

Mixing by Langmuir circulation in shallow lagoons

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Abstract Field measurements and observations in shallow basins (Vistula Lagoon and Darss–Zingst Bodden Chain, the Baltic Sea) are reported, revealing characteristics of Langmuir circulation (LC) patterns during moderate winds. A system of large–scale rolls with horizontal axes is shown to be different in the open ocean as compared to shallow areas. CTD horizontal tows across the windrows, GPS registration of the cell’ width, videotape recording were used. Regular patterns of windrows, marking the roll-shaped circulation cells, develop within 5–10 min after the wind onset. The most probable distance between streaks is about double the local water depth, so that the width–to–depth ratio for the rolls is equal to 1; 78% of the rolls have a ratio of width to depth from 0.65 to 1.6, with peak values at 0.75, 1, 1.2, 1.4. It is shown, that in a shallow basin the pattern of windrows is fully developed, and the growth of the roll’ diameters are limited by the depth of the basin. Thorough analysis of video–records of the rows’ breakdown and reconstruction has revealed four possible kinds of Y-junctions, whilst in deep areas only one of them is reported to prevail. One more major difference of shallow water LC is caused by the presence of shores: eventually, the wind, waves and water current in a lagoon propagate in different directions. This makes the streak lines curved, and they drift in the direction of the cross–current component of the Stokes wave transport. Mathematical analysis of the behaviour of suspended particles has revealed, that the flow within the LC transports particles of different size and buoyancy along different trajectories, making mixing more effective.

Keywords *Water mixing, Langmuir circulation, shallow water, Darss–Zingst Bodden Chain, Vistula Lagoon.*

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INTRODUCTION

Water mixing, induced by wind and waves, is of utmost importance for shallow lagoon water dynamics and water quality. Since influence of both bottom and boundaries is very significant, the resulting flow structure is much different from the principal picture, well known for deep and unbounded open ocean. Before the all, general wind driven flow is often deflected by boundaries. Then, since basin is closed, compensating currents occur inevitably along the bottom depressions. And the third—and the main

subject of the present study—is the roll–structured wind–wave mixing in upper layer, well known as the Langmuir circulation. In shallow closed basin it appeared to be much different from the open ocean case, being limited by water depth and deflected by local currents. We report our field measurements and observations in two shallow Baltic lagoons – the Vistula Lagoon and Darss–Zingst Bodden Chain, carried out during summer measurement campaigns of 2000–2006 years.

On windy days, one can often observe on water surface of large basins long parallel streaks of foam,

flotsam, algae, and called windrows. They have undoubtedly been familiar to sailors since long ago and even used to categorize wind speed (e.g., Thorpe 2004). These windrows make visible a pattern of parallel pairs of large alternate left-handed and right-handed horizontal rolls, or circulatory cells, called *Langmuir circulation* (hereinafter, LC). The phenomenon is named after Irving Langmuir, who noticed during an Atlantic crossing in 1927 that Sargasso weed aligned into nearly regular rows when wind exceeded 5 to 10 m/s, and that, when the wind suddenly shifted 90 degrees, the lines reformed within 20 minutes (Langmuir 1938). This phenomenon is now considered as one of turbulent processes in upper layers of large water bodies, driven by wind and waves, influential in producing and maintaining the uniform surface mixed layer and in driving dispersion (see Leibovich 1983). Even though Langmuir himself continued his investigations in smaller basin (Lake George, NY), and established the essential kinematics of alternating horizontal roll-vortices aligned with the wind there, the most serious attention was paid historically to LC features in the open ocean. In order to emphasise the features of LC, which are most important for our study, we just list here the most famous investigations. So, Stommel (1949) calculated particle trajectories based on idealized roll-vortices, and showed that particles, which sink (such as phytoplankton), or rise (such as micro-bubbles), are trapped within the cores of the vortices. Laboratory experiments of Faller (1971), Faller and Caponi (1978) showed that *both* wind and surface waves are required to produce the rolls. Asaf *et al.* (1971) used aerial photography to observe streak patterns on the ocean surface, and reconfirmed the existence of multiple scales, as noted originally in Langmuir (1938); three scales were seen in several photos, separated by just under an order of magnitude and ranging from a few to hundreds of meters between streaks. Some attempts to explain how the circulations are generated have been done by Garrett (1976), Craik (1977), and Leibovich (1977).

Theory suggests (Leibovich 1983), that LC is produced by the interaction of wave orbital motions with depth-varying upper layer current. Consider for clarity the simplest case, when wind and waves go in the same direction, what is typical for the open sea conditions. Taken separately, both wind and waves generate water flows directed down-wind: the wind-induced shear flow, decaying with depth, and the wave-induced Stokes' drift. The resulting down-wind flow, however, becomes unstable and breaks down into long rolls, aligned with the wind—what we see as appearance of windrows on water surface (Fig. 1).

In a shallow and closed basin, the features of LC (like roll spacing, direction, lifetime) are influenced by local bottom topography and depth, coast geometry, particular water density profile, mutual orientation of wind and coastline, probable near-shore currents.

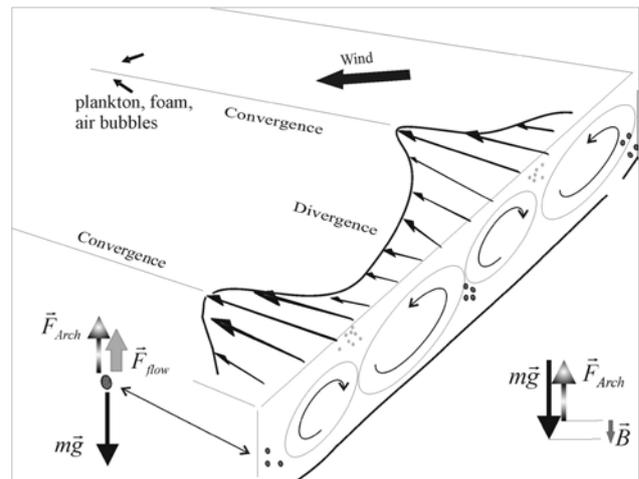


Fig. 1. Sketch of the Langmuir circulation. Important to note that the distance between convergence zones on the surface equals to two roll' diameters. In lower part forces are shown, acting on the sediment particle suspended by the flow: the dynamic pressure force F_{flow} , the Archimedean force F_{Arch} and the gravity force mg ; vector sum of the latter two gives the buoyancy force B of the particle.

Perhaps here is the reason why this phenomenon is not sufficiently investigated in such areas; a few references still can be mentioned here—laboratory work of Matsunaga and Uzaki (2004), and field measurements on 15 m deep oceanic shelf, reported by Gargett and Wells (2007). Lack of information had motivated us to perform a special field measurement campaign in shallow and semi-enclosed areas—the Darss-Zingst Bodden Chain and the Vistula Lagoon of the Baltic Sea. Apparently, natural conditions in brackish lagoons are very much favourable for the instrumental investigations of the specific features of LC: their waters have some vertical salinity and temperature gradients, with more cold and saline sea waters at the bottom and freshened riverine waters at the surface. When LC arises in such a system, it can easily be registered, for example, by CTD-towing in surface layer: water salinity and temperature will vary coherently, showing the temperature minimum/salinity maximum at the divergence zones, and the temperature maximum/salinity minimum in zones of convergence. Further statistical data analysis shows the distribution of line spacing, amplitude of temperature and salinity variations etc. Here, for the problem under investigation, we use mostly the data of GPS and echo-sounder, since they are in full agreement with the results of statistical analysis of CTD data, but are easier to handle with.

FIELD SITE AND MEASUREMENT TECHNIQUES

Field measurements and observations of LC have been performed in Vistula Lagoon (VL) and Darss-Zingst Bodden Chain (DZBC) during summer field campaigns in years 2001-2006 using small scientific boats *Ecolog* of Atlantic Branch of P. P. Shirshov Institute

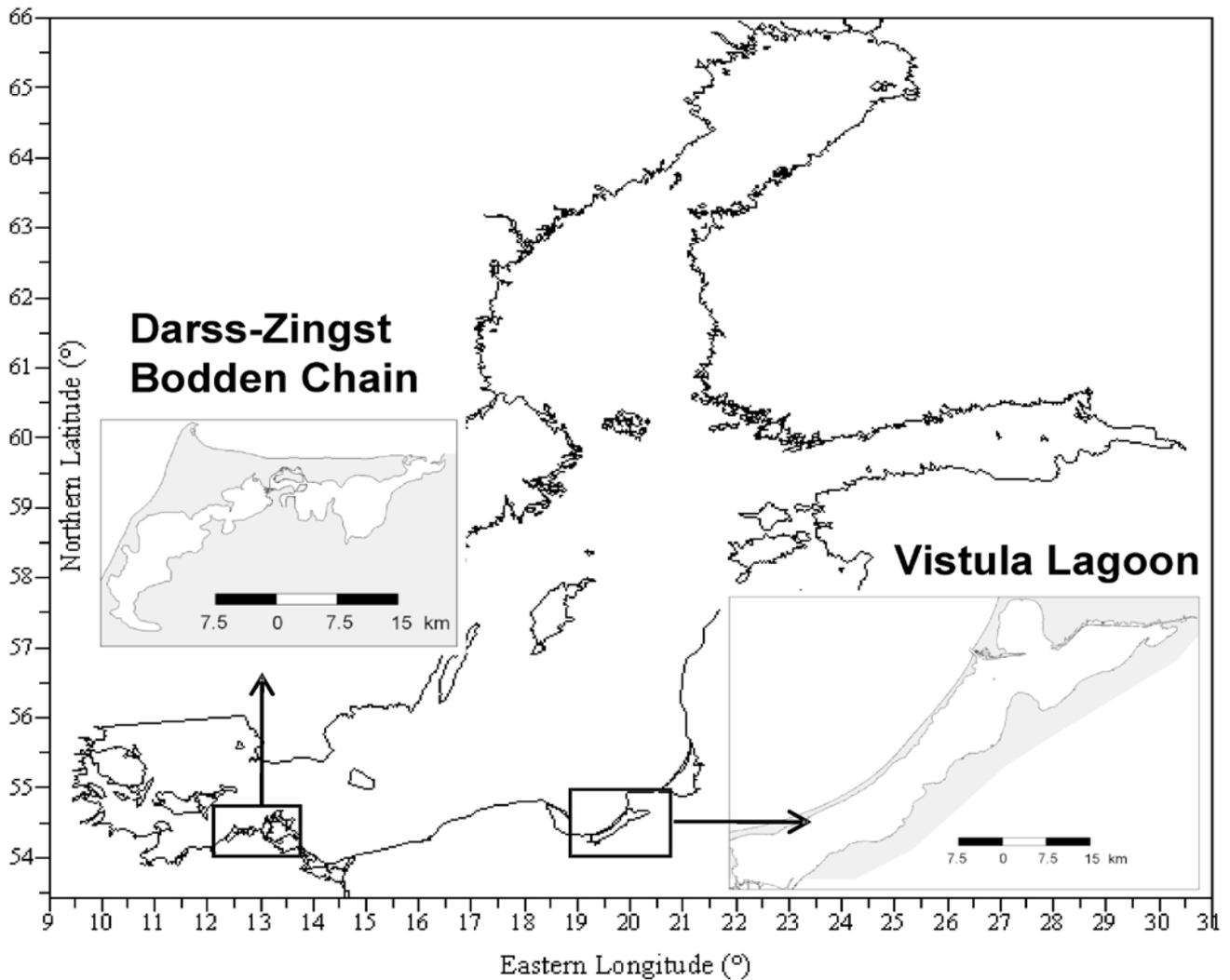


Fig. 2. Measurement sites: shallow Vistula Lagoon and Darss-Zingst Bodden Chain in the Baltic Sea.

of Oceanology of Russian Academy of Sciences and *Gammarus* of Field Biological Station Zingst of Rostock University (Fig. 2). These coastal lagoons have limited water exchange with the Baltic Sea (they are of the restricted and choked hydrological types, correspondingly; Chubarenko *et al.* 2005). Maximum length of 100 (60) km and average depth of 2.7 (2) meters, respectively, allow winds easily mix water column down to the very bottom. The observations were performed in central parts of both lagoons at the depths of about 4 and 2.5 m, under moderate winds of 3–6 up to 9 m s⁻¹ and stable heating conditions (sunshine; air temperature was higher than water temperature). Topography in these areas is very favourable for the formation of large fields of long regular windrows (see Fig. 1): even and flat bottom and distant shores with low sides.

Several measurement techniques were applied to register the features of LC. First, horizontal towing in subsurface layer (5–15 cm) across the streaks was carried out by CTD probes (CTD–90M, ASD Sen-

sortechnik GmbH and Idronaut). The CTD probe was fixed aside, so that measurements have been performed in undisturbed zone from the moving boat with a spatial resolution of CTD measurements of 0.5–1.0 m. The second technique used GPS and echo-sounding: coordinates of crossings of the streaks by the boat were registered by GPS simultaneously with the local depth echo-sounding, while the boat was moving perpendicularly to the windrows. Thirdly, 45 min. long movie was taken in order to analyze the dynamics of row' reconstruction process.

Both, the CTD records were rather easy to interpret, and the pattern displayed on the water surface was well pronounced; that enabled clear identification of the LC signal. Even though the lagoon undergoes significant wind mixing, water near the bottom is slightly colder and saltier than at the surface (due to connection with the sea). Langmuir' vortexes, arising in this weakly stratified environment, transport upward from the bottom more saline/cold water (in upwelling zones), while more fresh/warm water from the surface is carried down (in zones of down welling). Zone of upwelling

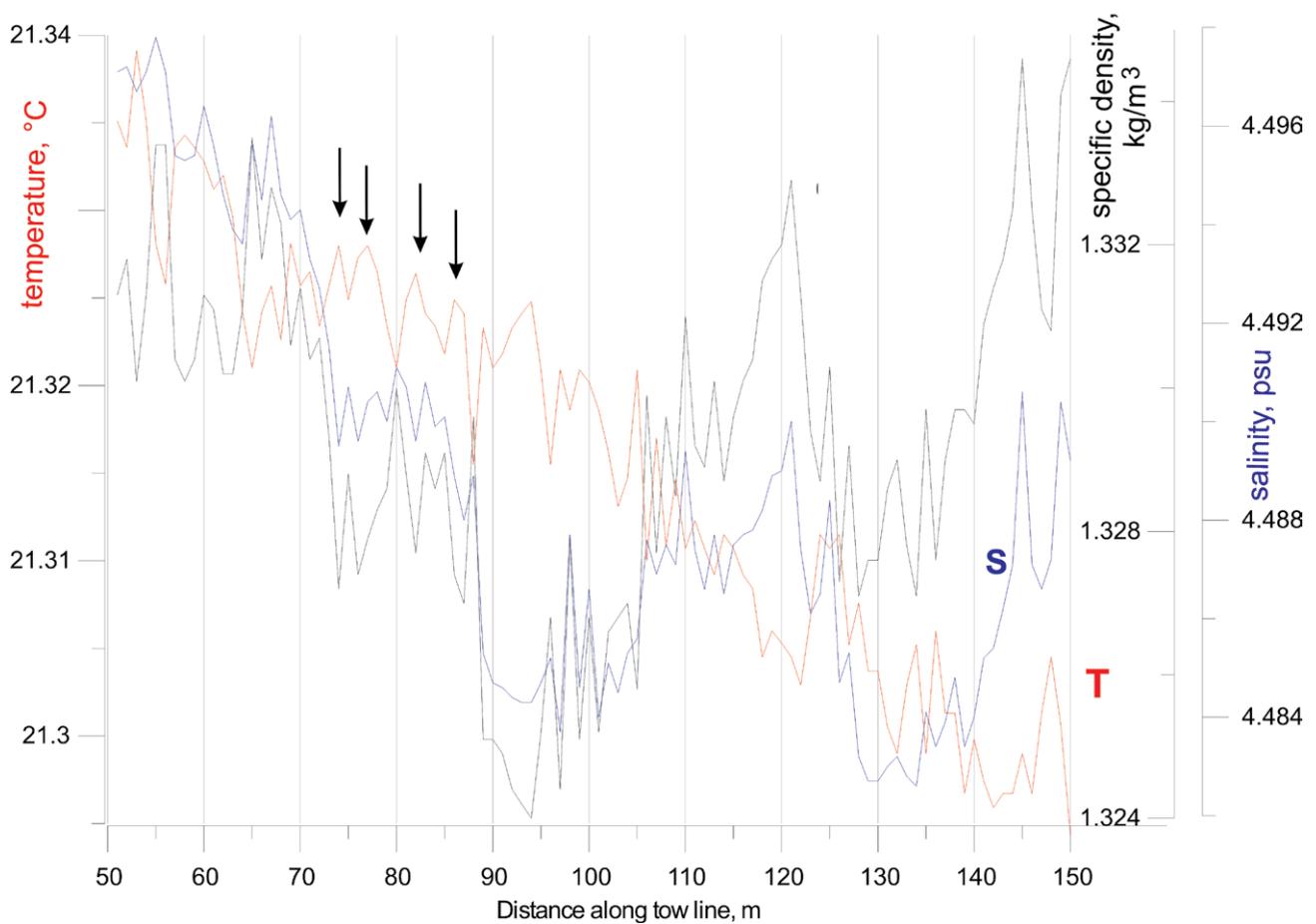


Fig. 3. Water temperature T , salinity S and specific density σ obtained by horizontal sub-surface towing of CTD-probe across Langmuir circulation cells in Vistula Lagoon, 21.07.2001. Wind speed 6-9 m s^{-1} ; local depth 2-3 m; distance between lines of the flow convergence (indicated by arrows) is 4-5 m.

is associated with flow divergence at the surface (and flow convergence at the bottom, see Fig. 1), while down welling zone is associated with surface flow convergence (bottom divergence). Horizontal CTD towing through this structure (at *any* depth) registers a characteristic regular ‘kissing’ behaviour of temperature and salinity curves: maximum temperature corresponds to minimum salinity and *vice versa*. To illustrate this, Fig. 3 displays data of towing of CTD probe at the depth of 5–10 cm across the LC cells formed in Vistula Lagoon on 21 July 2001 under wind 6–9 m s^{-1} . Local depth is about 2.5 m. Arrows point at the surface convergence zones (windrows; down welling regions). Distance between convergence lines is 4–5 m, with the temperature / salinity / density difference between the convergence and divergence zones of about $0.005\text{ }^{\circ}\text{C} / 0.001\text{ psu} / 0.001\text{ g cm}^{-3}$. Data of CTD towing had agreed very well with the data of GPS registration. Since the latter is easier to handle with, we have preferred them in presentation.

OBSERVATIONS

Threshold wind speed and line spacing

Surface streaking is generally reported to occur when wind speed exceeds some threshold value, most frequently placed at 3 m s^{-1} (Thorpe 2004). Under thermally unstable conditions, streaking was observed at lower wind speeds. Theoretical considerations (Leibovich 1977), numerical modelling (Levina *et al.* 2000) and laboratory experiments show that helical structures of various scales are inherent feature of wind–wave–induced flow. They appear *how only* wind–induced current and waves emerge at the surface. As far as we are aware, the minimum scale, observed in laboratory, is 1–2 mm (Thorpe 2004). With time of wind/wave action and further development of LC, small scale instabilities (smaller rolls) are swallowed by bigger ones, so that distance between streaks and intensity of helical motion increase (Levina *et al.* 2000). Observers in field use to detect the surface

streaking visually, what means the availability of some tracers at the surface, which make the pattern visible. Therefore, the value of minimum required wind speed is necessarily subjective. Thorpe (2004) suggested that the strength of surface-sweeping currents in LC scales with the speed, and in field there is some minimum sweeping speed required to overcome the random surface speed fluctuations that resist organization of surface tracers into rows.

In the observations in DZBC in August 2004, we were lucky to monitor the very process of wind strengthening (from 1 to 9 m s⁻¹) and appearance of LC. Under weak winds of 2–3 m s⁻¹, ripples and small waves appeared at water surface, however, we could *not* detect any streaks, even scattering over the surface additional tracers—long wide lines of small pieces of paper. Under winds of 4–5 m s⁻¹, narrow and weak windrows became at last detectable. Spacing between them was surprisingly large: 4–5 m, practically the same distance, as persisted later on, when in three hours winds became much stronger (up to 8–9 m s⁻¹). This means, that either (i) flow structure with smaller rolls existed for some period, but the observer could not recognize them because they are too weak, or (ii) the process of energy transfer from smaller to larger scales proceeds too fast, “swallowing” of smaller rolls and permanent change of the spacing between lines causes variations in surface currents too often, so that floating material has not enough time to be trapped into more or less defined rows. In a view of our efforts to

visualize the picture of streaks during the observations, we are inclined to the latter explanation.

The results of measurements of the distance between the windrows (undimensionalised by the local water depth of 2 m), observed in August 2004 in flat and shallow lagoon of Darss–Bodden (see Fig. 1) under steady SSW wind of 8–10 m s⁻¹, are presented (Fig. 4). Water and air temperature were 21.3 °C/25 °C, correspondingly. The boat had crossed the windrows perpendicularly, and the observer registered by GPS the coordinates of 161 crossing (total length of the traverse was more than 800 m). Later, they were recalculated into the distances between the points, which varied from 2 to 12 m (with the accuracy of GPS registration of 0.1 m). The resulting distribution has many peaks. Since the roll diameter is roughly one half of the measured distance, the results show the peak roll diameters at 1.5 m, 1.8–2 m, 2.4–2.5 m, 2.9 m, 3.4 m, 3.9 m. Since the local depth D was 1.8–2 m, the ratio of the roll’ width to the roll’ depth is (0.75–1.9):1, with the main peak at the circular cell with proportion 1:1. 78% of roll diameters fall in range from 0.65:1 to 1.5:1. Only in 2.5 % of cases the roll width was smaller than 0.65 D , whilst in 20 % of cases it was larger than 1.9 D . In the latter, high percentage include the cases, when the observer had simply missed some streaks in between, if they were weak. The mean distance between windrows is 5.1 m (calculated for the whole set) and 4.2 m (for the most probable 78% of cases); this statistical parameter, however, has rather limited sense for the given problem.

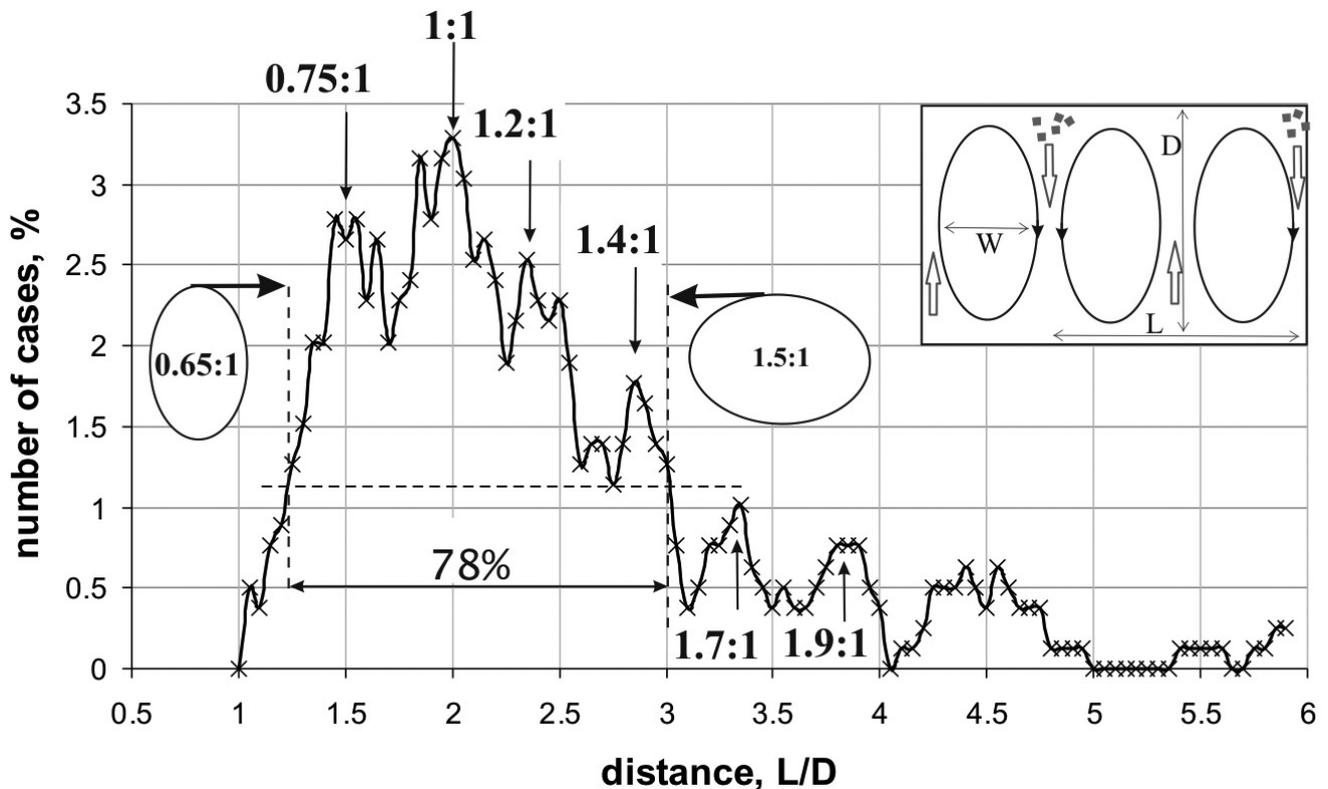


Fig. 4. Distribution curve for dimensionless distance between the windrows, as registered by GPS in Darss-Zingst Bodden Chain. Total number of counts 161; the length of the traverse is 818 m; local depth 1.8–2 m.

The distribution curves from three such experiments are displayed together: the described above (in DZBC, presented in Fig. 4 in more details), and in VL (the other two; Fig. 5). The curves are the best fit (polynomial, 5 power) of the experimental data, with the reliability of approximation not less than $R^2=0.93$. Each of data sets from VL had 80 experimental points with the total length of transverse of 480/490 m. Horizontal axis is the same as in Fig. 4: the ratio of the distance

first formula is not applicable (it would give $L_1 \approx 25$ m for the wind speed of about 5 m s^{-1}), while the second one gives $L_2 \approx 4.6$ m, what is within the measured range. Even though we believe, that the diameter of Langmuir rolls is prescribed by water depth, available for mixing, these estimates at least show that open ocean LC is much different from one in shallow water.

Observations of Langmuir circulation in the North Sea by Graham and Hall (1997) showed the ratio of

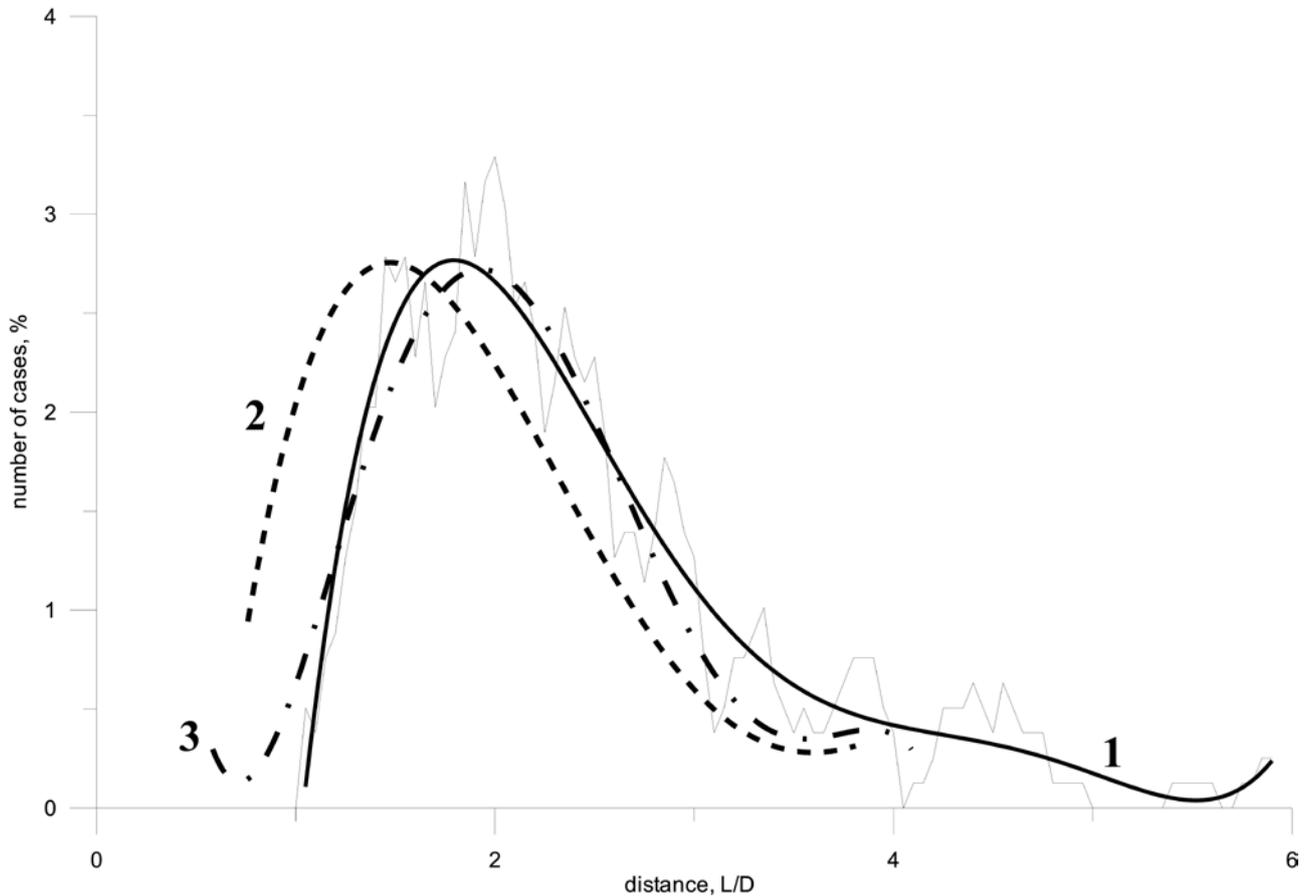


Fig. 5. Distribution curves from three experiments: (1) - in Darss-Zingst Bodden Chain (the same experiment as in Fig. 4, which for convenience is reproduced here with thin line); (2) and (3) - in Vistula Lagoon. The curves are the best fit of the experimental data ($R^2 > 0.93$).

between windrows at the surface to the local water depth. The figure shows, that in all three experiments the distributions are much alike, with the main peak at the roll diameters, close to the local depth. In VL, the peak spacing is 10% smaller, what may be explained by the existence of water stratification near the bottom (the rolls are smaller, because do not reach the very bottom).

In the open ocean, Faller and Woodcock (1964) found that there was a significant correlation between the mean crosswind separation of the windrows, L , and the wind speed, W , taking it to be $L = (4.8 \text{ s}) \times W$ (m), while Graham and Hall (1997) found the relation to be $L = (0.68 \text{ s}) \times W + 1.2$ (m), using measurements taken in a shallow sea. For our shallow water measurements, the

windrow spacing to the water depth to be between 0.3 and 0.5. These values are believed to be typical of fetch limited, shallow seas where cells may not be fully developed (Thorpe 2004). The values for these ratios, reported by Leibovich (1983), are between 0.66 and 1.66, what is very close to our observations. Asaf *et al.* (1971) found the spacing of the largest streak scales to be 280 m, with a mixed-layer depth of 200 m or $L/D = 1.4$ (in our observations – 1.5).

Orientation of windrows, their twist and drift

In order to estimate the deflection of the streaks' direction from the wind direction, we have used kind of a weather vane of a size of ca. 30 cm x 50 cm. During

the time of observations (≈ 6 h), the windrows were found to deviate significantly from the wind direction: up to 30° in both directions (both to the right and to the left from the direction of wind). It happens because in a close basin water currents are much influenced by coastlines, and, finally, are significantly deflected from the direction of wind (Chubarenko, Chubarenko 2002; Chubarenko *et al.* 2004). An impressive example from coastal zone of the Curonian Lagoon is given (Fig. 6). Living dunes of the lagoon side of the Curonian Spit supply by their sand a large shoal of Curonian Lagoon with the depths of 20–50 cm (on the photo, see Fig. 6). They stretch out of the shore up to several

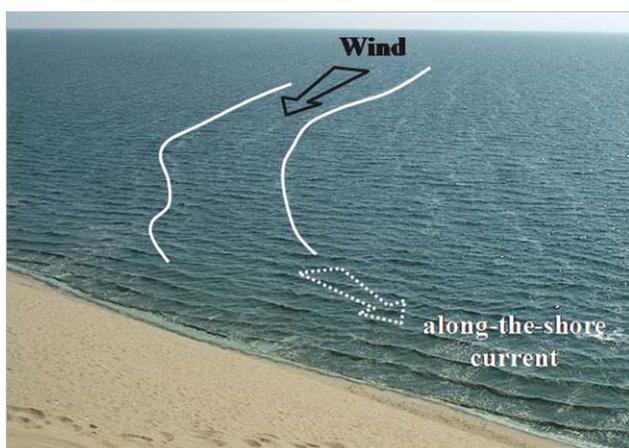


Fig. 6. Langmuir circulation in coastal zone of the Curonian Lagoon (the Baltic Sea). Windrows are curved by along-the-shore current.

hundreds of meters, providing perfect conditions for the formation of LC. Fine net of convergence lines between Langmuir' rolls and regular picture of surface ripples develop over this submerged plateau even under the weakest winds. Important is (see Fig. 6) that the orientation of windrows change considerably near the shore, because wind induced current here is transformed into the coastal jet. The same mechanism works over the entire area of the lagoon: water current, generated by direct wind shear, interacts with another kinds of current, most often—topographically induced ones (gradient currents, coastal jets etc.). As the result, water current is not of the same direction as wind, hence, the windrows, generated by the currents, are not parallel to the wind either, but mainly following the current direction.

There is another complication in this problem. In open areas, typically, wind and waves propagate in the same direction. In shallow or coastal areas, where waves 'feel' the bottom, they experience refraction, and wave fronts tend to become parallel to isobaths (in particular, to the shore line, see Fig. 6). Thus, current and waves are not parallel. This situation was investigated analytically by Cox (1997). He showed that rolls, aligned with the current, drift in the direction of

the cross-wind component of the Stokes drift. For the Fig.6 this means, that near the coast, windrows should experience the onshore drift.

Formation times and persistence

Observers in the ocean usually estimate the time of formation of the LC in 15–20 min. We have found it difficult to obtain it in our observations, because either wind speed increased with time (or it was impossible to say when was 'the onset' of wind), or wind was strong enough, so that LC were just present from the beginning to the end of measurements. Rough estimation is, that both in VL and in DZBC, regular picture of windrows develops very fast: within 10 min. after the wind onset. As it was mentioned above, we haven't observed the very process of developing of LC: it had just gradually become apparent in its final spacing, and then persisted for a long time. Windrows may twist and curve, however, are rather stable, and it was impossible to give any characteristic length of them. Variations and change of the structure goes through the formation of so-called Y-junctions (Thorpe 1992).

Y-junctions

Although LC was usually regarded as regular and steady, the windrows are often twisted and subject to amalgamation one with another. Observations of Farmer and Li (1995) and Thorpe (1992, 2004), performed in sea in winds >12 m s⁻¹ indicated for the first time that the convergences, as delineated by lines of bubble clouds, can merge into so-called 'Y-junctions' (because it looks like the letter Y), predominantly pointing downwind, with an angle between the pair at the junction of about 30° . They wrote that the physical reason for this could be the growth of roll' diameters with growing wind fetch. Among just a few observations published about this reorganization of lines, there is no information about sleek-lines amalgamation (i.e., the divergence zone amalgamation). In our observations in lagoons, we have paid special attention to the process of surface pattern reorganization (see also Chubarenko, Baudler (2006).

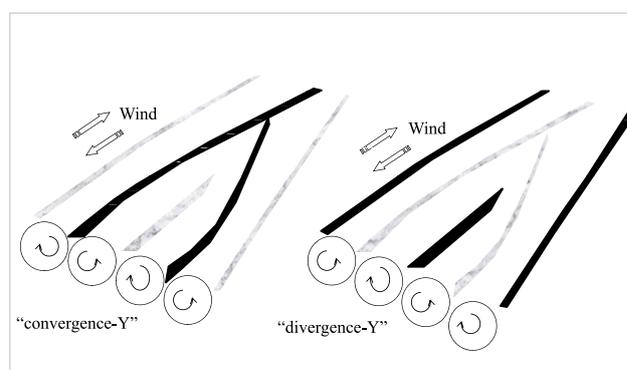


Fig. 7. Four principally possible variants of amalgamation/destruction of Langmuir circulation cells: both convergence and divergence lines can merge together, with narrow end of the resulting Y-junction pointing either up- or downwind.

In order to understand the kinematics of rolls beneath water surface when one observes the described above merging of windrows (convergence zones) on it, consider the process in more detail (see Fig. 7). If to consider four neighbouring rolls in regular picture of LC as it is shown in the left upper panel of Fig. 7; there are two convergence zones (windrows) and one divergence zone (sleek line) in between. Wind blows ‘into picture’. The amalgamation of windrows on the water surface means that instead of four rolls in the beginning one has after reconstruction two rolls only, but their size is twice larger. Thus, in the most often observed ‘classical oceanic case’ of (convergence) Y–junction pointing downwind, the outside rolls gradually (i. e. when the observer *moves downwind*) swallows up the internal ones and grow in size. This way, the presence of (convergence) Y–junctions at the surface is an indicator of increase of roll’ diameters.

In principle, not this single one, but four kinds of merging of convergence and divergence lines are possible in such system (see Fig. 7). They are:

- (i) when two *divergence* zones (sleek lines) merge together – one observes the “Y” of divergence zones, what can naturally be called “*d–Y*”;
- (ii) when two *convergence* zones flow together – the well known “classical” Y–junction is formed, which can be called more exactly now as the “*c–Y*”;
- (iii) splitting up of one convergence zone into two ones gives the *inverted* “*c–Y*”;
- (iv) and splitting up of the divergence zone gives the *inverted* “*d–Y*”.

The observation in DZBC revealed that *all the types* of Y–junctions exist in the same time in LC picture in a shallow basin. Kinematically this means, that rolls must both merge together (in some locations) and disintegrate (in another locations) at the same time. Often, if one convergence zone vanished in “*c–junction*”, the next after it (the neighbouring one) convergence zone is very well pronounced, but the next after it (in some time) will be the “*d–junction*”. We have not yet explanation for this; from the point of view of roll’ structure, the both junctions mean the same: disappearance of one divergence zone and one convergence zone (see Fig. 7).

The life–time of Y–junction in our observations was around 2–5 min., i.e. after 2.5 min. after its formation the regular picture in given area was re–established again. From the board, the observer was able to monitor the origination and development of a certain Y–junction (usually the single one, sometimes – two junctions at once, never more) during these ca. 5 min.; then, the regular picture was re–established for another 5–10 min.

Rather often, Y’s was caused by the very boat. Almost all the time (when anchored), the boat was naturally turned by wind to the position, roughly parallel to windrows; and one of the windrows adjusted

itself to embrace the boat, so that it was always staying in foam line (convergence zone). Neighboring convergence zones often became twisted and formed Y–junction (either in front or behind the ship). In all such re–constructions, the number of rolls increased, what is logically correct: the boat had disturbed the existed regular structure and large rolls broke out into smaller ones.

DISCUSSION

The described observations provide an opportunity to get better insight into both (i) development of LC with time and (ii) mixing in presence of LC in shallow basins. Below we show that theory of Craik and Leibovich and theory of the developed turbulence lead to a very similar and complementary results, the former providing physical background of the roll’ appearance, and the latter showing the way of their development with time. The final picture, predicted by the theory of the developed turbulence, is greatly like that observed in our measurements in shallow lagoons, what allows revealing the specific features of mixing by LC in shallow areas as compared to deep ones.

Fully developed picture

In shallow areas and near the coasts, Langmuir rolls arise readily, as a result of instability of wind–induced shear flow in the presence of depth variable surface Stokes’ drift. Theory of Craik and Leibovich (Craik 1977; Leibovich 1977, 1983) has demonstrated the reasons and mechanism of the roll formation, but it cannot predict the parameter, most suitable for observation—the rolls’ spacing. In order to explain the formation of Langmuir cells, Craik and Leibovich have introduced into the equation of water motion (the Navier–Stokes equation) an additional force – the “*vortex force*” $\vec{F} = U_s \times \text{curl} \vec{U}$, which is the vector product of the wave Stokes drift, $U_s(z)$, and the vorticity $\omega = \text{curl} U$, associated with the wind–induced current.

Along with the theory of LC, the mechanism similar to the above described was investigated in theory of the developed turbulence, or so–called *dynamo–theory* (see, for example, Levina *et al.* 2000). There, the quantity of *helicity of the flow*, s , was introduced as $s = \int \langle U \times \text{curl} U \rangle dr$ to describe the presence in it of lots of small chaotic whirls. Numerical modelling of the flow possessing the helicity, had demonstrated (Levina *et al.* 2000) that the development of turbulence leads to the growth of the whirl’ sizes, to their amalgamation and strengthening, until the only gyre is formed, *whose dimensions are limited by the scale of the numerical domain only* (so–called hydrodynamic α –effect). In particular, this theory was successfully applied to an explanation of typhoon and tornado generation in highly turbulent atmosphere.

The similarity is obvious: the “helicity” in the theory of developed turbulence and the “vortex force” of Craik and Leibovich introduce in fact the same term in the equation of motion (Chubarenko, Baudler 2006). There is a difference as well, and deeply physical one: in the “helicity” the vector product is taken from the velocity vector and *its own* vorticity, whilst in the “vortex force” the same combination is made from *physically independent quantities* – the velocity U_s of the Stokes wave drift, and the vorticity $w = \text{curl}U$ of the decreasing with depth wind-induced current. Thus, the physical meaning now is: the nonlinear interaction between the surface wave drift and wind-induced current supplies the flow with an additional *helicity*. Now, following Levina *et al.* (2000), the generated by turbulence small whirls *are to grow* in size, to interflow in bigger ones and give them their energy. Finally, numerical simulations predict the structure of the maximum possible size, limited by just external geometry of the problem.

Thus, if in a system there is a source of helicity, the small whirls with time will flow together and form one big revolving cell, which occupies all allowed space. Turning back to a shallow basin, we find out that it is the depth of it, what limits the growth of the Langmuir cells. We see, that the cells are to grow *naturally*, and the final (“developed”) size of rolls should be (roughly, since the flow is turbulent) equal to the depth of the basin. The picture we observed in field (see Fig. 1)—with mainly equidistant streaks—can be then classified as a “fully developed” LC, since the cells can no longer increase their size being restricted by water depth. In the ocean, the size of rolls can increase together with the thickness of the upper mixed layer, so, the picture of windrows is never “fully developed”.

Y-junctions in fully developed LC field

The kinematics of Y-junctions supports our suggestion that, in contrast to the deep areas, the LC in a shallow basin becomes fully developed soon after the beginning of the wind action. Indeed, in the ocean, observer report typically the Y-junctions, delineated by clouds of air bubbles and foam (i.e., *convergence* zones), with the narrow end of the Y’s overwhelmingly pointing downwind (Thorpe 2004). This means (see Figs 7, 8), that with increasing wind fetch (or time of the action), four cells (rolls) merge into two rolls. Thus, the process indicates: the rolls grow in size. The fact, that only the “c-junctions” are reported in the ocean, but not the “d-junctions” (which are the same merging of four cells into two cells), we can explain only by difficulties in identification: the “d-Y” is manifested as chain of sleeks (flattened spots) on the water surface, and are really difficult to observe. In shallow basins, we have registered *all four possible kinds* of Y-junction (presented in Fig. 7): they demonstrated, that the

picture of windrows is already fully developed (the rolls have reached the size, limited by water depth), and now the rolls, growing in size, are balanced with the rolls, splitting into smaller ones (in inverted Y-junctions).

Transportation of material of different buoyancy

In order to disclose specific features of mixing by LC in shallow areas, consider the influence of LC onto transport of particles of different buoyancy. It has been known for many years that LC causes an increased concentration of motile or buoyant algae; it enhances mixing, transports organisms between high and low light levels, promotes patchiness of swimming or buoyant algae, and affects their exposure to light and pollution. Concentration of buoyant particles, sediments, oil droplets, or bubbles within LC varies both in time in space.

It was shown however (see Thorpe 2004) that system of currents, produced by such coherent structures, limits rather than favours the spreading of floating material, especially in transverse direction. It can easily be observed for the material, floating on the surface: on reaching the windrows, it remains trapped until time when the local circulation breaks up, when adjacent cells split or merge together. Beneath the surface, where different particles have different buoyancy, the process of mixing is more complicated. Stommel (1949) has calculated particle trajectories based on idealized (steady) roll-vortices, and showed that the particles which slowly sink (such as phytoplankton) or slowly rise (such as micro-bubbles) should be trapped within the cores of the vortices (so-called Stommel retention zone). Later, Bees *et al.* (1998) calculated numerically the steady cross-sectional streamlines for the particles of neutral, slightly positive and slightly negative buoyancy, and demonstrated that the process is much more complicated. He found, for example, that for particles of positive buoyancy, there are two qualitatively different behaviours: some particles are trapped in closed orbits at some distance below the surface (Stommel retention zone), whereas others accumulate at the lines of convergence at the fluid surface, and they cannot change one type of motion to another.

Not only the initial position of a particle is important, but also its density and size. In order to reveal more details of the motion of particles of different buoyancy, consider the forces driving the motion of some small particle within LC cell (bottom of Fig. 1). These forces are the gravity force F_g , the Archimedeian buoyancy force F_{Arch} and the dynamic pressure force F_{flow} . The second Newton’ law applied to the particle of mass, volume V_p and density ρ_p gives

$$m_p \cdot \vec{a} = \vec{F}_{Arch} + m_p \cdot \vec{g} + \vec{F}_{flow}, \quad (1)$$

where a is the particle acceleration, $\vec{F}_{Arch} = \rho_w \cdot V_p \cdot \vec{g}$ is the Archimedean force, ρ_w is the water density, and \vec{F}_{flow} is the dynamic pressure force, exerted on the particle by the flow. The sum of the first two forces $\vec{B} = \vec{F}_g - \vec{F}_{Arch} = (\rho_p - \rho_w) \cdot V_p \cdot \vec{g}$, we obtain the buoyancy force, which can be directed both upward (for floating material) and downward (for sediment particles).

The third force (force of the dynamic pressure) is proportional to the difference of the Lc flow velocity u_L and the particle velocity u_p . It pushes the particle in the flow direction, if it moves slower than the water does, but drags it back if it moves faster than the flow. This way, floating material in the LC surface convergence (down welling zones) is carried down, while sediment particles in the bottom convergence zones are lifted up (see Fig. 1). Commonly, this relation is assumed as

$$F_{flow} = 1/2 \rho_w \cdot v^2 \cdot S \cdot C_x(\text{Re}),$$

where $v = u_{Lc} - u_p$ is the particle-flow relative velocity, S is the cross-flow particle area and $C_x(\text{Re})$ represents the particle resistance coefficient.

Since in shallow water body the mixing by LC reaches the very bottom, it plays a certain role in sediment re-suspension. Let us apply the equation (1), as for example, to the vertical motion of a sediment particle in the LC bottom convergence zone (see Fig. 1) leads to the expression for the acceleration a of a particle in the form:

$$a = \left(\frac{\rho_w}{\rho_p} - 1 \right) \cdot g + \frac{\rho_w}{\rho_p} \cdot \frac{v^2 \cdot S \cdot C_x}{2V_p} \quad (2)$$

where the ratio of a particle volume to its cross sectional area $V/S = h$ represents in fact the characteristic size of the particle. The analysis of the expression (2) shows that: (i) particle acceleration depends on its density (ρ_p), shape and size (C_x, h_p); (ii) the bigger are the density and the size of a particle, the smaller is its acceleration. Thus, from the very beginning of vertical motion, lighter and smaller sediment particles get bigger vertical lifting accelerations and obtain higher vertical velocities.

While accelerating upward, the particles *move together with* flow of upwelling, and thus get lesser velocities *relative* to it. This makes smaller the upward force of dynamic pressure. Since sediment particles have always negative buoyancy and the upward force F_{flow} becomes smaller and smaller, the balance between them will be reached at some depth, acceleration will become zero, then downward directed, and finally

the negative buoyancy will stop the upward motion and drive the particle back to the bottom. Since less-dense (smaller ρ_p) and tiny (smaller h_p) particles got *higher accelerations and higher upward velocities*, they are trapped by the upwelling flow for longer periods of time. These small particles pass longer ways in water, following the circular flow of LC for a longer portion of the cell, while more heavy and big pieces of sediment escape the circle earlier. This conclusion is in full agreement with the result of laboratory experiments by Dethleff *et al.* (2009).

Thus, the existence of the LC not just maintains the sediments in suspended state, but really mixes different fractions of it by forcing different particles to follow different trajectories. The same idea can be applied to a floating material: particle with significant positive buoyancy will just stay on the water surface (in surface convergence zone) or describe small circles near this position, while less buoyant ones will be carried down by the flow into the water body.

One more aspect of water mixing and transport in the presence of LC in shallow lagoon in comparison to that in an open ocean follows from the above described differences in the picture of Y-junctions. As it was shown for the first time by Thorpe (2004), the dispersion of the material *across* the LC depends on cell's life time, thus on formation of Y-junctions. If for example some material of positive buoyancy was initially trapped into two convergence lines at a certain distance one from the other, after the re-construction (the roll's amalgamation), the material is carried into one line. Thus, the dispersion of the material is reduced. Such qualitative analysis of the behaviour of the materials with different buoyancy in amalgamating and disintegrating rolls shows, that the material *in the ocean* undergoes the described above two preferred ways of cell re-organization (*c-Y* and *d-Y*). At the same time, the distribution of variants of the rolls re-construction in shallows is equiprobable. Finally, as compared to the open ocean LC conditions, the *dispersion of the material with positive buoyancy is higher* in shallows, whilst *for the negatively-buoyant material the dispersion is smaller* (since it is trapped into bottom convergence zones).

CONCLUSIONS

The Langmuir circulation is the phenomenon widely observed both in the ocean and in shallows. This process induces the vertical currents, which grow in size, amalgamate into bigger and bigger rolls, occupying all the space (depth) allowed by input energetic. In the ocean the 'allowed' space is limited by the depth of the upper mixed layer, which grows with

time, mostly due to the very LC-work. The diameters of the rolls grow simultaneously with the thickness of the upper mixed layer, favouring roll amalgamation rather than destruction. In shallow areas, the LC is limited by the bottom depth, so some equilibrium state is reached soon, with the diameter of rolls prescribed by the local water depth. In this state, roll' amalgamation and destruction are balanced. Observations show, that the picture of windrows in shallow area becomes fully developed soon after the beginning of the wind action (5–10 min). However, even in fully developed structure, the rolls continue amalgamation/destruction process, which causes the formation of the Y-junctions of four kinds at the water surface.

In the fully developed picture of the windrows in a shallow basin, the most probable are the rolls of regular circular shape (what is in full agreement with Thorpe (2004), who termed them to be of 'square shape'). The distribution of the roll' diameters has other obvious peaking values, where the ratio of the horizontal roll' diameter to the roll' depth is 0.75, 1.2 and 1.4. In a whole, 78% of the roll' diameters in shallow basin are in range 0.65–1.5 of water depth.

Analysis of the motion of particles of different buoyancy in the LC showed that they experience different forcing in the flow, get different accelerations and velocities, and finally describe different trajectories. Thus, the existence of LC not just maintains sediments in suspended state and entrains the floating material into the water body, but really mixes different fractions of them by forcing different particles to follow different paths.

To sum up, we conclude that LC is a very important environmental phenomenon, because it essentially influences the dispersion and transportation of dissolved and suspended matter, especially in shallow basins. In spite of its evident importance, LC is still not yet represented (or even parameterized) in environmental models: neither in global circulation nor in climate modelling, nor even in operational models, including small scale models for prediction of oil spill propagation.

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