Quantifying the role of marine phytoplankton (DMS) in the present day climate system

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1.

INTRODUCTION

1.1 The Earth's Climate System

In the field of Atmospheric Sciences, the specific definition of *climate* is "the average weather as described by mean statistics and variability of relevant meteorological quantities (e.g. temperature, precipitation and wind), typically over a period of 30 years as described by the World Meteorological Organisation (WMO), but may also be valid for periods ranging between months and millions of years" [IPCC, 2001]. The Earth's climate is maintained by a balance between the energy that reaches the Earth from the sun and that which goes from the Earth back out to space (Figure 1). The lithosphere, biosphere, hydrosphere, cryosphere and atmosphere all work interactively in regulating this balance, and together form part of the Earth's *climate system* [IPCC, 2001].

Several factors within the Earth's climate

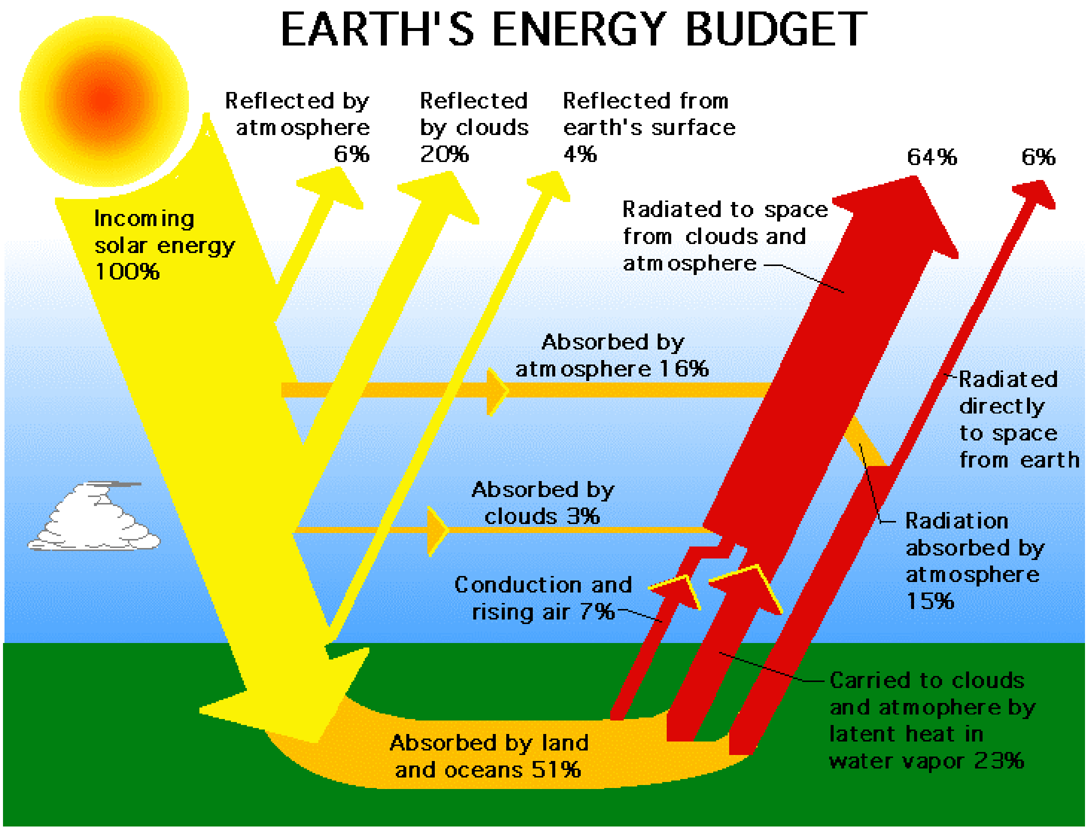

Figure 1: The climate of the Earth depends on the balance between the energy absorbed from solar radiation and outgoing radiation emitted by earthly elements in the form of longwave radiation. The atmosphere, land and oceans all work interactively in regulating this balance.

Figure 2: Microscopic images of phytoplankton (s*ource: various websites, see references section*). The amount of DMSP produced per species is variable, with members of the classes Dinophyceae (dn) and Prymnesiophyceae (pr) producing copious amounts of DMSP; members of the classes Bacillariophyceae (diatoms, dt) and Prasinophyceae (ps) producing intermediate amounts; and members of the classes Chlorophyceae (cl), Cryptophyceae (cr) and Cyanophyceae (cy) producing the least amounts of DMSP [Turner *et al*., 1988; Keller *et al*., 1989; Corn *et al*., 1996; Keller and Korjeff-Bellows, 1996]. Phytoplankton, which can be found in most of the ocean surface, account for more than half of the photosynthesis on earth, utilising the greenhouse gas carbon dioxide and producing oxygen. Dimethylsulphide gas (DMS), which is indirectly produced by phytoplankton, gives the sea the characteristic sea-smell that most people recognise when they approach a coastline [Stefels *et al*., 1997].

system may perturb the Earth's energy balance causing a response in climate. For instance, sulphur dioxide (SO_2) emissions from volcanic eruptions within the lithosphere [Andres and Kasgnoc, 1998] undergo chemical transformation to form sulphate aerosol particles ($SO_4^{=}$). These particles are highly effective in the backscattering of incoming solar radiation and, thereby, affect energy flows within the climate system.

Within the biosphere, a change in the earth surface albedo due to deforestation can affect the amount of solar energy absorbed by the ground surface, which may in turn feed back on the local moisture balance and heat fluxes in the atmosphere above [e.g. Gondwe and Jury, 1997; Jury *et al*., 1997; D'Abreton *et al.*, 1998; IPCC, 2001].

Within the hydrosphere, physical oceanographic processes also play a role in climate-relevant radiative processes. The oceans, which cover

70% of the Earth's surface and are in close proximity to most of the lower atmosphere, have an immense capacity to store heat in comparison to land and air. A fraction of absorbed incoming solar energy is transferred to the atmosphere through evaporated water (latent heat). Due to its greenhouse properties water vapour in the atmosphere regulates energy balances on micro-, meso- and global scales.

Furthermore, pressure gradients caused by differential heating and salinity differences of individual water masses drive ocean currents. The ensuing thermohaline circulation facilitates the redistribution of heat within the ocean which in turn feeds back on air temperatures and motion above [Malkus, 1962]. Ambient air temperatures determine the reaction rates of air chemical constituents such as ozone, which is both a greenhouse gas and an important precursor to hydroxyl radicals [Brühl *et al*., 2001]. These radicals play an important role in many climate-relevant photochemical reactions.

1.2 The Importance of Marine Phytoplankton in the Earth's Climate System

Ocean biota, in particular phytoplankton (Figure 2), also play a fundamental role in regulating the Earth's energy balance. Three general climatic impacts of phytoplankton are distinguished. Firstly, photosynthetic carbon fixation by these organisms and the subsequent downward transport of organic carbon facilitate oceanic storage of one of the major greenhouse gases: CO_2 [Smith *et al*., 1991; Aiken *et al*., 1992; De Baar, 1992; De Baar and Suess, 1993; Buitenhuis *et al*., 2001; Bigg *et al*., 2003]. Secondly, some of these microscopic algae form extensive blooms in coastal areas, temperate and polar regions of the global ocean (Figure 3). The absorption and scattering properties of these biogenic particles in surface waters affect the water-leaving radiance and heating of surface waters [Sathyendranath *et al*., 1991; Holligan, 1992; Tyrell *et al*., 1999]. Thirdly, phytoplankton contribute to the global atmospheric sulphate aerosol burden, cloud condensation nuclei and cloud albedo through the indirect production of the cloud-aerosol precursor dimethylsulphide gas (DMS; CH_3SCH_3) [Charlson *et al*., 1987; Ayers *et al*., 1991; Falkowski *et al*., 1992; Liss, 1999]. Clouds and aerosols are highly effective in backscattering incoming solar radiation [Andreae *et al*., 2001].

In this thesis, specific focus is laid on the quantification and discussion of the role of marine

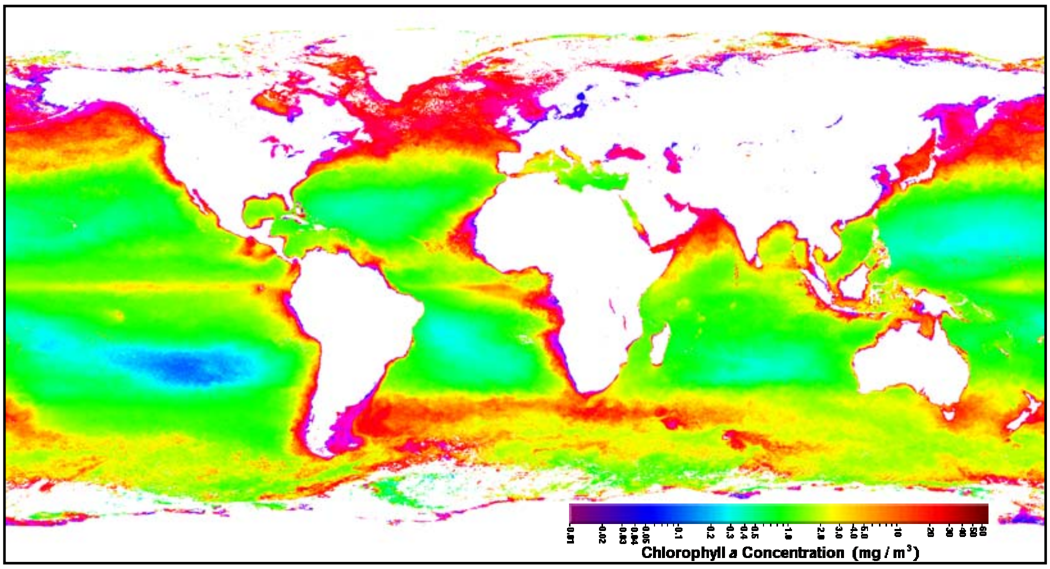

Figure 3: The 2002 mean annual geographical distribution of the concentration of the photosynthesising (thus chlorophyll-containing) phytoplankton deduced from satellite-measured chlorophyll *a* concentration at the ocean surface. The image is courtesy of NASA and is a product of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) aboard the Orbview-2 satellite.

phytoplankton on climate through increasing ocean surface albedo and through DMS production. Various methodologies such as the interpretation of satellite remotely sensed data, three-dimensional atmospheric chemistry and climate modelling, as well as 3-D atmospheric radiative transfer modelling are used to derive a quantitative understanding of the strength and significance of these climatic impacts. There is an unfortunate tendency to think of satellite data as only photographic imagery. However, these imagery are always also accompanied by corresponding quantitative data which can shed light on processes not discernible by the human eye. When used in combination with *in situ* data and model results the imagery have markedly expanded the marine scientist's ability to interpret numerous hydrographical and biological, geological and chemical events and processes taking place within a given oceanic region.

In this thesis, most analyses are made globally on a monthly scale in order to identify locations and seasons on the globe where and when the impacts are greatest. Wherever available, *in situ* data are also utilised to confirm model results and findings of the remotely sensed data analyses.

1.3 Thesis Outline

The analyses in this thesis begin with an assessment of the influence of surface ocean bio-particle composition on climate and ends with an analysis of indirect marine algal influences at cloud level. Specifically, data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) aboard the Orb-View 2 satellite are used in Chapter 2 to quantify the amount of incoming solar energy that is returned back to space by the highly reflective coccolithophore particles in the ocean (*i.e.* the water-leaving radiance), Figure 4. This is done in order to assess whether or not the amount of energy lost to space through this pathway is significant enough to perturb climate. Analyses in this chapter are made for the North Atlantic open ocean only, where the blooms are most prevalent. Coastal water data are not included in the analysis since reflectance in these waters may also be caused by suspensed sediment and cannot be distinguished from the coccolithophore bloom optical signal.

In Chapter 3, three-dimensional global atmospheric chemical transport modelling [Houweling *et al*., 1998] is conducted to quantify the contribution of ocean-leaving DMS to atmospheric chemistry and composition, in particular, to the atmospheric burdens of DMS, MSA (methanesulphonate), SO_2 and non sea salt (nss) $SO_4^=$, relative to other sources (Figure 4). Sulphur dioxide and sulphate aerosols are both pollutants and $SO_4^=$ may affect climate directly through backscattering of incoming solar radiation and indirectly through cloud formation. Model results are validated against observations.

Results from Chapter 3 are used in Chapter 4 mainly to test theories of atmospheric DMS oxidation and the relative yields of individual DMS oxidation products under different physical and photochemical conditions in the atmosphere. Focus is specifically laid on MSA and nss $SO_4^=$, whose ratio has historically been used to assess the marine algal contribution to observed sulphate levels. In this chapter, the atmospheric MSA: nss $SO_4^=$ ratio is modelled on a global scale and its temporal and spatial variation is analysed. Model performance in simulating this ratio is tested against globe-wide measurements.

In Chapter 5, global three-dimensional atmospheric radiative transfer modelling [van Dorland *et al*., 1997] is conducted to quantify the amount of energy that can be reflected back to outer space by sulphate particles of marine algal origin quantified in Chapter 3 (See Figure 4). Furthermore an assessement is made on whether or not the magnitude of this reflected energy is significant for climate. Two scenarios are considered for the present day climate: a control scenario, in which marine phytoplankton (algal-derived sulphate particles) are neglected and a pertubation scenario, in which marine phytoplankton (algal-derived sulphate particles) are included in the analysis. Results from the control scenario provide information on the amount of energy that would be scattered back to space by sulphate aerosol particles if phytoplankton did not exist while the pertubation scenario provides information on the amount of energy that is scattered back to space in the present day climate due to the presence and existence of marine phytoplankton.

In Chapter 6, a simple sub-linear empirical paramerisation [Boucher and Lohmann, 1995, relationship D] is utilised to quantify the contribution of ocean-leaving DMS to the global column integrated cloud droplet number concentration (CDNC) (Figure 4). The column density of cloud droplets determines the cloud optical depth, which in turn regulates the penetration of solar and terrestrial radiation through a cloud cover.

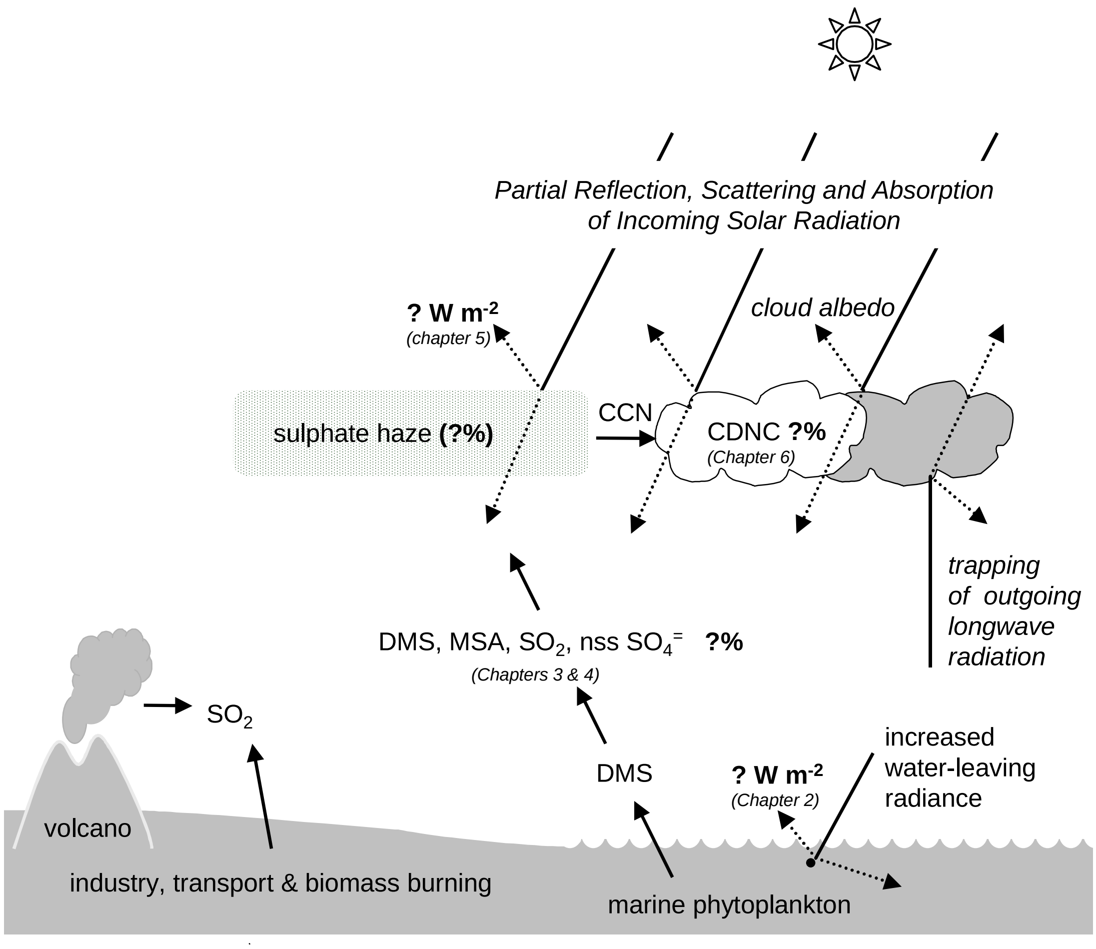

Figure 4: Some of the pathways of influence of marine phytoplankton on climate. Question marks are shown where the marine algal contribution to the concentrations, burdens and radiative pertubation is to be quantified in this thesis.

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