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Air–sea gas exchange at extreme wind speeds measured by autonomous oceanographic floats

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Abstract

Measurements of the air–sea fluxes of N_2 and O_2 were made in winds of 15–57 m s^{-1} beneath Hurricane Frances using two types of air-deployed neutrally buoyant and profiling underwater floats. Two "Lagrangian floats" measured O_2 and total gas tension (GT) in pre-storm and post-storm profiles and in the actively turbulent mixed layer during the storm. A single "EM-APEX float" profiled continuously from 30 to 200 m before, during and after the storm. All floats measured temperature and salinity. N_2 concentrations were computed from GT and O_2 after correcting for instrumental effects. Gas fluxes were computed by three methods. First, a one-dimensional mixed layer budget diagnosed the changes in mixed layer concentrations given the pre-storm profile and a time varying mixed layer depth. This model was calibrated using temperature and salinity data. The difference between the predicted mixed layer concentrations of O_2 and N_2 and those measured was attributed to air–sea gas fluxes F_{BO} and F_{BN}. Second, the covariance flux $F_{CO}(z)=\langle wO_2'\rangle(z)$ was computed, where w is the vertical motion of the water-following Lagrangian floats, O_2' is a high-pass filtered O_2 concentration and $\langle\rangle(z)$ is an average over covariance pairs as a function of depth. The profile $F_{CO}(z)$ was extrapolated to the surface to yield the surface O_2 flux $F_{CO}(0)$. Third, a deficit of O_2 was found in the upper few meters of the ocean at the height of the storm. A flux F_{SO}, moving O_2 out of the ocean, was calculated by dividing this deficit by the residence time of the water in this layer, inferred from the Lagrangian floats. The three methods gave generally consistent results. At the highest winds, gas transfer is dominated by bubbles created by surface wave breaking, injected into the ocean by large-scale turbulent eddies and dissolving near 10-m depth. This conclusion is supported by observations of fluxes into the ocean despite its supersaturation; by the molar flux ratio F_{BO}/F_{BN}, which is closer to that of air rather than that appropriate for Schmidt number scaling; by O_2 increases at about 10-m depth along the water trajectories accompanied by a reduction in void fraction as measured by conductivity; and from the profile of $F_{CO}(z)$, which peaks near 10 m instead of at the surface.

At the highest winds O_2 and N_2 are injected into the ocean by bubbles dissolving at depth. This, plus entrainment of gas-rich water from below, supersaturates the mixed layer causing gas to flux out of the near-surface ocean. A net influx of gas results from the balance of these two competing processes. At lower speeds, the total gas fluxes, F_{BO}, F_{BN} and $F_{CO}(0)$, are out of the ocean and downgradient.

1. Introduction

The greatest uncertainties in air–sea gas transfer rates and mechanisms are undoubtedly associated with high

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