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In situ angular measurements of thermal infrared sea surface emissivity—Validation of models

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Abstract

In this paper, sea surface emissivity (SSE) measurements obtained from thermal infrared radiance data are presented. These measurements were carried out from a fixed oilrig under open sea conditions in the Mediterranean Sea during the WInd and Salinity Experiment 2000 (WISE 2000). The SSE retrieval methodology uses quasi-simultaneous measurements of the radiance coming from the sea surface and the downwelling sky radiance, in addition to the sea surface temperature (SST). The radiometric data were acquired by a CIMEL ELECTRONIQUE CE 312 radiometer, with four channels placed in the 8–14 μm region. The sea temperature was measured with high-precision thermal probes located on oceanographic buoys, which is not exactly equal to the required SST. A study of the skin effect during the radiometric measurements used in this work showed that a constant bulk–skin temperature difference of 0.05±0.06 K was present for wind speeds larger than 5 m/s. Our study is limited to these conditions. Thus, SST used as a reference for SSE retrieval was obtained as the temperature measured by the contact thermometers placed on the buoys at 20-cm depth minus this bulk–skin temperature difference.

SSE was obtained under several observation angles and surface wind speed conditions, allowing us to study both the angular and the sea surface roughness dependence. Our results were compared with SSE models, showing the validity of the model of Masuda et al. [Masuda, K., Takashima, T., & Takayama, Y. (1988) Emissivity of pure seawaters for the model sea surface in the infrared window regions. Remote Sensing of Environment, 24, 313–329.] for observation angles up to 50°. For larger angles, the effect of double or multiple reflections on the sea surface produces discrepancies between measured and theoretical SSEs, and more complex models should be used to get accurate SSE values, such as the model of Wu and Smith [Wu, X., & Smith, W.L. (1997). Emissivity of rough sea surface for 8–13 μm: modelling and verification. Applied Optics, 36, 2609–2619.].

Keywords: Emissivity; Sea surface emissivity; Sea surface temperature; Thermal infrared; Angular measurements

1. Introduction

The requirement of a maximum uncertainty of ±0.3 K in sea surface temperature (SST) as input to climate models and the use of high observation angles in the current space missions, such as the 55° for the forward view of the Advanced Along Track Scanning Radiometer (AATSR) (Llewellyn-Jones et al., 2001) on board ENVISAT, need a precise and reliable determination of sea surface emissivity (SSE) in the thermal infrared region (TIR), as well as analyses of its angular and spectral dependences.

The emission of a rough sea surface has been studied over the last years due to the importance of the SSE for accurate SST retrieval. A reference work for many subsequent studies has been the paper written by Cox and Munk (1954), in which the sea surface roughness produced by the intensity of wind was characterized as an approximately normal and isotropic facet slope distribution. Saunders (1967) estimated the radiances emitted by a rough sea surface based on geometrical optics and the Cox and Munk (1954) distribution, observing that radiances from a

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rough sea surface are larger than those over a calm one. Later, Takashima and Takayama (1981) simulated emissivities of rough water surfaces as a function of wind speed up to 15 m/s for the Advanced Very High Resolution Radiometer (AVHRR) channels placed at 11 and 12 μm, and for observation angles of 0° and 55°. Sidran (1981) calculated rough sea surface emissivities and reflectivities for a large range of wavelengths, focusing the study on the angular reflection effect of the downwelling sky radiance. Then, Masuda et al. (1988) determined SSE for pure and seawaters in the spectral windows 3.5–4.1 and 8–13 μm as a function of the surface wind speed and the observation angle, results that have been extensively used for SST retrieval. With the use of the dual angle observation technique in current space missions, SSE at 55° for the forward view of the Along-Track Scanning Radiometer (ATSR) was studied by François and Ottlé (1994), and simulated by Watts et al. (1996). However, the theoretical determination of SSE was later improved with the model developed by Wu and Smith (1997), where the effect of multiple surface reflections was taken into account.

In addition to theoretical models to understand the dynamics of SSE, ground measurements of SSE are needed. Liu et al. (1987) studied the surface emissivity variation with the suspended sediment concentrations, measuring surface emissivity of fresh (tap) and seawater samples at nadir with a 8–14 μm radiometer in the laboratory. They also observed that tap water emissivity is higher than seawater emissivity. Salisbury and D'Aria (1992) gave SSE experimental spectra within the region 8–14 μm for calm seawater measured also at nadir in the laboratory. Konda et al. (1994) determined sea surface emissivity using a 8–14 μm radiometer on an oceanographic tower placed in a bay of Japan. Measurements were carried out for a nadir view under high wind speed conditions. Smith et al. (1996) obtained SSE using radiance measurements collected with the Atmospheric Emitted Radiance Interferometer (AERI) Fourier transform spectrometer placed on a ship under a wind speed of 5 m/s and three observation angles.

Nowadays the SSE determination is still a current issue mainly due to its importance for emissivity correction in algorithms to retrieve SST using off-nadir viewings of satellite sensors. Moderate and low resolution satellite sensors with channels in the TIR, such as the AVHRR on board NOAA and the Moderate Resolution Imaging Spectrometer (MODIS) (Barnes et al., 1998) on board EOS Aqua/Terra, have wide swaths in the across-track direction, and so the observation angles at the image edges are large, up to 55° for AVHRR and MODIS. Moreover, current satellite sensors permit observations centered on off-nadir angles in the along-track direction, such as the AATSR-ENVISAT at 55° or the future ESA mission Surface Processes and Ecosystem Changes Through Response Analysis (SPECTRA) with seven along-track directions between −60° and 60°. Table 1 shows a summary of experimental and theoretical SSE values at 55° for several wind speed conditions found in the bibliography. It shows the experimental values obtained by Smith et al. (1996) using the AERI, with an accuracy of ±0.1%. Theoretical emissivities determined by Masuda et al. (1988), Watts et al. (1996) and Wu and Smith (1997) are also included in this table. Moreover, SSEs for an observation angle of 0° are given as reference in order to show the SSE decrease for an off-nadir observation, a fact that must be considered for accurate SST retrievals with the dual-angle technique. There are discrepancies between the SSE values given for 55°, mainly for high wind speed, which could cause SST uncertainties up to ±0.5 K. Thus, additional SSE measurements are required in order to validate models and to select the most suitable model to retrieve accurate SSE values for any observation angle.

In this paper, we present SSE experimental values as a function of the observation angle and the surface wind speed for four channels placed in the TIR region: 8.2–9.2, 10.5–11.5, 11.5–12.5, and 8–14 μm. These SSE measurements were carried out from a fixed oilrig placed in the Mediterra-

Table 1
Experimental, E, and theoretical, T, SSE values for an observation angle of θ=55° and several wind speeds, U, given by different sources

θ (°)	Source	U (m/s)	8–14 μm	8.2–9.2 μm	10.5–11.5 μm	11.5–12.5 μm
55	Smith et al. (1996), E[a]	5	0.962	0.961	0.9725	0.961
	Masuda et al. (1988), T	5	0.966	0.963	0.974	0.962
		10	0.962	0.959	0.971	0.959
		15	0.960	0.957	0.968	0.956
	Watts et al. (1996), T[b]	5	–	–	0.977	0.961
		10	–	–	0.976	0.960
		15	–	–	0.976	0.960
	Wu and Smith (1997), T	5	0.964	0.962	0.974	0.964
		10	0.964	0.962	0.973	0.964
		15	0.965	0.963	0.974	0.965
0	Salisbury and D'Aria (1992), E	–	0.985	0.984	0.990	0.986
	Masuda et al. (1988), T	–	0.987	0.985	0.991	0.988

These SSEs are integrated values for four classic TIR regions within the 8–14 μm (corresponding to the CE 312 radiometer, see Section 2).

[a] Observation angle of 56.5°. Accuracy of ±0.1%.

[b] ATSR channels at 12 and 11 μm.