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MEASUREMENT OF GAS TRANSFER, WHITECAP COVERAGE, AND
BRIGHTNESS TEMPERATURE IN A SURF POOL: AN OVERVIEW
OF WABEX-93

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Measurement of Gas Transfer, Whitecap Coverage, and Brightness Temperature in a Surf Pool: An Overview of WABEX-93

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Abstract

Ocean regions that global carbon cycle models show are large sinks of carbon dioxide (CO_2) are known to have high wind speeds. Therefore, estimates of the global ocean uptake of CO_2 could be improved through better prediction of the air-sea gas transfer velocity, k_L , at high wind speeds. Because high winds are also associated with increased whitecapping, development of an accurate method for estimating k_L for CO_2 from remote measurements of whitecap coverage, W_C , could provide a method for predicting k_L at high wind speed. It could be possible to measure W_C using the remote-sensing technique of passive microwave radiometry.

Gas transfer data from laboratory experiments conducted in a "tipping-bucket" whitecap simulation tank (WST) have been used to develop a parameterization of k_L in terms of W_C ; Schmidt number, Sc ; and aqueous-phase solubility, α . Due to the difficulty in measuring k_L under oceanic conditions, it would be advantageous to apply the parameterization from the WST to air-sea gas exchange rather than to acquire enough field data to independently derive a similar relation for the ocean. However, it must first be shown that the results from the WST can be applied to more realistic breaking waves.

Extension of the WST results to oceanic conditions should be made using direct oceanic measurements of k_L and W_C . However, this would require a dual-tracer gas exchange experiment with its associated cost and difficulty. In addition, with such a field experiment there is a risk that the wind conditions during the measurement period would not be high enough to cause significant whitecapping. As an alternative to an oceanic experiment, gas transfer measurements were made in a large outdoor surf pool capable of generating breaking waves that were very similar to one in the ocean. The use of a wave basin provided the additional benefit of a controlled, reproducible field of breaking waves. Furthermore, gas transfer velocities, whitecap coverage, brightness temperature, aqueous-phase turbulence, bubble populations, and other data necessary to apply the WST data to large-scale waves could be measured concurrently. Although the surf pool experiment was not a direct replacement for the oceanic measurements necessary to verify the whitecap-passive microwave gas exchange model, it allowed the empirical relation developed from the WST data to be tested using breaking waves that were more characteristic of oceanic whitecaps. More importantly, the reproducible waves in the surf pool allowed systematic study of the effect of breaking waves on air-water transfer.

Because the surf pool was outdoors, a passive microwave radiometer could be used to measure microwave brightness temperature, σ . With this data, the remote-sensing applications of this research could be studied. A passive radiometer could not be used effectively in a wind/wave tunnel because blackbody microwave emissions from interior walls and surfaces of the tunnel would mask the radiometric signal from the breaking waves. Although the experiment was principally designed to verify and refine a model for estimating k_L from W_C developed using gas exchange data acquired in the WST, measurement of σ also will permit correlation of σ with W_C for developing a remote-sensing-based method for estimating k_L .

The surf pool called "Hurricane Harbor" is located at Wild Rivers Waterpark in Irvine, California. It is an unheated, freshwater pool approximately 20-m wide by 70-m long with a 1.2-m average depth. It can generate a 0.3-m to 1.3-m plunging or spilling breaking wave every 3.5 s. W_C could be varied from 0% to 7% and was measured by grey-scale computer analysis of video records of the water surface. Microwave brightness temperature was measured by a 19-GHz dual-polarization radiometer at an incidence angle of 0.925 rad and an

elevation of 18 m. Basin-averaged values of σ ranged from 120 K to 180 K at 19 GHz, horizontal polarization (h-pol) and 150 K to 210 K at 19 GHz, vertical polarization (v-pol). Gas fluxes were measured for CO₂, nitrous oxide (N₂O), oxygen (O₂), helium (He), and sulfur hexafluoride (SF₆). Other data collected included bubble size spectra, aqueous-phase turbulence, wave height spectra, void fraction, and wind speed and direction.

The surf pool data agrees with the results of Asher et al. (1992) from the WST in that k_L increases linearly with W_C . This is an important result, because the surf pool wave conditions provide an order of magnitude increase in the range of available W_C compared to the WST, and the linear correlation with the surf pool data was the same for both plunging and spilling breaking waves. Furthermore, the physical characteristics of the waves in Hurricane Harbor are very similar to oceanic breaking waves, suggesting that k_L could be linearly correlated with W_C under oceanic conditions.

In the absence of bubbles, k_L is proportional to $Sc^{-1/2}$, and increases in Sc will decrease k_L . Therefore, for transfer across an unbroken water surface k_L measured for SF₆, $k_L(SF_6)$, will be less than k_L measured under the same conditions for O₂, $k_L(O_2)$, because $Sc(SF_6)$ is greater than $Sc(O_2)$. When W_C is less than 1%, the data agree with this analysis and $k_L(SF_6)$ is less than $k_L(O_2)$. In contrast to the flat-surface case, bubble-mediated transfer processes cause k_L to be a function of both Sc and α , with k_L increasing as α decreases at a constant Sc . At constant α however, k_L will decrease with increasing Sc . Although $Sc(SF_6)$ is 1.8 times larger than $Sc(O_2)$, $\alpha(SF_6)$ is 5.5 times smaller than $\alpha(O_2)$. When bubble-mediated transfer processes are important, it might be expected that the effect of decreasing α will dominate the effect of the increase in Sc and $k_L(SF_6)$ will be greater than $k_L(O_2)$. In support of this hypothesis, the surf pool data show that $k_L(SF_6)$ is greater than $k_L(O_2)$ when W_C is greater than 1%. This demonstrates that bubbles were an important gas transfer pathway in the surf pool.

W_C and σ values were averaged over the surface of the pool for both breaking wave patterns at wave heights of 0.3 m, 0.6 m, 0.9 m, and 1.2 m. For both wave patterns and at both polarizations, W_C was found to be linearly correlated with σ . The radiometer data also show that k_L is linearly correlated with σ measured at either h-pol or v-pol for both plunging and spilling breaking waves. The observed linear correlation between k_L and σ is very significant because it shows that measurements of aqueous-phase transfer velocities can be linearly correlated with a directly measured remote-sensing parameter. The correlation of W_C with σ and k_L with σ is discussed in detail elsewhere (see Wang et al., this volume).

One of the goals of the experiment was to determine whether the empirical parameterization of k_L for bubble-plume driven gas transfer developed using data collected in the WST could be applied to breaking waves. The WST data have shown that k_L can be expressed in terms of W_C as (Asher et al., 1994)

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

where k_M is defined by transfer from mechanically generated turbulence, k_T defines transfer from turbulence generated by the breaking wave, and k_B defines transfer from the bubble-mediated gas flux. For freshwater, WST measurements have shown k_B is given by (Karle et al., 1994)

$$k_B = b \alpha^{-0.043} Sc^{-0.36} \quad (2)$$

where the exponents for α and Sc were determined by linear regression of the WST data. For a clean water surface, both k_M and k_T have the form

$$k_X = A_X Sc^{-1/2} \quad (X = M, T) \quad (3)$$

where A_X is determined by the turbulence intensity and length scale. A_M , A_T , and b were determined by linear regression of the directly measured k_L values to the functional form given by Equation 1 incorporating Equations 2 and 3, using W_C measured in the surf pool, and the relevant Sc and α values. Using this simple model shown in Equation 1, it was found that k_L calculated from the measured W_C values and Equations 1, 2, and 3 could predict the measured k_L values for He, SF₆, CO₂, N₂O, and O₂ with an accuracy of $\pm 30\%$ for $W_C > 1\%$. However, at lower W_C values the method underpredicts the observed transfer velocities by a factor of 2 to 3. It is believed this underprediction of k_L at low W_C is caused by the assumption of constant k_M and k_T (see Sherwood et al., this issue). Overall, Equations 1, 2, and 3 do a reasonable job of predicting k_L in the wave basin, and this shows the functional form of the parameterization developed using data from the WST can be applied to more realistic wave conditions.

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