Wind Drift in a Homogeneous, Equilibrium Sea

Yes, "15 degrees to the right of the wind at 3% of the wind speed"* – but why?

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Abstract

In a homogeneous equilibrium sea, the only mean divergence of momentum flux is that from the vertical gradient of the vertical flux of horizontal momentum. An exact result for the surface wind drift in this case is derived from a universality and symmetry argument. The resulting surface wind drift is approximately 3.5% of the vector difference of the free-stream velocities outside the respective momentum boundary layers.

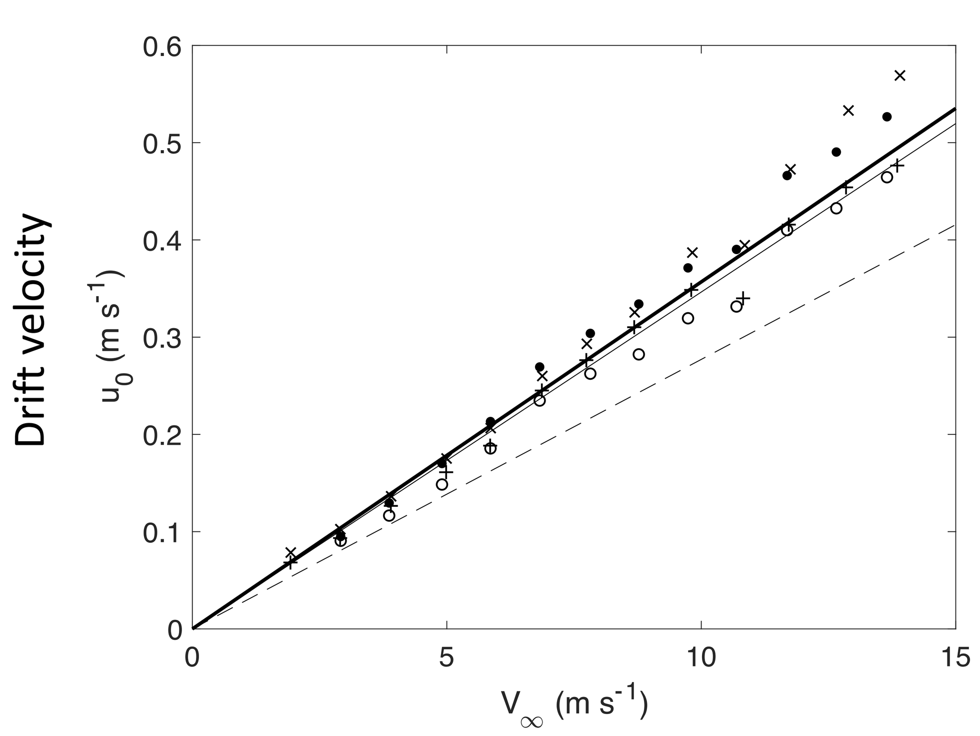
General Result

$$\mathbf{U}_0 = u_* \bar{\mathbf{U}}_0 = \frac{\rho_1^{1/2}\mathbf{V}_\infty + \rho_2^{1/2}\mathbf{U}_\infty}{\rho_1^{1/2} + \rho_2^{1/2}}$$

The predicted drift velocity is the weighted mean of the free-stream velocities in each fluid, where the weighting factors are the square roots of the densities of the two fluids, normalized by their sum.

Air-Water Interface

A detailed comparison is made with the classical laboratory experiment of Wu (1975)*. Good agreement is found, with a logarithmic correction giving an improved estimate.



Drift velocity vs. free-stream velocity for measured total (solid dot) and "wind-induced" (o) drift from Wu (1975), two sets of explicit analytical model solutions (+,x), and three estimates (solid and dashed lines) based on the theoretical prediction with and without the logarithmic correction and an additional correction for wind-wave disequilibrium.

Air-Sea Interface

For ocean-atmosphere conditions, the density ratio is approximately 1.2 x 10^{-3} and the free stream velocities are geostrophic:

$$\alpha = \left(\frac{\rho_1}{\rho_2}\right)^{1/2} \approx 0.035, \quad (\mathbf{U}_\infty, \mathbf{V}_\infty) = (\mathbf{U}_G, \mathbf{V}_G), \quad |\mathbf{U}_G| \ll |\mathbf{V}_G|$$

The predicted surface wind drift relative to the geostrophic current

$$\boxed{\mathbf{U}_0 - \mathbf{U}_G = \frac{\alpha}{1+\alpha}\,(\mathbf{V}_G - \mathbf{U}_G) \approx \alpha\,\mathbf{V}_G}$$

is then approximately 3.5% of the geostrophic wind speed and in the direction of the geostrophic wind vector.

This relation explains both components of the well-known empirical "oil-spill" rule of thumb, which has remained essentially unchanged for over 50 years*, according to which the surface drift is predicted to be

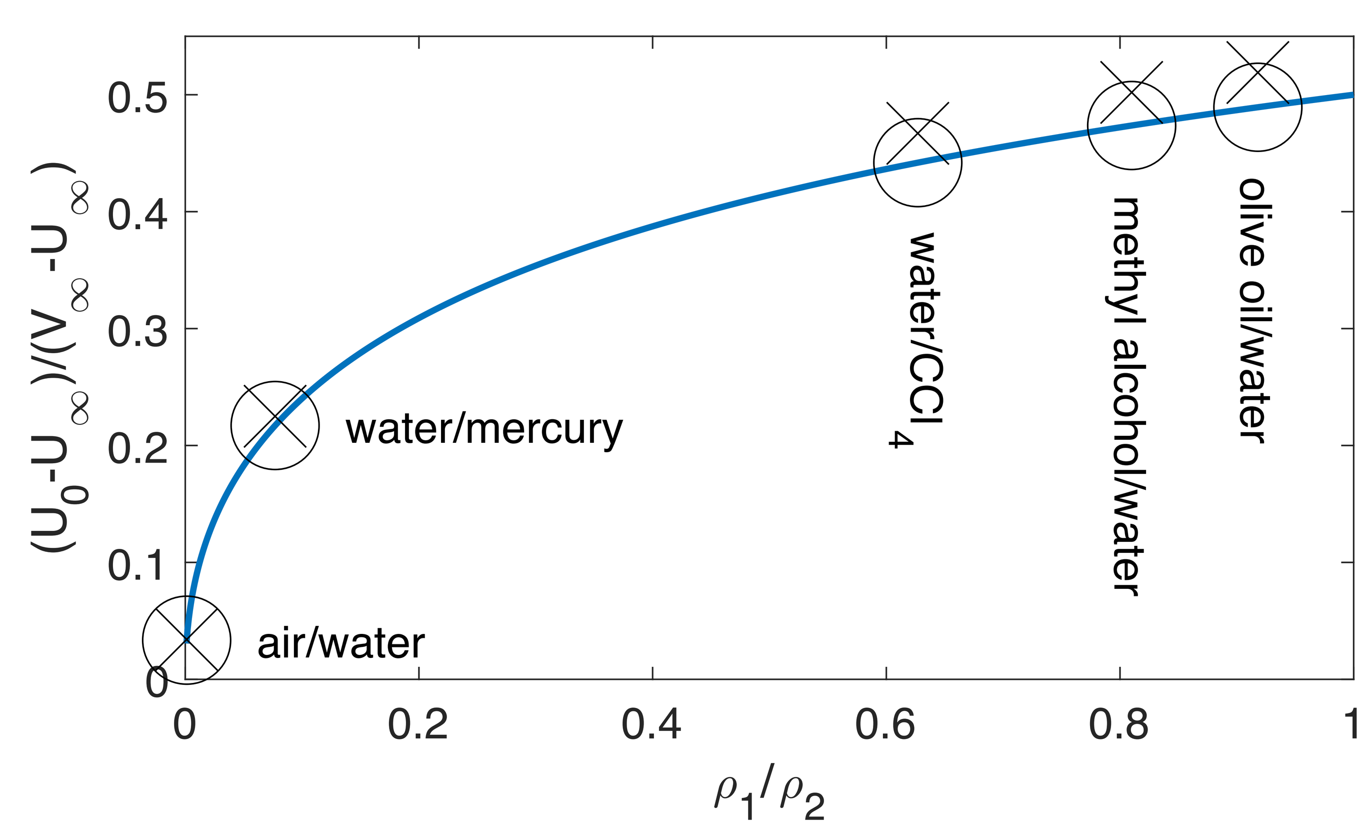
(1) "15 degrees to the right of the [10-m] wind" and

(2) "3% of the [10-m] wind speed":

Ocean surface winds are generally characterized in terms of the 10-m wind, where the 10-m height is near the base of the planetary boundary layer but often near the top of the logarithmic surface layer. A frequently used estimate is that **the 10-m wind speed and direction are roughly 70% and 15 degrees to the left (in the northern hemisphere), respectively, of the low-level geostrophic wind speed and direction****. [NB: 70% x 0.035 = 2.5% ≈ 3%]

Other Fluid Systems

The result gives predictions for other fluid systems. The predictions compare well with analytical solutions for the Wu (1975) flow, if the densities are adjusted accordingly and all other parameters are left unchanged. As the densities become more comparable, it is of course increasingly likely that the turbulence would destroy the interface.



Theoretical prediction for the ratio of drift velocity to free-stream velocity as a function of density ratio (solid line). Five different specific fluid combinations are indicated (o), with corresponding analytical model solutions for the Wu (1975) flow (x).

Corrections to General Result

The exact general result depends on a strict universality argument that, like many other turbulent universality results (e.g., spectral slopes for cascades), is founded in dimensional analysis. The appearance of additional dimensional scales then suggests a need for corrections to the general result. Surface (interfacial) waves, physical roughness lengths, and stratification are three examples of possible sources of such additional dimensional scales.

Surface Waves and Stokes' Drift: A Proposal

In a homogeneous equilibrium sea, the surface-wave processes that drive Stokes' drift, and therefore also the Stokes' drift itself, are indistinguishable from the rest of the wave-turbulent shear flow dynamics that force the mean flow, and this wind drift response therefore must include any Stokes' drift that may occur. Moreover, there is evidence for a thin near-surface log-layer beneath surface waves in the laboratory and the ocean***. The proposed approach is to allow a wave-modified von Kármán constant $\kappa' = \phi\kappa$ near the surface, i.e., an empirical wave-correction factor ϕ equivalent to the stability correction functions in Monin-Obukhov similarity theory. Preliminary tests of this approach suggest $\phi \approx 0.6$ and motivate more systematic future study.

References

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