Description of the Science Plan for the April 1995 CoOP Experiment, 'Gas Transfer in Coastal Waters', Performed from the Research Vessel New Horizon

Erik J. Bock[1], *James B. Edson*[1], *Nelson M. Frew*[1], *Andrey V. Karachintsev*[1], *Wade R. McGillis*[1], *Robert K. Nelson*[1], *Kurt Hansen*[2], *Tetsu Hara*[2], *Mete Uz* [2], *Bernd Jähne*[4], *Jochen Dieter*[4], *Jochen Klinke*[4], *and Horst Haußecker*[3]

[1] Woods Hole Oceanographic Institution (WHOI)
[2] Graduate School of Oceanography, University of Rhode Island (URI)
[3] Interdisciplinary Center for Scientific Computing, University of Heidelberg (UH)
[4] Scripps Institute of Oceanography (SIO)

Abstract

A description of the scientific questions, the engineering approach to answering those questions and preliminary results from an experiment off the coast of southern California are presented. The experiment's main focus was on how local variability, caused primarily by nutrient availability (and hence surfactant concentration) and wind stress variability, influences gas exchange in coastal waters. To address this issue, a suite of instruments was developed to characterize interfacial phenomena in the coastal region off Monterey Bay, in conjunction with other platforms that intended to measure both atmospheric and ocean-mixed layer properties.

1 Introduction

Accurate estimates of air-sea gas-transfer rates are essential for understanding the global cycles of carbon dioxide, dimethyl sulfide and other trace gases that affect the earth's radiation budget. As part of the National Science Foundation's (NSF) Coastal Ocean Processes (*CoOP*) program, our main goal is to improve the understanding of air-sea gas-transfer under different environmental conditions at the real air-sea interface. Improved estimates require new advances in techniques to measure in situ gas transfer rates and governing environmental parameters. Jointly, groups from Woods Hole Oceanographic Institution (WHOI), University of Rhode Island (URI), Scripps Institute of Oceanography (SIO), and University of Heidelberg (UH) are developing a new in situ instrument suite that can measure the gas-transfer velocity on time scales (minutes to hours) that are much shorter than conventional tracer techniques (days or longer). The instruments are combined to provide coincident measurements of the gas-transfer velocity, small scale roughness, wind stress, near surface turbulence and surface chemical enrichments.

In its first year, we participated in the joint NSF(CoOP)-ONR (*MBL-ARI*) field experiment off Monterey Bay in April – May, 1995. One of the main purposes of this operation was to integrate the intensive meteorological/oceanic measurements by MBL-ARI investigators into the measurements of air-sea gas exchange and related surface processes by CoOP participants. Such integration would provide necessary information to investigate the air-sea gas exchange processes in the coastal environment in detail. During the operation, we successfully accomplished all the measurements of the surface physical processes and the surface chemical characterization. We also maximized our possible opportunities to coordinate our measurements with those obtained from the R/P FLIP. Currently, preliminary data analyses are underway and we have started to integrate our data with MBL-ARI data. In the following sections, we summarize in detail the logistics of the experiment, and then report some preliminary data analyses.

A concise summary of past field studies of air-sea gas-transfer has been given by *Wanninkhof et al.* [1985]. The results have consistently exhibited a strong correlation between the gas-transfer velocity and the mean wind speed. In particular a sharp change in the wind speed dependence of the gas exchange coefficient was found at wind speeds of a few meters per second, which led to the so-called 'Liss-Merlivat' relationship [*Liss and Merlivat*, 1986]. Nevertheless agreement between different experiments are still within an order of magnitude at best. This is not surprising because the only available techniques for measuring air-sea gas-transfer in the field environment have been either the radon deficit method [*Broecker and Peng*, 1974] or purposeful tracer-injection techniques [*Wanninkhof*, 1985]. Both require time-averaging over days or longer. Since the wind field is never constant over such time scales, the correlation between the mean wind speed and k may likely be biased [*Wanninkhof*, 1992]. Another important factor that has been ignored is the presence of surfactant films. This effect is expected to be particularly important in coastal and inland waters where most of the past measurements have been performed.

In addition, the relation between wind speed and wind stress (drag coefficient) introduces a secondary effect that may further complicate the field observations. Although it is wind stress that is dynamically related to transfer velocity, the field measurements usually yield only the wind speed, and an empirical drag coefficient is used to estimate the wind stress. Recent studies [e. g., *Smith et al.*, 1992; *Geernaert et al.*, 1993] have shown that the drag coefficient may be strongly influenced by the nature of surface gravity waves and by the atmospheric stability. Therefore this factor can influence the estimate of the gas-transfer velocity unless direct stress measurements are performed in situ.

Figure 1: The LADAS air–sea interaction catamaran.

2 Experimental Techniques

2.1 Surface Characterization

Surface characterization is performed using the *LADAS* air-sea interaction catamaran that was developed at WHOI. Figure 1 shows LADAS during a typical deployment during the CoOP experiment. LADAS is equipped with a *scanning laser slope gauge* (SLSG), a surface *microlayer sampler* (SMS), a hot film probe for high frequency measurements of current fluctuations, an acoustic current meter, an attitude measuring unit, and a series of capacitance wire-wave staffs. These instruments are secured to the 4.8 m catamaran, which was then towed from the side of the R/V New Horizon. LADAS has electric motors and remotely actuated rudders that enable it to be maneuvered to maintain a position outside the disturbance caused by the bow wake of the research vessel.

Surface capillary and *capillary-gravity waves* are measured using the SLSG. A better description of the SLSG is given by *Bock and Hara* [1995]. The device makes use of the refraction of a narrow pencil-like beam from a laser beneath the air-sea interface, and uses a repetitive scanning pattern to obtain temporal and spatial spectra of short waves. Another paper in this proceedings [*Hara et al.*, 1995] shows laboratory results confirming the relation between slope of short waves and gas transfer velocity.

A sample of the microlayer was obtained with the drum sampler first developed by *Carlson et al.* [1988]. The technique relies on a rotating glass cylinder that drags a sample of the sea surface into a drip cup that is drained by a pump and pushed through a fluorometer. The fluorometer measures emission at 450 nm and yields a measure of the *colored dissolved organic matter* (CDOM). There has been demonstrated a strong correlation between CDOM and surfactant concentration using polarographic techniques to quantify the surfactant concentration. Data from CDOM measurement during this experiment are presented below.

High-frequency measurements of water-side velocity fluctuations were obtained from the *hot film sensors* mounted at the bow of LADAS. These films were configured in a crossed geometry to measure two components of fluctuations, and frequency domain processing of the data produces estimates of ϵ, the dissipation. One intrinsic drawback common to hot-film sensors is that the sensors drift due to accumulation of surface films and contamination. Historically, this drawback has been combated by frequent calibration and cleaning. In the field, however, this is impractical and the problem of drift was solved by dynamically calibrating the long-term mean output of the hot films against measurements obtained from a Sontek current meter. This device was mounted in close proximity to the hot films and allowed the films to be used for periods in excess of six hours.

Additionally on LADAS was mounted an array of tantalum *wire-wave staffs*. These staffs were built in accordance to those described by *Chapman and Monaldo* [1991] and were used in conjunction with an attitude measuring unit (AMU, the inertial guidance system, MK50 AMU-200B, from a MK50 torpedo) to measure gravity waves in the earth's coordinate frame by means of complimentary filtering of the linear accelerometer signals and the outputs of the rotational rate gyros. This data will be useful for analysis of wave-wave interactions but will not be addressed in the context of this paper.

2.2 Meteorological Characterization

High frequency wind velocity and virtual temperature measurements were obtained from a *sonic anemometer*/thermometer mounted 10 m above the mean water height at the bow of the R/V New Horizon. The anemometer also had its own dedicated AMU, allowing stress and buoyancy flux calculations from both the direct covariance and inertial-dissipation methods. *Wind stress* measurements are limited to situations when the wind direction was within $\pm$ 45 °of the New Horizon's bow in order to eliminate records that are distorted by the ship's superstructure. Mean air and sea temperature and humidity measurements were also recorded in order to compute the sensi-

Figure 2: The Controlled Heat Flux boom on the R/V New Horizon during the April/May 1995 NSF CoOP cruise off Monterey Bay.

ble and latent heat fluxes from the bulk aerodynamic method. These fluxes will be used in conjunction with the LADAS and CFT measurement to study the effects of wind-wave coupling on the gas flux measurements.

2.3 Heat and Mass Fluxes

This experiment was the first time that the *Controlled Flux Technique* (CFT), developed by Jähne of SIO/UH and his group, was deployed in situ. The use of a pivoting extension boom from the bow of the research vessel enabled the CFT to image an area unaffected by reflections of the sky from the hull. A carbon dioxide laser was used to locally heat a patch of the ocean surface

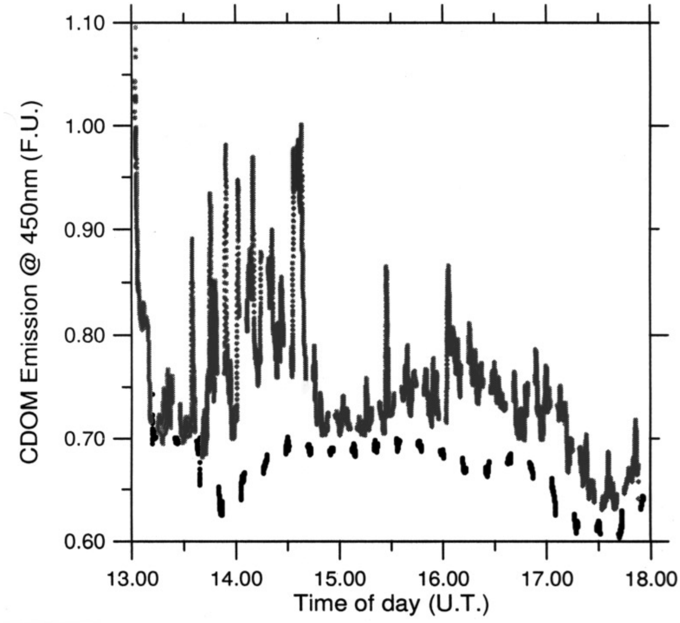

Figure 3: Data obtained on Julian Day 130 from the NSF CoOP cruise of April/May 1995 aboard the R/V New Horizon. Results are from the time period between 13:00 to 18:00 Universal Time. The enhanced surface enrichment observed during the period between 13:30 and 14:30 correspond to a transit across a visibly slicked area.

and an infra-red camera imaged the heated area in a range of wavelengths not encompassing the laser wavelength. Gas transfer coefficients can be derived from heat transfer coefficients obtained in this manner by scaling the mass transfer coefficient proportional to the relative diffusivities of mass and heat. We have successfully obtained both passive and active infrared images that can be used to investigate the heat/gas flux across the air-sea interface of the coastal ocean. Figure 2 shows the CFT boom as it was aboard the R/V New Horizon. *Haußecker et al.* [1995] describe the principle of the CFT, while preliminary results from the April/May 1995 CoOP cruise are reported by *Haußecker and Jähne* [1995].

3 Results and Discussion

3.1 Example of an Ocean Slick

Figure 3 shows the surface-microlayer CDOM (grey) and the subsurface CDOM (black) for the period of time between 13:00 and 18:00 U.T. on Julian Day 130. What is evident in this figure is the spatial variability that is common to coastal environments. The source of this variability lies in the sources

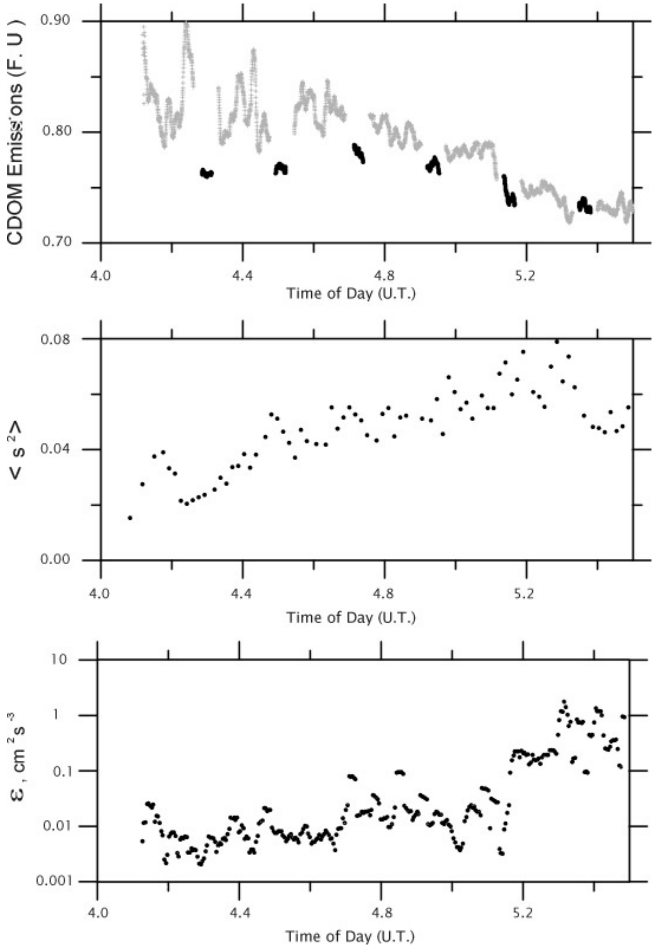

Figure 4: Data obtained on Julian Day 131 from the NSF CoOP cruise of April/May 1995 aboard the R/V New Horizon. Results are from the time period between 04:00 to 05:30 Universal Time.

and sinks of marine nutrients and phytoplankton distributions. Since the enhancement of CDOM has been well correlated to surfactant concentration, it is clear that surfactant modulation of gas transfer across the air-sea interface is a significant factor in coastal gas transfer. The need to be able to make gas transfer velocity measurements on time and space scales equal to the resolution of the variability observed in situ has initiated the study of using the CFT technique to estimate gas transfer velocity.

3.2 Example of a Steady Wind Stress

Preliminary analyses have been initiated, and some of these results are shown below. Figure 4 shows results of CDOM fluorescence, *mean-square surface slope*, $\langle S^2 \rangle$, and *turbulent dissipation rates*, ϵ for Julian Day (JD) 131. The top panel in this figure represents the surface microlayer sample ($< 100\,\mu$m) sample in grey and the subsurface sample, taken at nominally 10 cm depth in black. During the time period between 04:00 and 05:00, the surface shows a significant enrichment relative to the subsurface sample. During the entire time period represented in the figure, the wind stress was nearly constant. For those times of significant surface enrichments, correspondingly low mean-square surface slope and turbulent dissipation were recorded. These enrichments progressively decreased along the ship's track, while the mean-square surface slope and turbulent dissipation increased correspondingly. This would suggest that the heat flux (and therefore gas flux) should also be increasing during this period. Results from the CFT studies are presently in progress and will be intercompared with these data.

3.3 Example of a Modulating Wind-Stress

The same measured quantities, namely CDOM, $\langle S^2 \rangle$, and ϵ are shown as a function of time of day for JD 135 in Figure 5. During this time frame, the wind speed varied, starting at 6 m/s at times between 01:30 to 02:30, then lowering to 3.5 m/s during the time frame between 02:30 and 03:30, and then increasing to 5 m/s after about 03:30. While trends consistent with this modulated wind speed are evident in the records, several issues need to be considered before a quantitative description of the situation is attained. For example, the decrease in surface enriched CDOM observed during the periods of higher wind correlates well with the increase observed in the mean square slope and turbulent dissipation. It is not immediately evident whether the causality of this correlation is explainable as a decrease in surfactant resulting in less damped waves and a higher mean square slope; or, conversely, that an increased wave and turbulence field was responsible for enhanced near-surface mixing that depleted the sea-surface of *surfactants*. These questions will be the object of further analyses.

Acknowledgements

The authors would like to thank Nick Witzell, Dave Schroeder, and Bob Nelson for their help in the preparation and execution of this cruise. They also thank the captain and crew of the R/V New Horizon for their assistance during this experiment. This research supported by the National Science Foundation, OCE-9410537.

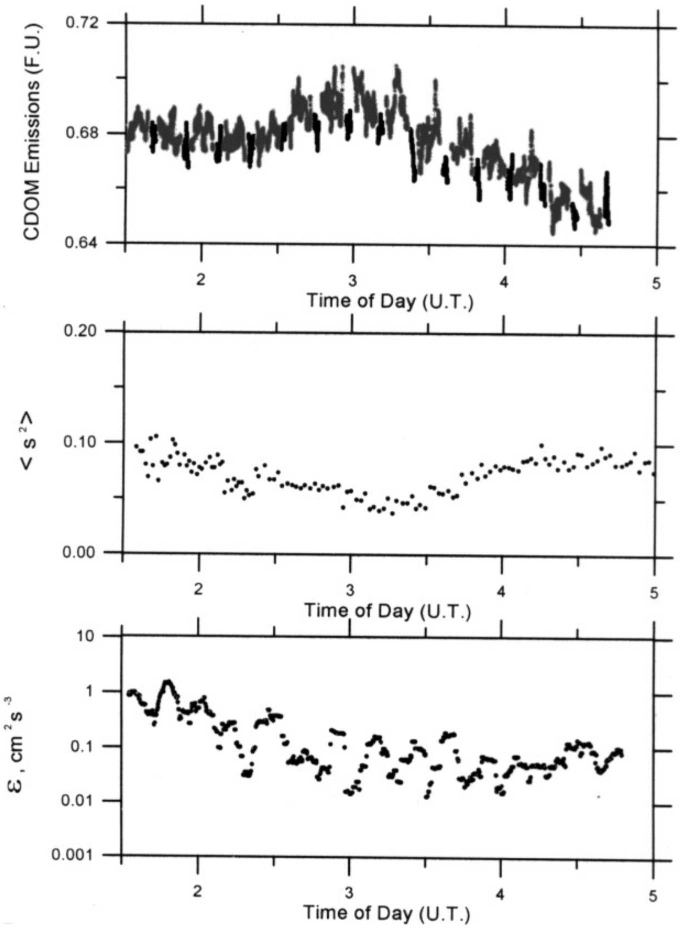

Figure 5: Data obtained on Julian Day 135 from the NSF CoOP cruise of April/May 1995 aboard the R/V New Horizon. Results are from the time period between 01:30 to 05:00 Universal Time.

References

Bock, E. J., and T. Hara, Optical measurements of capillary-gravity wave spectra using a scanning laser slope gauge. *J. Atm. Ocean. Tech.*, 12, 395–40, 1995

Broecker, W. S., and T. H. Peng, [1974] Gas exchange rates between air and sea. *Tellus*, 26, 21–35.

Carlson, D. J., J. L. Canty, and J. J. Cullen, Description of and results from a new surface microlayer sampling device, *Deep-Sea Res.*, 35, 1205–1212, 1988

Chapman, R. D., and F. M. Monaldo, Anodized tantalum wire wave gauges, *APL Technical Report* S1R–91–041U, August, 1991

Geernaert, G. L., F. Hansen, M. Courtney, T. Herbers, Directional attributes of the ocean surface wind stress vector. *J. Geophys. Res.*, 98, 16571–16582, 1993

Hara, T., E. J. Bock, N. M. Frew, and W. R. McGillis, Relationship between air-sea gas transfer velocity and surface roughness, *This volume*

Haußecker, H., and B. Jähne, In situ measurements of the air-sea gas transfer rate during the MBL/CoOP West Coast Experiment, *this volume*.

Haußecker, H., S. Reinelt, and B. Jähne, Heat as a proxy tracer for gas exchange measurements in the field: principles and technical realization, *this volume*.

Liss, P. S. and L. Merlivat, Air-sea gas exchange rates: introduction and synthesis, in *The Role of Air-Sea Exchange in Geochemical Cycling* (P. Buat-Menard ed.), Reidel, Dordrecht, pp. 113–127, 1986

Smith, S. D., R. J. Anderson, W. A. Oost, C. Kraan, N. Maat, J. DeCosmo, K. B. Katsaros, K. Bumke, L. Hasse and H. M. Chadwick, Sea surface wind stress and drag coefficients: the HEXOS results, *Bound. Layer Meteor.*, 60, 109–142, 1992

Wanninkhof, R., Relation between wind speed and gas exchange over the ocean, *J. Geophys. Res.*, 97, 7373–7382, 1992

Wanninkhof, R., J. R. Ledwell, and W. S. Broecker, Gas exchange-wind speed relation measured with sulfur hexafluoride on a lake. *Science*, 227, 1224–1226, 1985