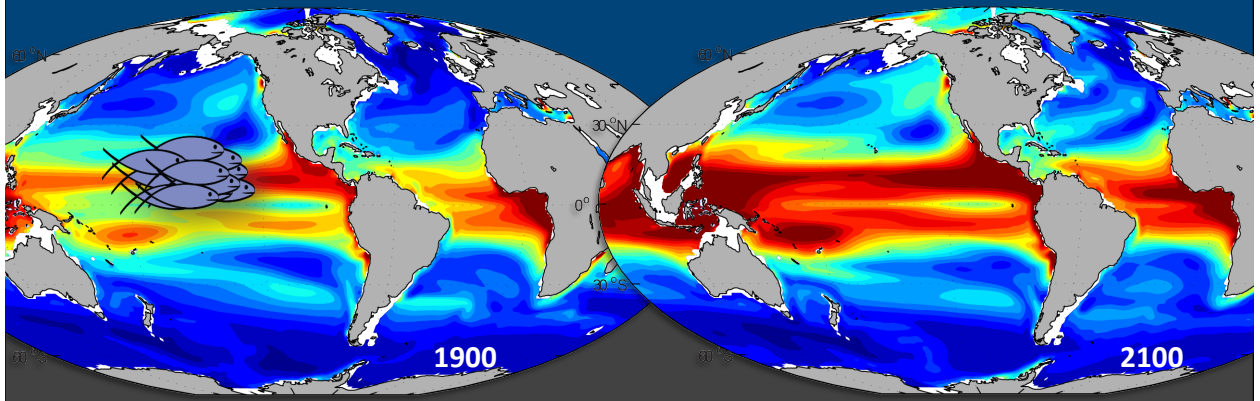
Consequences of large-scale climate change on the nutrients supplied to upwelling ecosystems



UNIVERSITY OF SOUTH CAROLINA

PRINCETON UNIVERSITY

NOAA

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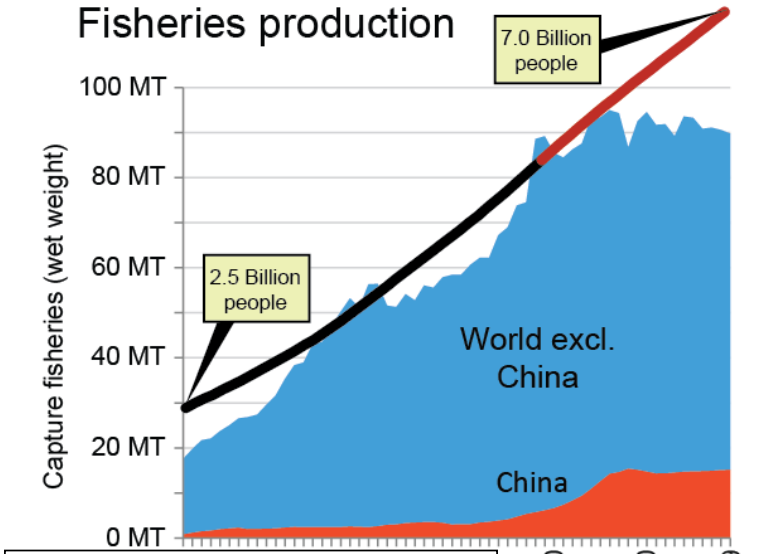
University of South Carolina

ryk @ sc.edu

Long-term goal: *understand the dynamics of upwelling ecosystems*

Upwelling systems:

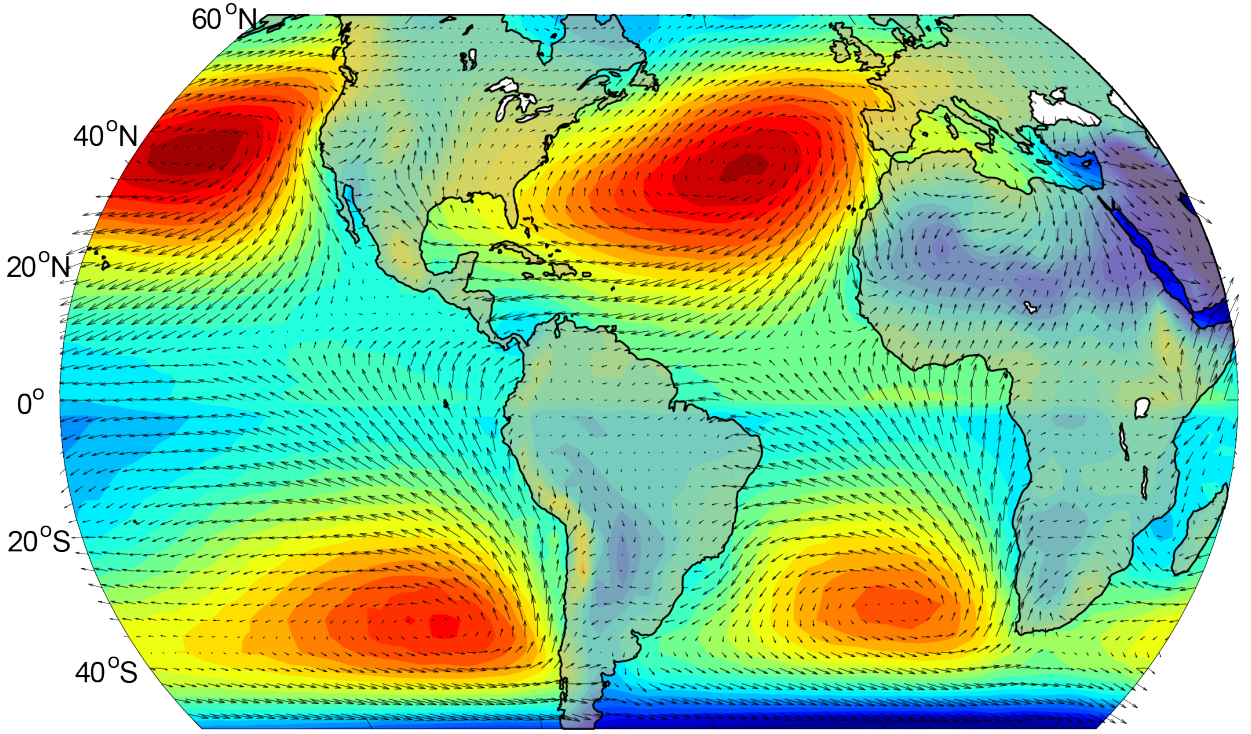
- support highly productive food webs.
- may play a role in large-scale climate processes.
- sustainable fisheries critical to the world's food supply.



~25% of global landings; source of good, quality protein.

FAO, United Nations (2010)

Physical variability has clear influence on these systems



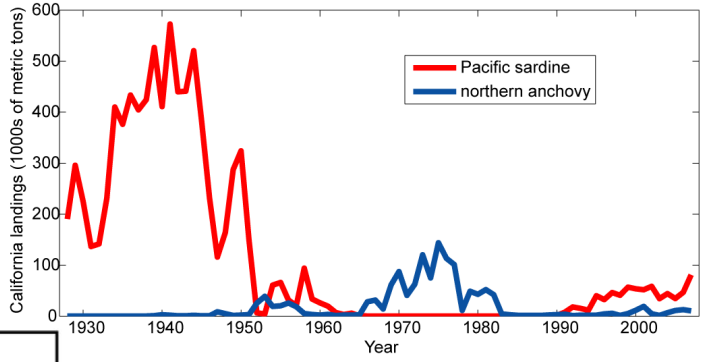
Many hypotheses relate fisheries fluctuations to physics

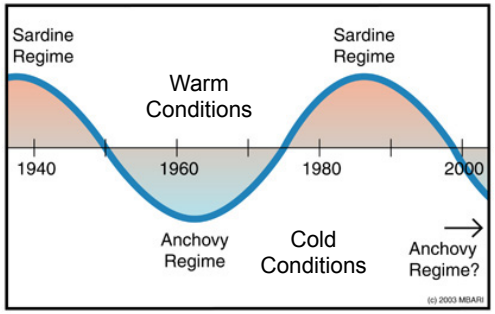
What drives past changes in fish abundance?

Overfishing?

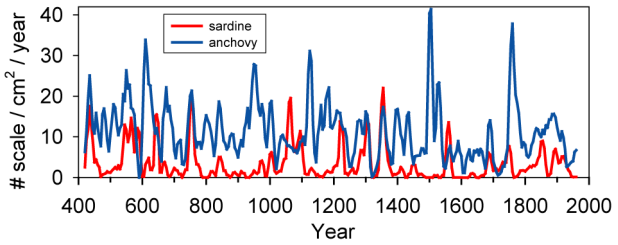
Environmental variability?

How?
Why?





Chavez *et al.* (2003)



Soutar and Isaacs (1969); Baumgartner *et al.* (1992)

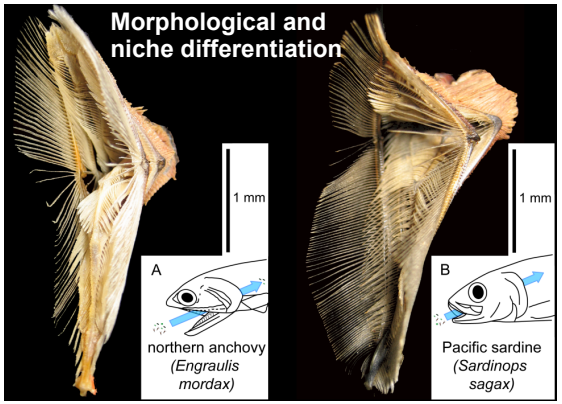
Size distributions of plankton may influence species' success

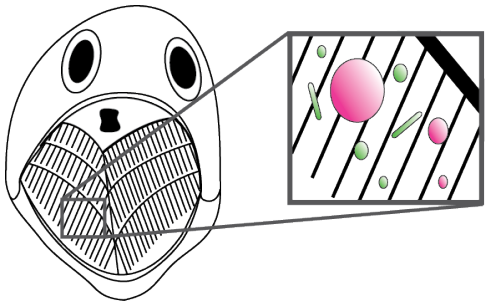
What drives past changes in fish abundance?

Overfishing?

Environmental variability?

How?
Why?

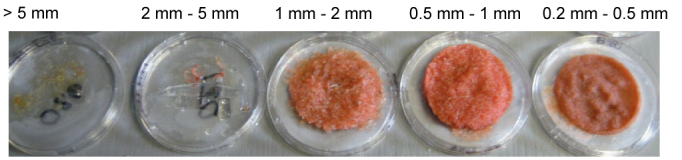


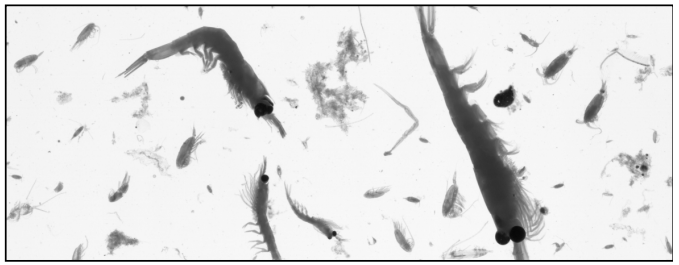


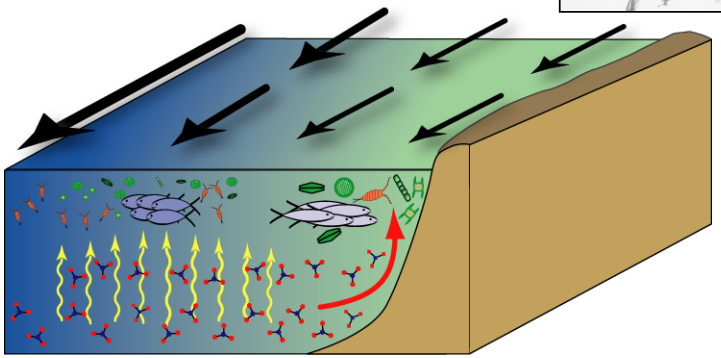
Rates of nutrient supply impact plankton composition

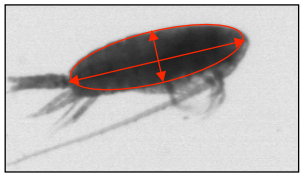
What drives past changes in fish abundance?

H: Physical changes influence the size structure of the zooplankton community.

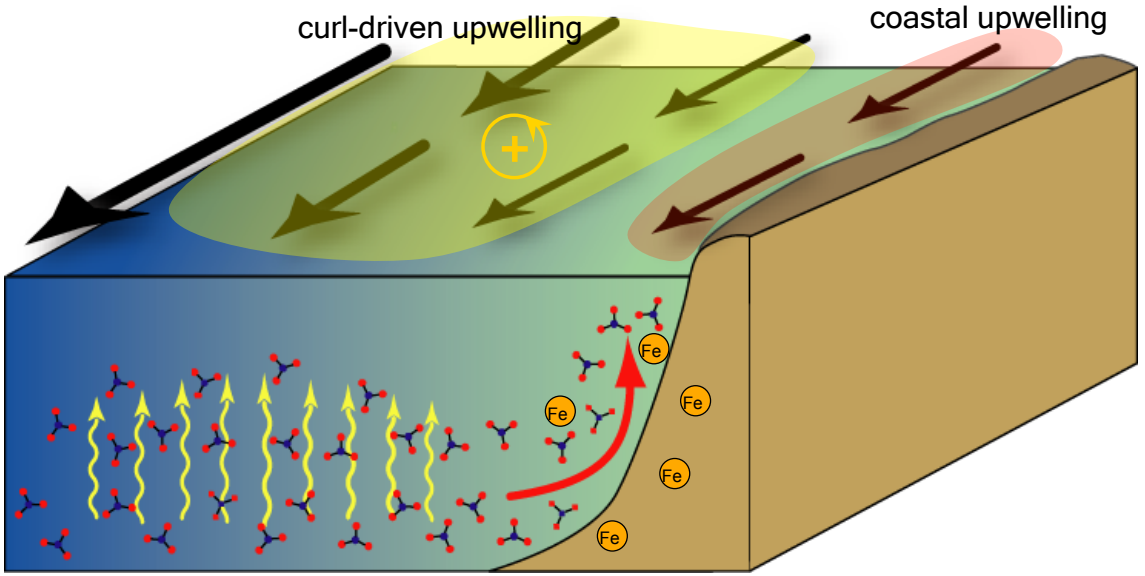






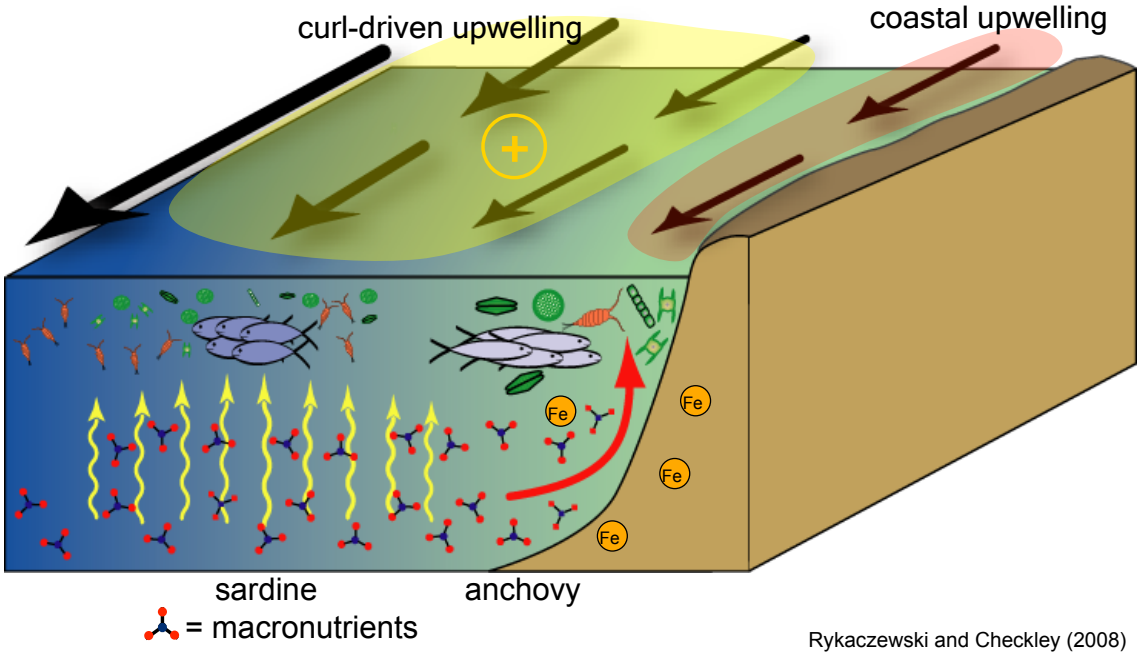


Wind-driven upwelling processes and the food web



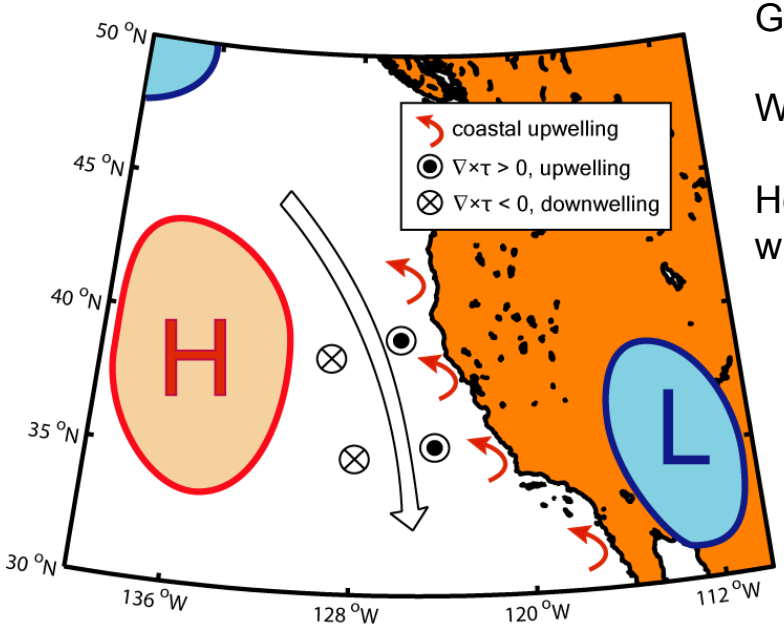
Rykaczewski and Checkley (2008)

Wind-driven upwelling processes and the food web



Rykaczewski and Checkley (2008)

Can this idea be applied to look at future changes?



Great.

What about the future?

How much fish production will there be?

Will anthropogenic climate change favor sardines, anchovies, or something else?

Project seen as an opportunity to bridge divisions within NOAA

Research offices of NOAA (the National Oceanic and Atmospheric Administration):

National Marine Fisheries Service:

"Responsible for the stewardship of the nation's living marine resources and their habitat."

stock assessment; fishing regulations

Oceanic and Atmospheric Research:

"Provides the research foundation for understanding the complex systems that support our planet."

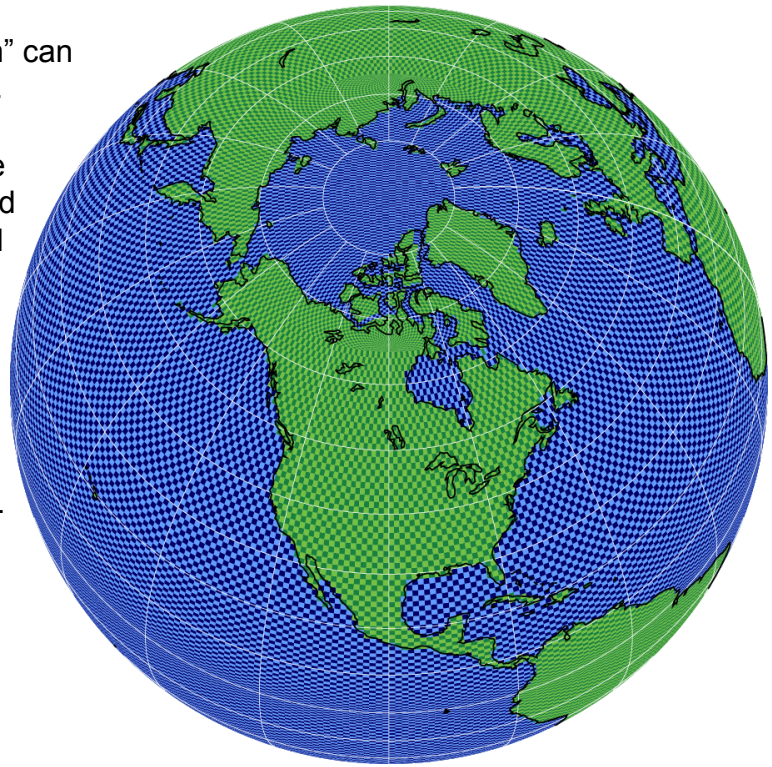
physics, chemistry, and biogeochemistry of climate change; GCMs and "earth-system" modeling

Earth-System Modeling: *atmosphere, hydrosphere, cryosphere and biosphere*

The complete “earth system” can be modeled mathematically.

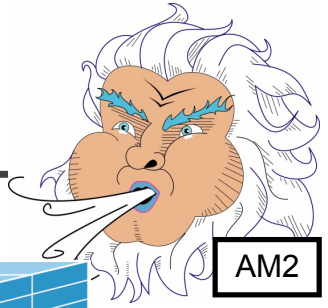
Atmosphere, ocean, and ice components are represented by interacting grid cells, and this composes a coupled General Circulation Model (GCM).

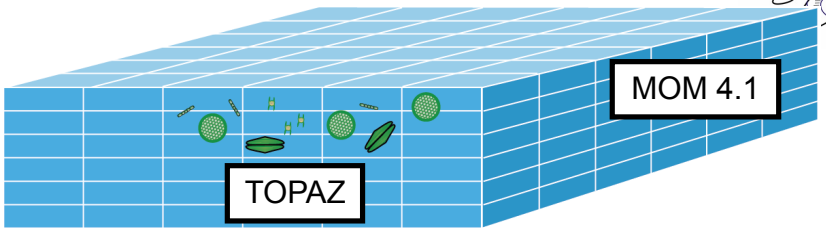
Including the **biosphere** within a GCM makes an Earth-System Model (ESM).



Configuration of NOAA's ESM 2.1

Here, I made use of model runs with projected CO_2 emissions for the 21st century following **IPCC** emissions scenario **A2**.



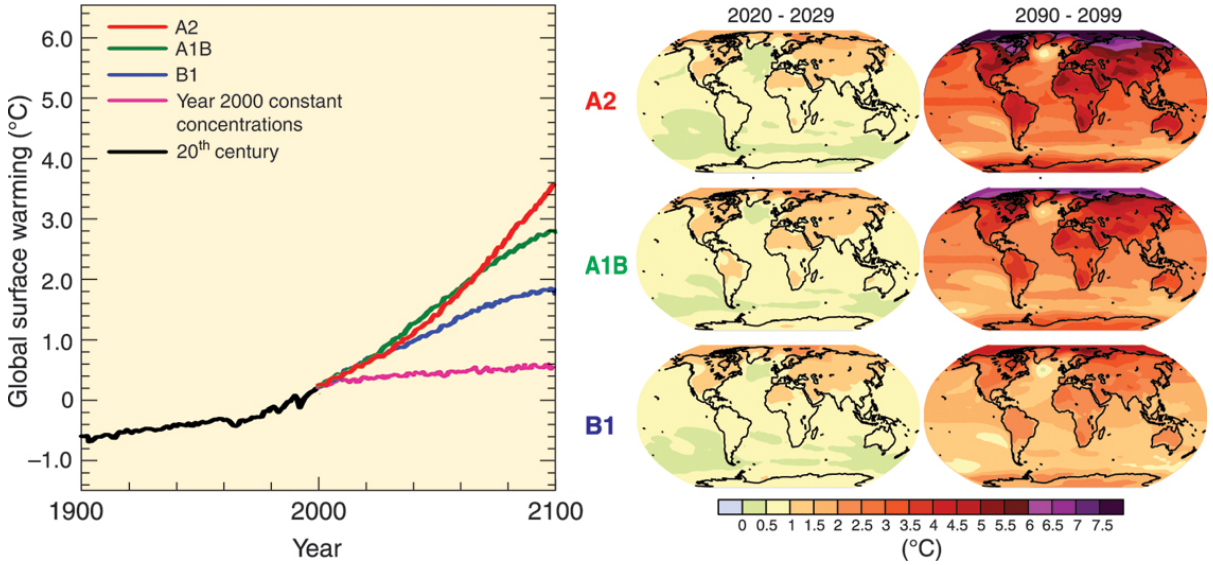


Atmosphere: NOAA-GFDL **AM2** (Anderson et al., 2004); 2° x 2.5° horizontal resolution

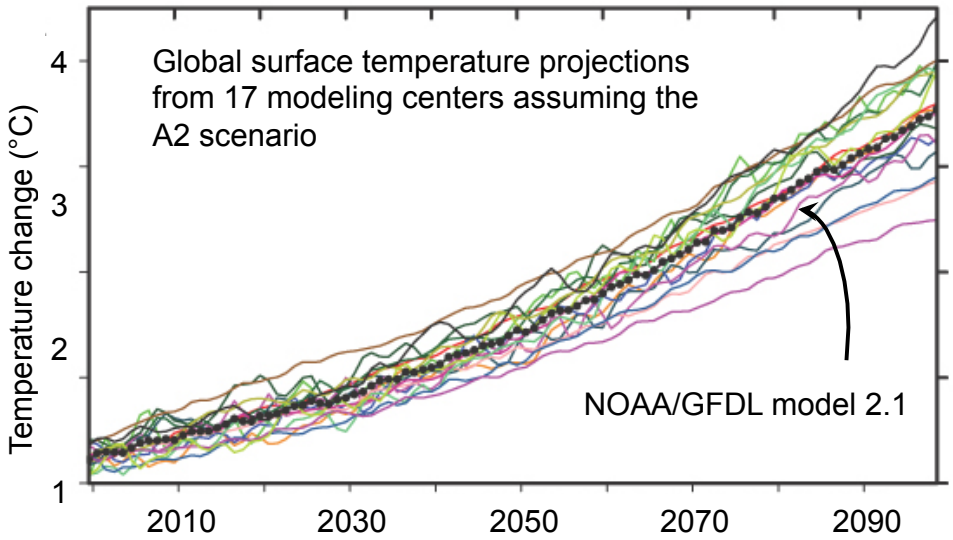
Ocean: NOAA-GFDL **MOM 4.1** (Modular Ocean Model; Pacanowski and Griffies, 1999); 1° x 1° horizontal resolution

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).

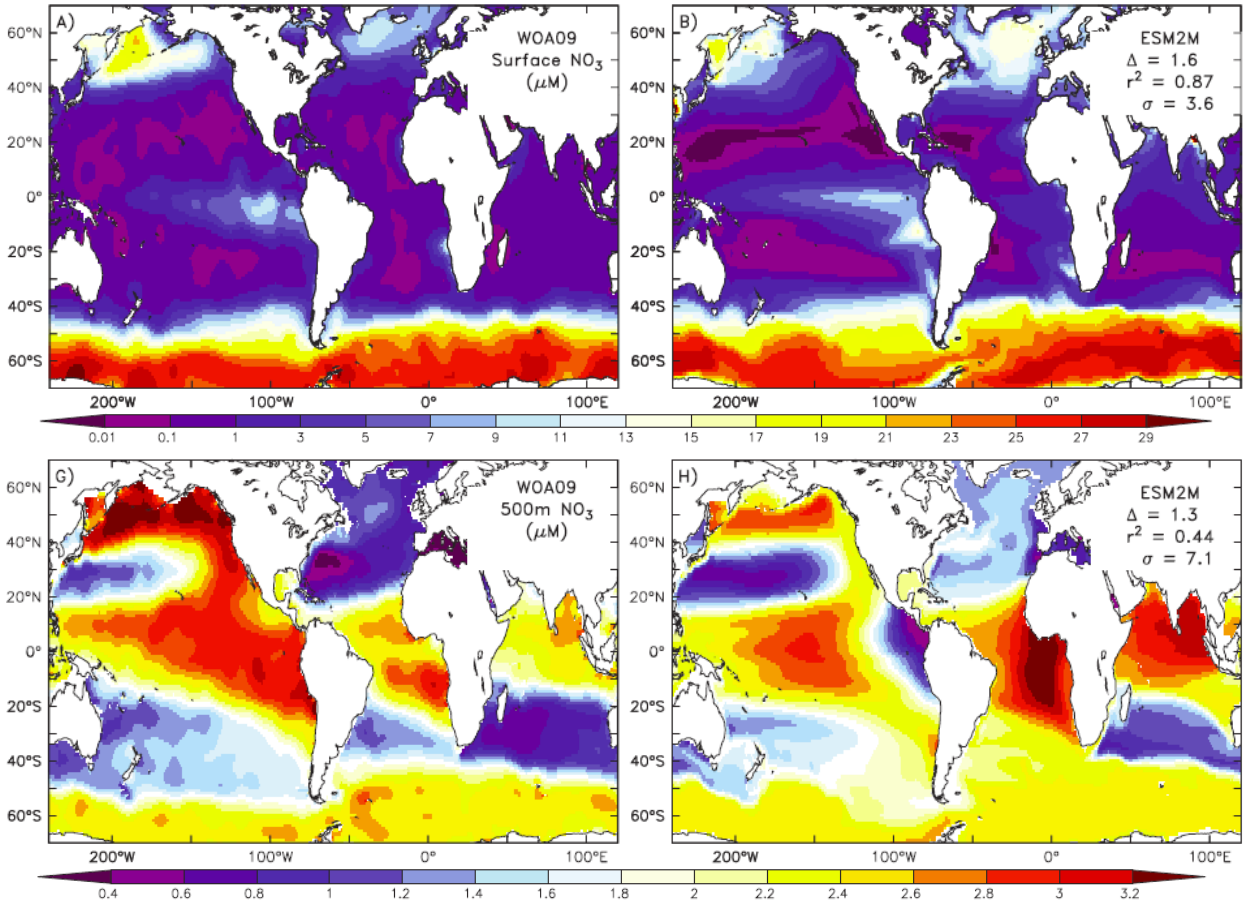
IPCC Emissions Scenario A2



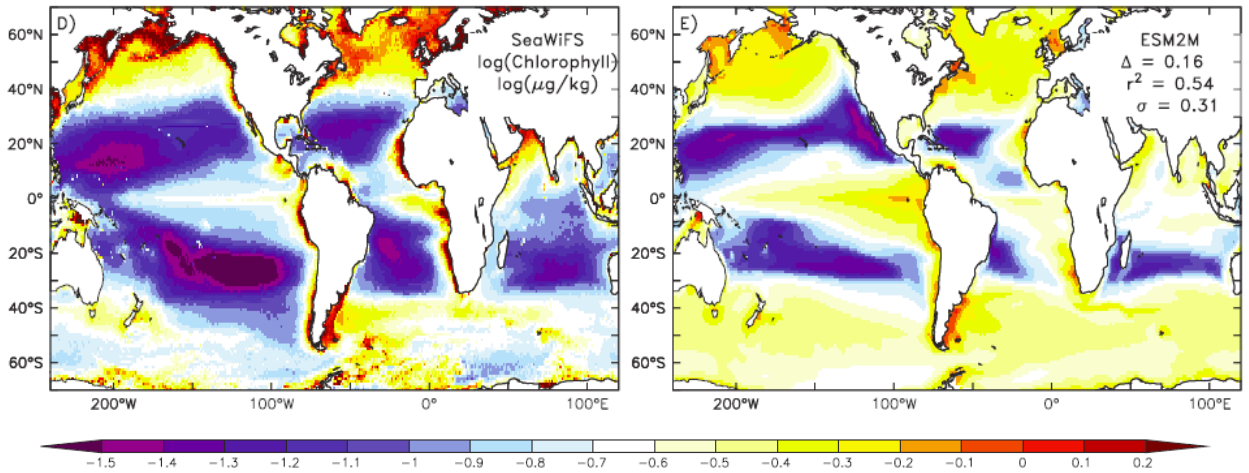
IPCC Emissions Scenario A2



How well does the model represent basic biogeochemical property distributions during the 20th century?


A)
WOA09
Surface NO_3
(μM)
B)
ESM2M
Δ = 1.6
r^2 = 0.87
σ = 3.6
G)
WOA09
500m NO_3
(μM)
H)
ESM2M
Δ = 1.3
r^2 = 0.44
σ = 7.1
60°N
40°N
20°N
0°
20°S
40°S
60°S
200°W
100°W
0°
100°E
0.01 0.1 1 3 5 7 9 11 13 15 17 19 21 23 25 27 29
0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2

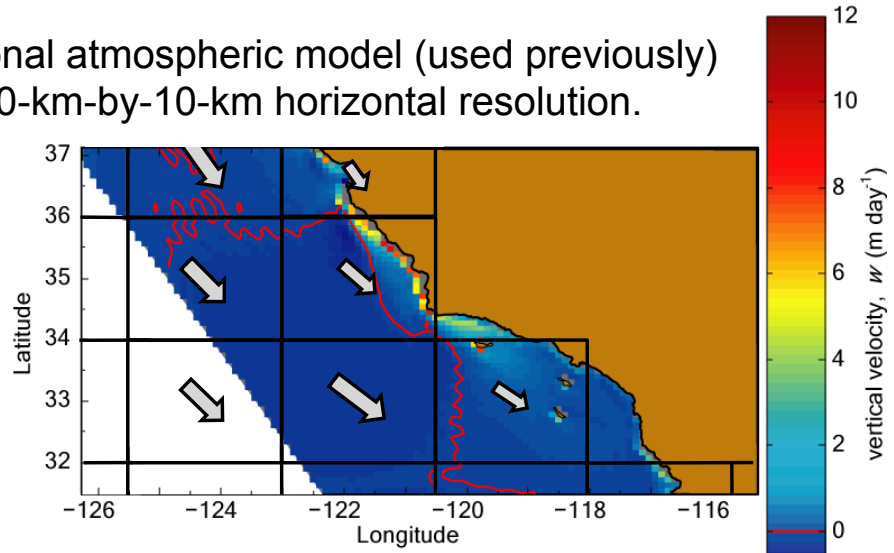
The model continues to be improved while attempting to minimize added complexity…



Dunne *et al.*, 2013, *Journal of Climate*

Limited spatial resolution also poses challenges

Regional atmospheric model (used previously) has 10-km-by-10-km horizontal resolution.



The current global model uses 2-by-2.5 degree horizontal resolution.

Reframing of project goals

Available tools do not permit investigation of changes in the detailed spatial structure of wind fields in upwelling systems.

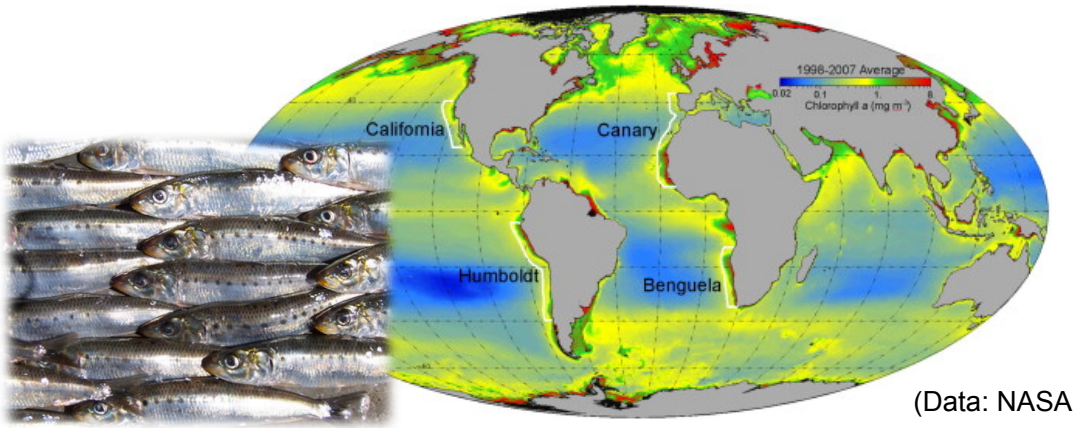
A more general, large-scale question might be:

> What are the impacts of future climate change on the nutrients supplied to marine ecosystems?

Eastern boundary upwelling ecosystems-
The low hanging fruit?

***Eastern boundary current upwelling ecosystems* have some advantages for studying climate's influence on ecosystems:**

1. of critical importance to marine fisheries, producing >25% of the world's capture fisheries production while covering <1% of the globe (*e.g.*, Pauly and Christensen, 1995)

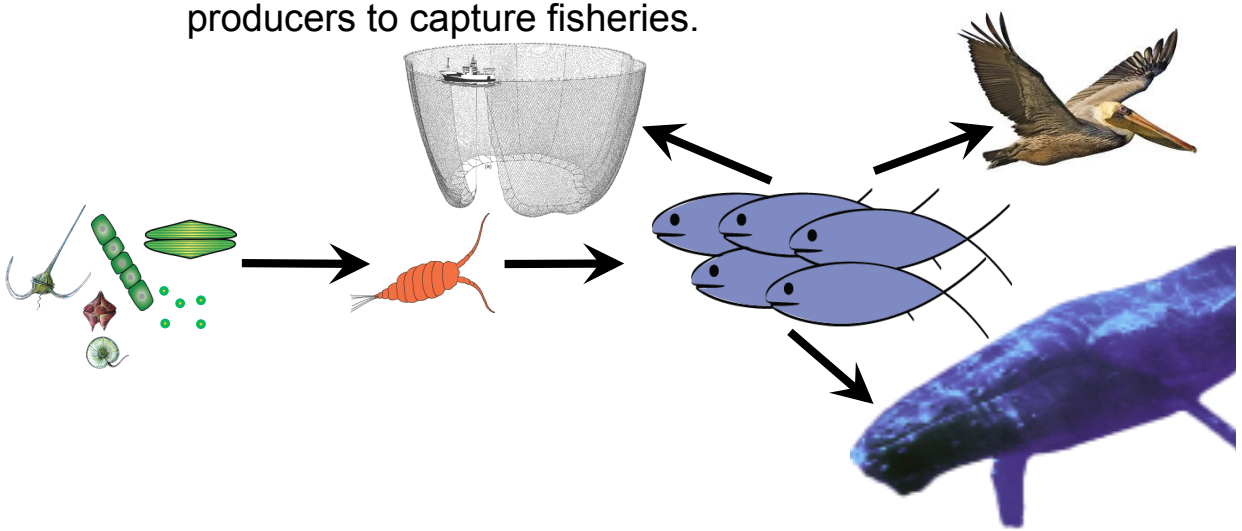


(Data: NASA SeaWiFS)

Eastern boundary upwelling ecosystems-
The low hanging fruit?

***Eastern boundary current upwelling ecosystems* have some advantages for studying climate's influence on ecosystems:**

2. short and relatively simple food web connecting primary producers to capture fisheries.



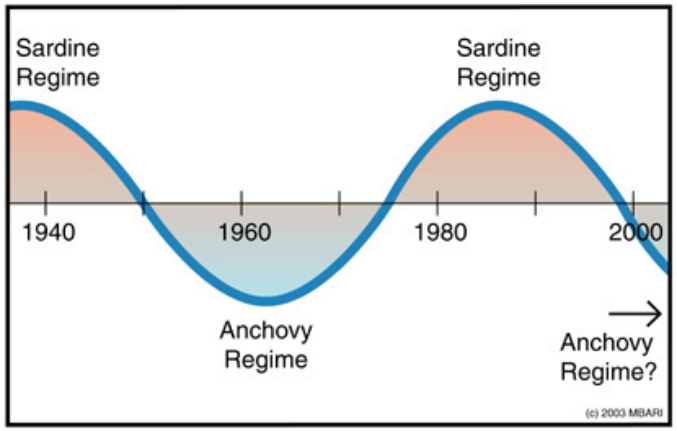
Eastern boundary upwelling ecosystems-

The low hanging fruit?

Eastern boundary upwelling ecosystems- The low hanging fruit?

***Eastern boundary current upwelling ecosystems* have some advantages for studying climate's influence on ecosystems:**

3. example of "bottom-up" forcing in an ecosystem influenced by atmospheric changes.



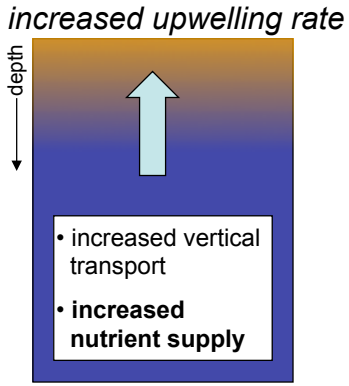
Chavez et al. (*Science*, 2003)

Eastern boundary upwelling ecosystems-
The low hanging fruit?

***Eastern boundary current upwelling ecosystems* have some advantages for studying climate's influence on ecosystems:**

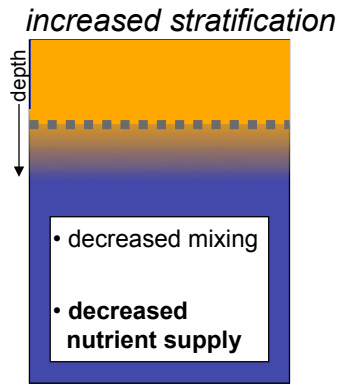
4. two previously posed, plausible hypotheses—

Bakun
(*Science*, 1990)



VS.

Roemmich and McGowan
(*Science*,1995)

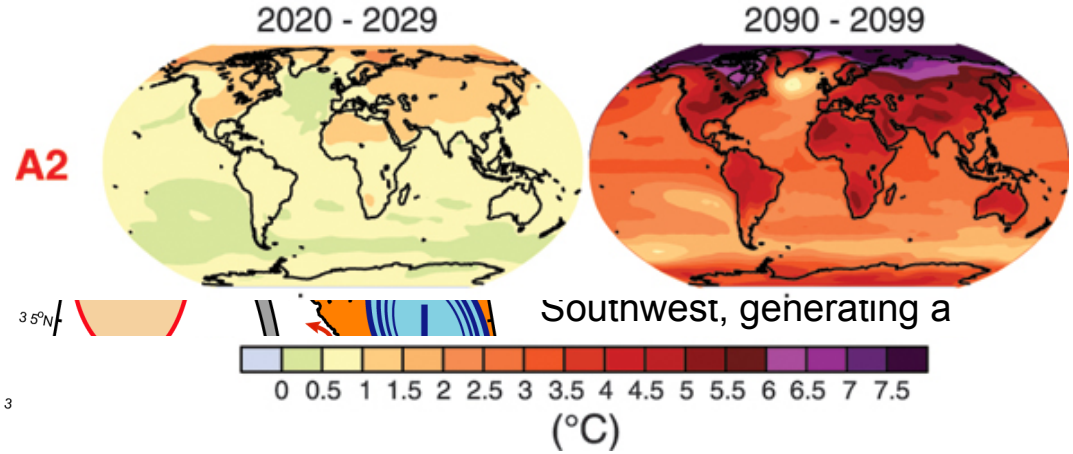


Two qualitative hypotheses posed previously

#1 - Increased continental warming rate = increased nutrient supply

Bakun (*Science* 1990) 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



Two qualitative hypotheses posed previously

#1 - Increased continental warming rate = increased nutrient supply

Bakun (*Science* 1990) 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

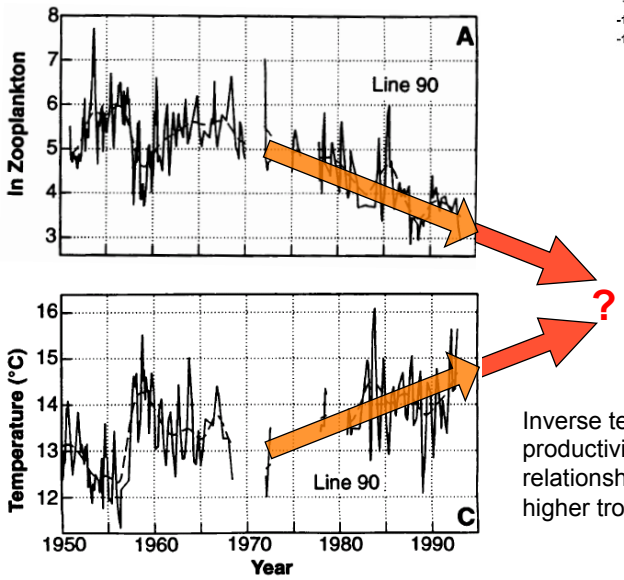
#2 - Increased stratification = decreased nutrient supply

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

increased SST → increased water-column stratification → reduced mixing, reduced efficacy of upwelling, reduced production

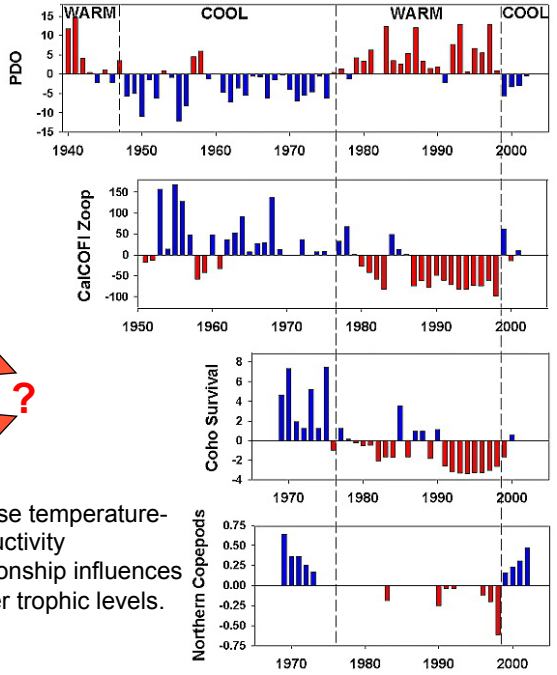
Historical observations support this inverse temperature-production relationship

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



?

Inverse temperature-productivity relationship influences higher trophic levels.



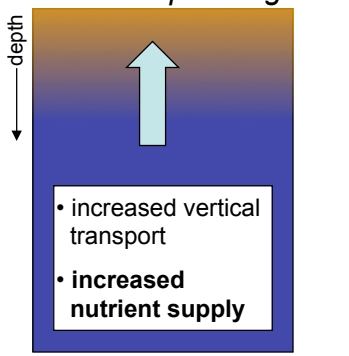
Roemmich and McGowan (*Science* 1995)

Peterson and Schwing (*GRL* 2003)

What dominates: increased winds or increased stratification?

Bakun
(*Science*, 1990)

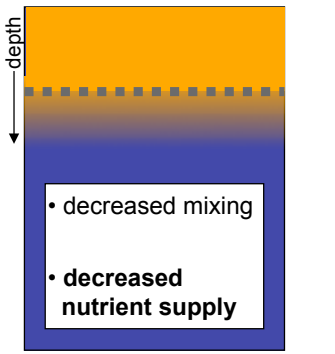
increased upwelling rate



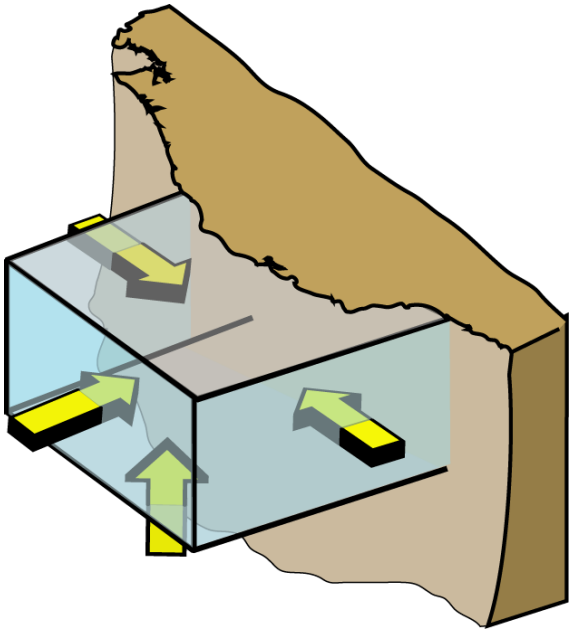
VS.

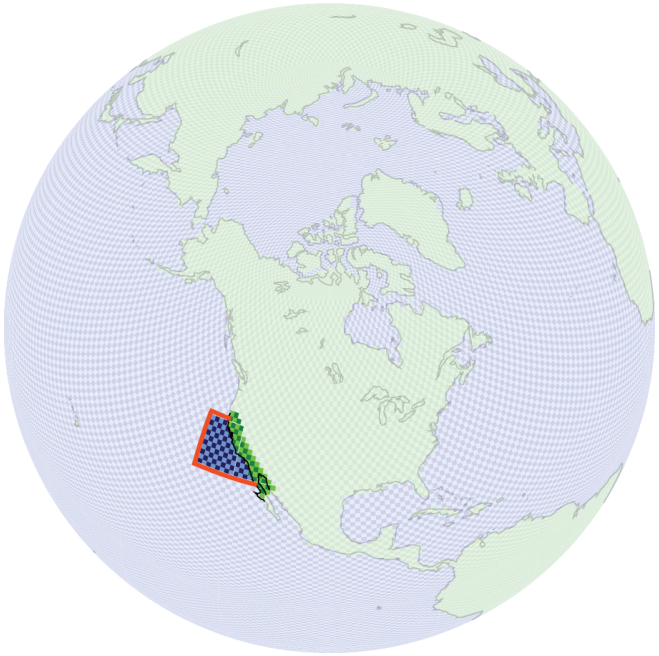
Roemmich and McGowan
(*Science*,1995)

increased stratification



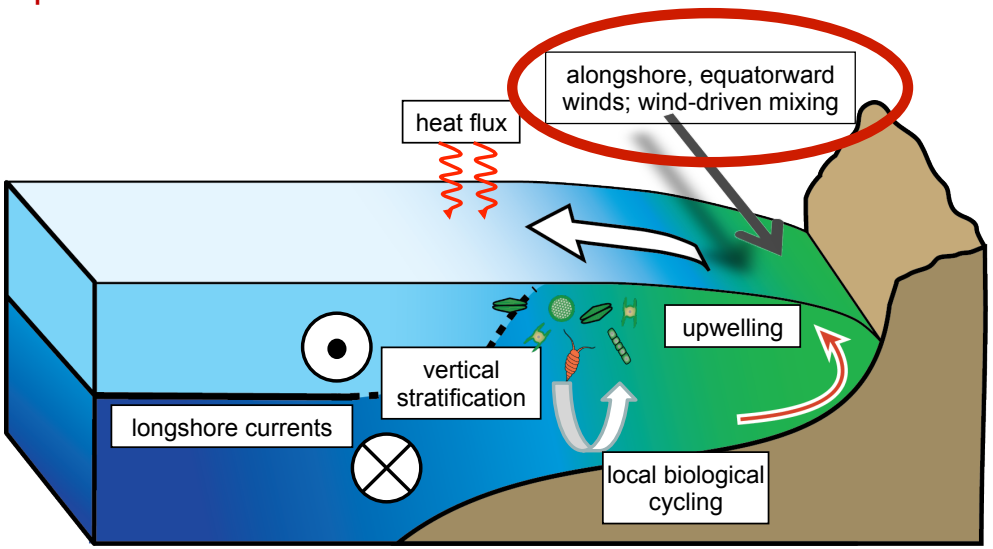
A "control volume" was specified in which fluxes were examined





Expected factors governing ecosystem responses to future changes

What processes should we consider?

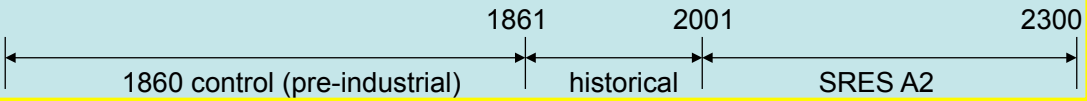


Projected changes in the North Pacific

The following plots will have four panels:

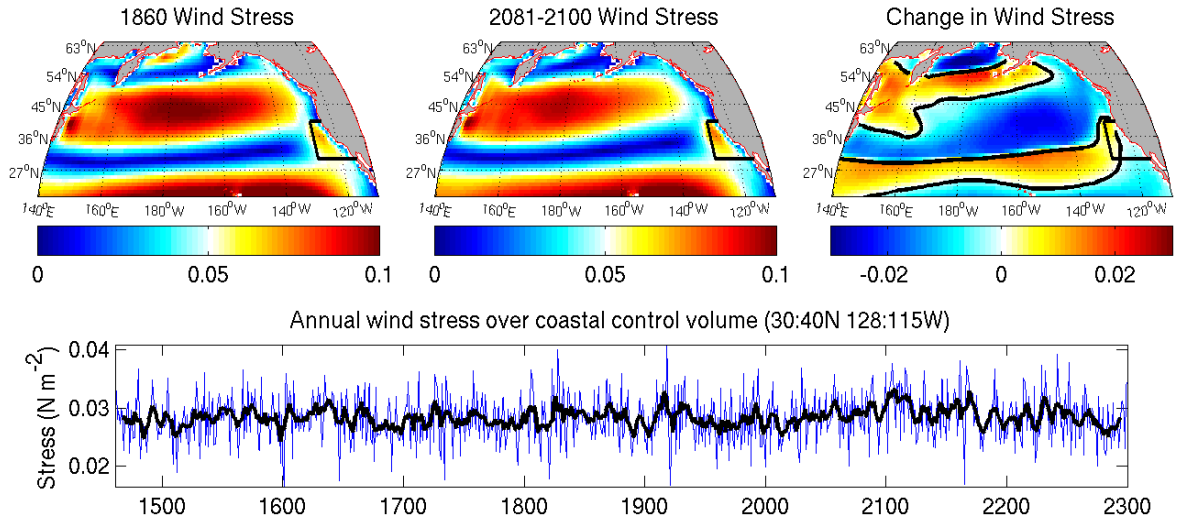
Pre-industrial mean (1860, 20-yr run)	Fossil-fuel intensive mean (SRES A2 2081-2100)	Difference (Future – pre-industrial)
PAST	**FUTURE**	**DIFFERENCE**

Time series for the CCE (128°W to coast, 30°N to 40°N , upper 200-m avg.)



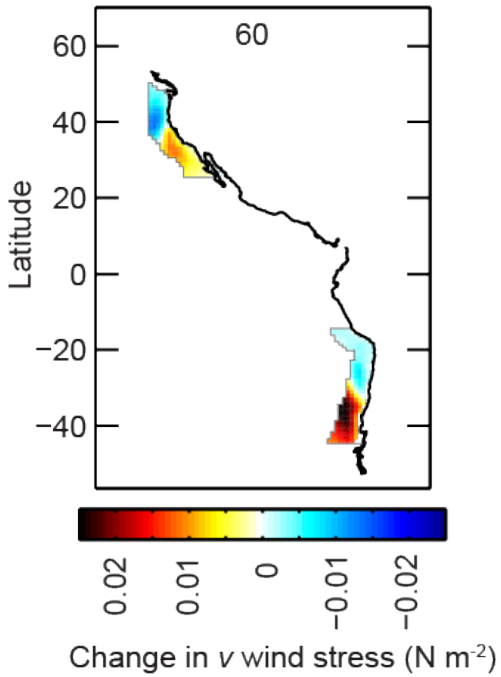
Zonal winds: *weaken and shift poleward*

Meridional winds: *little change in magnitude*



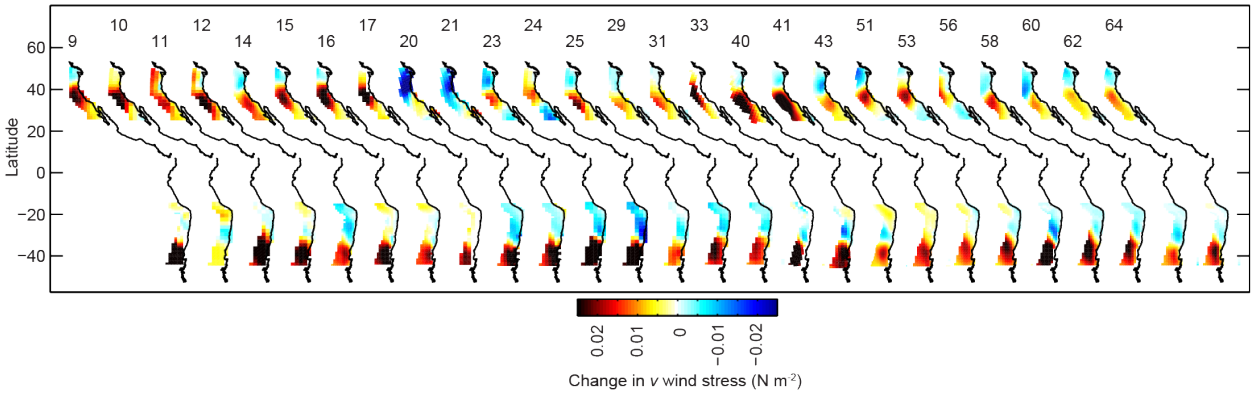
The magnitude of alongshore winds at the coast does not change significantly.

Projected changes in winds are more nuanced than an increase or a decrease



Projected responses of alongshore winds do not confirm Bakun's (1990) predictions.

Multi-model comparison does, however, demonstrate some consistent responses when examining seasonal and latitudinal trends across the four upwelling systems.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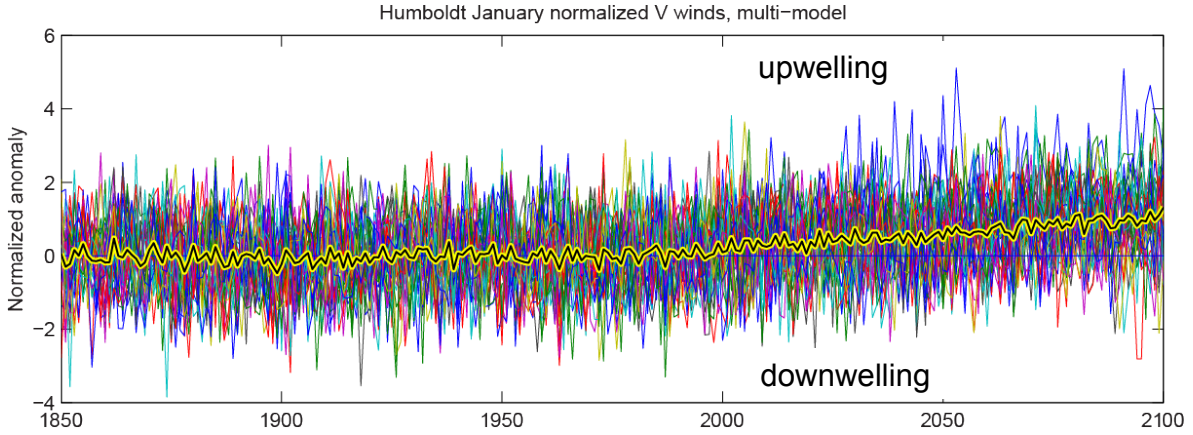
31
33
40
41
43
51
53
56
58
60
62
64
60
40
20
0
−20
−40
Latitude
0.02
0.01
0
−0.01
−0.02
Change in v wind stress (N m⁻²)


Humboldt January normalized V winds, multi−model
upwelling
downwelling
Normalized anomaly
6
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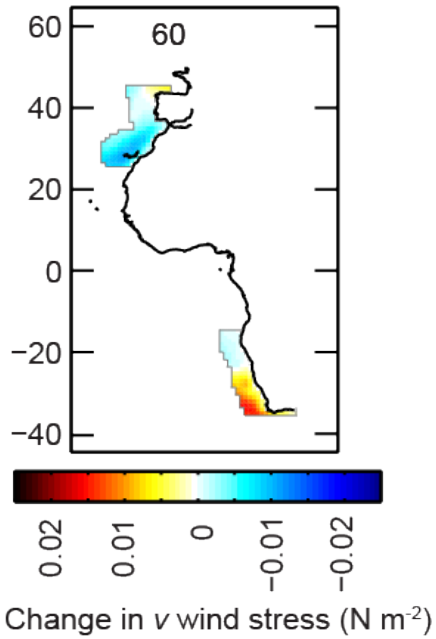
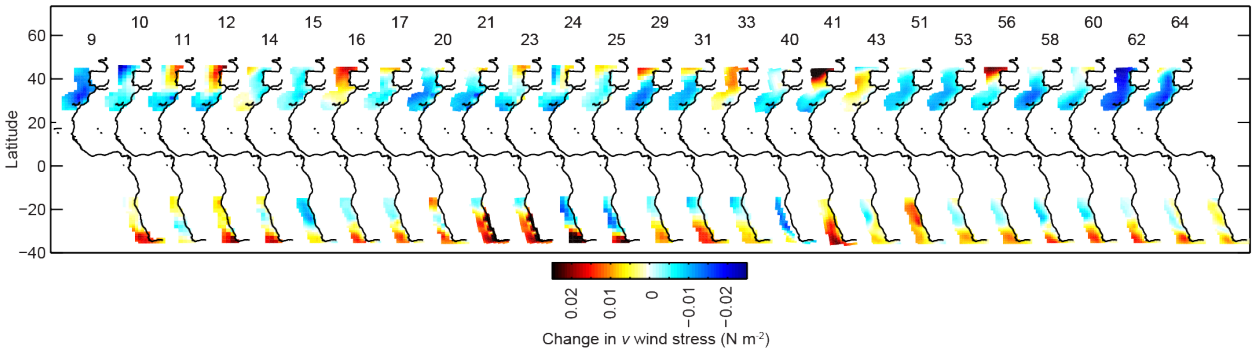
0
−2
−4
1850
1900
1950
2000
2050
2100

Projected changes in winds are more nuanced than an increase or a decrease



The Canary and Benguela also show latitudinally dependent changes in upwelling magnitude.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−20
−40
Latitude
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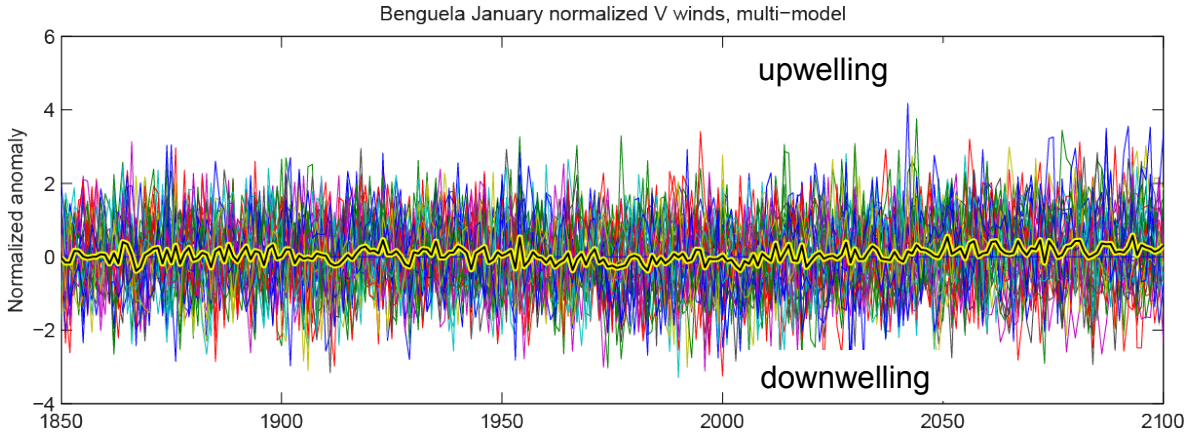
−0.01
−0.02
Change in v wind stress (N m-2)


Benguela January normalized V winds, multi−model
upwelling
downwelling
Normalized anomaly
6
4
2
0
−2
−4
1850
1900
1950
2000
2050
2100

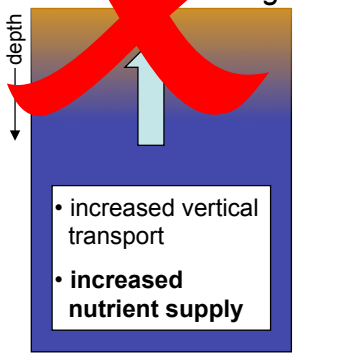
Perhaps, for now, we can cross this one off…

Eastern boundary current upwelling ecosystems

Previously posed hypotheses:

Bakun
(*Scienc* 1990)

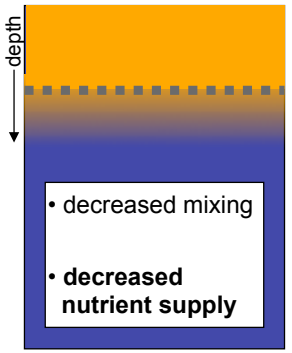
increas welling rate



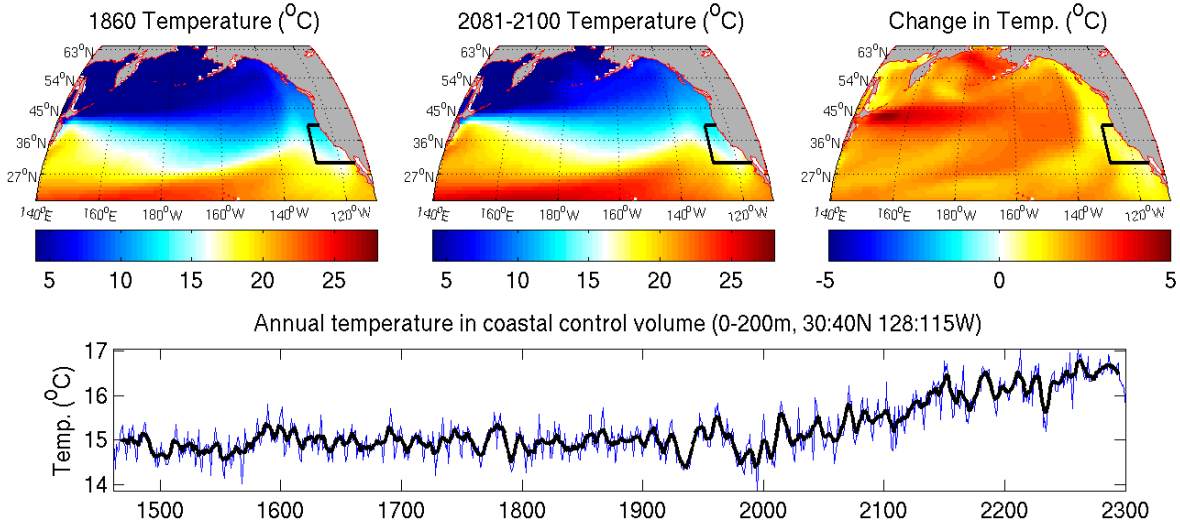
VS.

Roemmich and McGowan
(*Science*,1995)

increased stratification

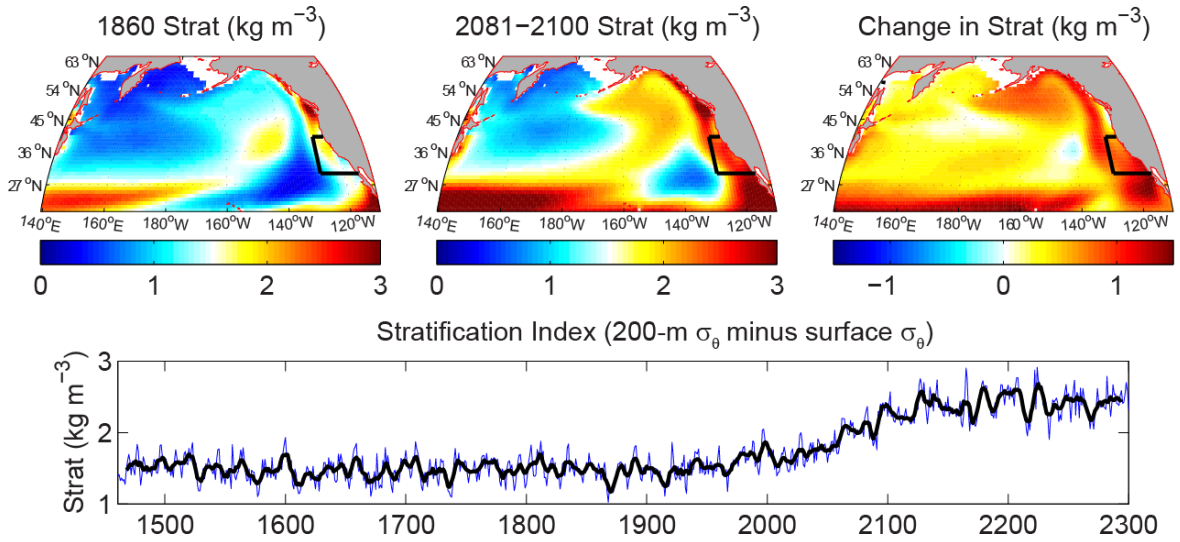


Temperature increases across the basin

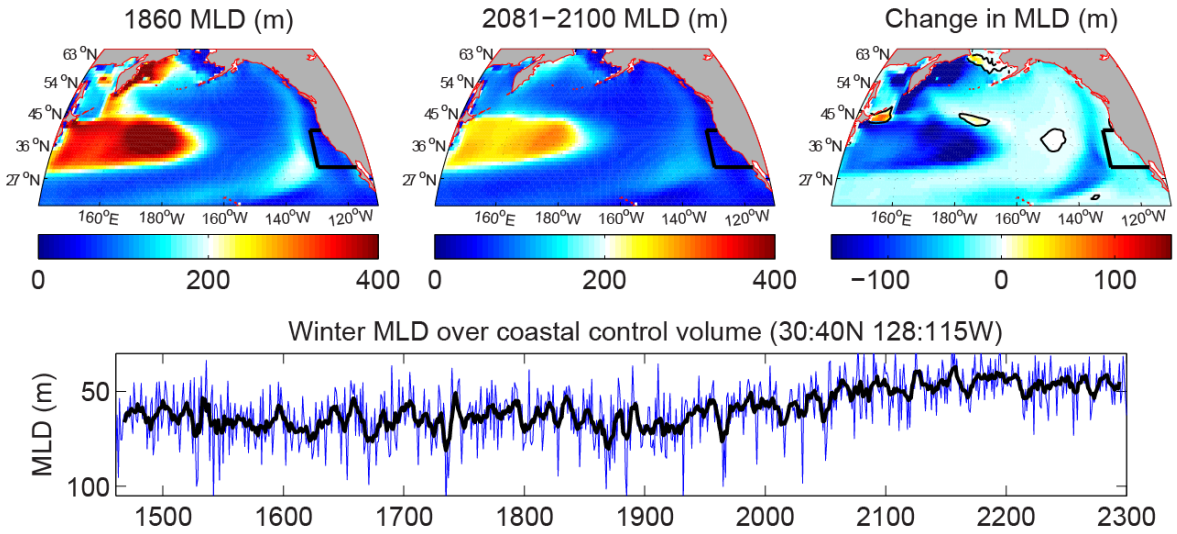


The magnitude of the upper-ocean temperature change varies, but the direction of the change is uniform: the whole Pacific becomes warmer at the surface.

Changes in local forcing suggest decreased nutrient supply

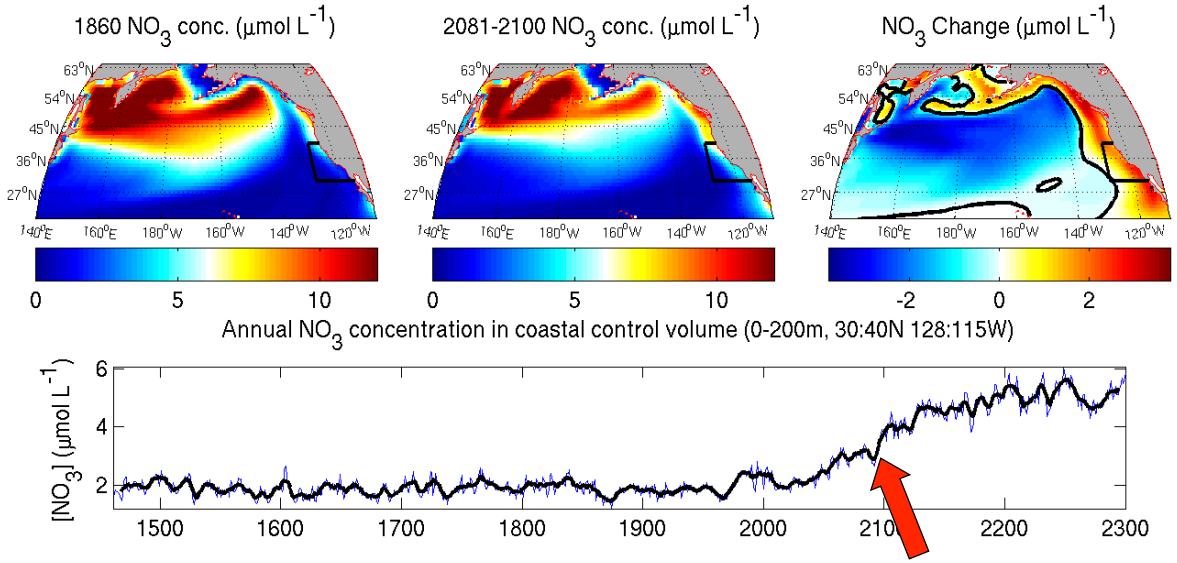


Winter mixed-layer depth shoals



Projected responses include a shallower mixed-layer depth, warmer surface layer, and little change in winds. Given the historical record, we might expect decreased nutrient supply and reduced production.

Surface-layer NO_3 increases despite stratification and winds



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

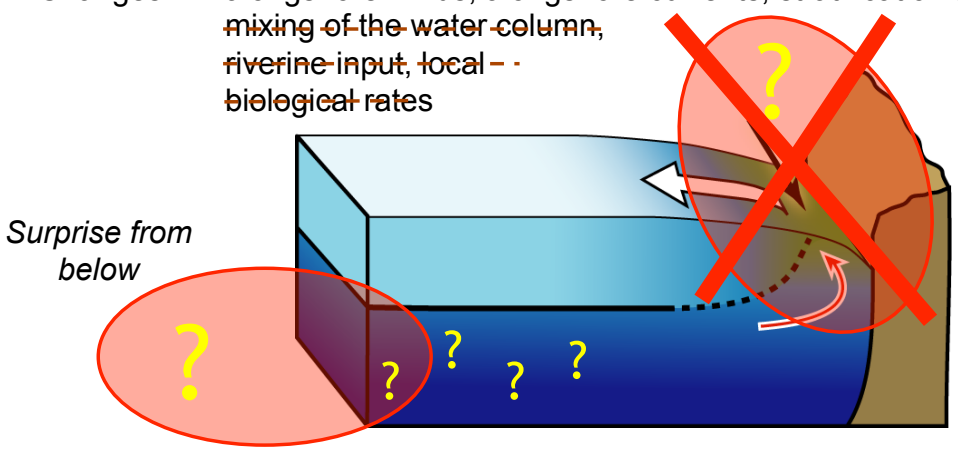
85% increase in average nitrogen concentration between 2000 and 2100 along the US West Coast.

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~~



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

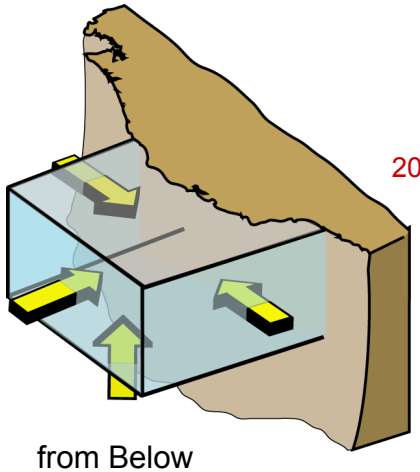
NO3 budget in a control volume

from North

	0.8 kmol s^{-1}	0.3 Sv
	1.0 kmol s^{-1}	0.2 Sv
Δ =	0.1 kmol s^{-1}	0.0 Sv

from West

	3.1 kmol s^{-1}	2.4 Sv
	5.8 kmol s^{-1}	3.1 Sv
Δ =	2.7 kmol s^{-1}	0.7 Sv



FLUX KEY:

	NO_3 flux	H_2O flux
1860, 60-yr avg:		
2081-2100 avg:		
change =	Δ NO_3	Δ H_2O

1st column: NO_3 flux
2nd column: H_2O flux

from Below

	6.3 kmol s^{-1}	0.7 Sv
	10 kmol s^{-1}	0.8 Sv
Δ =	4.0 kmol s^{-1}	0.1 Sv

from South

	0.5 kmol s^{-1}	0.5 Sv
	1.1 kmol s^{-1}	0.4 Sv
Δ =	0.6 kmol s^{-1}	-0.1 Sv

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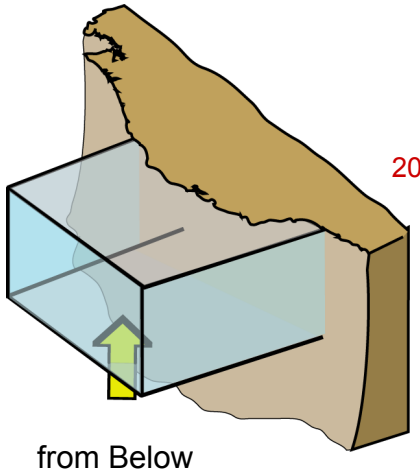

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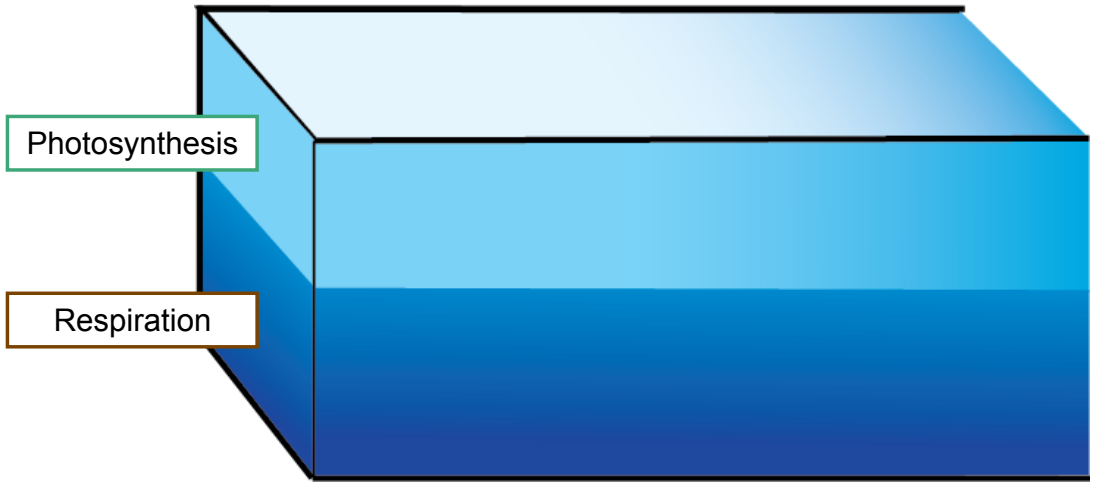
+ 60% + 10%

But WHY?

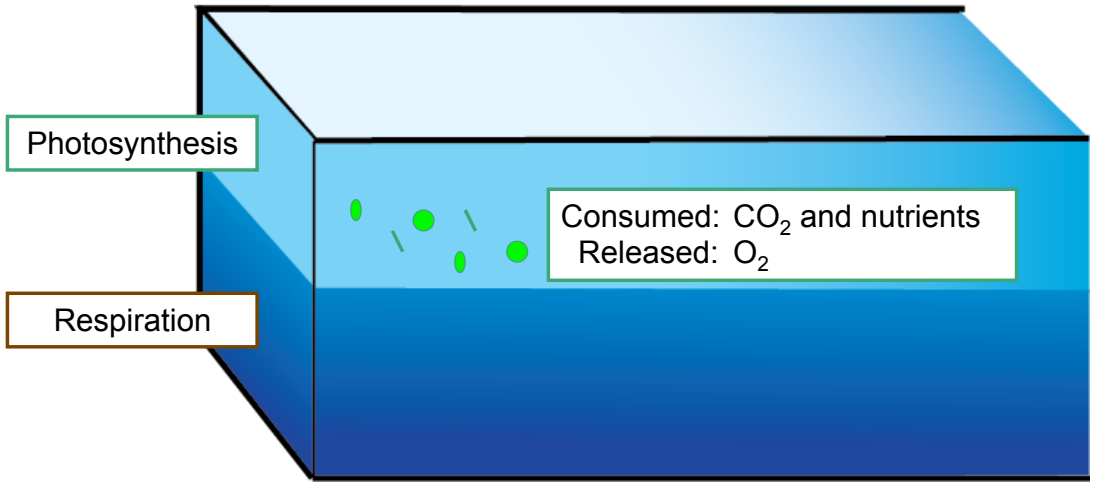
Review of photosynthesis and respiration

What makes deep, cold waters nutrient rich?



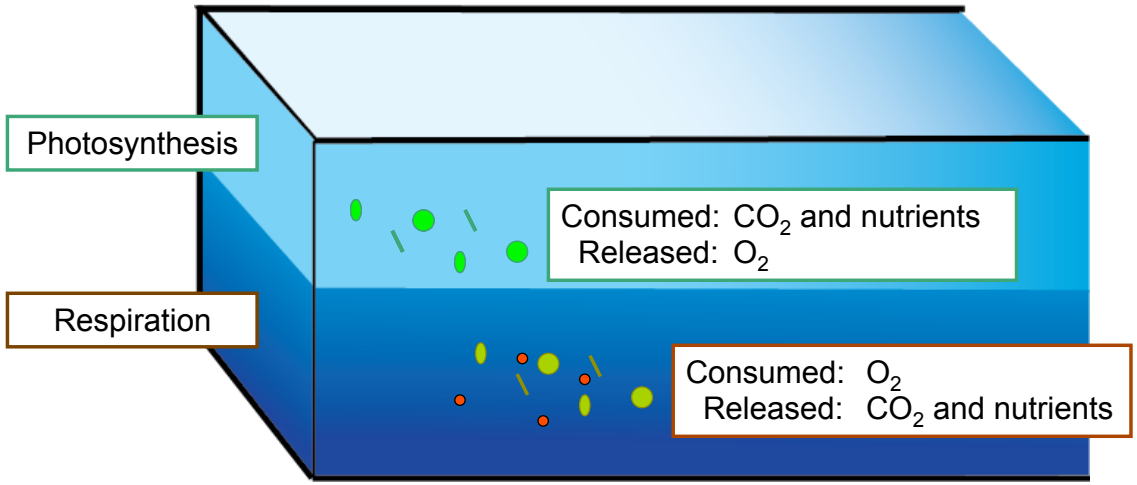
Review of photosynthesis and respiration

Nutrients are depleted by photosynthesis in the surface, sunlit layer.



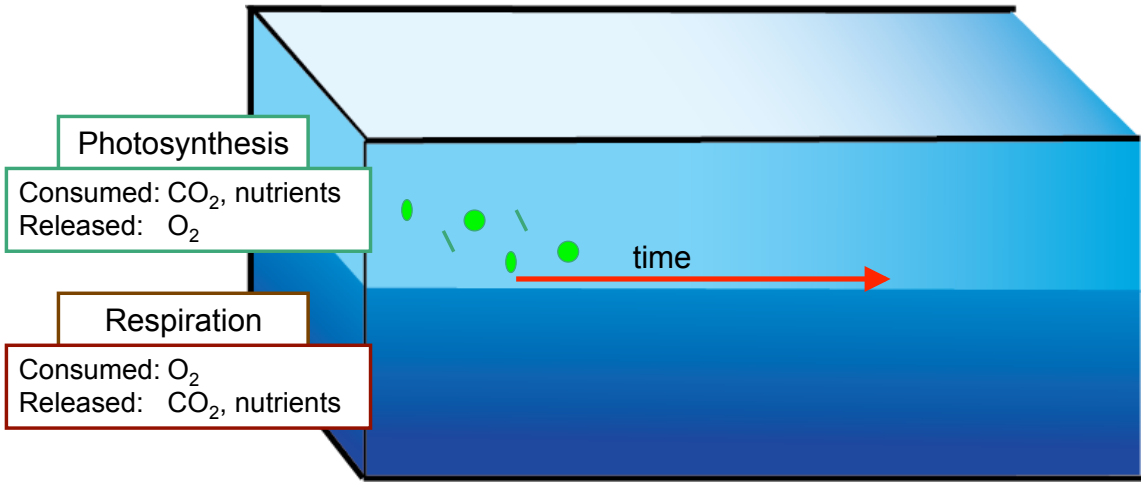
Review of photosynthesis and respiration

Biological respiration (microzooplankton and bacteria) remineralize these nutrients in the deeper, colder layer of the ocean.



Review of photosynthesis and respiration

Over time, phytoplankton continue to sink out of the surface layer to depth, where nutrients and CO_2 accumulate while O_2 is depleted.



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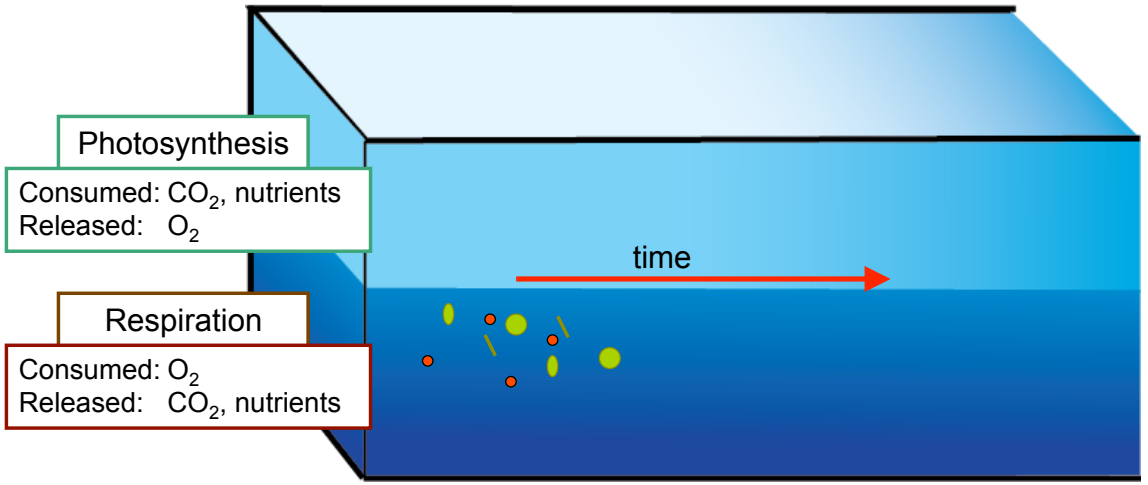

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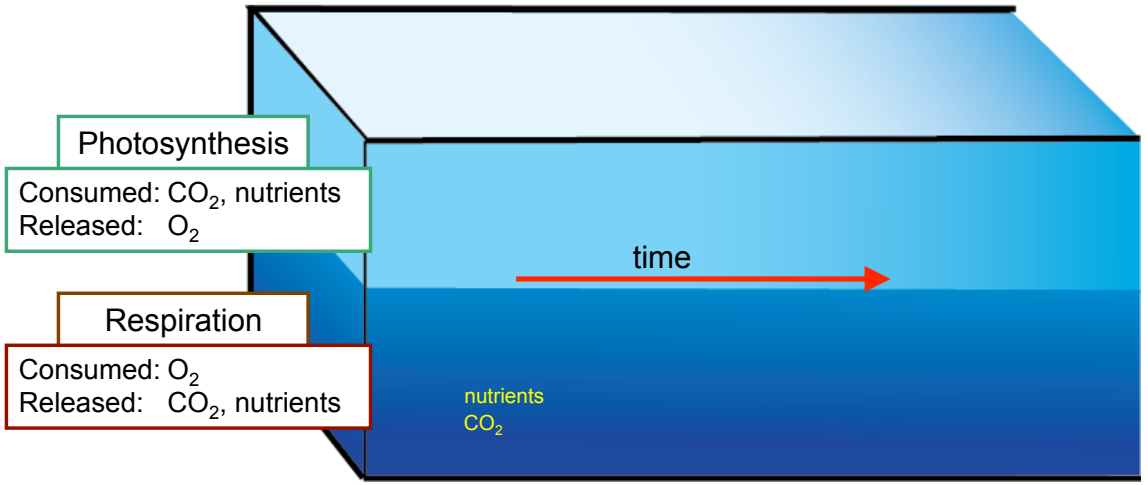

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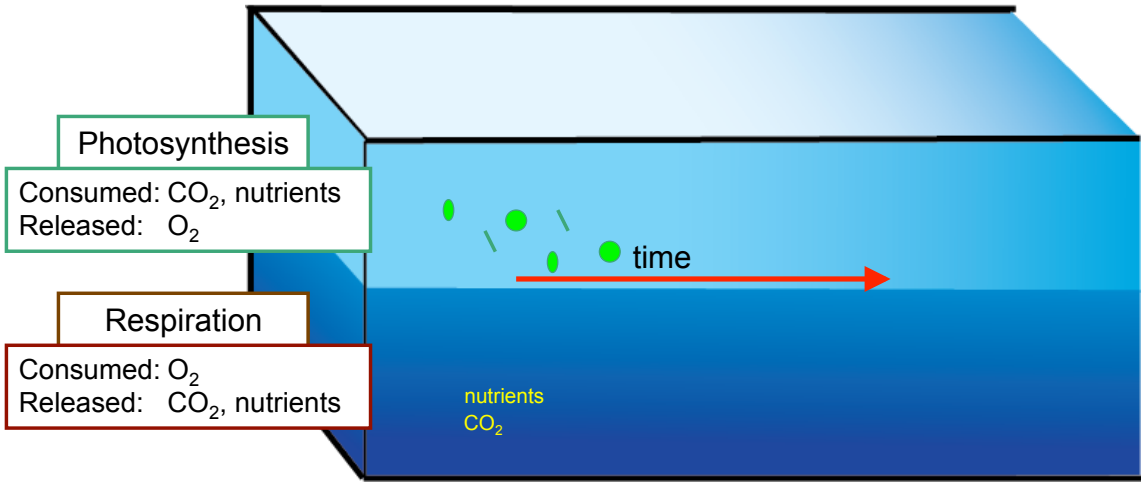

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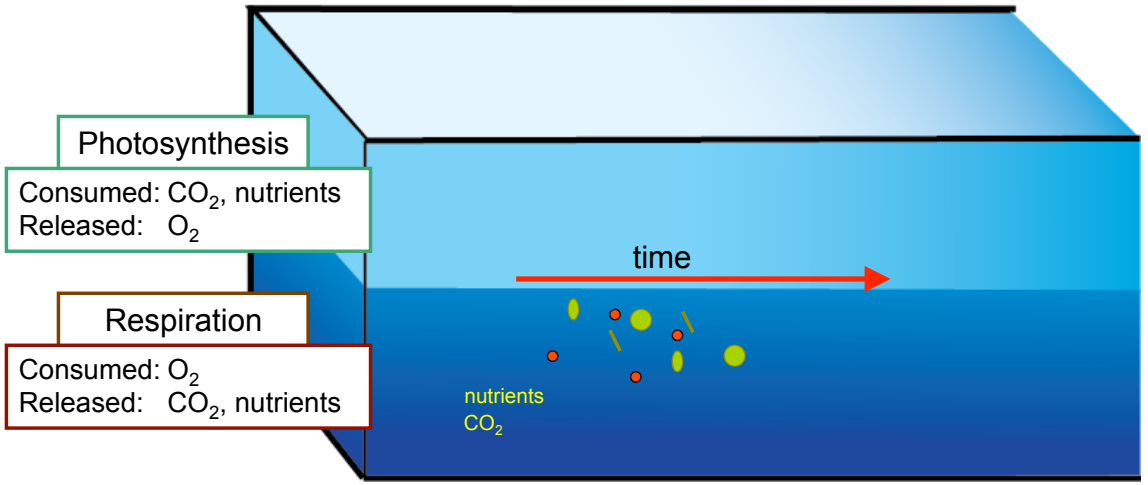

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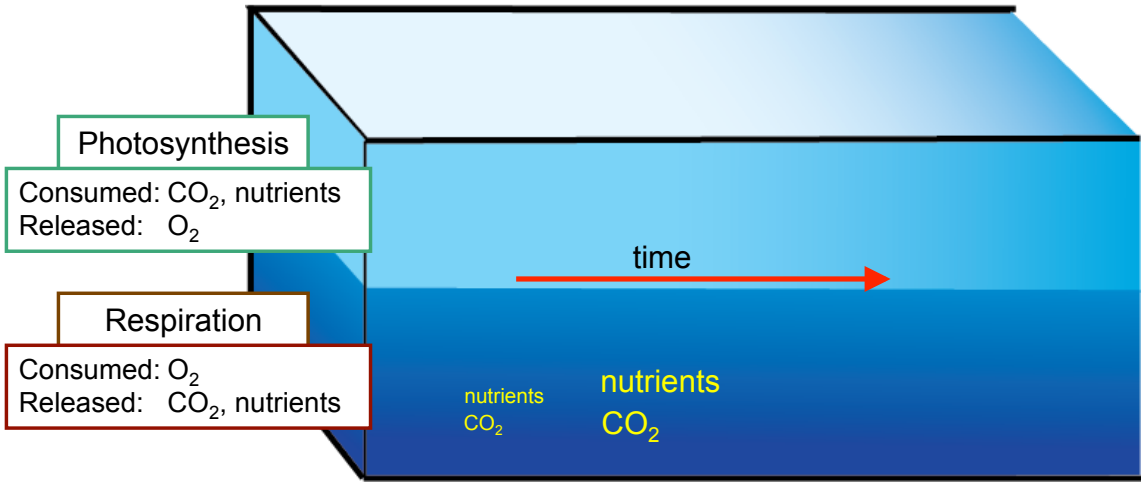

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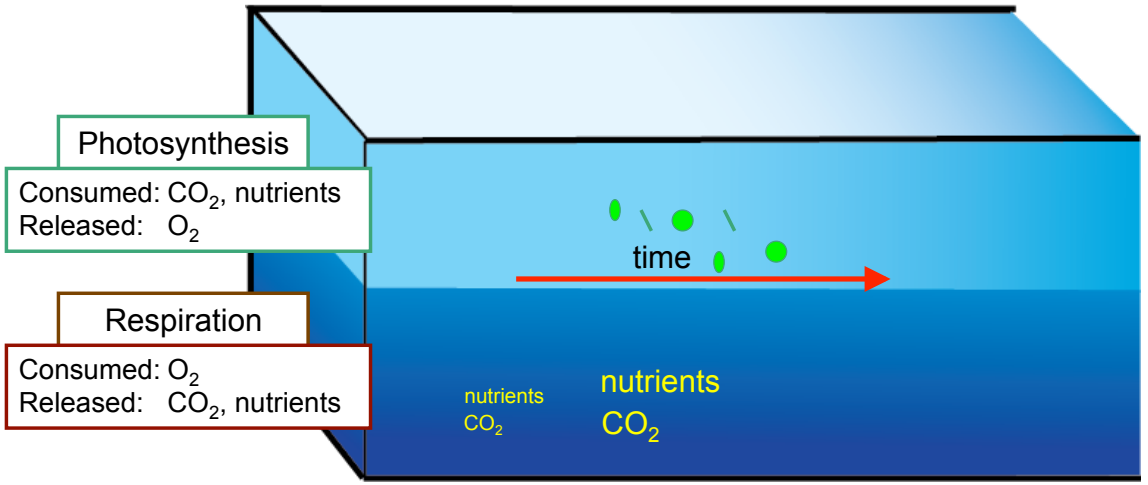

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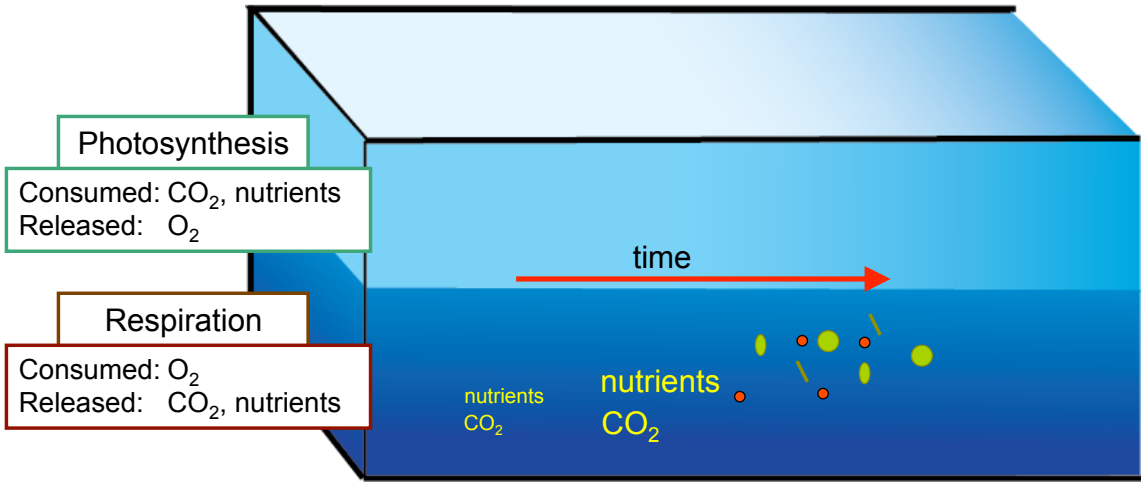

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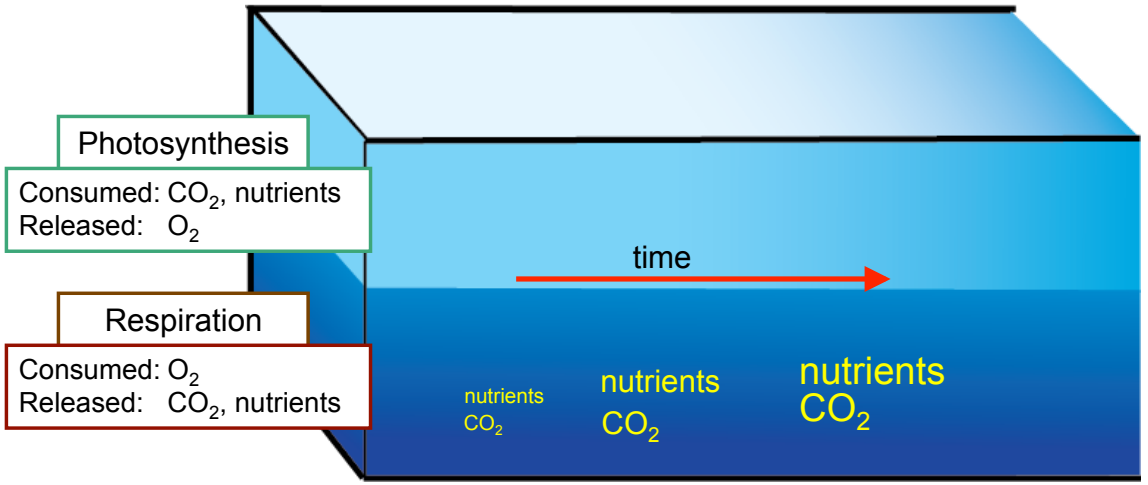

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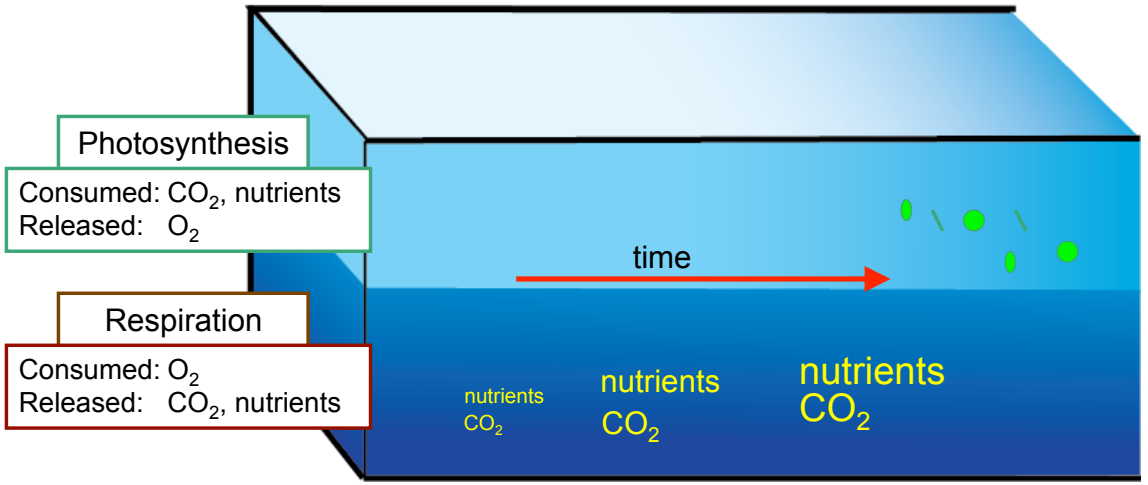

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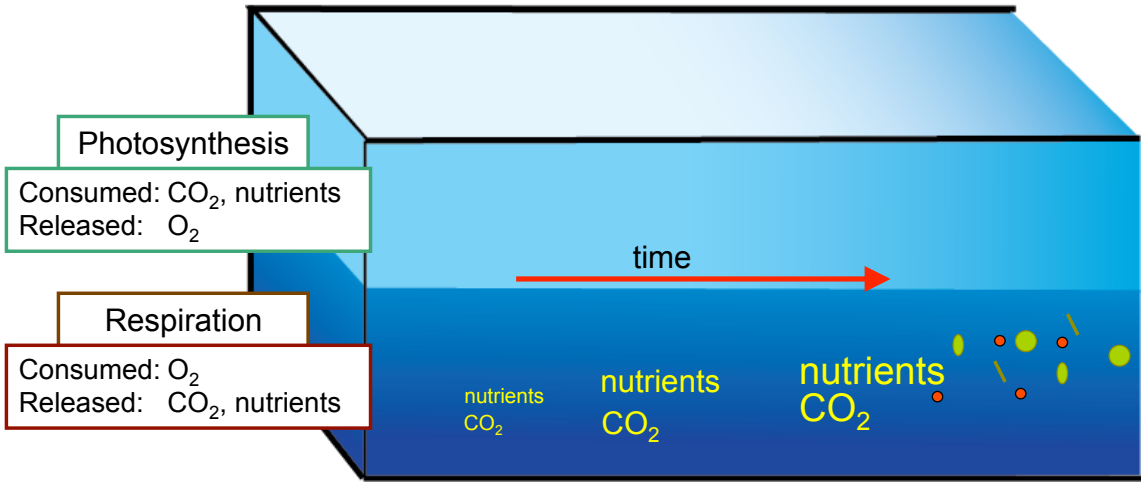

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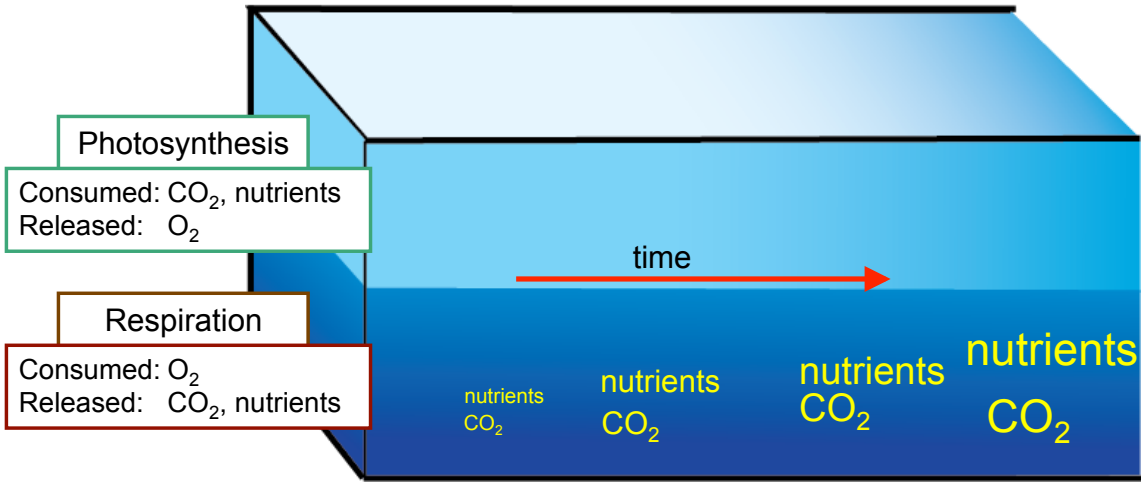

Ventilation of deep waters interrupts this accumulation

This accumulation is interrupted only when the deep water mass is ventilated with the atmosphere.

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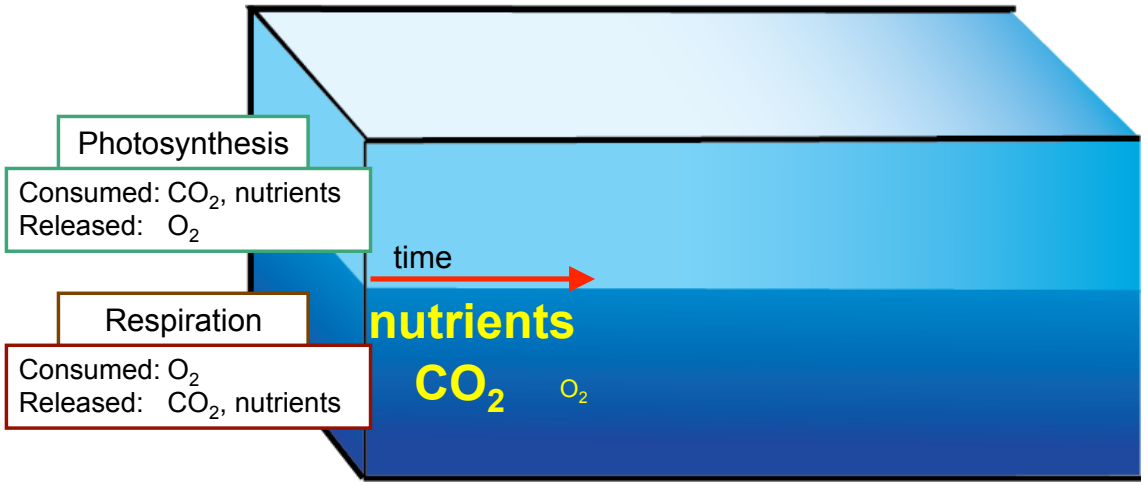
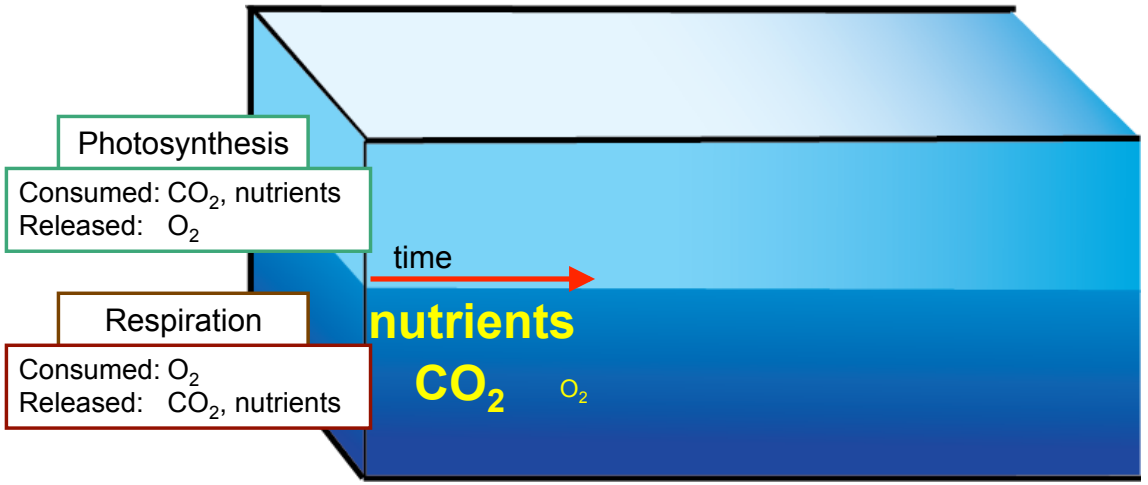


Ventilation of deep waters interrupts this accumulation

This accumulation is interrupted only when the deep water mass is ventilated with the atmosphere. Mixing supplies nutrients and permits gas exchange.



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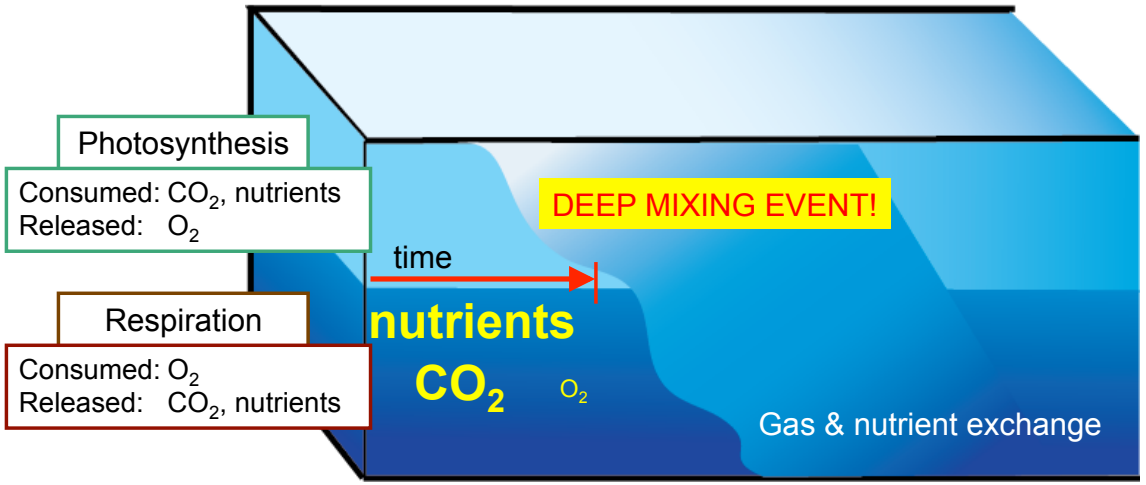

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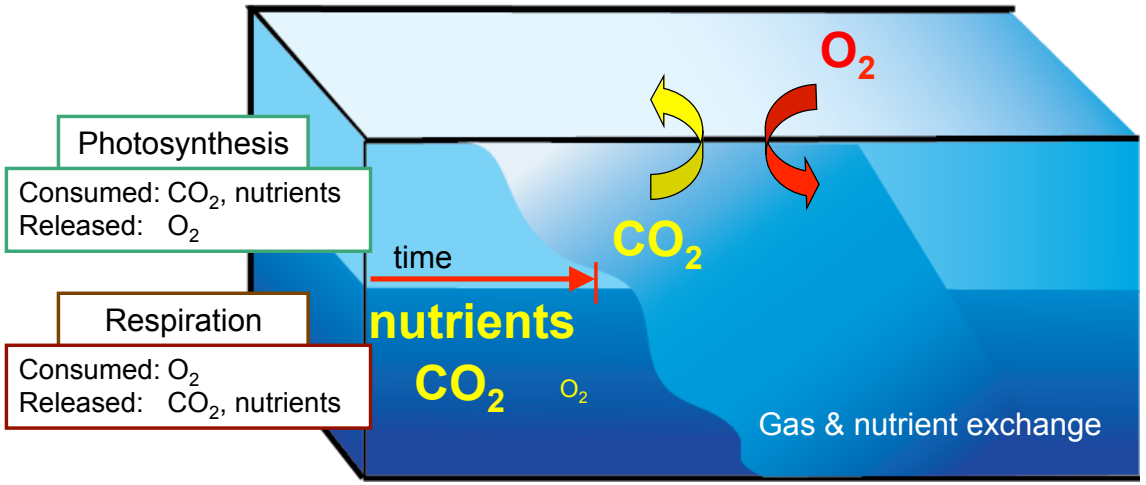

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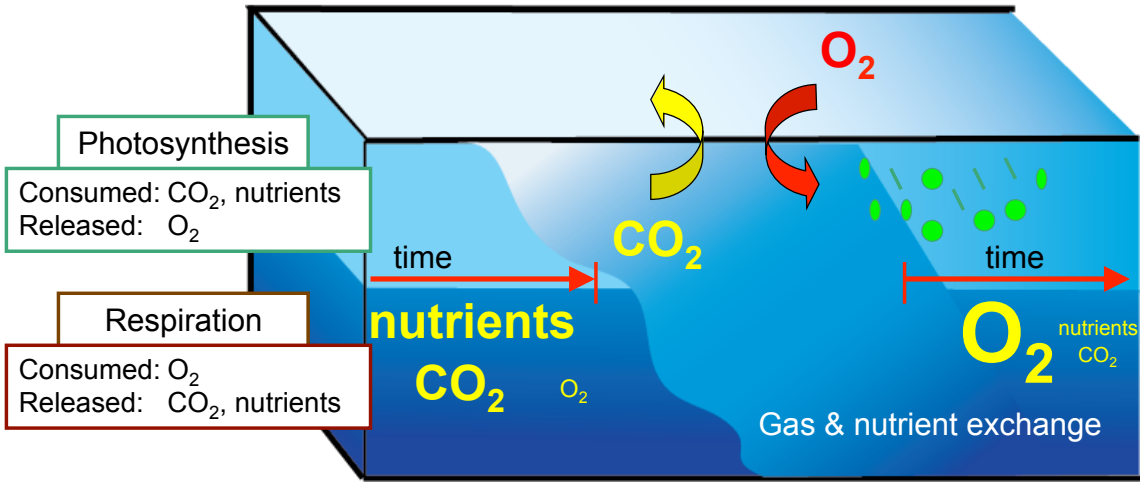
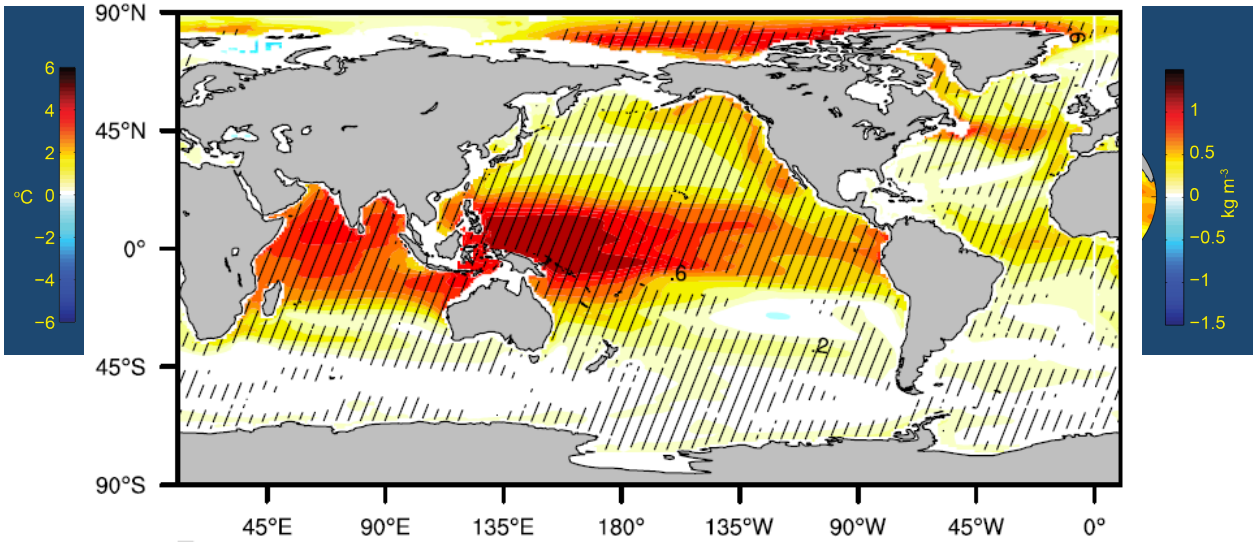


Anthropogenic changes are large scale and long term

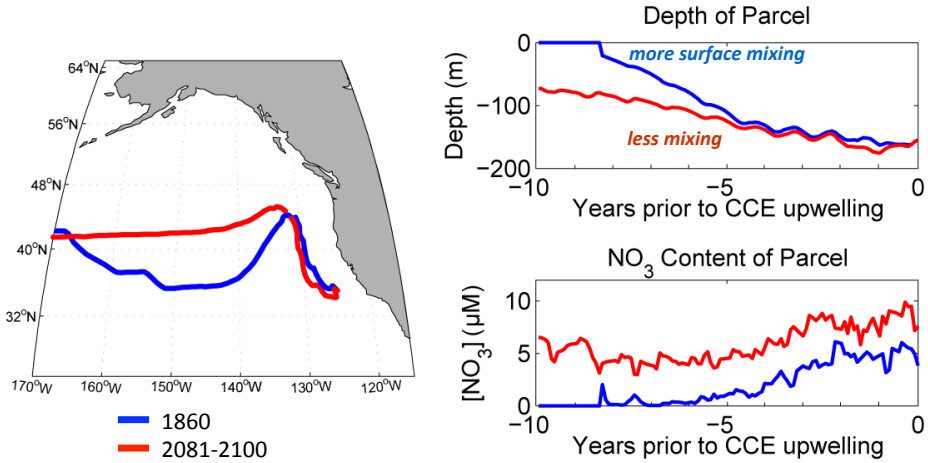
Future warming is unlike observed variability in that it is global and persistent.

Assumption that local forcing dominates local changes is incorrect.



Capotondi *et al.* (2012)

Waters that are upwelled in the future have a "deeper, darker, history"



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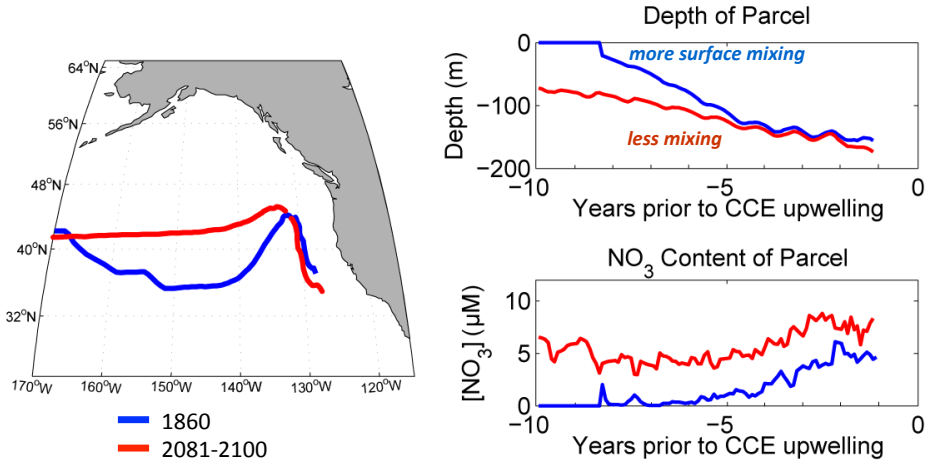

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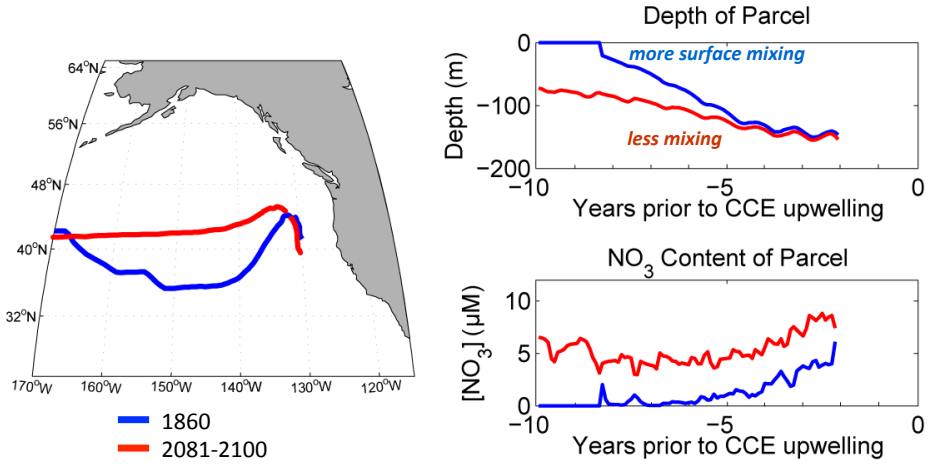

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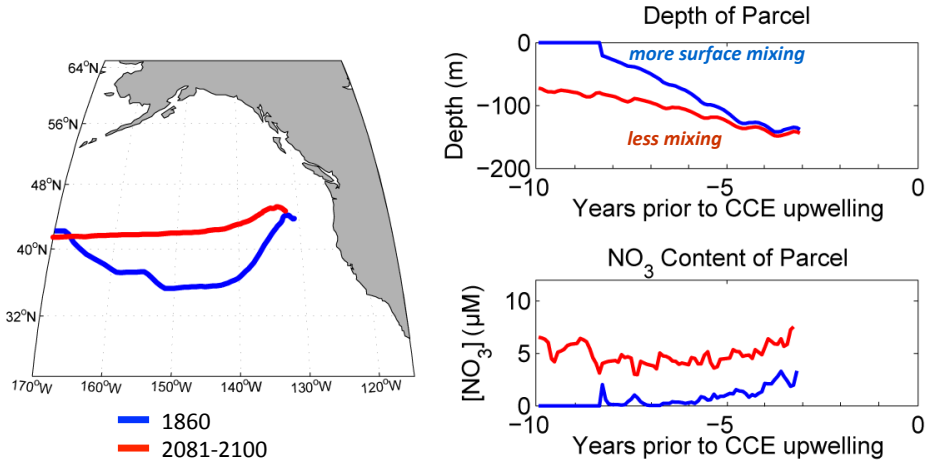

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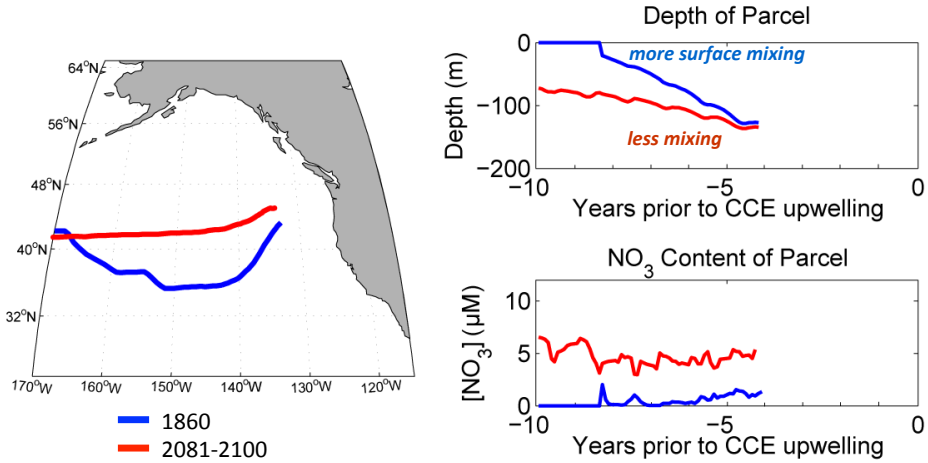

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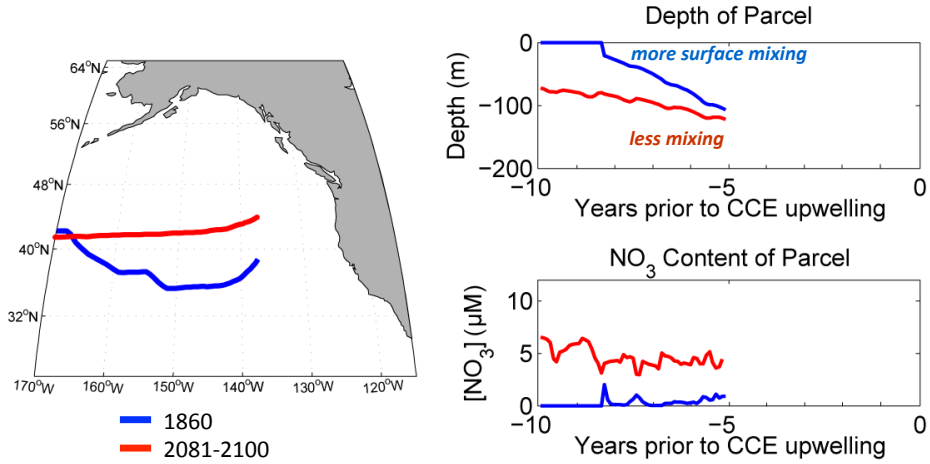

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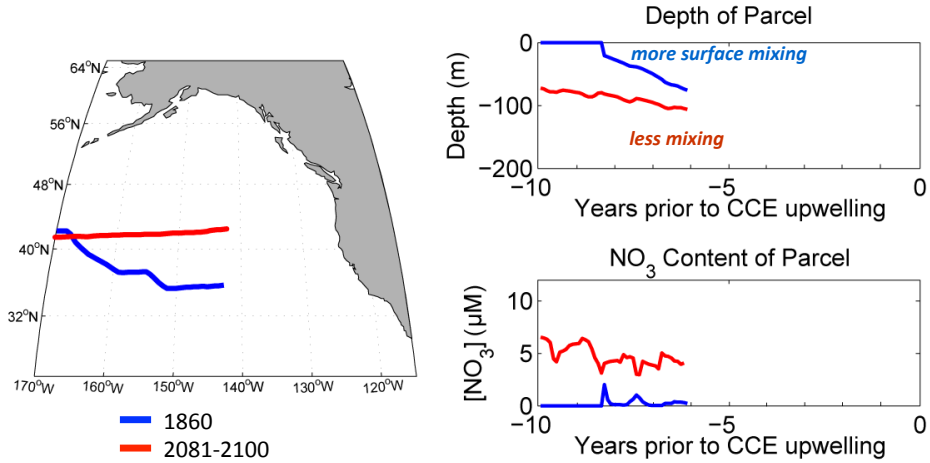

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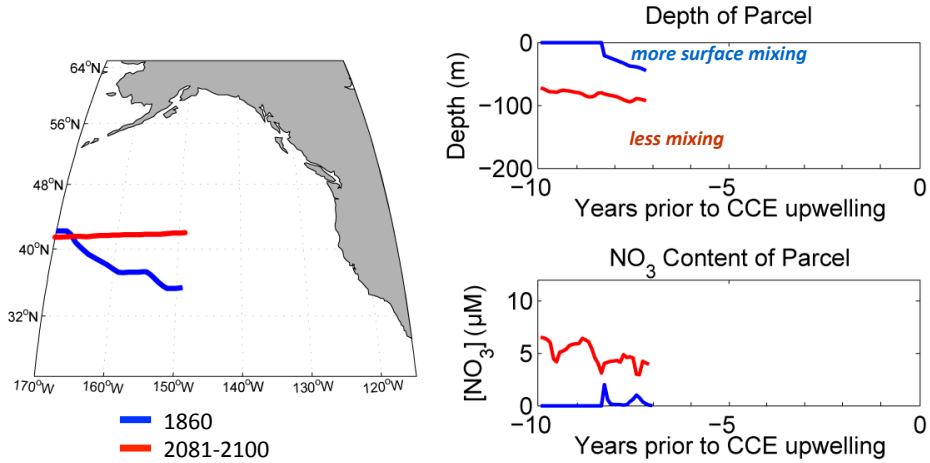

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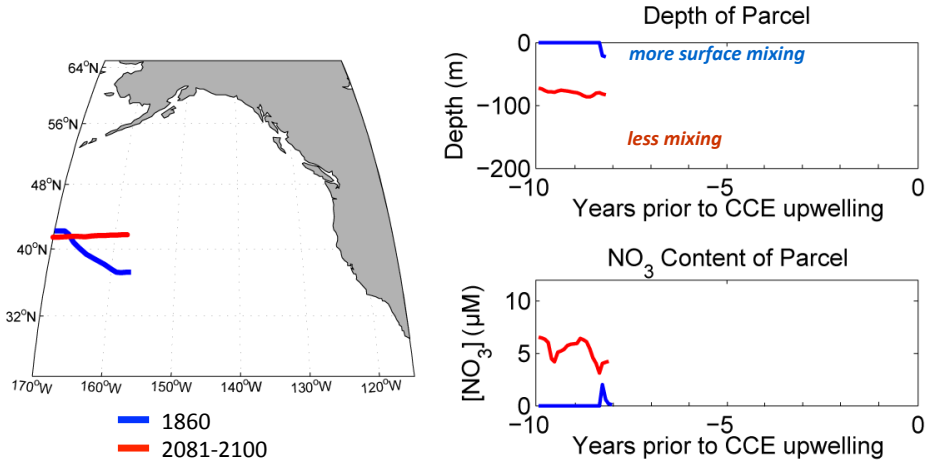

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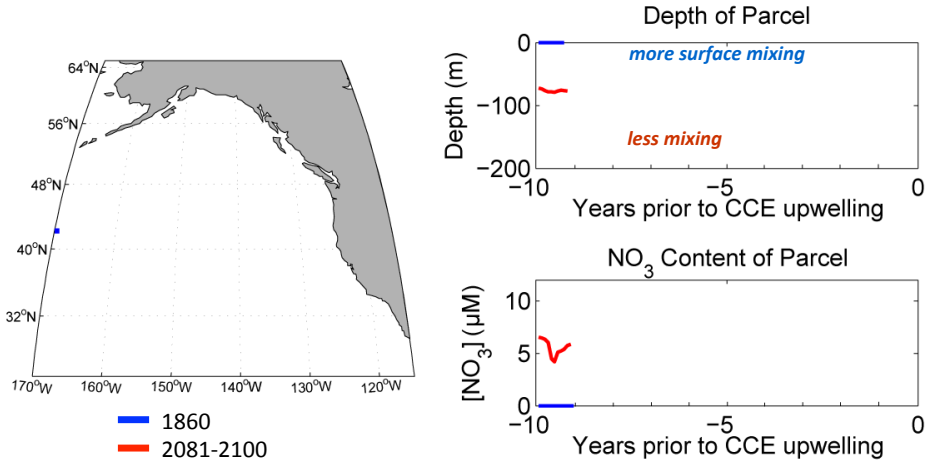


What general relationships can be gleaned from this example?

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

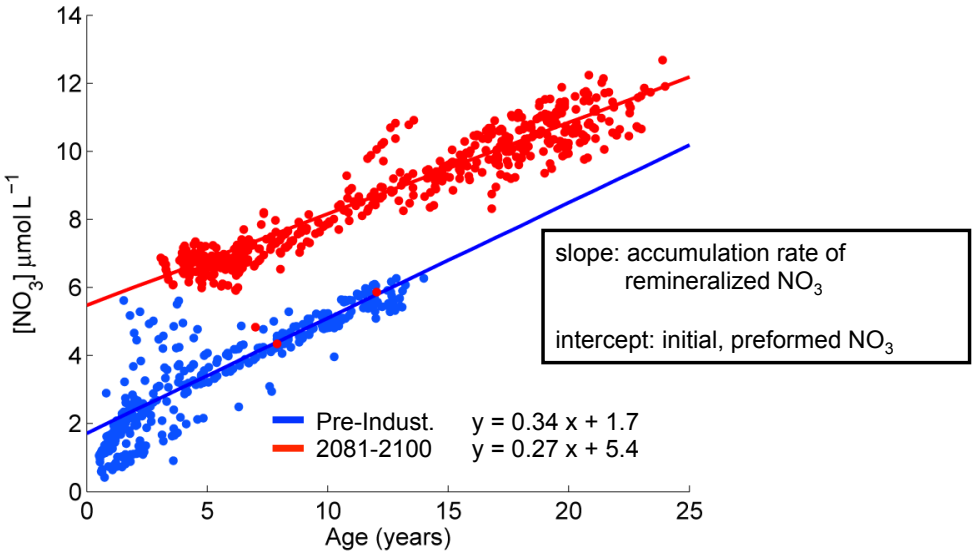
Three main factors control the dynamics of nutrients found in a water parcel:

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



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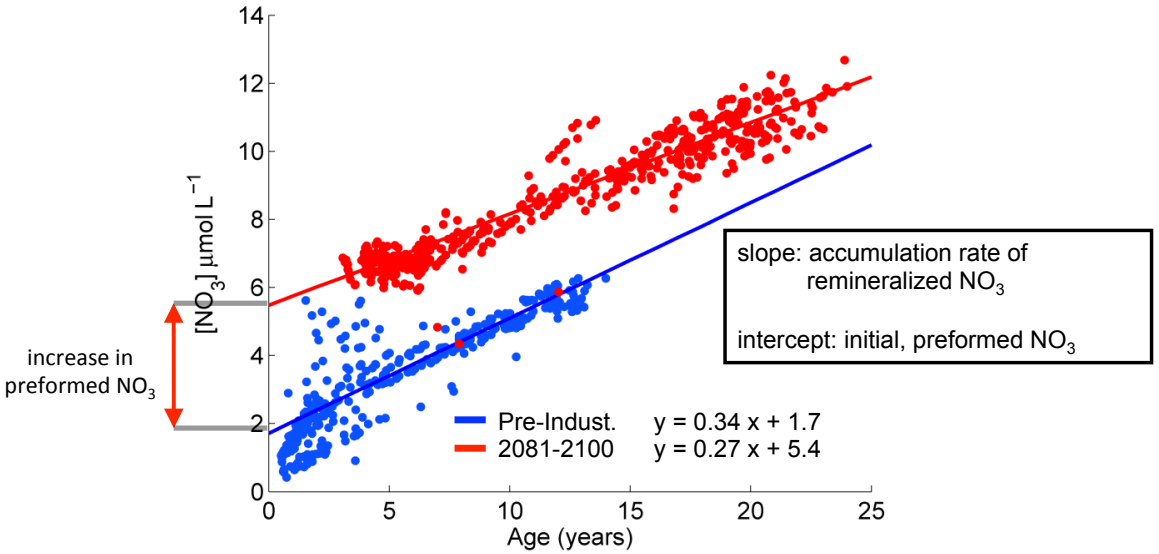

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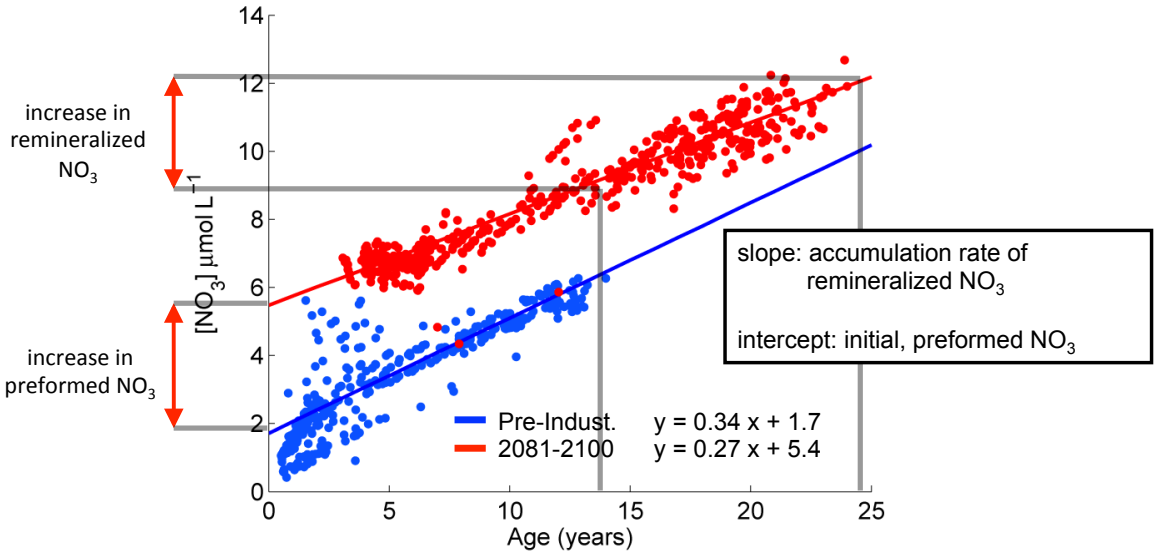
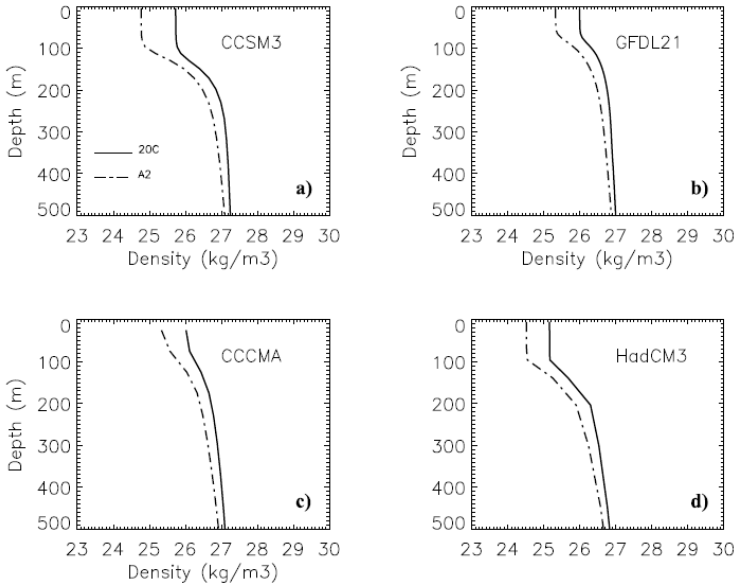


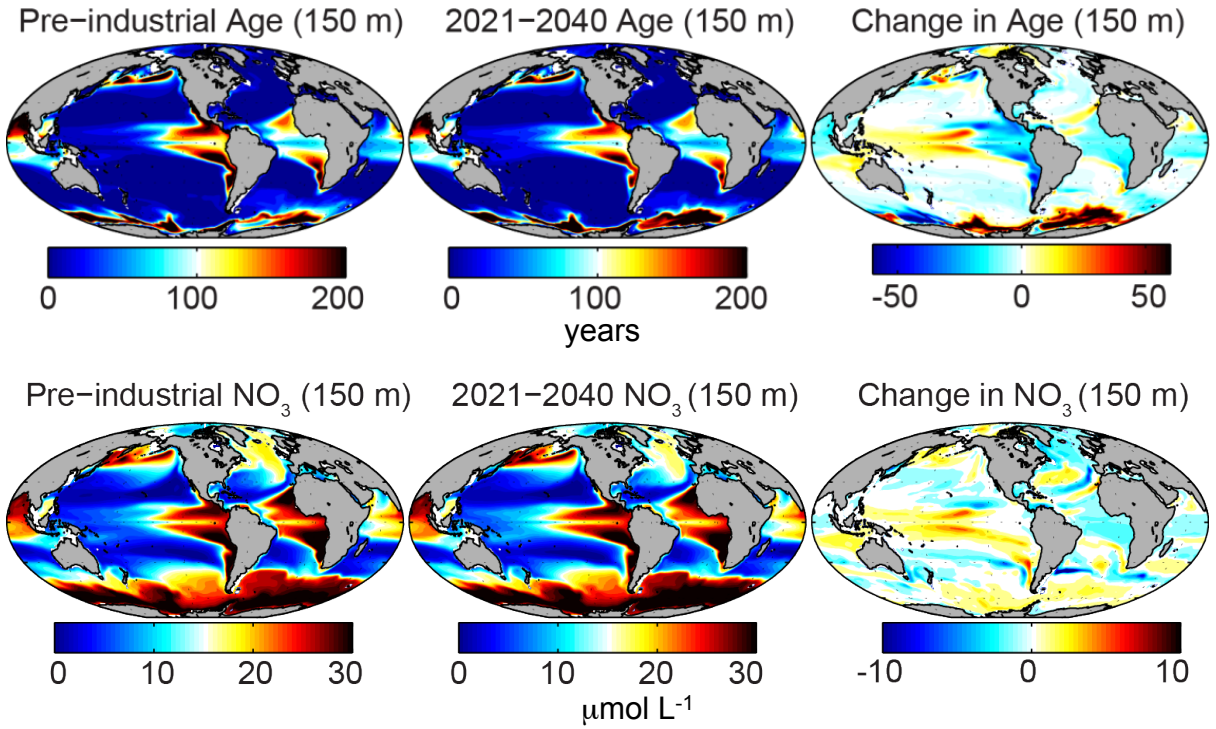
Is this result for the CCE applicable to all upwelling systems?

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

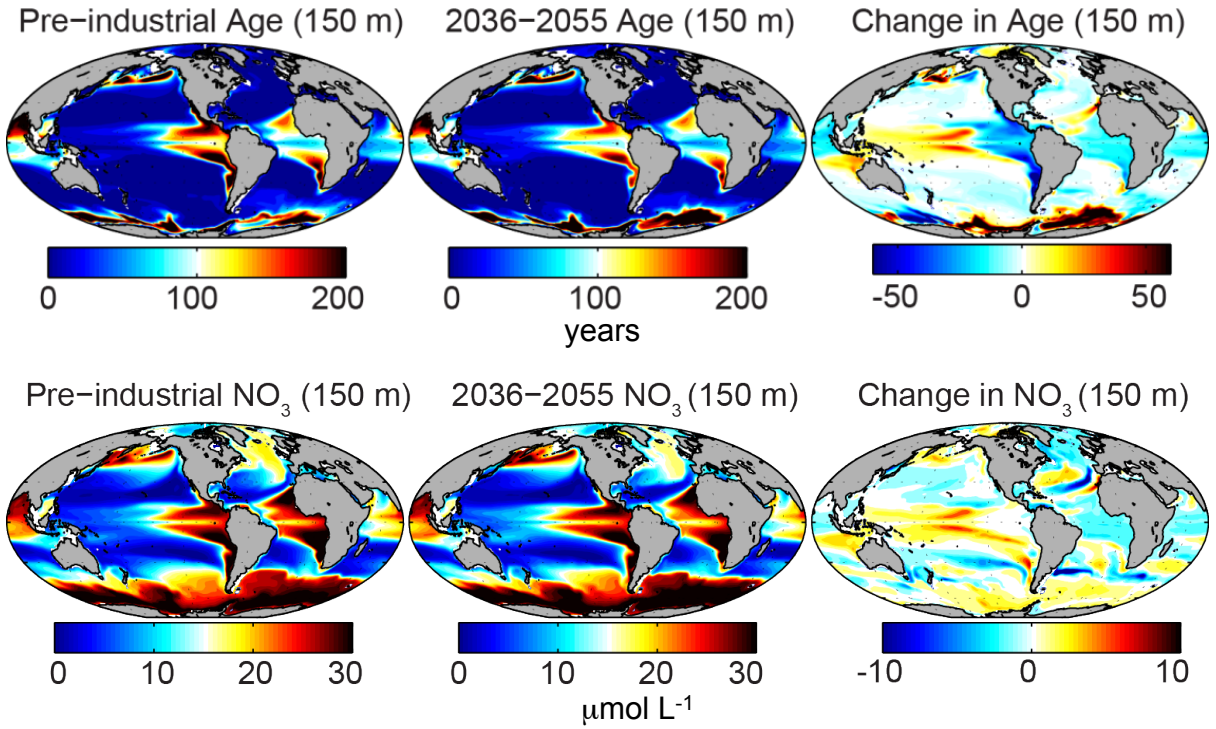


Capotondi *et al.*, (2012, JGR)

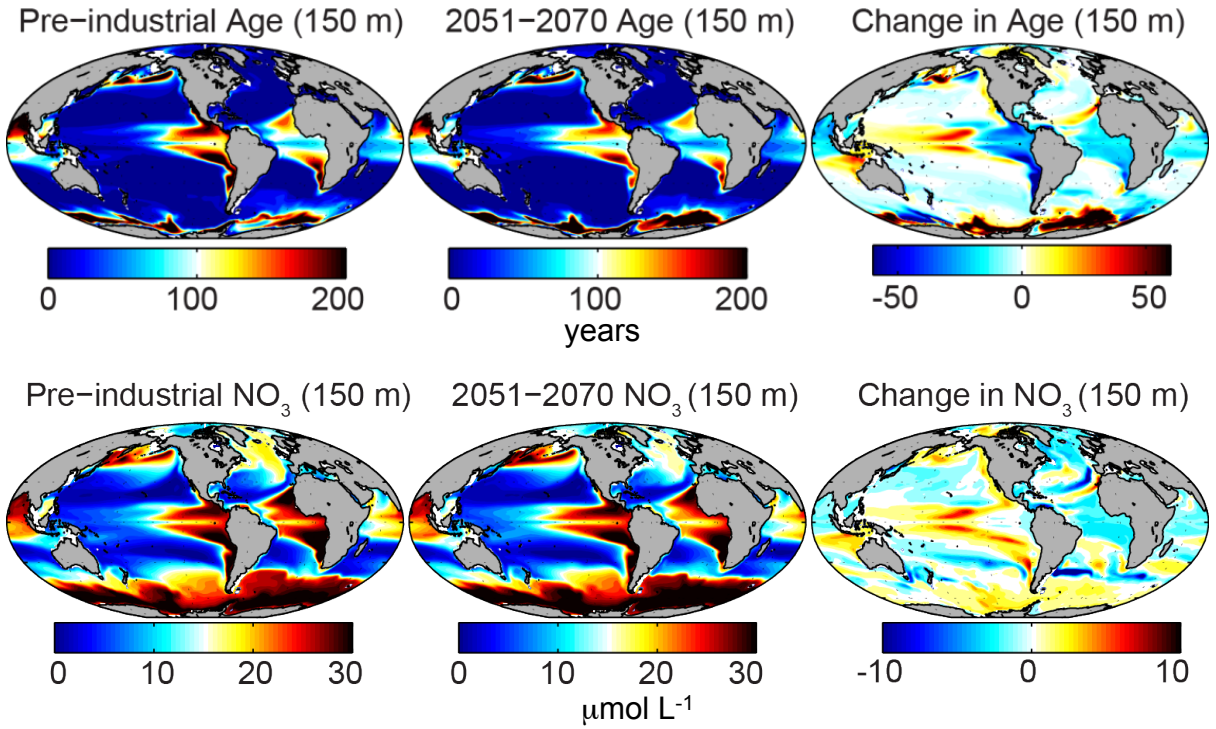
2040: Global age and NO_3 changes (150 m)



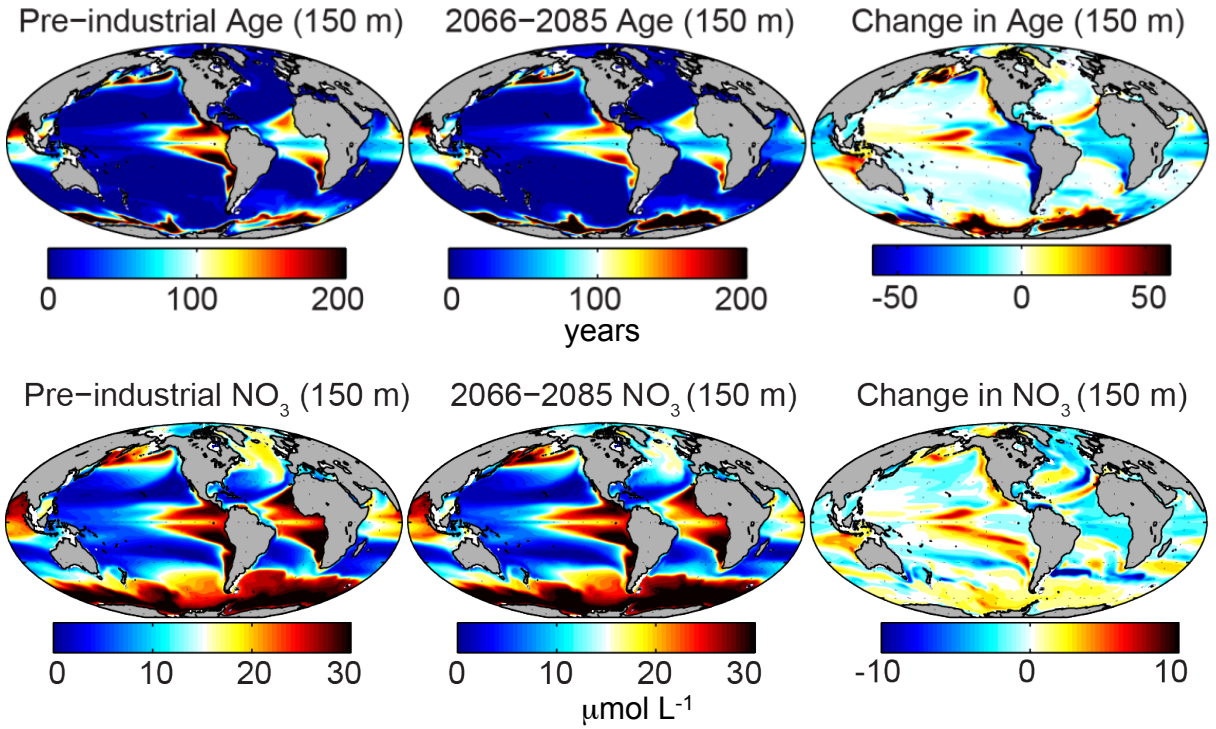
2055: Global age and NO_3 changes (150 m)



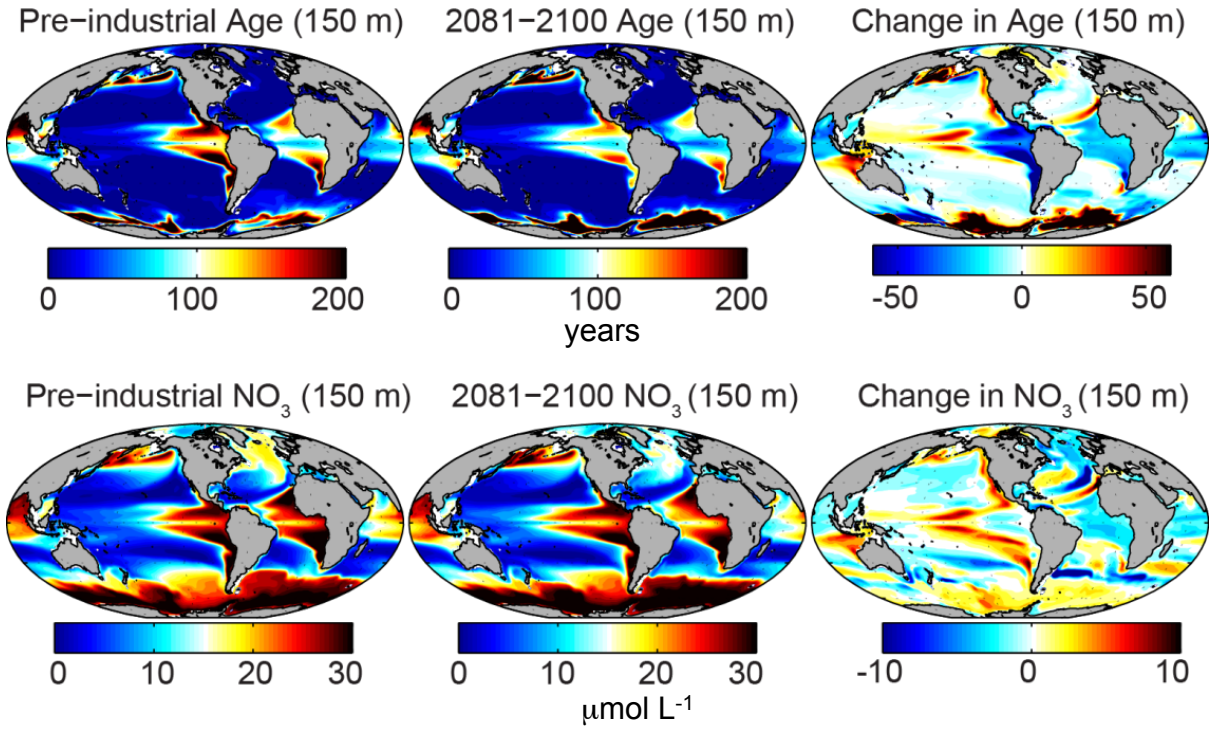
2070: Global age and NO_3 changes (150 m)



2085: Global age and NO_3 changes (150 m)



2100: Global age and NO_3 changes (150 m)



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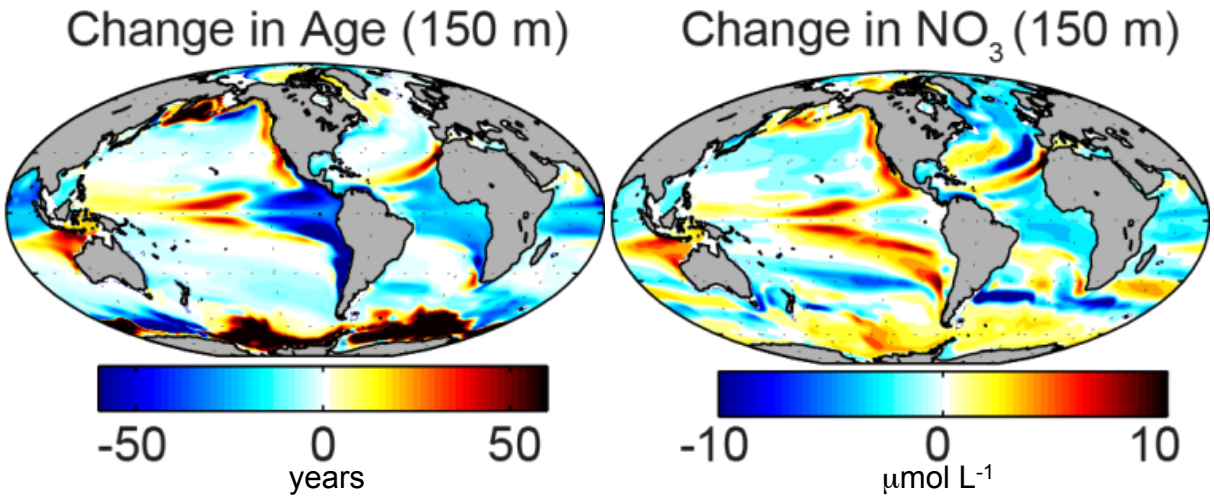
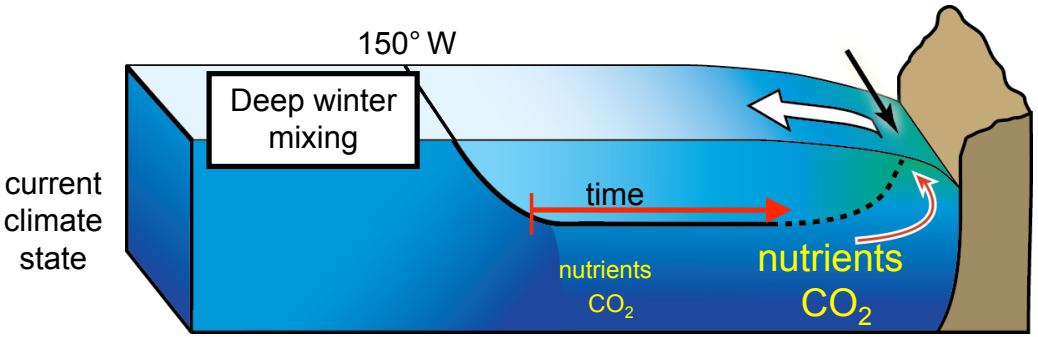


Future global warming inhibits this ventilation

Currently, deep waters which supply the California Current originate near about 150° W, or about 1600 km offshore in the Central Pacific.

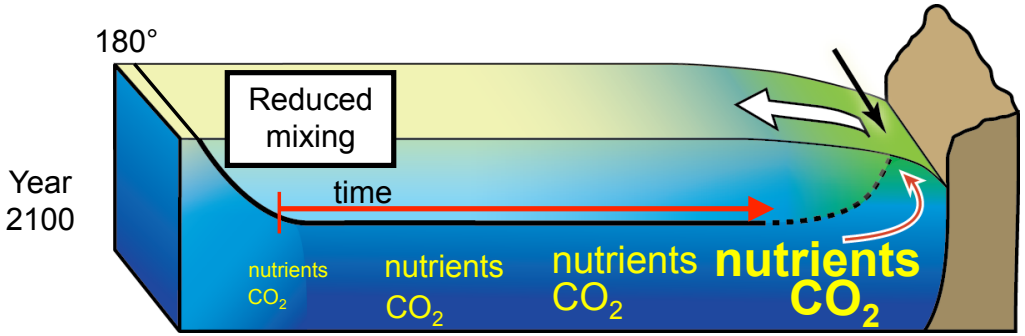
These deep waters eventually upwell at the coast, rich with nutrients.



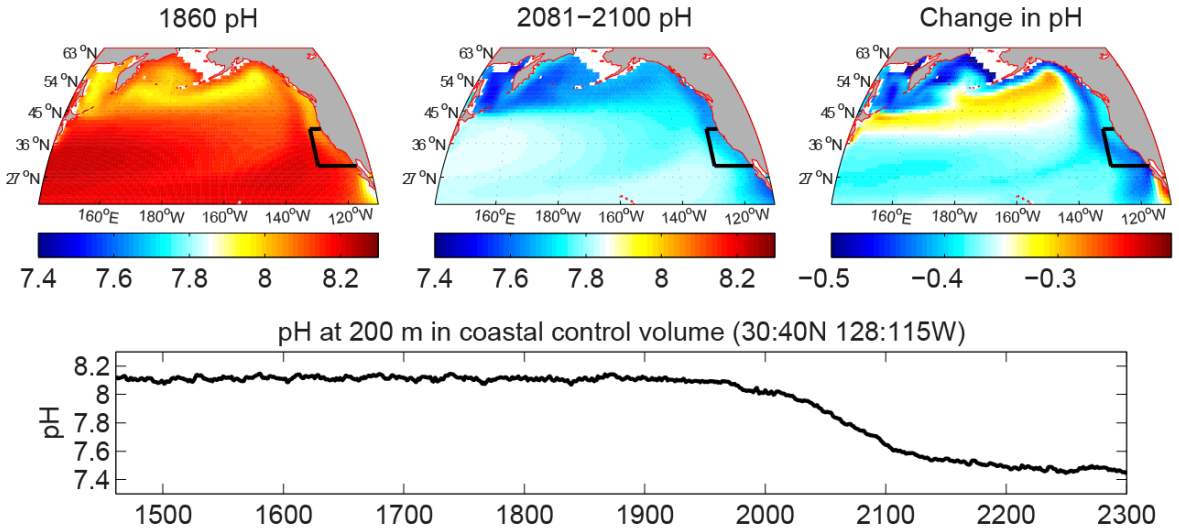
Future global warming inhibits this ventilation

Future warmer sea-surface temperatures associated with global warming increase stratification across the entire Pacific.

Waters upwelling in along the eastern boundary of the Pacific contain much higher concentrations of nutrients and CO_2 and reduced O_2.

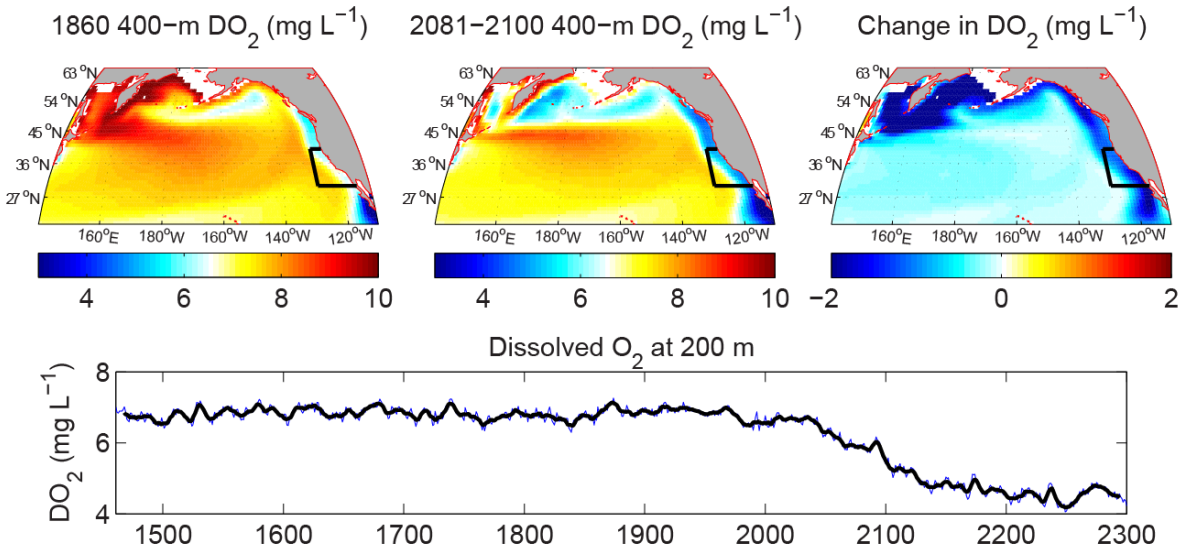


pH and oxygen are also sensitive to ventilation changes



Rykaczewski and Dunne (2010, GRL)

pH and oxygen are also sensitive to ventilation changes



Rykaczewski and Dunne (2010, GRL)

pH and oxygen are also sensitive to ventilation changes

Few survey programs have been measuring NO_3 or O_2 long enough to distinguish decadal variability from long-term trends.

However, those that have examined O_2 identified consistent long-term trends:

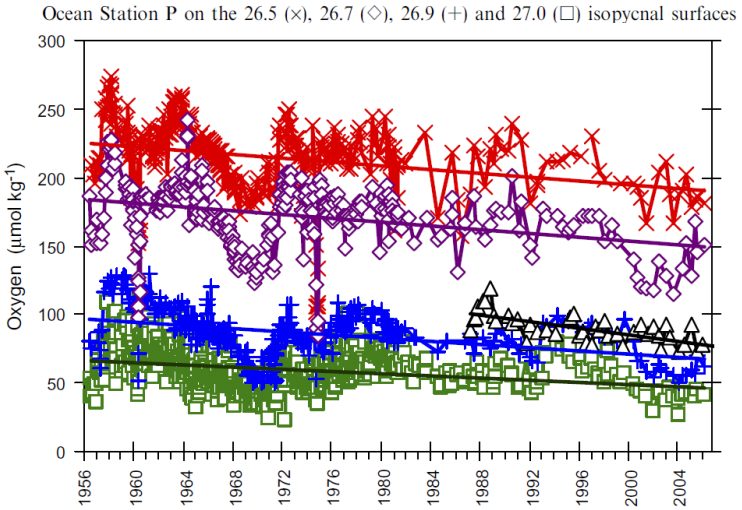
Whitney, *et al*. (2007)

Nakanowatari, *et al.* (2007)

Chan, *et al.* (2008)

Bograd, *et al.* (2008)

Aksnes and Ohman (2009)



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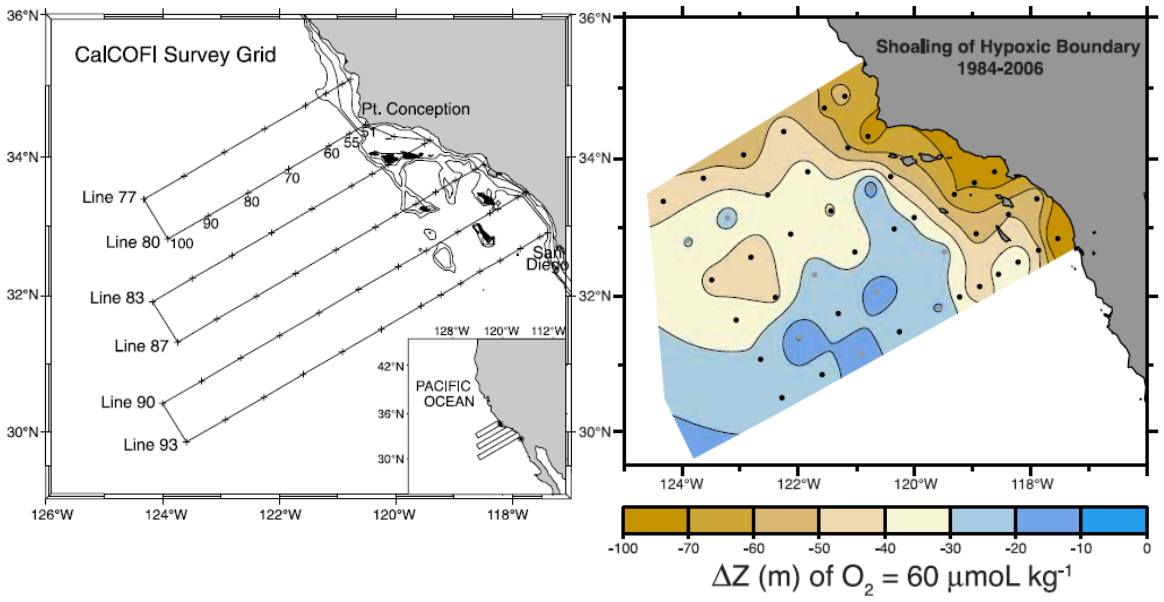


Where did I go wrong in my expectation of ecosystem response to increased stratification?

Roemmich and McGowan (1995) were keen to observe a relationship between increased local stratification and decreased biological production over interannual to decadal time scales…

But hypotheses constructed given observations of past, interannual climate variability cannot be directly applied to the global climate change question.

This brings me to my first realization concerning fisheries-climate interactions…

Point 1 of 3: Understanding the past is sometimes insufficient

Point 1 of 3

An understanding of the past is sometimes insufficient to project future ecosystem responses.

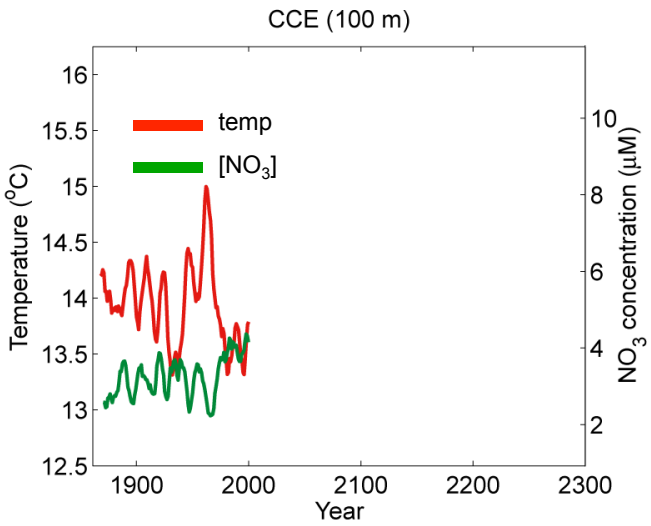
Our observations of past ecosystem changes have been associated with local physical forcing over relatively short temporal (seasonal to decadal) and spatial scales.

This biases our hypotheses about future responses.

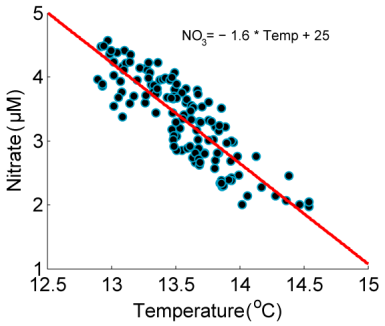
Past empirical correlations may fail in the long term

Conventional view of CC variability:

Cool Period	Warm Period
replete nutrients high biologic production	limited nutrients low biologic production



The nitrate-temperature relationship is negative over interannual to multidecadal periods.



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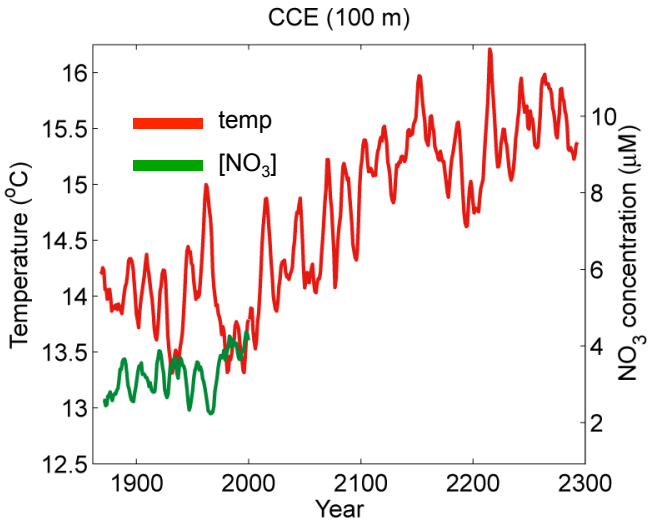

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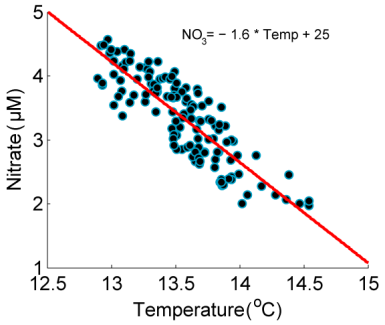

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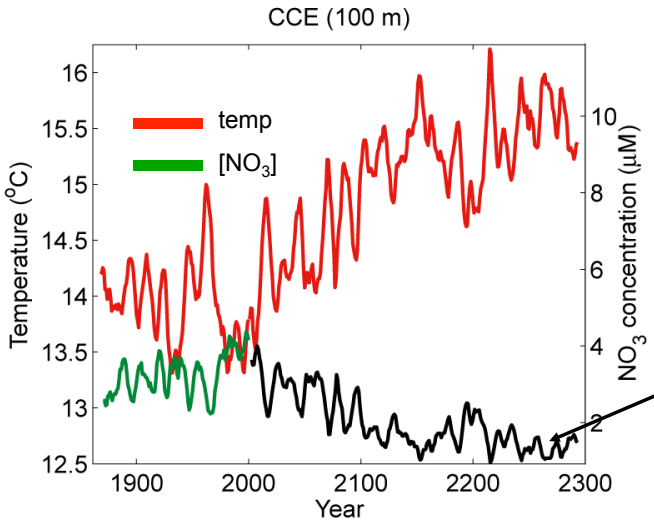
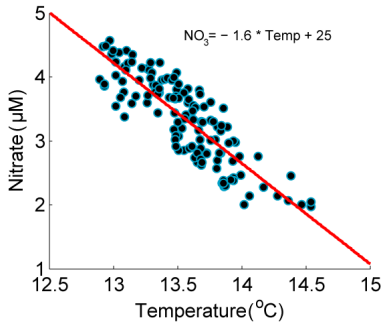




linear expectation for [NO_3] given historical temperature relationship

Past empirical correlations may fail in the long term

Conventional view of CC variability:

Cool Period

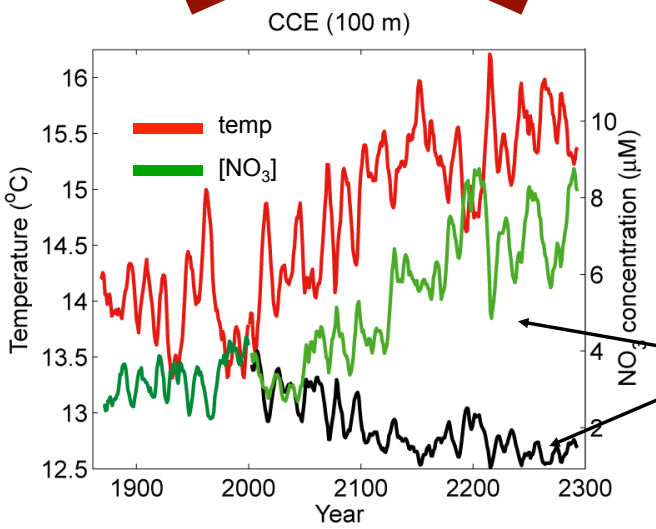
replete nutrients

high biologic pr

ts

roduction

May not apply to long-term warming



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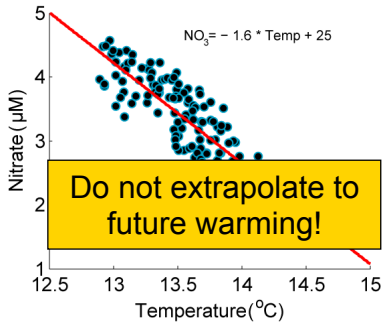


Do not extrapolate to future warming!

ESM 2.1 projection for [NO3]

linear expectation for [NO_3] given historical temperature relationship

Point 2 of 3: Boundary conditions cannot be assumed constant

In the case of eastern boundary currents, changes in water mass properties at the oceanic boundary may be the major source of climate-change related trends in the future.

Point 2 of 3

Changes in boundary conditions may be essential to projecting future responses to climate change. Use caution if boundaries are assumed to be constant!

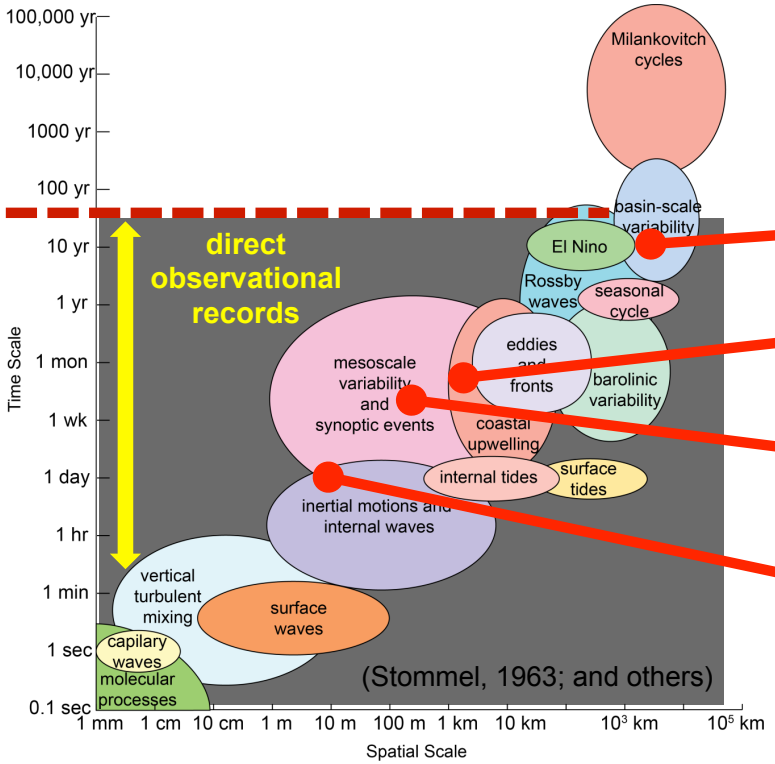
While one might reasonably assume climatological boundary conditions for a regional model that is limited to a few years in scope, I would advise against relying on a regional model for longer projections.

*Point 3 of 3: Explore new **ecological** hypotheses*

Point 3 of 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.

Traditional hypotheses are based on observed variability and insufficient for all times scales and modes of change



Gargett's "optimal stability window" hypothesis (1997)

Hjort's "critical period" hypothesis (1914, 1926)

Lasker's "Stable ocean" hypothesis (1978, 1981)

Cury and Roy's "optimal environmental window" hypothesis (1989, 1992)

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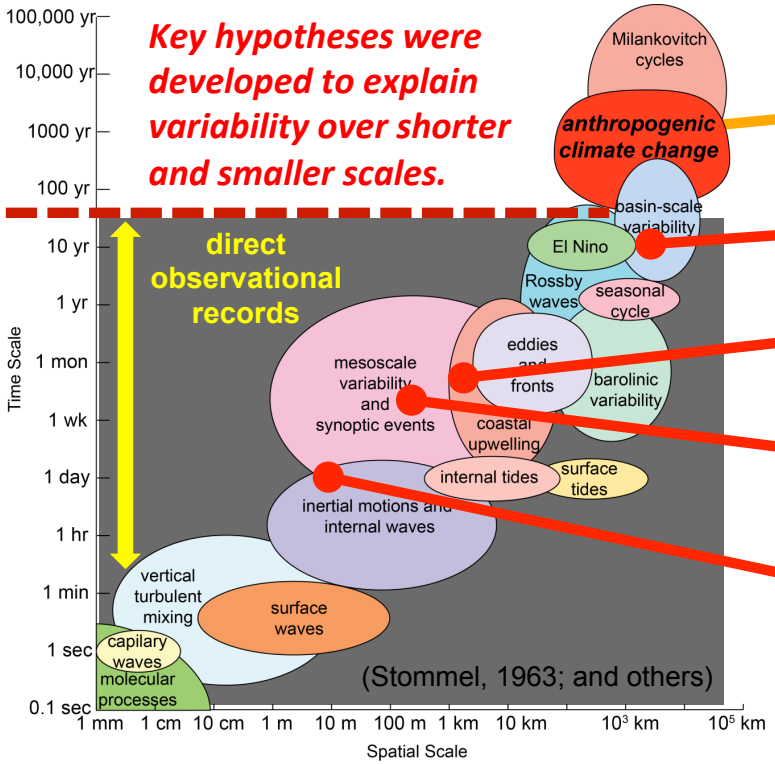

??? Fisheries responses to anthropogenic climate change

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*Point 3 of 3: Explore new **ecological** hypotheses*

Point 3 of 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!

Ryan Rykaczewski
ryk@sc.edu

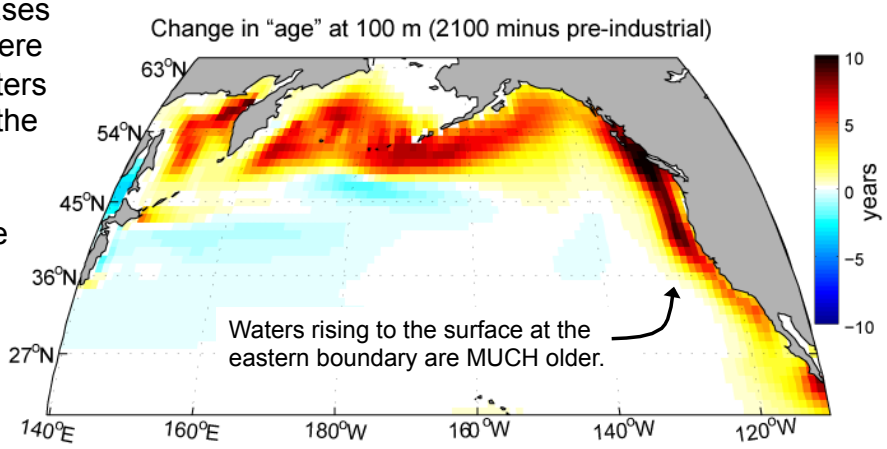
Basin-wide reduced ventilation

Increased stratification reduces ventilation of deep waters.

This reduces NO_3 supply and production in most regions…

But then increases NO_3 supply where those deep waters are brought to the surface.

O_2 changes are opposite NO_3.



Ventilation of CCE source waters

In the future, waters follow a deeper, *less ventilated* trajectory en route to the CCE. Reduced ventilation of CCE source waters leads to an increase in NO_3 concentration.