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

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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 $Ri = \frac{U/10}{k/10}$. Here, $U$ and $k$ are the mean wind speed and kinetic eddy viscosity above the water surface, respectively. The transition from convection- to shear-dominated gas transfer is shown to be at $Ri = 0.004$. This means that buoyancy fluxes in natural conditions are not important for gas exchange at wind velocities $U_{10}$ above approximately $3 \text{ m s}^{-1}$. Below this wind speed the buoyancy fluxes should be taken into account.

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 therefore of both regional and global importance.

Available gas transfer velocity parameterizations show mutual large variability for low wind conditions and are often given as functions of the mean wind velocity $U_{10}$ at a height $10 \text{ m}$ above the water surface, only and do usually not consider the influence of buoyancy flux (as a result of vertical heat flux).

A positive (negative) buoyancy flux due to a heat flux out of the water increase (decrease) the gas transfer velocity and mixing due to destabilization (stabilization) of the water in the vicinity of the surface.

The flow pattern for buoyancy driven flows is characterized by thin descending plumes of cold dense water, warm wider ascending plumes, and occasionally surface-normal 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 bent and stretched and a fish-scale pattern becomes visible.

Wall-bounded flows have been shown to typically create streaky structures in the vicinity of a wall with a spanwise spacing of about $100 \text{ mm}$, where $L_s = \nu_\ast / \nu$. It can here be seen that these coherent structures typically are finer with than without buoyancy comparing $120 \text{ mm}$ with $120 \text{ mm}$ and $180 \text{ mm}$ with $180 \text{ mm}$.

The large influence of surfactants on the gas flux is also seen. The computations were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at CSE (Chalmers Center for Computational Science and Engineering) computing resources.

Material and methods

The interfacial gas-flux for $\text{CO}_2$ and $\text{CH}_4$ is controlled by the water-side. The gas-flux, $F_{\text{gas}}$, is for such gases typically estimated as $F_{\text{gas}} = k_g \left( C_{\text{gas}} - C_{\text{gas},a} \right)$ where $k_g$ is the gas transfer velocity, $C_{\text{gas}}$ and $C_{\text{gas},a}$ are the gas concentrations in the water bulk and in the air at the surface, and $\theta$ 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-transports depend on different flow conditions. The gas is modeled as a passive scalar, $s$, which can be seen as an inert gas. The flow conditions are varied via (i) different surface boundary conditions for the velocity (including shear and surfactants) and the temperature (surface heat flux), (ii) different and (iii) different molecular diffusivities for the scalar.

Results and conclusions

The parameterization in equation (1) is here plotted for surface heat fluxes in the range of $0 < q_h < 400 \text{ W m}^{-2}$. Here the buoyancy flux influences the gas-transfer velocity up to approximately $2.4 \text{ m s}^{-1}$.

It is seen that the parametrization (3-5), however not explicitly, most likely implicitly account for some background heat flux. For low wind conditions it is thus advisable to take into account the buoyancy influence.

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REFERENCES


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