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EXPLORING THE UPPER DECIMETER OF A WIND DRIVEN WATER BODY

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Management Perspective

The properties of the very thin layer (a few centimeters thick) at the top of a water body determines the mass transfer rate for most toxic anthropogenic gases. Consequently, a great deal of effort is put into measuring and understanding the mechanical properties of this layer. This paper describes a new method of estimating the velocity profile in this layer. The method uses the measured propagation speed of surface waves as a tracer of the velocity profile. It has the considerable merit that the measurements, like the waves, are referenced to the moving surface rather than a fixed probe. This is a short version of 'Drift Velocity Profiles as Inferred from Measurements of Surface Wave Celerity', by F. J. Ocampo-Torres and M. A. Donelan for early publication as a letter in Nature.

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PERSPECTIVE DE LA DIRECTION

Les propriétés de la très mince couche supérieure (quelques centimètres d'épaisseur) d'un plan d'eau déterminent la vitesse de transfert de masse pour la plupart des gaz toxiques se retrouvant dans l'environnement suite aux activités de l'homme. Beaucoup d'efforts sont donc consacrés à la mesure et à la compréhension des propriétés mécaniques de cette couche. On décrit dans le présent article une nouvelle méthode d'estimation du profil de vitesse dans cette couche. À cette fin, on a utilisé des données de mesure de la vitesse de propagation des vagues de surface comme marqueurs du profil de vitesse. Cette approche possède l'immense avantage que les mesures, comme les vagues, sont considérées par rapport à la surface en mouvement contrairement à une sonde fixe.

RÉSUMÉ

Le profil de vitesse dans les premiers décimètres d'une colonne d'eau a été évalué. La méthode employée repose sur l'utilisation d'un rayon laser pour effectuer, en un même endroit, des mesures non perturbatrices de la hauteur et de la pente de la surface de l'eau. On a montré que ces mesures permettent d'estimer le nombre d'onde apparent (comme fonction de la fréquence) des vagues soulevées par le vent. Bien qu'une approche axée sur la distribution verticale des vitesses induites par les vagues entraîne des difficultés au niveau des calculs, elle offre néanmoins les moyens de déduire le profil de vitesse à partir de l'excès (par rapport à la théorie) de célérité des différentes composantes du spectre. Il est ainsi possible de reconstruire le profil de vitesse s'appliquant à la couche située à moins de quelques millimètres de la surface en mouvement soumise à l'action de vagues beaucoup plus grandes.

Exploring the upper decimeter of a wind driven water body.

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Abstract

The velocity profile in the upper decimeter of the water column is estimated. The method hinges on the use of a laser beam to make non-intrusive co-located measurements of elevation and slope of the water surface. It is demonstrated that these measurements allow the estimation of the apparent wavenumber (as a function of frequency) of the wind generated waves. The structure of the wave induced-velocities both leads to computational difficulties and provides the means to deduce the velocity profile from the excess (over theory) celerity of various components of the spectrum. The velocity profile is reconstructed to within a few millimiters of the moving surface excited by waves an order of magnitude higher.

The interface between atmosphere and oceans has long been an active area of study by fluid dynamicists, oceanographers and meteorologists. In recent years particular attention has been focused on the very thin (a few centimeters) layer just beneath the surface for it is there that the principal resistance to gas transfer occurs for most environmentally significant gases, both natural and anthropogenic. Furthermore, the small waves that determine the reflectivity of the ocean to microwave radar probing are affected by the currents in this thin layer.

The interface is highly mobile and consequently frustrates attempts to measure its properties with any accuracy. In all but the lightest winds the surface is covered by a spectrum of waves of varying wavelengths. Longer waves make their presence felt to greater depths and, conversely, are affected by flow fields at greater depths. These wind-generated waves are natural tracers of the flow field near the surface. In this article we explore the idea that the apparent phase speed of waves on the surface may, by comparison with expected phase speeds, yield useful information on the flow structure of the very near surface layers. The apparent phase speeds are deduced from spectral estimates of elevation and slope at a common point in a laboratory tank using a single beam of laser light for both measurements.

It has been previously suggested that the difference between theoretical and experimental estimations of phase celerity is due to wind drift [1, 2]. However, even if some of the discrepancies between experimentally estimated phase speed had been already clarified [3], no attempt had been made prior to the experiments reported here, to relate the theoretical and experimental phase speed difference to the drift velocity profile in the upper decimeter of the water column, properly accounting for the wave orbital velocity and the depth dependence effects. Backscattering of high frequency radio waves (2 - 20 MHz) from the ocean surface have shown a wavelength dependence of the difference in measured wave speed with respect to the theoretical value [4], suggesting that different frequencies would lead to probing the mean currents at different levels. The use of these frequencies with wavelengths of the order of meters to tens of meters, allowed some current estimations in the upper meters of the water column, when a logarithmic current profile was assumed. Higher frequencies (up to 30 MHz) were used to estimate the current at four discrete levels in the upper 1 or 2 m of the ocean [5]. However, a predetermined current profile shape was still needed. Since we are dealing with shorter surface waves and their measured properties allow us to estimate the spectral quantities continuously over a frequency range from about 10 to over 100 rad/s, the resultant drift current profile represents some unique measurements in the uppermost part of the water column. Furthermore, we require no apriori assumption of the velocity profile shape.

The experiments were conducted in the 32.2m long Gas Transfer Flume at the National Water Research Institute [6]. Wave slope and elevation were measured at 5.3m fetch by a 25 mW argon-ion laser based system, for 5 and 9.5m/s wind speed. The measurement methods are similar to those previously reported [7, 8]. Subsequently uniform currents of 20 and 40 cm/s were imposed with the use of a water pump. Measurements at longer fetches with similar and lower wind speeds, as well as a more detailed discussion and modelled results on the effect of the wave orbital velocities are presented elsewhere [9].

Time series of water surface slope and elevation 32768 data points long were processed with a standard FFT routine to estimate the frequency spectra $S_x(\omega)$,$S_y(\omega)$, and $S_\eta(\omega)$, with 128 degrees of freedom. The observed frequency ω, is related to the intrinsic frequency σ, through

$$\omega = \sigma + \mathbf{k} \cdot \mathbf{U} \tag{1}$$

where $\mathbf{k} = (k_x, k_y)$ is the wavenumber (vector) and $\mathbf{U}$ = (U,V) is the velocity advecting the waves, with along-wind (k_x and U) and cross-wind (k_y and V) components. This advecting velocity, can be considered as the sum of the wave- and wind- induced drift and the imposed (pumped) current. In addition, the long wave orbital velocity, shifting back and forth the shorter waves, also contributes to U, and influences the instantaneous measurements. The sum of the drift contribution and the pumped current is the quantity we wish to measure.

The wavenumber can be estimated through the relation between slope and elevation spectra

$$S_\eta = k^{-2}(S_x + S_y) \tag{2}$$

where k is the modulus of k. Equations (1) and (2) may be combined with the theoretical dispersion relation $\sigma(k)$ to yield the drift current U. The orbital velocities of the longer waves cause some smearing of the slope and elevation spectra, but these can be accounted for [9] to allow an accurate estimation of the drift current.

This particular version of the drift current is given as a function of frequency (or wavenumber), and it is the depth dependence that interests us. Our measurements are limited to the surface expression of the waves (slope and elevation) and hence to the propagation rate of wave potential energy. To assign an appropriate weighting of the effect of the drift current profile on the propagation of wave potential energy, we make use of the equipartition of potential and kinetic energy in a wave field and assess the effect of the current on the vertically distributed kinetic energy. For any given wavenumber k the average rate of advection of wave kinetic energy is:

$$U_e(k) = \frac{\int_{-\infty}^{0} U_d(z) E_k(z)\, dz}{\int_{-\infty}^{0} E_k(z)\, dz} \tag{3}$$

where the value of $U_e(k)$ at each level z is being affected by the kinetic energy $E_k(z)$ at that level and all levels above. In practice the integrals in equation (7) are evaluated from the depth of the deepest measuring point ($z = z_2$) to the closest to the surface ($z = z_1$), and an iterative procedure is adopted to find the drift current $U_d(z)$ for which $U_e(k)$ = the measured $U(k)$.

Measurements were performed for wind speeds of 5 and 9.5 m/s. Examples of the corresponding spectra are shown in figure 1. Subsequently uniform currents (20 and 40 cm/s) were imposed with the use of a water pump. The wind drift profiles for these cases are shown in figure 2. The cases where no pump current is imposed clearly show a shear layer in the upper centimeters, with an obviously higher drift velocity for the highest wind case. The pumped current cases confirm the validity of the proposed method to estimate the drift current, as an average 20 cm/s difference is encountered between cases (a) and (b), and cases (b) and (c).

Since the waves are being used as tracers, the maximum depth of the estimated drift profile depends on the length of the waves present. The longer waves developed by the 9.5 m/s wind action allowed us to probe down to about 2 cm beneath the surface, while the maximum depth of the profile for the case of 5 m/s wind was only about 1 cm. We were able to measure the drift profile as close as 7 mm beneath the surface for the case of 9.5 m/s wind and up to 2 to 3 mm for 5 m/s wind.

Our measurements demonstrate the potential of the method and we are currently improving the design of the elevation measuring apparatus in order to be able to explore the development of the profile at greater fetches (ie. in the presence of larger waves). Ultimately, we would like to know the turbulence levels near the interface and there is reasonable hope that detailed velocity profiles coupled with suitable turbulence models will help lead us to this goal.

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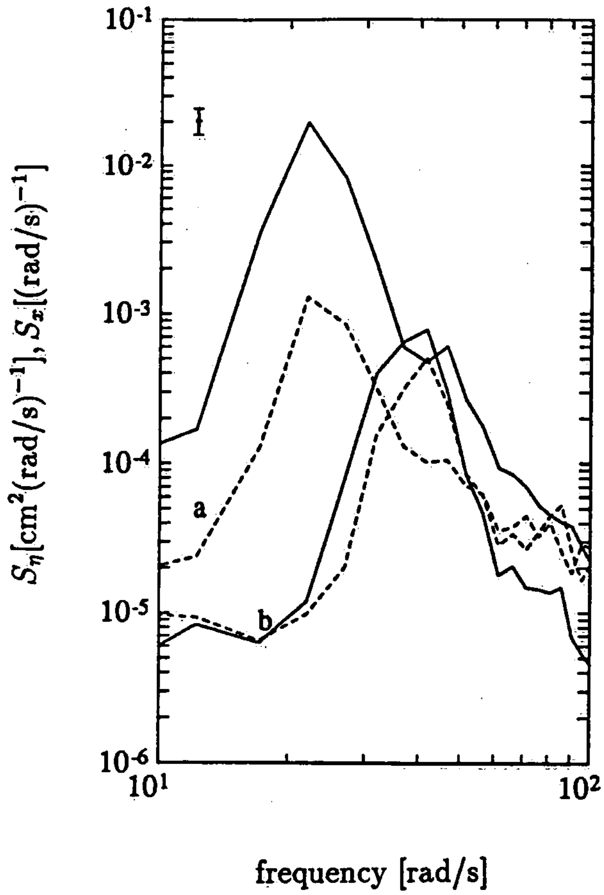
List of Figures



10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{1}
10^{2}
a
b
$S_\eta[\mathrm{cm}^2(\mathrm{rad/s})^{-1}]$, $S_x[(\mathrm{rad/s})^{-1}]$
frequency [rad/s]

Fig 1

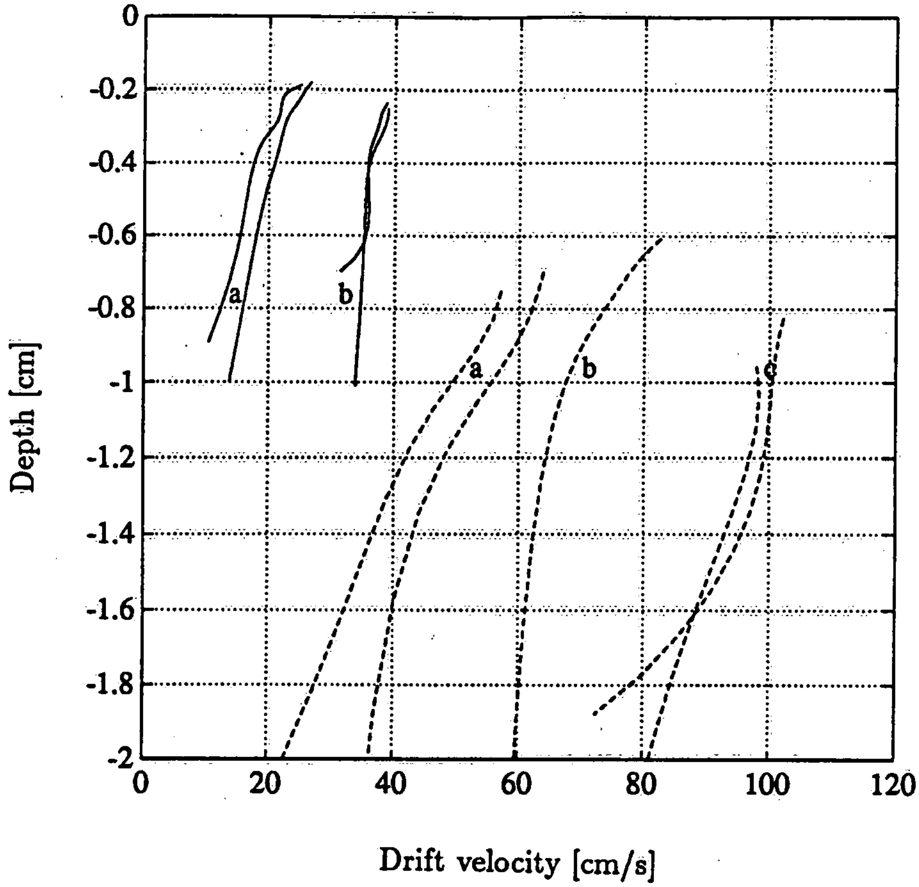

0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
Depth [cm]
a
b
a
b
c
0
20
40
60
80
100
120
Drift velocity [cm/s]

Fig 2.

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