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Suppressing breakers with polar oil films: Using an epic sea rescue to model wave energy budgets

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Key Points:
- An 1883 sea rescue that used oil to reduce breakers provides the basis for a wave energy model
- We model responses to reduced wind energy input; results consistent with the rescue suggest that this reduced input suppressed breakers
- A possible cause of this reduced energy input is modified surface roughness that alters energy flow

Supporting Information:
- Supporting Information S1

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Abstract Oil has been used to still stormy seas for centuries, but the mechanisms are poorly understood. Here we examine the processes by using quantitative information from a remarkable 1883 sea rescue where oil was used to reduce large breakers during a storm. Modeling of the oil film's extent and waves under the film suggests that large breakers were suppressed by a reduction of wind energy input. Modification of surface roughness by the film is hypothesized to alter the wind profile above the sea and the energy flow. The results are central to understanding air-sea momentum exchange, including its role in such processes as cyclone growth and storm surge, although they address only one aspect of the complex problem of wind interaction with the ocean surface.

1. Introduction

Oil has been known since antiquity to still angry seas, but how it does so remains mysterious. In the 1880s the U.S. Hydrographic Office collected information on use of oil by mariners to reduce breakers. These data were published on pilot charts and in books [*Beehler*, 1888; *Dyer,* 1886]. Unfortunately, much of this information does not provide convincing evidence because there is no way to judge the reported reduction of breakers.

In the past, many assumed that oil acted mechanically on the sharp crests of waves to prevent breaker formation. This viewpoint was expressed by an educated seaman, the commander of the French naval vessel *Naiade* [*de Cuverville*, 1893]: "It appears that the oil takes effect on the breakers due to horizontal translation produced by the wind, leaving the orbital motion or swell unaffected." Because such motions cannot affect major storm breakers, some fluid dynamicists concluded that "oil stilling the angry sea" is illusory. Indeed, many reported suppressions by oil probably represent wishful thinking. There are no modern observations of the effect of oil films on storm waves. However, an inadvertent experiment was carried out by a courageous ship's crew while making a rescue in 1883, thanks to careful record keeping by the ship's master. The incident provides unique observations of wave conditions made under challenging conditions inside and outside of oil films and involved dispersion of two types of oil.

Here we use these data to guide modeling of ocean surface waves under these conditions, supporting the hypothesis that presence of a polar oil film arrests wave breaking by reducing energy flux into ocean waves. Decades of experimental work show that the sea surface drag coefficient depends on surface conditions, expressed as wave-age-, wind-speed-, or wave age and sea-state-dependent parameterizations [*Edson et al.,* 2013]. By inference, wind energy-scaled momentum flux is also dependent on surface conditions. The incident record suggests that oil films, which are known to damp the shortest waves present [*Hühnerfuss et al.,* 1984], can influence the airflow in a way that quenches growth of the dangerous longer waves and quells breakers. This provides a glimpse into air-sea interactions under conditions (parameter regimes) not encountered in ocean field work.

2. Existing Explanations of Oil/Water Dynamics

Several researchers have considered dynamical explanations of the mechanical influence of oil on water [*Reynolds,* 1880; *Aitken*, 1883; *Lamb,* 1932; *Cini and Lombardini,* 1978; *Cini et al.,* 1985; *Alpers and Hühnerfuss,* 1989]. *Lamb* [1932] remarks that if the action of oil is to make the water surface inextensible, the amplitude of short waves suffers viscous dissipation with a time scale of

$$(2/k)[2/(\nu\omega)]^{1/2}.$$

Here k and ω are the wave number and frequency of the waves and v is the kinematic viscosity of water. Only very short waves are affected. More recently, in an artificial oil slick in the North Sea, indirect effects of the film caused dampening of waves with frequencies between 0.12 and 0.7 Hz [*Hühnerfuss et al.,* 1981]. *Lange and Hühnerfuss* [1984] showed that horizontal surface tension gradients in an oil film are "instrumental in wave damping processes" for waves with a wavelength of about 150 cm in a laboratory wave channel. Subsequent laboratory work showed that this wave dampening effect is dependent on details of the chemical structure of the oil molecules [*Gade et al.*, 1998] and occurs at specific frequencies [*Cini et al.,* 1985; *Hühnerfuss et al.,* 1984]. *Alpers and Hühnerfuss* [1989], in a review of both lab and field studies, show that resonant coupling between Marangoni waves (lateral oscillations created by surface tension) and gravity waves, as well as among gravity waves, can extend viscous dissipation to longer wavelengths and intensify it. They surmise that nonlinear energy transfers from still-longer waves into a dissipative spectral sink at wavelengths of 3 to 20 cm will also diminish longer gravity waves. However, energy input into waves of 20–100 m wavelengths in storms is so large (see supporting information) that this mechanism cannot appreciably influence the waves that contribute maximally to breakers. Our interpretation is that suppression of storm breakers is not a direct mechanical response of the sea surface to an oil film but rather that smoothing of small-scale surface roughness causes a major change in the structure of the wind profile over the sea (within the boundary layer) such that energy input to gravity waves up to 150 m wavelength is substantially reduced.

3. A Historical Incident Provides the Basis for Understanding Wave Dynamics

We have found data that allow modeling of these processes in a single episode recorded by the Hydrographic Office, the saving of the crew of a sinking vessel by the ship *Martha Cobb* under storm conditions in 1883 [*Beehler*, 1888]. Storm breakers were annulled in a limited area using oil for (our estimate) an hour, while breakers remained outside the area. Although this rescue is wrongly dated in Beehler's text, we assume that the direct quotations from Thomas Greenbank, master of the *Martha Cobb,* are factually correct. We have described this episode previously [*Cox and Zhang*, 2013; *Cox*, 2015].

The *Martha Cobb* came upon the sinking *Grecian* in a raging storm at daybreak on 15 November 1883. There appeared to be no way to transport crew from the *Grecian* since deck boats on both vessels had been destroyed by breakers. A 5 m dinghy survived on the *Martha Cobb*, but Greenbank considered it incapable of surviving the breaking seas. He stood by, hoping for improvement. *Cox* [2015] includes a photograph that provides a visual impression of the conditions.

With dusk arriving and no signs of better weather, Greenbank decided to attempt to save the *Grecian* crew. Some of the petroleum cargo of the *Martha Cobb* had leaked into the bilges. Greenbank's crew pumped this petroleum, which smoothed the sea but failed to stop the breakers. Greenbank then hauled up close to the *Grecian*, hove to, and started the pumps again. He also dumped 19 L of fish oil in the scuppers of the *Martha Cobb* which dribbled into the sea. Greenbank recorded the result as "magical" after what he states was a 20 min delay. The breakers disappeared around both vessels, and the dinghy was successfully launched. Two seamen and the second mate rowed the dinghy upwind against the gale and over the mountainous waves. The entire crew of the *Grecian* (10 men) was ferried back to the *Martha Cobb*, three or four at a time [*Cox*, 2015]. In Greenbank's words, "The boat was deeply loaded and did not ship any water, although the sea was breaking fiercely outside the 'charmed' space in which the vessels lay on oiled seas." [*Beehler*, 1888] The evidence is unambiguous: No breakers in the slicked area around the vessels while storm breakers remained visible beyond.

4. A Model of the *Martha Cobb* Observations

With current knowledge, we can construct a wave model consistent with Greenbank's observations to partly understand the magical effect of the fish oil. First the film patch is modeled, and then waves in the patch. When large amounts of oil are poured on water, spreading is initially driven by buoyancy, but after the oil forms a thin film, it continues to move despite viscous drag of underlying water if the spreading tension

$$S = \sigma_{13} - (\sigma_{12} + \sigma_{23})$$

is positive. Here σ_{ij} is surface tension with subscripts 1, 2, and 3 referring to water, oil, and air, respectively. One end of fish and vegetable oil molecules is strongly attracted to water. The other end is a triplet of hydrocarbons with no love for water. Such polar oils have a large spreading tension and expand rapidly to monomolecular thickness. The monolayer consists of oil molecules packed together with the hydrocarbons upwards. *Foda and Cox* [1980] describe the one-dimensional spreading rate of polar films; the spreading tension of fish oil is roughly 30 m N/m. Consequently the radial spreading over a period of 2 s is expected to be 0.28 m. This may be sufficient to repair small tears in the oil film following fragmentation by wave action. *Phillips* [1997] showed, with some assumptions, that the spreading of polar oils, over still water, from an unlimited continuous point source extends to a radius of

$$r = 1.08\left[S/\left(\rho \ \nu^{1/2}\right)\right]^{1/2} t^{3/4},$$

where ρ and ν are the water density and kinematic viscosity, respectively, and t is time since commencement of flow. The area covered therefore increases with $t^{3/2}$.

Pure hydrocarbons have a negative spreading tension, remain as lens-like clumps on the water, and are less effective at stilling breakers than animal and vegetable oils [*Beehler*, 1888; *Wyckoff*, 1886]. When polar oils are mixed with hydrocarbons, the polar oils form rims around the hydrocarbon lenses, so that spreading continues as long as enough polar molecules remain stuck to the water surface [*Camp and Berg*, 1987].

In 20 min such spreading will cover roughly 3600 m^2 on still water, from a 5 gallon (19 L) localized source of polar oil if $S = 30$ m N/m, and there are no losses. The petroleum pumped is not included in this estimate. *Tanford* [2004], analyzing the olive oil slick created by Benjamin Franklin on Chatham Pond [*Franklin*, 1774], concludes that the film expanded to one monolayer thickness, with essentially no losses on this windy pond. Under windier conditions the calculated thickness of the film is greater. *Korinenko and Malinovsky* [2014] observed that 340 mL of vegetable oil spread to 12,000 m^2 on the Black Sea in 20 min when exposed to winds at 11 m/s, after which the slick disappeared. The average thickness at maximum expansion was about 15 monolayers if there were no losses. *Cox and Munk* [1954a, 1954b], using mixed fish oil, used crank case oil (which has some polar properties), and diesel oil, were able to form unbroken slicks of about 1 km^2 for periods of about an hour in winds up to 9.8 m/s near Maui and Molokai Islands. *Hühnerfuss and Garrett* [1981] remark that amounts corresponding to 10 monolayers are needed to maintain slicks of approximately 1 km^2 in near shore waters under light to moderate wind conditions. The duration of these slicks is not stated.

When the supply of oil is interrupted, the leading edge of a spreading monolayer evaporates into a two-dimensional gas of separated oil molecules stuck to the water that no longer has the ability to attenuate short waves.

Breakers will break the film created by surface tension flow. If the broken film remains sufficiently thick after the break has subsided, tension-driven flow will restart at all edges of the break so that film coverage increases. On the other hand, breakers will enhance losses of oil to bubbles, spray, and subsurface downflow.

The 20 min delay reported by Greenbank before breakers ceased is crucial information. It is certainly an estimate made under trying circumstances or recollected after a delay.

When hove-to, sailing ships drift rapidly because of the high wind drag of their masts, rigging, sails, bulwarks, and deckhouses. If the areas of ship exposed to the wind were 3 to 5 times the underwater areas exposed to water drag, and the drag coefficients were the same, the vessels drifted at a rate of 4% to 8% of the wind speed. During the 20 min delay following the dumping of fish oil, both vessels probably drifted 1 to 1.5 km downwind if the wind speed was 20 m/s or more.

The midpoint of the initially discharged fish oil, also exposed to wind drag, would have drifted at 2.5% to 4% of the wind speed, based on our recent observations of an experimental oil slick we created off the California coast during wind speeds of 9.5–11.5 m/s (see supporting information) and laboratory measurements [*Zhang and Harrison*, 2004].

Because of surface straining by turbulence, wave-induced diffusion, and disruption by breakers, it is probable that the oil film diffused rapidly in all directions and some was carried below the surface. Broken patches of oil slick would often be rejoined by the spreading tendency of fish oil, and the fragmented slick would spread out in 20 min over a broad, fan-shaped area in a 1 to 3 km region to windward of the vessels, with the apex at the vessels. We estimate that the time required to rescue the *Grecian*'s crew with the rowboat was at least 40 min.

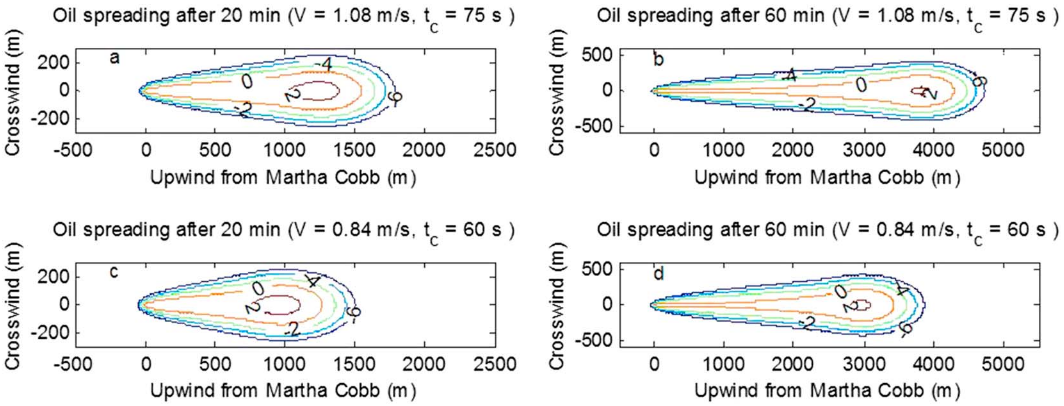

Figure 1. Smoothed distributions of fish oil thickness, (left column) 20 min and (right column) 60 min after oil discharge commenced. Contours show $\log_{10}$ of thickness in monolayers (1.6 nm). Vessel position is at the downwind (Figure 1, left column) edge of the contours (0,0), and the oil discharge location is to the right of the contours. Both oil and vessels have drifted downwind (moved to the left) at speeds of V_{oil} and V_{ship}, respectively. The actual oil distribution was irregular because of currents, waves, and breakers. The figure shows average patches, from which actual patch realizations would deviate. Ships drift at V ($V_{\mathrm{ship}} - V_{\mathrm{oil}}$) = 1.08 m/s relative to (top row) surface water and (bottom row) at a slower speed (assuming less wind drift). The constant t_c that determines the rate that oil drains is 75 s in Figure 1 (top row) and 60 s in Figure 1 (bottom row). The general pattern of oil spreading is similar regardless of which values are selected.

After the 1 h interval we model the slicked area to extend 3 to 6 km windward of the vessels, as follows. The preliminary results of the LatMix Experiment [*Shcherbina*, 2015] indicate that diffusivity at the sea surface in mild weather is approximately 1 m^2/s on spatial scales of 100 m in the Sargasso Sea. In stormy seas, increased surface turbulence and wave driven diffusivities [*Hasselmann,* 1962; *Leibovich*, 1983; *Langmuir*, 1938; *Melville*, 1996; *Melville and Matusov*, 2002] will increase diffusivity. Figure 1 illustrates the smoothed distribution of the fish oil fraction of film thickness calculated on the assumption that effective diffusivity was anisotropic with up-down-wind diffusivity of 2.8 m^2/s and crosswind diffusivity of 0.7 m^2/s. We assume that the fish oil drained into the sea at a declining rate proportional to $(1 + t/t_c)^{-2}$ where t is time since draining started and t_c is 75 s. The initial rate was 253 mL/s; after 20 min it was 0.88 mL/s. We chose this rate because higher rates led to rapid emptying of the oil container resulting in no oil film in front of the ship. We also assume the vessels drifted downwind at 1.08 m/s relative to the midpoint of initial oil deposition and make no allowance for losses of oil because we believe that these were small during the short time of the rescue.

Breaking of large combers in storms occurs where superposition of waves with wavelengths between 20 and 150 m creates a local wave crest of unsustainable slope with downward acceleration exceeding 0.5 g [*Longuet-Higgins*, 1969; *Babanin*, 2011]. Small-scale whitecaps stem from short waves [*Plant*, 1982], but large storm breakers require superposition. Wave energy in this “equilibrium range” of the storm spectrum can diminish rapidly if input of energy from wind stops. At these wavelengths wind energy input is normally balanced by dissipation from breaking, turbulence damping, and nonlinear transfers. If input stops, the initial rate of decay is simply the preceding input rate. The input rate in clean water is high in storm conditions; so if input stops, the initial rate of decay is rapid. If waves are sufficiently reduced in size, no breakers will form.

Initial decay rates and decay distances of waves under the assumed 24 m/s wind speed can be calculated from growth rates for waves moving in the wind direction [*Plant*, 1982; *Snyder et al.,* 1981; *Yan*, 1987]. These authors suggest that the angular variation of energy input follows $\cos(\theta)$ where θ is the angle of propagation relative to the wind and that growth vanishes for $|\theta| > 90°$. (*Yan* [1987] has a cutoff just short of 90°.) Consequently, waves moving at large angles to the wind direction were little affected by growth cessation, as they traveled only a short distance through the slick before reaching the vessels and their initial decay rate was small. However, those waves have less energy, and the waves traveling along the long axis of the slick must have been considerably attenuated, so that superposition of the full wave bandwidth remained weakened and avoided breaking. Waves well outside the fan-shaped area would continue to break. These breakers would be visible from the hove-to vessels in directions normal to the wind, as described by Capt Greenbank. In the equilibrium range of wavelengths, wave energy loss is primarily through breaking. If wave

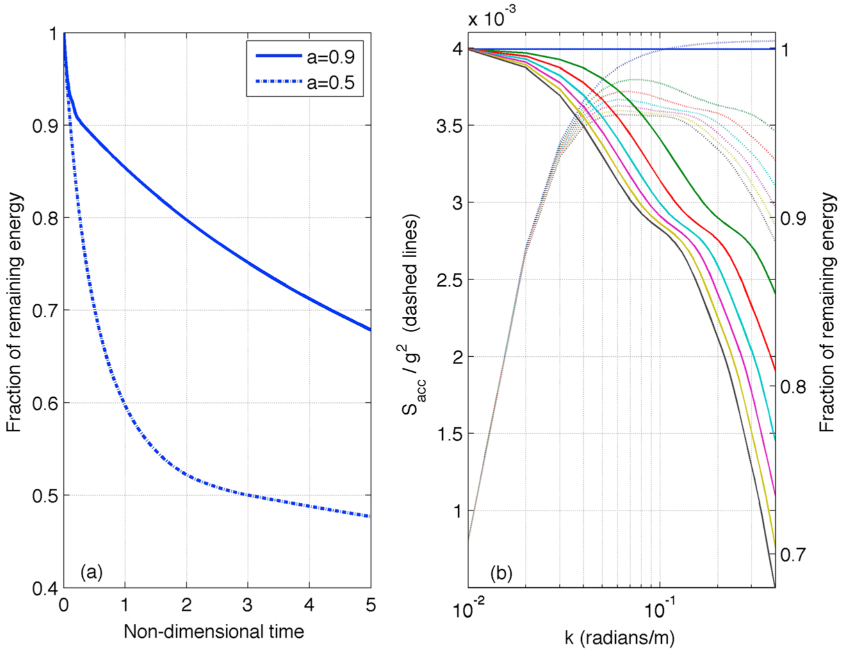

Figure 2. (left) Fraction of remaining wave energy as a function of nondimensional time, $e'(t')$. Here $a = 0.9$ (solid line) or 0.5 (dotted line) and $b = 0.1$ for a specific wave number or wavelength. (The model is weakly sensitive to b.) The solid line represents a lower bound for energy dissipation; the values are conservative estimates that are consistent with Greenbank's observations. (right) Reduction of wave acceleration spectrum (dotted lines), and fraction of remaining wave energy (solid lines), after deposition of oil, assuming wind energy to all wave numbers k ceases during propagation of these waves through the expanding slick and $a = 0.9$. The initial wave dissipation rate used here, $\tau_0 = 1/B_0(1 + b)$, equals the wave energy growth rate [*Yan*, 1987]). The original acceleration spectrum (blue dotted line) is the Pierson-Moskowitz spectrum for $U_{10} = 24$ m/s. S_{acc} are normalized by g^{-2} and are plotted in variance preserving form. Values at 5 min intervals after oil spreading (from 0 to 30 min) are blue, green, red, cyan, magenta, yellow, and black, respectively.

energy input ceases, the initial rapid energy decay rate will decrease as breakers cease. We model this process assuming that the energy losses in breakers are local in wave number space, discounting the contribution to effective acceleration of wave crests from higher wave number components. Suppose decay is mainly through energy dissipation in breaking and that breakers within this band remove energy from this band only. Our parameterization of energy losses by breakers is similar to equation (2) of *Babanin and van den Westhuysen* [2008], with $m = 2$. Beginning when wind input ceases, $t = 0$,

$$\mathrm{d}e/\mathrm{d}t = -B_\mathrm{r}\,e - B_\mathrm{t}\,e,$$

where e is the energy in the band, B_r is the relative decay rate due to breakers, and B_t is the decay rate of all other processes. B_r diminishes as breaker frequency diminishes and will cease when $e < a\,e_0$, with e_0 being the initial energy. We make the conservative assumption that a is about 0.9 and also assume that the energy loss rate has a linear relation to the excess of e over ae_0:

$$B_\mathrm{r} = B_0[(e/e_0 - a)/(1 - a)], \text{ or zero if } e < a\ e_0.$$

B_0 is the time scaling factor calibrated to wave growth rate [*Yan*, 1987]. B_t is taken as proportional to e^2 for simplicity. This implies that energy loss is mainly through energy transfers of wave-wave nonlinear interactions after breakers diminish,

$$B_\mathrm{t} = b\ B_0(e/e_0)^2.$$

The introduced parameter b is much less than 1, as wave breaking is the main dissipation source. In nondimensional form where $e' = e/e_0$, and $t' = B_0\,t$, this becomes (dropping primes),

$$\mathrm{d}e/\mathrm{d}t = -\{[(e - a)/(1 - a)] + b\ e^2\}e \text{ if } e > a, \text{ or } \mathrm{d}e/\mathrm{d}t = -b\ e^3, \text{ if } e <= a.$$

Figure 2 (left column) shows energy versus time for one set of parameters.

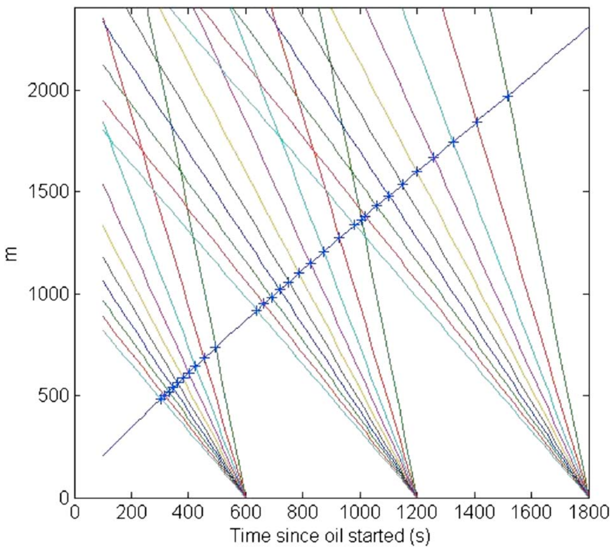

Figure 3. Hodograph illustrating waves moving downwind in an oil slick. The graph shows waves with 10 different wave numbers k (1/m), each in a unique color and equally spaced from 0.04 to 0.40 m^{-1}. The associated wavelengths λ vary from 157 to 15 m, the periods T from 10.03 to 3.17 s. Waves enter the oil patch at locations marked by “x” and travel at their group velocities relative to deep water $1/2(g/k)^{1/2}$, but $1/2(g/k)^{1/2}$- V_{oil} relative to the oil. After the slick has spread for 1800 s, the time duration of waves traversing the oil slick varies from 249 to 685 s.

We now consider the time interval during which waves are traveling through the oil film. We assume that the effective upwind edge of the oil film occurs where the average thickness is one monolayer (contour zero, Figure 1). The increasing distance from the vessels with increasing time is shown by the line of positive slope in Figure 3. The lines with negative slope illustrate the time durations that waves of selected wave numbers travel in the slick before arriving at the vessels.

One mechanical aspect controlling formation of breakers is downward acceleration of the wave crest, which on average is proportional to the acceleration spectrum. In the Pierson-Moskowitz spectrum of fully developed waves, the acceleration spectrum (defined as the conventional frequency spectrum multiplied by the frequency raised to the fourth power) is

$$S_{\mathrm{acc}}(k) = (\alpha/(2k))g^2\exp\left[-\beta(k_0/k)^2\right],$$

where α is the P-M constant 0.801×10^{-3}, β depends on the height at which wind is measured, g is gravitational acceleration, and k_0 is the wave number of waves with phase speed equal to the wind speed. Figure 2 (right) shows the spectral reduction via negative de/dt as waves move through the modeled slick.

5. Wave Growth Cessation by Surface Smoothing

Several scenarios can explain the damping or halting of energy flux into waves. According to Miles-Janssen’s quasi-linear theory [*Miles*, 1957; *Janssen,* 1991], wind pressures coherent with wave slopes are created by distortion of the profile of the mean wind $U(z)$ as it flows over the wavy ocean surface. In this theory, the wave growth rate parameter M has an implicit dependence on the gravity-capillary wave roughness length z_0, one thousandth (or less) of the significant wave height [*Edson et al.*, 2013]; the dependency is obscured by the dual influence of z_0 on w (perturbation vertical velocity) and $U(z)$. Effects of short gravity waves on the airflow are included via a second roughness length, z_1. Using some of Janssen’s notation, M (gamma in the Janssen paper) is proportional to $u_*^2\mu\ \ln^4\mu$, where u_* is friction velocity, $\mu = k(z_0 + z_1)$ is the dimensionless critical height, and k is wave number. The length scale z_0 is commonly expressed as $\chi\ u_*^2/g$ where χ is Charnock’s coefficient. (See supporting information for additional details.)

Hypotheses to explain greatly reduced γ under oil include effects symbolized by changes to one or more of u_*, χ, z_0, and z_1. A reduction in u_* by action of an oil film [*Barger et al.*, 1970] is likely to reduce z_0 with or without changes to χ. Reduction of z_1 is more speculative and not considered here. Analyzing u_* reduction, a modern parameterization [*Edson et al.*, 2013] provides the function $u_*(U_{10})$, where U_{10} is wind speed at 10 m height. This is linear and increasing at low U_{10} and tilts upward to a steeper slope near $U_{10} = 7$ m/s. Eliminating this upward tilt (i.e., reducing momentum flux in high wind) reduces M by a factor of 7, typically, for wind speeds greater than 15 m/s for long waves ($\mu << 1$).

Alternatively, the situation of little change in u_*, high wave-induced stress, high z_1, and rough airflow (larger eddies and low U'') consistent with ln μ approaching zero will also quench growth of waves with long wavelengths [*Janssen,* 1991]. This is consistent with elimination of the effects of capillary and gravity-capillary waves (parameterized by z_0) as follows. The effective roughness length may be associated with surface boundary turbulence generated by the shortest waves. In clean water these are capillary and short gravity waves, so that $\mu << 1$ in the Miles-Janssen theory. If these capillaries are removed by oil, μ would then equal kz_1 and could approach 1 (i.e., ln μ and thus M approach 0) if boundary turbulence continued to be generated by flow over the shortest remaining gravity waves.

6. Significance

There are a few essential elements of our model of the successful rescue of *Grecian* by *Martha Cobb*. Both ships drifted downwind faster than the oil slick. In the oil slick upwind of the ships, wind stress was reduced, calming the breakers. The polar oil film was nearly continuous on the sea surface and actively repaired itself for close to an hour.

The model suggests that a realizable reduction of energy input into gravity waves up to 150 m wavelength can explain the calming effect. Alteration of the small-scale roughness of the sea surface can plausibly cause a major change in the structure of the wind profile over the sea such that input is reduced.

Important questions remain. How long do polar oil films persist despite losses from entrainment and subsurface solution? What is the structure of wind flowing over the smoothed surface of large waves? How does this reduce growth of large and long wavelength waves within an oil slick? Can our knowledge of momentum flux to the sea under strong wind conditions be improved? Further experiments are crucial.

A significant question concerns the possible use of films in modifying weather. Films affect evaporation from the sea surface, the formation of spray, and frictional losses of wind energy. These, in turn, can modify weather. For example, when the ratio of evaporation to turbulent energy losses in wind controls hurricane development, the small amount of polar oil necessary to form a monolayer (2 kg/km^2) means that modification of storms is conceivable if persistence is long enough, and logistical challenges are addressed.

Finally, surface films from natural and man-made sources reduce gas transfer (particularly if breaking is inhibited), increase the sea-surface temperature, change the reflection of sunlight, and reduce the intensity of backscattered radiation, and therefore are important in many aspects of the upper ocean. Understanding these effects is crucial to accurate modeling of this critical environmental and climatic regime.

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