From surface measurements to atmosphere-ocean gas fluxes

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Sun has warmed by 25% over this period, but we’re ok!

How is this possible?
Sun has warmed by 25% over this period, but we’re ok!

How is this possible? Carbon and water!
Typical composition of atmosphere

The byproduct of this carbon and water regulation is air we can breathe.

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* In a dry atmosphere, by volume

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Carbon pools on land and in the ocean.

* In a dry atmosphere, by volume.
Our climate and the importance of the ocean

• Carbon is the basis of all life on Earth.

• Carbon cycle and water are key for regulating the temperature on Earth.

• Bi-product is that it also regulates CO₂ in the atmosphere (CO₂ is a trace gas)

• Earth holds a lot of carbon, but very little is airborne.

• The two largest stores of carbon on Earth are the Earth’s crust and the ocean!
Global carbon budget and the importance of the oceans

25% of all anthropogenic carbon (since 1870!) has been absorbed by the ocean (Le Quere, 2018).

Source: CDIAC; Le Quéré et al 2018; Global Carbon Budget 2018
Nations Unies
Conférence sur les Changements Climatiques 2015
COP21/CMP11
Paris, France
Critical aspects oceanic carbon cycle
Marine carbon cycle
Marine carbon cycle
Two-film model of air-sea gas exchange

Two-film model of air-sea gas exchange

Surface CO$_2$ transfer and export to the deep ocean

\[ F = k (\alpha_w pCO_{2w} - \alpha_s pCO_{2a}) \]

Some sort of turbulence description called the gas transfer velocity

Atmosphere

Surface ocean

Deep ocean

\( pCO_{2a} \) = Partial pressure of CO$_2$ in the atmosphere

\( \alpha = \) Solubility

\( pCO_{2w} \) = Partial pressure of CO$_2$ in the surface water

Simplified box model neglecting the mixed layer pump (Dall’Olmo et al., 2016).
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Some sort of turbulence description called the gas transfer velocity

Simplified box model neglecting the mixed layer pump (Dall’Olmo et al., 2016).
Solubility pump ($F_{SOL}$)

- Sometimes called the physical carbon pump (as it is determined by physics – i.e. temperature, salinity and turbulence).
- $CO_2$ diffuses across the atmosphere-ocean interface.
- Cold water can hold more $CO_2$ in solution than warm water (solubility).
- Cold, denser (and $CO_2$ rich) water is then transported away via thermo-haline processes and vertical circulation.
- $CO_2$ is outgassed in areas where warmer water exists or comes to the surface.
Surface CO$_2$ transfer and export to the deep ocean

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Simplified box model neglecting the mixed layer pump (Dall’Olmo et al., 2016).
Biological pump ($F_{BIO}$)

- Biological growth within upper layers of ocean.
- Occurs in the Euphotic zone (Greek ‘well lit’).
- As on land as plants grow they take up CO$_2$ and breath out oxygen.

- Removes CO$_2$ from the water and ‘locks’ it away as living matter.
- CO$_2$ is ‘fixed’ into carbon compounds of the living matter (i.e. removed from solution).
- Combination of soft tissue and carbonate systems.
- Some is then deposited to the sea bed when the living matter dies (hence large carbon pool locked away).
- Some is re-mineralised. i.e. decay by bacteria causes some CO$_2$ to be released back into the water.
Surface CO$_2$ transfer and export to the deep ocean

\[ F = k \left( \alpha_w pCO_{2w} - \alpha_s pCO_{2a} \right) \]

\[ pCO_{2a} = \text{Partial pressure of CO}_2 \text{ in the atmosphere} \]

\[ \alpha = \text{Solubility} \]

\[ pCO_{2w} = \text{Partial pressure of CO}_2 \text{ in the surface water} \]

Simplified box model neglecting the mixed layer pump (Dall’Olmo et al., 2016).
Surface CO$_2$ transfer and export to the deep ocean

$$F = k \left( \alpha_w \, pCO_{2w} - \alpha_s \, pCO_{2a} \right)$$

$\alpha = $ Solubility

$pCO_{2a} =$ Partial pressure of CO$_2$ in the atmosphere

$pCO_{2w} =$ Partial pressure of CO$_2$ in the surface water

CO$_2$ is predominantly water-side controlled.

Some sort of turbulence description called the gas transfer velocity. Can be air-side or water-side controlled (gas dependent).

Simplified box model neglecting the mixed layer pump (Dall’Olmo et al., 2016).

Total exchange is driven by the system wanting to move towards thermodynamic equilibrium.
Indirect calculation of atmosphere-ocean gas exchange using bulk parameters

The air-sea flux of CO$_2$ is estimated using:

$$ F = k \left( \alpha_w \ pCO_{2w} - \alpha_s \ pCO_{2a} \right) $$

$\alpha$ = solubility, at depth (w), at the interface or skin (s)

$k$ = gas transfer velocity

$pCO_2$ = partial pressure of CO$_2$, at depth (w), at the interface (a)

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$pCO_2 = \text{partial pressure of CO}_2, \text{ at depth (w), at the interface (a)}$

Need: measurements or proxies for physics (temperature, salinity, surface turbulence), biology (e.g. dissolved oxygen), the amount of gaseous CO$_2$ in the water ($pCO_{2w}$) and atmosphere ($pCO_{2a}$).

Two-film model of air-sea gas exchange

Air phase
- Air-side mass boundary layer (0.1–1 mm)
  - $C_{a,0}$
  - $C_{w,0} = \alpha C_{a,0}$

Water phase
- Viscous boundary layer (0.6–2 mm)
- Reference level
  - $C_{w, \text{bulk}}$

What is the surface?

Consolidated methods for temperature and salinity handling within gas flux calculations


Consolidated methods for temperature and salinity handling within gas flux calculations

Quantified the thermal influences on calculation of air-sea gas fluxes:

Table 1. Thermal Effects on the Calculation of Air-Sea Gas Fluxes (Carbon Dioxide and Other Poorly Soluble Gases), Notation, and the Significance of Each

<table>
<thead>
<tr>
<th>Origin of Effect</th>
<th>Subsection and Scaling</th>
<th>Scaling Parameter</th>
<th>Approximate Scaling Factor (CO₂)</th>
<th>Effect on Unreactive, Ideal Gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor pressure and nonideality</td>
<td>Section 2.1, ( \Phi_1 )</td>
<td>( C_i )</td>
<td>(-0.2%/K)</td>
<td>Similar, but smaller effect related to nonideality vanishes</td>
</tr>
<tr>
<td>Solubility</td>
<td>Section 2.2, ( \Phi_2 )</td>
<td>( C_i )</td>
<td>(-2.5%/K)</td>
<td>Variable, but typically most important</td>
</tr>
<tr>
<td>Carbonate chemistry</td>
<td>Section 2.3, ( \Phi_3 )</td>
<td>( C_M )</td>
<td>(+1.5%/K)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Schmidt number</td>
<td>Section 2.4, ( \Phi_4 )</td>
<td>( C_i - C_M )</td>
<td>(+2.5%/K)</td>
<td>Variable, but typically significant</td>
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Clarified a misconception

\[
F = k\alpha_w (fCO_{2w} - fCO_{2A}) \\
\neq \\
F = k(\alpha_w fCO_{2w} - \alpha_s fCO_{2A}),
\]

Reduced accuracy

More accurate calculation


Open source FluxEngine air-sea gas flux toolbox (Python)

https://github.com/oceanflux-ghg/FluxEngine

Toolbox developed for community use:

- Open source license (Python).
- Stand alone functions or Python library.
- Net flux tool with traceable land/ocean/basin templates.
- User configurable gas flux calculation.
- Extensively verified using published data.
- Used within 8 journal papers (e.g. uncertainty ensembles, inter-comparison, investigating the role of biology)


Example mean daily flux output

Example process indicator layer output using ESA Climate Change Indices chl-a
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Example process indicator layer output using ESA Climate Change Indices

Example mean daily flux output

https://github.com/oceanflux-ghg/FluxEngine/blob/master/README.md
Example 1: Impact of mishandling temperature for an in-situ research cruise

Example 2: Impact of mishandling temperature for calculating the global oceanic sink of carbon

16 year time series analysis using SOCATv4 + climate quality satellite datasets.
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16 year time series analysis using SOCATv4 + climate quality satellite datasets.
Ignoring concentration difference results in an underestimate (bias) of $0.35 - 0.44$ Pg C yr$^{-1}$ (or 18 - 21% of oceanic net sink).
Two methods of calculating fCO$_2$ fields for 2010 yield the same result of 0.35 Pg C.
Example 3: Impact of surfactants


Invisible scum on sea cuts CO2 exchange with air 'by up to 50%'

Example 4: monitoring estuary gas fluxes

• Important pathways from land to seas
• **Highly variable** – mixing of tidal & freshwater sources
• Cover **0.2% of global ocean area**
• Emit up to **28 mol C m\(^{-2}\) yr\(^{-1}\)**: Equivalent to that absorbed by 96% of continental shelf area

_Joesoef et al, 2015_
Example 4: monitoring estuary gas fluxes

- Develop a **low-cost & high quality** method to quantify **in-situ CO₂ gas fluxes** in the **Fal estuary**

- Test approach for **3 months** to evaluate accuracy & precision of a low-cost CO₂ sensor.

- Identify where & how the method could be **expanded throughout Europe**

- Use the **FluxEngine toolbox** for all calculations.
Requirements:
- Collect continuous data every 30 mins
- Minimal power and data use
- Small & light
- Low cost & simple to install
- High accuracy

Sensors deployed:
- Temperature x2
- Conductivity (Salinity)
- Dissolved oxygen
- Pressure
- $pCO_2$
Importance of collecting water samples to monitor calibration and the need for supporting measurements to quality control all critical measurements.
The average lifetime = 79 years, means that our personal CO$_2$ emission allocation is 1.4 Tonnes of CO$_2$ per year for each year of our life on Earth.

(Recent journal papers have stated between 1 to 2 Tonnes of CO$_2$ per year)
Annual emissions globally per person

Target for a safe climate is 1.4 Tonnes of CO₂ (calculated from IPCC data).

1 long-haul flight (e.g. transatlantic) results in ~2 Tonnes of CO₂

Source: CDIAC; Le Quéré et al 2018; Global Carbon Budget 2018
We study the environment, is our carbon footprint sustainable?

Towards a culture of low-carbon research for the 21st Century

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Use your CO₂ emissions wisely and be aware of how your work is impacting the environment and climate.
Practical session
Run by Dr Tom Holding and Dr Ian Ashton

2.5 hours long practical

Interactive tutorials using Jupyter notebooks (iPython). e.g. you can edit the example code within each tutorial and re-run the code!

Worked examples of how to use the FluxEngine atmosphere-ocean gas flux toolbox.

All examples are from Holding et al. (2019, in-review) and include how to calculate gas fluxes from i) a globally collated dataset (SOCAT), ii) CO$_2$ cruise in situ data, iii) a fixed monitoring station, iv) N$_2$O in situ data.
The global carbon cycle by David Archer (Princeton Primers in Climate). Available online for free.

Surface ocean processes, edited by Corinne Le Quere and Eric S. Saltzman. Available online for free.

Edited by Peter Liss and Martin Johnson. Available online for free.
References


Shutler, J. D., Holding, T., (in-review), Wind, wave and current contributions to cross shelf water exchange and carbon export; new observations and the potential of SKIM, for submission to Environmental Research Letters.


Jamie Shutler, Rik Wanninkhof ², Philip D. Nightingale ³, David K. Woolf ⁴, Dorothee C. E. Bakker ⁵, Andy Watson ¹, Ian Ashton ¹, Thomas Holding ¹, Bertrand Chapron ⁶, Yves Quilfen ⁶, Chris Fairall ², Ute Schuster ¹, Masakatsu Nakajima ⁷, Craig J. Donlon (in-review), Satellites will address critical science priorities for quantifying ocean carbon, Frontiers in Ecology and Environment.