Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate

Charlson, Lovelock, Andreae, Warren

Presented By

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Major significance

- Proposal that biota could regulate climate
  - Hypothesized possible mechanisms
  - More data was needed to support theory
- Stimulated a great deal of scientific interest
- Cited 1203 times!
- Many assumptions made
What we knew before

• Radiation—Twomey 1977, indirect effect
• Gaia hypothesis – Lovelock 1974
• Aerosols (SO$_4^{2-}$) as CCN
• Global sulfur budget – Andreae 1985
# Global Sulfur budget

## TABLE 6. Sulfur emissions from natural and anthropogenic sources expressed in $10^6$ mol/a

<table>
<thead>
<tr>
<th>Region</th>
<th>Oceanic</th>
<th>Terrestrial</th>
<th>Volcanic</th>
<th>Biomass burning</th>
<th>Anthropogenic</th>
<th>Biogenic/total$^1$</th>
<th>Natural/total$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80°-65°N</td>
<td>4</td>
<td>0.02</td>
<td>2</td>
<td>0.4</td>
<td>3</td>
<td>40%</td>
<td>62%</td>
</tr>
<tr>
<td>65°-50°N</td>
<td>19</td>
<td>0.40</td>
<td>43</td>
<td>2.3</td>
<td>534</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>50°-35°N</td>
<td>31</td>
<td>0.95</td>
<td>53</td>
<td>3.3</td>
<td>942</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>35°-20°N</td>
<td>46</td>
<td>2.05</td>
<td>37</td>
<td>7.1</td>
<td>598</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>20°-5°N</td>
<td>79</td>
<td>2.52</td>
<td>54</td>
<td>20.7</td>
<td>106</td>
<td>31</td>
<td>52</td>
</tr>
<tr>
<td>5°N-0°</td>
<td>26</td>
<td>1.14</td>
<td>17</td>
<td>4.2</td>
<td>18</td>
<td>41</td>
<td>67</td>
</tr>
<tr>
<td>0°-5°S</td>
<td>25</td>
<td>1.10</td>
<td>27</td>
<td>3.6</td>
<td>16</td>
<td>36</td>
<td>73</td>
</tr>
<tr>
<td>5°-20°S</td>
<td>82</td>
<td>2.11</td>
<td>45</td>
<td>17.3</td>
<td>47</td>
<td>44</td>
<td>67</td>
</tr>
<tr>
<td>20°-35°S</td>
<td>60</td>
<td>0.86</td>
<td>2</td>
<td>9.2</td>
<td>153</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>35°-50°S</td>
<td>60</td>
<td>0.08</td>
<td>8</td>
<td>0.7</td>
<td>24</td>
<td>65</td>
<td>73</td>
</tr>
<tr>
<td>50°-65°S</td>
<td>50</td>
<td>0.00</td>
<td>0</td>
<td>0.2</td>
<td>1</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>65°-80°S</td>
<td>4</td>
<td>0.00</td>
<td>1</td>
<td>0.0</td>
<td>0</td>
<td>79</td>
<td>100</td>
</tr>
<tr>
<td>N. Hemisphere</td>
<td>200</td>
<td>7.1</td>
<td>210</td>
<td>38</td>
<td>2200</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>S. Hemisphere</td>
<td>280</td>
<td>4.1</td>
<td>83</td>
<td>31</td>
<td>240</td>
<td>45</td>
<td>58</td>
</tr>
<tr>
<td>Global</td>
<td>480</td>
<td>11.9</td>
<td>290</td>
<td>69</td>
<td>2400</td>
<td>15</td>
<td>24</td>
</tr>
</tbody>
</table>

$^1$ (Marine + Terrestrial)*100/(Marine + Terrestrial + Volcanic + Anthropogenic + Biomass burning).

$^2$ (Marine + Terrestrial + Volcanic)*100/(Marine + Terrestrial + Volcanic + Anthropogenic +
DMS oxidation by OH

FIGURE 8.25 Overview of oxidation of DMS by OH in the troposphere (note that many of the reactions after the first step are the same in DMS reactions with SO$_3$, Cl, etc.).

NSS-SO$_4^{2-}$ particles are the main contributor to CCN

1) Significant fraction of submicrometer particles are active CCN

2) Most CCN are composed of water soluble materials

3) The total number-population of NSS-SO$_4^{2-}$ agrees with measured CCN population

4) Much of the light-scattering aerosol in marine air is volatile at elevated temperatures

5) The turnover time of CCN is the same order as NSS-SO$_4^{2-}$
CLOUD DROPLET NUMBER CONCENTRATION

Dependence on Non-Seasalt Sulfate

Boucher and Lohmann, 1995
Potential effects of NSS-SO$_4^{2-}$ variations on cloud properties

Basic equation: 
$$L = \left(\frac{4}{3}\right)\pi r^3 \rho N$$

Three variables: 
- L (liquid water content, gm$^{-3}$)
- N (number-density of droplets, m$^{-3}$)
- r (droplet radius, m)

1) Hold r fixed: $\uparrow \quad \rightarrow \quad \downarrow$

2) Hold N fixed: $\uparrow \quad \rightarrow \quad \downarrow$

3) Hold L fixed: $\uparrow \quad \rightarrow \quad \downarrow \quad \rightarrow \quad \uparrow$

--- Twomey’s effect
DEPENDENCE OF CLOUD ALBEDO ON CLOUD DEPTH

Influence of Cloud Drop Radius and Concentration

LWC = 0.3 g m$^{-3}$

g = 0.858

Figure 1

Relative number-density of cloud droplets $N/N_0$

Visible albedo at top of reference cloud $(r_{eff}/r_{eff}^0)$

Relative effective radius of droplets $r_{eff}/r_{eff}^0$

Albedo of ocean surface
### Table 1

#### a) Global annual average cloud cover (ocean areas only)

<table>
<thead>
<tr>
<th>Cloud type*</th>
<th>Ocean area covered (%)</th>
<th>Earth covered by oceanic clouds (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-overlapped St/Sc†</td>
<td>25.2</td>
<td>17.6</td>
</tr>
<tr>
<td>Non-overlapped As/Ac‡</td>
<td>10.8</td>
<td>7.5</td>
</tr>
<tr>
<td>As/Ac overlapped with</td>
<td>8.8</td>
<td>6.1</td>
</tr>
<tr>
<td>St/Sc§</td>
<td>not applicable</td>
<td></td>
</tr>
<tr>
<td>Nimbostratus, cumulus</td>
<td>not applicable (optically thick; high albedo)</td>
<td></td>
</tr>
<tr>
<td>cumulonimbus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cirrus‡</td>
<td>not applicable (ice)</td>
<td></td>
</tr>
<tr>
<td>Total cover of oceanic stratiform water clouds (As/Ac + St/Sc) not overlapped with cumuliform clouds</td>
<td>44.8¶</td>
<td>31.2</td>
</tr>
</tbody>
</table>

#### b) Example: effect on surface climate due to increasing CCN concentration \( N \) by 30% while holding liquid water path fixed

<table>
<thead>
<tr>
<th>For area covered by oceanic stratiform water clouds</th>
<th>Averaged over Earth's surface area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imposed change in ( N )</td>
<td>+30%</td>
</tr>
<tr>
<td>Change in ( r_{s,ff} )</td>
<td>−10%</td>
</tr>
<tr>
<td>Change in 0.5–0.7-( \mu ) m albedo at TOA‡</td>
<td>+0.02</td>
</tr>
<tr>
<td>Change in 0.5–0.7-( \mu ) m albedo at TOA**</td>
<td>+0.018</td>
</tr>
<tr>
<td>Change in solar albedo at TOA**</td>
<td>+0.016</td>
</tr>
<tr>
<td>Equivalent change in solar constant†</td>
<td>−0.7%</td>
</tr>
<tr>
<td>Change in global-average surface temperature‡‡</td>
<td>−1.3 K</td>
</tr>
</tbody>
</table>
SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION

Schwartz and Slingo (1996)
Global climate and DMS emission

A stable negative feedback

Sea-to-air mass flux of DMS:

\[ F = A \cdot k \cdot \Delta c \]

- \( A \): total ocean surface
- \( T \): transfer velocity
- \( C \): concentration gradient across the air/sea interface

\( T \) \( \rightarrow \) \( A \) \( \rightarrow \) \( F \)

DMS counteract cooling

\( \uparrow \) \( \downarrow \) \( \uparrow \)

CCN \( \uparrow \) SO\(_4^{2-} \) \( \uparrow \) NSS-
Atmospheric DMS concentrations

• Independent of the rate of primary production, the warmest, most saline, and most intensely illuminated regions of the oceans have the highest rate of DMS emission to the atmosphere

• Key fact when considering possible climatic feedback mechanisms
Gaia theory*

• Early after life began it acquired control of the planetary environment
• This homeostasis by and for the biosphere has persisted until the present
• Why would phytoplankton evolve to produce DMS?
  – Many theories for the mechanism, little supporting data
    • Reaction to salt stress
    • Increased rainfall leading to more nutrients from land

Future work

• Intense study in many areas in attempts to support or disprove the theory