Autonomous Measurements of Sea Surface Temperature Using In Situ Thermal Infrared Data

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ABSTRACT

In situ and autonomous measurements of sea surface temperature (SST) have been performed with a thermal infrared radiometer mounted on a fixed oil rig. The accuracy limit was established at $\pm 0.3$ K for these SST measurements in order to meet the requirements of the Tropical Ocean Global Atmosphere (TOGA) program for global climate research and the Soil Moisture and Ocean Salinity (SMOS) mission for salinity retrieval. With this aim, the optimal observation angle and spectral channel for SST measurements have been identified. Then, a methodology has been developed for the radiometer calibration and the emissivity correction, including the reflection of the downwelling sky radiance, which was directly measured simultaneously to the sea surface observation. The effect of the atmospheric path between the sea surface and the sensor has been found negligible for the particular viewing conditions. A sensitivity analysis of the proposed methodology has shown a precision of $\pm 0.15$ K in the retrieved SST. Finally, the measured SSTs have been validated with coincident buoy temperatures, resulting in an average difference of 0.0 K and a standard deviation of $\pm 0.2$ K.

1. Introduction

Sea surface temperature (SST) is a key geophysical variable in understanding the surface exchange processes between the atmosphere and the oceans, especially in the framework of global climate research. Over the last two decades, significant progress has been made in the measurement and mapping at global scale of SST from satellite remote sensors. The accuracy limit for the satellite-derived SST is $\pm 0.3$ K as defined by the international Tropical Ocean Global Atmosphere (TOGA) program (Barton 1992).

To achieve this accuracy, in situ measurements of SST are required for the definition and validation of SST retrieval algorithms. These measurements were based mostly on several types of contact sensors deployed on ships and on moored or drifting buoys (Schluessel et al. 1987). The main problem with these observations is that contact sensors measure the temperature at a certain depth (of the order of centimeters or meters), while infrared instruments measure the temperature of the sea surface skin, which comprises only a few microns. The thermal stratification of the upper-ocean layers during the day, for low wind speeds mainly, may complicate the relationship between both temperatures, introducing a degree of uncertainty in the interpretation of results (Barton 2001; Donlon et al. 2002). For this reason, significant efforts have been made to set up validation systems based on the use of in situ infrared sensors that are usually mounted on ships (Barton 1985; Schluessel et al. 1990; Smith et al. 1996; Wick et al. 1996; Wu and Smith 1997; Donlon et al. 1998) or aircrafts (Saunders 1967; Hagan et al. 1997). Some authors have used drifting platforms, such as the Floating Instrument Platform (FLIP) used in the California bight by Jessup and Hesany (1996).

In this paper, SST determination is carried out using in situ thermal infrared data measured from an oilrig in the Mediterranean Sea using a CIMEL Electronique CE 312\(^1\) radiometer mounted on an autonomous system. The measurements took place during the 2000 and 2001 Wind and Salinity Experiment (WISE) campaigns conducted in the framework of the Soil Moisture and Ocean Salinity (SMOS) mission, sponsored by the European Space Agency (ESA). The SMOS request in salinity accuracy is $\pm 0.1$ psu (1 psu = 1 g of salt in 1 kg of seawater), which is derived from the Global Ocean Data Assimi-

\(^1\) The use of company and brand names is for information only and does not imply endorsement by the authors.
The thermal infrared radiometer used during the WISE campaigns was the CIMEL Electronique model CE 312 (Sicard et al. 1999; Legrand et al. 2000). It has four spectral bands, two broadband channels, 8–14 μm (bands 1 and 2), and three narrow channels, 11.5–12.5, 10.5–11.5, and 8.2–9.2 μm (bands 3 and 4, respectively). Figure 1 shows the spectral bandpasses of the CE 312 narrow channels, together with the atmosphere transmittance corresponding to the tropical and midlatitude summer standard atmospheric profiles shown in the secondary axis.

![Figure 1: Spectral response functions of the CE 312 radiometer channels.](image)

The WISE campaigns were held at Repsol YPF’s Casablanca fixed oil rig placed at 40°43’4”N and 1°21’34”E, 40 km off the mouth of the River Ebro on the coast of Tarragona, Spain. In this location, the sea conditions are representative of the open Mediterranean with periodic influence of the River Ebro freshwater plume. Measurements were taken in two different periods: from 15 November 2000 to 13 January 2001 (WISE 2000) and from 23 October to 22 November 2001 (WISE 2001).

A calibration function was obtained for each channel:

\[ R_{m,i} = \frac{\tau B_i(T_s) + \rho B_i(T_i) + \alpha B_i(T_w)}{B_i(T)} + \zeta, \quad (1) \]

where \( R_{m,i} \) is the CE 312 radiance measured through the ZnSe window in channel \( i \); \( B_i(T) \) is the channel \( i \) averaged Planck’s function for a temperature \( T \); \( T_i \) is the thermometric temperature of the source; \( T_w \) is the internal temperature of the radiometer’s optical head; and \( \tau, \rho, \alpha, \) and \( \zeta \) are the window absorbance, reflectance, and transmittance, respectively. Equation (1) can be rewritten as

\[ R_{m,i} - B_i(T) = \tau [B_i(T_s) - B_i(T_i)] + \zeta, \quad (2) \]

with \( \zeta = \alpha [B_i(T_w) - B_i(T_i)] \). Since \( T_i \) and \( T_w \) were similar and correlated, \( \zeta \) was practically constant. Thus, a linear regression of \( R_{m,i} - B_i(T) \) on \( B_i(T_s) - B_i(T_i) \) allowed the determination of the calibration parameters \( \tau \) and \( \zeta \). The calibration coefficients are presented in Table 1.

Equation (2) can be rewritten as

\[ B_i(T) = \frac{R_{m,i} + (1 - \tau) B_i(T_i) - \zeta}{\tau}, \quad (3) \]
from which the calibrated brightness temperature, \( T_s \), is obtained. The accuracy of \( T_s \) can be determined by applying the error theory to Eq. (3). Thus the error in \( B_i(T_s) \) will be

\[
\sigma[B_i(T_s)] = \sqrt{\left( \frac{\partial B_i(T_s)}{\partial T_s} \right)^2 \sigma^2(T_s) + \left( \frac{\partial B_i(T_s)}{\partial \tau_i} \right)^2 \sigma^2(\tau_i) + \left( \frac{\partial B_i(T_s)}{\partial \zeta_i} \right)^2 \sigma^2(\zeta_i) + \left( \frac{\partial B_i(T_s)}{\partial T_i} \right)^2 \sigma^2[B_i(T_i)]},
\]

where \( \sigma(B_m) \) is the CE 312 radiance error, \( \sigma(\tau) \) and \( \sigma(\zeta) \) are the errors in the calibration coefficients (these are the standard deviations given in Table 1), and \( \sigma[B_i(T_i)] \) is the error of Planck’s function for the internal temperature of the radiometer’s optical head. Note that \( \sigma(B_m) \) was evaluated from several previous calibration processes of the radiometer carried out under a wide range of thermal conditions, obtaining values of \( \pm 1.4 \times 10^{-5}, \pm 2 \times 10^{-5}, \pm 1.4 \times 10^{-5}, \) and \( \pm 1.8 \times 10^{-5} \) mW cm\(^{-2}\) sr\(^{-1}\) cm\(^{-1}\) (equivalent to \( \pm 0.10, \pm 0.12, \pm 0.09, \) and \( \pm 0.14 \) K) for channels 1–4, respectively. To determine \( \sigma[B_i(T_s)] \), the internal temperature error, \( \sigma(T_s) \), is used:

\[
\sigma[B_i(T_s)] = \left| \frac{\partial B_i(T_i)}{\partial T_i} \right| \sigma(T_i),
\]

where \( \sigma(T_s) = \pm 0.1 \) K is the accuracy of the platinum probe placed inside the optical head.

Finally, the brightness temperature accuracy for each CE 312 channel, \( \sigma(T_{s,i}) \), is obtained from (4):

\[
\sigma(T_{s,i}) = \left| \frac{\partial T_{s,i}}{\partial B(T_{s,i})} \right| \sigma[B(T_{s,i})].
\]

Applying Eqs. (4)–(6) to the CE 312 data measured during both WISE campaigns, sea surface brightness temperature errors of \( \pm 0.14, \pm 0.16, \pm 0.12, \) and \( \pm 0.18 \) K were obtained for the CE 312 channels 1–4, respectively. These results show that the variability of the calibration coefficients \( \tau, \zeta \) given by the standard deviation presented in Table 1 \([\sigma(\tau), \sigma(\zeta)]\), had a negligible impact on the accuracy of the brightness temperatures, due to a minimum contamination effect of the ZnSe window.

Simultaneous measurements of the temperature of the sea surface at some depth \( (\text{SST}_{\text{bulk}}) \) were carried out during both campaigns to validate the SST retrievals given by the measurement strategy proposed in this paper. Measurements of \( \text{SST}_{\text{bulk}} \) were made with Sea-Bird Electronics (SBE) 37-SM MicroCAT thermal probes (property of the Institute of Marine Sciences, ICM-CSIC, Spain) placed in oceanographic buoys measuring at 20-cm depth. These thermal probes are high-precision thermistors, providing an accuracy of \( \pm 0.002 \) K after manufacturer calibrations previous to each campaign (Font et al. 2003; Budeus and Schneider 1998). The buoys were located very close to the thermal radiometer target and took \( \text{SST}_{\text{bulk}} \) measurements every 2 min.

### 3. Methodology

The radiance measured by channel \( i \) of a thermal infrared radiometer located at a height \( h \) and observing the sea surface under a direction \( (\phi, \theta) \), \( R_i(\theta, \phi, h), \) is the sum of two main components: (i) the radiance at surface level, \( R_{s,i}(\theta, \phi, 0) \), which is attenuated by the absorption of the atmosphere between the sea surface and the instrument; and (ii) the upwelling sky radiance emitted by the atmosphere in the viewing direction, \( L_{\uparrow_{\text{atm}}}^i(\theta, \phi) \). The measured radiance, \( R_i(\theta, \phi, h) \), can be expressed by the following two equations:

\[
R_i(\theta, \phi, h) = R_{s,i}(\theta, \phi, 0) \tau_i(\theta, \phi, 0, h) + L_{\uparrow_{\text{atm}}}^i(\theta, \phi),
\]

\[
R_{s,i}(\theta, \phi, 0) = e_i(\theta, \phi) B_i(\text{SST}) + [1 - e_i(\theta, \phi)]L_{\uparrow_{\text{atm}}}^i(\theta, \phi),
\]

where \( B_i(\text{SST}) \) is the channel \( i \) averaged Planck’s function for a skin SST, \( e_i(\theta, \phi) \) is the sea surface emissivity, and \( \tau_i(\theta, \phi, 0, h) \) is the transmittance of the atmosphere between the sea surface and the instrument. For a flat sea surface the reflection of the downwelling sky radiance can be considered specular. In this case the contribution of this term to \( R_{s,i}(\theta, \phi, 0) \) is simply the downwelling sky radiance coming from the angle complementary to \( \theta \), that is, \( \pi - \theta \). However, for a sea surface roughed by the wind, the reflection of the sky radiance comes from a range of different angles rather than from a definite one, due to the anisotropy of the downwelling sky radiance. In this case it is possible to consider an effective reflection angle, \( \bar{\theta}_i \), for which \( L_{\uparrow_{\text{atm}}}^i(\bar{\theta}_i, \phi) \) equals the actual downwelling radiance coming from that angle interval. Sidran (1981) evaluated the error introduced by the approximation of using the complementary angle to \( \theta \), that is, \( \bar{\theta}_i = \pi - \theta \), in the calculation of the reflection for a rough sea surface, showing that the effect on the retrieved SST was negligible \((\approx \pm 0.05 \) K). Thus, we finally took \( \pi - \theta \) as the effective angle.
Equations (7) and (8) allow the recovery of SST from the radiometer measurements \([R_i(u, f, h)]\). In order to obtain an accurate SST estimation from the measured radiance, \(\tau_i(u, f, 0, h), L_{i,\text{sun}}(u, f), L_{i,\text{atm}}(\pi - \theta, \phi)\), and the sea surface emissivity have to be evaluated to correct the measurements for the mentioned effects through Eqs. (7) and (8). In the following sections the determination of these quantities is addressed.

### a. Emissivity determination

The effective emissivity for the sea surface was determined using the Masuda et al. (1988) model. They considered the sea surface roughness as a slope distribution associated with the swell faces produced by the intensity of the surface wind, which was defined using a probability density function (Cox and Munk 1955). This model constitutes a good approximation for the sea surface emissivity in the case of small observation zenith angles (Smith et al. 1996; Wu and Smith 1997). The only input to the model is the surface wind speed, which was defined by Cox and Munk (1955) at a height of 12.5 m over the sea surface.

A preliminary campaign was carried out in El Puig, Valencia, Spain, to check the consistency of the Masuda et al. (1988) model with actual measurements. The sea surface emissivity was measured for different angles from a breakwater. To avoid the influence of the breakwater on the sea surface, viewing angles larger than 30° were considered. Thus, measurements at angles from 35° to 85°, at steps of 10°, were performed. Surface and sky were observed alternately in order to measure the downwelling sky radiance. The sea temperature was measured using the CE 312 external probe placed in a small buoy. Figure 3 shows the measured emissivities. The experimental values obtained by Rees and James (1992) and Sobrino and Cuenca (1999), as well as the theoretical emissivities determined by Masuda et al. (1988), are also included in Fig. 3. A good agreement is obtained between the model and the data. The sea surface emissivity shows a clear angular dependence. The emissivity is high and almost constant with respect to the observation angle for low angles, up to 30°, and a decrease in emissivity is observed beyond this viewing angle.

The emissivity dependence on both viewing angle and wind speed was analyzed using the Masuda et al. (1988) model (see Fig. 4). For observation angles lower than 30°, sea surface emissivity is almost independent of the surface wind speed and viewing angle. Beyond this point the angular dependence arises, and from an angle of 40° the wind speed influence becomes noticeable. This suggests the use of viewing angles lower than 30°, in order to minimize the impact of possible error sources such as wind speed accuracy, sensor pointing errors, etc.

The influence of the measurement system structure, that is, the oil rig, must also be avoided. Taking into account the size of the platform, a viewing angle larger than 20° was used in order to minimize the effect of the reflection of the oil rig thermal radiance on a roughed sea surface toward the sensor, and also to avoid the effects of the oil rig shadowing on the observed sea surface. From these considerations and in view of the oil rig structure, the sensor was pointed to the sea surface with an observation zenith angle of 25°.
In addition to the viewing conditions, another important issue is which spectral channel should be used in order to reduce the impact of the emissivity accuracy on the SST retrieval. Figure 5 shows the emissivity values calculated by means of the Masuda et al. (1988) model, and integrated for the CE 312 channels, for an observation angle of 25° and several wind speeds. The highest emissivity value is obtained in channel 3 (10.5–11.5 μm), and consequently this band shows the lower impact of emissivity on SST retrieval.

b. Atmospheric and emissivity corrections

Atmosphere takes part in the radiation transmission between the surface and the radiometer by means of three effects: 1) absorption of the radiance at surface level transmitted between surface and radiometer, characterized by the atmospheric transmittance, \( \tau_i \); 2) atmospheric emission upward, defined by the upwelling sky radiance, \( L_{\text{atm}}^i(\theta, \phi, h) \); and 3) reflection of the downwelling sky radiance, \( L_{\text{atm}}^i(\pi - \theta, \phi) \), in the surface, which is taken into account in the emissivity correction by means of the term

\[
1 - e_i(\theta, \phi) L_{\text{atm}}^i(\pi - \theta, \phi)
\]

in Eq. (8).

A quantification of the atmospheric and emissivity effects on the thermal measurements from the oil rig is addressed in this section in order to determine which corrections were necessary and their order of magnitude.

Equation (7), used to evaluate the atmospheric correction of the data, can be expressed as

\[
R_{\text{a}}(\theta, \phi, 0) - R_i(\theta, \phi, h) = \frac{1 - \tau_i(\theta, \phi, 0, h) R_i(\theta, \phi, h) - L_{\text{atm}}^i(\theta, \phi)}{\tau_i(\theta, \phi, 0, h)},
\]

where the difference between at-surface and at-sensor radiances is estimated depending on \( \tau_i(\theta, \phi, 0, h) \) and \( L_{\text{atm}}^i(\theta) \). From Eq. (9) the atmospheric correction in terms of temperature can be calculated as

\[
\Delta T_a = \frac{R_{\text{a}}(\theta, \phi, 0) - R_i(\theta, \phi, h)}{\partial B_i(T)/\partial T},
\]

where \( \partial B_i(T)/\partial T \) is the derivative of Planck’s function with temperature, which is used as a conversion factor from radiance to temperature. To quantify the atmospheric correction with Eqs. (9) and (10), \( \tau_i(\theta, \phi, 0, h) \) and \( L_{\text{atm}}^i(\theta, \phi) \) have to be evaluated for specific cases.

Since radiosounding data were not available at the oil rig area, local air pressure, temperature, and relative humidity data measured at different altitudes at the plat-
form (from 2.5 to 69 m over the sea surface) for several atmospheric conditions during both campaigns were used. These data were introduced into the MODTRAN 4 code (Berk et al. 1999) to get the estimates of $\tau_i(\theta, \phi, 0, h)$ and $L_{\text{am}}^i(\theta, \phi)$. These reduced profiles can be used for this purpose since only the perturbation introduced by the first 32 m of atmosphere (the path between the sea surface and the sensor) is relevant in this case.

Equation (10) was calculated for the experimental conditions corresponding to each individual CE 312 measurement for an observation angle of $25^\circ$. All the individual $\Delta T'_e$ calculated values were averaged, and the results are presented in the first row of Table 2 for each CE 312 channel. These results show (i) a low variability of the atmospheric correction during the WISE campaigns, since the standard deviations are lower than $\pm 0.03$ K; (ii) that channels 2 and 3 present the lowest atmospheric correction; and (iii) that this correction is negligible (lower than the calibration uncertainties given in section 2), due to the short atmospheric path between the sea surface and the sensor.

Equation (8) was used to evaluate the emissivity correction. The difference between the channel $i$ averaged Planck’s function for the SST, $B_i(\text{SST})$, and the corresponding at-surface radiance is

$$B_i(\text{SST}) - R_e(\theta, \phi, 0) = \frac{[1 - e_i(\theta, \phi)][R_e(\theta, \phi, 0) - L_{\text{am}}^i(\pi - \theta, \phi)]}{e_i(\theta, \phi)}.$$  

(11)

The emissivity correction can be calculated from Eq. (11) as

$$\Delta T_e = \frac{B_i(\text{SST}) - R_e(\theta, \phi, 0)}{\partial B_i(T)/\partial T}.$$  

(12)

To apply Eqs. (11) and (12), both the sea surface emissivity and the downwelling sky radiance must be determined. The emissivity was calculated for the four channels using the model of Masuda et al. (1988) with a viewing angle of $25^\circ$, and for wind speeds ranging from 0 to 30 m s$^{-1}$ to cover all the cases found in both WISE campaigns. Considering these conditions, average emissivity values of 0.9864 ± 0.0008, 0.9865 ± 0.0009, 0.9905 ± 0.0006, and 0.9839 ± 0.0008 were obtained in channels 1–4, respectively.

The downwelling sky radiance also has to be evaluated in Eq. (11). To calculate this term, atmospheric profiles representative of the whole atmosphere are needed. These were not available, and the local pressure,

![Figure 5. Emmissivity values integrated for the CE 312 channels against the surface wind speed, U(m s$^{-1}$), and using an observation zenith angle of $25^\circ$, calculated from the Masuda et al. (1988) model.](image)

### Table 2. Atmospheric correction, $\Delta T_e$ (K), emissivity correction, $\Delta T'_e$ (K), emissivity correction without the downwelling sky radiance contribution, $\Delta T'_c$ (K), and effect of the downwelling sky radiance in the SST retrieval, $\Delta T'_s$ (K), for midlatitude (ML) and tropical (TR) atmospheric standard profiles and all of the CE 312 channels. Shown for each term are the mean value and the std dev as $\Delta T \pm \sigma(\Delta T)$, followed by the min and max values of each correction, given in italics between brackets ($\Delta T_{\text{min}}, \Delta T_{\text{max}}$).

<table>
<thead>
<tr>
<th></th>
<th>Channel 1 (8–14 $\mu$m)</th>
<th>Channel 2 (11.5–12.5 $\mu$m)</th>
<th>Channel 3 (10.5–11.5 $\mu$m)</th>
<th>Channel 4 (8.2–9.2 $\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_e$</td>
<td>0.12 ± 0.03</td>
<td>0.04 ± 0.02</td>
<td><strong>0.025 ± 0.008</strong></td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td>(0.04, 0.17)</td>
<td>(0.001, 0.08)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta T'_{\text{ch,summer}}$</td>
<td>0.71 ± 0.04</td>
<td>0.83 ± 0.02</td>
<td><strong>0.56 ± 0.04</strong></td>
<td>0.75 ± 0.04</td>
</tr>
<tr>
<td>(0.66, 0.79)</td>
<td>(0.77, 0.94)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta T'_{\text{ch,summer}}$</td>
<td>0.46 ± 0.03</td>
<td>0.45 ± 0.03</td>
<td><strong>0.39 ± 0.03</strong></td>
<td>0.53 ± 0.03</td>
</tr>
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<td>(0.42, 0.52)</td>
<td>(0.40, 0.51)</td>
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<tr>
<td>$\Delta T_{\text{TR}}$</td>
<td>0.32 ± 0.02</td>
<td>0.24 ± 0.02</td>
<td><strong>0.27 ± 0.02</strong></td>
<td>0.41 ± 0.03</td>
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<tr>
<td>(0.28, 0.36)</td>
<td>(0.21, 0.29)</td>
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<td></td>
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</tr>
<tr>
<td>$\Delta T_{\text{ch,summer}}$</td>
<td>0.59 ± 0.13</td>
<td>0.6 ± 0.2</td>
<td><strong>0.48 ± 0.09</strong></td>
<td>0.64 ± 0.11</td>
</tr>
<tr>
<td>(0.42, 0.79)</td>
<td>(0.4, 0.9)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta T'_c$</td>
<td>0.82 ± 0.05</td>
<td>0.94 ± 0.06</td>
<td><strong>0.59 ± 0.04</strong></td>
<td>0.83 ± 0.04</td>
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<tr>
<td>(0.76, 0.91)</td>
<td>(0.86, 1.05)</td>
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<td></td>
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</tr>
<tr>
<td>$\Delta T_e - \Delta T'_c$</td>
<td><strong>-0.103 ± 0.006</strong></td>
<td>-0.104 ± 0.007</td>
<td><strong>-0.034 ± 0.002</strong></td>
<td>-0.085 ± 0.004</td>
</tr>
<tr>
<td>(-0.115, -0.095)</td>
<td>(-0.117, -0.096)</td>
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</tr>
<tr>
<td>$\Delta T_e - \Delta T'_{\text{ML,summer}}$</td>
<td>-0.36 ± 0.02</td>
<td>-0.49 ± 0.03</td>
<td><strong>-0.200 ± 0.013</strong></td>
<td>-0.30 ± 0.02</td>
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<tr>
<td>(-0.40, -0.33)</td>
<td>(-0.55, -0.45)</td>
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<tr>
<td>$\Delta T_e - \Delta T'_{\text{TR}}$</td>
<td>-0.50 ± 0.04</td>
<td>-0.70 ± 0.05</td>
<td><strong>-0.32 ± 0.02</strong></td>
<td>-0.43 ± 0.03</td>
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<tr>
<td>(-0.59, -0.44)</td>
<td>(-0.82, -0.62)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\Delta T_e - \Delta T'_{\text{ML,summer}}$</td>
<td>-0.23 ± 0.13</td>
<td>-0.3 ± 0.2</td>
<td><strong>-0.12 ± 0.09</strong></td>
<td>-0.19 ± 0.11</td>
</tr>
<tr>
<td>(-0.40, -0.10)</td>
<td>(-0.6, -0.1)</td>
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</table>

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temperature, and relative humidity measurements mentioned above were not useful in this case, since they only describe the first 69 m of atmosphere. Thus, to get an estimation of the emissivity effect, three standard atmospheres given in the MODTRAN 4 code, namely, the midlatitude winter, midlatitude summer, and tropical profiles, were used in the calculations.

The emissivity correction for both campaigns was estimated using these emissivity values and downwelling sky radiances along with a different average value of the brightness temperature for each campaign (288.3 K for WISE 2000 and 291.2 K for WISE 2001) into Eqs. (11) and (12). The results are presented in rows 2, 3, and 4 of Table 2 considering each atmosphere type. In all cases channel 3 shows the lowest emissivity correction, except for the tropical case, in which it is shown by channel 2. Nevertheless, taking into account the atmospheric conditions found in the WISE campaigns (both carried out in autumn), the most approximate case would be an average between the midlatitude winter and midlatitude summer results. This case is shown in the fifth row of Table 2 (ML mean case), which presents a slightly better performance of channel 3.

In addition, the effect of the downwelling sky radiance on the emissivity correction was estimated separately to check its importance and to decide which of the atmospheric quantities should be accounted for in correcting the measured data. The values of the emissivity correction if the downwelling sky radiance was neglected ($\Delta T'_e$) are shown by channels in the sixth row of Table 2. The next rows present the contributions to the emissivity correction due to $L_{\text{down}}(\pi - \theta, \phi)$ alone, which are obtained by simply subtracting $\Delta T'_e$ from the previous values of $\Delta T_e$ for the same atmospheres discussed above. It becomes clear that the lowest impact of this term is observed in channel 3.

Three conclusions can be drawn from these results. First, channel 3 shows the lowest impact on both the atmospheric and emissivity corrections on the SST retrieval, and thus it is a clear candidate for the remote SST measurements. This conclusion is also supported by the fact that sea surface emissivity is the highest in this channel, as has been shown in section 3a. Second, it is reasonable to assume that the atmospheric correction is negligible for that band ($\Delta T_e = 0.025 \pm 0.008$ K), due to the small air–sea temperature difference, which shows a value of $\pm 1$ K on average (Camps et al. 2002), and the short optical path (35.3 m). Thus, it is not necessary to include this correction in the retrieval of accurate SSTs in this case. Last, the emissivity correction can introduce significant temperature errors if it is not considered ($\Delta T_e = 0.48 \pm 0.09$ K for channel 3), and consequently the downwelling sky radiance must be accurately determined. For this reason, it cannot be simply calculated using standard profiles, but it should be directly measured for each individual radiance acquisition. This is a well-known correction for infrared-derived SST measurements (Hagan et al. 1997; Donlon et al. 1998; Nalli et al. 2001), which only under very optically thick clouds diminishes to potentially low values. Donlon and Nightingale (2000) made a detailed analysis of the effect of errors in the atmospheric radiance measurement on SST retrieval from in situ radiometers, and concluded that for clear-sky, overcast, or high-humidity atmospheric conditions SST is relatively insensitive to sky-pointing errors of $\pm 10^\circ$ and to temporal mismatches between the sea and sky views. However, in mixed-cloud conditions the impact of these errors could be significant (larger than $\pm 0.25$ K).

c. Measurement strategy

Considering the results of the preceding sections, the sea surface radiances were measured from 32-m height under the defined optimum spectral and angular conditions: the spectral band 10.5–11.5 $\mu$m (CE 312 channel 3) was used with an observation angle of 25$^\circ$, under which atmospheric and emissivity effects, and the influence of the oil rig, are minimum. Under these conditions, and taking into account the CE 312 field of view of 10$^\circ$, the sensor was observing an elliptical area of 30 m$^2$ over the sea surface.

In addition to the sea surface radiance measurements, the downwelling sky radiance must also be directly measured for each individual sea surface measurement to account accurately for the emissivity effect. Consequently, the downwelling sky radiance was measured during both campaigns directly and alternately with the sea observations using the complementary angle to 25$^\circ$, that is, 155$^\circ$. The use of simultaneous sky measurements avoids the need for local radiosoundings to account for the downwelling atmospheric radiance and allows accounting adequately for the effect of clouds, especially under variable cloud cover conditions.

Finally, each sea surface radiance measurement was corrected in order to retrieve SST. First, the calibration equation defined in section 2 [Eq. (3)] was applied to correct possible systematic errors due to the radiometer itself and the protective ZnSe window. Then, the emissivity correction was assessed using (i) the Masuda et al. (1988) emissivity determined for the existing wind speed at the measurement moment and for an observation angle of 25$^\circ$, and (ii) the value of the downwelling sky radiance measured most closely in time.

4. Precision and accuracy

a. Sensitivity analysis

Since the atmospheric correction was shown to be negligible [i.e., $\tau(\theta, \phi, 0, h) = 1$ and $L_{\text{down}}(\theta, \phi) = 0$], SSTs can be computed from sea surface radiance and downwelling sky radiance directly using Eq. (8). The SST accuracy [$\sigma$(SST)] can be derived from this equation by applying error theory as
\[ \sigma_{\text{SST}} = \left| \frac{\partial \text{SST}}{\partial B_{\text{SST}}} \right| \sigma[B_{\text{SST}}], \] (13)

where \( \sigma[B_{\text{SST}}] \) is the error in the Planck's function at SST, given by

\[ \sigma[B_{\text{SST}}] = \left\{ \left[ \frac{\partial B_{\text{SST}}}{\partial e_{s}} \right]^2 \sigma^2(e_s) + \left[ \frac{\partial B_{\text{SST}}}{\partial R_{s,i}} \right]^2 \sigma^2(R_{s,i}) \right\}^{1/2}, \] (14)

in which \( \sigma(e_s) \) is the error for the surface emissivity, and \( \sigma(R_{s,i}) \) and \( \sigma(L_{\text{atm}}^{i,i}) \) are, respectively, the errors of the sea surface and downwelling sky measured radiances.

The main error sources are the sensor radiometric error and the calibration error, which contribute to the error of the radiance measured by the CE 312, both for the sea surface radiance, \( \sigma(R_{s,i}) \), and for the downwelling sky radiance, \( \sigma(L_{\text{atm}}^{i,i}) \). Errors of both radiances have been determined in section 2 to be \( \pm 2 \times 10^{-5} \text{ mW cm}^{-2} \text{ sr}^{-1} \text{ cm}^{-2} \) for CE 312 channel 3 (\( \pm 0.12 \) K in terms of brightness temperature).

With regard to the emissivity error \( \sigma(e_s) \), two sources have been taken into account: the error of the Masuda et al. (1988) model, \( \sigma_{\text{M}}(e_s) \), and the uncertainty resulting from error propagation of the model inputs, \( \sigma_p(e_s) \). Thus,

\[ \sigma(e_s)^2 = \sigma_{\text{M}}(e_s)^2 + \sigma_p(e_s)^2. \] (15)

Here \( \sigma_p(e_s) \) is obtained from propagation of the model inputs errors, taking into account the emissivity dependence on wind speed and observation angle. Then, this error can be written as

\[ \sigma_p(e_s) = \left[ \left( \frac{\partial e_s}{\partial U} \right)^2 \sigma^2(U) + \left( \frac{\partial e_s}{\partial \theta} \right)^2 \sigma^2(\theta) \right]^{1/2}, \] (16)

where \( \sigma(U) \) is the error of the wind speed measured at the surface level, and \( \sigma(\theta) \) is the radiometer pointing error. Surface wind speed was determined with a calibrated anemometer with an error of \( \pm 0.9 \) m s\(^{-1}\). The radiometer pointing inclinometer error was \( \pm 0.01^\circ \); however, an error of \( \pm 5^\circ \), which includes any possible sensor movement due to the wind effect and oil rig vibrations, was considered. Anyway, the angular dependence of emissivity is negligible at low observation angles (\( \left| \partial e_s/\partial \theta \right| < 0.0001 \)). Introducing these values in Eq. (16), it turns out to be \( \sigma_p(e_s) = \pm 0.0009 \).

By comparing the theoretical calculations with measured emissivities, \( \sigma_{\text{M}}(e_s) \) can be estimated. Measurements taken during the WISE 2000 campaign and the preliminary campaign in El Puig, Spain, showed us an average difference between the modeled and measured values of \( \pm 0.0012 \) in emissivity for low observation angles. This value is in agreement with the results obtained by Smith et al. (1996), who compared sea surface emissivity spectra measured at different viewing angles with the Atmospheric Emitted Radiance Interferometer (AERI) with the values calculated from the model of Masuda et al. (1988). They found excellent agreement, especially for observation angles lower than 35°.

Introducing the estimated values of \( \sigma_p(e_s) \) and \( \sigma_{\text{M}}(e_s) \) into Eq. (15), \( \sigma(e_s) = \pm 0.0015 \) was obtained. Finally, considering all the different error sources in Eqs. (13) and (14) for both campaigns, a final SST error of \( \pm 0.15 \) K was estimated.

b. Validation

The SSTs measured with the proposed methodology were compared with simultaneous measurements of sea temperature at 20-cm depth (SST\text{bulk}) given by the SBE 37-SM MicroCAT thermal probes, which were taken as reference temperatures.

Figure 6 gives a percentage histogram of the differences between buoy-measured temperatures (\( T_b \)) and the SST calculated by means of the described methodology (\( T_{\text{ce}} \)). It shows a slightly skewed distribution of the differences toward the negative values, with an asymmetry coefficient of \( -0.005 \). The average value is 0.0 K, and the standard deviation is \( \pm 0.2 \) K, showing a good accuracy in the retrieved SSTs that is coherent with the results of the sensitivity analysis given above. Figure 7 shows a detail of this intercomparison for three days during the WISE 2001 campaign. There is good correspondence between both measurements. The curves for \( T_b \) and \( T_{\text{ce}} \) are close to each other, and their difference is mostly lower than the limits given by the \( T_{\text{ce}} \pm \sigma(T_{\text{ce}}) \) lines.

However, there are also temperature differences larger
by means of the described methodology, including the SSTs retrieved from the CE 312 radiometric measurements (Tce) by means of the described methodology, including the Tce range of error as the interval between $T_c \pm \sigma(T_c)$ and $T_c + \sigma(T_c)$, where $\sigma(T_c)$ is the SST error for each individual measurement.

than ±0.2 K in the histogram shown in Fig. 6, both positive and negative. These differences may be due to the bulk–skin temperature difference. The difference between the temperatures measured by contact thermometers at some depth and the temperatures measured with thermal infrared radiometers, which correspond to the first few micrometers of the sea surface, is well known (Saunders 1967; Robinson et al. 1984; Harris et al. 1994; Donlon et al. 1999; Murray et al. 2000). The so-called bulk–skin temperature difference depends on the wind speed and the net heat flux at the sea surface (Wick et al. 1996), and may take values from +1.0 to −1.0 K (Schluessel et al. 1990). At night, the bulk–skin temperature difference is usually positive (i.e., there is a cold skin); however, during daytime it is positive for wind speeds larger than 6 m s$^{-1}$ (0.17 ± 0.07 K) and may have both signs for lower wind speeds (Donlon et al. 2002). During the WISE campaigns, the measured wind speed was usually lower than 6 m s$^{-1}$, and consequently our measurements were in concordance with the observations of Donlon et al. (2002).

The data of Fig. 7 suggest the existence of a diurnal cycle in the bulk–skin temperature difference, especially for days with high solar radiation and low wind speeds (i.e., 13 November 2001). In this case, $T_b$ is lower than $T_o$ around solar noon, whereas $T_b$ is larger than $T_o$ during the night and first morning hours. These observations agree with the results of Webster et al. (1996), which show such an effect for clear and calm conditions. This behavior can be better observed in Fig. 8, where the hourly distributions of buoy–radiometer temperature differences (for $|T_b - T_o| > 0.5$ K) are shown for all the WISE data.

5. Conclusions

The purpose of this paper is to develop a methodology in order to measure SSTs with accuracy higher than ±0.3 K following the requirements of both the global climate research, defined by the TOGA program and the SMOS mission. Autonomous measurements recorded by a thermal infrared radiometer have been used with this aim.

First, the most adequate measurement conditions have been determined taking into account calibration, emissivity, and atmospheric effects. An observation angle, $\theta$, lower than 30° and the 10.5–11.5-$\mu$m spectral region have been identified as the most suitable conditions. Second, the atmospheric correction can be considered negligible for the altitude at which the radiometer was placed (32 m), and it is not necessary to include this correction in the retrieval of accurate SSTs in this case. However, direct measurements of the downwelling sky radiance are necessary in order to account for the reflection term in the emissivity correction. This sky radiance was measured simultaneously to the sea surface radiance by observing the sky at the complementary angle, $\pi - \theta$.

Finally, calibration and emissivity corrections have been applied to the sea surface measurements of both WISE campaigns. Emissivity correction has been calculated using emissivities of the Masuda et al. (1988) model for the measurement conditions, and the value of downwelling sky radiance measured most closely in time. A precision of ±0.15 K has been obtained with this methodology. Furthermore, the determined SSTs have been compared with simultaneous values of sea temperature measured by buoys, and an average difference of 0.0 K and a standard deviation of ±0.2 K have been obtained, showing good accuracy in the retrieved SSTs.

This methodology, designed to obtain autonomous and accurate SST from an oil rig, could be used as a reference temperature for the validation of SST retrieved using other thermal infrared radiometers. In this way, calibration and SST retrieval algorithms of current sensors, like the Advanced Along-Track Scanning Radiometer (AATSR) onboard the ESA’s Environmental Satellite (Envisat), could be validated.
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