GEOPHYSICS

PERIODIC PATTERNS OF RIPPLED AND SMOOTH AREA'S ON WATER SURFACES, INDUCED BY WIND ACTION

BY

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In the course of the years 1948 and 1949 the author carried out marine geological researches in the Dutch Wadden sea [1]). This Wadden sea is a tidal flat area, the bottom of which is uncovered for the greater part at every ordinary low tide. During the researches two phenomena were observed almost invariably whenever the relevant conditions as to wind velocity, depth etc. were fulfilled. Both phenomena, though quite different as to their mechanism of development, are connected with the presence of small quantities of contaminations on the surface of the water. By the action of the wind (either direct or indirect) these contaminations become concentrated in strips or streaks. The first phenomenon consists in a longitudinal concentration, a streak pattern being formed parallel to the direction of the wind; it has already been the subject of several investigations [2]). By the other phenomenon elongated concentrations are produced transversely to the wind direction.

I. *The longitudinal phenomenon: foam streaks, lines of smooth water.*

When strong winds blow there appear streaks of foam on the water surface, running parallel to the direction of the wind. Usually these streaks do not continue very far: they soon split up in two, or combine with each other, or interfinger. Nor, as a rule, do the distances between these streaks present much regularity. Sometimes however, especially when viewed from some height, there can be detected a certain dominating interspace value. And under special conditions (mostly a moderate wind and small depths of water) remarkably regular spacing of the streaks may be observed.

The foam of these streaks is ordinary sea foam, which originates in different ways, the most important being:

a. The breaking of the wave crests in strong winds and the consequent inclusion of atmospheric air bubbles;

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[2]) See references 1, 2, 3, 5.

b. The breaking and splashing of waves against solid objects and beaches;
c. The escape of air and gas from bottom sediment that has been uncovered at low tide and is again inundated by the rising tide (foam front of flood water);
d. The contact of water masses of different temperatures and salinities (current junctions). It may often be clearly seen (especially from the air) that from such current junctions, orientated at any angle to the wind, there is formed a set of smaller foam streaks parallel to the direction of the wind.

Together with foam there are concentrated in these streaks all kinds of other materials: weeds, bird's feathers, leaves of eelgrass etc. Also, when small floating objects such as matches, are scattered at random over the foam streaked water, one may note how they are gradually driven together in these lines, to remain there with their long axes preferably parallel to the wind.

Another property of these streaks, although not so conspicuous as the white foam, is their smooth surface. Big waves pass unhindered through the streaks, but the smaller wavelets and ripples, which give the water surface between the streaks its rough appearance, are obstructed. And when there is little or no foam available, in calmer weather and away from current junctions or beaches, this smoothness of the water surface is often the only feature by which the phenomenon may be detected (photo 1).

LANGMUIR, in 1938, pointed out that "the effect of the wind is to produce a series of alternating right and left helical vortices in the water, having horizontal axes parallel to the wind". The materials floating on the water surface: foam, algal detritus, oil etc. are taken by this movement from both sides to the zones of descent, where they remain in streaks as long as the water keeps converging in these same streaks.

Later, similar phenomena have been investigated by WOODCOCK (1941) and have been interpreted in the first place as due to thermal instability in the upper layers of the water. It was found that the water was cooler at the surface than below. This cooling of the surface water is probably caused mainly by the wind itself (evaporation). The cold water at the surface will tend to exchange places with the underlying warmer and specifically lighter water. The result is convection, whereby, owing to the wind induced flow of the water, a pattern of horizontal longitudinal rolls evolves. As mentioned above the paths described by the water particles in these rolls have the shape of screw threads, alternately right and left.

Often it is difficult to observe directly this screwing motion in the water itself. Exceptionally clear cases however were observed by the author in the Easter Scheldt (province of Zealand) near Bergen op Zoom (Oct. 1949). The water which had depths of about 10 to 40 cm flowed off with the ebb tide in a N.W. direction, parallel to a moderate wind from the S.E. On the surface there were regularly spaced sets of smooth streaks, in which the scarce foam present was concentrated. The motion in the water itself was rendered directly visible by the presence of large quantities of rather coarse, suspended mud flakes. This suspended mud was homogeneously distributed in the zones of rising water, halfway between the streaks of smooth water. Below these latter streaks, however, the lines of descent themselves were conspicuous by their relatively clear water [1]).

The velocity of the ebb current at the surface in the smooth streaks was about twice that in the zones of upwelling water. The upwelling water showed little more than the small nearbottom current velocity, whereas the water arriving in the smooth streaks had been near the level of maximum velocity and in direct contact with the downstream wind for the maximum length of time.

The velocity of the convective flow itself was difficult to measure. In one of the Easter Scheldt cases the following approximative data were obtained:

Depth of water	9 cm
Distance between smooth streaks	40 cm
Ebb flow velocity at surface in smooth streaks . .	35 cm/sec
Ebb flow velocity at surface in zones of upwelling water	18 cm/sec
Time in which mud flakes covered distance along surface from zones of ascent to streaks of descent . .	4 — 5 sec
∴ Average velocity of convective flow at surface. .	4 — 5 cm/sec.

Unfortunately the observer was not equiped to measure temperatures or wind velocities. According to data of synoptic weather stations in the vicinity the wind velocity during the observation was about 12 knots; the temperature of the air was 9° C; that of the bottom probably 11° C or more.

In shallow water, from 1 cm to a few meters deep, there is often an obvious relation between depth and distance between the lines of convergence (see photo 1). This distance is from ca. 2 to ca. 4 times, usually about 3 times the depth. The relation is maintained even when the depth changes considerably over short distances, as for example along beaches.

The regularly spaced parallel foam streaks observed by SEILKOPF (as communicated by NEUMANN (5)) in the Baltic near the German coast seem to be of the same kind. He found distances from 8 to 10 m at a water depth of 2 m, that is a ratio from 4 to 5 between mutual distance and depth.

Theoretical investigations by PELLEW and SOUTHWELL, and others (Ref. 6, 7), have yielded a numerical value for this ratio, for the first cells which are formed when the thermal instability of the water layer

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[1]) This peculiarity has a nice parallel in many cloud systems (cf. reference no. 4).

is just sufficient to give rise to maintained convective motion. The simplifying assumptions made in these treatments, however, detract somewhat from their value in applying them to the case in question. So e.g. the displacement of the water mass as a whole and the velocity shear in the wind direction are not taken into account, and in each of both horizontal boundaries of the water layer considered the temperature is supposed to be a constant. The mentioned ratio between mutual distance and depth should be 2.83 if both horizontal boundaries are supposed to be "free", that means, if besides the vertical convection velocities the horizontal shearing stresses owing to the convection vanish there. It should be 2.34 if the upper boundary is supposed to be free and the lower one to be "rigid", that means, if all components of the convection velocities vanish there. This condition will apply if the convection extends to the bottom.

In the above mentioned Easter Scheldt case the ebb current had the same direction as the wind. The streaks of smooth water travelled downstream in their own direction. Usually the tidal currents diverge from the direction of the wind. The series of streaks are then seen to travel with the current, preserving their orientation parallel to the wind. This is conceivable, because it is to be expected that the direction of the convection rolls is determined by the direction of the velocity shear beneath the surface, as induced by the wind.

II. *The transverse phenomenon: intermittent rippling.*

The transverse phenomenon appears only in very shallow water. It consists in the succession of more or less ellipse-shaped patches of rippled water in an environment of entirely smooth water or, more frequently, in the formation of series of ellipses of smooth water in an environment of rippled water (see photo 2 and fig. 1). Instead of ellipses other shapes

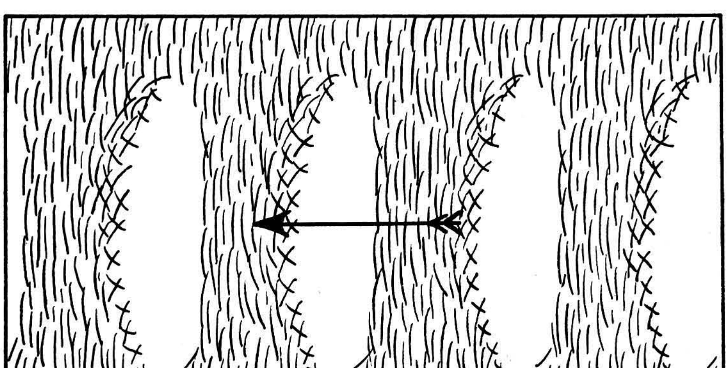

Fig. 1. Train of patches of smooth water travelling from right to left.

may appear, but always with a long axis at right angles to the wind. The long axes of these isolated patches may be no more than one decimeter, but are usually longer: a few decimeters to a few meters. The maximal breadth (i.e. in the wind direction) of the ellipses is usually about 20 — 30 cm and is mostly approximately equal to the minimal breadth of the interspaces. However, when the long axes of the patches are smaller than a few decimeters, are the breadths reduced correspondingly. During very strong winds there may form, instead of trains of ellipses, series of strips, extending over lengths of 2 to 20 m, transversely to the wind.

The phenomenon is observed only in water with average depths of about 1.5 cm (usually great areas of sand flats are covered with bottom ripple marks with heights of ca. 1 cm; an average water depth of 1.5 cm means therefore a depth of 1 cm above the crests of the ripple marks). Only exceptionally may distinct intermittent rippling phenomena be observed in deeper water with depths up to ca. 5 cm. The condition of the bottom: ripple marked (if not too coarsely) or smooth is without any influence.

Furthermore the phenomenon is only seen when the wind surpasses a certain velocity. This critical velocity seems to be about 6 m/sec at a height of 2 m above the water surface. Finally a necessary condition is that the water is flowing. In pools of the required shallowness where the water is stagnant, intermittent rippling was never observed, however large the dimensions of the pools might be. The trains of alternately rippled and smooth patches resp. strips travel downstream.

Owing to the very small depths in which the phenomenon occurs, the wind is usually the main factor determining the direction of flow.

The intermittent rippling may be observed during both ebb and flood stages. During the rising of the water with the flood the duration at a given locality is usually very short. The water then rises with a velocity differing but little from that in deeper parts. During ebb however the sinking of the water level above the flats is retarded, due to the friction of the off-flowing water with the bottom. This friction increases with decrease of depth and it is not to be wondered at, that the range of depths necessary for the occurrence of intermittent rippling is maintained relatively long. Another favourable factor is the wind. The wind may itself ensure a long maintenance of a depth of about 1.5 cm over certain areas by the supply of water it brings along from elsewhere. Strong winds may even push water from deeper reservoirs upwards over sloping banks onto level flats. Thus a continuous flow of shallow water from one channel, over a flat, to another channel may be maintained during the whole period of "emergence" of this flat.

A list of measured data concerning one case is given below:

Date of observation	17 — IX — 1948
Hour	14.h.00 — 16.h.00
Tide	Ebb tide
Locality	Tidal flat immediately W. of jetty at Nes (Ameland)
Bottom	Sand with *Arenicola marina*
Ripple marks on bottom	Asymmetrical ripples, steep towards the East
Orientation of crests of bottom ripple marks	N.N.W.
Wave length of ,, ,, ,,	6.7 cm
Ripple height of ,, ,, ,,	1.0 cm
Index asymmetry of ,, ,, ,,	1/2
Depth of water	1.0 — 2.0 cm
Wind velocity at 1 m above water[1]	9.7 m/sec
,, ,, ,, 3 cm ,, ,,	7.1 m/sec
Wind direction	towards E
Direction of flow of water	E
Approximate velocity of water at surface[2]	23 cm/sec
,, velocity of water at 5 mm below surface[2]	12 cm/sec
Velocity of patches of smooth water	31 cm/sec
Velocity, parallel to current, of water ripples	43 cm/sec
Velocity, diag. to current, of water ripples	25 cm/sec
Wave length of water ripples	larger ones 5.0 — 6.0 cm smaller ones 0.5 — 1.0 cm
Height of water ripples	larger ripples ca. 0,5 cm
Profile of water ripples	very asymmetrical, especially the larger ripples (see fig. 2)
Dimension of smooth patches and of rippled interspaces parallel to wind	ca. 25 cm
Dimension of smooth patches at right angles to wind	ca. 100 cm
Shape of smooth patches	front (downstream) convex, back straight or concave
Diverse observations	Downstream, where the water flows into a channel, the direction of flow deviates considerably from the wind direction (max. about 45°). The long axes of the smooth patches remain at right angles to the wind, but the patches themselves move with the water.

1) Determined with the aid of a simple hand anemometer.

2) Determined by means of small objects, floating upon and in the water (e.g. small pieces of dry resp. wet paper).

While testing various hypotheses to explain the observed phenomenon the following properties were also ascertained.

1. At a given moment the wind, a few centimeters above the water surface, has the same velocity above smooth patches and the adjacent rippled interspaces. At different times, shortly after each other, these velocities sometimes differed greatly, without influence on the surface pattern.
2. The depth of the water of the smooth patches and the average depth of the rippled strips were equal (with an accuracy of about 1 mm).
3. Experiments with a pipette with capillary opening, from which milk was allowed to escape into the flowing water, showed that the flow in both smooth and rippled patches was turbulent.

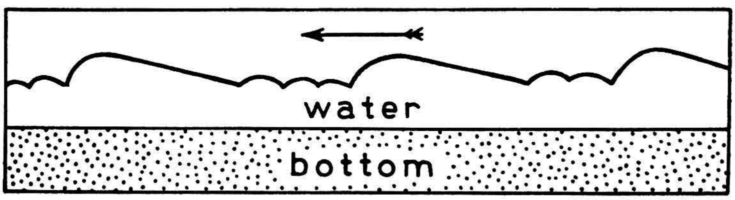

Fig. 2. Profile of water ripples (intermittent rippling phenomenon).

The following hypothesis appears to agree with all known data. On the water there must be an invisible, monomolecular layer. For convenience the material of this layer is referred to as oil although proteins or other capillary active substances may be present as well. When there is no wind and no convection in the water, the thickness of this layer is about equal over large surfaces in consequence of the spreading tendency of the substances composing the film.

Wind, however, when reaching a certain velocity, is able in some way to tear up this layer and to accumulate the oil as a coherent film in between the rents. The rents present water practically freed from oil in which therefore ripples and wavelets immediately appear. It may be observed how these ripples form at the leeward side of a smooth patch, as simple parabolic disturbances (photo 3), then gradually interfere with one another to give parallel wave fronts at right angles to the wind, and then, at the beginning of the next smooth patch abruptly disappear. These smooth surfaces present the places where the oil is pushed up and through which therefore only bigger (solitary) waves may pass.

It is natural that the oil patches travel downstream with the underlying water, also when this flows at an angle to the wind. Nevertheless, there may be some dependance also on the wind, as the velocity of the patches seems always to be a little higher than that of the surface water (see table below).

Velocity of	1948 15–7	21–7	26–8	26–8	6–9	17–9	17–9	28-7-'49
Wind at 2 m above water . . .	—	—	—	—	—	—	—	1080
„ „ 1 m „ „ . . .	—	—	960	960	890	970	970	1020
„ „ 3 cm „ „	—	—	760	760	650	730	710	770
Wind "at watersurface" [1]) . . .	500	1000	—	—	—	—	—	710
Smooth patches	17	47	25	25	20	29	31	—
Surface water.	—	—	16	17	10	23	23	—

All values are expressed in cm/sec.

[1]) I.e. the velocity of the dark ripple shadows shooting over the water which may usually be observed during strong and gusty winds (cf. the longitudinal depressions in the water surface as shown by Photo 4).

It is only when the water is very shallow and no larger waves can arise, that the phenomenon becomes conspicuous. The smaller waves which are the only ones formed cannot pass across the film of oil.

In a paper to be published later in these Proceedings R. DORRESTEIN will give more detailed theoretical considerations based upon the above hypothesis.

In order to test the hypothesis in the field, some simple experiments were carried out.

1. When vigorously sweeping aside the uppermost sheet of water from the smooth patches (by means of a board, for instance) there soon appear ripples in the formerly unrippled spaces.

2. On a smooth water surface, where an oil film can be assumed preventing the formation of ripples while the wind is strong enough to cause the phenomenon elsewhere, artificial rents in that oil film can be made. This may be done by holding a small board vertically above the water, at right angles to the wind, with the lower edge for instance 1 dm above the surface. Behind the board wind vortices then form and below these vortices the wind velocity is much higher. Here a rippled area appears. When taking the board away (and only then) the rippled area starts moving downstream with about the velocity of the surface water itself. This patch however gradually diminishes in size by the spreading tendency of the oil and after covering some 10 meters distance the oil layer finally closes again over the gap and the whole water surface is smooth again.

3. In opposition to the above mentioned circumstances, it also often

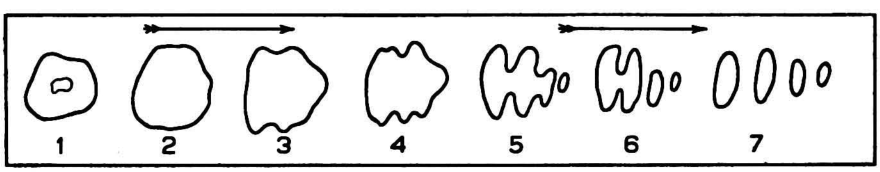

Fig. 3. Intermittent rippling phenomenon developed from solitary smooth patch of gasoline: 1—7 subsequent stages.

occurs, especially during strong winds, that big area's with water of suitable depth, present an evenly rippled surface without any smooth patches. When in such cases a few drops of low grade gasoline are poured on the water, the following series of events can be observed (see fig. 3).

a. A large patch appears on the water, in which all ripples are completely smoothed out. In the centre of this patch there is a coloured area (colours of thin films); the outer parts remain entirely uncoloured (fig. 3 : 1).

b. After a few seconds the coloured centre has disappeared, obviously due to rapid evaporation of the most volatile constituents of the gasoline mixture; the size of the patch has not increased much (fig. 3 : 2).

c. From the sides of the patch the ripples of the surrounding water penetrate in wedge-shaped areas. At the same time small patches detach themselves from the front of the main patch (fig. 3 : 3 — 6).

d. Finally the wedges of ripples penetrating the smooth patch from both sides join together and a series of smooth ellipses has been formed, indistinguishable from natural series (fig. 3 : 7).

Appendix 1. *Origin of the film.*

As to the origin of the substances forming the monolayers two sources are apparent. In the first place oil may come from ships, but perhaps a more important part of the material of the monolayers may be derived from organisms. It has been stated already that the smooth patches occurring on rippled water or the rippled patches occurring on smooth water, have a certain constant length at right angles to the wind (see photo 2). The patches are arranged in parallel trains of a constant width. At first it was thought that these trains, separated by belts of either evenly smooth or evenly rippled water had something to do with longitudinal convective rolls in the air (cf. the longitudinal convective rolls in water treated in section I of this paper). This however was disproved in two ways. Some experiments with smoke showed that the distance between the parallel trains was independent of the motion of the air. Further it was observed that the space between the trains always remained constant, even when the trains curved round with the water towards a tidal channel and thus deviated from their original direction parallel to the wind.

On the other hand it was frequently noted that trains of smooth patches or longitudinal belts of smooth water separating trains of rippled patches, originated at small clumps of mussels (Mytilus edulis). Probably oil is given off by these clumps, although it is difficult to ascertain whether the mussels themselves are responsible, or micro-organisms concentrated in these clumps, or even the mud, containing organic matter, deposited by the mussels (faecal pellets).

Also it is a common observation that during ebb tide narrow streaks of smooth water appear on the evenly rippled surface of the water in deeper channels, starting at the mouth of minor gullies incised in mud banks. These gullies carry water, often derived from mud flats without any mussels to speak of, but usually containing large quantities of freshly eroded mud in suspension. From chemical analyses it is known that the mud of the tidal flats is always relatively rich in organic matter. So it is not unlikely that most of the material for the monolayers of the intermittently rippled trains is derived from bottom deposits.

Appendix 2. *Bottom ripple marks.*

It was mentioned already that the presence of ordinary sand ripple marks with heights of $\pm$ 1 cm does not interfere with the intermittent rippling phenomenon.

Meanwhile it is sometimes seen that together with the occurrence of intermittent rippling of the water new bottom ripple marks are formed, preferably when the bottom surface was originally smooth. These ripple marks may form in sand, but are much more prominent when composed of mud. In the few observed cases they formed systems of diagonally crossing ridges with angles of about 35° to each side of the direction in which the water flowed (see photo 4). It is not clear whether the flow of the water alone is responsible or whether a part is also played by the water ripples, which originate at the windward side of the ripple spaces as more or less parabolic disturbances (see photo 3 and fig. 1).

Summary.

Two phenomena are described in this paper which may be observed very frequently in the Wadden sea. The first phenomenon is the development of a system of convective rolls in the water due to the action of the wind blowing over the water. The rolls are parallel to the wind. The convective movement of the water brings about the concentration of floating objects, such as seaweeds, foam and oil, above the lines of descent between adjacent rolls. The concentration of oil results in the formation of approximately equidistant streaks of relatively smooth water parallel to the wind. In shallow water there is often a relation of the distance between these streaks (which is equal to the transverse horizontal diameter of pairs of two adjacent convective rolls) and the water depth, the former being usually 2 — 4 times the latter.

The other phenomenon has not been described before in print. The author proposes to refer to it under the name of *intermittent rippling.* It consists in the alternation of patches of smooth water and rippled interspaces or vice versa. The patches have their long axes at right angles to the wind, and are arranged in trains which run parallel to the wind. The phenomenon appears only in very shallow water (average depth normally no more than 1.5 cm) which flows off, mainly under influence of the wind.

L. M. J. U. VAN STRAATEN: *Periodic patterns of rippled and smooth area's on water surfaces, induced by wind action.*

Photo 1. Set of smooth streaks on water surface in "zwin" ("low", longshore depression of sandbeach). Low tide, North Sea coast of Ameland. Note the narrow spacing of the streaks in the shallower water at both sides.

Photo 2. Trains of ellipses of smooth water travelling against observer. (Tidal Flat South of Ameland).

Photo 3. Detail of train of smooth water patches, travelling against observer (Tidal Flat, Ameland).

Photo 4. Detail of train of smooth water strips travelling from right to left. Direction of (strong) wind is marked by narrow longitudinal depressions in water surface. Dark ridges of faecal pellet mud (from Molluscs) are formed diagonally to direction of water flow, on flat sand bottom. Mussels at left (Tidal Flat, Ameland).

The patches move downstream with the water, even when the direction of flow deviates from that of the wind. It is assumed that there is an invisible film of oil and/or other substances on the water surface. When the wind surpasses a critical velocity this film is torn up rhythmically. In the rents the water is rippled and between the rents the surface remains smooth. This hypothesis was supported by some simple experiments in the field.

Groningen, March 1950.

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