"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 biogeochemistry 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
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
The role of the ocean in the Earth system centers on three ecosystem services:

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Our concern about the ocean’s role in the Earth System centers on three ecosystem services:
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Strong interactions
Outline

CHALLENGES of the past decade

Emergent DIRECTIONS

OVERVIEW

Key NEW insights

SUMMARY & CONCLUSION

CHALLENGES of the coming decade
Outline

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

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

**Air-sea CO₂ flux climatology**


**Anthropogenic CO₂ inventory**

*Sabine et al., (2004)*
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 \( \text{CO}_2 \) flux at the scale of an ocean basin to <0.2 PgC yr\(^{-1} \).

Determine the uptake, transport and storage of anthropogenic \( \text{CO}_2 \) 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 \( \text{CO}_2 \) 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?
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Key NEW insights
Key development on the data side: two complementary networks

**SURFACE OCEAN NETWORK**
(Bakker *et al.*, 2014, updated)
Based on ~10’000’000 observations of surface ocean pCO2.

**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
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.

2-step neural network method

Landschützer et al. (2014, 2016)
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

Most mapping pCO₂ mapping methods agree that the 1990s were a period of a weakening sink in the Southern Ocean, and the 2000s a period of strengthening sink, with the multi-model mean showing a significant difference between the two decades.

http://www.bgc-jena.mpg.de/SOCOM/
Dealing with sparse data…
requires sophisticated analysis and mapping methods

SURFACE OCEAN $pCO_2$

Landschützer et al. (2013, 2014)
2step neural network method
1x1°, 1982 through 2013

AIR-SEA $CO_2$ FLUX

INTERIOR OCEAN DATA

Clement and Gruber (in prep.)
eMLR(C*) method
1x1°, 2007 minus 1994

CHANGE IN $C_{ant}$
Storage rate of anthropogenic CO$_2$ (1994-2007)

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

The carbon-climate feedbacks are suggested to be much smaller in the ocean than on land, with mostly negative values of $\gamma$.
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.
The ocean’s biogeochemical cycles (and biology) will be seeing large and correlated changes in a warm and high CO$_2$ world.
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OVERVIEW
The development 2006-2016
The future?
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**

Ocean Carbon Sink

Ecosystem Impact & Feedbacks

Climate Engineering

**EMERGENT DEVELOPMENTS**

The Data Revolution

The Expanding Scales

The OMIC/ECO Steam Train
Emergent Directions I: Expanding scales

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.
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)
Undersaturation events tend to be associated with low oxygen events, i.e., organisms are experiencing the double whammy.
The saturation horizon i.e., the depth at which $\Omega_{rag} = 1$

The three-dimensional fitness landscape

Animation by David Byrne
Emergent Directions II

THE OMIC/ECO STEAM TRAIN
The genomic/proteomic characterization of ecosystem communities permit us to take a completely new look at the dispersion of (passive) plankton across ocean basins.
Emergent Directions III

THE DATA REVOLUTION

- Observations
- In situ experiments
- 1000 km basin scale
- Long century-millenia
- 2006
- Spatial scale
- Temporal scale
- Chemical
- Ecology
- Model
- Idealized experiments
- Organism scale
- MM seconds

Approach

Interactivity
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

Map Sep 15, numbers Sep 16

- Oxygen (884 deployed, 274 operational)
- Nitrate (146 deployed, 87 operational)
- Bio-optics (230 deployed, 129 operational)
- pH (63 deployed, 51 operational)

Float-sensors have developed to the stage where they can (mostly) provide long-term accurate and precise measurements (see also SCOR WG 142).
Biogeochemical Argo can address (among other):

**Air-sea CO$_2$ fluxes**

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

**Biological Productivity**

- e.g. Riser and Johnson (2008)

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Incorporation of wintertime float data
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).