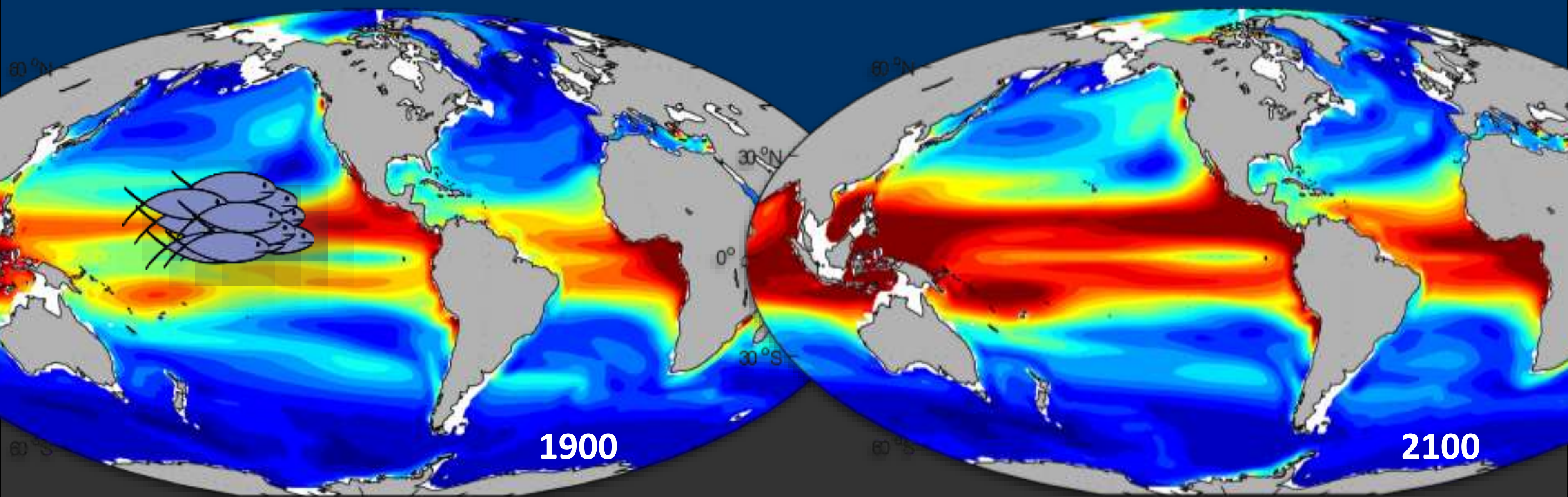
Responses of Eastern Boundary Current Ecosystems to Anthropogenic Climate Change



UNIVERSITY OF SOUTH CAROLINA

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NOAA

NEREUS
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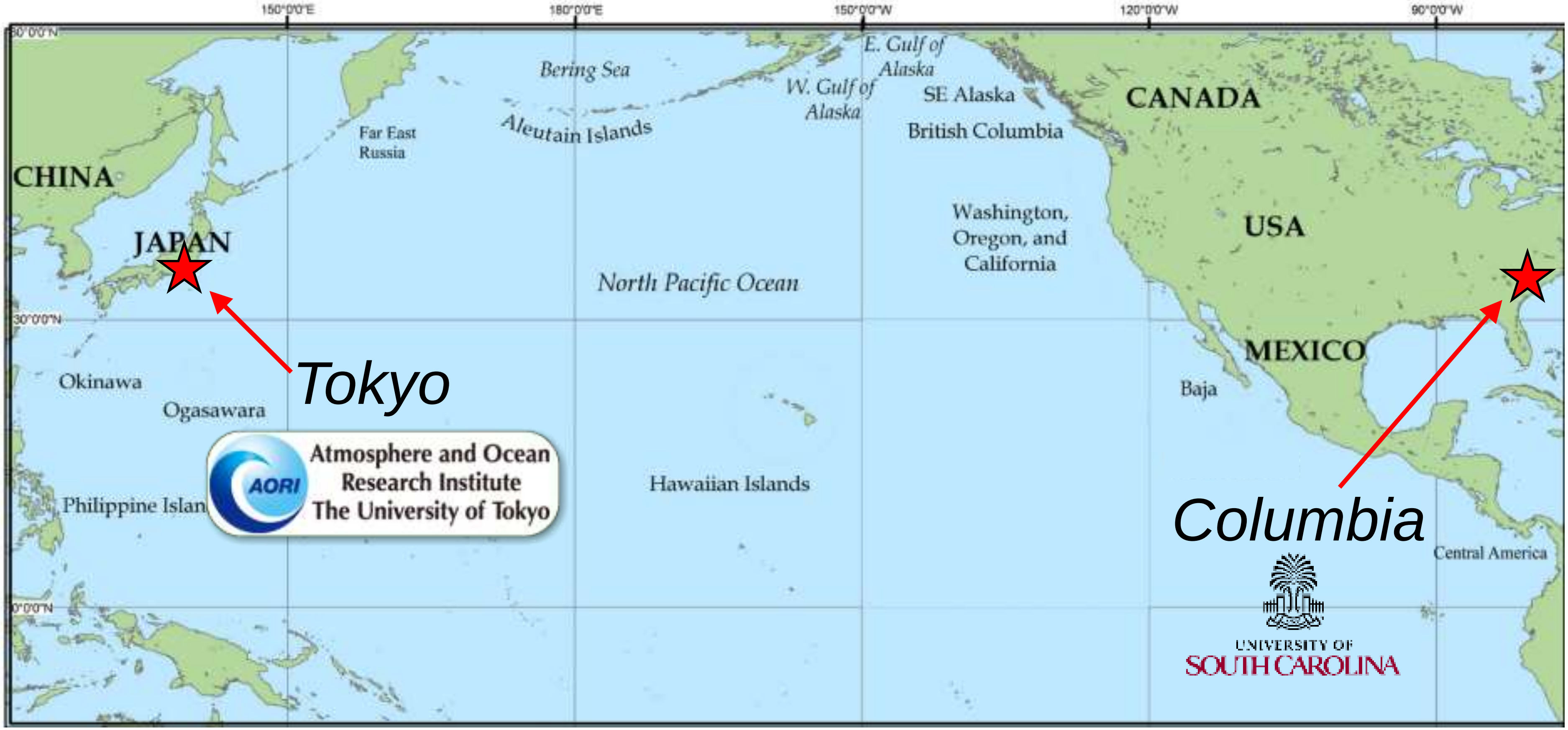
ryk @ sc.edu

We are united by an interest in understanding ecosystem dynamics in the North Pacific



~35,000 students
(~300 students in Marine Sciences, with 13 faculty members)

RYKACZEWSKI LAB
Ecosystem Oceanography and Climate Change

Q: What sorts of scientific topics do we study in my group?

A: We want to understand why abundances of fish go up and down.

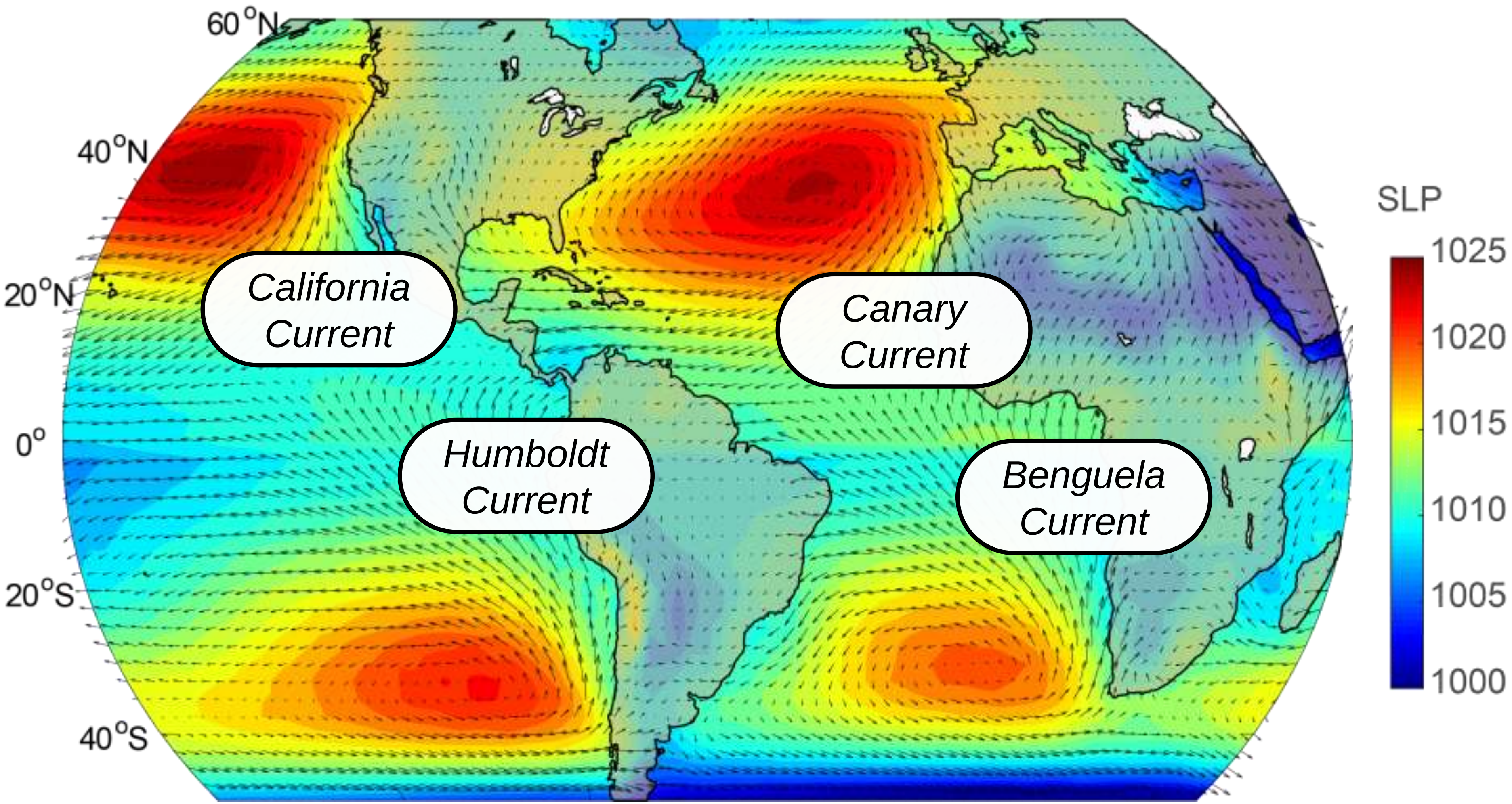
Why is it that fish populations are so abundant (and lucrative to exploit!) during some years and absent during others?

How do changes in ***large-scale physical processes*** influence…

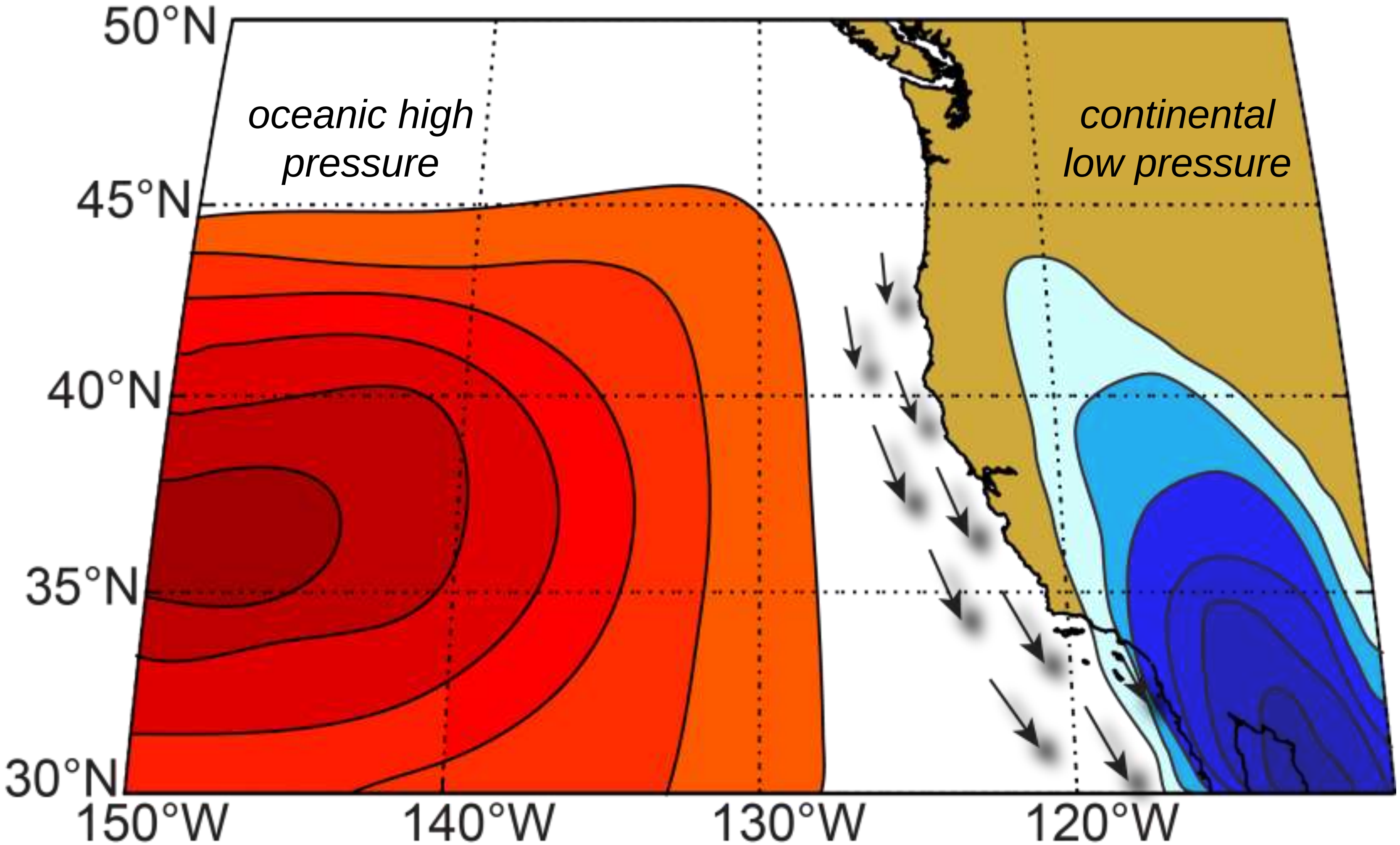
…the structure of the marine ecosystems*—species composition and size distribution of the plankton, inter and intra-specific interactions, trophic transfer efficiency…*

…and affect the world’s ***marine fish stocks***?

Variability in eastern boundary current upwelling systems



Variability in eastern boundary current upwelling systems



Long-term goal: understand the dynamics of upwelling ecosystems

Upwelling systems:

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

Major genera include *Sardinops* and *Engraulis* inhabiting each of the four major eastern boundary currents.

The Kuroshio stands out as the non-eastern boundary current with major stocks of sardine (*Sardinops melanostictis*) and anchovy (*Engraulis japonicas*).

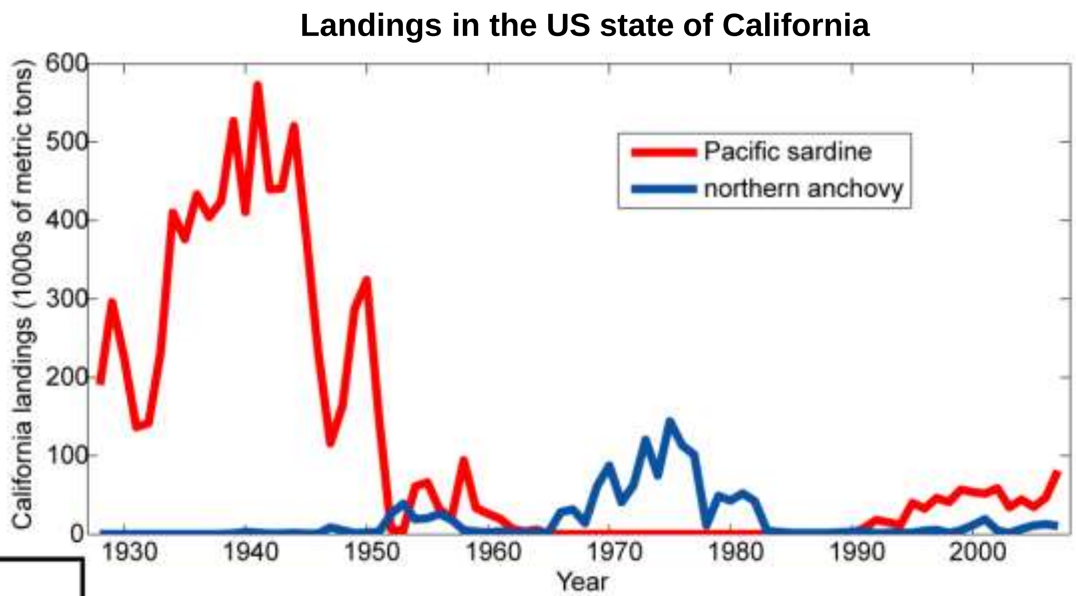
Many hypotheses relate fisheries fluctuations to physics

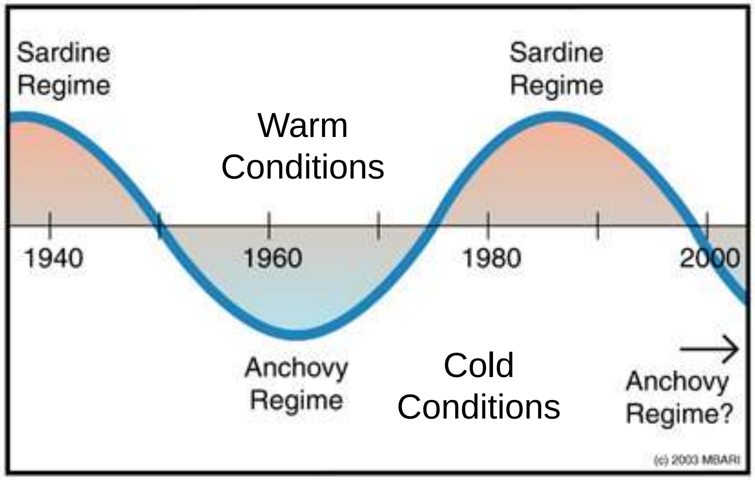
What drives past changes in fish abundance?

Overfishing?

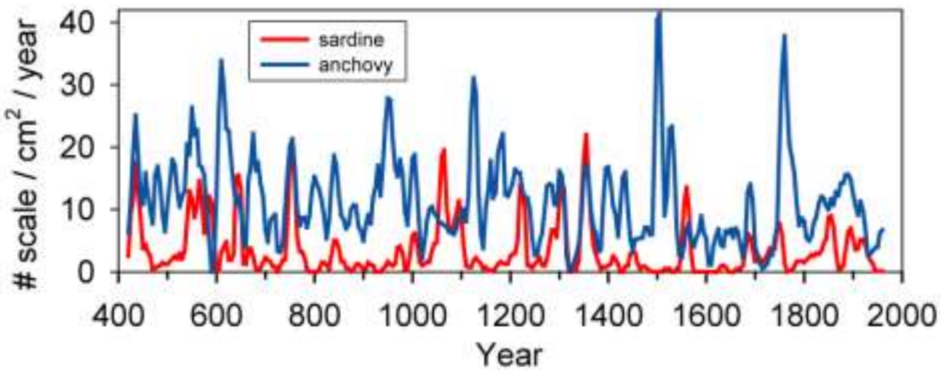
Environmental variability?

How?
Why?





Chavez *et al.* (2003)



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

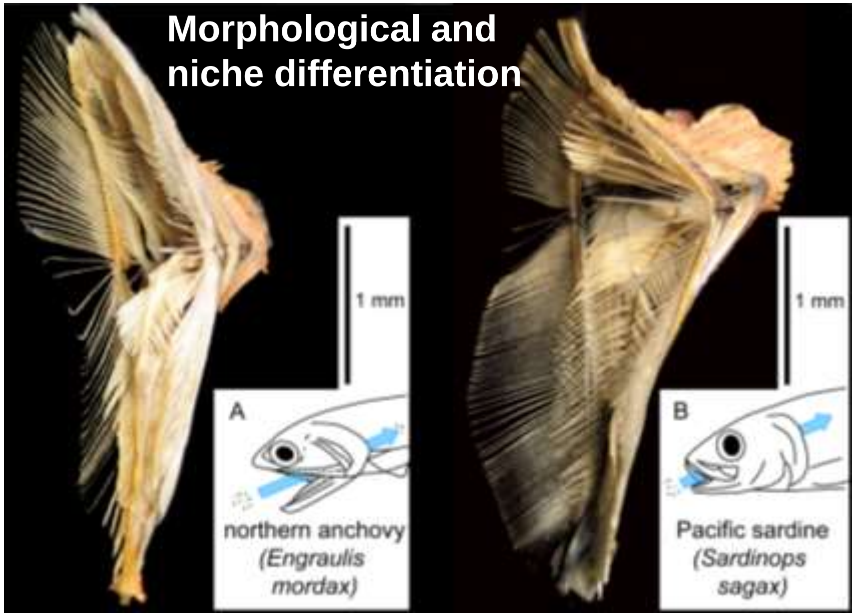
Size distributions of plankton may influence species' success

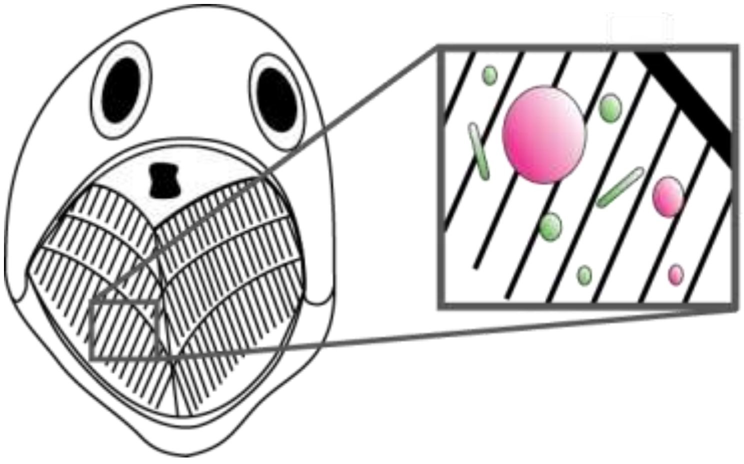
What drives past changes in fish abundance?

Overfishing?

Environmental variability?

How?
Why?



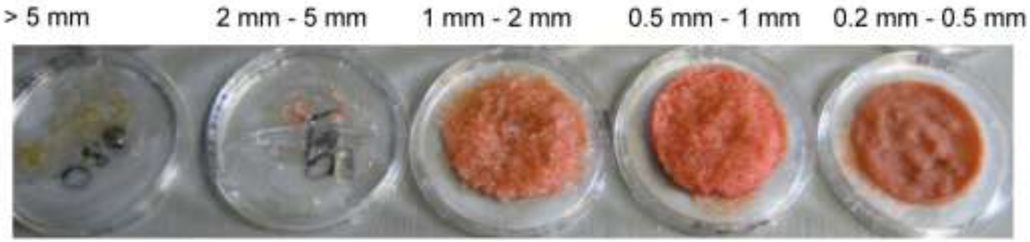


Rates of nutrient supply impact plankton composition

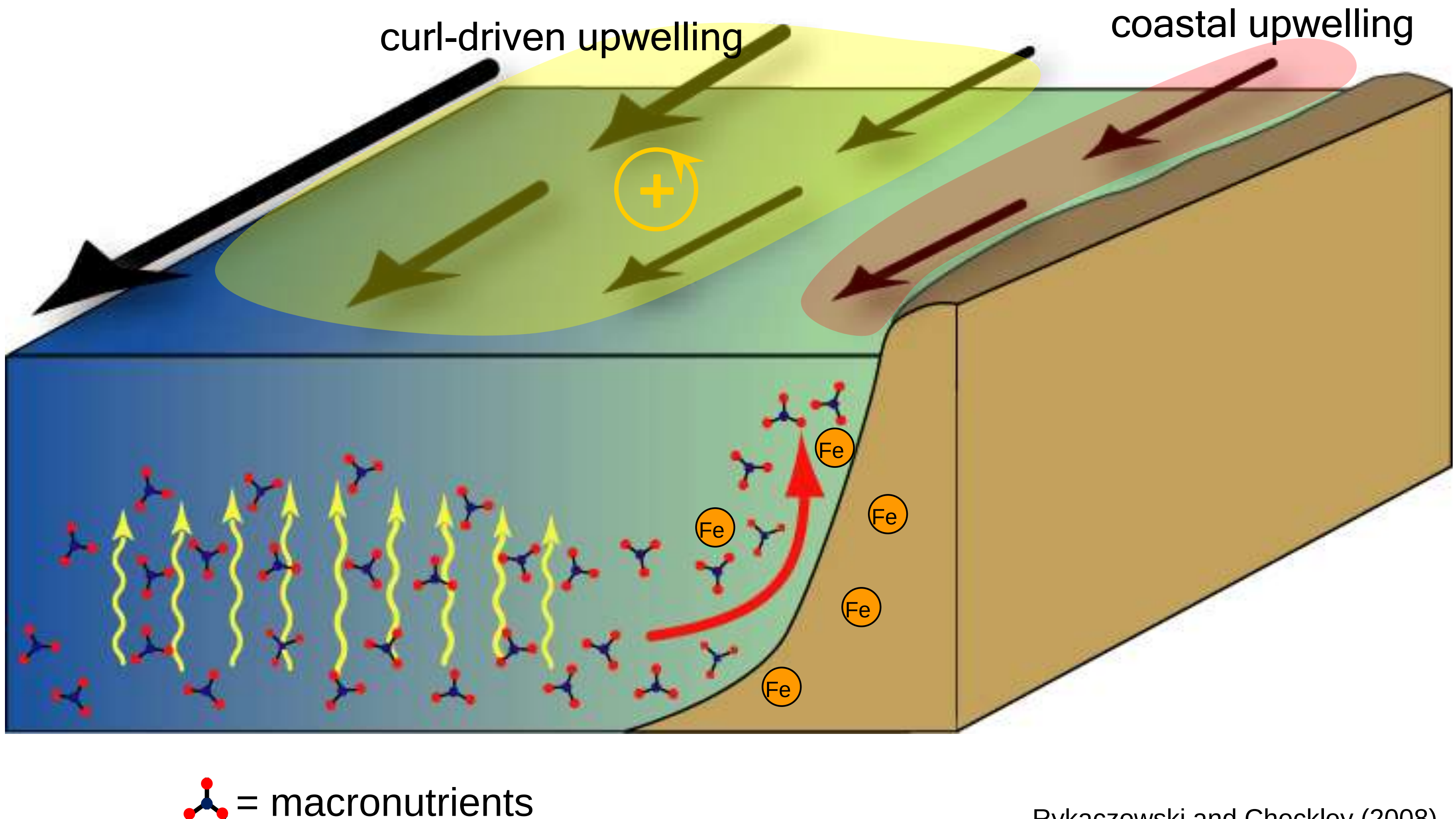
What drives past changes in fish abundance?

H1: The abundance and size structure of the zooplankton community influences productivity of sardine and anchovy stocks.

H2: Variability in the supply of nutrients to the euphotic zone influences the composition of the zooplankton.

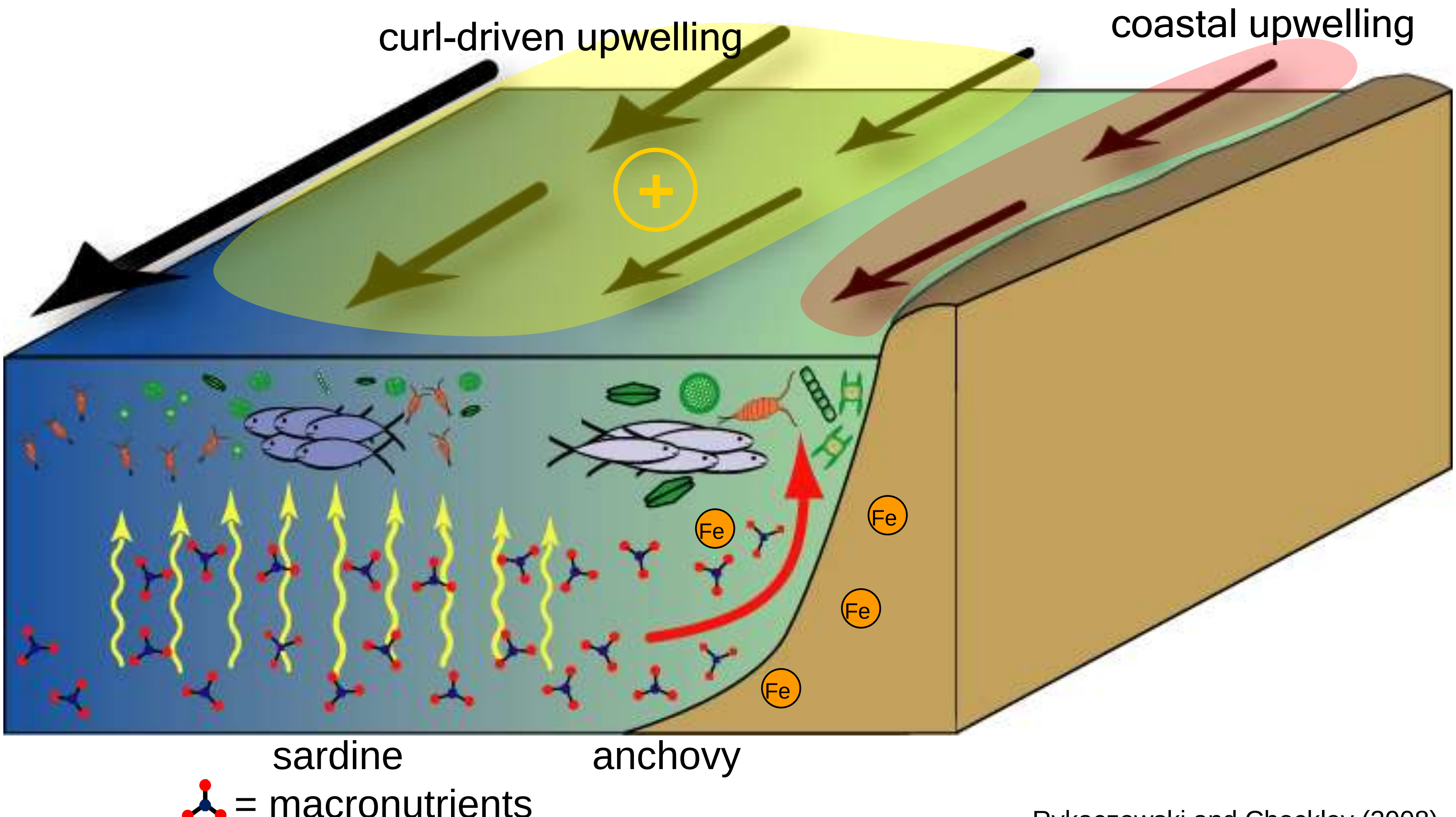


Wind-driven upwelling processes and the food web



Rykaczewski and Checkley (2008)

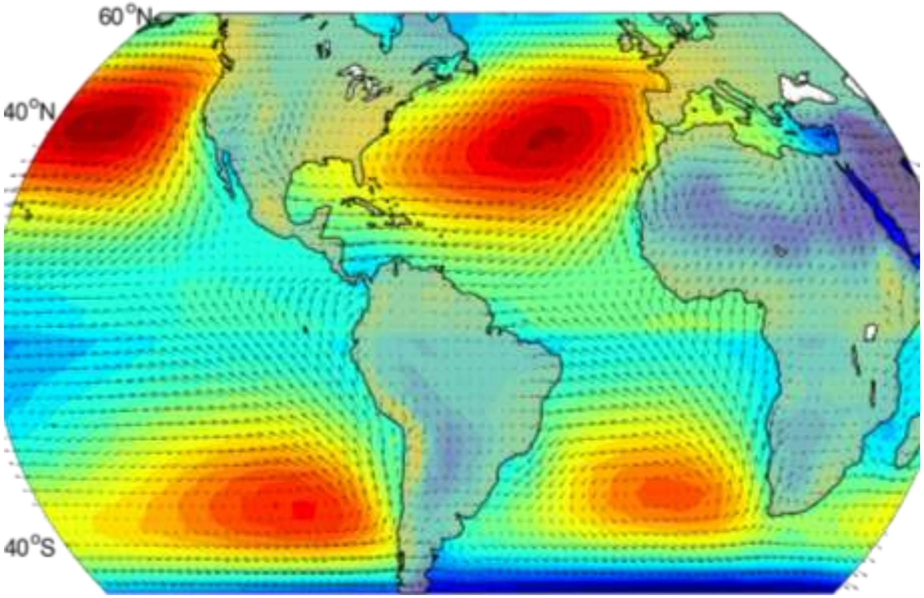
Wind-driven upwelling processes and the food web

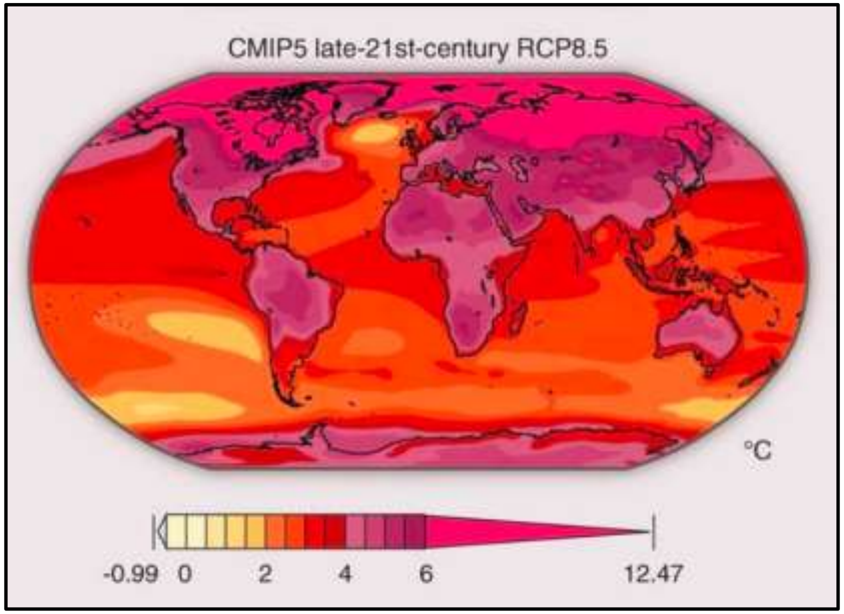


Rykaczewski and Checkley (2008)

Ongoing research: responses to anthropogenic change

What is the response of the upwelling process to anthropogenic climate change?





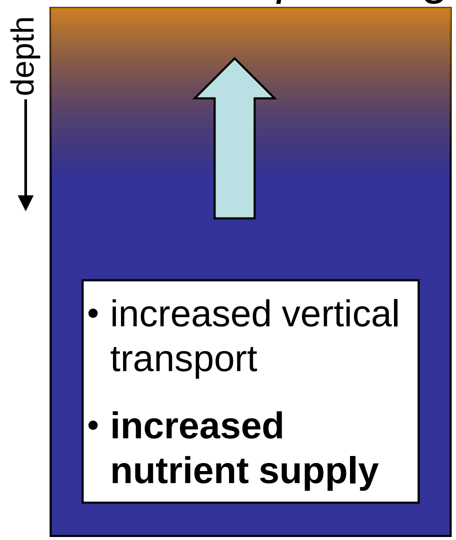
Can we expect that these changes will be similar across eastern boundary current ecosystems?

How will nutrient supply to eastern boundary currents change in the future?

There are two previously posed hypotheses regarding the response of upwelling to anthropogenic global warming.

#1 – Bakun (*Science*, 1990)

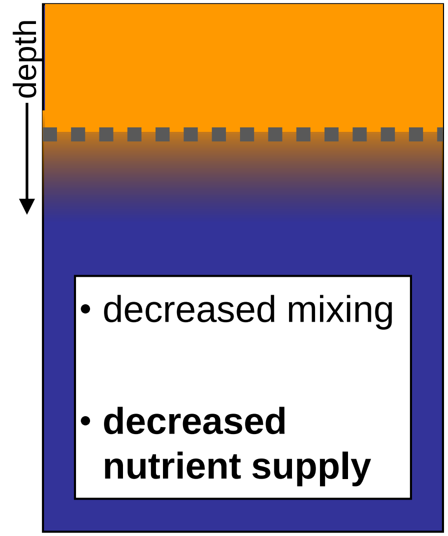
increased upwelling rate



vs.

#2 – Roemmich and McGowan (*Science*, 1995)

increased stratification

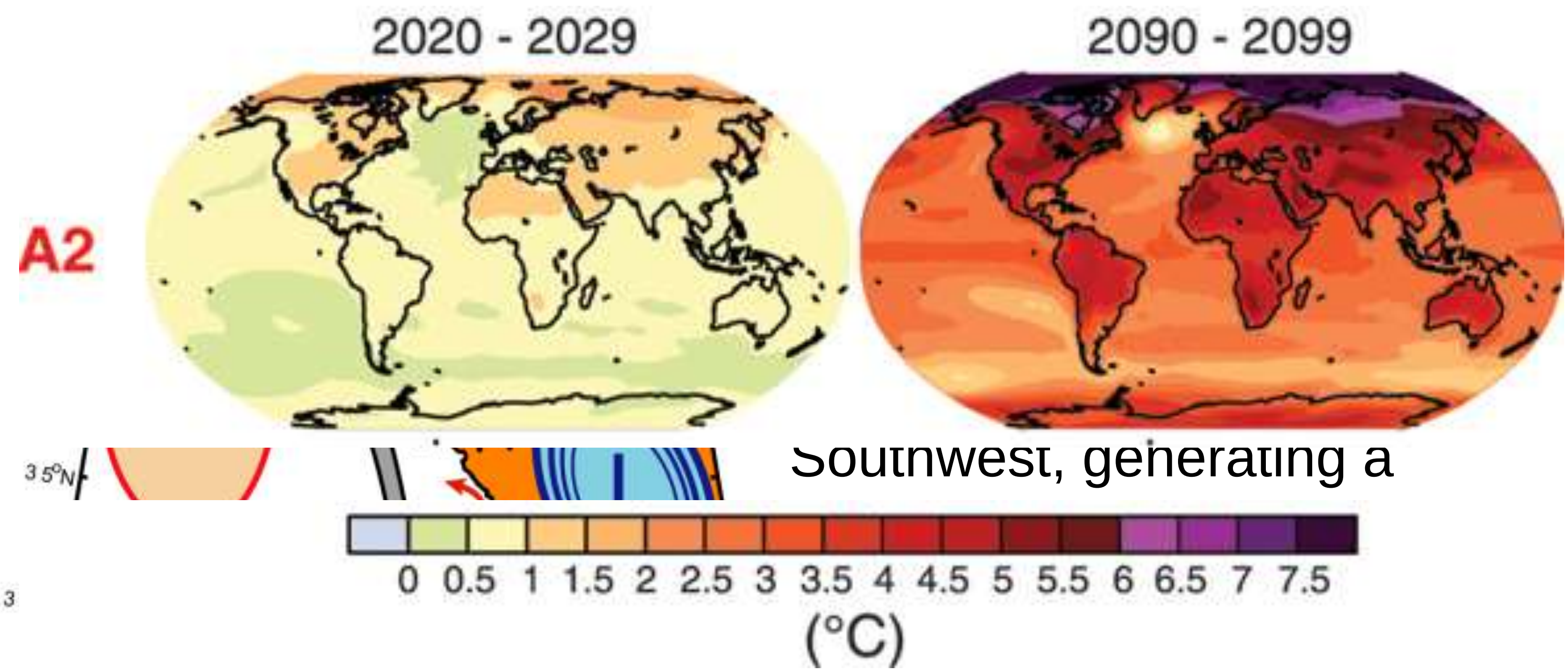


Two qualitative hypotheses posed previously

#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



Southwest, generating a

3

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

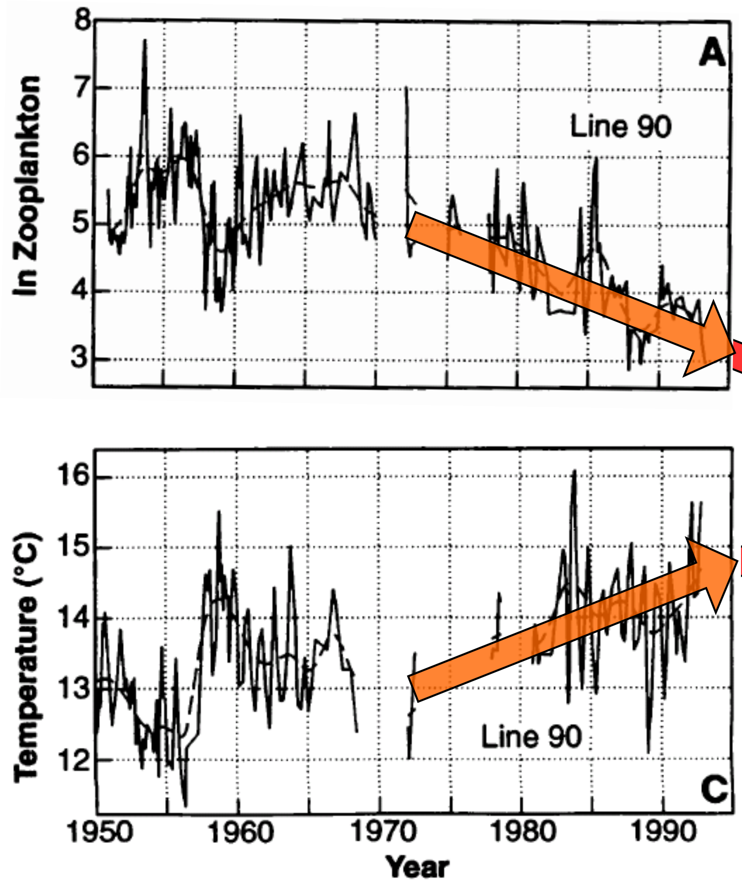
#2 - Increased stratification = decreased nutrient supply

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

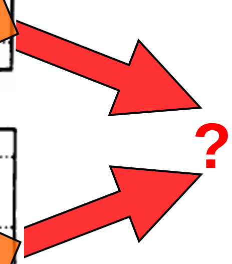
increased SST → increased water-column stratification → reduced mixing reduced efficacy of upwelling reduced production

Historical observations support this inverse temperature-production relationship

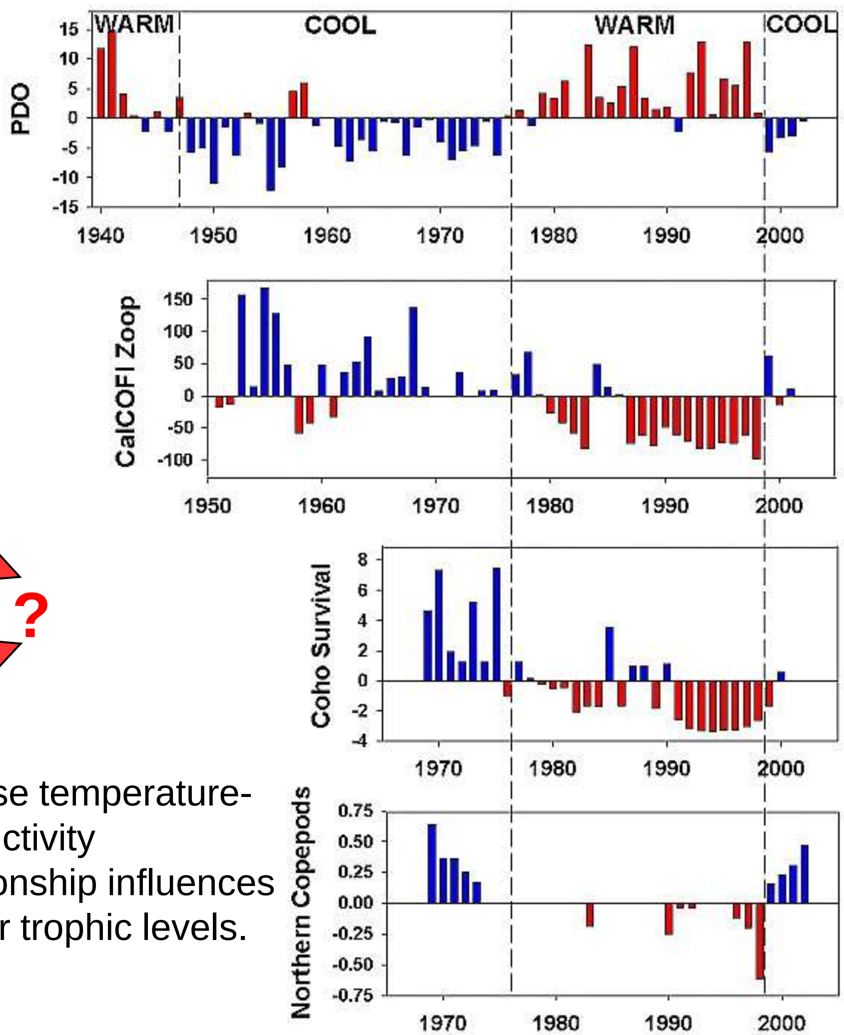
Historical observations support the R&M (1995) hypothesis.



Roemmich and McGowan (*Science* 1995)



Inverse temperature-productivity relationship influences higher trophic levels.

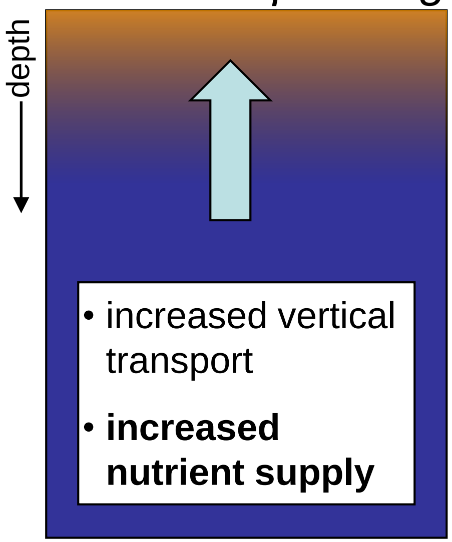


Peterson and Schwing (*GRL* 2003)

What dominates: increased winds or increased stratification?

Bakun
(*Science*, 1990)

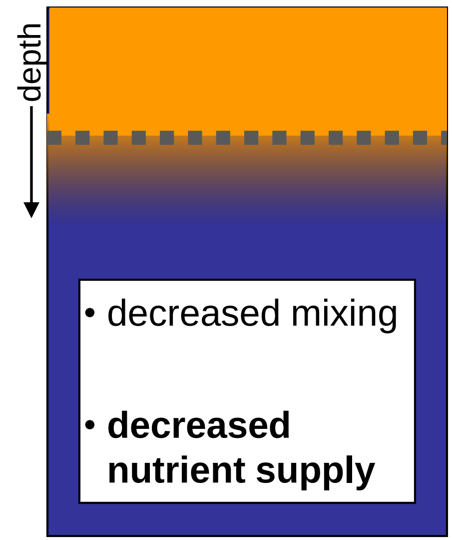
increased upwelling rate



vs.

Roemmich and McGowan
(*Science*,1995)

increased stratification



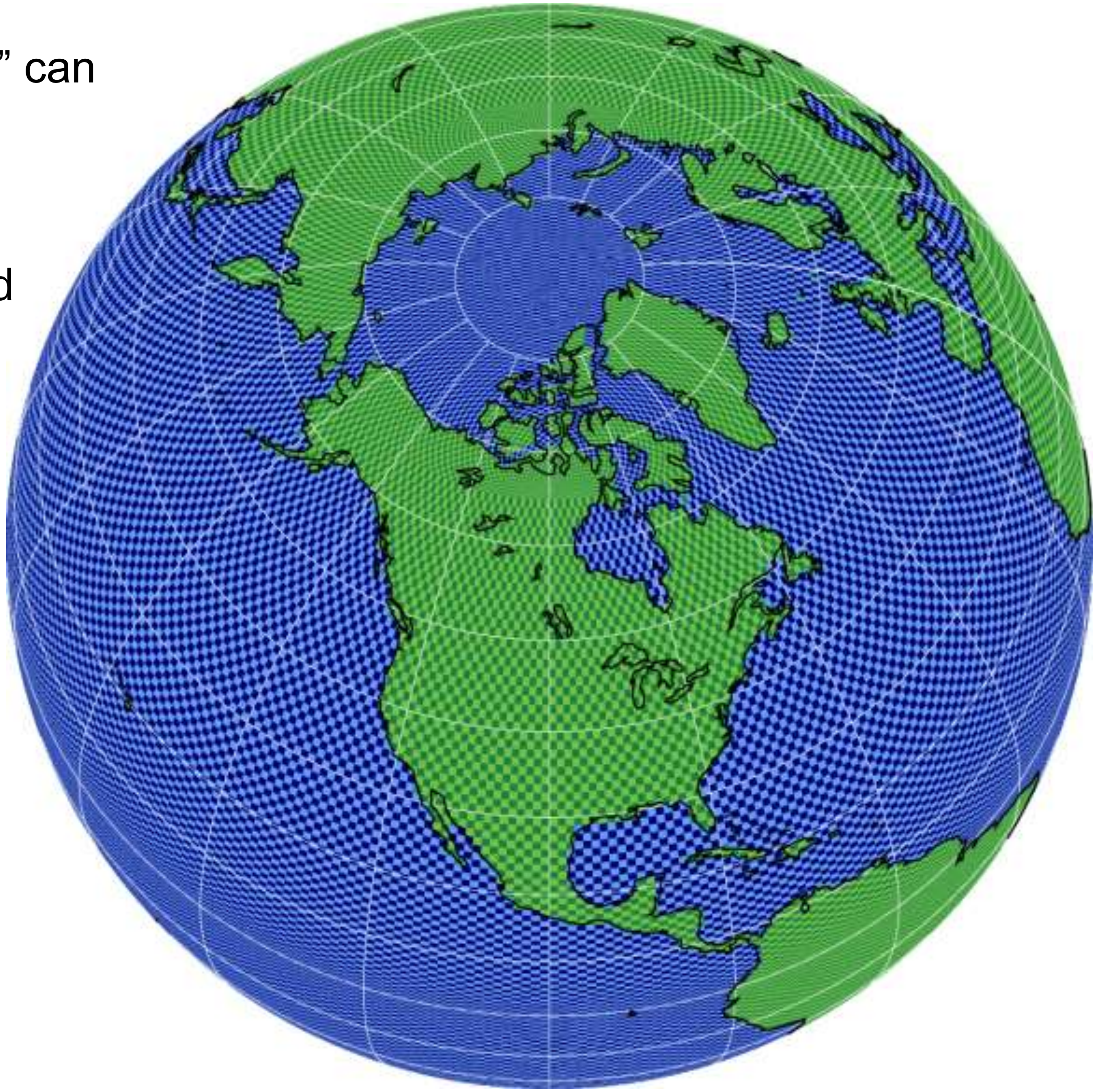
Answering such a question requires us to make use of models that simulation ocean dynamics.

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

The complete "earth system" can be modeled mathematically.

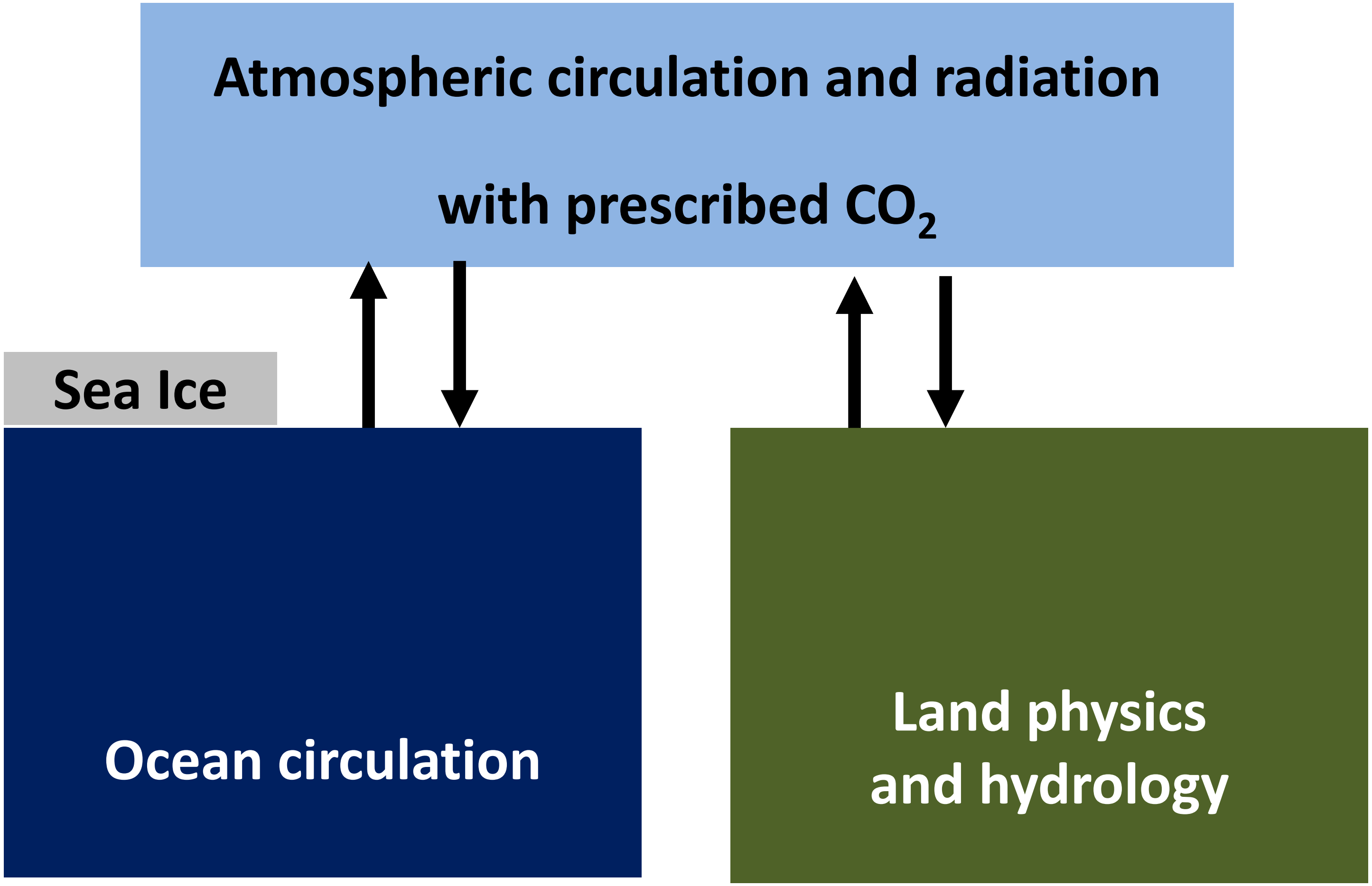
Atmosphere, ocean, and ice components are represented by interacting grid cells, and this composes a coupled General Circulation Model (GCM).

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



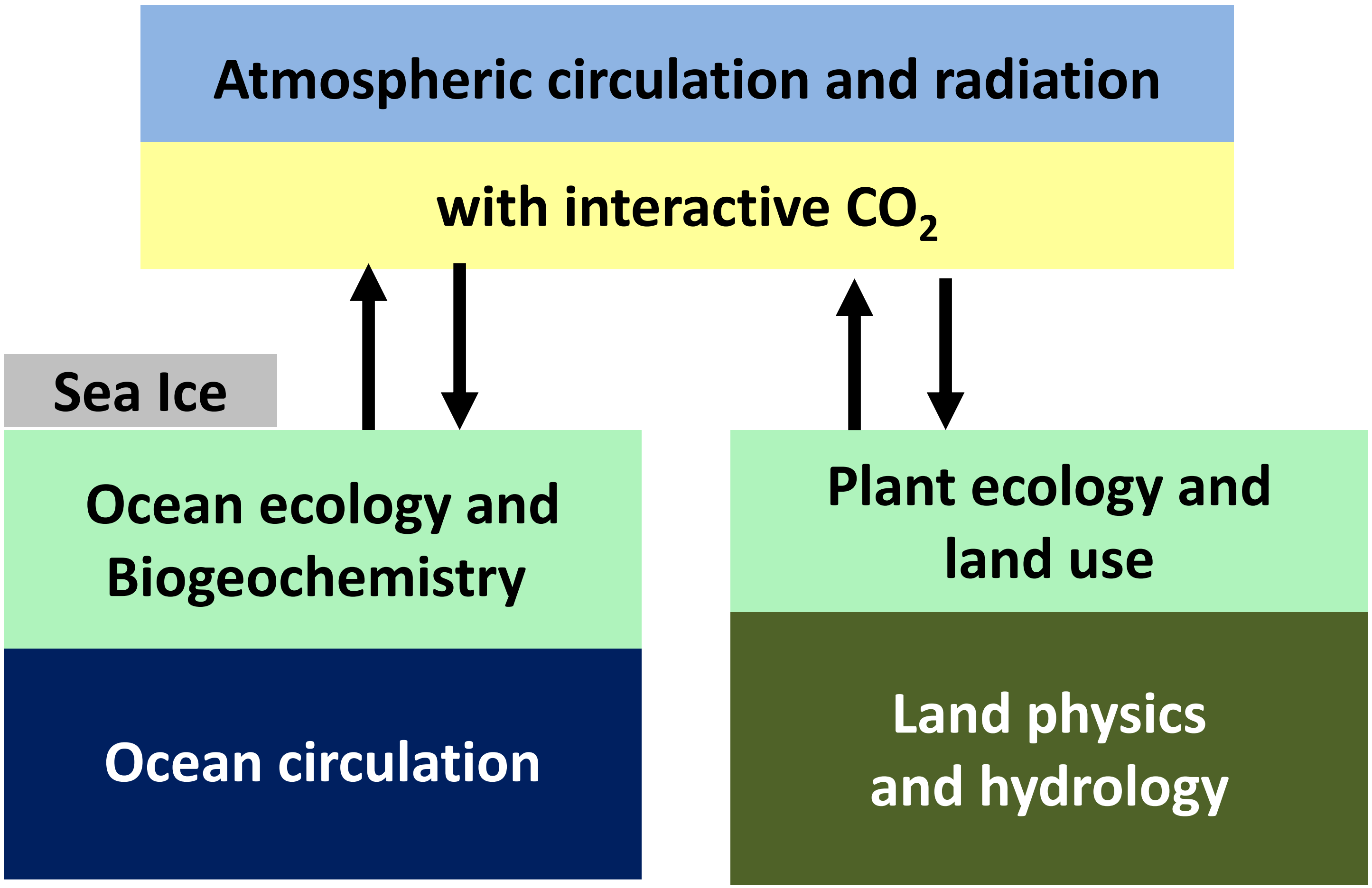
NOAA

Earth System Models: adding the biosphere to simulate the coupled carbon-climate system



Dunne *et al.* (2013)

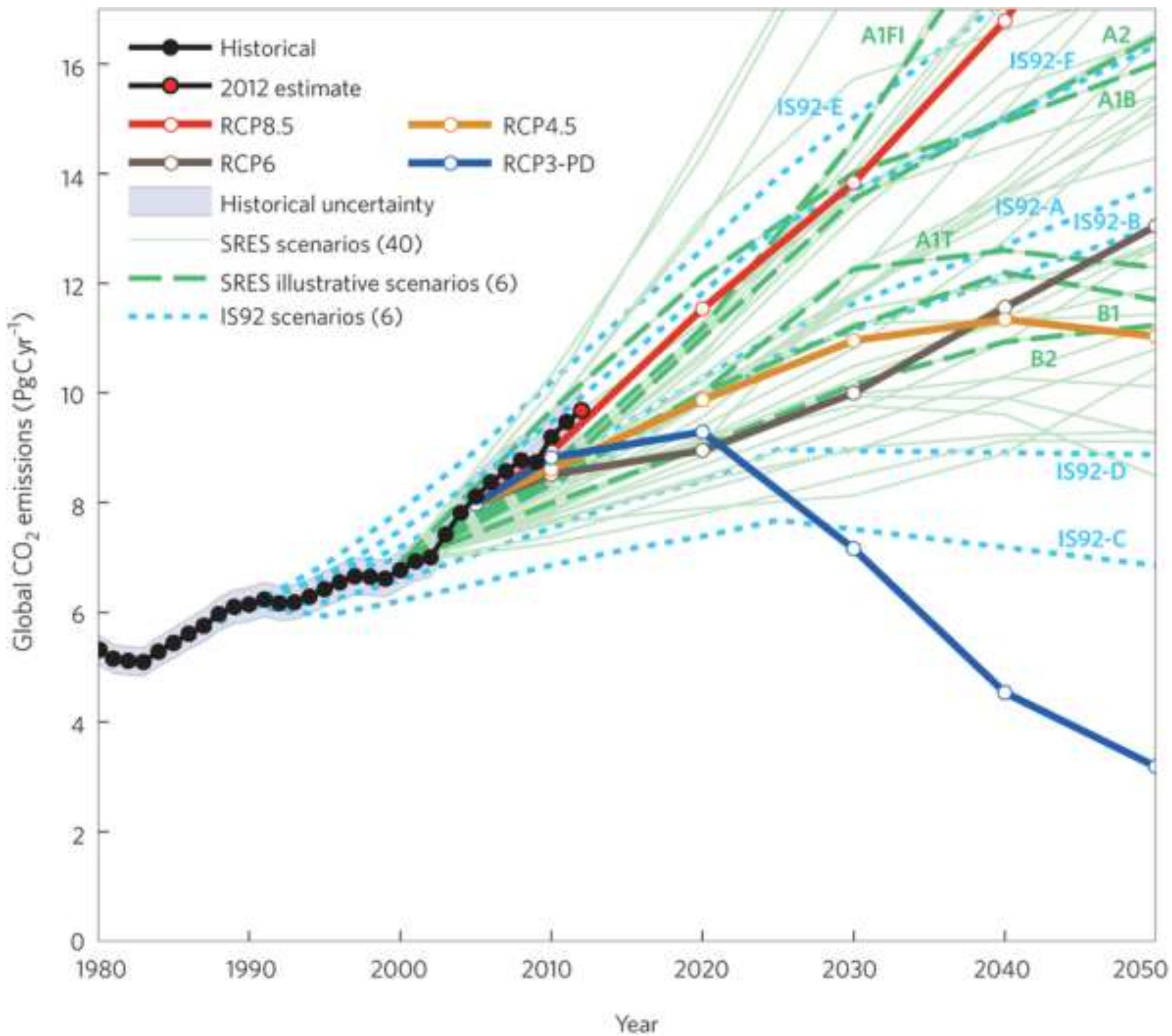
Earth System Models: adding the biosphere to simulate the coupled carbon-climate system



Dunne *et al.* (2013)

A note on IPCC Representative Concentration Pathways (RCPs; AR5) and Emissions Scenarios (AR4)

RCP 8.5 offers the largest "signal to noise".



While once viewed as "overly pessimistic", it appears increasingly realistic.

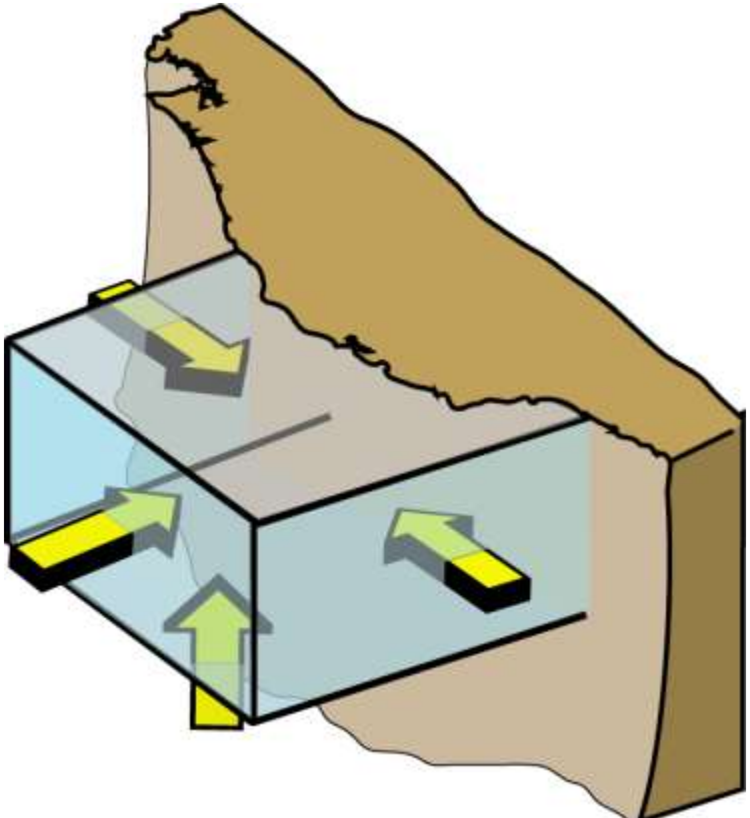
Peters *et al.* (2013)

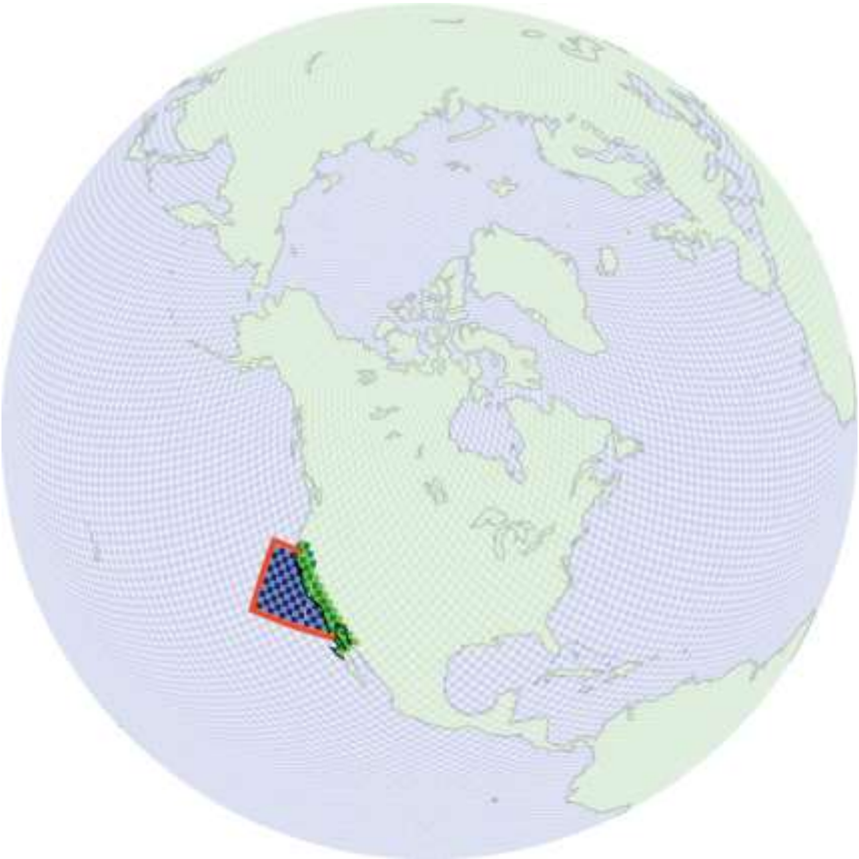
Our two questions of interest…

#1 – Do upwelling winds intensify as land-sea temperature gradients increase?

or

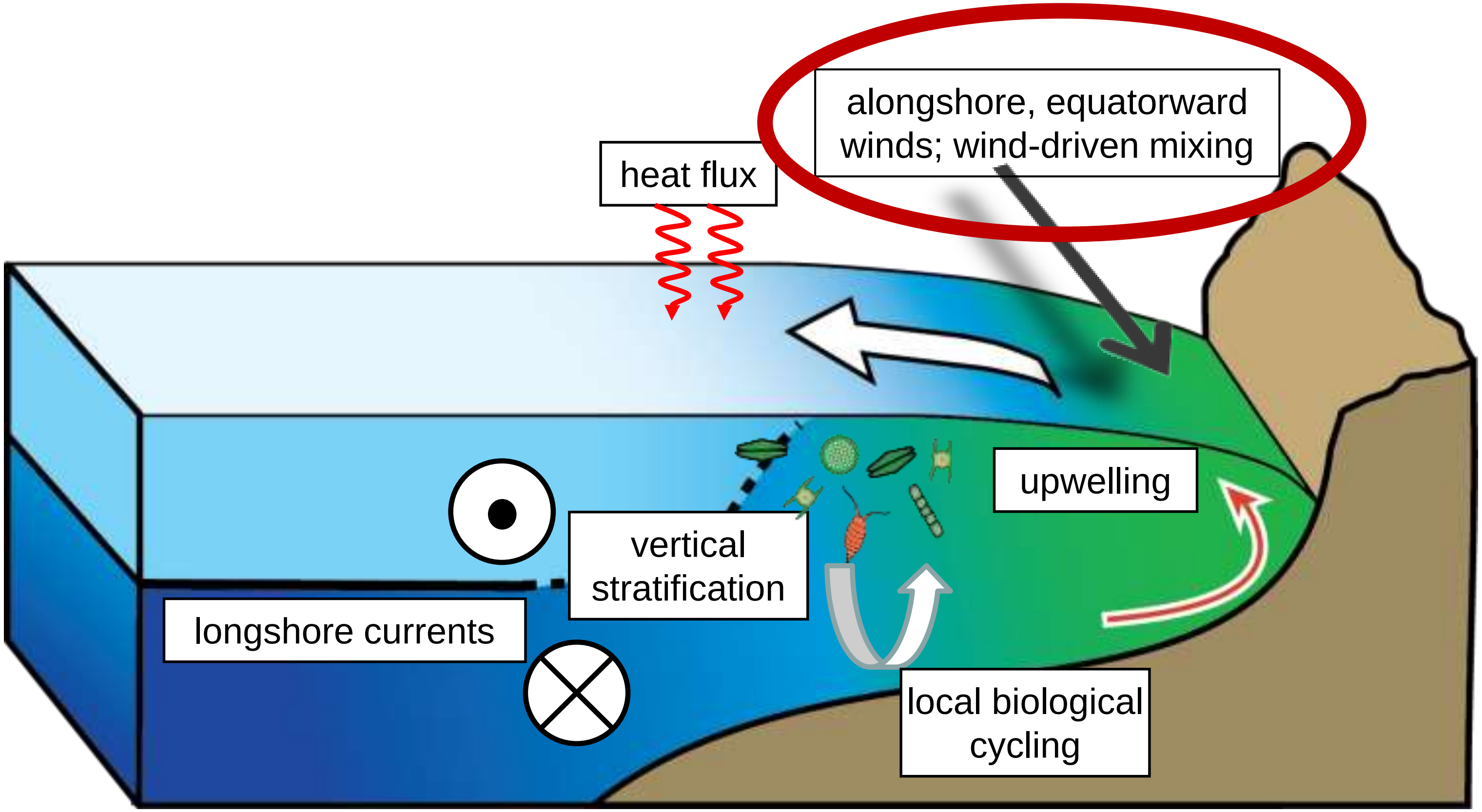
#2 – Does increased density stratification reduce nutrient supply?





Expected factors controlling ecosystem responses to future changes

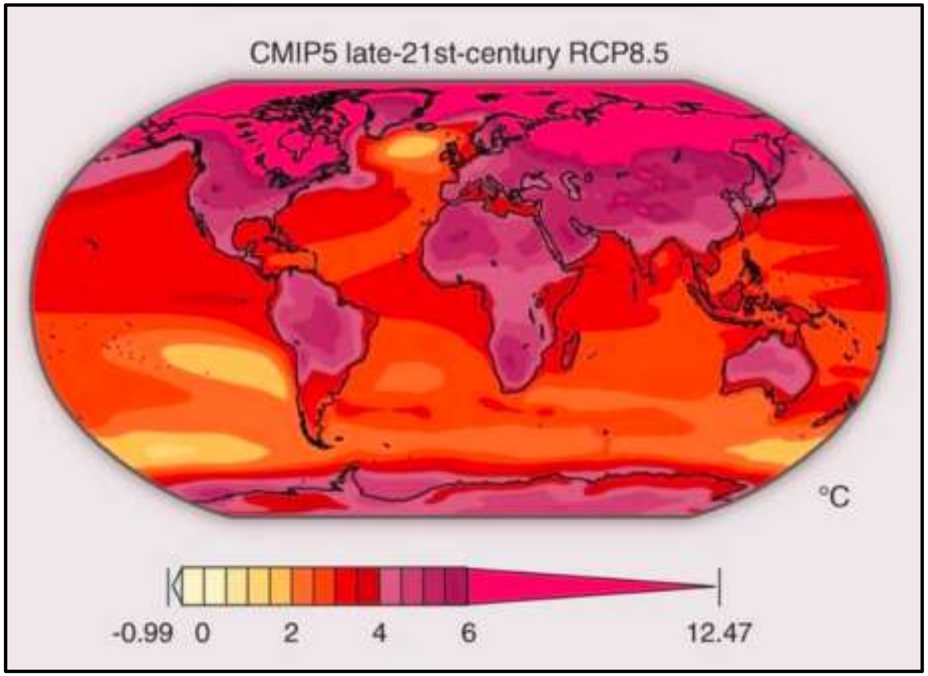
What processes should we consider?



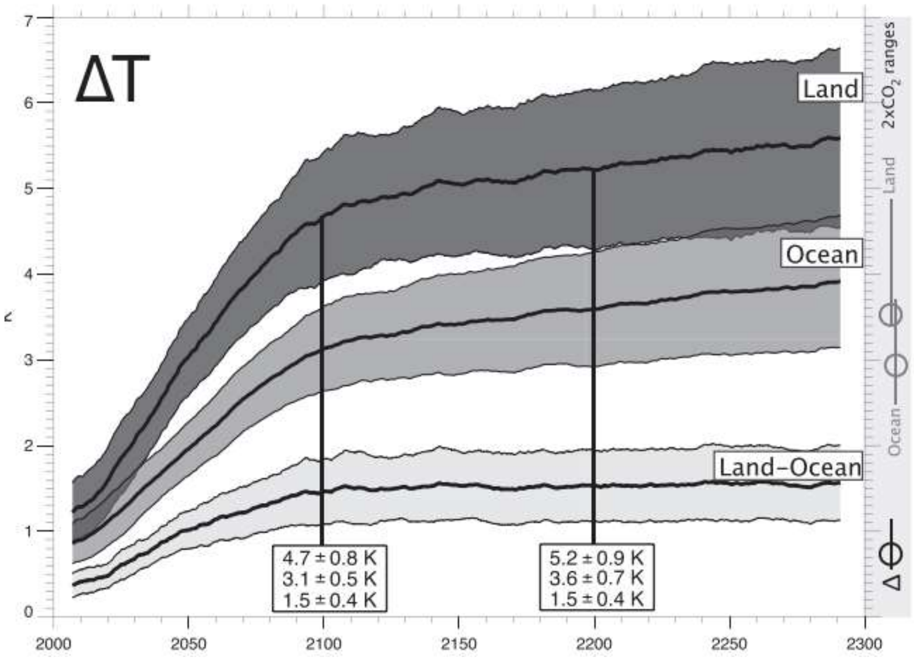
Model name	*Atmospheric resolution (km)*	*Oceanic resolution (km)*
1. CanESM2	310 × 262	103 × 131
2. CNRM-CM5	156 × 131	92 × 93
3. ACCESS1.3	139 × 174	107 × [illegible]
4. ACCESS1-0	139 × 174	107 × [illegible]
5. CSIRO-Mk3-6-0	207 × 175	104 × [illegible]
6. inmcm4	167 × 186	68 × [illegible]
7. IPSL-CM5A-LR	211 × 348	182 × 184
8. IPSL-CM5A-MR	141 × 233	182 × 184
9. IPSL-CM5B-LR	211 × 348	182 × 184
10. MIROC5	156 × 131	115 × 116
11. MIROC-ESM	310 × 262	103 × 131
12. MIROC-ESM-CHEM	310 × 262	103 × 131
13. MRI-CGCM3	125 × 105	56 × 93
14. MRI-ESM1	125 × 105	56 × 93
15. NorESM1-M	211 × 232	54 × 104
16. NorESM1-ME	211 × 232	54 × 104
17. GFDL-CM3	222 × 231	111 × 93
18. GFDL-ESM2G	225 × 234	111 × 93
19. GFDL-ESM2M	225 × 234	111 × 93
20. CESM1-BGC	105 × 116	54 × 104
21. CESM1-CAM5	105 × 116	54 × 104

CMIP5 models

Land-sea temperature differences do, indeed, increase

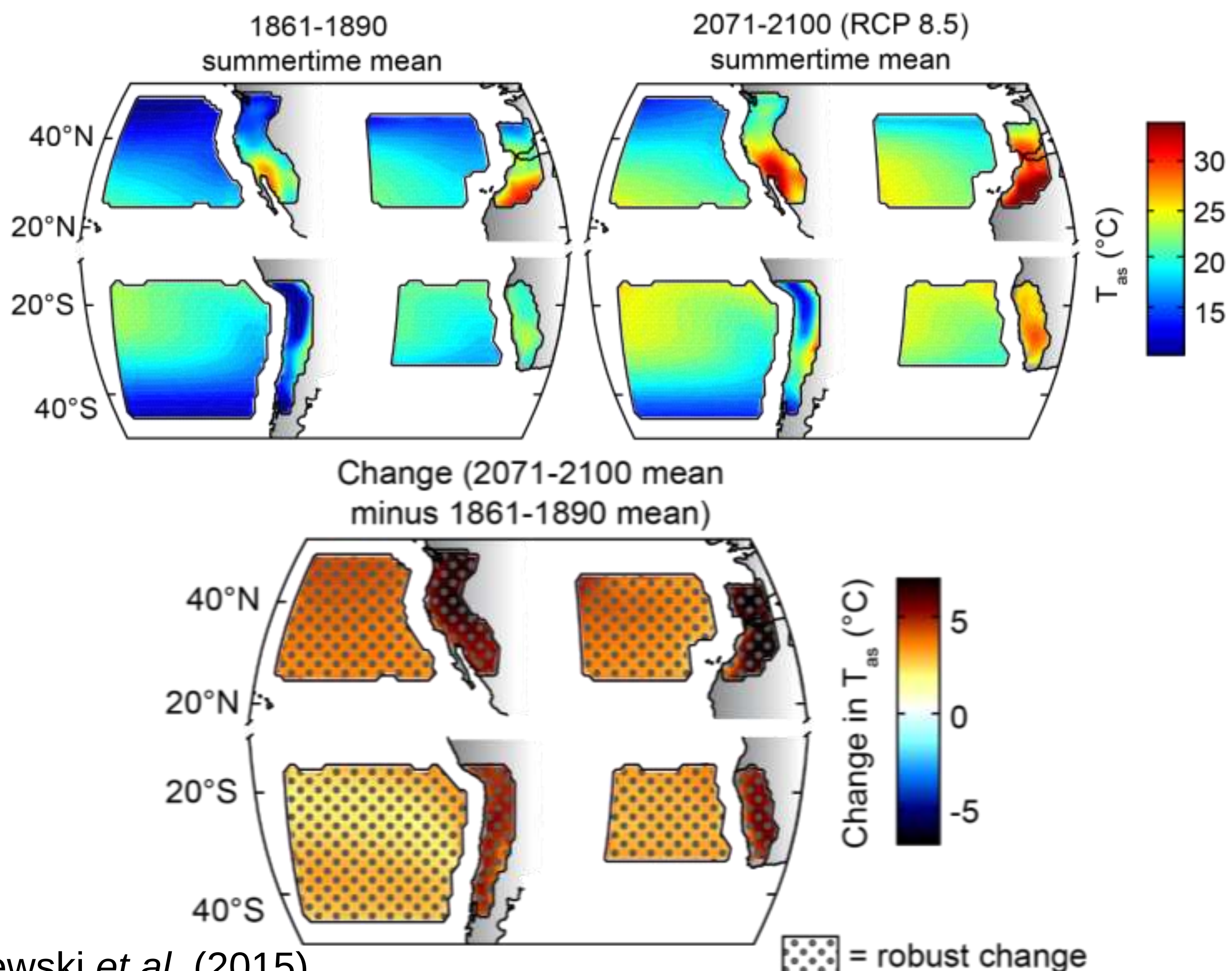


Diffenbaugh and Field (2014)



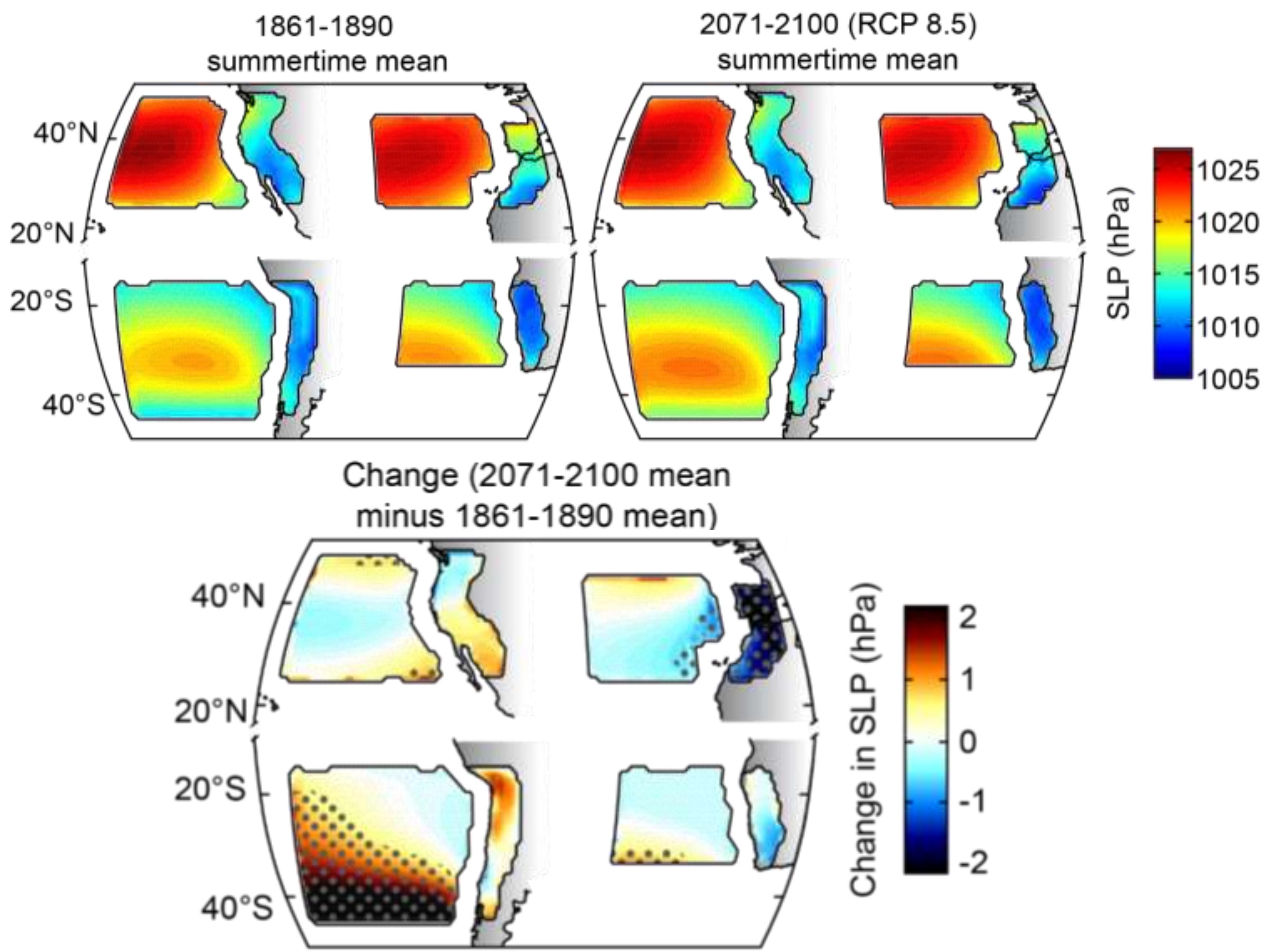
Fasullo (2010)

Land-sea temperature differences do, indeed, increase



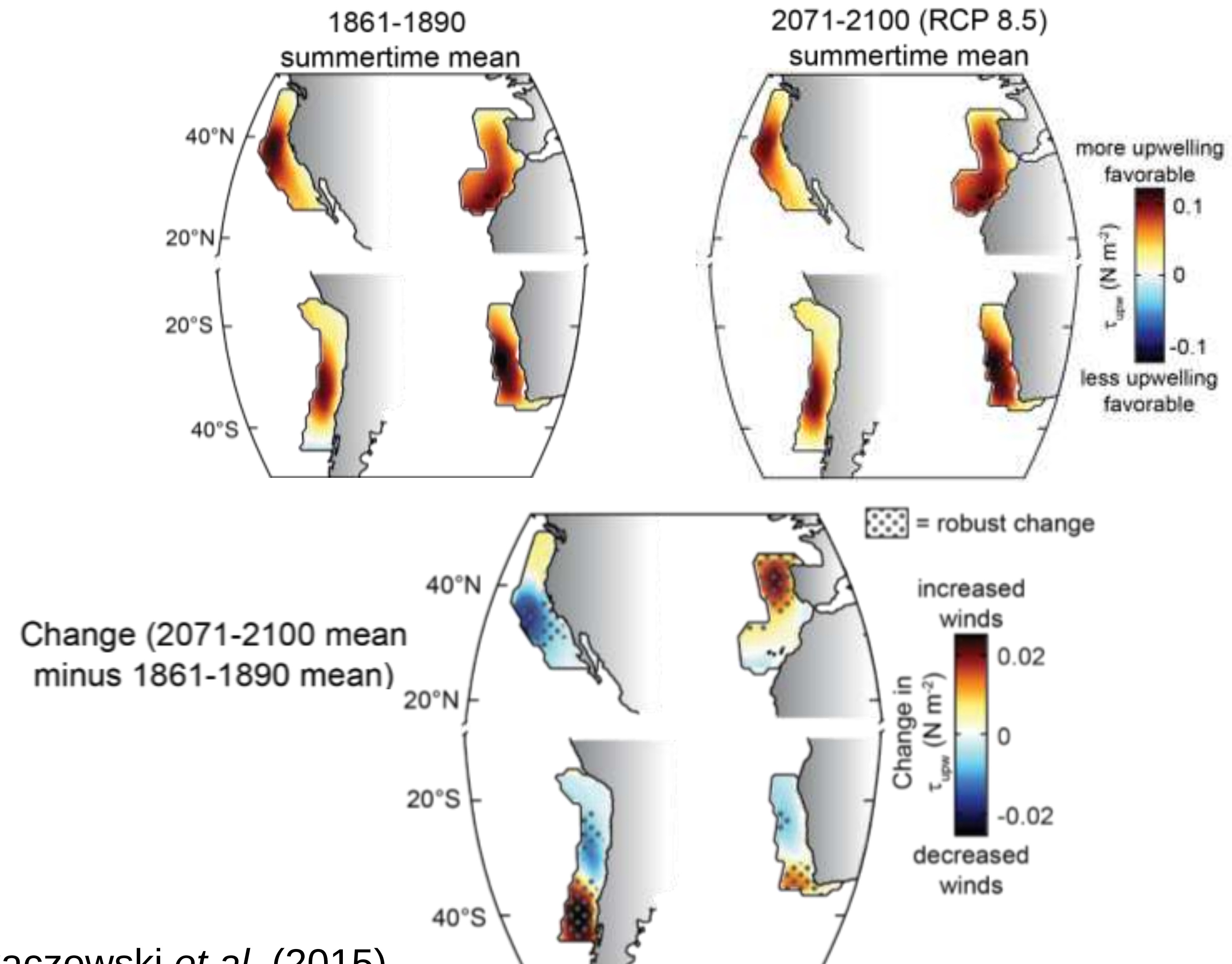
Rykaczewski *et al.* (2015)

However, continental SLP does not uniformly decrease



Rykaczewski *et al.* (2015)

Changes in wind intensity are fairly subtle…

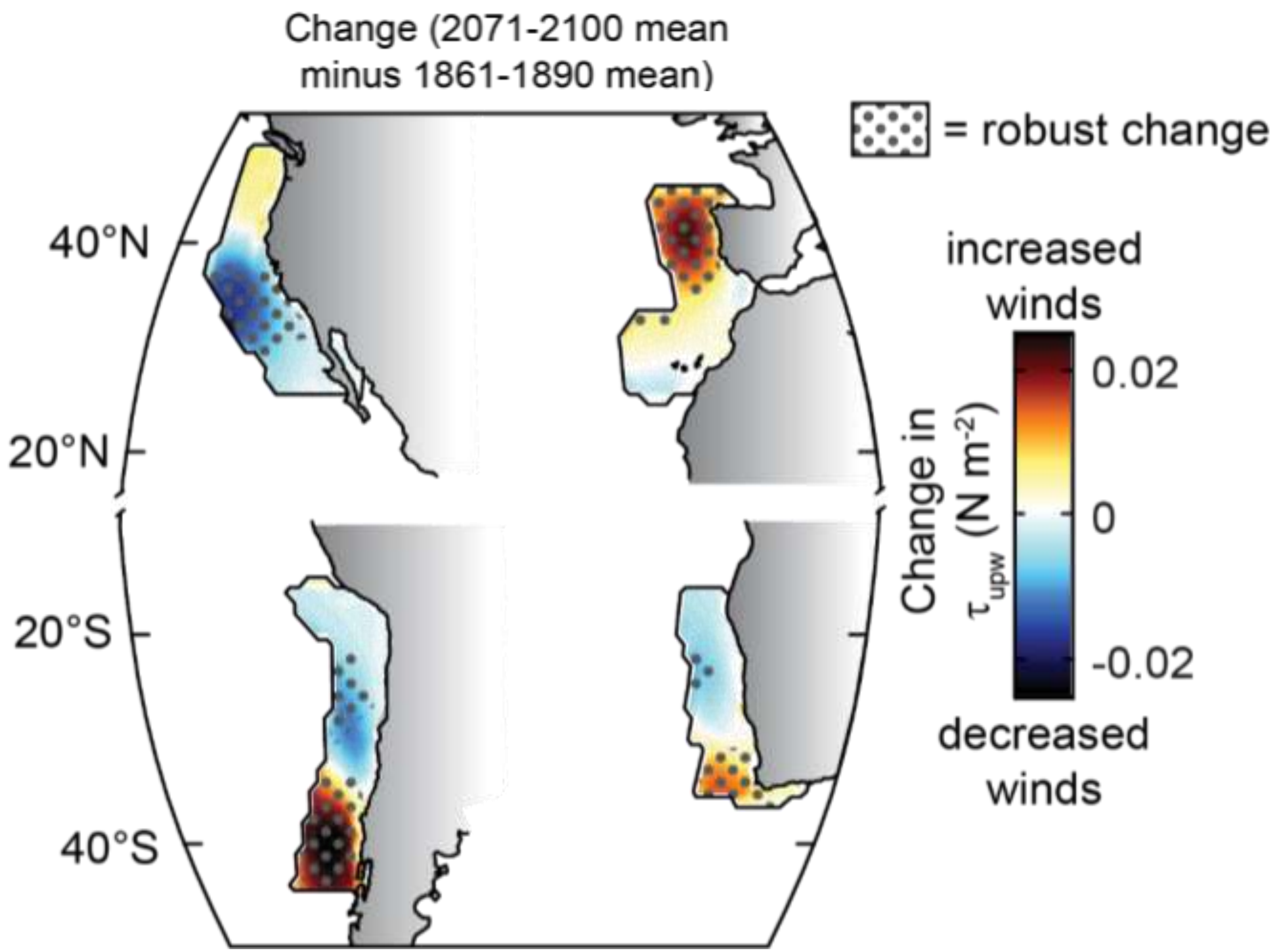


Rykaczewski *et al.* (2015)

Changes in wind intensity are fairly subtle…

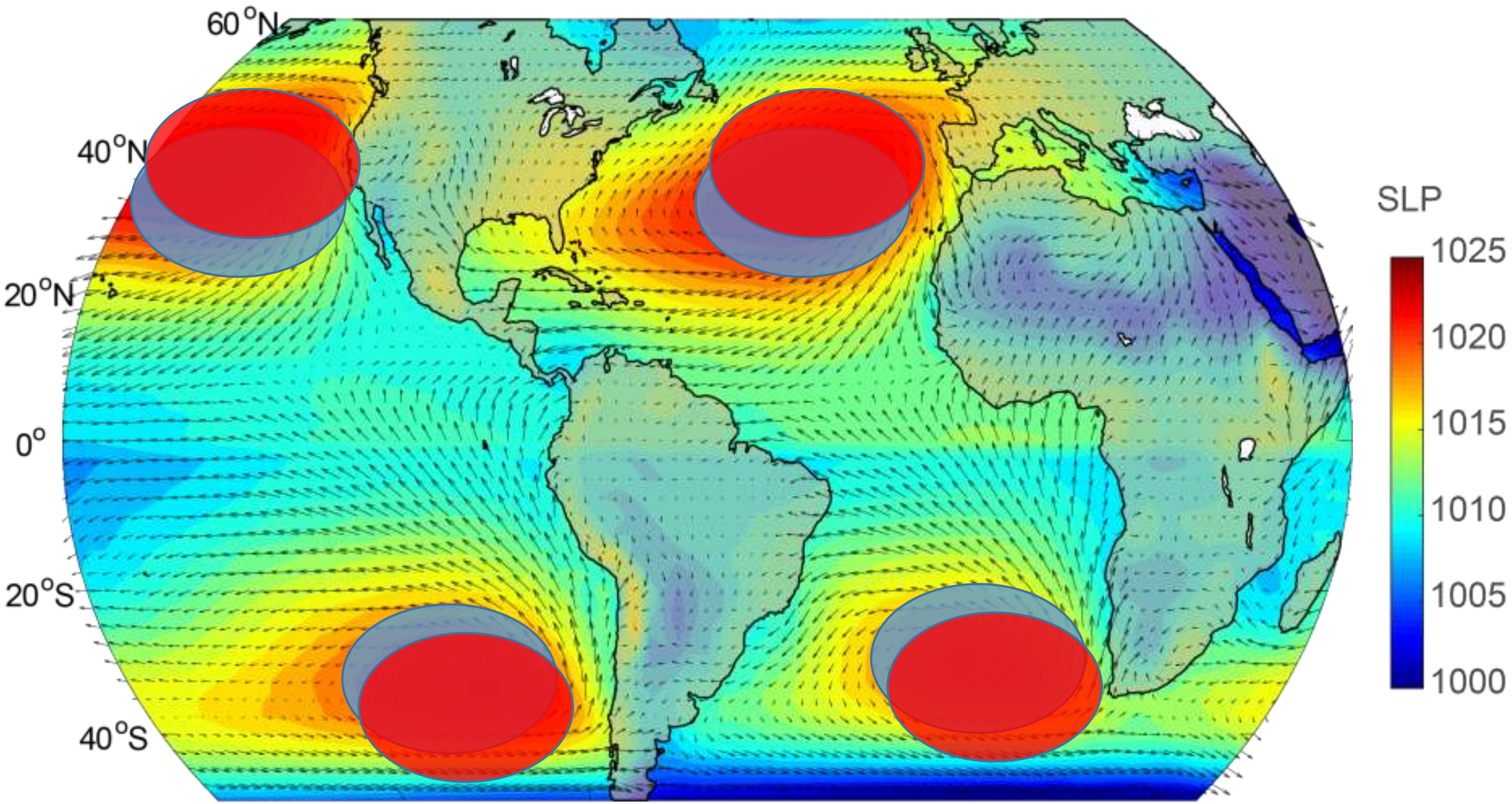
Upwelling intensity tends to increase in the poleward halves…

… but decrease in the equatorward portions of the upwelling systems.



Rykaczewski *et al.* (2015)

Poleward shifts in high-pressure systems are dominant over land-sea temperature gradients



Our two questions of interest…

#1 – Do upwelling winds intensify as land-sea temperature gradients increase?

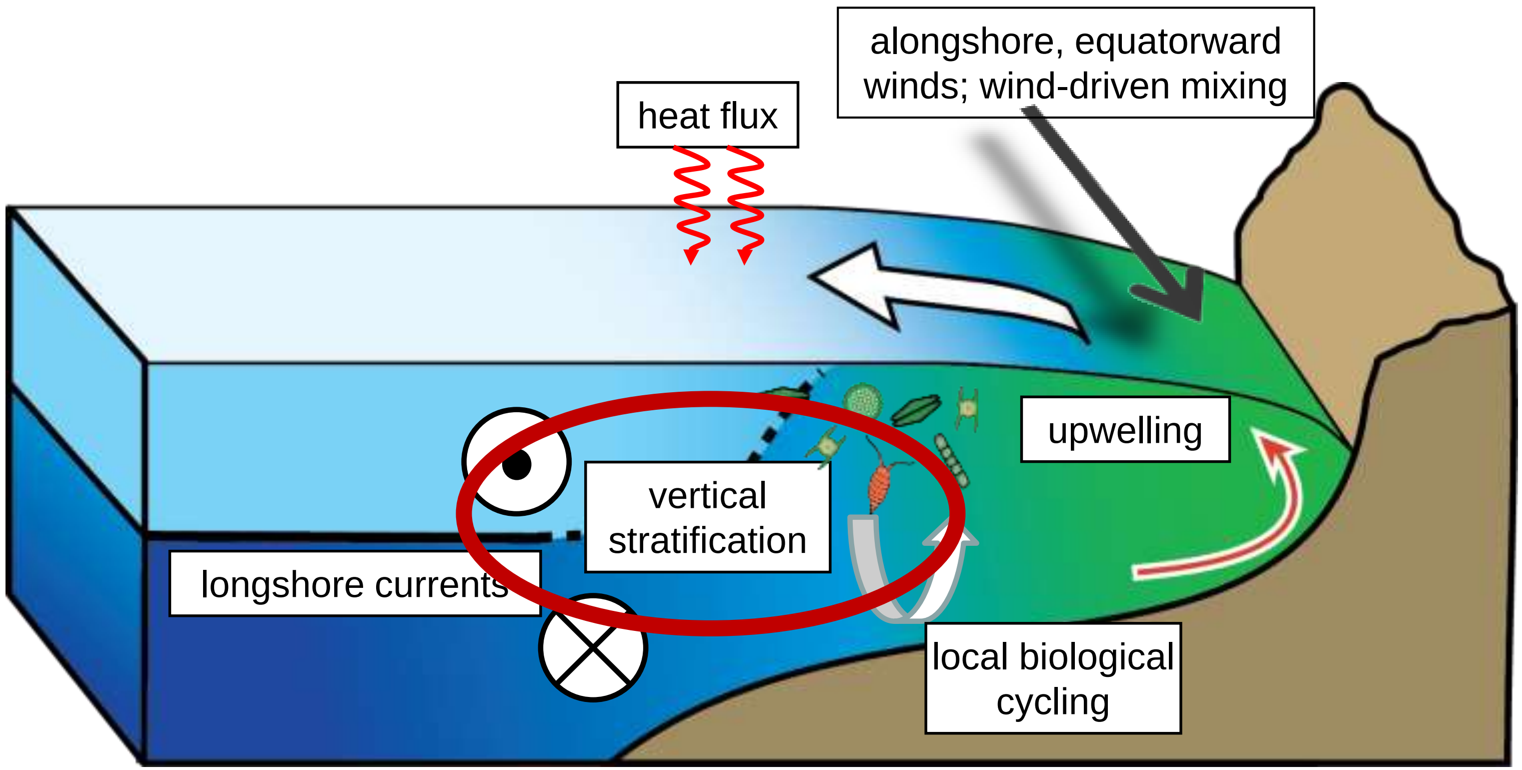
No! (at least not as proposed previously)

or

#2 – Does increased density stratification reduce nutrient supply?

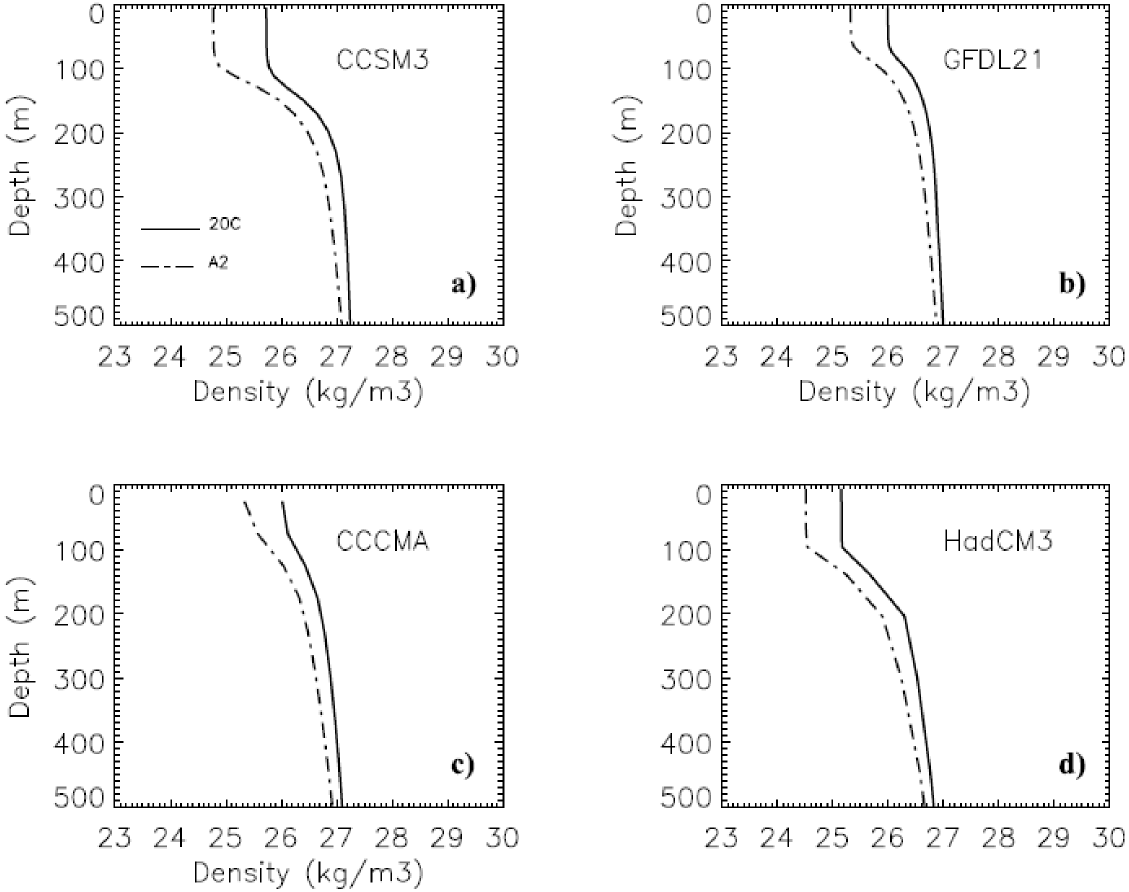
Expected factors controlling ecosystem responses to future changes

What processes should we consider?



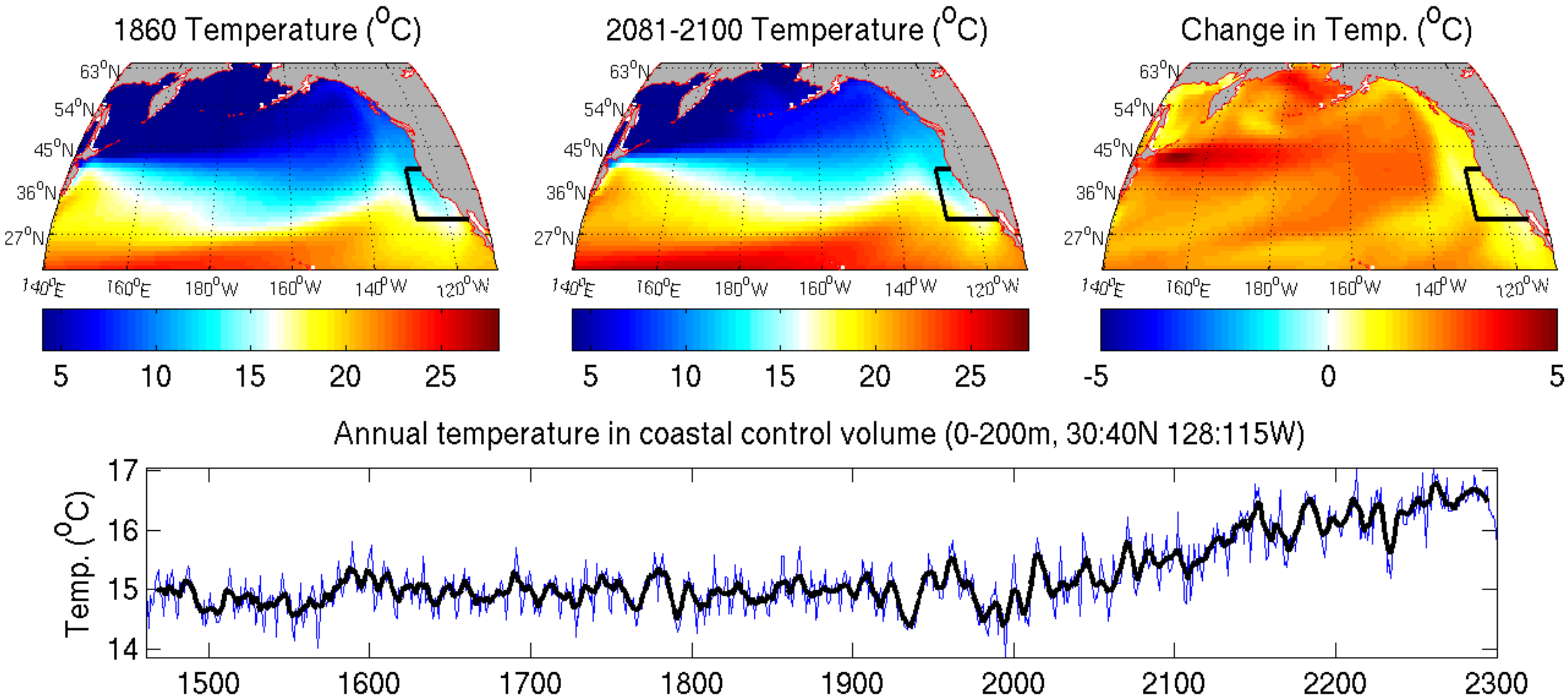
Globally, stratification does increase with surface warming

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



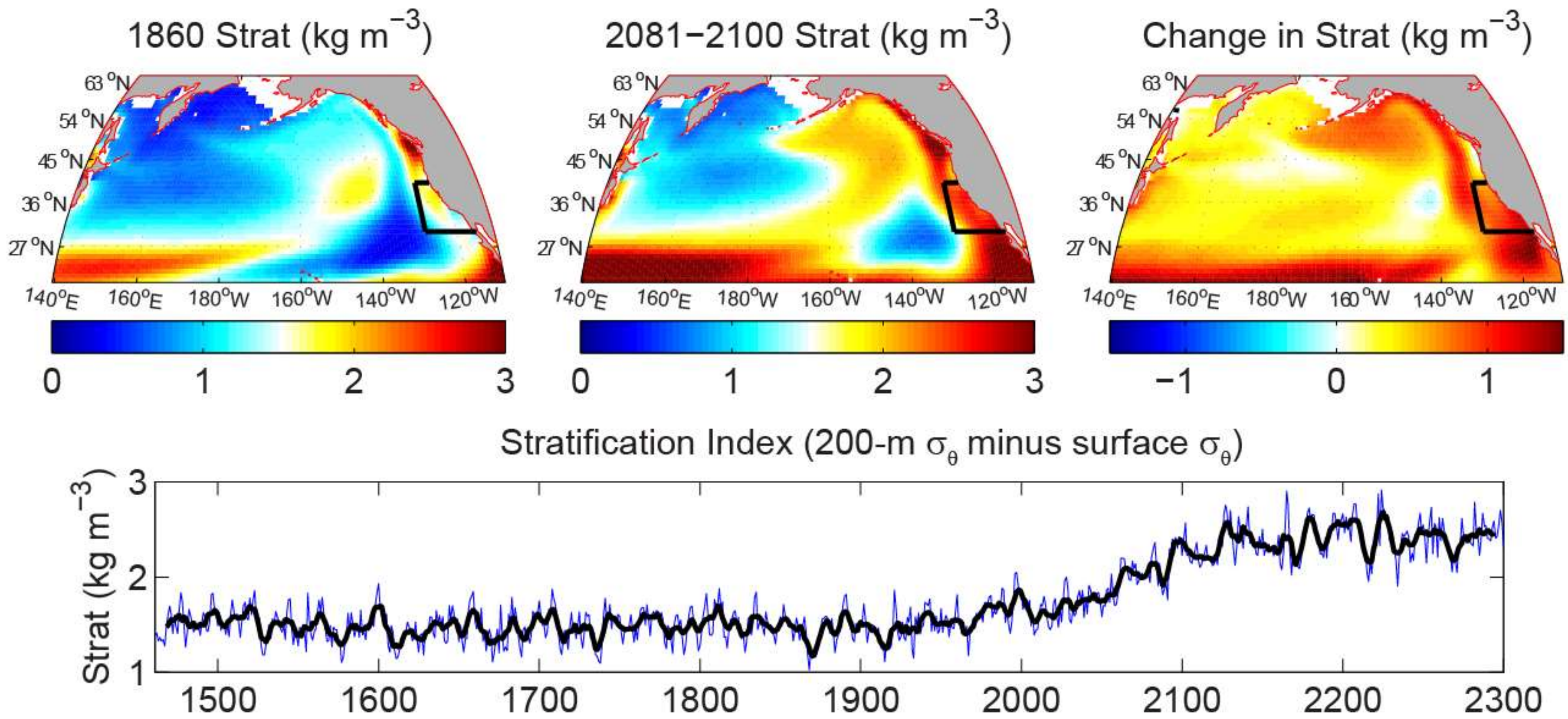
Capotondi *et al.*, (2012, JGR)

Temperature increases across the basin

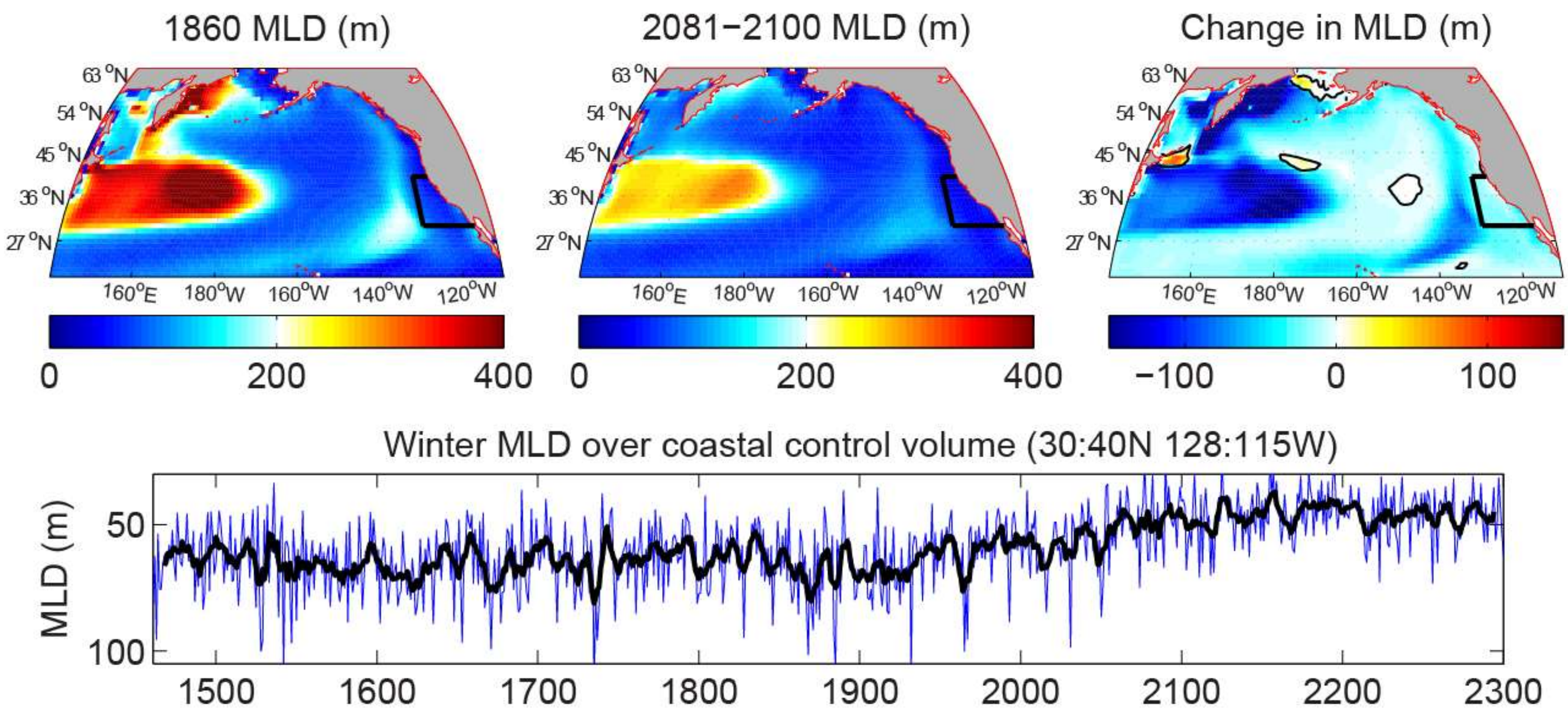


The magnitude of the upper-ocean temperature change varies, but the direction of the change is uniform: the whole Pacific becomes warmer at the surface.

Changes in local forcing suggest decreased nutrient supply

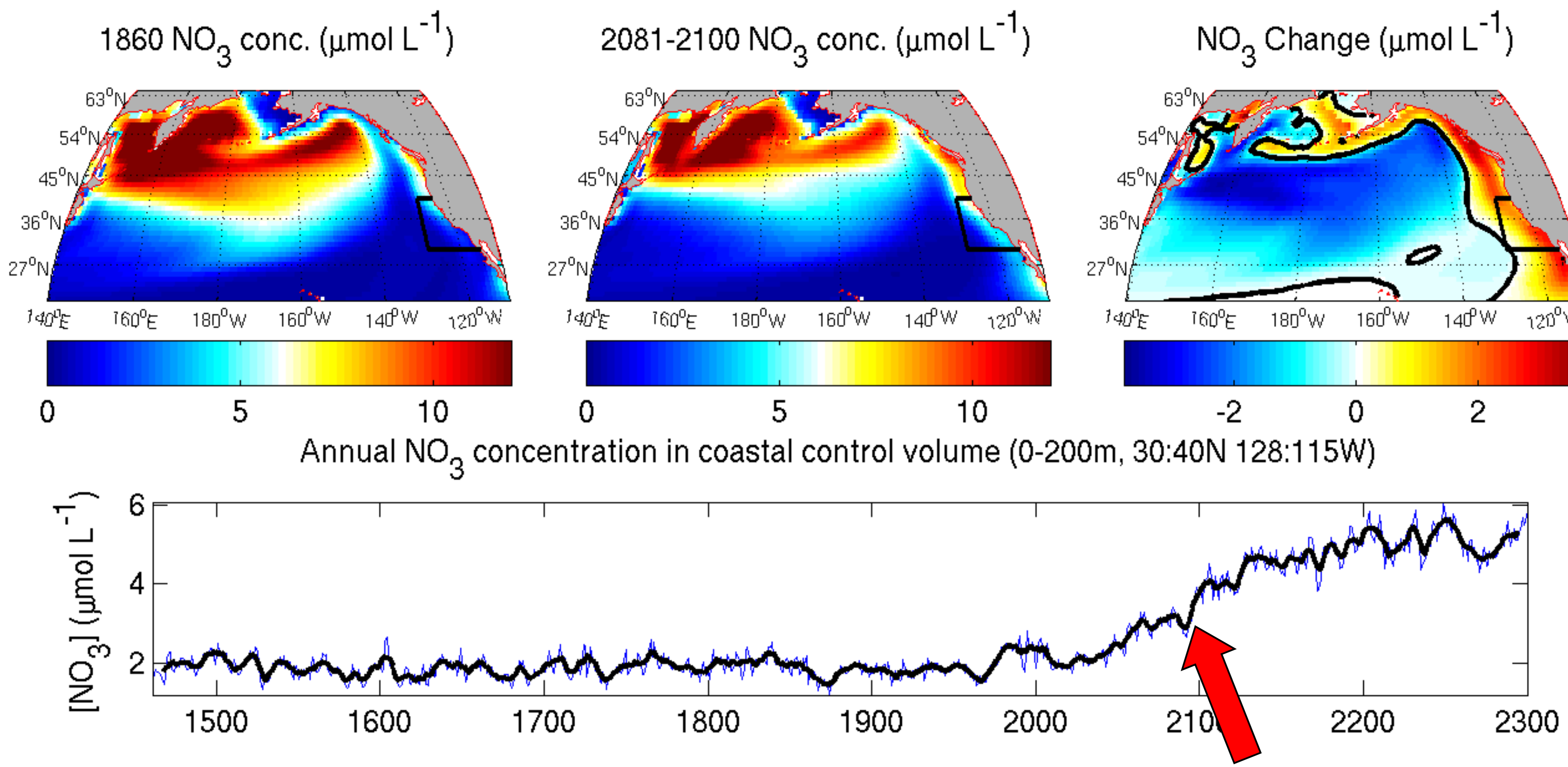


Winter mixed-layer depth shoals



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)

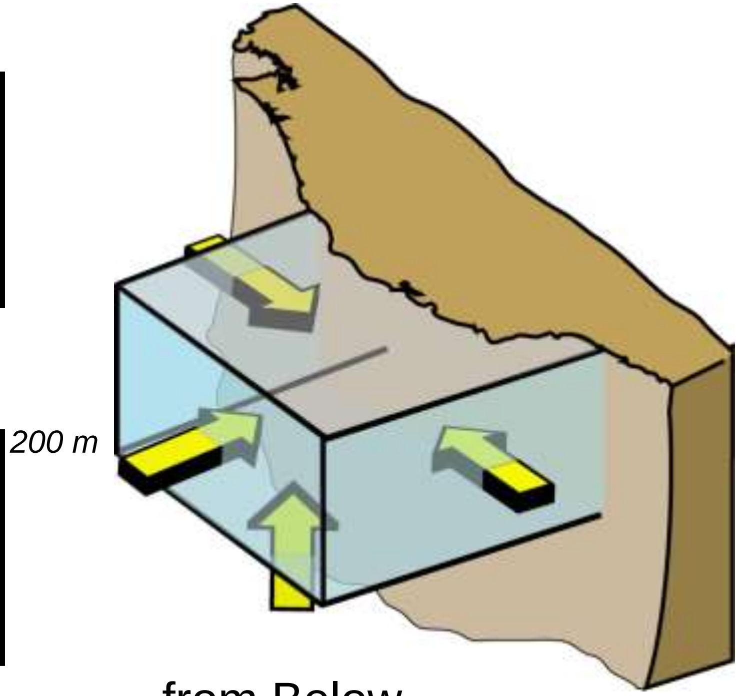
NO3 budget in a control volume

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:

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

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

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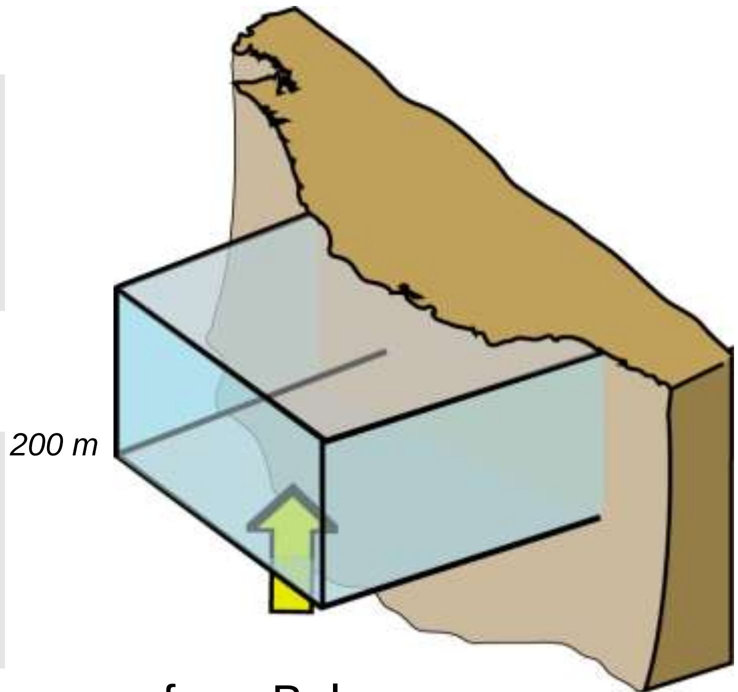

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	1.1 kmol s^{-1}	0.4 Sv
Δ =	0.6 kmol s^{-1}	-0.1 Sv

+ 60% ***+ 10%***

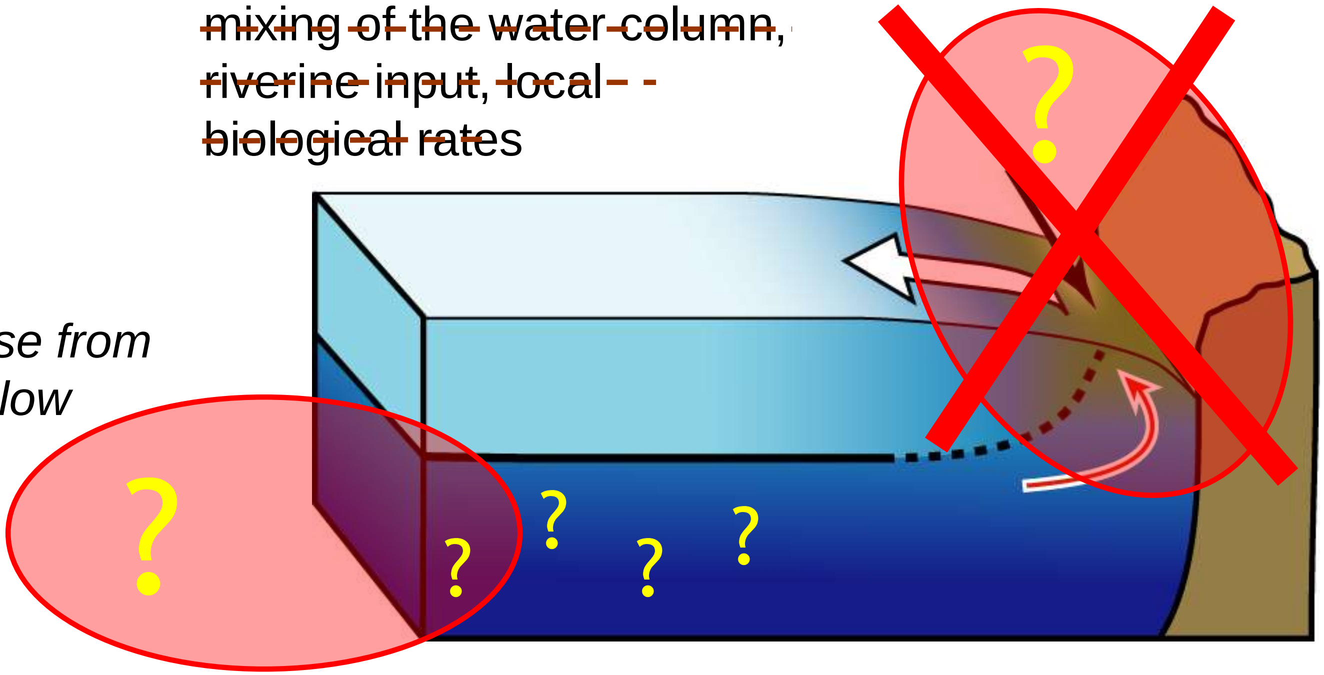
But WHY?

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~~

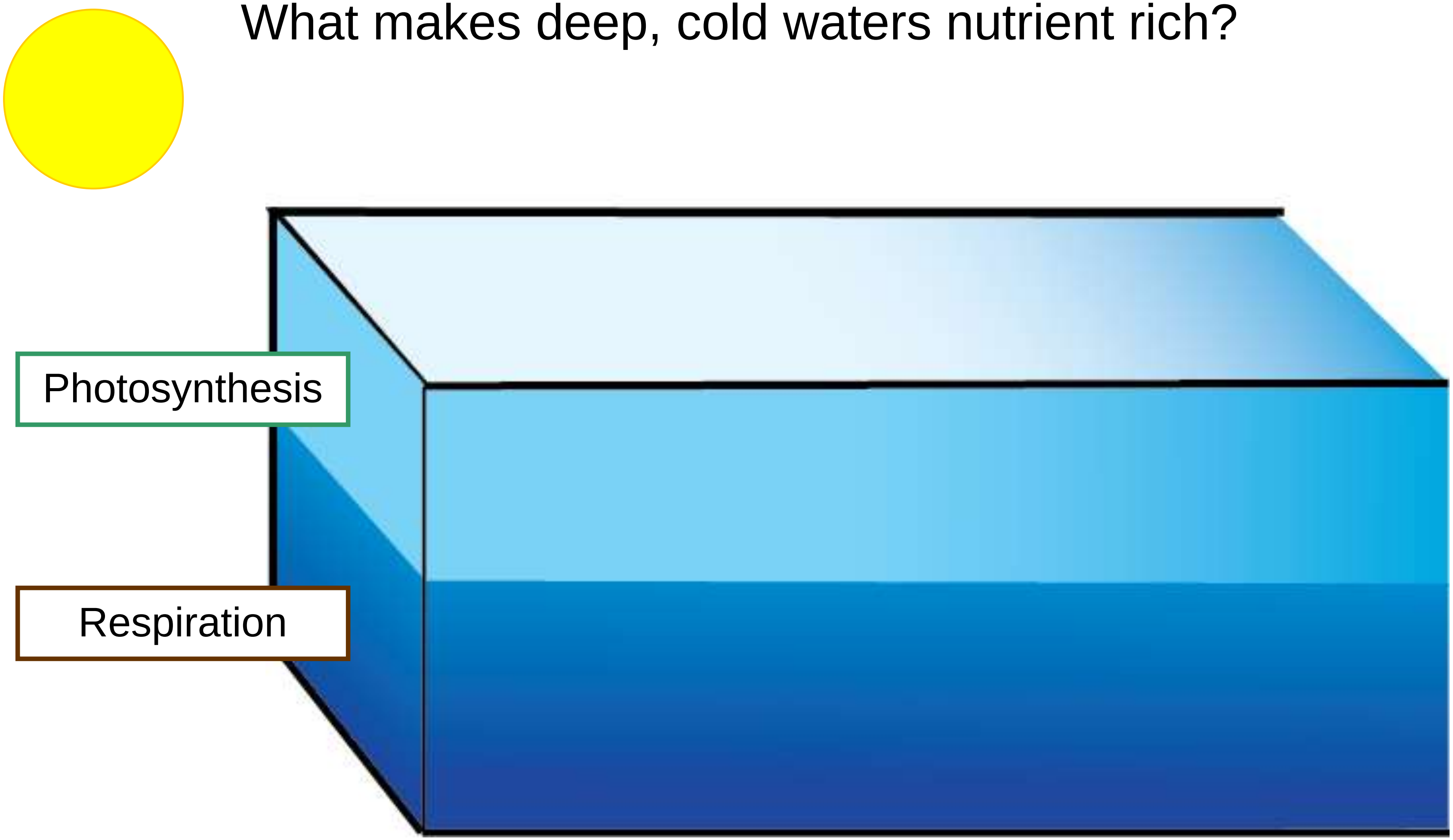
Surprise from below



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

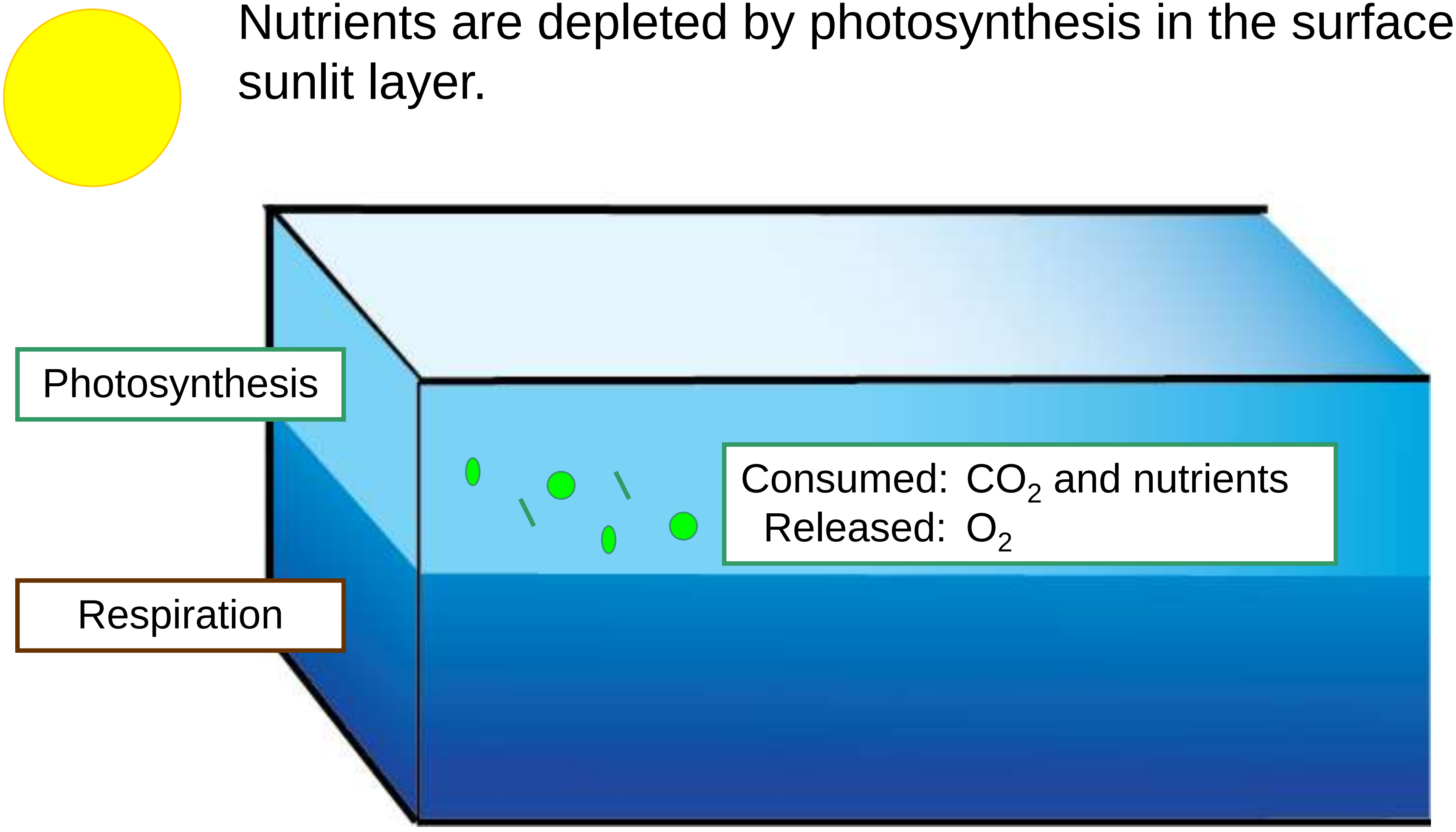
Review of photosynthesis and respiration

What makes deep, cold waters nutrient rich?



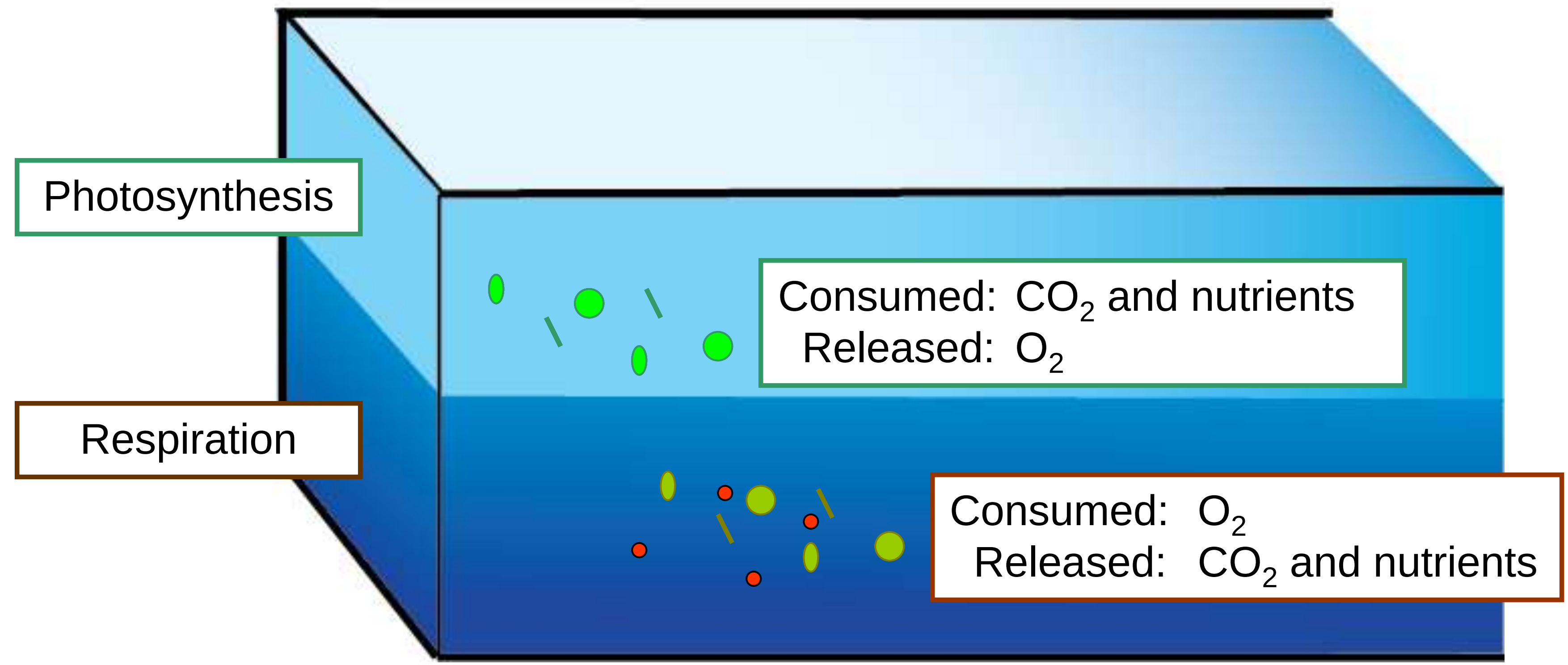
Review of photosynthesis and respiration

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



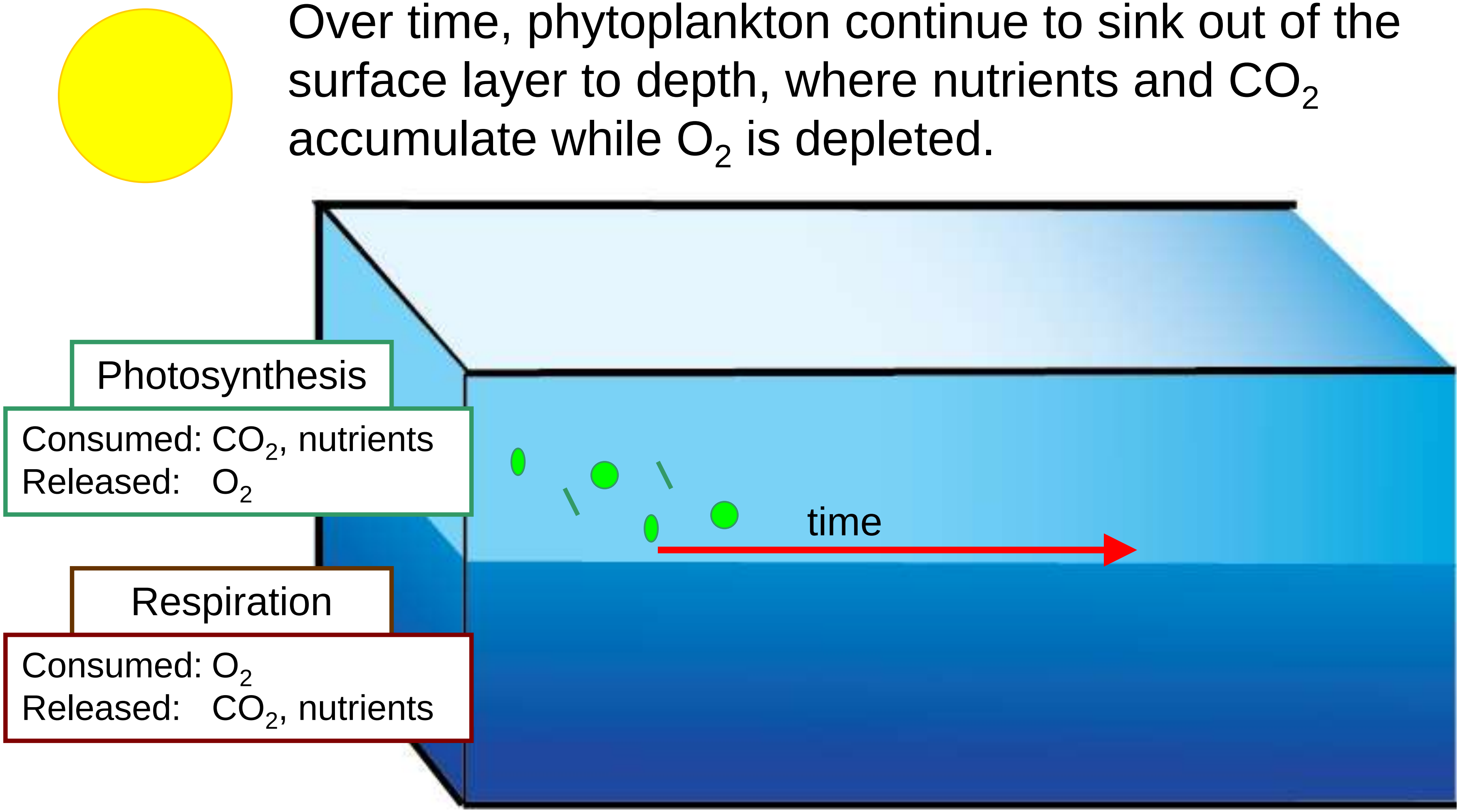
Review of photosynthesis and respiration

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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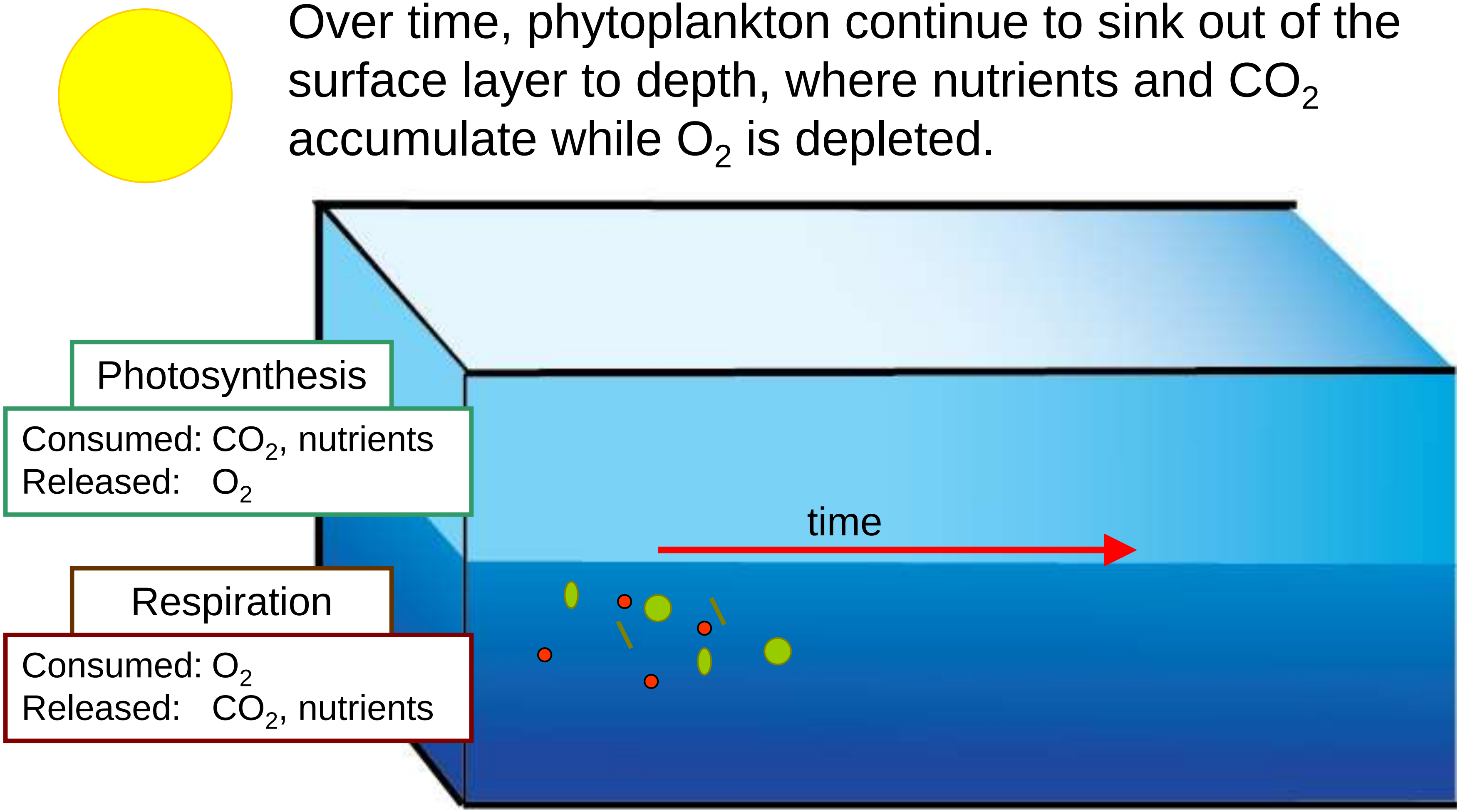

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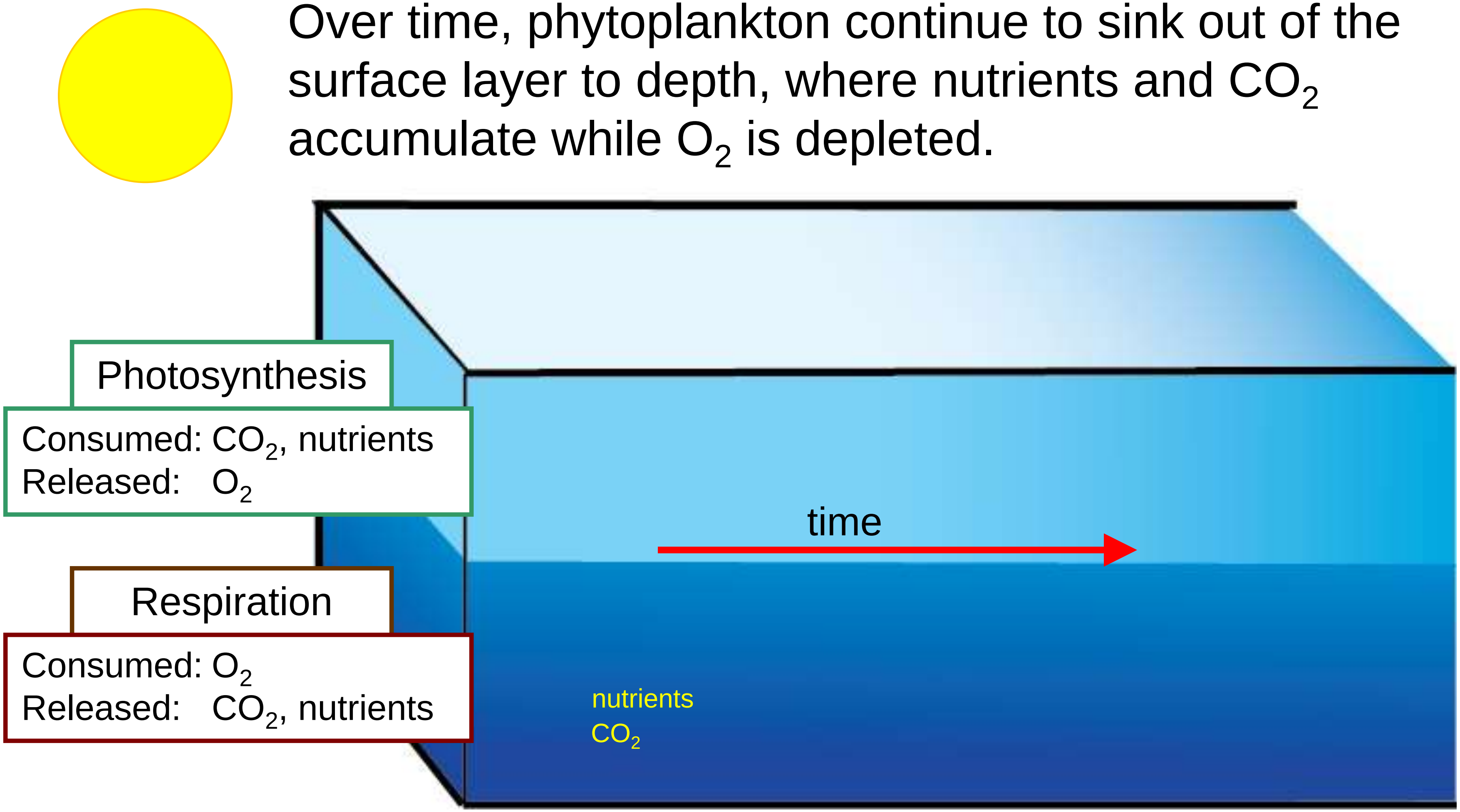

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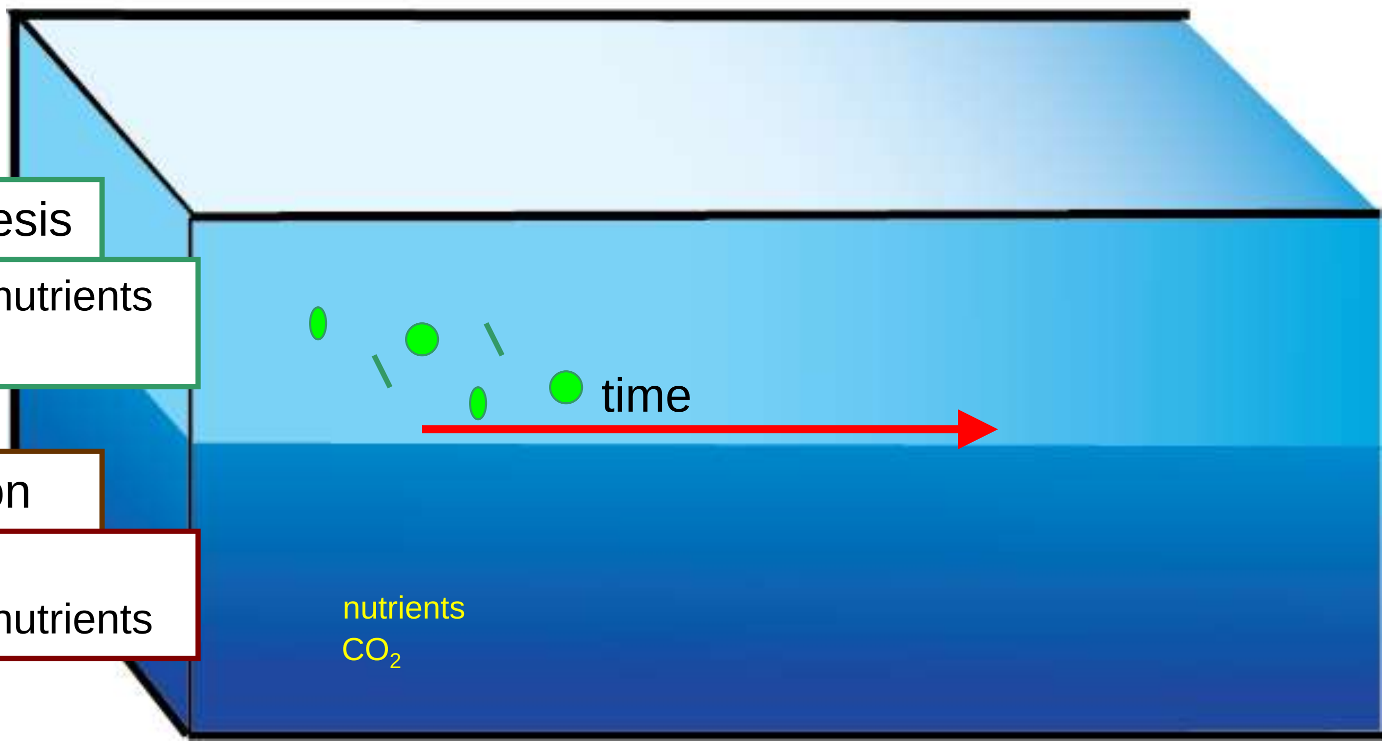
Photosynthesis

Consumed: CO_2, nutrients
Released: O_2

Respiration

Consumed: O_2
Released: CO_2, nutrients



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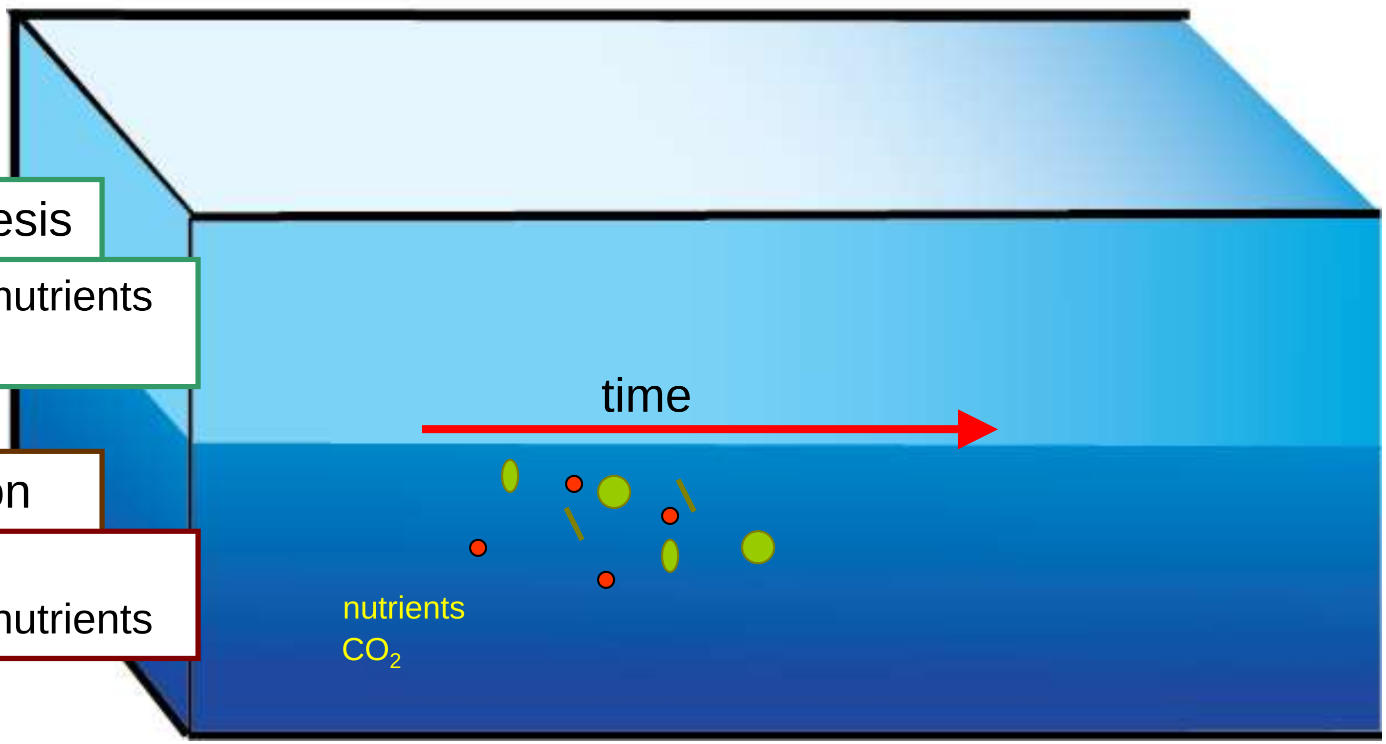

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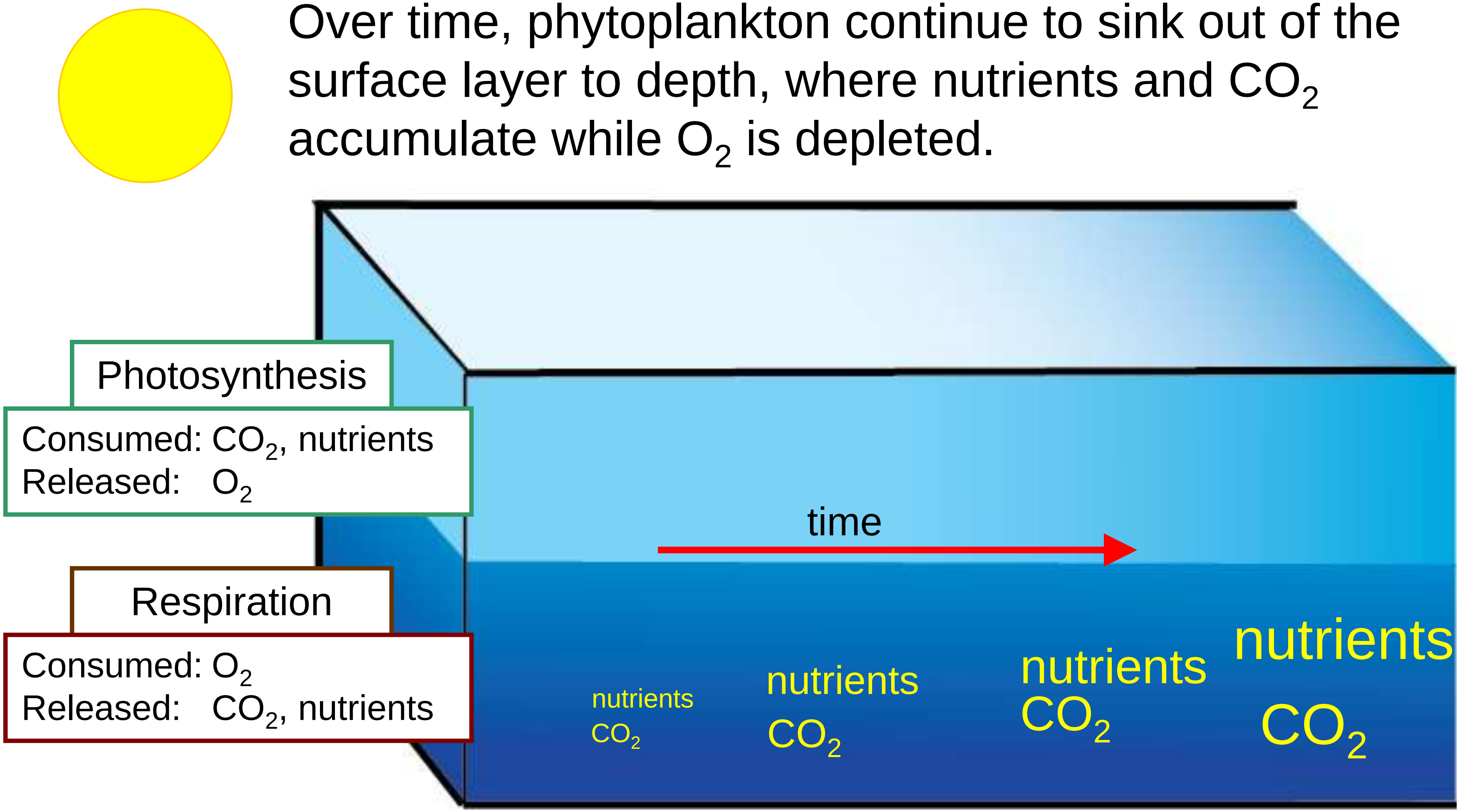
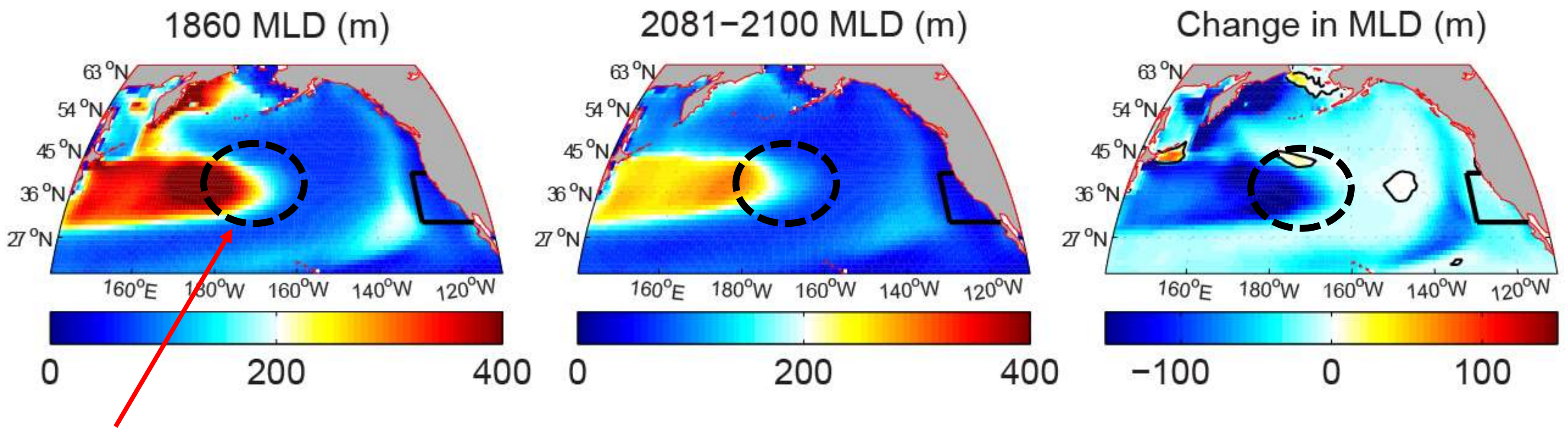


For the California Current System, ventilation changes in the Kuroshio/Oyashio Extension region are critical

Decreased ventilation of the water mass that supplies the California Current upwelling system is a key factor in the projected increase in nutrient supply to the coastal ecosystem.

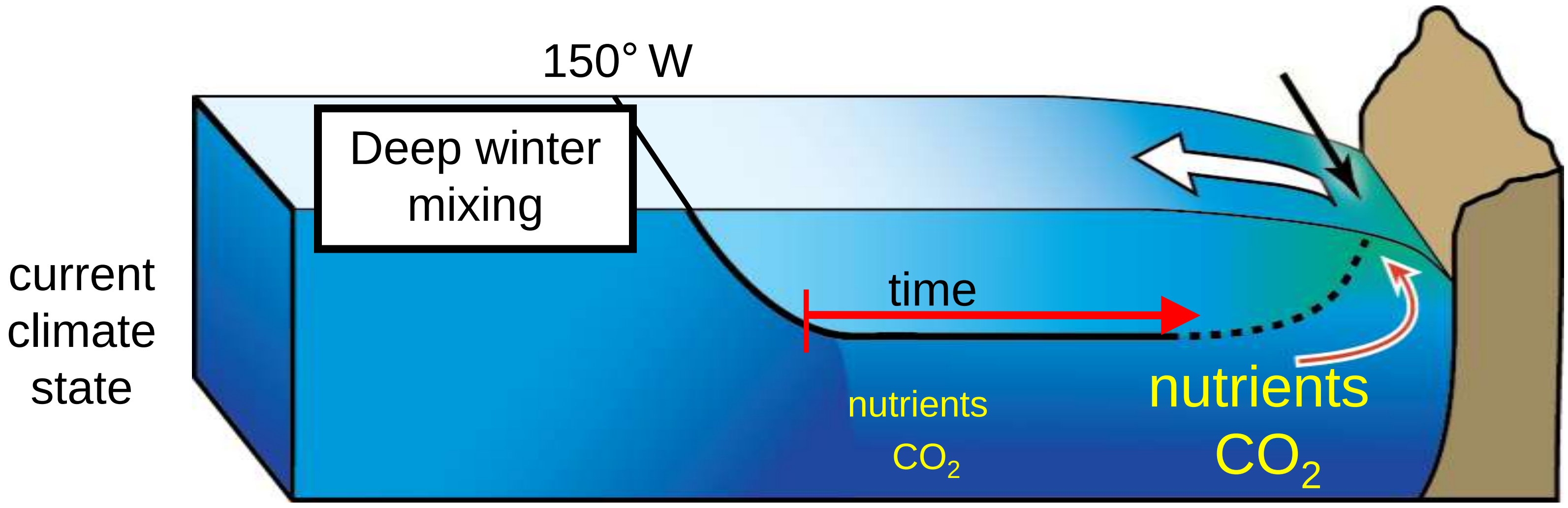


Reduced ventilation of this water mass results in increased nutrient (and DIC) and reduced dO_2 supply to the eastern boundary current.

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.

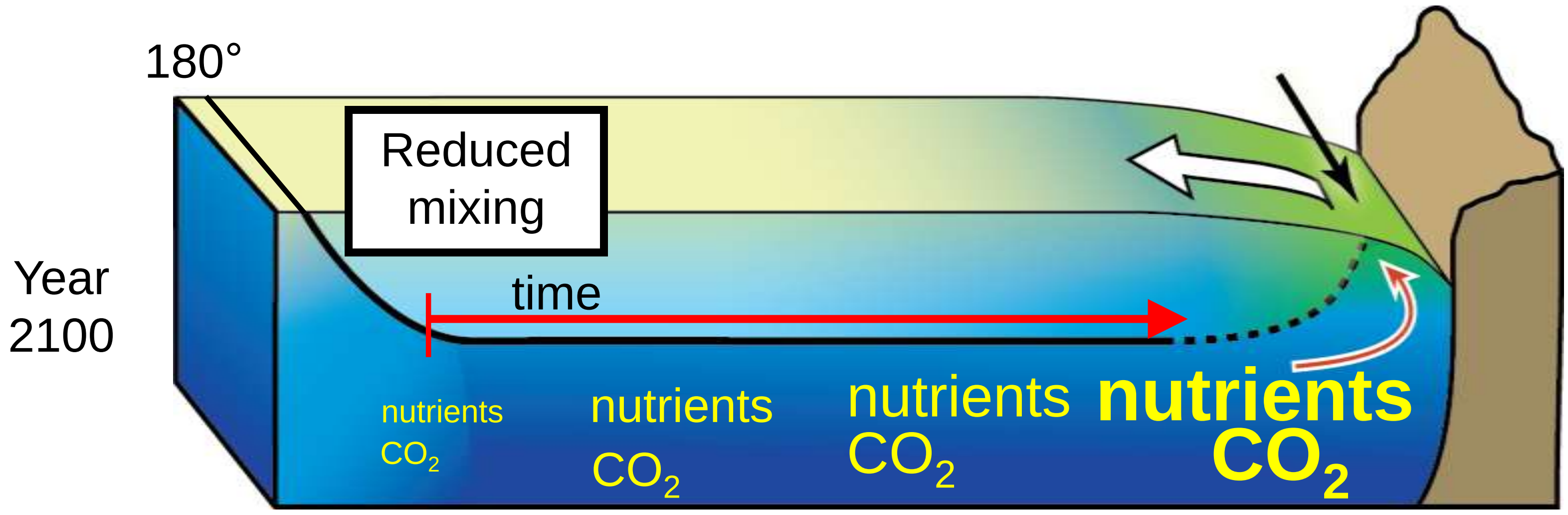
These deep waters eventually upwell at the coast, rich with nutrients.



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.



Main points

There are ***3 main points*** I have learned from this analysis…

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.

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!

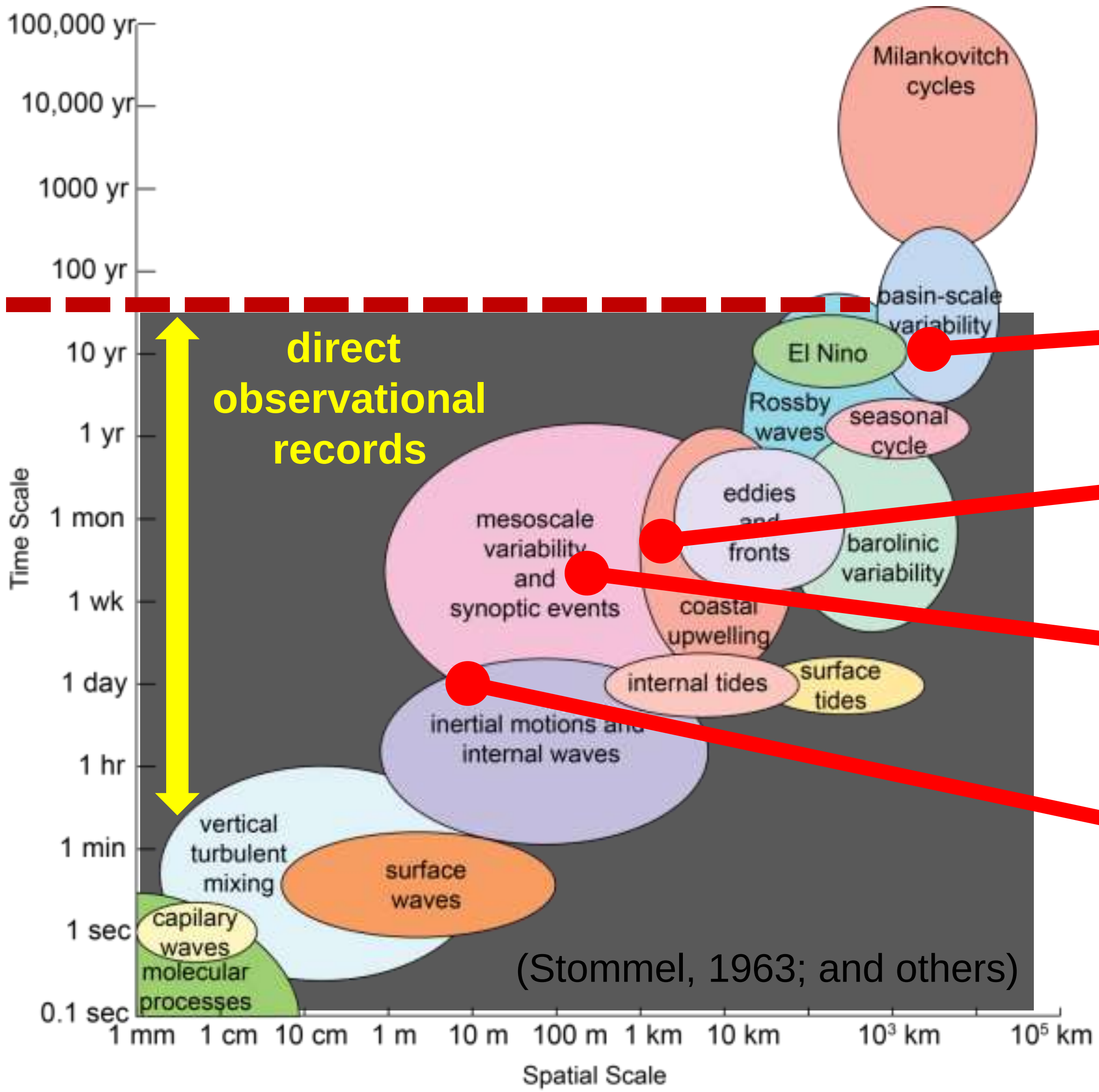
While one might reasonably assume climatological boundary conditions for a regional model that is limited to a few years in scope, I would advise against relying on a regional model for longer projections.

*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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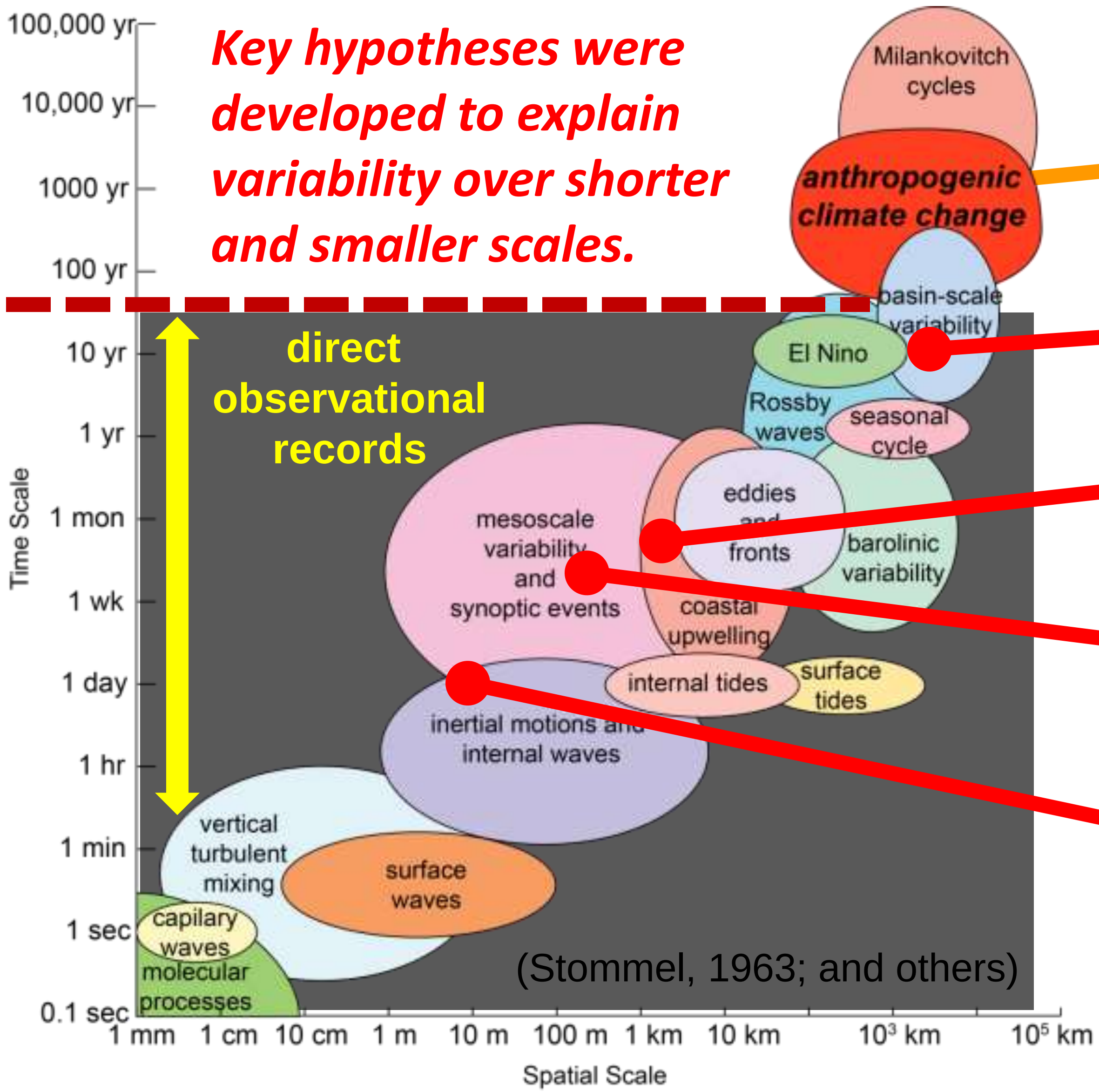

??? Fisheries responses to anthropogenic climate change

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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
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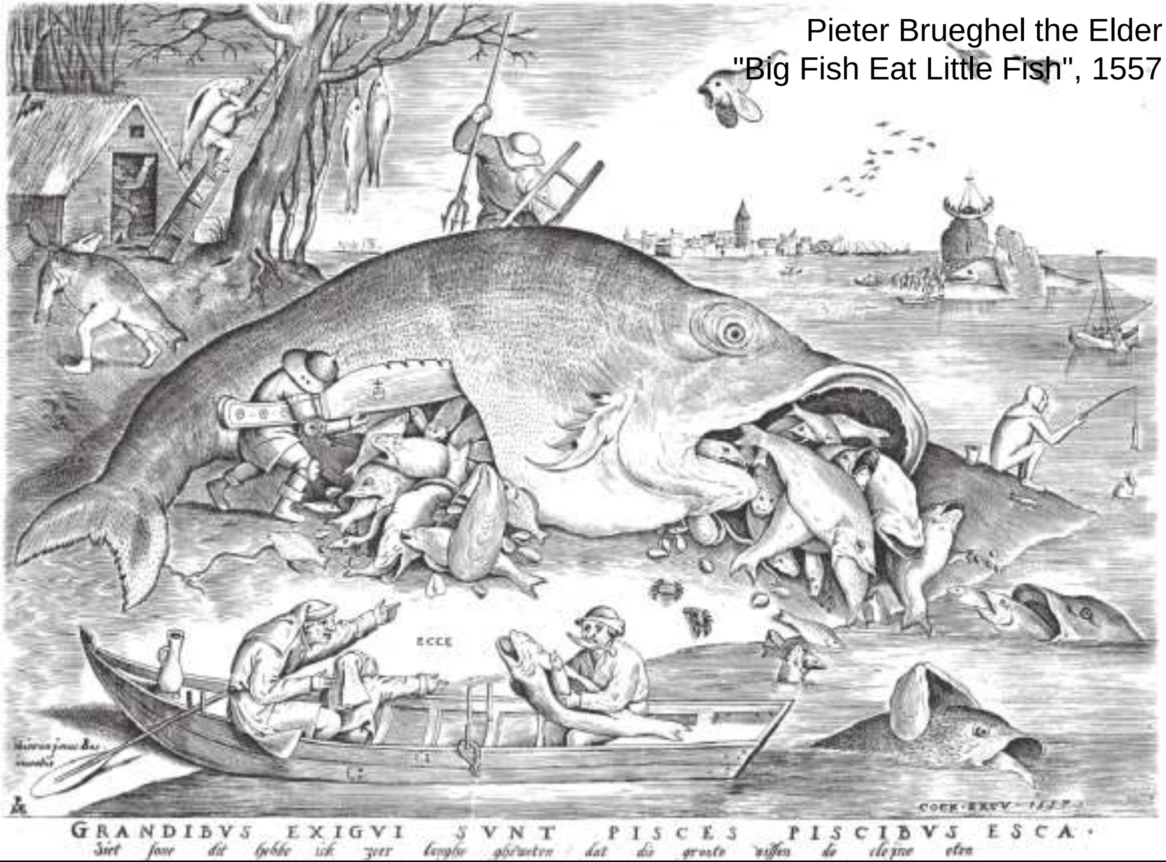

Pieter Brueghel the Elder
"Big Fish Eat Little Fish", 1557