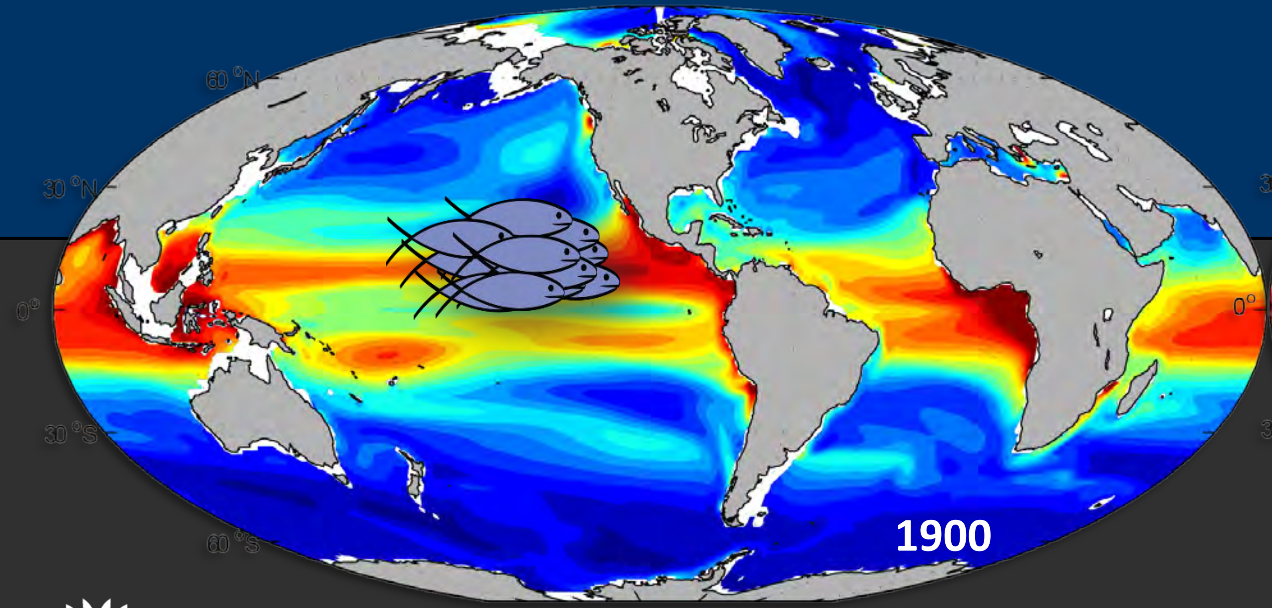
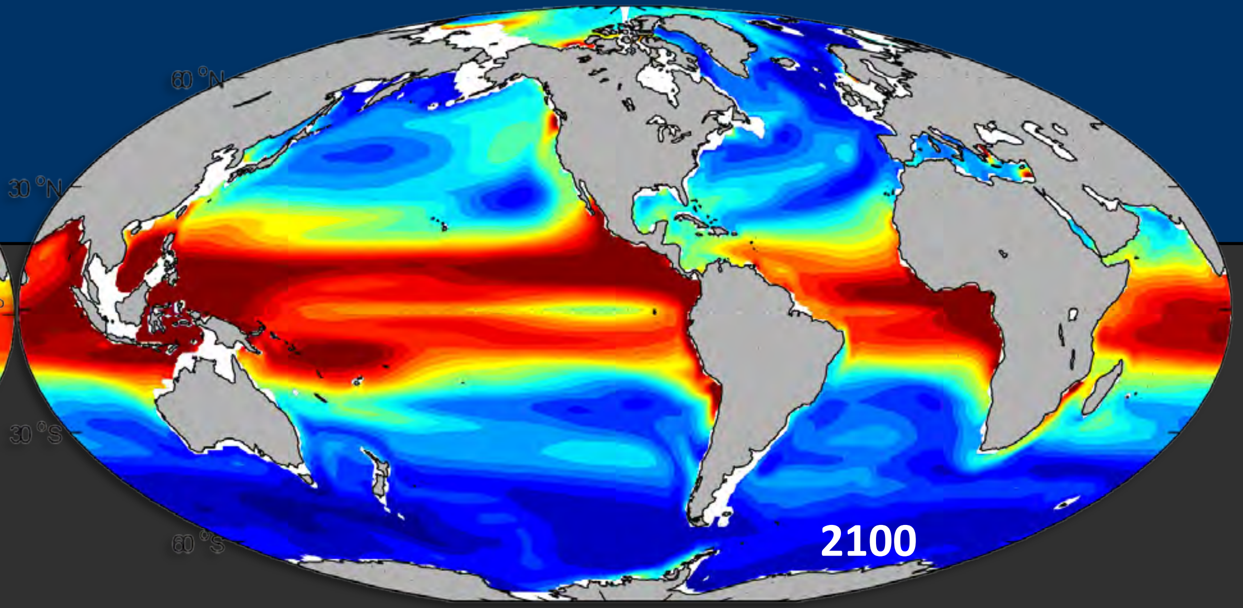
Wind stress, stratification, and source waters: How will eastern boundary current upwelling processes respond to climate change?





UNIVERSITY OF SOUTH CAROLINA

NEREUS
ネレウス
未来の海を考える

PRINCETON UNIVERSITY

NOAA

Ryan R. Rykaczewski
University of South Carolina
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John P. Dunne, William J. Sydeman, Marisol García-Reyes, Bryan A. Black, Steven J. Bograd, Riley X. Brady, and Michael A. Alexander

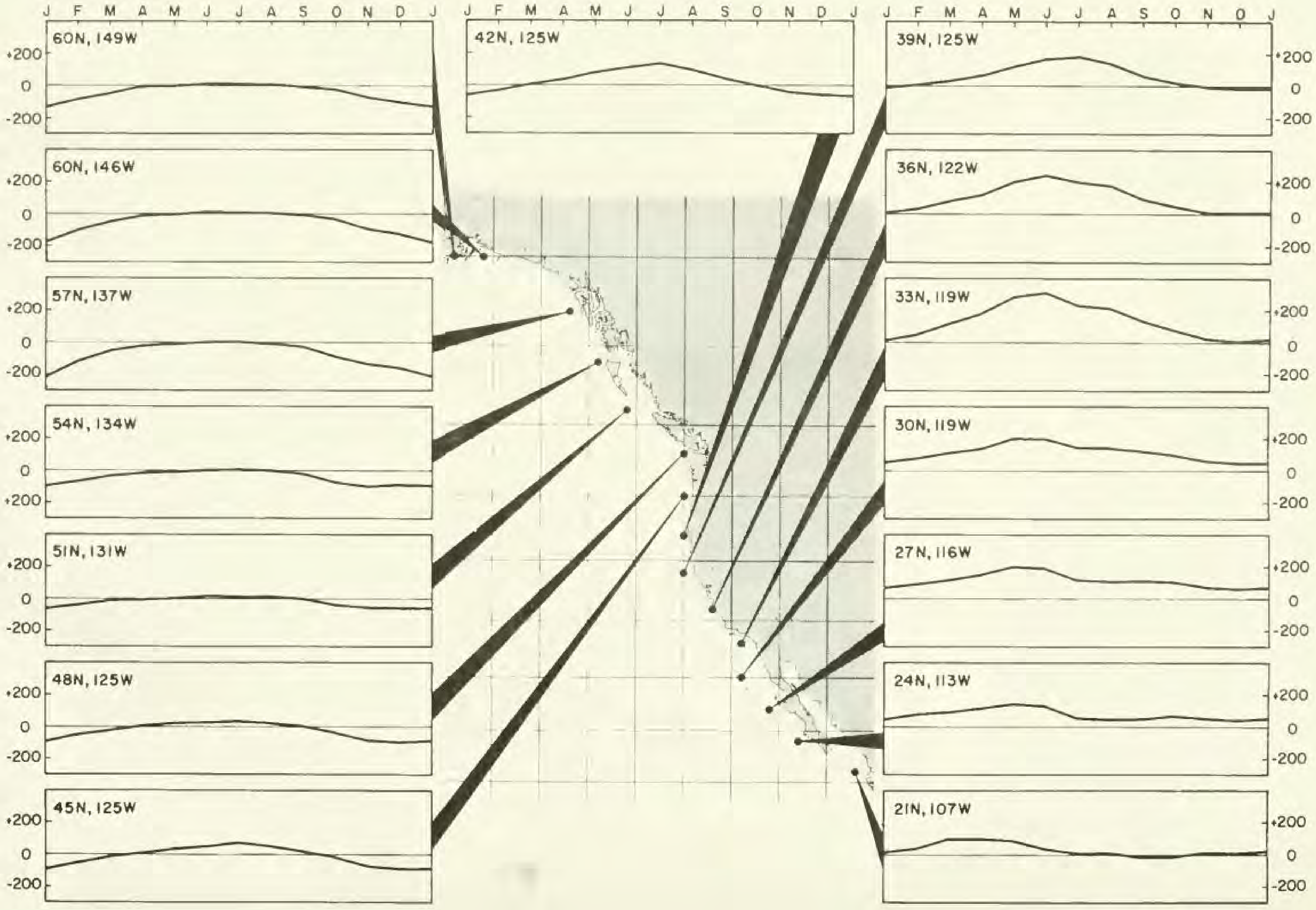
Long-term goal: improve understanding of variability in upwelling ecosystems

Upwelling ecosystems:

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

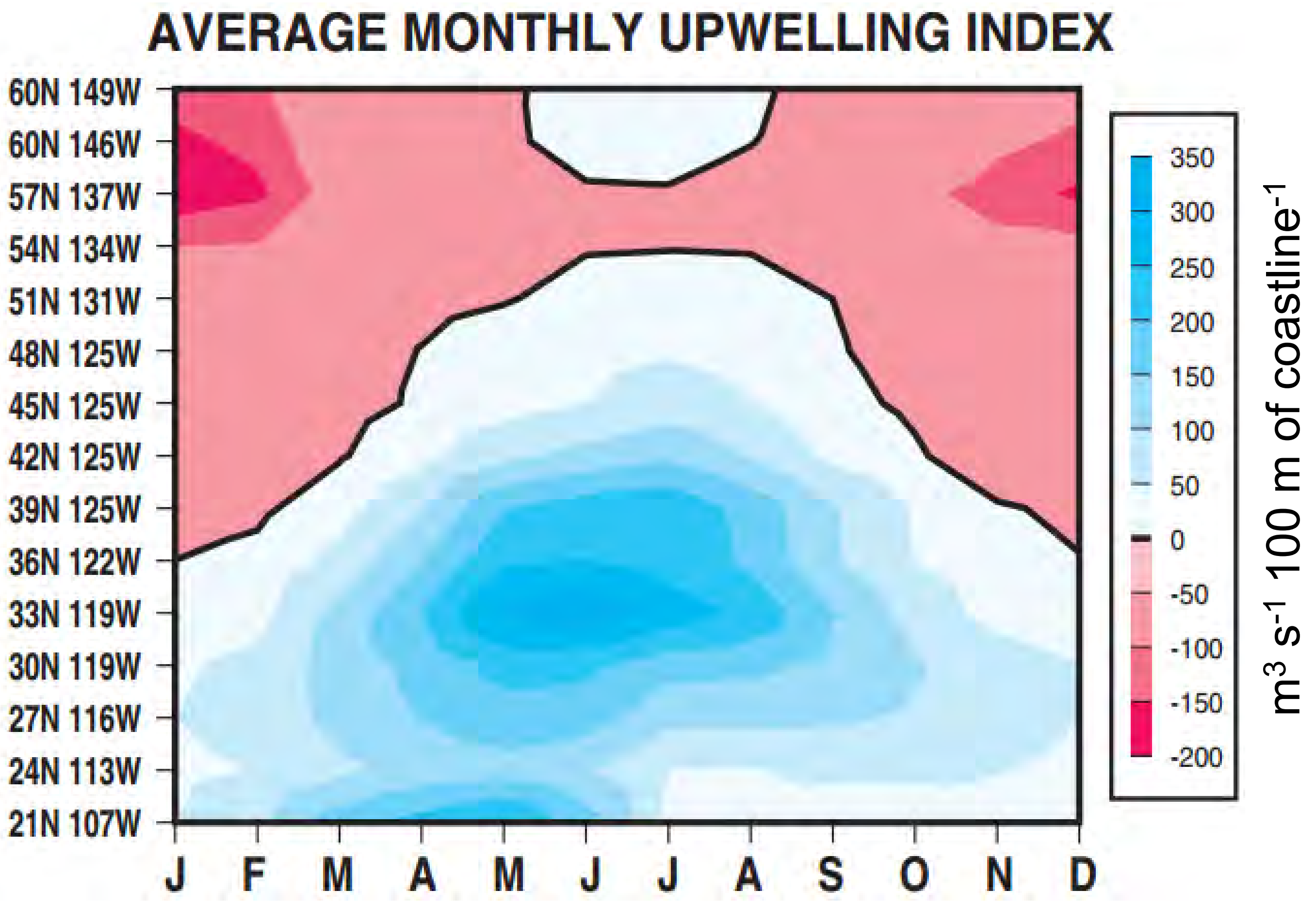
Major genera include *Sardinops* and *Engraulis* inhabiting each of the four major eastern boundary currents.

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


J F M A M J J A S O N D J
60N, 149W
60N, 146W
57N, 137W
54N, 134W
51N, 131W
48N, 125W
45N, 125W
42N, 125W
39N, 125W
36N, 122W
33N, 119W
30N, 119W
27N, 116W
24N, 113W
21N, 107W
+200
0
-200

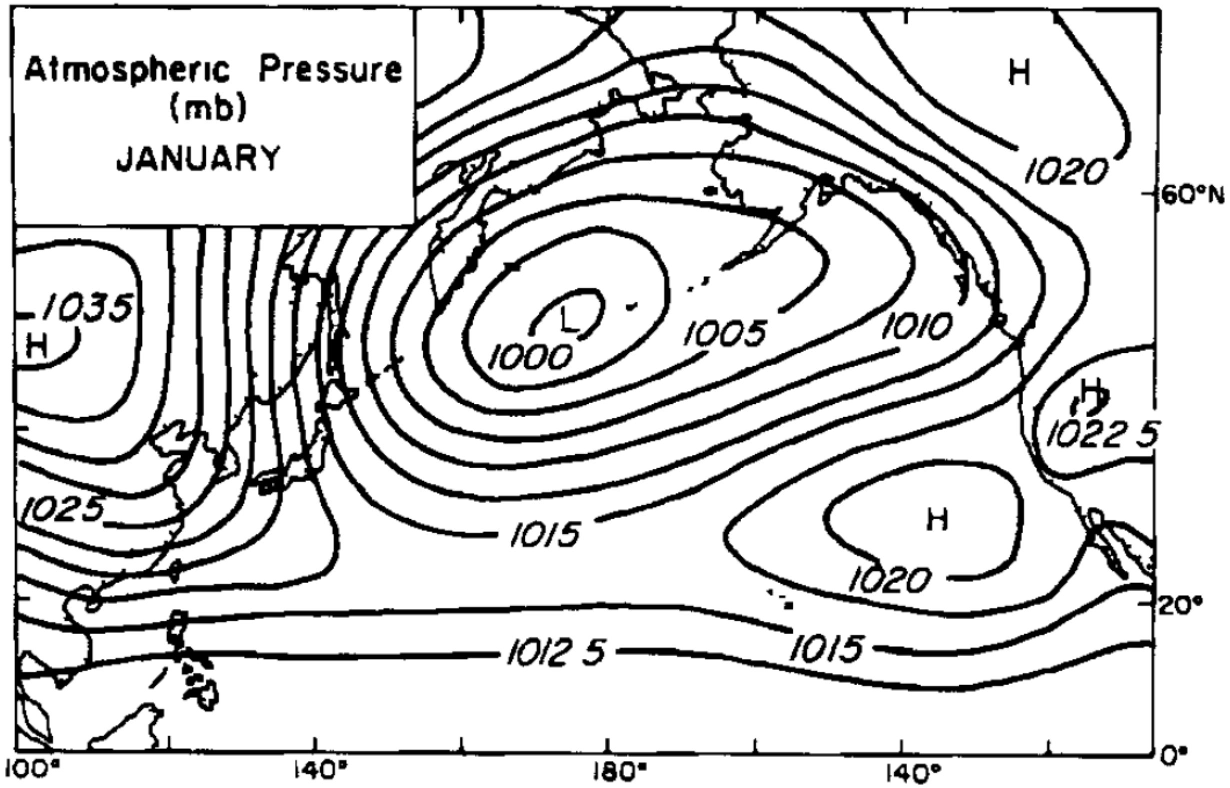
Bakun (1973)

Upwelling winds show clear seasonal and latitudinal patterns



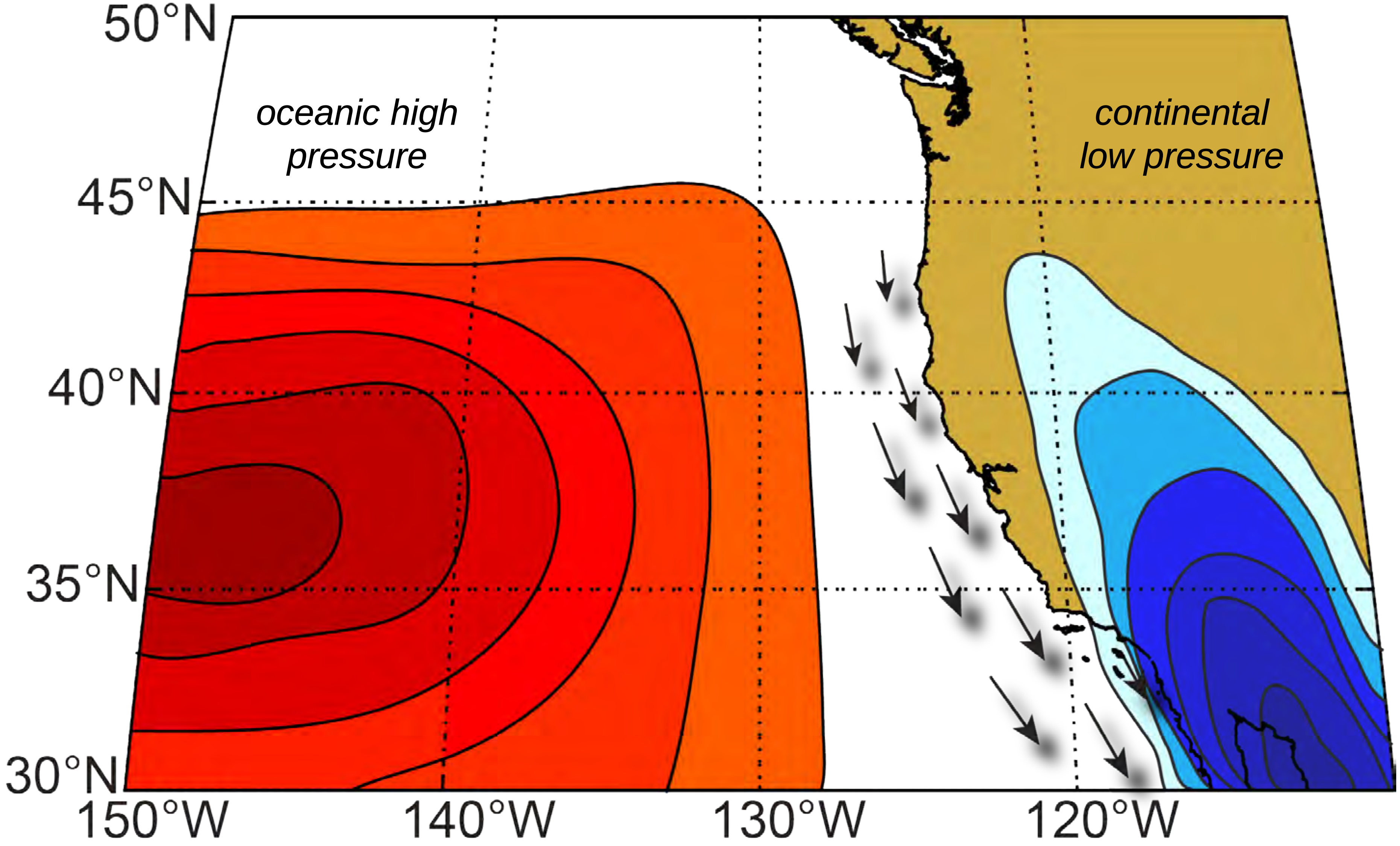
Schwing *et al.* (1996)

Alongshore, equatorward winds driven by large-scale pressure fields

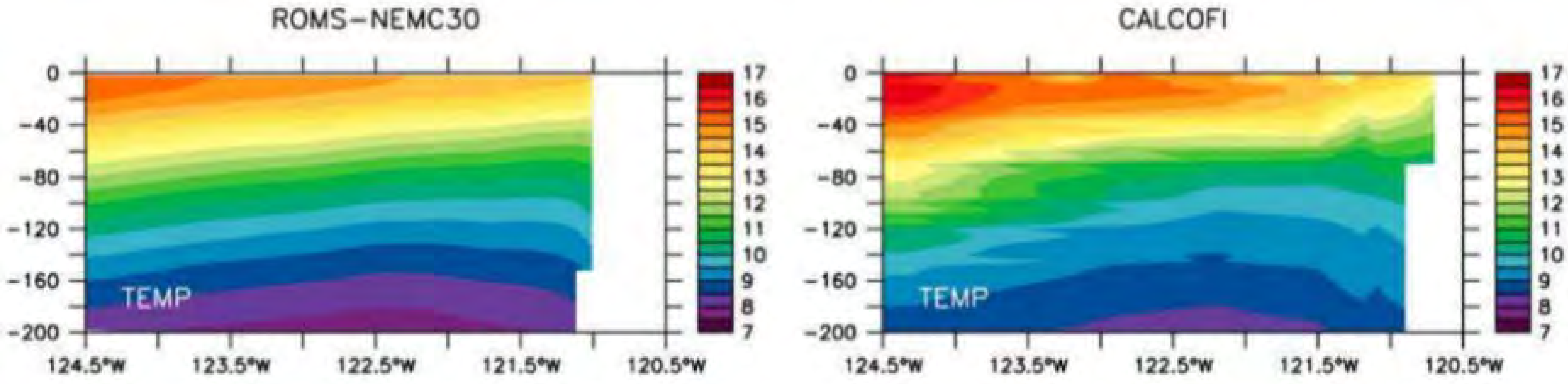


Huyer (1983)

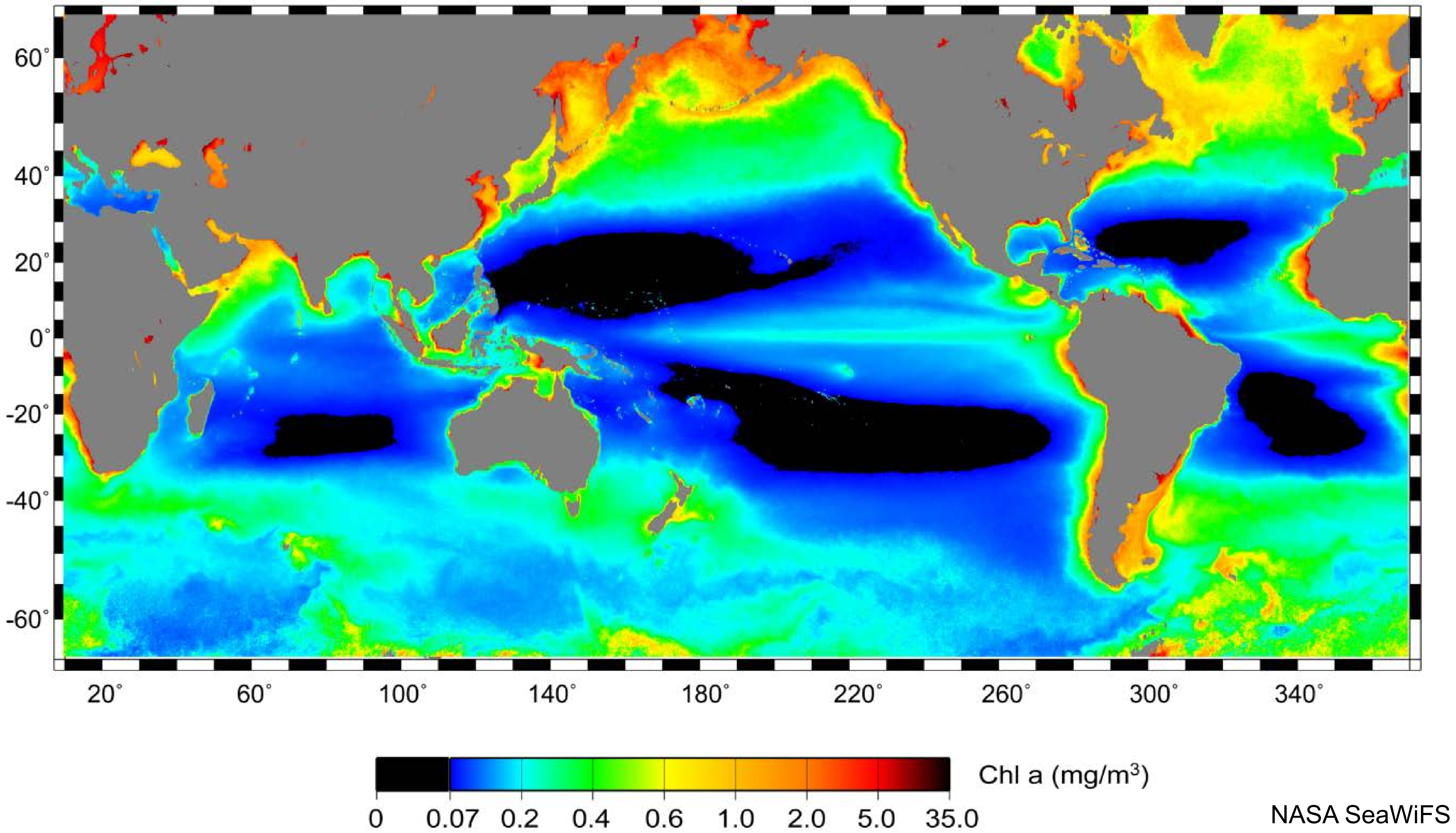
Alongshore, equatorward winds driven by large-scale pressure fields



Isotherms outcrop and nutrient-rich waters are brought to the surface

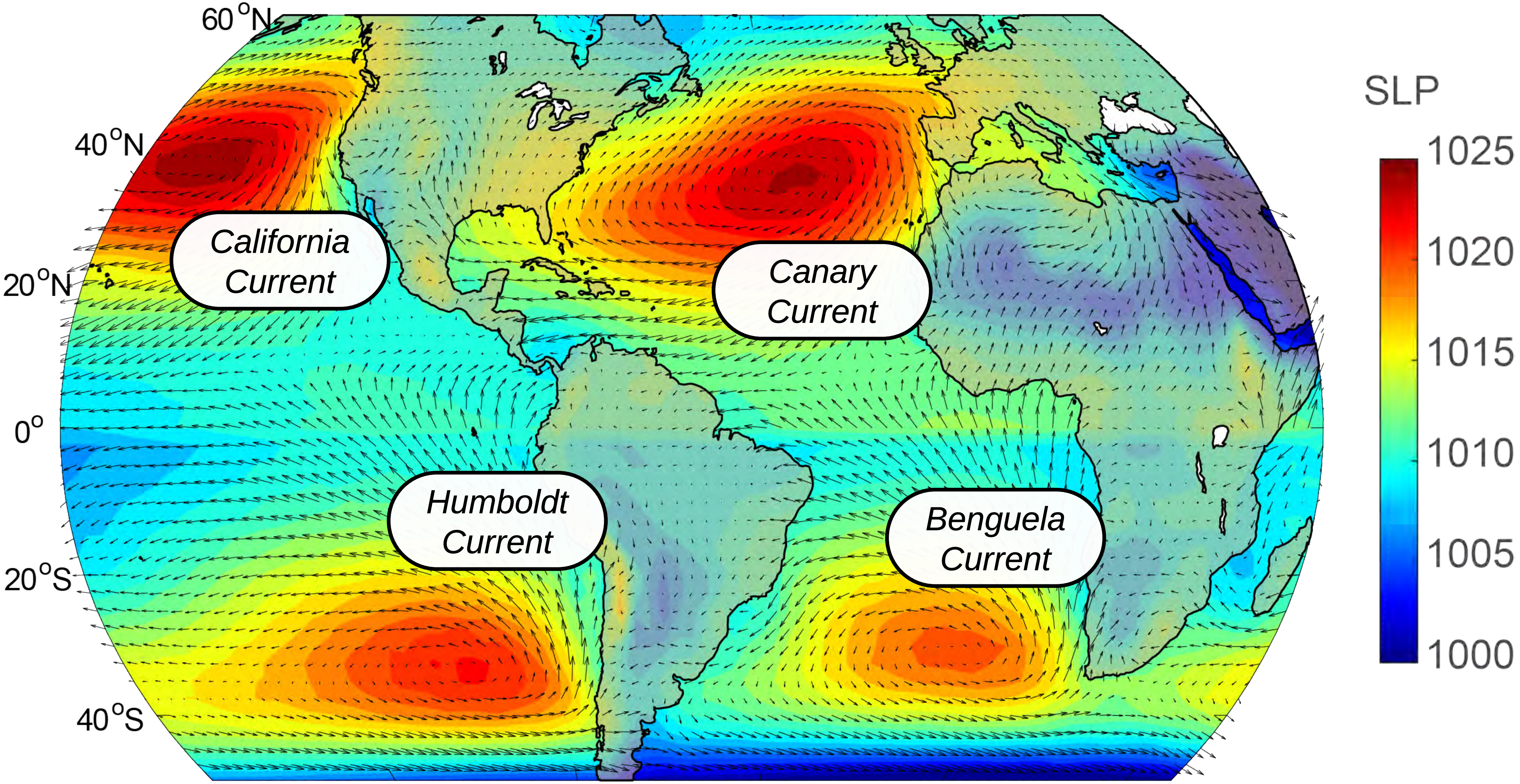


Fiechter *et al.* (2014)



60°
40°
20°
0°
-20°
-40°
-60°
20°
60°
100°
140°
180°
220°
260°
300°
340°
0
0.07
0.2
0.4
0.6
1.0
2.0
5.0
35.0
Chl a (mg/m3)
NASA SeaWiFS

Subtropical eastern boundary current upwelling systems



Wind stress, stratification, and source waters

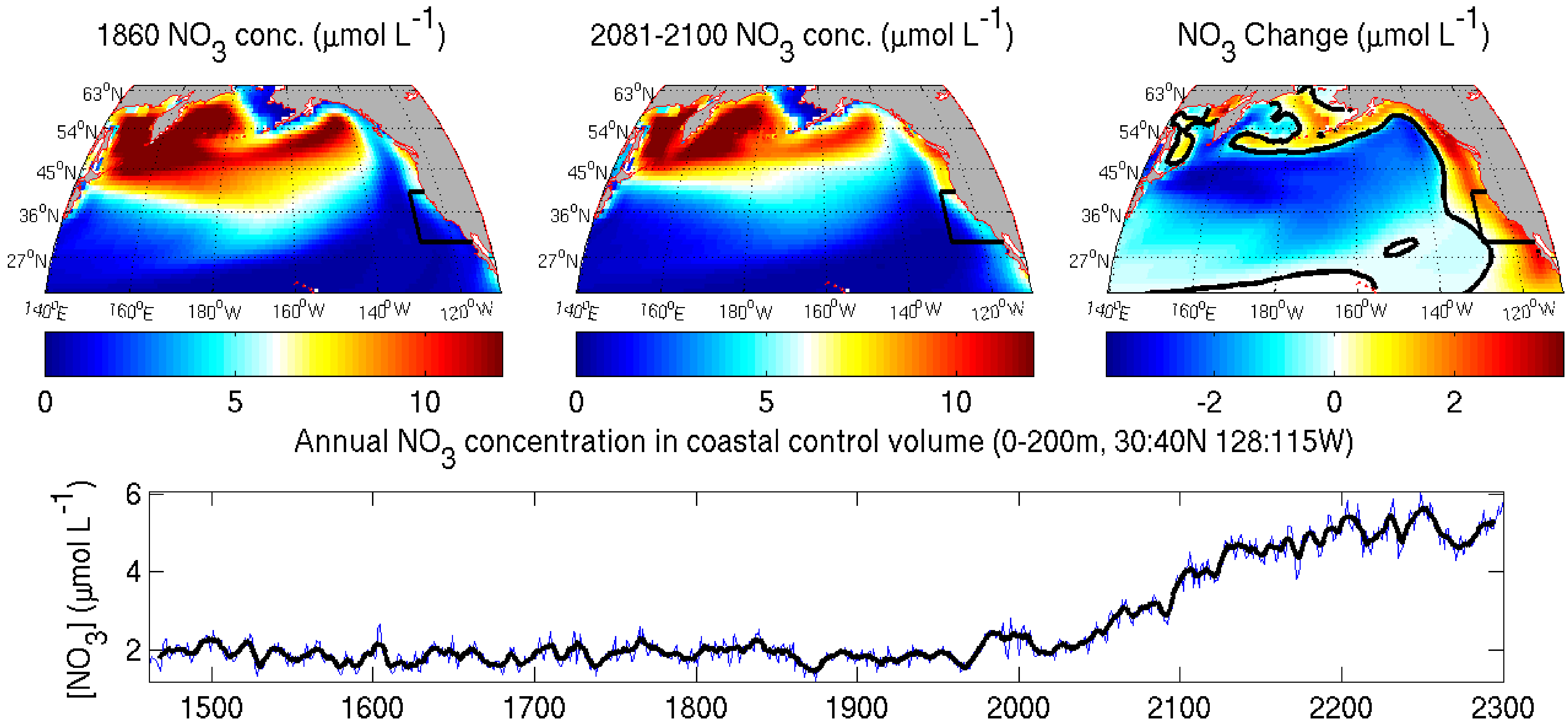
Changes in what physical processes can conceivably alter the supply of macronutrients in response to anthropogenic global warming?

1) The magnitude of upwelling favorable winds along the coast. (Bakun, 1990)

2) Stratification of the water column that might alter the depth from which upwelling waters are drawn. (Huyer, 1976; Roemmich and McGowan, 1995; Palacios *et al.*, 2004; Lentz and Chapman, 2004)

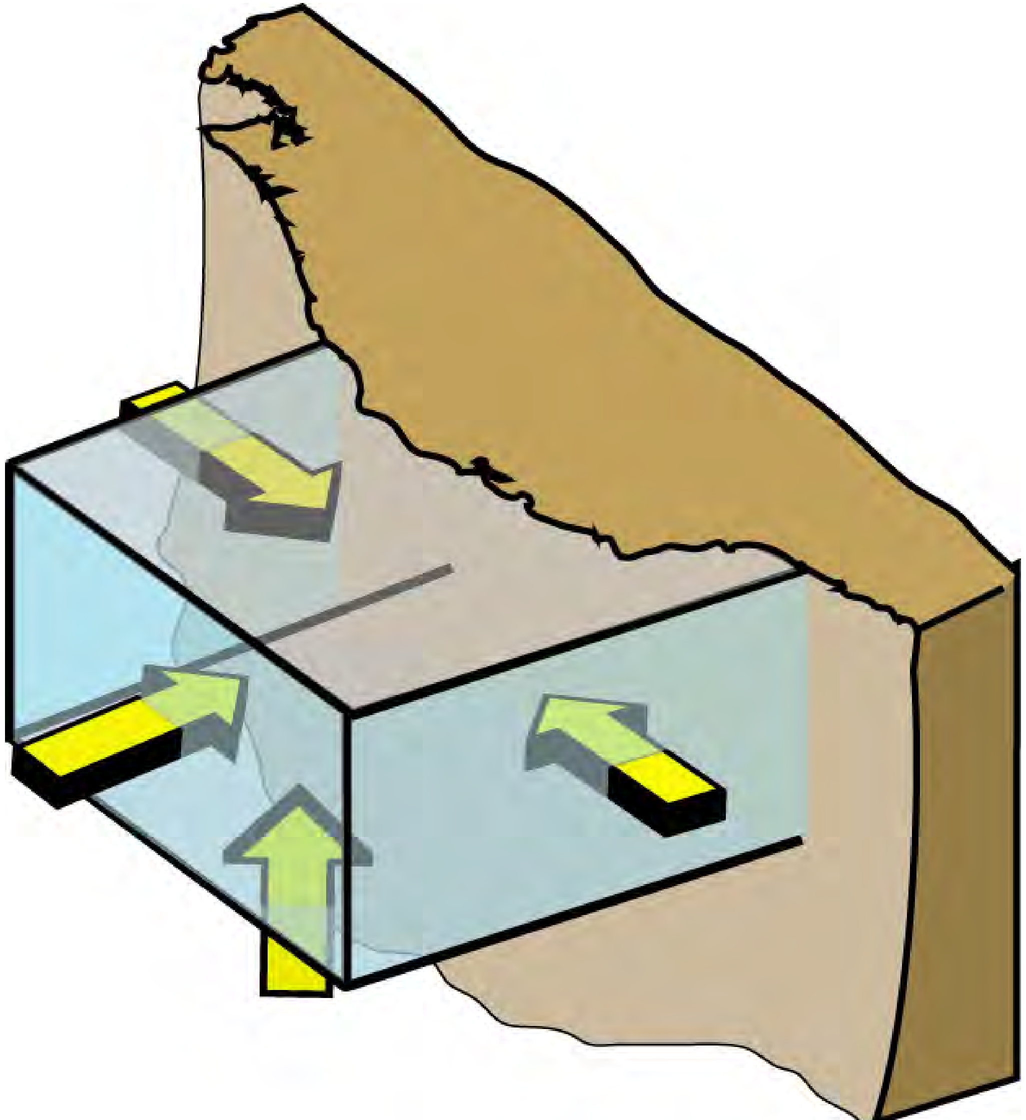
3) Changes in the nutrient concentrations in source-water masses supplied to the region. (Rykaczewski and Dunne, 2010; Bograd *et al.*, 2015)
    A. Change in concentration within a source-water mass
    B. Change in the relative contributions of different water masses to the region

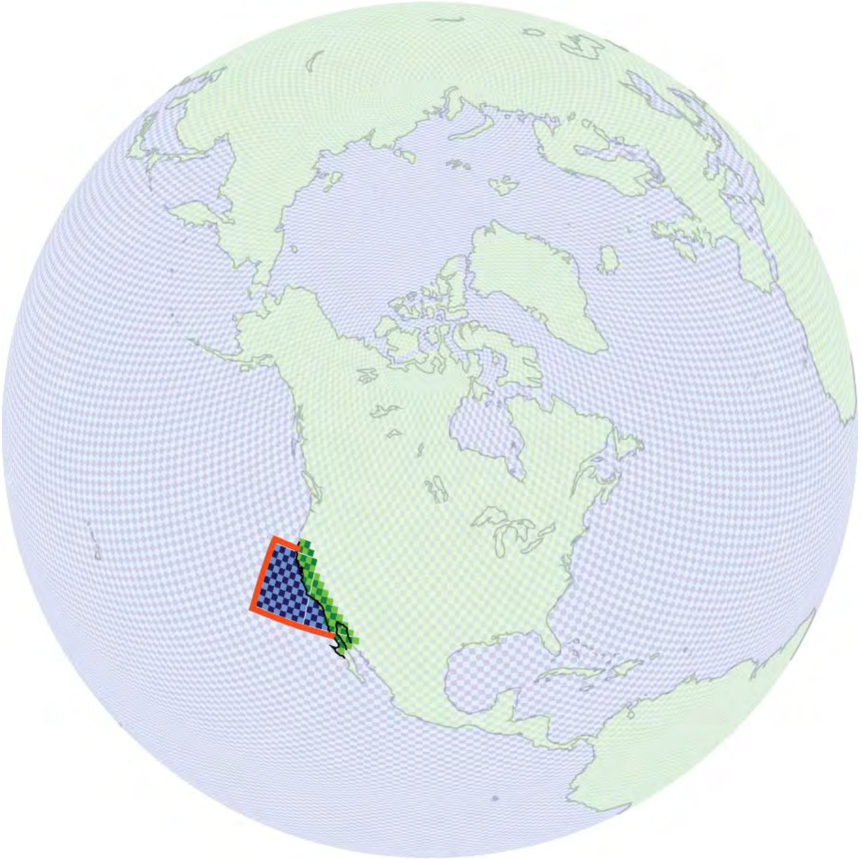
Surface-layer NO_3 increases despite stratification and winds



Rykaczewski and Dunne (2010)

Sources of nutrient input can be easily assessed (in a model world)





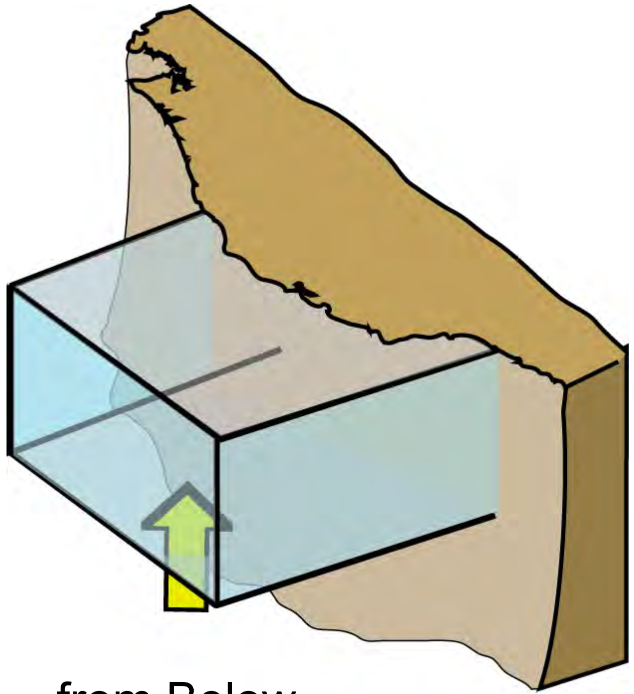
NO3 budget in a control volume

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

1[st] column: NO_3 flux
2[nd] 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

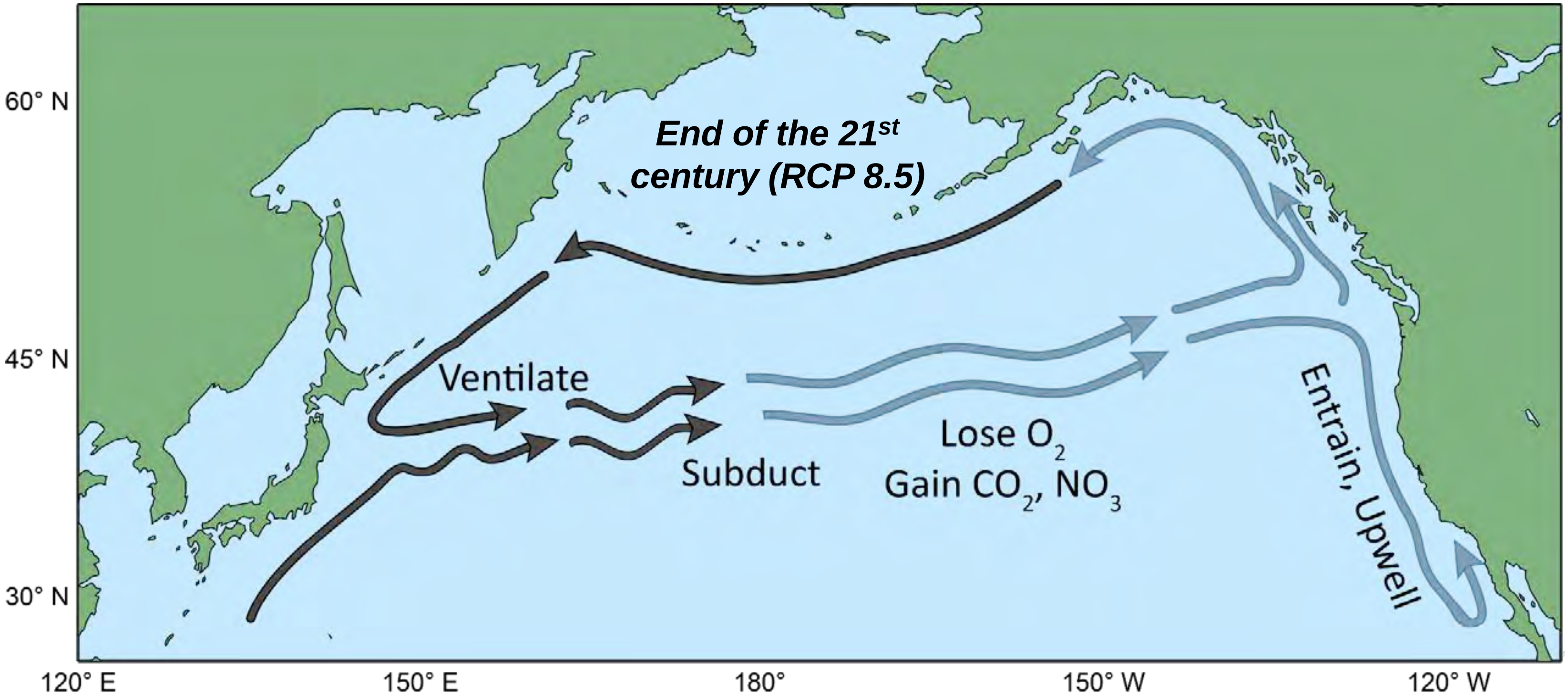
+ 60% + 10%

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

Ventilation plays a dominant role at centennial scales

The dominant process influencing nutrient supply differs between the historical time period (with which we are accustomed) and the 21st century.



Reduced ventilation in the central and western North Pacific leads to increased accumulation of NO_3 and CO_2 and loss of O_2. This has significant implications for productivity, deoxygenation, and acidification in ecosystems of the eastern North Pacific.

NO3 budget in a control volume

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

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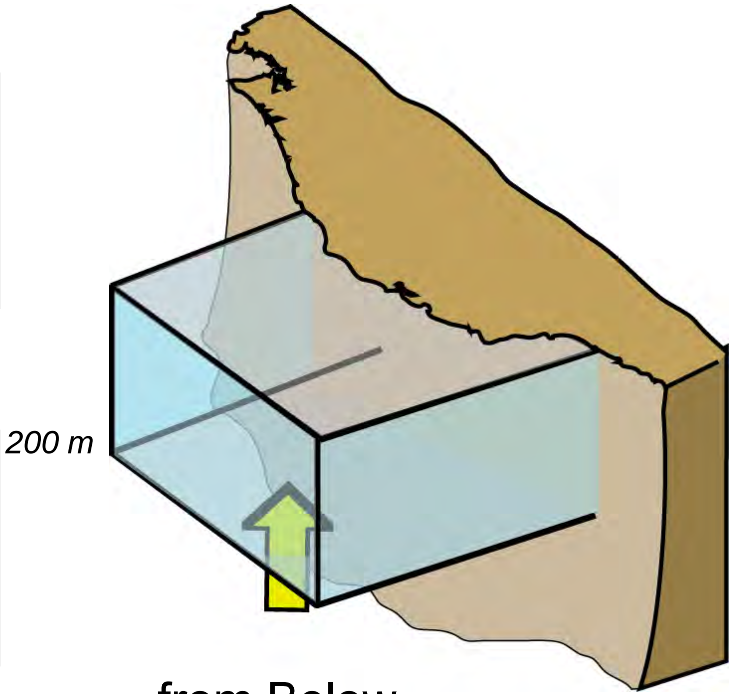

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Global Climate Change and Intensification of Coastal Ocean Upwelling

SCIENCE, VOL. 247 12 JANUARY 1990

ANDREW BAKUN

A mechanism exists whereby global greenhouse warming could, by intensifying the alongshore wind stress on the ocean surface, lead to acceleration of coastal upwelling.

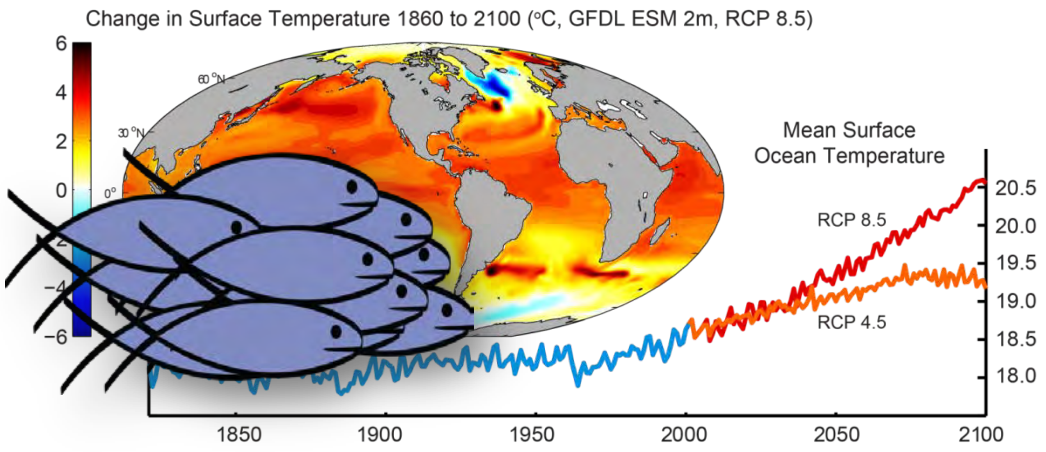
Effects of enhanced upwelling on the marine ecosystem are uncertain . . .

. . . but potentially dramatic.

This is a *captivating* hypothesis, involving:

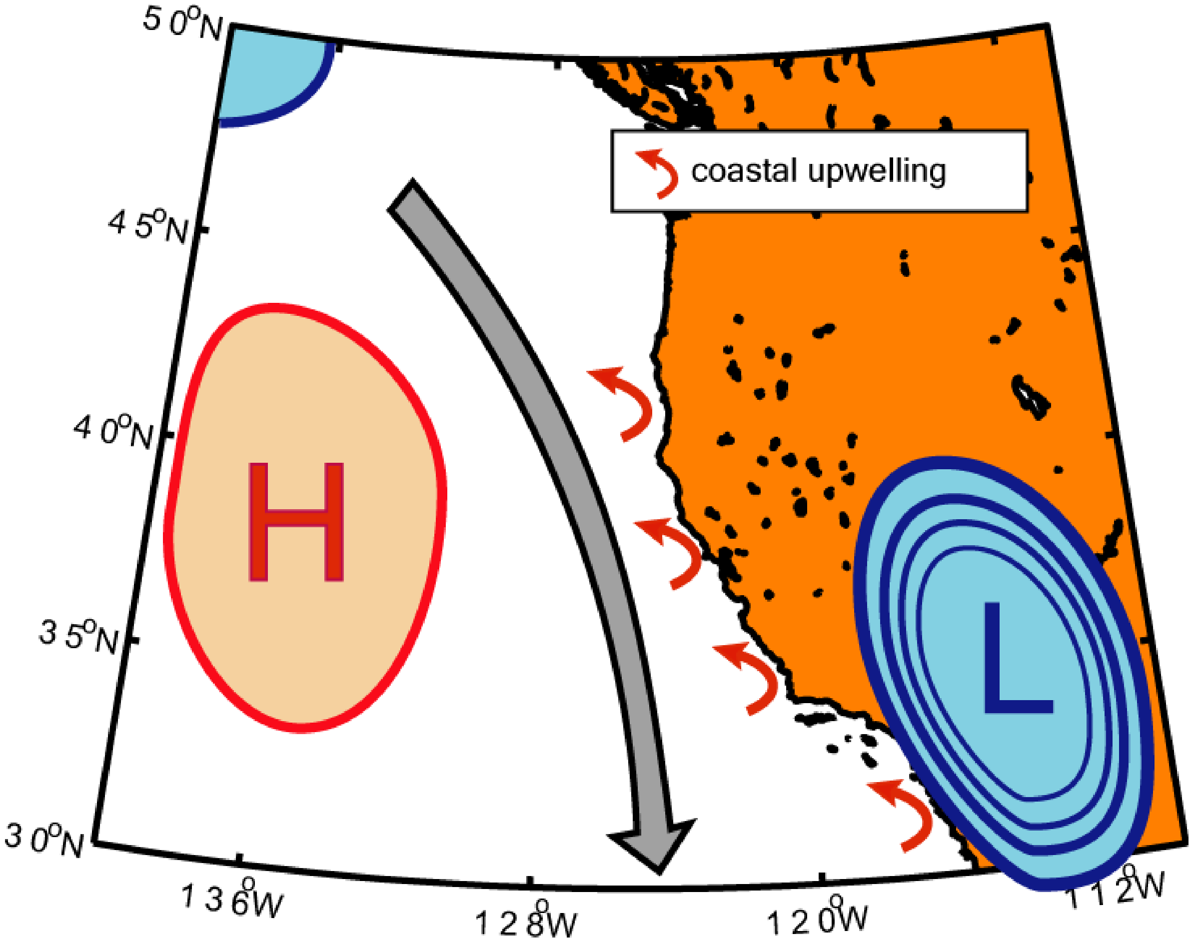
global warming/climate, atmospheric science, oceanography, and ecological impacts

all tied together in a fairly straightforward conceptual explanation.



Bakun's proposed mechanism of upwelling intensification

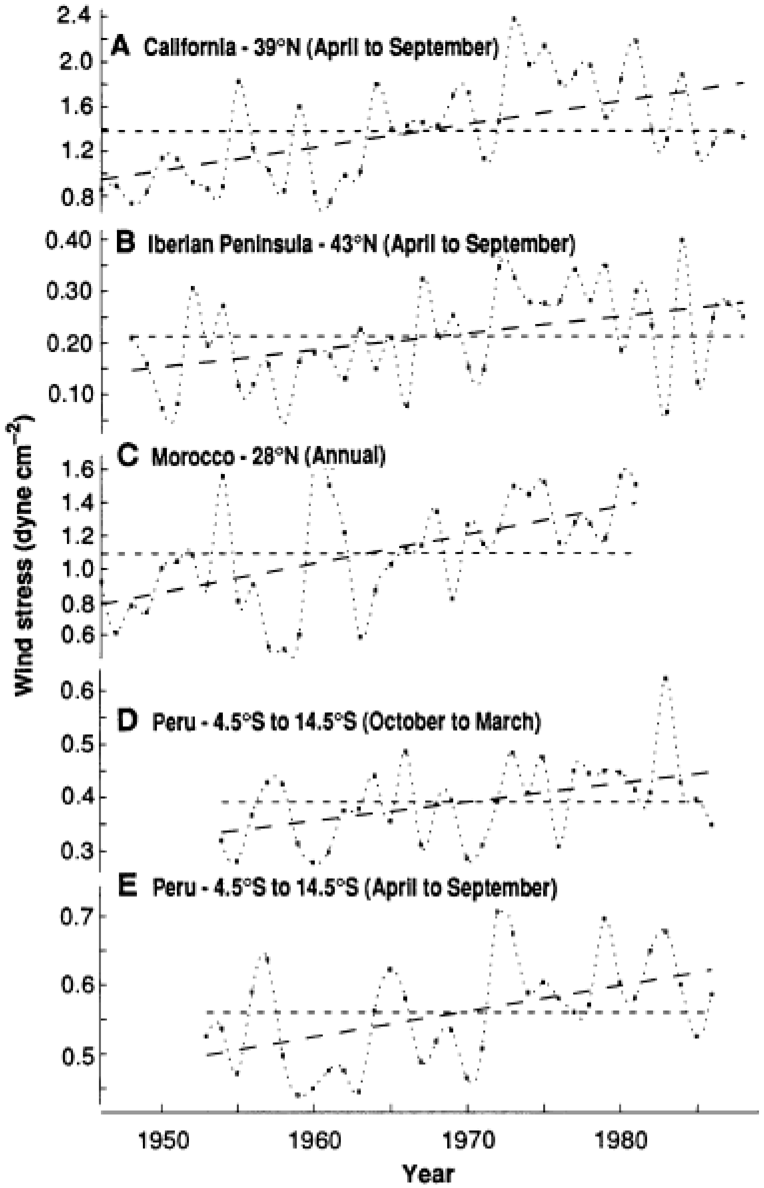
Bakun suggested that global warming would enhance summertime upwelling winds in eastern boundary currents.



Differential heating of the surface air over the landmass relative to the ocean…

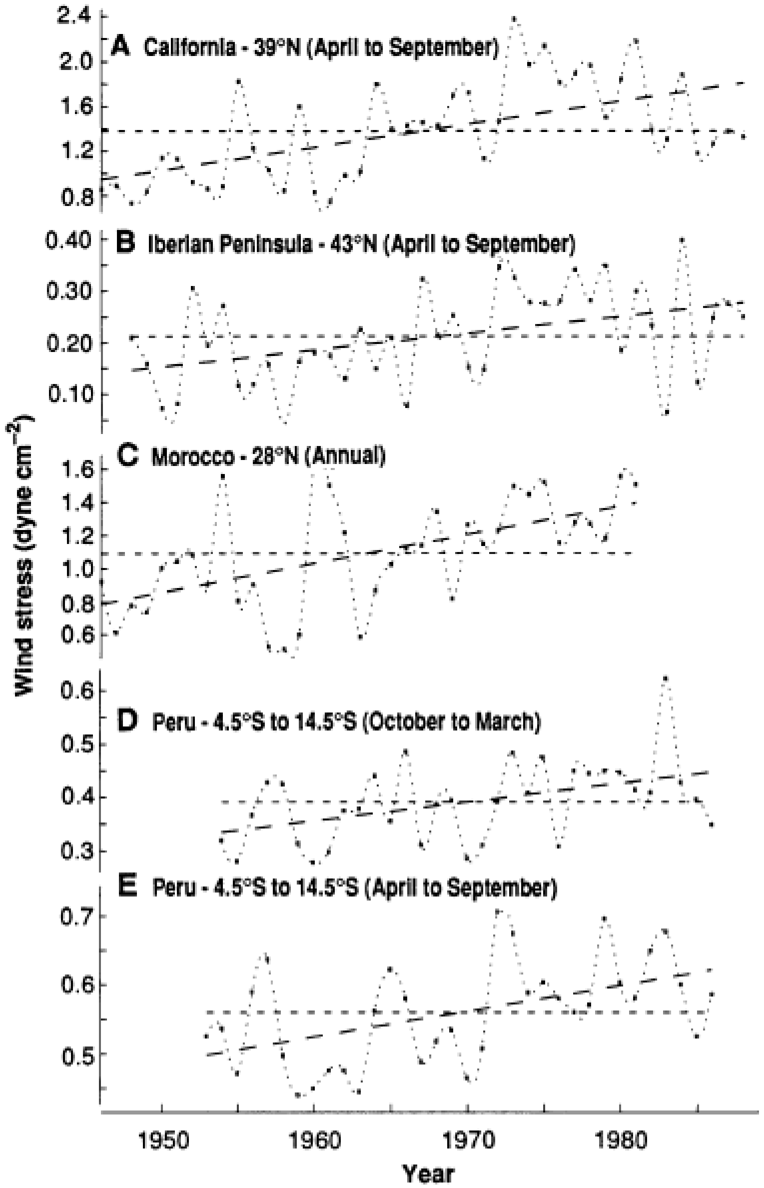
…will result in intensification of the thermal Low over the Southwest, generating a stronger pressure gradient.

Supporting evidence and qualifications…



Early observations supported Bakun's hypothesis.

Supporting evidence and qualifications…



Bakun noted the following qualifications in his proposal:

- Intensification should be limited to the main upwelling season and the core of the upwelling zone.

- Interannual and decadal variability is present.

- Impacts on the ecosystem may not be straightforward.

What observations exist…

Observational records of ocean winds are available:

- archived vessel reports (Beaufort and anemometer, since 1946 and earlier)
- coastal stations and buoys (since 1970s)
- data-based reanalyses targeted towards meteorological efforts (since 1948, with some earlier evidence)
- satellite estimates (since 1979)

Issues with reliance on an observational approach

Two <u>major issues</u> with observational datasets come to mind:

1. Although the duration of observational time series has increased, so too has our recognition of decadal scale variability. ***Time series are short***.

2. The magnitude of historical climate change is rather small relative to what is expected in the future.

The "signal" is relatively weak.

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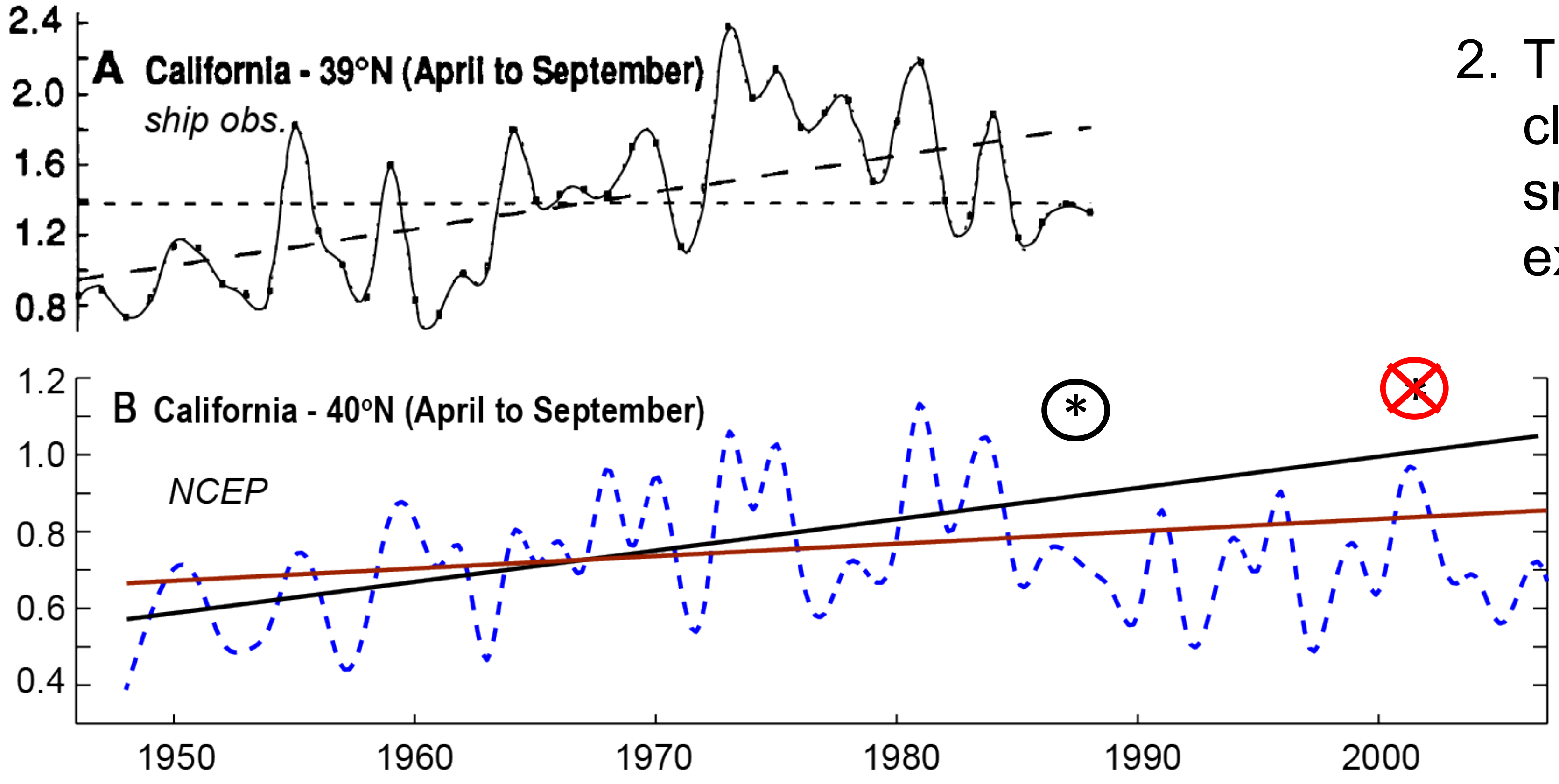


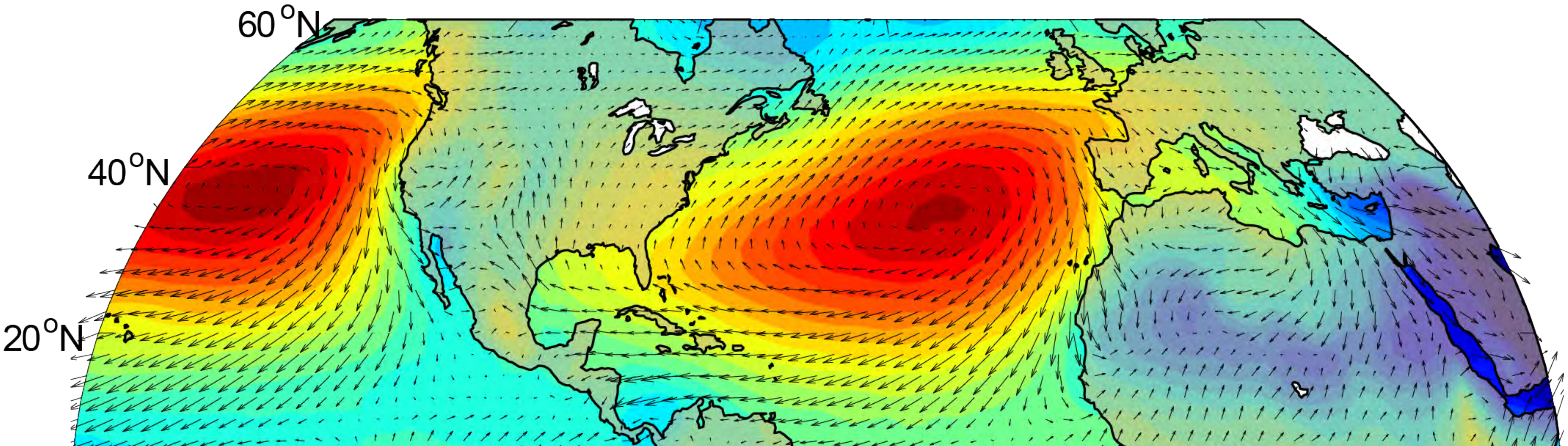
2. The magnitude of historical climate change is rather small relative to what is expected in the future.

The "signal" is relatively weak.

Models can be useful in examining the concept

Atmosphere-ocean coupled climate models (IPCC-style) alleviate some of these issues:

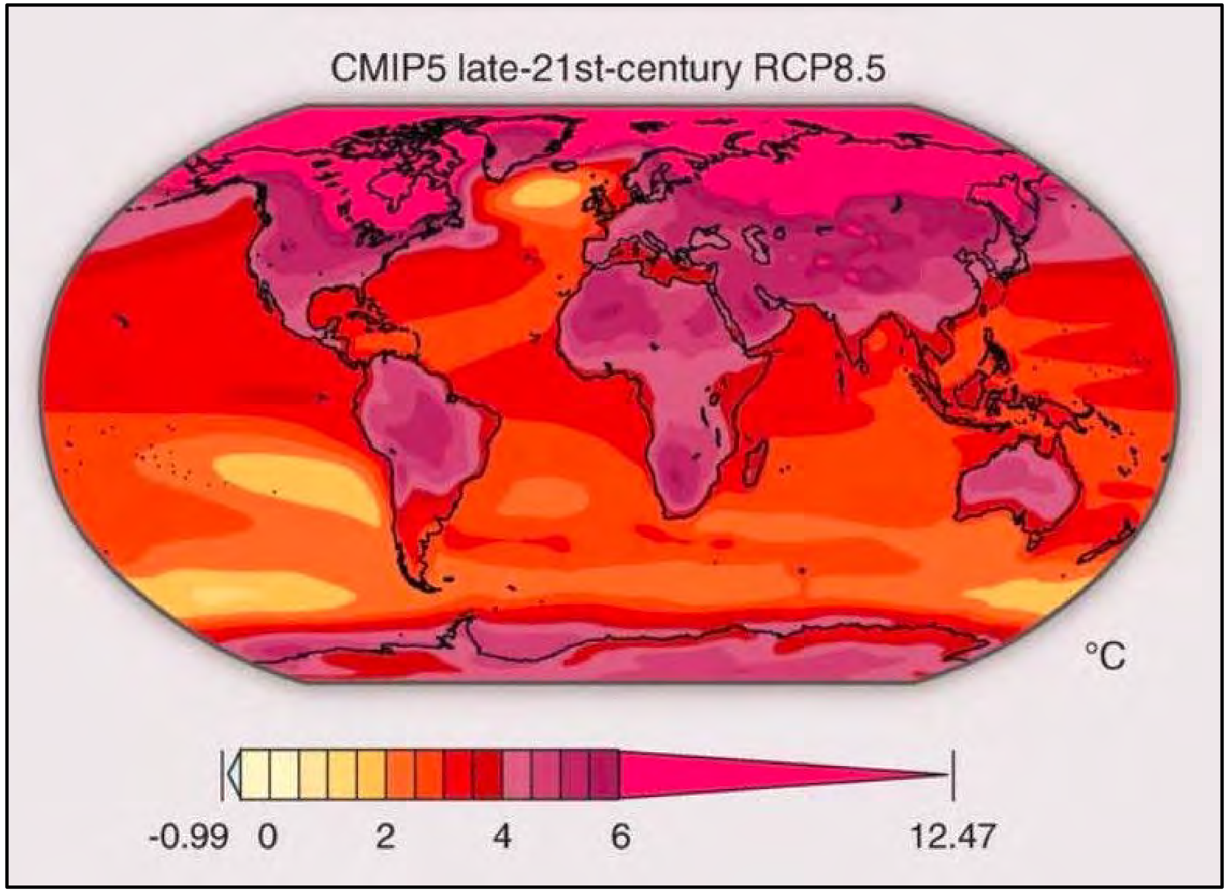
- Not limited by data length or magnitude of historical forcing.
- Not limited by data quality or methodology.
- Offer comprehensive and quantitative results, as well as the ability to test each step (not just the final result).



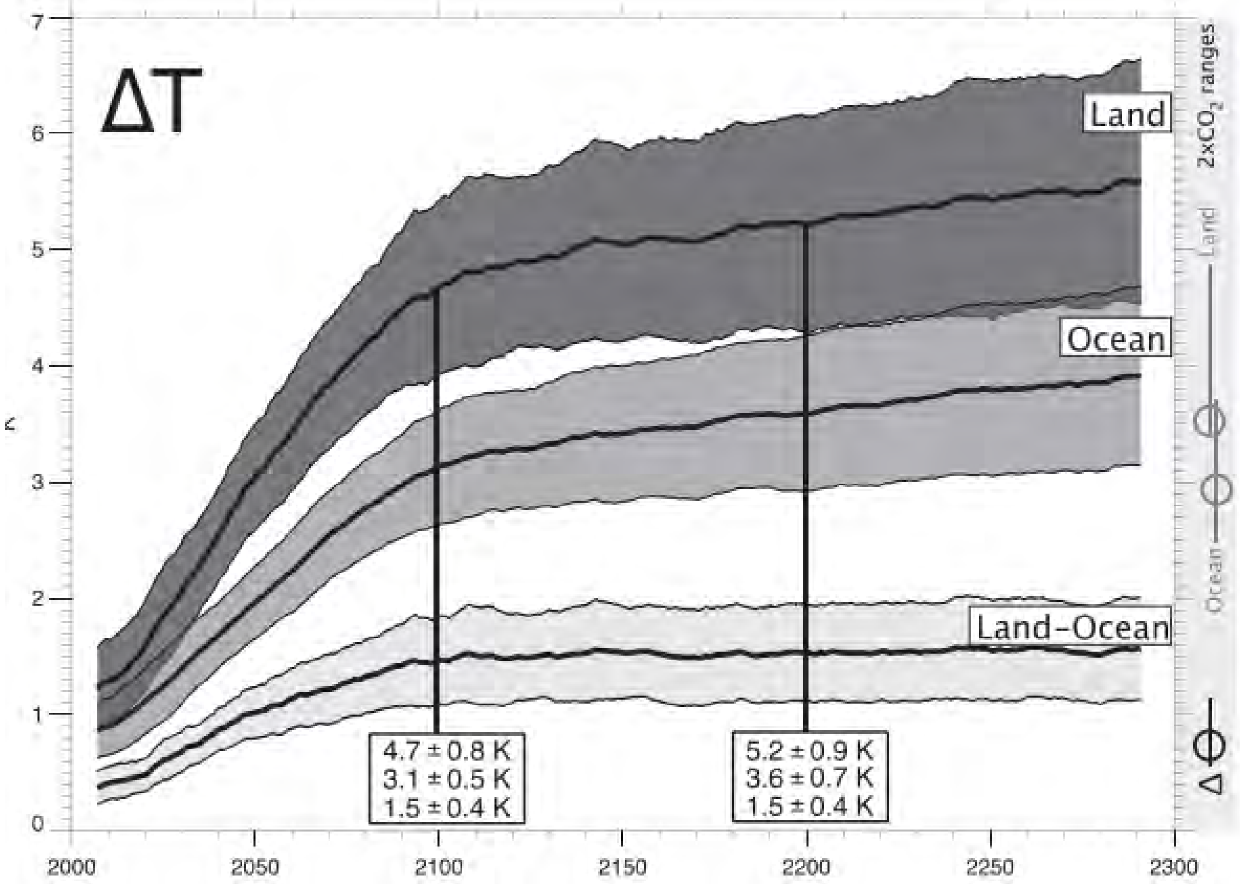
Model name	***Atmospheric resolution (km)***	***Oceanic resolution (km)***
1. CanESM2	310 × 262	103 × 131
2. CNRM-CM5	156 × 131	92 × 93
3. ACCESS1.3	139 × 174	107 × [illegible]
4. ACCESS1-0	139 × 174	107 × [illegible]
5. CSIRO-Mk3-6-0	207 × 175	104 × [illegible]
6. inmcm4	167 × 186	68 × [illegible]
7. 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

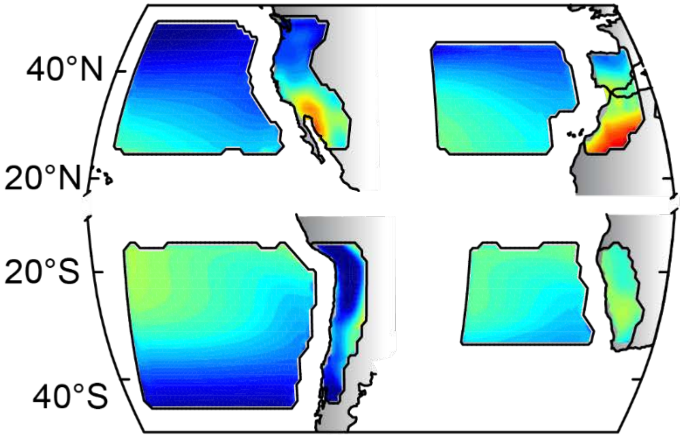


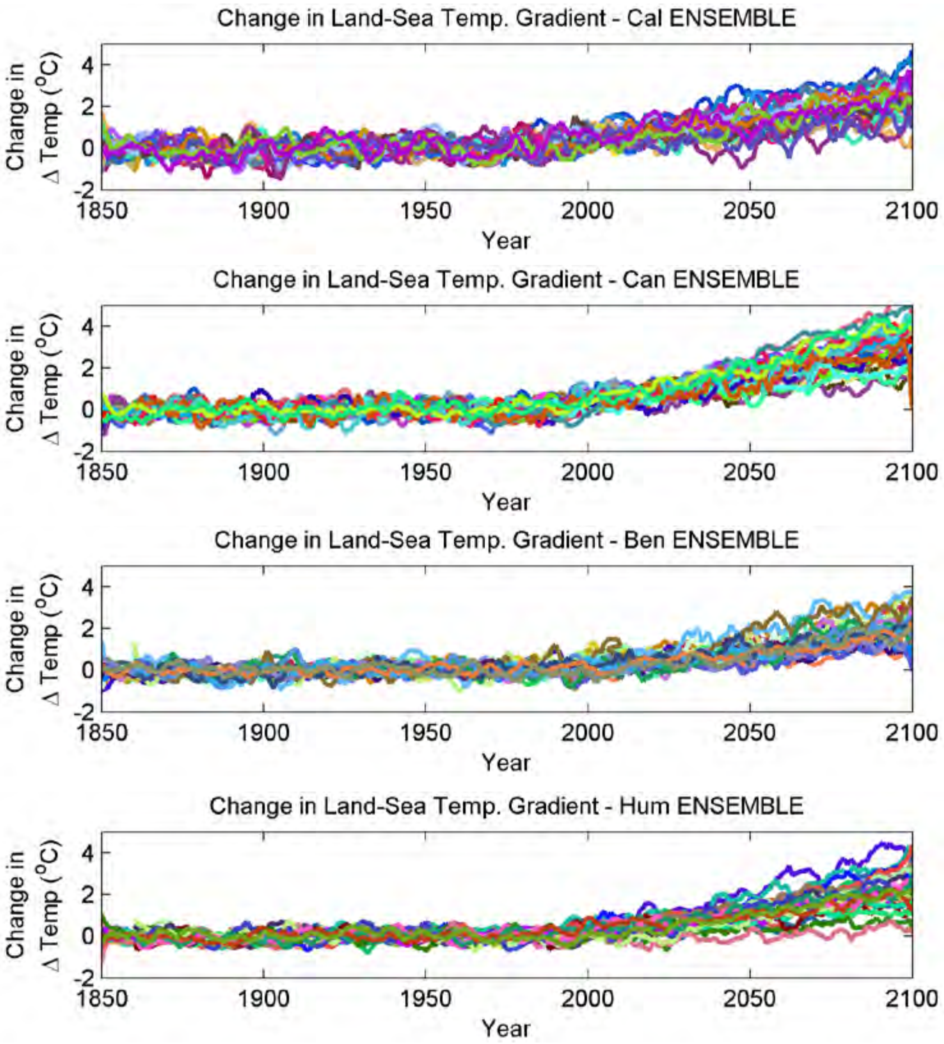
Diffenbaugh and Field (2014)



Fasullo (2010)

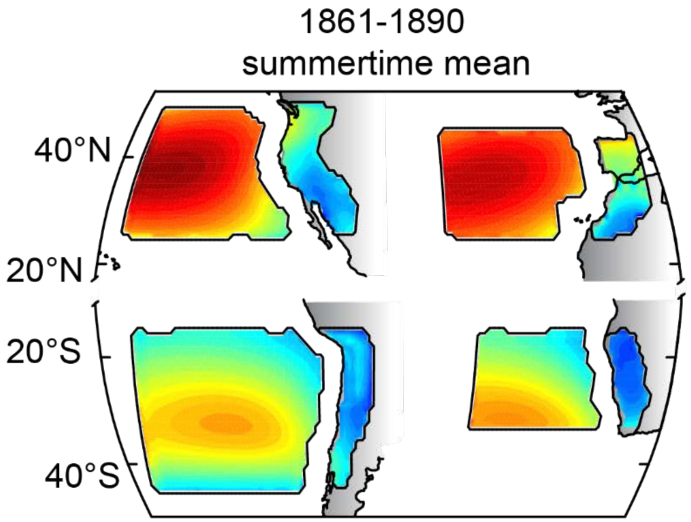
Land-sea temperature differences do, indeed, increase

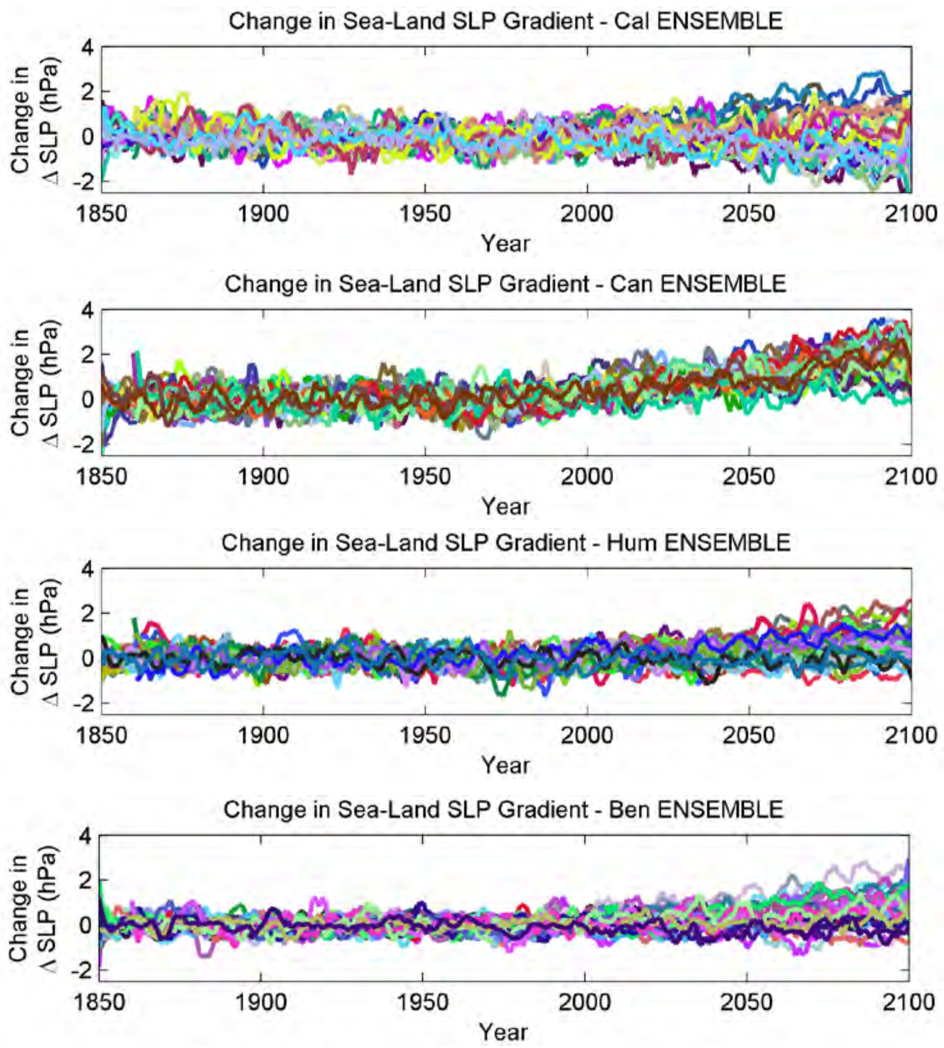




Rykaczewski *et al.* (2015)

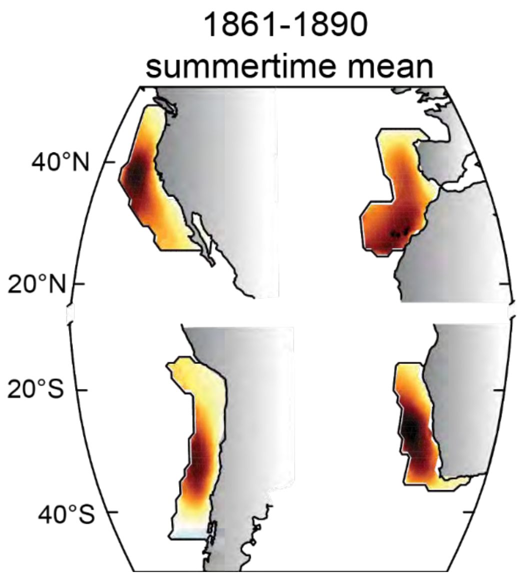
However, continental SLP does not uniformly decrease

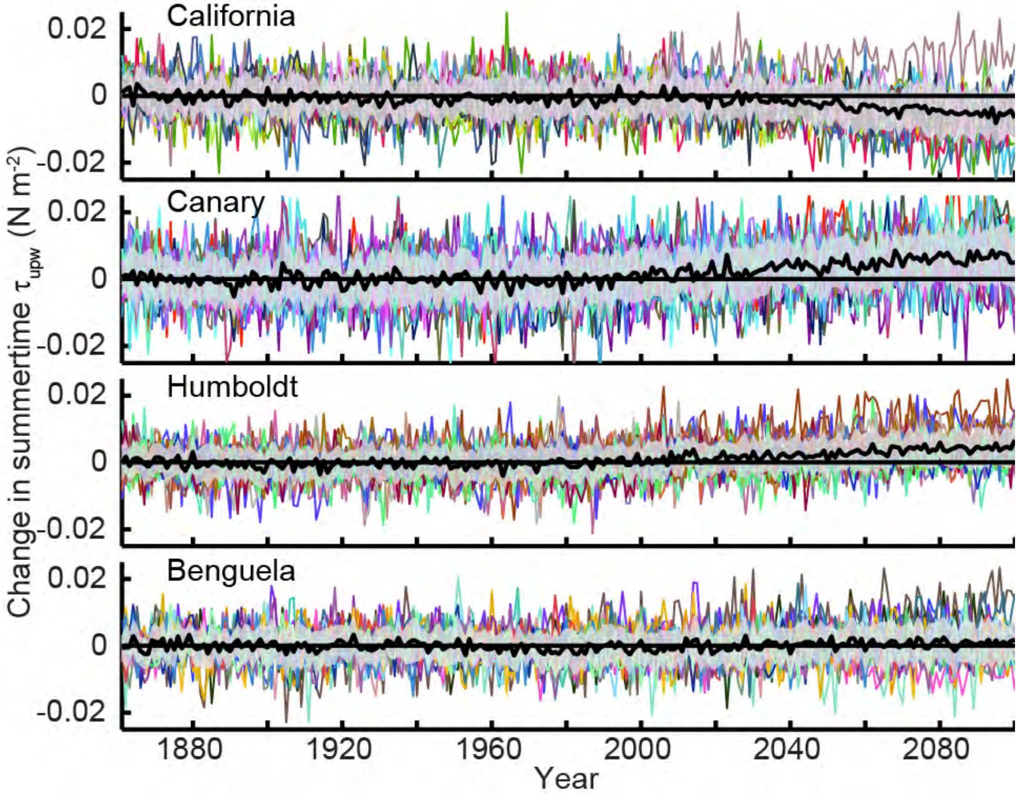




Rykaczewski *et al.* (2015)

Changes in wind intensity are fairly subtle…





Rykaczewski *et al.* (2015)

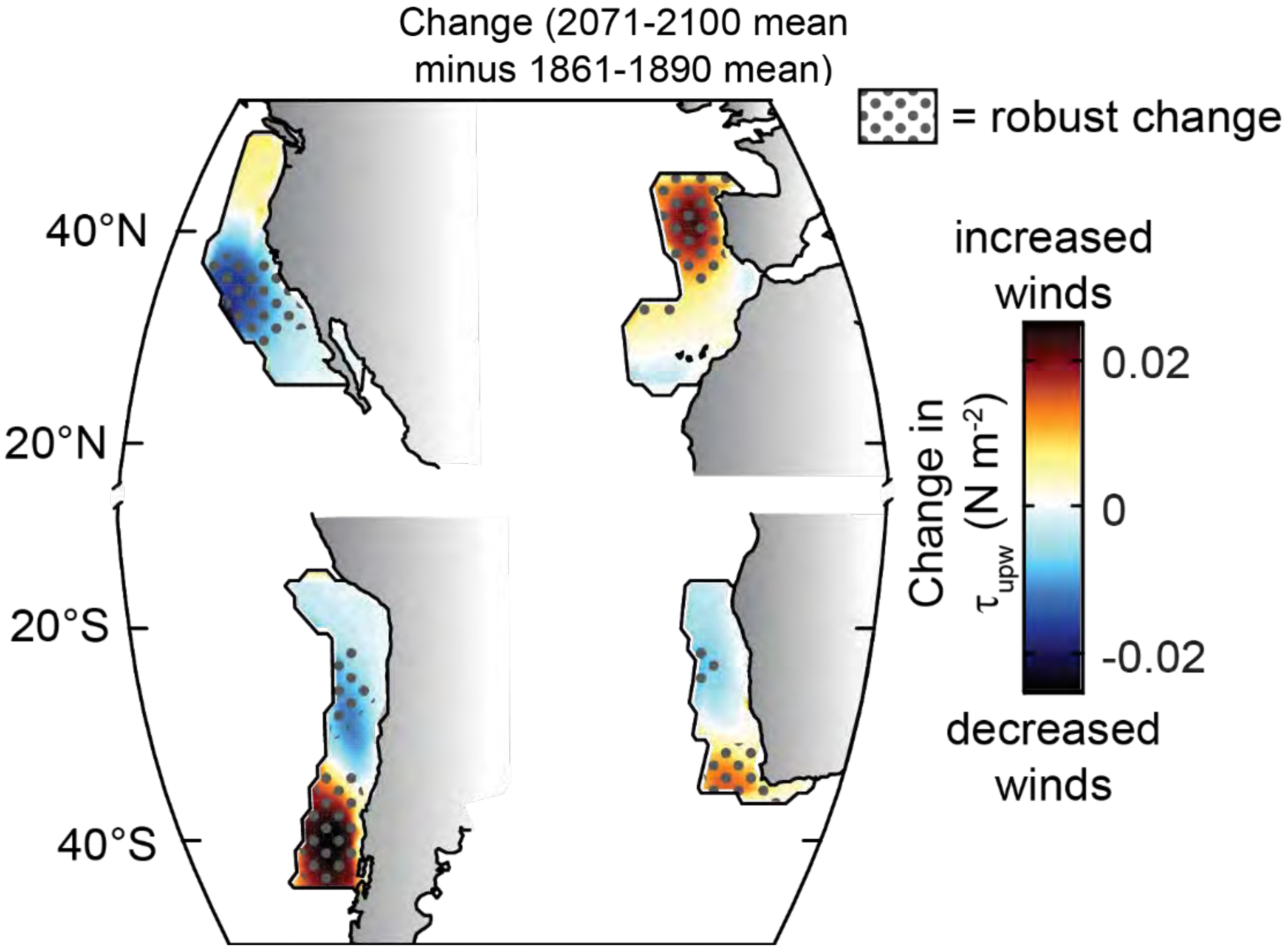
Changes in wind intensity are fairly subtle…

Upwelling intensity tends to increase in the poleward halves…

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

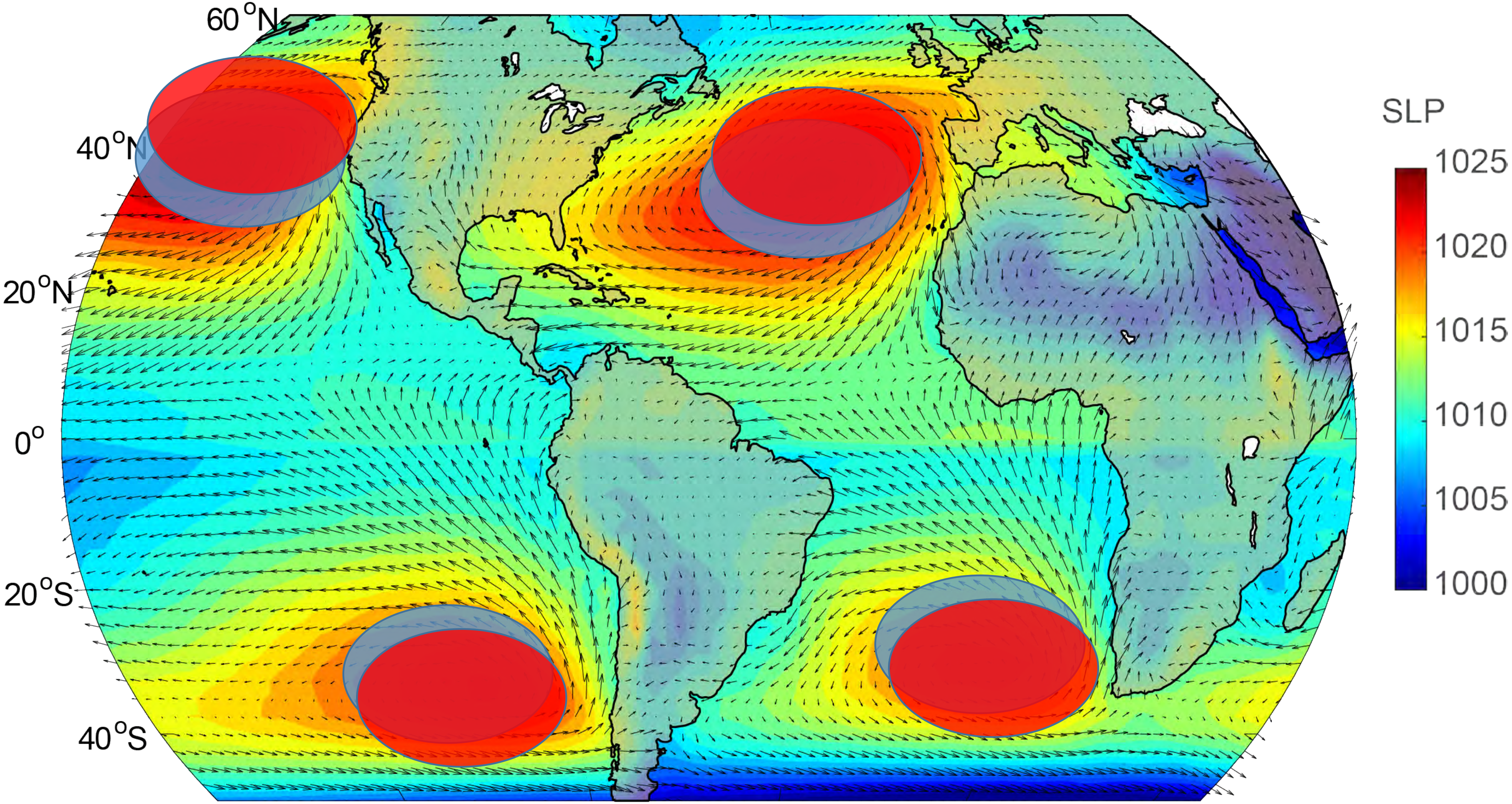
Percentage change in summertime τ_{upw} during the 2071-2100 period relative to an 1861-1890 base period.

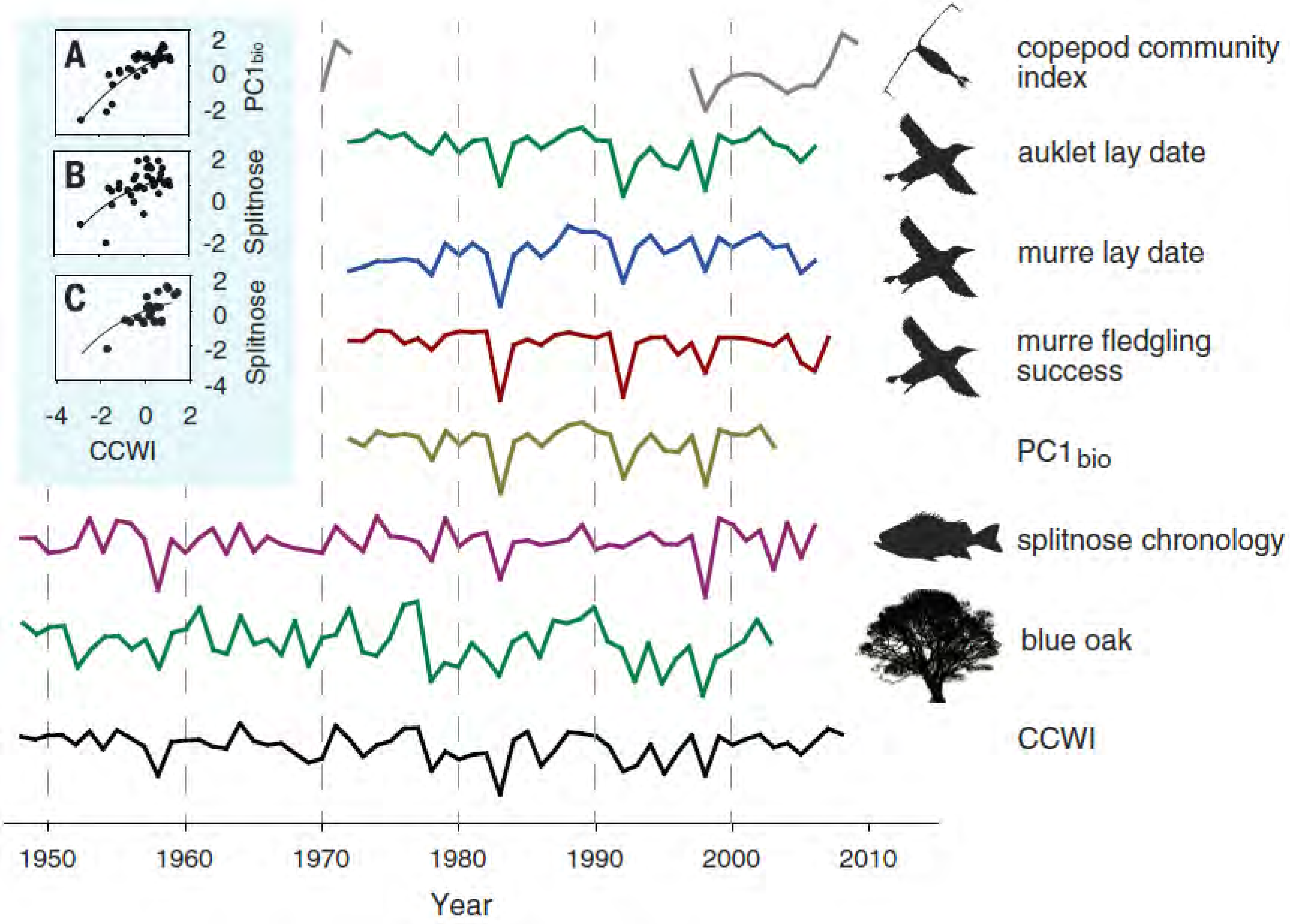
	Complete region	Poleward portion	Equatorward portion
California	-8% (±10 s.d.)	-2% (±18 s.d.)	-13% (±10 s.d.)
Canary	10% (±10 s.d.)	26% (±18 s.d.)	2% (±11 s.d.)
Humboldt	10% (±12 s.d.)	47% (±34 s.d.)	-9% (±9 s.d.)
Benguela	1% (±7 s.d.)	9% (±10 s.d.)	-6% (±9 s.d.)



Rykaczewski *et al.* (2015)

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

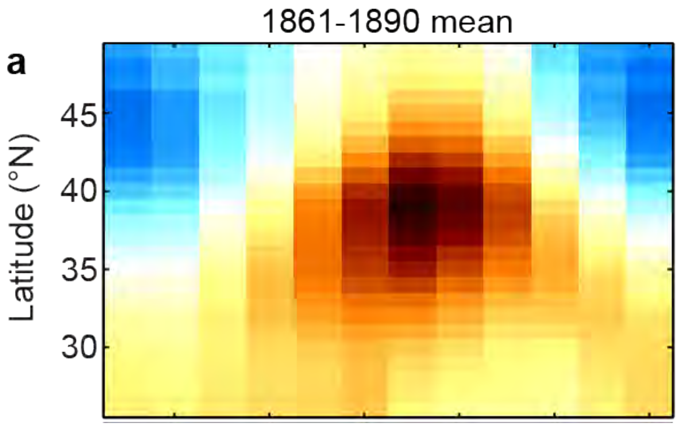




Black *et al.* (2014)

Projected changes are not limited to the summer seasons

In the eastern North Pacific, springtime upwelling winds (March-April) are projected to intensify in north of Point Conception.



Increased upwelling in poleward portions of the regions

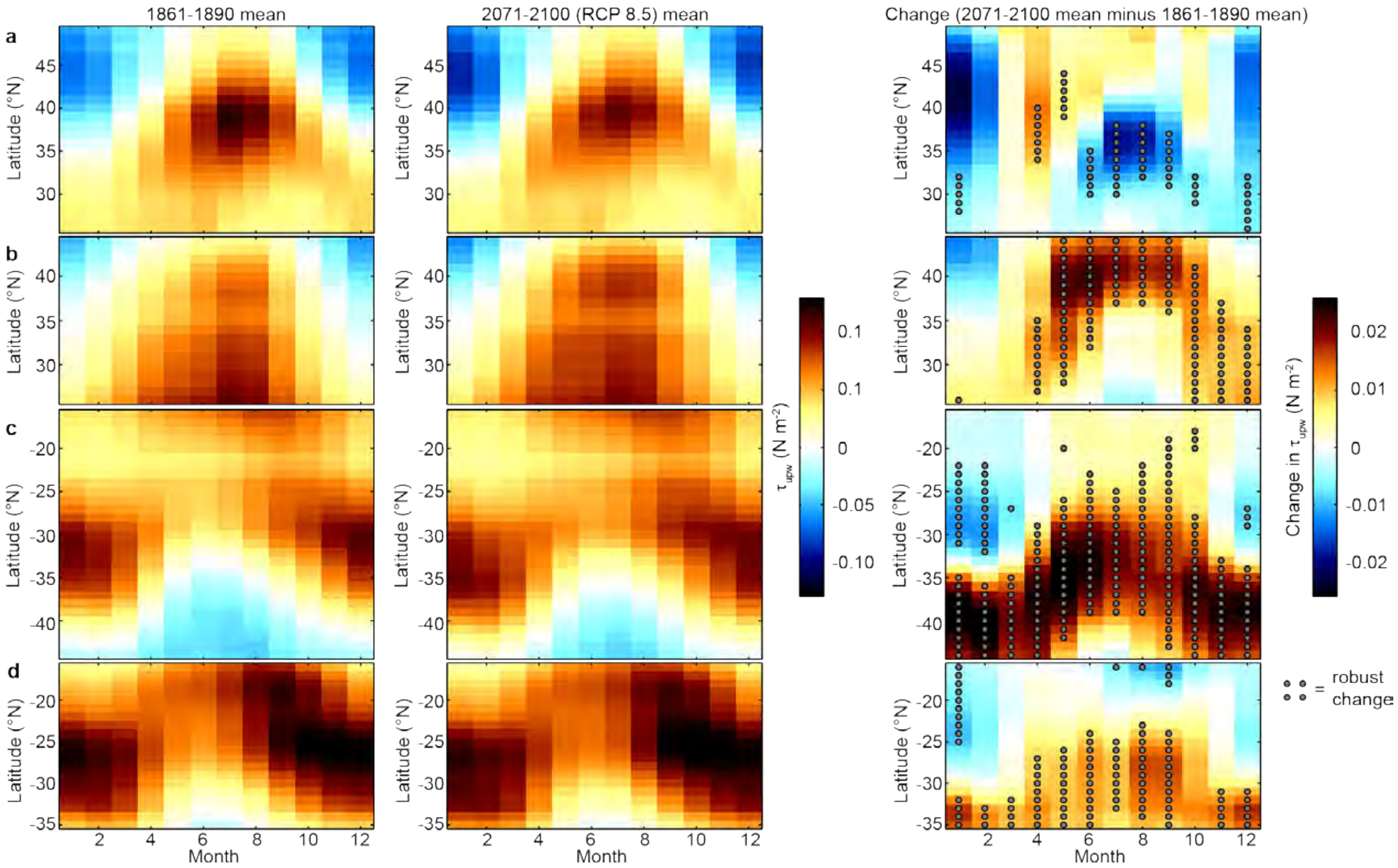
Projected changes are not limited to the summer season.

California

Canary

Humboldt

Benguela



Summary

1) *Intensification of upwelling-favorable winds is NOT clearly projected for the California Current. The strongest responses appear to be that of earlier upwelling in spring north of Point Conception and weaker upwelling in central and southern California during summer.*

2) *Model projections suggest that upwelling-favorable winds may intensify in the poleward portions of upwelling systems, but weaken in equatorward portions for those systems. This is consistent with a "poleward displacement" of upwelling winds associated with a shift in the location and development of subtropical highs.*

3) *Resolution of global models remains rather coarse to properly resolve coastal winds. Additionally, poor representation of marine stratus clouds may further bias coastal temperatures and winds.*

Wind stress, stratification, and source waters

What remains on our list of relevant processes to consider?

1) The magnitude of upwelling favorable winds along the coast. (Bakun, 1990)

2) Stratification of the water column that might alter the depth from which upwelling waters are drawn. (Huyer, 1976; Roemmich and McGowan, 1995; Palacios *et al.*, 2004; Lentz and Chapman, 2004)

3) Changes in the nutrient concentrations in water masses supplied to the region. (Rykaczewski and Dunne, 2010; Bograd et al., 2015)
   A. Change in concentration within a source-water mass
   B. Change in the relative contribution of different water masses to the region

Thanks for your attention!