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Original article

A numerical estimate of the plankton-induced sea surface tension effects in a Langmuir circulation

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Abstract

Marine phytoplankton is known to produce surface-active materials as part of its metabolism. The sea surface tension gradient due to the presence of plankton produced surfactants leads to a surface shear stress, commonly known as Marangoni stress, that can be of non-negligible intensity in areas of converging (or diverging) flows, where surface-active material concentrates (or lacks). A natural set-up where this condition can be observed is the Langmuir circulation that establishes in presence of wind and waves and exhibits periodic and permanent areas of alternating convergence and divergence. In the present work we adopt a simplified Large Eddy Simulation model for describing the Langmuir circulation and, by the use of a numerical model previously published, obtain an estimate of the Marangoni stress. The computed Marangoni stress peaks in the converging flow areas to values that are two orders of magnitude higher than in the case of absence of wind burst, previously studied by the authors. Such stress, usually disregarded within the numerical simulations of sea and other basin waters, is in fact capable to modify sensibly the distribution of the ecosystem biological components and should be considered for inclusion in the mathematical modelling.

Keywords: Large Eddy Simulation; Finite volumes; Film pressure; Plankton; Langmuir circulation

1. Introduction

Natural surface-active substances (*surfactants*) are often found in large quantities at the sea surface. Such surfactants are thought to be produced mostly by marine organisms, essentially phytoplankton, which exude them as metabolic by-products [33].

The action of these substances applies on either the plankton individuals surface and the sea surface but, here, we focus our attention only on their effects on the sea surface whose physical and optical properties result sensibly modified. In particular we suppose that the adsorption of surfactants at the surface happens almost instantaneously and is not affected by the flow field at the surface.

Thin organic films, invisible to naked eyes, are ubiquitous in aquatic systems and become concentrated in areas of physical convergence. Under light and moderate wind conditions, in such areas the organic film damps the small waves, it becomes visible as surface slicks and enhances the appearance of sea-surface flow structures in satellite views

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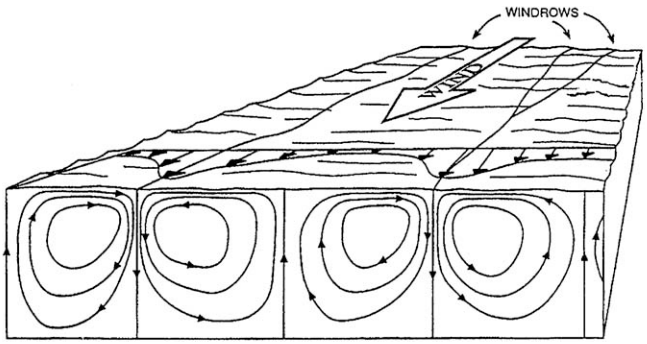

Fig. 1. Diagram tracing water through Langmuir circulation cells.

[27,26,22]. Strong surface tension forces exist in these films and create a boundary layer where sub-surface turbulent mixing is attenuated [1].

There is strong evidence of the importance of surface films in the transfer of mass, heat and momentum across the air–sea interface. It is well known that the presence of surfactants reduces the surface tension at the air/water interface. The resulting surface tension gradient leads to a surface shear stress, commonly known as Marangoni stress, that, via viscosity, influences the bulk flow which is accelerated or retarded, depending on the orientation of such a gradient versus the main driving mechanism [13].

The first approach to numerical modelling of the Marangoni stress induced by plankton-generated surfactants on the sea surface is due to Botte and Mansutti [3], referred to as BM hereafter. Because of the insufficient data on both quantity and chemical composition [24,12,11], they did not try to model directly such surfactants. Instead, they obtained a simplified model of the surface tension reduction caused by surfactant adsorption using the data of surface activity of seawater samples presented by Zutic et al. [33] and Zutic and Legovic [34], practically the only "quantitative" data available in the literature on such phenomenon. In BM several estimates of the Marangoni stress were presented by using satellite data and a theoretical chlorophyll profile at a front, and also by numerical simulation of an artificial basin, where a sharp horizontal variation of surfactants was caused by the converging flows of a thermal bar. The computed values of the Marangoni stress were ranging from $10^{-6}\,\mathrm{N\,m^{-2}}$ to $10^{-5}\,\mathrm{N\,m^{-2}}$, that is, in the areas of higher concentration of surfactants, one order of magnitude lower than inertia and the pressure gradient and then unable to influence significantly the motion in the bulk. The estimates presented by BM were evaluated on relatively large scales, of several hundreds of meters. The doubt remains if the effects of the Marangoni stress should be examined on smaller scales, and in cases with areas of converging flows stronger than in the tests presented by BM. In fact, more significant values of the Marangoni stress will certainly appear in areas of strong convergence at the surface, where sharp variations in the concentration of surface active material are expected.

A notable case of appearance of areas of convergence at the surface of sea (or lakes as well) occurs within the so-called Langmuir circulation that is a feature linked to the interaction of motions due to sufficiently strong wind and surface waves: the down-wind drift, generated by surface shear force exerted by the wind, becomes with the time unstable in the presence of the Stokes' drift, induced by surface waves (Craik and Leibovich [8]). As the result of this instability, the general down-wind flow is re-organized into a set of long horizontal counter-rotating rolls, with their axes approximately parallel to the wind direction (Fig. 1). At the water surface, areas of surface current convergence (so called *windrows*) alternate with areas of surface current divergence (sleek lines). The windrows are oriented with overall surface transport, that is, in general, not necessarily the same as the wind direction. If the wind-driven flow and the Stokes drift are by some reason not parallel to each other (e.g. in the presence of bottom, lateral boundaries or gradient flows of another origin), then the windrows may drift, twist and significantly (up to 20°) deviate from the wind direction (Cox [7]; Chubarenko et al. [5]). Floating material accumulates in the windrows due to the surface flow convergence; we expect an accumulation of surface active material there as well, and, then, a significant value of the Marangoni stress. The typical distance between two windrows is about 10–50 m and the whole motion develops within upper water layer (units to tens of meters, depending pre-existing stratification and energy supplied by the wind action). Typical wind speed that allows the formation of well-detectable windrows averages between $3\,\mathrm{m\,s^{-1}}$ and $24.4\,\mathrm{m\,s^{-1}}$;