Modeling the carbon cycle in the polar oceans:

Present and Future Challenges

Manfredi Manizza

Scripps Institution of Oceanography
University of California - San Diego

mmanizza@ucsd.edu
Outline

1) Carbon cycle in the polar oceans and the role of (changing) sea-ice

2) BGC key-processes involving Sea-Ice

3) Models : Status and Gaps to fill

4) Conclusions
Life in a (fizzy) freezer

Modified from Vancoppenolle et al. (2013)

1) Open Water
2) Marginal Ice Zone
3) Ice-covered zone

Southern Ocean Food Web
Southern Ocean Carbon Cycle

Ito et al. (2010) (PgC yr⁻¹)

(From Princeton U.)
Arctic Ocean Carbon Cycle – I

Bates & Mathis (2009)
Arctic Ocean Carbon Cycle – II

Bates & Mathis (2009)
Polar Oceans Carbon Cycle

**Arctic Ocean**
- Smaller Area
- **CO₂ Uptake:** 0.12 - 0.06 PgC yr⁻¹
  - Schuster *et al.* (2013)
- Strong River Influence
- Land Surrounded
- Thicker Sea-Ice

**Southern Ocean**
- Bigger Area
- **CO₂ Uptake:** 0.4 – 0.27 PgC yr⁻¹
  - Lenton *et al.* (2013)
- No River Influence
- Land Centered
- Thinner Sea-Ice
Antarctic Sea-ice: Current State

1979 - 2012

More Sea-Ice

Fractional Ice cover decade$^{-1}$

Less Sea-Ice

King (2014)
Arctic Sea-ice: Current State

Arctic sea-ice becoming more “Antarctic”??

Post et al., 2013
So Similar and so Different

AR5, WG4, CRYOSPHERE
Different trajectories of Polar Carbon Sinks - SO

Le Quéré et al. (2007)

Wind dominant driver for CO₂ uptake

Toggweiler & Russell (2008)
Different trajectories of Polar Carbon Sinks - SO

OBSERVATIONS

Air-sea CO$_2$ fluxes

RECCAP, Lenton et al., 2013

Nevertheless, in the period 1990–2009 ocean biogeochemical models do show increasing oceanic uptake consistent with the expected increase of $-0.05$ Pg C yr$^{-1}$ decade$^{-1}$. In contrast, atmospheric inversions suggest little change in the strength of the CO$_2$ sink broadly consistent with the results of Le Quéré et al. (2007).

Le Quéré et al. (2007)
Different trajectories of Polar Carbon Sinks - AO

The AO is mosaic of different biogeochemical provinces.

Will the trend in CO₂ uptake continue in all the bgc provinces?

Manizza et al., (2013)
Flux > 0 : Ocean CO₂ uptake

Very many mechanisms will respond to climate change and drive the flux.

Trend in sea-ice tends to drive the CO₂ uptake in the AO
Different trajectories of Polar Carbon Sinks - AO

Changes in the Arctic Ocean CO$_2$ sink (1996–2007): A regional model analysis
M. Manizza,1,2 M. J. Follows,1 S. Dutkiewicz,1 D. Menemenlis,3 C. N. Hill,1 and R. M. Key4

2013
Ocean C-Cycle Model

CO$_2$ uptake increase
1.4 TgC yr$^{-1}$

Will it continue at the same rate, slow down, stop or reverse?

Sea-Ice data + Ocean carbon obs.

An increasing CO$_2$ sink in the Arctic Ocean due to sea-ice loss
Nicholas R. Bates,1 S. Bradley Monin,2 Dennis A. Hansell,3 and Jeremy T. Mathis3

2006
Future (Warmer) Scenarios

Vancoppenolle et al. (2013)
CMIP5 - ESMs

Stroeve et al. (2012)
Changes in sea-ice: what does it mean for ocean BGC?

Changes in the seasonal cycle of sea-ice

Earlier blooms in the Arctic Ocean

Consequences for:

1) C-export
2) Benthic feeders
3) Timing of migration of sea birds and large marine mammals

Kahru et al. (2010)
Sea-Ice, Plankton Ecology, and C-Cycle

Canada Basin - Western Arctic Ocean

Arctic Freshening

Ecological Shifts
Planktonic Ecosystem

Implications for
C-export & CO₂ uptake

Li et al., (2009)
Polar Oceans Carbon Cycle

What do we need in our models?

1) Correct sea-ice cover (time and space)

2) Inclusion of key-processes (physics and bgc)

3) Don’t forget the data (their use + evaluation) !!
Modeling Sea-Ice
Modeling Sea-Ice Cover

Flux = \alpha \cdot K \cdot (\Delta C) \cdot (1 - \gamma)

\gamma = f(x,y,t)

\alpha = f(SST)

K = f(wind speed)

(\text{Wanninkhof, 1992})

\alpha = \text{solubility factor}

K = \text{gas transfer velocity}

\Delta C = \text{air-sea gas gradient}
Learning from pitfalls

Problems with the sea-ice model can hamper our CO₂ sink estimates in the polar oceans.

Can we do better than this?

YES WE CAN!!

Manizza et al. (2013)
Modeling sea-ice: how can we have it right?

Sea-ice state estimation
Adjoint techniques
(ECCO-ICEs Effort)

Forward Model Run + Parameter exploration

“Hitting a target after several throws and failed attempts”

(Courtesy of D. Menemenlis & Ian Fenty, JPL)
Data-model fusion

Sea-Ice extent at different iterations

Optimized parameters for physical simulation coupled to C-cycle

Same thing for bgc state
Lots of computation !!!

e.g. : SOBOM-proposed effort
(PI J. Sarmiento)

(Courtesy of D. Menemenlis & I. Fenty, JPL)
Changes in Sea-Ice & Implications for Biogeochemistry and Biogeophysics
Melt Ponds

Full Sea-Ice + Snow

VS

Sea-Ice + Melt Ponds

(From cutterlight.com)

During ICESCAPE
Melt Ponds: Implications for Physical Climate

BUT ALSO Increase in PAR for photosynthesis and Primary Production under ice

(From phys.org)
Melt Ponds: Implications for Biogeochemistry

Frey et al. (2011)

Just below sea-ice
Melt Ponds: Observations, Processes & Models

A snapshot from a Transition Scenario?

Towards a more oligotrophic Arctic Ocean?

CMIP5 models suggest a future reduction in Arctic PP per unit of ocean area (Vancoppenolle et al., 2013)

ICESCAPE - Arrigo et al., (2012)
Other Potential Effect of Melt Ponds

Present Arctic Ocean

Future (Warmer) Arctic Ocean

Snow

Sea-ice

Ocean

Phytoplankton

Climate Warming

Melt Ponds
Other Potential Effect of Melt Ponds

Present Arctic Ocean

Future (Warmer) Arctic Ocean
What do we need?

K_i = Light Attenuation Coefficient in Sea-ice

K_i = f(Chl)

Zeebe et al., (1996)

K_sw = Light Attenuation Coefficient in Water

k(λ) = k_sw(λ) + χ(λ) ⋅ [Chl]^{e(λ)}

Phytoplankton influence on ocean physics and sea-ice in the polar zones

Manizza et al., (2005)
Future “greening” of the polar oceans?

As Climate progressively warms:

1. Snow
2. Sea-ice
3. Ocean

→ Ice-Free Ocean

Climate Model

→ Phytoplankton

Earth System Model

As Climate progressively warms
Sea-ice presence & planktonic assemblages

Ice-covered vs Open Water

Phytoplankton assemblages
Ecological Shits

Need for models with several Plankton Functional Types
(Le Quéré et al., 2005)
(Follows et al., 2007)

Impact on C-export & CO₂ uptake

ICESCAPE - Neukermans et al., (2014)
Sea- Ice & Nutrients
Iron in the Arctic Ocean

Klunder et al. (2012)

Manizza et al. (2009)
Iron & sea ice in the Arctic Ocean

Fe release from sea-ice into seawater

Fe uptake by sea-ice from seawater

Wang et al. (2014)

WHAT IF summer sea ice disappears in the Arctic Ocean?

A Fe-limited Future Arctic Ocean?
The case of Iron in sea ice

1) Aeolian Dust Deposition

2) BGC

3) Seasonal Exchange

\[
\frac{d(Fe_{si})}{dt} = 1 + 2 + 3
\]

Activity of Sea-ice biota might control the availability of Fe for water column phytoplankton.
Sea- Ice
&
Air-Sea Gas exchange
Flux = $\alpha \ K \ (\Delta C) \ (1 - \gamma)$

- $\alpha = \text{solubility factor}$
- $K = \text{gas transfer velocity}$
- $\Delta C = \text{air-sea gas gradient}$

Loose et al., 2014
Moving forward

\[ F = k_{\text{eff}} \Delta C, \]

\[ k_{\text{eff}} = (1 - f) k_{\text{ice}} + f k, \]

\( f \) is the fraction of open water

\( K = \) gas transfer velocity

**MODEL INPUT PARAMETERS:**

1) Wind Speed
2) Air-temperature
3) Sea-Ice velocity
4) Sea-Ice concentration

**MECHANSIMS TO MODEL**

1) Buoyancy/Stratification
2) Sea-Ice/Water Shear
3) Gravity Waves/ice floes

(Loose et al., 2014)

**OGCM + C-CYLE MODEL**

**OF POLAR OCEANS**
Still a long way to go...

Two Missing Processes:

1) Brine & CO₂ rejection:
   Deep water formation process and CO₂ uptake.

2) Sea-ice Decay & ALK release:
   Enhances CO₂ uptake at sea-ice margin during summer melting

Rysgaard et al. (2011)
CONCLUSIONS & FUTURE DIRECTIONS

THOUGHTS: Changes in sea-ice will play an important role at modulating the CO₂ uptake in the polar oceans both in the near and distant future as climate continues to change due to anthropogenic activities.

GOALS: Incorporation of new processes in ocean biogeochemical models will help us to better understand and predict the response of the ocean carbon cycle to the modifications of sea-ice due to climate change.

NEEDS: Extensive observational programs and tools are and will remain VITAL to our community to understand the changing carbon cycle of the polar oceans and predict its impact on Earth’s climate. This will help us to monitor the changes, constrain the rates of processes, and improve our models.
Sea-Ice thickness estimation

Improved representation of ice thickness during the Oct 3-Nov 8, 2004 ICESat campaign following the synthesis of sea ice concentration data

(Courtesy of D. Menemenlis & I. Fenty, JPL)