The Abdus Salam
International Centre for Theoretical Physics

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Educational, Scientific and
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IAEA
International Atomic Energy Agency

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Workshop on Aerosol Impact in the Environment: from Air Pollution to Climate Change

8 - 12 August 2011

The Effect of Ocean Biogeochemistry on Aerosols, Clouds and Climate

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The Effect of Ocean Biogeochemistry on Aerosol, Clouds and Climate

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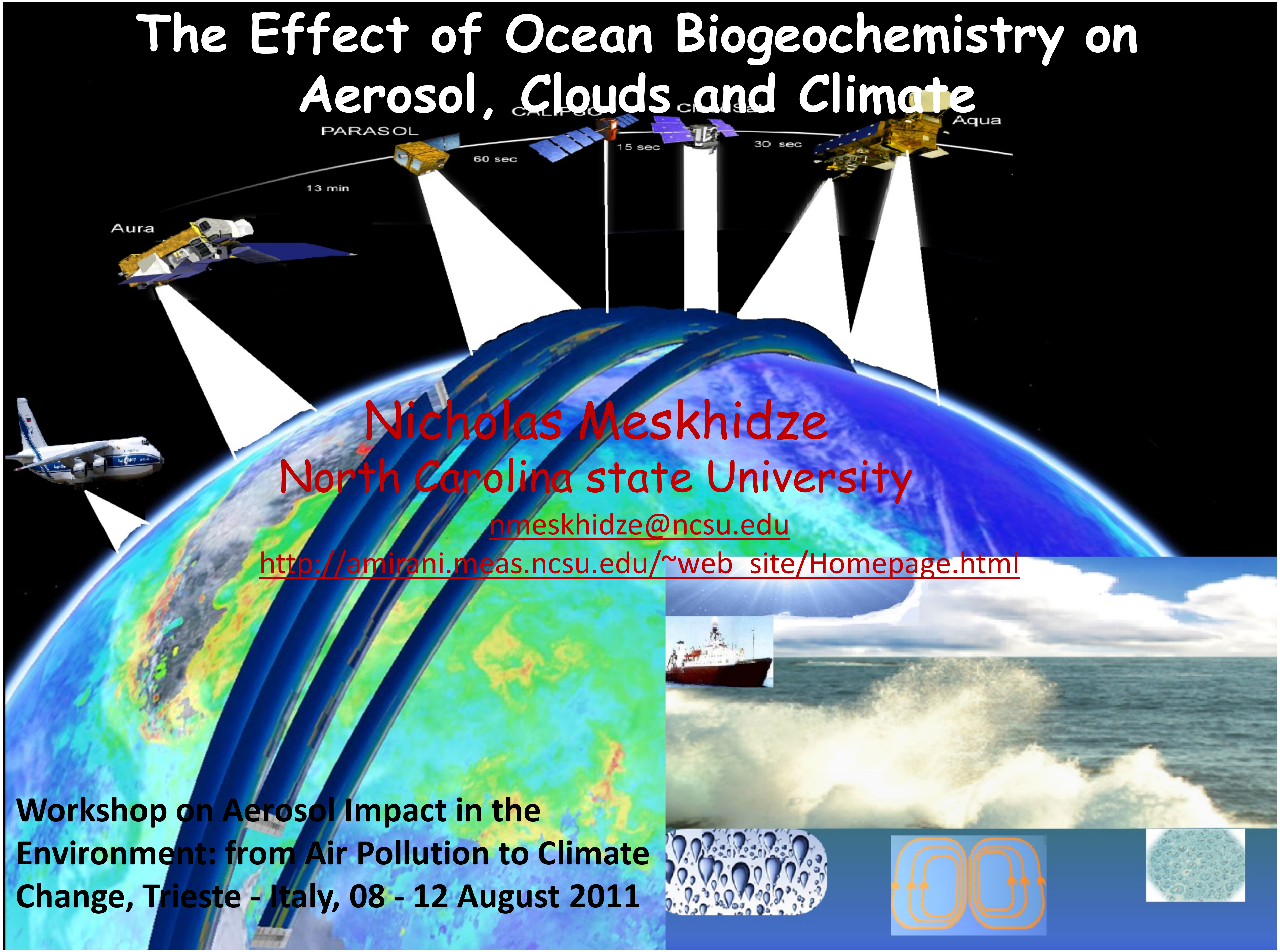


Workshop on Aerosol Impact in the Environment: from Air Pollution to Climate Change, Trieste - Italy, 08 - 12 August 2011

Outline

1) Introduction

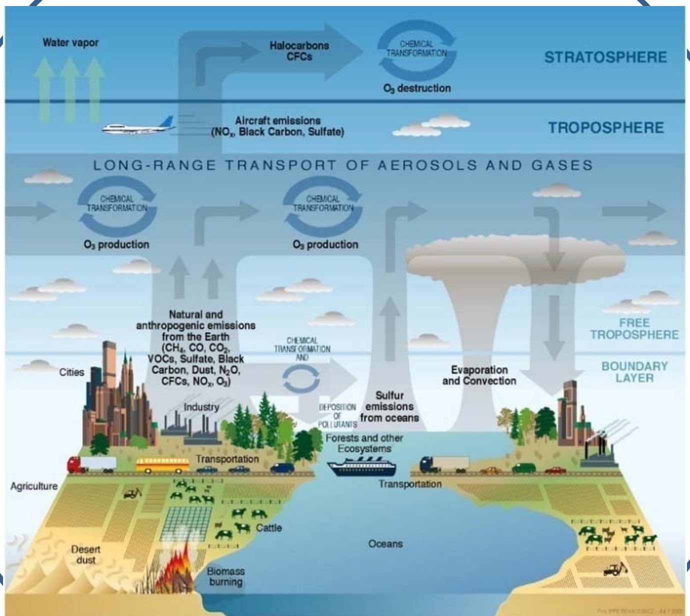
2) Biogenic gas emissions from the ocean and their impact on aerosol/cloud interaction and radiative properties of the overlying atmosphere

3) Sources, chemical composition and size distribution of ocean-derived primary organic aerosols

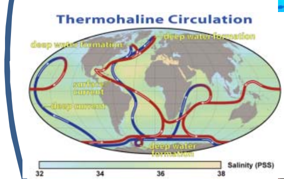
4) Model results

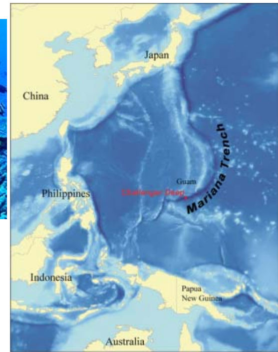
5) The future

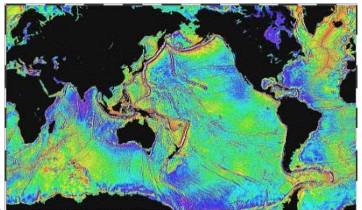
We used to think about Atmospheric Sciences and Oceanic Sciences independently…



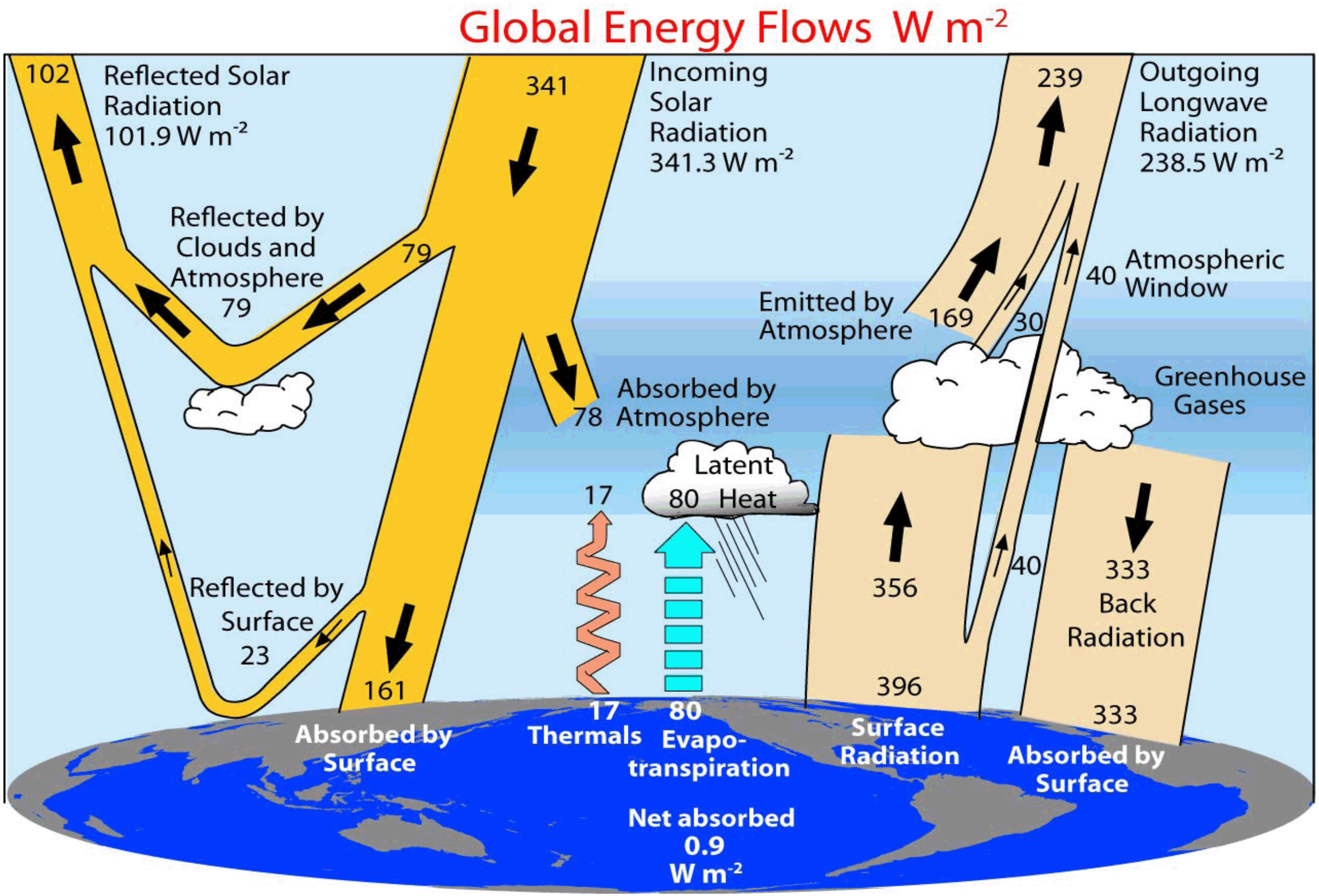
- Biological oceanography
- Chemical oceanography
- Geological oceanography
- Physical oceanography





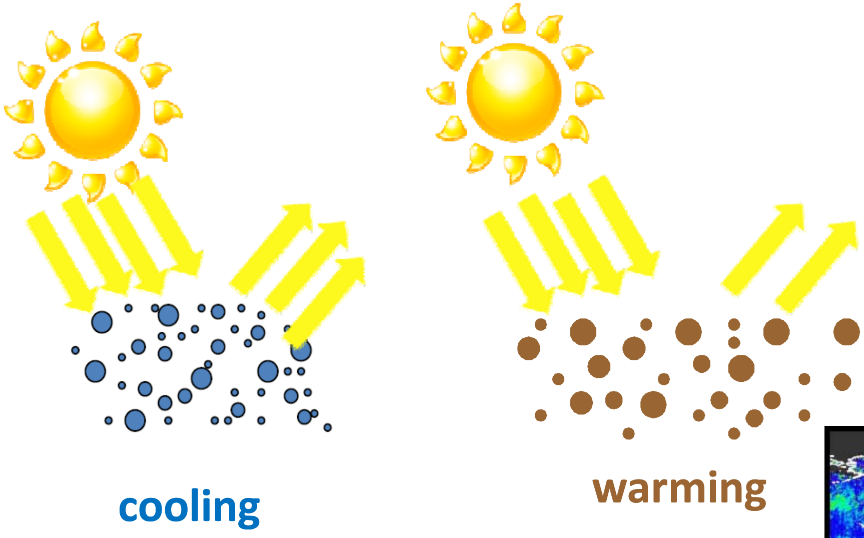


Source: www.wikipedia.org



Global Energy Flows W m-2
102
Reflected Solar Radiation 101.9 W m-2
341
Incoming Solar Radiation 341.3 W m-2
239
Outgoing Longwave Radiation 238.5 W m-2
Reflected by Clouds and Atmosphere 79
79
40
Atmospheric Window
Emitted by Atmosphere
169
30
Greenhouse Gases
Absorbed by 78 Atmosphere
Latent 80 Heat
17
356
40
333 Back Radiation
Reflected by Surface 23
161
396
333
Absorbed by Surface
17 Thermals
80 Evapo-transpiration
Surface Radiation
Absorbed by Surface
Net absorbed 0.9 W m-2

The Direct Radiative Effects of Aerosols



Aerosol Optical Depth (AOD)

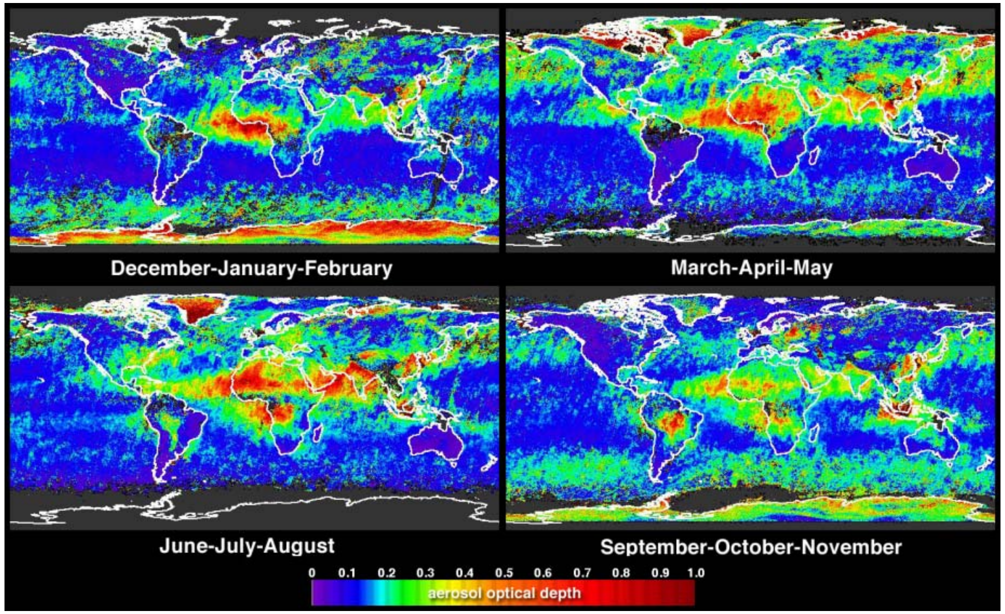
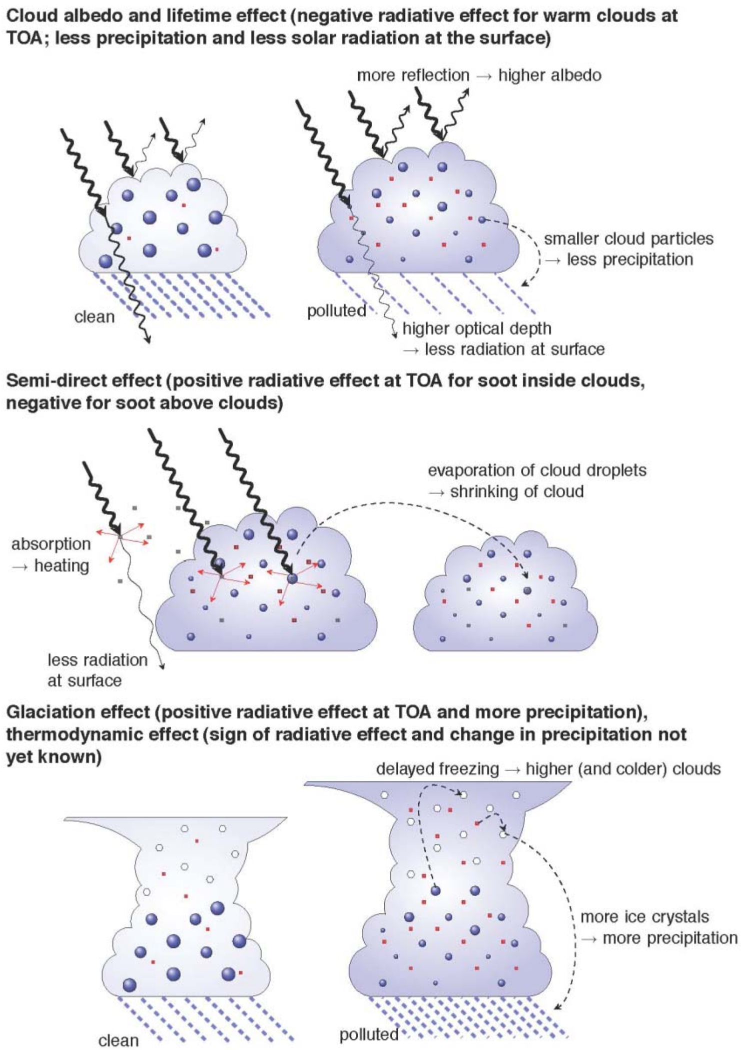


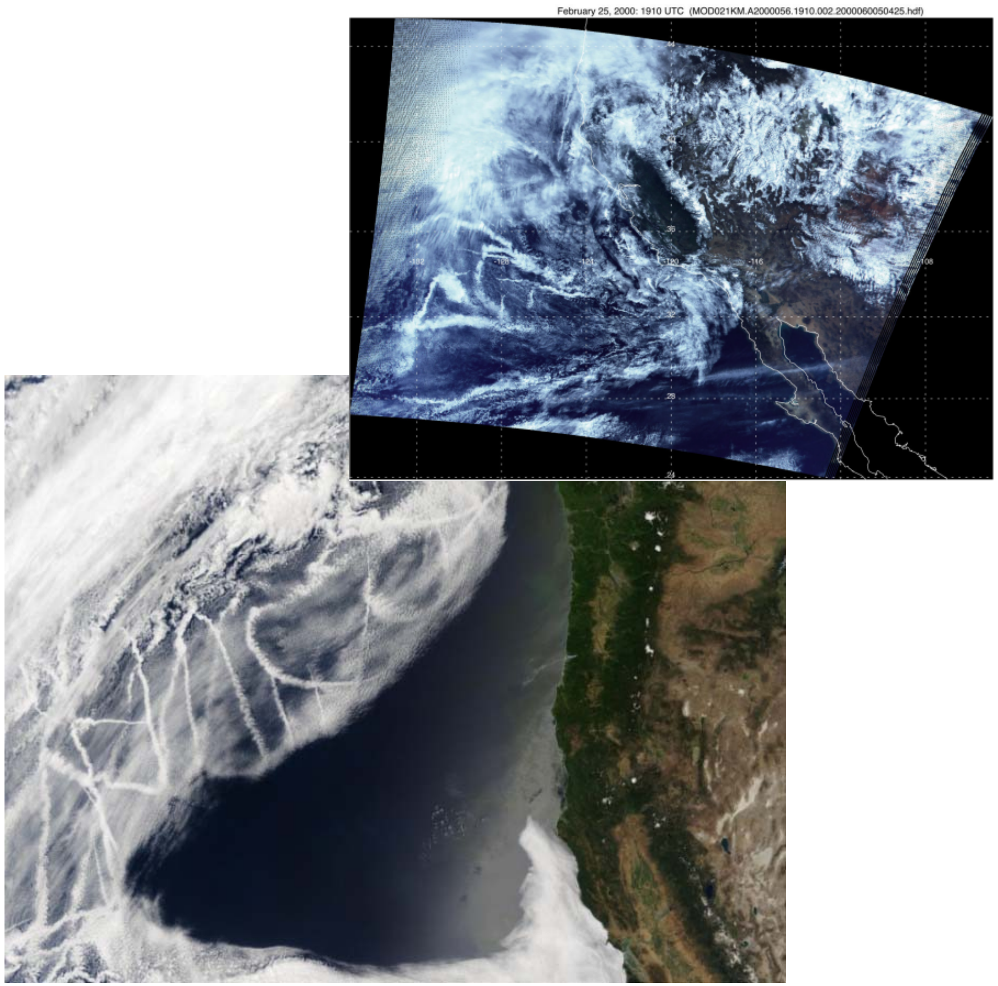
Image courtesy NASA/GSFC/LaRC/JPL, MISR Team
(http://visibleearth.nasa.gov/view_rec.php?id=16472)

The Indirect Radiative Effects of Aerosols



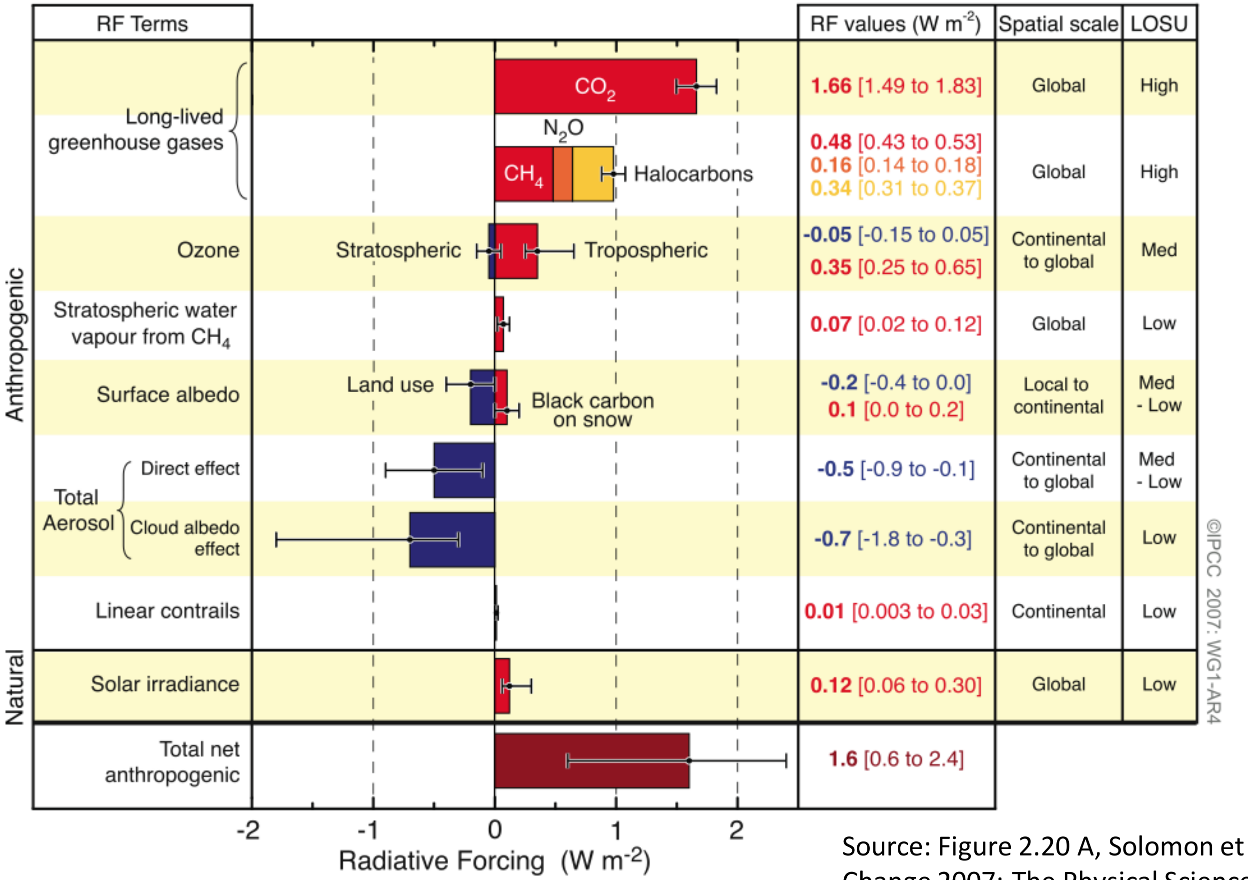
Source: Figure 7.20, Solomon et al., IPCC AR4 WG I, Climate Change 2007: The Physical Science Basis, 2007

Ship tracks



Credit :MODIS Atmosphere Science Team
http://visibleearth.nasa.gov/view_rec.php?id=224

Global Average Radiative Forcing (RF) Estimates and Ranges



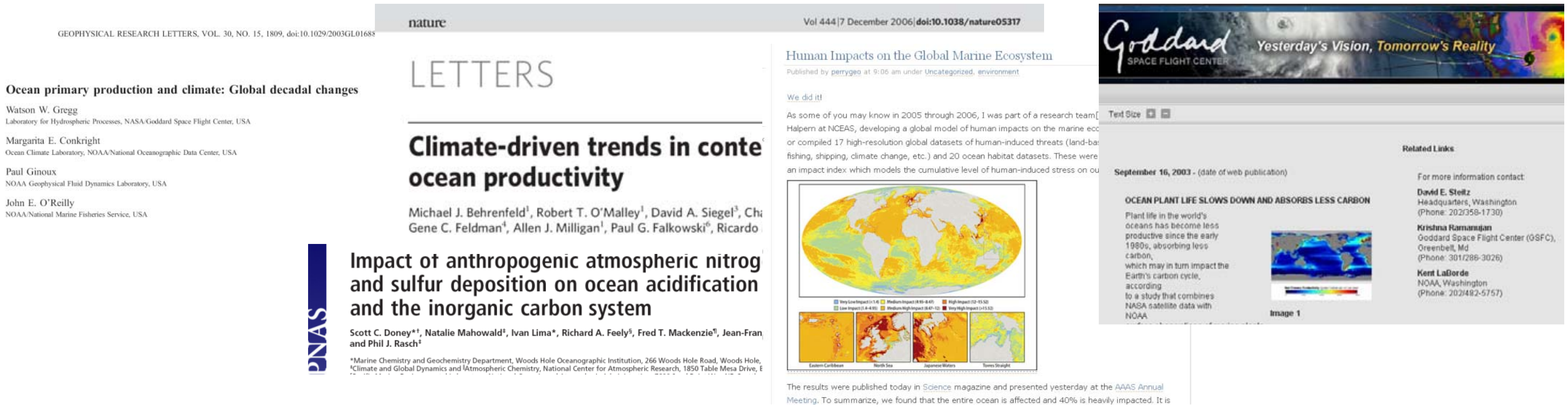
Source: Figure 2.20 A, Solomon et al., IPCC AR4 WG I, Climate Change 2007: The Physical Science Basis, 2007

- **No marine aerosols, why?**

Introduction | Gas emissions | POM emissions | Model Results | Future

Why Do We Need Improved Quantification of Marine Aerosol?

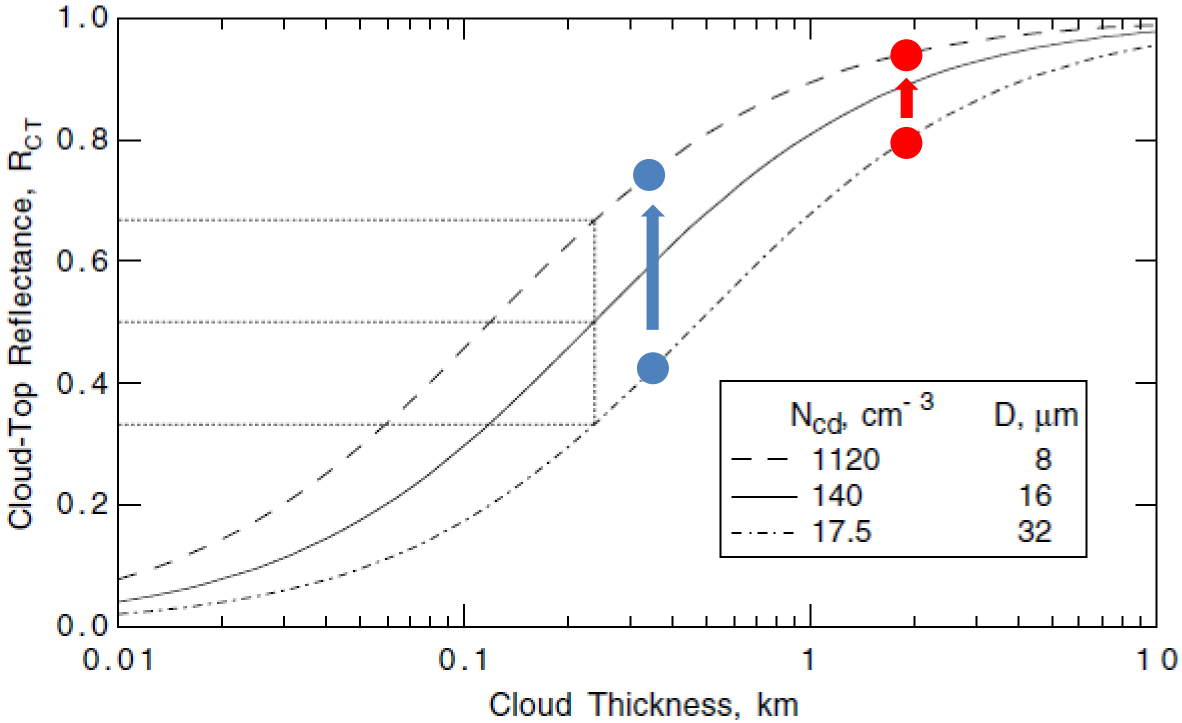
- Anthropogenic activities seem to influence marine ecology



Why Do We Need Improved Quantification of Marine Aerosol?

- Modeling studies do not always consider proper quantification of natural/background aerosols
- Pristine conditions small changes can be important
- Large fraction of the Earth is covered by the oceans
- Prescribing lower bounds of CDNC in GCMs could introduce up to **80%** uncertainty in AIE (Lohmann et al., 2001; Ghan et al., 2001; Wang and Penner, 2008; Hoose et al., 2009)
- **Model predicted extent of human-induced climate change**

Cloud Susceptibility



[Sourse: Schwartz and Slingo, 1996]

A definition of cloud susceptibility has been proposed as a measure of the extent of CCN influence on cloud albedo.

For a nonabsorbing, horizontally homogeneous cloud the cloud albedo can be parameterized in terms of cloud optical thickness

albedo

Optical thickness

$$\alpha_c = \frac{\tau}{7.7 + \tau}$$

$$S = \frac{\partial \alpha_c}{\partial N_{d,col\_avg}} = \frac{\alpha_c(1 - \alpha_c)}{3N_{d,col\_avg}}$$

Improved Quantification of Sea Spray

- Modeling studies do not always consider proper quantification of natural/background aerosols
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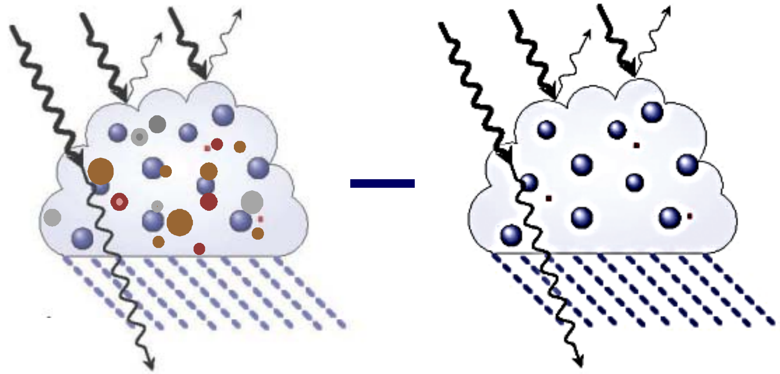
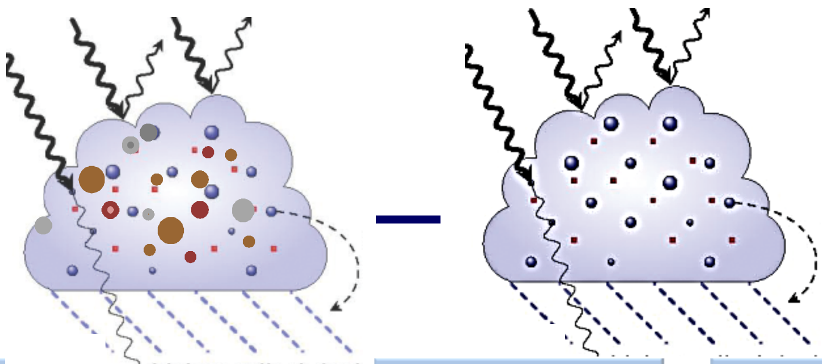
- **Model predicted extent of human-induced climate change**

Improved Quantification of Sea Spray

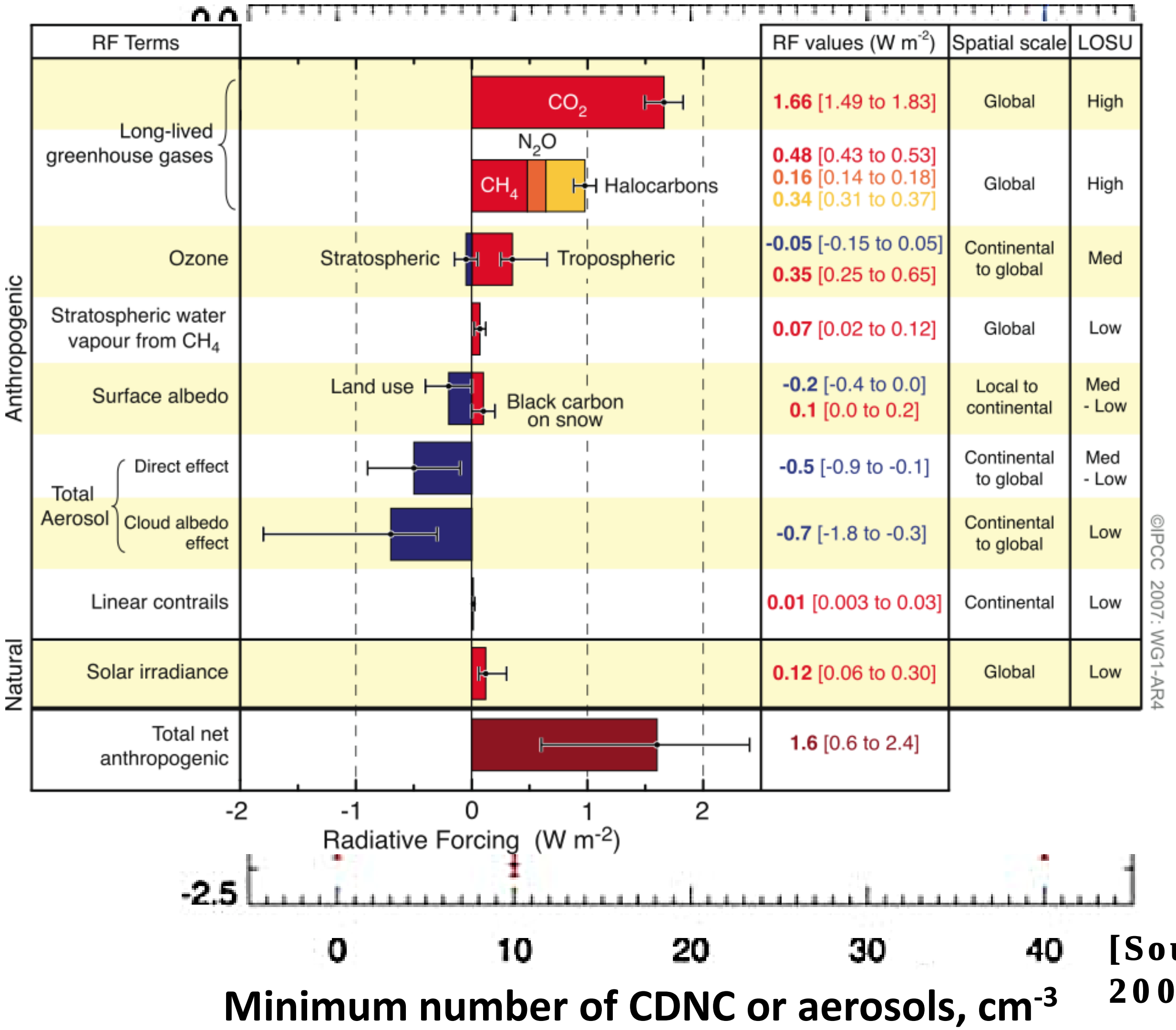
"Background" CCN/CDNC ~ 10 to 20 cm^{-3}



"Background CCN/CDNC ~30 to 40 cm^{-3}



Difference in Short-wave Cloud Forcing (SWCF)



[Source: Hoose et al., 2009]

Difference in Short-wave Cloud Forcing (SWCF)

- Improving *Ocean-Aerosol Interaction* will go a long way toward narrowing this large uncertainty
- Will also help reconcile the differences between the model predictions and satellite estimates/inverse calculations

Terminology

Chlorophyll – a: an index of phytoplankton biomass

- The main photosynthetic pigment
- Present in all phytoplankton
- Present only in phytoplankton

Units : mg m^{-3} ($\equiv \mu g\ L^{-1}$)

Measurement methods:

✓ Remote sensing (Chlorophyll a absorbs well at a wavelength of about 400-450 nm and at 650-700 nm

- Colorimetric
- High Performance Liquid Chromatography
- Fluorometric

Factors Controlling Primary Production

External

- Nutrients
- Light
- Grazing pressure
- Temperature

Internal

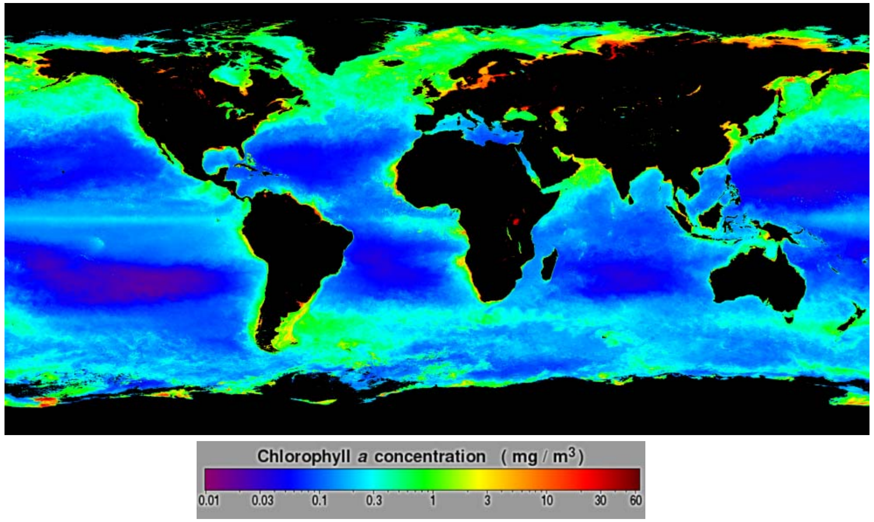
- Pigments
- Cell size
- Enzyme concentration
- Nutrient pool

$$CO_2 + H_2O + \text{Nutrients} + \text{Light} \rightleftharpoons \text{Organic matter} + O_2$$

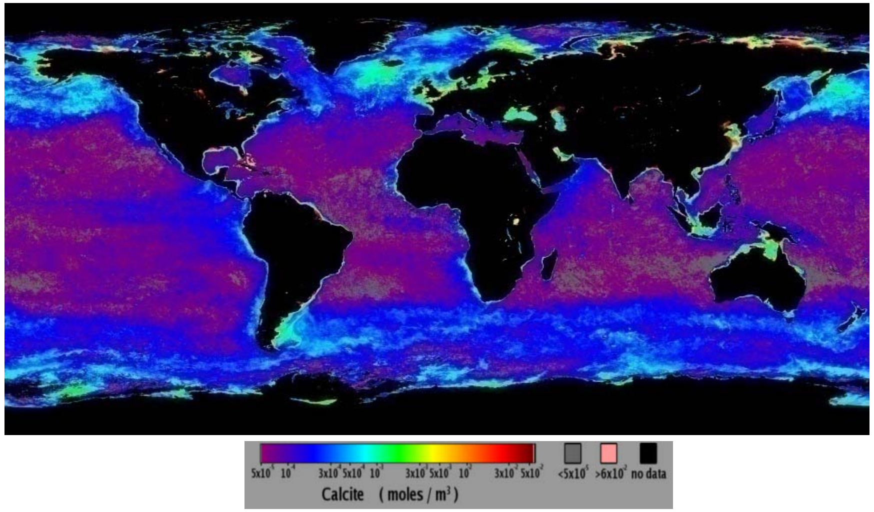
➢ **Ocean Net Primary Production (NPP) contributing roughly half of the biosphere's NPP!**

Phytoplankton Functional Groups

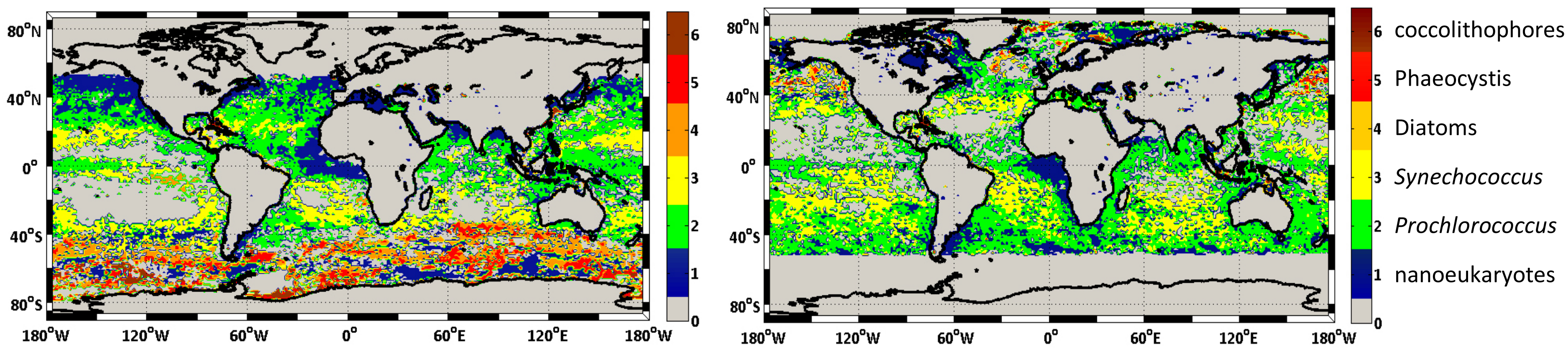
Aqua MODIS [Chl a] (year 2008)



Aqua MODIS Calcite (year 2008)



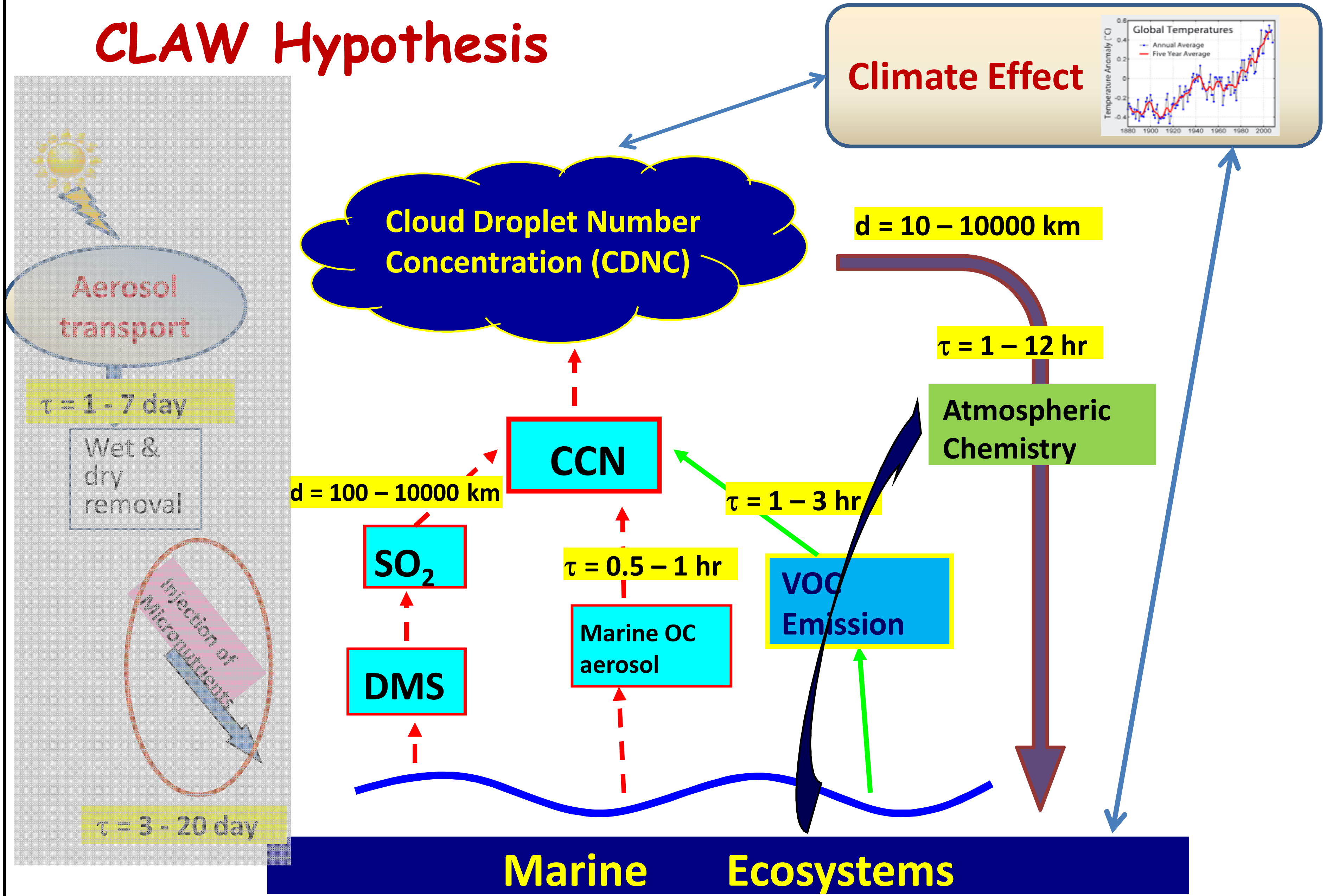
January **July**



Maps are created after Alvain, S., C. Moulin, Y. Dandonneau, and H. Loisel (2008), Seasonal distribution and succession of dominant phytoplankton groups in the global ocean: A satellite view, Global Biogeochem. Cycles, 22, GB3001.

Introduction | Gas emissions | POM emissions | Model Results | Future

CLAW Hypothesis



Extended CLAW

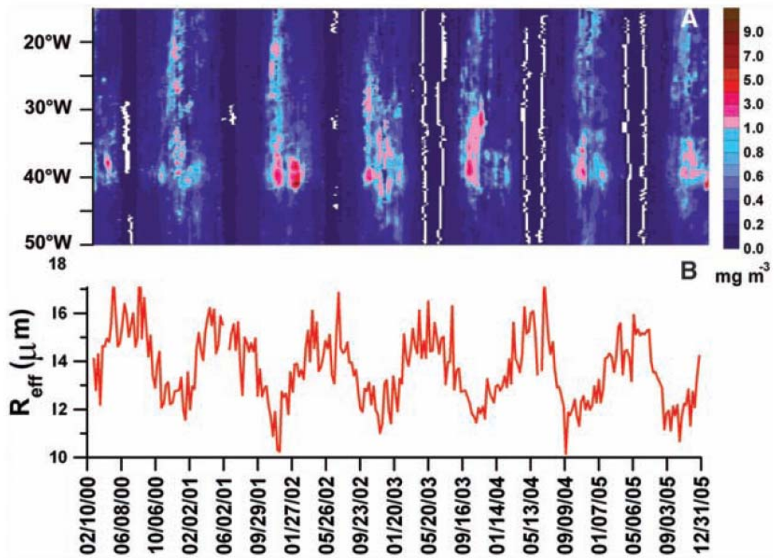
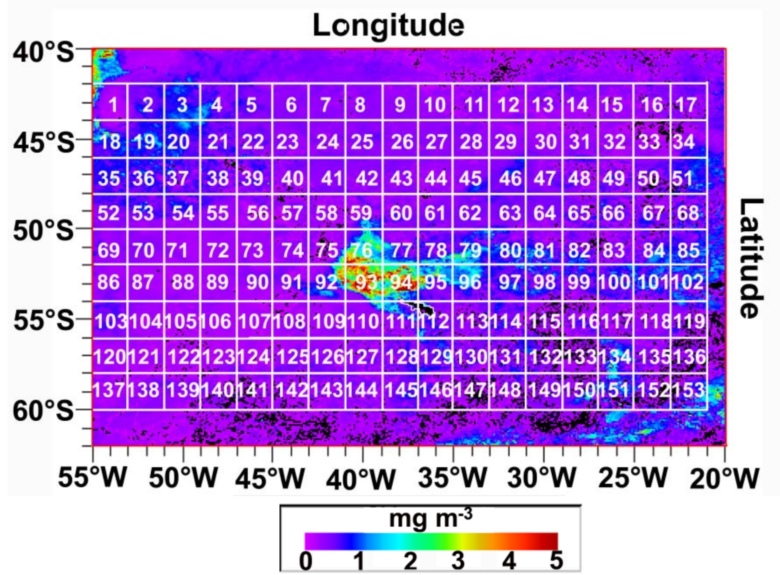


Fig. 1. The 8-day averaged (**A**) SeaWiFS-observed chlorophyll *a* and (**B**) MODIS-retrieved cloud effective radius. Data for [Chl a] is gridded at a resolution of 9 by 9 km and zonally averaged between 49°S and 54°S; data for R_{eff} is gridded at a resolution of 1° by 1° and averaged in the area of 49° to 54°S and 35° to 41°W. White areas in (A) indicate missing data.



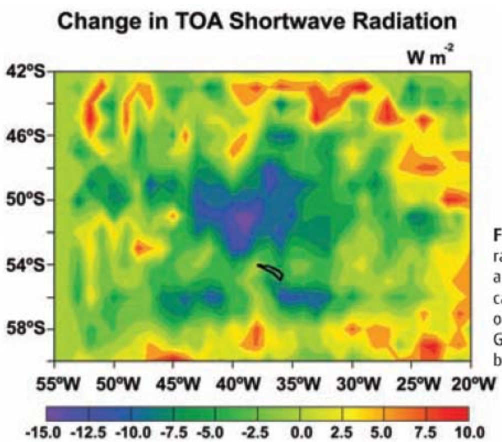
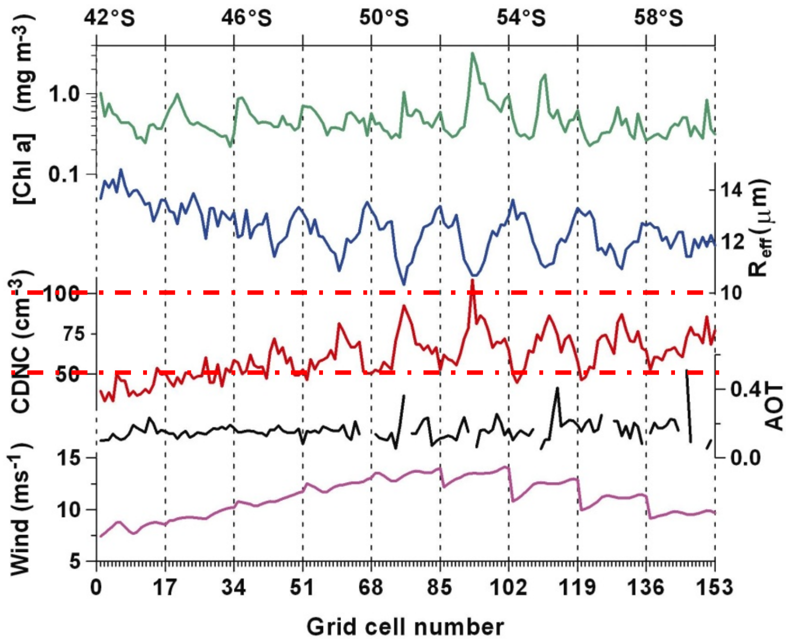


Fig. 3. Change in TOA short-wave radiation. The radiative effect was evaluated for the change in albedo of warm marine clouds. Calculations are carried out using monthly averaged MODIS-observed data at 1° by 1° resolution and the GMI-supplied monthly averaged solar flux at 4° by 5° resolution.

SOCEX II - polluted

SOCEX II - "background"



Source: Meskhidze, N. and A. Nenes, Phytoplankton and Cloudiness in the Southern Ocean, Science, Vol 314, 2006.

Outline

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2) Biogenic gas emissions from the ocean - impact on aerosol/cloud interaction and radiative properties of the overlying atmosphere

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Biogenic Gas Emissions From the Ocean

Basic Concepts

$$F = K\,\Delta C$$

Gas flux (***F***) across the interface is driven by a concentration difference (ΔC) between air and surface water.

K is a proportionality constant known as gas transfer velocity or transfer coefficient or a piston transfer velocity (cm h^{-1})

$$\Delta C = \frac{C_a}{H} - C_w$$

Where C_a and C_w are the gas concentrations in air and water, respectively and H is Henry's Law constant

$$H = \frac{p_g}{C_w}$$

Tables: http://www.mpch-mainz.mpg.de/~sander/res/henry.html

Ratio of the gas in air to its concentration in unionized form dissolved in water

Basic Concepts (continued)

It is often convenient to think in terms of reciprocal of the transfer velocity – a measure of the resistance to interfacial gas exchange

$$\frac{1}{K} = \frac{1}{\alpha k_w} + \frac{1}{H \cdot k_a}$$

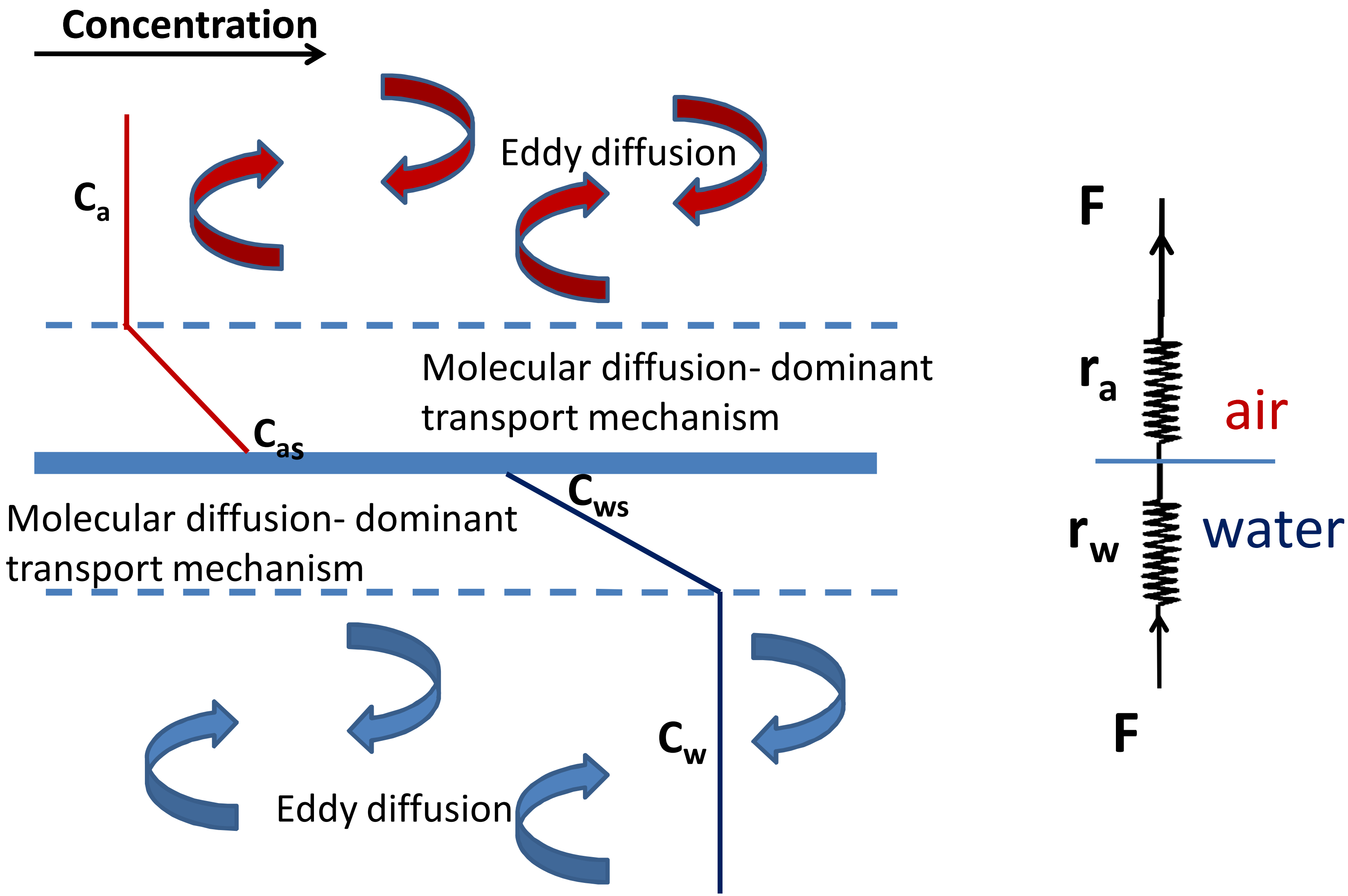
α – is a factor accounting for the chemical enhancement of gas exchange due to gas-aqueous rxs

For trace gases which are chemically "unreactive" in the aqueous-phase (DMS, CH_4, N_2O, CO_2, inert gases) $\alpha=1$

For highly aqueous-phase gases (SO_2, NH_3, HCl) $\alpha \approx 10^3$

$$R = r_w + r_a$$

Two Film Model



Basic Concepts (continued)

$$k_a = \frac{F}{(C_a - C_{as})} \qquad k_w = \frac{F}{(C_w - C_{ws})}$$

For aqueous-phase reactive gases $r_a >> r_w$ $\Rightarrow$ bulk of the resistance to the gas transfer is in the air-phase (i.e., $k_w << k_a$ and $K \sim k_a$.

For "chemically unreactive" gases $r_w >> r_a$ $\Rightarrow$ all of the resistance to the gas transfer is in water phase (i.e., $k_w >> k_a$ and $K \sim k_w$)

$$C_w - C_{ws} = C_w - \beta C_a$$

β – Bunsen solubility coefficient, v/v atm^{-1}

$$\boxed{F = K(C_w - \beta C_a)}$$

Measurement Techniques

1. Measurement of *F in the air above the sea surface and ΔC in the water to determine K*. These methods are referred to as direct flux measurements or micrometeorological approaches and include covariance (or eddy correlation), eddy accumulation, atmospheric concentration profile, and inertial dissipation techniques.

2. Measurement of C_a *(in air) and the change in* C_w *(in water) as a function of time. Assuming* the water volume and surface area are known, *F is then equal to the change in* C_w *multiplied* by the ratio of the volume to the surface area. Then, *K can be calculated with* C_a and C_w*. These bulk concentration techniques include mass-balance and* perturbation studies where the concentration of gases in air and water are out of equilibrium through biological consumption/production, water heating/cooling (N_2, O_2, CO_2, noble gases), radioactive decay (^{222}Rn), or by purposeful addition (^{3}He, SF_6).

3. Proxy techniques where a nongaseous tracer whose air-sea flux is more easily measured is used as a surrogate for a gas using the principle that all air-water transfer is controlled by the near surface hydrodynamics. In field applications, proxy methods are limited to thermographic methods that use heat.

Wanninkhof, R. et al., Advances in Quantifying Air-Sea Gas Exchange and Environmental Forcing, Annu. Rev. Mar. Sci. 2009. 1:213–44, 10.1146/annurev.marine.010908.163742

Basic Concepts - Schmidt number

$$\text{Schmidt number } (Sc) = \frac{\text{Kinematic viscosity of seawater}}{\text{Gas diffusivity}}$$

If *K* is known for any given gas, its value may be inferred for any other gas

Gas transfer velocities are typically normalized to Sc_{600} (the values for CO_2 in freshwater and seawater at 20 °C)

$$\frac{K_1}{K_2} = \left(\frac{Sc_2}{Sc_1}\right)^n$$

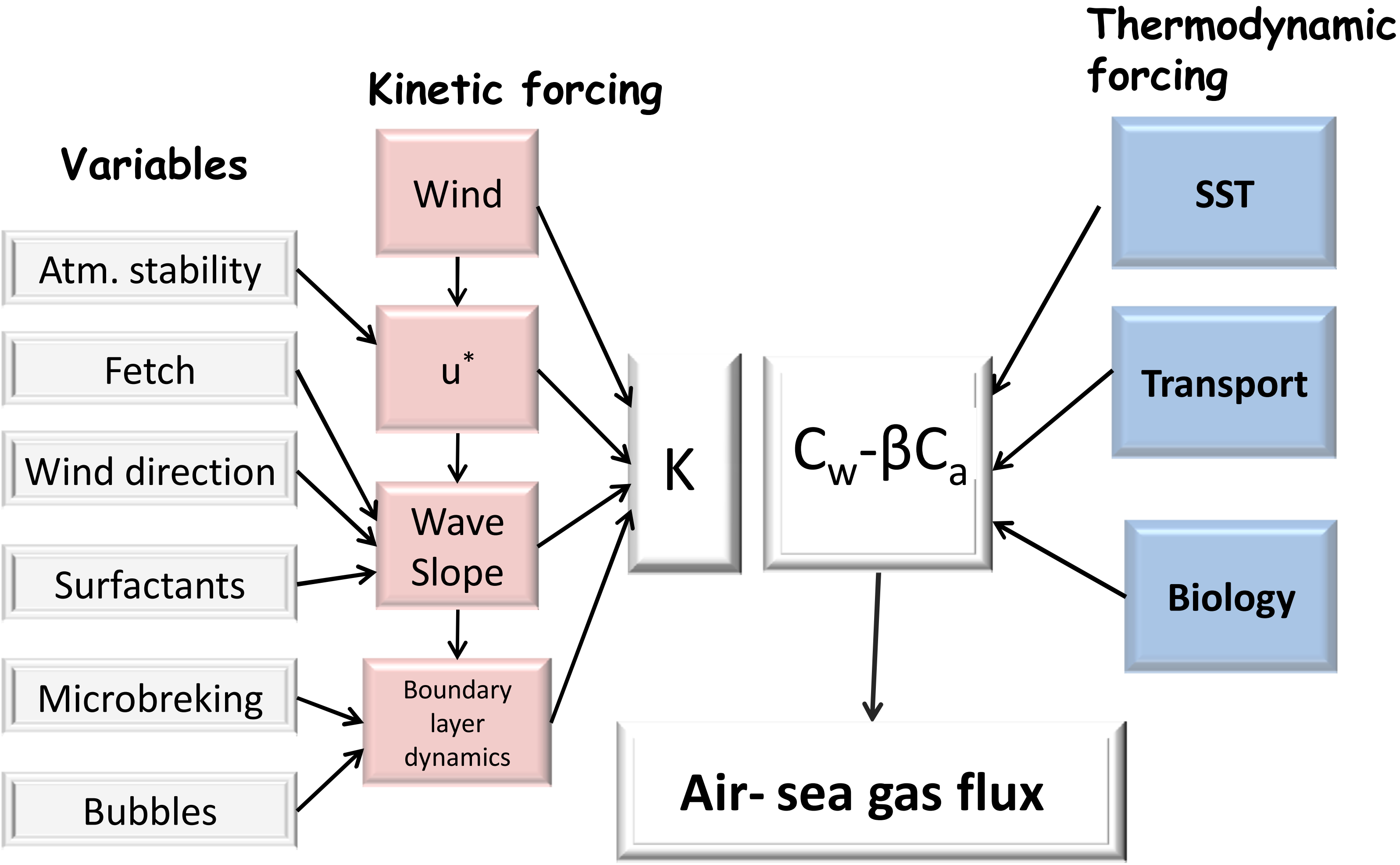
n=-1 for the thin film model

Value of *n* changes from 0 to -1.22 in different publications

Variables Affecting K

1. Wind speed
2. Fetch
3. Breaking waves and bubbles
4. Surfactant films
5. Chemical enhancement of gas exchange
6. Temperature and humidity gradients
7. Rain

Factors Affecting Air-sea Fluxes of Weakly Soluble, Non-reactive Gases

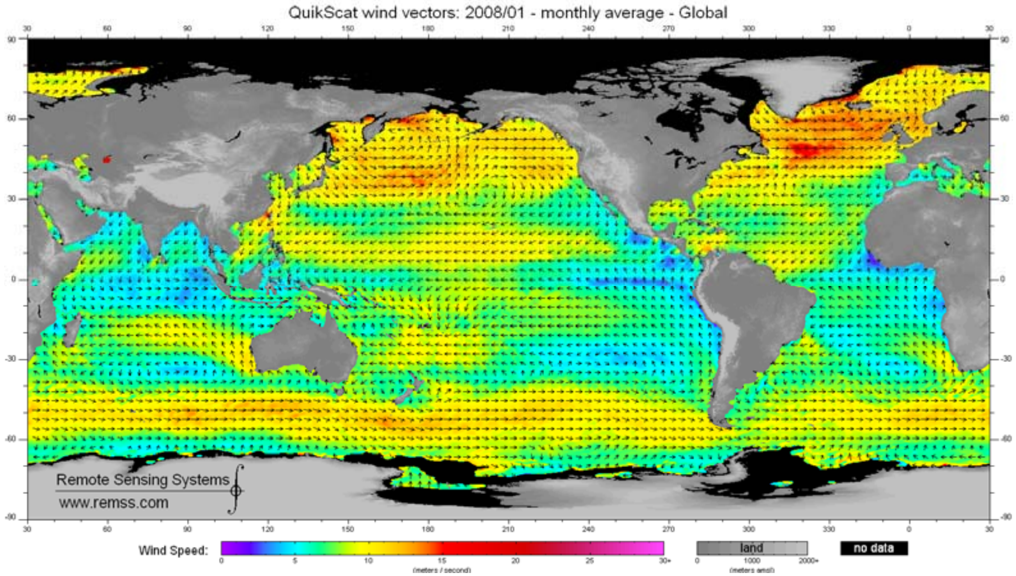


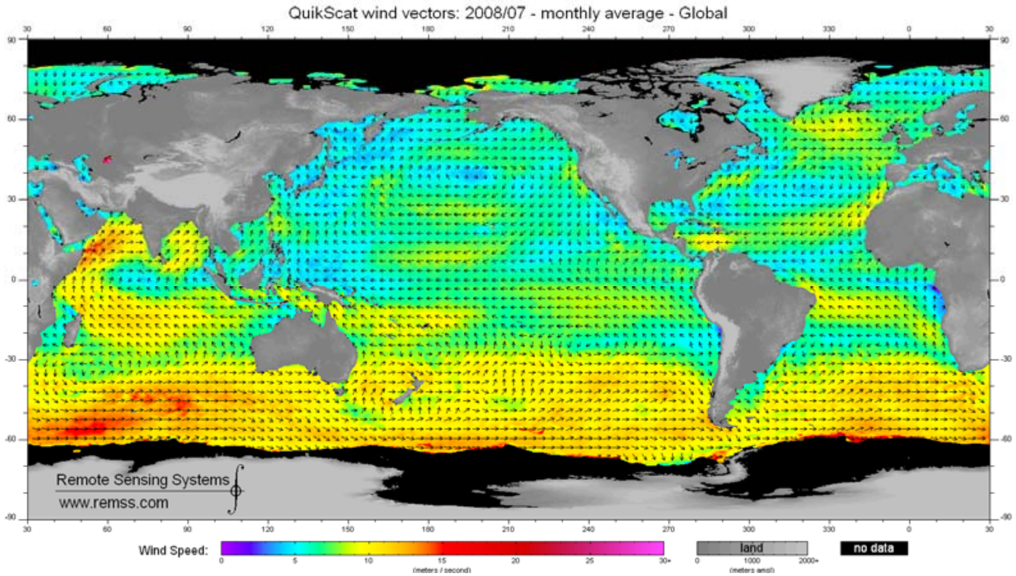
Wanninkhof, R. et al., Advances in Quantifying Air-Sea Gas Exchange and Environmental Forcing, Annu. Rev. Mar. Sci. 2009. 1:213–44, 10.1146/annurev.marine.010908.163742

Gas Exchange - Wind Speed Relationships

Relationship	Equation
Liss and Merlivat, 1986	**$K=0.17 \cdot U_{10} \cdot (600/Sc)^{0.67}$** ($U_{10} < 3.6\ m\ s^{-1}$) **$K=(2.85 \cdot U_{10}-9.65) \cdot (600/Sc)^{0.5}$** ($3.6\ ms^{-1} < U_{10} < 13\ ms^{-1}$) **$K=(5.9 \cdot U10 - 49.3) \cdot (600/Sc)^{0.5}$** ($U_{10} > 13\ ms^{-1}$)
Wanninkhof, 1992	**$K=0.39\ (U_{10ave})^2\ (660/Sc)^{0.5}$** (long term average winds) **$K=0.31\ (U_{10})^2\ (660/Sc)^{0.5}$** (instantaneous wind speeds)
Nightingale et al., 2000	**$K=0.333(U_{10})^2 + (600/Sc)^{0.5}$**

SeaWinds on QuikSCAT





http://www.remss.com/qscat/qscat_browse.html

http://winds.jpl.nasa.gov/missions/quikscat/index.cfm

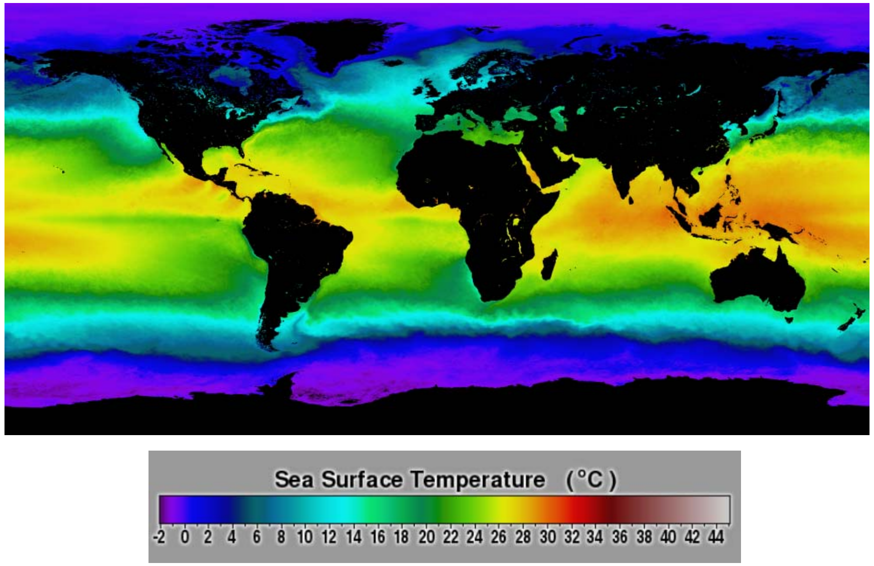
Wind speed at 10 meters over the ocean surface (U_{10})

We Need a "Couple" of Other Parameters…

$$Sc = 3875.21 - 180.80T_C + 2.69T_C^2$$

Where T_C is sea-surface temperature in (°C) [Moore and Groszko, 1999]

MODIS sea-surface temperature



Assume $C_a \approx 0$

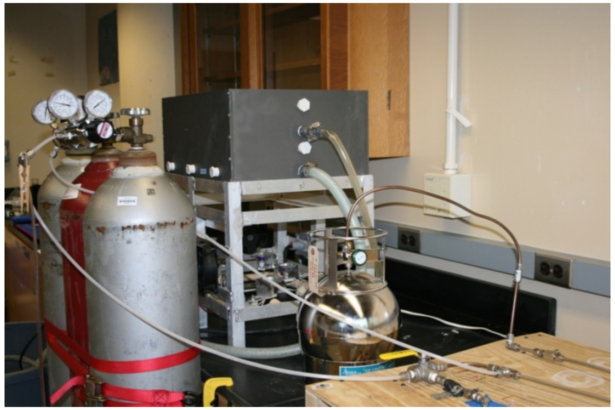
$$P = C_w\left(K - \sum_i K_{Chem,i}C_{xi} - K_{Biol}\right)$$

Mean lifetime against rx with OH and O_2 in seawater = 19 and 115 days
Mean lifetime against bacterial consumption 17 days

Palmer, P. I. and Shaw, S. L.: Quantifying global marine isoprene fluxes using MODIS chlorophyll observations, J. Geophys. Res., 32, L09805, doi:10.1029/2005GL022592, 2005.

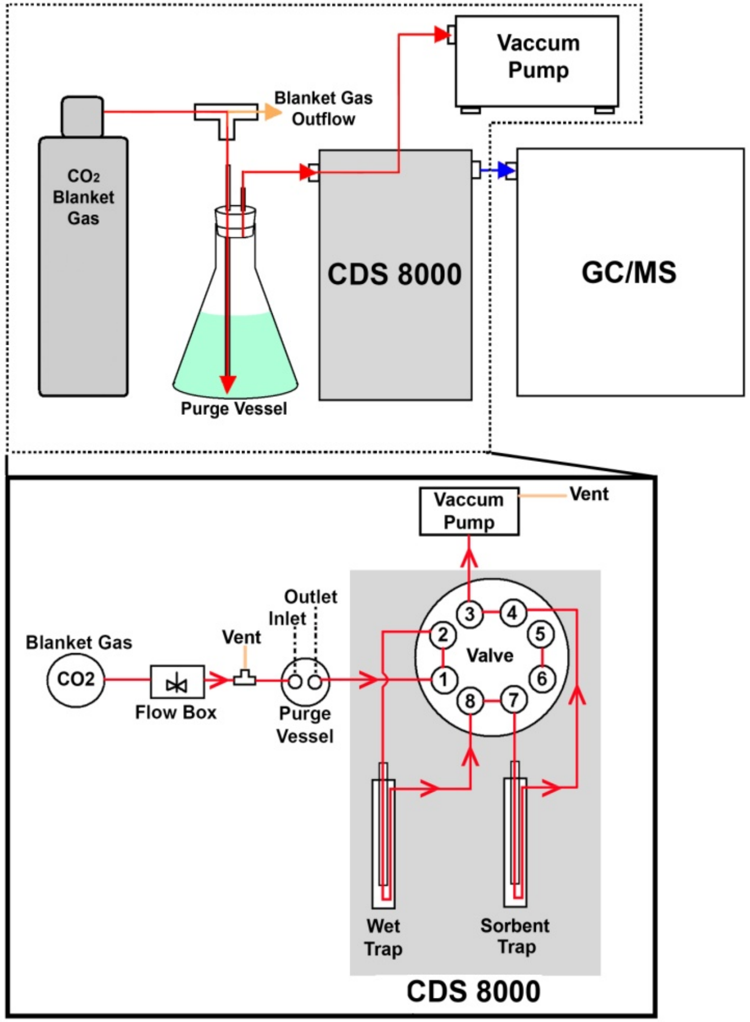
Light And Species Dependent Production Rates Of Marine Isoprene And Monoterpenes

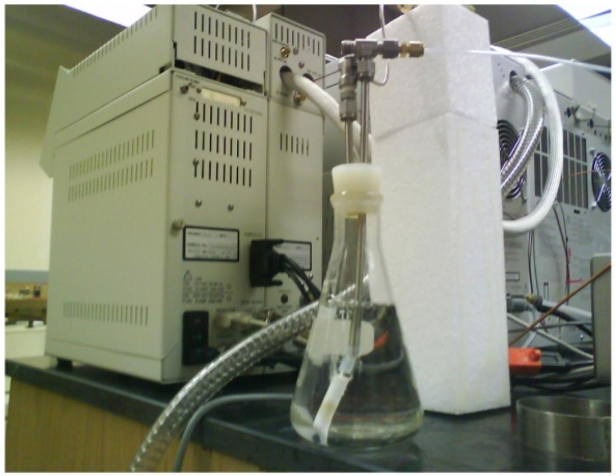
Laboratory grown phytoplankton monocultures: diatoms *Thalassiosira weissflogii* (*T. weiss.)* (CCMP 1336) and *Thalassiosira pseudonana* (*T. pseud.)* (CCMP 1335), prymnesiophyte strains- *Pleurochrysis carterae* (*P. carter.)* (CCMP 645);   dinoflagellate strains- *Karenia brevis* (*K. brevis*) (CCMP 718, CCMP 2229) and *Prorocentrum minimum* (*P. minim.*) (CCMP 1329); cryptophyte strains- *Rhodomonas salina* (*R. salina*) (UTEX 2423)



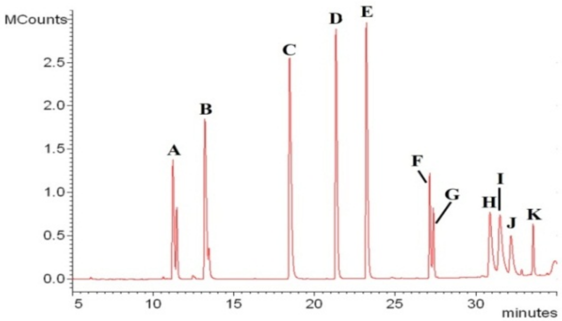
Light And Species Dependent Production Rates Of Marine Isoprene And Monoterpenes

Instrumentation Setup

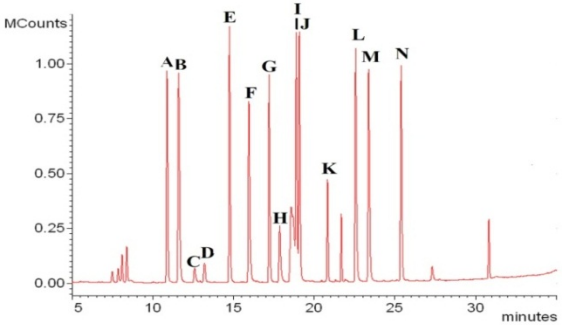




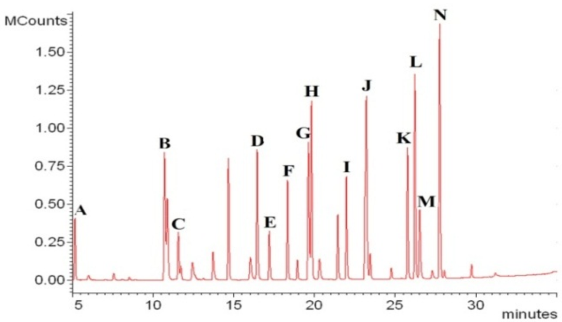
Sample chromatographs for 38 BVOC



Compound	
A	Dimethyl sulfide
B	Isoprene
C	Benzene
D	Dimethyl disulfide
E	Toulene
F	m-Xylene
G	Ethylbenzene
H	alpha-Pinene
I	Camphene
J	beta-Pinene
K	D-Limonene



Compound	
A	Dichloromethane
B	1,2-Dichloroethane
C	1,1-Dichloroethene
D	2-Chloropropane
E	1,2-Dichloroethene
F	Chloroform
G	1-Chlorobutane
H	Carbon Tetrachloride
I	Trichloroethene
J	1,1,1-Trichloroethane
K	1,3-Dichloropropene
L	1,1,2-Trichloroethane
M	Tetrachloroethene
N	Chlorobenzene

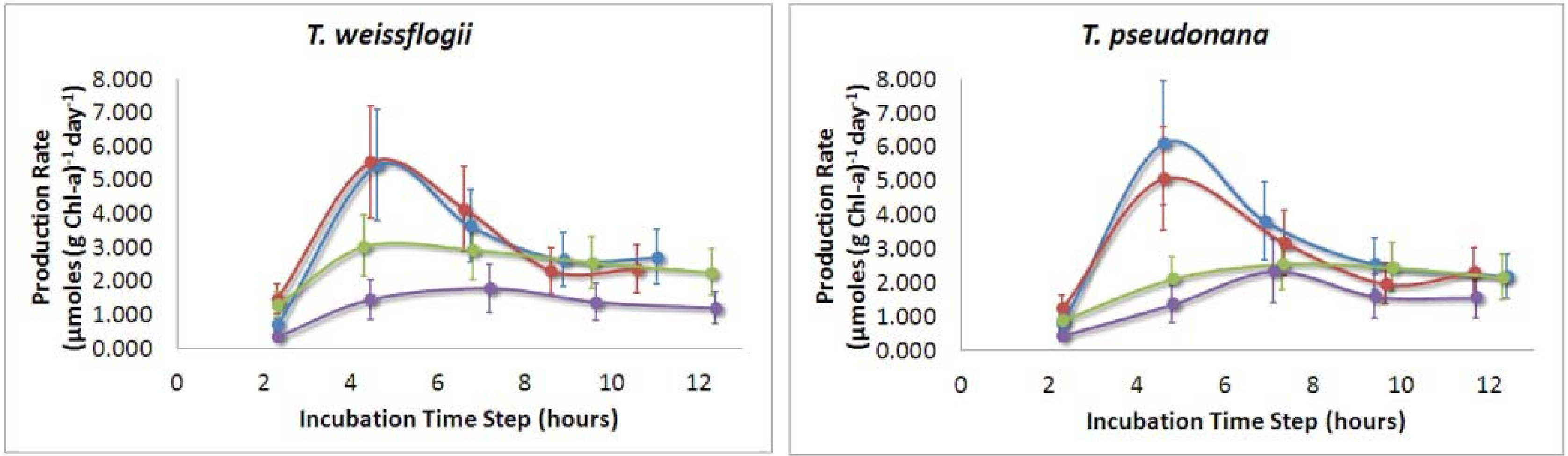


Compound	
A	Bromomethane
B	Iodomethane
C	1-Bromoethane
D	1-Bromopropane
E	Iodoethane
F	Dibromomethane
G	Bromodichloromethane
H	Chloroiodomethane
I	2-Iodopropane
J	Dibromochloromethane
K	1-Bromopentane
L	1-Iodobutane
M	Bromoform
N	Diiodomethane

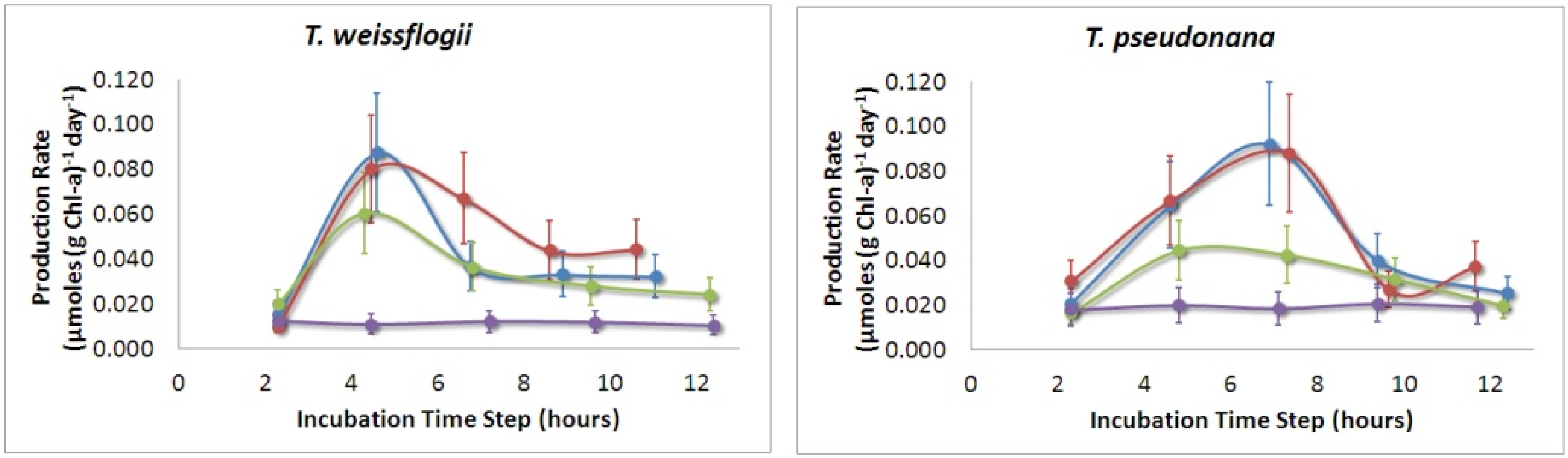
- We measured 38 different VOCs emitted from phytoplankton including α- and β-pinene, d-limonene, camphene, halocarbons…

Results Of Light Experiments

Stress induced isoprene production as a function of time



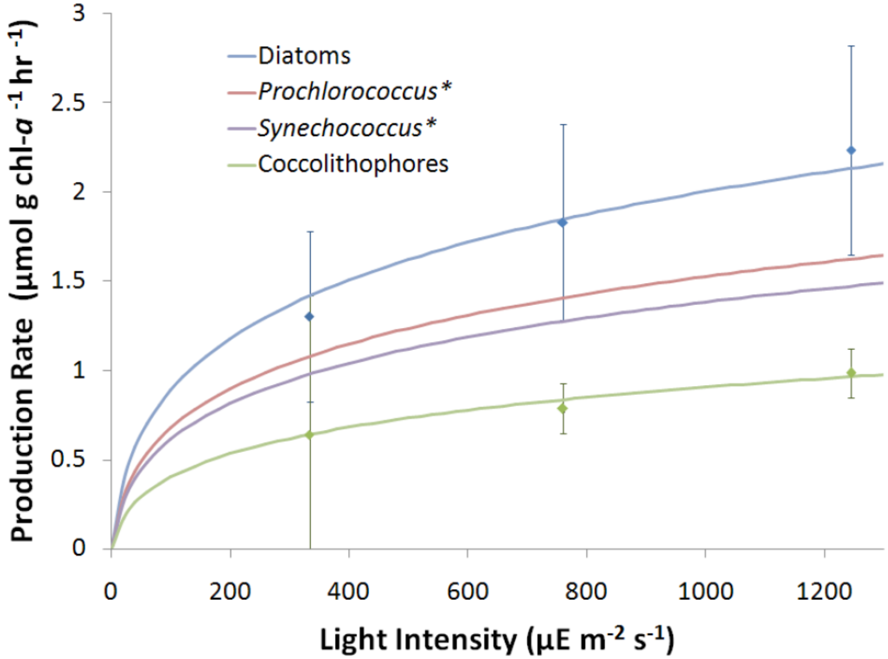
Stress induced α-pinene production as a function of time



90 μE m^{-2} s^{-1} 150 μE m^{-2} s^{-1} 420 μE m^{-2} s^{-1} 900 μE m^{-2} s^{-1}

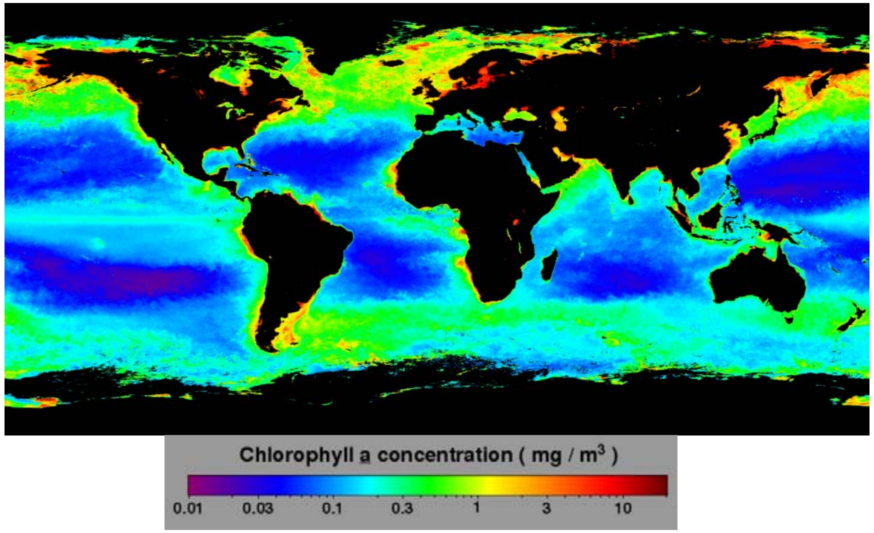
[Sabolis et al., in prep]

Light Dependent Production Rates

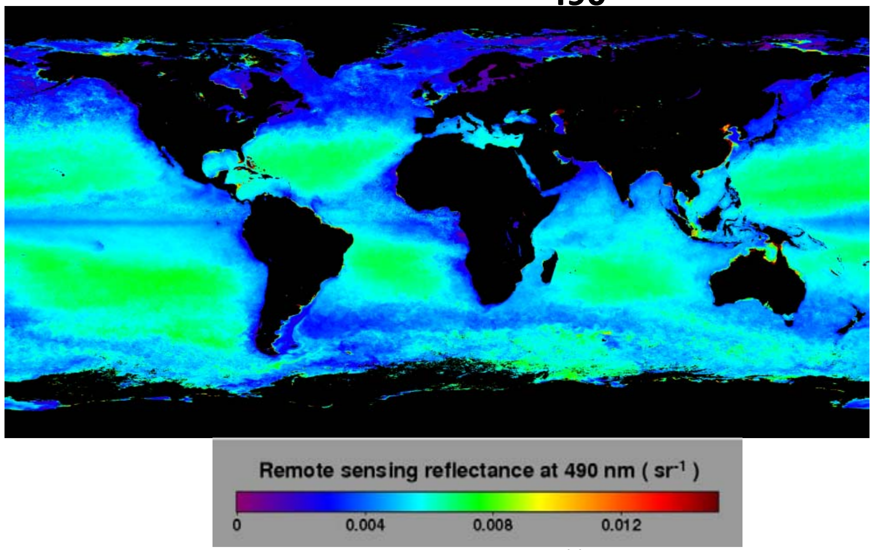


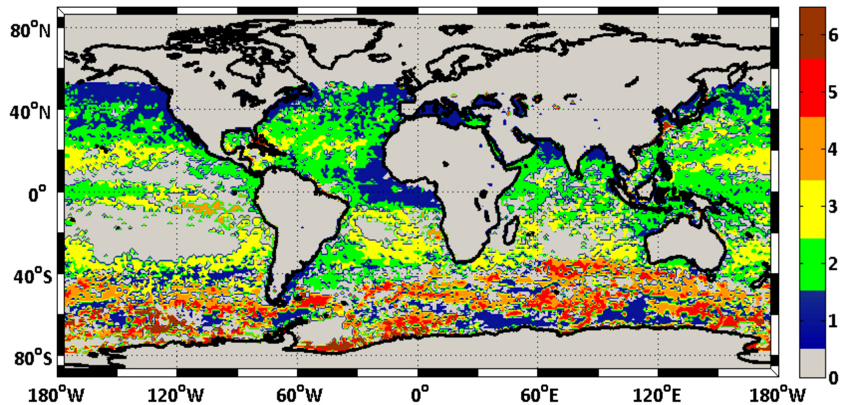
Source: Gantt, B., N. Meskhidze, and D. Kamykowski, Atmos. Chem. Phys., 9, 4915–4927, 2009

SeaWiFS [Chl a]



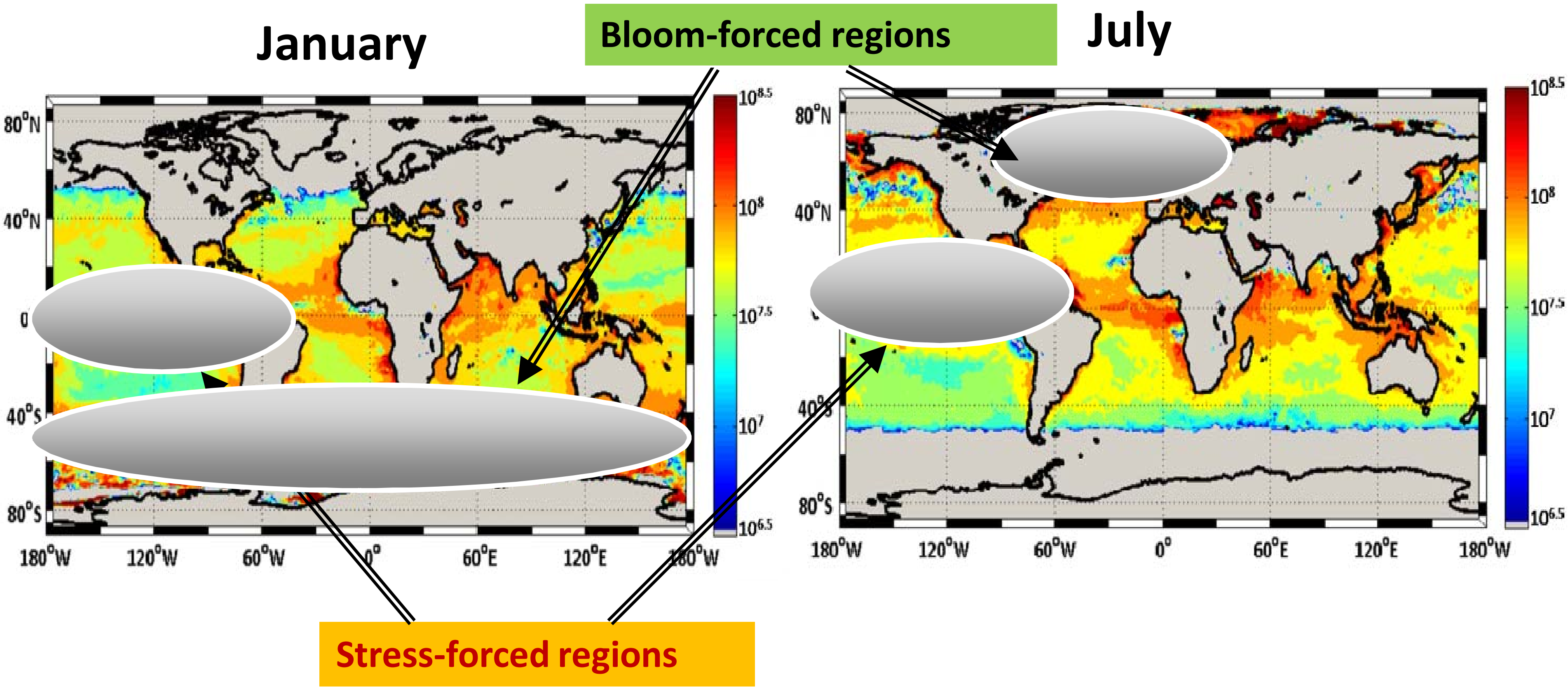
SeaWiFS K_{490}



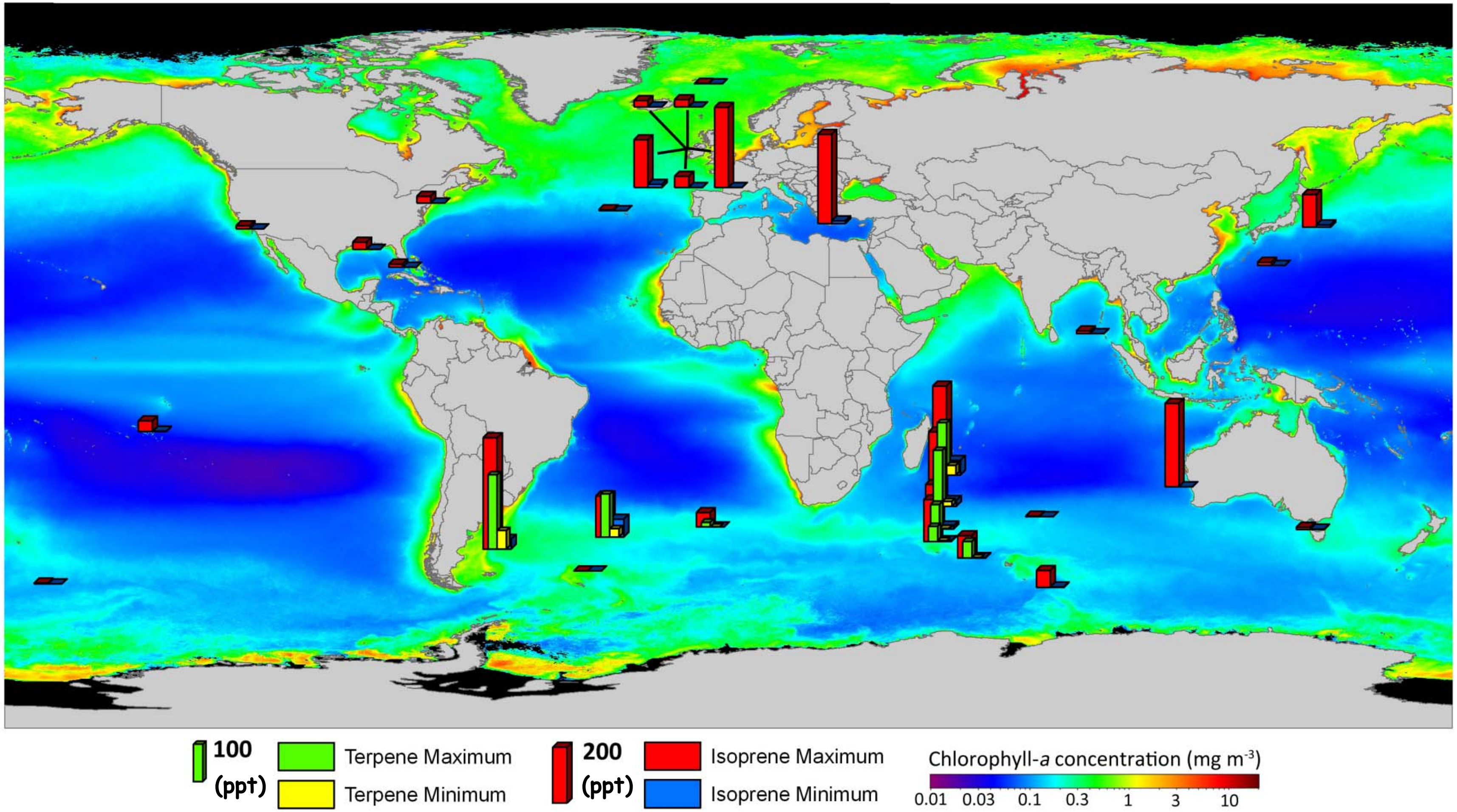


http://oceancolor.gsfc.nasa.gov

Marine Isoprene Emissions



Observed Marine Boundary Layer Hydrocarbon Concentrations



[Shaw et al., 2010 AMET]

Global Annual Total Marine Isoprene Emissions

Global Marine Isoprene Emissions (Tg C yr^{-1})	Source
1.1	Bonsang et al. (1992)
0.1	Palmer and Shaw (2005)
1.2	Sinha et al. (2007)
0.27	Arnold et al. (2008)
1.68	Arnold et al. (2008)
0.92	Gantt et al. (2009)
2.5	Luo and Yu (2009)

- Global terrestrial emissions ~ 440 to 660 Tg C yr^{-1} (500 to 750 Tg isoprene)

Primary and Secondary Organic Aerosol Formation and Growth

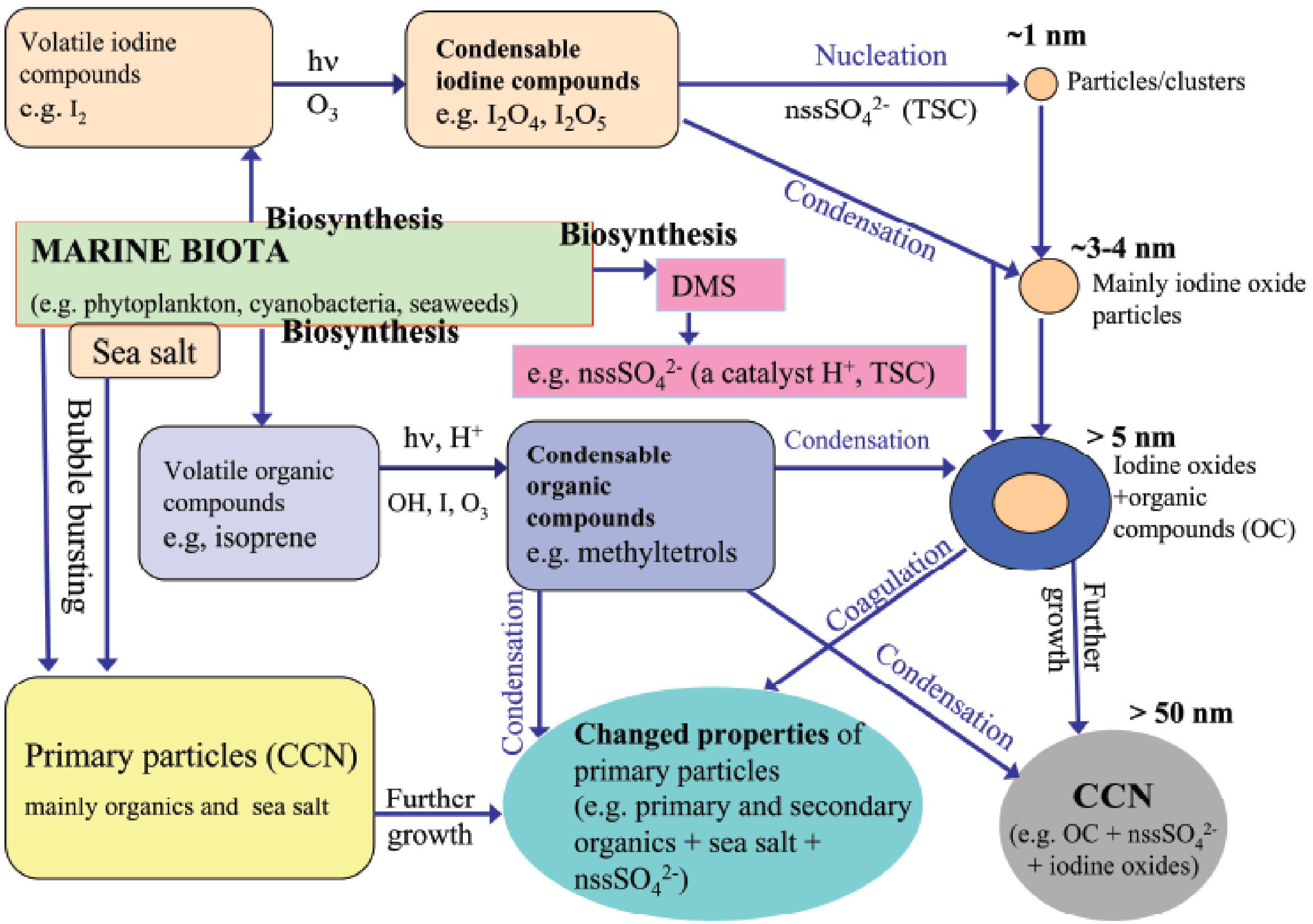


Fig. 13 Vaattovaara, P., Huttunen, P. E., Yoon, Y. J., Joutsensaari, J., Lehtinen, K. E. J., O'Dowd, C. D. & Laaksonen, A. 2006 The composition of nucleation and Aitken modes particles during coastal nucleation events: evidence for marine secondary organic contribution. Atmos. Chem. Phys. 6, 4601–4616.

Outline

1) Introduction

2) Biogenic gas emissions from the ocean and their impact on aerosol/cloud interaction and radiative properties of the overlying atmosphere

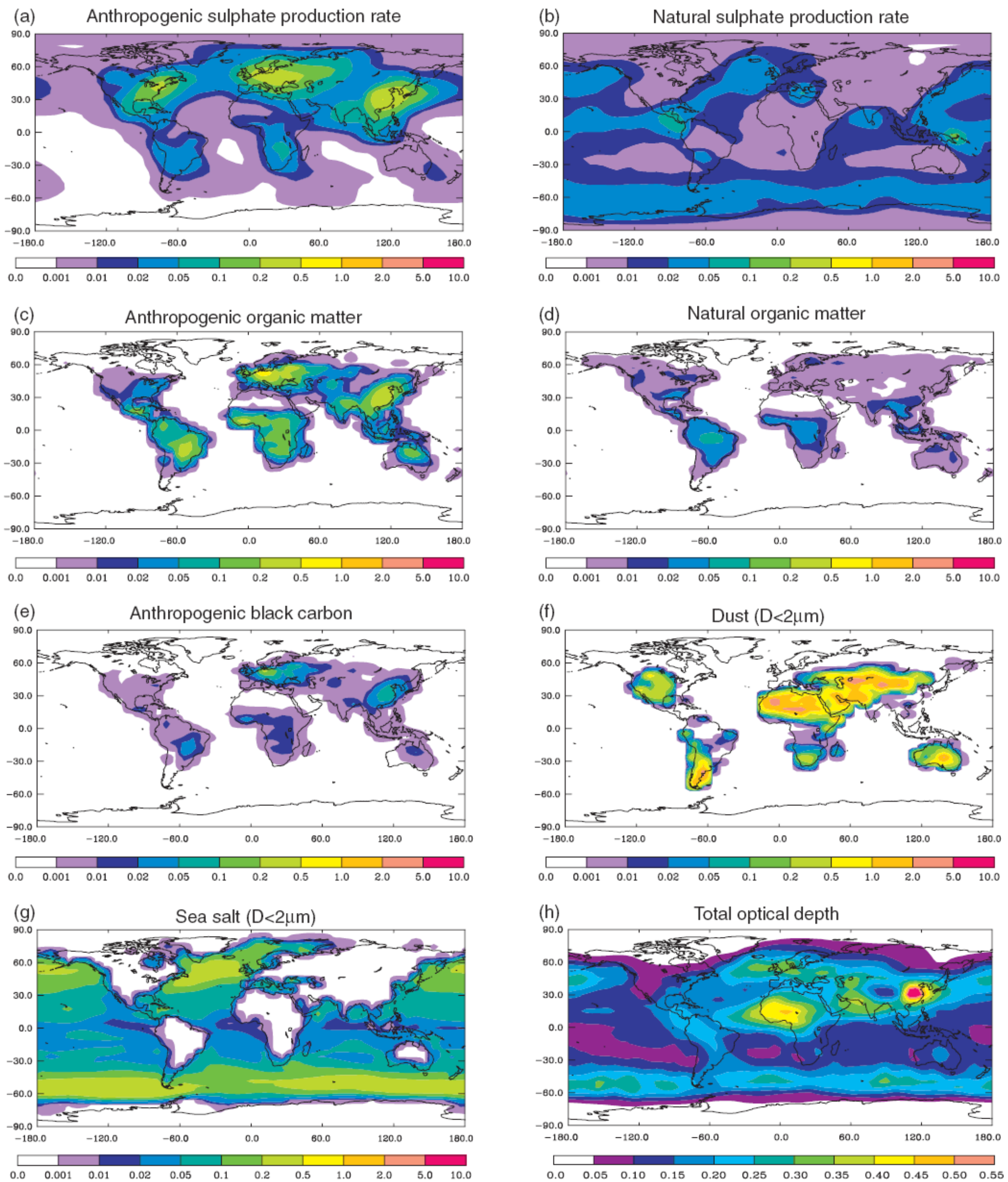
3) **Sources, chemical composition and size distribution of ocean-derived primary organic aerosols**

4) Model results

5) The future

Annual average source strength in four major aerosol types [kg km^{-2} hr^{-1}]

- Predicted sea salt emissions 3,340 Tg in 2000 could increase to 5,880 Tg in 2100
- The present day direct radiative impact of sea salt is -0.60 and -1.52 Wm^{-2} (Ma et al., 2008)
- Total indirect forcing of sea salt is −2.9 Wm^{-2} (Ma et al., 2008)
- Potentially important negative climate feedback



Source: Figure 5.2, Penner et al., Climate Change 2001:Working Group I: The Scientific Basis, IPCC 2001

Global Emission Estimates for Major Aerosol Types

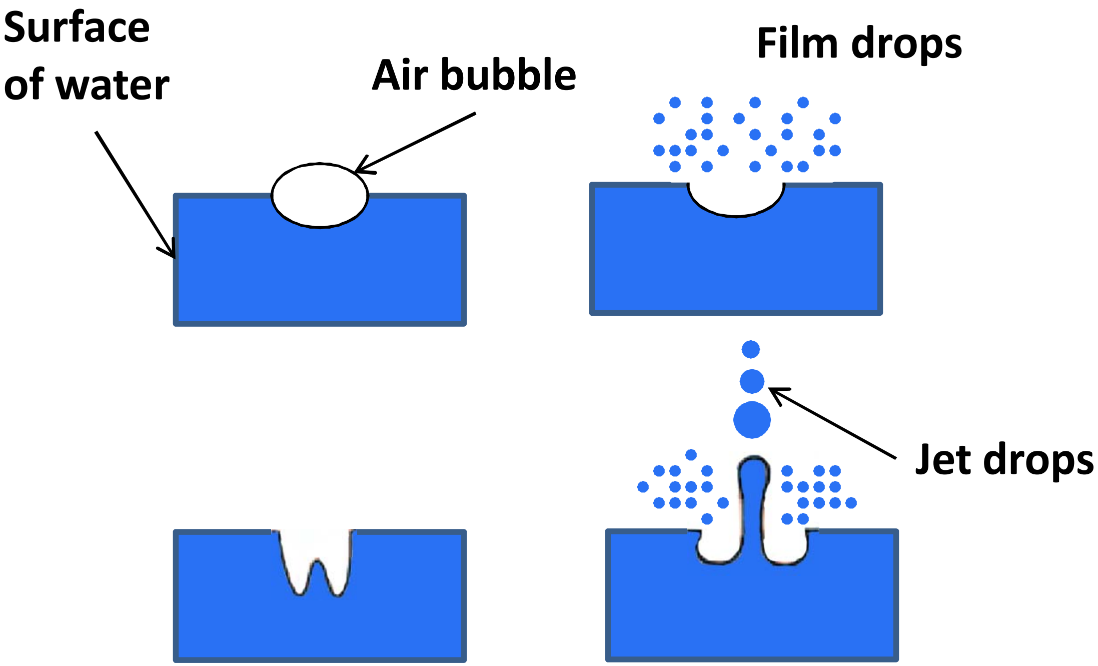
Table 5.3: Primary particle emissions for the year 2000 (Tg/yr)[a].

	Northern Hemisphere	Southern Hemisphere	Global	Low	High	Source
Carbonaceous aerosols						
Organic Matter (0–2 µm)						
Biomass burning	28	26	54	45	80	Liousse *et al.* (1996), Scholes and Andreae (2000)
Fossil fuel	28	0.4	28	10	30	Cook *et al.* (1999), Penner *et al.* (1993)
Biogenic (>1µm)	—	—	56	0	90	Penner (1995)
Black Carbon (0–2 µm)						
Biomass burning	2.9	2.7	5.7	5	9	Liousse *et al.* (1996); Scholes and Andreae (2000)
Fossil fuel	6.5	0.1	6.6	6	8	Cooke *et al.* (1999); Penner *et al.* (1993)
Aircraft	0.005	0.0004	0.006			
Industrial Dust, etc. (> 1 µm)			100	40	130	Wolf and Hidy (1997); Andreae (1995)
Sea Salt						Gong *et al.* (1998)
d< 1 µm	23	31	54	18	100	
d=1–16µm	1,420	1,870	3,290	1,000	6,000	
Total	1,440	1,900	3,340	1,000	6,000	
Mineral (Soil) Dust [b]						
d< 1 µm	90	17	110	—	—	
d=1–2µm	240	50	290	—	—	
d=2–20µm	1,470	282	1,750	—	—	
Total	1,800	349	2,150	1,000	3,000	

[a] Range reflects estimates reported in the literature. The actual range of uncertainty may encompass values larger and smaller than those reported here.
[b] Source inventory prepared by P. Ginoux for the IPCC Model Intercomparison Workshop.

Table 5.3, , Penner et al., Climate Change 2001: Working Group I: The Scientific Basis, IPCC 2001

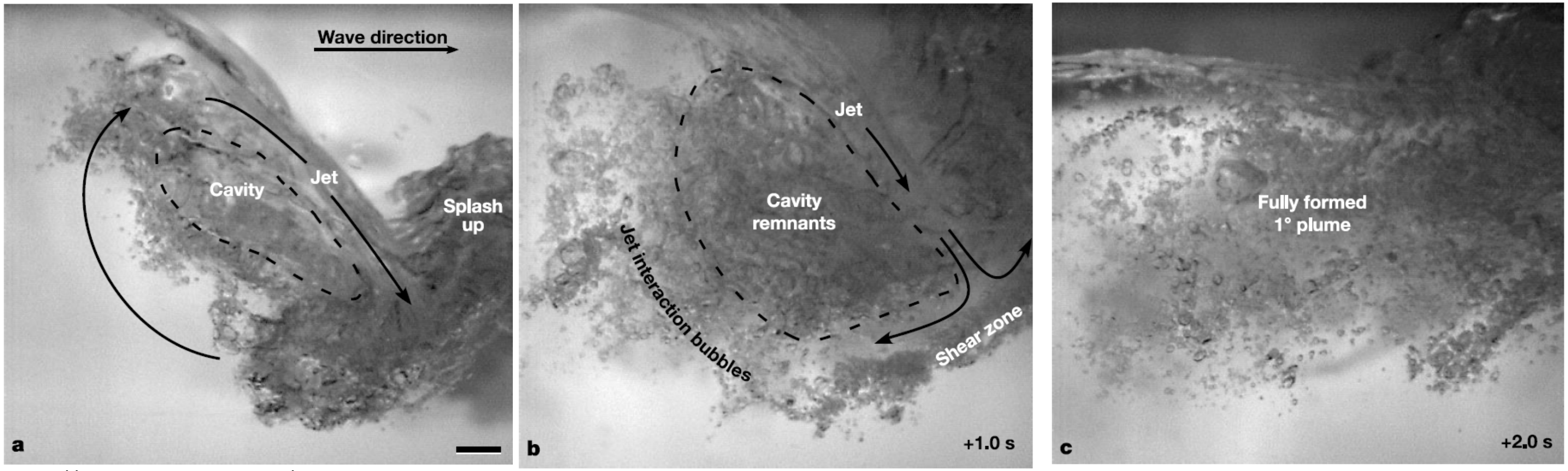
Sea Spray Aerosol Production



Sea-salt production through bubble bursting:

- ✓ **Film drops** (many and small) ; contain material from the surface microlayer
- ✓ **Jet drops** (fewer and larger) ; Mostly sea-salt

Sea Spray Aerosol Production



http://www.filetransit.com/screenshot.php?id=37223

[Deane & Stokes, Nature, 2002]

Quantifying Sea Spray

- Bubble bursting experiments
- Aerosols observations combined with meteorology
  - Direct particle measurements with condensation particle counter (CPC) or differential mobility analyzer (DMA)
  - Indirect aerosol measurements of aerosol optical depth (AOD) with a sun photometer

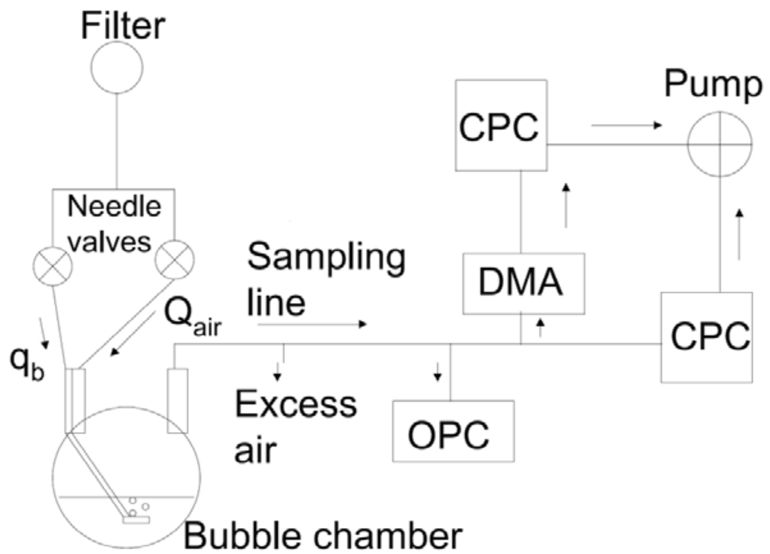


Figure 1. Martensson, E. M., E. D. Nilsson, G. de Leeuw, L. H. Cohen, and H.-C. Hansson, Laboratory simulations and parameterization of the primary marine aerosol production, J. Geophys. Res., 108(D9), 4297, doi:10.1029/2002JD002263, 2003.

http://www.nuigalway.ie/ccaps/images/Mace_Head.jpg

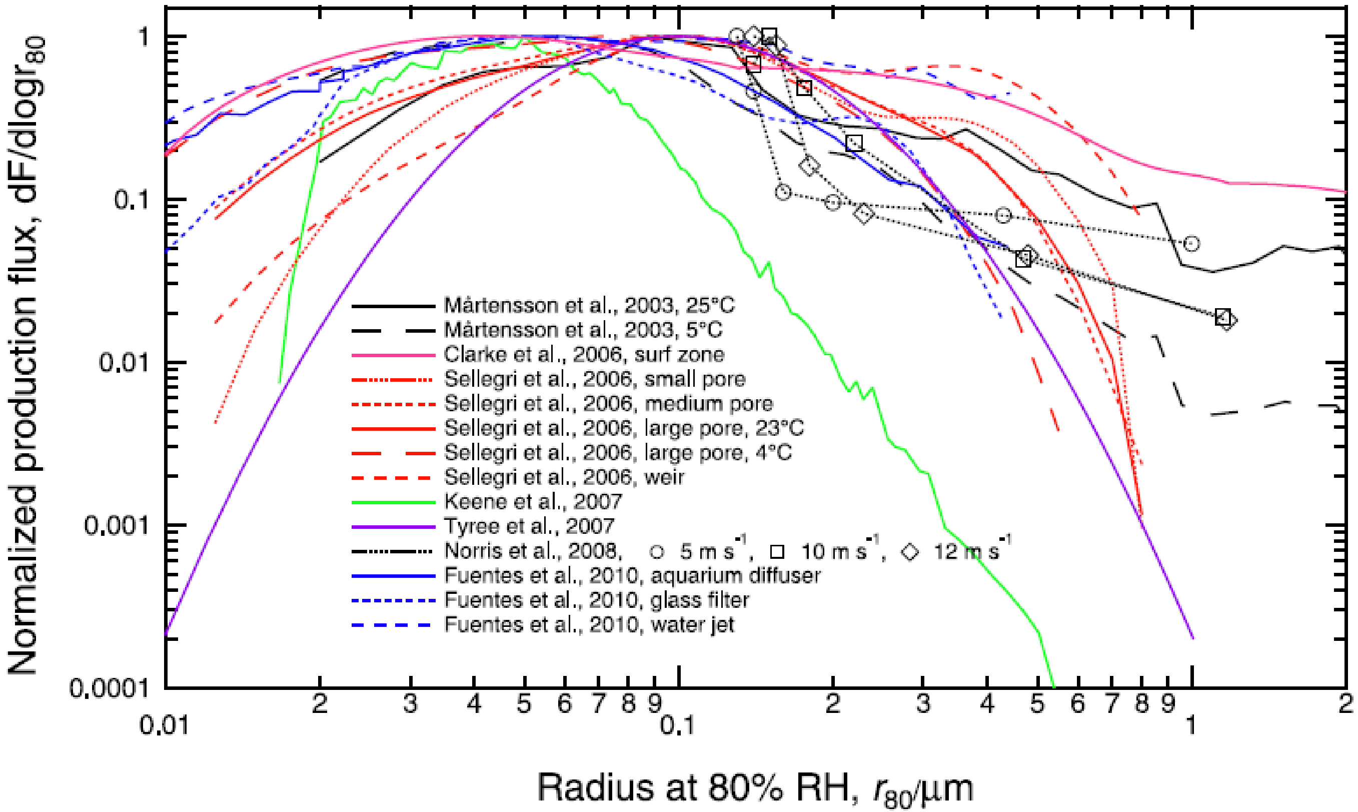
CPC + sonic anemometer

Sun photometer + sonic anemometer

http://mynasadata.larc.nasa.gov/images/AERONET_sunphotometer.jpg

Sea Spray Number Emissions

- Based on two relationships
  - Wind speed and white cap formation
  - White cap formation and sea spray
- Number emissions are predominantly in the sub-micron range, although there are significant numbers in the coarse mode



Sea Spray Source Functions and Range of Applicability [O'Dowd and de Leeuw, 2007].

reference	method	Formulation ($m^{-2}\mu m^{-1}s^{-1}$)	Size (µm)	WS ($m\ s^{-1}$)	SST (°C)
Monahan et al. (1986)	whitecap/lab	$\mathrm{d}F_{M86}/\mathrm{d}r = 1.373 U_{10}^{3.41} r^{-3}(1+0.057r^{1.05}) \times 10^{1.19\,e^{-B^2}}$ $B = (0.380 - \log r)/0.650$	$0.3<r_{80}<20$	n.a.	lab temp (~ 20)
de Leeuw et al. (2000)	whitecap/surf	$\mathrm{d}F_N/\mathrm{d}D = W \times 1.1 \times e^{0.23\times U} \times D^{-1.65}$	$1.6<D_0<20$	0–9	~ 16
de Leeuw et al. (2003)	model/field	$\mathrm{d}F_N/\mathrm{d}r = c\left(\sum_{i=1}^{2} A_i e^{-c_1 * \ln(r/r_1)^2}\right)$ units: $\mu m^{-1}\ m^{-2}\ s^{-1}$ $A_1 = 1.41u + 0.98$ $A_2 = 0.51u - 1.82$ $C_1 = -0.1u + 1.69$ $C_2 = 1.09$ $c = (0.24u + 0.4) \times 10^4$	0.063<R<7.996	0–9	~16
Vignati et al. (2001)	model/field	$\mathrm{d}F_{v00}(\log r_{80})/\mathrm{d}\log r = \sum_{i=1}^{3} N_i/(\sqrt{2\pi}\log\sigma_i)\ \exp(-(\log r_{80} - \log R_i)/2\log^2\sigma_i)$ $\mathrm{d}\log r = 0.1$ $i=1;\ N_i = 10^{(0.095U+0.283)};\ R_i = 0.2;\ \sigma_i = 1.9$ $i=1;\ N_i = 10^{(0.0422U-0.288)};\ R_i = 2;\ \sigma_i = 2$ $i=1;\ N_i = 10^{(0.069U-3.5)};\ R_i = 12;\ \sigma_i = 3$	$0.04<r_{80}<13$	6-17	~ 13
Märtensson et al. (2003)	whitecap/lab	$\mathrm{d}F_0/\mathrm{d}\log D_p = W(A_k T_w + B_k)$, T_w is water temperature in K $A_k = c_1 D_p^4 + c_2 D_p^3 + c_3 D_p^2 + c_4 D_p + c_5$ $B_k = d_1 D_p^4 + d_2 D_p^3 + d_3 D_p^2 + d_4 D_p + d_5$ $k=1$, size ranges $j=1$–13, 0.018–0.168 µm $k=2$, size ranges $j=13$–26, 0.168–0.949 µm $k=3$, size ranges $j=26$–38, 0.949–5.700 µm[b]	$0.018<D_d<20$	n.a.	2–25
Gong (2003)	modified Monahan/ lab	$\mathrm{d}F_{M86}/\mathrm{d}r = 1.373 U_{10}^{3.41} r^{-A}(1+0.057r^{3.45}) \times 10^{1.19e^{-B^2}}$ $A = 4.7(1+\theta r)^{-0.017r^{-1.44}}$ $B = (0.433 - \log r)/0.433$	$0.07<r_{80}<20$ $0.04<r_d$	n.a.	see Monahan et al. (1986)
Clarke et al. (2006)	whitecap/surf	$(\mathrm{d}F_N/\mathrm{d}\log D_p) = w\sum_{i=1}^{3} A_i$ $A_i = \beta_0 + \beta_1 D_p + \beta_2 D_p + \beta_3 D_p + \beta_4 D_p + \beta_5 D_p$[c]	$0.01<D_p<8$	n.a.	~25

For Geever 100 nm<D<1000 nm *f (x)*=ax^b ,*f (x)*=Number flux, a=1.854X10^{-3}, x=wind speed 1–20 m s^{-1}, r^2=0.8, b=2.706. For Geever 10 nm<D<10 000 *f (x)*=ax^b, a=9.204x10^{-5}, b=4.1. SST, sea-spray temperature; WS, wind speed; *W(U$_{10}$)*=3.84x10^{-6} U$_{10}$$^{3.41}$, where U$_{10}$ (m s^{-1}) is the wind speed at 10 m.

Sea-water Composition

Table 6. Composition of Seawater of Salinity 35

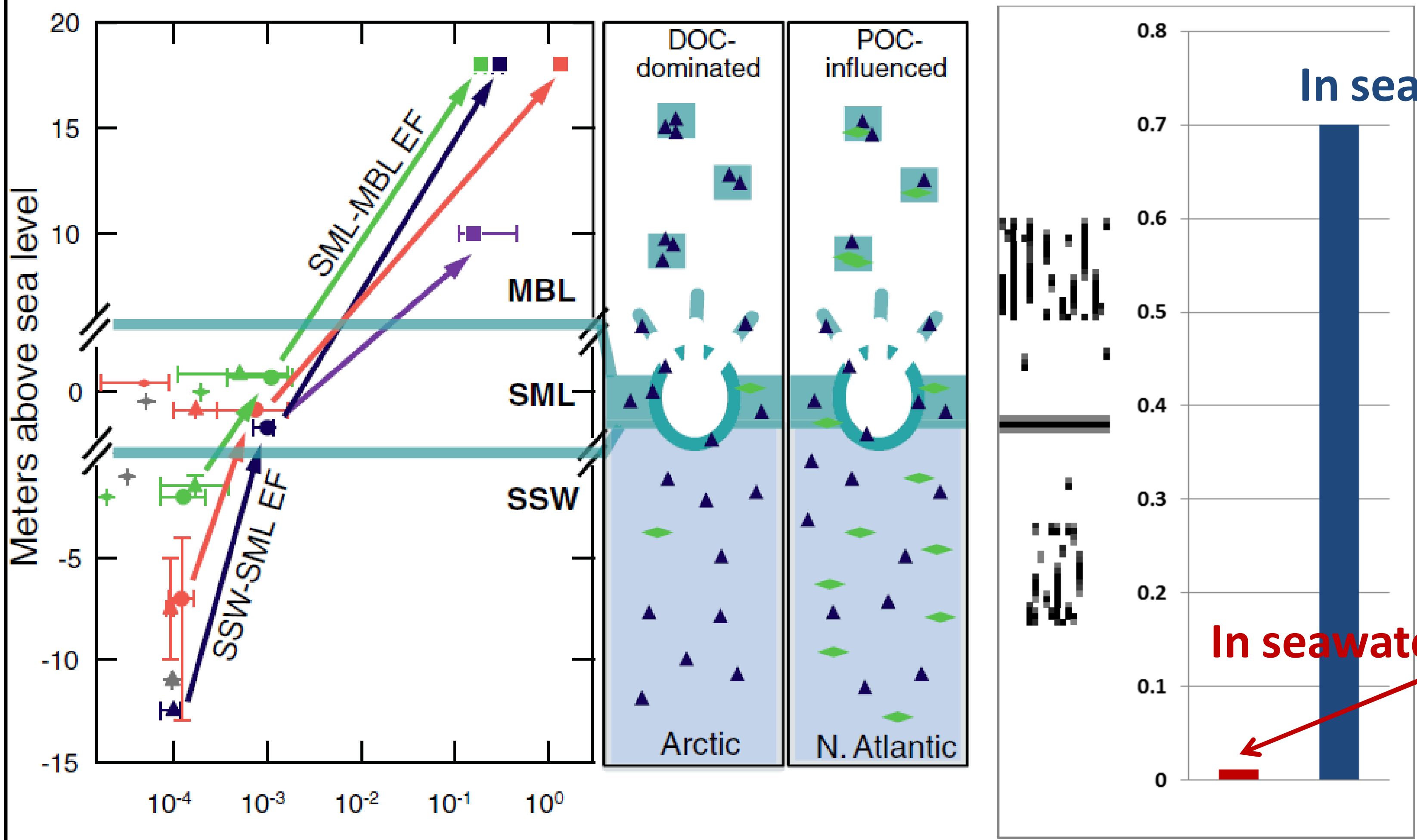
Species	Mass Fraction	Mass Ratio g (kg-sw)$^{-1}$	g (kg-H_2O)$^{-1}$	Mole Fraction	mol (kg-sw)$^{-1}$	Molarity mol (kg-H_2O)$^{-1}$	equiv (kg-sw)$^{-1}$	Ionic Strength mol (kg-sw)$^{-1}$
H_2O	0.9648	964.83	1000.00	0.9795	53.558	55.510	—	—
Cl^-	0.0194	19.35	20.06	0.0100	0.546	0.566	0.546	0.273
SO_4^{2-}	0.0027	2.71	2.81	0.0005	0.028	0.029	0.056	0.056
HCO_3^-	0.0001	0.11	0.11	< 0.0001	0.002	0.002	0.002	0.001
Br^-	0.0001	0.07	0.07	< 0.0001	0.001	0.001	0.001	< 0.001
Na^+	0.0108	10.78	11.18	0.0086	0.469	0.486	0.469	0.235
Mg^{2+}	0.0013	1.28	1.33	0.0010	0.053	0.055	0.106	0.106
Ca^{2+}	0.0004	0.41	0.43	0.0002	0.010	0.011	0.020	0.020
K^+	0.0004	0.40	0.41	0.0002	0.010	0.011	0.010	0.005
minor species	< 0.0001	0.06	0.05	< 0.0001	0.001	0.001	0.001	0.001
Σ salts	0.0352	35.17[a]	36.45	0.0205	1.120	1.162	1.211	0.698
Total	**1.0000**	**1000.00**	**1036.45**	**1.0000**	**54.678**	**56.672**	**54.769**	**0.698**

Source: Table 6, Ramaswamy et al., Climate Change 2001: Working Group I: The Scientific Basis, IPCC 2001

Why do we even need to even worry about anything other than sea salt?

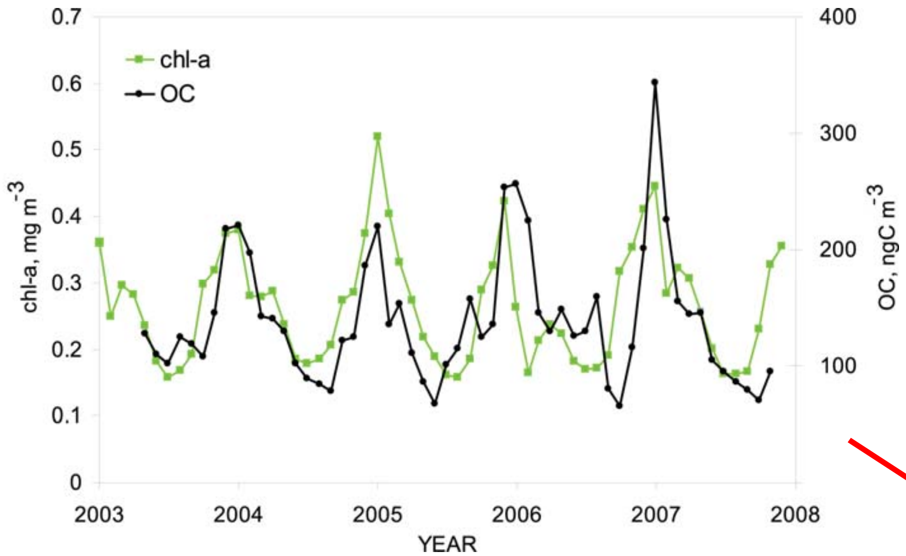
From Sea Water To Aerosol

- Chemical composition?
- Controlling mechanism?
- Number or Mass?



[Russell et al., PNAS, 2010]

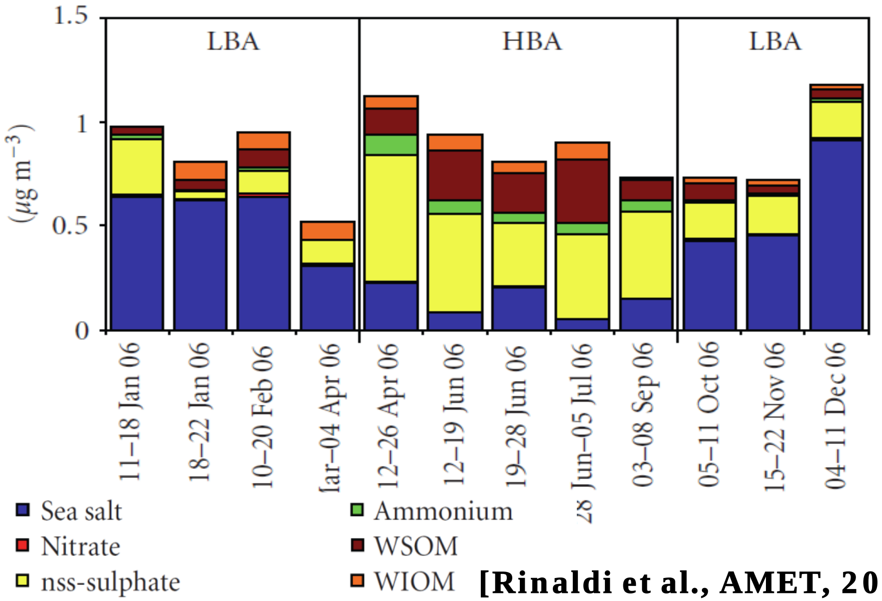
Marine Organic Aerosols: A Biological Source



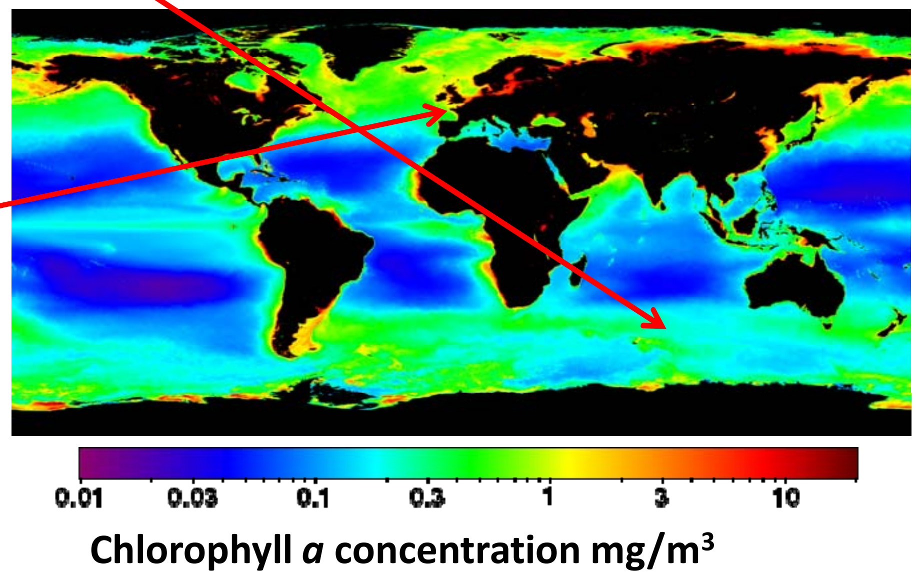
[Sciare et al., JGR, 2009]

A <u>direct</u> evidence

- Long term measurements of OC at Amsterdam Island
- Submicron marine aerosol chemical composition at Mace Head



[Rinaldi et al., AMET, 2010]



Flux of an ultrafine sea-salt or marine organic matter?

- "Dry" (RH = 40%) sea salt particle size distributions for 0.01 μm ≤ Dp ≤ 8 μm
- 60% of all sea salt particles were smaller than 0.1 μm diameter

Clarke et al., 2006

- Airborne micro-organisms of marine origin and their fragments peaking at D_p of 0.03 – 0.04 μm do not appear to have any association with sea salt
- The presence of airborne marine aggregates consisting of amorphous transparent exopolymer (EP) secretions (gels) of algae and bacteria
- Sea salt was not detected in particles < 0.2 μm diameter

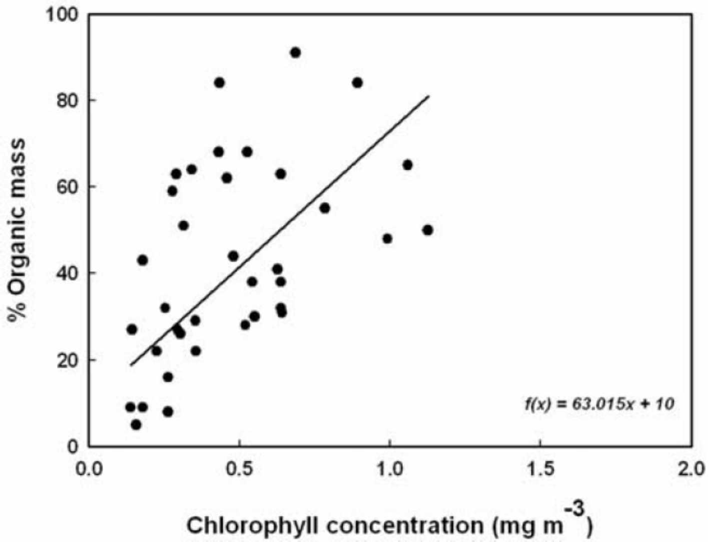
Leck and Bigg, 2008

- ➢ During high biological activity organic fraction can contribute up to 60% of sub-micrometer mass
- ➢ During low biological activity periods fraction reduces to 10-15%

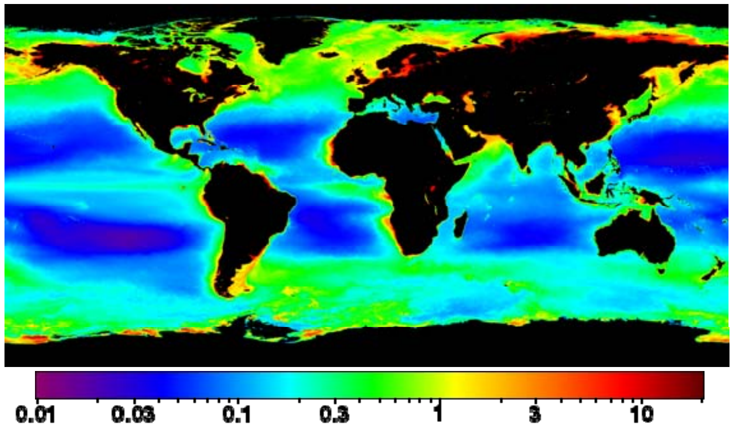
O'Dowd et al., 2007; Facchini et al., 2008

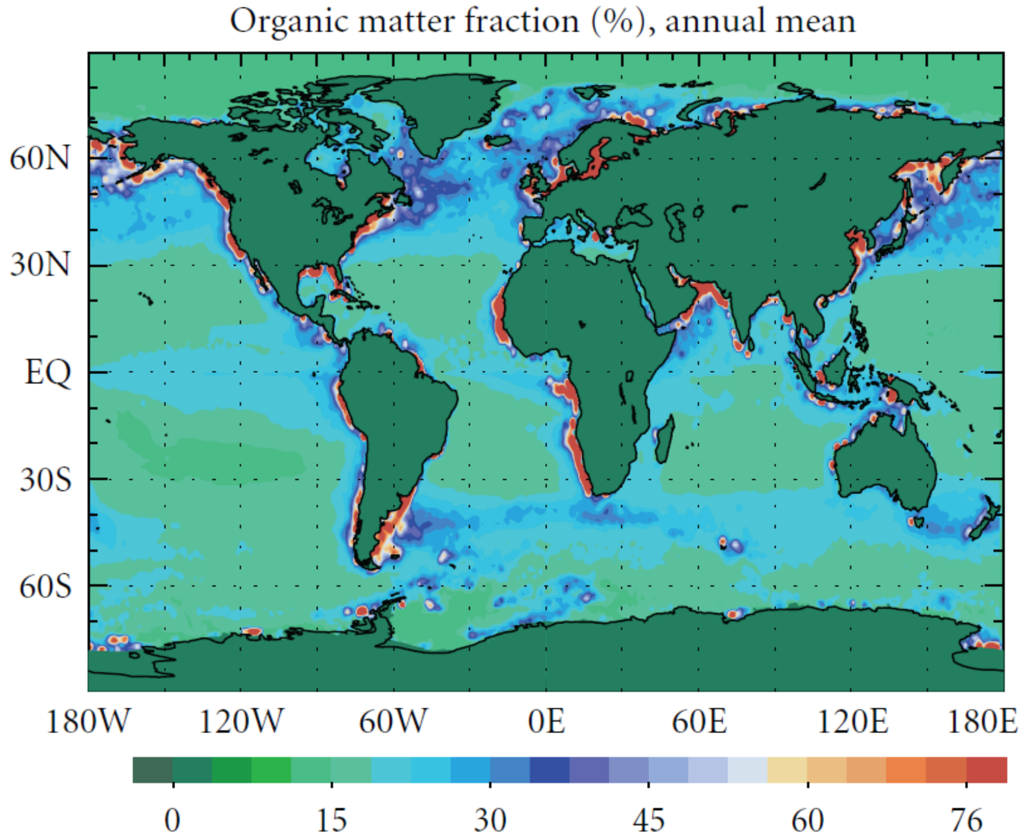
Surface films can be highly enriched in organics: "marine microcolloids", "mucus-like" or gel-like material, *Exopolymer gels,* airborne marine aggregates (AMA)

Modeling Of Marine Primary Organic Aerosol (POM) Emissions



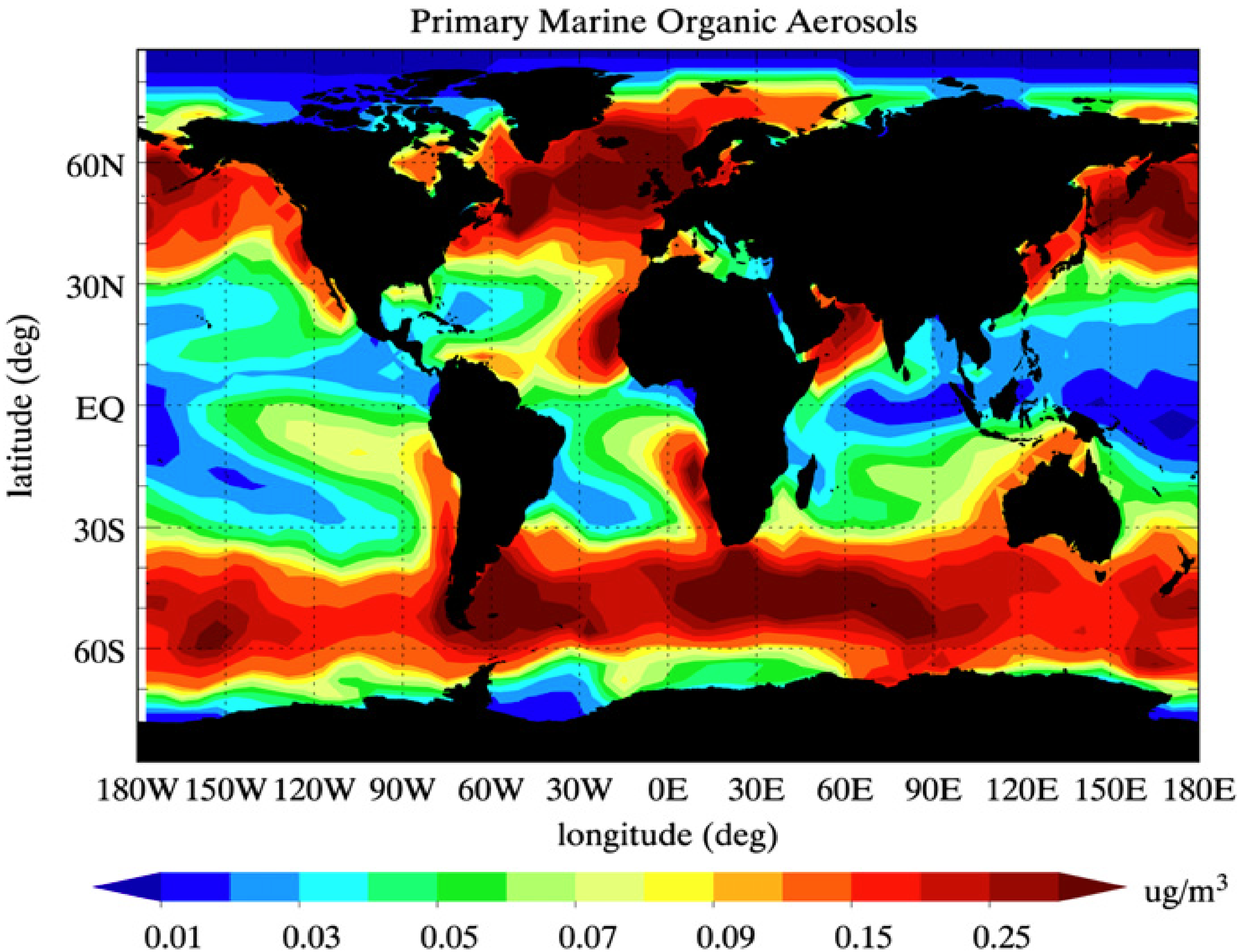
[O'Dowd et al., GRL, 2008]





[Myriokefalitakis et al., AMET, 2010]

Marine Primary Organic Aerosols



[Vignati et al., Atmos Environ, 2010]

Marine Primary Organic Aerosols

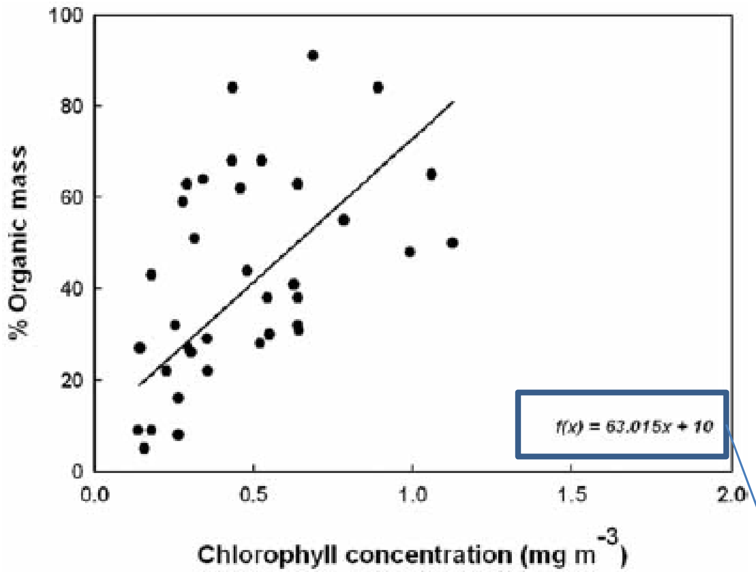
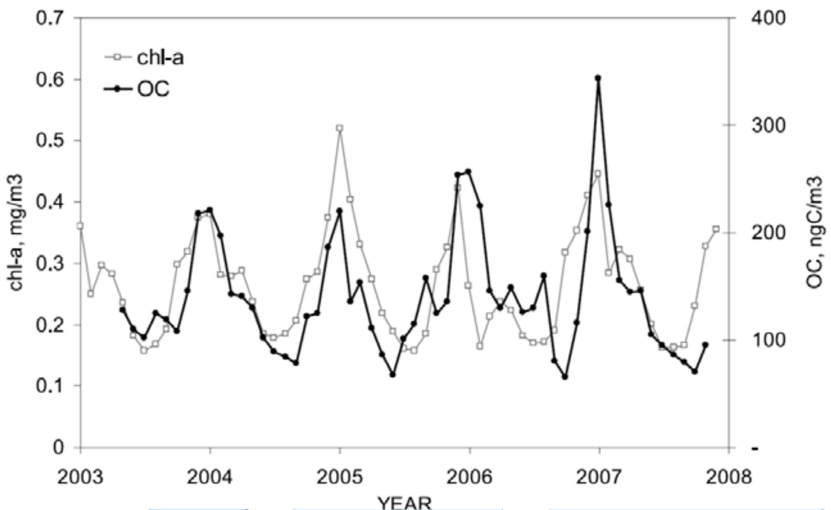


Figure 2. O'Dowd, C. D., B. Langmann, S. Varghese, C. Scannell, D. Ceburnis, and M. C. Facchini (2008), A combined organic-inorganic sea-spray source function, Geophys. Res. Lett., 35, L01801, doi:10.1029/2007GL030331.

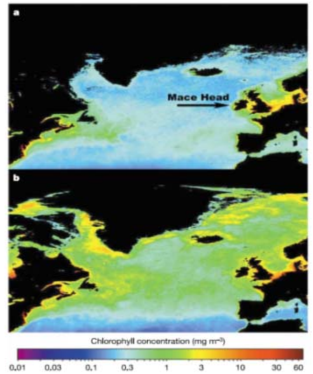


- Strong observed relationship between [Chl a] and organic fraction of sea spray mass
- Two steps to calculate organic emissions
  - Convert sea spray number emissions to mass by integrating by particle size, assuming spherical shape, and using the apparent density
  - Multiply the sea spray mass emission rate by organic fraction determined by [Chl a]

$$F_{sub} = 0.63015 * [\text{Chl-}a] + 0.1$$
$$F_{super} = F_{sub} * 0.03$$

Figure 6. Sciare, J., O. Favez, R. Sarda-Este`ve, K. Oikonomou, H. Cachier, and V. Kazan (2009), Long-term observations of carbonaceous aerosols in the Austral Ocean atmosphere: Evidence of a biogenic marine organic source, J. Geophys. Res., 114, D15302, doi:10.1029/2009JD011998.

Marine Organic Aerosol Emissions



- Two classes: primary and secondary
  - Primary
    - Formed by bubble bursting of organic surface layer
    - Mainly water insoluble
  - Secondary
    - Formed by condensation of organic gases (isoprene, monoterpenes, amines, etc)
    - Mainly water soluble
- Both tied to the productivity of the ocean with particular focus on [Chl-*a*]

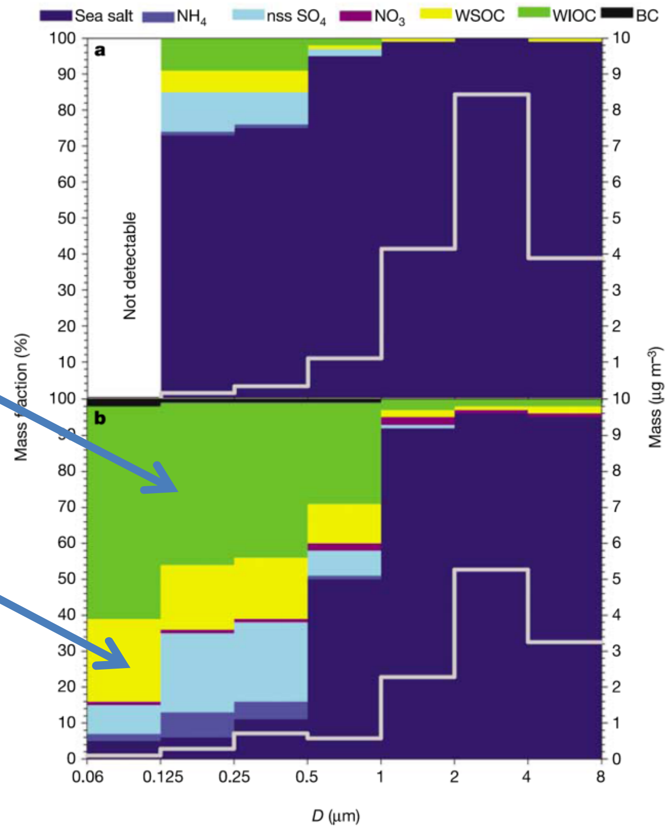
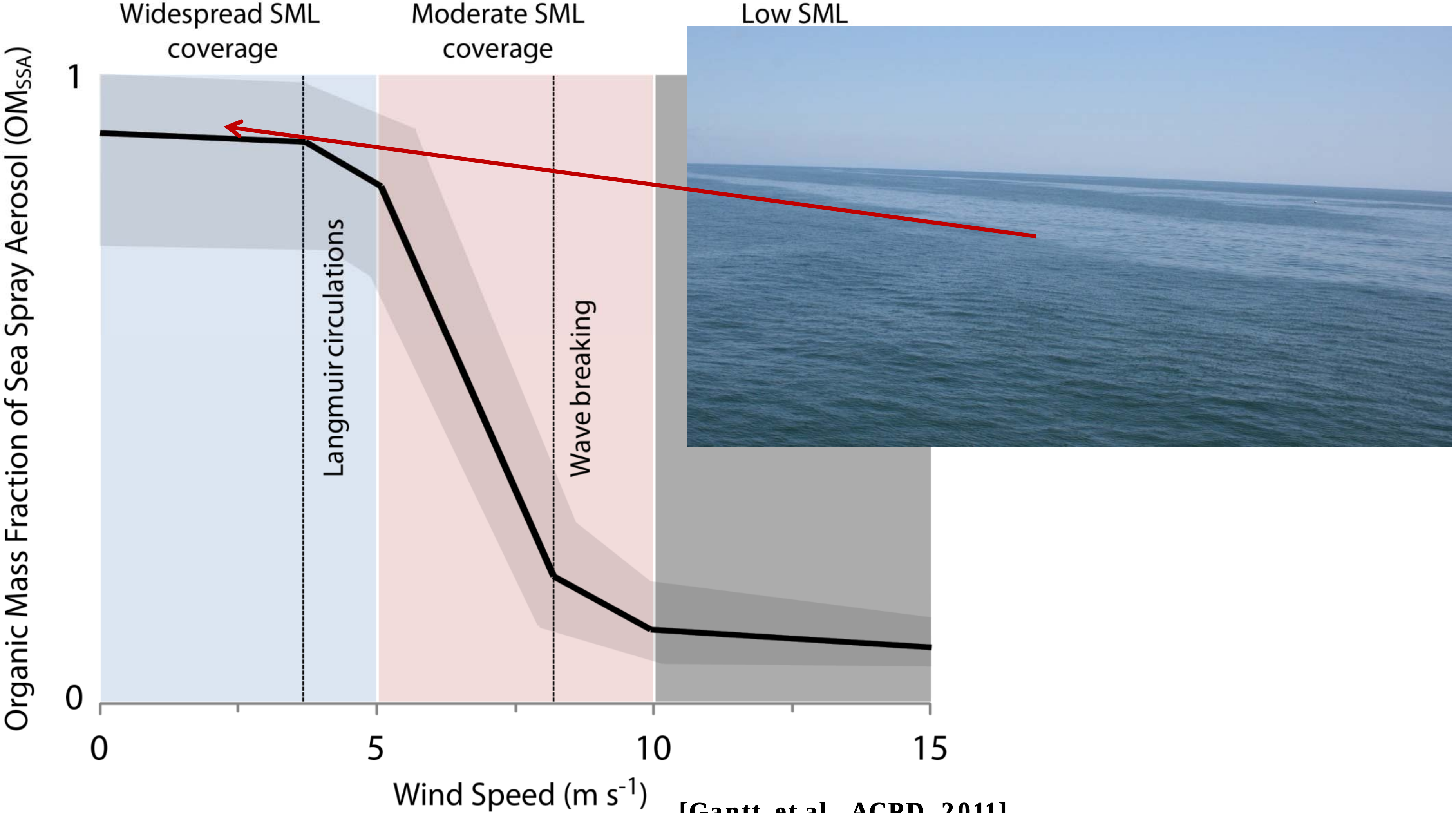


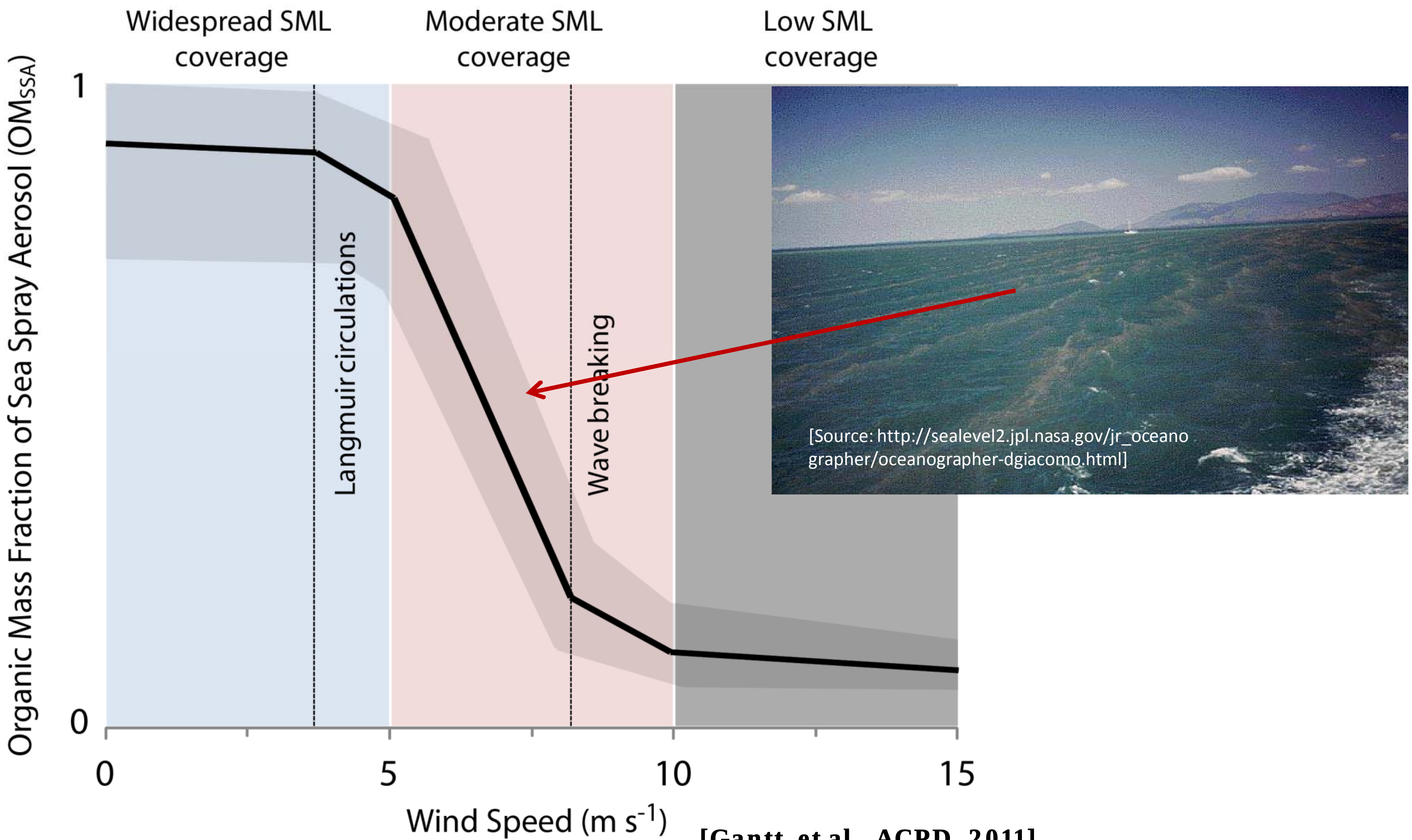
Figure 2. O'Dowd, C. D., M. C. Facchini, F. Cavalli, D. Ceburnis, M. Mircea, S. Decesari, S. Fuzzi, Y. J. Yoon, and J. P. Putaud (2004), Biogenically driven organic contribution to marine aerosol, Nature, 431, 676–680, doi:10.1038/nature02959

Organic Enrichment Of The Air-sea Interface And Surface Wind Speed



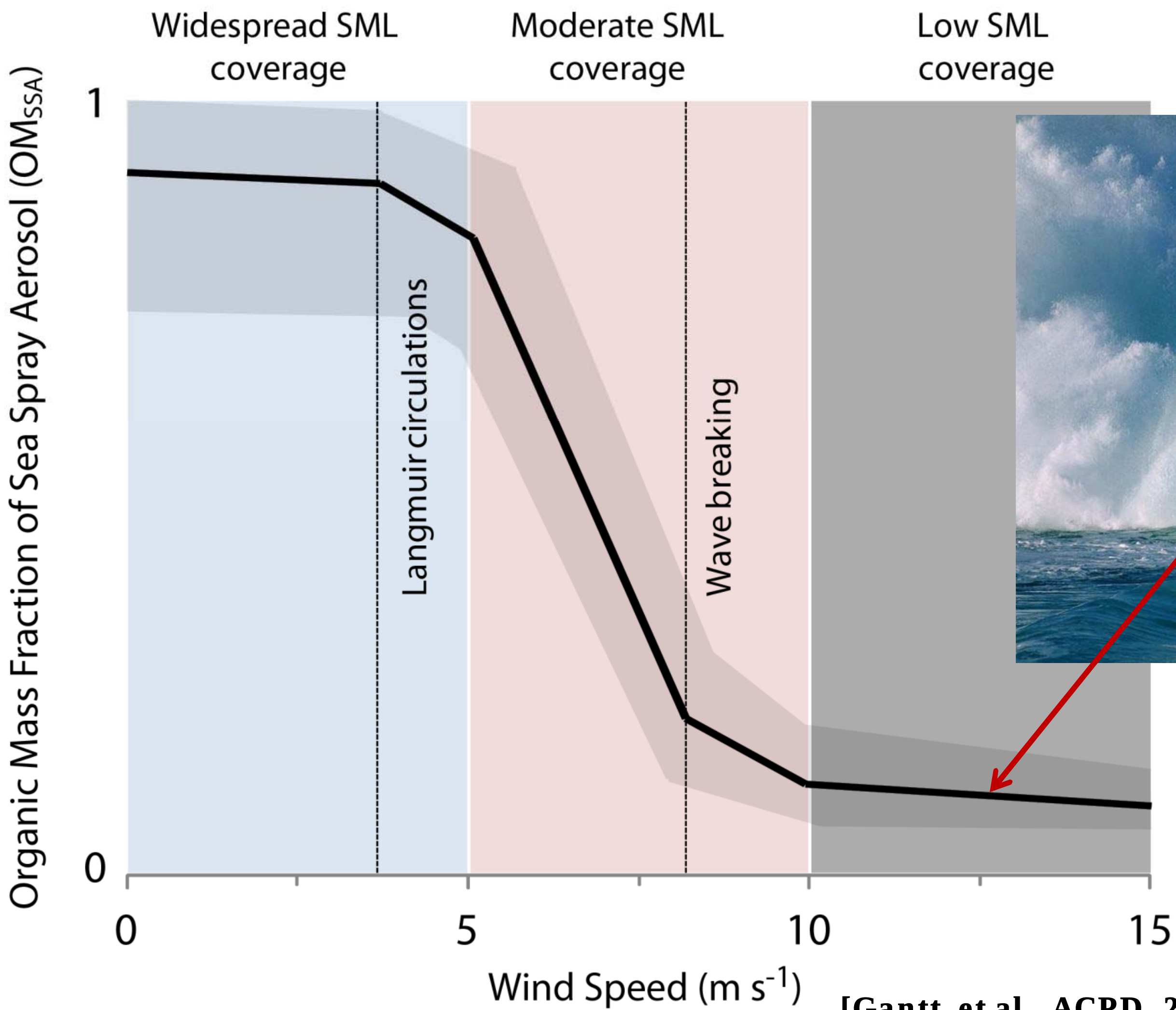
[Gantt et al., ACPD, 2011]

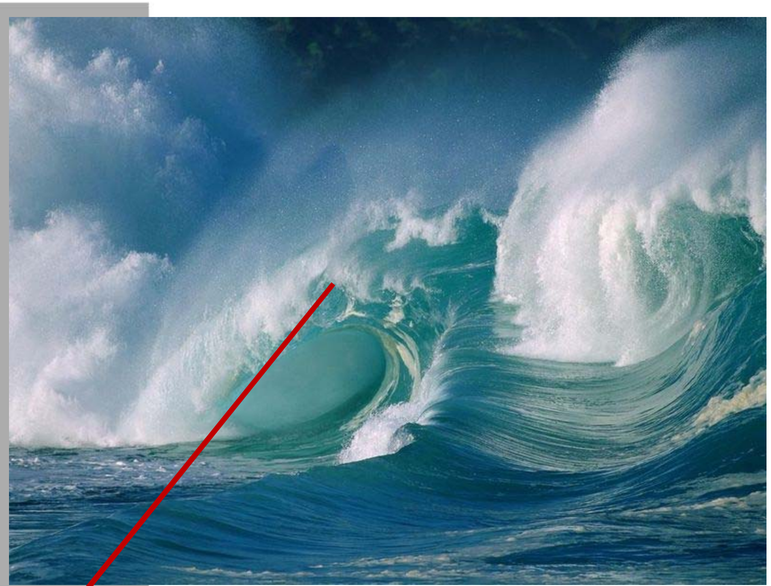
Organic Enrichment Of The Air-sea Interface And Surface Wind Speed



[Gantt et al., ACPD, 2011]

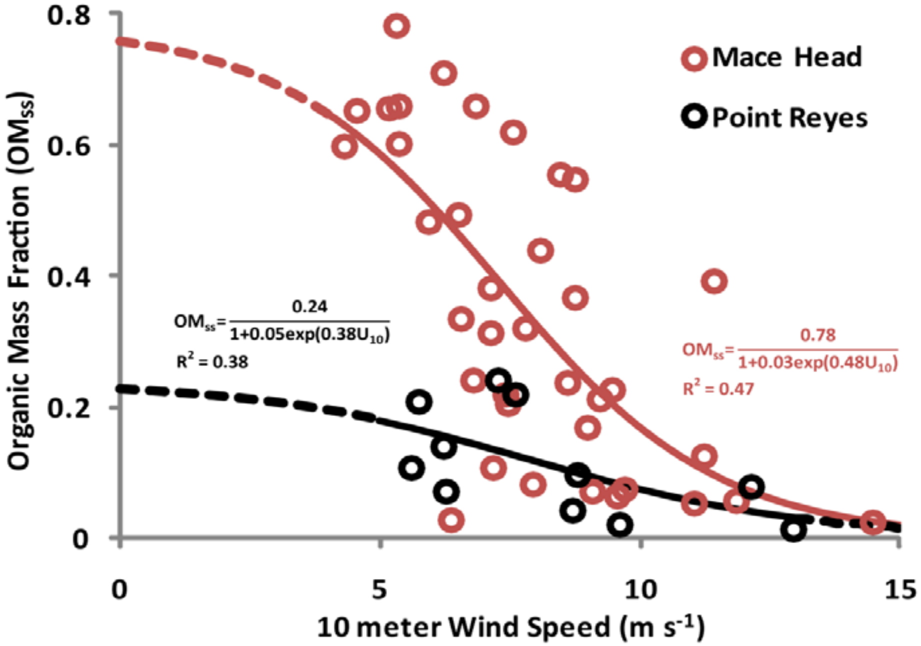
Organic Enrichment Of The Air-sea Interface And Surface Wind Speed



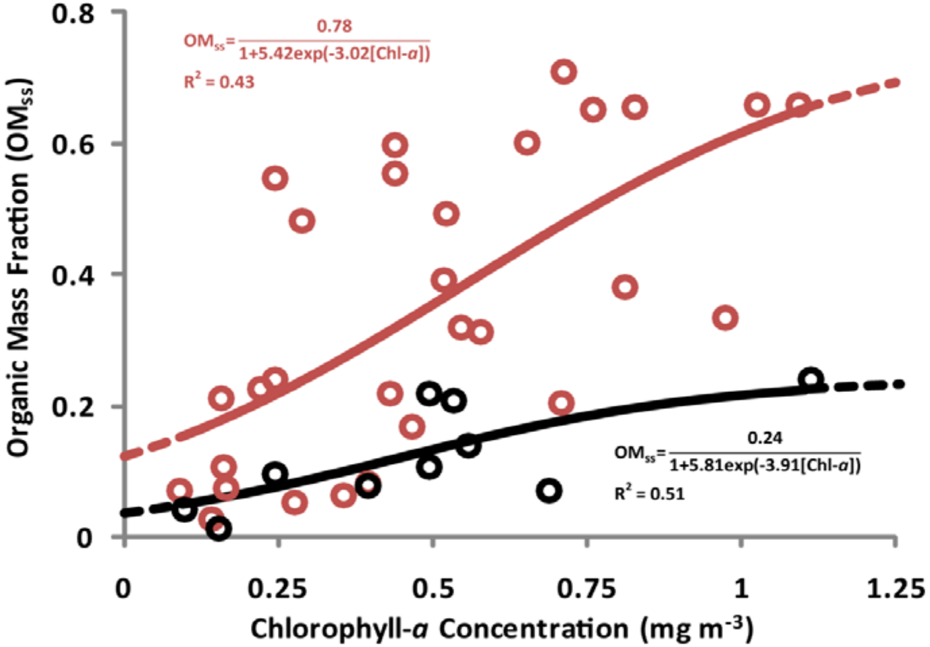


[Gantt et al., ACPD, 2011]

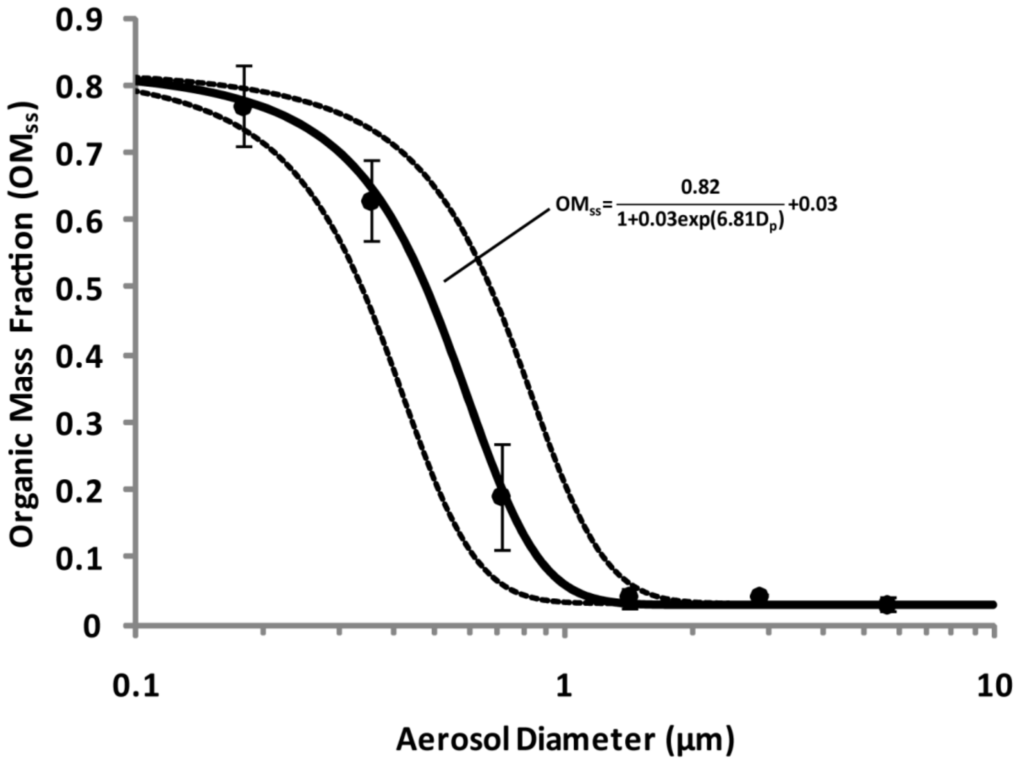
Organic Mass Fraction of Sea Spray

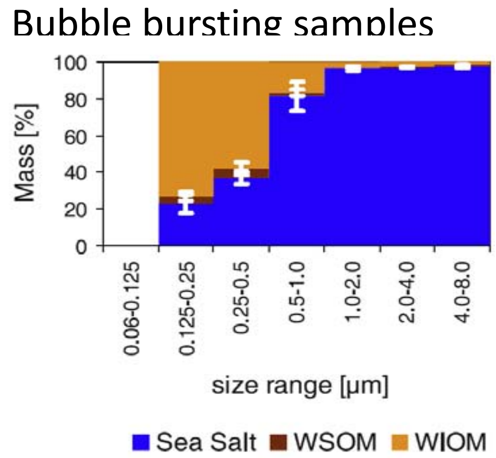


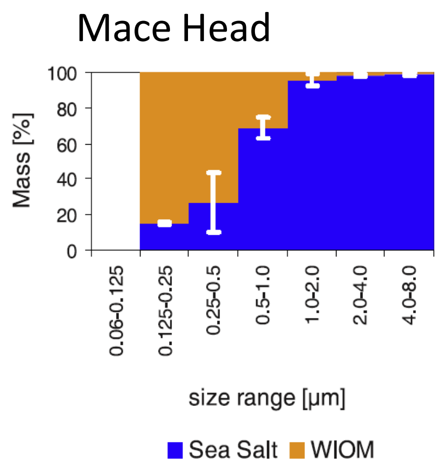
[Source: Gantt et al., ACPD, 2011]



OC_{ss} as a Function of Ambient Aerosol Aerodynamic Diameter







$$OC_{ss}(D_p) = \frac{OC_{ss}^{max}(D_p)}{1+0.05\exp(6.64D_p)} + OC_{ss}^{min}(D_p)$$

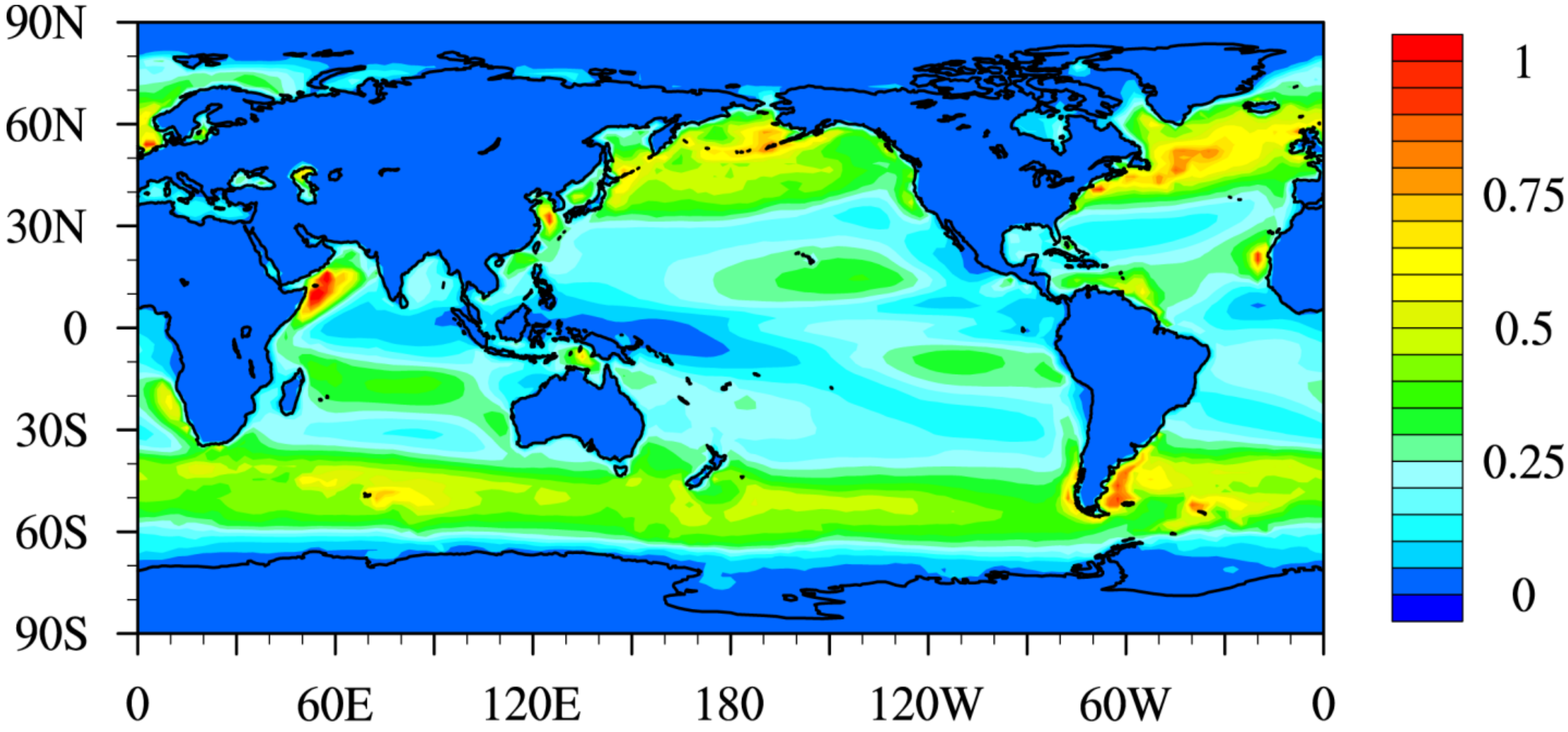
[Source: Gantt et al., ACPD, 2011]

[Facchini et al., GRL, 2008]

Annual Average Submicron Marine Primary OC Emission Rate

2.8 to 5.6 Tg C yr^{-1}

Units: ng C m^{-2} s^{-1}



[Source: Gantt et al., ACPD, 2011]

Global Annual Marine Primary Organic Aerosol Emission

Sub-micron Primary Organic Carbon (Tg C yr^{-1})	Source
5.5	Spracklen et al. (2008)
2.5	Langmann et al. (2008)
2.9	Gantt et al. (2009)
5.8	Vignati et al. (2010)
2.8 to 5.6	Gantt and Meskhidze (2011)
Super-micron Primary Organic Carbon (Tg C yr^{-1})	
75	Spracklen et al. (2008)
8	Roelofs (2008)
19.4	Gantt et al. (2009)
29	Long et al. (2011)
17.2	Vignati et al. (2010)

Outline

1) Atmospheric aerosol deposition as a control of ocean biological productivity

2) Biogenic gas emissions from the ocean and their impact on aerosol/cloud interaction and radiative properties of the overlying atmosphere

3) Sources, chemical composition and size distribution of ocean-derived primary organic aerosols

4) **Model results**

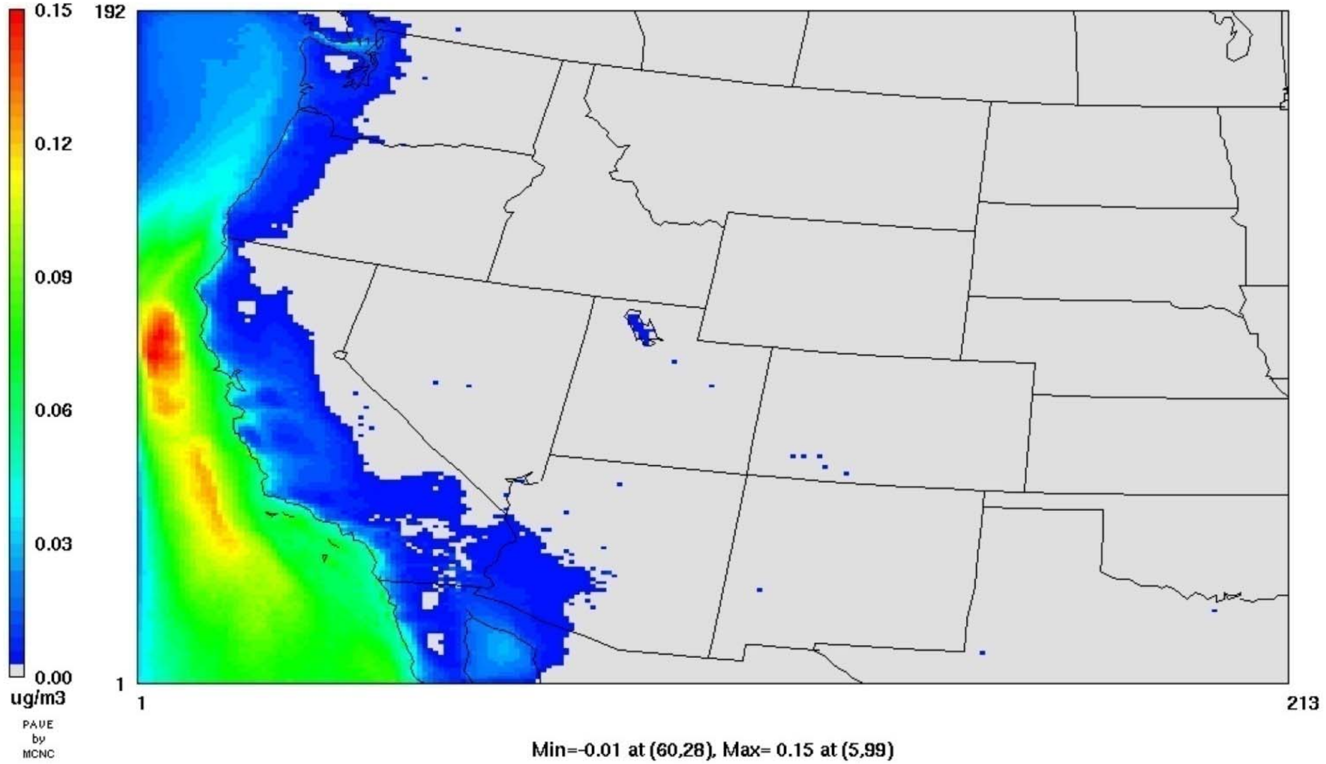
5) The future

Model Setup

Model	CMAQ V. 4.7
Time Period	June, July, August 2005
Domain	Western US, Pacific coast
Horizontal Resolution	12 x 12 km^2
Vertical Resolution	14 layers from the surface to 100mb
Emissions	Anthropogenic 2005 NEI Natural: BEIS
Meteorology	MM5
Simulations	1) Baseline without marine emissions 2) Isoprene and primary emissions included 3) "Real" simulation using Southern Ocean (SO) data from Columb et al., (2009)

Impact on $PM_{2.5}$

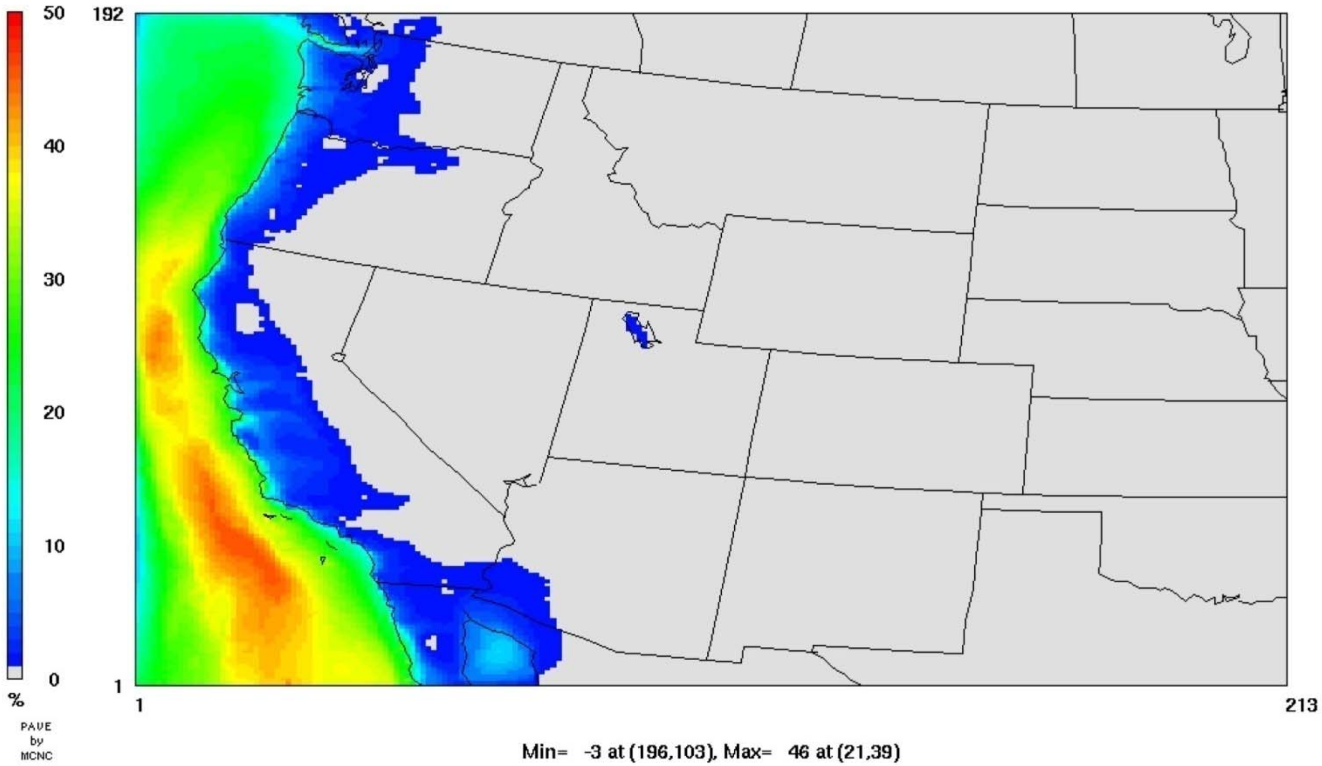
Change in $PM_{2.5}$ concentrations due to marine emissions



- ✓ Greatest impact offshore where winds are the strongest
- ✓ Much of the California coast has an average concentration increase of 0.1 $\mu g\ m^{-3}$ (still small)

Impact on OC Aerosol

Marine OC Aerosol Contribution to Baseline OC



✓Marine OC aerosol (POM + marine isoprene-derived SOA) may contribute up to 20% of CMAQ predicted OC at the coastal regions and up to 10% inland (not small)

Implementation Of Marine Carbonaceous Aerosols In CAM5

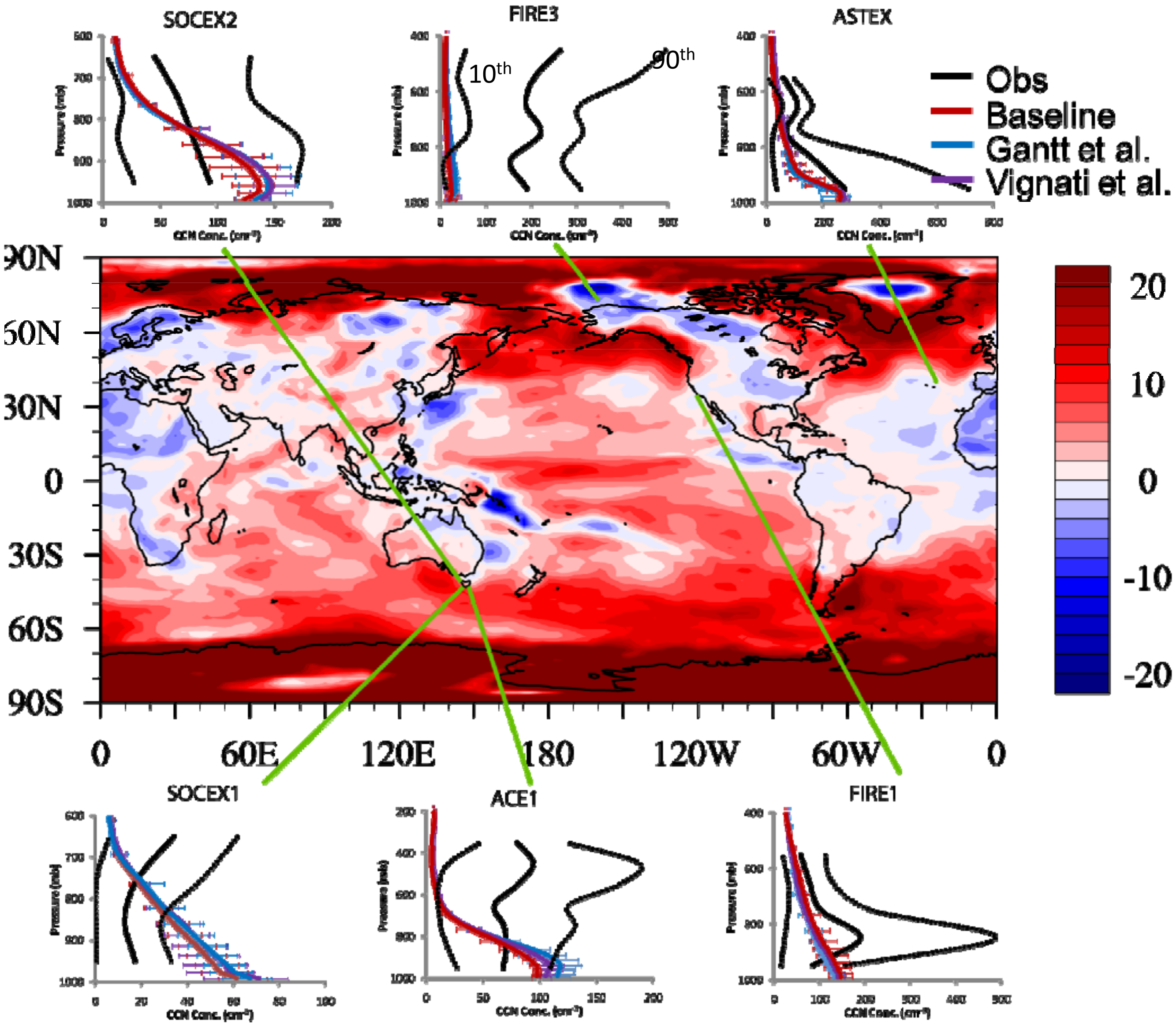
Model Configurations

- Horizontal Resolution: 1.9° x 2.5°; Vertical: 30 layers
- Aerosol: 5 sub- and 2 super-micron modes
- Simulation: 5 years; Spin up period: 3 months
- Mårtensson et al. [2003] for 0.02 < Dp < 2.5 μm
- Gong [2003] for 2.5 < Dp < 20 μm
- SOA from isoprene, monotrpenes & MSA (CH_3SO_3H)

Marine Organic Aerosols in CAM5

	Sub-micron					Super-micron	
Mode	Accumulation	Atiken	Primary Carbon	Sea salt	Fine Soil Dust	Coarse Sea salt	Coarse Soil Dust
Aerosol component	Sulfate, Ammonium, POM, SOA, BC, Sea salt, Marine POM & SOA	Sulfate, Ammonium, SOA, Sea salt, Marine POM & SOA	POM, BC	Sea salt, Sulfate, Ammonium, Marine POM	Dust, Sulfate, Ammonium	Sea salt, Sulfate, Ammonium, Marine POM	Dust, sulfate, Ammonium

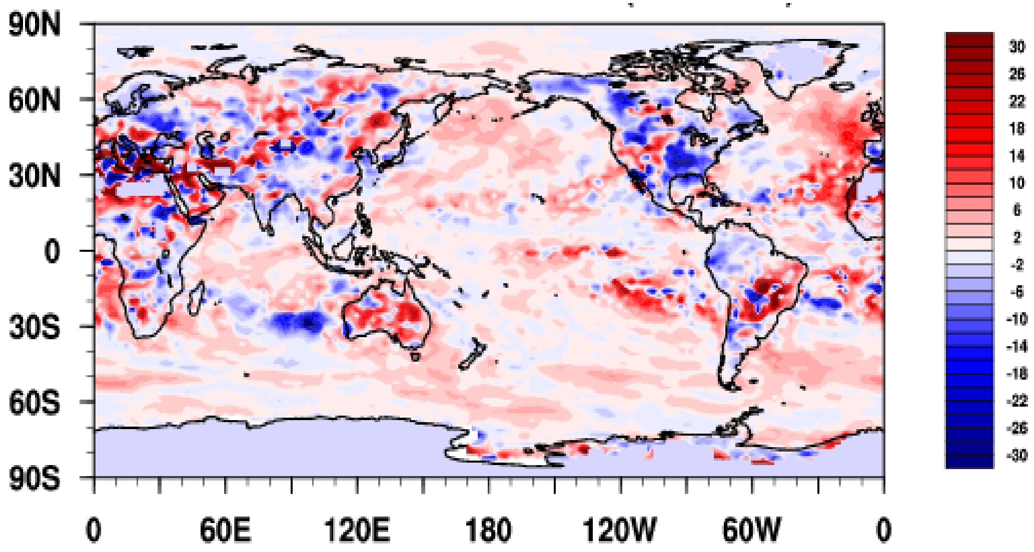
Difference In Annually Averaged CCN (0.2%)



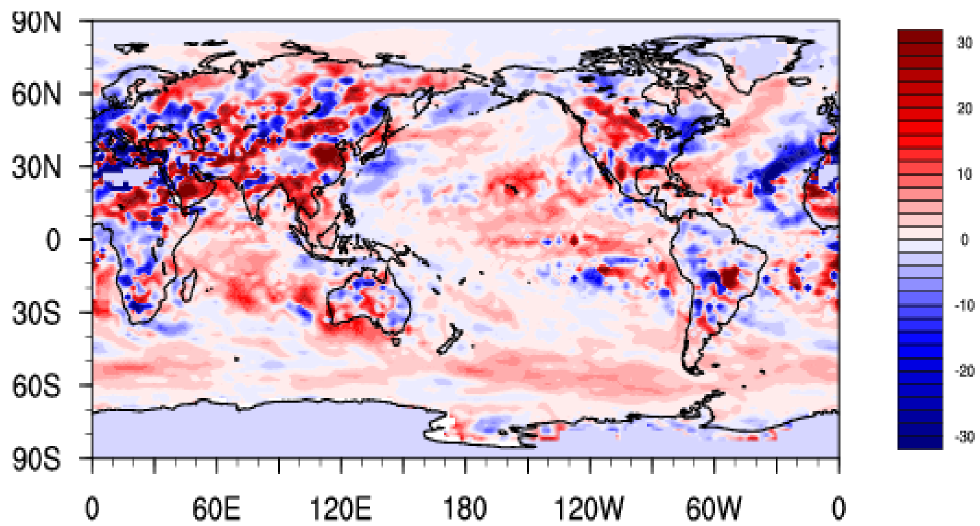
- Up to 10% higher CCN in marine BL
- Slightly improved agreement with measurements

Change In Cloud Droplet Number Concentration

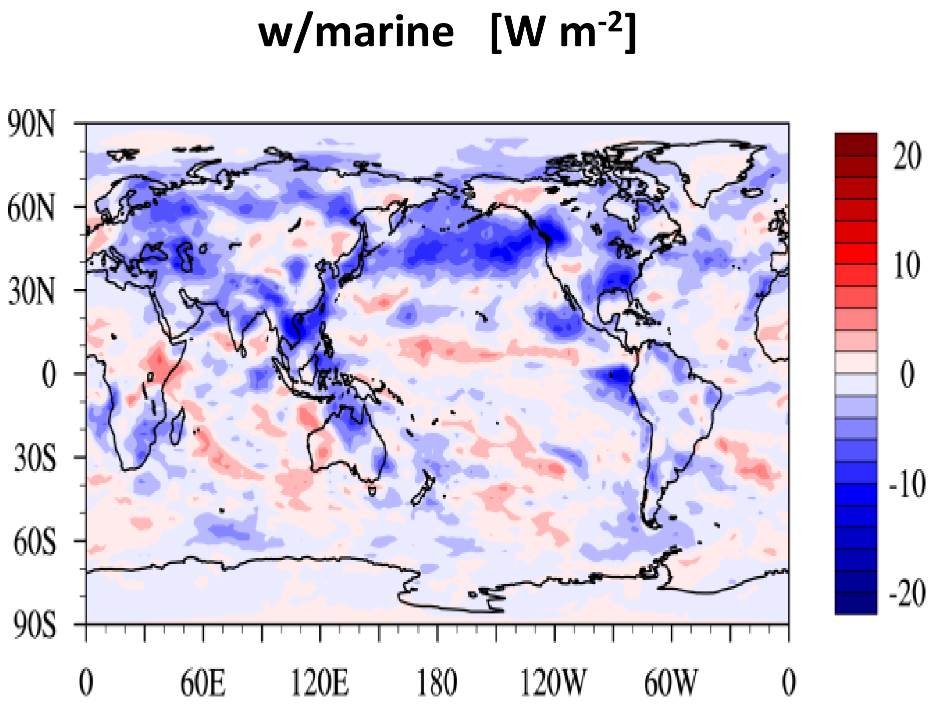
PI (w/marine – w/o)

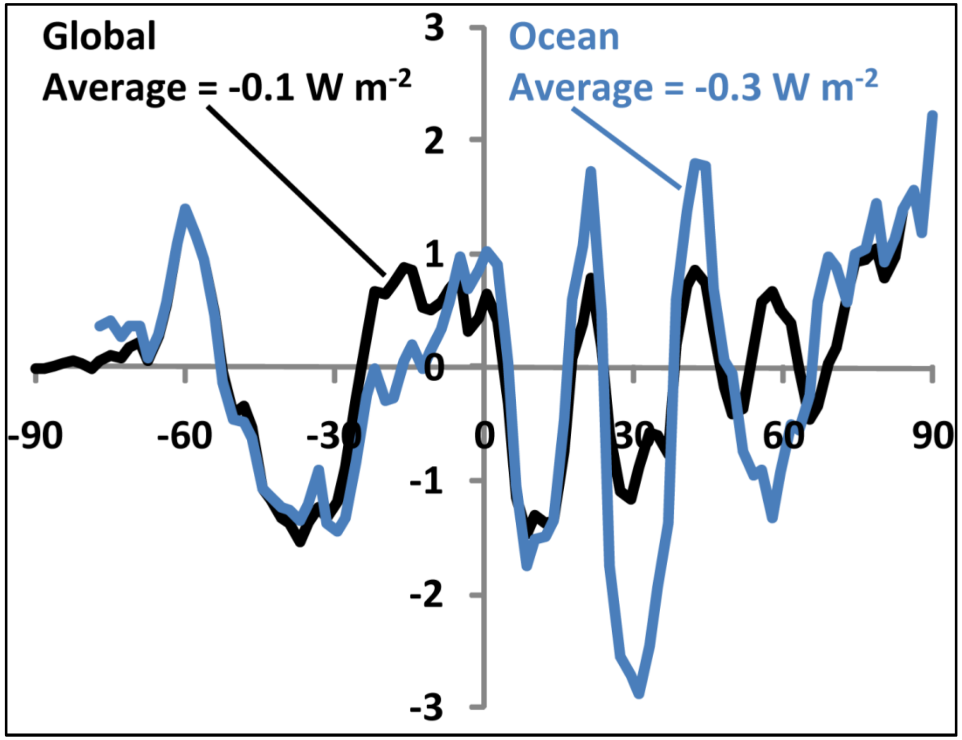


PD (w/marine – w/o)



ΔSWCF (PD-PI)


w/marine [W m-2]
90N
60N
30N
0
30S
60S
90S
0
60E
120E
180
120W
60W
0
20
10
0
-10
-20


Global
Average = -0.1 W m-2
Ocean
Average = -0.3 W m-2
3
2
1
0
-1
-2
-3
-90
-60
-30
0
30
60
90

Conclusions

Updates to CAM5 resulted in:

- ✓ Increased shallow in-cloud **CDNC [cm^{-3}]** from **0** to **1.5 (2.6%)** over the global oceans and from **0.2 (0.6%)** to **2.2 (5.4%)** over the Southern Ocean
- ✓ Increased **LWP [$g\ m^{-2}$]** from **0.04** to **0.06 (~1%)** over the global ocean and by **0.03** to **0.2** (**0.2** to **4%**) over the Southern Ocean
- ✓ Decreased cloud top r_e by **<0.3%** over the global ocean and **<0.5%** over the Southern Ocean
- ✓ Increased global mean **SWCF [Wm^{-2}]** from **0** to **- 0.3** over the ocean and from **- 0** to **– 0.1** globally

Outline

1) Introduction
2) Biogenic gas emissions from the ocean and their impact on aerosol/cloud interaction and radiative properties of the overlying atmosphere
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4) Model results
5) **The future**

www.shortsshortsshorts.com/.../

My Take on Near Future Marine Organic Aerosol Research

"It is time to go and sample in pristine environments…"

Jos Lelieveld (MPI Mainz)

❖ Extensive lab measurements for phytoplankton emitted biogenic volatile organic compounds (BVOC) under different light/ temperature regimes

❖ More field campaigns in pristine marine environments (e.g., Southern Ocean)

❖ Improved satellite retrievals of aerosols (low AOD), Ocean ecosystems ([Chl-a], phytoplankton functional groups, CDOM) and trace gases within boundary layer (Sulfur dioxide (SO_2), formaldehyde (HCHO), glyoxal (CHOCHO), nitrous oxide (N_2O), bromine monoxide (BrO), chlorine dioxide (OClO), ozone (O_3))

❖ Improved quantification of marine POM emissions

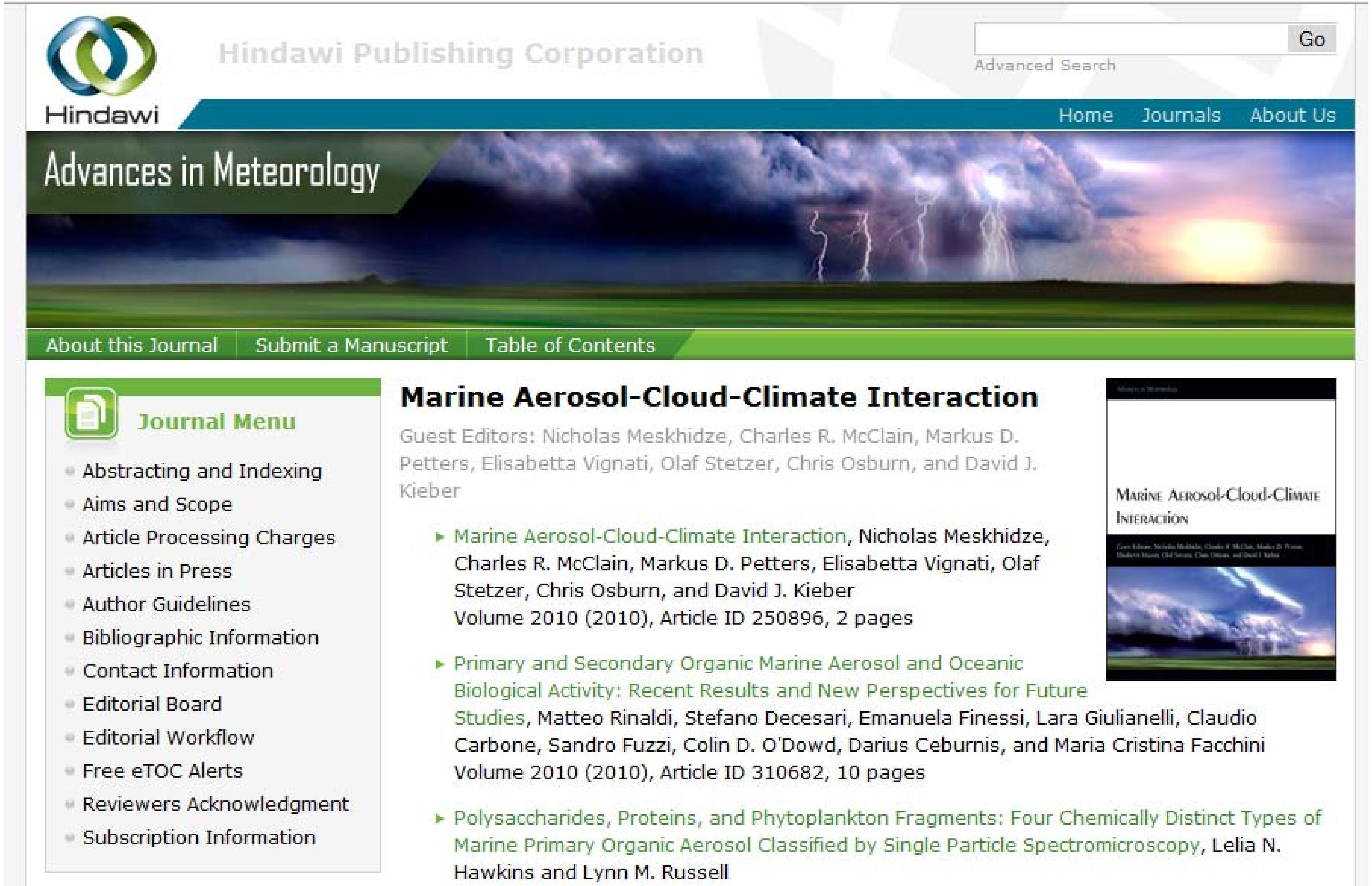
❖ Marine sources of SOA (e.g., monotrpenes such as α-pinene, β-pinene, myrcene, camphene, limonene and others)

❖ Finer model spatial resolution (estuary emissions)

❖ Future air quality studies should consider marine sources of OC aerosol

Special Issue on Marine Aerosol-Cloud-Climate Interaction

http://www.hindawi.com/journals/amet/osi.html



References

MODIS - http://ladsweb.nascom.nasa.gov/data/search.html
SeaWiFS - http://oceancolor.gsfc.nasa.gov/
QuikScat - http://www.remss.com/qscat/qscat_browse.html
AMSR-E - http://www.remss.com/amsr/amsr_browse.html
CALIPSO - http://www-calipso.larc.nasa.gov/products/lidar/browse_images/show_calendar.php
GIOVANNI - http://disc.sci.gsfc.nasa.gov/giovanni/
Henry’s Law Constants - http://www.mpch-mainz.mpg.de/~sander/res/henry.html

Alvain, S., Moulin, C., Dandonneau, Y., and Breon, F. M.: Remote sensing of phytoplankton groups in case 1 waters from global SeaWiFS imagery, Deep-Sea Res. I, 52, 1989–2004, 2005.

Alvain, S., Moulin, C., Dandonneau, Y., and Loisel, H.: Seasonal distribution and succession of dominant phytoplankton groups in the global ocean: A satellite view, Global Biogeochem. Cycles, 22, GB3001, doi:10.1029/2007GB003154, 2008.

Andreae, M. O., Charlson, R. J., Bruynseels, F., Storms, H., Grieken, R. V., and Maenhaut, W.: Internal Mixture of Seasalt, Silicates, and Excess Sulfate in Marine Aerosols, Science, 27, 232(4758), 1620–1623, doi:10.1126/science.232.4758.1620, 1986.

Boyd, P.W., et al. Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions, Science, Vol. 315, 612-617, 2007.

Charlson, R. J., Lovelock, J. E., Andreae, M. O. & Warren, S. G. 1987 Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate. Nature 326, 655–661. (doi:10.1038/326655a0)

References (continued)

Chisholm, S.W., Stirring times in the Southern Ocean, NATURE, 407, 2000

Clarke, A. D., Owens, S. R. & Zhou, J. 2006 An ultrafine sea-salt flux from breaking waves: implications for cloud condensation nuclei in the remote marine atmosphere. J. Geophys. Res. 111, D06202. (doi:10.1029/2005JD006565)

Colomb, A., Gros, V., Alvain, S., Sarda-Esteve, R., Bonsang, B., Moulin, C., Kl¨upfel, T., Williams, J.: Variation of atmospheric volatile organic compounds over the Southern Indian Ocean (30–49 S), Environ. Chem., 6(1), 70–82, doi:10.1071/EN08072, 2009.

De Leeuw, G., Neele, F. P., Hill, M., Smith, M. H. & Vignati, E. 2000 Sea spray aerosol production by waves breaking in the surf zone. J. Geophys. Res. 105, 29 397–29 409. (doi:10.1029/2000JD900549).

de Leeuw, G., E. L Andreas, M. D. Anguelova, C. W. Fairall, E. R. Lewis, C. O'Dowd, M. Schulz, and S. E. Schwartz

(2011), Production flux of sea spray aerosol, Rev. Geophys., 49, RG2001, doi:10.1029/2010RG000349.

Duce, R.A. et al., Impacts of Atmospheric Nitrogen on the Open Ocean, Science, Vol. 320, 893-897, 2008.

Erickson, D. J. & Duce, R. A. 1988 On the global flux of atmospheric sea salt. J. Geophys. Res. 93, 14 079–14 088.

Gantt, B., N. Meskhidze, and D. Kamykowski, A new physically-based quantification of marine isoprene and primary organic aerosol emissions, Atmos. Chem. Phys., 9, 4915–4927, 2009

Gong, S. L. 2003 A paramterization of sea-salt aerosol source function for sub- and super-micron particles. J. Geophys. Res. 17, 1097. (doi:10.1029/2003GB002079)

Guenther, A. B., Zimmerman, P. R., and Harley, P. C.: Isoprene and monoterpene emission rate variability: model evaluations and sensitivity analysis, J. Geophys. Res., 98, 12609–12617, 1993.

References (continued)

Ho, D. T., C. S. Law, M. J. Smith, P. Schlosser, M. Harvey, and P. Hill (2006), Measurements of airsea gas exchange at high wind speeds in the Southern Ocean: Implications for global parameterizations, Geophys. Res. Lett., 33, L16611, doi:10.1029/2006GL026817.

Lewis, E. R. & Schwartz, S. E. 2004 Sea salt aerosol production. Mechanisms, methods, measurements, and models. Washington, DC: American Geophysical Union.

Ma°rtensson, E. M., E. D. Nilsson, G. de Leeuw, L. H. Cohen, and H.-C. Hansson, Laboratory simulations and parameterization of the primary marine aerosol production, J. Geophys. Res., 108(D9), 4297, doi:10.1029/2002JD002263, 2003.

Mahowald, N., et al. (2008), Global distribution of atmospheric phosphorus sources, concentrations and deposition rates, and anthropogenic impacts, Global Biogeochem. Cycles, 22, GB4026, doi:10.1029/2008GB003240.

Mahowald, N.M., et al., Atmospheric Iron Deposition: Global Distribution, Variability, and Human Perturbations, Annu. Rev. Mar. Sci., 1:245–78, 2009.

Meskhidze, N., A. Nenes (2006), Phytoplankton and Cloudiness in the Southern Ocean, *Science*, DOI: 10.1126/science.1131779.

Meskhidze, N., W. L. Chameides, and A. Nenes Dust and pollution: A recipe for enhanced ocean fertilization?, *J. Geophys. Res.*, *110*, D03301, 2005, doi:10.1029/2004JD005082.

O’Dowd, C. D., B. Langmann, S. Varghese, C. Scannell, D. Ceburnis, and M. C. Facchini (2008), A combined organic-inorganic sea-spray source function, Geophys. Res. Lett., 35, L01801, doi:10.1029/ 2007GL030331.

O’Dowd, C. D., M. C. Facchini, F. Cavalli, D. Ceburnis, M. Mircea, S. Decesari, S. Fuzzi, Y. J. Yoon, and J. P. Putaud (2004), Biogenically driven organic contribution to marine aerosol, Nature, 431, 676–680, doi:10.1038/nature02959

References (continued)

O'Dowd, C.D., de Leeuw, G, Marine aerosol production: a review of the current knowledge, Phil. Trans. R. Soc. A (2007) 365, 1753–1774, doi:10.1098/rsta.2007.2043

Palmer, P. I. and Shaw, S. L.: Quantifying global marine isoprene fluxes using MODIS chlorophyll observations, J. Geophys. Res., 32, L09805, doi:10.1029/2005GL022592, 2005.

Sciare, J., O. Favez, R. Sarda-Este`ve, K. Oikonomou, H. Cachier, and V. Kazan (2009), Long-term observations of carbonaceous aerosols in the Austral Ocean atmosphere: Evidence of a biogenic marine organic source, J. Geophys. Res., 114, D15302, doi:10.1029/2009JD011998.

Shaw, G. 1983 Bio-controlled thermostasis involving the sulfur cycle. Clim. Change 5, 297–303. (doi:10.1007/BF02423524)

Shaw, G.E., Bio-controlled thermostasis involving the sulfur cycle, Climatic Change, 5, 297-303, 1983.

Sinha, V., Williams, J., Meyerhfer, M., Riebesell, U., Paulino, A. I., and Larsen, A.: Air-sea fluxes of methanol, acetone, acetaldehyde, isoprene and DMS from a Norwegian fjord following a phytoplankton bloom in a mesocosm experiment, Atmos. Chem. Phys., 7, 739–755, 2007.

Solmon, F., P. Y. Chuang, N. Meskhidze, and Y. Chen (2009), Acidic processing of mineral dust iron by anthropogenic compounds over the north Pacific Ocean, J. Geophys. Res., 114, D02305, doi:10.1029/2008JD010417.

Vaattovaara, P., Huttunen, P. E., Yoon, Y. J., Joutsensaari, J., Lehtinen, K. E. J., O'Dowd, C. D. & Laaksonen, A. 2006 The composition of nucleation and Aitken modes particles during coastal nucleation events: evidence for marine secondary organic contribution. Atmos. Chem. Phys. 6, 4601–4616.

References (continued)

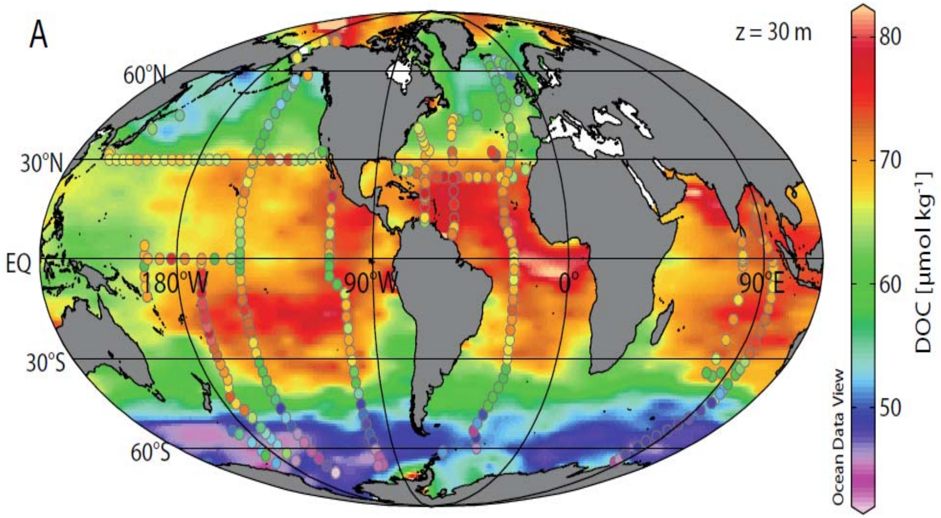
Vignati, E., de Leeuw, G. & Berkowicz, R. 2001 Modeling coastal aerosol transport and effects of surf-produced aerosols on processes in the marine atmospheric boundary layer. J. Geophys. Res. Atmos. 106, 20 225–20 238. (doi:10.1029/2000JD000025)

Wanninkhof, R. et al., Advances in Quantifying Air-Sea Gas Exchange and Environmental Forcing, Annu. Rev. Mar. Sci. 2009. 1:213–44, 10.1146/annurev.marine.010908.163742

Yassaa, N., Peeken, I., Zollner, E., Bluhm, K., Arnold, S., Spracklen, D., and Williams, J.: Evidence for marine production of monoterpenes, Environ. Chem., 5, 391–401, doi:10.1071/EN08047, 2008.

Yoon, Y. J. et al. 2007 Seasonal characteristics of the physico-chemical properties of North Atlantic marine atmospheric aerosols. J. Geophys. Res. 112, D04206. (doi:10.1029/2005JD007044)

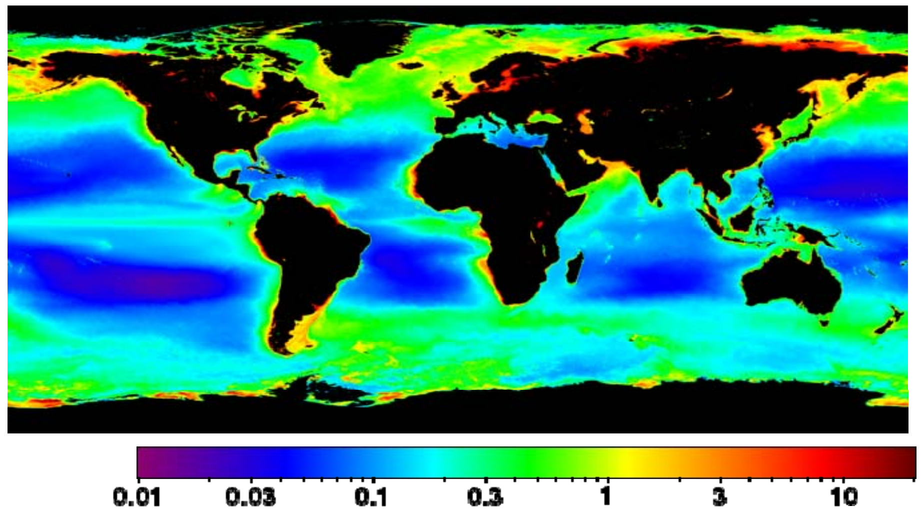
Ocean Carbon Inventory



0 – 200 m DOC = 47 x 10^{15} C

[Hansell et al., Oceanography, 2009]

Carbon inventory of ocean biomass ~ 3 x 10^{15} C



Chlorophyll *a* concentration nmol/kg^{-1}

What Are The Right Parameters For Organic Enrichment Of Sea Spray ?