

On the generation of wind streaks on the sea surface by action of surface film

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(Manuscript received January 23, 1963)

ABSTRACT

It is difficult to explain the generation of wind streaks and the associated cellular motion in the sea by convective or shearing instability. It is suggested that the streaks are primarily caused by dynamic effects of an organic surface film. Variations in the film concentration over the sea surface have a feedback effect on the wind field through the associated variations in surface roughness, and a self-amplifying system can be obtained. Observations of wind streaks in the Baltic give some support for the idea. In particular, it was observed that the streaks and the associated motions disappear when the surface film was destroyed by rain.

1. Introduction

When sufficiently strong winds blow over the sea one often observes a regular array of streaks lined up in the direction of the wind. These wind streaks are marked by foam from breaking waves and by small floating objects (seaweed, driftwood, ice, etc.). It has been established that the streaks are associated with a roll-type cellular motion. The streaks themselves represent the convergence zones of these rolls (LANGMUIR, 1938; WOODCOCK, 1944).

Isolated streaks may be caused by different mechanisms. Topographic effects in the wind field may set up more or less permanent streaks. At the border of two different water masses and at the edge of a fast current streaks are often seen. For example, one finds at the Bornö oceanographic station in Gullmarsfjorden, Sweden, a large permanent streak running parallel to the shore at a distance of a few hundred meters.

Irregular streaks marked by surface film ("slicks") are observed in many harbours and in other areas where the water is contaminated. More regular slicks running parallel to the shore have been observed at the California coast. They seem to be generated by internal waves (DIETZ and LaFOND, 1950; EWING, 1950; LaFOND, 1962).

The discussion in this paper will not include the last mentioned types of streaks but will be confined to the pure wind streaks. In the past it has been suggested that the wind streaks are caused by convective or by shearing instability. The instability may occur either in the water or in the air. In the latter case the cells in the water should be created by the frictional coupling at the air-sea interface.

Convective instability in the water is theoretically possible. Because of the loss of heat at the sea surface by outgoing radiation and by evaporation one expects an unstable stratification in a thin surface layer. If convection occurs the cellular motion is expected to take the form of a roll motion, because of the basic shear in the water created by the wind-stress. However, nobody has been able to find a correlation between the occurrence of wind streaks and such parameters as the radiation conditions, the air-sea temperature difference, the humidity, etc., which must come in critically in this case. For the same reason an explanation by convection in the air is unlikely. The observation of a well-defined critical wind speed, below which wind streaks do not occur, is also further evidence against an explanation based on convection as the dominating mechanism.

When trying to explain the wind streaks by a shearing instability the existence of a critical

wind speed is positive evidence. FALLER (1962) has studied shearing instability in rotating fluids experimentally and found a critical shear at which roll-type instability begins. Calculating a corresponding critical wind speed for the oceanic case he obtains order of magnitude agreement with the observations. His experiments further predict that the rolls should be deviated somewhat to the right of the wind (on the northern hemisphere) and such a deviation has actually been found in streaks observed in the trade wind area. Nevertheless, it seems unlikely that the rotation of the earth is a critical factor for the generation of the streaks. Wind streaks are generated within a few minutes when a strong wind suddenly starts to blow. During such a short time interval the effect of the rotation of the earth cannot possibly come in. In the Baltic, where the wind conditions are relatively irregular, the direction of the streaks does not differ noticeably from the wind direction. Measurements that were carried out by the author in the Åland Sea show that the angle between the streaks and the wind must be less than 2° . In the trade wind region one expects more steady conditions, and a basic shear flow of spiral type (Ekman flow) is probably developed. An interaction of the rolls with this spiral flow may occur, which makes the streaks deviate from the wind direction. However, such a deviation may show up regardless of which mechanism that generates the rolls. The observed deviation between the directions of the streaks and of the wind in itself thus provides no proof for the correctness of Faller's idea.

There is one type of observation that speaks against the idea of shearing instability in the water. When the wind suddenly shifts direction the streaks quickly rearrange in a regular array parallel to the new wind direction, while the motion lower down is hardly affected. For example, on one occasion streaks about 8 m apart were observed in the Baltic. The wind was blowing from SW with a strength of 8 to 9 m/sec whereupon, with the passage of a thunderstorm front, it shifted within a few minutes to W and WNW. After 10 minutes the streaks had rearranged themselves in the new wind direction with the same spacing as before. Several floats were put out at the surface and at 1 and 2 m depth. The surface floats converged into the streaks, while both

the 1 and 2 m floats proceeded closely in the original wind direction and thus crossed the new streaks. STOMMEL (1951) has also noticed the rapid response of the streaks to changes in the wind direction. He concludes that the generating mechanism must be confined to a relatively thin surface layer.

If one assumes that the instability occurs in the air and that the water motion is driven frictionally by the air rolls, the quick response of the surface layer to changes in the wind direction can be understood. However, one then runs into another difficulty. In the open sea, far from controlling topographic effects, the phase of the air rolls is a free variable. In a turbulent air motion one thus expects the rolls to move around with more or less random phases. Such air rolls are not likely to produce the steady regular array of streaks that is observed.

Arguments of this type some time ago led the author to consider a new model for the wind streaks in which surface film effects are dynamically important. The model, which is described in the next section, seemed to be consistent with observed features of the streaks. More direct evidence for the correctness of the model was, however, lacking. To test the idea further the author therefore undertook some observations of streaks in the Baltic during the summer and fall of 1962. The theoretical model and the more important results of the field study are given in the following two sections.

2. Qualitative discussion of the surface film model

Consider a water surface uniformly covered with a surface film and let a wind start to blow uniformly over this surface. Assume a small disturbance in the film concentration, such that an excess of film material is found in a band along the wind. This causes an increased damping of the capillary waves in the band. A damping of the capillary waves means a decrease in the surface roughness, and a wind that is driven by a given pressure gradient will thus locally speed up along the band. This will create a secondary frictional circulation in which the air close to the sea surface flows toward the band. To see this last result one can consider

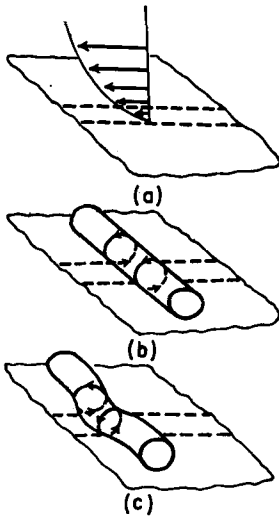


FIG. 1. Deformation of a vortex tube over a streak: (a) shows the basic wind profile; (b) the vortex tube in an initial position; and (c) the vortex tube as deformed by the wind, when the wind speed over the streak is speeded up by decreased surface roughness.

a vortex tube in the air. Fig. 1a shows the basic wind profile, and Fig. 1b the vortex tube in its initial position. If the wind is speeded up along the band the tube will a moment later have acquired a deformation as shown in Fig. 1c, and one sees that the result is a frictional inflow toward the band in the lowest layer. This frictional inflow will now strengthen the effect by driving more surface film material into the band, and the process can thereby amplify itself until the surface tension is strong enough to balance the stresses from the inward air and water motions (the film then acts as solid boundary for transverse motions). If the film concentration is low, as is mostly the case in natural water masses, one expects that the film is concentrated in a relatively thin band, and that the intermediate surface is swept clean from the film material.

There are many questions that remain. For example, it is not clear from the present reasoning that a steady and regular array of bands should be formed. The complete solution of the problem requires a mathematical study of the stability of a film-covered surface acted on by a uniform windstress. Work on this problem has started but so far little progress has been made. A preliminary analysis suggests that no strictly

steady solution exists but that the cells continue to grow until the effects of a lower boundary (sea-bottom, thermocline, etc.) become important.

3. Observation of wind streaks in the Baltic

The observations were carried out during five expeditions in the Åland Sea between July and November 1962. The vessel used was the 40' pilotboat "Mamsell" recently acquired for oceanographic studies in the Baltic. During the cruises the occurrence of streaks and their general appearance was observed. Fig. 2 shows a streak in the Åland Sea at a wind speed of about 9 m/sec. The streak is marked by drifting ice. Measurements of wind speed, wind direction, air temperature and sea temperature were carried out regularly. Measurements of the velocities along and perpendicular to the streaks were carried out by means of floats in the form of water-filled balloons. The balloons hung in thin strings fastened to small cork floats. The depths used were surface, 50 cm, 100 cm, 200 cm and 500 cm. The velocities in the uppermost layer of water were observed by means of dye (rodamin B and uranin). The direction of the streaks relative to the wind was measured by cruising at full speed downwind along a selected streak and measuring the direction of the relative wind by help of a reversed wind vane. As the speed of the boat was known, the absolute deviation could be computed. The accuracy was better than 2° .

A few of the results have already been mentioned. The velocity measurements were not

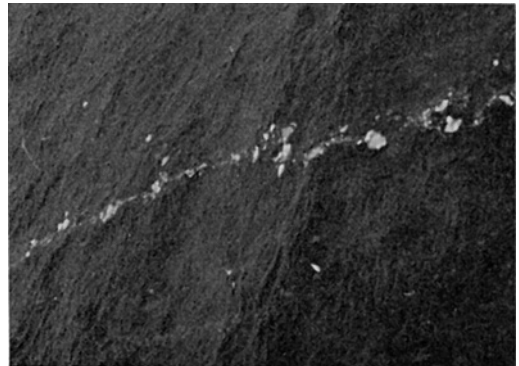


FIG. 2. A wind streak in the Åland Sea marked by drifting ice. The wind speed is about 9 m/sec.

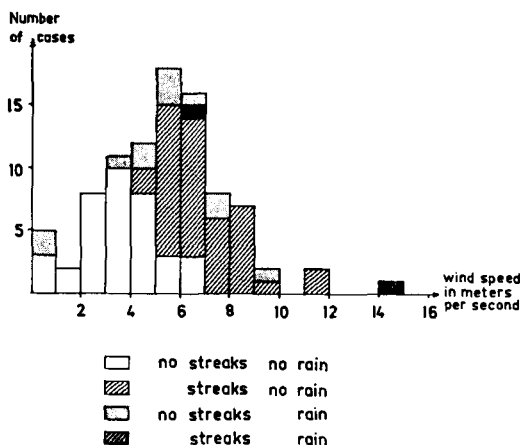


FIG. 3. Distribution of the number of cases when streaks have been observed as a function of wind speed and precipitation conditions.

complete enough to allow a construction of the streamline field for the cellular motion. The result agrees, however, qualitatively with the earlier measurements by Langmuir, Woodcock and others. Some observations that are of particular importance for the discussion of the surface film model are listed below.

(i) Spreading dye close to the streaks revealed a rapid motion of water toward the streak within a surface layer only a few millimeters thick. The velocities were in the range 5–10 cm/sec. When the dye reached the streak it spread downward as a concentrated jet.

(ii) In all observations of the streaks a band where the capillary waves were markedly damped could be seen, indicating the presence of a surface film. The width of the band varied from about 1 cm to over 20 cm for the largest streaks. The band coincided with the foamline.

(iii) There was a strong correlation between the occurrence of rain and non-occurrence of streaks. The observations are summarized in Fig. 3. Streaks generally appeared at wind speeds above 5 m/sec when no rain was falling. (See also (iv).) In the same range of wind velocities the streaks disappeared in seven out of nine cases when rain occurred. In these cases one could observe that the surface film was destroyed by the rain (by which mechanism is yet not known). The breaking waves still produced foam but this had no stability and the bubbles collapsed almost immediately. To

see whether circulation cells still existed, 10–15 surface floats were thrown out within a radius of a few meters. This was attempted in three of the cases and in all these cases the spread of the floats was random, indicating that no convergence zones existed. After the raining had ceased one could observe a build up of the streaks again within a time that varied from 10 minutes to over half an hour. In two cases at wind speeds of little more than 6 meters per second the streaks did not appear again for the whole day.

(iv) In four cases entering the material of (Fig. 3) streaks did not appear for wind speeds in the range 5–7 m/sec and no rain. These observations were all made close to the Stockholm harbour, where the water was strongly contaminated by surface film.

4. Conclusions

The above observations indicate that:

- (i) the wind stress drives the circulation cells in the water
- (ii) the presence of surface film is important for the phenomenon.

An indication that the wind stress drives the cells is found in the observation of a rapid in-flow of water in the surface layer toward the

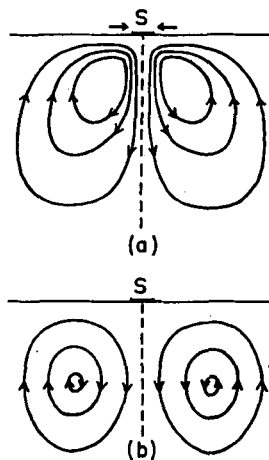


FIG. 4. Schematic cellular motion in the water in a plane normal to the streak. *S* indicates the streak. (a) shows an asymmetric cell, indicating a driving force at the sea surface and in close neighbourhood of the streak; (b) a more or less symmetric cell, indicating a "body" instability in the water. The first type of cell was suggested by the observations.

See also Woodcock (1944).

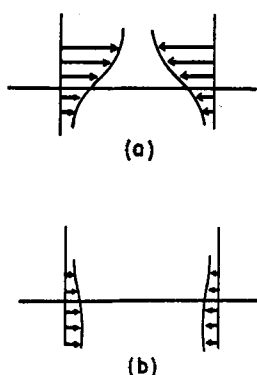


FIG. 5. Velocity profile at the air-sea interface, in a plane normal to the streak: (a) shows the case where the motion originates in the air; (b) the case where the motion originates in the water. The motion of the dye observed in the surface layer was in agreement with case (a).

streak and a concentrated downflow under the streak. The general appearance of the streamline field of the cellular motion is thus like Fig. 4a. In the case of a "body" instability in the water one expects a more symmetric cell type, like the one shown in Fig. 4b. The definite evidence lies, however, in the observation of the sign of the shear of the cellular motion at the sea surface. If a wind stress drives the cellular motion in the water the transverse velocity at the air-sea interface would vary as shown in Fig. 5a. The same sign of the shear was also observed in the dye experi-

ments. If the motion originates in the water a small shear of the opposite sign is expected, as shown in Fig. 5b.

The indication that surface film is important comes from the observation of the disappearance of streaks and the cellular motion in the presence of rain. The rain was observed to change the character of the foam. One would certainly like to understand this phenomenon better. Also it would be of great value if one could make direct measurements of the surface tension in the water.

The observation that no streaks formed in water that was highly contaminated, at wind speeds above the normal critical value 5 meters per second, can be explained in terms of the suggested mechanism. When the surface film is sufficiently thick, the variations in the wind stress will not lead to an effective separation of the film, and the critical wind speed will be higher.

5. Acknowledgements

The author wants to thank Professors George Veronis and Louis Howard, and Mr. Claes Rooth for valuable discussion on the present problem as well as for help during the cruises in the Baltic.

The work has been carried out by support from the Office of Naval Research in U.S.A. through contract N62558-3506, and from the Swedish Natural Science Research Council.

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