Heterotrophic activity in the sea revisited

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2010 C-MORE summer course in Microbial oceanography,
Univ. of Hawaii, 15 June, 2010
Outline

- A brief history.
- Carbon flux through prokaryotes
- Metabolic balance
- Do we measure primary production properly?
- Cell mortality and the emperor new suite of clothes.
- Non-phytoplankton drivers of heterotrophic activity.
- External sources of organic matter: significance and use
Measurement of Microbial Activity and Growth in the Ocean by Rates of Stable Ribonucleic Acid Synthesis

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Received for publication 28 August 1979

Selected Nucleic Acid Precursors in Studies of Aquatic Microbial Ecology

DAVID M. KARL

Department of Oceanography, University of Hawaii, Honolulu, Hawaii 96822

Received 26 January 1982/Accepted 27 April 1982
Heterotrophic activity in the sea, 1981
15 Volume NATO conference series: Marine sciences
John E. Hobbie and Peter Le.B. J. Williams
“The acceptance by non-microbiologists that bacteria plays an important role in the marine food web has been, and to some extent still is, an act of faith

Varios considerations lead to the conclusion that a substantial proportion of plankton production reaches eventually the bacteria—The exact fate of this material...is not known”

P.J.LeB Williams (1981)
The Ecological Role of Water-Column Microbes in the Sea*

F. Azam¹, T. Fenchel², J. G. Field³, J. S. Gray⁴, L. A. Meyer-Reil⁵ and F. Thingstad⁶

ABSTRACT: Recently developed techniques for estimating bacterial biomass and productivity indicate that bacterial biomass in the sea is related to phytoplankton concentration and that bacteria utilise 10 to 50% of carbon fixed by photosynthesis. Evidence is presented to suggest that numbers of free bacteria are controlled by nanoplanktonic heterotrophic flagellates which are ubiquitous in the marine water column. The flagellates in turn are preyed upon by microzooplankton. Heterotrophic flagellates and microzooplankton cover the same size range as the phytoplankton, thus providing the means for returning some energy from the ‘microbial loop’ to the conventional planktonic food chain.
Bacterial production equal, on average, 20% of primary production

Fig. 3. Areal relation between primary production (NPP; X-axis) and bacterial production (BP; Y-axis) expressed per unit area for the entire water column. Symbols are as in Fig. 1. Regression line ($\log Y = 0.75\log X + 0.093$) is shown with 90% confidence limits for the individual predictions of BP.
DOM $\rightarrow$ Bacteria $\rightarrow$ Grazers

respiration

DIC

Carbon Flux = Production + Respiration

Bacteria Growth Efficiency = \( \frac{\text{Production}}{\text{C Flux}} \) (Growth Yield)

viernes, 18 junio 2010
Measurement

\[ C \text{ flux} = B_{\text{production}} + B_{\text{respiration}} \]

\[ C \text{ flux} = \Delta B_{\text{biomass}} + B_{\text{respiration}} \]

\[ C \text{ flux} = \Delta \text{DOC} \]

BGE recalculating these expressions

in regrowth cultures in the dark and the absence of protists grazers
“Estimates of BGE for natural planktonic bacteria range from <0.05 to as high as 0.6... In the most dilute, oligotrophic systems, BGE is as low as 0.01; in the most eutrophic systems, it plateaus near 0.5. Planktonic bacteria appear to maximize carbon utilization rather than BGE. A consequence of this strategy is that maintenance energy costs (and therefore maintenance respiration) seems to be highest in oligotrophic systems.”
BR = 3.70 × BP^{0.41}, r^2 = 0.46 (model I)

BR = 3.42 × BP^{0.61}, r^2 = 0.46 (model II)
We report here that bacterial respiration is generally high and tends to exceed phytoplankton net primary production in oligotrophic systems.
A general (non-linear) relationship between $R$ and $P$ in aquatic ecosystems

$(R \sim P^{0.4-0.8})$

Confirmed with a larger \((N = 3,000)\) data set

**Threshold GPP for metabolic balance** = 

\[1.50 \text{ mmol } O_2 \text{ m}^{-3} \text{ d}^{-1}\]
Heterotrophic communities abound in the N Atlantic, Arctic and Mediterranean

Regaudie-de-Gieux and Duarte (in prep)
Global Scaling of Plankton Metabolism in the Upper Ocean

GPP = 144.78 Gt C y\(^{-1}\)
CR = 169.60 Gt C y\(^{-1}\)
NCP = -19.22 Gt C y\(^{-1}\)

GPP > 3 times estimated from remote sensing

1. GPP underestimated?
2. External sources of C
### What does primary production measure?

<table>
<thead>
<tr>
<th></th>
<th>$^{14}$C-TOC/$^{14}$C-POC</th>
<th>$^{14}$C-TOC/$^{14}$C-DOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (± SE)</td>
<td>2.30 (± 0.12)</td>
<td>7.89 (± 3.28)</td>
</tr>
<tr>
<td>Median</td>
<td>1.99</td>
<td>2.01</td>
</tr>
<tr>
<td>Min.</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Max.</td>
<td>8.34</td>
<td>376.43</td>
</tr>
<tr>
<td>n</td>
<td>117</td>
<td>117</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$^{14}$C-TOC/$^{14}$C-TOC</th>
<th>GPP-$^{18}$O / $^{14}$C-TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (± SE)</td>
<td>1.99 (± 0.24)</td>
<td>2.68 (± 0.38)</td>
</tr>
<tr>
<td>Median</td>
<td>1.18</td>
<td>1.94</td>
</tr>
<tr>
<td>Min.</td>
<td>0.02</td>
<td>0.36</td>
</tr>
<tr>
<td>Max.</td>
<td>28.2</td>
<td>15.57</td>
</tr>
<tr>
<td>n</td>
<td>157</td>
<td>52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>GPP-$^{18}$O / $^{14}$C-POC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (± SE)</td>
<td>3.25 (± 0.44)</td>
</tr>
<tr>
<td>Median</td>
<td>2.08</td>
</tr>
<tr>
<td>Min.</td>
<td>0.16</td>
</tr>
<tr>
<td>Max.</td>
<td>39.45</td>
</tr>
<tr>
<td>n</td>
<td>117</td>
</tr>
</tbody>
</table>
Regaudie-de-Gioux et al. (in prep)
Phytoplankton cell death explains high organic carbon release in the subtropical ocean

Patricia Alonso-Laita & Susana Agustí
DOC release for any given Total PP depends on the cell lysis rates

Alonso-Laita and Agustí (in prep)
Lysis rates control the partition between POC and DOC production

Duarte et al. (in prep)
Predicting DOC release from lysis rates and the % death cells

\[ \text{TPP} - (\text{TPP} \cdot e^{-\text{lysis}}) \]

\[ \frac{\text{TPP} \cdot \% \text{DC}}{100} \]

Alonso-Laita and Agustí (in prep)
Time series DI$^{14}$C addition experiments reveal intense dynamics at short time scales

NE Subtropical Atlantic Gyre
(Station 48; COCA 2)

NE Subtropical Atlantic Gyre
(Station 42; COCA 2)

NE Subtropical Atlantic Gyre
(Station 32; COCA 2)

Bransfield Strait, Southern Ocean
(Station 13 ICEPOS)

W Mediterranean
(25 09 03, BADE I)

NE Subtropical Atlantic Gyre
(Station 7; BADE II)

Agustí et al. (in prep)
The flux from DIC into POC, then DOM and uptake and subsequent respiration by bacteria can be extremely fast (a few minutes).
Consequences:

1. $^{14}\text{C}$ incorporation into particulate material grossly underestimates gross primary production in oligotrophic waters since much of the organic carbon is incorporated by bacteria and respired within the incubation interval.

2. Phytoplankton mortality and subsequent lysis allows for the rapid [minutes; see Stocker et al. (2008)] use of primary production by bacteria, so that much of primary production goes unnoticed by conventional measurements ("The Emperor New Suite of Clothes").
Thoughts

- Difficulties to reconcile autotrophic and heterotrophic activity may be partially due to flaws in the basis for the comparison, which should be a total C budget. $^{14}$C-PP grossly (by a factor of 3, underestimates GPP in oligotrophic water)

- Is phytoplankton the sole source of DOC to support heterotrophic activity?
One more caveat

Does it incorporate all relevant fluxes?

ANOXIGENIC photosynthesis ~ 5 % of photosynthesis (claims up to 15%)

ANAMOX ?

Ammonium oxidation by Archaea (claims of 2 - 5
Respiration increases faster than primary production with increasing temperature.

Consequences under global warming?

Regaudie-de-Gioux and Duarte (in prep)
Major drivers of bacterial dynamics
Krill is highly patchy

50 miles

35 miles

0 m

100 m
Krill releases large amounts of DOC

Table 1. **DOC and nutrient release rates.** Median and range of DOC and nutrient release rates by Antarctic krill (N = 8 experiments). The rates reported are those calculated after 30 min. of incubation.

<table>
<thead>
<tr>
<th>Rate</th>
<th>( \mu \text{mol g DW}^{-1} \text{ h}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>median</td>
</tr>
<tr>
<td>DOC</td>
<td>232.48</td>
</tr>
<tr>
<td>TN</td>
<td>27.43</td>
</tr>
<tr>
<td>TP</td>
<td>2.76</td>
</tr>
<tr>
<td>( \text{NH}_4^+ )</td>
<td>15.52</td>
</tr>
</tbody>
</table>

Ruiz-Halpern et al. (submitted)
Krill releases 78% of the total (phytoplankton + krill) release of DOC to the environment.

Ruiz-Halpern et al. (submitted)

<table>
<thead>
<tr>
<th>experiment</th>
<th>DOC mol m^{-2}</th>
<th>POC mmol C m^{-2} d^{-1}</th>
<th>DOC mmol C m^{-2} d^{-1}</th>
<th>PER %TPP</th>
<th>biomass g DW m^{-2}</th>
<th>DOC release mmol C m^{-2} d^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>29-Jan-09</td>
<td>2.91</td>
<td>148.11</td>
<td>126.22</td>
<td>46.01</td>
<td>1.98</td>
<td>14.12</td>
</tr>
<tr>
<td>2-Feb-09</td>
<td>2.91</td>
<td>18.23</td>
<td>34.84</td>
<td>65.65</td>
<td>13.77</td>
<td>37.83</td>
</tr>
<tr>
<td>9-Feb-09</td>
<td>2.62</td>
<td>57.84</td>
<td>89.44</td>
<td>60.73</td>
<td>34.50</td>
<td>158.09</td>
</tr>
<tr>
<td>12-Feb-09</td>
<td>2.77</td>
<td>10.95</td>
<td>7.43</td>
<td>40.43</td>
<td>59.38</td>
<td>373.52</td>
</tr>
<tr>
<td>13-Feb-09</td>
<td>2.92</td>
<td>53.07</td>
<td>52.56</td>
<td>49.76</td>
<td>13.25</td>
<td>n.d.</td>
</tr>
<tr>
<td>16-Feb-09</td>
<td>2.31</td>
<td>n.d.</td>
<td>n.d.</td>
<td>27.70</td>
<td>166.41</td>
<td></td>
</tr>
<tr>
<td>23-Feb-09</td>
<td>2.43</td>
<td>32.87</td>
<td>44.16</td>
<td>57.33</td>
<td>n.d.</td>
<td></td>
</tr>
<tr>
<td>25-Feb-09</td>
<td>3.05</td>
<td>12.58</td>
<td>33.43</td>
<td>72.65</td>
<td>n.d.</td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>2.74</td>
<td>47.66</td>
<td>55.44</td>
<td>56.08</td>
<td>25.10</td>
<td>149.99</td>
</tr>
<tr>
<td>s.e</td>
<td>0.10</td>
<td>19.64</td>
<td>16.26</td>
<td>4.64</td>
<td>9.11</td>
<td>71.30</td>
</tr>
</tbody>
</table>

Helps explain why bacterial C demand is greater in the Southern Ocean than phytoplankton DOC production.
Exp 3 (Bransfield)
Huge Increase in bacterial abundance and metabolism

Control

LDNA
HDNA
All

cells ml⁻¹

Tiempo (horas)

Krill

LDNA
HDNA
All

cells ml⁻¹

Tiempo (horas)

viernes, 18 junio 2010
Respiration rates
μmol O$_2$ L$^{-1}$ h$^{-1}$

<table>
<thead>
<tr>
<th>Periodos tiempo</th>
<th>Control</th>
<th>Amonio</th>
<th>Krill</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (0-36.6)</td>
<td>0.017</td>
<td>0.023</td>
<td>0.112</td>
</tr>
<tr>
<td>2 (36.6-68.6)</td>
<td>0.033</td>
<td>0.072</td>
<td>0.619</td>
</tr>
<tr>
<td>3 (68.6-94.5)</td>
<td>-0.001</td>
<td>0.060</td>
<td>1.288</td>
</tr>
<tr>
<td>4 (94.5-116.16)</td>
<td>0.024</td>
<td>0.135</td>
<td>0.726</td>
</tr>
<tr>
<td>5 (116.16-142.7)</td>
<td>0.014</td>
<td>0.108</td>
<td>0.218</td>
</tr>
<tr>
<td>Final</td>
<td>0.018</td>
<td>0.073</td>
<td>0.553</td>
</tr>
</tbody>
</table>
Bacterial Production (pmol Leu L$^{-1}$ h$^{-1}$)

Exp 1

Exp 2

Exp 3

viernes, 18 junio 2010
Are there lateral and atmospheric organic C inputs to the ocean?

**Lateral (coastal) inputs**

<table>
<thead>
<tr>
<th>Shelf Region</th>
<th>DOC export (G mol C yr(^{-1}))</th>
<th>Shelf length (km)</th>
<th>DOC export per km shelf break length (Gmol C km(^{-1}) yr(^{-1}))</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>East China Sea</td>
<td>414.00</td>
<td>250.02</td>
<td>1.66</td>
<td>Hung et al. 2000 (55)</td>
</tr>
<tr>
<td>Mid-Atlantic Bight</td>
<td>1595.83</td>
<td>777.84</td>
<td>2.05</td>
<td>Vlahos et al. 2002 (638)</td>
</tr>
<tr>
<td>East China Sea</td>
<td>2975.00</td>
<td>666.72</td>
<td>4.46</td>
<td>Hung et al. 2003 (936)</td>
</tr>
<tr>
<td>Cape Ghir (NW Africa)</td>
<td>258.33</td>
<td>111.12</td>
<td>2.32</td>
<td>Garcia-Muñoz (1234)</td>
</tr>
<tr>
<td>Mid-Atlantic Bight</td>
<td>500.00</td>
<td>950.00</td>
<td>0.53</td>
<td>Bauer (1243)</td>
</tr>
<tr>
<td>North Brazilian Shelf</td>
<td>2200.00</td>
<td>212.50</td>
<td>10.35</td>
<td>Dittmar</td>
</tr>
<tr>
<td>Ría de Vigo (Spain)</td>
<td></td>
<td></td>
<td>0.22</td>
<td>Álvarez Salgado (433)</td>
</tr>
<tr>
<td>Global</td>
<td>500000.00</td>
<td>300000.00</td>
<td>1.67</td>
<td>This work (55)</td>
</tr>
</tbody>
</table>

DOC is exported from the coastal into the open ocean because of the existence of a DOC differential between coastal and open ocean waters.

*Barrón et al. (in prep)*

*viernes, 18 junio 2010*
Are there atmospheric organic C inputs to the ocean?

Atmospheric inputs

Oceanic Rain water DOC: $59 \pm 14 \mu\text{mol C/L}$

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) [VOC]atm - [VOC]sea = 1 µmol C/L (concs. ~35 µmol C/L) then flux 5.5 Gt C/yr (Jurado et al. 2008)
Atmospheric inputs

Gaseous organic carbon

Aerosol Organic C

0.058 Gt C yr\(^{-1}\)

Particulated

Few rate estimates

Dachs et al. (2005), Jurado et al. (2008), Ruiz-Halpern et al. (2010), Arrieta et al. (submitted)
Atmospheric inputs

Subtropical NE Atlantic

- 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)

Dachs et al. (2005)
Figure 1.

- Arrieta et al.

Figure 2.

- Production (μg C L⁻¹ d⁻¹)
- Respiration (μg C L⁻¹ d⁻¹)
- Growth Efficiency (%)
The major known gaseous organic components of the troposphere are methane, methanol, acetone and acetaldehyde, all are more reduced than the average bacterial biomass.

The degree of reduction of the substrate has been found to determine largely the carbon use efficiency. Maximum “carbon conservation” was observed when the degree of oxidation of the substrate was higher than 5 (microbial biomass having a degree of reduction of ~4.8).

Bringing more reduced substrates to the level of oxidation of biomass preserves C since there is no need to burn additional material to generate reducing power.

**Figure 1.** Relationship between the degree of reduction of heterotrophic substrates and the carbon conversion efficiency (CCE) of aerobic growth. Microbial biomass as a yardstick for the classification of heterotrophic substrates. Values in brackets denote the respective degrees of reduction.
Estimates for the photic layer only

- Photic layer
- Mesopelagic
- Ocean interior
- Ocean floor

Depth (m)

0 100 1000 2000 3000 3500
Biomass and activity of deep-water (>1000 m) bacteria is very significant.

Aristegui, Gasol Hendl & Duarte (en revisión)
Average composite cumulative respiration in the dark ocean

50% below 800 m

90% within top 4,500 m

Fractional Cumulative Respiration in the dark ocean

Total $R$ in the dark ocean = 38.1 Gt C yr$^{-1}$

A respiration maximum at 1,000 - 2,000 m depth

Summary

- Estimates of heterotrophic activity in the ocean have increased over the past decades.

- The large magnitude of heterotrophic activity questions our understanding of autotrophic processes as well (even if ignoring the deep ocean).

- A high carbon flux through heterotrophs compared to autotrophs in the oligotrophic ocean depends on a very fast turnover of carbon mediated by high mortality rates of phototrophs.

- Atmospheric inputs of organic carbon are significant and fuel prokaryote production in surface waters.

- Improved assessments of heterotrophic activity are essential to better understand the C budget of the ocean.
### Respiration in the open ocean:

<table>
<thead>
<tr>
<th>Component</th>
<th>Gt C year⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Respiration in the Open Ocean</strong></td>
<td></td>
</tr>
<tr>
<td>Photic ocean (0 - 200 m)</td>
<td>37 - 42¹</td>
</tr>
<tr>
<td>Dark ocean (200 - 1000 m)</td>
<td>18 - 38</td>
</tr>
<tr>
<td>Mesozooplankton</td>
<td>3²</td>
</tr>
<tr>
<td>Vertebrates</td>
<td>0.01²</td>
</tr>
<tr>
<td>Benthic R</td>
<td>0.65²</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>~ 58 - 83</td>
</tr>
</tbody>
</table>

Requires New production (+ lateral inputs) to be ~ 20 - 40 Gt C/year

---

# Benthic respiration in the coastal ocean

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Surface area (10^6 km²)</th>
<th>Respiration (mmol m⁻² d⁻¹)</th>
<th>Global respiration (Gt C yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral reefs</td>
<td>0.6</td>
<td>359</td>
<td>0.92 (13%)</td>
</tr>
<tr>
<td>Mangroves</td>
<td>0.2</td>
<td>426</td>
<td>0.32 (5%)</td>
</tr>
<tr>
<td>Salt-marshes</td>
<td>0.4</td>
<td>459</td>
<td>0.74 (11%)</td>
</tr>
<tr>
<td>Seagrasses</td>
<td>0.6</td>
<td>158</td>
<td>0.38 (6%)</td>
</tr>
<tr>
<td>Macroalgae</td>
<td>1.4</td>
<td>188</td>
<td>2.80 (41%)</td>
</tr>
<tr>
<td>Sediment</td>
<td>23.9</td>
<td>R = f(depth)</td>
<td>1.68 (24%)</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>27</strong></td>
<td></td>
<td><strong>6.84</strong></td>
</tr>
</tbody>
</table>

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*Middelburg, Gattuso and Duarte (2004)*
Constraints on respiration

Organic Carbon Budget
Production + Import = Export + Burial + Respiration

Autochthonous Inputs:
Phytoplankton \(4.5 \text{ Gt} \text{ C yr}^{-1}\)
Benthic producers \(5.5 \text{ Gt} \text{ C yr}^{-1}\)
Total \(9.9 \text{ Gt} \text{ C yr}^{-1}\)

Imports\(^1\) (river delivery): \(0.4 \text{ Gt} \text{ C yr}^{-1}\)

Export\(^1\) \(2.0 \text{ Gt} \text{ C yr}^{-1}\)
Burial\(^1\) \(0.15 \text{ Gt} \text{ C yr}^{-1}\)

Respiration\(^2\) \(8.15 \text{ Gt} \text{ C yr}^{-1}\)

\(^1\) Low estimates
\(^2\) Includes planktonic respiration
Organic Carbon Budget

Net Production Coastal Ocean = 9.9 - 8.15 = 1.75 Gt C yr$^{-1}$

P/R ratio = 1.21

The Coastal Ocean is Net Autotrophic, Removing CO$_2$ and Exporting Organic C to the Open Ocean$^1$

1. A fraction is exported to land ecosystems as well.
Respiration in the open ocean:

<table>
<thead>
<tr>
<th>Area</th>
<th>Type</th>
<th>Rate (Gt C year(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estuaries</td>
<td></td>
<td>1.32</td>
</tr>
<tr>
<td>Coastal Ocean</td>
<td>Benthic</td>
<td>7.44</td>
</tr>
<tr>
<td></td>
<td>Pelagic</td>
<td>13.44</td>
</tr>
<tr>
<td>Open Ocean</td>
<td>Upper</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Mesopelagic</td>
<td>16.32</td>
</tr>
<tr>
<td></td>
<td>Bathypelagic</td>
<td>2.04</td>
</tr>
<tr>
<td></td>
<td>Sediment</td>
<td>2.04</td>
</tr>
<tr>
<td>Total Ocean R</td>
<td></td>
<td>162.6</td>
</tr>
</tbody>
</table>

*del Giorgio & Williams (2004)*
Metabolic balance of the open ocean

Production 35 - 60 Gt C year $^{-1}$

Respiration 160 Gt C year $^{-1}$

Deficit > 100 Gt C year $^{-1}$

Where does the necessary carbon come from?

<table>
<thead>
<tr>
<th>External C inputs</th>
<th>Gt C year $^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Rivers</td>
<td>0.45</td>
</tr>
<tr>
<td>• Excess coastal production</td>
<td>5 - 5.5</td>
</tr>
<tr>
<td>• Atmospheric inputs</td>
<td>2 - 3?</td>
</tr>
</tbody>
</table>

**TOTAL** 7.5 - 9

The E Subtropical Atlantic is an area with very high aerosol load.
Evidence of important respiratory activity in the deep ocean from oxygen fields
This respiratory activity is only partially supported by use of semirefractory DOC.
Enhanced respiration at 000 - 2000 layer

A recurrent feature in all oceans investigated

Increased activity at the base of the permanent thermocline?

Gaseous Organic C flux (mmol C m\(^{-2}\) d\(^{-1}\))

Aerosol Org. C flux (mmol C m\(^{-2}\) d\(^{-1}\))

Dachs et al. (submitted)
Atmospheric inputs

• 5 to 10 Gt C year\(^{-1}\)
• 2 to 5 fold greater than CO\(_2\) uptake
• A neglected flux
One more detail

Are the estimates free of error or uncertainty?
Data 3

Emissions vs. Year

Year:
- 1990
- 1995
- 2000
- 2005

Emissions:
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Legend:
- Fossil fuels & cement production to Atm
Surface Ocean to Biota
Surface Ocean to Int & Deep W.
Oceanic uptake (Air to surface ocean)

Ocean fluxes

-3.5 -3 -2.5 -2 -1.5 -1 -0.5 0 0.5


viernes, 18 junio 2010
CO2 flux (Gt C/year)

Air to Sea
Sea to Air

Air-Sea exchange

Year

1990
1995
2000
2005