In Situ Measurements of the Air-Sea Gas Transfer Rate during the MBL/CoOP West Coast Experiment

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Abstract

The controlled flux technique (CFT) uses heat as a proxy tracer for gases to measure air-sea gas transfer rates. It has been used during the MBL/CoOP West Coast experiment in April/May 1995 aboard R/V New Horizon for the first time at sea. In this paper the technical realization of the sea-going instrument is outlined and first measurements of the gas transfer rate in the field are shown. The high temporal resolution reveals that the gas transfer rates are intermittant with respect to space and time. Depending on surfactant concentration and the patchiness of surfactants they vary up to ±25 % of their temporal average for a certain wind speed within some minutes.

1 Introduction

Conventional techniques to measure the transfer velocity k

$$k = \frac{j}{\Delta c} \tag{1}$$

of gases across the ocean interface are based on mass balance of the gas tracer in the water body. In order to determine the flux j the temporal change $\dot{c}_w$ of the tracer concentration in a volume of water V_w has to be measured. The corresponding time constant τ_w is in the order of days to weeks in the ocean. This long integration time hinders empirical parameterization of the gas transfer rate with friction velocity and other parameters such as the wave field and prevents any insight into the mechanisms. Also the enormous difficulties in closing the mass balance for classical geochemical trace gases such as ^{222}Rn [*Roether and Kromer*, 1984], lead to systematic errors. Dual-tracer experiments as used by *Wanninkhof* [1993] and *Watson* [1991] partly overcome these problems but still suffer from the long time constant.

An alternative approach, the *controlled flux technique* (CFT) is based on the simple idea applying a controlled flux density j of a tracer across the interface. Now, the only unknown parameter according to equation (1) is the concentration difference Δc across the aqueous mass boundary layer.

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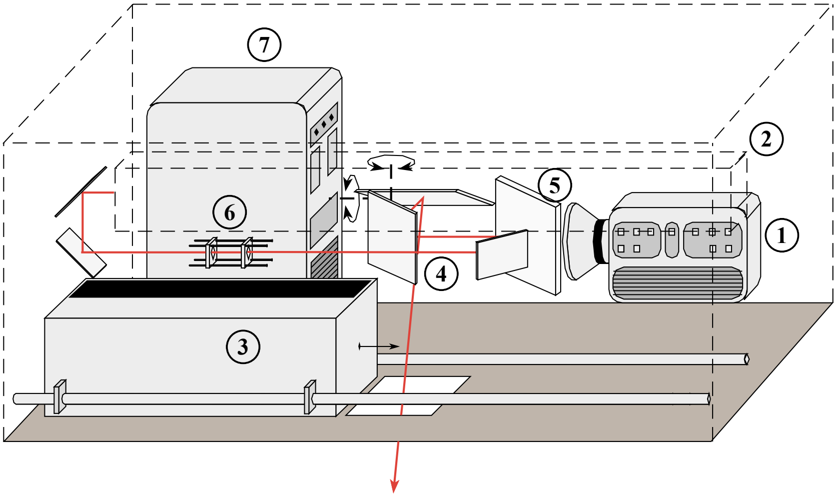

Figure 1: Schematic setup of the CFT field instrument (without detailed mountings, laser drawn transparent). 1: IR camera, 2: CO_2 laser, 3: calibration box, 4: x-y scan unit, 5: beamsplitter, 6: IR laser optic, 7: Computer.

With the assumption that the transport close to the interface is dominated by molecular diffusion, the time constant t_* for the transport across this layer with the thickness z_* is given by

$$t_* = \frac{z_*}{\langle k \rangle} = \frac{D}{\langle k \rangle^2}, \tag{2}$$

where D is the diffusion constant of the tracer in water [*Jähne et al.*, 1989]. The time constant t_* is of the order of only 0.1 to 10 s. In order to get a well defined tracer flux density, heat is used as a proxy tracer for gases. The heat concentration (temperature) at the water surface is measured with an infrared radiometer. The temperature difference ΔT can be determined by simply switching on and off the radiation. Knowing the *Schmidt number* dependency, the transfer velocity of any gas tracer can be estimated.

2 Experimental setup

Figure 1 shows the setup of the field instrument as it was used during the MBL/CoOP West Coast Experiment in April/May 1995. The main part consist of a 25 Watt CO_2 infrared laser at a wave length of 10.6 μm as a heat source and an AMBER Radiance 1 256 × 256 focal plane array (FPA) *infrared camera* with a NETD of 0.025 K, sensitive in the 3 – 5 μm wave length region. The laser is used to heat up a small area on the water surface, either in continuous or in pulsed mode. The camera observes a footprint of about 140 × 140 cm.

Figure 2: Photograph of the instrument at the boom on the foredeck of R/V New Horizon.

With an infrared optic, the size of the laser spot can be remotely adjusted from some centimeters up to the whole area observed. With this setup a large variety of heat patterns can be applied to the water surface and the temperature increase and temporal behavior of the heat distribution on the water surface can be observed.

The infrared camera has to be carefully calibrated in order to reliably use its temperature resolution of 25 mK. For this purpose a special calibration box was designed, which contains 3 different temperature standards with an extended aperture to cover the whole field of view of the camera. The geometrical arrangement of the calibration bodies, reference bodies and the box itself, together with a special IR-coating make it possible to reduce reflections of the incoming radiation flux significantly and make the calibration box almost behave like an ideal blackbody. With this special setup a relative temperature calibration can be performed with an accuracy of approx. 1 mK.

In our instrument both the camera and the laser together look via an x-y-scan unit at the water surface. The laser beam is aligned with the optical axis of the IR-camera with the help of a specially designed beamsplitter that has a reflectivity of $\rho > 0.95$ at the laser wave length (10.6 μm) and a transmitance of $\tau > 0.9$ at the camera wavelength (3 - 5 μm).

The CFT field instrument was used for the first time during the combined ONR 'Marine Boundary Layer' and NSF 'Gas Transfer in Coastal Waters' experiment (MBL/CoOP) at the US West Coast in April/May 1995 aboard the Research Vessel New Horizon (SIO). The instrumental setup was mounted at the end of a 7 m long boom right at the bow of the ship. The box was hanging 7 above the water surface and looked under an angle of 20° off bow. This aluminum construction could be retrieved to reach the instrument and to secure it. Once deployed, the boom behaved very stably and did not shake or swing even under rough sea states. With this arrangement the influence of the ship could successfully be minimized. During the measurements the ship was steaming with a speed of 0.5 m/s headed up into the wind.

3 Preliminary Results of the MBL/CoOP CFT-Measurements

During the MBL/CoOP cruise off the West Coast from April 27, 1995 to May 16, 1995, extensive measurements were made with the new instrumentation aboard R/V New Horizon. The cruise covered an area that extends from Monterey Bay at the most northern position along the California coast down to San Diego within a range of up to 30 sea miles off shore.

The cruise on R/V New Horizon offered a unique variety of simultaneous measurements of key parameters influencing gas transfer velocity. The investigations focused on wind stress, dynamic surface viscoelasticity (surfactants of biological origin), short wind waves, gravity waves and atmospheric stability. Besides the CFT the instruments aboard R/V New Horizon included a catamaran (LADAS) with a scanning laser slope gauge (SLSG), a surface film sampler (SCUMS), a sonic anemometer and a meteorological package, a bouy with an imaging slope gauge (ISG) and a combined stereo height-slope-curvature imaging device (HSCI). The participating research groups were from Woods Hole Oceanographic Institution (WHOI), University of Rhode Island, Scripps Institution of Oceanography (SIO), and University of Heidelberg [*Bock et al.*, 1995].

Samples of the acquired infrared images at wind speeds from 2.5 to 13 m/s are shown in Figure 3. It is amazing to see how sensitive the camera imaging is at faint temperature differences at the water surface, giving major direct insight into the spacial structure of the micro turbulence at the ocean interface.

It was a main discovery of this cruise, that the typical heat fluxes across the air-water interface by radiative cooling, evaporation or sensitive heat transfer are sufficiently large to cause significant temperature variations at the water surface. Nevertheless the heat patterns in Figure 3 seem to be dominated by noise. A closer evaluation of the temperature standard deviation within single images shows that the temperature variations are well above the noise level even for high wind speeds. Figures 4–5 show a time series of single-image temperature standard deviations. A sequence of 8 images was acquired every 5 seconds. Because the image content is only

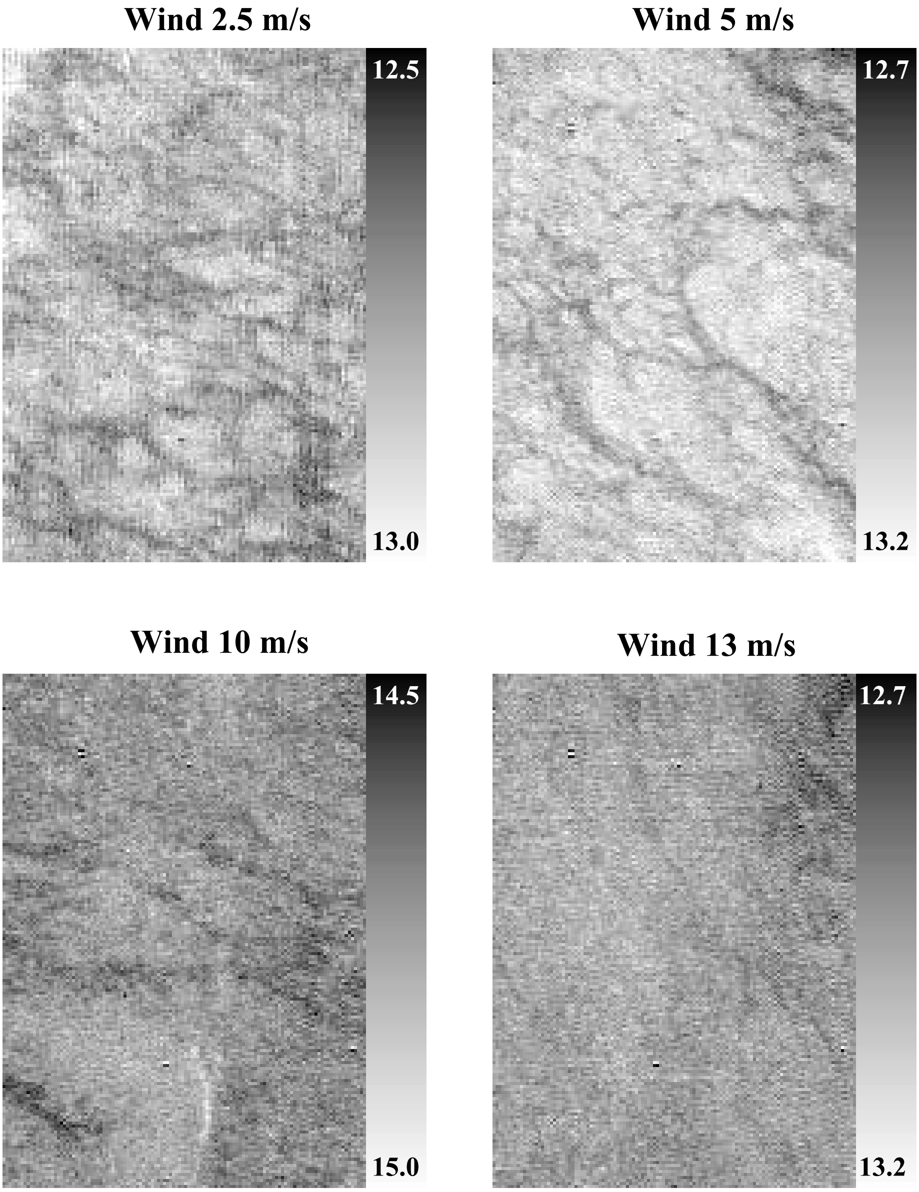

Figure 3: Examples of high resolution temperature images acquired during the MBL/CoOP West Coast experiment (temperature calibrated [° C]). The size of the images is about 1 × 1 m

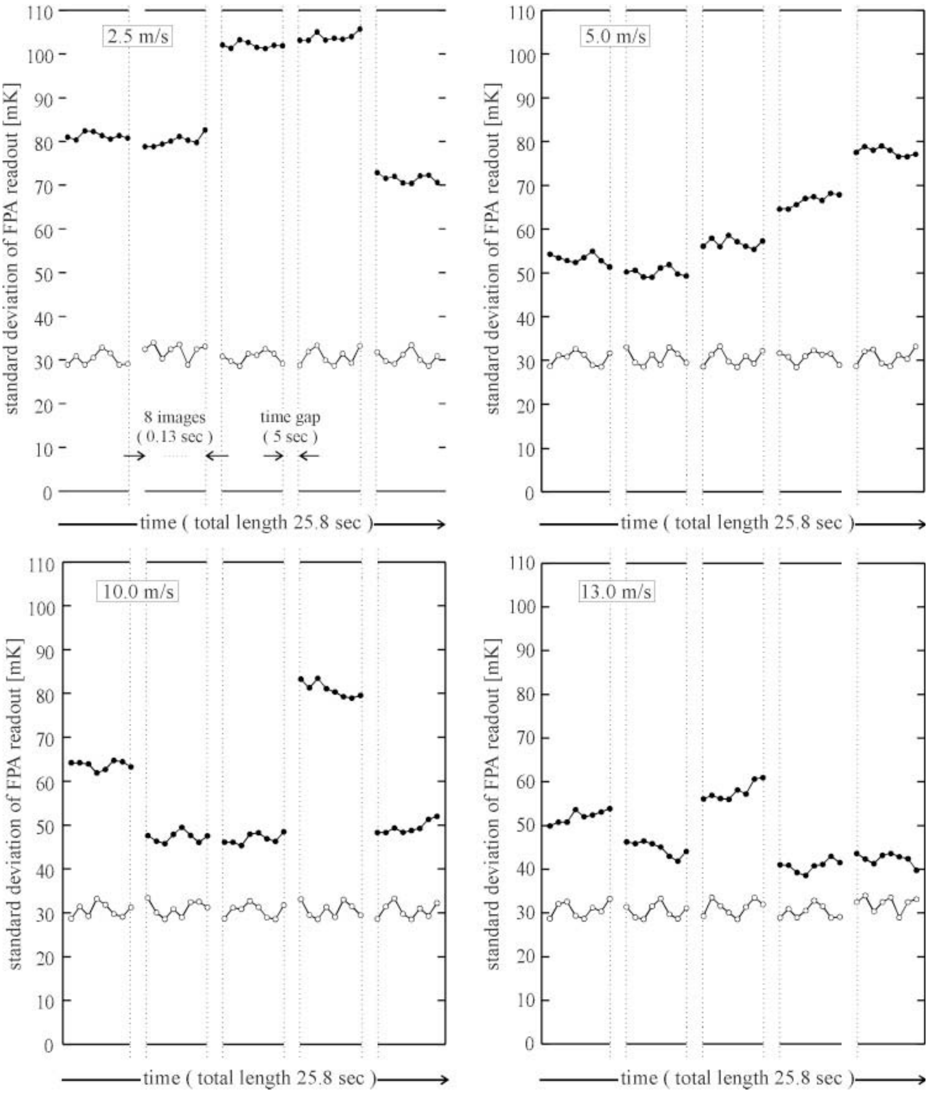

Figure 4: Standard deviation of the image temperature distribution for consecutive sequences of 8 images. The sequences were acquired at time steps of 5 seconds. Black circles: Ocean surface data for different wind speeds. Open circles: Uniformly heated calibration surface.

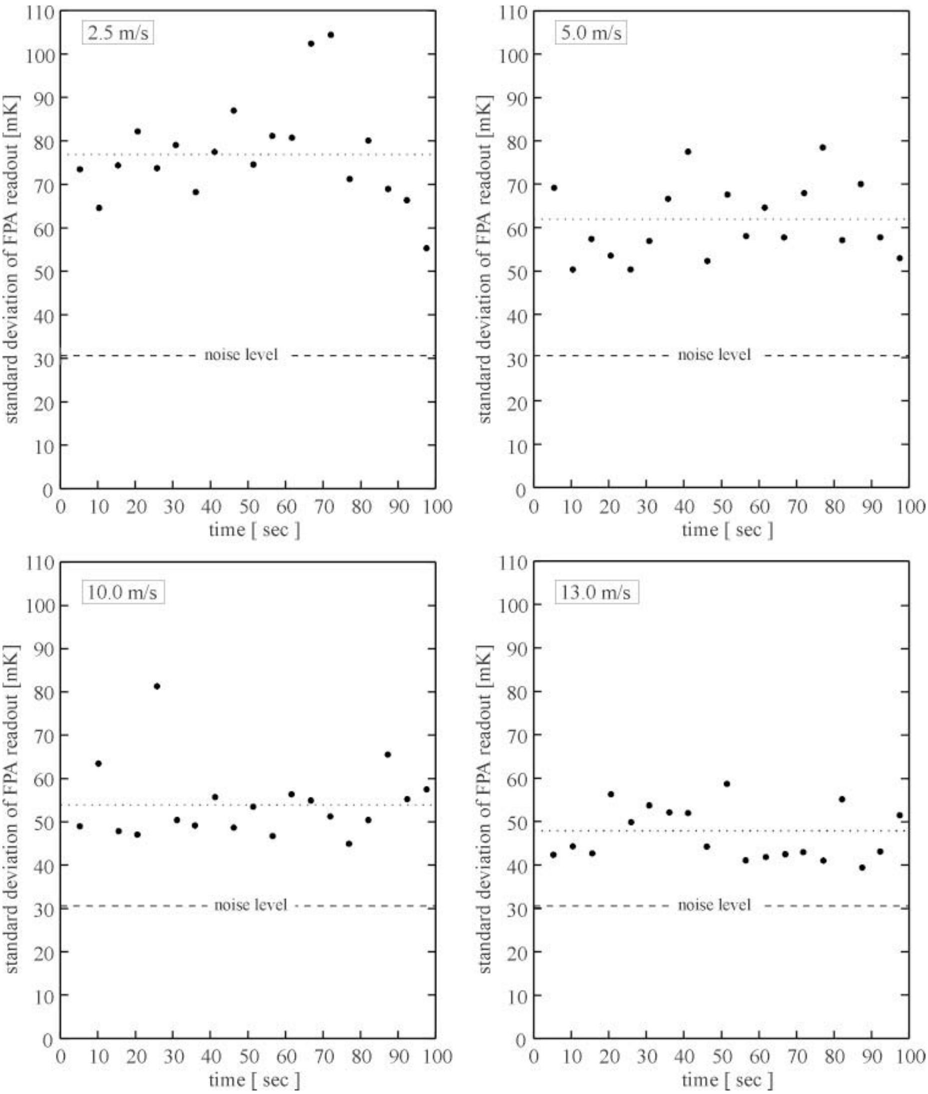

Figure 5: Standard deviation of the temperature distribution within a single image over a time interval of 100 seconds. Each dot represents the average value of one short sequence of 8 images in Figure 4. The dashed line indicates the temporal average of the camera noise in Figure 4. The dotted line shows the temporal average of the data, which is used to compute k.

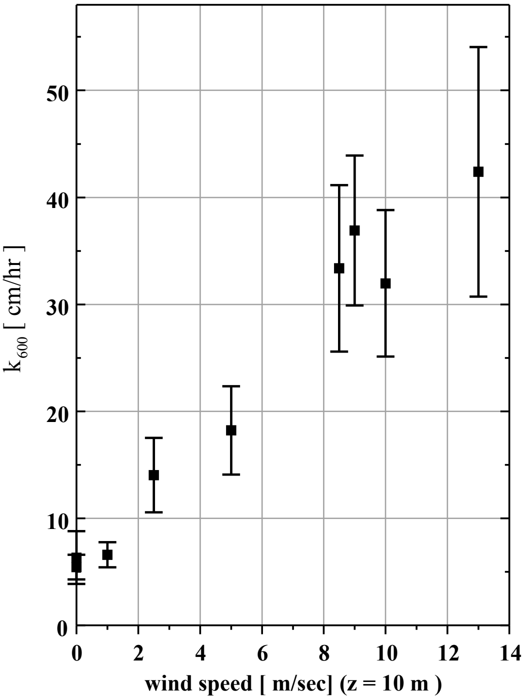

Figure 6: Gas transfer rates computed from the field data, normalized to Schmidt number Sc of 600 for different wind speeds. The error bars indicate the temporal variability (standard deviation) of the transfer rates during a period of 4 min. The black dots are the mean values of the transfer rates within this time span.

slightly shifted within 0.13 s the temperature distribution stays almost constant within the short sequences. After a time gap of 5 seconds the image content has changed and the camera observes another water surface element with different heat patterns. When the camera was pointed only at the homogenously heated surface of the calibration device, a constant standard deviation of about 30 mK was measured. This shows the noise level of the camera in good accordance with the specifications of the manufacturer. It becomes obvious that the high temporal sensitivity of the camera is very important. A twice as high noise-equivalent temperature difference ($NE\Delta T$) would already suppress the heat patterns for wind speeds higher than 5 m/s!

The temporal averages of the temperature standard deviation were used to compute the gas transfer rate k_{600} with the *spatio-temporal temperature fluctuation method*, described in *Haußecker et al.*, [1995]. Figure 6 shows some preliminary results for k_{600} at different wind speeds. These data are in good correspondence with previous ocean measurements of other researchers (Figure 7). However, k seems to be slightly increased towards

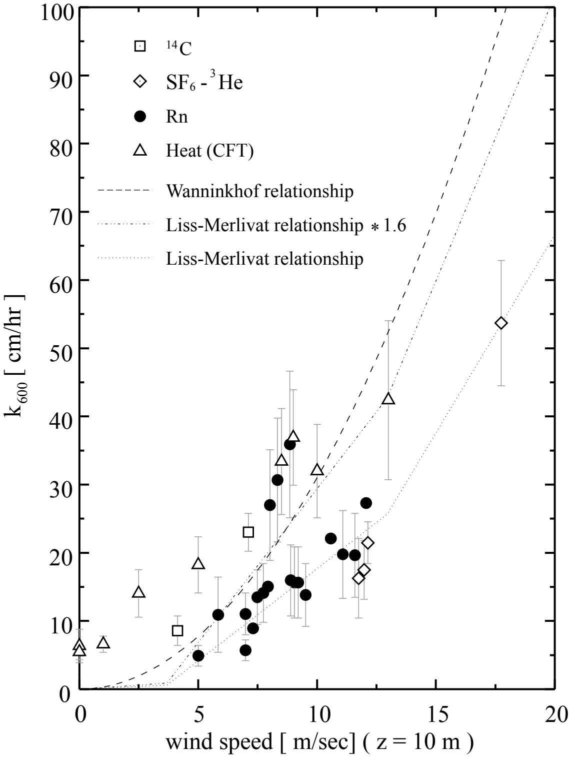

Figure 7: Summary of gas exchange measurements in the ocean and transfer velocity/wind speed relations, including some preliminary heat exchange data.

low wind speeds. This result is reasonable because at sea gravity waves are always present. One never gets a calm water surface as in wind wave facilities. There, the water surface is absolutely at rest if the wind is turned off. The data in Figure 6 shows some evidence of a slope change around a wind speed of 6 m/s, which has to be verified within further data evaluation.

The error bars in Figures 6–7 indicate the temporal variability of the transfer rate within 5 minutes. From Figures 4–5 it becomes obvious that the temperature standard deviation – and therefore the transfer rates – show fluctuations of up to 50 % of the temporal average. This discovery clearly demonstrates the importance of gas exchange measurements with a high temporal resolution. A very important issue for future research projects will be to investigate, whether the temporal variability of gas transfer rates is due to an increased *intermittence* of parameters such as wind speed and the wave field or due to a spatially inhomogenous surfactant concentration.

4 Conclusions

The field going instrument proved to work well. Gas transfer rates could be computed with a high temporal resolution of less than a minute. However, not all data are yet evaluated. The measurements also have to be related to simultaneous measurements of other parameters influencing gas transfer, e. g., surfactant concentration.

Acknowledgements

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