Sea Surface Temperatures from MODIS

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Introduction

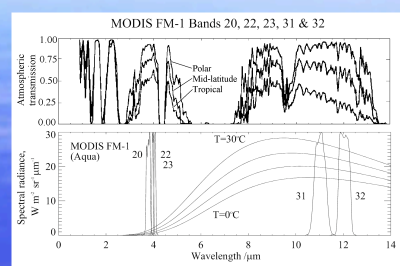
Sea-surface temperature (SST) is one of the main geophysical variables derived from MODIS measurements. It continues a long history of satellite-based SST retrievals (>2 decades), conducted primarily with the radiance time series of the Advanced Very High Resolution Radiometer, AVHRR. Accuracy requirements for MODIS SSTs are that they be no worse than those derived from the heritage instrument (AVHRR); and thus place the following requirements on SST retrieval from satellite-borne infrared radiometer data:

- Good understanding of the behavior of the radiometer
- Good onboard calibration to give calibrated spectral radiances
- Accurate corrections for the effects of the intervening atmosphere
- Reliable techniques for identifying pixels contaminated by infrared emission from clouds and aerosols
- A reliable method of determining residual inaccuracies

MODIS SST bands

MODIS measures radiances in five spectral bands in the infrared atmospheric windows from which SST can be derived. Bands 31 and 32 in the thermal infrared window correspond roughly to AVHRR channels 4 and 5, and band 20, in the mid-infrared window, is similar to AVHRR channel 3. MODIS has two additional, narrow bands in the mid-infrared window (Bands 22 and 23). Although the mid-infrared window is "cleaner" than that in the thermal infrared, measurements at the shorter wavelengths are susceptible to contamination by solar radiation reflected at the sea surface.

MODIS is a much more complex instrument than its predecessors, and as such has several unique sources of instrumental artifacts, including those resulting from multiple detectors (10) in each spectral band, and the use of a two-sided paddle wheel scan mirror with a surface reflectivity that is dependent on angle of incidence, wavelength and mirror side. These have a time-dependent component. Empirical corrections, developed using on-orbit data, have been successful in reducing the impact of these effects.



Top: Spectra of atmospheric transmission for three representative atmospheres. Note that the variations in atmospheric transmission is smaller at 4µm than at 10-12µm.

Below: Spectral response functions for the Terra MODIS bands used for retrieving SST, with the Planck Function for temperatures 0, 10, 20 and 30°C. The emission at ~4µm is much smaller than at 10-12µm, but the temperature sensitivity is much greater.

Form of the algorithm

The form of the daytime and night-time algorithm is:

$$SST = c_1 + c_2 * T_{11} + c_3 * (T_{11}-T_{12}) * T_{sfc} + c_4 * (\sec(z)-1) * (T_{11}-T_{12})$$

where T_n are brightness temperatures measured in the channels at n µm wavelength, T_{sfc} is a 'climatological' estimate of the SST in the area, and z is the satellite zenith angle. This is based on the Non-Linear SST algorithm. (See *Walton, C. C., W. G. Pichel, J. F. Sapper and D. A. May,1998, "The development and operational application of nonlinear algorithms for the measurement of sea surface temperatures with the NOAA polar-orbiting environmental satellites." Journal of Geophysical Research,* ***103,*** *27,999-28,012.*)

The night-time algorithm, using two bands in the 4µm atmospheric window is:

$$SST4 = c_1 + c_2 * T_{3.9} + c_3 * (T_{3.9}-T_{4.0}) + c_4 * (\sec(z)-1)$$

Note: the coefficients in each expression are different.

Coefficient Generation

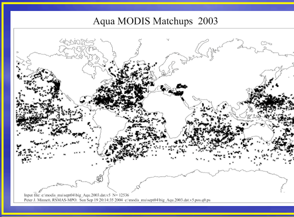
Coefficients have been derived by:

1. Radiative transfer modeling to simulate the MODIS brightness temperatures.
2. Matchups with near-simultaneous AVHRR SST fields that have been independently validated against the M-AERI (See *Kearns, E.J., J.A. Hanafin, R.H. Evans, P.J. Minnett, and O.B. Brown, "An independent assessment of Pathfinder AVHRR sea surface temperature accuracy using the Marine-Atmosphere Emitted Radiance Interferometer (M-AERI)." Bulletin of the American Meteorological Society,* ***81,*** *1525-1536, 2000)*
3. Matchups with drifting and moored buoys and the M-AERI

Method 3 provides coefficients that have smallest bias and standard deviation in the MODIS- derived SSTs.

SST Validation

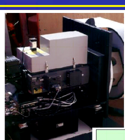
Validation of the SST uses two main data sources: highly-accurate ship-based infrared radiometers, and the large number of drifting and moored buoys with thermometers at a depth of a meter or so. The distribution of match-ups between the Aqua MODIS and the buoys is shown at right.



Positions of buoys reporting SST (at a nominal depth of 1m) during 2003. Only measurements within 30 minutes of the satellite overpass, and which pass the most stringent quality test for MODIS SSTs are shown and used in the analyses.

The radiometric skin SSTs are provided by the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI; *Minnett, P.J., R.O. Knuteson, F.A. Best, B.J. Osborne, J.A. Hanafin, and O.B. Brown, The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI), a high-accuracy, sea-going infrared spectroradiometer, Journal of Atmospheric and Oceanic Technology, 18 (6), 994-1013, 2001).*

The M-AERI is a Fourier Transform InfraRed (FTIR) Spectroradiometer that measures spectra in the wavelength range of ~3 to ~18 µm. It has two very stable internal black-body cavities for real-time calibration. This is periodically checked against a laboratory water-bath black-body calibration target, built to a NIST (National Institute of Standards and Technology) design (*Fowler, J.B., A third generation water bath based blackbody source., J. Res. Natl.Inst. Stand. Technol., 100 (5), 591-599, 1995*), which has been characterized by the NIST EOS TXR (Thermal-infrared Transfer Radiometer; *Rice, J.P., S.C. Bender, and W.H. Atkins, Thermal-infrared scale verifications at 10 micrometers using the NIST EOS TXR, Proc. SPIE, 4135, 96-107, 2000*), providing radiometric traceability to NIST standards (*Rice, J.P., J.J. Butler, B.C. Johnson, P.J. Minnett, K.A. Maillet, T.J. Nightingale, S.J. Hook, A. Abtahi, C.J. Donlon, and I.J. Barton, The Miami2001 Infrared Radiometer Calibration and Intercomparison: 1. Laboratory Characterization of Blackbody Targets, J. Atm. Ocean. Tech., 21, 258-267, 2004*).



Specifications

Spectral interval	~3 to ~18µm
Spectral resolution	0.5 cm^{-1}
Interferogram rate	1Hz
Aperture	2.5 cm
Detectors	InSb, HgCdTe
Detector temperature	78°K
Calibration	Two black-body cavities
SST retrieval uncertainty	<< 0.1K (absolute)

Laboratory tests of M-AERI accuracy

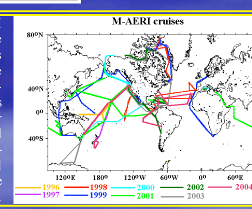
Target Temp.	LW (980-985 cm^{-1})	SW (2510-2515 cm^{-1})
20°C	+0.013 K	+0.010 K
30°C	-0.024 K	-0.030 K
60°C	-0.122 K	-0.086 K

The mean discrepancies in the M-AERI 02 measurements of the NIST water bath blackbody calibration target in two spectral intervals where the atmosphere absorption and emission are low. Discrepancies are M-AERI minus NIST temperatures.

M-AERI specifications and accuracies

The MODIS SST retrievals, based on algorithm coefficients derived from comparisons with buoy measurements, ie bulk temperatures, are rendered into a skin temperature using a simple offset based on at-sea measurements. (*Donlon, C.J., P.J. Minnett, C. Gentemann, T.J. Nightingale, I.J. Barton, B. Ward, and J. Murray, Towards improved validation of satellite sea surface skin temperature measurements for climate research., Journal of Climate, 15, 353-369, 2002*).

Schematic of the tracks of M-AERI cruises providing data for the validation of satellite SSTs. The tracks in the Caribbean include those of the *Explorer of the Seas* which has a M-AERI permanently installed and has maintained a consistent cruise track for over four years. The repeated sampling lends itself to MODIS match-ups as well as studies of interannual variability and instrument drift (see http://www.rsmas.miami.edu/rccl/).



MODIS SST accuracies (V.4)

Terra	Buoy + M-AERI			Buoy (bulk)			M-AERI (skin)		
	$\overline{\_T}$	$\_T'$	n	$\overline{\_T}$	$\_T'$	n	$\overline{\_T}$	$\_T'$	n
SST (day+night)	-0.160	0.490	30488	-0.165	0.488	29284	-0.025	0.527	1196
SST (night)	-0.190	0.481	15398	-0.196	0.477	14579	-0.082	0.524	816
SST (day)	-0.129	0.498	15090	-0.135	0.497	14705	0.096	0.513	380
SST4 (night)	-0.080	0.363	14634	-0.083	0.361	13846	-0.026	0.400	785

Aqua	Buoy + M-AERI			Buoy (bulk)			M-AERI (skin)		
	$\overline{\_T}$	$\_T'$	n	$\overline{\_T}$	$\_T'$	n	$\overline{\_T}$	$\_T'$	n
SST (day+night)	-0.008	0.503	29259	-0.009	0.502	28737	0.037	0.559	522
SST (night)	-0.030	0.500	14155	-0.033	0.498	13744	0.038	0.550	411
SST (day)	0.012	0.505	15104	0.012	0.504	14993	0.036	0.595	111
SST4 (night)	0.175	0.465	12040	-0.107	0.397	5258	0.263	0.477	332

Comments on Accuracies

- Few M-AERI SSTs compared with buoy SSTs (but many M-AERI cruise data are still in the processing pipeline)
- Biases w.r.t. buoys generally more negative than w.r.t. M-AERI – Skin effect
- Scatter at night smaller than during the day (diurnal thermocline effects)
- Scatter of SST4 uncertainties are smaller than SST uncertainties

Summary

- Most instrumental artifacts are corrected.
- Possible time dependences of artifacts require constant monitoring.
- "Empirical" atmospheric correction algorithm (buoys to sample parameter space; M-AERI to provide skin temperature offset) accounts for residual instrumental effects.
- Accuracy is established by comparison to buoy and M-AERI measurements. M-AERI is NIST traceable.

Future directions

- Derive new, time-dependent coefficients for V5 SST derivation. See the companion poster by Robert Evans for the residual errors with V.5, time-dependent coefficients for *Terra* MODIS. V5 reprocessing will occur in 2005. Coefficients for the *Aqua* MODIS will be derived in 2005.
- Continue comparisons with drifting buoys and M-AERI at-sea data to ensure longer-term accuracy of the SST fields and monitor the time-dependent effects of instrumental artifacts. Include additional radiometric measurements from other sensors as appropriate (*Barton, I.J., P.J. Minnett, C.J. Donlon, S.J. Hook, A.T. Jessup, K.A. Maillet, and T.J. Nightingale, The Miami2001 infrared radiometer calibration and inter-comparison: 2. Ship comparisons, Journal of Atmospheric and Oceanic Technology, 21, 268-283, 2004*).
- Improve atmospheric correction algorithm especially in regions of aerosols contamination.
- Improve cloud screening algorithms to reduce residual cloud contamination.
- Develop techniques for physically-based merging of multi-sensor SST data including microwave measurements from the European Advanced Along-Track Scanning Radiometer (AATSR) on *Envisat* and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) on *EOS-Aqua*.

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