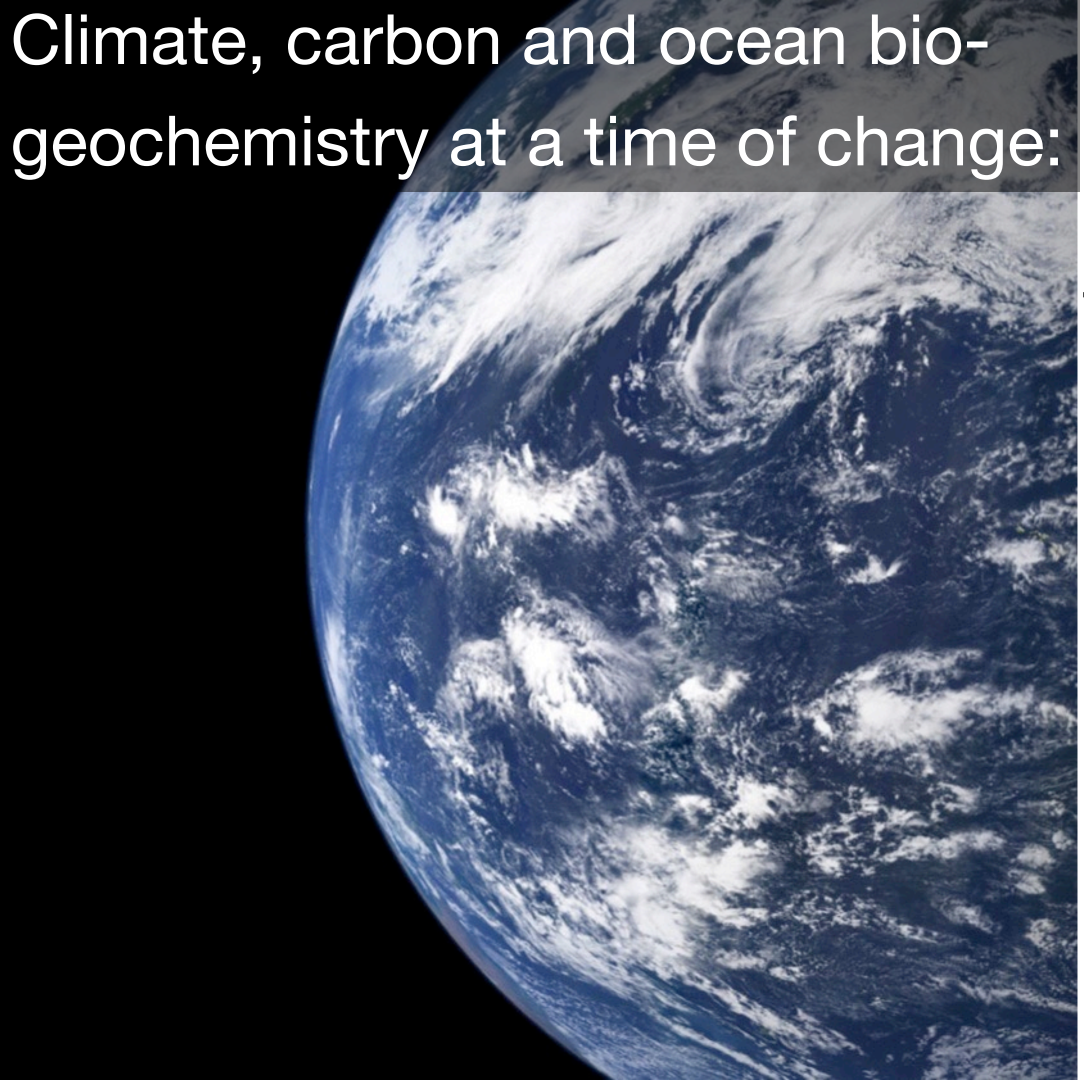
"I always avoid prophesying beforehand because it is much better to prophesy after the event has already taken place. ”

Winston Churchill

Climate, carbon and ocean bio-geochemistry at a time of change:



Recent insights, emerging trends, and future outlook

Nicolas Gruber

Environmental Physics, ETH Zürich

Zürich, Switzerland.

Acknowledgment:

Peter Landschützer & David Byrne & the community at large

The role of the ocean in the Earth system

Our concern about the ocean's role in the Earth System centers on three ecosystem services:

Uptake of heat

Uptake of carbon

Provision of Food

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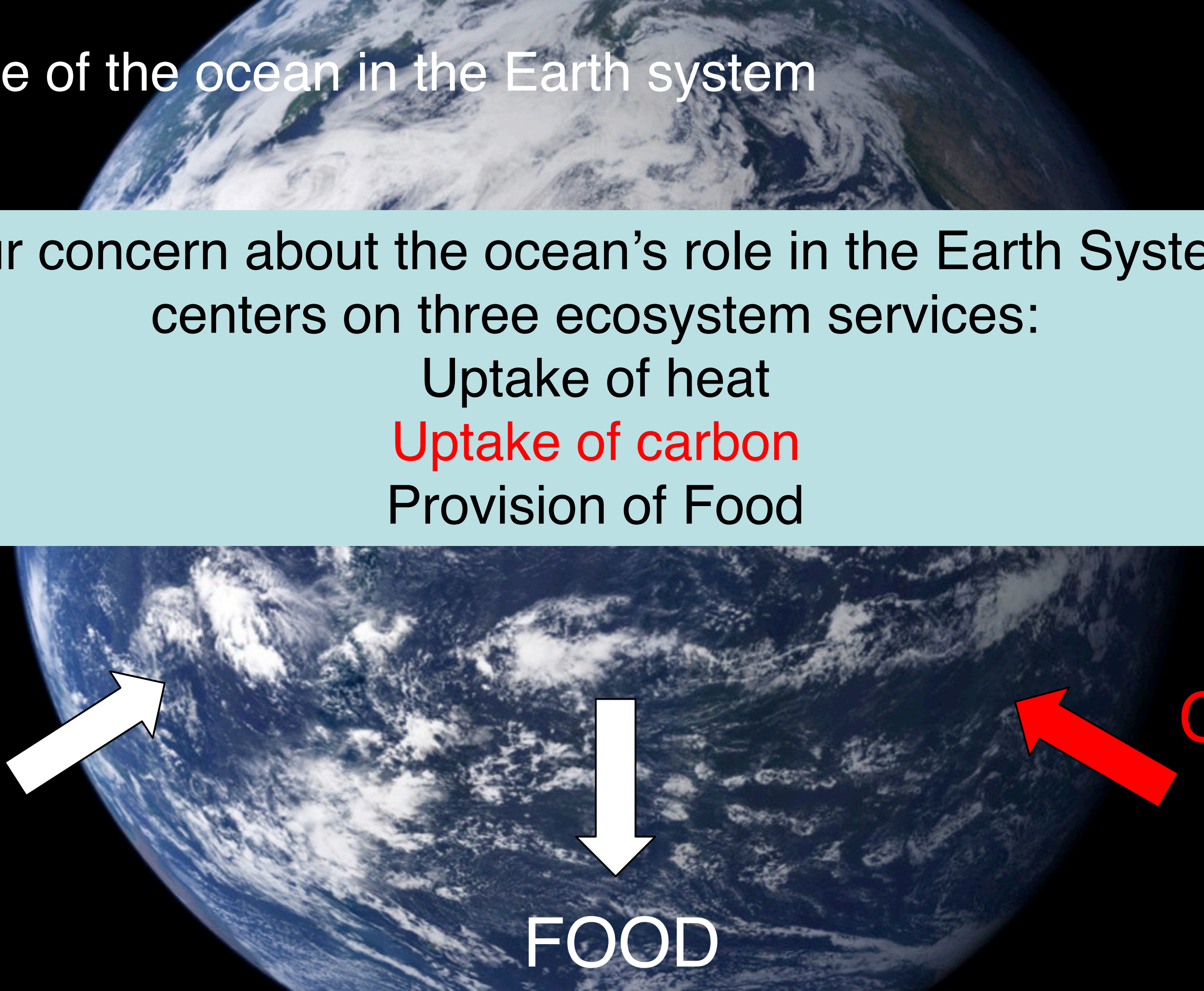

The role of the ocean in the Earth system

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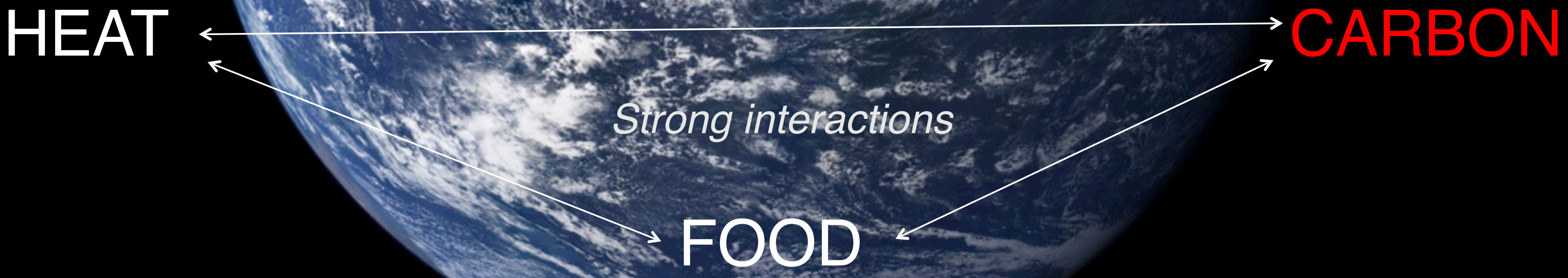
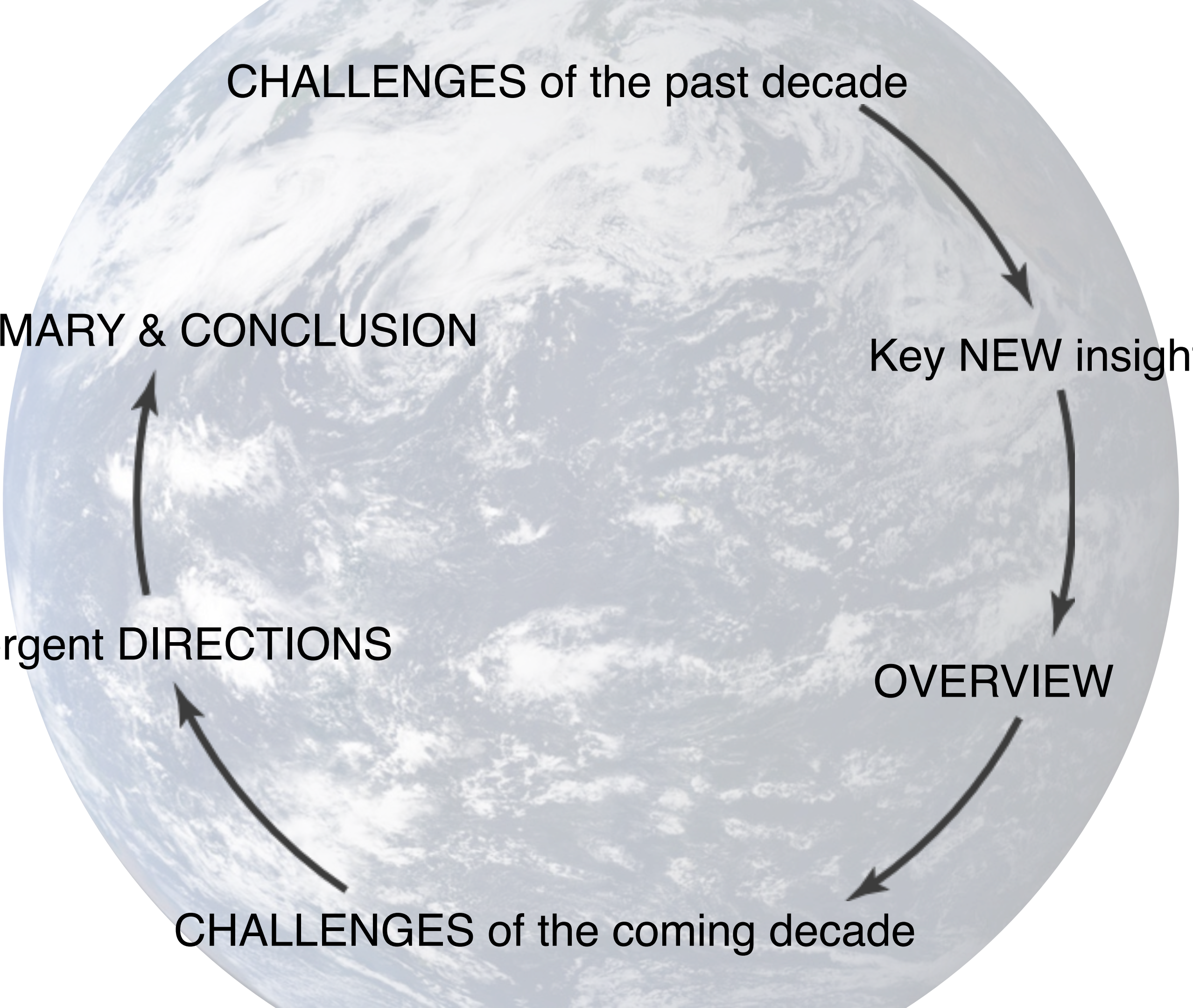


Outline


CHALLENGES of the past decade
Key NEW insights
OVERVIEW
CHALLENGES of the coming decade
Emergent DIRECTIONS
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Outline


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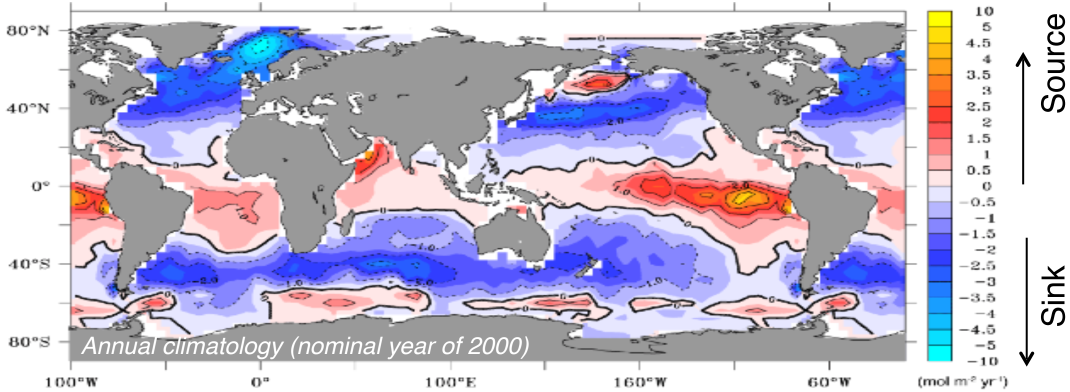
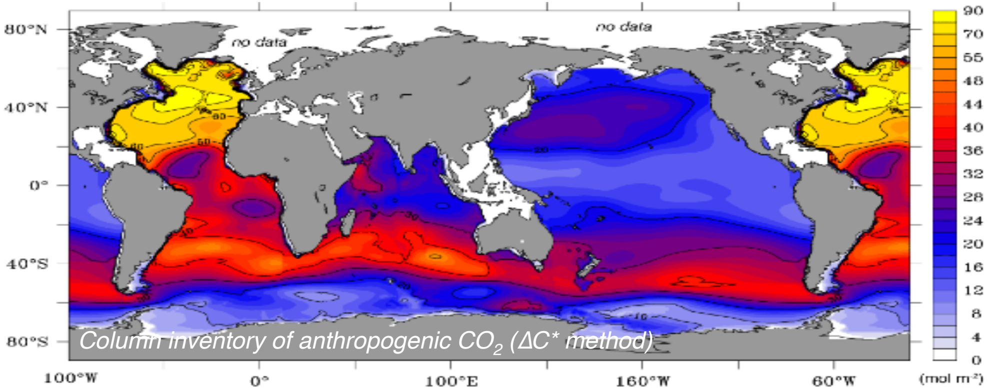
The situation ~2006: The iconic maps of the ocean carbon sink



Air-sea CO_2 flux climatology

Takahashi et al., (1999, 2002, 2009)

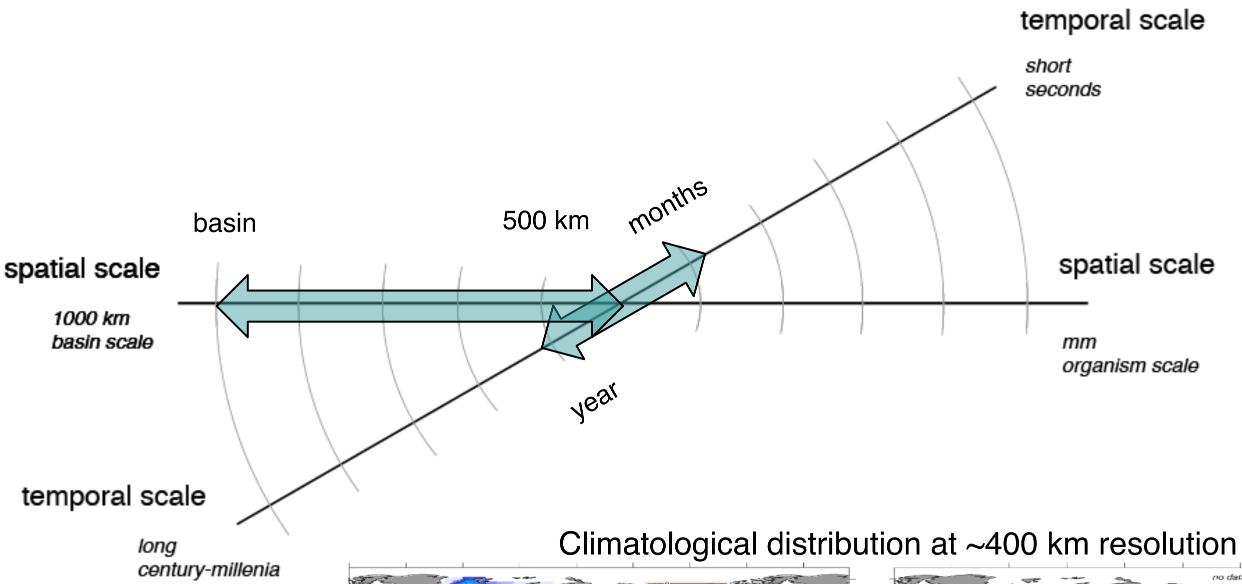


Anthropogenic CO_2 inventory

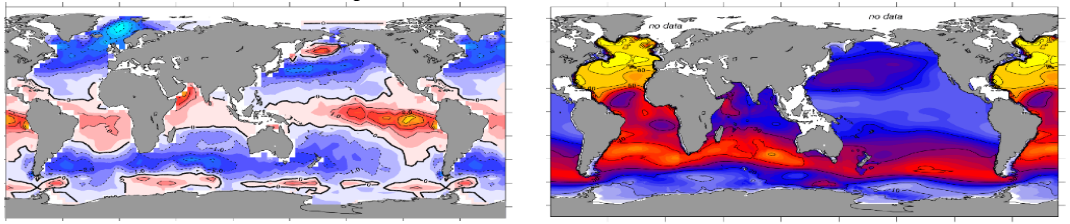
Sabine et al., (2004)

These maps represent major steps in our ability to constrain the global and regional carbon budgets

But limited coverage in terms of spatial and temporal scales



Climatological distribution at ~400 km resolution



Challenges of the past decade

Support the establishment of surface ocean and atmosphere carbon observing systems [..]suited to constraining net annual ocean-atmosphere CO_2 flux at the scale of an ocean basin to <0.2 PgC yr^{-1}

Determine the uptake, transport and storage of anthropogenic CO_2 on decadal timescale to within 10%

Examine the existence, and then direction, of feedbacks between projected changes in forcing and processes transforming carbon in the ocean.

Quantify the feedback to the atmospheric CO_2 reservoir (improve estimates of magnitude in Pg C yr^{-1}) on decadal and centennial timescales.

Challenge of the past decade: in a nutshell

How much carbon will the ocean take up from the atmosphere over the next 100 years?

Outline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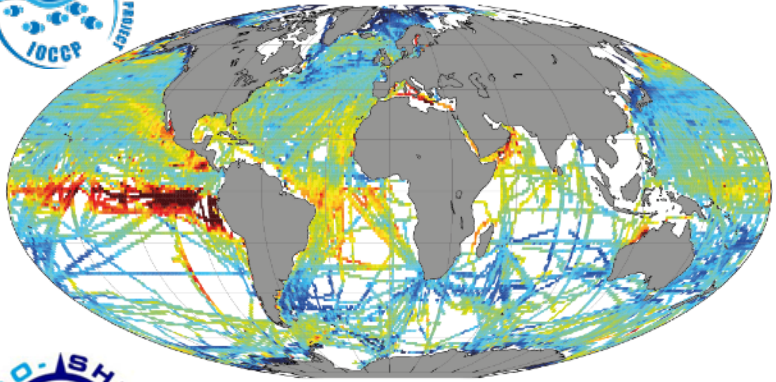
Key development on the data side: two complementary networks



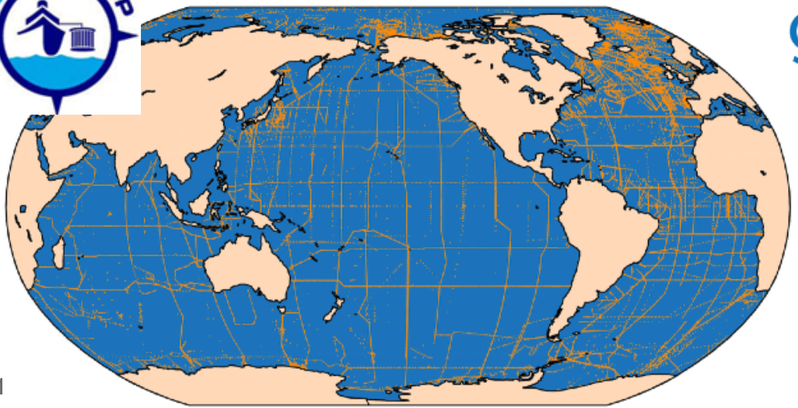
SOCAT · SURFACE OCEAN CO_2 ATLAS ·

SURFACE OCEAN NETWORK

(Bakker *et al*., 2014, updated)

Based on ~10’000’000 observations

of surface ocean pCO2.



glodap v2

INTERIOR OCEAN NETWORK

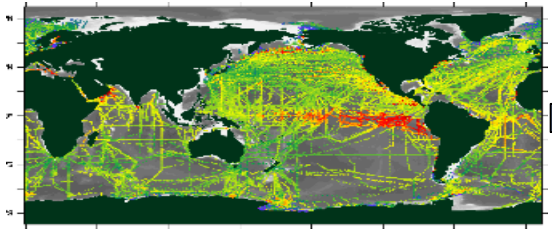
(Olsen *et al*., 2016)

Based on ~724 cruises with ~500’000 observations

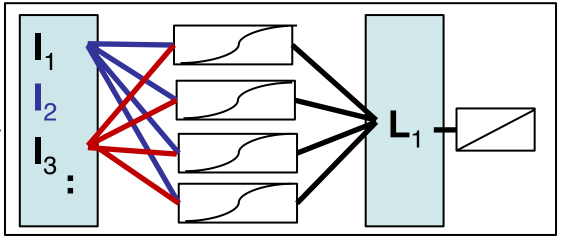
primarily DIC and Alk

Dealing with sparse data…
requires sophisticated analysis and mapping methods

SURFACE OCEAN pCO_2

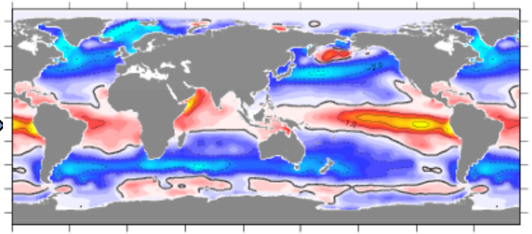


Landschützer et al. (2013,2014)

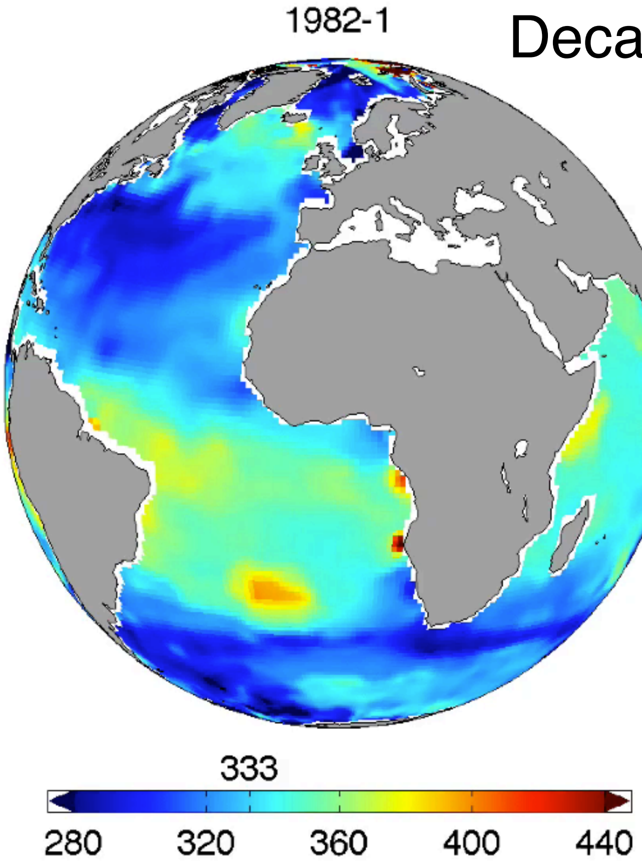


2step neural network method

AIR-SEA CO_2 FLUX



1x1°, 1982 through 2013



Decadal variations of the ocean carbon sink

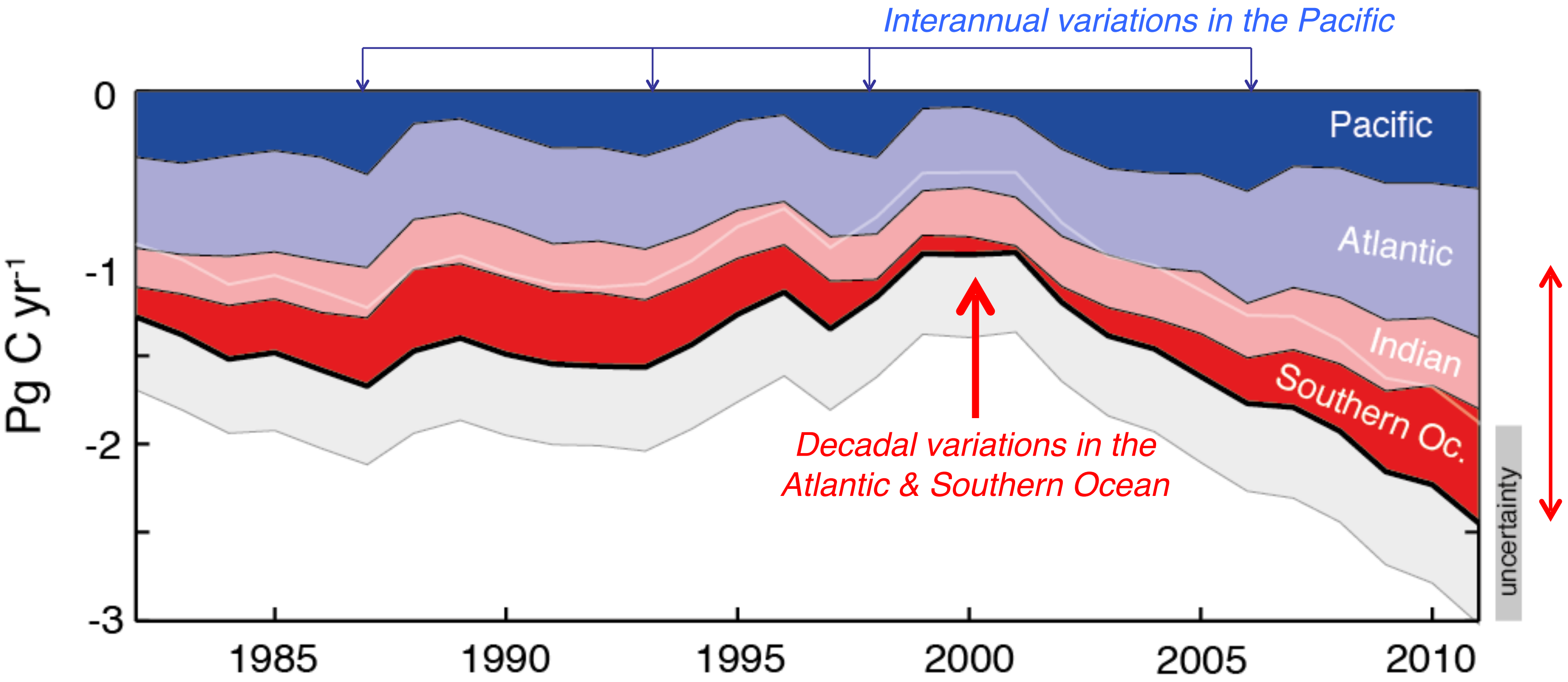
The reconstructed air-sea CO_2 fluxes reveal much structure in time and space, with a magnitude that is much larger than predicted by models.

Atmospheric CO_2

2-step neural network method

Landschützer et al. (2014, 2016)

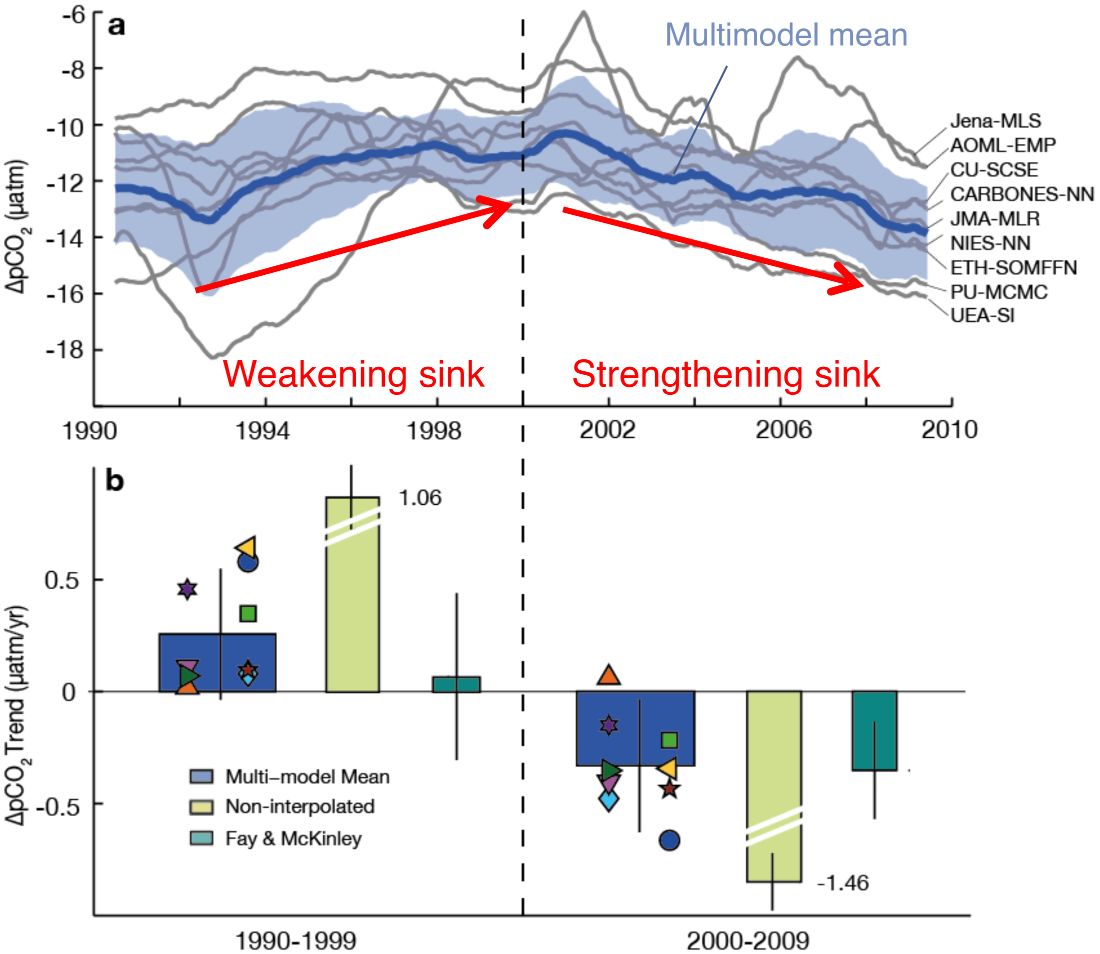
Decadal variations of the global ocean carbon sink



The global ocean carbon sink varies much more strongly on decadal timescales than previously thought, and also much more than simulated by models

Landschützer et al. (2016)

The Southern Ocean carbon sink variations: seen by observations



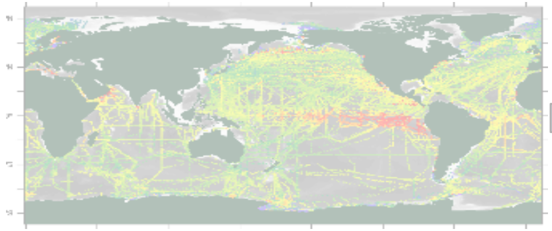
http://www.bgc-jena.mpg.de/SOCOM/

Most mapping pCO_2 mapping methods agree that the 1990s were a period of a weakening sink in the Southern Ocean, and the 2000s a period a of strengthening sink, with the multi-model mean showing a significant difference between the two decades.

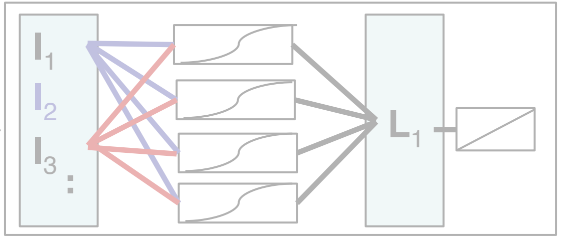
Ritter et al. (in prep.)

Dealing with sparse data…
requires sophisticated analysis and mapping methods

SURFACE OCEAN pCO_2

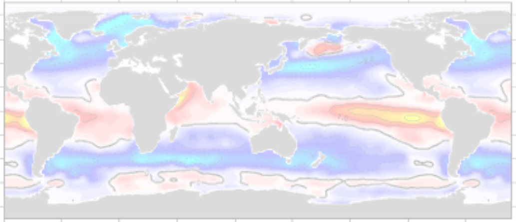


Landschützer et al. (2013,2014)



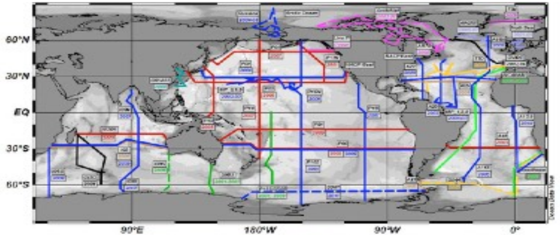
2step neural network method

AIR-SEA CO_2 FLUX

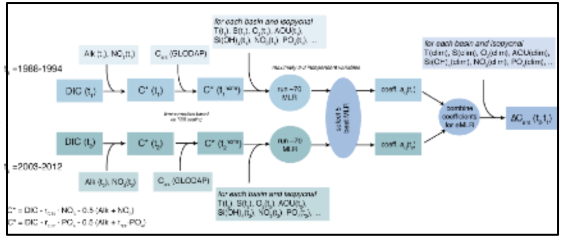


1x1°, 1982 through 2013

INTERIOR OCEAN DATA

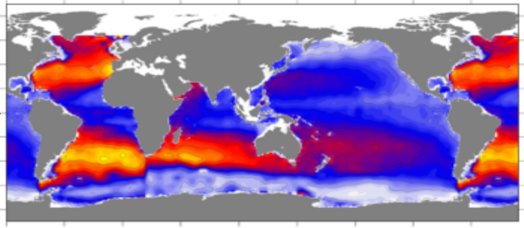


Clement and Gruber (in prep.)



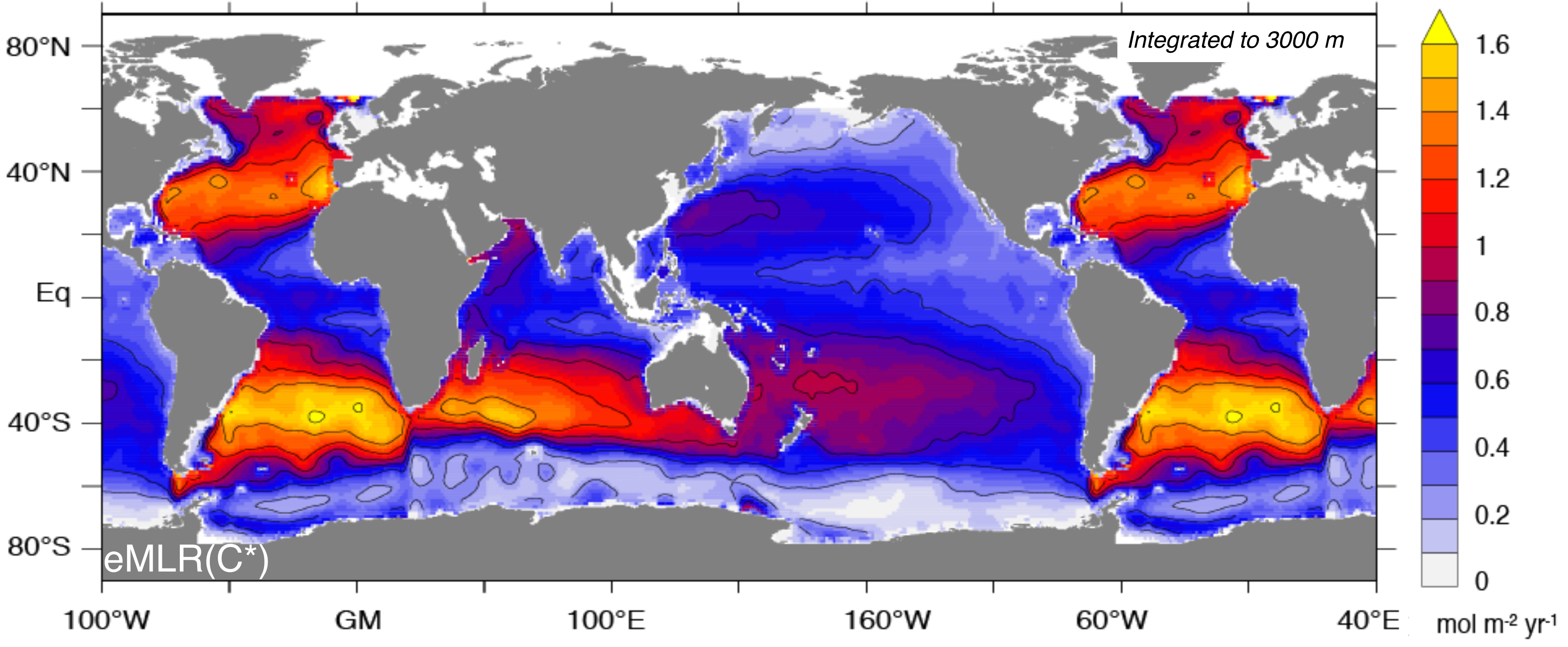
eMLR(C*) method

CHANGE IN C_{ant}



1x1°, 2007 minus 1994

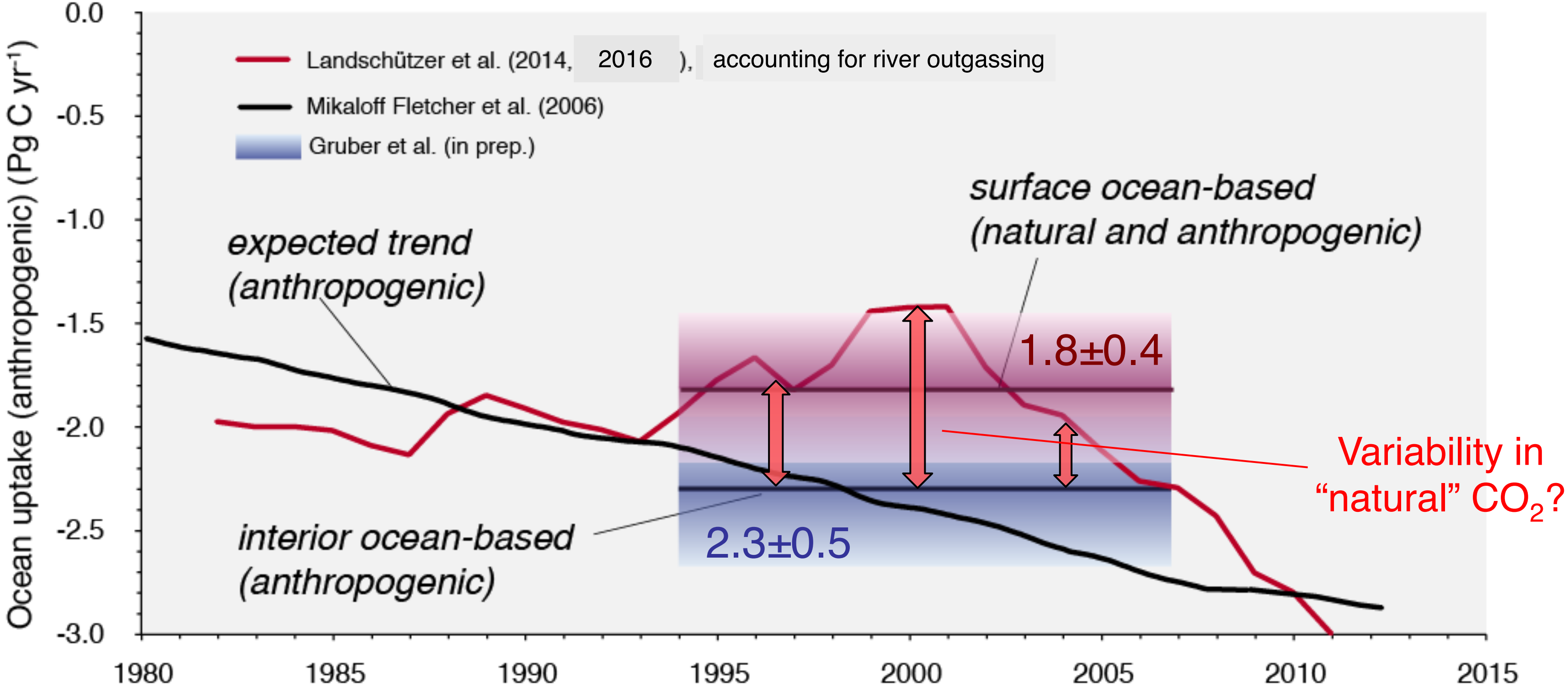
Storage rate of anthropogenic CO_2 (1994-2007)



Global Integral: 30 ± 7 Pg C *(2.3 ± 0.5 Pg C yr^{-1})*

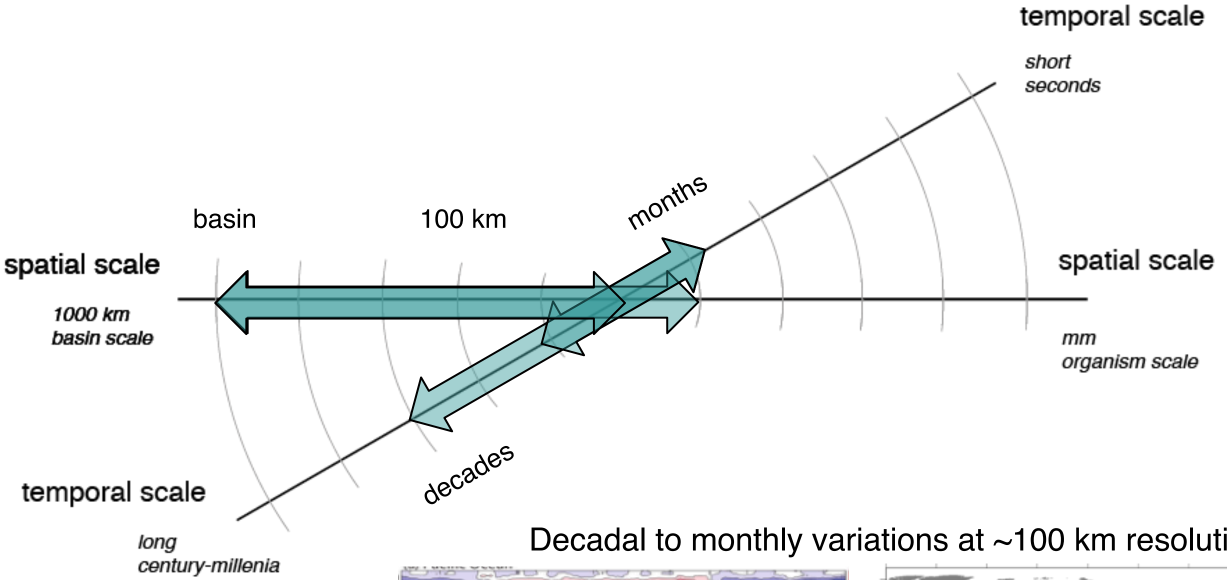
Gruber et al. (in prep)

The ocean sink – bringing the elements together

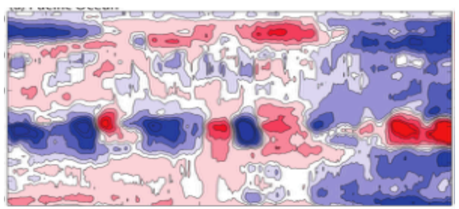


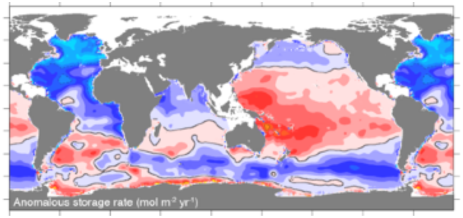
The ocean interior and surface ocean perspective provide a remarkably consistent perspective of the ocean carbon sink in the past decades.

Goals achieved: substantial expansion of (temporal) scales

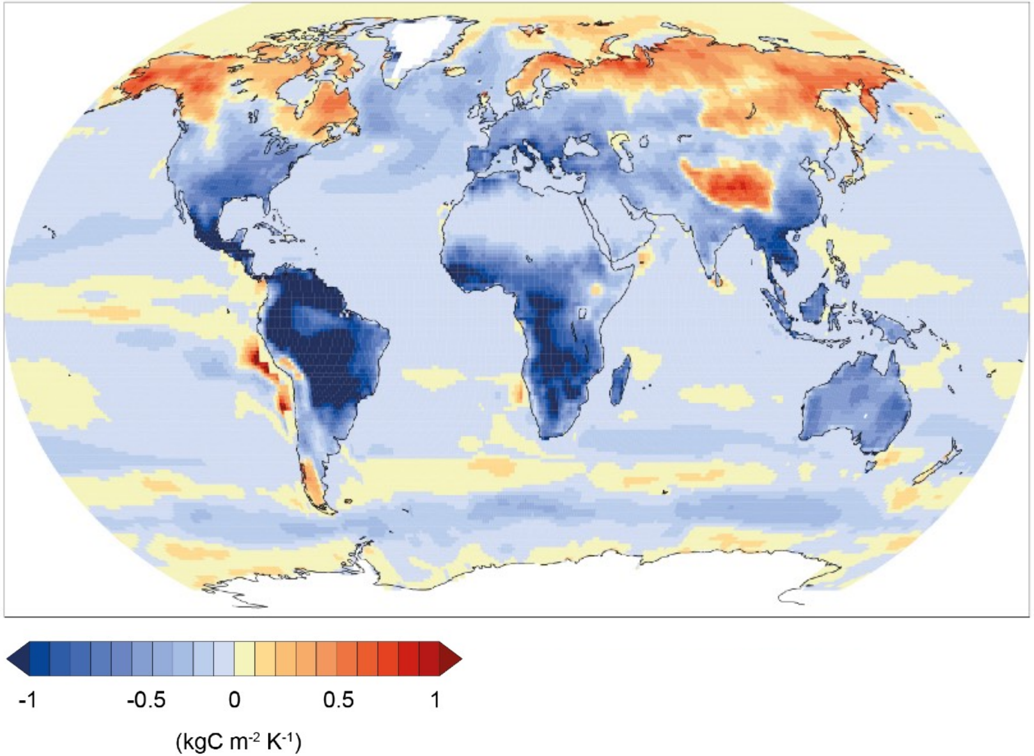


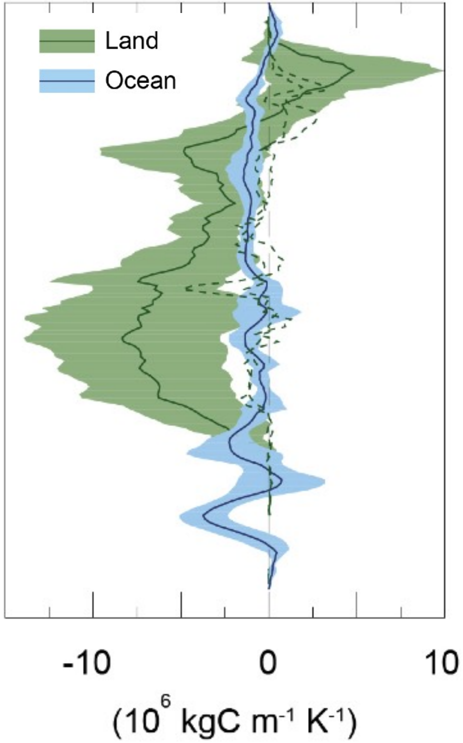
Decadal to monthly variations at ~100 km resolution





And what about feedbacks? Climate-Carbon Feedback γ

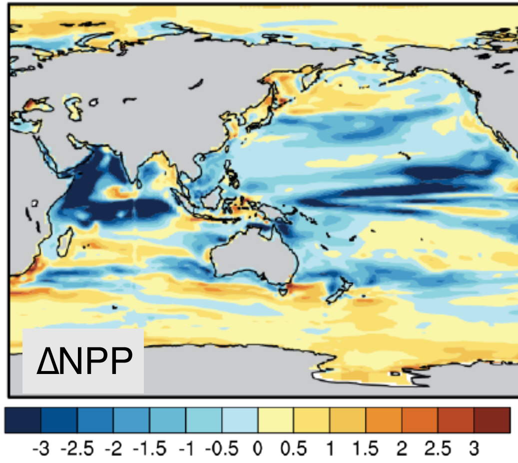


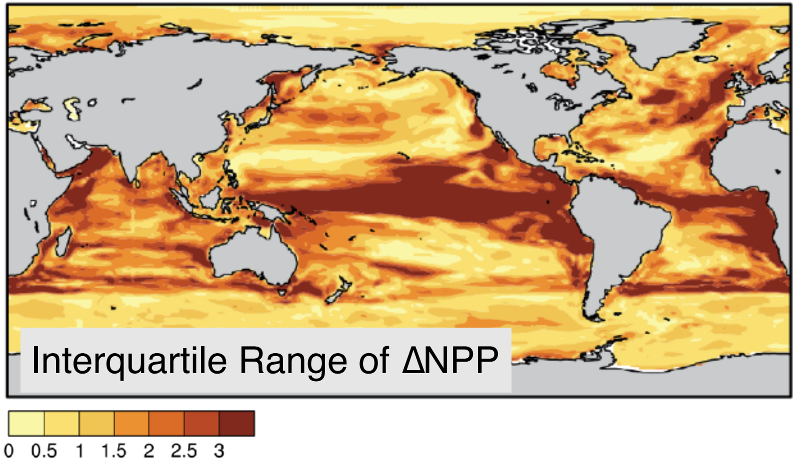


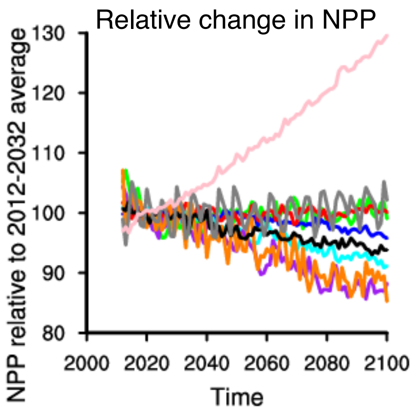
The carbon-climate feedbacks are suggested to be much smaller in the ocean than on land, with mostly negative values of γ

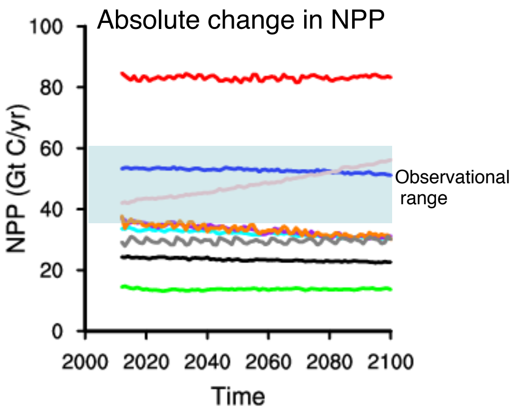
IPCC (2013) WG1 Fig 6.22

The dirty linen: Changes in ocean primary production





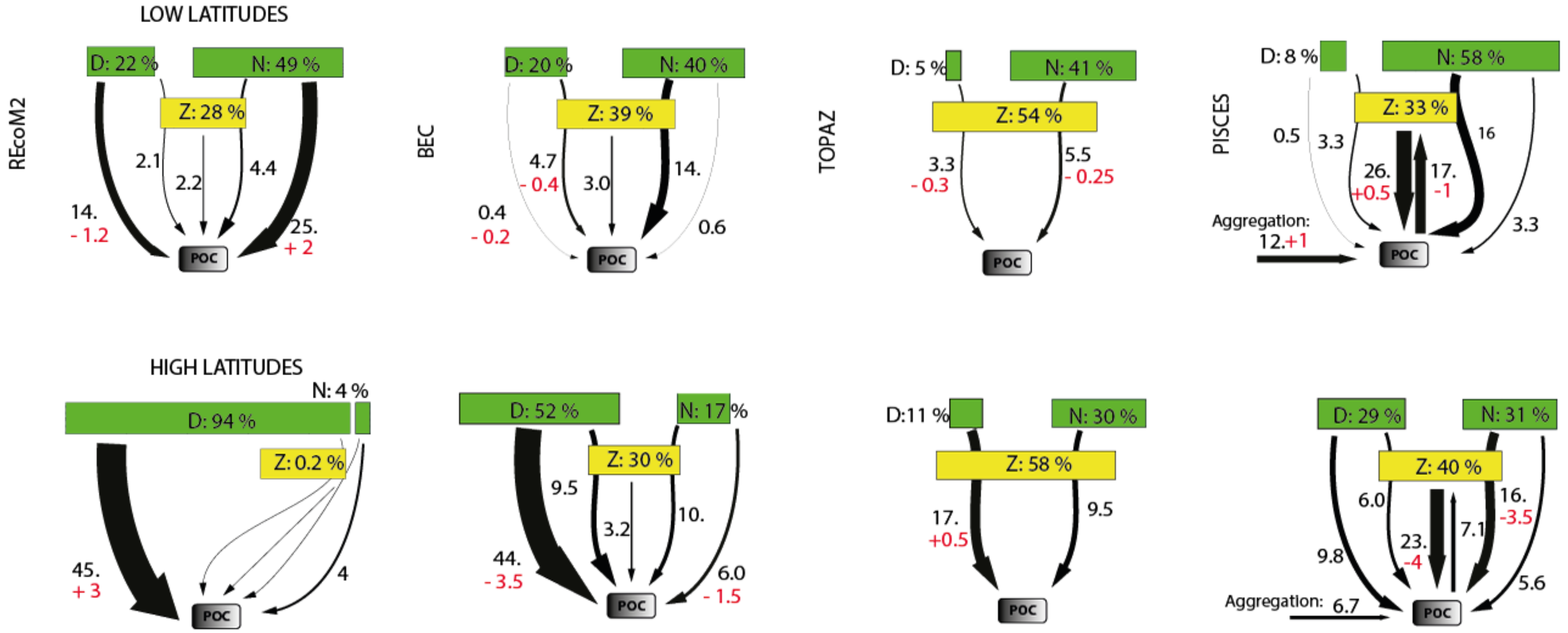




The is low confidence in the model-based projections of the changes in ocean primary production owing to a large spread in the control and in the simulated changes

Laufkötter et al. (2015)

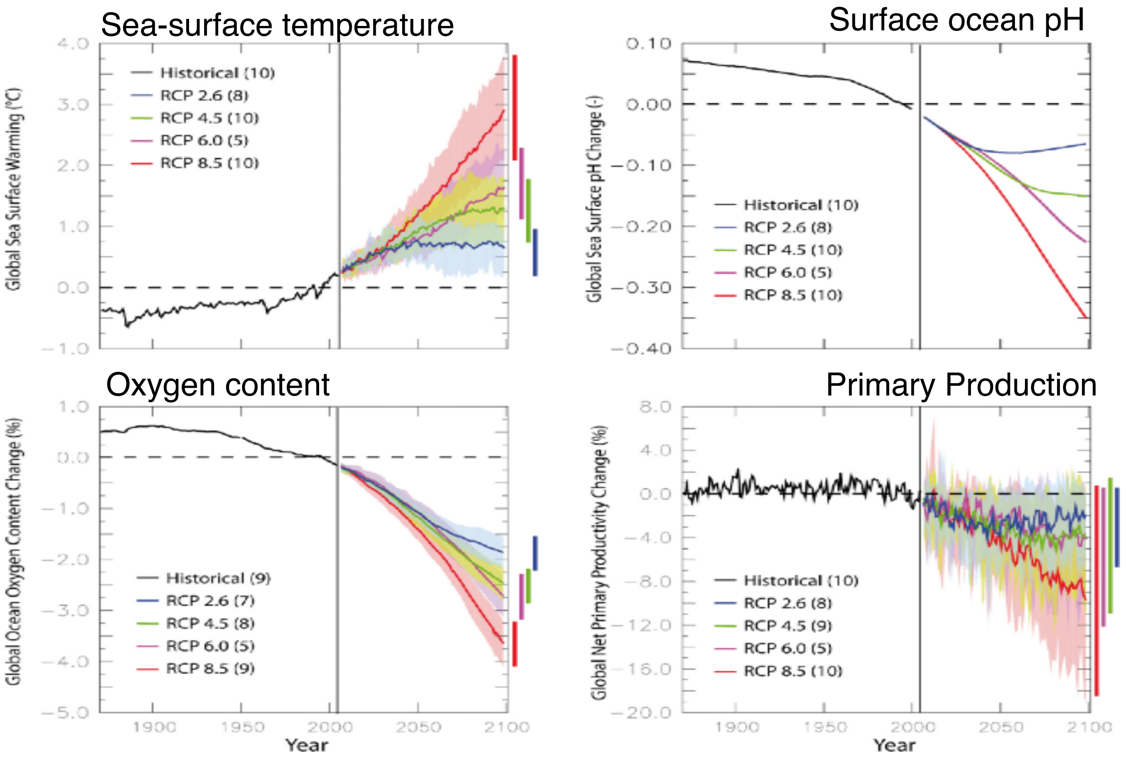
The dirty linen: Ecosystem Processes in the Earth System Models



The large differences in the control are seen not only in NPP, but also in by whom organic matter is produced and how the carbon is routed through the ecosystem.

Laufkötter et al. (2016)

The key role of multiple stressors



The ocean's biogeochemical cycles (and biology) will be seeing large and correlated changes in a warm and high CO_2 world.

Bopp et al. (2013)

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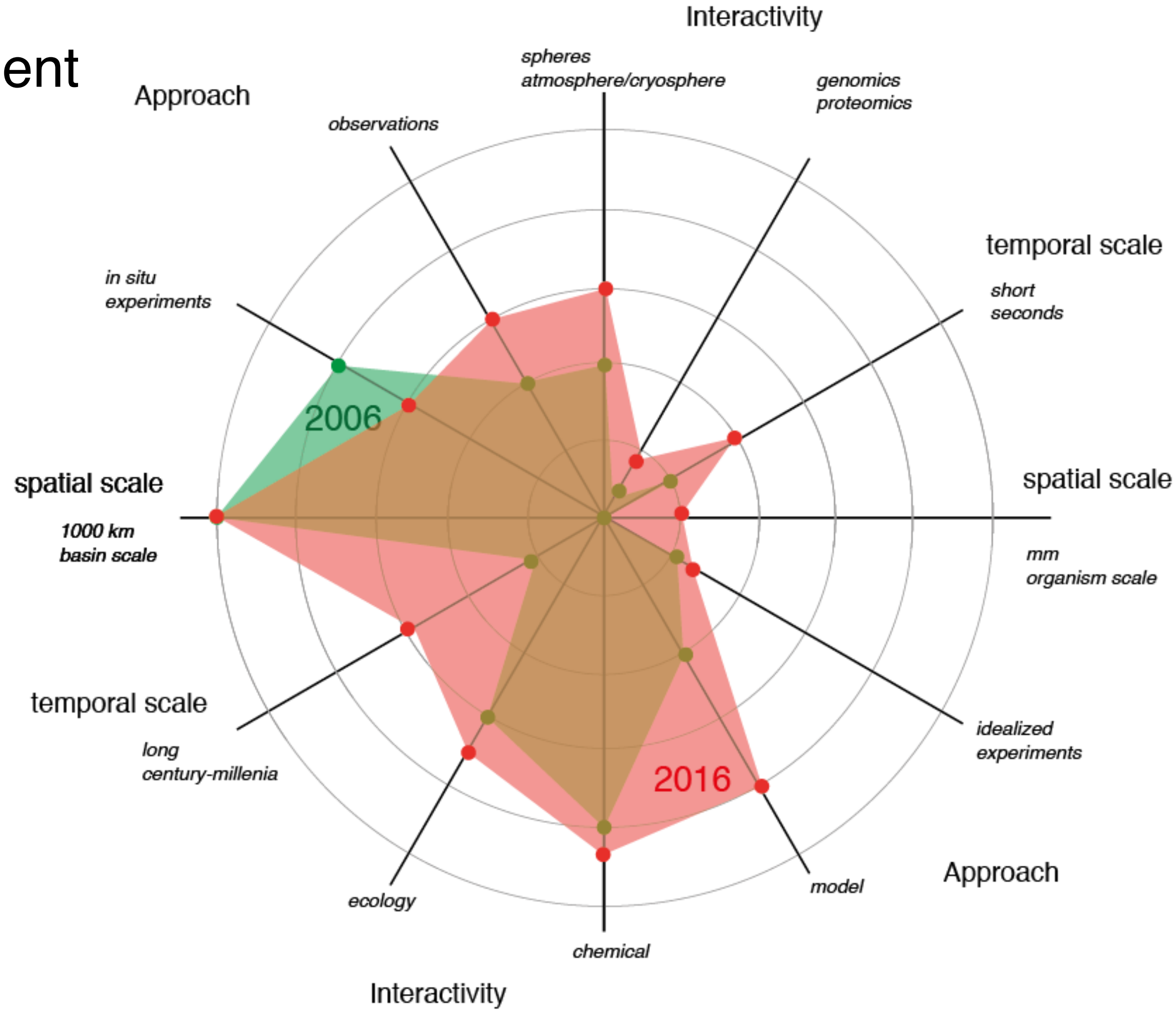
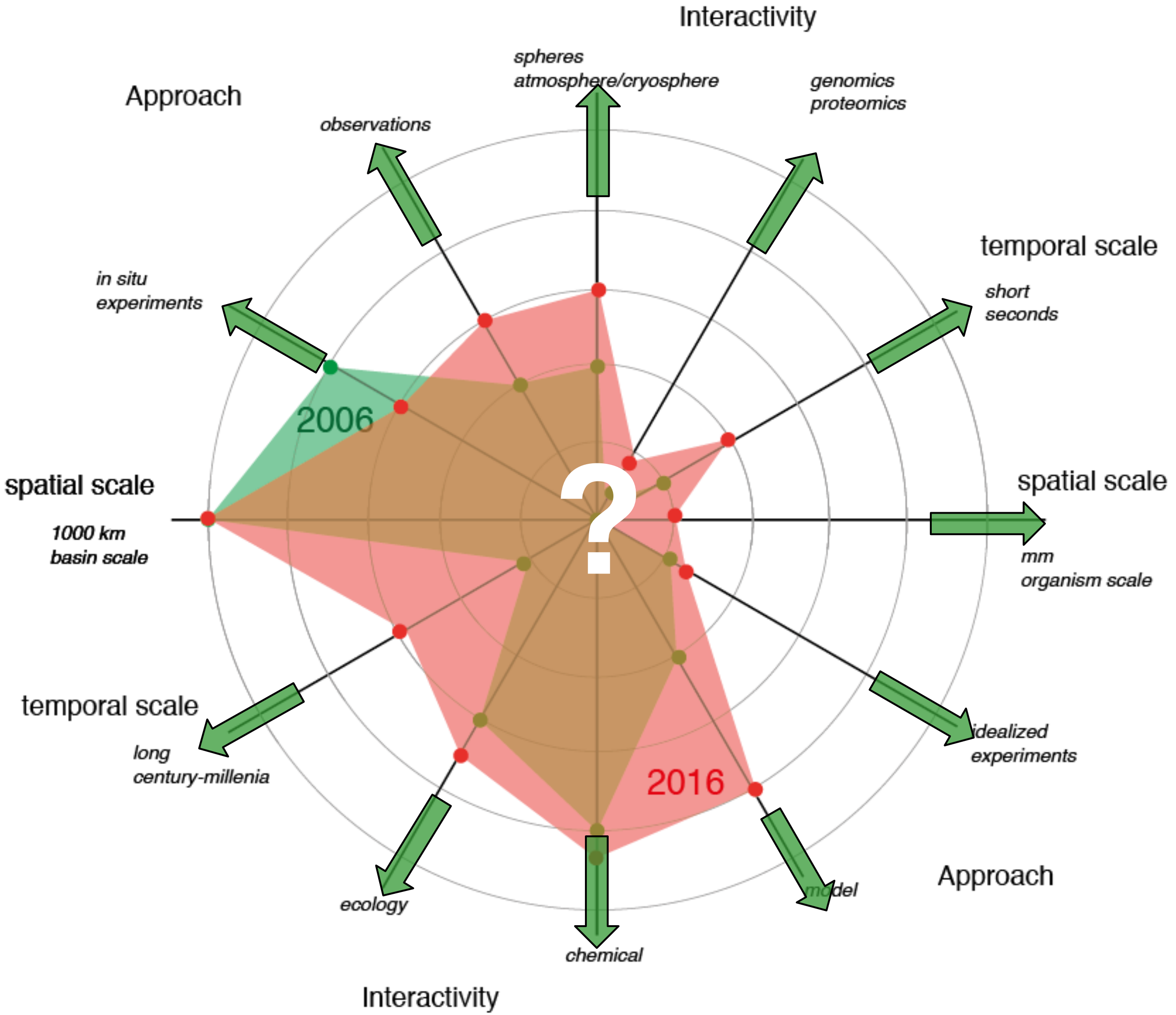
The development 2006-2016



The future?


Interactivity
spheres
atmosphere/cryosphere
genomics
proteomics
Approach
observations
temporal scale
short
seconds
in situ
experiments
2006
?
spatial scale
1000 km
basin scale
spatial scale
mm
organism scale
temporal scale
long
century-millenia
idealized
experiments
2016
ecology
chemical
model
Approach
Interactivity

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Challenges of the next decade

How much carbon will the ocean take up from the atmosphere over the next 100 years?

What is the impact of the climate change driven ocean stressors (warming, ocean acidification, nutrient stress, deoxygenation) on marine ecosystems?

Climate engineering and negative emissions:
What is the role of the ocean?

Challenges and emergent developments

CHALLENGES		*EMERGENT DEVELOPMENTS*
Ocean Carbon Sink	⟷	The Data Revolution
Ecosystem Impact & Feedbacks		The Expanding Scales
Climate Engineering		The OMIC/ECO Steam Train

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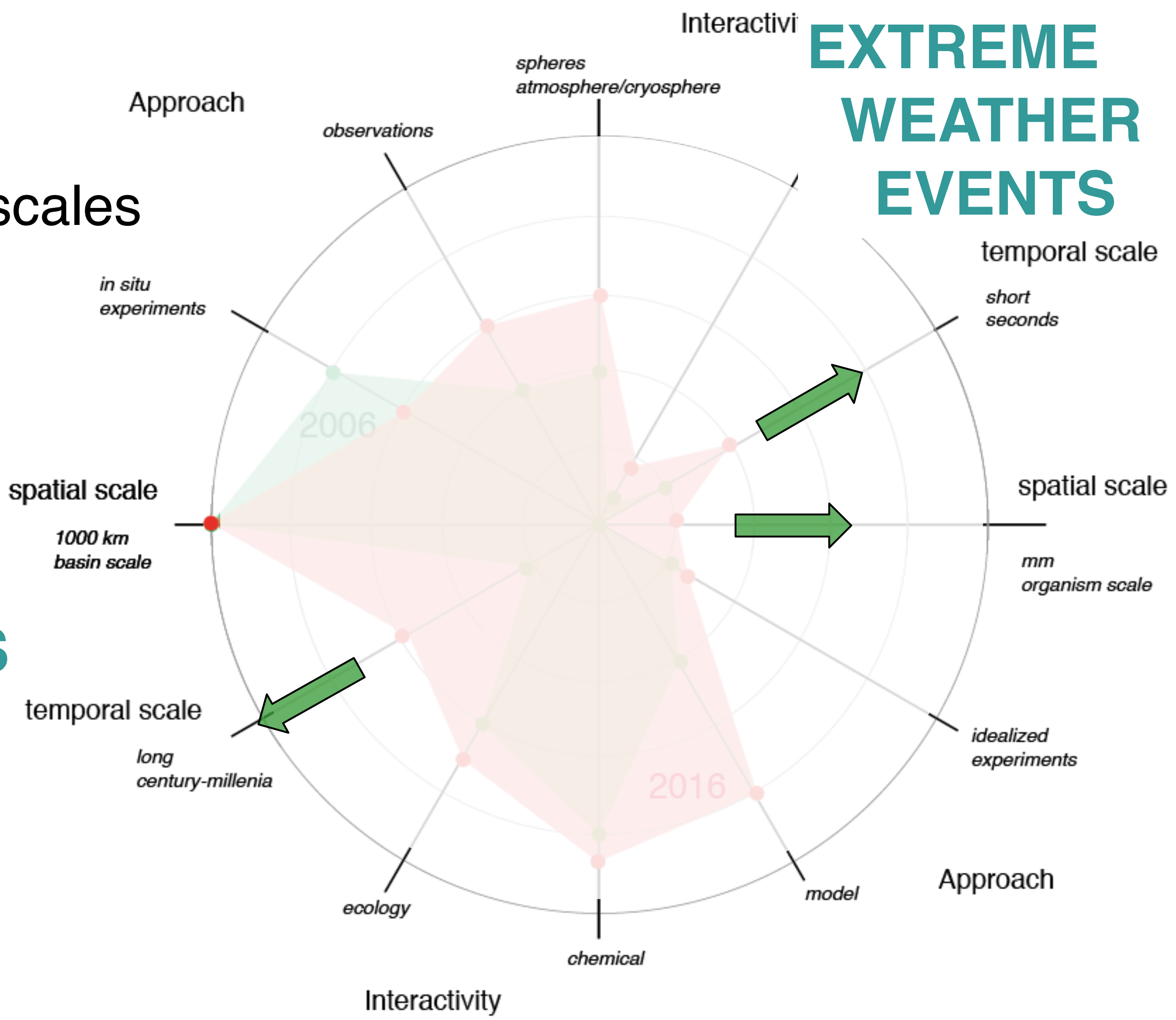
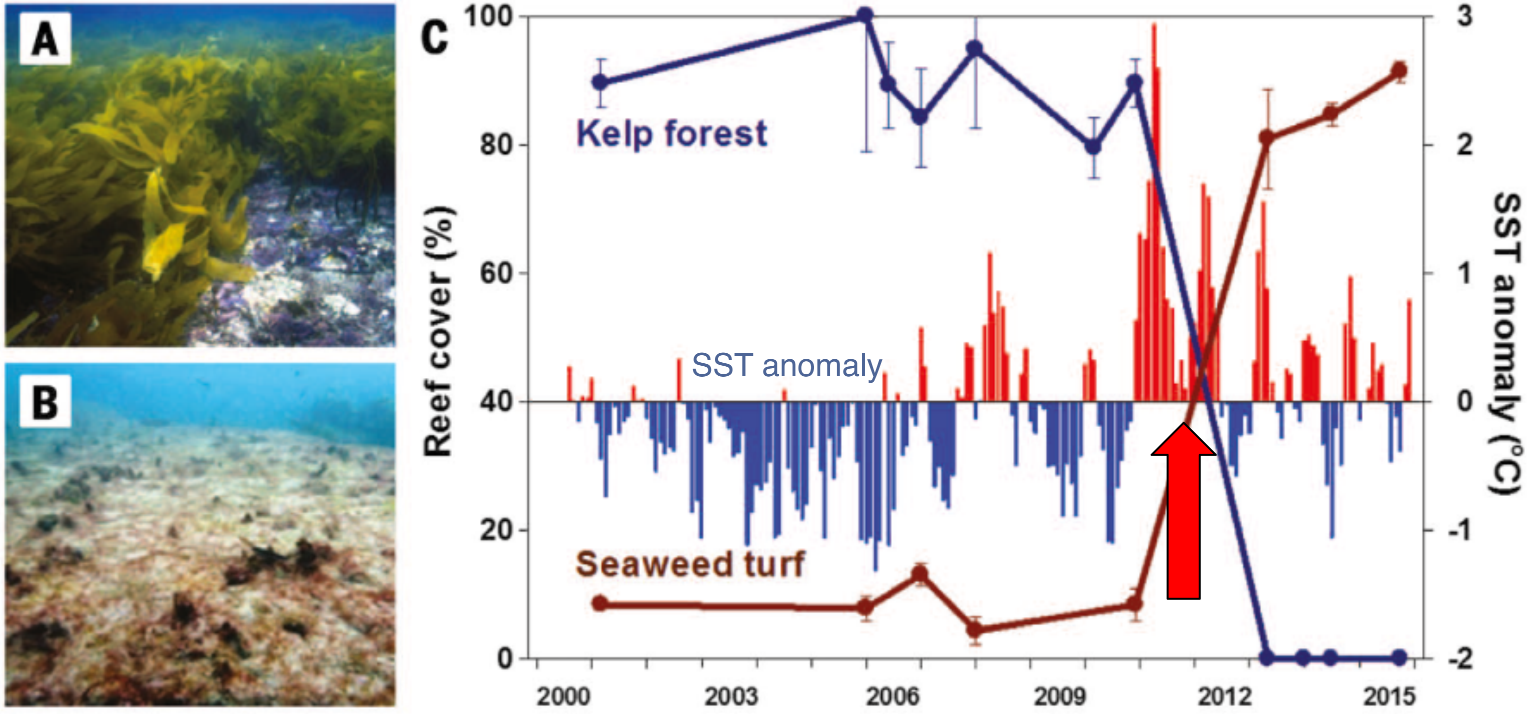
Emergent Directions I: Expanding scales



EXTREME WEATHER EVENTS

MILLENIAL VARIATIONS

A regime shift in response to a marine heat wave

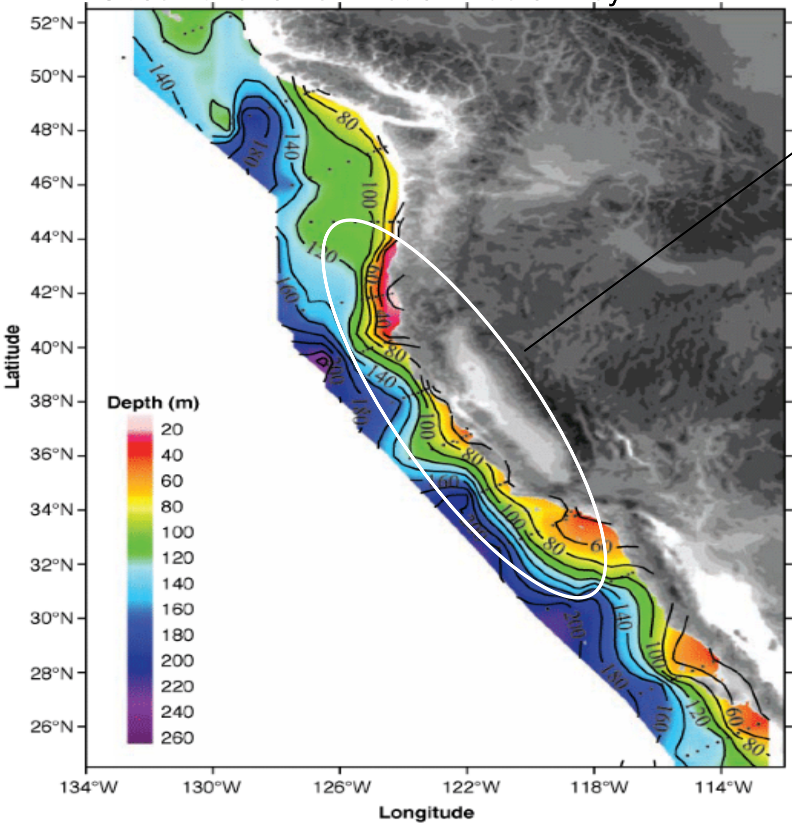


This heat wave caused a nearly complete replacement of the kelp forest ecosystem with a seaweed turf ecosystem, with associated changes in all ecosystem components.

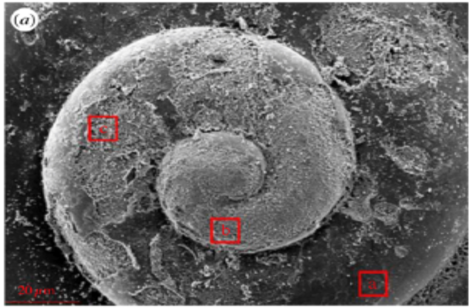
Wernberg et al. (2016)

Ocean Acidification in the California Current System

Observations from coast-wide survey



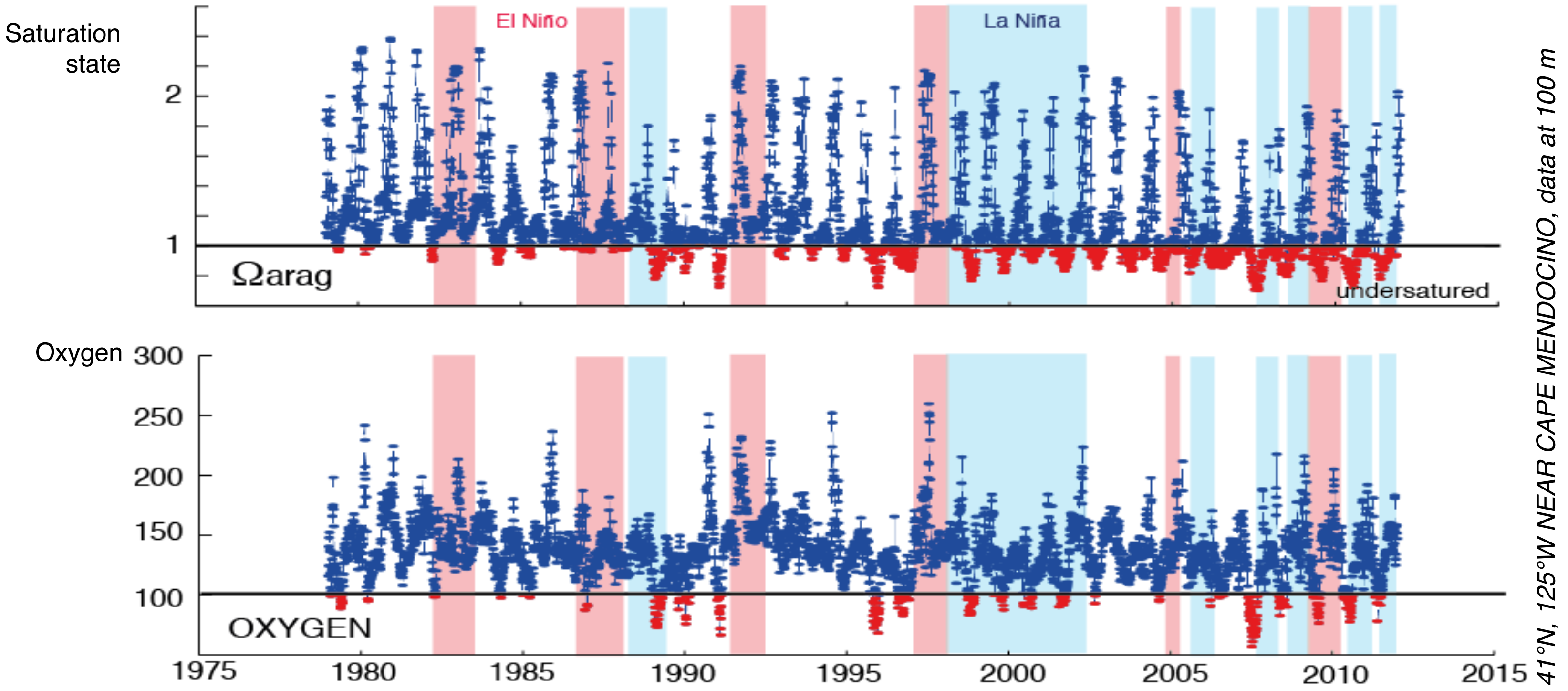
In the California Current System, the depth of saturation horizon for aragonite shoals into the euphotic zone already today!



Pteropods as potential Canaries in the coal mine

Feely et al. (2008

Simulations of extreme events in the California Current System



Undersaturation events tend to be associated with low oxygen events,

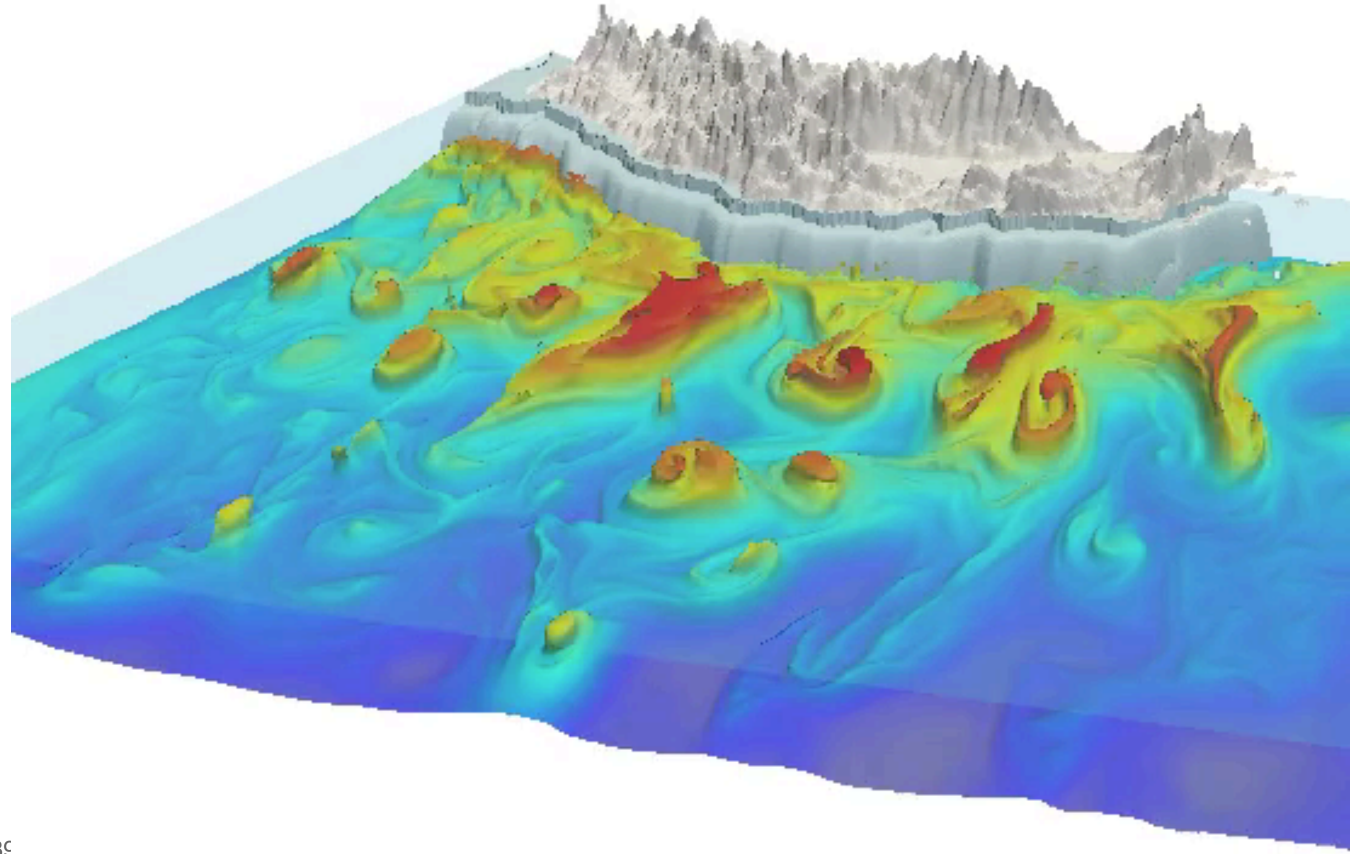
i.e, organisms are experiencing the double whammy.

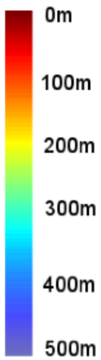
Byrne et al. (in prep.)

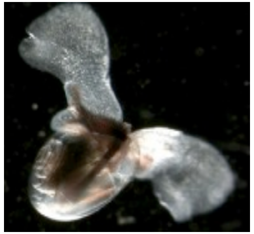
2005 Day: 1

The three-dimensional fitness landscape

The saturation horizon i.e., the depth at which Ω_{rag}=1

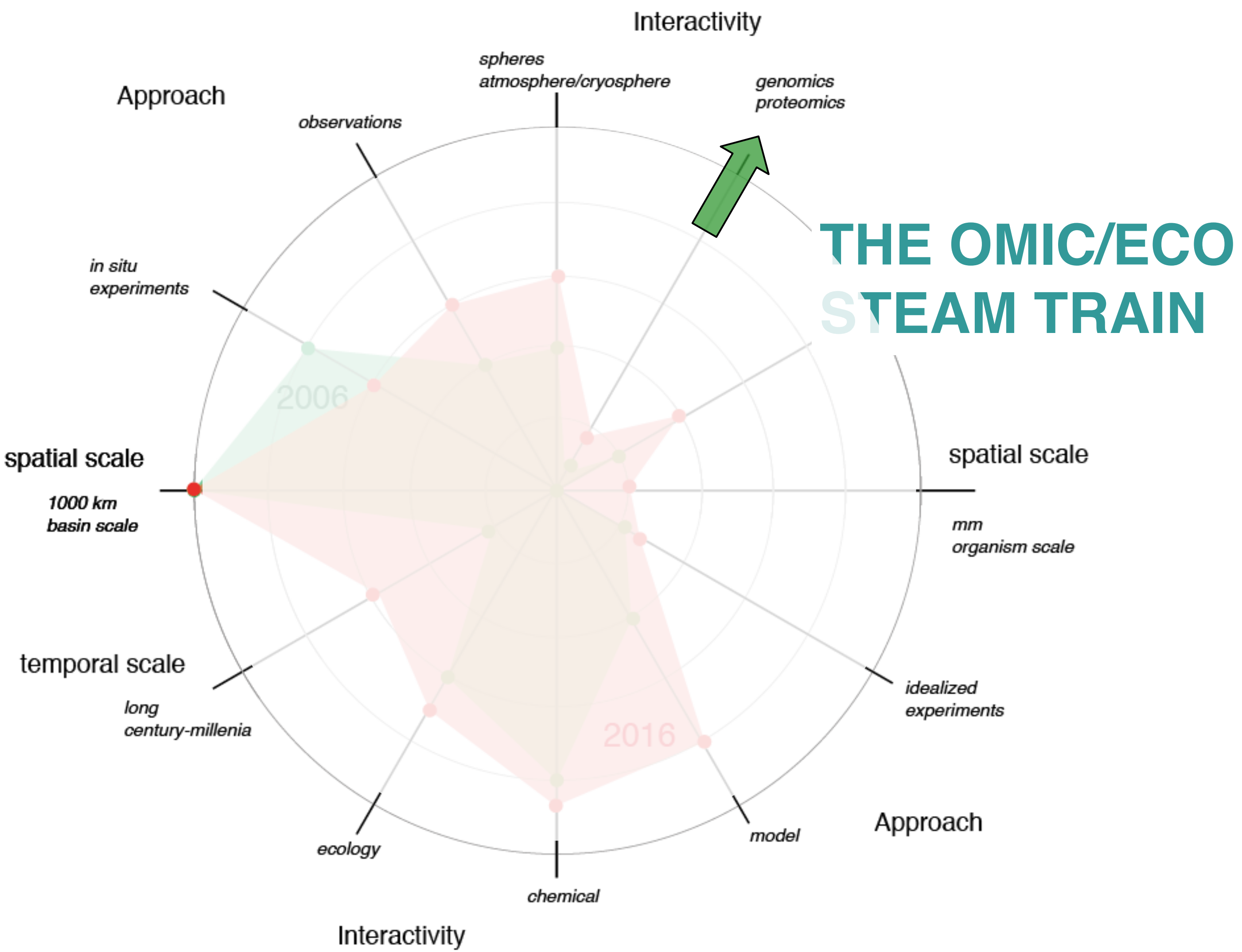




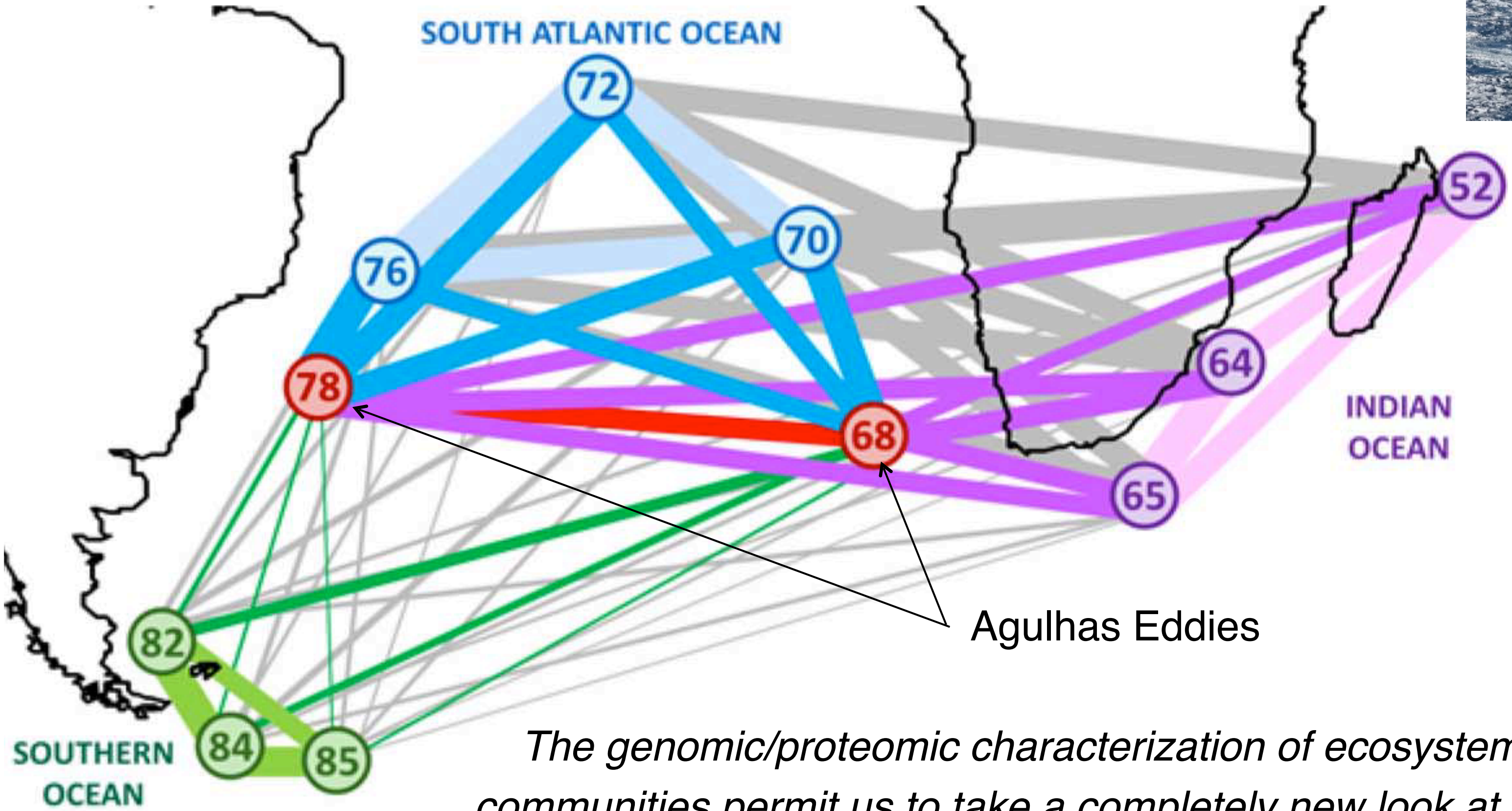


Animation by David Byrne

Emergent Directions II



The OMIC Steam Train: Community Structure

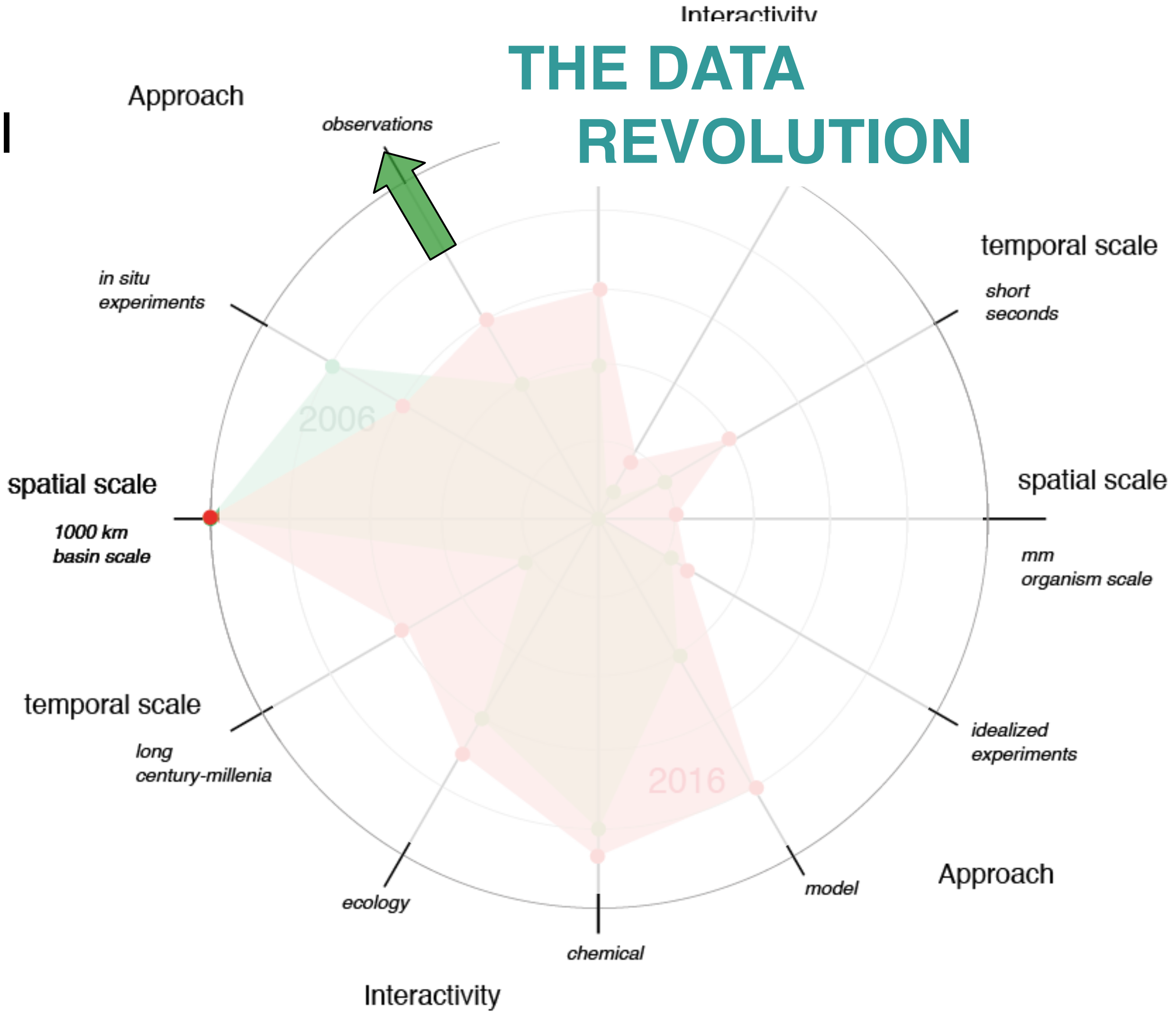


The genomic/proteomic characterization of ecosystem communities permit us to take a completely new look at the dispersion of (passive) plankton across ocean basins.

Villar et al. (2015)

Emergent Directions III

THE DATA REVOLUTION



Draft 9 June 2016

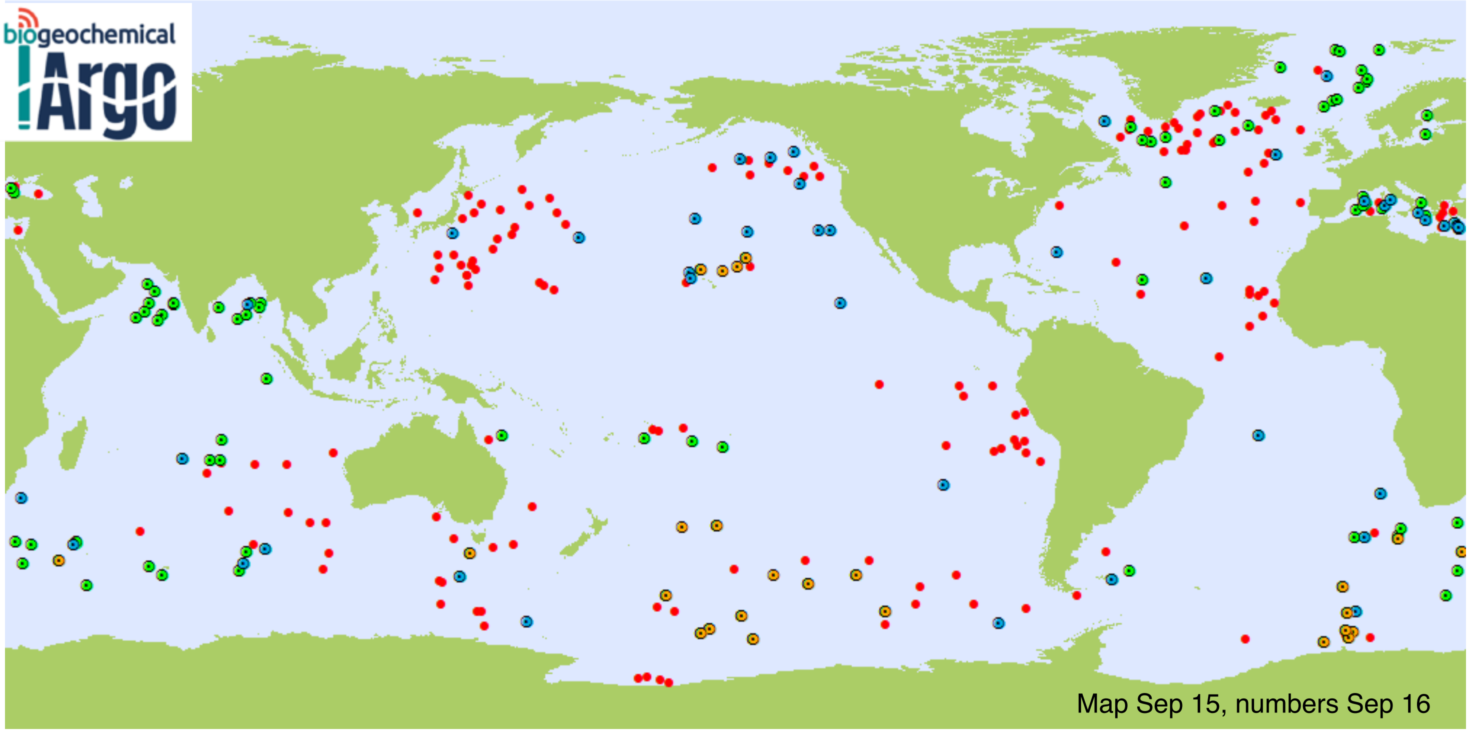
biogeochemical Argo

The Rationale, Design, and Implementation Plan for Biogeochemical-Argo

The extension of the Argo array of profiling floats to include biogeochemical sensors for pH, oxygen, nitrate, chlorophyll, suspended particles, and downwelling irradiance

http://biogeochemical-argo.org

The biogeochemical revolution in the making: BGC-Argo



Oxygen (884 deployed, 274 operational)

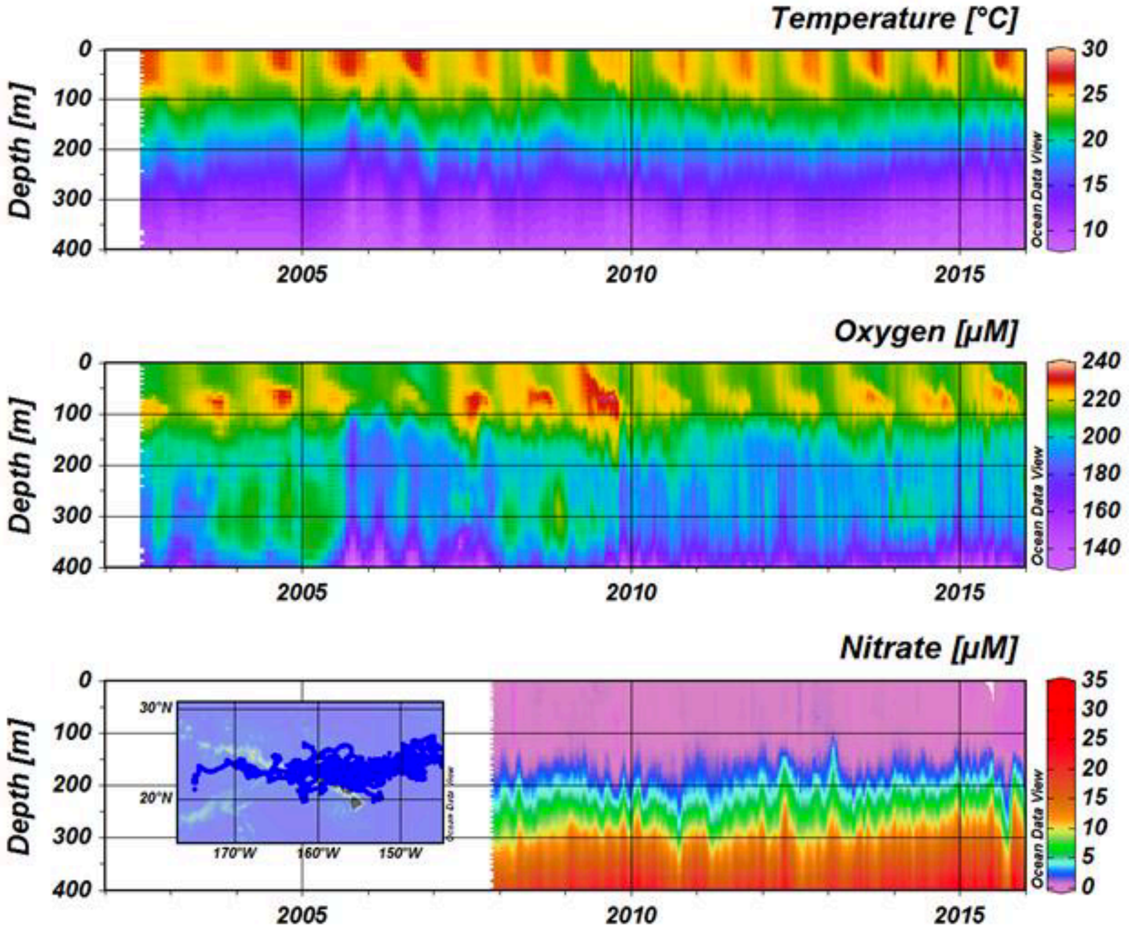
Bio-optics (230 deployed, 129 operational)

Nitrate (146 deployed, 87 operational)

pH (63 deployed, 51 operational)

JCOMMOPS & K. Johnson pers. Comm.

Proof of concept: long-term observations from Sta. ALOHA



Float-sensors have developed to the stage where they can (mostly) provide long-term accurate and precise measurements

(see also SCOR WG 142)

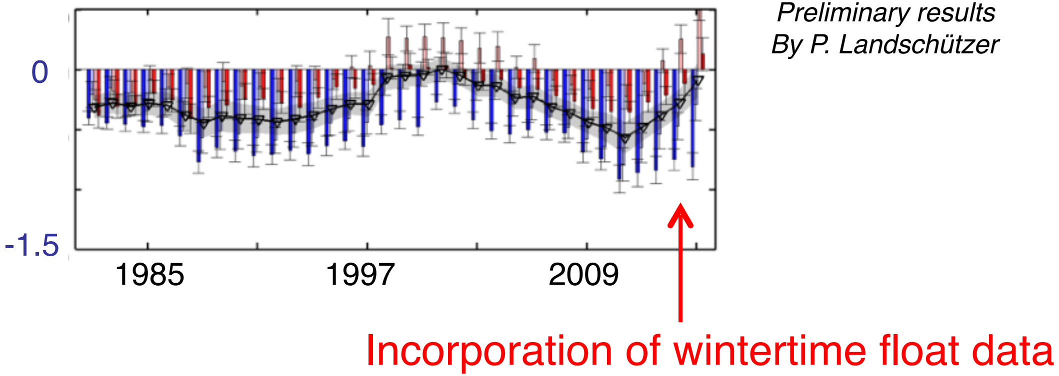
Extended from Johnson et al., [2010, 2013]

Biogeochemical Argo can address (among other):

Air-sea CO_2 fluxes

e.g. Sarmiento et al. (in prep.)

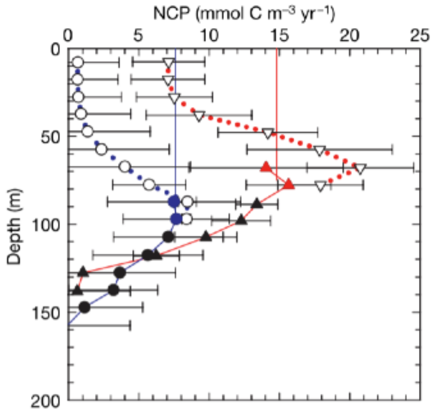
Merged estimate SOCAT & SOCCOM



Preliminary results
By P. Landschützer

Biological Productivity

e.g. Riser and Johnson (2008)



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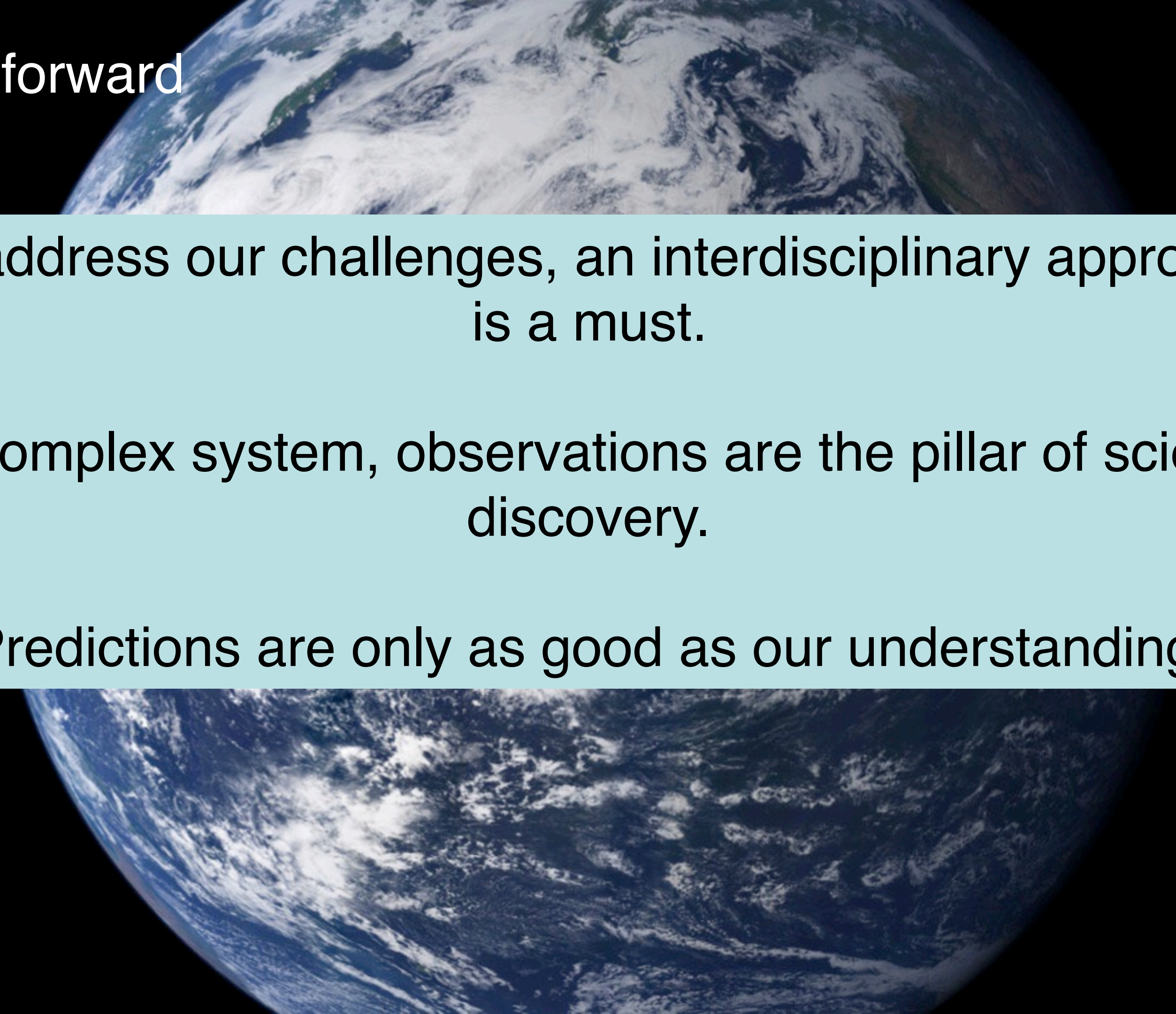
The path forward



To address our challenges, an interdisciplinary approach is a must.

In a complex system, observations are the pillar of scientific discovery.

Predictions are only as good as our understanding.

Summary and conclusions

The challenges faced by the Ocean carbon-cycle community provide many exciting opportunities for collaborations across the fields.

Biogeochemical Argo is ready to revolutionize our research and will constitute the basis for many discoveries (and solutions)

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