Negligible direct radiative forcing of basin-scale climate by coccolithophore blooms

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Abstract. The water-leaving radiance, defined as radiation from the sun reflected off particles in water and exiting the ocean surface back into the atmosphere and space, is often used to derive ocean-colour information from remotely sensed data. However, it is in itself a measure of the amount of solar irradiance reflected by oceanic constituents and, therefore, not available to the Earth's heat reservoir (changes in which can affect the Earth's energy balance and climate). A strong influence on the water-leaving radiance is observed from coccolithophore blooms, owing to the highly reflective calcareous platelets or coccoliths covering these marine algae. We analysed remotely sensed water-leaving radiances (1998-1999) over the N. Atlantic, where the blooms are spatially and temporally most abundant, and found that the direct radiative forcing of climate between 402-565 nm (the major range of optical influence) by coccolithophores in this ocean is negligible (~0.05 W m^-2 mean annually). This is in contrast to what in situ or laboratory measurements on the immense local intensity of coccolithophore visible light scatter in the past two decades have led us to believe.

1. Introduction

In the past two decades, numerous bio-optical studies [e.g. Holligan et al., 1983; Bricaud and Morel, 1986; Balch et al., 1991, 1996a, b; Ackleson et al., 1994; Tyrell and Taylor, 1996; Tyrell et al., 1999] have shown that marine phytoplankton, specifically, coccolithophores, locally diminish the ocean's absorption of incoming visible radiation through scattering from the oceans back to space, i.e. a direct negative forcing (Fig. 1). Coccolithophores form external calcium carbonate (CaCO3) scales (ø ~1-10μ; thickness ~0.25-0.75μ) called coccoliths, which form multiple layers and eventually detach from the cells, sometimes reaching concentrations 10-20 times that of the cells themselves [Gordon et al., 1988; Balch et al., 1993]. Due to the high refractive index of calcite, the coccoliths result in increased light backscatter, which, under bloom conditions, has been reported as intense discoloration of ocean surface waters (turquoise to whitish colour) by both sailors and oceanographic scientists alike. In situ optical measurements, laboratory experiments and satellite data analyses have provided similar reports [e.g. Holligan et al., 1983; Viollier and Sturm, 1984; Balch et al., 1991, 1996a, b; Ahn et al., 1992; Ackleson et al., 1994; Voss et al., 1998]. Modelling studies [Tyrell and Taylor, 1996; Tyrell et al., 1999] have shown that for a typical ocean, the proportion of photons re-emitted by ocean water increases from 0.4% when there are no coccolithophores in the water to 2% with 100 mg CaCO3 m^-3 (representative of coccoliths) in the water, to 5.2% with 300 mg CaCO3 m^-3. With the exception of these initial calculations by Tyrell et al. [1999], no other attempts have been made to analyse the implications of these localised backscattering effects on climate, i.e. at a larger scale.

2. Approach

Using above-surface normalised water-leaving radiances (henceforth nLw) measured in visible channels 1-5 of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) aboard the SeaStar satellite, we have determined the extent to which a return of visible solar energy to space by coccolithophore blooms is significant to global climate. Our estimates improve on those by Tyrell et al. [1999] who modelled the effect of coccolith scattering on the albedo (glint radiance plus water-leaving radiance in Fig. 1) of a water body in order to determine the climate radiative forcing effect of coccolithophores. A shortcoming in using albedo for this purpose is that the glint radiance component of the albedo is not influenced by algal presence, but rather by illumination geometry and the slope of the water surface [Payne, 1972]. By considering only the water-leaving component of the albedo, which in Case I waters (the open ocean) is almost entirely influenced by phytoplankton presence [Gordon et al., 1988; Sathyendranath and Morel, 1983; Lee et al., 1994], our estimates provide a more precise quantifica-
tion of the direct radiative forcing of climate by these algae. Furthermore, being direct (albeit remotely sensed) measurements of the water-leaving radiance (i.e., actual fluxes), our data validate the theoretical results obtained by Tyrell et al. [1999], which are expressed in terms of percentage reflectance of photons.

The nLw data (originally expressed in milliwatts per square centimetre per micron per steradian, mW cm\(^{-2}\) \(\mu\)m\(^{-1}\) sr\(^{-1}\)) are Level 3 equal-area gridded data at a spatial resolution of 9 km\(^2\). They are obtained from NASA's Goddard Distributed Active Archive Center and were atmospherically corrected from raw satellite-received radiances according to the methods of NASA's SeaWiFS Project [e.g., McClain et al., 1995; Barnes et al., 1996], by the project’s calibration and validation team. Since daily images are problematic to analyse due to their high and spatially variable cloud cover, analyses were conducted on 8-day composites.

The study area was the N. Atlantic ocean (23\(^\circ\)N to 75\(^\circ\)N; -86\(^\circ\)W to -7\(^\circ\)W), with focus on Case I waters. According to Brown and Yoder [1994] and Brown [1995], the N. Atlantic ocean is the most appropriate area (spatially and temporally) for the study of coccolithophore blooms in these waters. We examined and report on a two-year (1998-99) data record, and also present analyses for the spatially extensive (\(\sim 5 \times 10^5\) km\(^2\)) coccolithophore bloom which occurred south and southwest of Iceland, in the month of June 1998 (Fig. 2).

The June 1998 coccolithophore bloom is clearly visible in all SeaWiFS imagery of water-leaving radiances in wavebands 1-5, although the intensity of the nLw varies with waveband. The presence of coccolithophore blooms was initially detected by analysing nLw at 555 nm, where backscattering by ocean water is minimal, and where it is largely dominated by particulate calcite scattering when present [Holligan et al., 1983; Viollier and Sturm, 1984; Balch et al., 1991, 1996a, b; Ackleson et al., 1994]. The spatial location of the blooms was then noted in other wavebands where their reflectance signals were not easily distinguishable from those of the ocean water itself. These other wavebands or

**Figure 2.** The growth and decay of the June 1998 coccolithophore bloom. a-d: Julian days 153-160, 161-168, 169-176, and 177-184, respectively.

**Figure 3.** nLw at 555 nm over a coccolithophore bloom versus a no-bloom area. Trends at 490 and 510 nm are similar, however, those at 412 and 443 nm are only greater than those over the no-bloom area in the third week of June, when the bloom was at its most reflective.
channels are each 20 nm wide and are centred at 412, 443, 490 and 510 nm.

We quantified the phytoplankton effect illustrated in Fig. 1 by comparing nLw over the June 1998 bloom to those over an area where no algal blooms were detectable in the imagery (oligotrophic waters) (Fig. 3). In calculating the radiative forcing, the coccolithophore-contributed nLw was taken to be the difference between the nLw over the coccolithophore blooms and that over a no-bloom area of similar extent. Since there are data gaps between several of the channels in which SeaWiFS collects measurements, we linearly interpolated data to these gaps in an attempt to provide a better estimate of the total radiative forcing between 402 and 565 nm (the major range of coccolithophore optical influence). The first data gap (9 nm wide) occurs between channels 1 and 2; the second (25 nm wide) occurs between channels 2 and 3; while the third (23 nm wide) occurs between channels 4 and 5. Integration of within-channel radiances is already performed by the SeaWiFS instrument at measurement [Barnes et al., 1996]. We, therefore, calculated the radiative forcing in each of the 5 SeaWiFS channels separately. The approximate total radiative forcing for each gap was taken to be the average between the approximate total radiative forcing calculated for each of the two channels flanking the gap. The sum of the individual contributions from the 5 SeaWiFS channels and 3 gaps was taken to provide an estimate of the total radiative forcing of coccolithophores between 402 and 565 nm.

3. Results and Discussion

Although we confirmed that the presence of coccolithophore blooms in the ocean does result in an intense localised return of incoming visible light energy (Fig. 3), we also found that the associated radiative forcing, at the scale of the entire ocean, is marginal. In total, the June 1998 bloom effected a local radiative forcing of ~2.5 W m⁻² during its existence, while the mean annual radiative forcing effected by all coccolithophore blooms in N. Atlantic Case I waters was estimated at ~0.05 W m⁻².

This marginal effect is to be expected when one also considers the spatial extent of the bloom in relation to the entire surface area of the ocean. A bloom as extensive and intense as the June 1998 bloom examined here is astounding, but significant only on a local scale. The N. Atlantic ocean covers some ~36x10⁶ km², of which the June 1998 bloom covers only 1.4%. Only 42 other distinct blooms with differing intensities and spatial extents varying between ~8x10³ and ~1.68x10⁵ km² were identified in the SeaWiFS N. Atlantic dataset. Half of all identified blooms covered between 8x10³ and 5x10⁴ km² (Fig. 4), with most of these blooms covering between 3 and 3.5x10⁴ km². Eight, seven and six blooms fell within the 5.1x10³ - 1x10⁴ km², 1.01x10⁵ - 1.5x10⁵ km², and 1.51x10⁵ - 2x10⁵ km² categories, respectively. Only the bloom in June 1998 was >2x10⁵ km². At the global scale, analyses of remotely sensed data from the Coastal Zone Colour Scanner (CZCS) showed an annual coccolithophore bloom coverage of 1.4x10⁶ km² [Brown and Yoder, 1994; Brown, 1995]. When compared to a total surface area of the global oceans of ~335x10⁶ km², this coverage loses significance in terms of the potential of the blooms to influence climate.

The duration and frequency of the blooms (Fig. 5) further supports the notion that coccolithophore blooms cannot be a significant role-player in the Earth's energy budget. The June 1998 bloom lasted for 4 weeks and is not an annually recurrent feature (reported only once before in 1991 [Balch et al., 1996b]). Blooms between 1 and 2x10⁵ km² lasted 1-6 weeks, with a high tendency towards 2-3 weeks. Blooms between 5x10⁴ and 9.9x10⁴ km² (Fig. 4) lasted 1-4 weeks. The duration of blooms <5x10⁴ km² is the most variable (1-9 weeks). These periods (visible and scattering phases only) are considerable when the blooms are viewed in isolation, but short in relation to the rest of the year when impacts are absent or much more reduced.

4. Conclusions

Numerous research efforts in the past two decades have reported intense backscattering of solar irradiance by coccolithophore blooms [e.g. Holligan et al., 1983; Bricaud and Morel, 1986; Balch et al., 1991, 1996a, b; Ackleson et al., 1994; Tyrell and Taylor, 1996; Tyrell et al., 1999]. These studies focused on the local optical impacts of the blooms. Intense backscattering of solar irradiance by coccolithophore blooms on a local scale has the potential to affect local meteorological (e.g. wind patterns, evaporation, convection) and physical oceanographic processes (e.g. vertical mixing in the water column, currents), which may in turn be relevant to ecological issues (e.g. feedbacks of changes in water motion on plankton dynamics). In this study, we quantified...
the local radiative forcing of a large coccolithophore bloom (~5 × 10^4 km^2) in the N. Atlantic using satellite data. This forcing (2.5 W m^-2 between 402 and 565 nm - the major range of coccolithophore optical influence) may be large enough to affect physical processes in the surface ocean and lower atmosphere in the vicinity of and during the bloom. Microscale meteorological and oceanographic measurements in locations of coccolithophore blooms, which were beyond the span of the current study, would be necessary to confirm these proposed linkages.

In this study, we aimed to quantify radiative forcing by coccolithophores on a larger spatial (basin-scale) and temporal scale. Our interest was to determine whether the magnitude of solar irradiance reflected by coccolithophore blooms, throughout the year, is significant enough to perturb physical processes at the climatic scale. SeaWiFS data analysis has shown that the spatial extent, frequency and duration of significantly large coccolithophore blooms relative to the area covered by the rest of the N. Atlantic ocean is marginal, and that radiative forcing of climate by the blooms is insignificant at the basin scale (~0.05 W m^-2 mean annually). Considering that blooming coccolithophores are spatially and temporally most abundant in the N. Atlantic (Brown and Yoder, 1994), one may expect the total radiative forcing at the global ocean scale not to be excessively larger than what we have calculated here. It should be noted, however, that the (albeit minimal) optical effects of ubiquitous non-blooming coccolithophores [Balch et al., 1993; 1996a, b; 1999] have not been taken into account in this study. Since they are present in sub-bloom concentrations, these particles are not detectable by satellites making their contribution to a global forcing difficult to quantify using the methodologies used in the current study.

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References

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