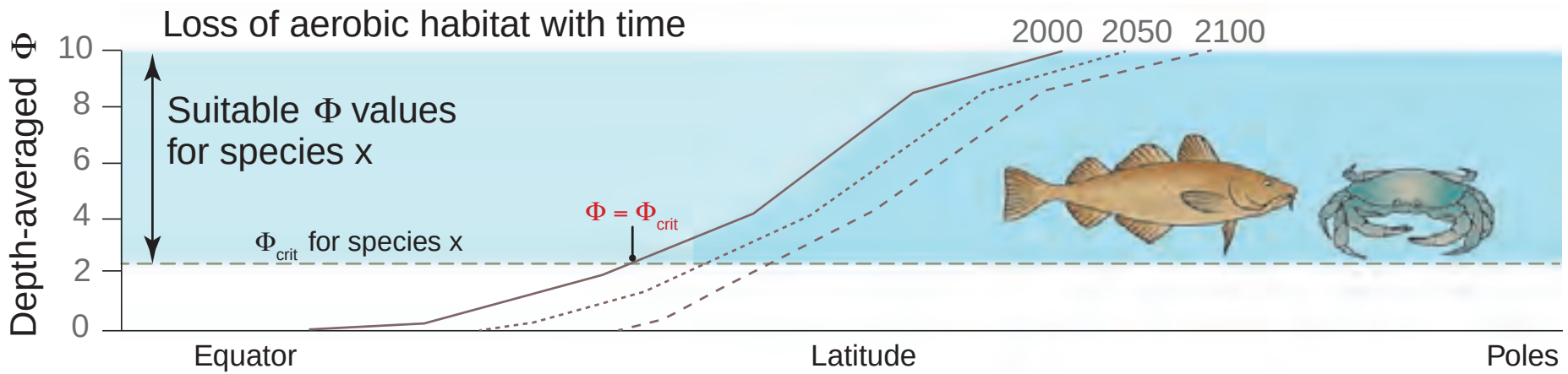
An ecophysiological framework to project habitat change

O_2 and temperature together constrain habitat

$$\Phi = \frac{\text{Oxygen supply}}{\text{Metabolic demand}} = \frac{[O_2]_{seawater}}{f(T, \text{physiology})}$$

Deutsch et al. 2015

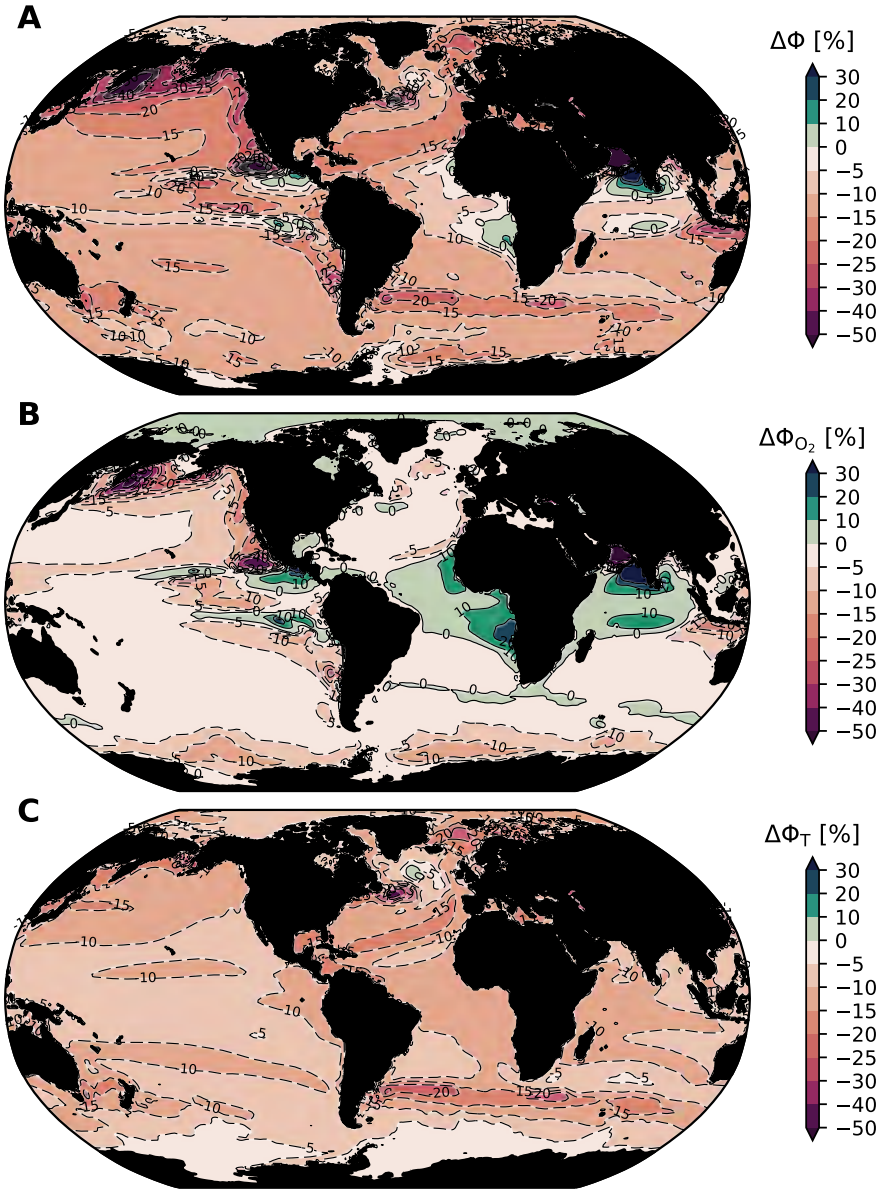




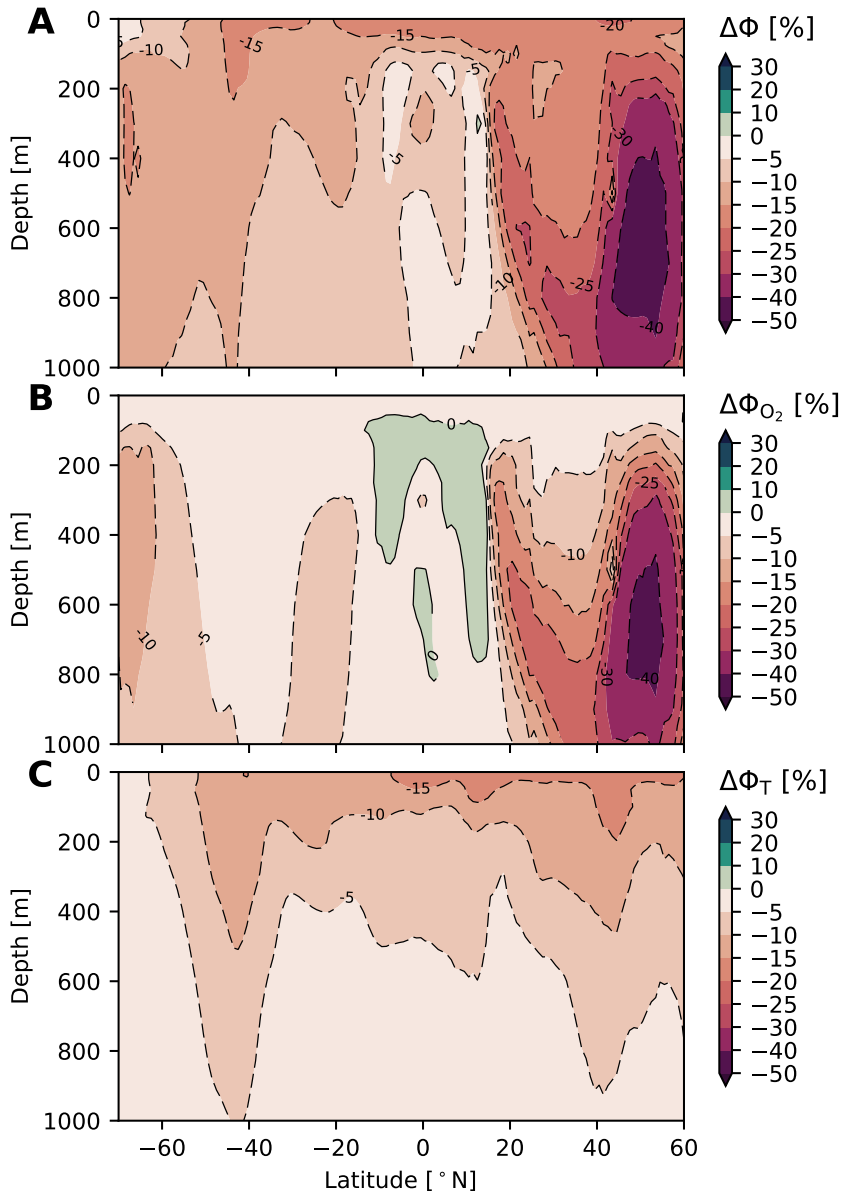
Kleypas 2015

Relative change in the metabolic index (bias-corrected CMIP5-mean)

Upper 400 m mean

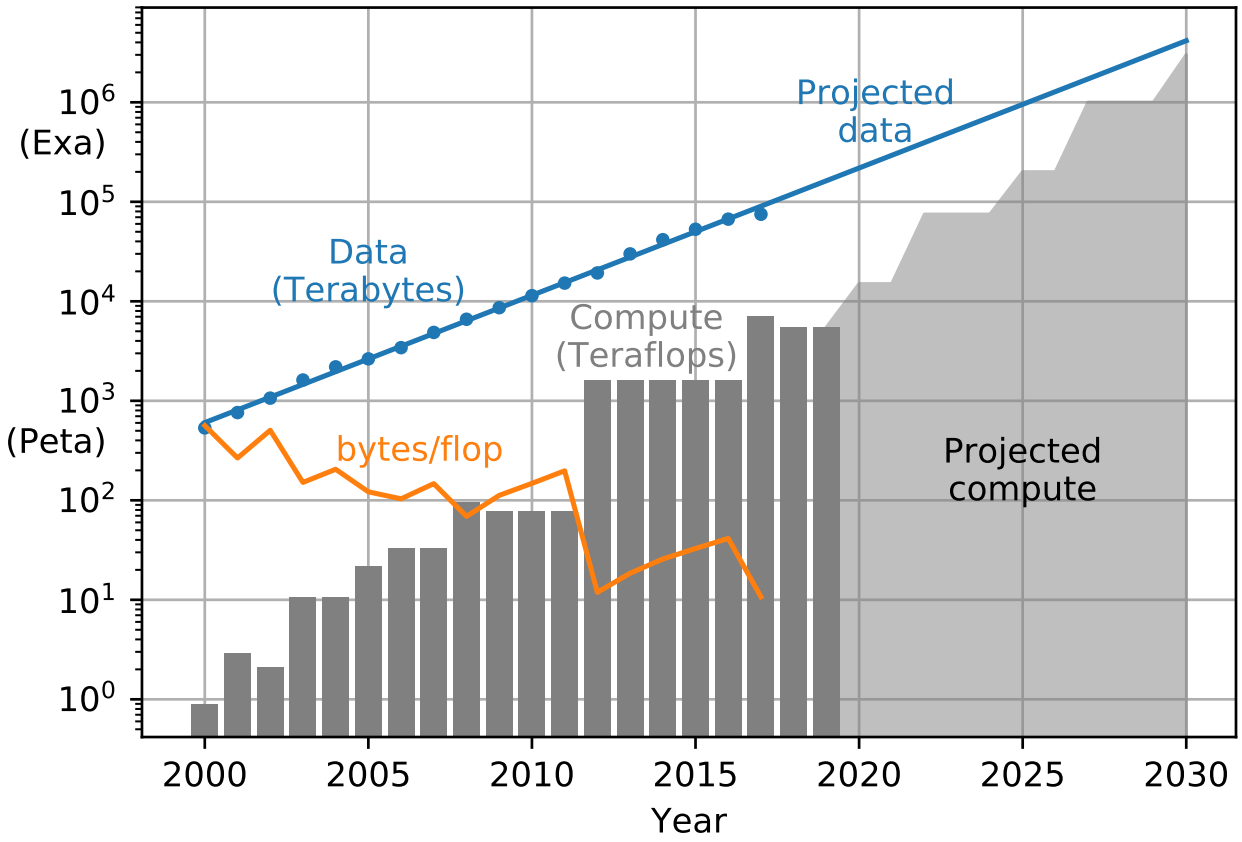


Global zonal mean



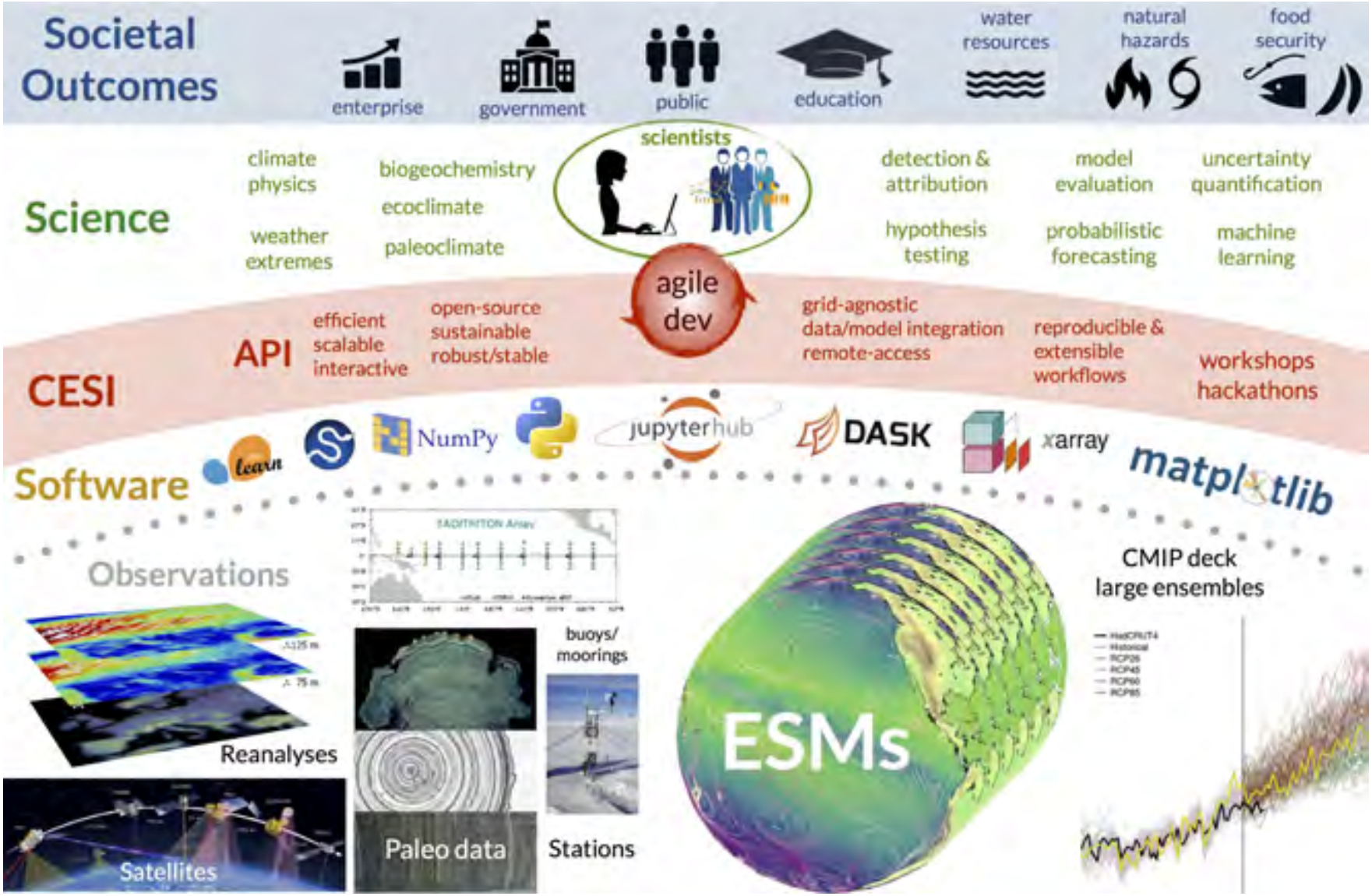
Computing landscape: Growth in computing power outpaces storage

Data storage and computing capacity at NCAR



data courtesy Gary Strand

Community Earth System Informatics (CESI)



with J. Emile-Geay

NCAR/CISL CMIP Analysis platform

- CMIP6 archive will ultimately comprise 20–300 petabytes (PB) of data from models from more than 20 modeling groups.
- CMIP Analysis Platform (CMIP-AP) will host a 10 PB “lending-library” of CMIP6 data on a high performance computing (HPC) resource.
- Opportunities for coordinated analysis?

https://www2.cisl.ucar.edu/resources/cmip-analysis-platform

Does CMIP meet marine science needs?

WCRP

GRAND CHALLENGES

Acknowledgements

Eddebbar, Y., K. Rodgers, M. C. Long, A. Subramanian, S.-P. Xie, and R. Keeling (2018), El Niño-like physical and biogeochemical ocean response to tropical eruptions, *J. Climate*, *in prep*.

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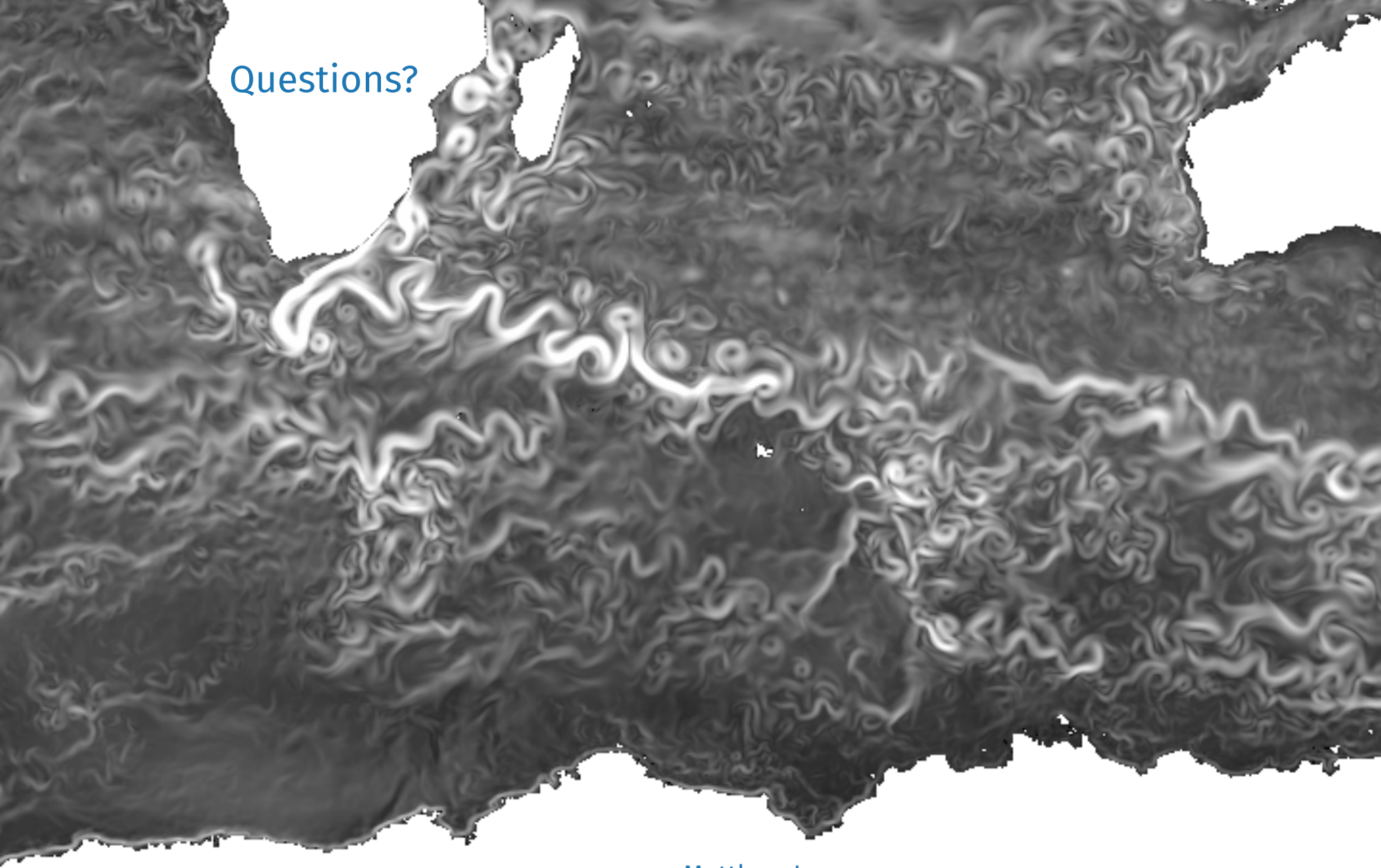
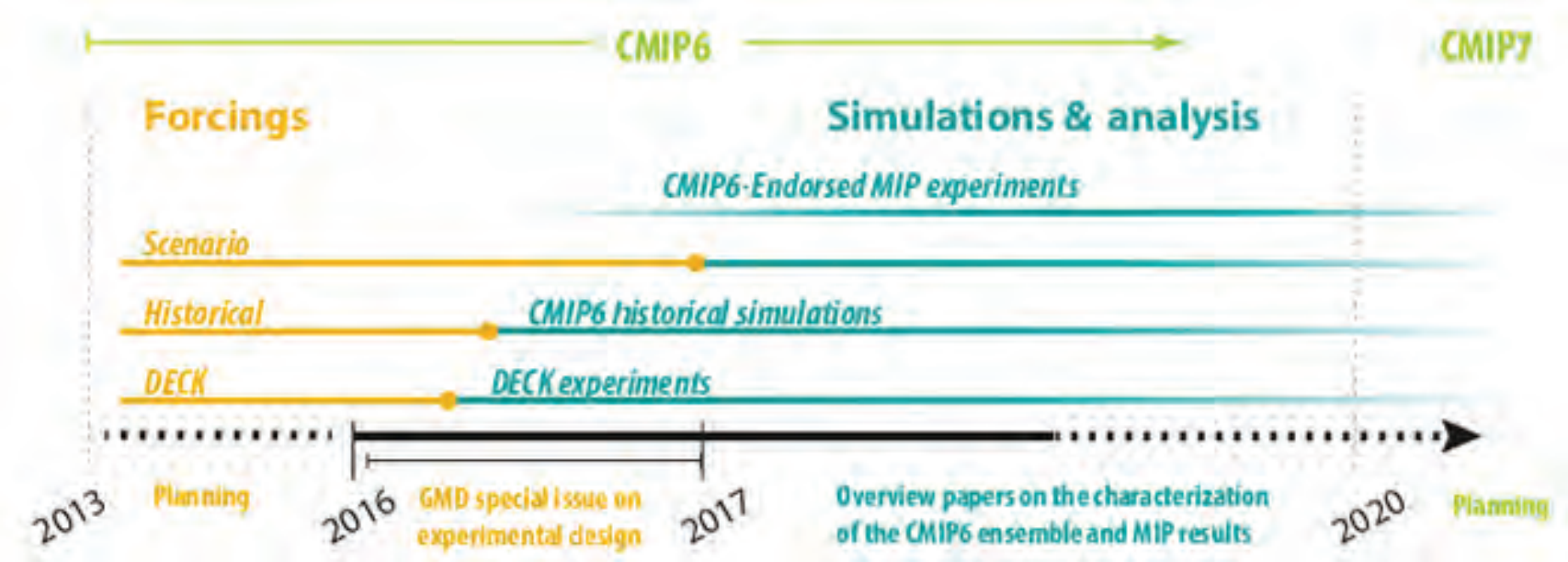
Questions?



Matthew Long
Climate & Global Dynamics Laboratory
National Center for Atmospheric Research
mclong@ucar.edu

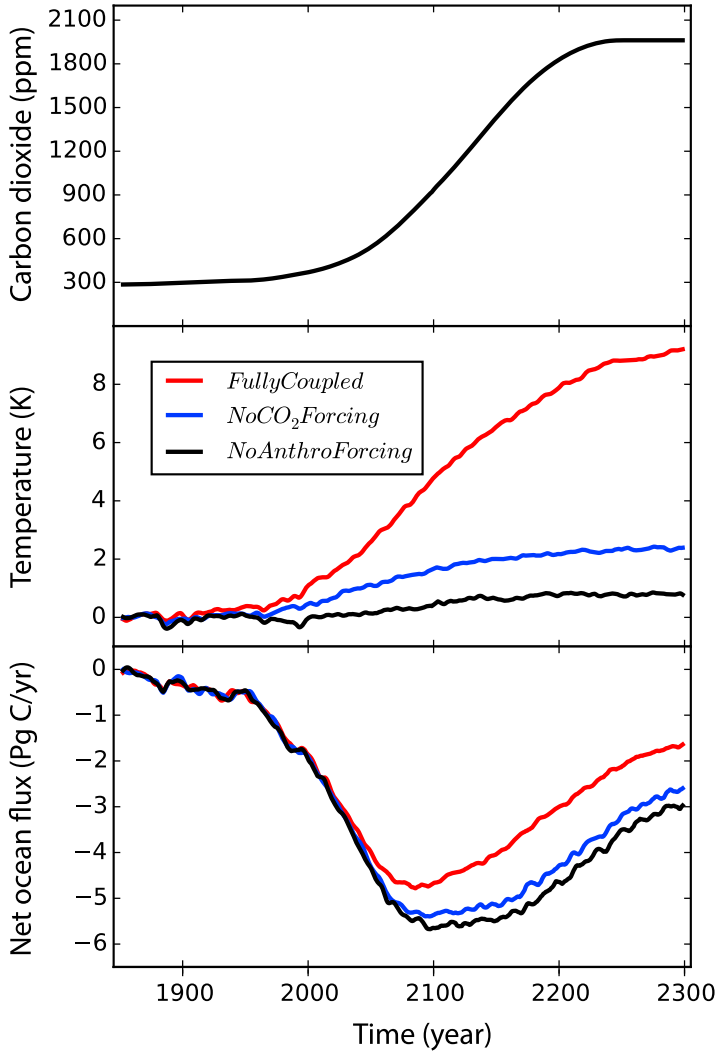
CMIP6 Timeline



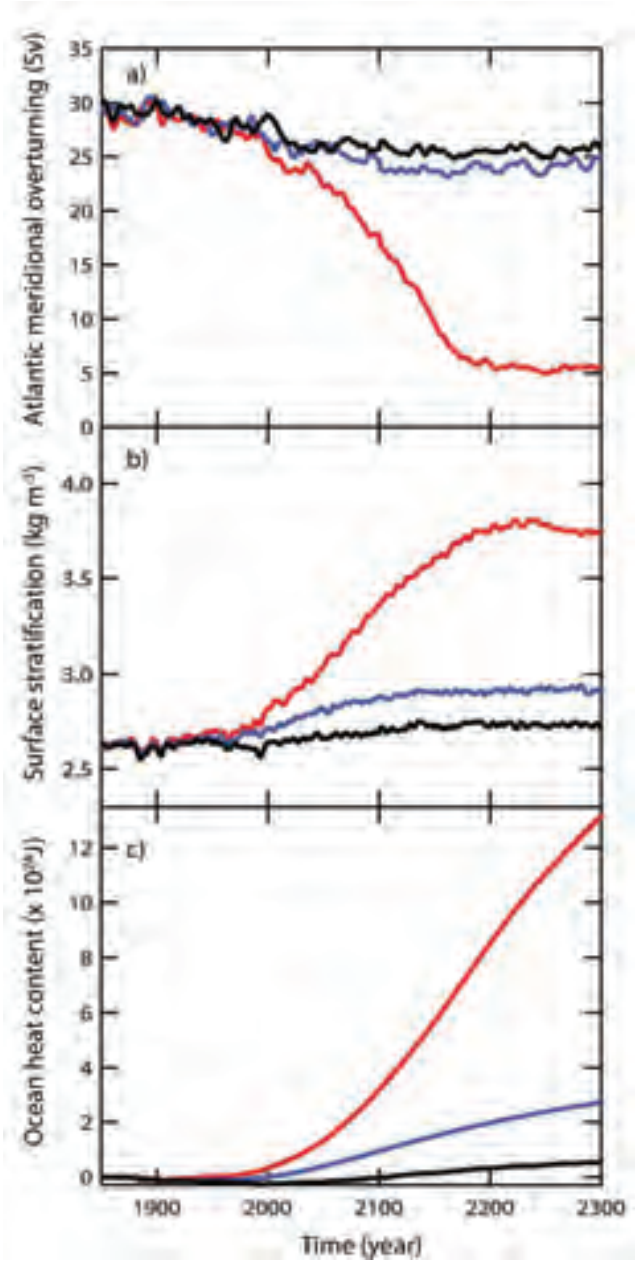
Eyring et al. 2016

ECP8.5: Feedbacks grow as warming continues

ECP8.5 forcing and CO_2 flux



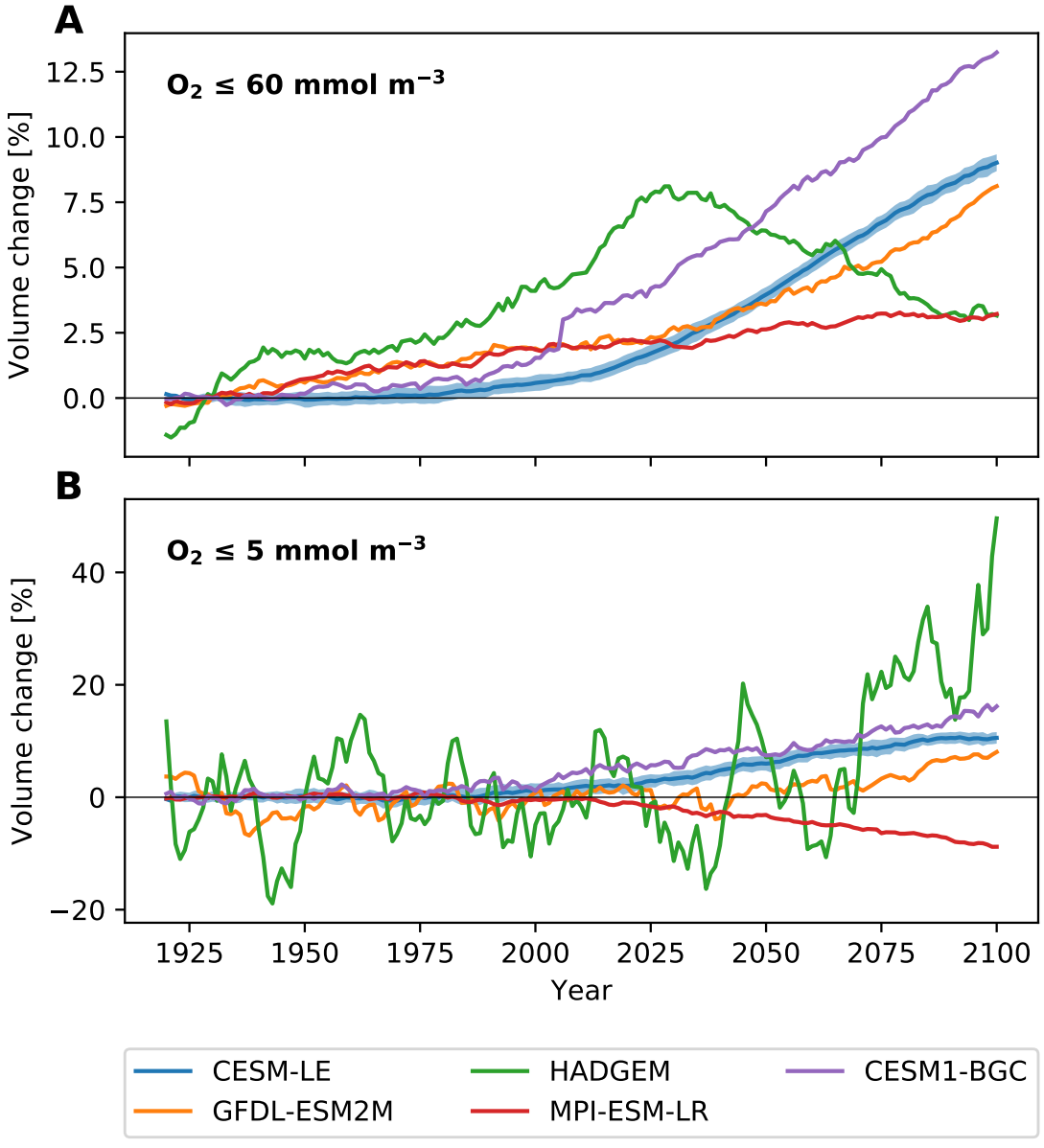
Ocean physical response



Randerson et al. 2015

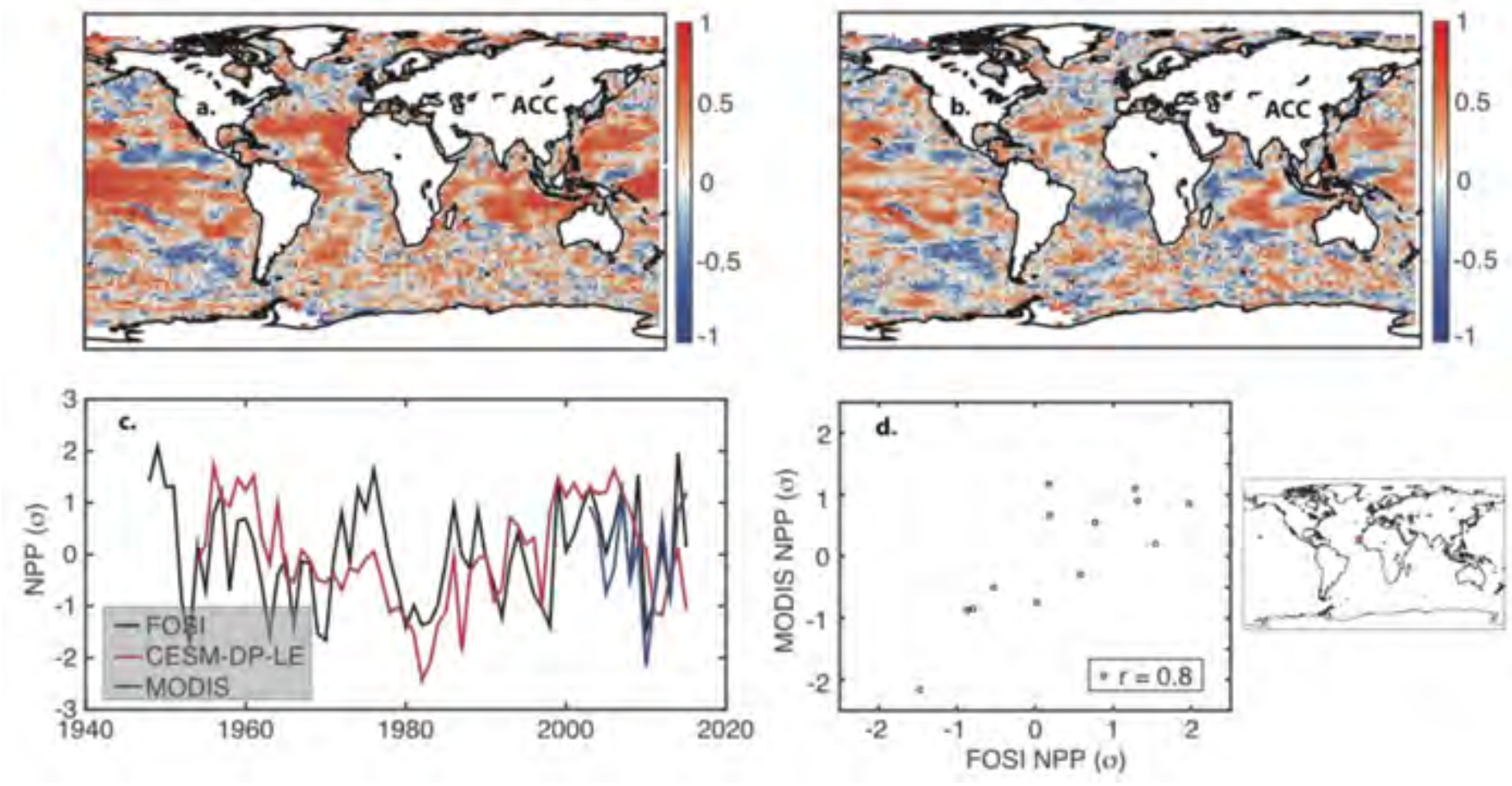
Suboxic and hypoxic volumes projected to increase

Simulated change in oxygen deficient zones



Predictability of annual net primary productivity

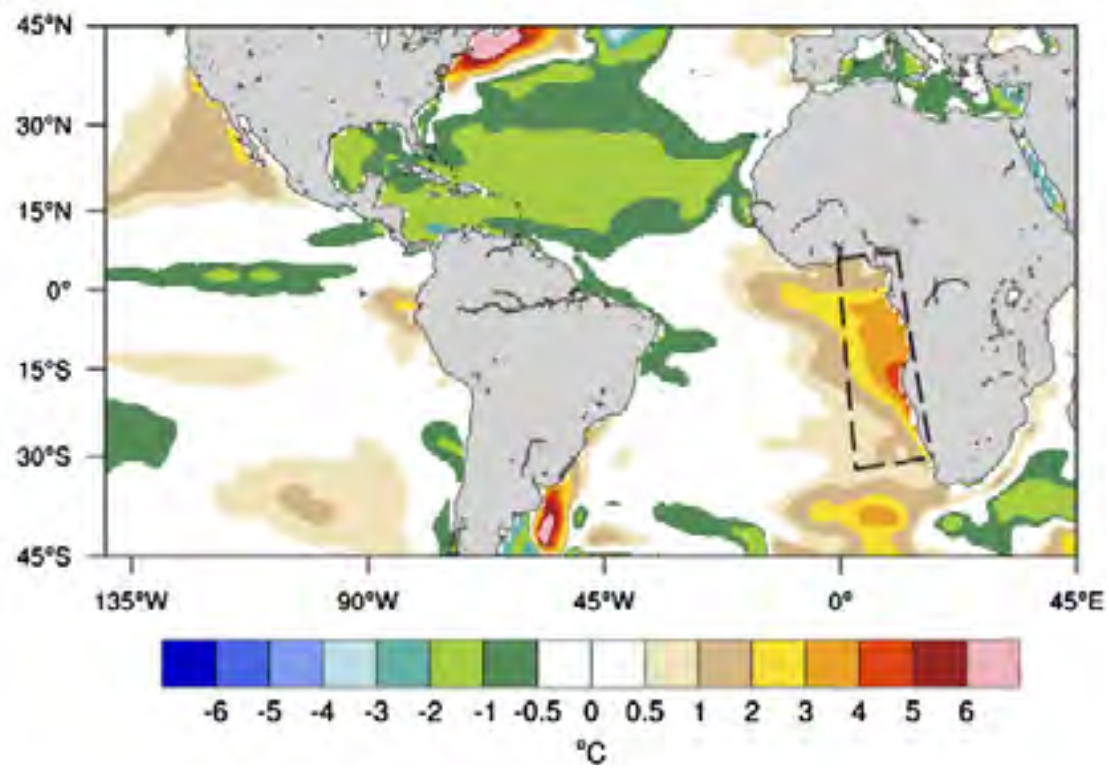
NPP prediction skill relative to MODIS-based estimates



Yeager et al., 2018

Earth system models: horizontal resolution

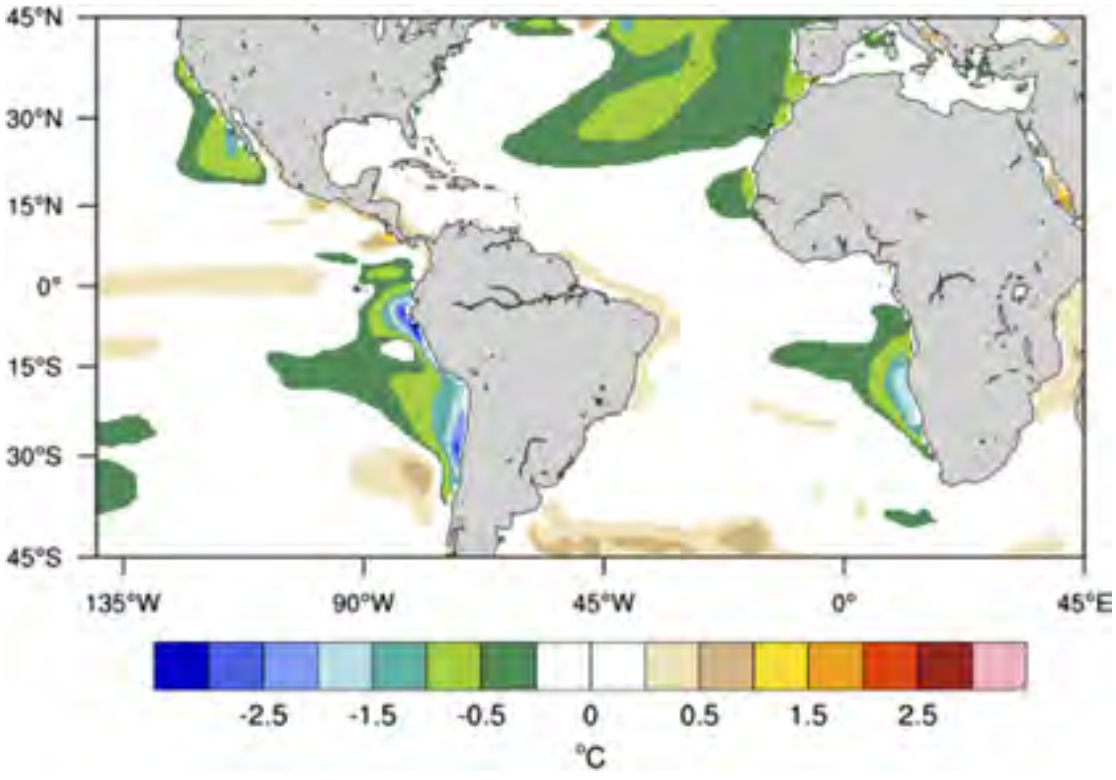
SST biases in CCSM4 with 0.5° atmosphere model



Small et al., 2015

Earth system models: horizontal resolution

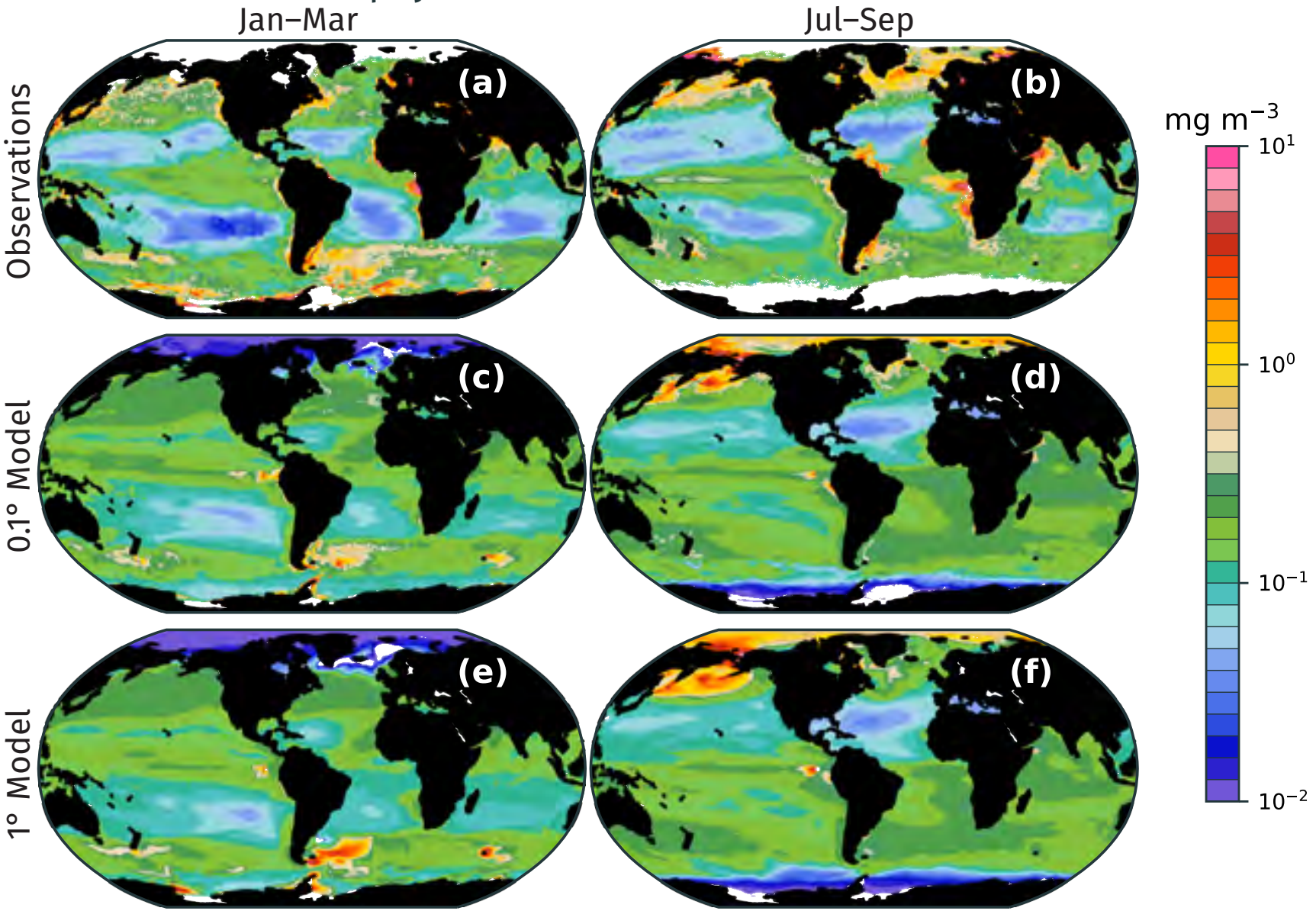
SST difference due to changing atmospheric resolution: 0.5° – 1°



Small et al., 2015

Earth system models: horizontal resolution

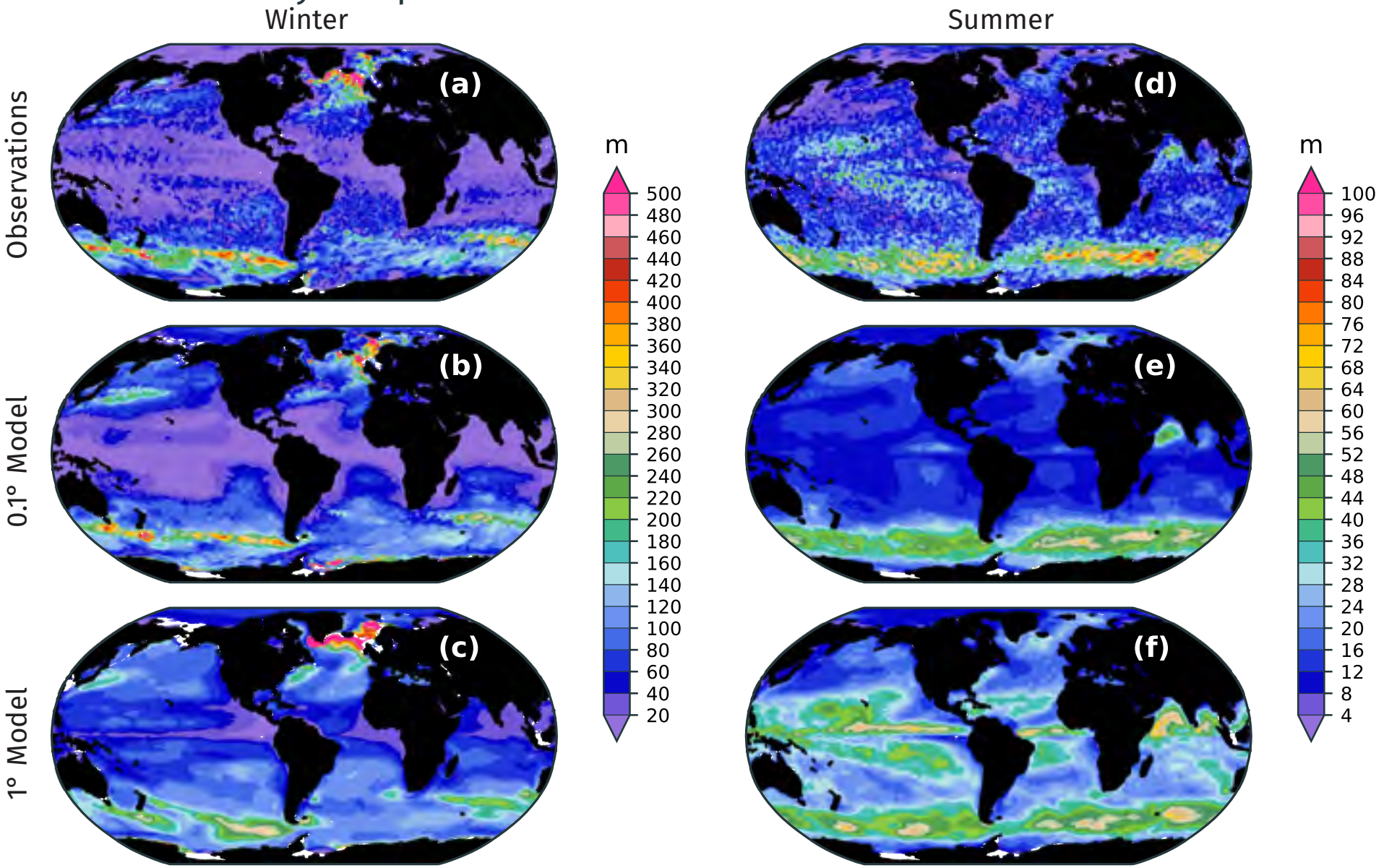
Seasonal surface chlorophyll distributions



Harrison et al., 2018

Earth system models: horizontal resolution

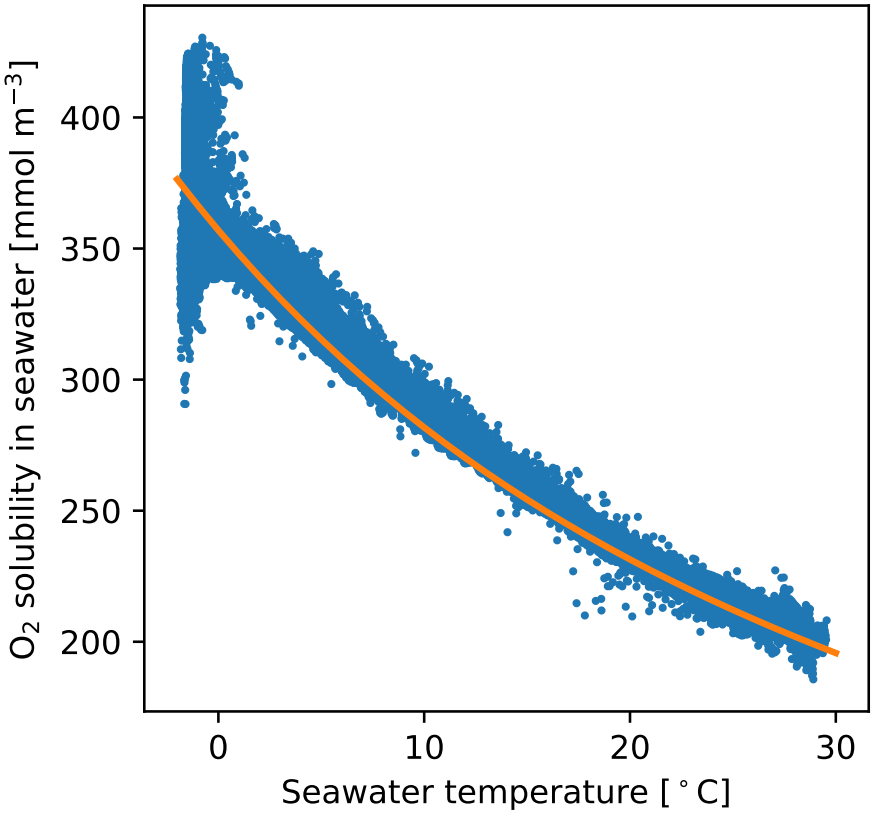
Seasonal mixed layer depths



Harrison et al., 2018

Understanding deoxygenation: Some definitions

Surface ocean O_2 and solubility

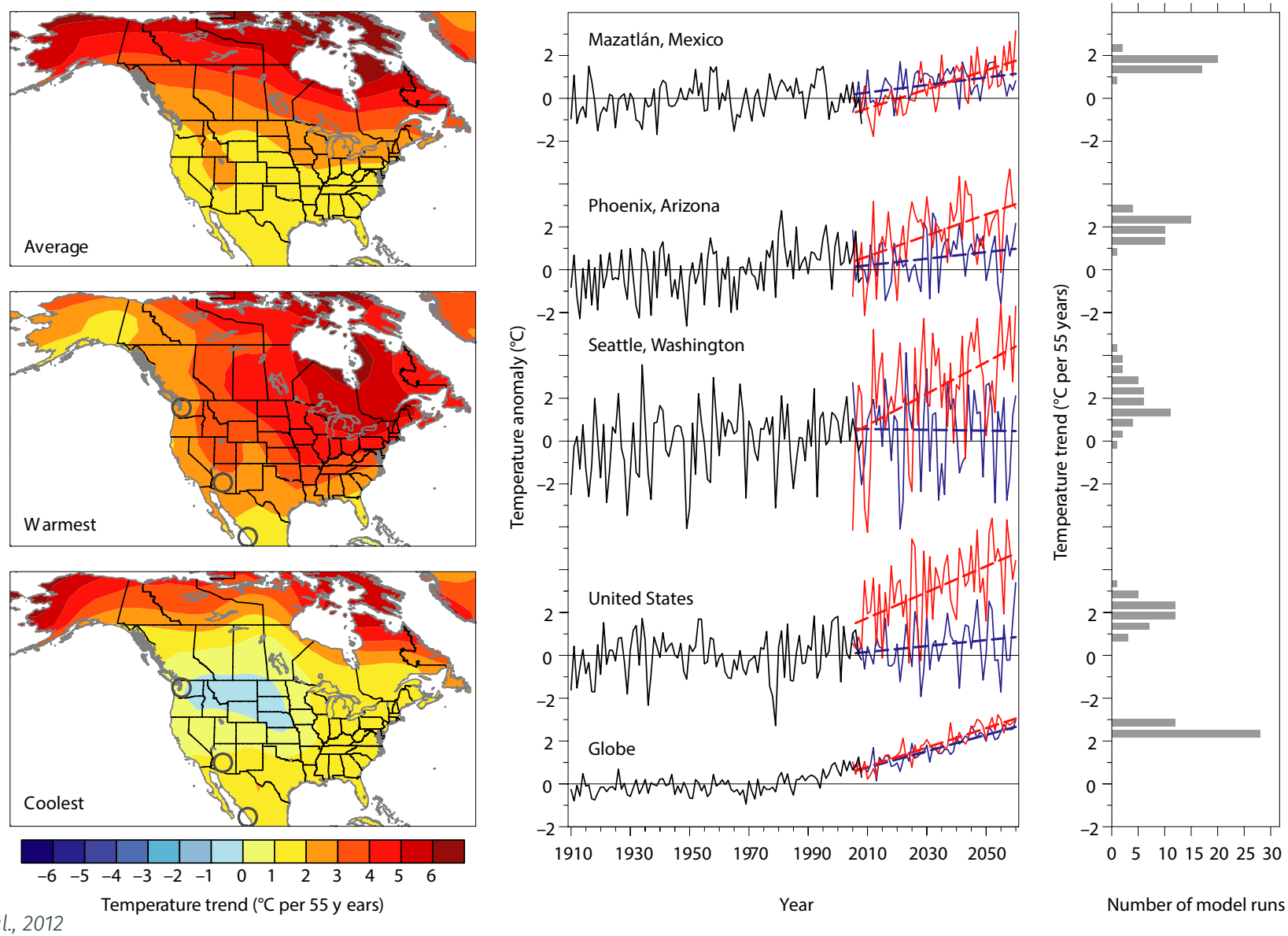


- Surface O_2 remains near saturation due to gas exchange and photosynthesis;
- O_2 is consumed at depth by respiration at the **Oxygen Utilization Rate** (*OUR*);
- Cumulative respiration can be estimated by **Apparent Oxygen Utilization** (*AOU*):

$$AOU = O_2^{sat} - O_2$$

Earth system models: internally generated variability

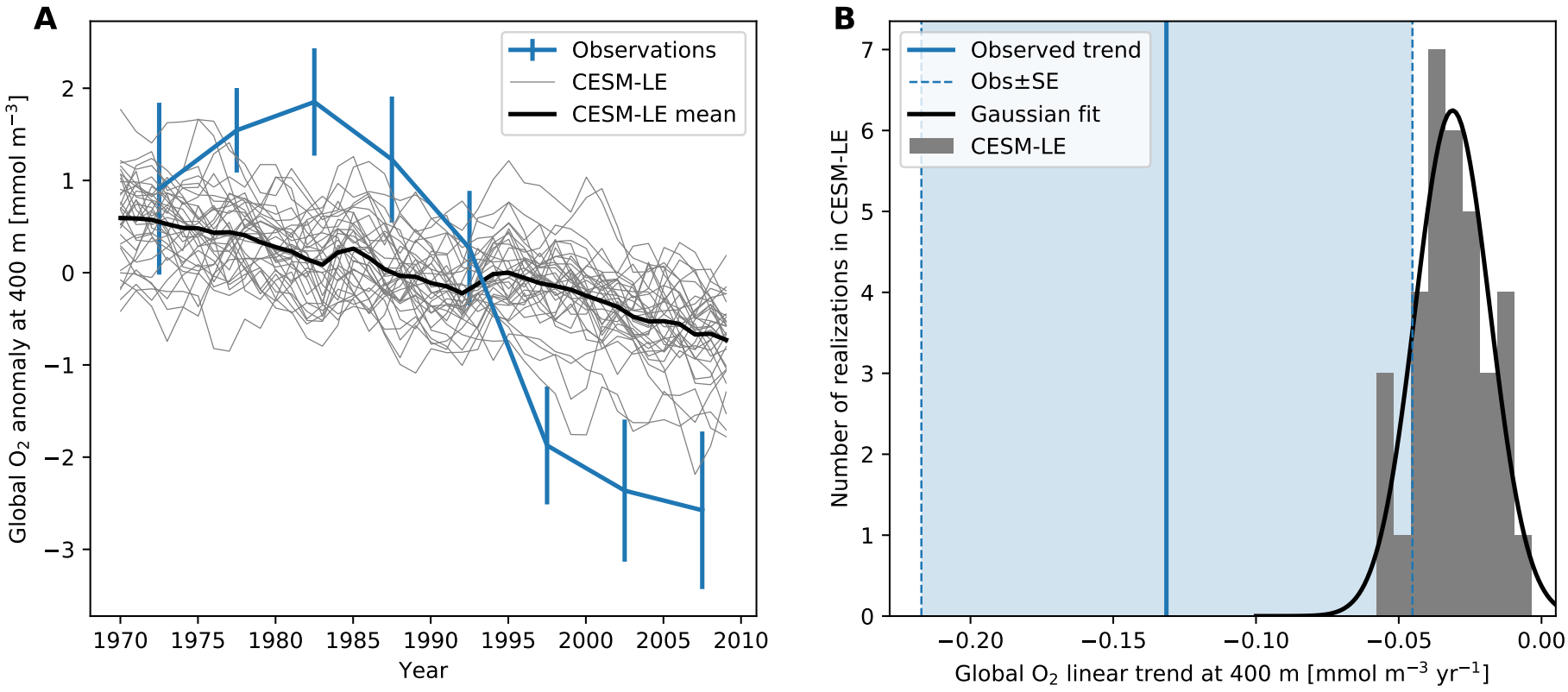
Range of future climate outcomes: DJF temperature trends (CCSM3, SRES-A1B)



Deser et al., 2012

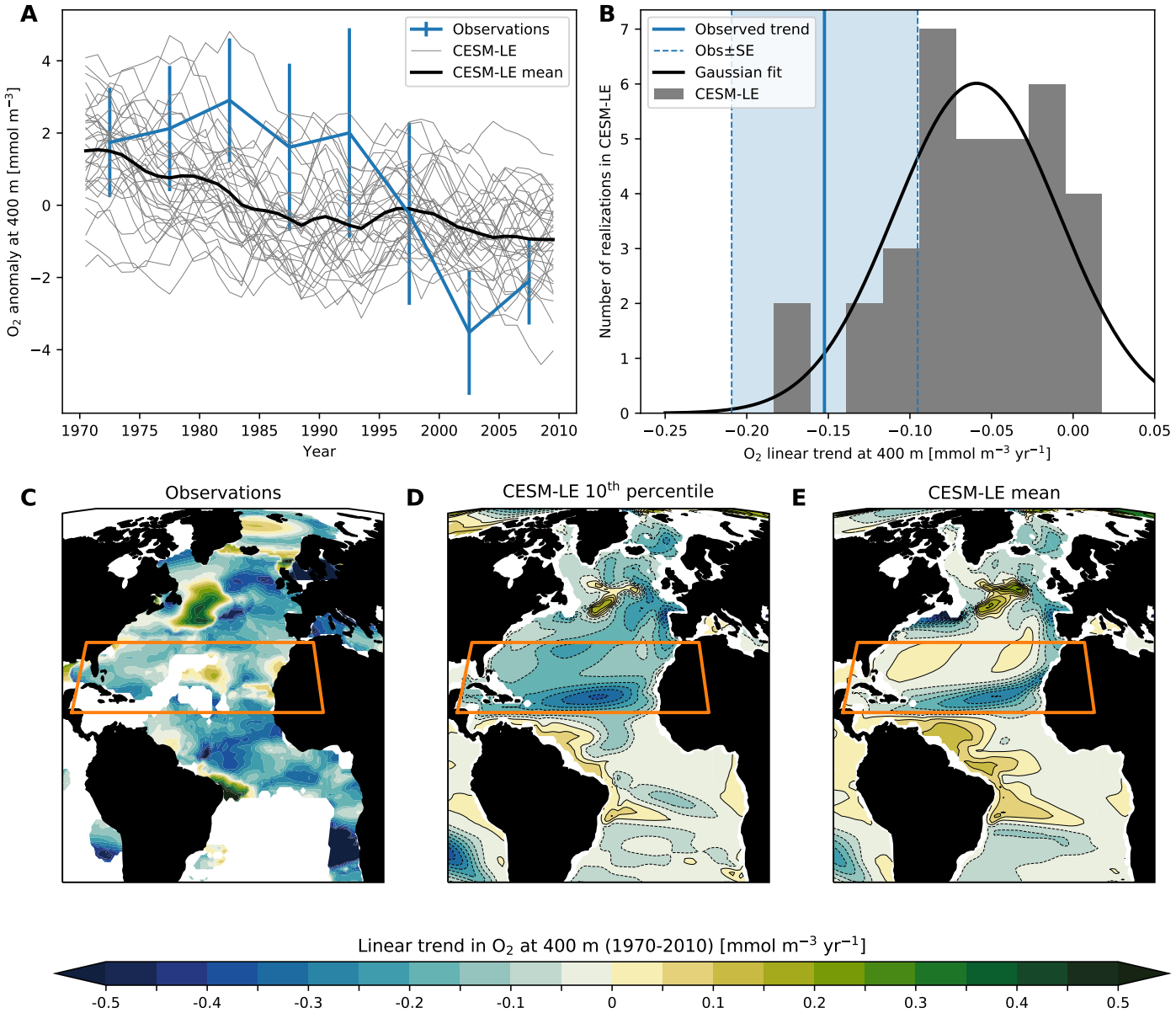
Are the models wrong?

Observed and simulated trends: global



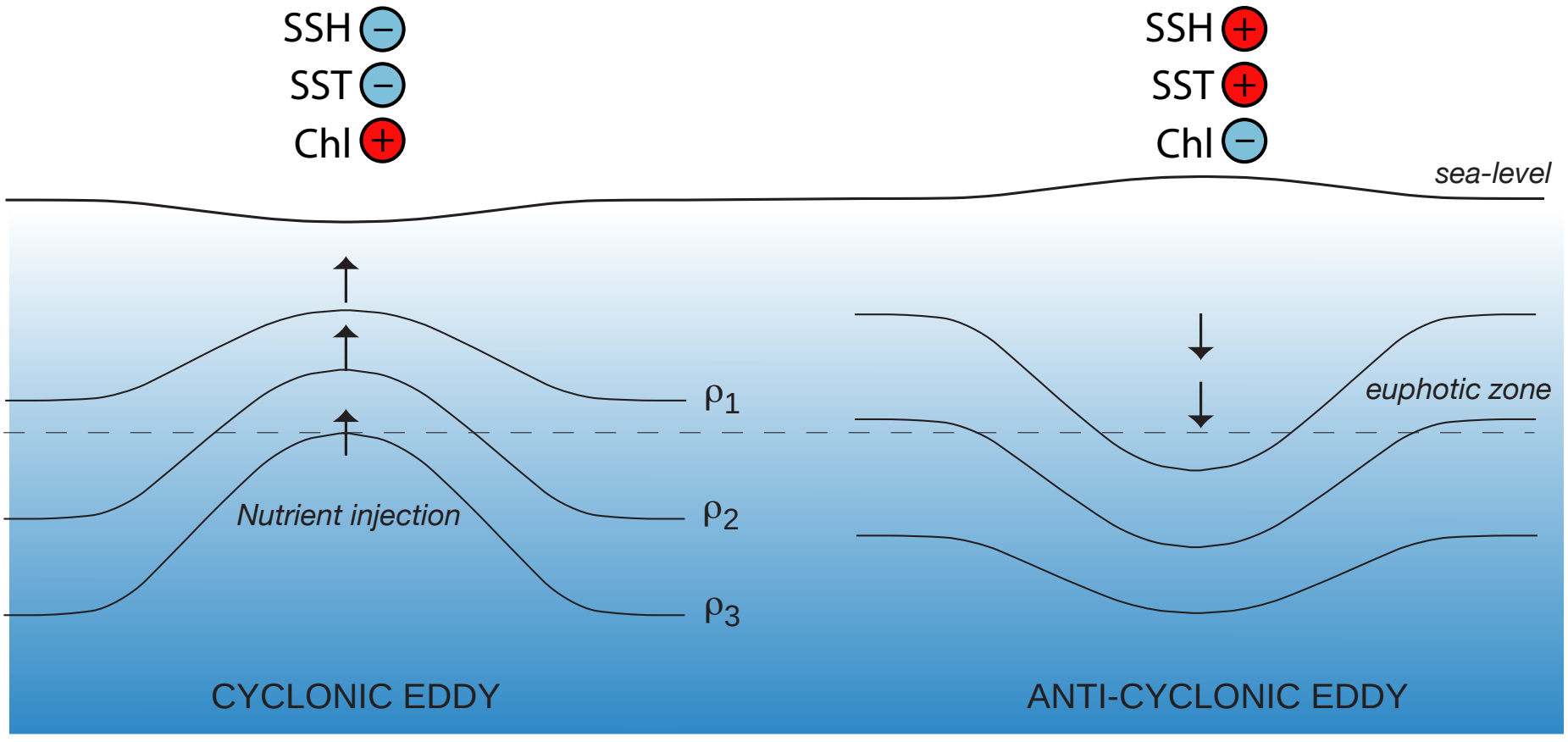
Are the models wrong?

Observed and simulated trends: Subtropical North Atlantic




50 km
earthobservatory.nasa.gov

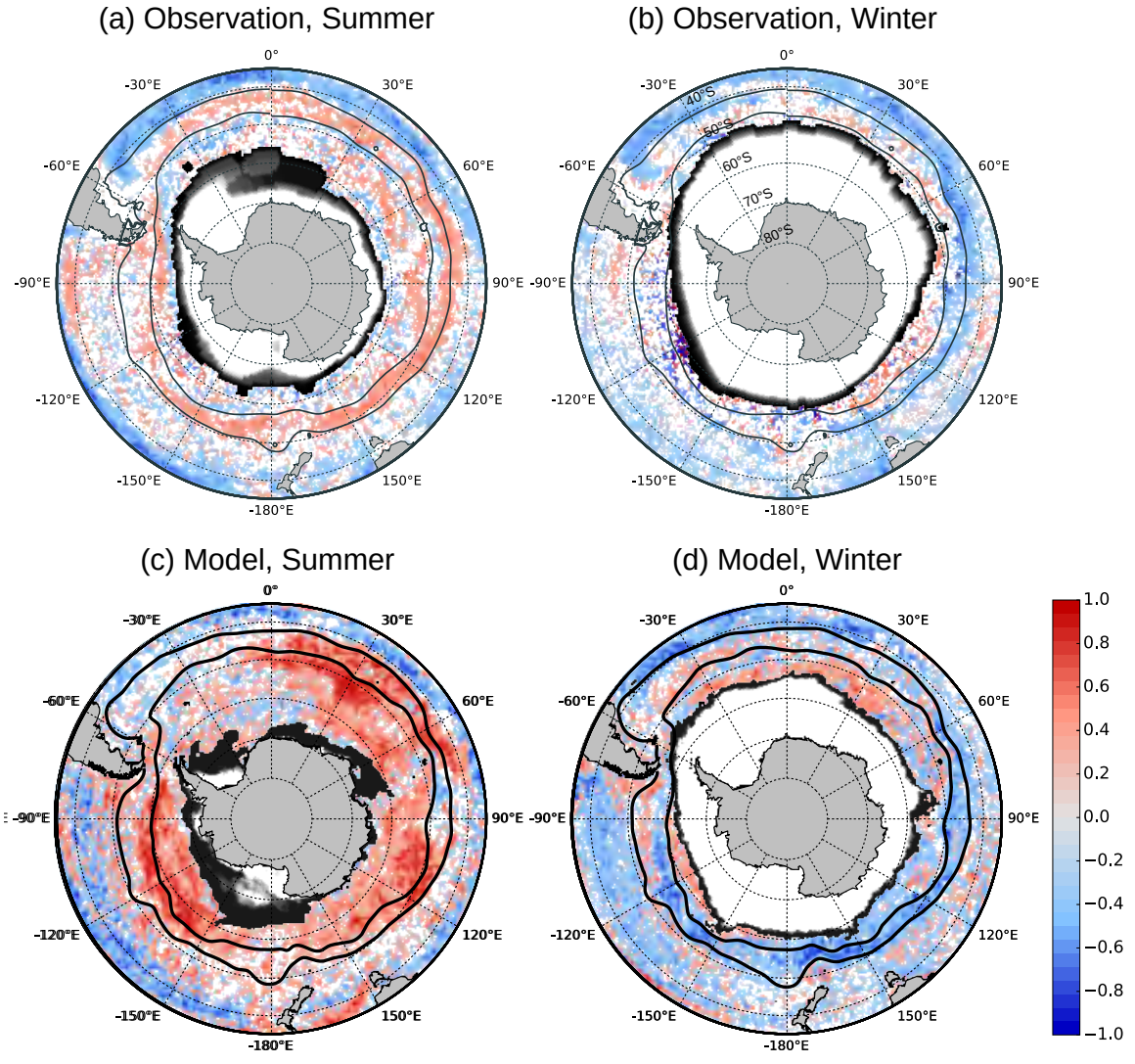
Eddies impact nutrient fluxes: Eddy pumping



after Sarmiento and Gruber 2006

Seasonal variation in eddy-driven chlorophyll anomalies

Correlation between SSH' and CHL'

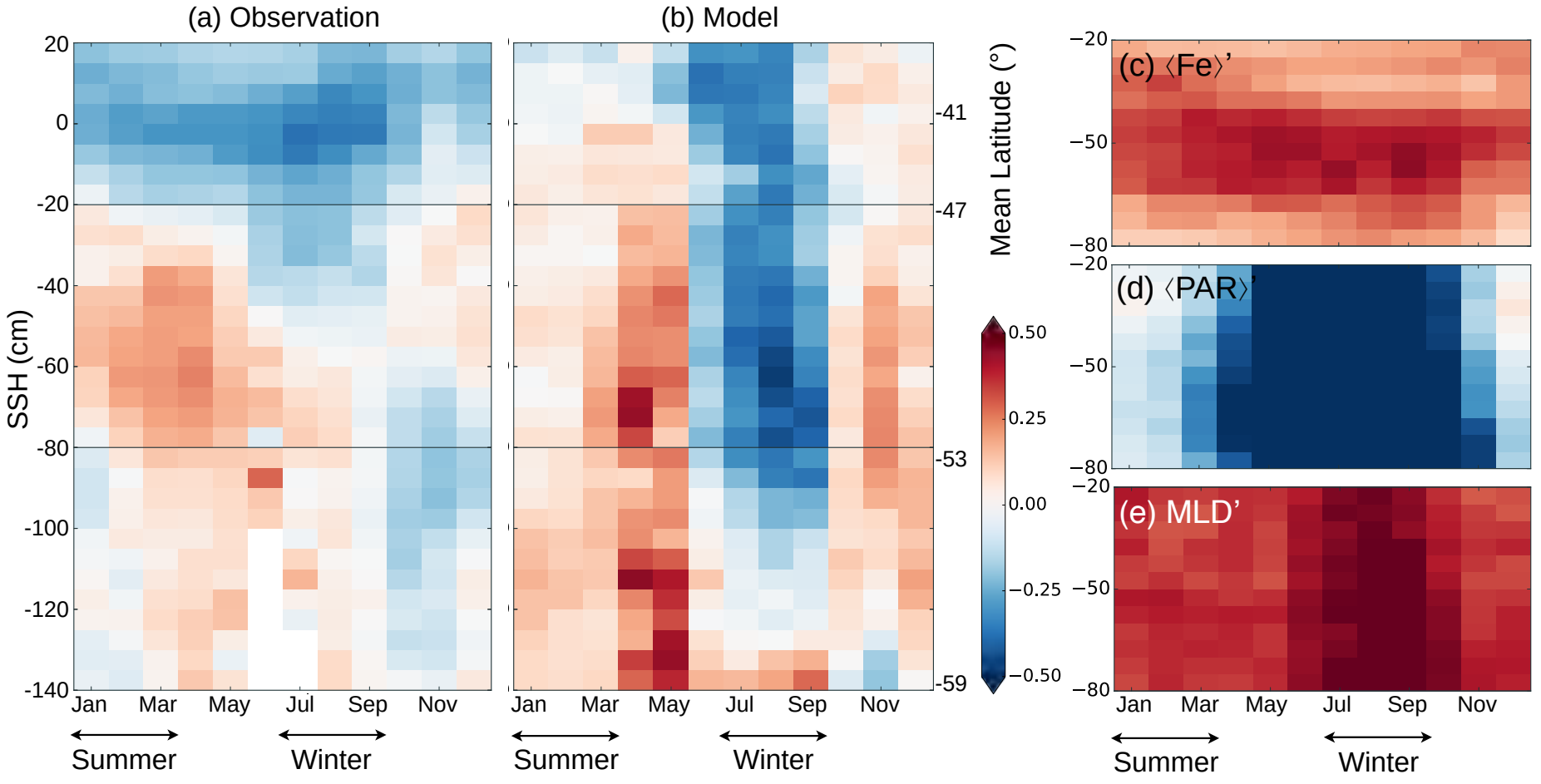


Song et al., GRL, 2018

Seasonal variation in eddy-driven chlorophyll anomalies

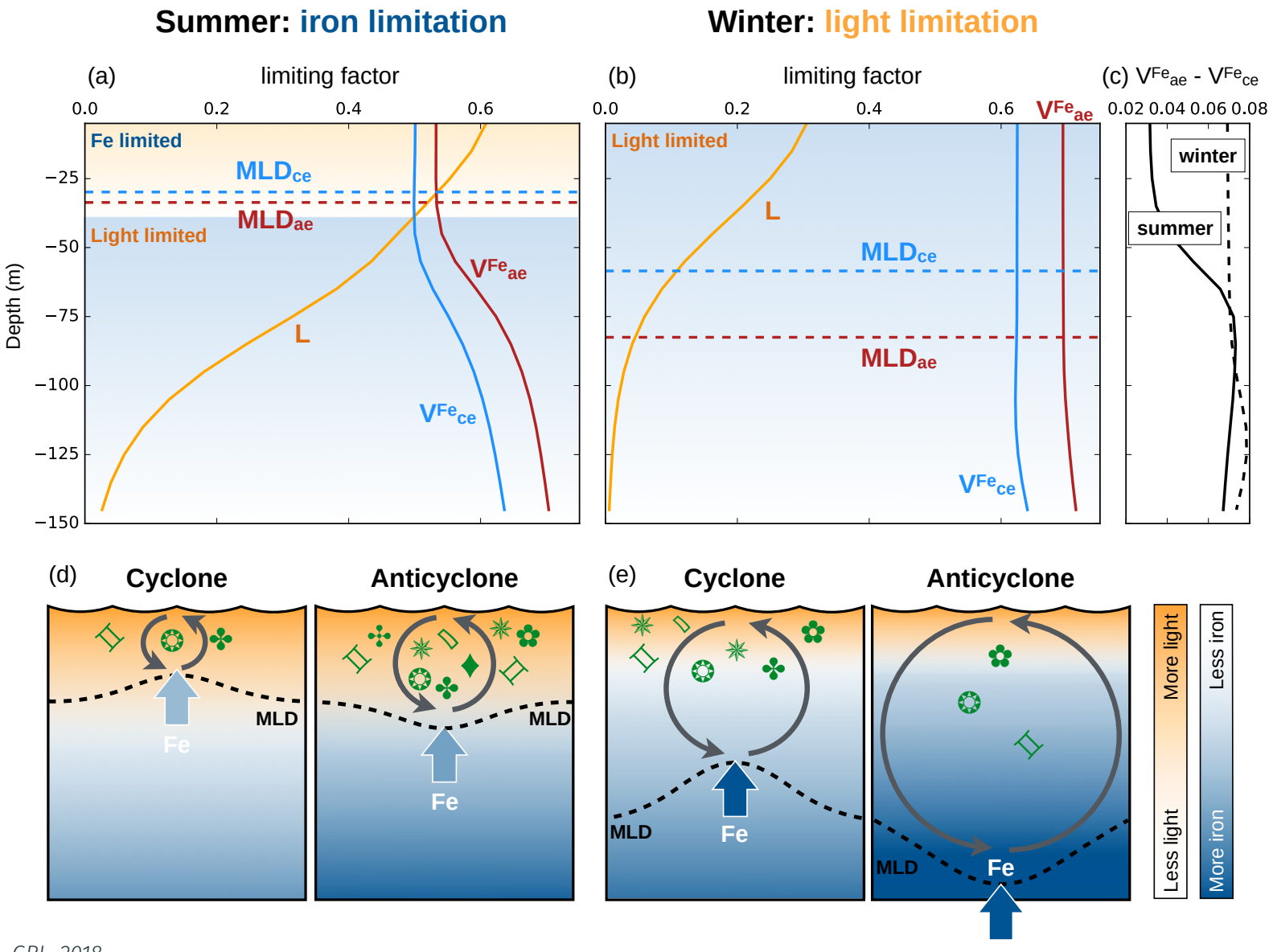
Correlation between SSH' and CHL'

Correlation with SSH'



Song et al., GRL, 2018

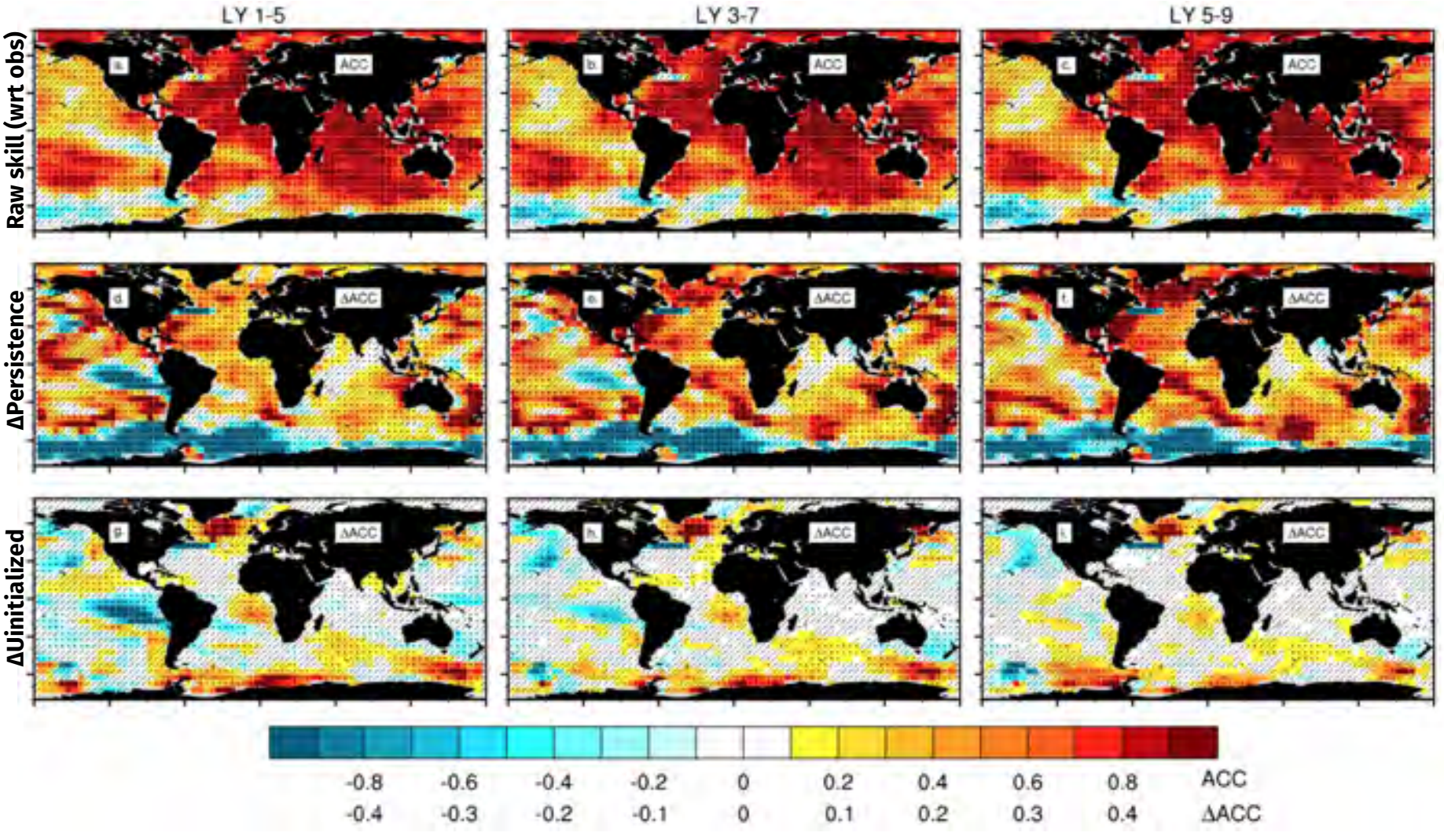
Seasonal variation in eddy-driven chlorophyll anomalies



Song et al., GRL, 2018

Predictability of annual sea surface temperature

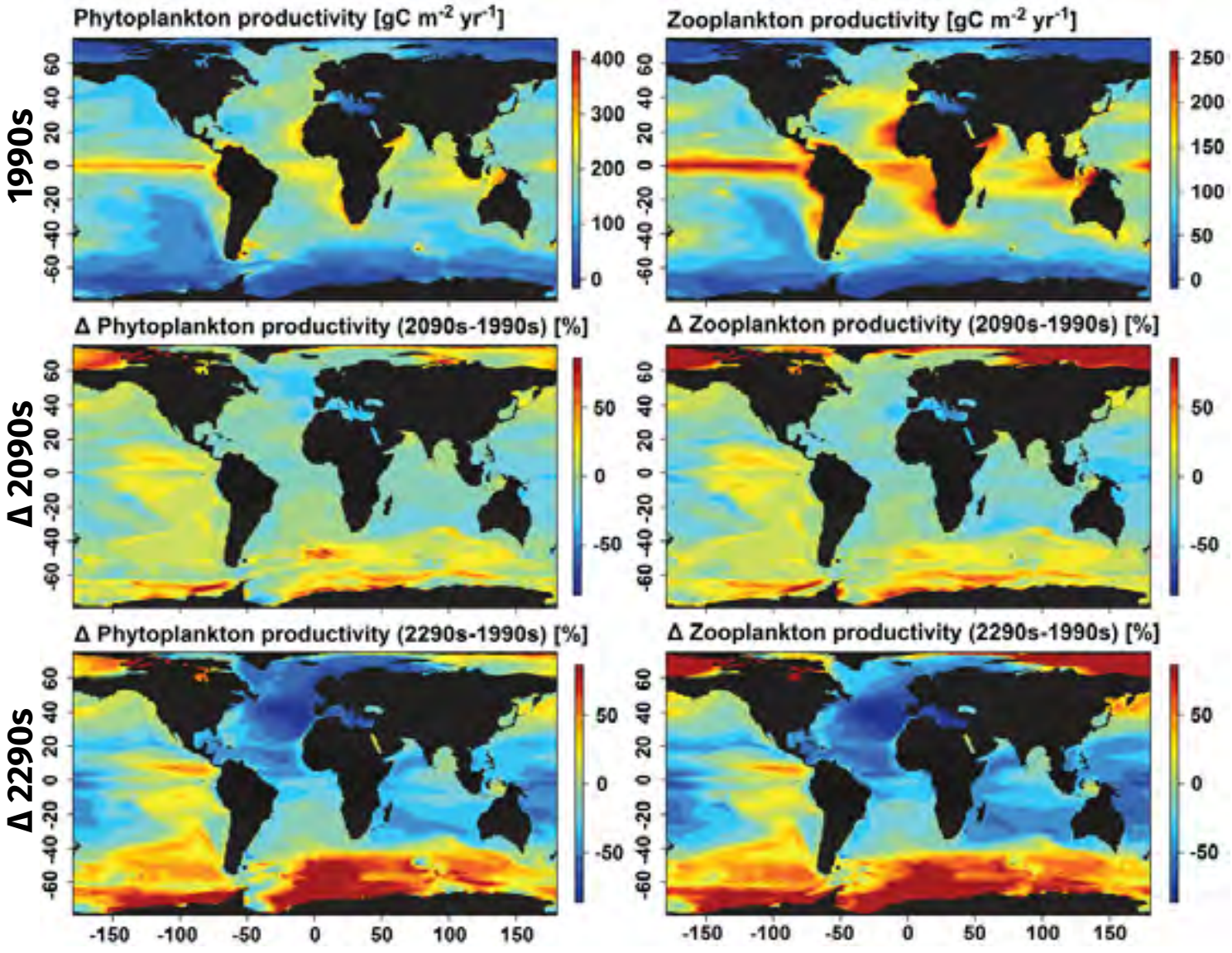
Anomaly correlation coefficient: SST



Yeager et al., 2018

Stratification continues to drive NPP decline

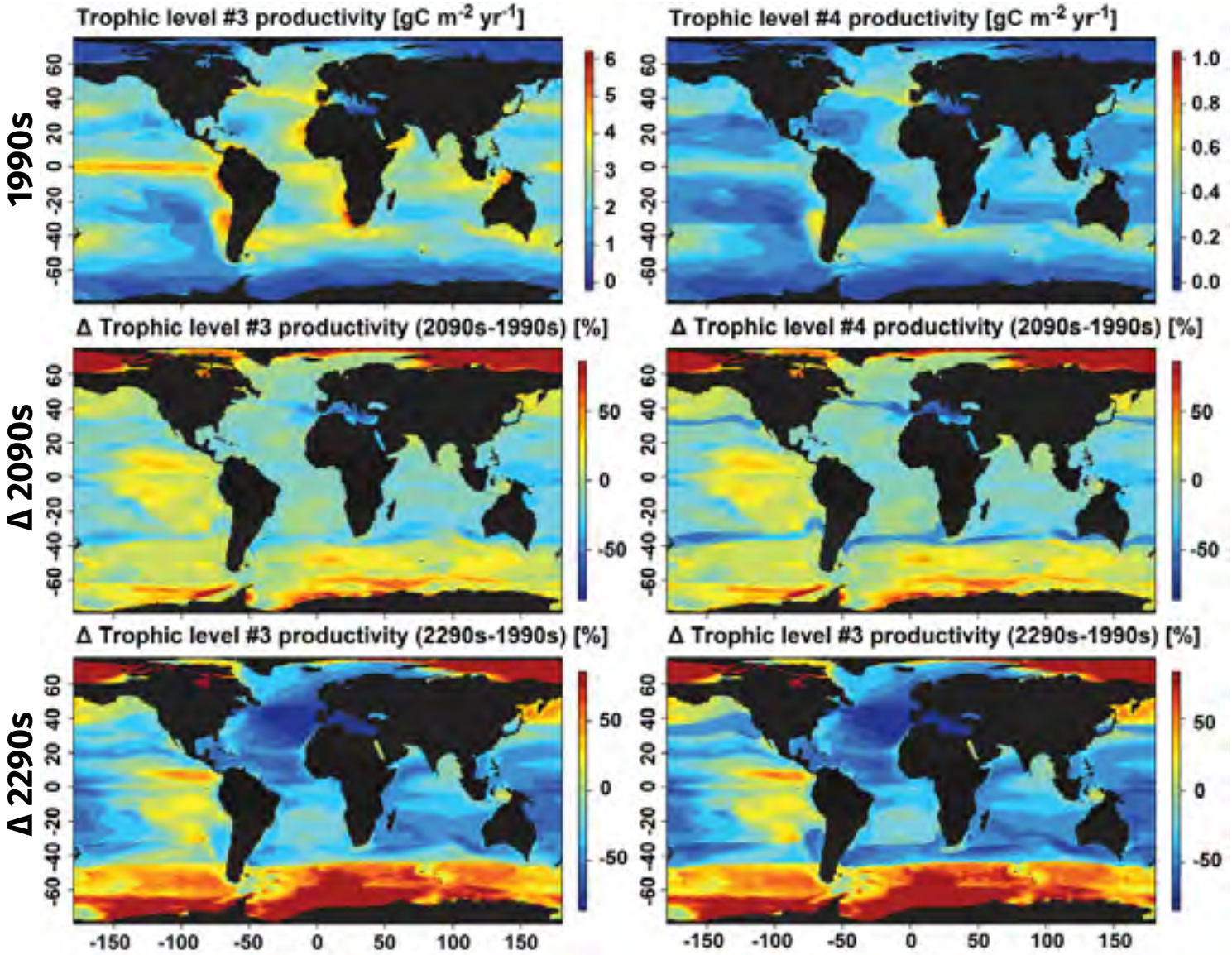
Primary productivity: mean and difference



Moore et al., 2018

Trophic cascades, fisheries collapse

Higher trophic level productivity: mean and difference



Moore et al., 2018