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Measurements of the oceanic thermal skin effect

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ABSTRACT

Spectroradiometric measurements of the ocean skin temperature and thermometric measurements of the bulk temperature at a depth of about 5 cm taken from the *R/V Tangaroa* during SAGE (SOLAS/SAGE: surface-ocean lower-atmosphere studies air–sea gas exchange experiment) off New Zealand are analyzed to reveal the wind speed dependence of the temperature difference across the thermal skin layer (ΔT). The wind speeds used here are corrected for flow distortion by the ship. Unlike most previously published measurements of ΔT, these data include those taken during the day, prior analyses being usually restricted to night-time measurements to avoid contamination of the data by diurnal heating. The results show the same dependence of ΔT on wind speed at night-time measurements, with an asymptotic behavior at a value of -0.13 K at high winds. These data show larger ΔT at low wind speeds than previous studies, and there is an indication that this may reveal a dependence on sea surface temperature.

1. Introduction

In the absence of bubble injection that results from wave breaking (Wallace and Wirick, 1992), the exchange of most gases between the ocean and atmosphere is mediated by molecular diffusion through the boundary layer on the aqueous side of the air–sea interface. The density difference across the interface dampens the turbulence that is very effective in the vertical transport of dissolved gases in the uppermost layer of the ocean, leaving the so-called diffusion sublayer on the aqueous side. This sublayer sustains large gradients of the concentration of dissolved gases that drive the diffusive exchanges between the ocean and the atmosphere. The concentration gradient can be expressed in terms of the differences in the partial pressures of the dissolved gas at the top interface of the sublayer with the atmosphere, and at the lower interface with the turbulent oceanic layer beneath. However, it is currently not technically feasible to measure the concentration gradient across the diffusion sublayer in the field, although there are promising approaches being applied in the laboratory (e.g. Variano and Cowen, 2007; Falkenroth et al., 2007), and so the physics of the gas exchange at the ocean surface is parameterized in terms of the concentration difference between the near-surface air and the subsurface water. In the case of carbon dioxide, the flux, F, is commonly calculated using

$$F = k_w \alpha_w (fCO_{2w} - fCO_{2a}) \quad (1)$$

where k_w is the exchange coefficient, often referred to as the piston velocity, α_w is the solubility of CO_2 in sea water, fCO_{2w} is the fugacity of CO_2 in sea water and fCO_{2a} is the fugacity in air (see Ward et al., 2004a, and the references therein). All the terms of this expression have a temperature dependence, and conventionally, the more readily available bulk sea surface temperature (SST) has been used in the calculations of CO_2 fluxes rather than the skin SST. The temperature of the sea-surface that is in contact with the atmosphere, the skin SST, is arguably the more relevant temperature to use. Previous studies have indicated that failure to account for the cool skin of the ocean can lead to a significant error in the estimates of global fluxes of CO_2 into the ocean from the atmosphere: an underestimate of up to $\sim$0.7 Gt C yr^{-1} was determined by Robertson and Watson (1992), but this has been subsequently revised to smaller values through the use of better representations of the wind speed distribution (Van Scoy et al., 1995), improved cool skin parameterizations (Ward et al., 2004a) and better representations of the physical processes across the skin layer (McGillis and Wanninkhof, 2006). A useful summary of the state of knowledge of the processes governing gas transfer at the ocean's surface is presented by Donelan et al. (2001) and Garbe et al. (2007).

Here we present measurements of the skin-to-bulk temperature differences taken during a cruise of the *R/V Tangaroa* during the SAGE (SOLAS/SAGE: surface-ocean lower-atmosphere studies air–sea gas exchange experiment) in the waters over the Campbell Plateau off the South Island of New Zealand. The conditions were such that some of the skin and bulk SST measurements were made in higher winds than previously reported, and using a surface following float to measure the bulk temperatures at a depth of about 5 cm, measurements were made during the day, thereby permitting confirmation that the thermal skin effects described previously using night-time measurements are indeed representative of the skin temperature differences during the day, even in

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conditions that are favorable to the generation of a diurnal thermocline and a warm surface layer (e.g. Gentemann and Minnett, 2008; Gentemann et al., 2008; and the references therein).

2. Background

The temperature of the surface of the ocean, at the interface between ocean and atmosphere, is commonly called the skin SST. It approximates to the temperature of the ocean that the gas molecules experience when they pass through the ocean surface and so the skin SST is a more appropriate parameter to determine the solubility of gases in sea water at the point of exchange with the atmosphere than the subsurface temperature, which is commonly referred to as the bulk temperature.

2.1. Radiometric measurements of SST

The most appropriate method of measuring the skin SST is using a ship-mounted infrared radiometer to measure the radiance having its origin in the thermal skin layer of the ocean. The bulk SST can be measured by in situ thermometers below the surface. The near-surface temperature gradients that introduce a difference in the skin and bulk temperatures result from three distinct processes: the absorption of insolation, the heat exchange with the atmosphere and levels of subsurface turbulent mixing. In conditions of low wind speed, the heat generated in the upper few meters of the water column by the absorption of solar radiation is not mixed through the surface layer, but causes thermal stratification and temperature differences between the uppermost layer of the ocean and the water below. There is a strong diurnal component to the magnitude of these temperature gradients, as well as a dependence on cloud cover, which modulates the insolation, and wind speed, which influences the turbulent mixing (e.g. Price et al., 1986; Fairall et al., 1996; Gentemann et al., 2003; Gentemann, 2007; Gentemann and Minnett, 2008). The surface, skin layer of the ocean, much less than 1 mm thick (Hanafin and Minnett, 2001; Hanafin, 2002), is nearly always cooler than the underlying water because the heat flux is nearly always from the ocean to the atmosphere. The heat flow, supplying energy for both the turbulent and radiant heat loss to the atmosphere, is accomplished by molecular conduction through the aqueous side of the interface and this gives rise to and is controlled by a temperature gradient in the surface skin layer. The presence of the cool skin at the air–sea boundary has been known for several decades from careful in situ (e.g. Woodcock and Stommel, 1947; Katsaros et al., 1977; Mammen and Bosse, 1990; Ward et al., 2004b; Ward, 2006) and radiometric measurements taken in a wide range of conditions (e.g. Saunders, 1967; McAlister and McLeish, 1969; Hepplewhite, 1989; McAlister and McLeish, 1969; Schluessel et al., 1990; Donlon and Robinson, 1996; Jessup and Hesany, 1996; Jessup et al., 1997; Kent et al., 1996; Smith et al., 1996; Zappa et al., 1998; Minnett et al., 2001; Donlon et al., 2002; Minnett, 2003). The more recent measurements show a wind-speed dependence of the size of the skin temperature difference at night, asymptoting to a non-zero value at higher wind-speeds (Minnett and Hanafin, 1998; Donlon et al., 2002; Minnett, 2003).

During the day, when the conditions allow a diurnal thermocline to form, the skin may appear warmer than a bulk temperature at some depth below (Jessup et al., 1997; Kent et al., 1996; Smith et al., 1996; Minnett and Hanafin, 1998; Murray et al., 2000; Donlon et al., 2002; Minnett, 2003), but this does not necessarily mean that the vertical temperature gradient within the skin layer has changed the sign. It is merely an artifact of the depth at which the bulk temperature measurements are taken (Jessup et al., 1997; Kent et al., 1996; Smith et al., 1996; Ward et al., 2004b; Wick et al., 2005; Ward, 2006). The relationship with deeper bulk temperature, at depths of a few meters where many bulk SST measurements are taken, is the same on average during the night and during the day for wind speed conditions of $> \sim 6\ \mathrm{m\ s^{-1}}$ (Donlon et al., 2002; Minnett, 2003). But under low winds the relationship is very variable—vertically, horizontally and temporally (Ward et al., 2004b; Wick et al., 2005; Ward, 2006). Thus the difference between the skin temperature and that measured by a bulk, in situ thermometer, is very variable and highly dependent on the depth of the bulk measurement. Thus, although bulk SST measurements are easier to make in a routine fashion, the measurement itself may not be appropriate for the study of air–sea gas exchanges, for example, or for the determination of quantities that exhibit a dependency on the sea-surface temperature.

A modeling study (Wick et al., 2005) attempted to improve the performance of the widely used Fairall et al. "warm-layer, cool-skin model" (Fairall et al., 1996, 2003) during the day modifying the absorption of solar radiation within the skin layer. Wick et al. compared the model predictions with measurements from the calibrated infrared in situ measurement system (CIRIMS) mounted on the NOAA Ship *Ronald H Brown* (Jessup and Branch, 2008). The model predicted daytime skin-layer cooling to increase by 0.03 K on average but by more than 0.25 K for winds below $1\ \mathrm{m\ s^{-1}}$ and surface irradiance exceeding $900\ \mathrm{W\ m^{-2}}$. However, their measurements generally revealed a skin layer cooler than modeled, and the wind-speed or surface temperature dependences of the measured skin-effect were not explicitly explored.

3. The SAGE cruise

The SAGE cruise of the *R/V Tangaroa* took place from 17 March to 15 April 2004 to the south-east of New Zealand in the vicinity of the S.W. Bounty Trough at 48°S, 173°E (Fig. 1).

A key objective of SAGE was to enhance the CO_2 gas flux stimulating a phytoplankton bloom adding iron fertilizer to iron-limited Sub-Antarctic waters. The iron injection was accompanied by the addition of two inert dissolved gas tracers, sulfur hexafluoride (SF_6) and helium-3 (^3He), with the intention of facilitating a Lagrangian patch/dual-tracer study with the dissolved gases defining a control volume, and providing vertical and lateral diffusion rates and estimates of air–sea gas exchange. It was anticipated that the enhanced CO_2 fluxes produced by the growth of the phytoplankton would result in a large signal for determining the rate of gas exchange and its response to changes in the key physical processes governing the exchange. The full experimental objectives and procedures are presented elsewhere (Harvey et al., 2011).

This area was chosen because it fulfilled four conditions:

- A relatively quiescent and homogeneous upper ocean, away from fronts or other regions of current shear, allowing tracer labeled patch tracking for up to a month.
- A moderate mixed layer depth (ideally < 80 m) for the optimal dilution of manageable quantities of the iron fertilizer.
- A range of wind speeds to support the study of wind speed dependences of the gas exchange processes.
- Waters with the potential for bloom development by iron fertilization, not suffering from limiting amounts of other nutrients, where gas fluxes (CO_2 and DMS) would be enhanced by the stimulated bloom.

The contributions of this study to the experimental objectives are focused on improving our understanding of the behavior of the thermal skin layer, in particular to wind forcing.