Algal blooms: how are they harming models used for climate management?

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Abstract

Microalgae blooms are generally associated with bacterial secondary producers. They produce organic matter (OM), some of which associates with the sea surface microlayer (SML). OM in the SML below the actual surface reduces fluxes of energy, including heat and momentum, and substances, including greenhouse gases, aerosols, algae, bacteria and viruses.
In addition to the SML-associated OM, another OM fraction, foam (including whitecaps), often lies above the primary SML when windspeeds exceed about 5 m s^{-1}, trapping gas bubbles. Such foam also dramatically increases albedo, reflecting solar radiation back into space, thus reducing solar heating and penetration of photosynthetically active radiation. Mean coverage of the ocean surface by foam has been measured to range between 1-6%, particularly in zones of Trade Winds.
Different types of OM, and particularly their mechanical properties, depend on ambient algal abundance, as well as on taxonomic composition, as do the dynamics of foam formation and decay. Air-sea fluxes may thus be influenced by genomic control through the blooming microalgae and Darwinian-type evolution. Bacteria may also play a role. In addition, foam patches on the ocean's surface serve as a unique microbial habitat. Such blooms, particularly when their taxonomic composition changes unpredictably, are likely to be harming the usefulness of climate models. Some of this harm might be mitigated by studying the relevant effects of these blooms on fluxes, and incorporating these effects into climate models.

Ph. Hess [Ed]. 2020. *Harmful Algae 2018 – from ecosystems to socioecosystems. Proceedings of the 18th Intl. Conf. on Harmful Algae.* Nantes, International Society for the Study of Harmful Algae. 214 pages. ISBN: 978-87-990827-7-3.

Introduction

Algae (here including cyanobacteria) bloom in ocean waters. They produce and consume CO_2 and other greenhouse gases, of which the concentrations and fluxes are incorporated into models of climate. Algae are the primary producers of most of the organic matter (OM) in aquatic ecosystems (Hansell et al., 2009). Some of this OM, as well as OM from secondary production by bacteria (Kurata et al., 2016; Howe et al., 2018) and other plankton, accumulate in the surface microlayer (SML). The mechanical effects of microalgal OM in the SML are still absent in models of how air-water fluxes of gases, particles and heat, affect climate. Here we propose some avenues for correcting this absence, and validating the effects empirically.

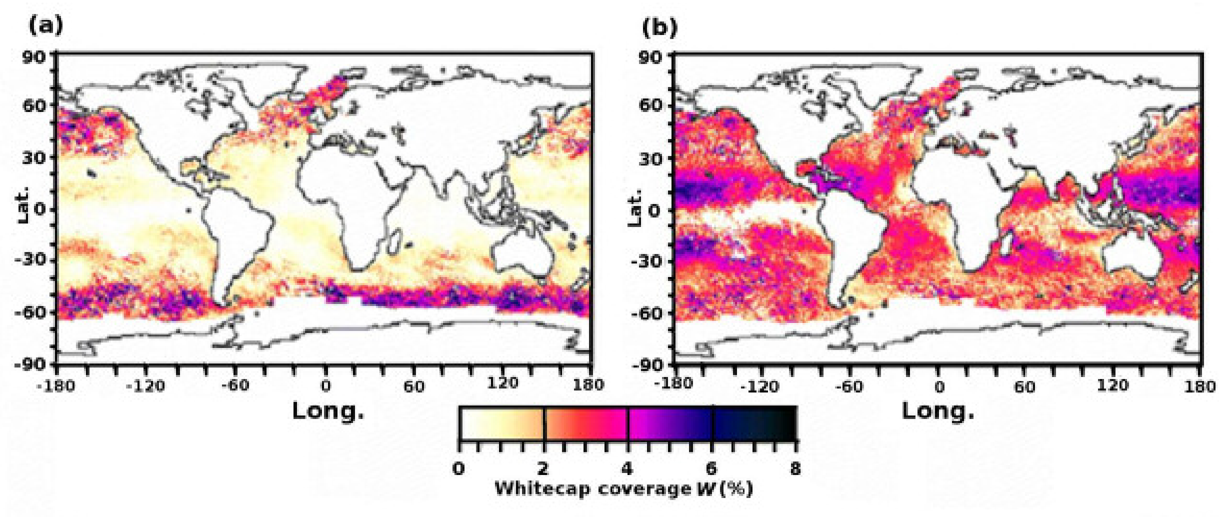

Fig. 1: Whitecap coverage (W) computed from models using daily fields of wind speed (a) and measured values of W observed from satellites (b), both for March 1998 (average of 31 daily maps of W). Redrawn from Anguelova & Webster (2006), as in Jenkinson et al. (2018). Note how in the Tropical areas, particularly the Trade Winds areas, observed values of W are higher than modelled values, while W values at around 60°S are smaller.

Fluxes modified by OM variation not modelled in climate models

The abundance, chemical composition and physical properties of OM secreted by blooming microalgae depend on algal abundance, taxonomic composition and physiological state (Seuront et al, 2006, 2010; Jenkinson & Sun, 2010, 2014; Jenkinson et al, 2018). Variation in the quality and quantity of algae-produced OM in the SML is not included in International Panel on Climate Change models (IPCC, 2018). However, such surface-associated OM reduces exchange of O_2, CO_2 and other greenhouse gases (GHG) (Goldman et al, 1998; Calleja et al, 2009), and may also reduce exchange of salts, humidity, aerosols and both thermal and mechanical energy, which are all important inputs to storm formation (Veron, 2015). In addition, OM in the surface film can damp ripples, gravity waves (Alpers & Hühnerfuss, 1989) and even low-frequency ocean swell (Henderson & Segur, 2013). In ocean cyanobacterial slicks (relative to nearby non-slicked water) both increase in temperature and reduction in salinity have been measured during daytime in and just below the SML (Wurl et al., 2018), indicating reduction in evaporation over slick areas. Furthermore, at low windspeeds in some oligotrophic ocean regions, CO_2 fluxes measured by Calleja et al. (2009) were up to 2.7 times more than in water of higher productivity under otherwise similar conditions.

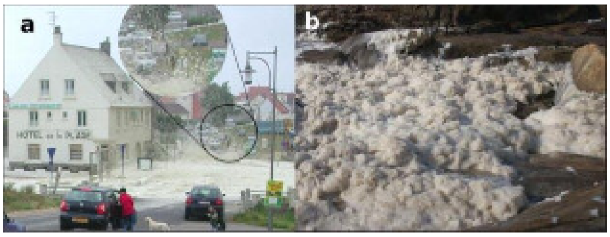

Fig. 2: Massive coastal foam events. (a) Foam event at Audresselles, Pas de Calais, France, associated with bloom of Phaeocystis globosa. Note the flying foam to the right of the hotel, and also that the hotel roof is partly white, from wind-blown and sticky foam (insert is enlarged to show wind-blown foam aggregates); (b) Foam at Cape Silleiro, Galicia, Spain, about a fortnight after gales in early February 2009. Such foam is produced by the action of breaking waves, entraining

air into seawater, itself containing polymeric organic matter produced mainly by algae. Photos by Laurent Seuront (a) and Tim Wyatt (b), as in Jenkinson et al, (2018).

Measurements of air-sea gas fluxes in relation to OM have so far been made only under calm to moderate winds (0-13 m s^{-1}), but not in heavy weather (Goldman et al, 1998; Calleja et al, 2009; Mari et al, 2017). Such studies, however, rarely report its tertiary polymeric structure or rheological properties of the OM. Algal-produced OM, however, shows huge inter- and intra- taxon variations in its rheological properties (Jenkinson et al, 2018). This suggests that sudden shifts in the taxon composition of microalgae, particularly in large offshore areas, could lead to abrupt changes in ocean modulation of climate.

Foam-production by algal blooms

OM produced by algae and bacteria, through its mechanical and surface-active properties, interacts with turbulence produced by wind, waves and other processes to produce whitecaps (Fig. 1a, b) and more persistent (>~1h) foam (Fig.2a, b). High levels of near-surface dissolved organic matter (DOM) in the Trade Winds areas are associated with ~3-8%, which is more than that in the Southern Ocean (~2-4% coverage), even though winds there are much stronger (Anguelova & Webster, 2006).

The higher foam coverage in the Trade Winds zones despite lower wind speeds may be caused by higher mean levels of DOM in the top 30 m (~50-75 µmol kg^{-1} in Trade Winds zones compared to only ~45-55 µmol kg^{-1} in the Southern Ocean) (Hansell et al, 2009). A supplementary explanation may be that the DOM in these different areas likely varies in molecular composition reflecting production by taxonomically different blooming microalgae as well as different OM histories after production.

Increase in ocean albedo

Change in albedo (i.e. proportion of radiation reflected) of the ocean can moderate global warming: increasing the albedo of the low-albedo ocean surface by about 5% could compensate the entire greenhouse gas (GHG)-driven perturbation of the Earth's radiation balance (Gattuso et al, 2018). The albedo of ocean foam is ~0.5 (Stabeno & Monahan, 1986). The present ocean-wide average albedo of about 2.5% × 0.5 = 1.25%. This therefore represents enough albedo to counter ¼ of current GHG perturbation and thereby seriously harm models of global warming through production of DOM and foam. At certain times and places, some algal blooms, such as those of *Phaeocystis* spp. (Seuront et al, 2006) (Fig. 2a, b) produce huge amounts of persistent foam with the potential to increase albedo much more. Adding "surfactants" to the ocean surface to produce persistent foam is being proposed to increase albedo and reduce global warming (Evans, 2010; Garciadiego Ortega & Evans, 2019). While concern about secondary ecological effects may preclude this (Crook et al, 2016), the ecological effects of foam coverage should also be studied.

Smaller-scale effects

At the scales of coastal blooms, modification of air-water gas exchange needs to be incorporated into models of aerosols responsible for respiratory distress in humans in HABs including those of *Ostreopsis* spp. (Vila et al, 2016) and *Karenia brevis* (Heil et al, 2014).

Conclusions

OM in the SML derives from primary and secondary production mainly by algae and bacteria. There is a need to characterize the tertiary chemical structure of OM especially in the surface film, in relation to its rheological and surface properties, and to the taxonomic composition of blooming microalgae throughout the oceans at all seasons and in all weathers. Such characterization should be combined with measurements of gas exchange and foam production. Algal blooms that somewhat invalidate (i.e. harm) the power of models to predict weather and climate represent a new type of HAB. The harm they do can be mitigated by conceiving and validating climate models incorporating biological modulation of marine foam production and longevity.

Funding

JS is supported by National Nature Science Foundation of China grant (41876134) and the Changjiang Scholar Program of Chinese Ministry of Education.

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