Projected changes in the relationship between water-column stratification and nutrient supply in the Northeast Pacific

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With advice from: Charlie Stock, Nick Bond, and Anand Gnanadesikan

Outline

I. **Purpose:**

To understand how the upwelling ecosystem of the Northeast Pacific will respond to anthropogenic climate change.

II. **Background:**

Physical and biogeochemical factors supporting high ecosystem productivity in the California Current.

III. **Methodology:**

Analysis of output from a global earth-system model.

IV. **Discussion and implications**

Contrast between observed mechanisms of broad-scale climate-ecosystem interaction of the 20th and 21st centuries.

Ecosystem response to climate variability and change

Dominant modes of climate-ecosystem relationships in subtropical ecosystems:

Relationship between stratification (SST) and nutrient supply	Interannual	Decadal to Multidecadal	Centennial
suggested by historical observations	***negative***	***negative***	limited observations
expected with ***anthropogenic warming***			

Ecosystem response to climate variability and change

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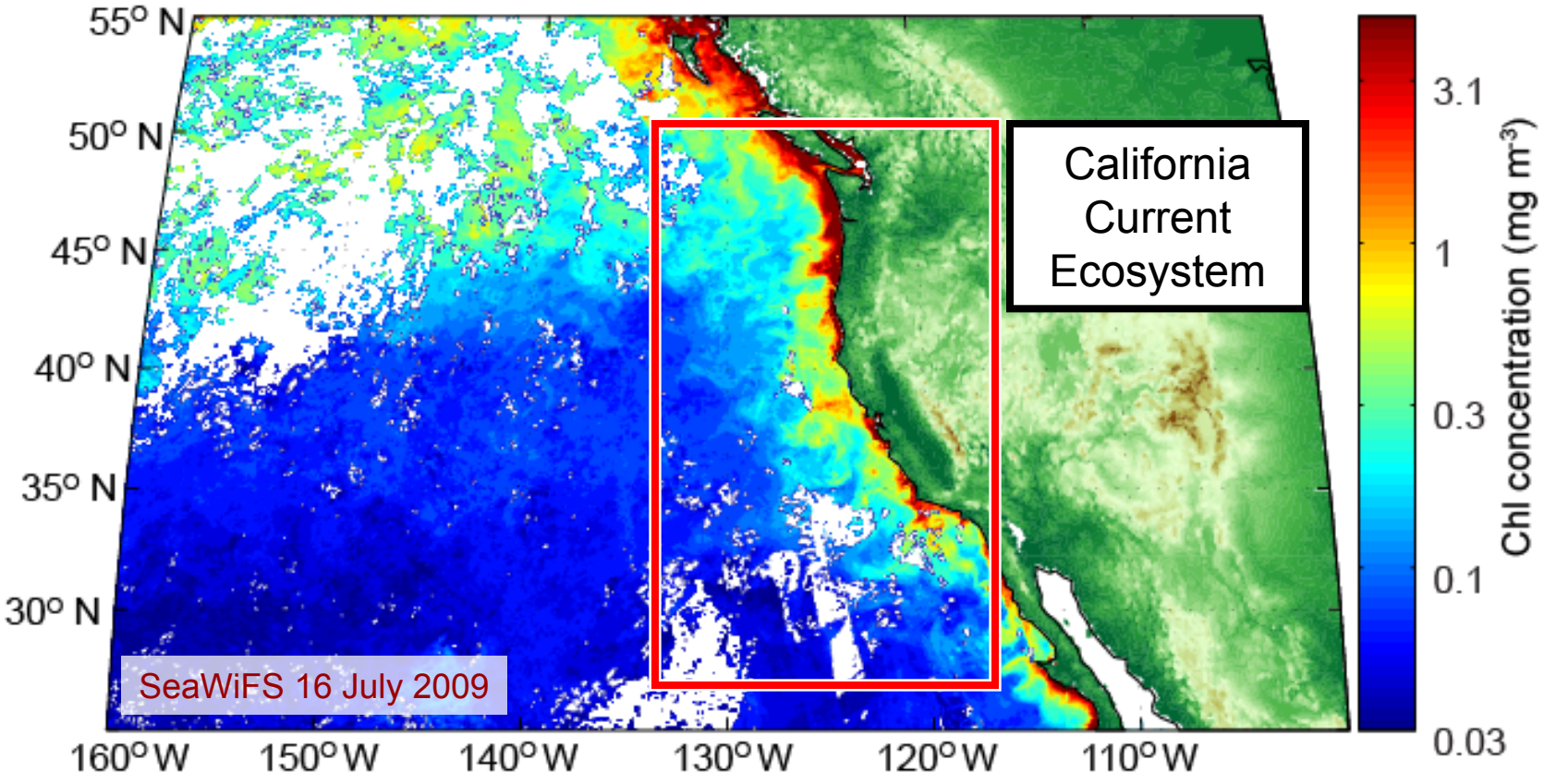
expected with ***anthropogenic warming***	?	?	?

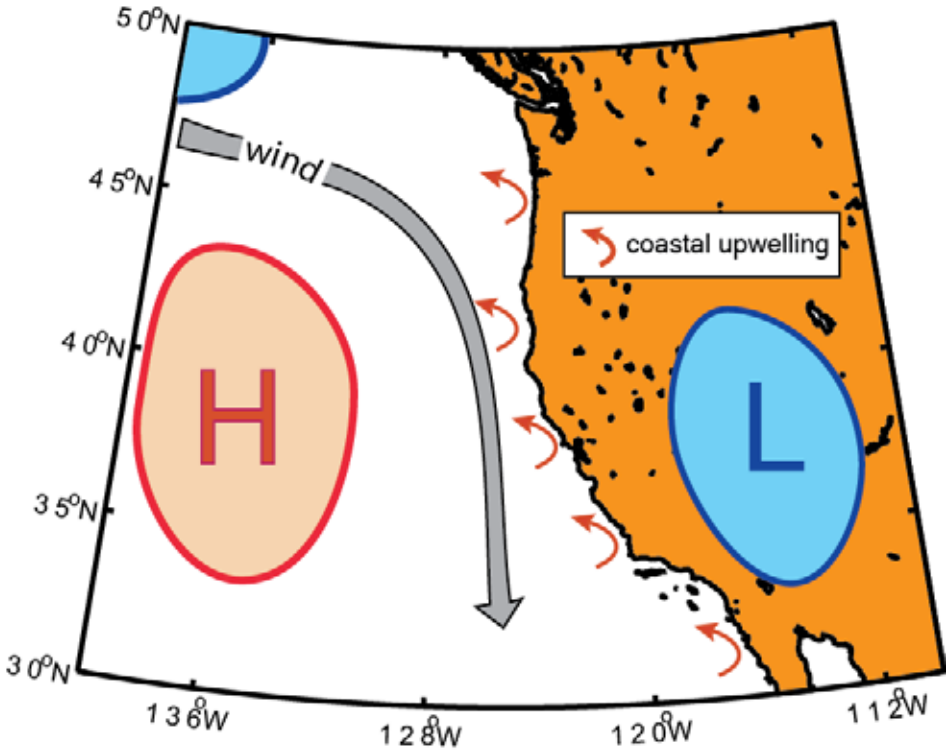
The Northeast Pacific ecosystem is highly productive

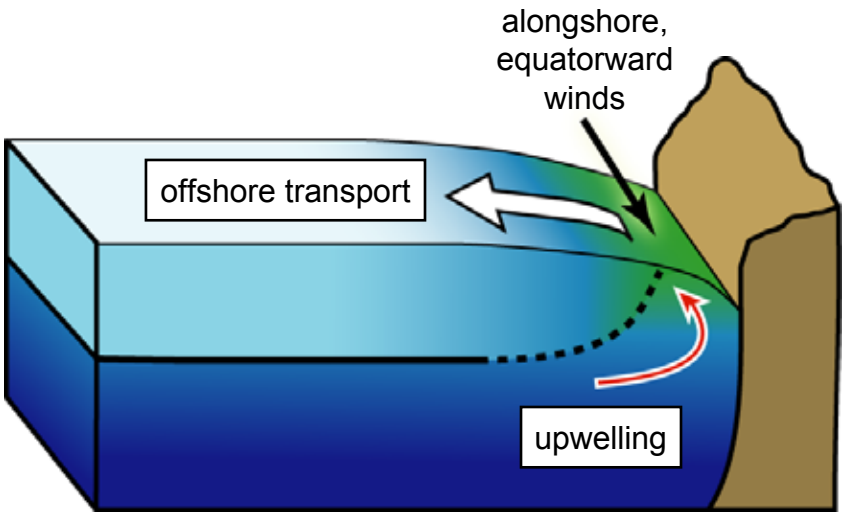
The eastern boundary of the subtropical Northeast Pacific is a region of high biological productivity.



Upwelling forces deep waters to the surface

Alongshore winds in summer force the **upwelling of cold, deep, nutrient-rich waters towards the surface**.

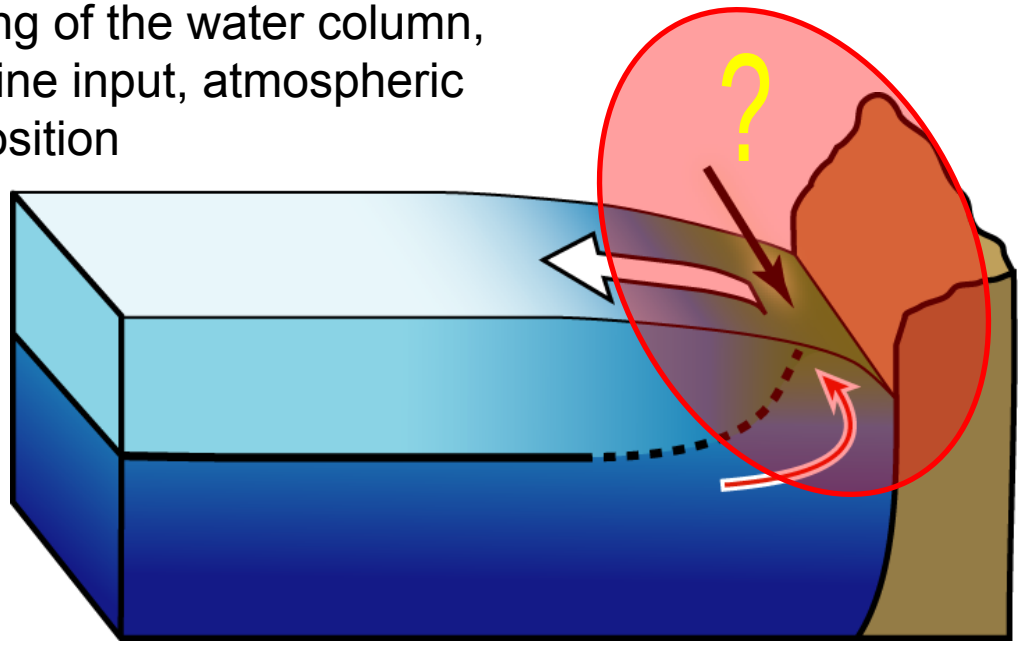




How might upwelling of nutrients change in the future?

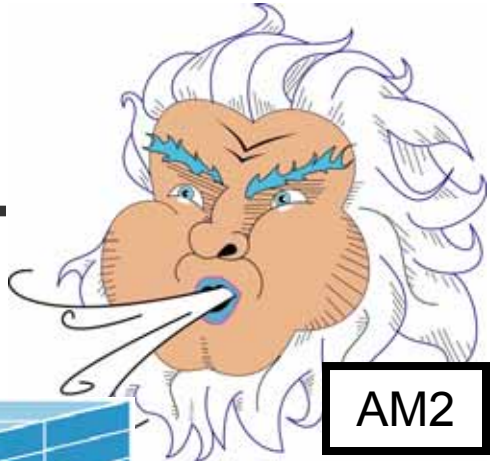
Local conditions may change and affect the upwelling process at the coast.

Changes in: alongshore winds, alongshore currents, stratification and mixing of the water column, riverine input, atmospheric deposition

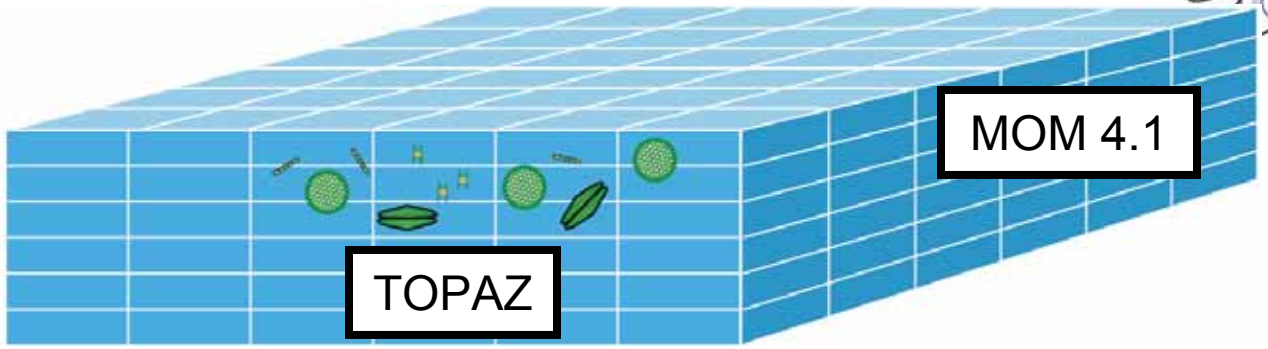


Methodology: earth-system modeling

An atmosphere-ocean general circulation model is coupled to an ocean biogeochemical model and forced with the **IPCC** emissions scenario **A2**.



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

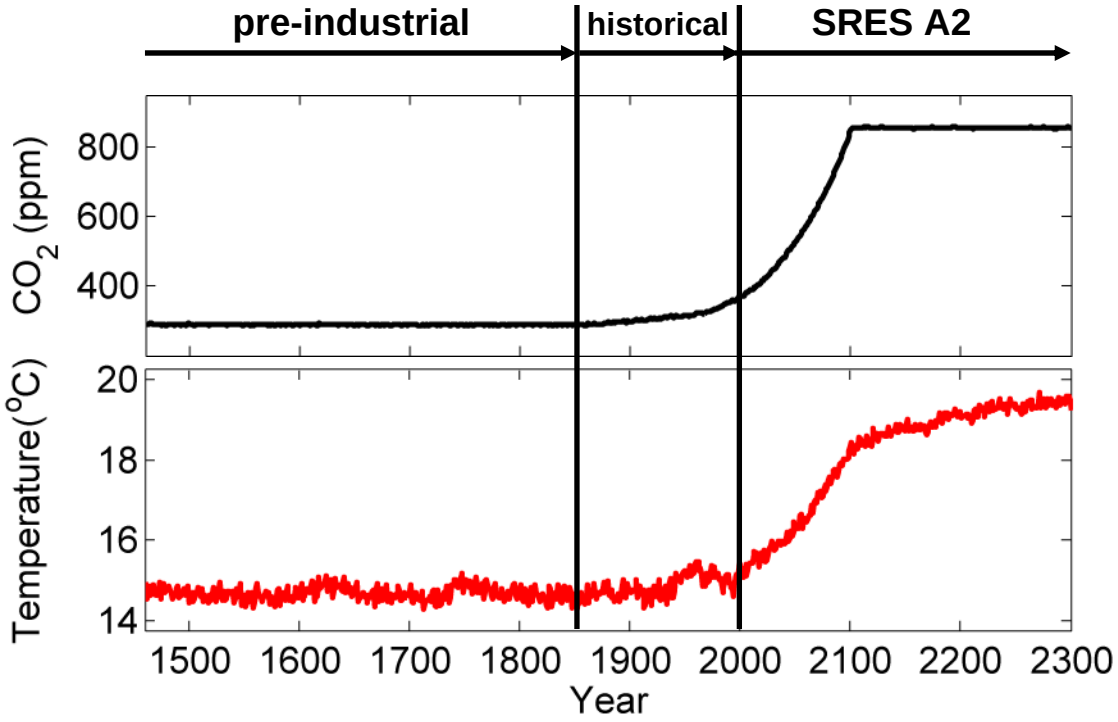


Ocean: NOAA-GFDL **MOM 4.1** (Modular Ocean Model; Pacanowski and Griffies, 1999); 1° x 1° horizontal resolution

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).

Global CO_2, pre-industrial through year 2300 (SRES A2)

IPCC Emissions Scenario A2:

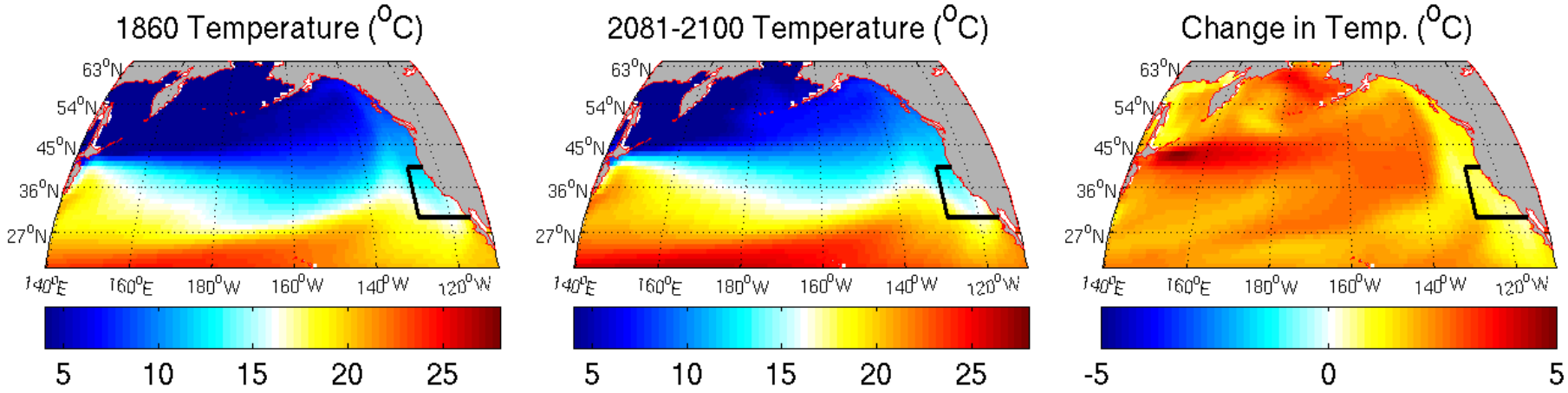


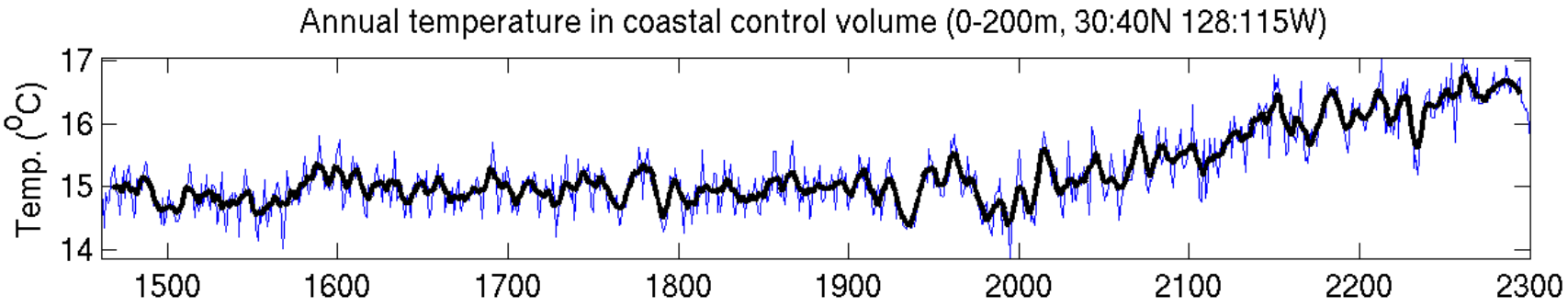
Prescribed CO_2 concentration

Global average surface temperature (+2.9 °C from 2000 to 2100)

What are the implications of such changes for the ecosystem of the Northeast Pacific?

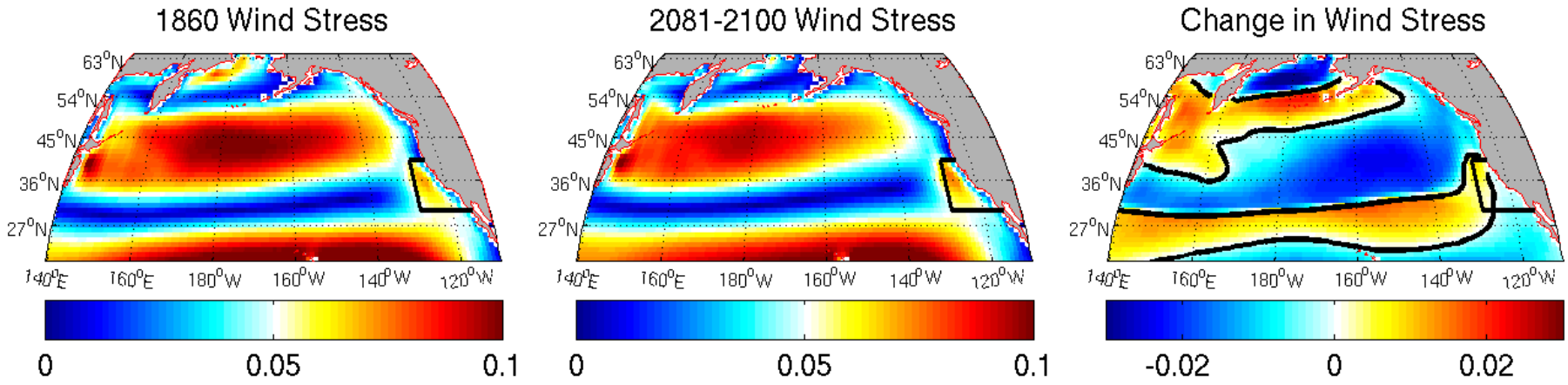
Temperature increases across the basin

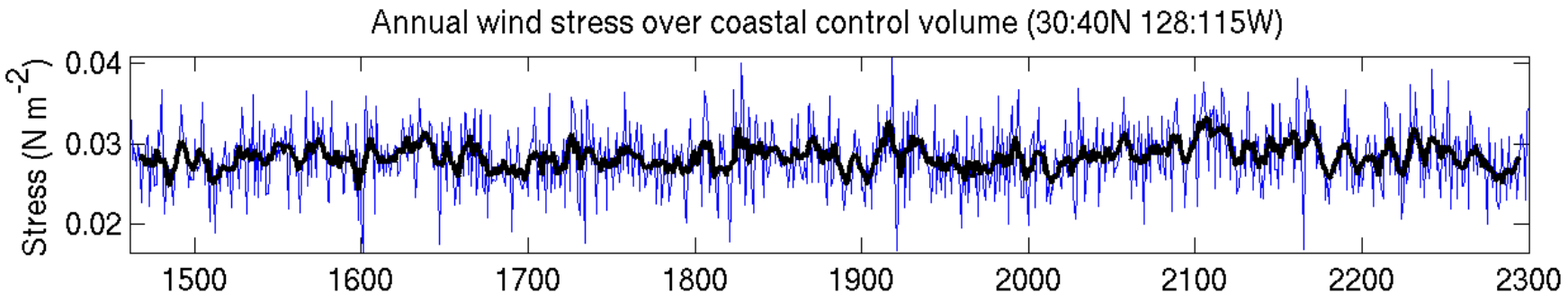




The magnitude of the upper-ocean temperature change varies, but the direction of the change is uniform: the whole Pacific becomes warmer at the surface.

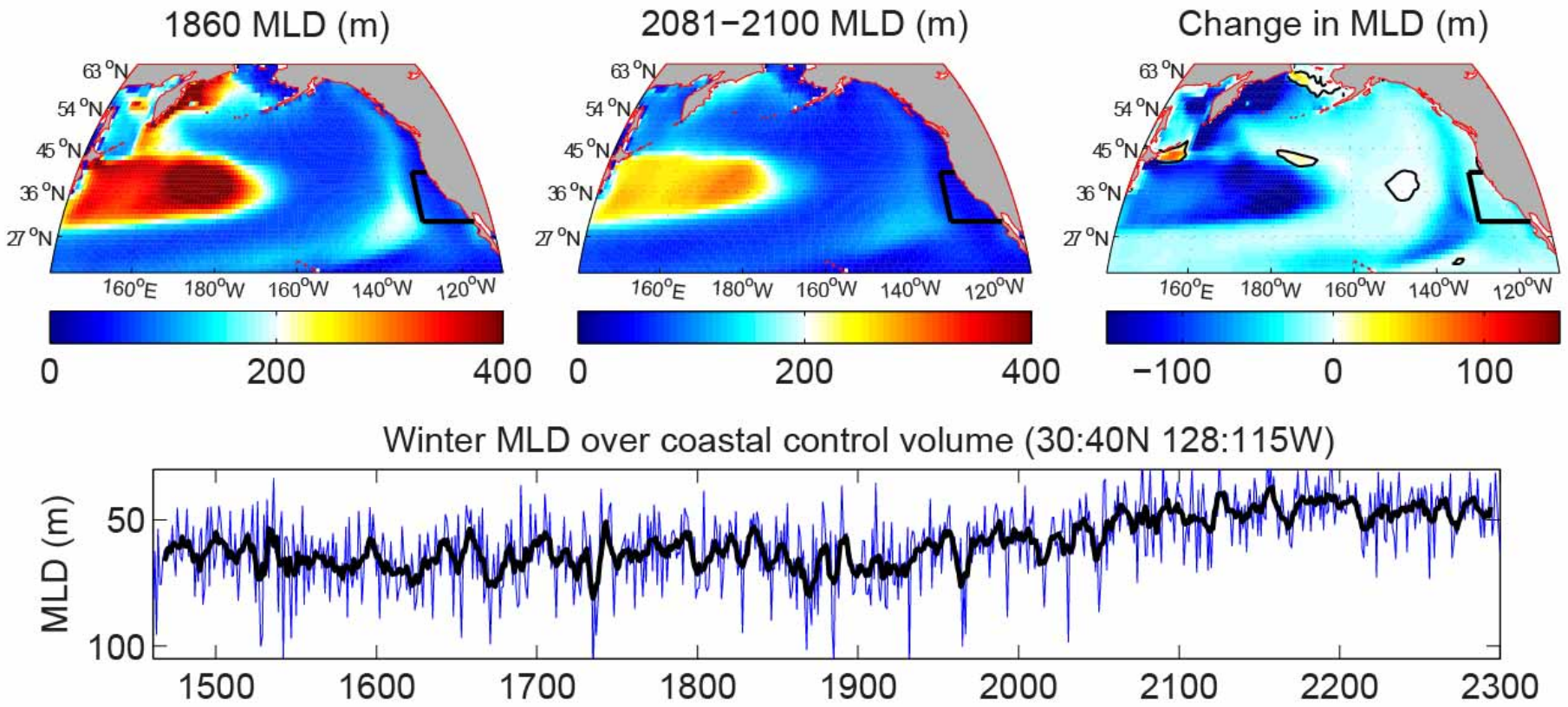
Zonal winds: *weaken and shift poleward*
Meridional winds: *little change*





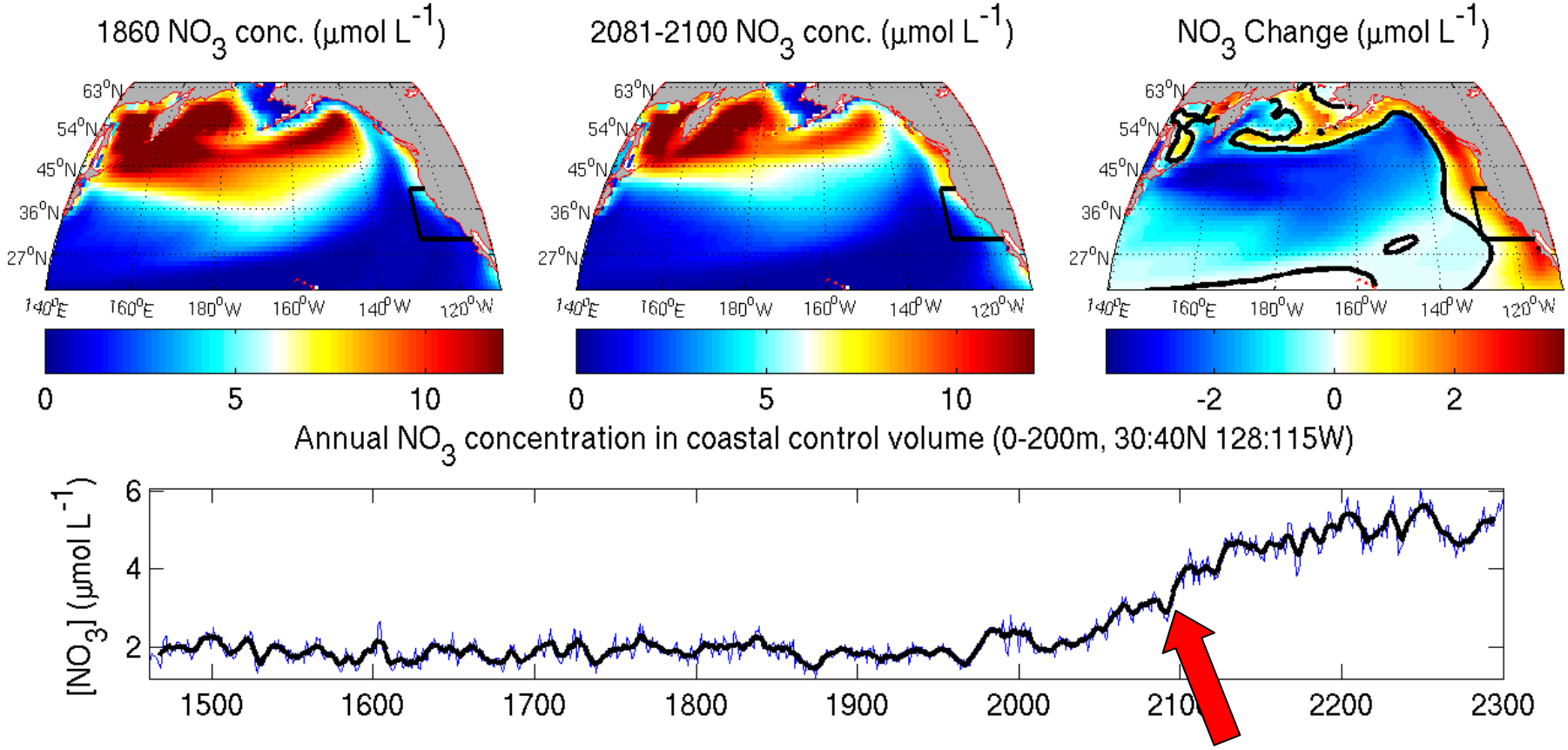
The magnitude of alongshore winds at the coast does not change significantly.

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.

However, NO_3 changes are counterintuitive



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

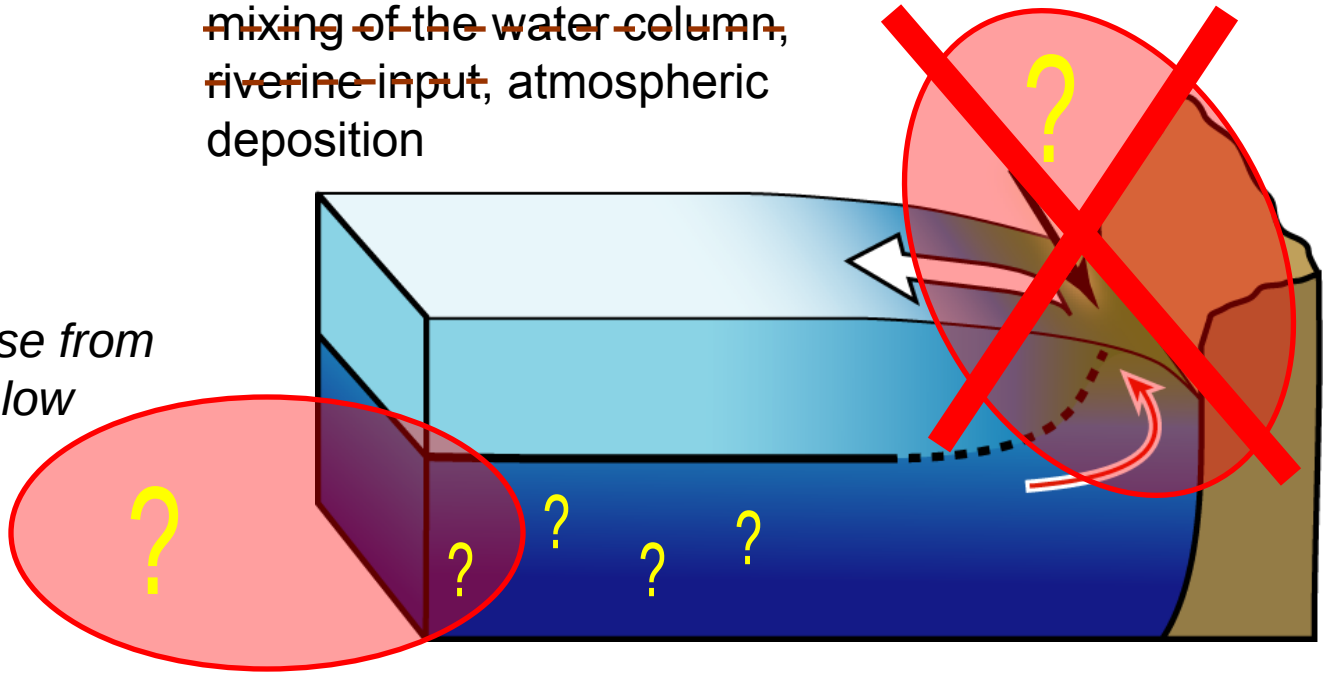
85% increase in average nitrogen concentration between 2000 and 2100 along the US West Coast.

Local changes cannot explain increased nutrient fluxes

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~~, atmospheric deposition

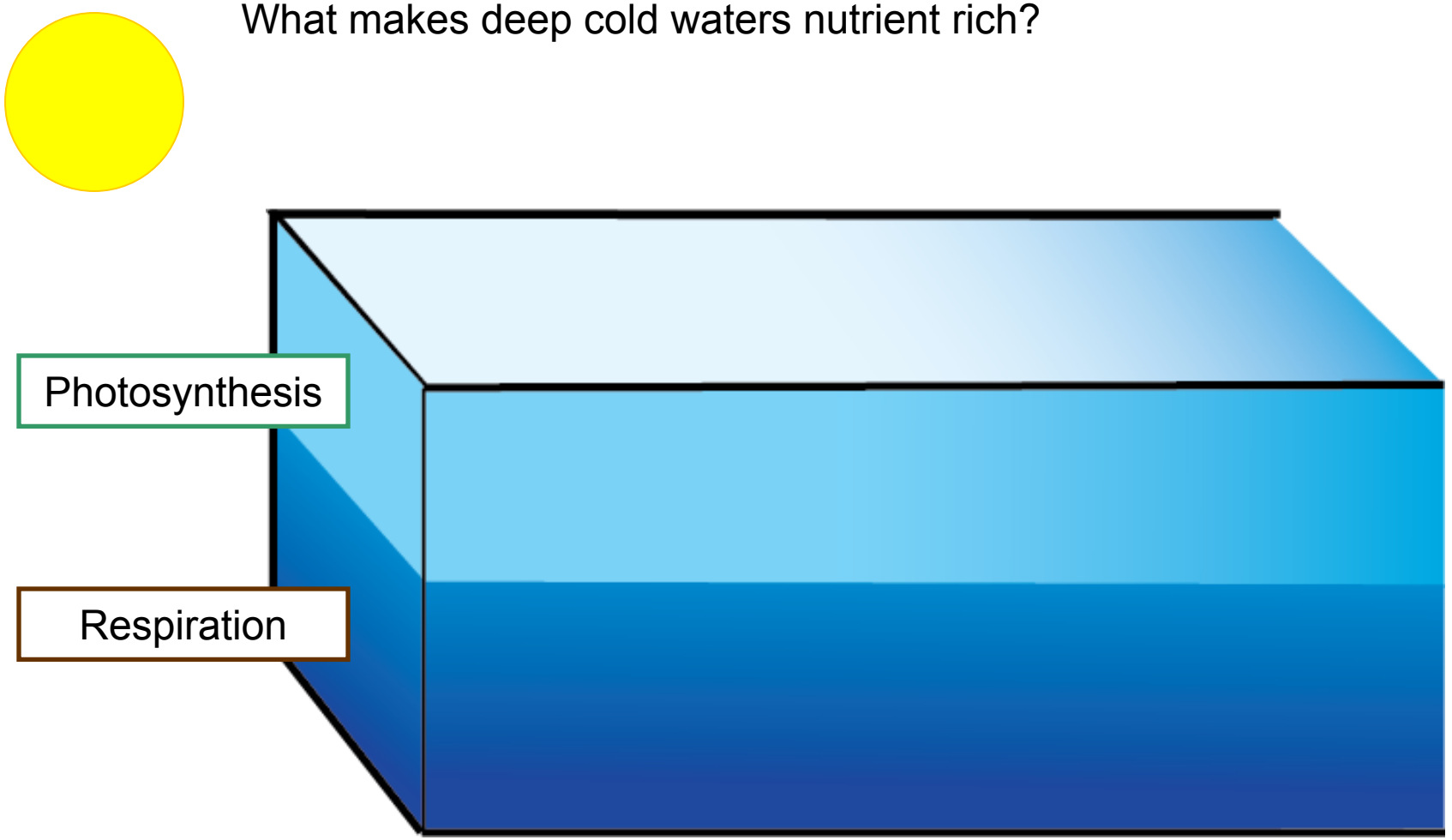
Surprise from below



Remote changes in the properties of the deep source waters which feed the upwelling system appear to be more important than local physical conditions.

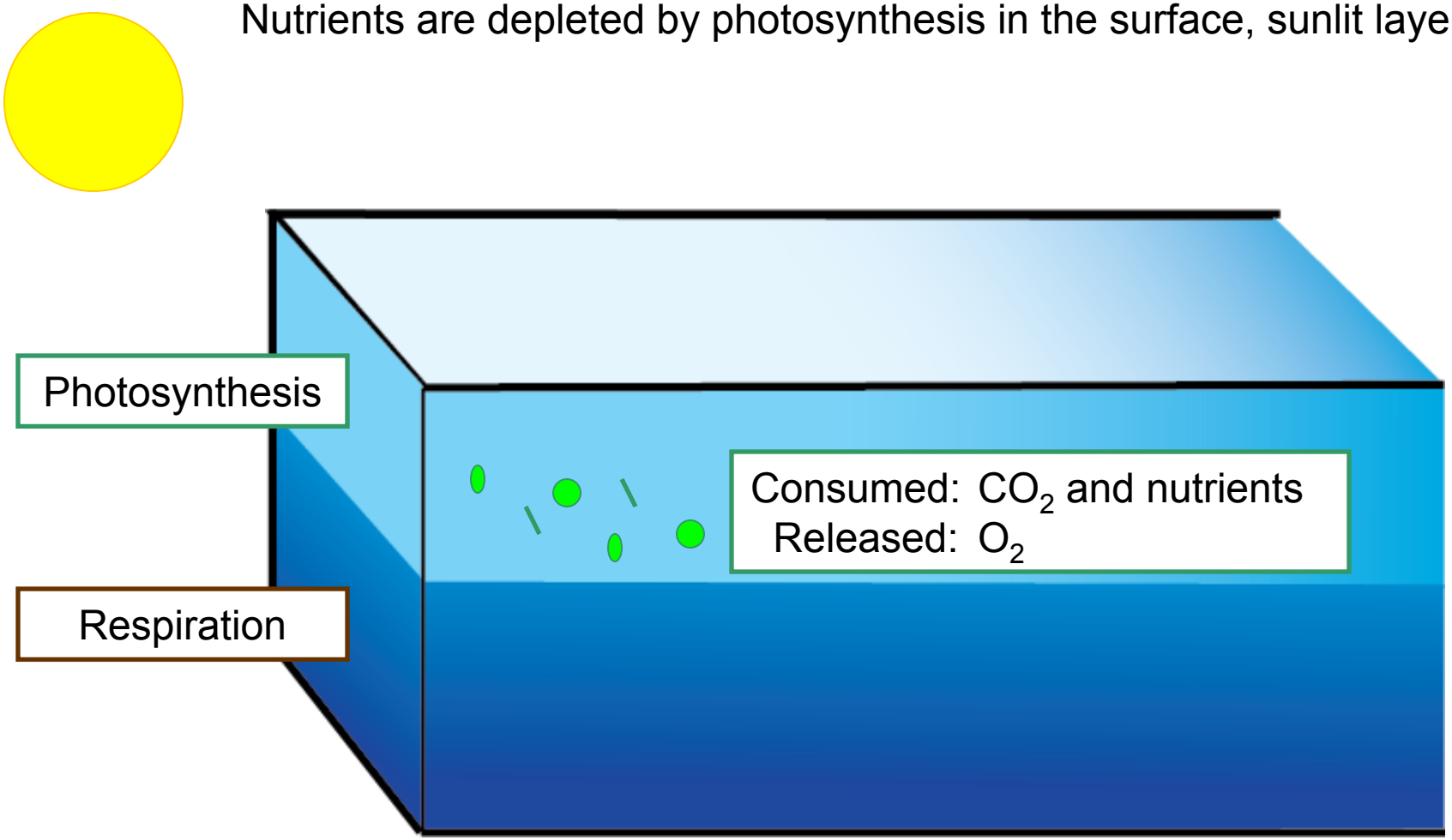
Review of photosynthesis and respiration

What makes deep cold waters nutrient rich?



Review of photosynthesis and respiration

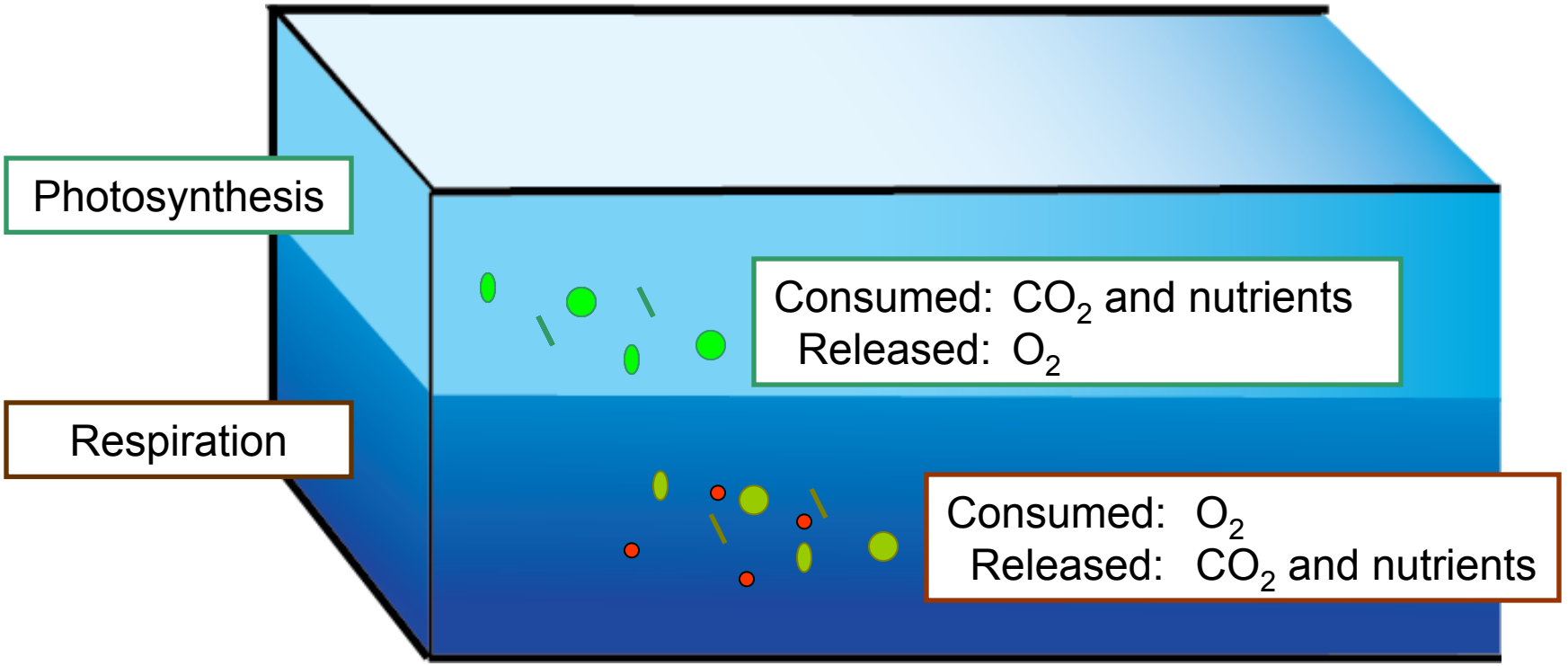
Nutrients are depleted by photosynthesis in the surface, sunlit layer.



Review of photosynthesis and respiration

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

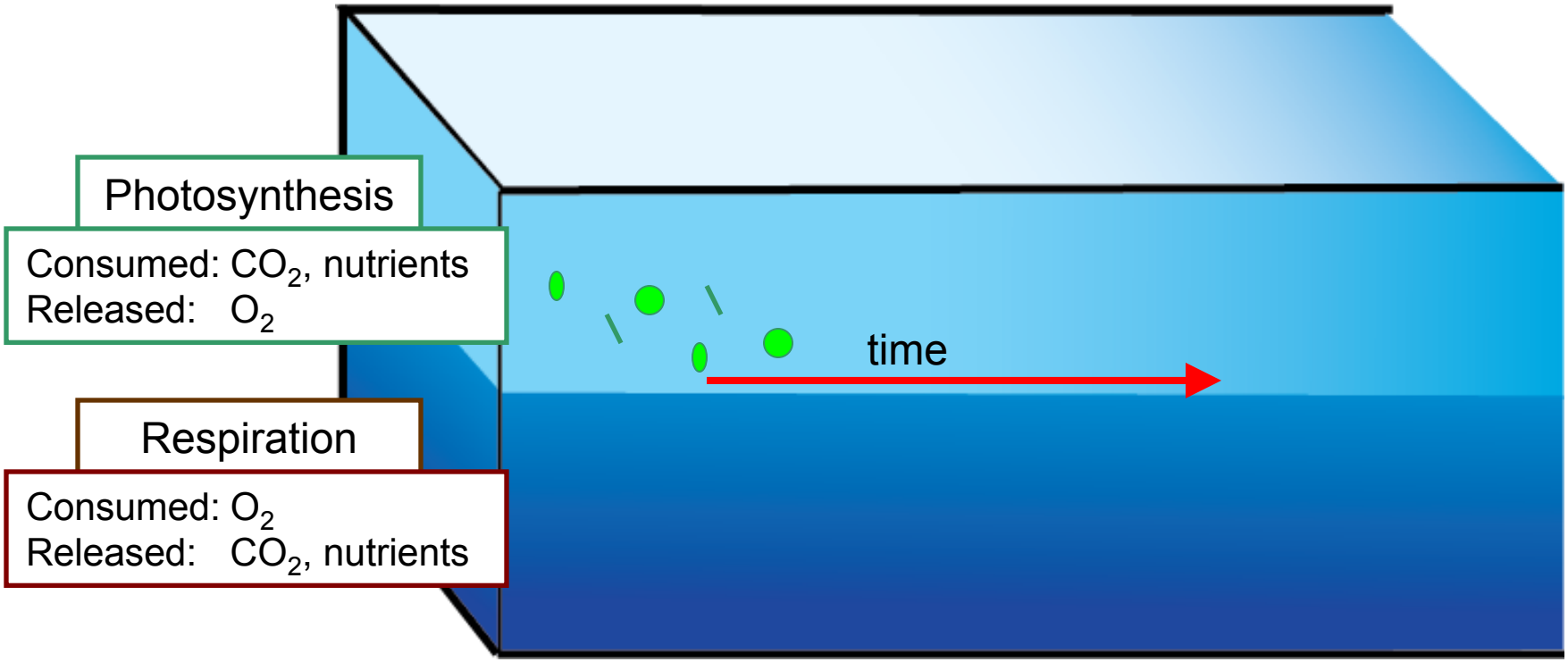
Biological respiration (microzooplankton and bacteria) remineralize these nutrients in the deeper, colder layer of the ocean.



Respiration enriches deep waters with nutrients

Over time, phytoplankton continue to sink out of the surface layer to depth.

At depth, nutrients and CO_2 accumulate while O_2 is depleted.



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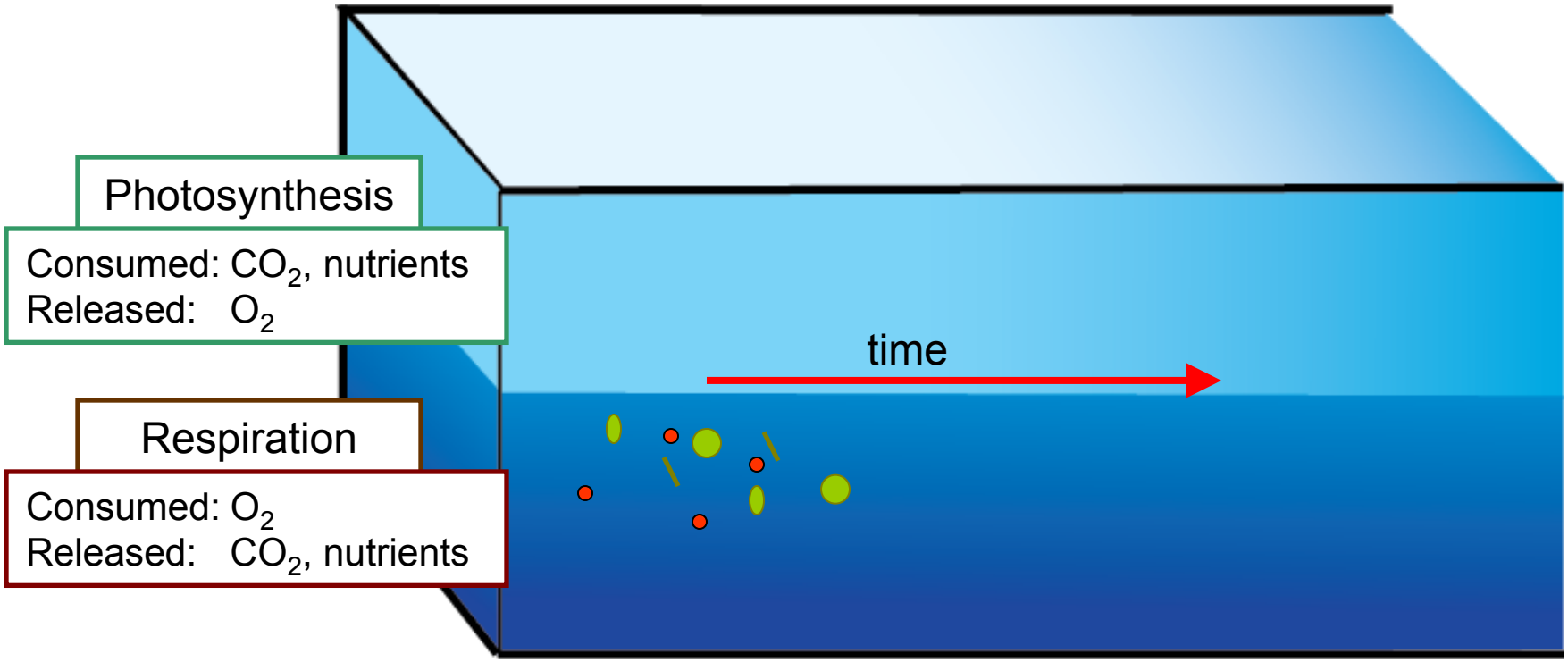

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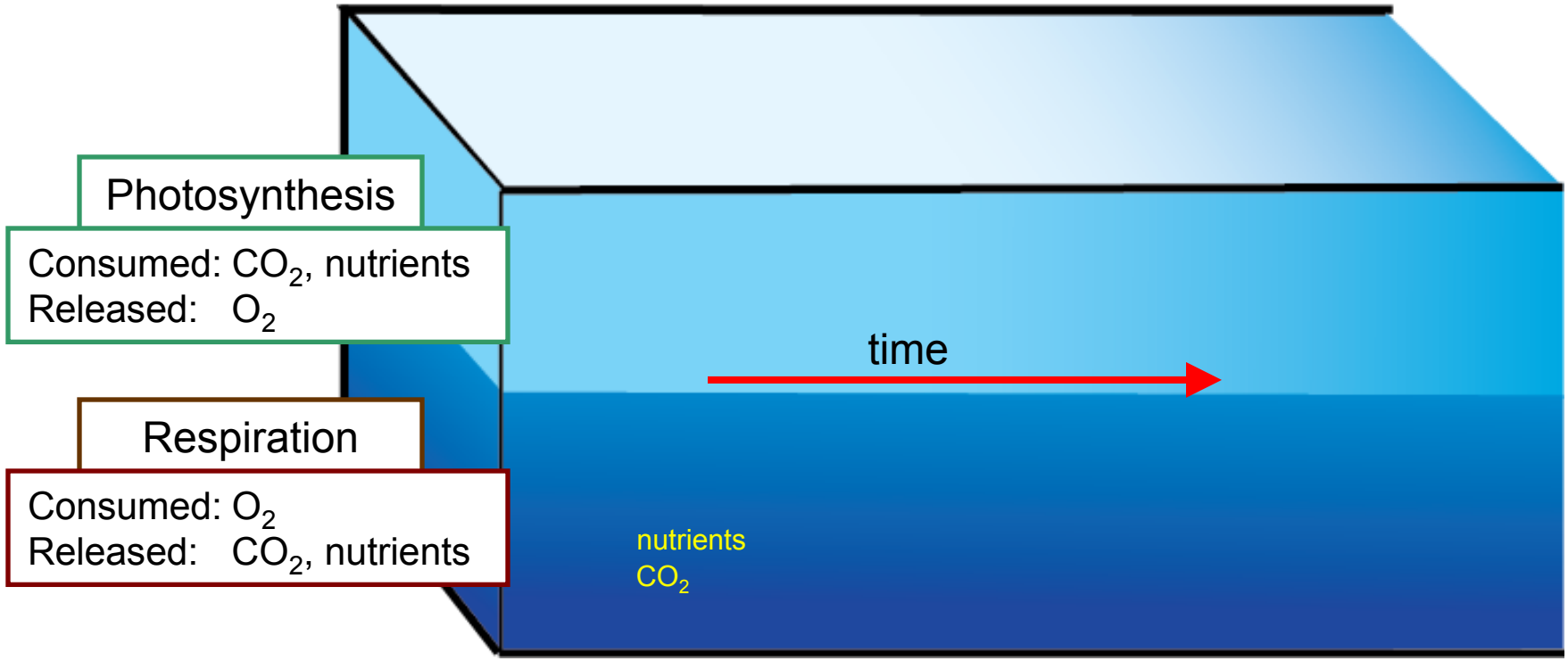

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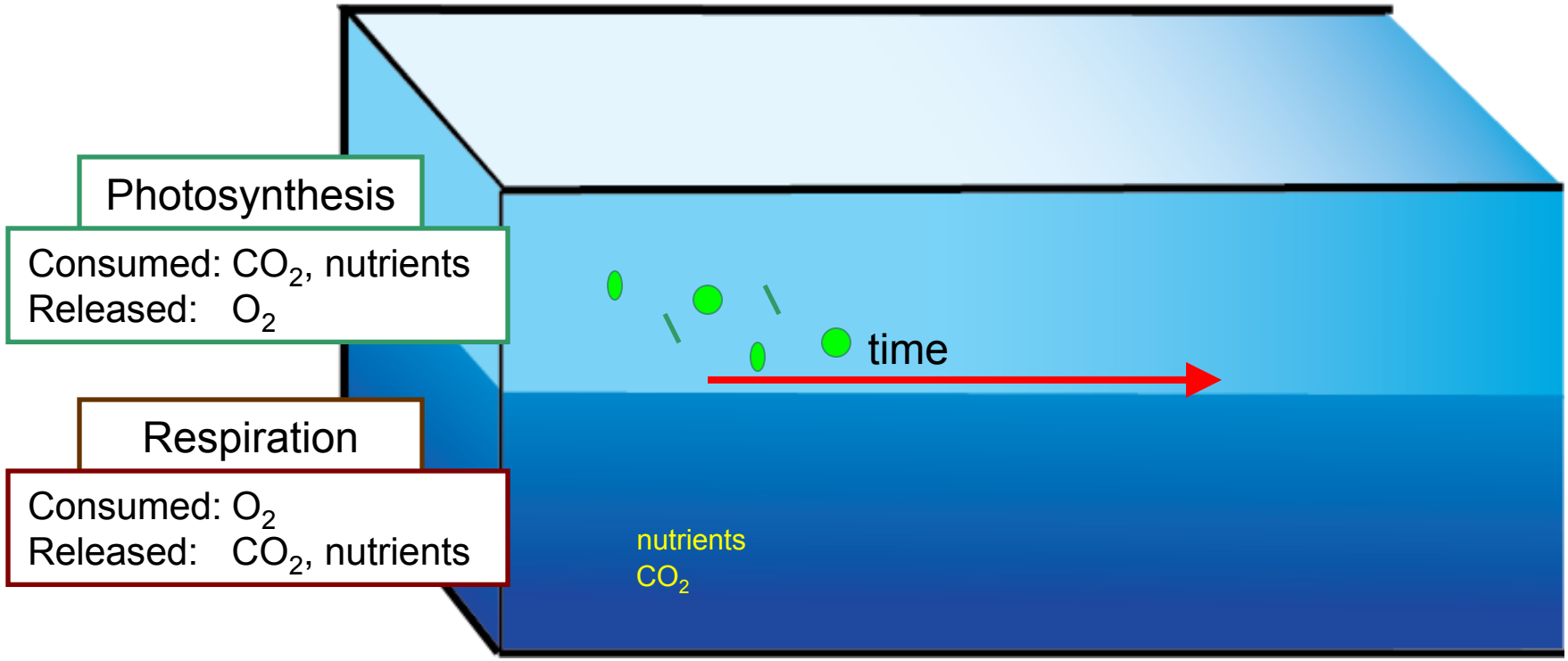

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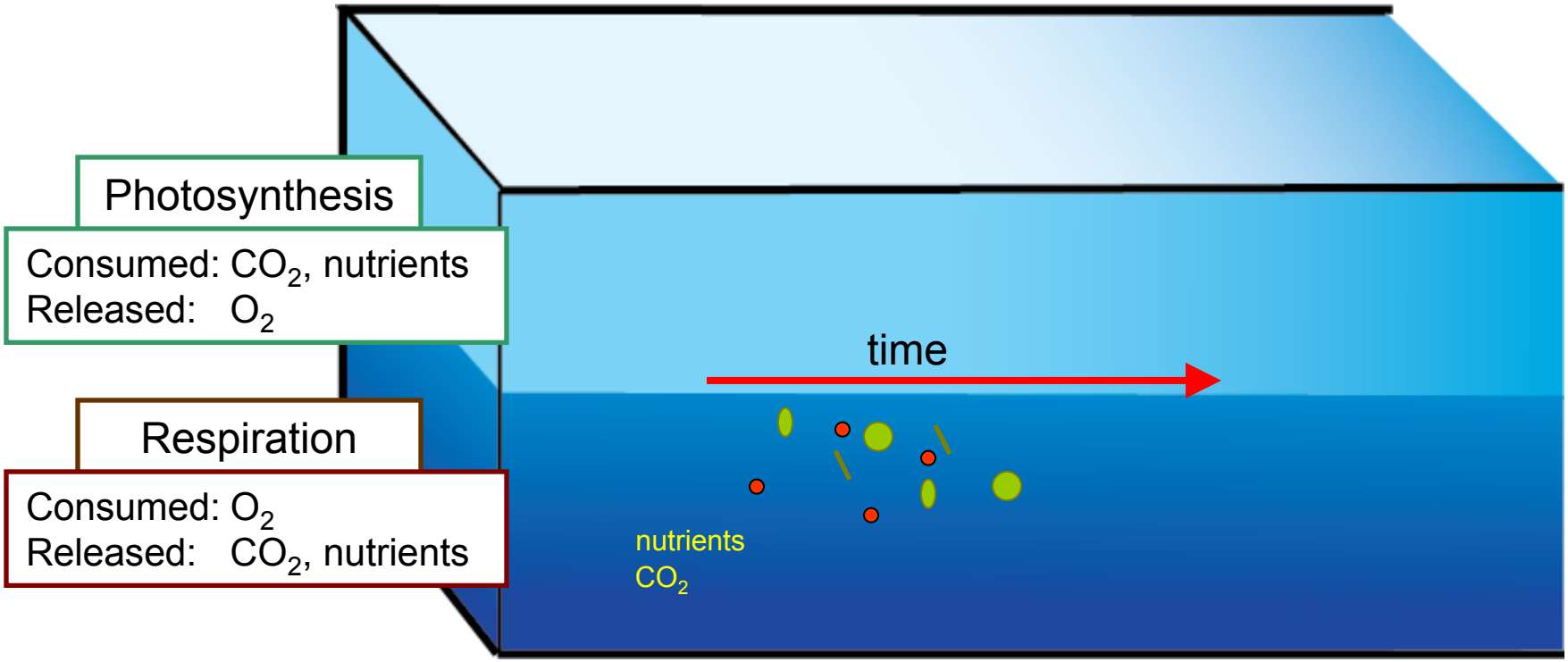

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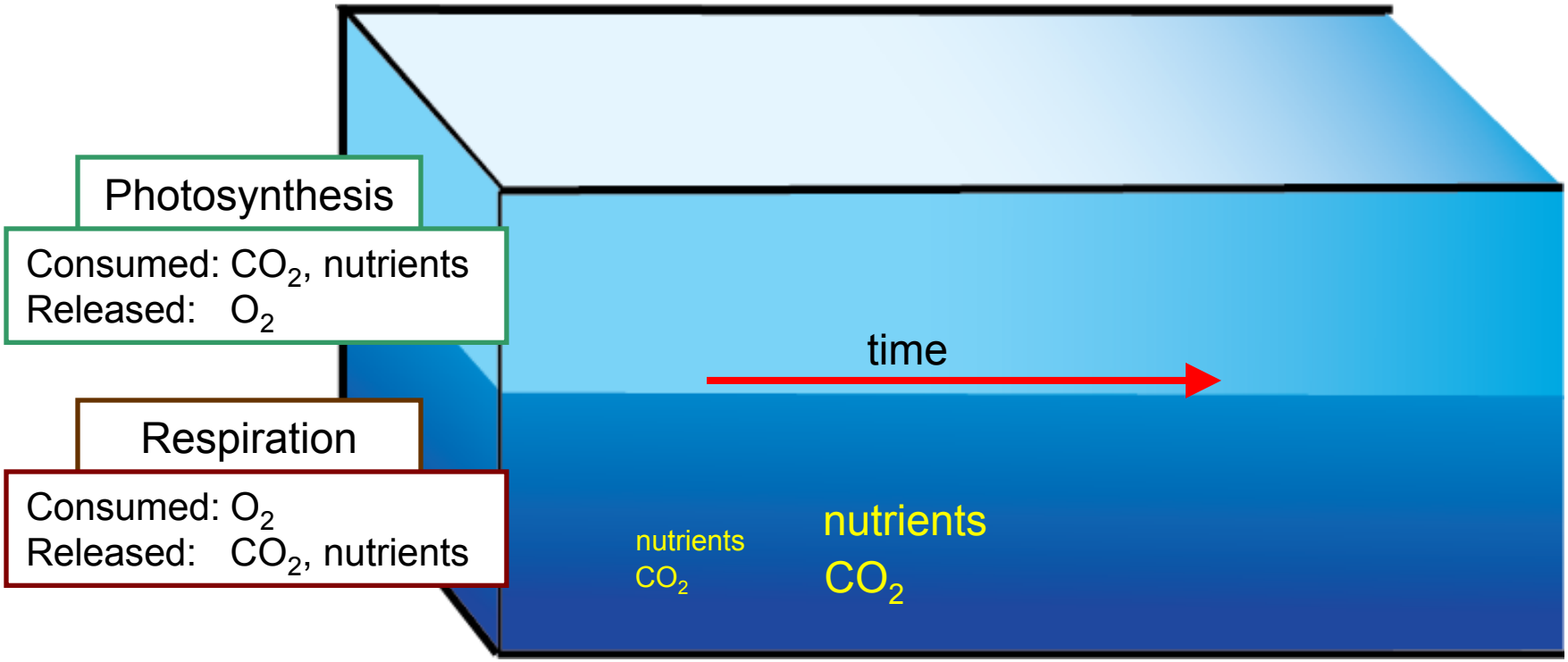

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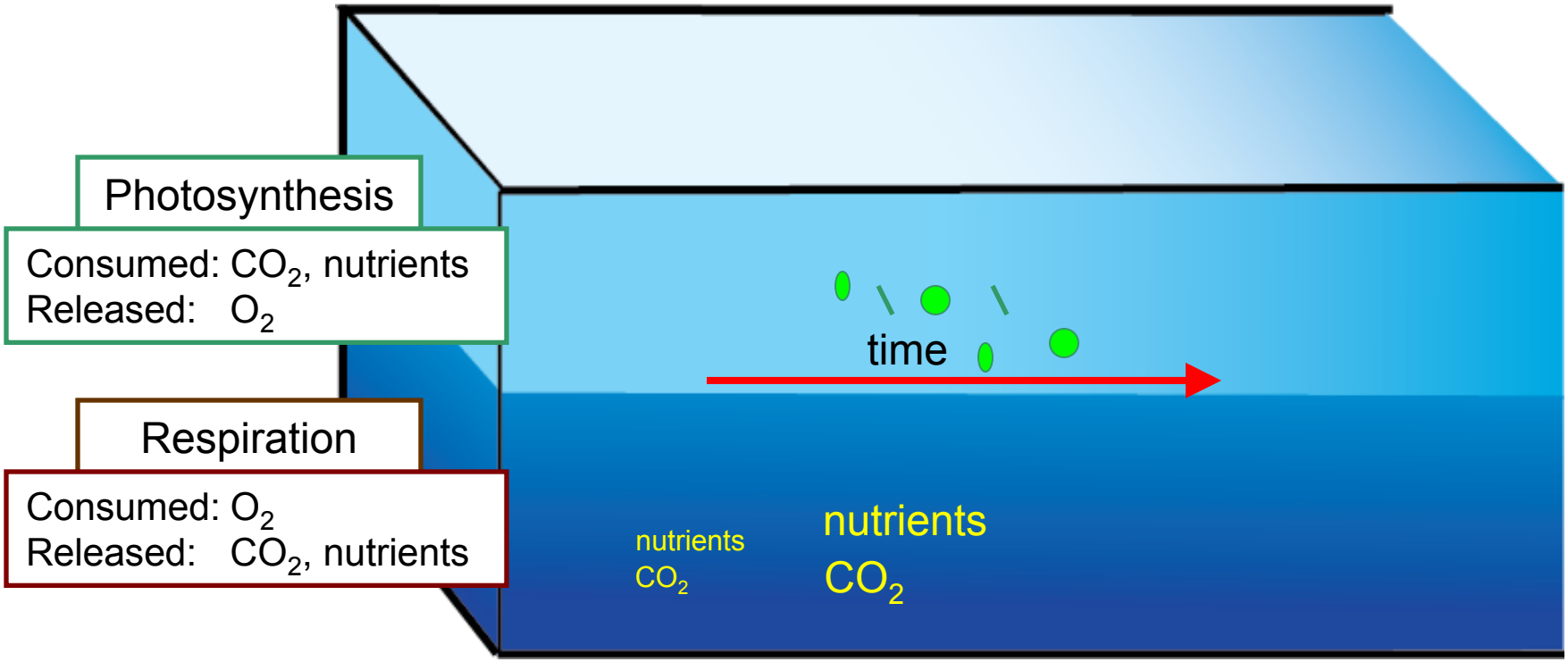

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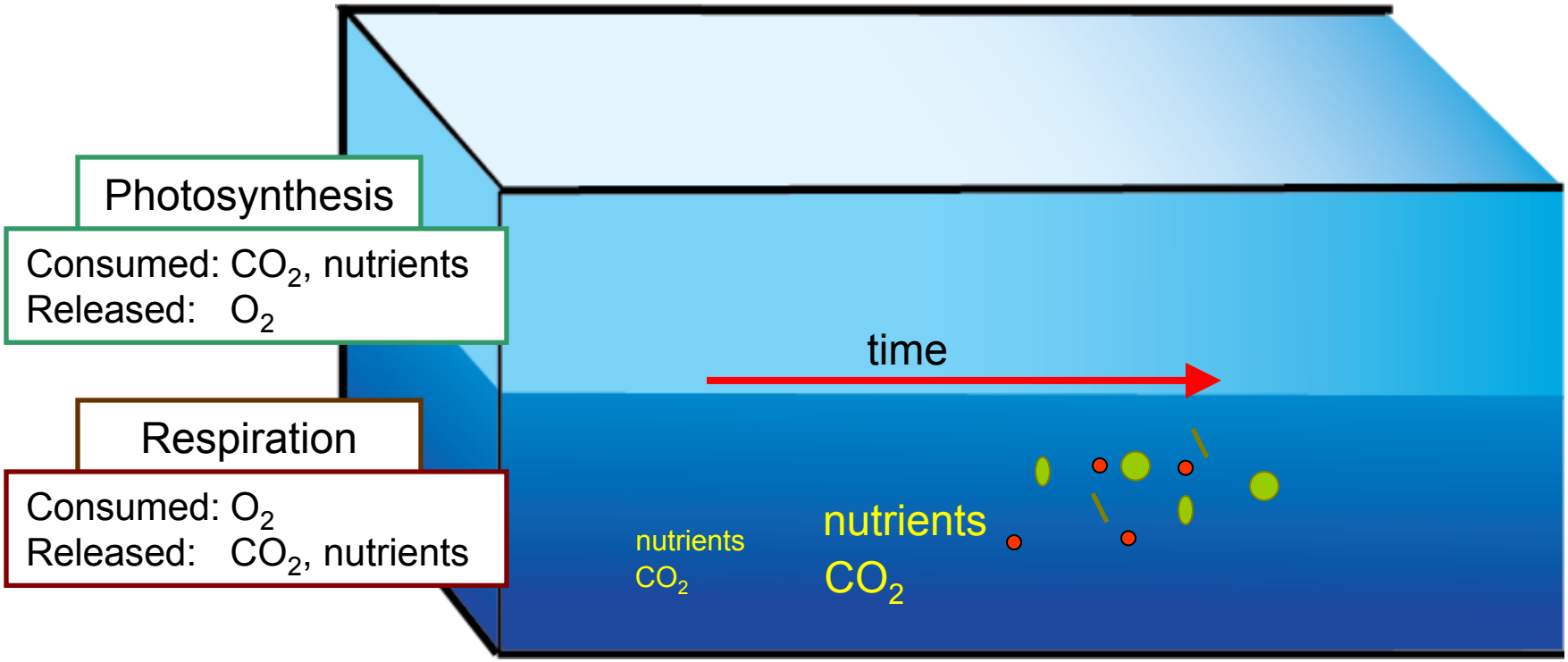

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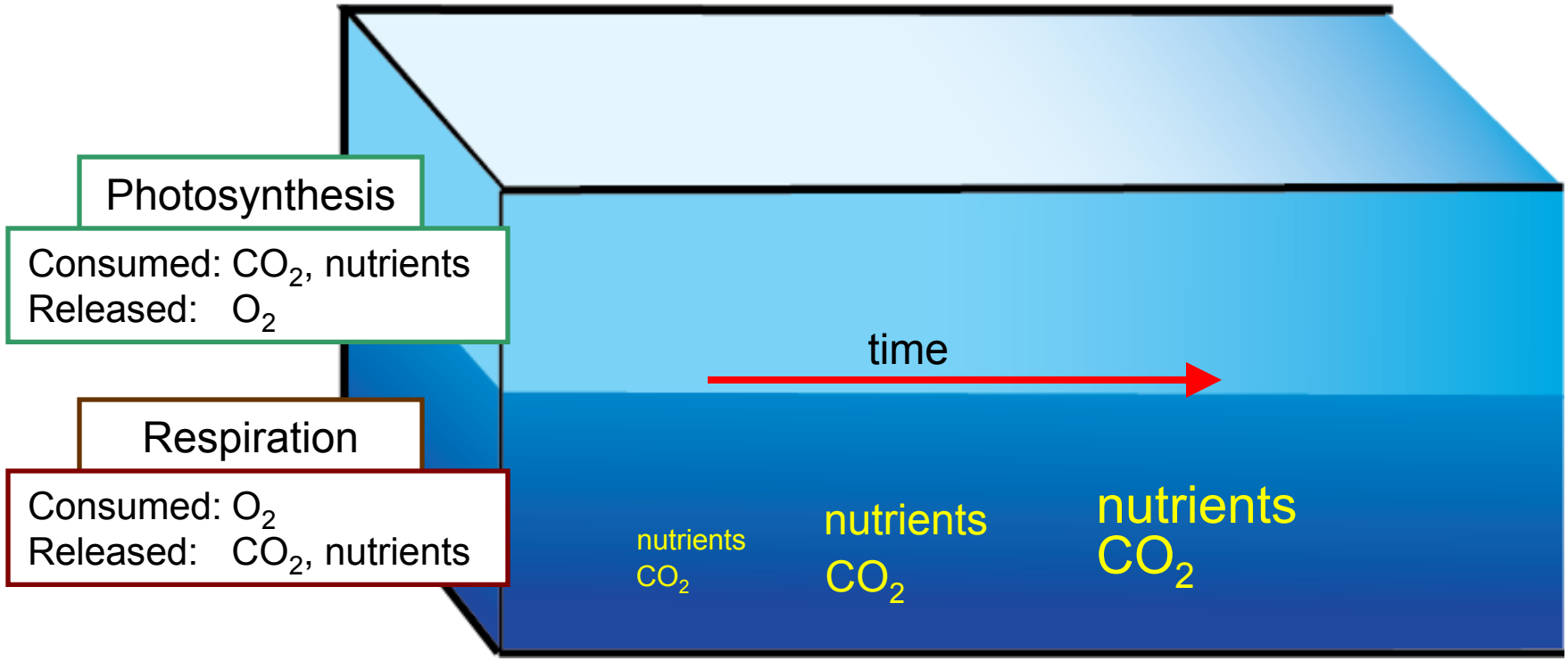

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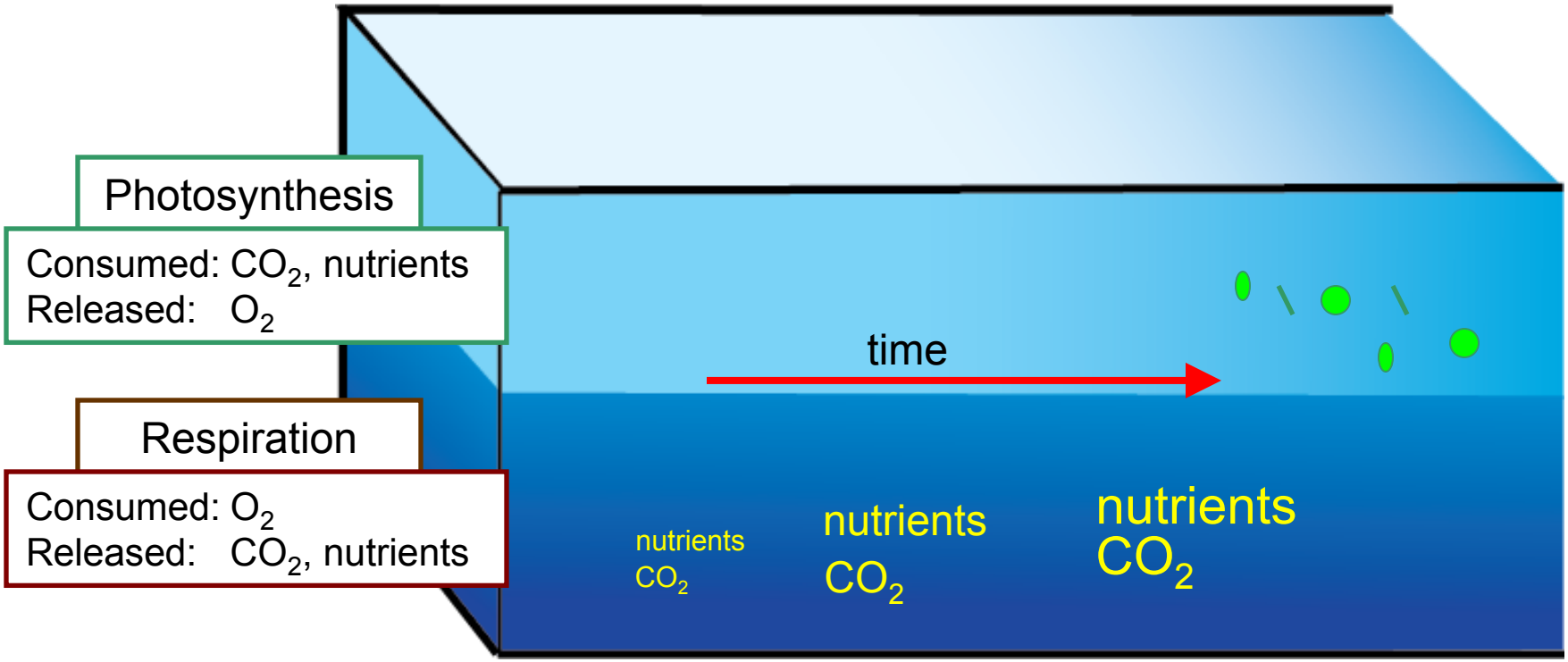

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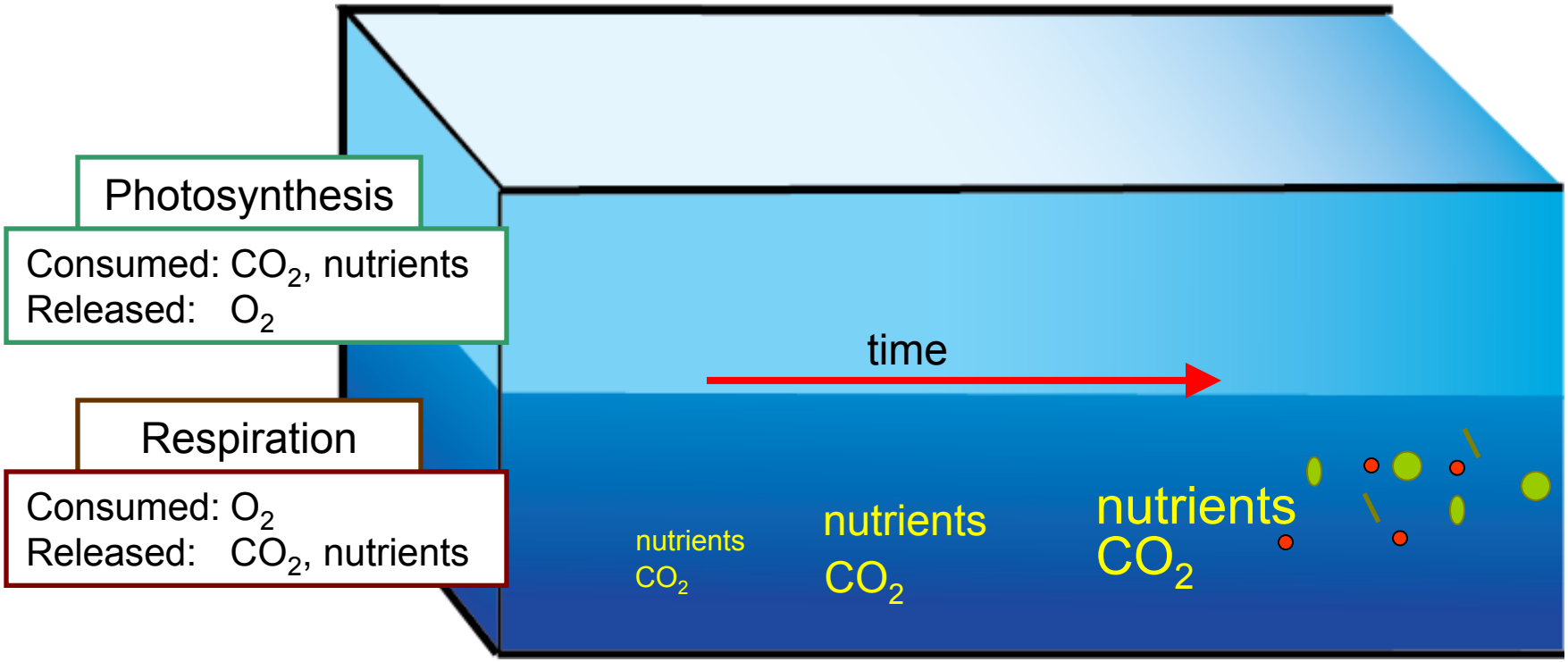

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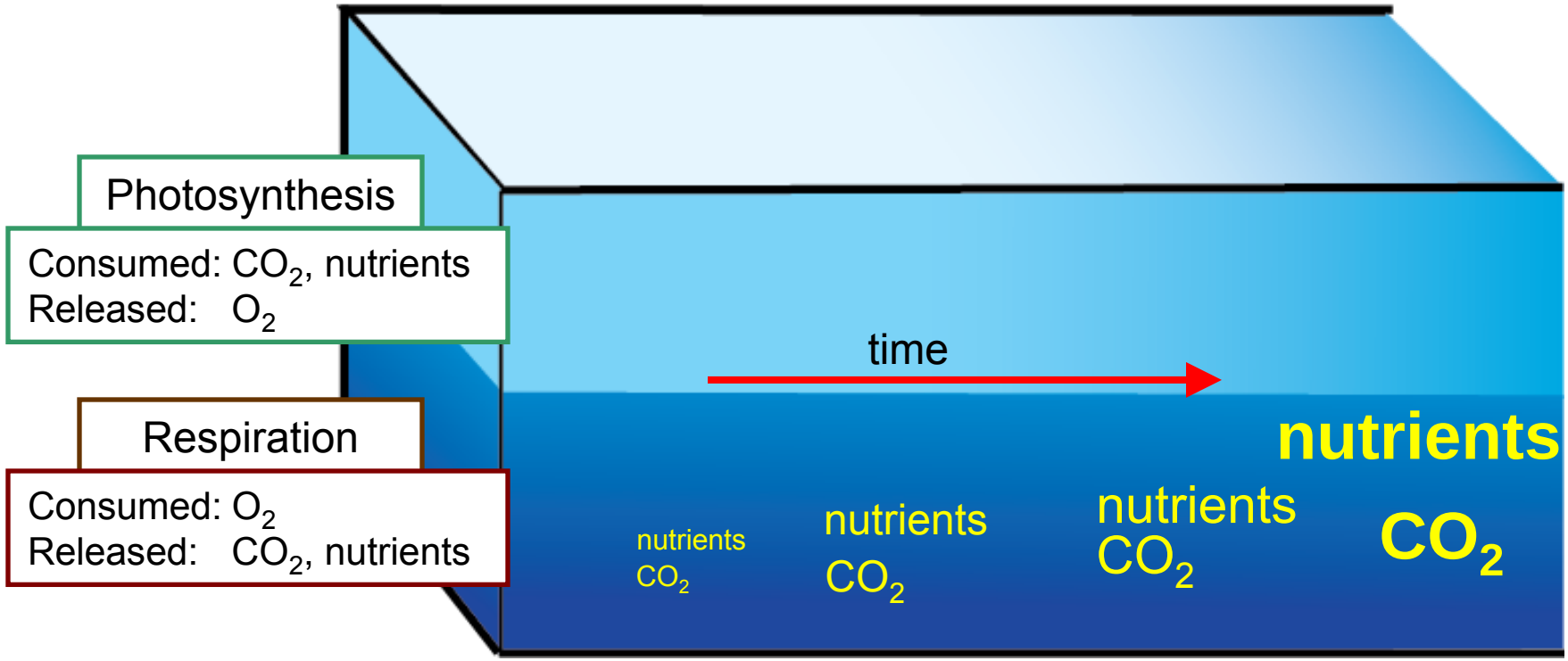

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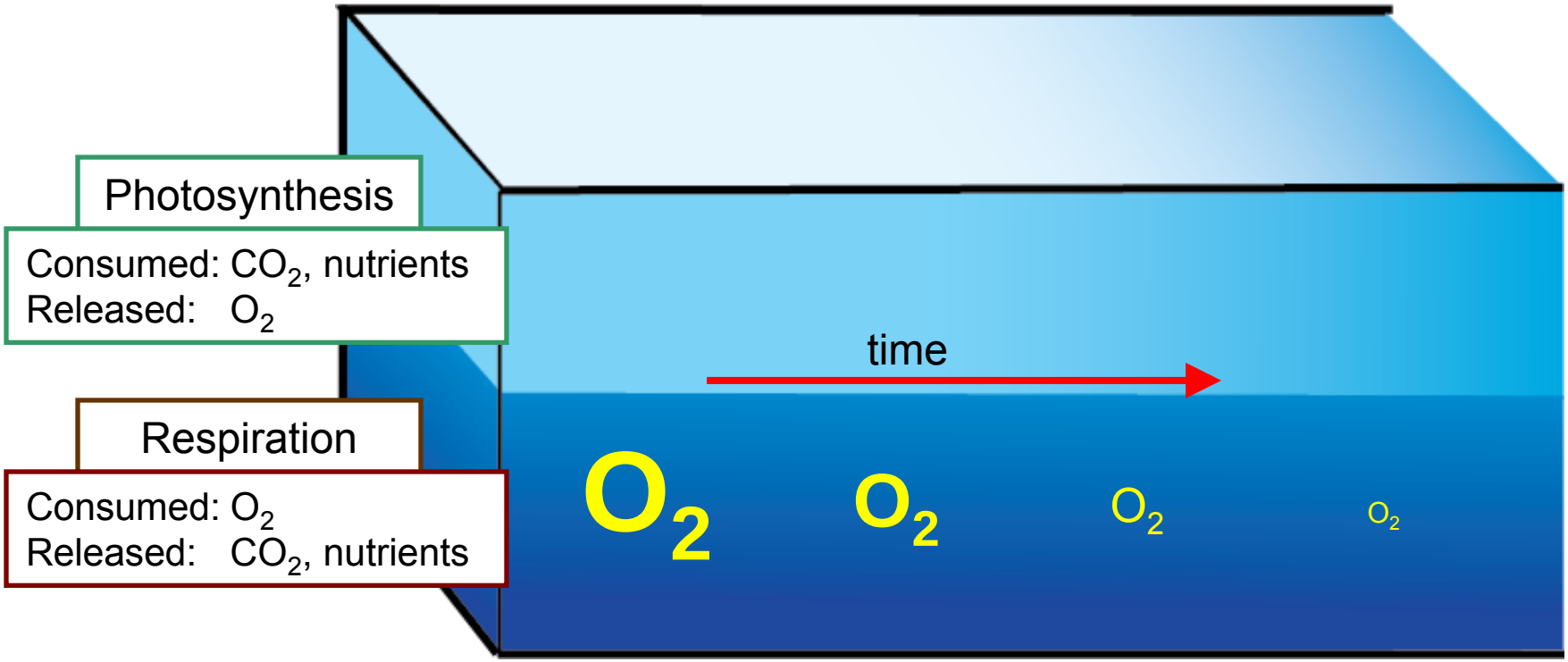

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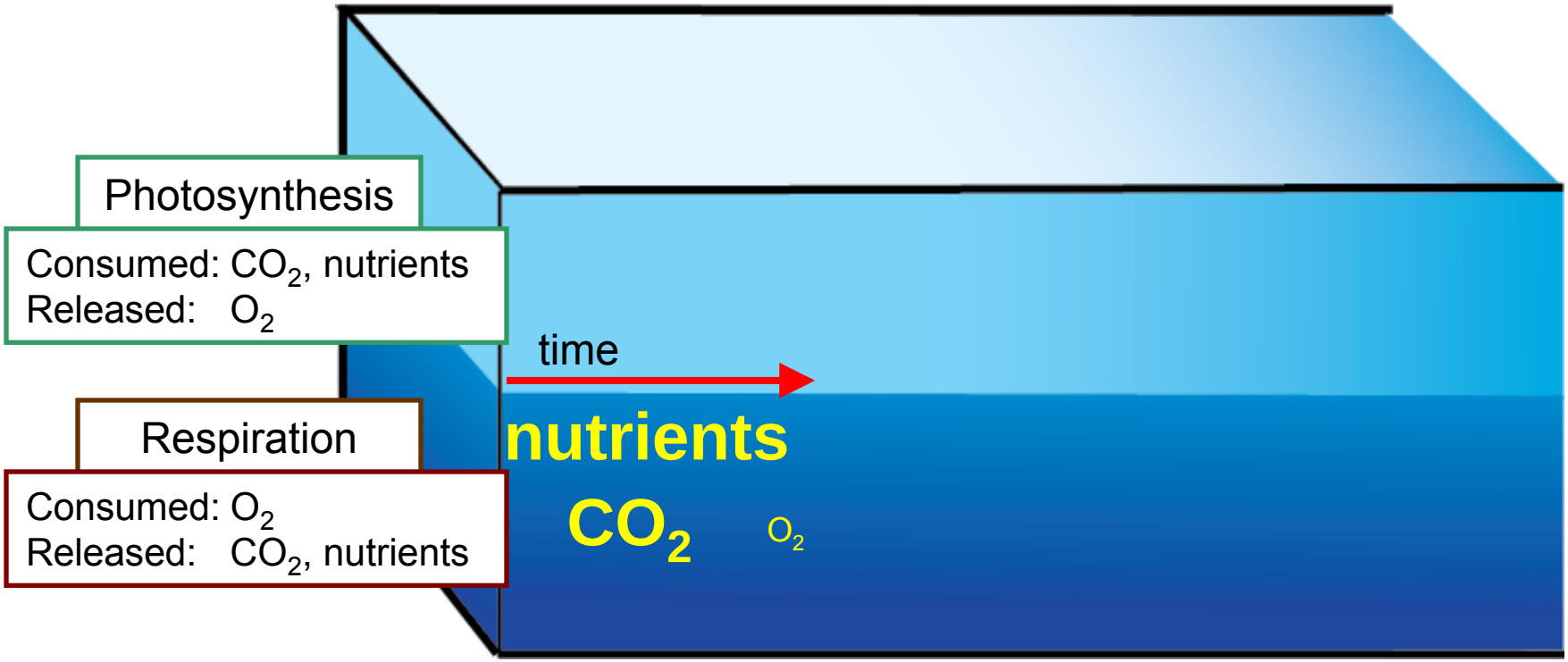

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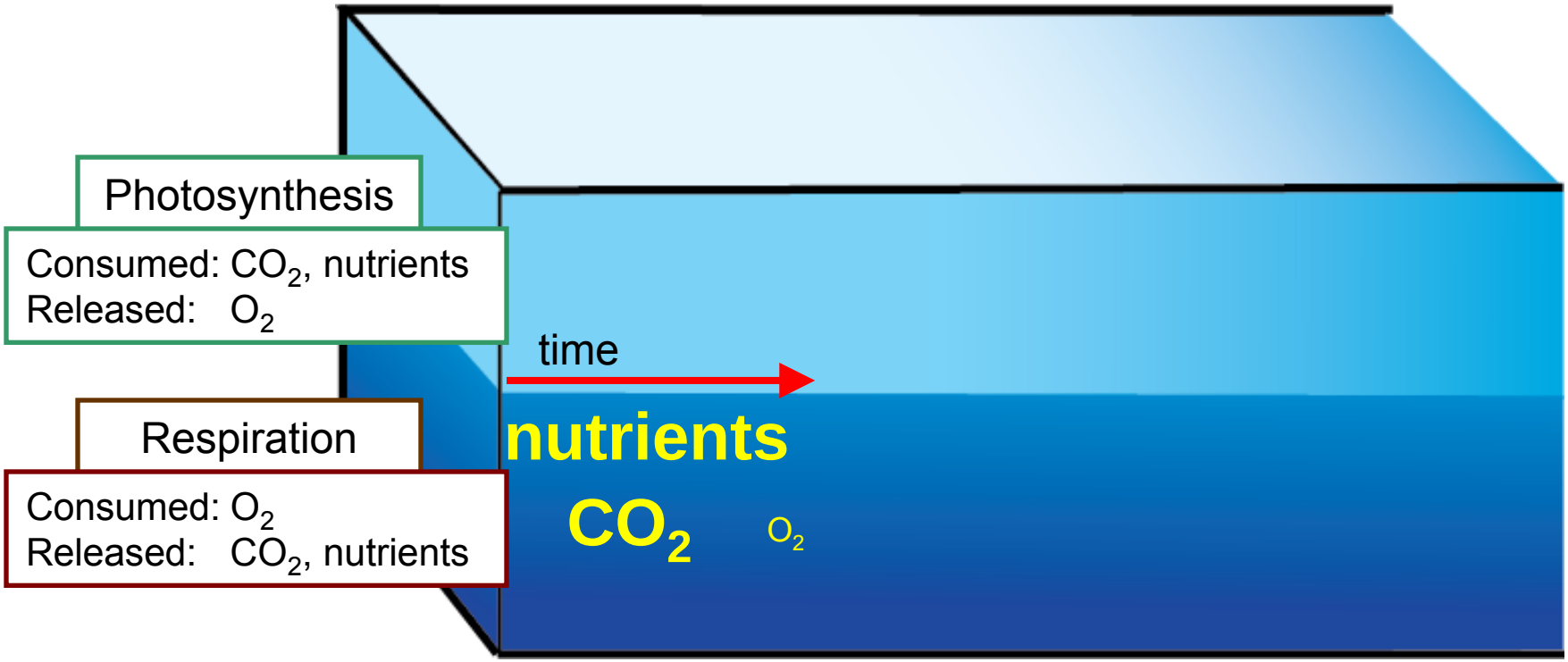

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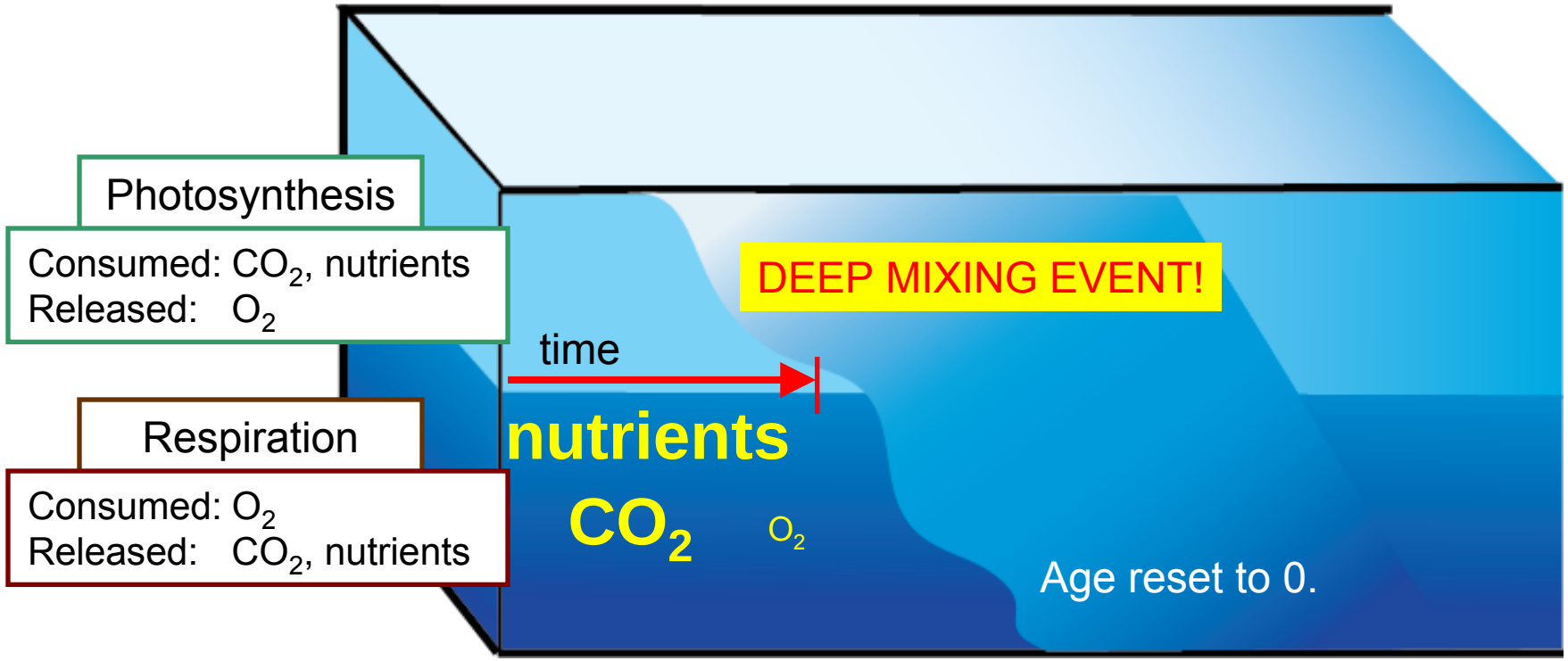

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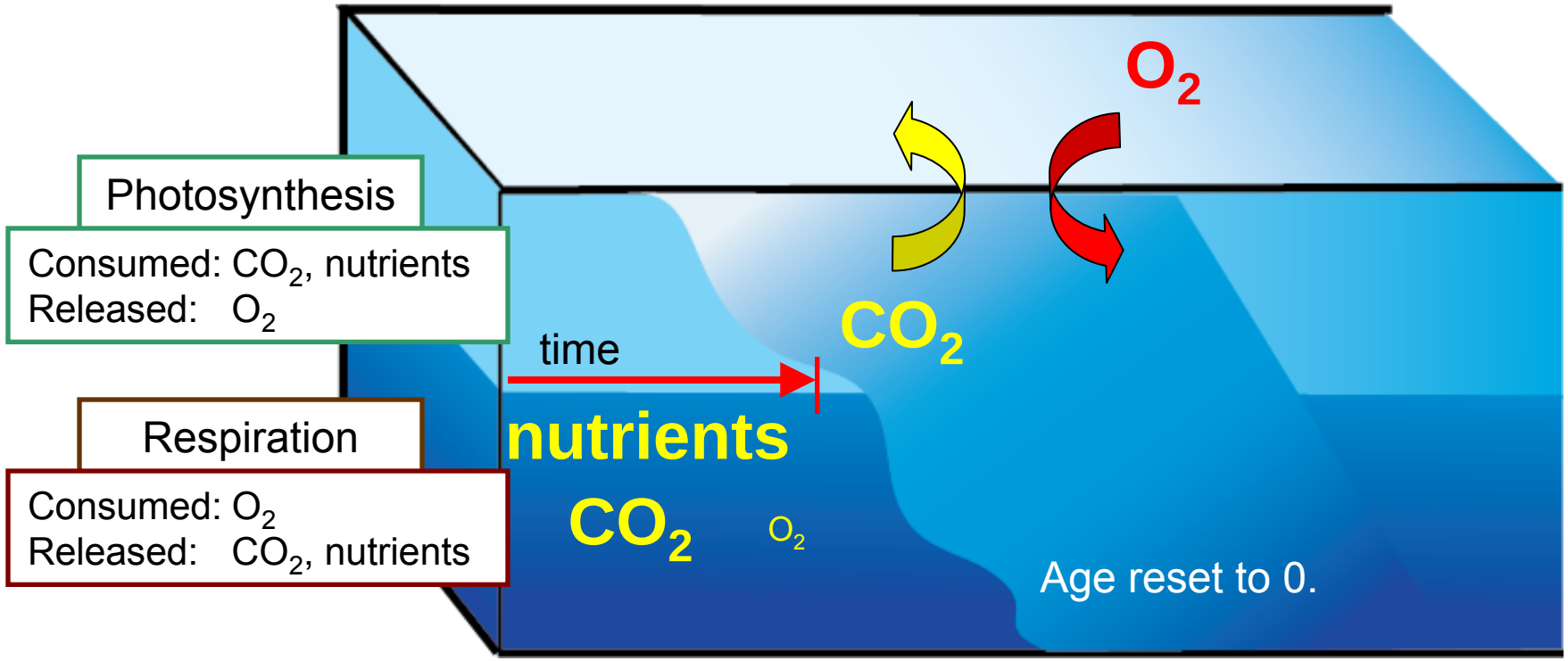

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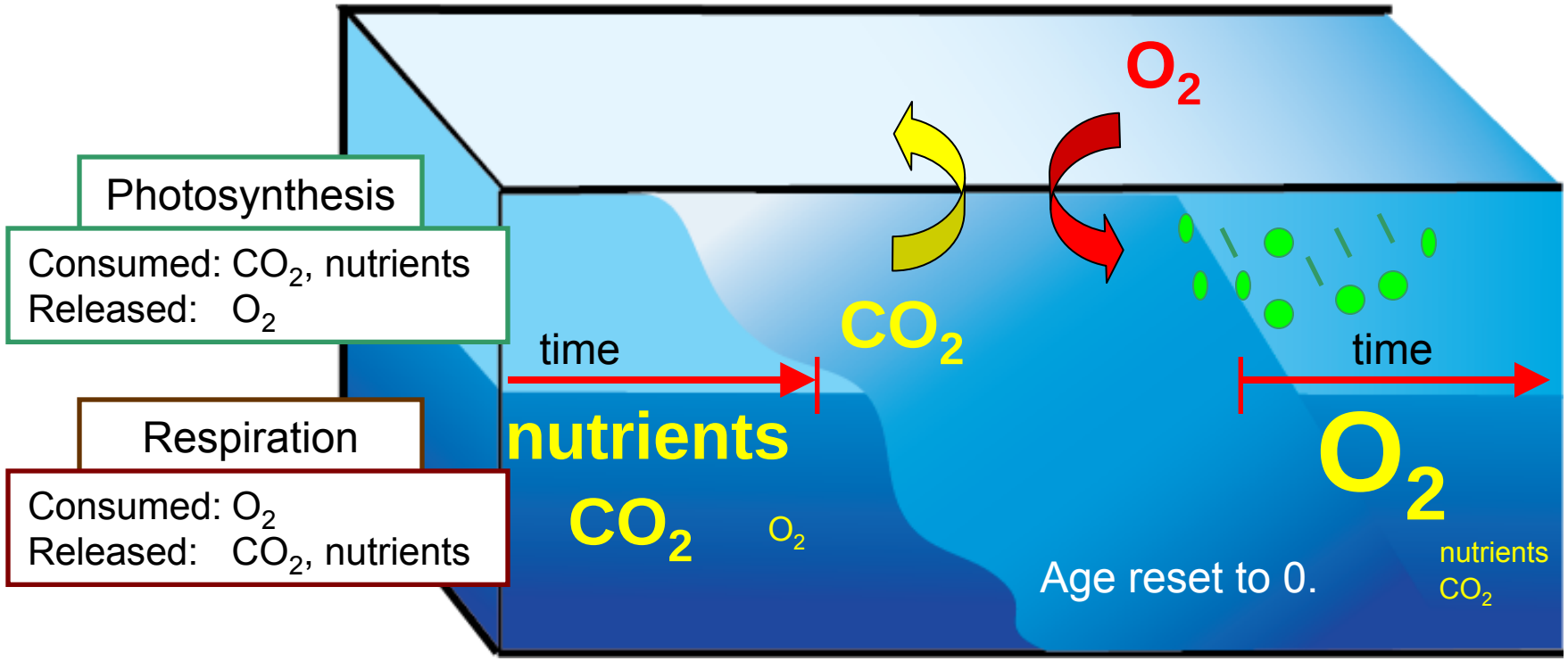
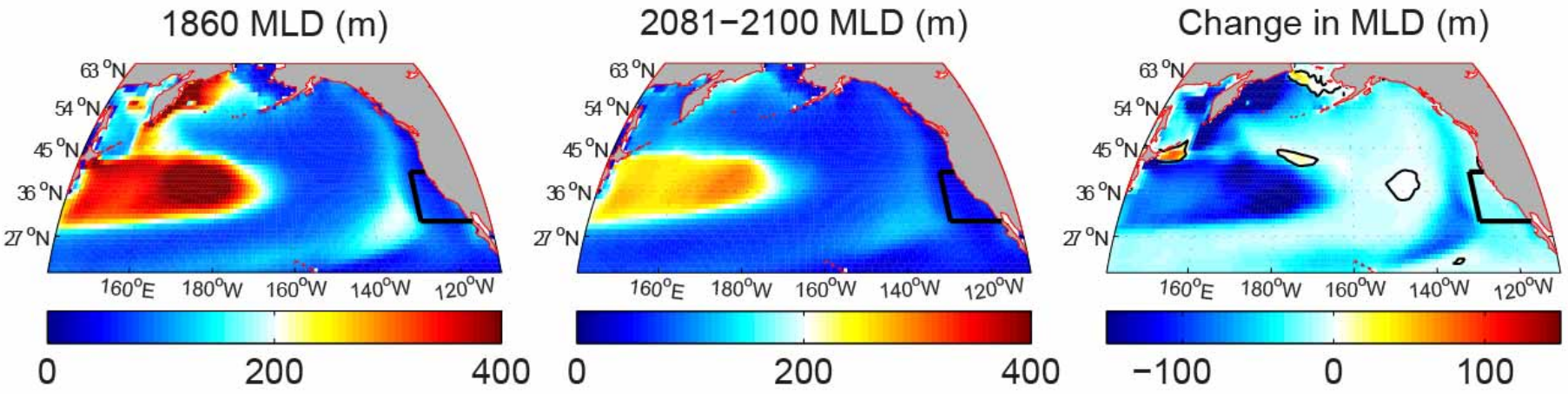


Stratification reduces mixing across the basin

Increased stratification and changes in wind reduce wintertime mixing in the central North Pacific.

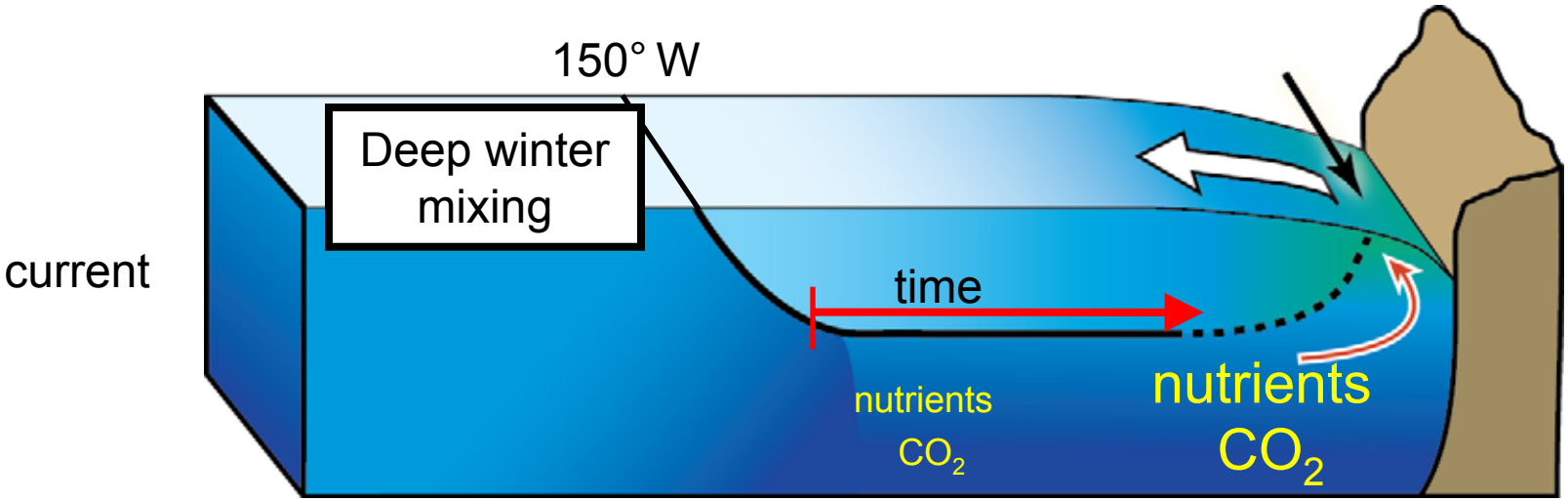
This decreased ventilation has implications for the deep waters of the Northeast Pacific.



Ventilation of deep waters is reduced

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.

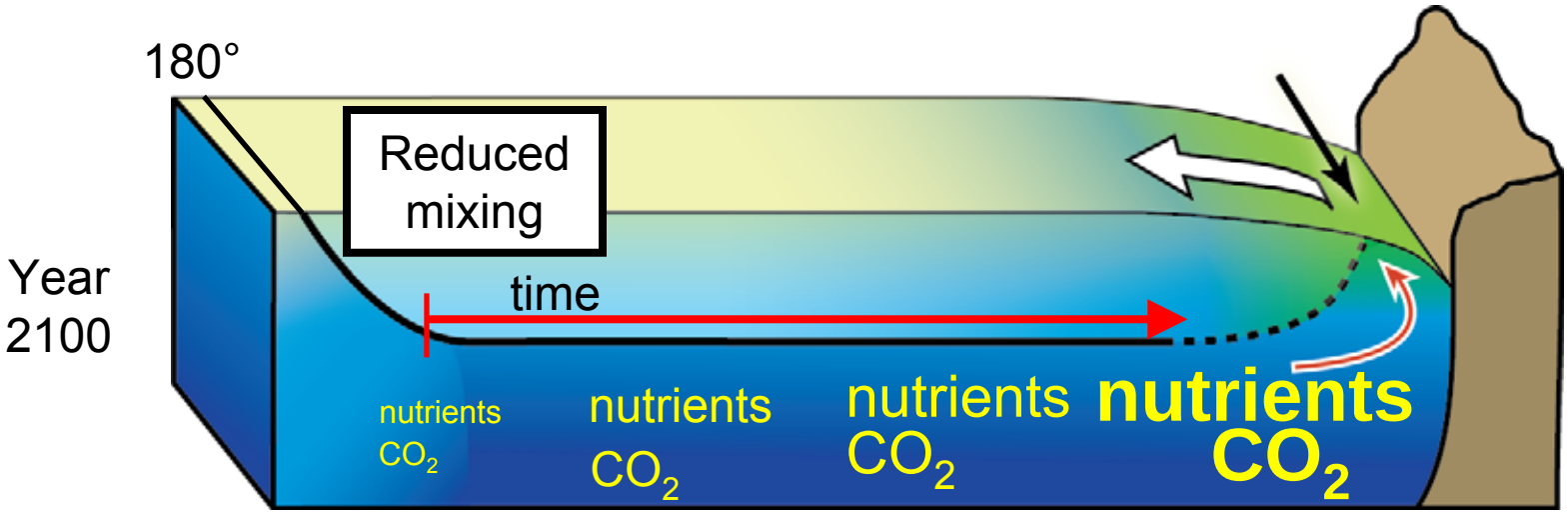


Ventilation of deep waters is reduced

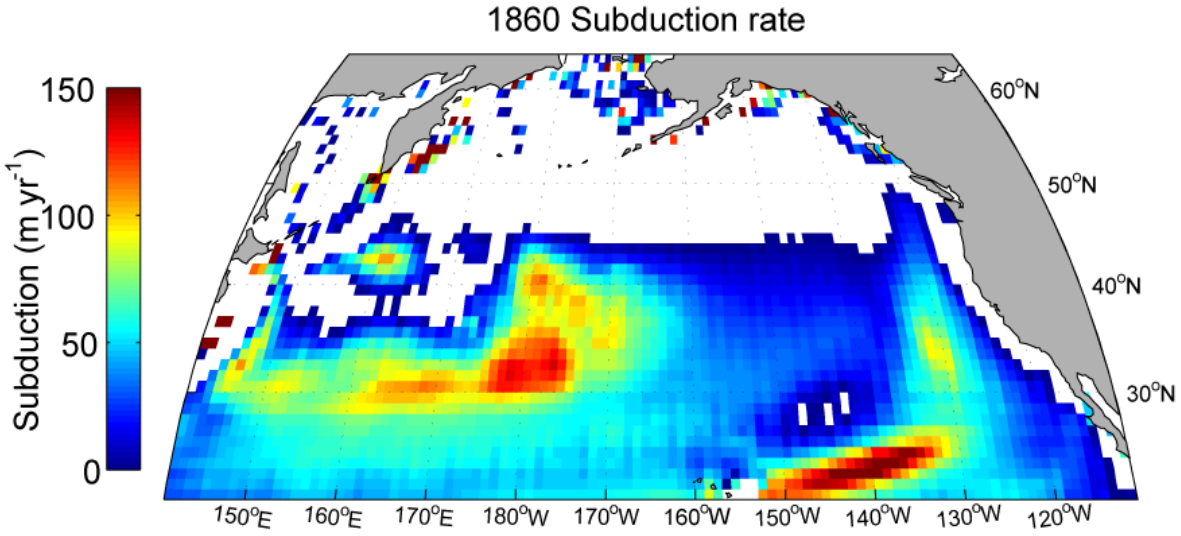
Warmer sea-surface temperatures associated with global warming increase stratification across the entire Pacific.

Local mixing in of waters in the Northeast Pacific decreases, but reduced mixing over the central and western North Pacific is more influential

The location of deep-water formation shifts westward.



Genesis of deep waters of the Northeast Pacific



Subduction is the process by which surface waters are forced into the ocean interior.

Subduction can be estimated from the temporal and horizontal change in mixed-layer depth and the velocity field.

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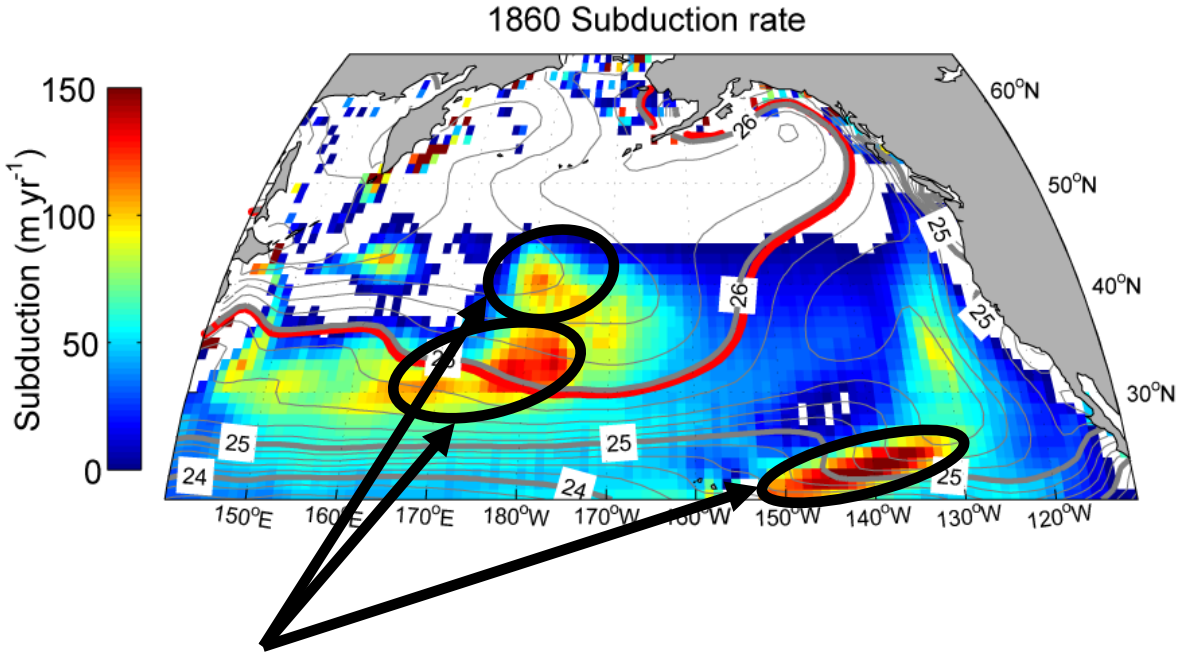

Central, Subtropical, and Eastern Subtropical Mode Waters

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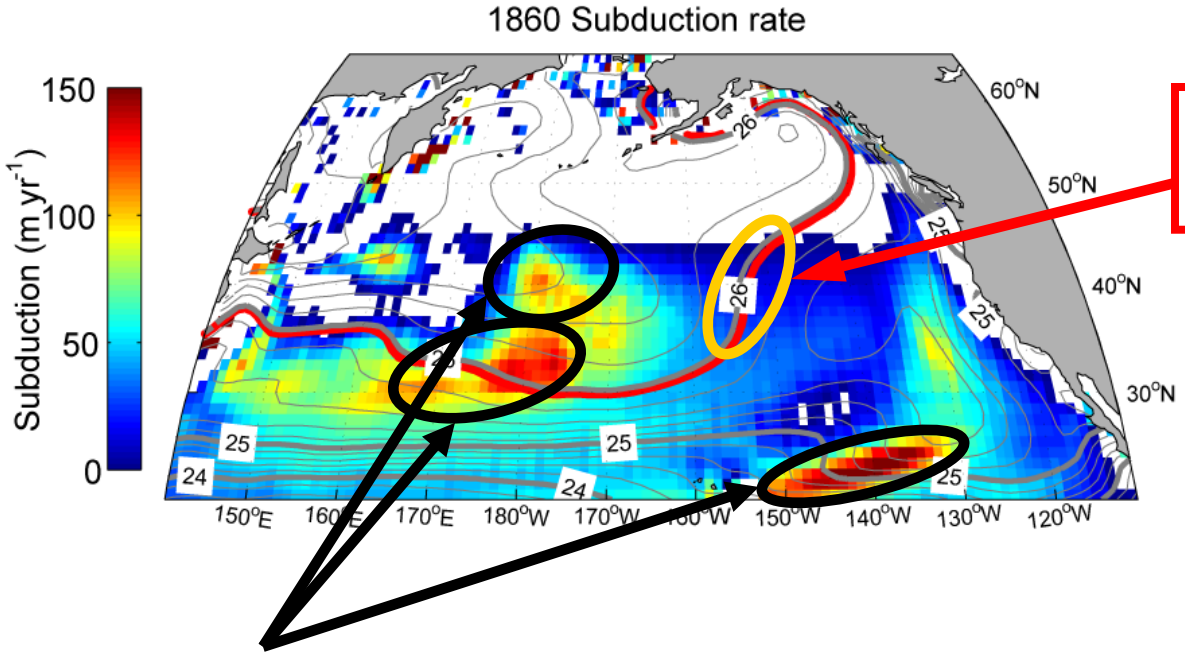
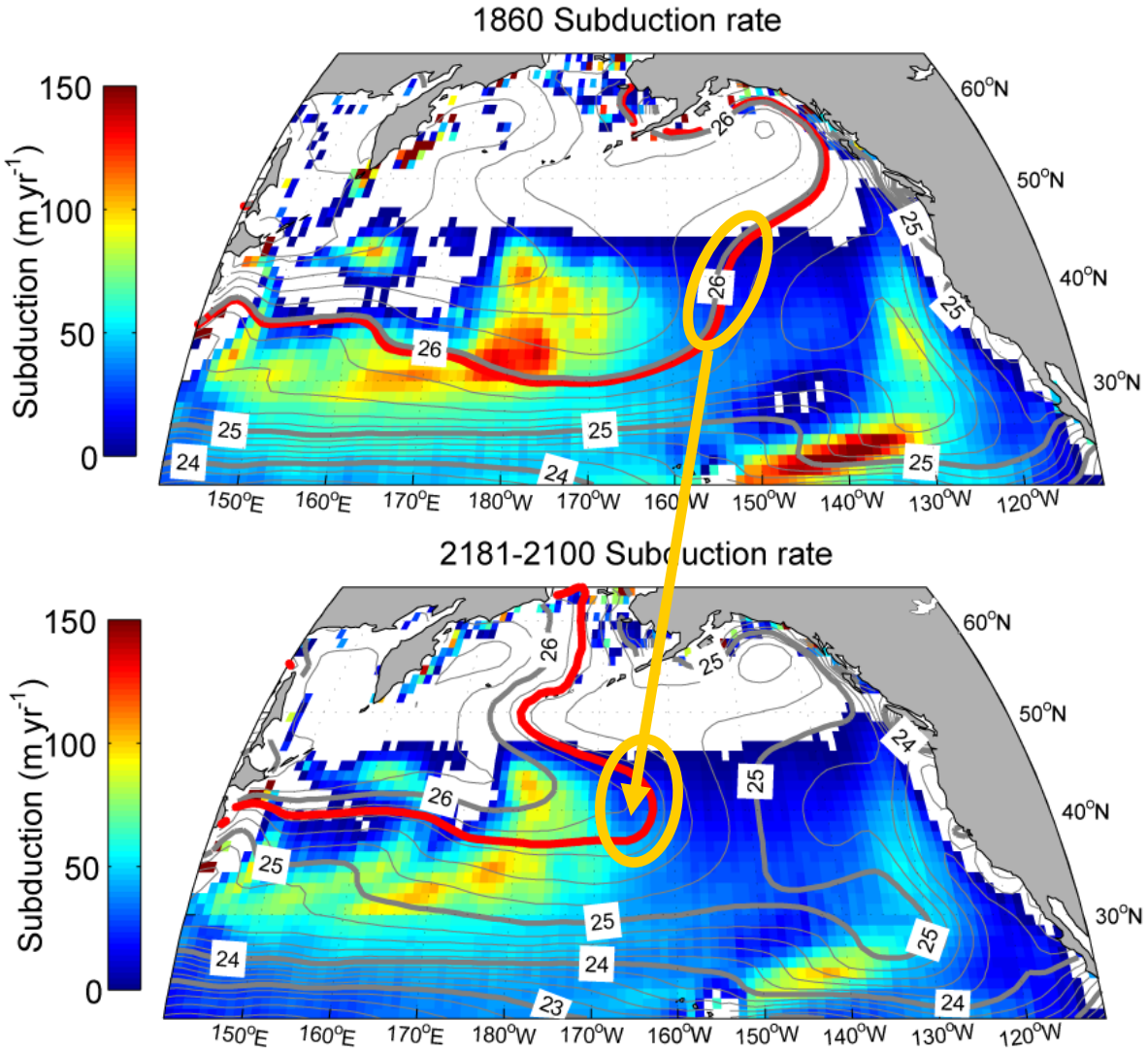


"Waters destined for the California Current"

200-m California Current
$\sigma_\theta \approx 26.0\ (\pm 0.04)$

Central, Subtropical, and
Eastern Subtropical
Mode Waters

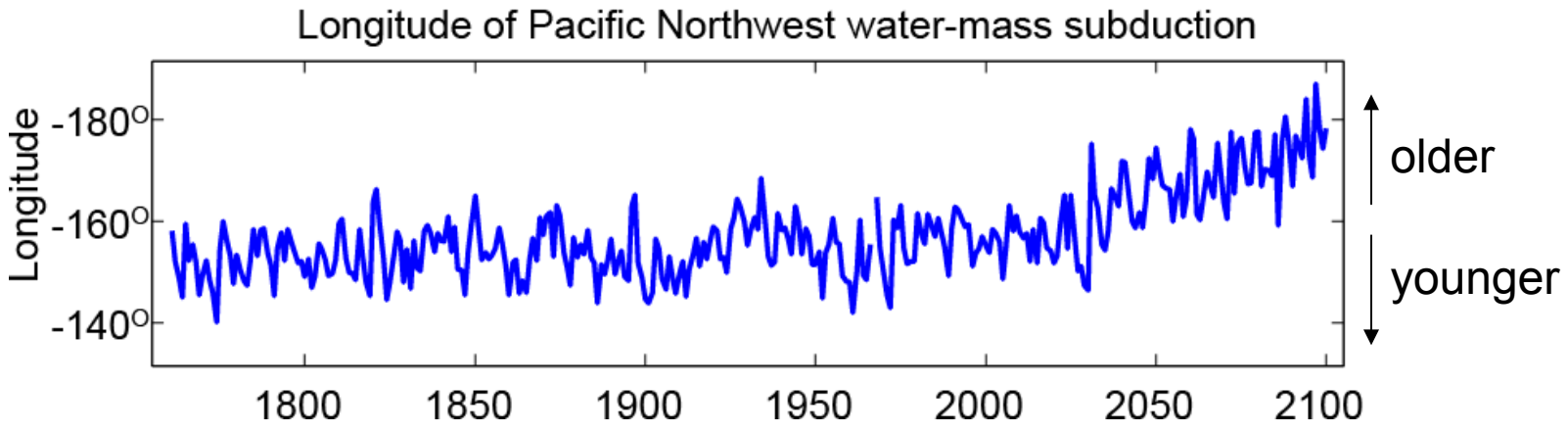
Deep mixing contracts; subduction location shifts west



200-m California Current
$\sigma_\theta \approx 26.0\ (\pm 0.04)$

200-m California Current
$\sigma_\theta \approx 25.7\ (\pm 0.04)$

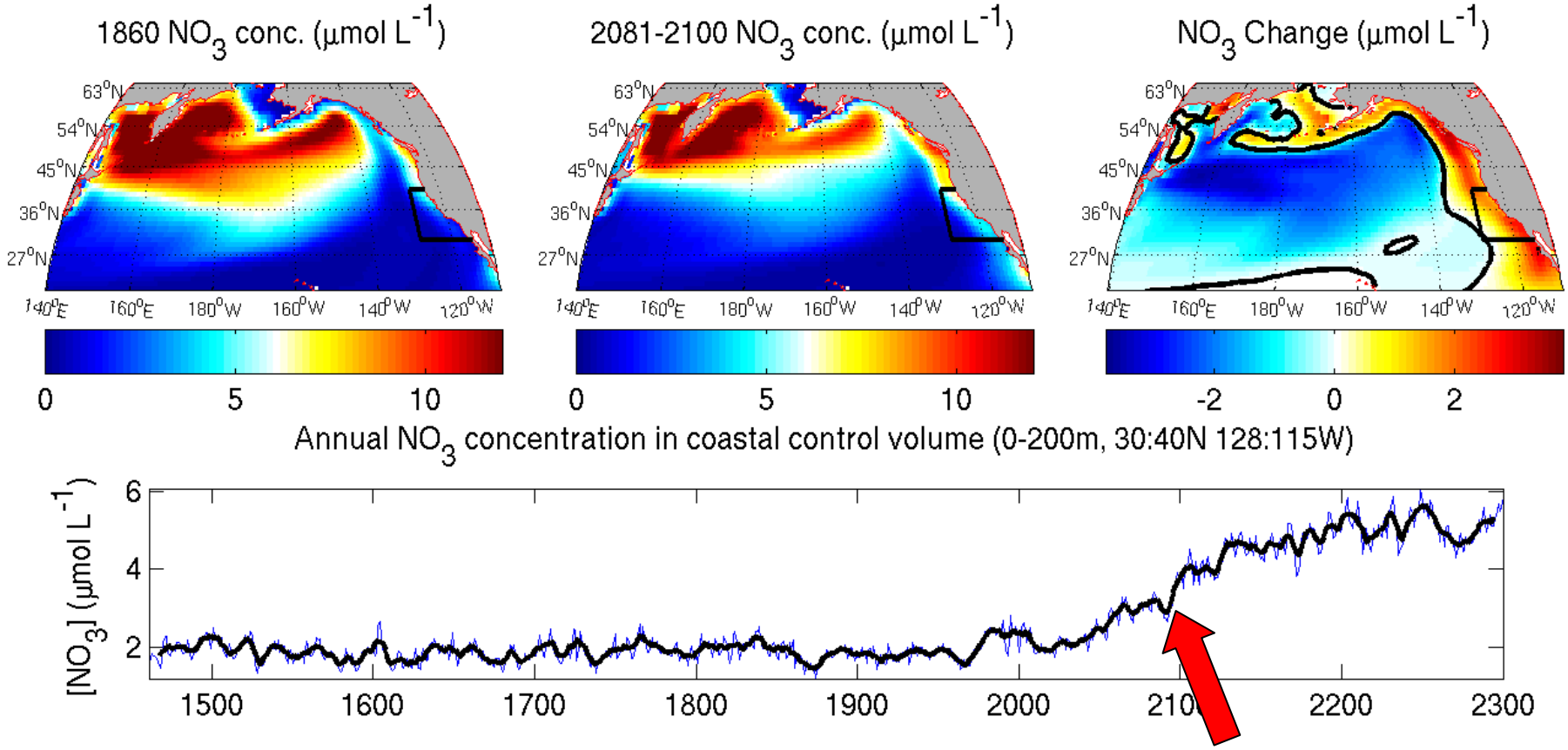
Source waters increase in age and in macronutrients



The convective area in which the deep waters of the Northeast Pacific are formed is projected to *move west*.

Deep waters which enrich the coastal ecosystem are projected to *increase in age* and in *nutrients*.

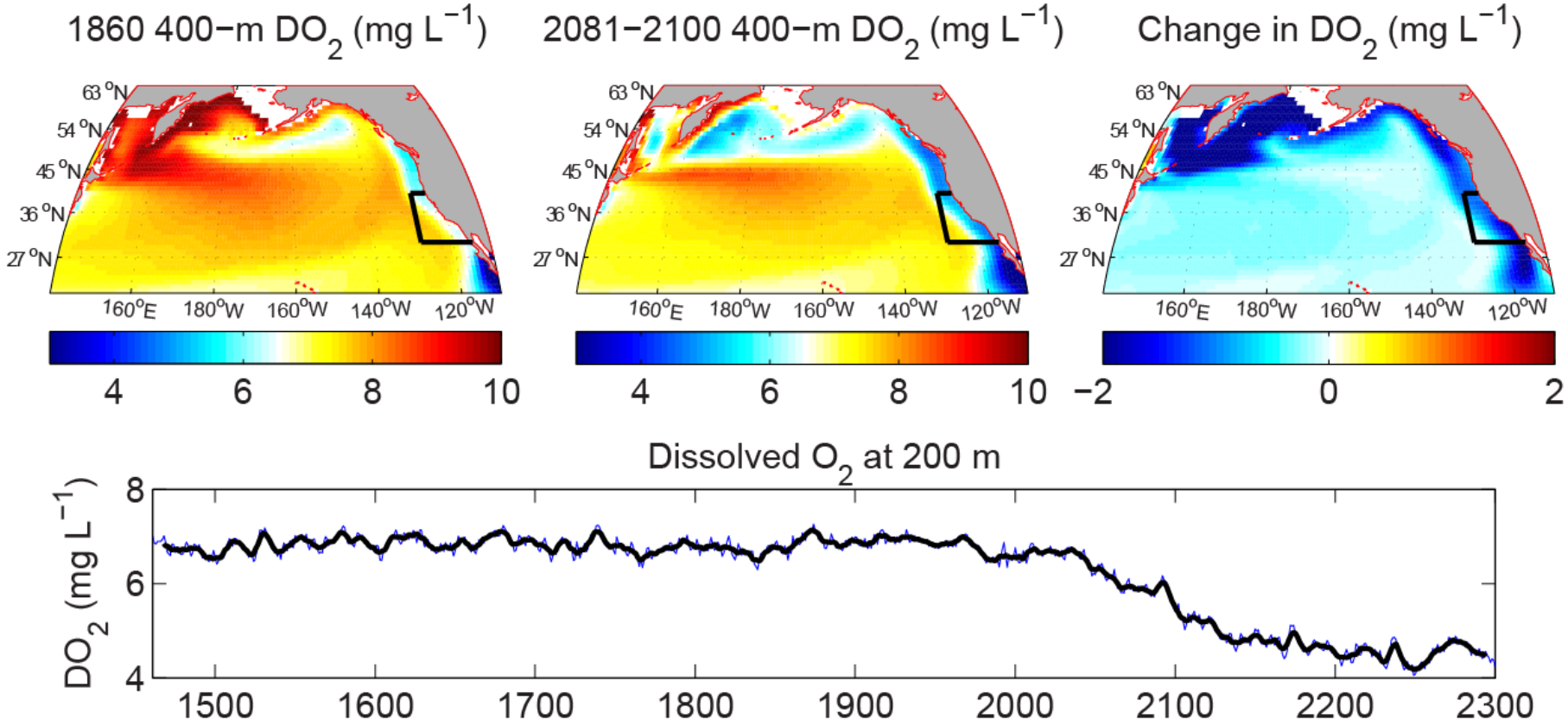
Nutrient content increases with increased stratification



What about the other properties associate with changes in age of the water mass?

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

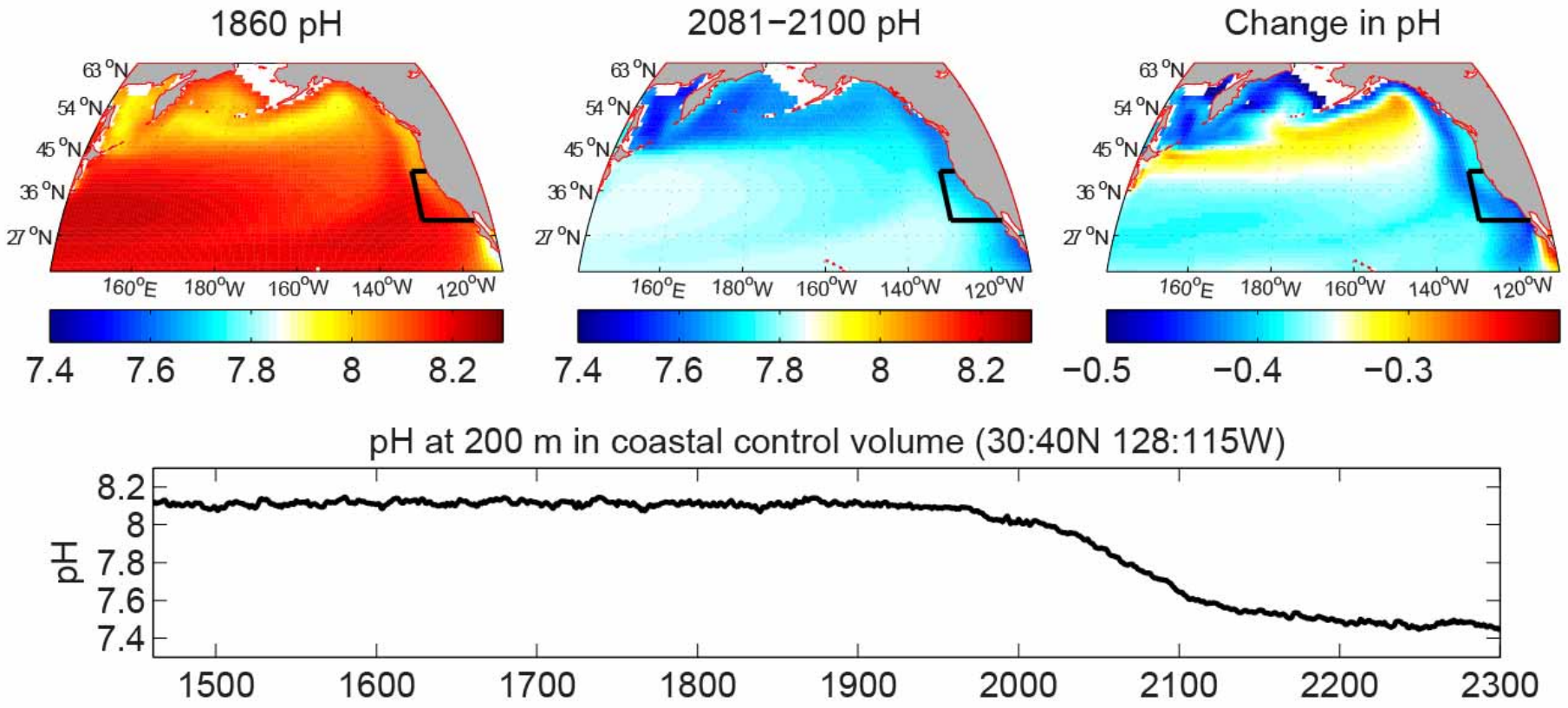
Dissolved O_2 decline is exacerbated near the coast



Increased temperature leads to a decline in dissolved oxygen everywhere.

The decline is amplified where old, oxygen-deplete waters are forced to the surface.

pH decline is exacerbated near the coast



pH declines everywhere with increased atmospheric CO_2.

While pH is expected to decline but 0.25-0.35 elsewhere, the acidification is intensified near the US West Coast.

Final thoughts…

Three important lessons for the subtropical North Pacific:

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Three important lessons for the subtropical North Pacific:

1. Modes of interannual and decadal variability will persist in the future, but **anthropogenically forced trends may be more influential** than the shorter-term oscillations.

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Three important lessons for the subtropical North Pacific:

2. **Long-term relationships can be counterintuitive** (and even opposite those observed at interannual to decadal time scales).

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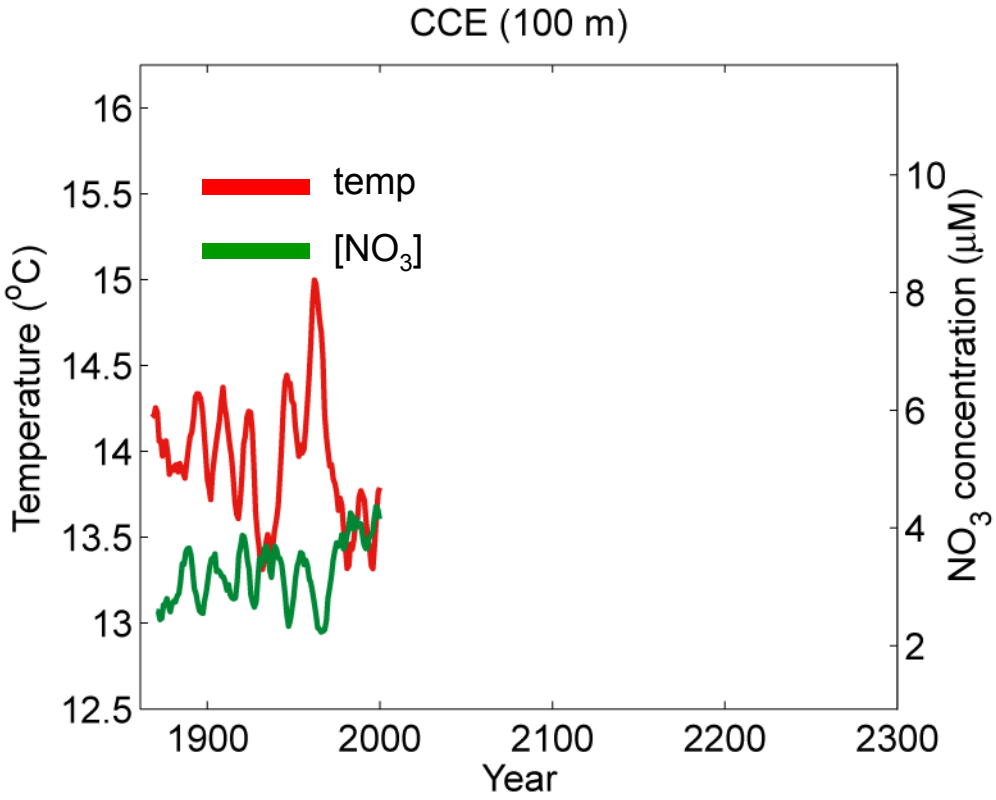

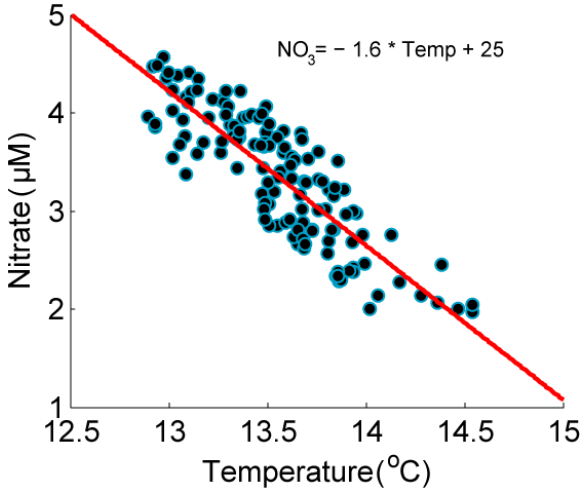

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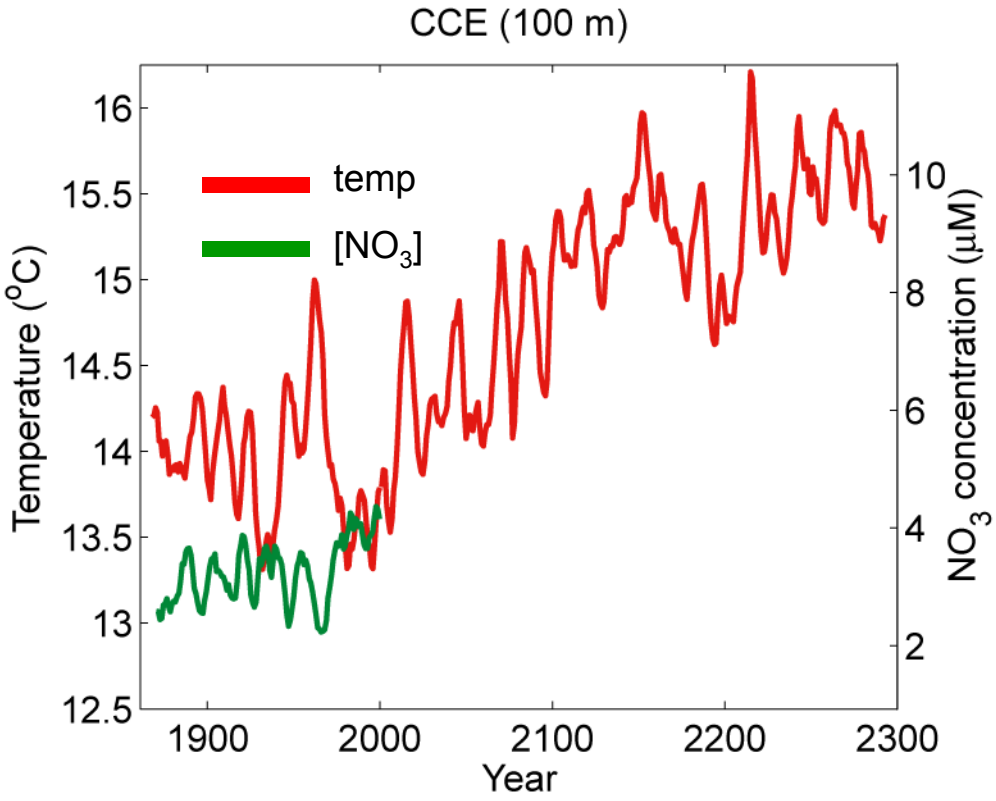

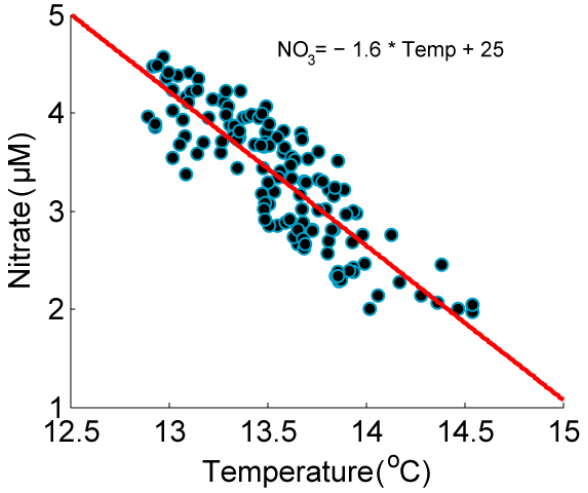

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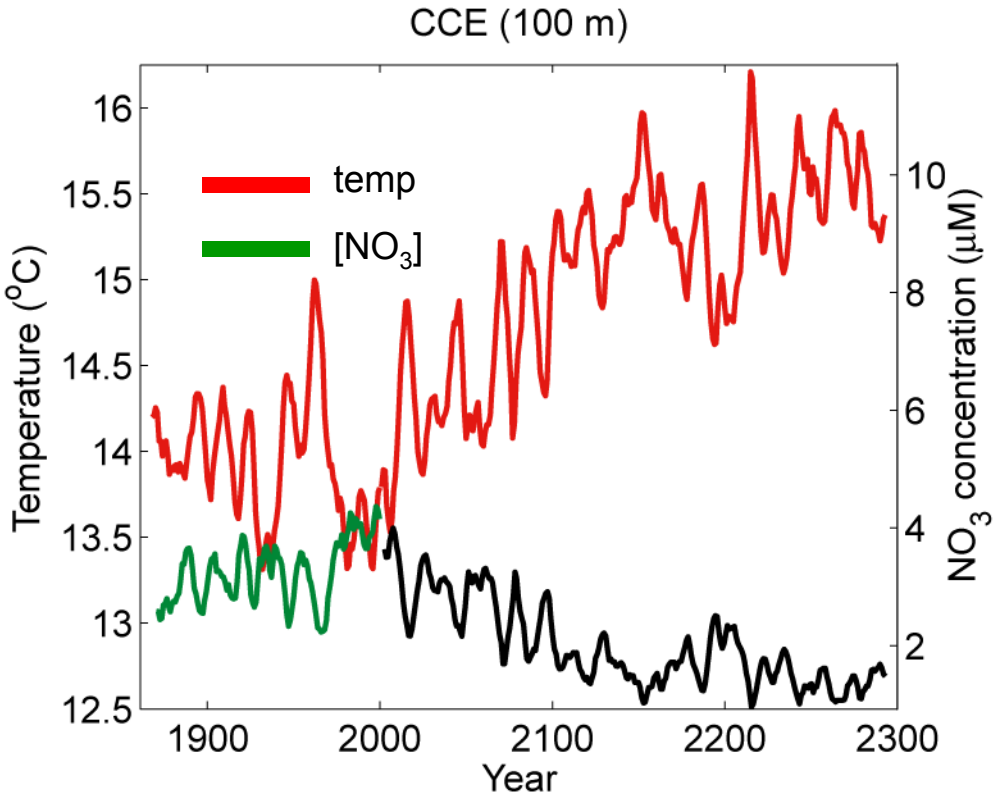

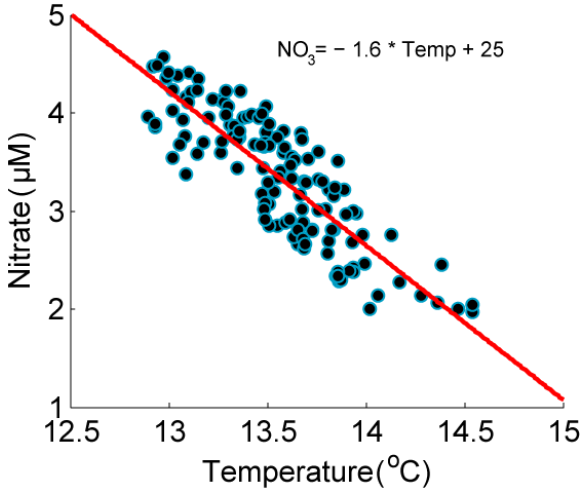

linear expectation for [NO_3] given historical temperature relationship

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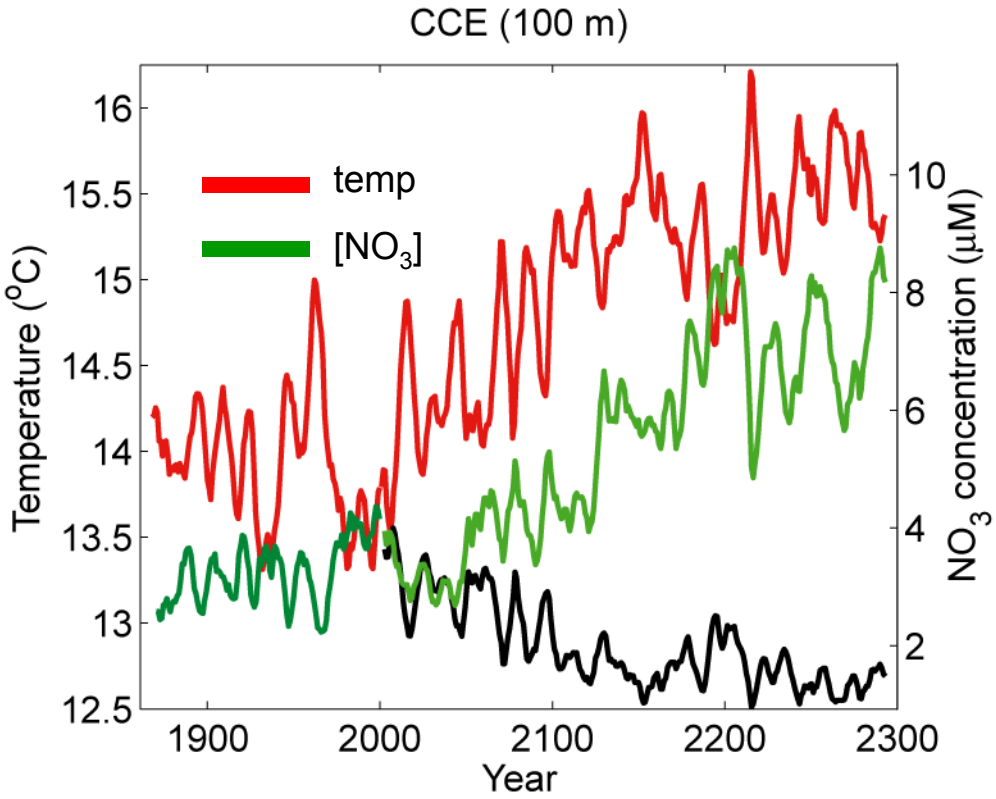

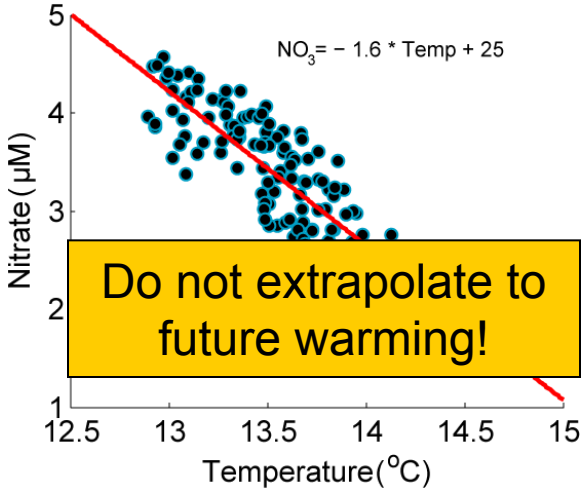

Do not extrapolate to future warming!

ESM 2.1 projection for [NO3]

linear expectation for [NO_3] given historical temperature relationship

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Relationship between stratification (SST) and nutrient supply	Interannual	Decadal to Multidecadal	Centennial
suggested by historical observations	***negative***	***negative***	limited observations
expected with ***anthropogenic warming***			

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Relationship between stratification (SST) and nutrient supply	Interannual	Decadal to Multidecadal	Centennial
suggested by historical observations	***negative***	***negative***	limited observations
expected with ***anthropogenic warming***	***negative***	***negative***	***regionally dependent****

Positive in the eastern boundary of the Northeast Pacific

Negative in the remainder of the North Pacific basin and marginal seas

Final thoughts…

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Three important lessons for the subtropical North Pacific:

3. Water-column changes at the regional boundary become increasingly important at longer time scales; **assuming constant boundary conditions may be inappropriate**, especially in the upwelling ecosystems of eastern boundary currents.

Thanks!

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