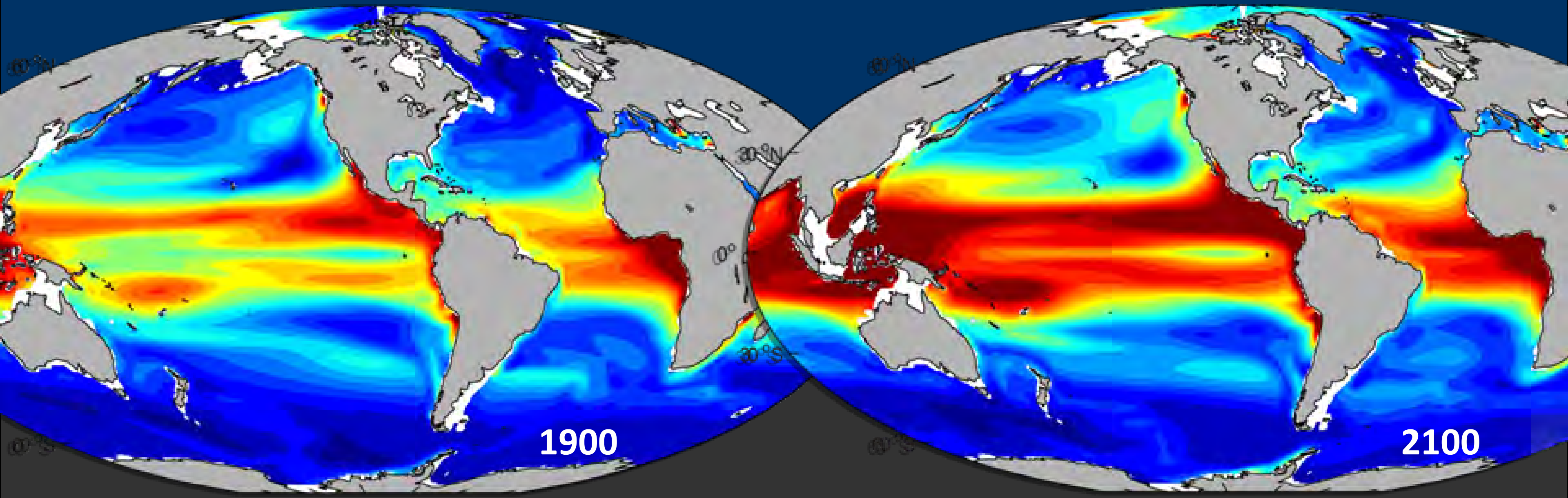
# *Basin-scale processes influence local ecosystem response to increased upper-ocean stratification*



NEREUS
PREDICTING THE FUTURE OCEAN
ネレウス
未来の海を考える

PRINCETON UNIVERSITY

日本財団
The Nippon Foundation

NOAA

Ryan R. Rykaczewski

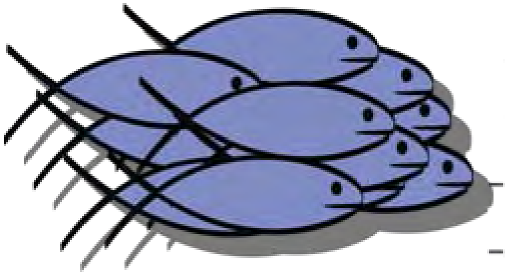
John P. Dunne, Charles A. Stock,
James R. Watson, and Jorge L. Sarmiento

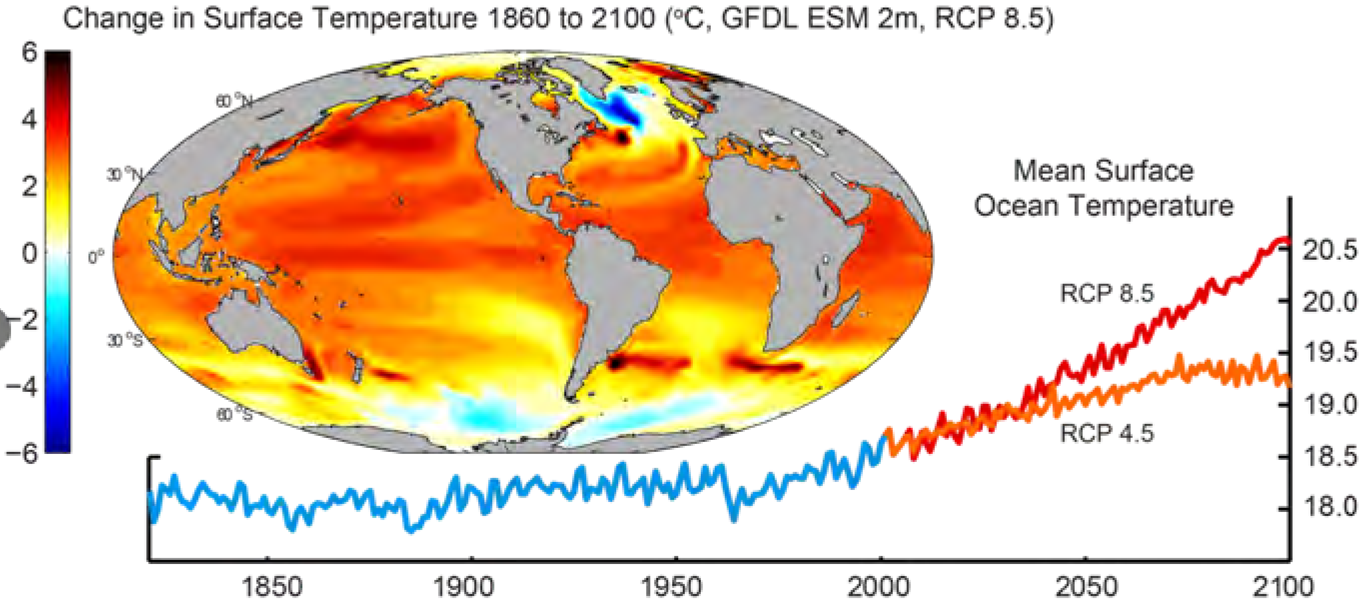
# *The objective which motivates our research…*

<u>What are the impacts of climate change on marine ecosystems?</u>

Understanding the dynamics of marine ecosystems and managing use of their resources is challenging enough given natural variability and current exploitation.

The prospect of additional and/or unanticipated variability is disconcerting.



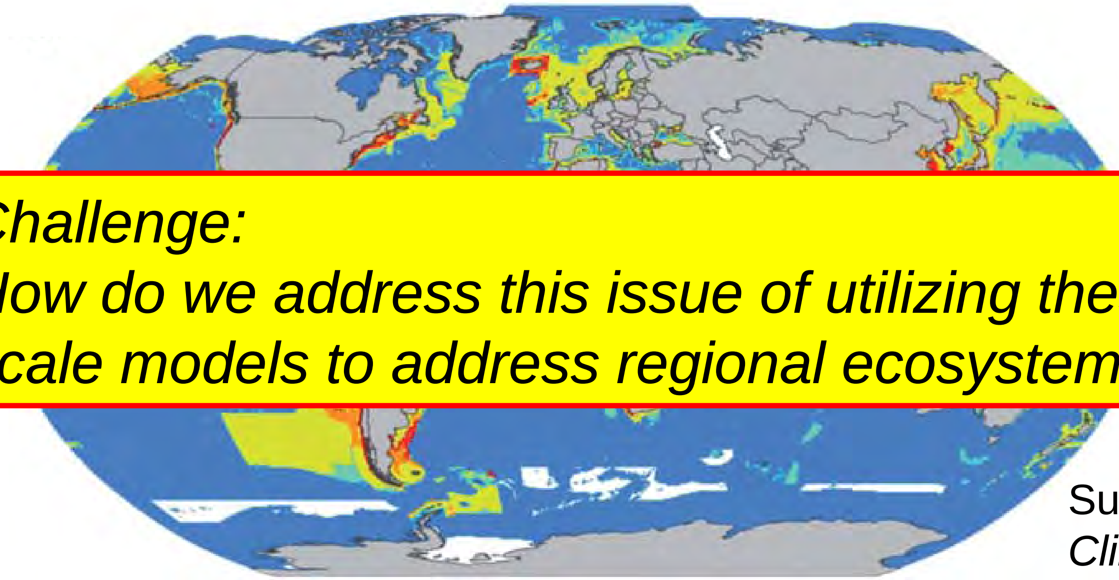


Change in Surface Temperature 1860 to 2100 (°C, GFDL ESM 2m, RCP 8.5)

# *A conflict of scale: regional responses to global change*

Global models are required to represent the response of the earth system to changes in concentrations of greenhouse gasses.

But components of human society (*e.g.*, fisheries management policies and economies) are concerned with climate changes at the regional scale.



*Challenge:*
*How do we address this issue of utilizing these large-scale models to address regional ecosystem issues?*

Sumaila *et al.* (*Nature Climate Change*, 2011)

# *A conflict of scale: regional responses to global change*

The most common approach is to force a local ecosystem model with the changes in local physical conditions as projected by a large-scale, IPCC-style global model.

That is, *potential changes in the far-field and deep-water biogeochemical properties are ignored* in favor of focusing on ecosystem responses to local, physical forcing of the surface ocean.

“How will *this ecosystem* respond to changes in temperature, wind stress, mixing and stratification, precipitation, sea ice, *etc.* that are projected for *this region*?”

# *Reasonable to ignore remote biogeochemical changes?*

This focus on ecosystem responses to changes in local forcing is a reasonable, first approach for a number of reasons:

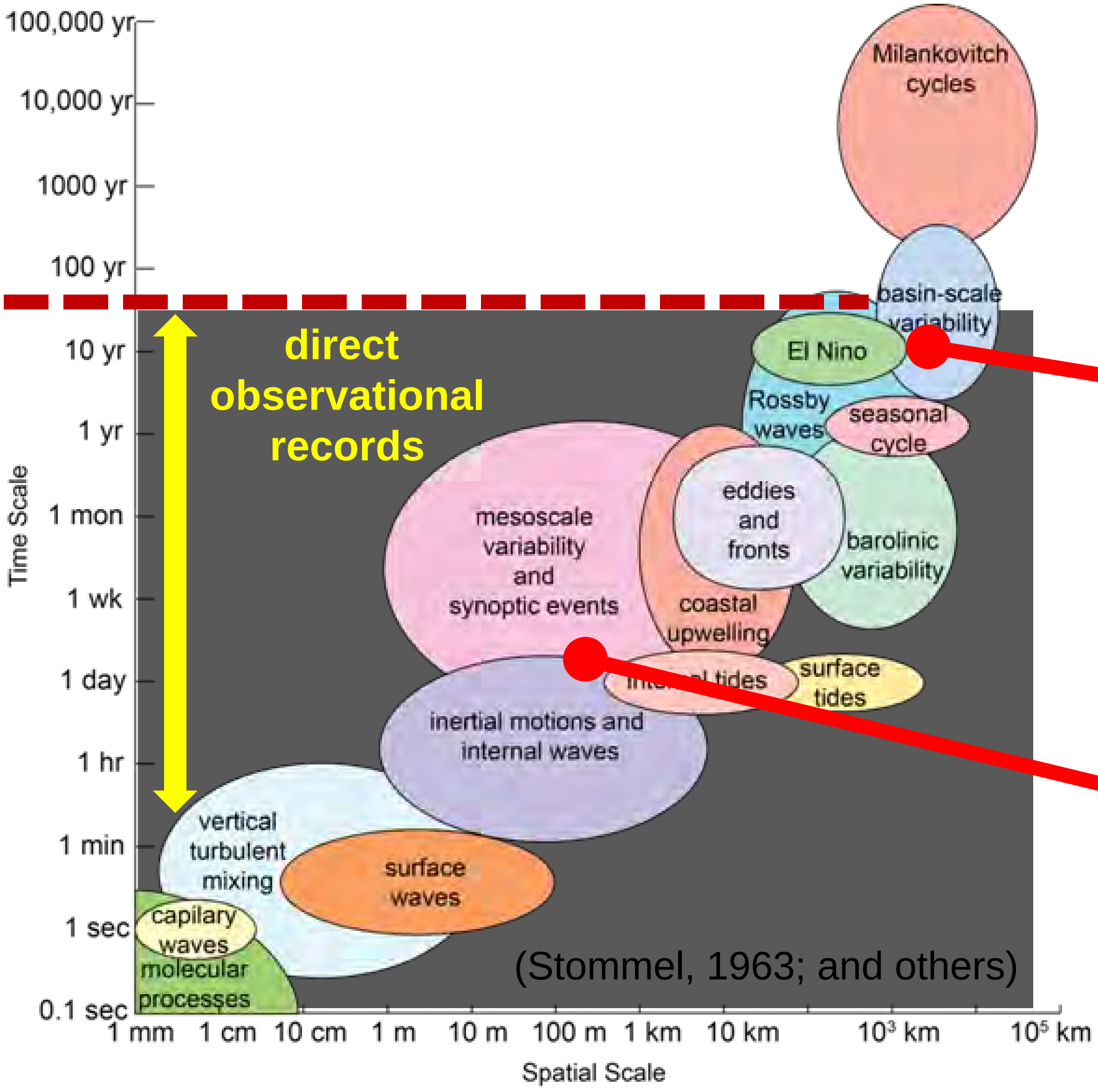
•Anthropogenic climate change, though global in nature, affects regional, physical processes that have been *observed*. Biogeochemical observations are limited in comparison.

•Projections of physical properties from IPCC-style models are more readily available (and more established).

•Our observations of past ecosystem changes have been associated with local physical forcing over relatively short temporal (seasonal to decadal) and spatial scales.

*This biases our hypotheses.*

# *Traditional hypotheses are based on observed variability*

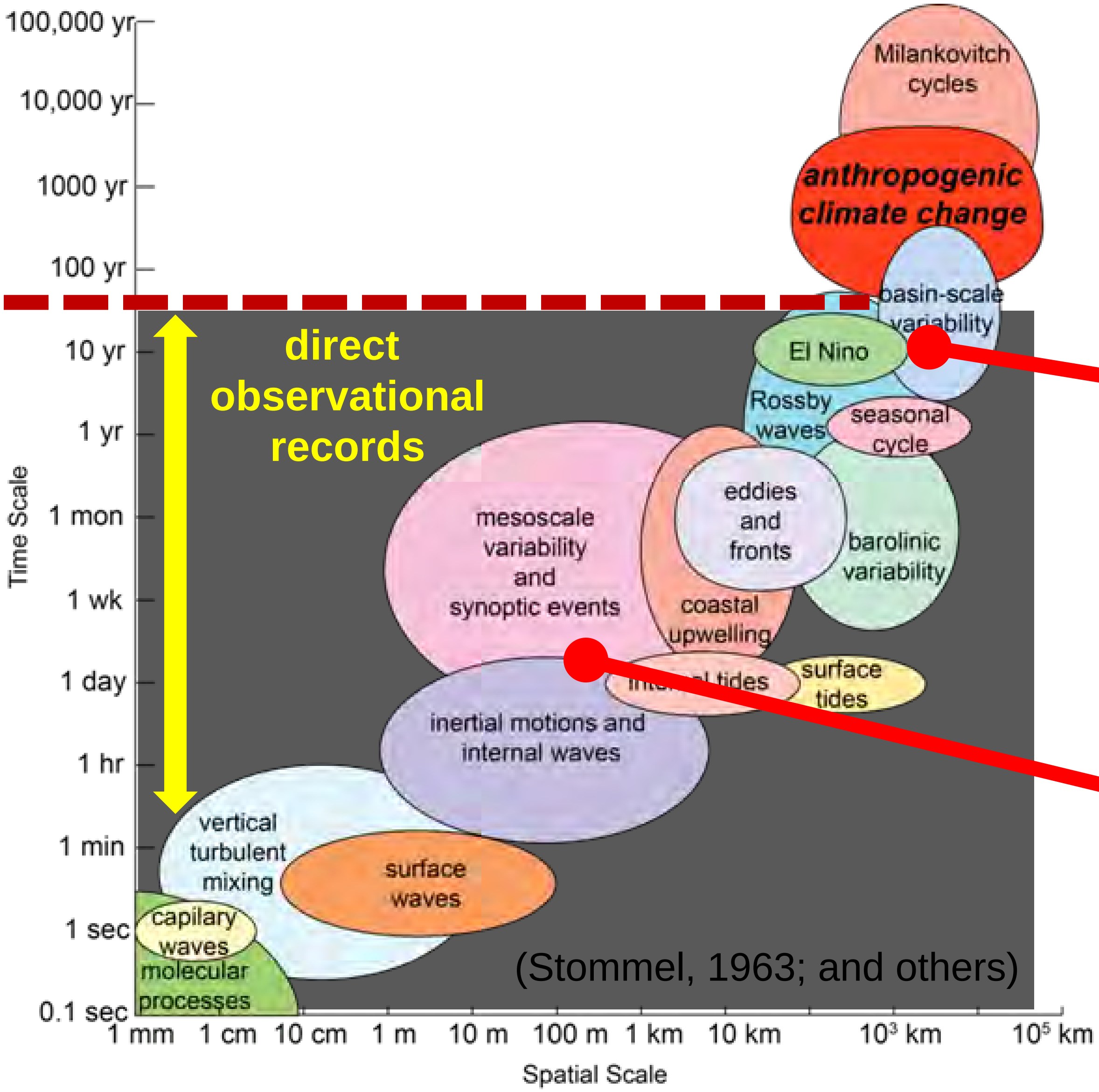


(Stommel, 1963; and others)

Gargett's "optimal stability window" hypothesis (1997, *Fish. Oceanogr.*)

Sverdrup's "critical depth" hypothesis (1953, *ICES J. Mar. Sci.*)

# *Traditional hypotheses are based on observed variability*



(Stommel, 1963; and others)

Gargett's "optimal stability window" hypothesis (1997, *Fish. Oceanogr.*)

Sverdrup's "critical depth" hypothesis (1953, *ICES J. Mar. Sci.*)

# *Assumption: changes in deep properties are minor*

Key hypotheses help frame our expectations of ecosystem responses to long-term climate change, but these hypotheses were developed to explain variability over shorter and smaller scales.

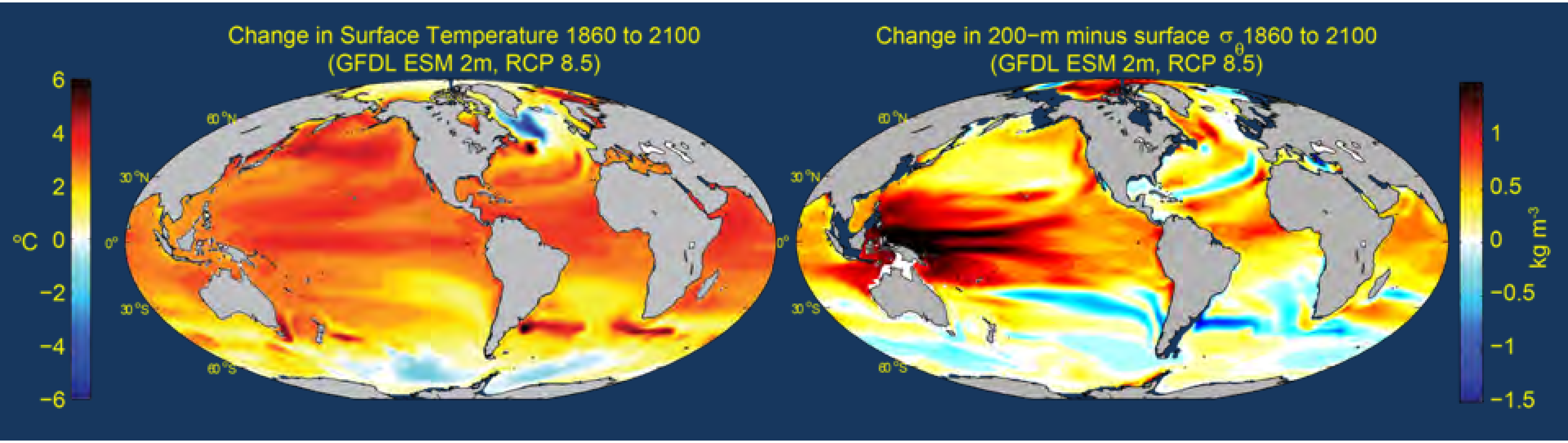
A major assumption of many of these hypotheses—Changes in deep, sub-pycnocline properties are much less important than local surface processes in their influence of ecosystem responses to physical variability.

These properties are set by large-scale processes—ocean ventilation or thermohaline circulation—and they don't change much in response to local atmospheric forcing.

> *Such changes would only need to be considered for some type of large-scale, long-term change.*

# *Anthropogenic changes are large scale and long term*

Such large-scale changes, approaching ‘geologic’ significance, describe the physical changes associated with anthropogenic warming… So perhaps we should readdress our assumptions.

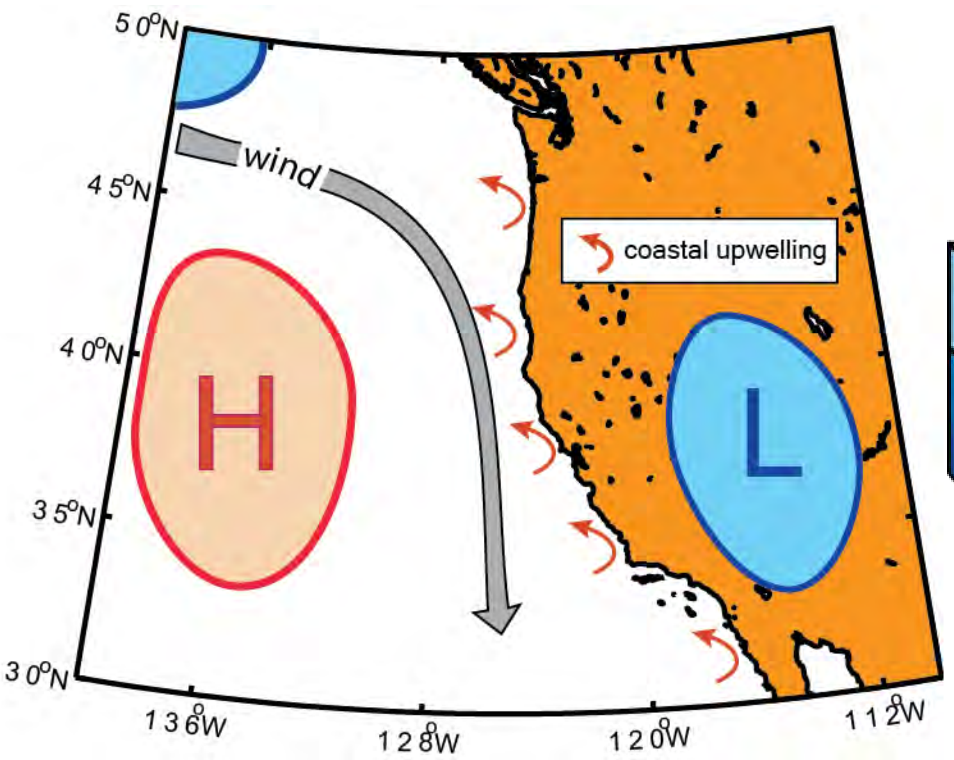


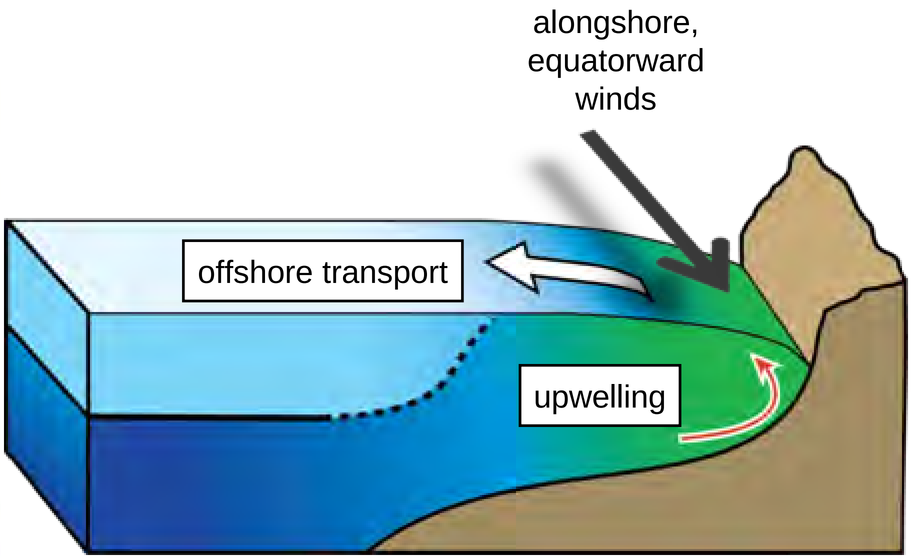
An example—

The response of the California Current Ecosystem to global warming.

# *Historical ecosystem dynamics respond to local forcing*

How might nutrient supply and ecosystem production respond to global warming?

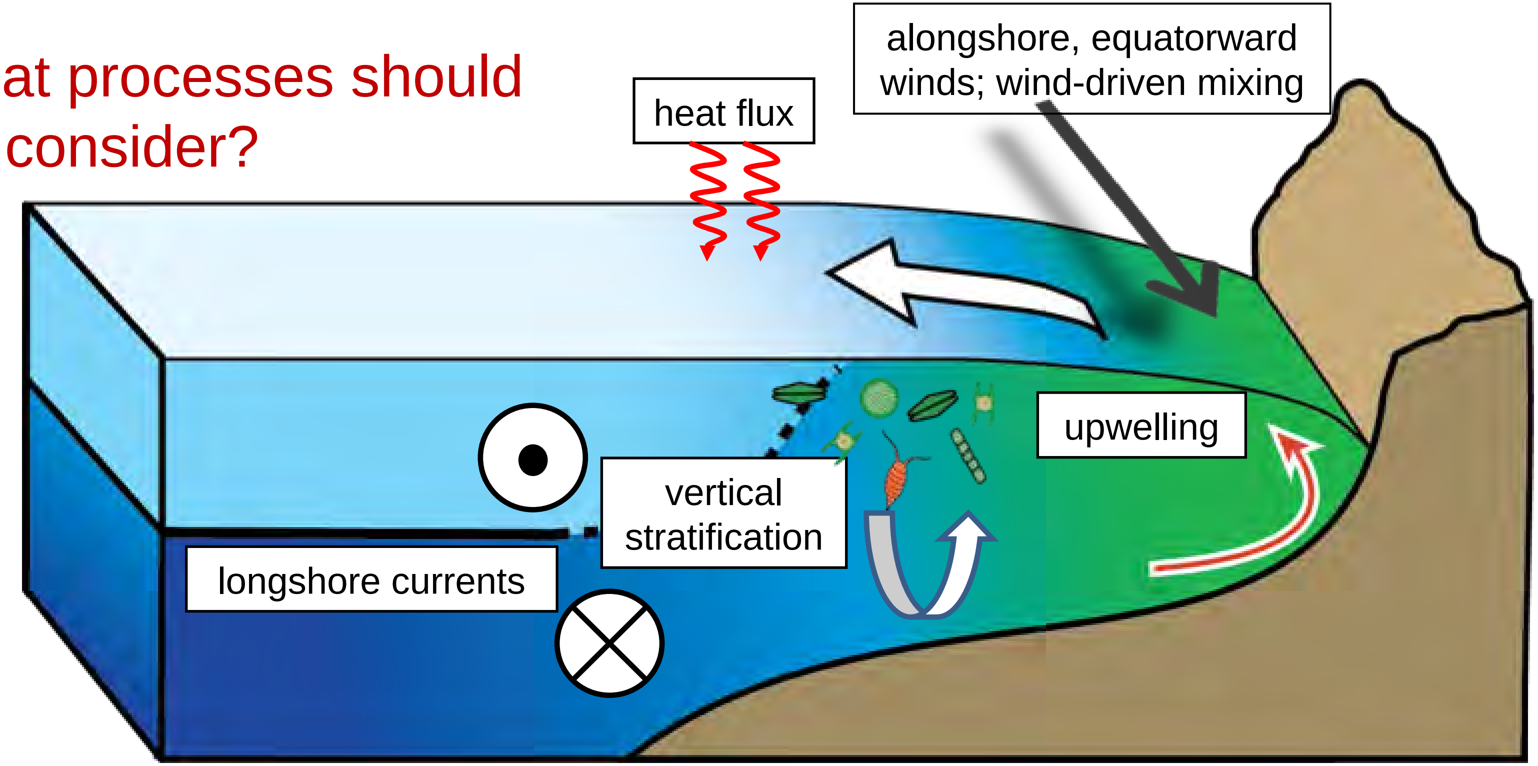




# *Historical ecosystem dynamics respond to local forcing*

How might nutrient supply and ecosystem production in the California Current respond to global warming?

What processes should we consider?



alongshore, equatorward winds; wind-driven mixing

heat flux

upwelling

vertical stratification

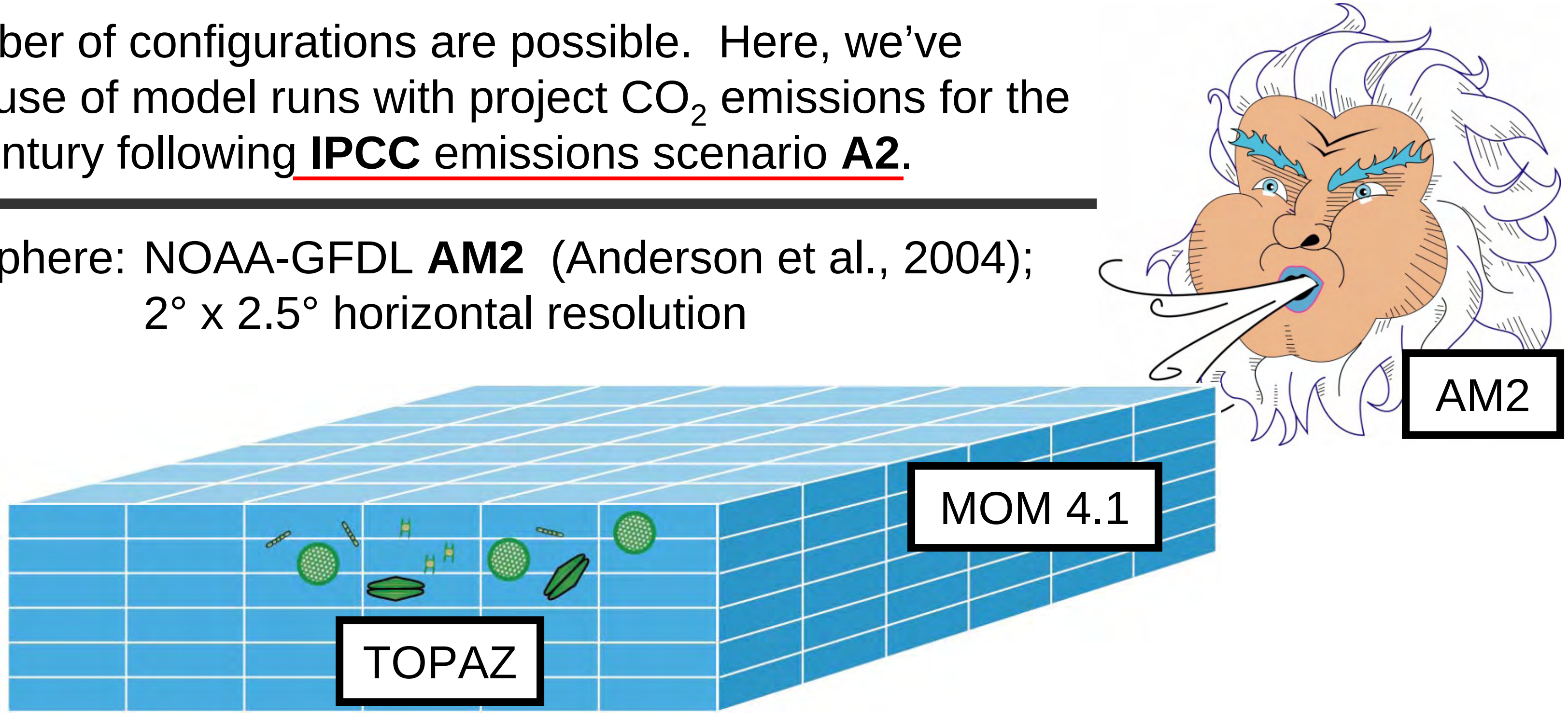
longshore currents

Strategy: Examine these processes in an Earth System Model.

# Configuration of GFDL's Earth System Model 2.1

A number of configurations are possible. Here, we've made use of model runs with project $CO_2$ emissions for the 21st century following **IPCC** emissions scenario **A2**.

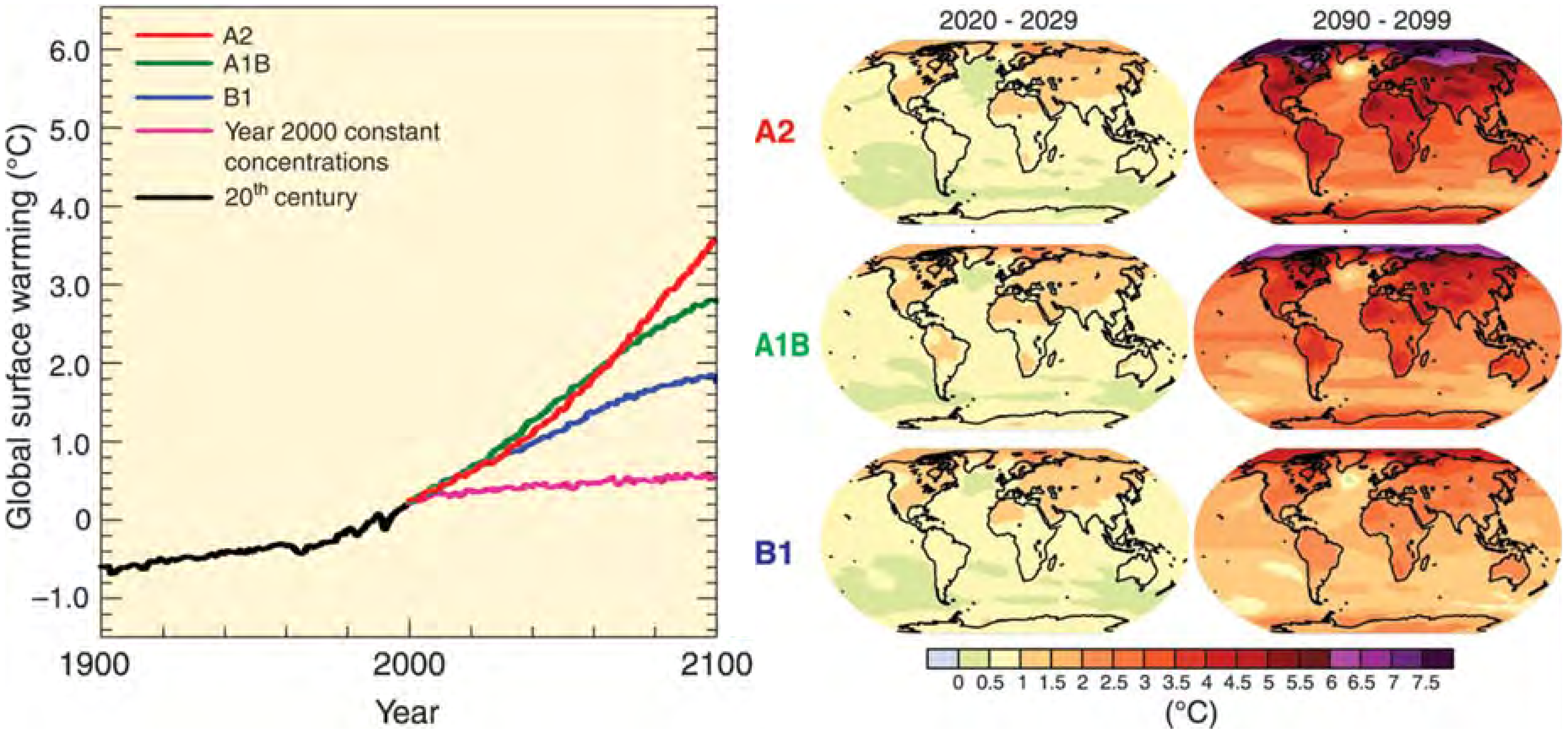
Atmosphere: NOAA-GFDL **AM2** (Anderson et al., 2004);
2° x 2.5° horizontal resolution



Ocean: NOAA-GFDL **MOM 4.1** (Modular Ocean Model; Pacanowski and Griffies, 1999); 1° x 1° horizontal resolution

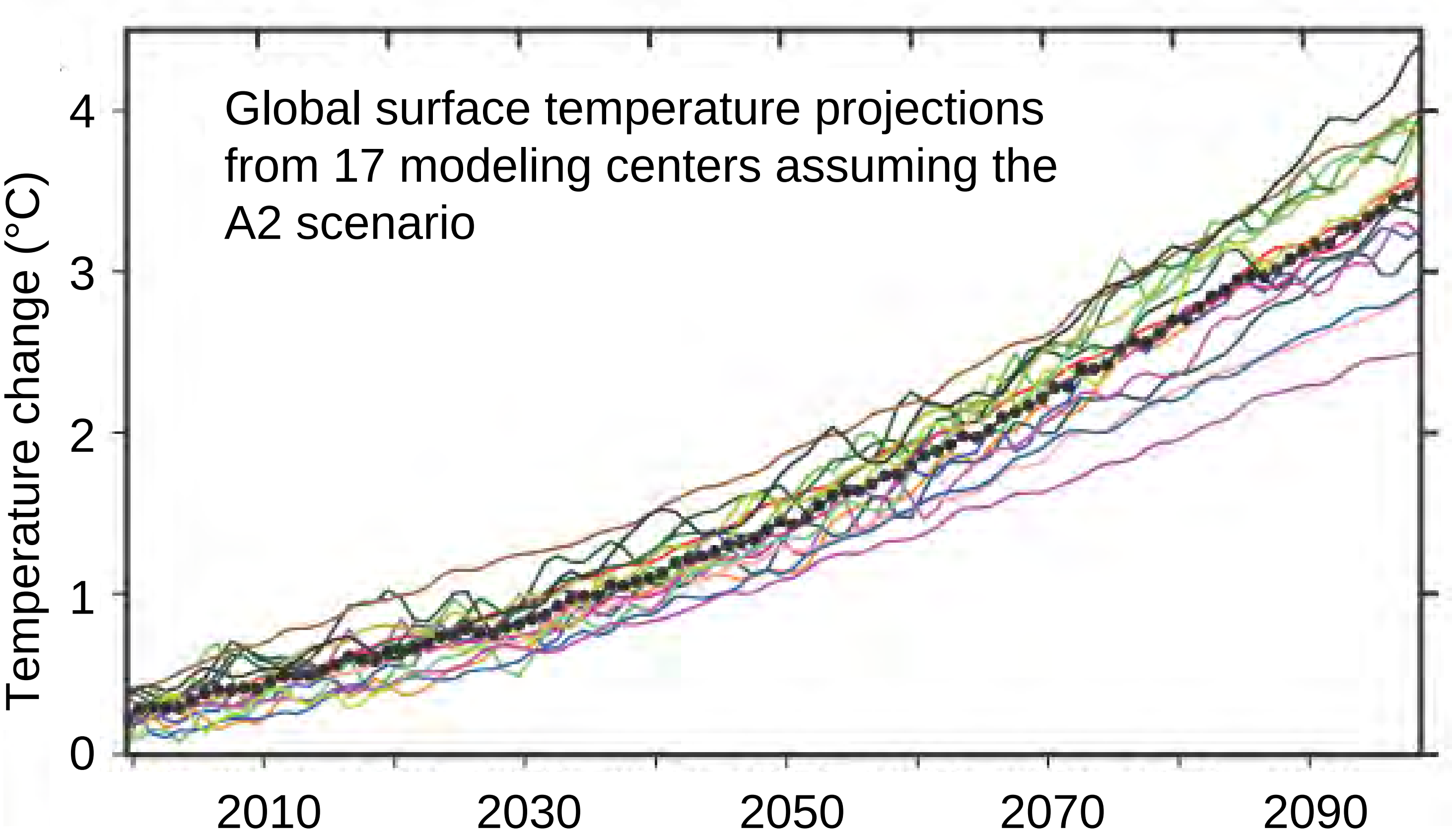
Biology: NOAA-GFDL **TOPAZ** (Tracers of phytoplankton with Allometric Zooplankton) which includes N, P, Si and Fe cycles and three phytoplankton classes (Dunne *et al.*, 2007).

# *AR4 generation IPCC Emissions Scenario A2*



IPCC AR4 (2007)

# *AR4 generation IPCC Emissions Scenario A2*



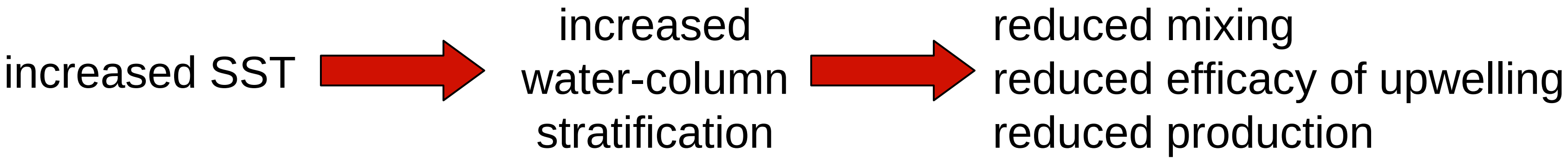
How does nutrient supply to the region change under this global warming scenario? What previous hypotheses do we have to draw from?

IPCC AR4 (2007)

# *Two qualitative hypotheses posed previously*

## #1 - Increased stratification = decreased nutrient supply

Roemmich and McGowan (1995, *Science*) hypothesized that global warming will result in:



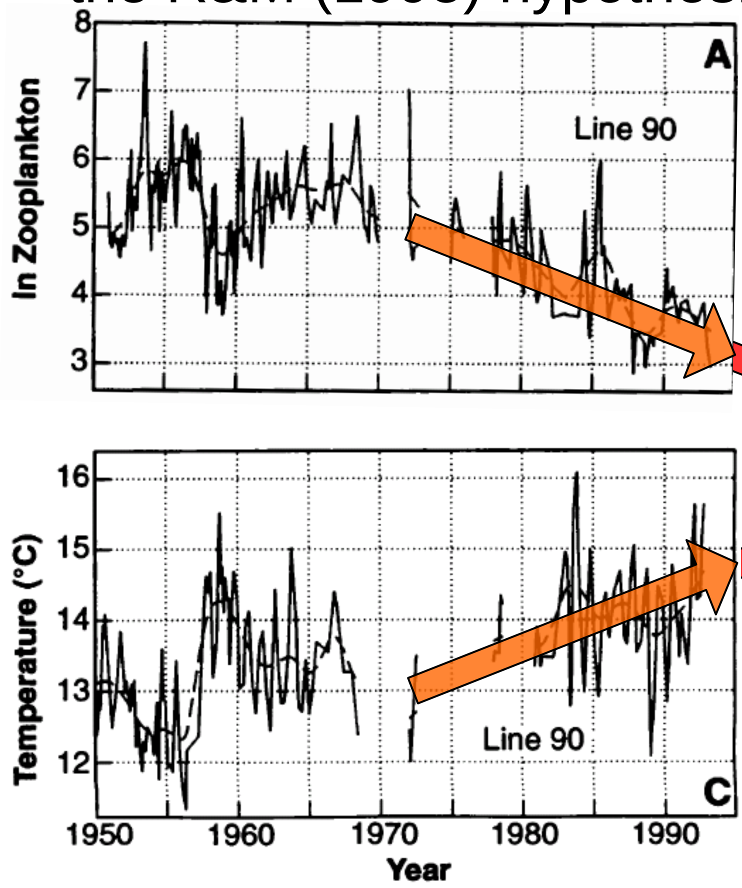
increased SST

increased water-column stratification

reduced mixing
reduced efficacy of upwelling
reduced production

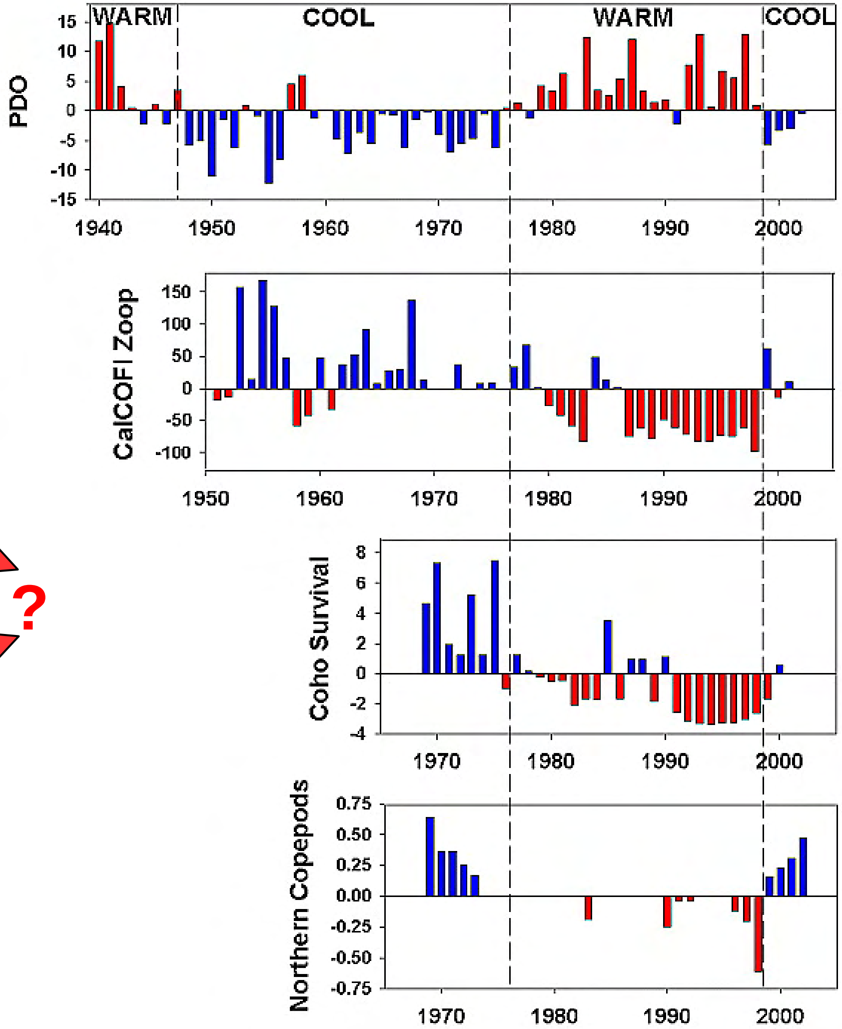
# *Observational support for lower production with warming*

Historical observations support the R&M (1995) hypothesis.



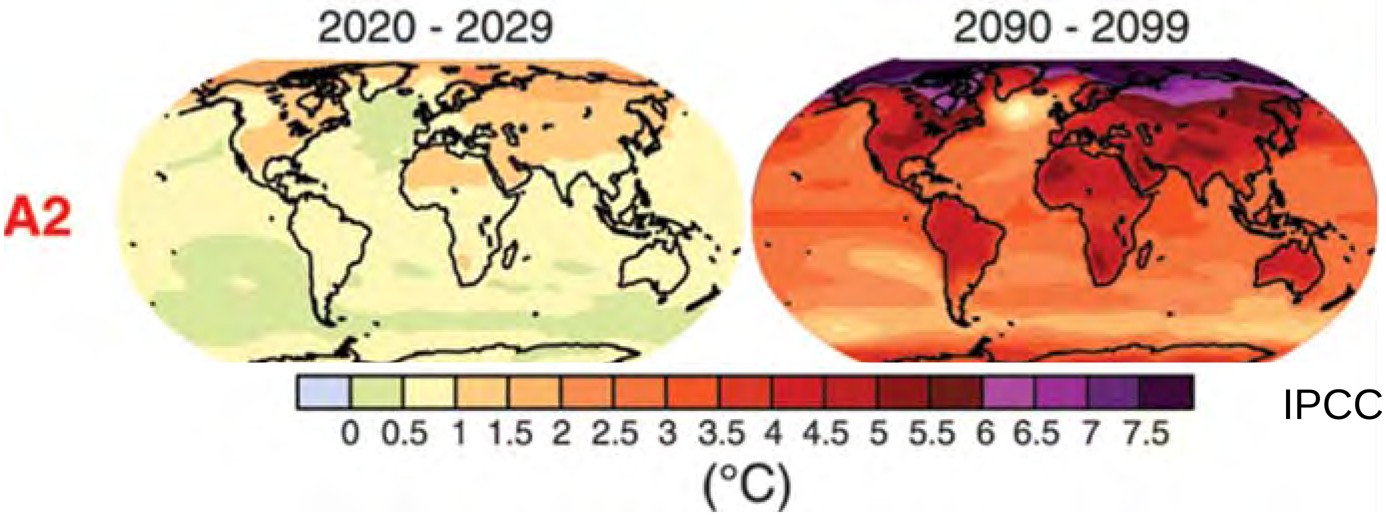
Roemmich and McGowan (1995, *Science*)

?



Peterson and Schwing (2003, *GRL*)

# *Two qualitative hypotheses posed previously*



IPCC AR4 (2007)

<u>#2 - Increased continental warming rate = increased nutrient supply</u>

Bakun (1990, *Science*) hypothesized that:

relative differences
in land and sea
heat capacities

→

more rapid warming
over land; increased
atm. pressure gradient

→

increased alongshore winds
increased upwelling
increased production

# *Changes in local forcing suggest decreased nutrient supply*

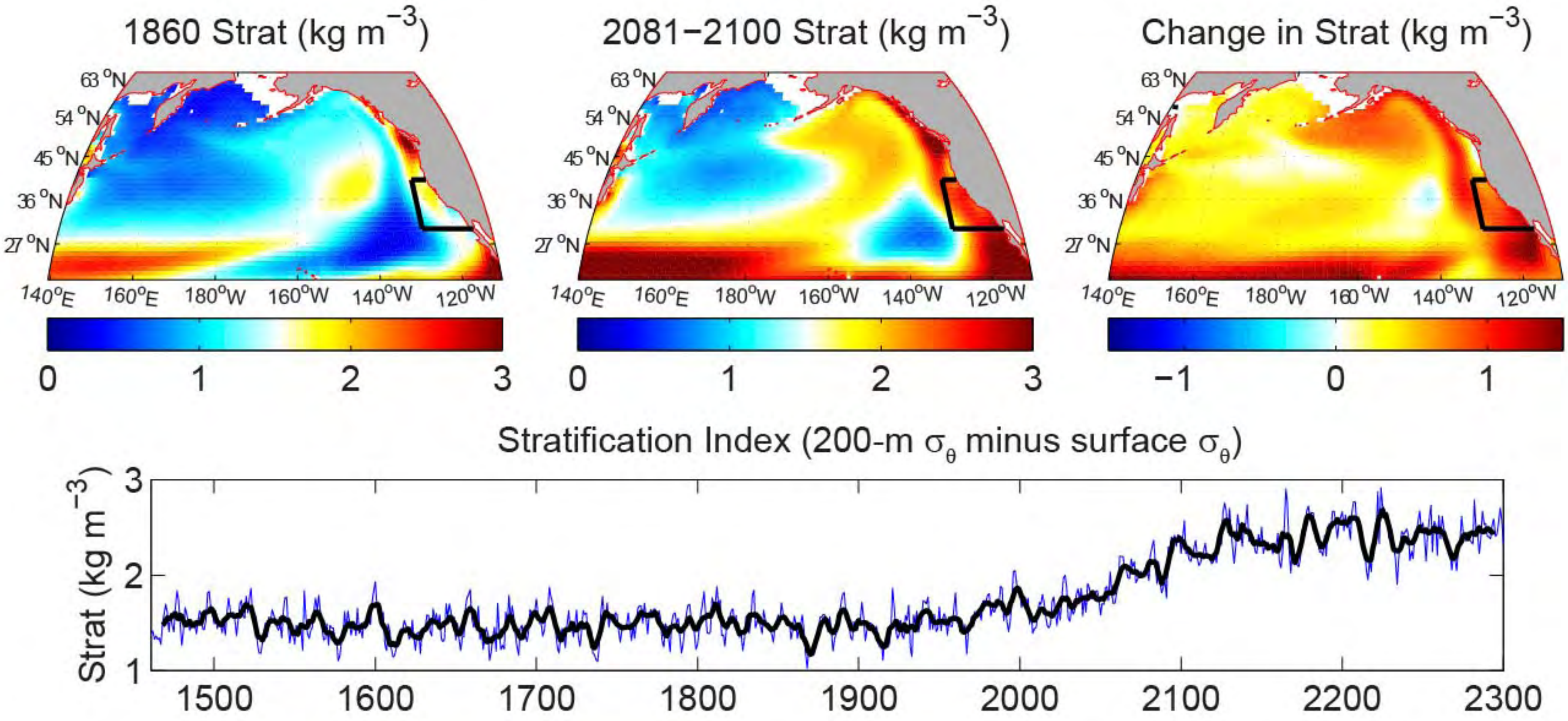
Results—

1. Local stratification increases are accompanied by a decrease in mixed-layer depth.

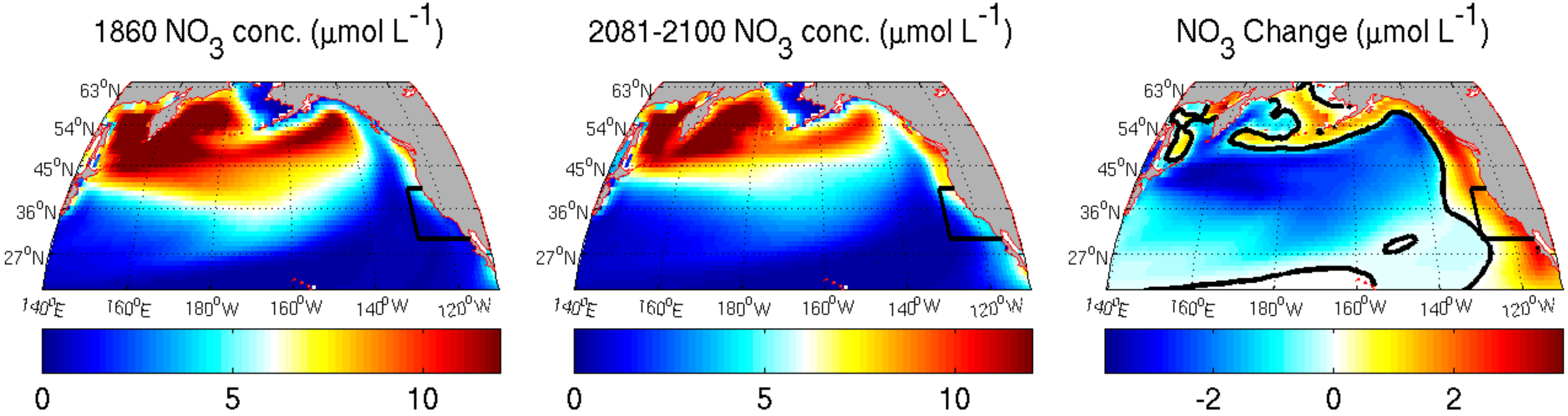
2. Wind changes are minor and display no trend. Upwelling transport into the region changes little.

3. Surprisingly, nutrient supply to the region increases substantially.

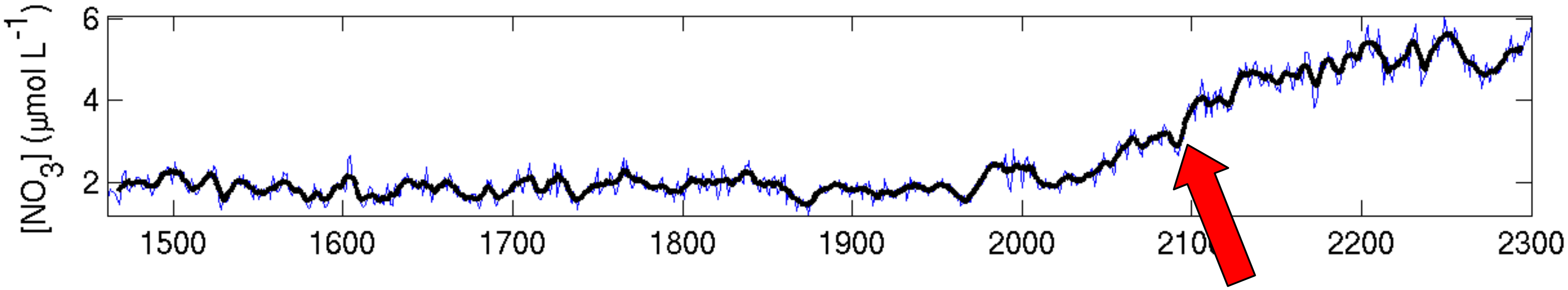
# *Changes in local forcing suggest decreased nutrient supply*



# *Surface-layer $NO_3$ increases despite stratification and winds*



Annual $NO_3$ concentration in coastal control volume (0-200m, 30:40N 128:115W)



35% decrease in the average nitrate concentration in the North Pacific (20° N to 65° N).

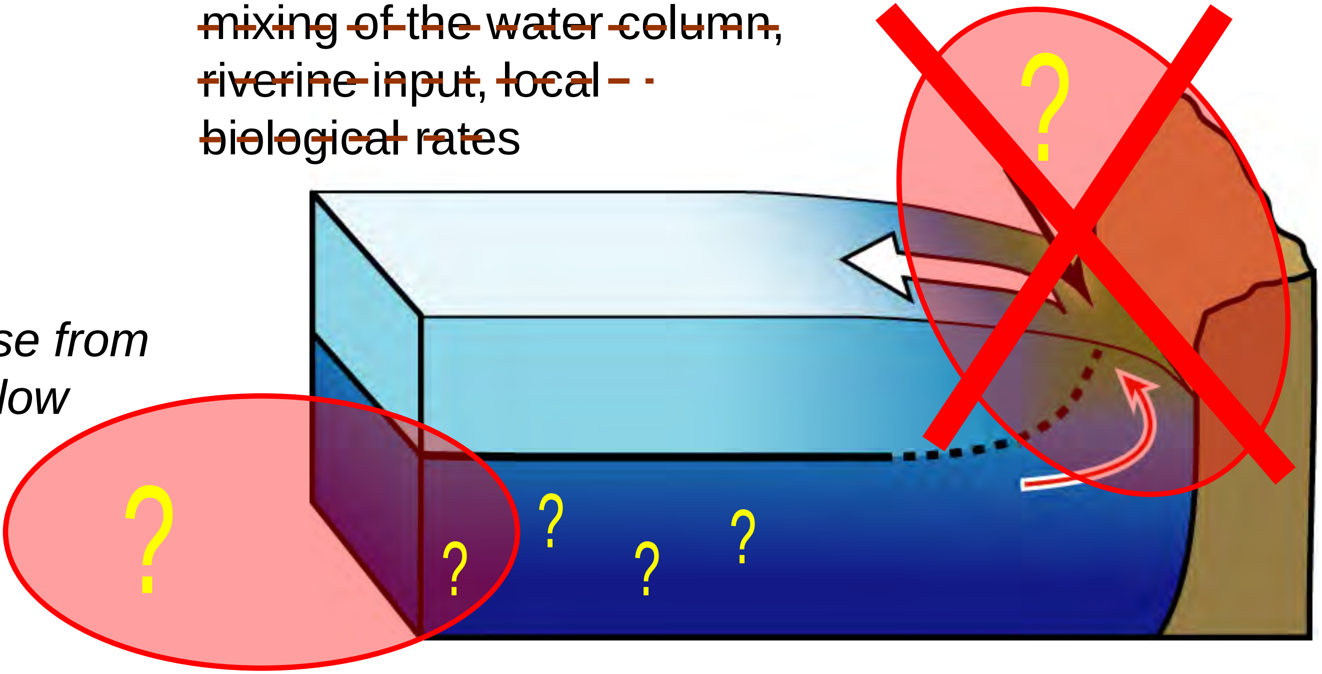
85% increase in average nitrogen concentration between 2000 and 2100 along the US West Coast.

Rykaczewski and Dunne (2010, GRL)

# *Local changes cannot explain regional nutrient changes*

**Local** conditions vary in the 21st century, *but not in a consistent manner that can explain the long-term increase in nitrate supply*.

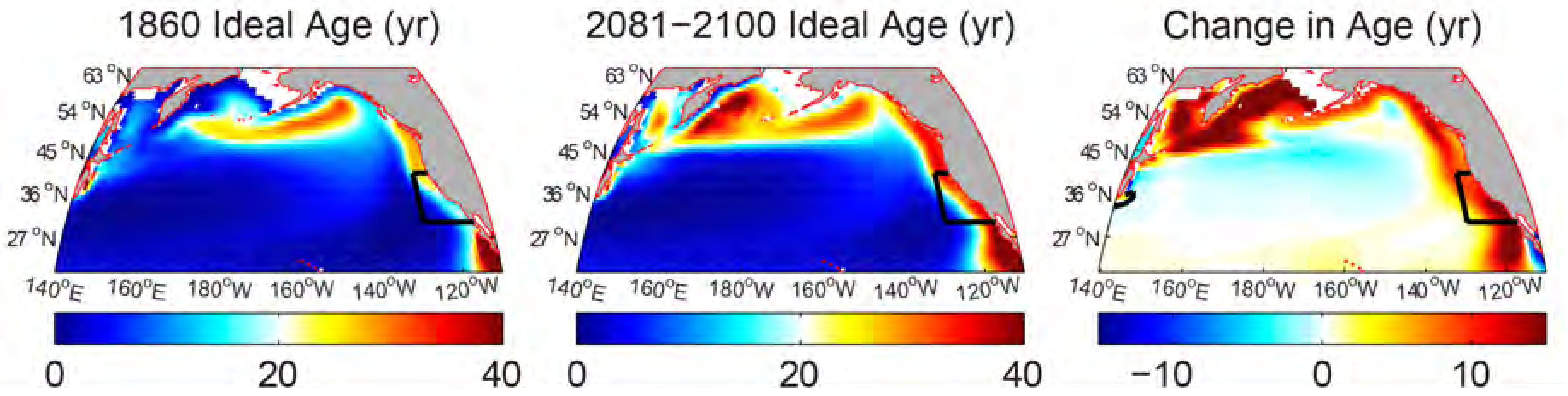
Changes in: ~~alongshore winds, alongshore currents, stratification and~~
~~mixing of the water column,~~
~~riverine input, local~~
~~biological rates~~



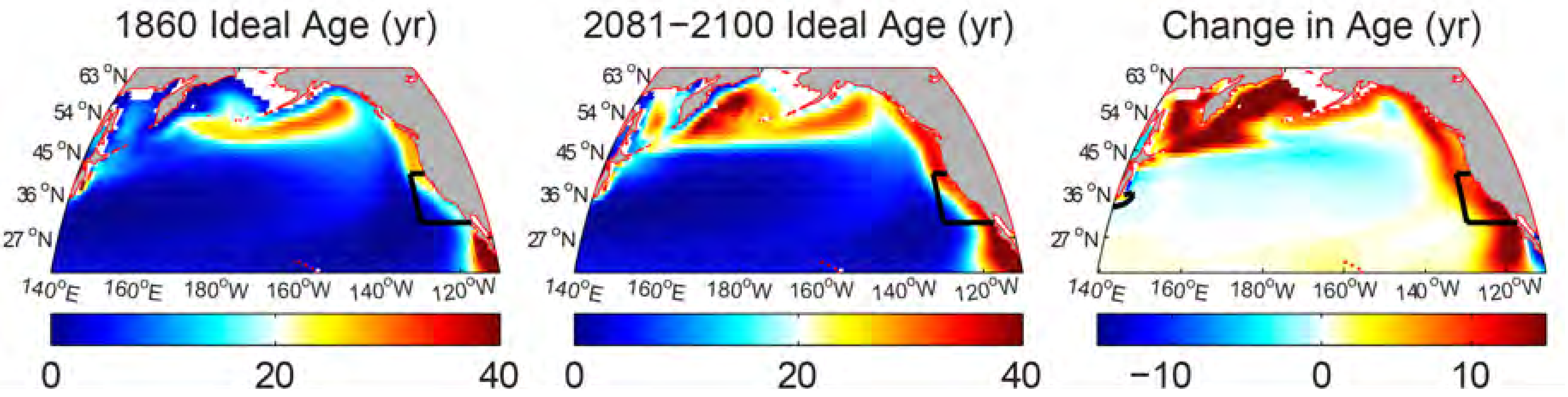
*Surprise from below*

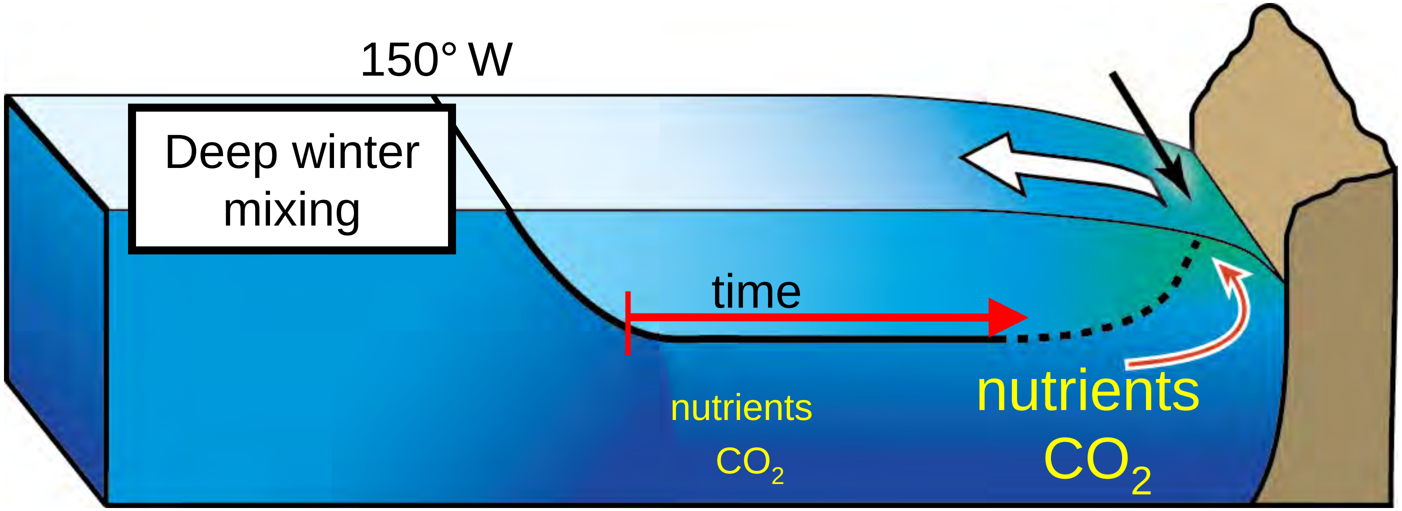
**Remote** changes in the properties of the deep source waters are more important than local physical conditions.

# *Decreased ventilation of the upwelled water mass is key*



# *Decreased ventilation of the upwelled water mass is key*





150° W

Deep winter mixing

time

nutrients

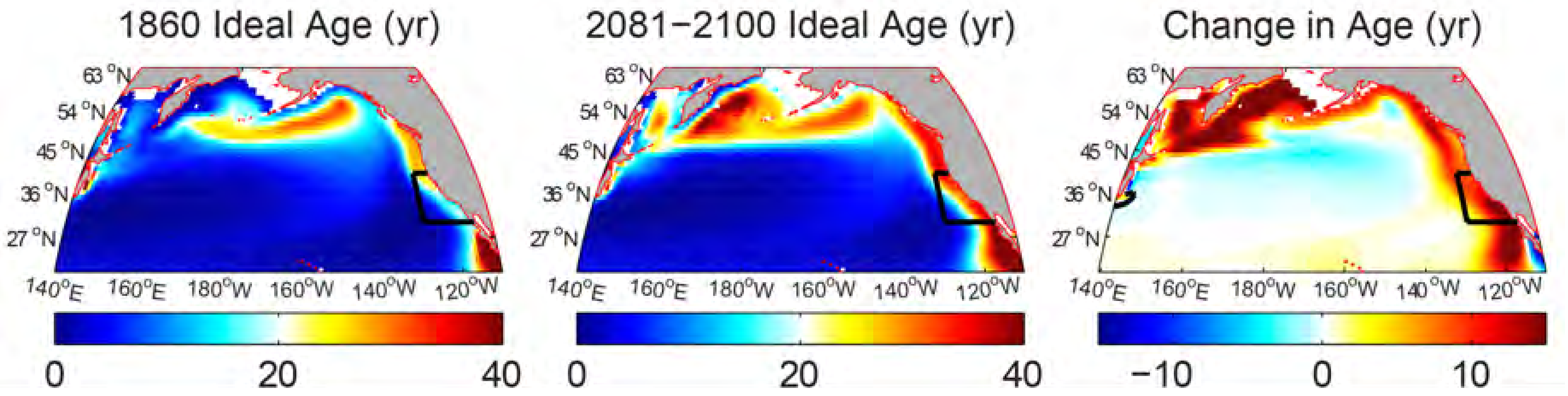
$CO_2$

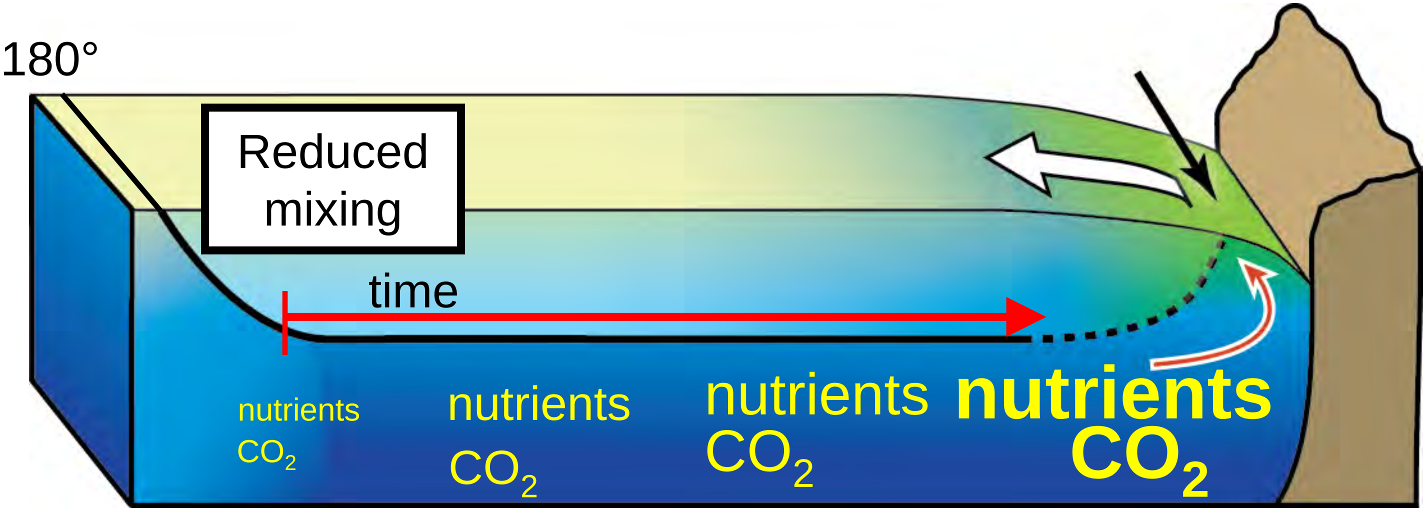
nutrients

$CO_2$

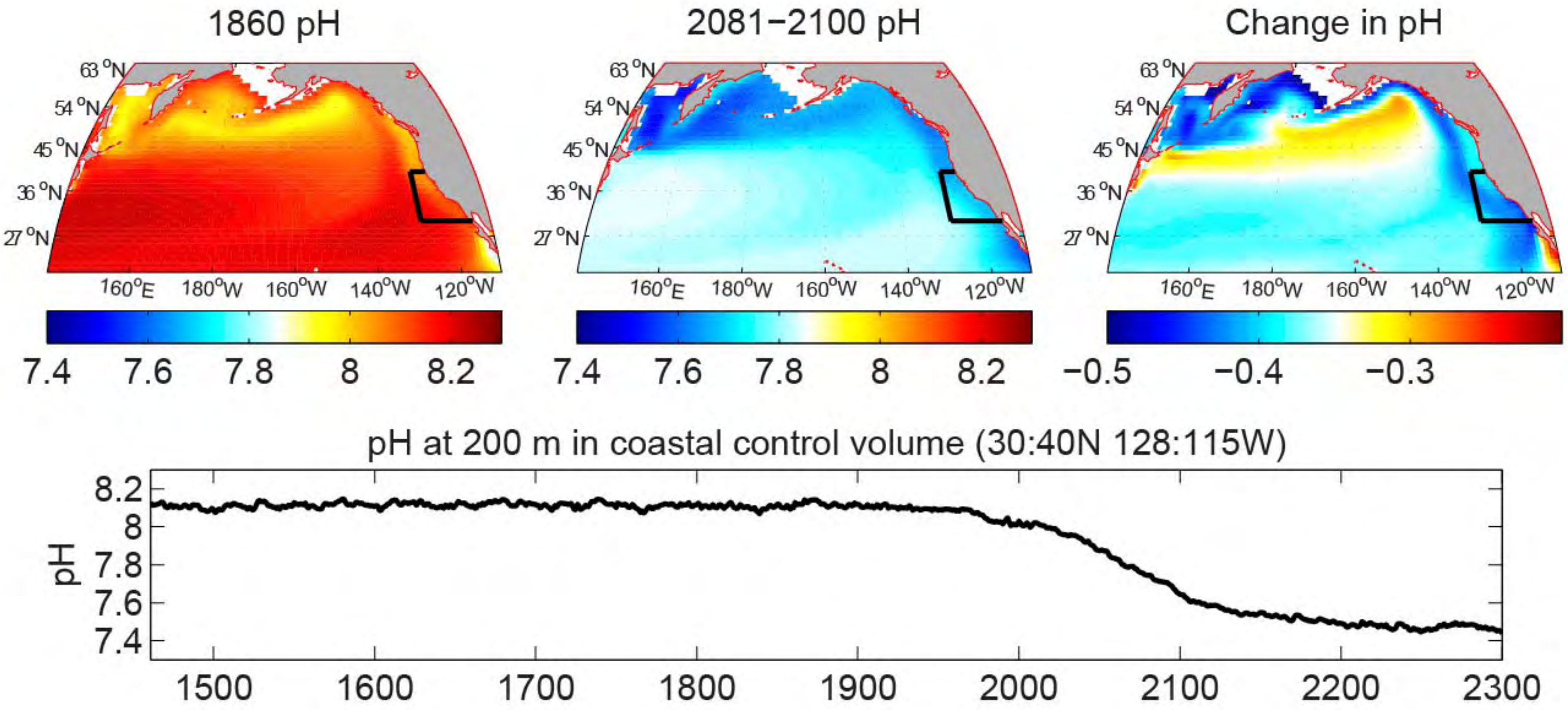
current
climate
state

# *Decreased ventilation of the upwelled water mass is key*



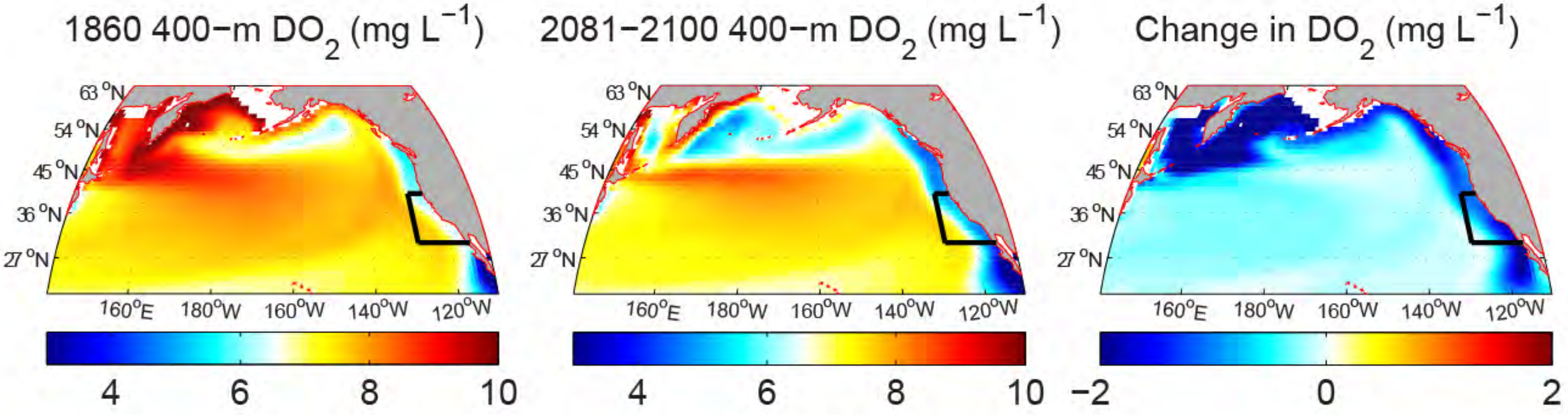


# *pH and oxygen are also sensitive to ventilation changes*



Rykaczewski and Dunne (2010, GRL)

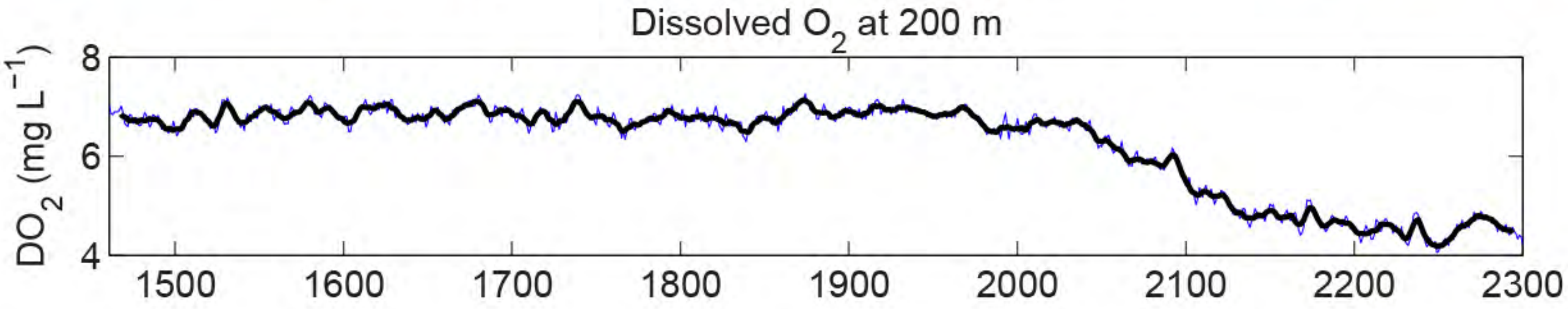
# *pH and oxygen are also sensitive to ventilation changes*



1860 400−m $DO_2$ (mg $L^{-1}$)

2081−2100 400−m $DO_2$ (mg $L^{-1}$)

Change in $DO_2$ (mg $L^{-1}$)

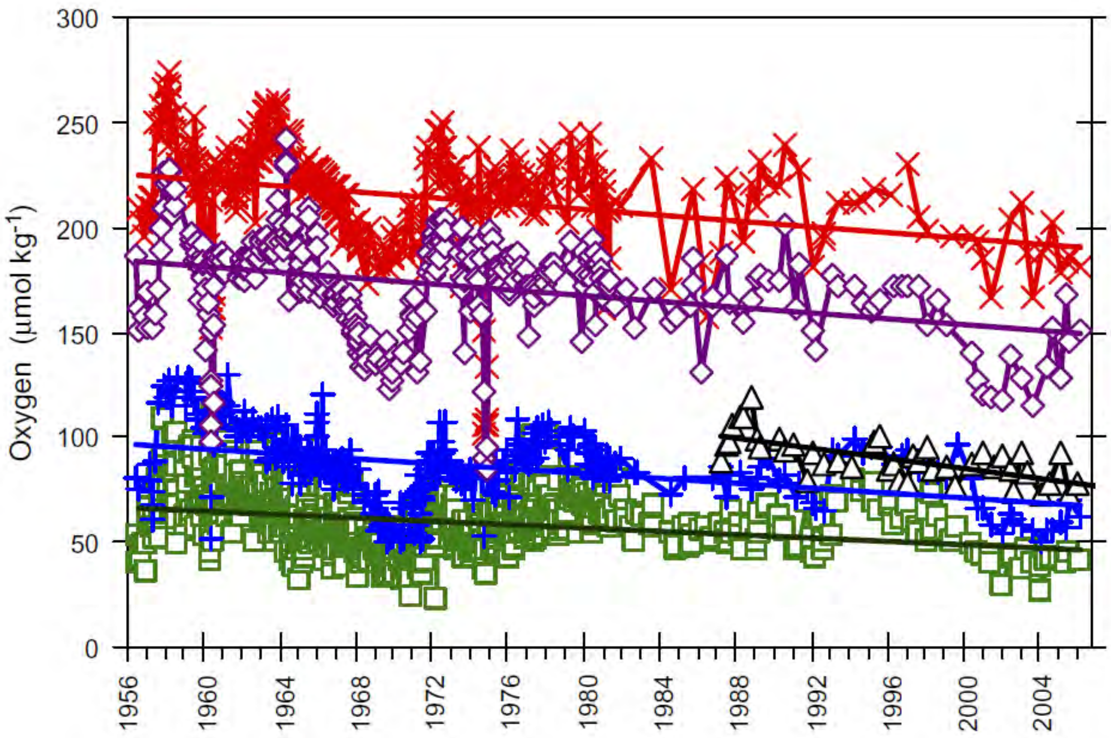


Dissolved $O_2$ at 200 m

Rykaczewski and Dunne (2010, GRL)

# *pH and oxygen are also sensitive to ventilation changes*

Ocean Station P on the 26.5 (×), 26.7 (◇), 26.9 (+) and 27.0 (□) isopycnal surfaces



Whitney, *et al*. (2007, *Prog. Oceanogr.*)

[Smith, Bograd, Whitney, Barth, Koslow, Gnanadesikan; session S8]

# *What general relationships can be gleaned from this example?*

The most surprising finding for me was realization of the dependence of coastal properties on basin-scale changes.

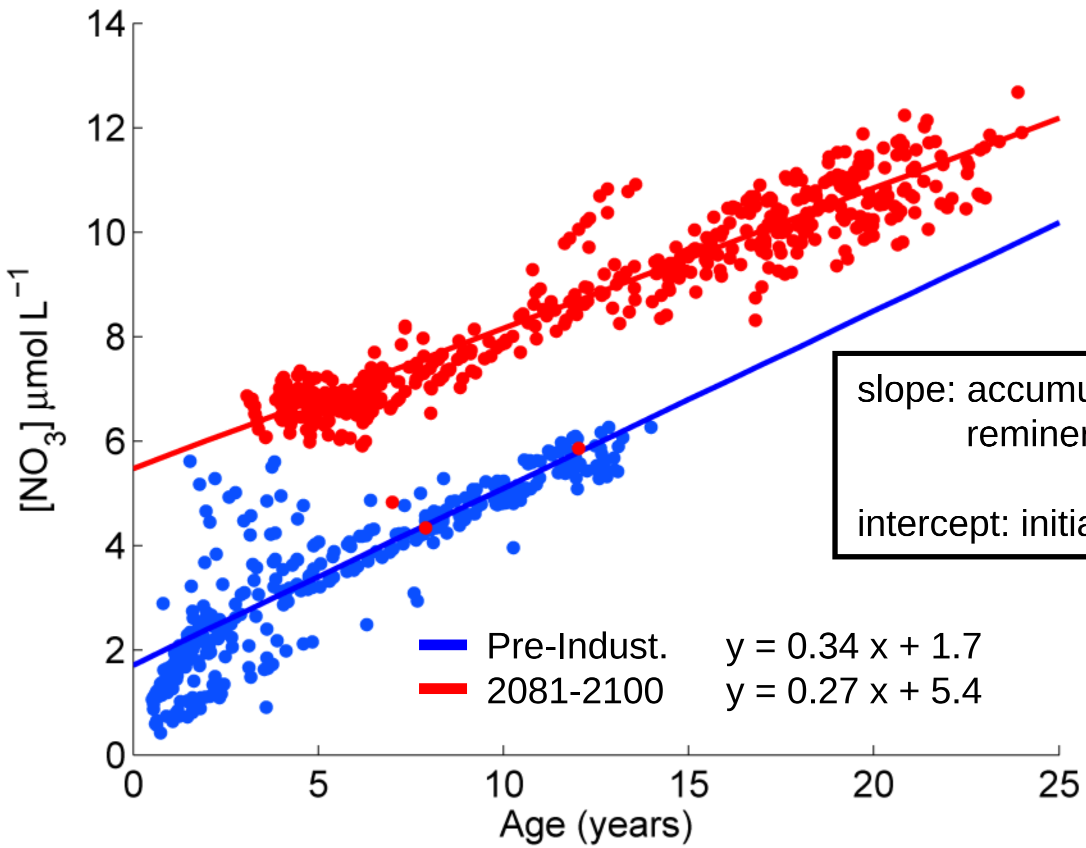
Three main factors control the dynamics of nutrients found in a water parcel:

1. Preformed concentrations— the concentration of nutrients in the water parcel when it is subducted from the euphotic zone at its place of origin.

2. The rate at which organic matter is remineralized, returning inorganic nutrients to the water mass.

3. The duration of time over which the parcel has accumulated remineralized nutrients (*i.e.*, the ventilation age)

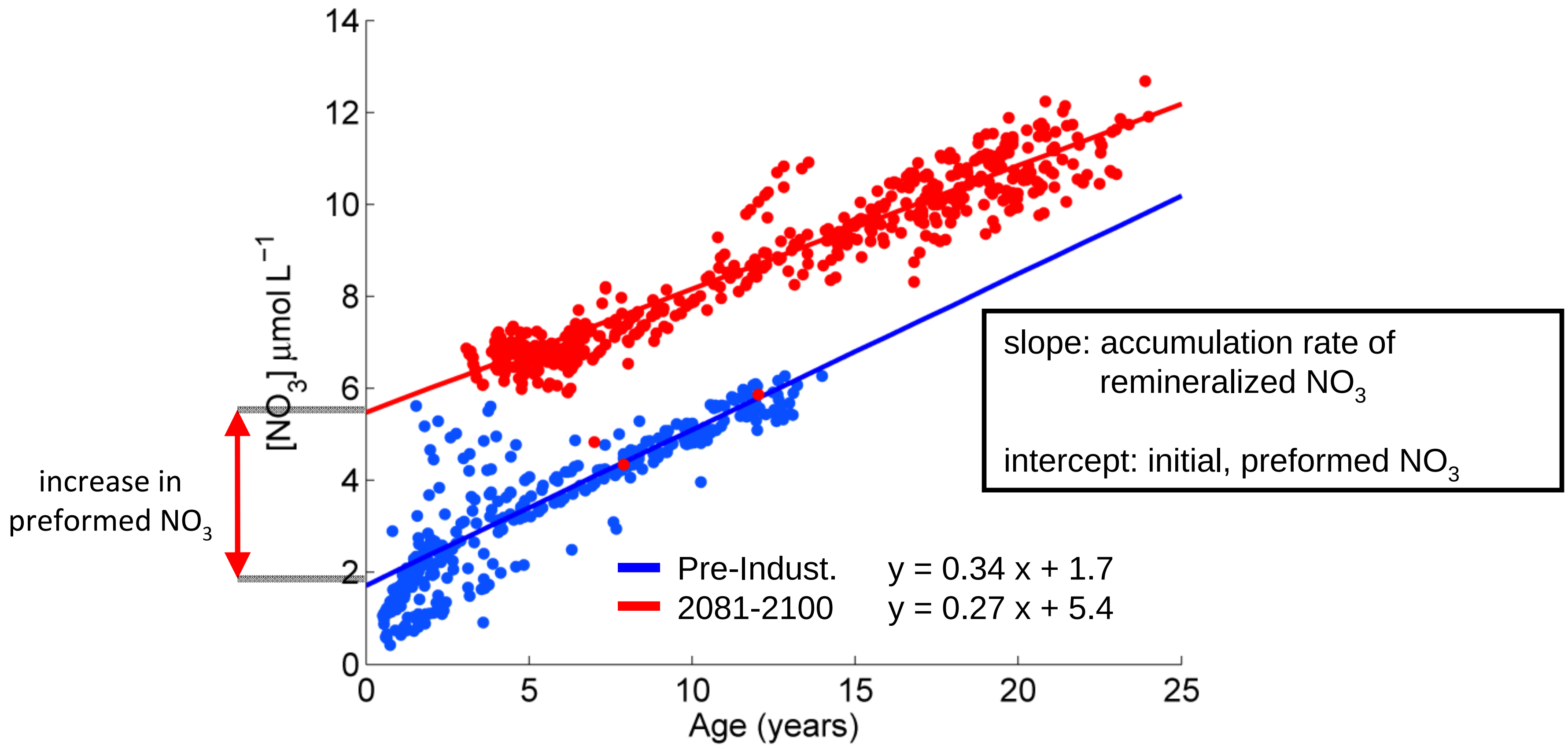
# *History of California Current source waters*



slope: accumulation rate of remineralized $NO_3$

intercept: initial, preformed $NO_3$

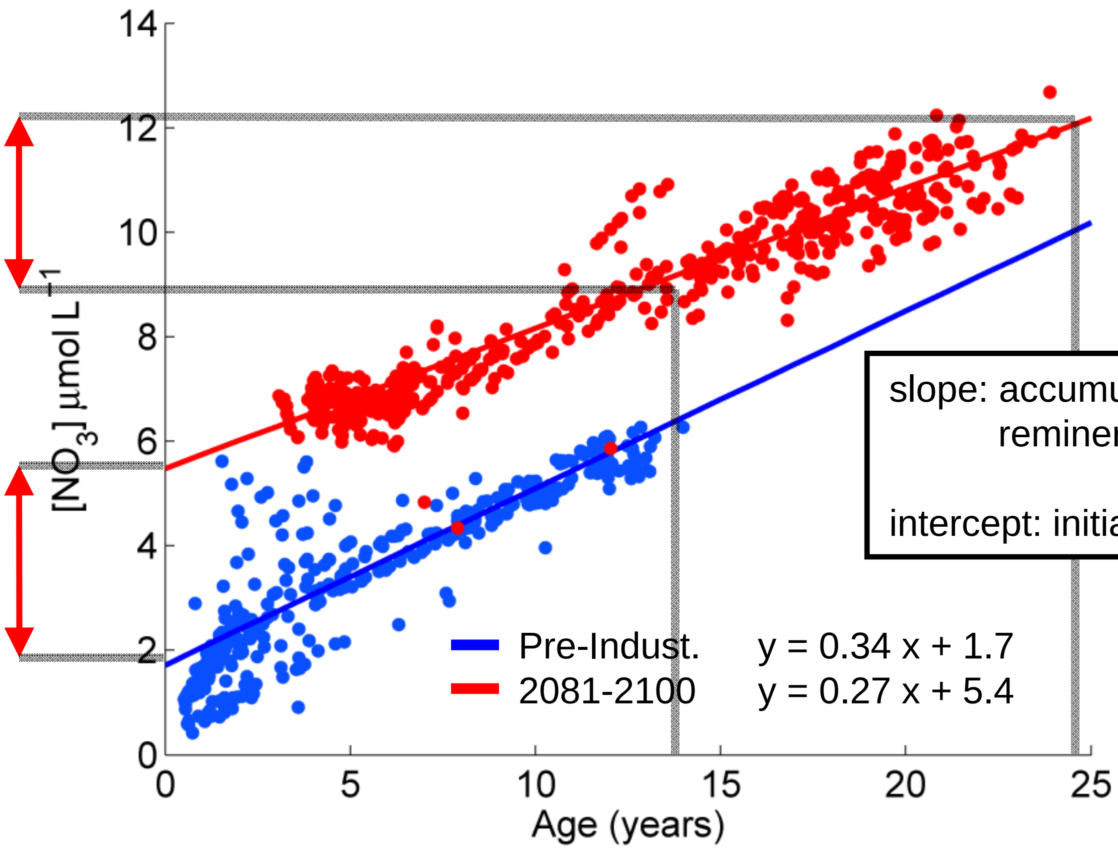
# *History of California Current source waters*



slope: accumulation rate of remineralized $NO_3$

intercept: initial, preformed $NO_3$

# *History of California Current source waters*



increase in remineralized $NO_3$

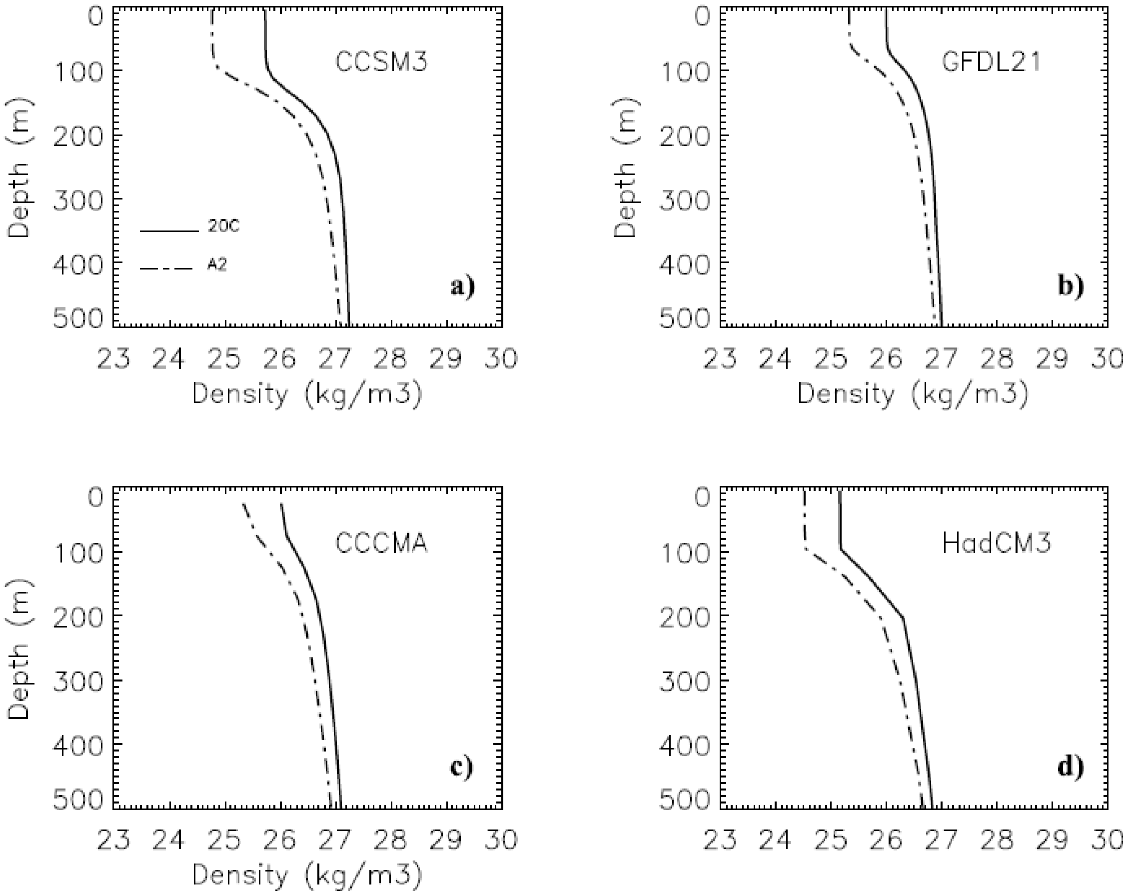
increase in preformed $NO_3$

slope: accumulation rate of remineralized $NO_3$

intercept: initial, preformed $NO_3$

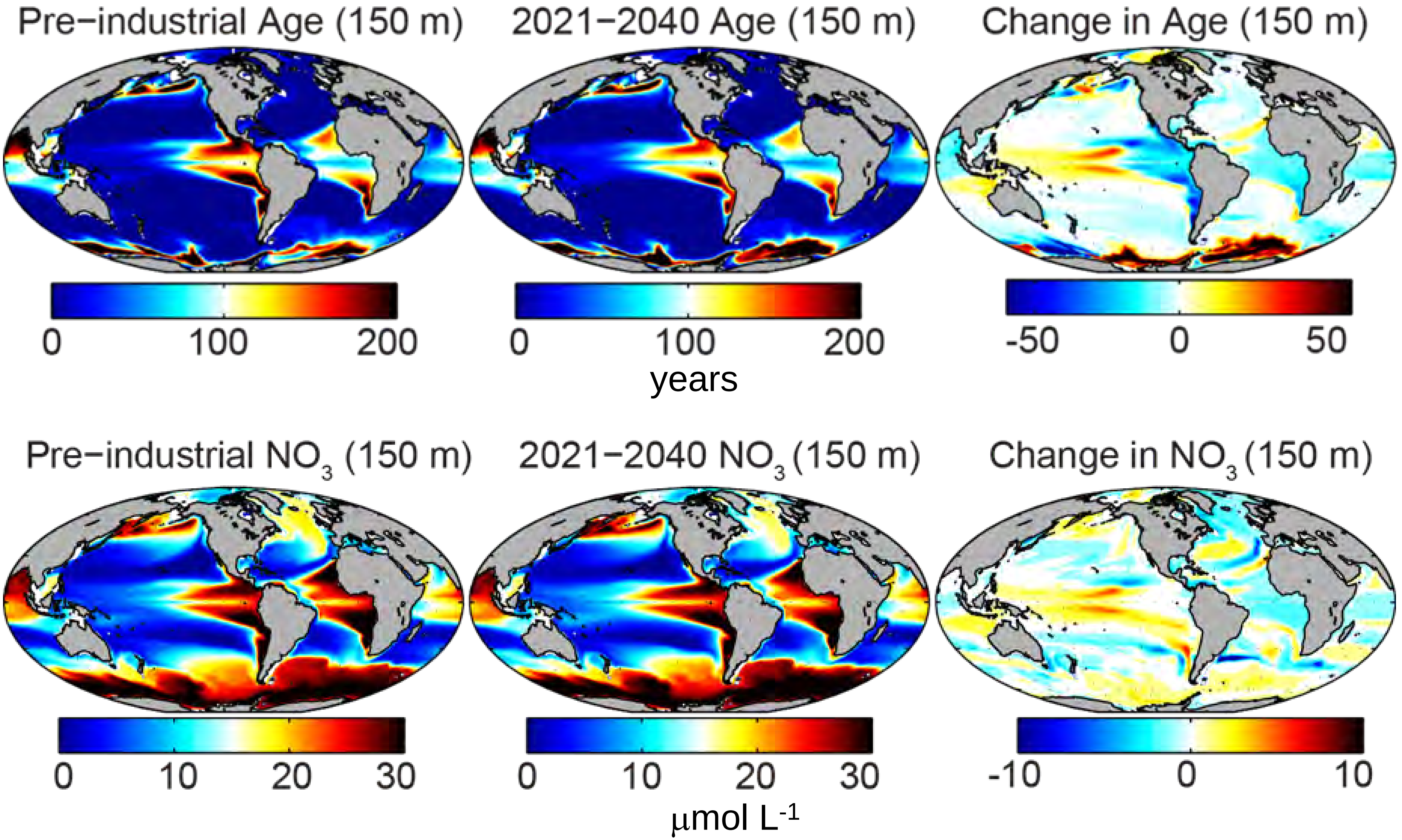
# *Is this result for the CCE applicable to all upwelling systems?*

Increased stratification is a global phenomenon and is consistent across model projections.

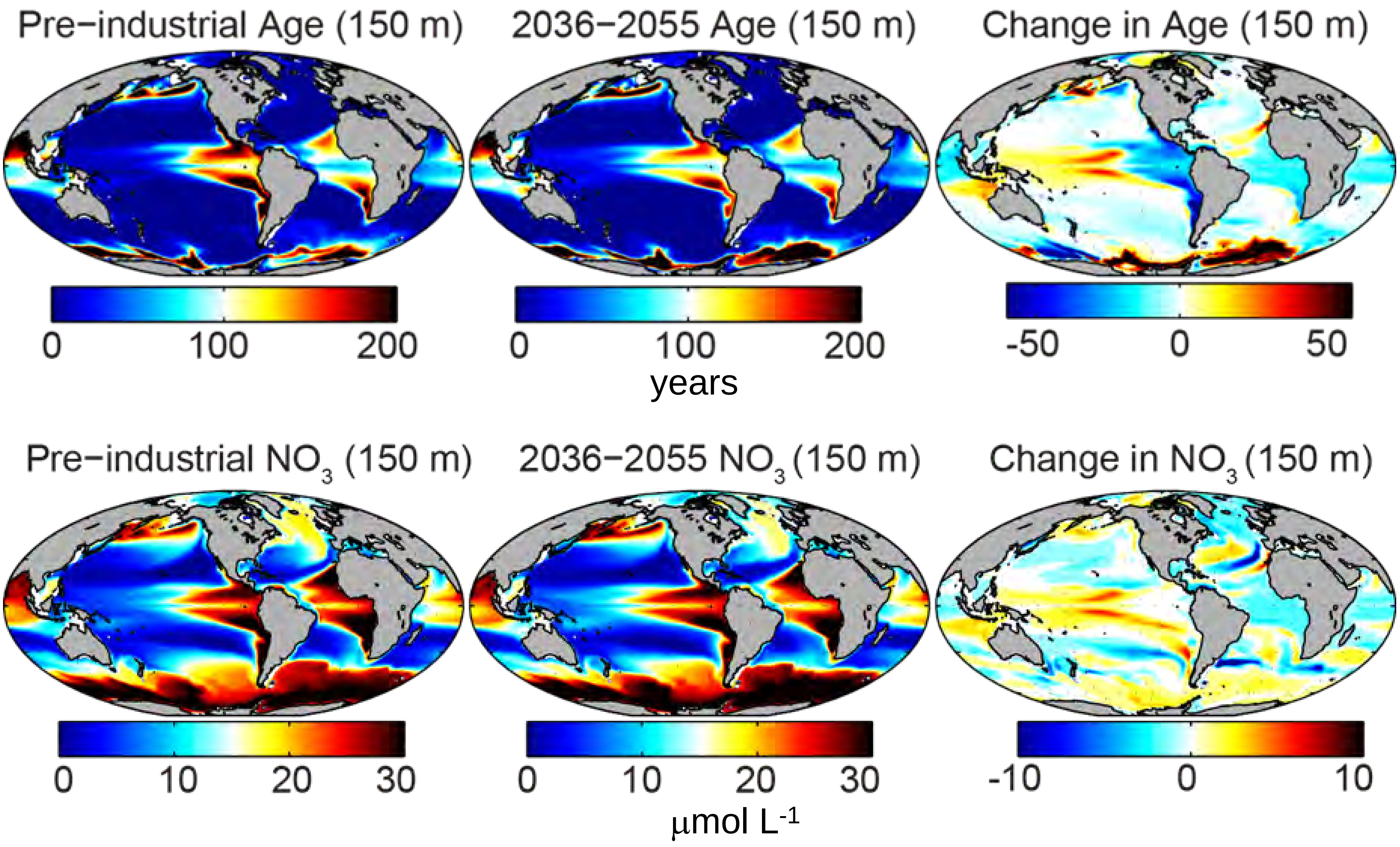


Capotondi *et al.*, (2012, JGR)

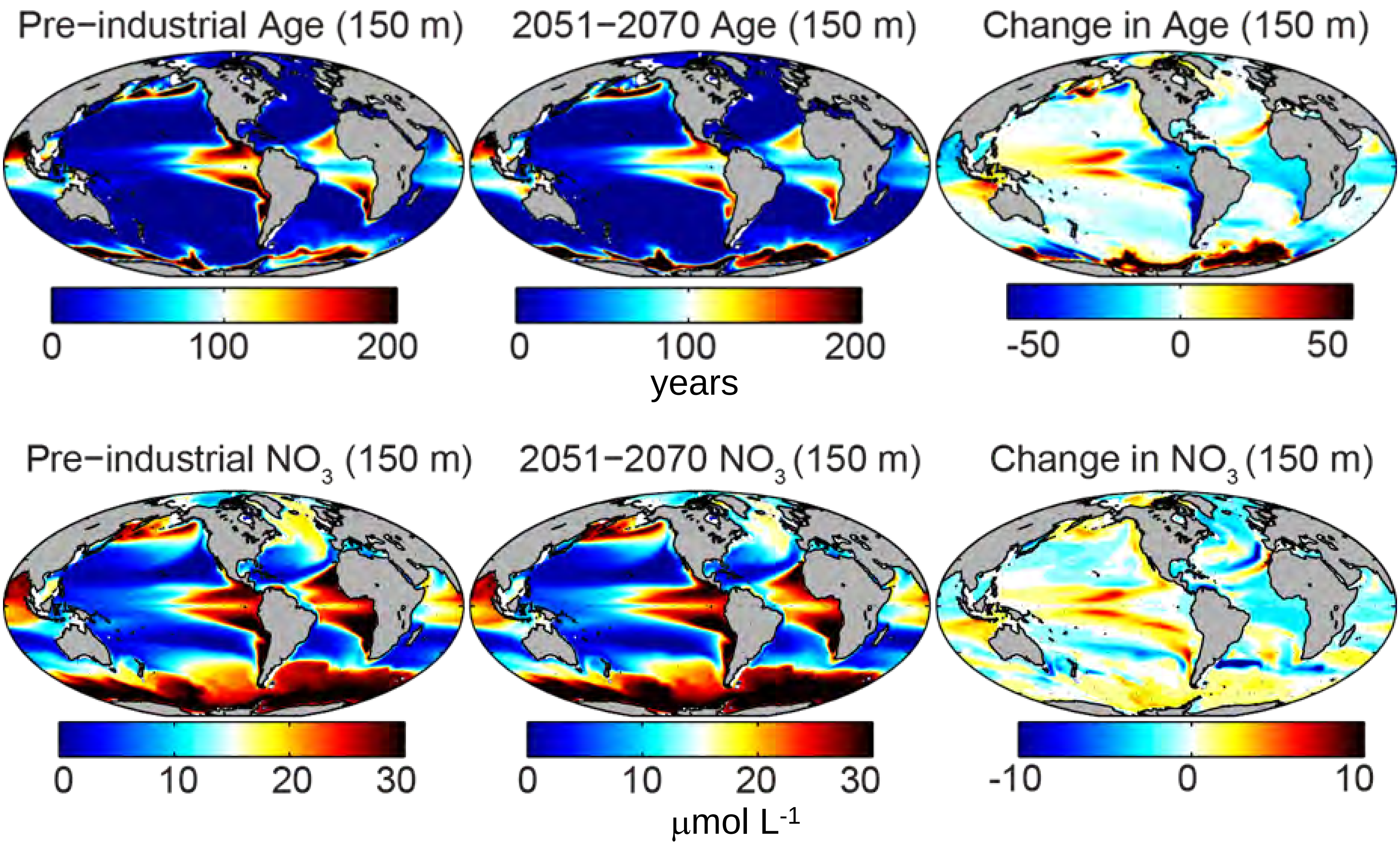
# *2040: Global age and $NO_3$ changes (150 m)*



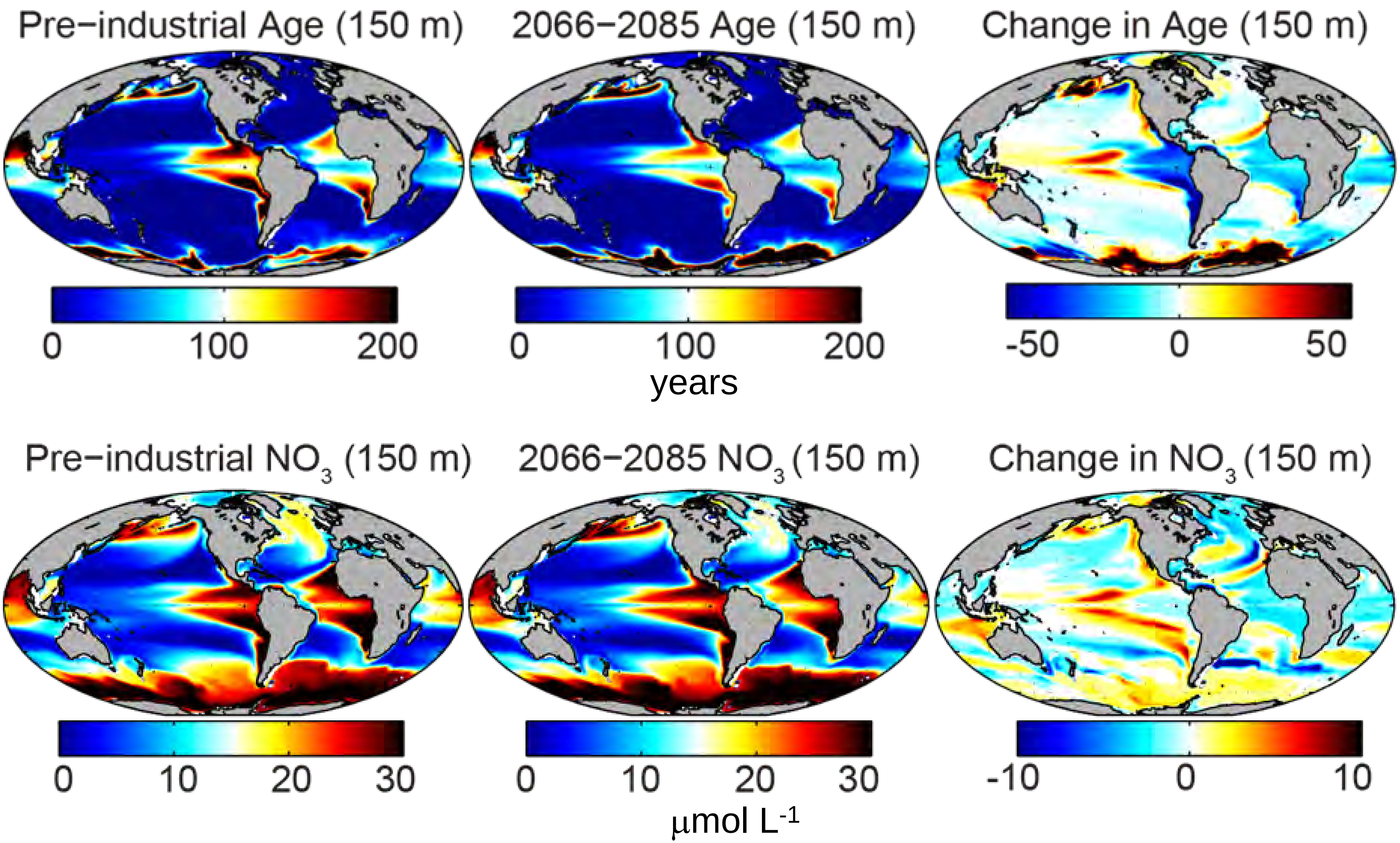
# *2055: Global age and $NO_3$ changes (150 m)*



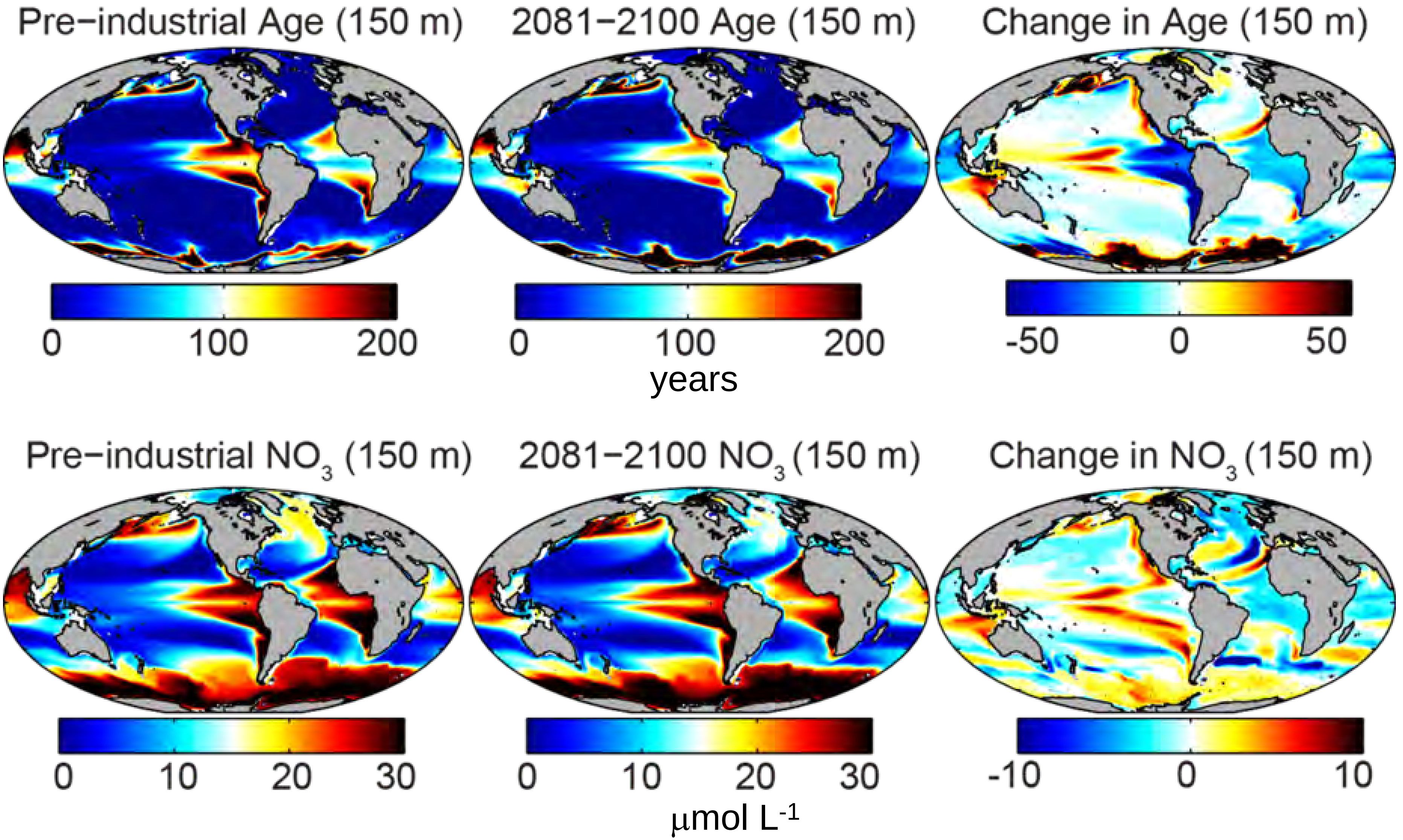
# *2070: Global age and $NO_3$ changes (150 m)*



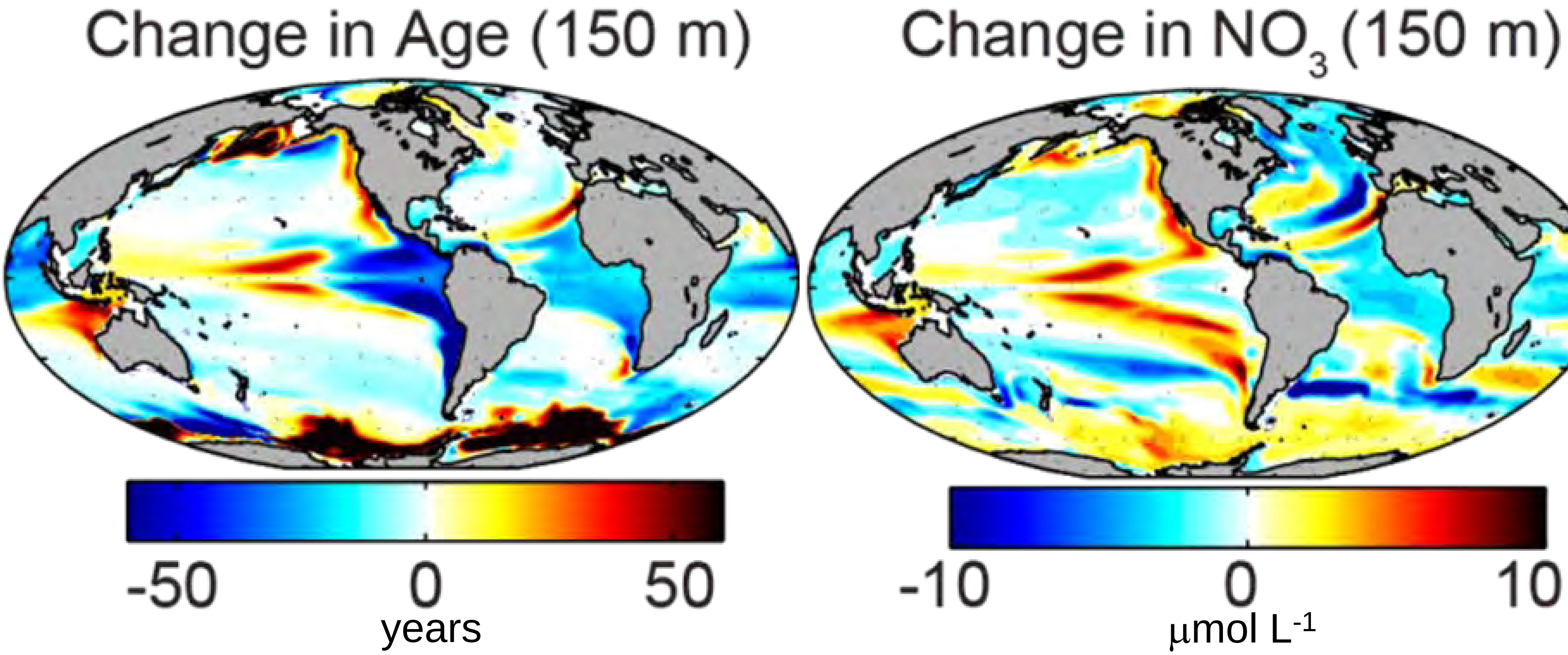
# *2085: Global age and $NO_3$ changes (150 m)*



# 2100: Global age and $NO_3$ changes (150 m)



# 2100: Global age and $NO_3$ changes (150 m)



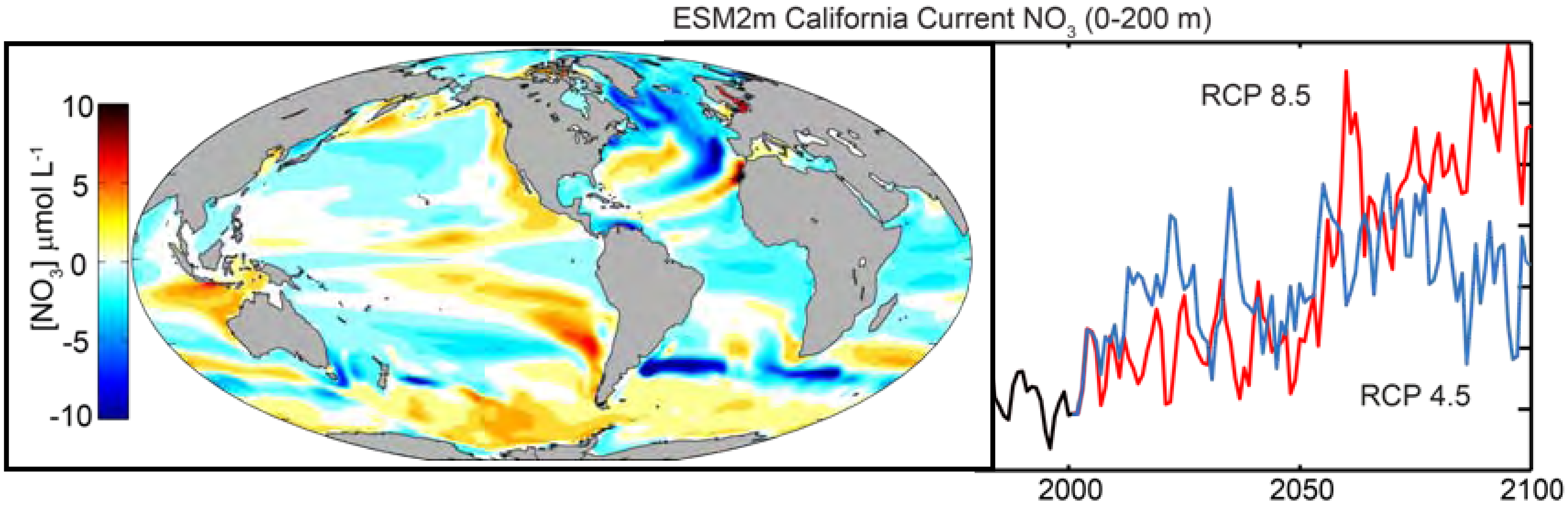
# *Changes in ventilation age and $NO_3$ differ across systems*

Ventilation age does not increase uniformly with increased stratification.

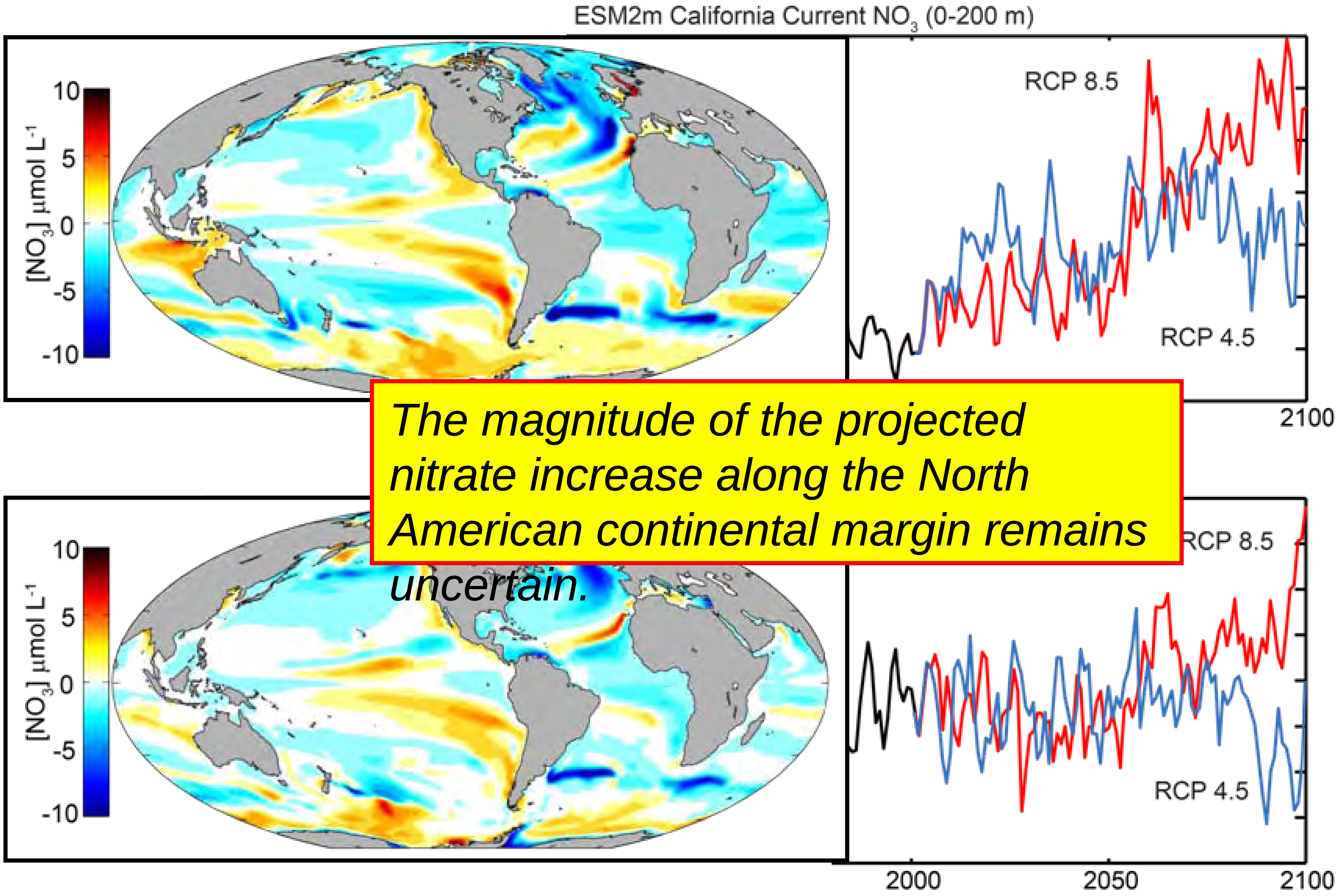
Increased ventilation of the tropics might be expected with future increased stratification (see Gnanadesikan *et al.*, 2007, *Ocean Sci.*), and this appears to dominate changes in low-latitude, coastal upwelling systems.

Though dominant mechanisms in other upwelling systems may differ from those in the California Current, it is important to recognize that trends in deep-water biogeochemical properties along coastal margins can be expected.

# *AR5 Generation of GFDL Earth System Models*


ESM2m California Current $NO_3$ (0-200 m)

# *AR5 Generation of GFDL Earth System Models*



*The magnitude of the projected nitrate increase along the North American continental margin remains uncertain.*

# *Two-pronged approach regarding uncertainty*

I would advocate for use of at least one (ideally both) of the following strategies:

1. Make use of multi-model projection ensembles, when possible.

2. Develop a process-level understanding of the key factors which structure ecosystem responses. This is not trivial, but provides insight into potential unexpected relationships.

Example—
The long-term trend in nutrient supply to the California Current may be sensitive to ventilation in the Central and Western North Pacific.

# *Concluding remarks…*

Three important messages:

1. Boundary conditions are dynamic along many coastal margins.

Changes at these boundaries cannot be attributed to a single mechanism, but it is important to consider how basin-scale processes can shift the biogeochemical baseline along continental margins.

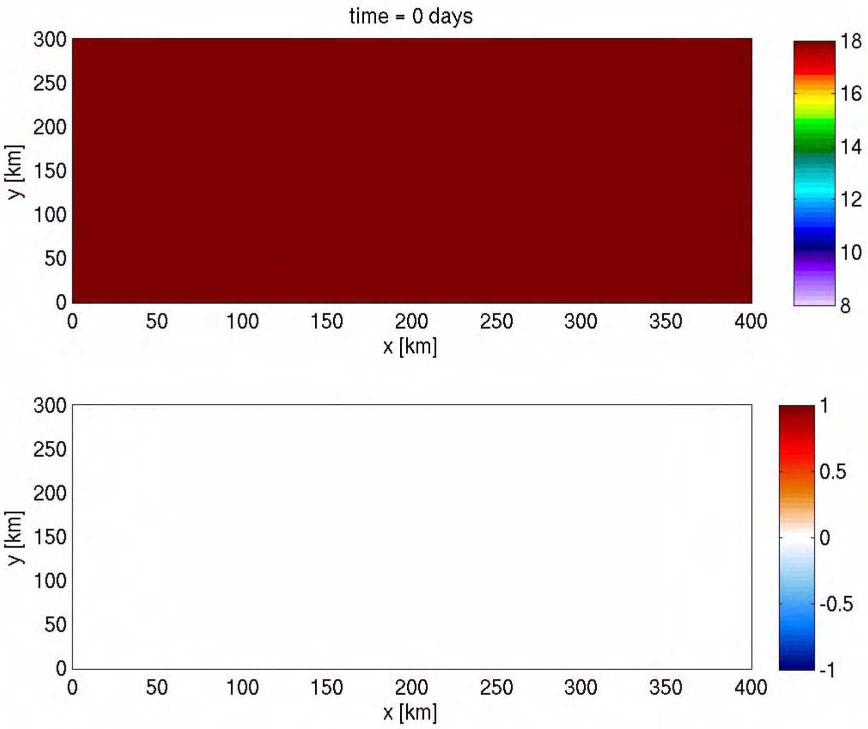
# *Concluding remarks…*

Three important messages:

2. **Assume climatological boundary conditions at your own risk!**

   Consideration of local physical forcing is essential to examine future changes in mesoscale to seasonal to decadal processes…

   But the long-term trend in deep-water properties may be the dominant component of future changes in nutrients, oxygen, pH and other biogeochemical properties.



# *Concluding remarks…*

Three important messages:

3. For fellow biologists— Let’s loosen our grip a bit on some of the past hypotheses relating lower-trophic-level ecosystem processes with physical forcing.

   We should try to think outside of the box a bit more and question the assumptions we’re making by turning study of lower-trophic-level biology to regional physical modelers.

# Thank you for your attention and the invitation!

Ryan Rykaczewski
*ryanrr@princeton.edu*

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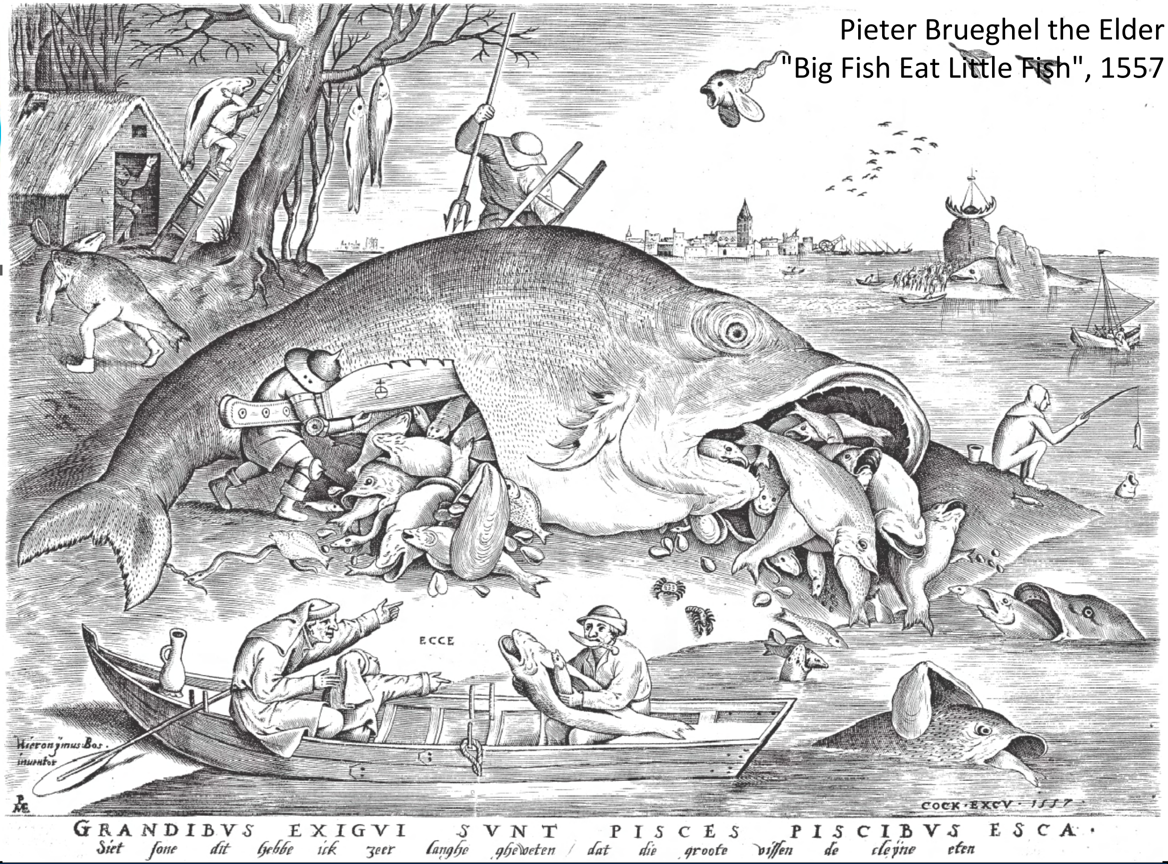

Pieter Brueghel the Elder
"Big Fish Eat Little Fish", 1557