Satellite detection of natural films on the ocean surface

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Abstract. Natural films on the ocean surface influence air–sea fluxes of momentum, heat and gas. It is therefore essential to be able to map the geographical extent and variability of such films to determine the resulting impact on the earth's climate system. Satellite based Synthetic Aperture Radar (SAR) may prove very useful, and perhaps the only way, to quantify global scale film distribution. In order to investigate the composition of natural film and its effect on radar return, in situ samples of the surface microlayer were for the first time taken simultaneously with ERS–1 SAR coverage of the sea. Our results show that the film was enriched in organic composition and that the concentration of fatty acids was generally one order of magnitude higher inside than outside natural film areas, resulting in a 6–17 dB decrease in radar backscatter.

Introduction

The composition of natural films on the sea surface varies, but substances such as proteins, lipids, organic acids, saccharides, and metals associated with the organic matter, are usually present at higher concentrations than in the corresponding bulk water [*Duce et al.*, 1994]. Several air–sea interaction processes may be affected by the presence of films caused by natural biological material, oil spills and other pollutants. Both a dynamic effect altering the hydrodynamical flow and a static effect caused by the film acting as a physical barrier, may be important for air–sea exchange of atmospheric gases, e.g. for the ocean uptake of CO_2. It has been found that natural films exert a first–order effect on gas exchange at low to moderate wind speeds, and the mechanisms responsible may be closely related to those involved in damping of capillary and short gravity waves which are sensed by radars [*Frew*, 1996; *Bock et al.*, 1995; *Frew et al.*, 1990]. Asher [1996] has estimated the impact on global air–sea CO_2 exchange for various hypothetical slick coverages. His model shows that, depending on wind speed and regional film coverage, slicks can increase or decrease the net global oceanic CO_2 flux. However, whether natural sea surface films really are extensive and effective enough to be an important factor in global change studies remains uncertain because film quantification has not been done [*Duce et al.*, 1994]. Efficient ways to quantify the geographical extent and variability of these films are therefore required. Radar satellites provide a very wide coverage and easy access to remote areas of the ocean. Due to

its high spatial resolution (25 m), spaceborne SAR may contribute significantly in mapping natural films.

Previous studies have shown that several phenomena may dampen out the capillary and short gravity waves which are sensed via Bragg scattering (7.3 cm surface waves using ERS–1 C–band SAR), and hence cause a low radar backscatter signal [*Hovland-Espedal et al.*, 1994]. These features appear as dark areas in the SAR imagery and are generally called slicks. No other satellite sensors are able to detect slicks at such high spatial resolution in the presence of clouds. Slicks may be caused by low wind speed (less than 2–3m/s), oil spills, grease ice (Fig. 1 a, b and c), drilling fluid from oil platforms, wind sheltering, rain cells, current wakes, internal waves, and current shear zones [*Hovland-Espedal et al.*, 1994]. Some slicks in the SAR images have also been hypothesised to be caused by natural film [*Hovland-Espedal et al.*, 1994; *Johannessen et al.*, 1993], but no in situ data have been obtained simultaneously. So far, only artificial monomolecular films [*Alpers et al.*, 1991] and oil slicks [*Wismann*, 1993; *Wahl et al.*, 1996] have been sampled in experiments with ERS–1 SAR. To be able to use SAR in global scale film quantification, we first need to verify that some dark patches in the imagery can be related to increased biological activity (i.e. to natural film). This is the objective of our work reported here.

Natural Film

Surface film is usually found in near–coastal regions due to terrestrial sources [*Garabetian et al.*, 1993], and in waters with high biological production rates [*Zutic et al.*, 1981] where upwelling and re–suspension of sediments and material from sediment pore water bring nutrients to the euphotic zone. Downwelling may also cause increased local concentration of film due to flow conversion. Terrestrial plant materials are introduced to the surface of the sea either by deposition from the atmosphere (particulate matter) or by riverine transport in the form of vegetative decay products [*Duce et al.*, 1994]. Anthropogenic inputs of materials to the surface microlayer [*Knulst and Sodergren*, 1994] include point sources, such as coastal industrial activity, agricultural run–off, and spills of mineral oil products from coasts or vessels. The relative importance of these sources is not known [*Duce et al.*, 1994]. Although the lipids do not represent the majority of surface film components, they consist of molecules with long tails of atoms ($\sim Å$) sticking out of the water, and hence have high surface active properties [*Hunter and Liss*, 1981]. Their low water solubility and high intermolecular attraction result in a high surface viscosity and thus a high wave

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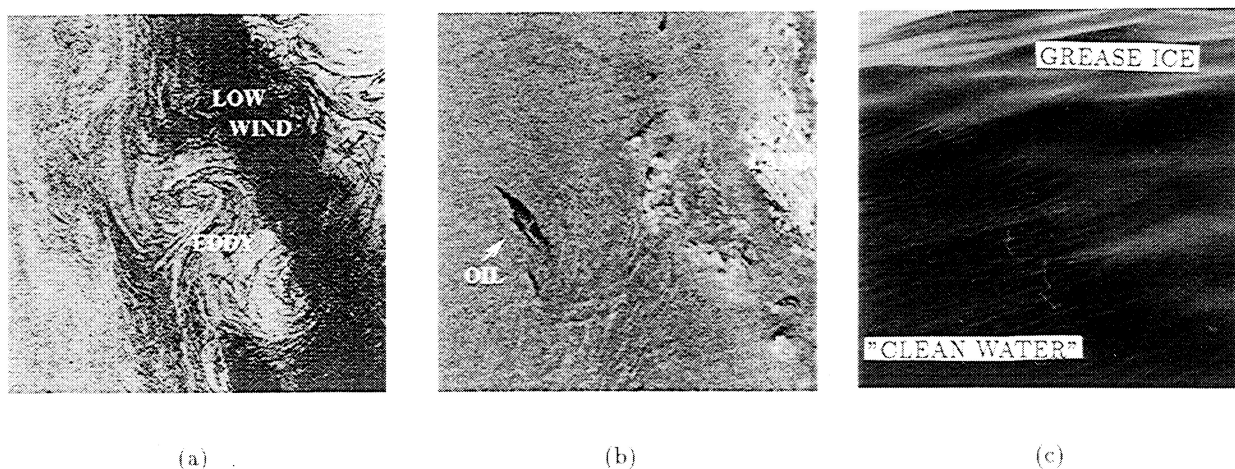
(a)　　　　　　　　　　　(b)　　　　　　　　　　　(c)

Figure 1. Examples of slicks of various origins. (a) ERS–1 SAR image of a low wind speed area and an eddy (100 × 100 km scene), (b) ERS–1 SAR image of a confirmed oil spill (25 × 25 km scene), and (c) a photograph of grease ice. The photograph illustrates how the short waves are damped in the region with grease ice, only the longer waves remain.

damping effect. Fatty acids (FA), the most abundant lipids in a natural system, are therefore chosen as the target chemical compounds in this study.

The Experiment

The purpose of our experiment was to collect surface film material simultaneously with ERS–1 SAR data, perform chemical analysis to identify the main constituents of natural films and study how SAR can be used in global scale ocean surfactant quantification. A remotely controlled model boat (length 1.2 m) fitted with a rotating hydrophilic teflon drum (Fig. 2) was used to sample the surface microlayer simultaneously with ERS–1 SAR image acquisition on 29 September 1994 in Korsfjord south–west of Bergen, (Fig. 3). The SAR image was processed at Tromsø Satellite Station


Figure 2. The slick sampler collecting sample 5–i. The photograph was taken soutward at about 4h30min after satellite overpass, with a wind speed of 2–3 ms^{-1}. Both wind and currents came from the north, extending the slick in the north–south direction compared to the situation in the SAR image (Fig. 3). The edges of the slick are clearly delineated along the center of the photograph.

(TSS), and the low resolution (pixel size 100 m) version was sent via Internet to NERSC where it was interpreted (the high–resolution image, pixel size 20 m × 16 m, arrived on Exabyte tape 2 days later). At 12.50 UTC the coordinates of several dark slicks and reference areas were communicated to the field team. A GPS (Global Positioning System) was used to navigate to the nearest slicks. Samples were taken both from areas which appeared dark in the SAR image, implying presence of slick, and in brighter, non–slick areas (suffixed -i and -o, respectively). To identify the characteristic chemical composition of the surface microlayer, sub–surface water samples were taken at about 50 cm depth for comparison. Wind, current and temperature information was obtained from an Aanderaa buoy in the experiment area. The wind was also measured with an anemometer (at approx. 3 meters height) both inside and outside slick areas to exclude low local winds as an explanation for the low backscatter regions (Table 1).

In the morning, the weather was ideal for slick detection by SAR (2–6 m/s wind), and as much as 10 % of the fjord shown in the image was covered with slicks. Near Sotra island (Fig. 3), a large elongated slick was stretched out by the current flowing southward out of the fjord. Samples 1 and 2 were obtained before the SAR image was available, using only visible slick appearances. Unfortunately the wind speed increased to about 6 m/s at about 13.00 UTC, and obtaining the necessary samples at location 3 was complicated. At such wind speeds, the rotating drum is no longer continuously in contact with the surface. However, a small sample was obtained, and visual slicking was observed (less whitecapping). Samples 4 and 5 were more easily gathered in a sheltered area located due south of Korsnes (wind from the north). Of the slicks sampled, 3–i and 5–i were seen to align in a more north–south direction by the time sampling began.

SAR Image Analysis

The wave damping caused by the slicks was reflected in the much lower backscatter of these areas compared to slick-free areas in the SAR image (Fig. 3). Backscat-
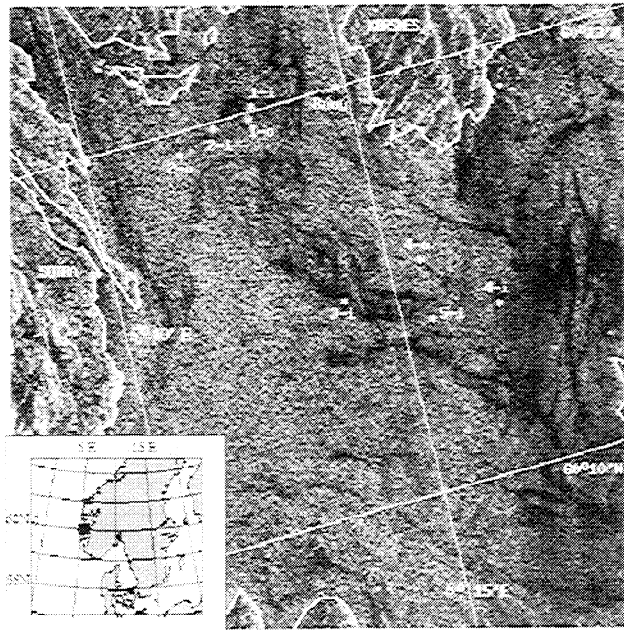
Original Data © ESA/TSS, Image Analysis NERSC

Figure 3. The part of a high resolution SAR image from 29 September 1994 (10.50 UTC) south of Bergen showing the experimental area, (the box on the map indicates the location of the SAR scene).

ter decreases were found to vary between 6 dB and 17 dB (Table 1). These values are typical for both natural films and the previously mentioned look-alikes [*Hovland-Espedal et al.*, 1994]. The shape of the slicks excludes internal waves (parallel dark bands with horizontal spacing of a few hundred meters) as an explanation [*Ouchi*, 1993]. Measurements taken from the

vessel which launched the model boat, showed that the wind conditions were fairly homogeneous both in slick and non–slick areas (Table 1), hence the lack of Bragg waves in the dark patches of the SAR image could not be explained by low local winds. Weather information also excluded rain cells. Thus, chemical analysis would prove if the slicks were caused by natural films or oil spills.

The Chemical Analysis

The chemical analysis indicates an enrichment of organic constituents and generally a higher concentration of total aliphatic hydrocarbons (ALK) in the surface microlayer when film was present, compared to the corresponding sub–surface water (Table 1). Concentrations in the surface microlayer and sub–surface water from different locations varied greatly. The individual fatty acids (FA) making up the surface microlayer were not the same as in sub–surface water, and varied between the different surface microlayer samples. In this study, none of the surface microlayer samples appeared heavily impacted by mineral oil products even though the fjord in which they were collected carried considerable ship traffic. The n–alkanes are known to sometimes associate themselves with FA [*Marty and Saliot*, 1976], but no evidence of a trend was seen in this study. The most abundant FA were C14 (tetradecanoic acid) and C16:0 (hexadecanoic acid). The concentrations of FA inside the investigated slicked areas were generally one order of magnitude higher than in those outside the slicked sites, except in area 4 (SumFA, Table 1). There, the non–slicked area was more enriched in both ALK and total FA than the slicked area. The acidity (pH) and ultraviolet (UV)–absorption values for the sub–surface water and surface microlayer at this site indicate that the 4–o surface microlayer is possibly of high humic substance type with a greater portion of coarse particulate

Table 1. Surface excess concentrations (SE) of total n–alkanes (ALK, C2–C26) and fatty acids (FA) C12–C18, ERS–1 SAR backscatter values (σ_0), the relative damping, $\sigma_0^{slick-free} - \sigma_0^{slick}$ (for cases 3–i and 5–i, site 4–o is used as a slick–free reference area) and the locally measured wind speed (WS).

Site:	ALK ($\mu g/l * \mu m$)	SumFA ($\mu g/l * \mu m$)	ALK/SumFA	σ_0 (dB)	Damping (dB)	WS (ms^{-1})
b-i	1257	142	8.85	−8.5		2.0
1-o	−1836	3823	−0.48	−8.9		2.5
1-i	6329	25691	0.24	−14.9	6.0	2.5
2-o	749	265	2.83	−8.8		3.0
2-i	267	1501	0.18	−19.7	10.9	3.0
3-i	0	1524	0.00	−18.7	11.0	5.5
4-o	1706	865	1.97	−7.7		2.0
4-i	−300	−180	1.67	−24.6	16.9	5.0
5-i	−49	2317	−0.02	−14.8	7.1	2.5

The surface excess concentrations are given by SE = $(c_\mu - c_b) \times d$, where c_μ is the concentration of a substance in the surface microlayer, c_b is the concentration of the same substance in the sub–surface water, and d is the thickness of the sampled film [*Hunter and Liss*, 1981]. The quantity d is calculated by dividing the sampled volume by the area sampled (the area of the drum times the number of rotations for one sample). SE were greatest for all components at site 1-i, smallest at site 4-i. Sample 5-i was not enriched in ALK, 4-i and 1-o were depleted, and the other sites had enrichment of ALK in the surface microlayer. Concentrations of dodecanoic acid (C12) are low in all surface microlayer and sub–surface water, as are the octadecadienoic acid (C18:2). All other FA were found at concentrations well above the detection threshold. The most abundant FA was hexadecanoic acid (C16:0), both in surface microlayer and sub–surface water. High concentrations of tetradecanoic acid (C14) in samples 1-i and 2-i indicate a different source to these slicks compared to the others, most likely of autochtonous exudates. Samples 2-o and 4-o are characteristic for those with a greater proportion of terrestrial influence, indicated mostly by the proportionally high presence of octadecanoic acid (C18:0).

material than the other sites. Except for 1–o which was possibly slightly contaminated by mineral oil products (the ALK/FA ratio was negative), all of the samples were found to be of natural origin.

Discussion

The results presented above confirm that a relationship does exist between sea surface chemistry and SAR backscatter values. The best agreement was found between backscatter and ALK/SumFA ratio (in Table 1). However, not only the relationship between ALK and FA is important. A relation was also found between concentration of organic acids and portion of particulate matter (turbidity), and backscatter.

The wide range of backscatter values found for the natural films, indicate another important problem in slick quantification. For example large areas of less concentrated films may cause less damping, and thus appear in the SAR imagery as dark grey areas [Nilsson and Tildesley, 1995], and not as distinct slicks.

At present, slick discrimination includes a direct analysis where relevant data is extracted from the slick in the SAR image (shape, size, dB–values, texture and gradients of the slick), and a contextual analysis where auxiliary data (meteorological data, currents, bathymetry, oil platform and ship lane information), is used. For example, a slick that remains connected at wind speeds above 7-8 m/s cannot be caused by natural film, because these films disperse at such winds [Scott, 1986].

Conclusions

We have for the first time shown that there exists a chemical difference between slicked and non–slicked areas corresponding to respectively dark and brighter areas in the ERS-1 SAR image. The concentration of FA was generally one order of magnitude larger inside than outside the slicks damping the short (~cm) waves. We were able to identify C14 (tetradecanoic acid) and C16:0 (hexadecanoic acid) as the most abundant FA in the investigated slicks. However, the composition of each sampled surface varied, indicating that both the non–slicked sea surface and the natural films are of a very patchy chemical nature. Generally, the slicks caused a 6–17 dB decrease in radar backscatter. To discriminate natural films from look-alikes in SAR imagery, auxiliary data are needed. An slick discrimination algorithm, including analysis of shape, size, texture, gradients and dB–values of the slick, meteorological data, currents, bathymetry, platform and ship lane locations, is under development. However, our results indicate that the use of spaceborne SAR may provide an opportunity to monitor and estimate the distribution of natural sea surface film. This is extremely important when assessing their impact on the global scale climate system.

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