Estimating air-water gas transfer velocity during low wind condition with and without buoyancy

Sam T Fredrikssoon,1 Lars Arneborg,2 Robert A Handler,2 and Häkan Nilsson3
1Dept. Of Marine Sciences, University of Gothenburg, Sweden, 2Department of Mechanical Engineering, George Mason University, USA, 3Dept. of Mechanics and Maritime Sciences, Chalmers University of Technology, Sweden

Aim

This work aims at refining the gas transfer velocity parameterization during low wind conditions with and without buoyancy, to be used in regional and global climate models. This parameterization and the enhanced understanding of the small-scale processes present in the vicinity of the air-water interfaces can of course be used for other purposes as well such as chemical and environmental engineering.

Main findings

The relative importance of buoyancy and shear forcing is characterized via a Richardson number \( R_i = (u' / \tau_0)^2 / (\nu + \kappa_s \nabla T^2) \), which is a critical Richardson number \( R_i \approx 1 \) below which gas exchange is dominated by buoyancy, and \( R_i \approx 10 \) above which gas exchange is dominated by shear forcing [1]. This means that buoyancy fluxes in natural conditions are not important for gas exchange at wind velocities below \( U \approx 5 \) \( \text{ms}^{-1} \) and environmental engineering. Parameterization during low wind conditions with and without buoyancy is important for gas exchange at wind velocities below \( U \approx 5 \) \( \text{ms}^{-1} \) and environmental engineering. Parameterization in equations (2-5) are given for reference. The parameterization in equation (1) is here plotted for surface conditions. The gas is modeled as a passive scalar, \( \Gamma \), which can be seen as an inert gas. The flow conditions are varied via different surface boundary conditions for the velocity (including shear and surfactants) and the temperature (surface heat flux), (ii) different molecular diffusivities for the scalar.

Background

The increasing abundance of atmospheric carbon dioxide, \( \text{CO}_2 \), and methane, \( \text{CH}_4 \), affects the global carbon cycle as well as the climate both regionally and globally. Understanding of the air-water gas exchange and its temporal and spatial distribution is important for both regional and global importance.

Available gas transfer velocity parameterizations show mutual characteristics. The transfer velocity coefficient for shear-forcing, \( k_s \), is defined as the transfer velocity coefficient for shear-forcing divided by the Schmidt number, \( \kappa_s / \nu \). The parameterization in equation (1) is here plotted for surface conditions. The gas is modeled as a passive scalar, \( \Gamma \), which can be seen as an inert gas. The flow conditions are varied via different surface boundary conditions for the velocity (including shear and surfactants) and the temperature (surface heat flux), (ii) different molecular diffusivities for the scalar.

Material and methods

The interfacial gas-flux for \( \text{CO}_2 \) and \( \text{CH}_4 \) is controlled by the water-side. The gas-flux, \( F_p \), is for gases typically estimated as \( F_p = k_s \left( C_a - C_w \right) \), where \( k_s \) is the gas transfer velocity, \( C_a \) and \( C_w \) are the gas concentrations in the water bulk and in the air at the surface, and \( \varnothing \) is the dimensionless Ostwald solubility coefficient. The transfer velocity is influenced by interfacial shear stress from wind, natural convection due to surface heat flux, microscale breaking waves at moderate wind speeds, breaking waves at high wind speeds, bubbles, surfactants, and rain. This work focuses on the low wind condition where the forcings due to shear stress, natural convection, and surfactants are important. Direct numerical simulations, DNS, are used to study how the turbulence and the gas-transport depend on different flow conditions. The gas is modeled as a passive scalar, \( \Gamma \), which can be seen as an inert gas. The flow conditions are varied via different surface boundary conditions for the velocity (including shear and surfactants) and the temperature (surface heat flux), (ii) different molecular diffusivities for the scalar.

References


Results and conclusions

The flow pattern for buoyancy driven flows is characterized by thin descending plumes of cold dense water, water and occasional surface-void vortices. The surface normal scalar flux follows this pattern. It is seen that once the shear stress is applied to the surface (in the x-direction towards in the figures), the pattern and vortices start to be bended and stretched and a fish-scale pattern becomes visible.

Wall-boundary flows have been shown to typically create streaky structures in the vicinity of a wall with a spanwise spacing of about 1000, which is close to \( \kappa_s / \nu \). It can be seen that these coherent structures typically are finer with than without buoyancy and when \( \kappa_s / \nu = 0 \). Here the parameterization from equation (1) is i.e. plotted for surface conditions. The gas is modeled as a passive scalar, \( \Gamma \), which can be seen as an inert gas. The flow conditions are varied via different surface boundary conditions for the velocity (including shear and surfactants) and the temperature (surface heat flux), (ii) different molecular diffusivities for the scalar.

Figure 1. Normalised surface-normal scalar flux fields. The cases are named as the Ri, n = 0 (F1) and F0 for Buoyancy and RiF0 for No-Buoyancy. The same scaling is used for all subplots. The length scale 1000, where \( \kappa_s / \nu \). is indicated in the subplots for cases with \( n > 0 \).

Figure 2. a) The scalar transfer velocity \( k_s \) (Sc = 7) increase linearly with \( u_w \) for cases with pure shear-stress forcing. These results are close to the measurements of gas transfer velocities in a wind tank (1), given in the same figure. Combined forcing gives on the other hand a more or less constant \( k_s \) for \( u_w \) and \( k_s \) seems to connect to the linear trend as \( u_w \) increases. Another way of expressing this can be seen in b) where \( k_s / u_w \), as a function of \( R_i \) is presented. Here \( k_s / u_w \), is declining down to a limiting magnitude for decreasing \( R_i \). This limiting magnitude is set by the no-buoyancy cases. A Richardson number \( R_i \) of 0.004 is found to express the conditions when the scalar transfer starts to change from being dominated by buoyancy forcing to shear-stress forcing which is relevant for determining the buoyancy influence.

The parameterization in equation (1) is here plotted for surface conditions. The gas is modeled as a passive scalar, \( \Gamma \), which can be seen as an inert gas. The flow conditions are varied via different surface boundary conditions for the velocity (including shear and surfactants) and the temperature (surface heat flux), (ii) different molecular diffusivities for the scalar.

Figure 3. Transfer velocity constant \( k_s \) according to equation (2) for gas transfer velocity parameterizations using DNS. (i) of Geophysical Research Oceans.

Figure 4. Computational domain for the cases with combined buoyancy and shear stress forcing. The domain is given by \( L_z = 0.12 \), \( L_x = 3 \), and \( L_y = 0 \), in the depth, streamwise, and spanwise direction, respectively. The surface is subject to a constant outward pointing gas flux \( \Gamma \) and the bottom boundary is subject to zero flux boundary conditions. The velocity boundary conditions are either slip, no-slip, or constant shear stress, \( u_w \) at the surface boundary and slip at the bottom boundary. Periodic (cyclic) boundary conditions are used for all variables in the horizontal (\( u \)- and \( v \)-directions).

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