Scaling Gas Transfer with Turbulent Dissipation for a Range of Environmental Processes

ZAPPA C.J.¹, W.R. MCGILLIS¹,², P.A. RAYMOND³, J.B. EDSON², E.J. HINTSA⁵, H.J. ZEMMELINK⁶, J.W.H. DACEY⁷, D.T. HO¹

¹ Lamont-Doherty Earth Observatory, Columbia University, USA
² Department of Earth and Environmental Engineering, Columbia University, USA
³ School of Forestry and Environmental Studies, Yale University, USA
⁴ Department of Marine Sciences, University of Connecticut, Avery Point, USA
⁵ Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, USA
⁶ School of Environmental Sciences, University of East Anglia, UK
⁷ Biology Department, Woods Hole Oceanographic Institution, USA

For sparingly soluble gases, theory predicts that the gas transfer velocity, \( k \), is controlled by turbulence in the surface aqueous boundary layer, which dictates the rate at which gases can be brought into contact with the surface to exchange with the atmosphere. Since gas transfer has been shown to scale with wind-generated turbulence in many field and laboratory wind-wave experiments, wind-based relationships to model \( k \) are typically used for gas exchange estimates from the open oceans to estuaries and rivers despite the acknowledged role of physical processes not related to wind (e.g., tidal currents, rain, stratification, surfactants, and water depth). In an effort to explicitly relate turbulence near the surface aqueous boundary layer to gas exchange, models have been developed for \( k \) based on the turbulent kinetic energy dissipation rate, \( \varepsilon \). A fundamental relationship shows \( k \) scales with \((\varepsilon \nu)^{\frac{n}{4}} \frac{1}{Sc^n}\), where the Schmidt number, \( Sc \), is defined as the ratio of the kinematic viscosity of water, \( \nu \), to mass diffusivity. The Schmidt number exponent \( n \) is believed to vary between \( \frac{2}{3} \) and \( \frac{1}{3} \) depending on the surface boundary conditions. This expression for \( k \) based on \( \varepsilon \) is consistent with mass diffusion across a layer of the thickness of the Batchelor [1959] scale [Melville, 1996], and has been derived by Lamont and Scott [1970] using surface-renewal theory [Danckwerts, 1951] and also has been derived by Kitaigorodskii [1984] in the context of modeling the influence of patches of enhanced turbulence by breaking.

Here, measurements will be presented on the turbulent dissipation rate using acoustic techniques and gas transfer velocity using micrometeorological and active controlled flux techniques in the coastal ocean, a macro-tidal river estuary with wind and tidal forcing, a large tidal freshwater river, a model ocean, and wind-wave tanks. The results clearly show that gas transfer under wind, waves, currents, rain, and surfactants indeed scales with the hypothesized model based on the turbulent dissipation rate over a wide range of environmental systems with different types of environmental forcing and processes. The effects of bubbles are considered for the case at high winds in the coastal ocean when the gas exchange was enhanced relative to the model based on turbulence.

REFERENCES

Danckwerts, P.V., 1951, Significance of liquid-film coefficients in gas absorption, Industrial and Engineering Chemistry, 43 (6), 1460-1467.
