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THE RESULTS FROM WABEX-93

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Estimation of Turbulence-Dissipation Rates and Gas-Transfer Velocities in a Surf Pool: Analysis of the Results from WABEX-93

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Abstract

Air-water gas exchange is an important biogeochemical cycling process and accordingly, it is necessary to know the gas flux. The flux to or from bodies of water can be estimated as the product of the air-water concentration difference, ΔC , of a gas and its transfer velocity, k_L . Because of the difficulties associated with direct oceanic measurements of k_L , it is often calculated from parameterizations derived empirically from wind speed, U . As part of an experiment designed to help develop a method for estimating k_L at high wind speeds, gas fluxes and turbulence were measured in a large outdoor surf pool during WABEX-93.

Results from the gas-exchange measurements suggest that k_L can be partitioned into a fraction due to near-surface turbulence generated by currents and nonbreaking waves (k_M), a component due to turbulence generated by breaking waves (k_T), and a component due to bubble-mediated transfer (k_B ; Karle et al., 1994). For gas evasion with ΔC much less than zero, k_L can be written in terms of the fractional area of whitecap coverage, W_c , as

$$k_L = (k_M + W_c(k_T - k_M)) + W_c k_B \quad (1)$$

Karle et al. (1994) showed that Equation 1 could be applied to gas transfer in the surf pool using an explicit functional form for k_B developed using data collected in a whitecap simulation tank (WST) by Asher et al. (1994). Although Equation 1 provided reasonable estimates of k_L in the surf pool, it was observed to systematically underpredict k_L when W_c was large (Karle et al., 1994). Karle et al. (1994) hypothesized that this discrepancy could have been caused by incorrect assumptions concerning the behavior of k_M and k_T .

Equation 1 was derived by assuming that k_M and k_T were constant and not functions of W_c . Because k_M and k_T are determined by the intensity of the near-surface aqueous-phase turbulence, they are constant only if the turbulence in the surf pool is constant with W_c . However, it is reasonable to expect that the turbulence associated with breaking waves increases with wave height and the background turbulence levels in the surf pool increase with increasing wave energy. This was confirmed in the surf pool by measurement-based estimates of turbulence-dissipation rates, ϵ , which showed that ϵ increased with increasing W_c . This means that Equation 1 could be substantially improved by including the effects of increasing turbulence on k_T and k_M .

Turbulence-dissipation rates were estimated from velocity measurements made with an acoustic-Doppler velocimeter (ADV) at a sampling rate of 25 Hz. The ADV measured three components of velocity in a small ($\sim 0.5 \text{ cm}^3$) sampling volume located in an undisturbed region of the flow, 10 cm from the sensor. Simultaneous measurements of water depth were made with a precision strain-gage pressure sensor with a response filtered to 12 Hz. Velocity and pressure statistics were computed from ~ 300 -s long time series that included approximately 75 waves. Profiles were obtained by combining point estimates from separate runs at several elevations above the bottom. Comparison of pressure measurements among runs and evaluation of long time series indicated that wave, current, and turbulence conditions were repeatable between runs and relatively stationary within 5-minute runs. Frequency spectra were calculated from time series of velocity after prewhitening by removal of the ensemble-average wave velocity and linear detrending. Root-mean-square (RMS) wave-orbital velocity was used to convert wavenumber spectra from frequency spectra. Turbulence-dissipation rates, ϵ , were estimated from the magnitude of the energy cascade in the inertial subrange of the wavenumber spectra.

Measurements were made at several locations in the surf pool for two types of waves ("roller" and "diamond" patterns) and four wave-energy levels, providing estimates of ϵ as a function of depth for a variety of wave conditions, including breaking waves (plunging and spilling), broken waves (bores), and unbroken waves. Background turbulence-dissipation rate, ϵ_M , was estimated from measurements made beneath unbroken waves or below the penetration depth for whitecap-generated turbulence beneath breaking waves. Whitecap-induced turbulence-dissipation rate, ϵ_T , was derived by subtracting background turbulence from estimates of ϵ made at

depths of less than one wave height beneath breaking waves. Results indicate that ϵ_T increased rapidly toward the surface under breaking waves and was higher for larger waves. Background turbulence was probably generated by strong rip currents. It was more uniform with depth and increased with wave energy. These estimates of ϵ_M and ϵ_T were used to calculate the turbulence-driven transfer velocities in the surf pool.

Using a surface-renewal model, Lamont and Scott (1970) showed that k_M and k_T can be expressed in terms of ϵ_M and ϵ_T as

$$k_X = B Sc^{-1/2} (\epsilon_X \nu)^{1/4} \quad (X = M, T) \quad (2)$$

where B is a dimensionless constant and Sc is the Schmidt number of the gas, ϵ_M and ϵ_T are the dissipation rates of wave-current-generated and whitecap-generated turbulence, respectively, and ν is the kinematic viscosity of water. In support of Equation 2, Asher and Pankow (1986) found that k_L for carbon dioxide (CO_2) scaled linearly with $\epsilon^{1/4}$. They also found B to be in the range 0.65 to 1.2, depending on cleanliness of the water surface.

Karle et al. (1994) assumed k_M and k_T were constant and fit Equation 1 to k_L measured in the surf pool for CO_2 , helium, sulfur hexafluoride, oxygen, and nitrous oxide as a function of W_c . Using the same functional form for k_B as that used by Karle et al. (1994), $B \approx 0.65$, and the dissipation rates estimated above in Equation 2, the gas transfer velocities measured in the surf pool were fit to the modified form of Equation 1. In contrast to the procedure used by Karle et al. (1994), k_T and k_M were calculated directly from the turbulence data rather than determined as part of a curve-fitting procedure.

Under the assumption that k_M and k_T were constant, it was found that k_L values predicted using Equation 1 for transfer of the gases listed above in the surf pool when $W_c < 1\%$ were a factor of two to three less than the measured k_L values. In contrast, the accuracy for k_L values calculated at $W_c > 1\%$ was found to be $\pm 30\%$ (Karle et al., 1994). Substitution of the direct estimates of k_M and k_T from Equation 2 and ϵ measured in the surf pool improved the prediction accuracy of Equation 1 at low whitecap coverage ($W_c < 1\%$) to $\pm 30\%$, an accuracy consistent with calculations at $W_c > 1\%$. This shows that for the conditions in the surf pool, where the increase in W_c was associated with increases in both ϵ_M and ϵ_T , the turbulence-driven transfer velocities cannot be assumed to be constant with W_c .

In the surf pool, increases in W_c were caused by increases in height of the breaking wave. It could be expected that a similar process occurs under oceanic conditions, where increasing wind speed leads to higher whitecap coverage and larger wave size. The success of the approach described here suggests that application of Equation 1 to the ocean will require knowledge of the dependence of k_M and k_T on wind speed.

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