Mass transfer at the ocean-atmosphere interface: the role of wave breaking, droplets and bubbles in sea spray generation and gas exchange

Luc Deike
Department of Mechanical and Aerospace Engineering and High Meadows Environmental Institute
Princeton University

Physical processes at the ocean-atmosphere interface have a large effect on climate and weather by controlling the transfer of momentum and mass. In particular, ocean spray aerosols are tiny water droplets and solid particles (from tens of nanometers to hundreds of microns) emitted at the ocean surface by wave breaking and bubble bursting during storms and residing into the atmosphere. Ocean spray aerosols provide a pathway to transfer salt, biological material or microplastics from the ocean into the atmosphere, affecting the climate system through the radiative balance and the formation of clouds. Separately bubble mediated gas exchange associated with wave breaking is a critical pathway for ocean-atmosphere exchange of low solubility gases such as oxygen, as they get squeezed by hydrostatic pressure or even collapse and fully dissolve.

In this invited talk, I will discuss recent efforts in my group towards improving our understanding and modeling of sea spray production by bubble bursting, as well as bubble mediated gas exchange through a multi-scale framework. We combine laboratory experiments and numerical simulations on turbulent multiphase flows and develop a multiscale framework to account for the wide range of scales. Leveraging a recent multilayer numerical representation of the upper ocean, we solve for a broad banded wave field including breaking events, resolved as shock-like events, and provide a link between the wave statistics and wave breaking statistics (scales O(1m-1km)). Individual wave breaking dynamics, including momentum flux, energy dissipation and air-bubbles entrainment is resolved through two-phase direct numerical simulations (scales O(0.1-10m)), which combined with air bubble fragmentation laboratory experiments and direct numerical simulations provide a universal description of the bubble size distribution under breaking waves. Finally the bubble dynamics in turbulence is investigated through direct numerical simulations and laboratory experiments, describing bubble dynamics and rise velocity in turbulence, individual bubble gas exchange as well as individual bubble bursting at the free surface, O(microns to mm). Collective bubble bursting is characterized through laboratory experiments, and connects the bubble population to individual bubble bursting events and the associated emitted droplets. Recombining the multiple scales resolved by the individual experimental and modeling studies leads to novel mechanistic formulation of sea spray aerosol emissions and gas exchange.

The resulting sea spray aerosols emissions are in remarkable agreement with field observations, without being adjusted to match any existing datasets, in terms of magnitude of sea salt emissions and size distribution. The remarkable coherence between the model and observations of sea salt emissions therefore strongly supports the mechanistic approach and paves the way for improved modeling of atmospheric processes controlled by aerosols of oceanic origin. On the bubble gas exchange side, integrating the role of bubble mediated gas exchange allows to understand the asymmetric flux for a wide range of gas solubility, with remarkable agreement to a wide range of laboratory and open ocean observations, with implication for global ocean oxygen loss.