Too close, yet so far: Exploring Microbial Ecology in the Top Meter of the Ocean

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2010 C-MORE symmer course in Microbial oceanography, Univ. of Hawaii, 15 June, 2010
Two closely-coupled geophysical fluids

Who, then, evolved the sea-blooms from the clouds
Diffusing balm in that Pacific calm?
C’était mon enfant, mon bijou, mon âme.

Sea Surface Full of Clouds

Wallace Stevens
The surface ocean

The “skin” of the ocean, where contact with the atmosphere is effective:

Interface for the exchange of irradiance, momentum and materials between atmosphere and ocean
A Fundamental Component of the Earth System
The Rosette sampler system is a rather large instrument (2 m tall) and only performs well at depths > 3 m.

Along-way sampling systems are located in the hull of the vessel, typically at depths > 2 m.

Indeed, the very structure of the vessels disturbed the top m of the ocean.
Global $\text{pCO}_2$ data base (sampled at $\sim$ 3 m depth): does this accurately characterize Surface p$\text{CO}_2$?
The ocean mixed layer is not constantly mixing: mixing times can span up to a week within the "mixed" layer: e.g. properties at 5 m ≠ 0.5 m

Operational (sampling) definition:
"The depth where Rosette systems and along-way pumps collect water form" ~ 3 - 5 m

Is this appropriate?
Results

Sampling and the Metagenomic Dataset

Microbial samples were collected as part of the Sorcerer II expedition between August 8, 2003, and May 22, 2004, by the S/V Sorcerer II, a 32-m sailing sloop modified for marine research. Most specimens were collected from surface water marine environments at approximately 320-km (200-mile) intervals. In all, 44 samples were obtained from 41 locations.

Sample collection.

A YSI (model 6600) multiparameter instrument (http://www.ysi.com) was deployed to determine physical characteristics of the water column, including salinity, temperature, pH, dissolved oxygen, and depth. Using sterilized equipment [91], 40–200 l of seawater, depending on the turbidity of the water, was pumped through a 20-μm nytex prefilter into a 250-l carboy. From this sample, two 20-ml subsamples were collected in acid-washed polyethylene
Sampling the top m of the ocean still requires going down in small boats

And the use of odd devices
Some equipment (toys...) to sample surface waters... but only operational under very calm conditions

Technologically, we remain in the 19th Century in terms of the instrumentation available to study the surface (top m) of the ocean
1. The mixed layer is not mixing
Assessing variability in pCO2 and O2 within the top 5 m of the ocean

Calleja et al. (submitted)
High variability in pCO2 and O2 within the top 5 m of the ocean

Calleja et al. (submitted)
Calleja et al. (submitted)

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High vertical variability within the top 5 m despite significant wind speed.

**Depth (m)**

**pCO₂ (ppm)**

- 15 μatm

**Wind Speed (m s⁻¹)**

- 5.3 m s⁻¹
- 4.74 m s⁻¹
- 2.85 m s⁻¹
- 7.15 m s⁻¹
- 2.6 m s⁻¹

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Not accounted for by T variability

Calleja et al. (submitted)
Enrichment of top cm in organic carbon
The ocean surface

Operational (sampling) definition:
“The depth where Rosette systems and along-way pumps collect water form” ~ 3 - 5 m
Is this appropriate?

- Top m’s of the ocean not well mixed for biogeochemical-relevant properties (e.g. DOC, CO₂).
- Top m of the ocean not well mixed for microbial communities or processes.
- Top cm’s of the ocean: sites of reception of dust and VOC inputs, site of gas exchange regulation.
- Top cm’s of the ocean: metabolic hot-spots.
2.

- It is not physics... Is it Biology?
The metabolism of the community on the top centimeters of the water column is more intense than that at 5m depth.

Calleja et al. (2005)
Metabolism at top centimeters of the ocean plays a disproportionate role in controlling air-sea CO₂ disequilibria in subtropical waters
A COUPLING BETWEEN AIR-WATER CO₂ EXCHANGE AND PLANKTONIC METABOLISM

Planktonic metabolism is the key biological process affecting $p\text{CO}_2 w$

$NCP = GPP - R$

$\Delta p\text{CO}_2 = p\text{CO}_2 w - p\text{CO}_2 a$

Thermodynamic driving force of the Air-Sea CO₂ flux.

Respiration (R)

$O_2 + (CH_2O)_x$

Gross Primary Production (GPP)

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3.

- It does matter.
The gas exchange coefficient increases with wind velocity, but with a lot of scatter

Calleja et al. (submitted)
The high TOC content of the upper cm’s of the ocean affect the gas exchange coefficient (K)

RK vs TOC

RK (cm h⁻¹) = 74.49 - 0.68 (± 0.13) TOC (µmol C L⁻¹)

P = 0.003

Mean values

All observations

TOC top cm (µmol C L⁻¹)
4.

• Why is biology so active within the top m of the ocean?
Atmosphere

Intermediate and deep water

Biota

Only CO$_2$ exchanged!

Upper Ocean

Intermediate & deep Ocean

CaCO$_3$ cycling not shown
The C Budget Ocean

Heterotrophy is logically impossible if allochthonous organic C inputs = 0, the only possible outcome is that NCP > 0

Is this reasonable?
Are there atmospheric organic C inputs to the ocean?

Atmospheric inputs

Oceanic Rain water DOC: 59 ± 14 μmol C/L

Aerosol have high organic C contents: 1.2 % to 37% OC

The ocean is the major sink of Persistent Organic Pollutans (~proxy for atm. TOC) Jurado et al. (2004, 2005)

If (aqueous equilibrium) \([\text{VOC}]_{\text{atm}} - [\text{VOC}]_{\text{sea}} = 1 \mu\text{mol C/L} \) (concs. ~35 μmol C/L) then flux 5.5 Gt C/yr (Jurado et al. In prep)
Atmospheric inputs

Gaseous organic carbon

Particulated

Aerosol Organic C

Poorly known rates
(not 1 direct estimate prior to 2005)
The E Subtropical Atlantic is an area with very high aerosol load.
Table 1. Average and Standard Deviation of Dry Deposition Fluxes of Aerosol Organic Carbon (OC), N, P, and Labile Fe to the NE Subtropical Atlantic

<table>
<thead>
<tr>
<th></th>
<th>Coastal Ocean</th>
<th>Open Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>North Transect (26°N)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC, mmol m⁻² d⁻¹</td>
<td>1.7 ± 0.9</td>
<td>3.5 ± 3.1</td>
</tr>
<tr>
<td>N, µmol m⁻² d⁻¹</td>
<td>465 ± 183</td>
<td>135 ± 28</td>
</tr>
<tr>
<td>P, µmol m⁻² d⁻¹</td>
<td>5.3 ± 5.2</td>
<td>3.9 ± 2.5</td>
</tr>
<tr>
<td>Fe, µmol m⁻² d⁻¹</td>
<td>1.7 ± 1.6</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>N/P</td>
<td>83 ± 43</td>
<td>47 ± 37</td>
</tr>
<tr>
<td>N/Fe</td>
<td>627 ± 45</td>
<td>369 ± 33</td>
</tr>
<tr>
<td>P/Fe</td>
<td>5.9 ± 5</td>
<td>12 ± 10</td>
</tr>
<tr>
<td><strong>South Transect (21°N)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC, mmol m⁻² d⁻¹</td>
<td>0.6 ± 0.3</td>
<td>0.4 ± 0.3</td>
</tr>
<tr>
<td>N, µmol m⁻² d⁻¹</td>
<td>245 ± 51</td>
<td>132 ± 94</td>
</tr>
<tr>
<td>P, µmol m⁻² d⁻¹</td>
<td>2.3 ± 1.7</td>
<td>5.8 ± 5.6</td>
</tr>
<tr>
<td>Fe, µmol m⁻² d⁻¹</td>
<td>0.46 ± 0.36</td>
<td>0.60 ± 0.29</td>
</tr>
<tr>
<td>N/P</td>
<td>55 ± 52</td>
<td>28 ± 10</td>
</tr>
<tr>
<td>N/Fe</td>
<td>346 ± 31</td>
<td>250 ± 165</td>
</tr>
<tr>
<td>P/Fe</td>
<td>1.6 ± 1.6</td>
<td>10.6 ± 7.4</td>
</tr>
</tbody>
</table>
Wet deposition of Organic C

Global dry deposition of aerosol OC is estimated to be 11 Tg C y\(^{-1}\), wet-particle and wet-gaseous deposition are estimated 47 Tg C y\(^{-1}\) and 187 Tg C y\(^{-1}\)

Jurado et al. (in press)
Exploring the biological impact

Aerosol collected on filter

Aerosol suspension 500 mL

200 100 50 25 12.5 6.25 BL1 BL2
Duarte et al. (2006)
Duarte et al. (2006)
Aerosol inputs greatly enhance planktonic metabolism (mostly microphytoplankton production)

Duarte et al. (2006)
Increased Aerosol inputs

Experimental aerosol additions stimulate the growth of specific bacteria groups consistently across experiments

Arrieta et al. (unpub)
Volatile organic carbon: Estimating the dissolved-equivalent concentration of atmospheric VOC in sea-water ($\text{VOC}_{\text{air}}/H'$) and the $\text{VOC}_{\text{aq}}$ in surface waters. The differential $\Delta\text{VOC} = \text{VOC}_{\text{aq}} - \text{VOC}_{\text{air}}/H'$ determines, along with wind velocity, the air-sea flux.
The surface ocean

Intense deposition of organic carbon onto the surface ocean

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</tr>
</thead>
<tbody>
<tr>
<td>Aerosol deposition (mmol m(^{-2}) d(^{-1}))</td>
<td>- 1.02±4.0</td>
<td>- 0.79±0.15</td>
</tr>
<tr>
<td>Volatile Organic Carbon (mmol m(^{-2}) d(^{-1}))</td>
<td>- 63±29</td>
<td>- 11±12</td>
</tr>
<tr>
<td>CO(_2) (mmol m(^{-2}) d(^{-1}))</td>
<td>-15.1±18.6</td>
<td>0.94±1.1</td>
</tr>
</tbody>
</table>

Dachs et al. (2005), Duarte et al. (2006)
Atmospheric inputs

- Organic C inputs 15 fold > CO$_2$ flux
- Dominated by gaseous inputs (gaseous organic carbon 90 % of flux)
- Atmospheric inputs to the Subtropical NE Atlantic 0.7 ± 0.2 Gt C/y vs. estimated organic C deficit (net heterotrophy) of 0.5 Gt C/y (Duarte et al. 2001)
More than 10 cruises completed since
All data

$6.0 \pm 2.2 \, \mu\text{mol C L}^{-1}$

$N = 153$

62 % negative
- Fluxes into the ocean.

+ Fluxes to the atmosphere.

The $\Delta$DOC is large, supporting a large flux (to be calculated still) predominantly into the ocean.
A Balanced C budget for the NE Subtropical Atlantic

VOC flux 17.6 ± 9.7
Aerosol_{OC} flux 1.5 ± 0.3
GPP 61.3 ± 14
R 70.7 ± 14

Missing = 19.1
Balanced!

Units = mmol C m^{-2} d^{-1}
N = 9 stations

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Atmospheric inputs

Gaseous organic carbon

Particulated

Aerosol Organic C

What is the fate of the VOC flux?
VOC utilization

- Atmospheric VOC fluxes dominate the air-sea exchange of organic carbon in the NE Subtropical Atlantic.


- The prokaryotes are the only significant consumers of dissolved organic matter in the ocean. Therefore the only likely consumers of VOC.

- Prokaryotic use of VOC may affect the air-sea equilibrium of VOC and therefore the magnitude
VOC is rapidly used by bacteria (18 hr half-life compared to ~48 for sea water DOC).

VOC as a highly labile source of carbon to support bacterial respiration

Calleja et al. (unpub)
VOC experiment setup

Filtered Atmospheric air

Vacuum pump

VOC added

High purity Synthetic air

Control

BoIles inoculated with 0.8µm filtered SW collected in situ

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Figure 1.

Figure 2.

Arrieta et al.
The ocean surface

A hotspot of biogeochemical activity

- Top m’s of the ocean present remarkable heterogeneity for biogeochemically-relevant properties (e.g. DOC, CO₂).
- Top cm’s of the ocean: sites of reception of large dust and VOC inputs.
- Top cm’s of the ocean: metabolic hot-spots
- Biogeochemical properties and processes at the ocean surface regulate air-sea CO₂ exchange.

The upper cm’s of the ocean deserve specific consideration and sampling attention