Surface Drift Currents Induced by Waves and Wind in a Large Tank

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ABSTRACT: The empirical features of surface drift currents induced by both mechanical and wind waves are presented. The measurements were made by using surface floats in a large tank with dimensions of $32.5 \times 1 \times 2 \text{ m}^3$. Three cases were studied: (i) regular (narrowband) mechanical waves, (ii) irregular (wideband) mechanical waves, and (iii) wind waves. The measured surface drift currents induced by mechanical waves U_d are compared with the Stokes drift at the surface U_{St} estimated by a well-known formula with an integral over the wave spectrum. In this case, the ratio U_d/U_{St} varies in the range of 0.5–0.93 and slightly increases with decreasing wave steepness. No visible dependence on the breaking intensity is observed. In the case of wind waves, the wind-induced part of the surface drift U_{dw} is compared with the friction velocity u_* . In our measurements, the ratio U_{dw}/u_* varies systematically in the range of 0.65–1.2. Considering the percentage of wave breaking Br, the wave age A , and the wave steepness $\mathcal{O}$, the parameterization of U_{dw} was obtained in the form $U_{dw} = (\text{Br} + \mathcal{O}A)u_*$, which corresponds to the observations with a mean error of 10%. For the first time, this ratio provides the dependence of wind-induced drift on the surface wave parameters. The obtained results and problems related to measuring surface drift currents are discussed.

KEYWORDS: Air-sea interaction; Small scale processes; Surface fluxes

1. Introduction

a. Initial information

Surface drift currents play a significant role in marine shipping, the spread of surface waste, and marine industry safety. Thus, studying and understanding this phenomenon, which was comprehensively described in the recent review by [Bremer and Breivik \(2017\)](#), is of physical and practical importance. From the physical perspective, the drift currents are interesting due to their observability, availability for measurements, and possibility of theoretical description (e.g., [Stokes 1847](#); [Longuet-Higgins 1953](#); [Craig 1982](#); [Bremer and Breivik 2017](#), and references therein). For this reason, a large number of surface drift current measurements have been obtained over long periods, started by [Shemdin \(1972\)](#), [Wu \(1975, 1983\)](#), [Churchill and Csanady \(1983\)](#), and [Bye \(1988\)](#), and continued at present (e.g., [Longo 2012](#); [Longo et al. 2012](#); [Zavatsky and Shemer 2017](#)). The earlier work was well described by [Tsahalidis \(1979\)](#), and an extended list of recent work was reported by [Bremer and Breivik \(2017\)](#). In addition, extensive theoretical work has

addressed numerous aspects of the dynamics of currents induced by waves in water, namely, the generation of current vorticity due to viscosity, particle trajectories in water, turbulence induced by waves, the oscillation of boundary layers, the occurrence of return currents in a tank, the origin of Langmuir circulations, and so on. Most of these topics have been well described in certain papers (e.g., [Longuet-Higgins 1953](#); [Craig 1982](#); [Teixeira and Belcher 2002](#); [Babanin and Haus 2009](#); [Teixeira 2018](#)), surveys (e.g., [Sullivan and McWilliams 2010](#); [Bremer and Breivik 2017](#)), and monographs (e.g., [Phillips 1977](#); [Janssen 2004](#); [Bühler 2014](#)). However, in this paper, we consider measurements of time-averaged surface currents induced by waves in water. The focus of the study is on the experimental aspects of the surface current problem rather than particle trajectories near the surface, turbulence generation by waves, or the depth profile of induced currents.

Despite the evident simplicity of surface drift current measurements, accurate measurements of a wavy water surface can have many sources of error. Field measurements (e.g., [Churchill and Csanady 1983](#); [Babanin 1988](#); [Malinovsky et al. 2007](#); [Kudryavtsev et al. 2008](#)) are influenced by the nonstationarity of the wind field, uncontrolled background currents U_b , the stratification of air and water in situ, numerous technical difficulties in field measurements, and other factors. In laboratory (tank) measurements

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(Toba 1973; Wu 1975; Tsahalidis 1979; Longo 2012; Longo et al. 2012; Paprota et al. 2016; Zavadsky and Shemer 2017), the sources of errors include the influence of the upper and lateral boundaries of the tank, presence of return currents, short wind and wave fetches, and difficulty of placing equipment in a tank. Some specific problems related to surface current measurements will be discussed in this paper.

All these limitations influence the wind and current profiles and establish dependencies of the surface drift on the wind and wave parameters of the air–water interface. Besides, small tank dimensions limit the range of wave state parameters, thereby decreasing the ability to identify the abovementioned dependencies. However, tank measurements have the evident advantage that all parameters in the air–water system can be completely controlled during an experiment. Therefore, the most exact and reliable results for surface drift currents have been obtained in laboratory measurements (Wu 1975, 1983; Longo 2012; Longo et al. 2012; Zavadsky and Shemer 2017). Nevertheless, many features of the drift current phenomenon are still not completely understood. In this paper, some of these issues will be addressed based on our own tank measurements.

b. Specification of the tasks

For completeness, consider two principally different cases: (i) mechanical waves and (ii) wind waves in water.

Regarding mechanical waves, one may expect that the surface drift current U_d should be of the same order as the Stokes mass-transport current U_{St} if the ideal fluid assumptions are applicable (Stokes 1847). In the potential approximation and the case of a monochromatic nonlinear gravity wave with amplitude a , frequency ω , and wavenumber $k = \omega^2/g$ (g is the gravity acceleration), the theory predicts the ratio (Stokes 1847; Phillips 1977)

$$U_{St} = (\omega/k)(ka)^2 = (\omega a)(ka), \quad (1)$$

where the first equality corresponds to the scaling of U_{St} by the phase velocity, ω/k , and the second equality corresponds to the scaling of U_{St} by the orbital velocity, ωa . The factor ka is the steepness of the wave (typically ~ 0.1), which determines the scale of the Stokes drift with respect to the mentioned velocities. For the wave spectrum $S(\omega)$, Eq. (1) for U_{St} can be generalized. In the case of quasi-monochromatic (narrowband) waves, Eq. (1) can be replaced by the following formula:

$$U_{St} = \omega_p k_p a^2, \quad (2)$$

where ω_p and k_p are the spectral peak frequency and the peak wavenumber, respectively. In the case of mechanical waves with wideband spectra, such as Pierson–Moscowitz (PM) or Joint North Sea Wave Observation Project (JONSWAP; JW) spectra (Komen et al. 1994), the Stokes drift can be estimated by the following formula (Churchill and Csanady 1983):

$$U_{St}(z) = (2/g) \int_{\omega_{\min}}^{\omega_{\max}} \omega^3 S(\omega) \exp(2\omega^2 z/g) d\omega. \quad (3)$$

Here, $[\omega_{\min}, \omega_{\max}]$ is the available frequency band of the wave spectrum $S(\omega)$, and z is the vertical coordinate directed positively upward. Equation (3) allows the Stokes drift for a given spectrum $S(\omega)$ to be estimated at both the surface and at any depth z ; besides, it shows that the Stokes drift decays exponentially with depth z . Note that ratios (2) and (3) are also used for the estimation of $U_{St}(0)$ in the presence of wind waves (Wu 1983; Toba 1973; Clarke and Gorder 2018).

Unfortunately, direct measurements of real surface drift currents U_d , induced by mechanical waves, are rather limited (according to Bremer and Breivik 2017). For example, Craik (1982) described the depth profile formation of currents induced by different kinds of waves in viscous and contaminated water. Herterich and Hasselmann (1982) provided results for the diffusion of tracers by surface waves. Monismith et al. (2007) presented results for return current formation in a water body of finite depth. Paprota et al. (2016) and Breivik et al. (2014) measured Stokes drift profiles. In all these works, the authors noted a discrepancy between the measured currents $U_{St}(z)$ and the theoretical results (e.g., Longuet-Higgins 1953; Craik 1982; Constantin 2006). However, none of the researchers did quantify the measured surface drift current U_d in comparison with the theoretical value $U_{St}(0)$. This relation needs further specification, and this issue will be addressed in this paper based on tank measurements.

In the case of wind waves, the total surface drift (in the absence of background currents) includes two terms (the case of one-dimensional tank measurements is assumed):

$$U_d = U_{St}(0) + U_{dw}, \quad (4)$$

where U_{dw} is the wind-induced part of the surface drift current U_d . To estimate U_{dw} , the Stokes drift needs to be excluded from U_d in Eq. (4); to this aim, the values of $U_{St}(0)$ are often estimated using Eq. (2). Based on such estimates, previous studies (Wu 1975, 1983; Churchill and Csanady 1983; Longo 2012; Longo et al. 2012; Zavadsky and Shemer 2017) showed that the Stokes drift at the surface $U_{St}(0)$ has a typical empirical value of approximately 10%–15% of the wind-induced drift U_{dw} . This indicates that U_{St} should be taken into account in measurements and practical tasks, especially in the presence of intensive long waves that have high phase velocities (e.g., swell). Moreover, in the field measurements by Clarke and Gorder (2018), the Stokes drift was considered as the total surface drift current, with no attention given to the wind-induced part U_{dw} .

In practice, the wind-induced drift currents U_{dw} have values on the order of the friction velocity in air u_{*a} . With no swell, such currents can be described by the simple ratio (Wu 1975; Longo et al. 2012; Zavadsky and Shemer 2017)

$$U_{dw} = c_d u_{*a}, \quad (5)$$

where coefficient c_d varies in the range from 0.3 in the laboratory measurements (Zavadsky and Shemer 2017) to 0.53 (Wu 1975), and from 0.2 (Babanin 1988) to 1.5 (Tsahalidis 1979) in the field measurements. In all cases, no authors considered the dependence of U_{dw} on specific wave parameters. In the present paper, we address this relation in detail.

FIG. 1. A sketch of the tank. WGs are the wave gauges, PT are the Pitot tubes, ADV is the set of the acoustic Doppler velocimeters, and IP is the set for injecting in water float particles or a color dye. The width of the tank is 1 m.

Until recently, it was unclear why the surface drift current U_{dw} has values on the order of the friction velocity in air u_{*a} rather than the friction velocity in water, $u_{*w} \approx 0.03u_{*a}$, as should follow from the condition of momentum-flux continuity at the interface. Second, it was unknown why the empirical ratio U_d/u_{*a} does not manifest any dependence on wave parameters. Despite of numerous theoretical work in this field (e.g., Huang 1979; Kitaigorodskii et al. 1983; Lumley and Terray 1983; Anis and Moum 1995; Mellor 2001; Rasche and Ardhuin 2009; Chalikov and Rainchik 2011; Babanin and Chalikov 2012; Benilov 2012; Teixeira 2018, and references therein), the answer to these questions was found only in the recent paper by Polnikov (2019).

In Polnikov (2019), a simple semi-phenomenological model was constructed based on the theoretical concept of the three-layer structure of the air–water interface (Polnikov 2011). Processing the numerical simulation data obtained by Chalikov and Rainchik (2011) and Polnikov (2011) showed that the profile of the total drift current, $U_d(z)$, corresponding to Eq. (4), is linearly related to depth z in the so-called “wave zone,” where the air and the water alternatively exist. This finding was empirically confirmed by the measurements of Longo (2012) and Longo et al. (2012) (see details in Polnikov 2019). This means that the wave zone plays the role of a friction layer between the air and the water layers.

Polnikov (2019) proposed that in the wave zone the following ratio is valid

$$\tau_{tw}/\rho_w = K_t \frac{\partial U_{dw}(z)}{\partial z}, \quad (6)$$

where $\tau_{tw}/\rho_w \approx 0.8u_{*a}^2$ is the vertical wind-induced momentum flux in the water, normalized by the water density ρ_w and related to drift current production; $U_{dw}(z)$ is the wind-induced drift; $K_t = f_t(\cdot)U_d h$ is the effective eddy viscosity in the water part of the wave zone, where h is the wave height and $f_t(\cdot)$ is a dimensionless fitting function that depends on surface wave parameters [the symbol $(\cdot)$ indicates the possible dependence of function f on the parameters of the interface]. As the values τ_{tw} and $\partial U_{dw}(z)/\partial z$ are constant in the wave zone, Eq. (6) yields

$$U_{dw} = [C_p/f_t(\cdot)]^{1/2} u_{*a}, \quad (7)$$

where C_p is a constant of the order of air-to-water density ratio ρ_a/ρ_w . Thus, the empirical ratio (5) describing the relation between U_{dw} and u_{*a} is theoretically justified. If the values of $f_t(\cdot)$ vary within the range of 0.01–0.03, ratio (7) quantitatively coincides with ratio (5) [note that in the above consideration, the smallness of $U_{St}(0)$ with respect to U_{dw} is taken into account].

One may expect that the wind-induced drift velocity U_{dw} is dependent on the following dimensionless parameters of the wave state: the steepness $\sigma = ak_p$, the wave age $A = g/(\omega_p u_{*a})$, and the breaking intensity Br. It was suggested in Polnikov (2019) that this dependence could be “hidden” in the fitting function $f_t(\cdot)$. However, the function $f_t(\cdot)$ cannot be theoretically derived because it has a turbulent (statistical) nature. Therefore, the proposed assumption must be empirically verified.

Based on our own direct drift current measurements obtained with surface floats in a tank, the above dependencies were successfully revealed. In parallel, we quantified the ratio between the measured surface drift currents U_d , induced by mechanical waves in water, and the expected Stokes drift $U_{St}(0)$, provided by Eq. (3). Obtaining a solution for the first task is the main objective of our experiment, while the second task is an auxiliary consideration following from the limitations of the studies listed above. On this way, we encountered some methodological difficulties related to measuring the surface drift currents with floats, and these issues are worthy of discussion.

The layout of the paper is as follows. Section 2 describes the equipment and measurement methods used. The results and analysis for mechanical waves and wind waves are presented in sections 3 and 4, respectively. Section 5 contains a general discussion, and the conclusions are given in section 6.

2. Equipment and measurement description

In our experiment, we used the wind-wave tank of the First Institute of Oceanography of the Ministry of Natural Resources (FIO) located in Qingdao, China. A sketch of the tank is shown in Fig. 1.

For the wave measurements, capacity wave gauges (WGs) were used. Pitot tubes (PTs) and three acoustic Doppler velocimeters (ADV) were used to measure the wind profile and current fluctuations, respectively. The dimensions of the tank, water depth, and air space, as well as the equipment locations, are given in Fig. 1. The locations of WG1–WG4 are denoted below as points P1–P4.

The wind is provided by the fan located at the outlet of the tank. Closed air circulation is designed (not shown). The PT set has five channels located at horizons of 7, 10, 14, 25, and 40 cm. For winds greater than 10 m s^{-1} , all the PTs were located 1.2 cm above these levels.

Two kinds of mechanical waves were studied: (i) regular quasi-monochromatic waves and (ii) stochastic waves with a wide spectral band similar to those of PM or JW wave spectra (Komen et al. 1994). These waves were generated by a wavemaker with three initial dominant frequencies f_0 of 1.5, 1.0, and 0.7 Hz and 3–5 amplitudes at each initial frequency, ranging from $H_S = 1 \text{ cm}$ to $H_S = 20 \text{ cm}$ (here, H_S is the programmed significant wave height for generated waves). All these parameters were established in the wavemaker computer.

As another type of wave, wind waves were generated by the fan. The fan wind W is approximately equal to the mean wind speed at the middle of the air part of the tank (i.e., at $z = 40 \text{ cm}$). Five values of wind W were applied: 4, 6, 8, 10, and 12 m s^{-1} .

The wave records were 10 min long with a sampling frequency of 50 Hz, and each run had different wave or wind parameters. The same duration was used for the wind measurements with PT, for which the record averaging over 1-min intervals was performed. The measurements of the surface currents were obtained during these 10 min for each run. The 10-min measurements of the current fluctuations in the water body (at three horizons: -10 , -20 , and -30 cm) were made by an ADV with a sampling of 100 Hz. The description of these fluctuations is beyond the scope of this paper and will be presented in a separate work.

All the measurements were made 5 min after switching on the wavemaker or the fan to allow for system stabilization. In total, 42 runs were executed.

The surface drift current was measured based on the visual timing of the surface floats passing through the fixed length L . The surface floats were spherical plastic balls with bright colors (red, orange, and yellow, to distinguish them on the water surface) and two different diameters of 3 and 5 mm. The specific gravity of the floats was approximately 500 kg m^{-3} . The fixed length L varied from 1 to 5 m based on the expected drift velocity. For each run, the floats' timing was recorded 3–7 times until getting a minimal scattering of the results. An acceptable scattering range is approximately 5%–10% of the mean timing, which defines the empirical accuracy of the drift-current measurements.

For mechanical waves, the drift measurements were made at two drift-starting points: P1 = 9 m and P2 = 12 m. It was assumed that the drift current features for mechanical waves depend weakly on location. The most intensive measurements were made at point P2; the measurements at point P1 were mainly made to check the homogeneity of the current field.

For wind waves, intensive measurements were made at three points: P1, P2, and P4 = 22 m. Small shifts in the locations of P1, P2, and P4 from the actual locations of WGs occurred due to technical reasons.

The floats were injected to the tank space with special equipment, IP, which included a 3-mm aluminum tube that was vertically fixed at the roof of the tank and continued to the level of 10 cm above the still water surface. Inside this tube, there was a 1 mm (capillary) flexible tube that was used to inject dye into the water at a fixed depth to study the wave-induced turbulent diffusion (this topic is beyond the scope of this paper). For each set of drift measurements, 2–3 plastic floats were simultaneously added to the tank at a point located 5–10 cm in front of the drift-starting point for each run. Several technical problems related to using spherical floats in this task will be discussed in section 5. The processing of the drift current data was performed without any software, as no records were collected with the equipment used.

The wave and wind data were processed with the MATLAB software. For the wave spectra evaluation, the autoregression (AR) and Welch methods were used. Because the data series had 30 000 points (more than 1000 dominant periods), the 95% confidence intervals were very small (approximately 1500 degrees of freedom). In the bilogarithmic coordinates, they were $[+10\%, -12\%]$ and $[+15\%, -20\%]$ for the AR method and the Welch method, respectively. The frequency spectra $S(f)$, shown in this paper, were estimated with the AR method and are presented based on the circular frequency f given in hertz (instead of the theoretical giving spectrum in the radian frequency, $\omega = 2\pi f$) (shown in Fig. 2).

The intensity of wave breaking (in percent) was visually fixed based on the relative numbering of the broken wave crests with respect to the total number of dominant crests. This numbering process was executed by two persons in parallel watching the dominant crests moving between points P2 = 12 m and P4 = 22 m during one minute of observation just before the main measurements were made. The intensity of the micro-breaking of small-size crests was not fixed.

3. Mechanical waves: Results and analysis

Regular (narrowband) and irregular (wideband) mechanical waves were considered separately. The results for the first kind of wave are described in detail, and these details are not repeated for the second kind of wave. The analysis of all the results is combined.

a. Results for regular waves

The results are summarized in Table 1. First, we should note a reasonable (up to 30%) difference between the estimations of the surface Stokes drift U_{St} found with Eqs. (2) and (3) (hereafter, the notation of the surface level, $z = 0$, is omitted for simplicity). An example of the relation between these estimates of U_{St} for regular waves is shown in Fig. 3a, and an example of the spectrum for narrowband waves, used to get the above estimations, is shown in Fig. 2a. Importance of using Eq. (3) is evident. Notably, in the integral of Eq. (3), we restricted the upper boundary at $f_{\max} = 15 \text{ Hz}$ due to the accuracy restrictions of the WGs with a 1-mm wave height. The

FIG. 2. Spectra at point P2 for waves with $H_s = 3$ cm, $f_p = 1.5$ Hz: (a) regular waves and (b) irregular waves. The 95% confidence intervals, shown by small bars, are on the order of $[+10\%, -12\%]$.

difference between the mentioned estimates suggests that Eq. (3) is the more accurate equation. Hereafter, only such estimations of U_{St} are presented.

The second peculiarity of the measurements is that the ratio U_d/U_{St} varies in the range of 0.5–0.8 (the second-to-last column in Table 1), reflecting a permanent underestimation of the expected surface Stokes drift. Specifically, there is no evident dependence of this ratio on the intensity of wave breaking (presented in the rightmost column in Table 1). Following the review by Bremer and Breivik (2017), the estimates of U_d/U_{St} for the tank measurements are pioneering, despite numerous empirical reports of the abovementioned discrepancies

between measurements and theoretical values. A more detailed analysis will be made in section 3c.

b. Results for irregular waves

These results are summarized in Table 2. In this case, the peculiarities are similar to those in the previous case. The role of spectral shape is well shown in Figs. 2a,b and 3a,b. From these figures, one can see that for a wideband spectrum, the estimates of U_{St} based on Eqs. (2) and (3) can be more than 2 times different.

The additional difference in the surface drift for irregular waves is a slightly greater ratio U_d/U_{St} varying from 0.6 to 0.9. In this case, the integral in Eq. (3) should be greater due to the

TABLE 1. Parameters of waves and surface currents for regular waves. Note that the two values for the Stokes drift, separated by a slash, correspond to the estimations with Eqs. (2) and (3), respectively; “n-dim” indicates nondimensional.

Paddle H_S (cm)	Wave amplitude a (cm)	Peak frequency f_p (Hz)	Peak frequency ω_p (s ⁻¹)	Peak wavenumber k_p (m ⁻¹)	Steepness $\bar{O}$ (n-dim)	Stokes drift U_{St} (cm s ⁻¹)	Mean drift U_d (cm s ⁻¹)	U_d/U_{St} (n-dim)	Intensity of breaking (%)
Paddle frequency $f_p = 1.5$ Hz									
3	1.36	1.49	9.36	8.9	0.12	1.5/1.7	1.35	0.79	No breaking
5	2.13	1.49	9.36	8.9	0.19	3.8/4.1	3.1	0.76	<10%
7	2.76	1.485	9.33	8.9	0.25	6.4/7.8	5.6	0.72	30%
10	3.20	1.48	9.29	8.8	0.28	8.3/11.7	9.1	0.78	50%
15	Data are not reliable due to bad wave formation								
Paddle frequency $f_p = 1.0$ Hz									
3	1.03	1.0	6.28	4.0	0.041	0.27/0.36	0.26	0.72	No breaking
5	1.74	1.0	6.28	4.0	0.070	0.77/0.98	0.71	0.72	—
7	2.45	1.0	6.28	4.0	0.10	1.54/1.90	1.43	0.75	—
10	3.48	1.0	6.28	4.0	0.14	3.1/3.5	2.5	0.71	—
15	5.03	1.0	6.28	4.0	0.20	6.3/8.2	4.5	0.55	<10%
Paddle frequency $f_p = 0.7$ Hz									
≤10	Data are not reliable due to bad wave formation								
15	3.70	0.7	4.4	1.97	0.073	1.2/1.4	1.1	0.78	No breaking
20	5.03	0.7	4.4	1.97	0.10	2.2/2.6	1.3	0.50	—

FIG. 3. Relation between the Stokes drift estimations with Eq. (2), U_{st2} , and with Eq. (3), U_{st3} . (a) Regular mechanical waves (Table 1): the solid trend line ($y_1 = 1.30x_1$) corresponds to $f_p = 1.5$ Hz; the dashed trend line ($y_2 = 1.27x_2$) corresponds to $f_p = 1.0$ Hz; the dotted trend line ($y_3 = 1.18x_3$) corresponds to $f_p = 0.7$ Hz. (b) Irregular waves with PM spectra (Table 2): the solid trend line ($y_1 = 1.98x_1$) corresponds to $f_p = 1.5$ Hz; the dashed trend line ($y_2 = 2.73x_2$) corresponds to $f_p = 1.0$ Hz.

consideration of a wider spectral band than in the previous case (Fig. 2b); therefore, the only explanation for the higher values of U_d/U_{st} is accounting for the small steepness $\mathcal{O}$ of irregular waves (see Table 2). Theoretically, it is reasonable to assume that for smaller wave steepness values, the observations of U_d should be closer to the theoretical values (Stokes 1847).

c. Combined analysis of mechanical waves

The presented results are novel, despite numerous empirical reports on the discrepancies between measurements and theoretical values of Stokes drift [e.g., Craik (1982), Breivik et al. (2014), Paprota et al. (2016), and so on, to the review by Bremer and Breivik (2017)]. Notably, for the first time, we

obtained empirically quantified ratios U_d/U_{st} for regular and irregular mechanical waves in a tank. These ratios are interesting from three points of view: (i) understanding the reasons for the empirical underestimation of the surface drift currents, (ii) methodical points of measurements, and (iii) identifying possible applications of these results.

Underestimating U_d is not new; nevertheless, this issue requires separate consideration. The following reasons for the empirical underestimation of surface drift currents in experiments are well known: (i) the viscosity of the water (which disrupts the potentiality of wave motion), (ii) return currents, (iii) water surface contamination, and (iv) the sailing of floats, including dynamic-pressure braking (McNally and

TABLE 2. Parameters of waves and surface currents for irregular waves; “n-dim” indicates nondimensional.

Paddle H_S (cm)	Wave amplitude a (cm)	Peak frequency f_p (Hz)	Peak frequency ω_p (s ⁻¹)	Peak wavenumber k_p (m ⁻¹)	Steep ness $\bar{\mathcal{O}}$ (n-dim)	Stokes drift U_{St} (cm s ⁻¹)	Mean drift U_d (cm s ⁻¹)	U_d/U_{St} (n-dim)	Intensity of breaking (%)
Paddle frequency $f_p = 1.5$ Hz, PM spectra									
3	0.86	1.335	8.38	7.16	0.062	0.89	0.69	0.77	No breaking
5	1.26	1.13	7.09	5.13	0.065	1.1	0.66	0.60	—
7	1.56	1.01	6.34	4.1	0.064	1.26	1.11	0.88	—
10	1.89	0.92	5.8	3.40	0.064	1.39	1.3	0.93	—
15	Data are not reliable due to bad wave formation								
Paddle frequency $f_p = 1.0$ Hz, PM spectra									
For $H_S < 10$ cm the data are not reliable									
10	1.90	0.84	5.28	2.84	0.054	1.49	1.0	0.67	No breaking
15	2.25	0.77	4.84	2.38	0.054	1.60	1.2	0.75	<10%
Paddle frequency $f_p = 1.0$ Hz, JW spectra									
For $H_S < 10$ cm the data are not reliable									
15	3.42	0.97	6.09	3.78	0.13	4.8	2.8	0.58	100%
Paddle frequency $f_p = 0.7$ Hz, JW spectra									
For $H_S \leq 10$ cm the data are not reliable									
15	2.83	0.705	4.43	2.0	0.056	2.4	1.5	0.62	<10%

White 1985). The first three reasons were discussed in previous studies (e.g., Longuet-Higgins 1953; Craik 1982; Herterich and Hasselmann 1982; see also Breivik et al. 2014; Paprota et al. 2016). We cannot add more to this discussion, noting that the first two reasons are inevitable and cannot be regulated; however, the third influence can be minimized by cleaning the water surface after each change in frequency, thus the third item should be excluded from the list of reasons discussed. Therefore, we do not dwell on the first three reasons, but the phenomenon of the float sailing is worthy of discussion.

Besides the return current influence (Monismith et al. 2007), which cannot be quantified in our case, in our mind, the sailing of floats on the water surface is the main reason for the above-mentioned discrepancy between the experimental and theoretical values of the Stokes drift. To validate this assumption, we tried to regulate the effect of sailing by choosing different sizes of floats. Indeed, when we used plastic balls with a diameter of 5 mm as the floats, the drift current values were fixed at values in 20%–30% smaller than those for floats that were 3 mm in diameter. Thereby, the assumption stated above is justified.

The nature of the sailing process is relatively evident. In the case of mechanical waves and spherical floats, the sailing has two negative constituents, namely, the air and the water components. The air component is associated with the air-induced resistance to float propulsion due to the viscosity and negative dynamic pressure of the ambient motionless air. On the other hand, the water sailing is influenced by the same manner due to the rapid decrease in the total drift current with depth, described by profile $U_d(z)$. For mechanical waves, this decrease follows from Eq. (3). In the case of wind waves, the rapid decrease in the wind-induced current $U_{dw}(z)$ has been empirically shown by Longo et al. (2012) and described in Polnikov (2011, 2019).

These considerations account for mismatch between theoretical and experimental values, and one may go on to methodical points of the surface-drift current measurements.

From a methodological perspective, a number of previous experiments (e.g., Wu 1975, 1983; Zavadsky and Shemer 2017), in which the volumetric surface floats were used, have suffered from the abovementioned problems, resulting in the underestimation of surface drift in these experiments. Therefore, it is important to make certain methodological changes when obtaining future measurements. To avoid the sailing of floats, it is reasonable to use floats that are fully flat. For example, floats could be pieces of thin flexible tissue (similar to gauze) with a net density less than that of water. Such experiments have been performed in the past (see references in Tsahalidis 1979), and they should be planned in the future to further improvement the results presented above.

Another alternative approach involves using PIV methods (e.g., Longo et al. 2012; Paprota et al. 2016) or the laser-warming method (thermal-marking velocimetry) (Savelyev et al. 2012) to measure surface drift currents. However, due to technical reasons related to the optical equipment location, such methods are mainly appropriate for small tanks. But in such cases, the tank boundaries could result in additional sources of errors. Another problem associated with using the optical methods to obtain current measurements in tanks is the restriction to equipment location and movement along a tank.

Ideally, technical progress will help overcome the mentioned methodological problems.

In practical applications, the obtained results can be used as the first guess for expected drift current estimates in the engineering of harbors and other marine infrastructure, taking in mind the influence by swell. On other hand, from the physical point of view, the presented results are useful for accurately estimating the observed wind-induced drift currents U_{dw} , based on Eq. (4). It is this idea (rather than simple estimating ratio U_d/U_{St}) was stimulating our measurements of surface drift currents U_d for mechanical waves, the results of which will be actively used below in the data analysis for wind waves.

4. Wind waves: Results and analysis

The results for wind waves are summarized in Table 3, where the following notations are used: $\bar{\sigma} = ak_p$ is the mean wave steepness, $A = g/(\omega_p u_*)$ is the wave age, and u_* is the friction velocity in the air. The last column in Table 3 is the main result of this work, demonstrating the correspondence between empirical and parametrical values of the ratio U_{dw}/u_* . We return to its analysis later, after considering the accuracy of the results.

a. Analysis of the accuracy of the results

First, let us estimate the accuracy of the results starting with the wind parameter u_* . The friction velocity u_* is usually obtained from Pitot tube measurements based on the traditional assumption of a logarithmic wind profile (Wu 1975; Longo 2012; Zavadsky and Shemer 2017). In our case, only three upper tubes of the PT set provide relatively accurate estimations of u_* . The mean error of these estimations, obtained using Microsoft Excel, is 5%–7%. It is important to note that the values of u_* (as well as U_d) reasonably increase with the fetch (in 1.5–2 times), what is typical for the tank measurements (Toba 1973; Longo 2012; Longo et al. 2012). This fact should be taken into account to obtain accurate values of U_{dw}/u_* based the data obtained in different parts of a long tank.

The wave parameters $\omega_p = 2\pi f_p$, $\bar{\sigma}$, and A were estimated with very high accuracy (errors less than 1%) from the wave spectra calculated within the MATLAB software (see section 2). For the completeness of the wind-wave spectra description, their spatial evolution is presented in Fig. 4. Due to a wide spectral band for wind waves, using Eq. (3) is quite important for estimation of theoretical value for the Stokes drift. In our case, these values have errors of approximately 5%–7%, what is defined mainly by the value of the upper limit of the integral in Eq. (3). It was chosen to be 15 Hz due to the technical restrictions of the WGs used. As shown in Fig. 4, the wave spectra are radically changing along the tank (this feature was ignored for mechanical waves), therefore the theoretical estimates of U_{St} are also varying, which plays a crucial role in the correct estimating the wind-induced drift currents U_{dw} based on using Eq. (3).

The visually obtained float movement timing resulted in the error on the order of 10% for the measured total mean drift U_d . In turn, the intensity of wave breaking was estimated (by two persons in parallel) with the same error. These values influence

TABLE 3. Parameters of wind, waves and surface currents for wind waves. Note that the $\leftrightarrow$ sign separates the empirical and parametrical values U_{dw}/u_* estimated with Eq. (8); “n-dim” indicates nondimensional.

Fan wind W (m s^{-1})	Friction velocity u_* (cm s^{-1})	Peak frequency ω_p (s^{-1})	Steepness σ (n-dim)	Wave age A (n-dim)	Stokes drift U_{St} (cm s^{-1})	Mean drift U_d (cm s^{-1})	Wind drift U_{dw} (cm s^{-1})	Intensity of breaking, (Br; %)	Empirical $\leftrightarrow$ parametric U_{dw}/u_*
Measurements at P1 = 9 m									
4	8.2	28.1	0.27	4.3	2.38	12.5	10.1	No breaking	1.2 $\leftrightarrow$ 1.16
6	11.7	24.9	0.29	3.4	4.92	16.7	11.8	—	1.0 $\leftrightarrow$ 1.1
8	14.4	20.1	0.34	3.4	6.89	23.5	16.6	—	1.1 $\leftrightarrow$ 1.1
10	20.4	18.0	0.33	2.72	9.58	30.8	21.2	5%	1.1 $\leftrightarrow$ 0.94
12	28.2	17.1	0.37	2.0	12.4	36.4	24.0	10%	0.86 $\leftrightarrow$ 0.84
Measurements at P2 = 12 m									
4	9.5	22.0	0.26	4.7	4.54	13.5	8.95	No breaking	0.98 $\leftrightarrow$ 1.2
6	14.2	18.1	0.26	3.8	5.93	17.6	11.7	—	0.82 $\leftrightarrow$ 0.99
8	17.7	16.6	0.28	3.34	7.77	22.2	14.4	—	0.81 $\leftrightarrow$ 0.93
10	25.4	14.6	0.29	2.64	10.6	33.3	22.7	10%	0.89 $\leftrightarrow$ 0.87
12	34.3	12.9	0.28	2.2	13.9	40	26.1	20%	0.78 $\leftrightarrow$ 0.82
Measurements at P4 = 22 m									
4	12.5	16.2	0.19	4.8	3.35	14.3	11.0	No breaking	0.88 $\leftrightarrow$ 0.91
6	17.5	14.1	0.21	3.98	5.25	20.0	14.7	—	0.84 $\leftrightarrow$ 0.83
8	27.8	12.9	0.25	2.73	7.9	26.7	18.9	—	0.68 $\leftrightarrow$ 0.68
10	40.0	11.5	0.27	2.13	11.5	40	28.5	15%	0.71 $\leftrightarrow$ 0.71
12	53.0	10.8	0.29	1.7	15.5	50	34.5	20%	0.65 $\leftrightarrow$ 0.7

the accuracy of the empirical results for the wind-induced drift currents U_{dw} .

b. Analysis of the main results

In the case of wind waves, we estimated the wind-induced drift currents as the difference between the measured value U_d and the theoretically estimated value U_{St} by assuming that the positive floats sailing in the air (due to the wind) is compensated for by the negative floats sailing in the water. This assumption was verified by the measurements with plastic balls of different diameters (3 and 5 mm) used as the floats. This means that the values of U_{dw} presented in Table 3 are the smallest possible values, taking in mind the results for mechanical waves discussed above in section 3a.

Based on Table 3, the determined empirical ratio U_{dw}/u_* varies in the wide range of 0.65–1.2, which corresponds to the range presented in the literature (see section 1b). This peculiarity of our results will be separately discussed below in section 5, but here, the main attention is paid on identifying the proper parameterization for the dependence of ratio U_{dw}/u_* on the parameters of the system under consideration. The theoretical basis for such parameterization is the following.

According to the theoretical model of the wind-induced drift currents proposed in a previous study (Polnikov 2019), one may expect U_{dw}/u_* to be dependent on the following wave parameters: steepness $\sigma = ak_p$, wave age $A = g/(\omega_p u_*)$, and breaking intensity (Br). After several attempts (see the assumption for the general approximation below), we obtained the following relation:

$$U_{dw}/u_* = \text{Br} + \sigma A. \quad (8)$$

In a graphic form, the relation between the empirical and parametrical values of U_{dw}/u_* is shown in Fig. 5. From Table 3

and Fig. 5, it is seen that parameterization (8) is valid with a mean error of approximately 10%, which is very good for experimental data.

Equation (8) provides the dependence relation between the wind-induced surface drift currents and the wind and wave parameters, which is the main aim of this paper. This dependence is

FIG. 4. Wind-wave spectra at points P1, P2, and P4 for the run with $W = 8 \text{ m s}^{-1}$. The straight line with digits shows the frequency-decay law of spectra in the tail range (the error is $\sim 3\%$).

FIG. 5. Correspondence between empirical and parametrical values of ratio U_{dw}/u_* estimated with Eq. (8) for wind waves. The trend line is described by the equation $y = 1.03x$ with a mean accuracy of 10%.

established for the first time during a long history of empirical investigations (section 1a). Below, it will be shown that ratio (8) corresponds relatively well to the results published earlier for the tank measurements (Wu 1975; Longo 2012; Longo et al. 2012; Zavadsky and Shemer 2017). In the future, parameterization (8) could be checked for the field data based on accurate measurements of wind and wave parameters.

5. Discussion

In this section, we discuss the following points: (i) the impact of tank dimensions and wind variations along a tank on the accuracy of estimates of u_* ; (ii) the role of theoretical estimates of the Stokes drift in assessing empirical measurements; (iii) the application of a parametric representation of ratio U_{dw}/u_* for other empirical data; and (iv) adjusting the methodology to minimize the float sailing in traditional and alternative approaches.

First, we should mention that the small dimensions of tanks used in some studies (Wu 1975; Longo et al. 2012; Zavadsky and Shemer 2017) could reasonably restrict the accuracy of the wind and wave measurements. Evidently, in such cases, the upper and lateral boundaries of tanks are the sources of errors in the wind profile measurements and, consequently, the estimations of u_* . The main reason for these errors is that the theoretical logarithmic profile cannot be fully formed in small tanks (Troitskaya et al. 2012), which leads to overestimating the wind gradient $\partial W/\partial z$, and consequently, overestimating the friction velocity u_* . For wind waves with mean heights $a > 2\text{--}3\text{ cm}$ (corresponding to significant heights $H_S > 6\text{--}9\text{ cm}$) in tanks with air-part heights less than 0.5 m (e.g., Toba 1973; Wu 1975; Longo 2012; Zavadsky and Shemer 2017), due to the reasons mentioned, the values of u_* could be overestimated. Moreover, tanks with working lengths less than 5–8 m, they usually use only one point for the wind profile measurements, thereby neglecting information about the wind profile changes

along a tank. Additionally, it is difficult to provide a wide range of wave parameters in a small tank, which restricts the possibility of revealing the dependence of drift currents on the parameters of the wave state. All these factors explain why we have observed greater values of U_{dw}/u_* than those previously reported, and established the dependence of U_{dw} on the wind-wave parameters, which was not fixed in the earlier laboratory work (Wu 1975; Longo 2012; Longo et al. 2012; Zavadsky and Shemer 2017).

Regarding the Stokes drift estimations, in the presence of mechanical waves, the current measurements inevitably underestimate the wave-induced drift at the water surface with respect to the theoretical value U_{St} . In turn, as shown in section 3, the theoretical estimates of U_{St} with Eq. (2) that are typically used in practice (e.g., Toba 1973; Wu 1975; Longo 2012; Longo et al. 2012) are incorrect. Therefore, the reported ratio between U_{St} and U_{dw} was underestimated, the value of which was fixed at approximately 15% (Toba 1973; Wu 1975; Longo et al. 2012). The more accurate estimates, especially in the presence of wind waves with wideband spectra, can be obtained with using Eq. (3). In such a case, as shown in Table 3, the ratio U_{St}/U_{dw} could reach values of 35%–40%. This circumstance is very important from a practical perspective. Of course, all these results should be checked again in future experiments conducted with highly accurate measurements.

Regarding the wind-induced drift parameterization, the general assumption is of the form

$$U_{dw} = [C_b Br^k + C_w \sigma^m (A)^n] u_*, \quad (9)$$

where factors C_b , C_w , and power parameters k , m , and n are the fitting dimensionless constants. Based on the trial-and-error method, we found that the simplest version of Eq. (9) has the form of Eq. (8), when all the parameters are equal to unity. According to Table 3, Eq. (8) provides a relatively good approximation, with a mean error for the value U_{dw}/u_* of 10%. The only weakness of parameterizations (8) and (9) is their dependence on the breaking intensity, which is difficult to estimate empirically. This issue requires additional consideration in the future.

At meanwhile, it is interesting to apply parameterization (8) to the other known results. For example, for results of the classical work by Wu (1975), we obtained the following findings. From Figs. 2 and 3 in Wu (1975), typical values for the wave parameters are $a = 0.02\text{--}0.03\text{ m}$, $\omega_p = 12.5\text{ s}^{-1}$, while $u_* = 0.5\text{--}0.6\text{ m s}^{-1}$, in the case of the tunnel wind $W = 10\text{ m s}^{-1}$. These values yield $\sigma A = a\omega_p/u_* \approx 0.5$, which, according to Eq. (8) in the case of no breaking, corresponds very well to the value $U_{dw} \approx 0.53u_*$ reported in Wu (1975).

Addressing the data from Longo (2012) and Longo et al. (2012), we obtained the following findings. From Tables 1 and 3 of Longo (2012), the typical wave parameters are $a \approx 0.002\text{--}0.003\text{ m}$ and $\omega_p = 30\text{--}40\text{ s}^{-1}$, which resulting in $\sigma \approx 0.2$, for a tunnel wind of $W = 10.9\text{ m s}^{-1}$. From Table 1 of Longo et al. (2012), in this case, $u_* = 0.6\text{--}0.7\text{ m s}^{-1}$. These values yield $\sigma A \approx 0.2$. According to Longo et al. (2012), the breaking intensity Br is approximately of 20% (which is very likely for $\sigma \approx 0.2$), thus

parameterization (8) results in the value $U_{dw} \approx 0.4u_*$ reported in Longo et al. (2012).

In Zavatsky and Shemer (2017), the analogous data for wind $W = 10.5 \text{ m s}^{-1}$ are as follows: $a \approx 0.01 \text{ m}$, $\omega_p \approx 15 \text{ s}^{-1}$, and $u_* \approx 0.7 \text{ m s}^{-1}$ (from their Fig. 8). According to (8), these values lead to the estimate $U_{dw} \approx 0.3u_*$, which is close to the reported value in this paper.

As one can see, parameterization (8) works well in all these cases. Similar examples can be explored for the other experimental works mentioned above if the proper data are supplied.

Finally, the methodology should be discussed. Naturally, using hard surface floats to measure surface drift currents seems obsolete. The more advanced methods are PIV (e.g., Longo 2012; Longo et al. 2012; Paprota et al. 2016) or laser-warming methods (Savelyev et al. 2012), although they cannot be used in large tanks due to the need to apply many optical devices through transparent tank boundaries and restrictions related to moving optical equipment throughout the tank. Most laboratories have no such equipment at their disposal. Nevertheless, traditional floats can still provide reasonable results.

The main problem, in this case, is the sailing of floats, as discussed in detail in section 3c. This problem could be overcome if one uses appropriate floats. The solution is to use flat floats in the form of pieces of thin flexible tissue (like gauze) with a net density less than that of water. If the width of the tissue is 0.1 mm, the sailing of the floats will be negligibly small; thus, they would not be disturbed by the wind or the vertical shear of drift currents. In such a case, the results of the drift measurements would be more accurate than in most other cases, what suggests that one could plan similar experiments in the near future. Thus, the best choice is to use tanks with lengths greater than 30 m, widths greater than 1 m and air part of approximately 1 m or more to ensure correct estimations of the friction velocity u_* , as discussed above. Under these conditions, the results presented in this paper could be further evaluated.

6. Conclusions

Finally, we state the following conclusions.

First, the surface drift currents U_d induced by mechanical waves in a tank were measured with plastic surface floats and compared with the Stokes drift at the surface U_{St} estimated by Eq. (3). The ratio U_d/U_{St} varies in the range of 0.5–0.93 and slightly increases with decreasing wave steepness, with no visible dependence on the breaking intensity. The reduction in empirical values of U_d with respect to the theoretical value U_{St} is mainly due to the following reasons: return currents, fluid viscosity, and the sailing of floats in the air and in the water. The significant effect of the latter reason could be minimized by using flat and flexible tissue floats or by employing modern optical methods to collect surface current measurements.

Second, in the case of wind waves, the wind-induced part of the surface drift U_{dw} was estimated by subtracting the theoretical value for the Stokes drift U_{St} found with Eq. (3) from the measured total drift U_d at three locations along the tank for a series of wind speeds. These values of U_{dw} were compared with the friction velocity u_* measured at the same three locations.

The obtained ratio U_{dw}/u_* varies systematically in the range of 0.65–1.2.

Third, the obtained ratio U_{dw}/u_* was parameterized by Eq. (8). For the first time, the dependence of the wind-induced drift current U_{dw} on the wave state parameters was found. The parameterization (8) corresponds to observations with a mean error of less than 10%. The application of parameterization (8) to other known results for measurements of U_{dw} and u_* in tanks showed encouraging results (see section 5).

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Data availability statement. The raw measurement data are available from the corresponding author (V. Polnikov).

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