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Studies of Air-Sea Gas Transfer and Micro Turbulence at the Ocean Surface using Passive Thermography

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Abstract

Knowledge about the mechanisms of mass transfer across the aqueous boundary layer is still marginal because of the lack of suitable experimental techniques. We present a new technique to measure the air-water gas transfer rate and the spatial structure of the micro turbulence at the ocean surface using passive thermography. We make use of the fact that due to radiative cooling, latent and sensible heat fluxes across the interface, the ocean surface is generally a few tenths of a degree colder than the water bulk ('cool skin of the ocean'). Therefore sea surface temperature fluctuations associated with the interplay of diffusive and turbulent transfer at the air/sea interface give a direct insight into the transport mechanisms. We modeled the relation between statistical properties of the temperature fluctuations and the mean temperature difference across the aqueous thermal boundary layer. Furthermore, a first study of the spatial structure of the micro turbulence by means of digital image sequence analysis is presented.

1 Introduction

The basic idea of the *controlled flux technique*, CFT [1], is to apply a known and controllable flux density j_h of heat across the interface to force a temperature difference ΔT. This gradient is established with a time constant $t_\star$ for the transport across the boundary layer in the order of seconds. Heat flux density, j_h, temperature difference, ΔT, and time constant $t_\star$ are related by the transfer velocity for heat, k_h, according to [2]:

$$k_h = \frac{j_h}{\rho c_p \Delta T} = \sqrt{\frac{D_h}{t_\star}}, \tag{1}$$

where D_h denotes the molecular diffusion coefficient for heat in water. Given the heat flux density, j_h, the local transfer velocity, k_h, can be determined by measuring the temperature difference ΔT across the aqueous heat boundary layer. From heat transfer velocities, k_h, the transfer velocities, k_g, of arbitrary gases can be estimated using the relation

$$\frac{k_g}{k_h} = \left(\frac{Sc_h}{Sc_g}\right)^n \tag{2}$$

with the Schmidt numbers Sc_h (heat) and Sc_g (gas) and the Schmidt number exponent n [3]. The large difference in the Schmidt number (7 for heat, 600 for CO_2) casts some doubt whether the extrapolation to much higher Schmidt numbers is valid. Laboratory experiments showed, that the extrapolation is correct within about 10 % provided the uncertainty in the diffusion coefficient of the gas is less than 5 % , the Schmidt number exponent n is known with an error less than ± 0.02 [2], and no bubble mediated gas exchange takes place.

2 Passive thermography

At the ocean surface natural heat fluxes including latent, j_l, sensible, j_s, and longwave radiative, j_r, fluxes cause the surface temperature to decrease or increase depending on the meteorological conditions. The net heat flux $j_h = j_l + j_s + j_r$ causes a temperature difference across the interface of $\Delta T = j_h/(\rho c_p k_h)$ according to (1). The average temperature drop at the surface is known as the *cool skin* of the ocean [4],[5]. The high temperature resolution of modern IR cameras allows measurements of temperature fluctuations at the ocean surface under natural flux conditions (Fig. 5). *Haußecker* [6] developed a method to estimate the heat transfer velocity, k_h, from the temperature distribution in IR ocean surface images provided a known flux density, j_h. The spatial distribution of the sea surface temperature (SST) directly reveals the structure of surface turbulence [7]. The classical surface renewal model [8] proved to perfectly fit the measured surface temperature distribution.

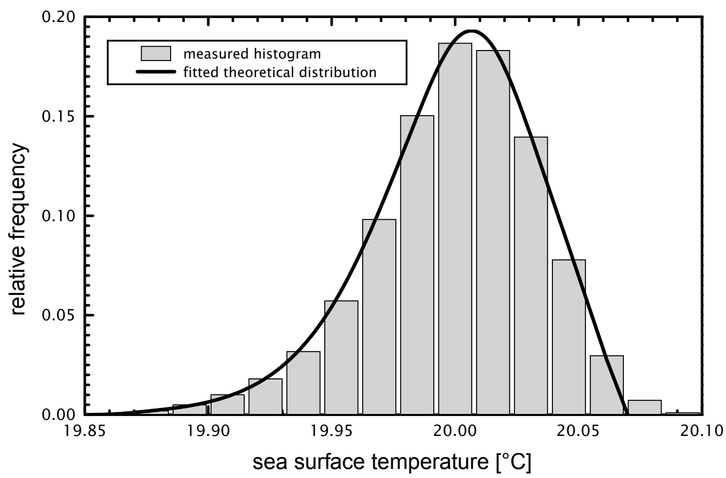

Figure 1: *The theoretical sea surface temperature distribution predicted by surface renewal model fits the measured data perfectly.*

Between two consecutive renewal events a temperature difference at the sea surface becomes $\Delta T(t) = \alpha j_h \sqrt{t}$, with $\alpha = 2(\rho c_p \sqrt{\pi D_h})^{-1}$ [9]. Given this temporal temperature change *Haußecker* [6] computed the theoretical distribution $h(T_s)$ of the temperature at the ocean surface T_s as

$$h(T_s) = \frac{2}{(\alpha j_h)^2}(T_s - T_b) \int_{t(T)}^{\infty} \frac{p(\tau)}{\tau}\, d\tau, \quad t(T) = \left(\frac{T_s - T_b}{\alpha j_h}\right)^2, \tag{3}$$

with the probability distribution $p(\tau)$ for the time in between two consecutive surface renewal events; T_b is the bulk temperature. For a log-normal distribution

$$p(\tau) = \pi^{-0.5}(s\tau)^{-1} \exp\left(-\frac{(\ln \tau - m)^2}{s^2}\right), \tag{4}$$

the theoretical distribution $h(T_s)$ is given by the following expression:

$$h(T_s) = \left\{ \begin{array}{rl} \Theta(T_s - T_b)H(T_s) & \text{if} \quad j_h > 0 \\ -\Theta(T_b - T_s)H(T_s) & \text{if} \quad j_h < 0 \\ \delta(T_s - T_b) & \text{if} \quad j_h = 0 \end{array} \right. , \tag{5}$$

where

$$H(T_s) = \frac{(T_s - T_b)}{(\alpha j_h)^2} \exp\left[\frac{s^2}{4} - m\right]\left(1 - \mathrm{erf}\left[\frac{s}{2} - \frac{m}{s} + \frac{1}{s}\ln\left(\frac{T_s - T_b}{\alpha j_h}\right)^2\right]\right). \tag{6}$$

The heat flux j_h is measured positive downwards. With $\Theta(T)$ and $\delta(T)$ we denote the binary step function, and Dirac's delta distribution, respectively:

$$\Theta(T) = \begin{cases} 1 & \text{if} \quad T > 0 \\ 0 & \text{if} \quad T \leq 0 \end{cases}, \quad \text{and} \quad \delta(T) = \begin{cases} 1 & \text{if} \quad T = 0 \\ 0 & \text{otherwise} \end{cases}. \tag{7}$$

The theoretical temperature distribution according to (5) fits the measured data perfectly (Fig. 1). Probability distributions suggested by other authors, such as periodical renewal and exponential probability distribution do not fit the data. The log-normal distribution was first proposed by *Rao et al.* [10] for statistical fluctuations in a turbulent air-flow.

Given the theoretical distribution (5) the parameters s and m of the log-normal distribution, and the *bulk temperature* T_b together with error estimates of the individual parameters can be estimated by fitting (5) to the measured histograms. The *temperature difference* ΔT across the interface can be estimated from the bulk temperature T_b and the fitted temperature distribution $h^f(T_s)$ by

$$\Delta T = \left[\int T_s h^f(T_s) dT_s\right] - T_b = \langle T_s \rangle - T_b \tag{8}$$

where $\langle T_s \rangle$ denotes the expectation value of the SST which corresponds to the measured mean SST. With ΔT, the heat transfer velocity k_h can be computed according to (1). The parameters s and m of the log-normal distribution are directly related to the time constant t_* by

$$t_* = \exp\left[m + s^2/4\right] \tag{9}$$

which allows an independent estimation of the heat transfer velocity to be obtained by equation (1).

This *statistical CFT technique* was used for the first time during the MBL/CoOP West Coast experiment in April/May 1995 aboard the R/V New Horizon. The influence of surfactants on air-sea gas transfer are subject to investigations carried out during the CoOP North Atlantic cruise

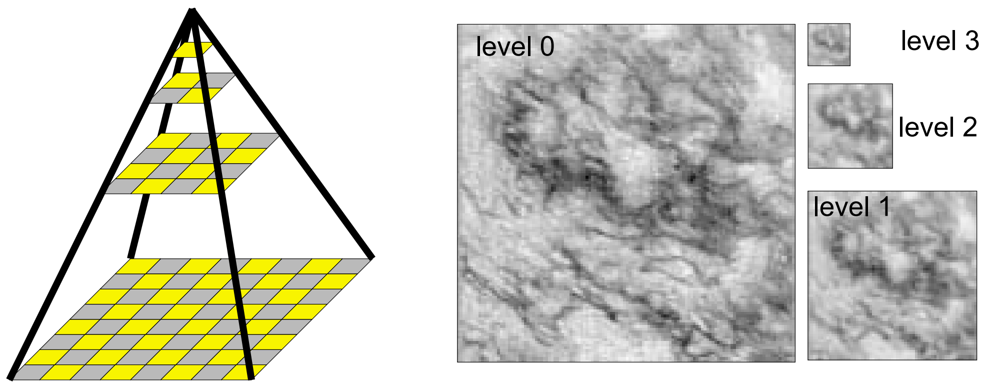

Figure 2: *Schematic representation of the Gaussian pyramid (left). Example of the transformation applied to an infrared image (right), captured during the CoOP 1997 North Atlantic cruise, wind 2.7 m/s.*

in July 1997. It could be demonstrated that the technique is capable of fast measurements even under intermittent meteorological conditions. A comparison with field data of other authors shows that the CFT data fit the general wind speed dependence [2].

3 Scale analysis

In order to perform a scale analysis of the micro turbulence at the ocean surface, the infrared image sequences are transformed into a multigrid data structure in the spatial domain. The original image is subsampled by taking every second pixel in every second line. Before this transformation the images are smoothed with an adequate filter in the wave number domain to fulfill the *sampling theorem* [11]. By repeating the smoothing and subsampling iteratively, the so called *Gaussian pyramid* is formed (Fig. 2). From level to level, the resolution decreases by a factor of two, the size of the images is decreasing correspondingly. The Gaussian pyramid constitutes a series of low pass filtered images in such a way that more and more coarse details remain in the image.

By subtracting the images between two consecutive levels the so called *Laplacian pyramid* (Fig. 3) is obtained. Only fine scales, removed by the smoothing operation to compute the next level of the Gaussian pyramid, remain in the finer level. The Laplacian pyramid is an effective scheme

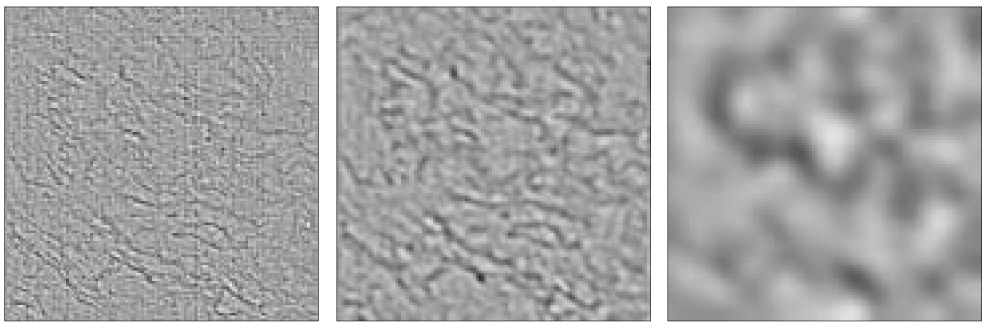

Figure 3: *Laplacian pyramid: level 0 (left), level 1 (middle), and level 2 (right). Only fine scales, removed by the smoothing operation to compute the next level of the Gaussian pyramid, remain in the finer level.*

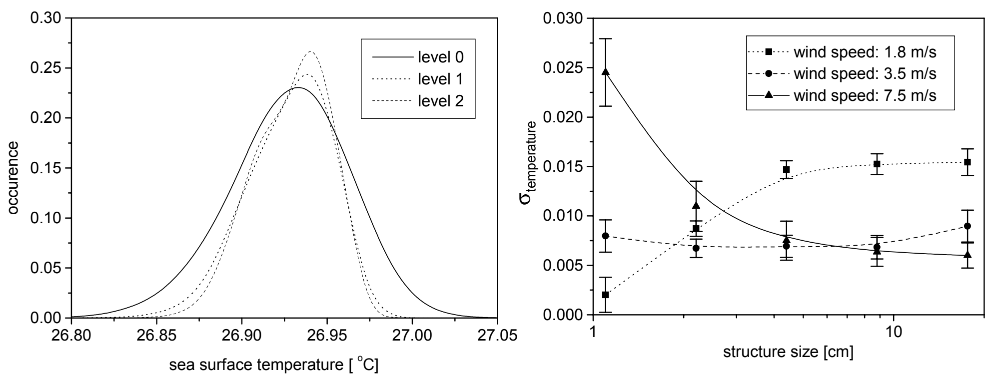

Figure 4: *Left: Histograms of different levels of Gaussian pyramid. Right: Variance of different levels of the Laplacian pyramid at different wind speed conditions.*

for *bandpass decomposition* of an image [11].

The concept of scale analysis by pyramids is a powerful tool for the investigation of micro turbulence at the ocean surface. Only a few levels of the pyramid are necessary to span a wide range of wave numbers, respectively structure sizes and allow a detailed study of the scales to be made. As shown in Sec. 2 the shape of the temperature distribution (histogram) at the ocean surface represents the underlying renewal statistics (Fig. 4). Since fine structures are progressively removed by the smoothing operation with increasing level the variance of the distributions decreases. However, the general shape of the histogram is the same at all scales and fits best with the theoretical distribution (5) which was derived from surface renewal events [4]. This observation leads to the

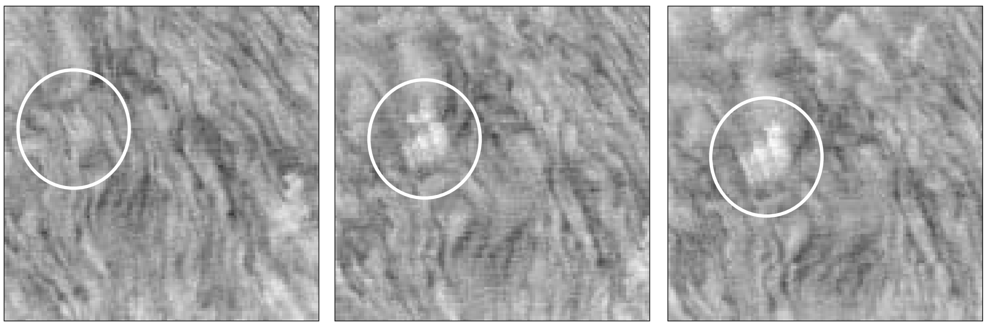

Figure 5: *Example of a surface renewal event during the CoOP 1997 North Atlantic cruise: the marked surface patch is replaced by warmer bulk water. Image size: 70×70 cm, wind direction: from left to right, wind speed: 3.6 m/s.*

assumption that the underlying renewal statistic for all analyzed scales is the same.
Since every level of the Laplacian pyramid spans a an octave of scales, the variance of a level is a measure for the dominance of a certain scale. At low wind speeds, large scales (level 3 and 4) dominate the temperature distribution whereas the variance at medium and small scales (level 0 and 1) are three times smaller (Fig. 4). At moderate wind speeds all scales contribute about equally to the temperature distribution. Finally, at higher wind speeds the smallest scales (level 0) dominate the temperature distribution.

4 Conclusion

The CFT measurements clearly support the surface renewal model. The data closely fit to theoretical dependencies such as temperature distributions predicted by the surface renewal model. Surface renewal is directly observable in the IR image sequences showing surface patches washed away even under low wind speed conditions (Fig. 5). The CFT technique is insensitive to bubble mediated gas transfer, i.e. it measures the transfer rate of a gas with very high solubility. Furthermore, the CFT is the only field technique available so far that does not only measures the transfer rate at high spatial and temporal resolution but also gives a direct insight into the spatio-temporal structure of the micro turbulence at the ocean surface and thus the mechanisms of air-water gas transfer.

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