

Measurements of the influence of ocean surface kinematics on air-sea heat fluxes

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Summary: We present results of several field experiments on the kinematics of small-scale surface turbulence, the influence on the surface skin layer, and the resulting transfers of heat across the diffusive layer at the surface of the ocean. A variety of optical and electro-mechanical instruments are used to measure the evolution of the surface and sub-surface velocity, and temperature fields. These include visible and infrared imaging of the surface, thermal/IR surface velocimetry, and fast-response thermometry. We show that at low wind speed, it is the small-scale turbulence at the surface of the ocean, rather than breaking waves that most influence and disrupt the surface skin layer. We find that the enstrophy of the surface turbulence correlates with the surface heat flux, and that the surface wave field modulates a component of the total air-sea heat flux.

INTRODUCTION

The top few meters of the oceanic boundary layer play a key role in the transfer of momentum, gas, heat and mass between the atmosphere and the ocean. The magnitude of these fluxes is strongly influenced by the dynamics of the surface layer. For the ocean-atmosphere heat flux, the sea surface temperature (SST) is a key variable [1, 2]; however, accurate measurements of SST are quite difficult. Directly beneath the surface is a thin diffusive sublayer where the exchange of momentum is principally governed by molecular processes. With the difference between kinematic viscosity and thermal diffusivity being almost an order of magnitude, there is also a thermal sublayer within the viscous sublayer. The thermal sublayer is typically a few mm thick, and with much of the net heat flux from the ocean to the atmosphere being positive upward, the surface temperature, or “skin temperature”, is often a few tenths of a degree colder than the bulk sea temperature. This temperature difference has long been a problem for remote SST measurements and is commonly referred to as the cool skin bias. To date, a robust parameterization of the skin temperature is still elusive.

With the globally averaged wind speed (traditionally U_{10} , the wind speed at 10m) in the range of 6-8 m/s, much of the time the air-sea interface is in a low-wind regime with the surface boundary layer in a transitional regime. From previous work [3], both in the laboratory and the field, it is the Langmuir circulations and small-scale turbulence, and not wave breaking, that first destroy the cool surface skin. However, if the winds are sustained, micro scale breaking may quickly follow [4]. Nevertheless, we expect that small-scale surface turbulence is a controlling factor of the temperature of the cool skin at low wind speeds.

EXPERIMENTS & RESULTS

Experiments were performed from the research platform FLIP during the spring of 2002 and summer of 2003. An infrared and video system was fabricated and consisted of an Infrared (IR) camera, a video camera, a CO₂ laser, a marking head assembly and a motion sensing package. The infrared camera captured images at a 60Hz frame rate. An active IR measurement is taken when the CO₂ laser is fired and the beam is redirected by the marking head to lay down a thermal pattern on the surface. (The penetration depth of the infrared radiation at the laser wavelength (10.6 μ m) is just a few microns.) In our experiments, we laid down a series of points in a sparse array such that the thermal marks could be followed within the IR images. The translation, rotation and deformation of the pattern give direct measures of

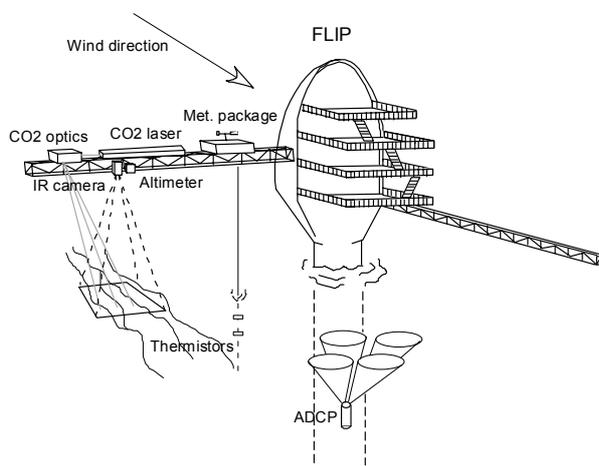


Figure 1. Experimental setup on the R/P FLIP

the velocity, vorticity, rate of strain, and divergence at the surface. In addition, the decay rate of the heat spots leads to an estimate of the surface heat flux.

Figure 2a) and b) show examples of infrared images of the ocean surface for a wind speed of 3.7m/s. The images are 2.5m x 2.5m and show a full temperature contrast of about 0.4°C. Thermal patterns consisting of three dots are clearly visible in the images. Also visible is the variance of the skin temperature due to the turbulence that disrupts the surface layer with warmer water from below. One can identify linear, semi-coherent structures on the images that resemble small-scale Langmuir circulations. The thermal pattern moves with the surface currents (including Stokes drift) and clearly deforms, indicating that the surface is sheared. Figure 2c) show the result of tracking the markers in the thermal images. In this example, the x-component of displacement exhibits wave activity, while the y-component is dominated by advecting surface currents. The temperature

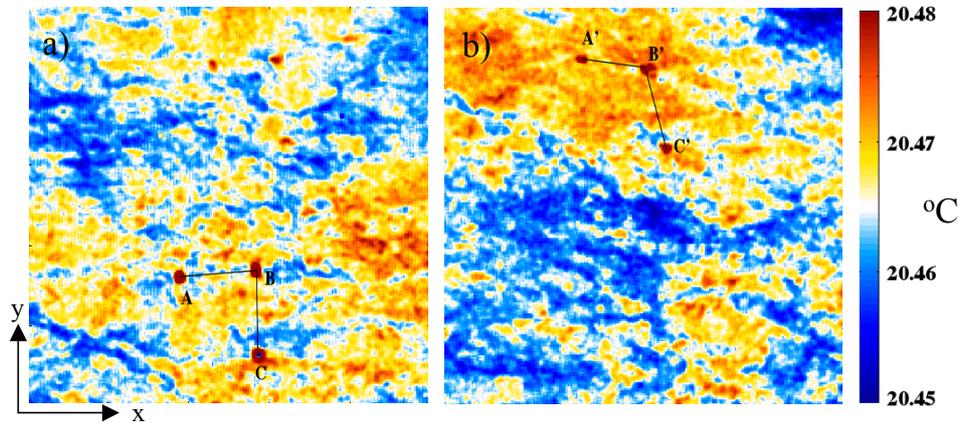


Figure 2 a) and b) Infrared images of the ocean surface taken 2s apart. Image size is 2.5m x 2.5m. The 3 warm dots labeled A, B, and C are the thermal marker laid down by the CO₂ laser.

of the spot decays exponentially, with the e-folding time being a direct measure of the air-sea heat flux through the thermal boundary layer.

The Eulerian surface velocity field is measured by cross-correlating successive IR images. It was found that the divergence of the Eulerian velocity correlates with the surface temperature. Where the divergence is positive (upwelling), the surface temperature is consistently warmer than the average image temperature. This is consistent with turbulent surface renewal events disrupting the cool surface skin

In this context, the control flux technique (CFT) developed by Jahne [5] gives an estimate of the surface heat flux based on the decay rate of the heat markers. Applying this technique to the active infrared data such as that shown in figure 2. leads to an estimate of the heat flux in various conditions. We found that the heat air-sea heat flux estimated with the CFT method correlates with the surface turbulence parameters (e.g. rms surface vorticity) better than it does with bulk parameters like wind speed. This indicates that, as expected, the small-scale turbulence is, at low speed, a controlling factor in determining the heat transfer.

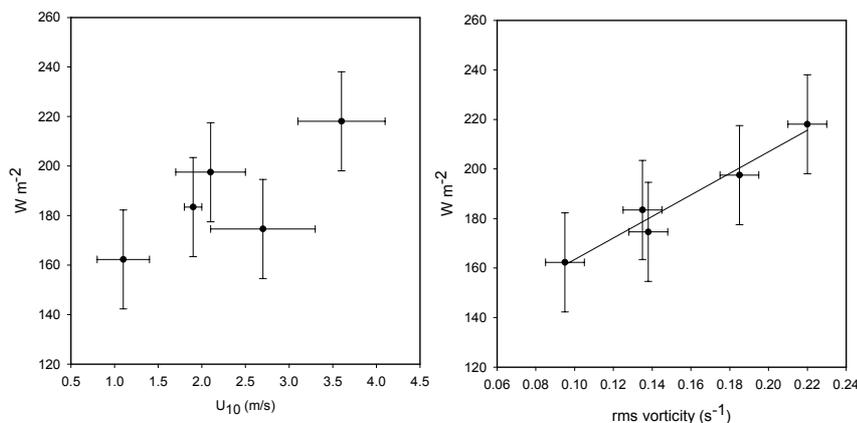


Figure 3. a) Surface heat flux as a function of wind speed and b) as a function of surface rms vorticity.

CONCLUSIONS

We have performed high-resolution measurements of the sea-surface temperature and kinematics using both active and passive infrared imaging techniques. We found that passive and active IR imaging techniques are well suited for the measure of both Lagrangian (tracking) and Eulerian (cross correlation) surface kinematics. It consequently appears that air-sea heat flux correlates well with the small-scale surface turbulence parameters.

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