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# Novel insights into heat transfer across the aqueous boundary layer by infrared imagery and its application to air sea exchange processes EUROTHERM 71 – 2002

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**Abstract.** Thermal imaging techniques visualize the transport of heat across the air-sea interface, revealing novel insights to aqueous boundary layer physics. Due to heat fluxes at the water surface, the ocean skin temperature is generally a few tenths of a degree cooler than the water bulk. 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 structure of near surface turbulence. The analysis of infrared image sequences reveals the statistics of surface renewal processes and the structure of near surface turbulence. The temperature difference in the order of a few tenths of a degree across the thermal boundary layer is estimated by a statistical analysis. Computing the optical flow in the infrared image sequences and the material derivative of the sea surface temperature simultaneously, the net heat flux at the sea surface s calculated. Given the net heat flux density and the temperature difference across the thermal boundary layer, the heat transfer velocity is estimated and subsequently the transfer coefficient of greenhouse gases such as carbon dioxide are calculated. The results of several laboratory and field studies are discussed.

## 1. Introduction

In recent years, the worry about the change of the global climate and the accumulation of extreme weather anomalies, e.g. droughts, floods, and storms, have directed the attention to the small-scale transport processes at the air-water interface. These processes in the viscous boundary layer have an important impact on the global carbon dioxide cycle, affecting directly the earth's climate. Due to human emissions of greenhouse gases, the atmospheric level of carbon dioxide increased continuously over the past 140 years. In 1860 the concentration in the atmosphere was about 280 parts per million, rising to a level of 370 parts per million in 1998, about a 30% increase. Over the same time period (from 1860 to present), the global average temperature has risen by about 0.6°C. The report of the Intergovernmental Panel on Climate Change (IPCC, 2001) showed a clear correlation between atmospheric carbon dioxide and temperature over last 160,000 years and predict a atmospheric concentration of carbon dioxide of more than 700 parts

per million by the year 2100, if emissions continue to grow at their present rate (1% per year). Current state-of-the-art global climate models project that anthropogenic emissions driving this carbon dioxide rise will result in a significant increase of 1.4 to 5.8°C in global average temperatures in the same time frame (IPCC, 2001).
The Ocean plays a vital role in the global climate system. Two-third of the earth's surface is covered by water, constituting an enormous capacity to absorb heat and dissolved gases. The net carbon uptake by the ocean is about 34% of the carbon released into the atmosphere and thus representing a major reservoir for carbon. The atmosphere and the biosphere play a minor role as a sink for carbon dioxide, they combine only one-tenth of carbon in comparison to the oceans. The development of reliable global climate models requires an understanding of the various parameters which influence the transfer of heat and mass across the air-sea interface. The knowledge of the underlying transport processes is quite incomplete because the transfer across the air-sea interface is very difficult to observe. To obtain new insights into these processes, infrared imaging techniques for the quantitative investigation of gas exchange have been developed in recent years (Jähne et. al., 1989, Haußecker et. al., 2001). A major progress in aqueous boundary layer physic could be achieved by using sophisticated infrared imagery in conjunction with newly developed digital image processing techniques (Garbe et. al., 2002).

## 2. Heat and mass transfer across the interface

The thickness of the aqueous boundary layer for gases is in the order of a few tenths to hundreds of micrometers, for heat hundreds of micrometers to one millimeter. Furthermore the flow and the motion of the water surface due to wind and waves make measurements of mass transport in the aqueous boundary layer an exceedingly difficult undertaking. Using heat as a tracer for gas transfer has brought tremendous experimental advances in the field of air sea interactions (Jähne and Haußecker, 1998). The basic concept of the controlled flux technique (Jähne et. al., 1989) is to apply a known and controllable flux density $j_h$ of heat across the interface to force a temperature difference $\Delta T$. This temperature gradient is established with a time constant $t_*$ for the transport across the boundary layer in the order of seconds. Heat flux density, temperature difference, and time constant are related by the transfer velocity for heat, $k_h$, according to (Jähne et. al., 1989):

$$k_h = \frac{j_h}{\rho c_p \Delta T} = \sqrt{\frac{D_h}{t_*}}, \qquad (2.1)$$

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

$$\frac{k_g}{k_h} = \left(\frac{Sc_h}{Sc_g}\right)^n, \qquad (2.2)$$

with the Schmidt numbers $Sc_h$ (heat) and $Sc_g$ (gas) and the Schmidt number exponent n (Haußecker et. al., 2001).

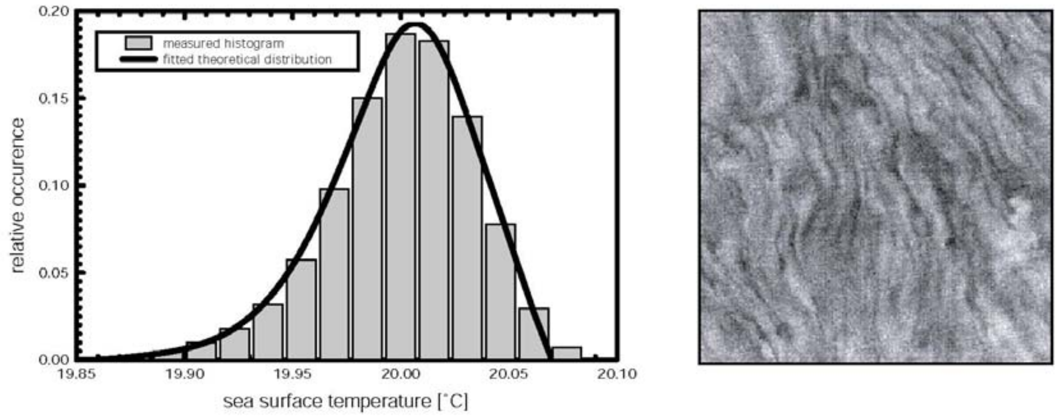


*Fig. 1: Sea surface temperature distribution (left) from an infrared image of the water surface (right) fitted with the theoretical distribution predicted by a surface renewal model.*

## 3. Modeling heat transfer across the aqueous heat boundary layer

Due to radiative cooling, latent and sensible heat fluxes at the ocean surface, the ocean skin is generally a few tenths of a degree colder than the water bulk (cool skin of the ocean) depending on the meteorological condition. The high temperature resolution of state-of-the-art infrared cameras allows measurements of temperature fluctuations at the ocean surface under natural flux conditions. Haußecker (1996) developed a procedure to calculate the temperature difference $\Delta T$ across the interface (Eq. 2.1) from the temperature distribution in infrared images from the ocean surface. The spatial distribution of the sea surface temperature (SST) directly reveals the structure of surface turbulence (Schimpf et. al., 1999). Assuming a surface renewal model (Danckwerts, 1970), the temperature difference at the sea surface the between two consecutive renewal events is given by (Soloview and Schlüssel, 1994):

$$\Delta T(t) = \alpha \ j_h \sqrt{t} \ \text{, with } \ \alpha = 2\rho \ c_p \sqrt{\pi \ D_h} \ . \qquad (3.1)$$

Given this temporal change in the temperature difference, the theoretical distribution of the temperature at the ocean surface $h(T_s)$ can be computed (Haussecker, 1996):

$$h(T_s) = \frac{2}{(\alpha \ j_h)^2}(T_s - T_b)\int_{t(T)}^{\infty} \frac{p(\tau)}{\tau} d\tau \quad , \quad t(T) = \left(\frac{T_s - T_b}{\alpha \ j_h}\right)^2 , \qquad (3.2)$$

with the probability distribution $p(\tau)$ for the time in between two consecutive surface renewal events, $T_b$ the bulk temperature and $T_s$ the bulk temperature. For a log-normal distribution the measured surface temperature distribution perfectly fits the data (Fig. 1.). Periodical renewal and exponential probability distribution do not fit the data. The used log-normal distribution for fitting the sea surface temperature distribution was first proposed by Rao et al. (1971) for statistical fluctuations in a turbulent air-flow. The temperature difference $\Delta T$ across the interface can be estimated from the bulk temperature $T_b$ and the fitted temperature distribution $h(T_s)$.

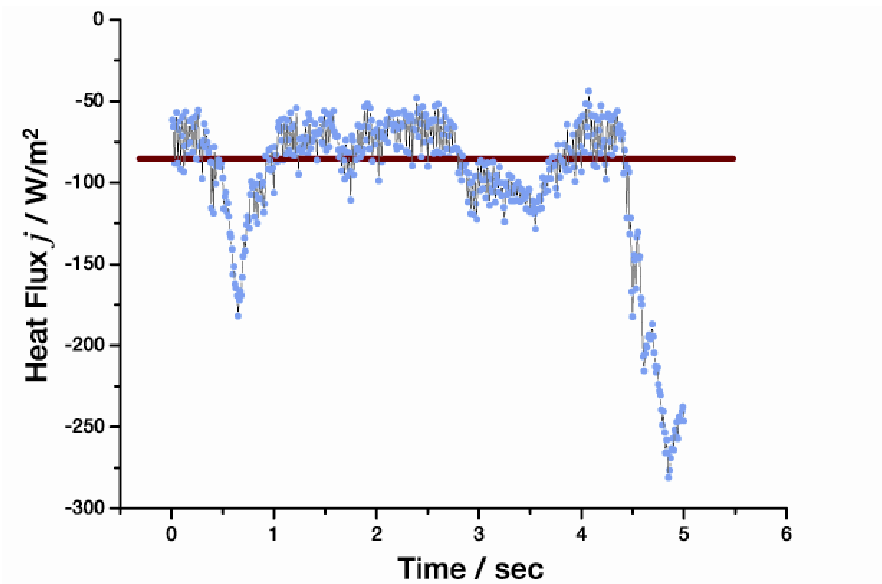


*Fig. 2: Example of the net heat flux at the sea surface during the GASEx II Experiment in the Pacific Ocean. Each data point represents the results from a single image of a sequence. The thick line shows a 5 minute average of the heat flux data.*

## 4. Estimating the net heat flux at the water surface

For gaining insights into the turbulent transport mechanisms of air water heat exchange and to estimate the heat transfer velocity (Eq. 2.1) it is essential to measure the net heat flux directly at the water surface. From equation 3.2 and the total derivative of this equation, the expression:

$$j = \frac{\sqrt{2}}{\alpha}\sqrt{\Delta T \frac{d}{dt}\Delta T} \qquad (4.1)$$

is derived. The temperature difference $\Delta T$ can be estimated from infrared image sequences, as outlined in section 3. Caused by turbulence, water from the bulk of the ocean is transported into the boundary layer. As it reaches the cooler interface, it is exposed to the heat flux at the sea surface. Traveling along the sea surface this water will eventually cool down. The rate of this cooling is equivalent to the total temporal derivative (Eq. 4.1) of the sea surface temperature. It can be estimated from digital image processing techniques by simultaneously computing the motion at the sea surface and the linear parameter of brightness change (Garbe et. al. 2002). Given the temporal derivative, equation 4.1 allows to compute the net heat flux at the water

interface. It is important to note, that the accuracy of the temporal derivative is only limited by the frame rate and the spatial resolution of the used infrared imager.
Figure 2 illustrates an example of the net heat flux estimation during the GASEx II Experiment in the Pacific Ocean in 2001. Each data point represents the results from a single image of a sequence. The high temporal resolution (*100 Hz*) of the infrared imager and thus the estimation of the heat flux allow an insight into physical processes influencing air-sea gas exchange, e.g. wave dynamics and wave breaking. Modulations of the net heat flux with wave motion could be measured for the first time.

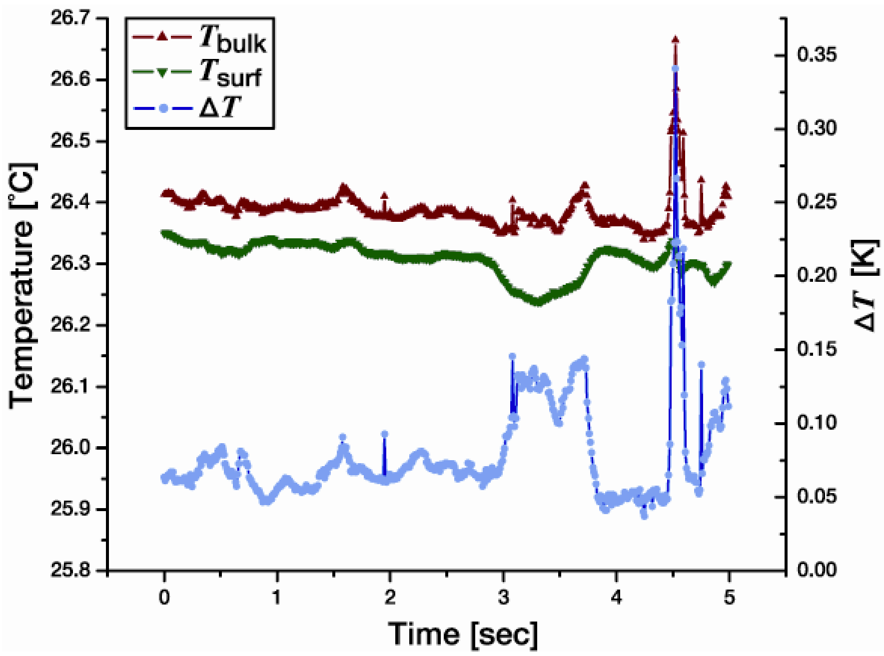


*Fig. 3: Example of surface/bulk temperature and temperature difference ΔT across the interface during the GASEx II Experiment in the Pacific Ocean. Each data point represents the results from a single image of a sequence.*

In Figure 3 an example of the surface/bulk temperature and temperature difference $\Delta T$ across the interface during the GASEx II Experiment is shown. Again, each data point represents the results from a single image of a sequence. Temporal and spatial resolution of the measurement makes it feasible to investigate the relevant physical transport processes. Surface renewal events can be identified by a sudden decrease of the sea surface temperature and the underlying renewal statistics is calculated.

## 5. Heat and gas transfer velocity

Given the net heat flux and the temperature difference across the thermal boundary layer, the heat transfer velocity is calculated according equation 2.1 and scaled to transfer velocity of carbon dioxide (Eq. 2.2). In Figure 4 the transfer velocities of carbon dioxide during the CoOP 97

Experiment in the Atlantic Ocean are plotted versus wind speed and compared with the empirical relationships from Liss (1986) and Wanninkhof (1992).

State of the art of modeling air-sea gas transfer is still a simple gas transfer rate/wind speed relationship. The large number of field and laboratory experiments taken in the recent years, however, clearly demonstrate that other parameters than wind speed are also significant. The scatter of the transfer velocity in Figure 4 can only partly be attributed to uncertainties and systematic errors in the measurements; most of it is certainly due to other factors that influence air-sea gas transfer. Consequently, the gas transfer velocity cannot simply be a function of the wind speed and a more complex model is required.

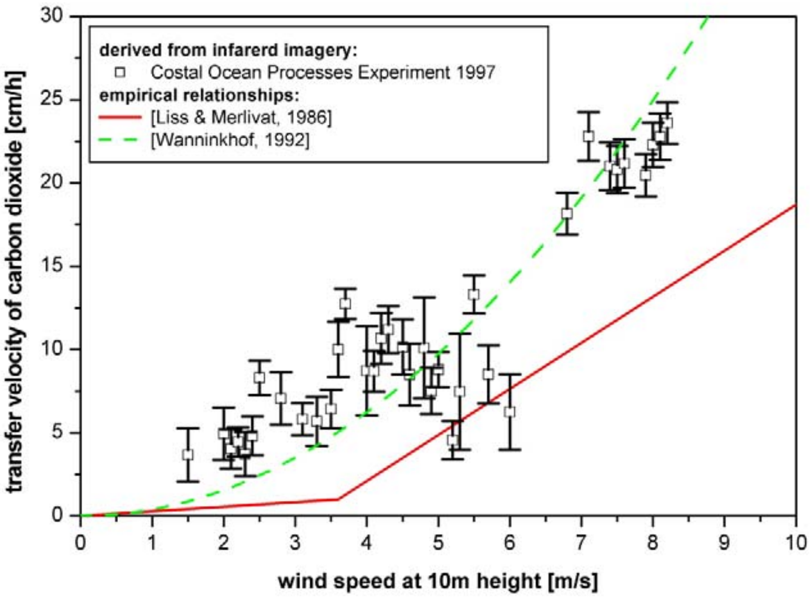


*Fig. 4: Transfer velocities of carbon dioxide versus wind speed during the CoOP 97 Experiment in the Atlantic Ocean. The wind speed dependence of the transfer velocity follows the empirical relationship from Wanninkhof (1992), whereas the difference decreases at higher wind speeds.*

## 6. Conclusion

It could be demonstrated that the applied digital image processing techniques are a suitable tool to investigate the transport of heat and gases across the air-sea interface. The presented methods allow measuring locally the net heat flux at the water surface, the temperature difference across the interface, and the transfer velocity with high temporal and spatial resolution. The obtained results reveal novel insights into the underlying transport processes and boundary layer effects. The details of near surface turbulence could be useful for a better understanding of the transport mechanisms at the air-water interface and a physically based parameterization of air-water gas transfer becomes feasible. This parameterization is essential for improving state-of-the-art global climate models which require an accurate estimate of global carbon dioxide uptake by the oceans. Current estimates of global carbon dioxide uptake using simple parameterization of gas exchange with wind speed (Liss and Merlivat, 1986, Wanninkhof, 1992, Wanninkhof & McGillis, 1999), yield estimates ranging from 1.1 to 3.3 Gt Carbon $yr^{-1}$ (Donelan and Wanninkhof, 2001).

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