Thickening in HABs and thin layers: The need to bring rheological expertise into research teams

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Abstract
The known and suggested effects of exopolymeric secretions by HABs and other phytoplankton are briefly summarized for the bulk phase of the hydrosphere, for the water-air interface, and for thin layers. An online presentation with videos is presented to provide an intuitive idea of the importance of rheology to deformation and turbulence. Finally future perspectives are reviewed for how to tackle research in phytoplankton-mediated biорheology and its control of both bio- and hydro-dynamics and biogeochemistry. I emphasise the need for bringing rheological expertise into HAB research teams.

1. Introduction
Rheology is the study of materials, particularly those with behaviour between that of fluids and that of solids. Rheology can be investigated in the hydrosphere in:
1. 3D, as in the bulk phase of the water (with its dissolved and suspended inclusions);
2. 2D, as in water-air films, and around bubbles;
3. In 3D in material concentrated from surface films.

The aim of this communication to present a short state of the art of thalassorheology, the rheology of seawater, in the bulk and surface-film phases, particularly as it is transformed by phytoplankton secretions. This thickening of the water can have harmful effects, and must furthermore reduce deformation and turbulence in the water in which the algae live.

3D viscosity in the bulk phase
Having demonstrated increased viscosity and elasticity in algal cultures, I measured viscosity in coastal seawater at a length scale of 0.5 mm and over a range of shear rates $\gamma$ from 0.002 to 0.2 s$^{-1}$ in oligotrophic Mediterranean water, and at 0.002 to 1 s$^{-1}$ in the North Sea in a bloom of *Phaeocystis* and *Noctiluca* (Jenkinson 1986, 1993) The viscosity was shown to consist of a Newtonian (independent of shear rate) component due to water and salt, plus a component due to phytoplankton-produced organic matter that was negatively related to shear rate. The organic matter doubled the total viscosity when $\gamma < 0.002$ s$^{-1}$ in the oligotrophic water and when $\gamma < 0.1$ s$^{-1}$ in the bloom water. In ocean waters, shear rates close to, or less than these values occur frequently, so the organic component of viscosity is far from negligible.

Although exceptions have been found at certain stages of *Phaeocystis* blooms (Seuront et al 2007), as a general rule the organic component of viscosity shows a strong positive relationship with phytoplankton biomass (Jenkinson & Biddanda 1995), supporting the idea that the organic component of viscosity is due mainly to exopolymeric substances (EPS) produced by phytoplankton.

A third factor influencing the organic component of viscosity is length scale (Jenkinson & Wyatt 2008). In sewage sludge, like natural waters a suspension of hierarchically distributed organic aggregates, Spinosa and Lotito (2003) showed data that shows the yield stress is a strong negative function of the length scale of the pipe in which it flows.

As summarised in GEOHAB (2008), the 3D shearing viscosity of the bulk phase of seawater thus depends on:
1. The Newtonian component due to water and salt;
2. The amount and nature of dissolved and colloidal polymers;
3. The shear rate;
4. Length scales in the process of interest.

**Getting the scales right**

In order to study the effect of thickening by algal polymers from harmful algae and algae-rich benthic organic "fluff" ichthyoviscometers have been developed in which the test material flows through the gills of a dead fish. Although the scales in flow through fish gills are difficult to characterise formally, we believe the gill ways of dead fish may imitate those of a live fish, and so get the scales right (Jenkinson & Arzul, 1998, 2002; Jenkinson et al. 2007a,b).

In thin layers, phytoplankton is frequently very concentrated, (Ryan et al. 2008, Velo-Suarez et al. 2008) where it may secrete copious EPS, and increase viscosity (GEOHAB 2008). To study the effect of this increased viscosity on the hydrodynamics in thin layers, studies are needed to measure the viscosity over appropriate scales.

**2D viscosity and elasticity in surface films**

All mariners are aware of the surface slicks frequent on the sea surface (SS) in calm weather. Ćosović (2005) has reviewed the physical and chemical properties SS films within and outside slicks. The films, formed mainly by visco-elastic polymers in exchange with the underlying bulk phase, are derived primarily from phytoplankton EPS. Due to their visco-elastic properties, they damp ripples and gravity waves, and reduce air-sea gas exchange. Their 2D visco-elastic properties have been measured chiefly by imposing compression-dilation (CD) cycles during which change in apparent surface tension is measured. Simultaneous measurement of electric charge in the surface film, gives information about changes in molecular conformation during CD. Maximum horizontal surface pressures are typically ~1-10 mN.m⁻¹, and are related to phytoplankton abundance in the underlying water. Surface viscosity resists CD, producing film relaxation times typically ~1-10 s (Pogorzelski & Kogut 2001), of the order of wave and ripple periods.

Kuhnenn et al. (2006) measured 2D surface-shear viscosity (SSV) in diatom cultures, and found values only up to ~25 μN.m⁻¹ nearly 3 orders of magnitude less than for CD viscosity, even in very high concentrations of the diatom *Nitzschia closterium*, ~2 x 10⁶ cells.mL⁻¹. They also found a “background” SSV value of 1 μN.m⁻¹ in reference seawater, which may have been due to *in situ* organic matter.

In material collected from the surface-film excess bulk-phase viscosity has been found to be 1.5 to 10 times that in the underlying water (Jenkinson & Biddanda 1995), and (in different studies) organic matter 1 to 8 times as concentrated (Ćosović 2005).

Like in the bulk phase, however, authors rarely report results in terms of the length scales or the deformation rates and forces characteristic of their measurements. Because of the heterogeneous distribution of surface organic material at the SS, the importance of doing this may be just as important as in the bulk phase.

**Biorheology hydrodynamics and biodynamics in thin layers**

Phytoplankton, particularly harmful species, often form thin horizontal layers of high concentrations. It is necessary to investigate what roles the resultant EPS has on both the dynamics of thin layers, through biorheology-mediated control of Richardson number and thus layer thickness. To do this it will be necessary to identify the relevant scales at which to carry out rheological measurements (GEOHAB 2008).

**Online presentation**

To get an idea of the importance of rheological modification on water deformation, including turbulence, readers are invited to go online and be guided at http://assoc.orange.fr/acro/hk_2008/.

**Future perspectives**

Few research teams have investigated the deformation around plankton cells and their grazers at scales of μm to mm.

To do this in relation to HAB-related dynamics, rheologists are needed as well as biophysicists, fluid dynamicists, chemists and good microscopists:-

Problems to be addressed include flow, adhesion, gelling, binding of enzymes to glycocalyxes, cell-cell recognition and allelopathy.

HABs are important to hydrosphere rheology research because:-

Many HABs may form slimy water since dense concentrations of cells my allow them to act together to engineer their environment; (Jenkinson
Slimes in HABs may be important as mechanisms of rheotoxicity (clogging of gills, reduction of diffusion away of toxins).

Money can be generated at short time scales (months-years) by using fluidifying agents (e.g. cysteine compounds) to protect aquaculture (Jenkinson & Arzul 2002).

This may help develop more fundamental work to elucidate biorheological control of the environment, and particularly biogeochemical fluxes.

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**References**


