

Sea-surface temperature measured by the Moderate Resolution Imaging Spectroradiometer (MODIS).

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Abstract-The Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Earth Observing System satellites *Terra* and *Aqua* include infrared bands that are designed for the accurate measurement of sea-surface temperature (SST). In addition to the conventional 'split-window' bands in the 10-12 μm atmospheric window (similar in spectral properties to the corresponding channels of the heritage instrument, the Advanced Very High Resolution Radiometer (AVHRR)) the MODIS also has three bands in the 3.5 to 4.2 μm interval for SST measurement. Here we present a validation of the MODIS SSTs, derived from the conventional measurements at the 10-12 μm window, by comparison with radiometrically-derived skin temperatures from ships, and with bulk measurements from buoys. These show the MODIS SSTs are comparable in accuracy to the AVHRR Pathfinder SST fields.

I. INTRODUCTION

The temperature of the ocean surface is an important variable for the study of the earth's climate system, for weather forecasting, and for oceanographic research. Patterns of sea-surface temperature (SST) reveal the complexity of the ocean surface currents, and large scale SST anomalies in critical oceanic areas presage climate perturbations, such as El-Niño events. The SST is a controlling variable in the coupling of the ocean and atmosphere in terms of the fluxes of heat, moisture, momentum and greenhouse gasses, such as CO_2 . Satellite remote sensing has provided a mechanism for deriving global SST fields by measuring the infrared and microwave thermal emission from the sea-surface. Infrared radiometry provides high spatial resolution ($\sim 1 \text{ km}^2$), but suffers from the fact that clouds obscure view of the sea-surface, while microwave radiometry provides data largely independent of cloud effects, but at a much coarser spatial resolution ($\sim 625 \text{ km}^2$). Infrared radiometers, specifically successive models of the Advanced Very High Resolution Radiometer (AVHRR) flown on the NOAA series of polar orbiting satellites, have provided SST measurements for over two decades. With the launch of the Earth Observing System satellite *Terra* in December 1999, a new generation of imaging radiometer, the MODIS (Moderate Resolution Imaging Spectroradiometer) was introduced which combines a more extensive suite of spectral measurements with improvements in instrument technology, and with which the time-series of infrared measurements of SST can be extended into the future.

Here we introduce the SST measuring capabilities of the MODIS and present an initial determination of the accuracy with which these measurements are being made. Given an accurately-calibrated spacecraft infrared radiometer, the uncertainties in the SST retrieval are determined largely by inadequacies in the algorithm used for the correction of the effects of the intervening atmosphere. The accuracy of the MODIS SSTs is established by comparison with collocated, independent measurements from ship-borne infrared spectroradiometers and a large number of drifting buoys.

II. MODIS

The MODIS is a 36-band sensor that spans the spectral range from 0.4 to 14.4 μm , *i.e.* through the visible into the thermal infrared. These bands were selected to satisfy the needs of a large user community in many fields of environmental science. The oceanographic applications of MODIS data include measurements of ocean color and SST [1]. The bands used for SST measurement are in the atmospheric 'windows' at wavelengths of 3.5 to 4.2 μm and 10 to 12 μm . There are two spectral bands (numbered 31 and 32) in the longer wavelength window, which correspond closely to the corresponding AVHRR channels (AVHRR channels 4 and 5), but there are three in the mid-infrared window (bands 20, 22 and 23) where AVHRR has just one (AVHRR channel 3). These bands have noise equivalent temperature differences (NE Δ Ts) of $\sim 0.05\text{K}$, and a spatial resolution of $\sim 1\text{km}^2$ at nadir. The swath width is 2330 km, which results in small regions near the equator not being sampled on adjacent orbits; these are covered on the next day. In-flight calibration of the infrared bands is achieved using a measurements of cold space and of a well-characterized, internal black-body reference target, the temperature of which is carefully monitored. In addition to the multiple spectral bands in the mid-infrared window, the technological innovations of MODIS include a bank of 10 detectors for each spectral band, a large two-sided 'paddle-wheel' scene mirror to scan the swath on the earth's surface, and 12-bit digitization for all data. The on-board data recording capabilities allow all of the data from all detectors to be stored and telemetered to ground receiving stations, offering full 1km^2 data over the entire oceans. Some of the radiometric resolution in Bands 31 and 32 offered by the 12-

bit digitizer has been lost by expanding the dynamic range of these bands to permit wild-fire monitoring (a situation largely remedied in the MODIS to be flown on *Aqua*). Additional data quality problems have resulted from the use of multiple detectors and a two-sided scene mirror used in such a way that the angle of incidence changes across the scan. This was exacerbated in the infrared at wavelengths longer than $\sim 8\mu\text{m}$ by the use of a multi-layer coating on the mirror which causes a marked change in the mirror reflectivity across the scan. Corrections for these effects have been devised successfully and implemented.

Here we focus on the SSTs derived from measurements of Bands 31 and 32 as these correspond closely to the data from AVHRR.

III. ATMOSPHERIC CORRECTION ALGORITHM

Building on the experience of deriving SST from AVHRR, the algorithm used to correct for the atmosphere is the same as that used for the Pathfinder SST product [2] which is based on the Non-Linear SST algorithm [3]. This takes the form

$$\text{SST} = a + bT_{31} + c(T_{31}-T_{32})T_{sfc} + d(T_{31}-T_{32})(\sec(\theta)-1) \quad (1)$$

where T_{31} and T_{32} are the brightness temperatures measured in Bands 31 and 32, θ is the satellite zenith angle measured at the sea surface, and T_{sfc} is a ‘first guess’ SST value, taken from the optimally interpolated SST weekly National Centers for Environmental Prediction (NCEP) SST analysis of global buoy, ship, and AVHRR SST data [4]. The numerical values of the coefficients a , b , c and d were derived in two ways: empirically by regression against SST values derived from AVHRR and theoretically by numerical simulations of the infrared radiative transfer through the atmosphere.

The empirical coefficient set was derived by identifying areas of the ocean that were cloud-free in both AVHRR and MODIS images on the same day (*i.e.* separated by about three hours), and performing a regression analysis between the MODIS brightness temperatures and the AVHRR SSTs. Independent validation of the AVHRR SSTs shows these to have small mean error ($\sim 0.1\text{K}$) and small scatter ($\sim 0.3\text{K}$) [5]. This approach leads to MODIS SST fields that should be directly compatible with the extant AVHRR Pathfinder SSTs.

The theoretically-derived coefficients were obtained by regression analysis of simulated MODIS brightness temperatures predicted by a line-by-line radiative transfer model [6]. The range of atmospheric variability is defined in these simulations by a large set of marine atmospheres derived from the data assimilation model of the European Centre for Medium-range Weather Forecasting (ECMWF). This approach should result in MODIS SSTs that are based on our understanding of the physics of the measurement.

IV. VALIDATION

An initial determination of the accuracy of the MODIS SSTs has been made by comparison with collocated, independent measurements of SST made by Fourier-Transform infrared interferometric spectroradiometers, M-AERIs (Marine – Atmospheric Emitted Radiance Interferometers [7]) mounted on ships, and by conventional in situ thermometers mounted on drifting buoys.

A. M-AERI skin temperatures.

The M-AERI is a robust, accurate, self-calibrating, sea-going Fourier-transform infrared spectroradiometer that is deployed on marine platforms to measure the emission spectra from the sea surface and marine atmosphere. The instrument works continuously under computer control with a high rate of data return. Spectral measurements are made in the range of ~ 3 to $\sim 18\mu\text{m}$ wavelength, and are calibrated using two internal, NIST-traceable blackbody cavities. The environmental variables derived from the spectra include the surface skin temperature of the ocean, surface emissivity, near-surface air temperature and profiles of temperature and humidity through the lower troposphere. The absolute uncertainty of the derived skin SSTs is $< 0.1\text{K}$.

Comparisons have been made between the MODIS SSTs derived with empirical coefficients and M-AERI data from four cruises, in the Mediterranean Sea (R/V *Urania*, April 2000), the Pacific Ocean (USCGC *Polar Sea*, March – April 2001; and NOAA S Ronald H. Brown, March – April 2001), and the Eastern Caribbean (*Explorer of the Seas* [8], April 2001). The mean error (MODIS – M-AERI) is 0.20K and the scatter has a standard deviation of 0.26K ($n=242$). These results are shown in Figure 1.

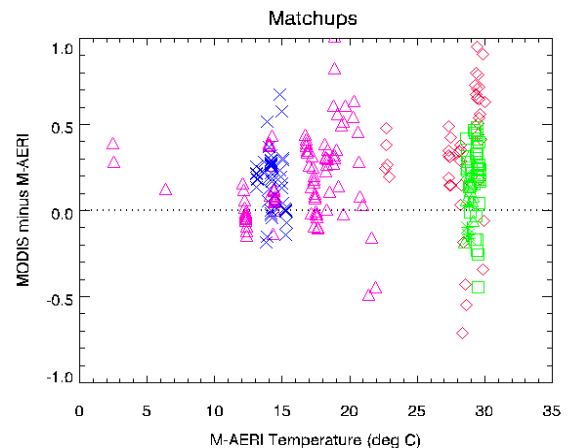


Fig. 1. MODIS SSTs errors determined by comparison with M-AERI skin SSTs. The colors indicate different cruises: blue – R/V *Urania*; red – USCGC *Polar Sea*; pink - NOAA S Ronald H. Brown; green – *Explorer of the Seas*.

B. Buoy bulk temperatures

The comparison between MODIS SSTs, derived with both the empirical and theoretical coefficients, and the bulk SSTs from drifting buoys is shown in Figure 2. The statistics of the

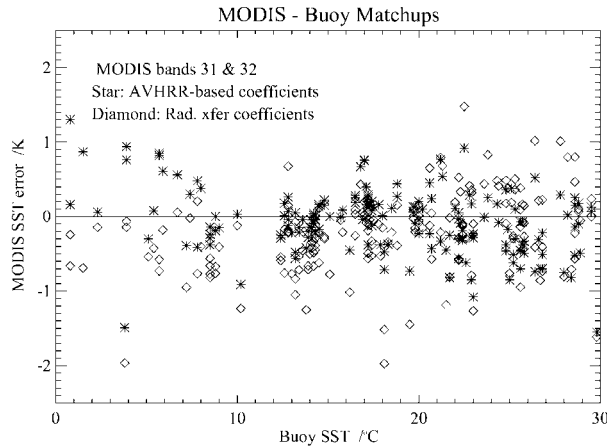


Fig 2. MODIS SSTs errors determined by comparison with buoy bulk SSTs.

errors (as mean \pm standard deviation) are:

a) empirical coefficients: $-0.070 \pm 0.433\text{K}$

b) theoretical coefficients: $-0.239 \pm 0.534\text{K}$

There are 174 matchups in this analysis.

V. DISCUSSION

The initial validation of *Terra* MODIS SSTs reported here is only for the temperatures derived from Bands 31 and 32; validation of the mid-infrared SSTs will follow. The initial results show that MODIS SSTs are comparable to the best SSTs produced by AVHRR [5], and the improved accuracy determined by M-AERI validation, compared to buoy validation is also in line with the findings of Kearns *et al.* [5] and others [9]. The poorer performance of the theoretical coefficients is somewhat surprising, and probably indicates unresolved sources of error that are self-compensating in the empirical coefficient set. These results are initial and represent the start of a continuing effort to validate MODIS SSTs in a wide range of conditions, and the estimates of the uncertainties will likely change as more data are analyzed.

The second MODIS is scheduled for launch on *Aqua* in April 2002, and a comparable validation exercise will be undertaken. It is anticipated that the SST accuracies will improve, particularly as the dynamic range of Bands 31 and 32 have been reduced, thereby increasing the radiometric resolution.

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