TECHNICAL REPORT

Contract Title:	Infrared Algorithm Development for Ocean Observations with EOS/MODIS
Contract:	NAS5-31361
Type of Report:	Semi-Annual
Time Period:	July - December 2002
Principal Investigator:	Otis B. Brown RSMAS/MPO University of Miami 4600 Rickenbacker Causeway Miami, Florida 33149-1098

INFRARED ALGORITHM DEVELOPMENT FOR OCEAN OBSERVATIONS WITH EOS/MODIS

Abstract

Efforts continue under this contract to develop and validate algorithms for the computation of sea surface temperature (SST) from MODIS infrared measurements. These include radiative transfer modeling, comparison of *in situ* and satellite observations, development and evaluation of processing and networking methodologies for algorithm computation and data access, evaluation of surface validation approaches for IR radiances, and participation in MODIS (project) related activities. Activities in this contract period have focused on field campaigns, analysis of field data, analysis of MODIS SST retrievals, and preparation of publications and presentations.

A. NEAR TERM OBJECTIVES

MODIS Infrared Algorithm Development and Maintenance

A.1. Algorithmic development efforts based on experimental match-up databases and radiative transfer models and inter-satellite comparisons.

A.2. Interaction with the MODIS Instrument Team through meetings and electronic communications, and provide support for MCST activities.

A.3 Maintain and develop at-sea instrumentation for MODIS SST validation.

A.4 *In situ* validation cruises for the MODIS IR bands.

A.5 Development and population of the MODIS Matchup Data Base.

A.6 Interactions with other EOS groups.

A.7 Interactions with international groups.

MODIS SST – Scientific Research

A.8 Study thermal structure of ocean-atmosphere interface.

A.9 Development of optimal skin-SST validation strategy.

A.10 MODIS cloud cover studies.

Overarching Contract Activities

A.11 Provide investigator and staff support for the preceding items.

B. OVERVIEW OF CURRENT PROGRESS

July – December 2002

Activities during the past six months have continued on the previously initiated tasks, and extended to the new measurements from the *Aqua* MODIS. Many of the initial problems found with the *Terra* MODIS are absent, or much reduced, in the measurements of the *Aqua* MODIS. Importantly, the experience gained with *Terra* MODIS has been very beneficial in dealing efficiently with *Aqua* MODIS data. There have been specific efforts in the areas of: (a) deriving an atmospheric correction algorithm for the *Aqua* MODIS; (b) refinement of SST retrieval algorithms for the *Terra* MODIS based on match-ups with M-AERI skin temperature data and buoy sub-surface measurements, and (c) undertake cruises to acquire M-AERI infrared validation data. Previously initiated activities, such as team related activities, continue, as have episodic efforts associated with MODIS characterization and response.

Special foci during this six-month period have been:

1) Derive atmospheric correction algorithms for the *Aqua* MODIS.
2) Refine *Terra* MODIS SST retrieval algorithms based on match-ups with surface data.
3) Continuation of the analysis of measurements from M-AERI research cruises.
4) Continuation of routine data collection on the *Explorer of the Seas.*
5) Preparation and participation in the cruises of the CCGS *Pierre Radisson*, the R/V *Urania* and the *USCGC Polar Sea.*
6) Maintenance of the at-sea hardware, which has involved more effort than usual as there have been two significant M-AERI failures. The first on the *Explorer of the Seas* on September 29 resulted from a hardware failure of the system disk, and the consequent failure of the deck unit resulted in a gap of two months before being repaired by replacement. The second happened on the *Polar Sea* on November 7 during a severe storm which caused a mechanical failure in the hardware mounting the instrument to the side of the ship, and the M-AERI deck unit fell inboard onto a steel deck causing severe damage. These two events have caused a very unfortunate loss of validation data at an important time in the *Aqua* MODIS mission, and placed unanticipated financial strain on this project. It is hoped that both M-AERIs can be repaired and recalibrated by the end of February 2003, as there are two cruise opportunities soon after.

7) Continue development of a database for validation cruise data, buoy data and associated satellite measurements.

8) In collaboration with Dr. B. Ward of WHOI, and Dr. M. Donelan of the University of Miami a study of the thermal skin layer with a micro-profiler and the M-AERI, in the University of Miami – Rosenstiel School ASIST facility, is underway (with ONR funding).

B.1. Algorithmic development efforts based on experimental match-up databases and radiative transfer models and inter-satellite comparisons.

With the growth of the Terra MODIS match-up data base, it has become possible to refine the atmospheric correction algorithm based on these matchups. As the data base grows, more of parameter-space is filled and this permits examination of dependences on season, region (or latitude), satellite zenith angle, and other pertinent parameters. There are now over 11,000 matchups between Terra MODIS and buoys and, over 400 matchups with the M-AERI. These numbers are sufficiently large to permit a new approach to deriving the coefficients for the atmospheric correction algorithms: using the large number of buoy matchups to determine the coefficients that multiply the brightness temperature differences in the pairs of bands, and the M-AERI matchups to provide the offset necessary to determine the skin temperature rather than an estimate of the sub-surface bulk temperatures. The new coefficients have been delivered to G-DAAC for inclusion in the next SST PGE upgrade. The SST fields, generated at both the 11μm and 4μm (night-time) atmospheric windows, have been declared 'validated'. The residual errors show no marked dependences on latitude or satellite zenith angle and 50% lie within 0.2K (Figure 1).

The error characteristics of the SST fields derived using atmospheric correction algorithm coefficients obtained by radiative transfer modeling remain not quite as good as those derived using the matchups.

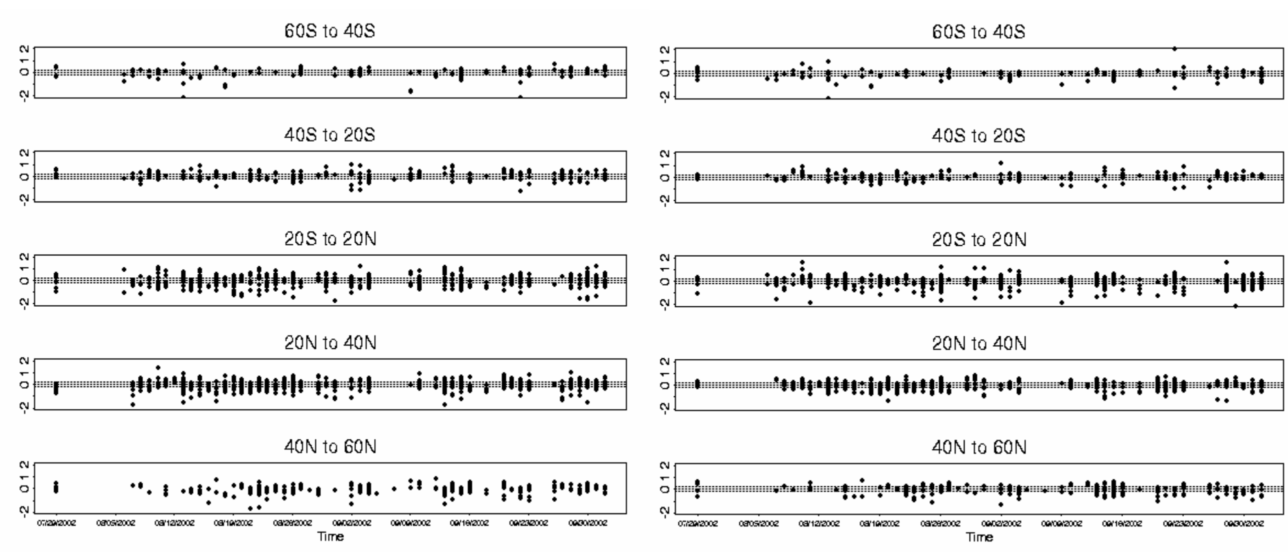

Figure 1. Time series of latitudinal dependence of the Terra MODIS SST fields derived at 11μm (left) and 4μm at night (right), using the latest atmospheric correction algorithms coefficients.

This is presumably caused by the effects of unknown sources of uncertainty in the MODIS measurements that are compensated in the empirical, matchup approach.

A similar approach has been followed for the *Aqua* MODIS data, and although the shorter period available for the matchups means the statistics are inevitably less stable, similar residual errors have been found, and the Aqua SST fields have also been declared 'validated'. As with the Terra MODIS, the 4m retrievals are valid only at night because of the risk of contamination by solar radiation.

<u>B.2. Interaction with the MODIS Instrument Team through meetings and electronic communications, and provide support for MCST activities.</u>

Dr. Robert Evans attended the MODIS Science Team Meeting at the Greenbelt Marriott, July 22-24, (Peter Minnett was at the First TRMM International Science Conference that was held at the same time), and presented " Sea Surface Temperature Measured by the Moderate Resolution Imaging Spectroradiometer (MODIS)" in the plenary session.

Material was provided to Dr Evans for his presentation at the Workshop at the International Summer School on Atmospheric and Oceanic Science, on the subject of "Remote Sensing of the Earth's Environment from Terra:, at L'Aquila, Italy, August 25-30, 2002. His presentation was entitled "MODIS Overview, Atmospheric Correction, and Calibration."

Drs Otis Brown and Peter Minnett attended the EOS Investigators Working Group Meeting, Ellicott City, MD. November 18, where Dr Brown gave a presentation entitled "Sea surface temperature measured by the MODerate resolution Imaging Spectroradiometer (MODIS)".

Throughout this reporting period, there has been interaction with Bob Evans (Contract NAS5-31362) and others at RSMAS on a daily basis to discuss the remediation of MODIS instrumental issues; participation in the weekly Ocean PI's teleconference, and numerous telephone discussions with Dr. Wayne Esaias, MODIS Oceans Team Leader on MODIS SST retrievals.

<u>B.3 Maintain and develop at-sea instrumentation for MODIS SST validation.</u>

For the first part of the reporting period, the maintenance of the M-AERI 1 on the *Explorer of the Seas* was routine, but on Sunday, September 29, the computer that controls the M-AERI and which logs the data suffered a disk crash. The system was shut down and attempts were made to correct the problem during the following Saturday port visit. This was unsuccessful and the computer was removed the following Saturday for repair at RSMAS. After installing a new disk and bench testing the computer, it was reinstalled on board, but the measured spectra were very noisy. Several Saturdays were spent trying to diagnose the problem, and it appears that the detectors are damaged or an element in the optical train is out of alignment. This is presumed to be a consequence of several weeks during which the instrument was not under power, and therefore not cooled during the cruises round the Caribbean. As a consequence, the whole deck unit was replaced with M-AERI 3, when that returned from an Arctic cruise (see B.4 below) and normal data acquisition was resumed on November 25. The long interval of data loss highlights the major problem of mounting an instrument on a ship with restricted periods of access; which is nevertheless outweighed by the measurement opportunities offered by this arrangement.

M-AERIs 2 and 3 were prepared for a series of research cruises for MODIS SST validation, beginning in September 2002 (see B.4 below).

Following the successful deployment on the R/V Urania M-AERI 2 was shipped from Livorno to Seattle for installation on the *USCGC Polar Sea* for the transit to Sydney. The ship sailed on November 4, and ran into a very severe storm. The ship was rolling badly and during an extreme roll one of the bolts securing the instrument to the railing above the bridge sheared and the support structure buckled. The M-AERI fell to the deck, causing damage to the stainless-steel enclosure, and severing the cable linking the M-AERI to the computer. The damage was irreparable at sea and the instrument was shipped back to Miami from Honolulu. It is currently being rebuilt and tested; replacement parts are on order. At present it is not known whether the damage is such that it must be returned to the manufacturer.

The damage to the two M-AERIs has resulted in a significant loss of validation data at an important time in the *Aqua* MODIS mission, and placed unanticipated financial strain on this project. It is hoped that both M-AERIs can be repaired and recalibrated by the end of February 2003, as there are two cruise opportunities soon after; the *Polar Sea* from Melbourne, Australia, to Seattle, and the *Urania* in the Western Mediterranean.

B.4 *In situ* validation cruises for the MODIS IR bands.

Since November 2000, M-AERI 1 has been permanently installed on the *Explorer of the Seas*, which undertakes alternate weekly cruises in the eastern Caribbean Sea and Bahaman Islands (white track in Figure 2), and through the western Caribbean Sea and Florida Straits (red track in Figure 2). The ship

Figure 2. Weekly tracks of the *Explorer of the Seas.* The ship follows the two tracks on alternate weeks.

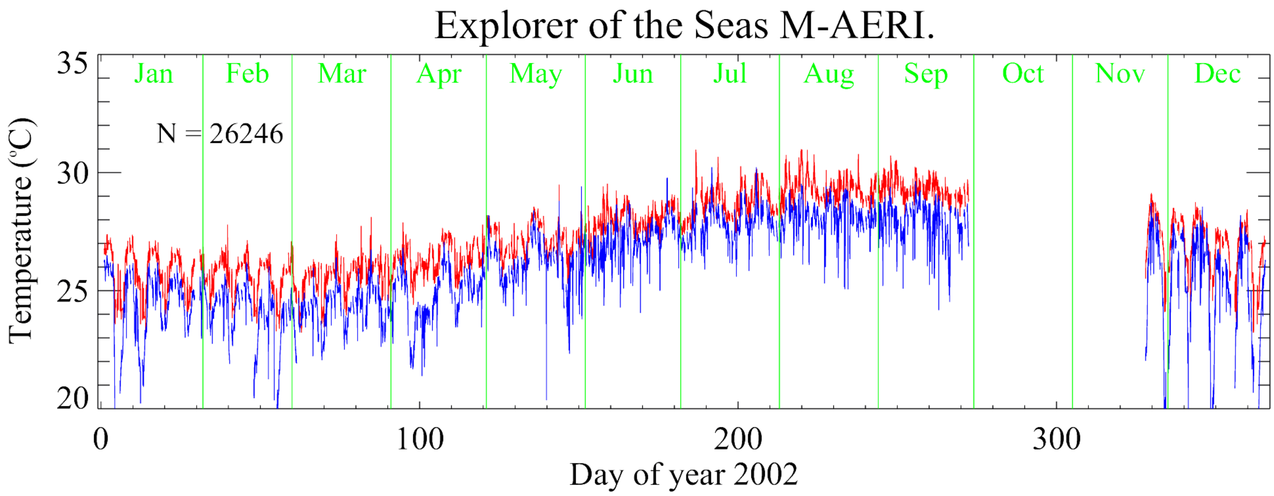

Figure 3. Measurements of skin SST (red) and near-surface air temperature (blue) measured by the M-AERIs on the *Explorer of the Seas* during 2002.

returns to Miami each Saturday at which time the data are retrieved and taken to RSMAS. During this reporting period, the track of the eastern Caribbean circuit was changed to include a port call at St Maarten, in place of Labadee, and so both outgoing and return passages are on the eastern side of the Bahamas. Up to the disk failure on September 29, M-AERI 1 on the *Explorer of the Seas* had operated continuously for 664 days, producing data of high quality with a very good rate of data return. The data for 2002 are shown in Figure 3.

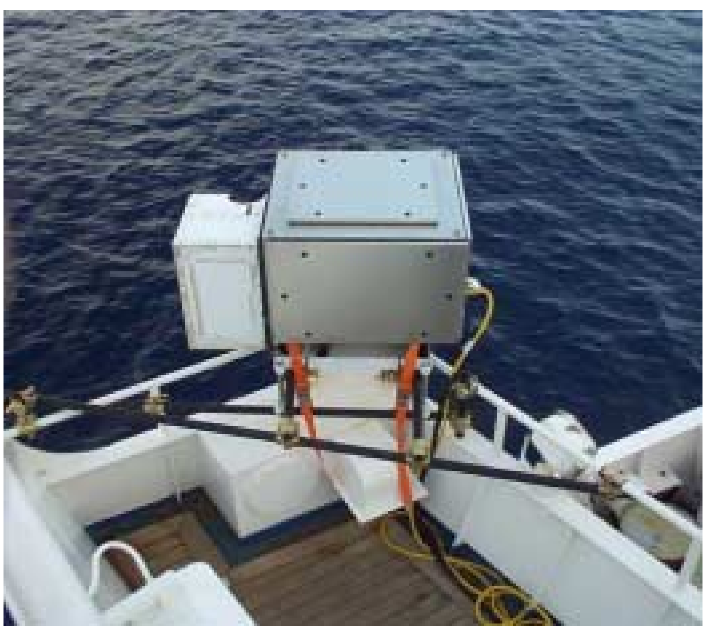

Figure 4. The M-AERI mounted on the *R/V Urania*

M-AERI 2 was installed on the *R/V Urania* in Naples, Italy, for a research cruise in the Western Mediterranean Sea. The installation of the M-AERI is shown in Figure 4. The *Urania* sailed on September 20 heading west to the study area, where the weather conditions were so bad that all scientific activities were postponed on grounds of safety. Validation data were taken from September 29 to October 8. The ship returned to Livorno, Italy, on October 9. The cruise track, during which M-AERI data were taken, is shown in Figure 5.

Directly following this cruise, M-AERI 2 was shipped to Seattle for installation on the UCSCG *Polar Sea* for a transit across the Pacific Ocean. Unfortunately the instrument was severely damaged in a storm soon after leaving port (see B.3 above).

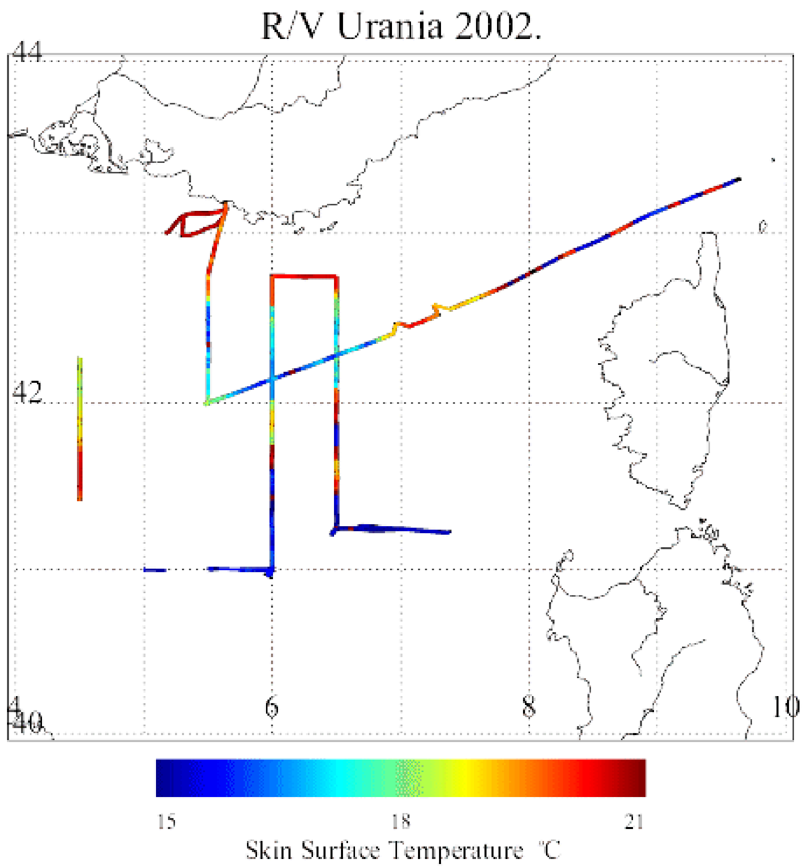

Figure 5. The track of the R/V Urania, colored by surface temperature measured by the M-AERI.

M-AERI-3 was embarked on the Canadian Coast Guard ice-breaker *Pierre Radisson* during the cruise in the Arctic Ocean off the coast of Canada. This cruise was part of a long-term, multi-disciplinary project called CASES, the Canadian Arctic Shelf Exchange Study, and provided an opportunity to gather MODIS SST validation data in high latitude conditions, which, because of the difficult logistics of operating in the Arctic, are very hard to obtain. Minnett flew from Miami to Quebec City on September 17 2002, and onwards to Resolute Bay by a Canadian Coast Guard charter flight on the 18. The ship was waiting offshore and people and gear were flown out by helicopter. The M-AERI was mounted on the foredeck (Figure 6). The ship transited the Northwest Passage while the equipment was being installed and tested. After about a month of measurements (Figure 7) the equipment was taken down on the passage back to Quebec City, where the ship arrived on October 26.

Figure 6. The M-AERI on the foredeck of the Pierre Radisson. The instrument was covered by a tarpaulin during storms, which coated the other foredeck equipment with snow and ice.

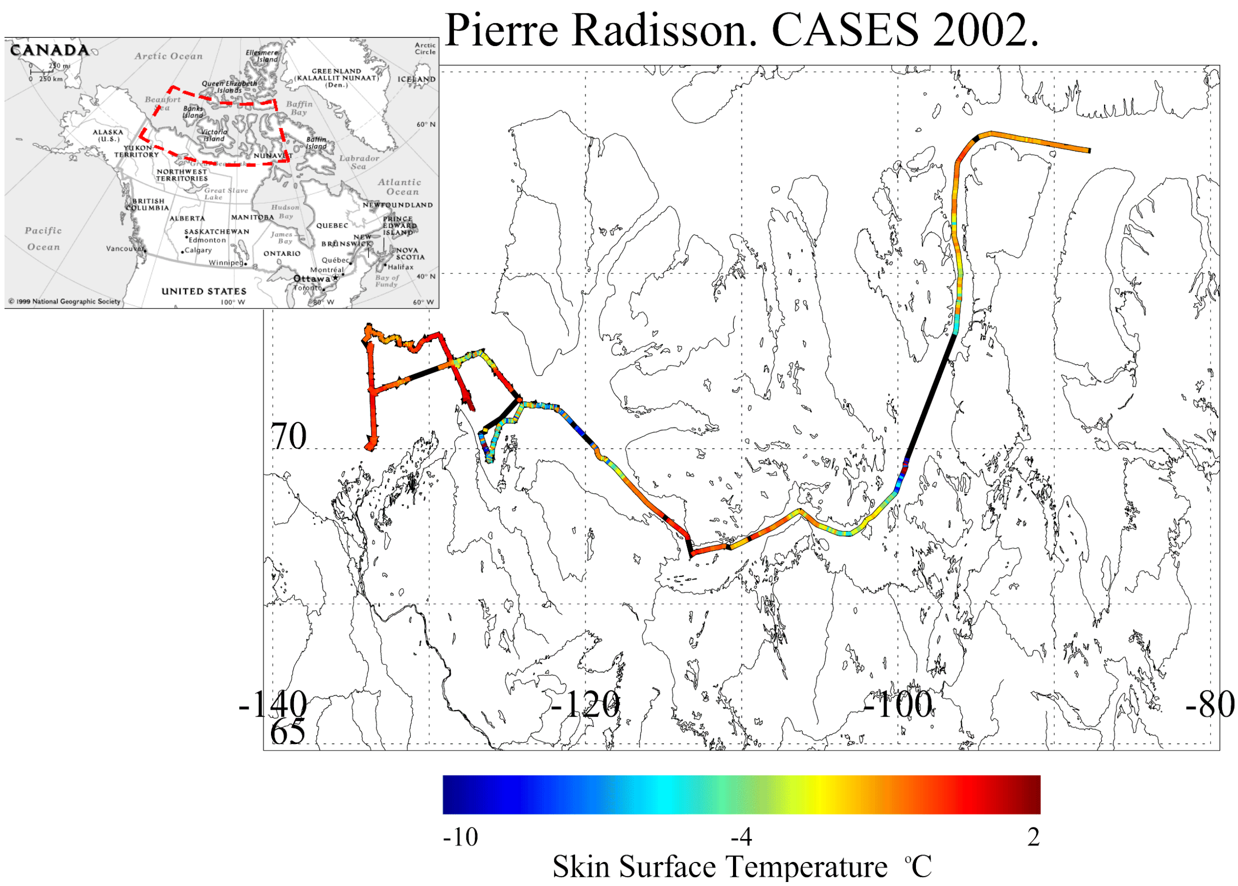

Figure 7. Study area and track of the Pierre Radisson, colored by surface temperature measured by the M-AERI.

B.5 Development and population of the MODIS Matchup Data Base

The process of developing a database of matchups between MODIS brightness temperatures, and derived SSTs, and in situ validation measurements from buoys and M-AERIs continues. This is a very time consuming activity as it requires extensive quality control of the buoy measurements, and the processing of all of the oceanic measurements from the two MODIS instruments on *Terra* and *Aqua.* Nevertheless this is a very important activity in providing the information to validate the MODIS SSTs and to provide insight into the behavior of the error characteristics of the SST retrieval algorithms. In response to requests from external groups, copies of the Matchup Data Base were delivered to Dr Pierre Le Borgne of Meteo France, and Dr William Gallery of Atmospheric & Environmental Research, Inc.

A related development is the provision of a web-accessible, on-line database for measurements taken from the *Explorer of the Seas* which has resulted from ONR funding. This means all M-AERI data, and those from other sensors on board, are accessible to the wider community. At present the data access is rather obscure to the neophyte, but a user-friendly graphical user interface will be implemented soon to permit efficient searching and downloading of the measurements.

B.6 Interactions with other EOS groups.

Collaborative activities have begun in this reporting period with the AIRS (Atmospheric Infrared Sounder) group at JPL who are using MODIS SSTs to validate the radiometric calibration of the AIRS on *Aqua*. At a wavenumber of 2616 cm^{-1}, the atmosphere is particularly transparent and the residual uncertainties in the AIRS measurements of skin SST are anticipated to be very small. Aqua MODIS SSTS have been sent to the JPL AIRS Team for comparison with the AIRS measurements. These measurements are contemporaneous and share the same emission angle at the surface and path through the atmosphere. The advantages of MODIS over AIRS lies in the higher spatial resolution (~1km *vs* ~15km) that leads, at least in principle, to more reliable identification of measurements contaminated by clouds, and the more established validation of the skin SST retrievals using buoys and M-AERIs. The initial results are very good, with a small bias of ~0.3K (AIRS cooler than MODIS), and standard deviation of 0.14 to 0.21K. The preliminary results are available at ftp://thunder.jpl.nasa.gov/hha/sst/modis-airs-comparions.htm.

MODIS SST fields covering the US east coast have also been supplied to Dr Wallace McMillan at the University of Maryland, Baltimore County, who is working on the validation of AIRS measurements using an AERI mounted on the Chesapeake Bay Light Tower.

B.7 Interactions with international groups.

The M-AERI measurements have been made available to the Advanced Along-Track Scanning Radiometer (AATSR) Team at the University of Leicester for validating the AATSR SST retrievals. The AATSR is the third in the series of dual-view imaging radiometers to fly on European polar orbiting satellites, and is part of the scientific payload of the *ENVISAT* satellite. In return for the M-AERI data, we will receive copies of AATSR data which will be used in comparative studies with MODIS SSTs. By measuring the same swath of the earth's surface at two view angles, the AATSR provides a direct measurement of the effect of the atmosphere on the infrared signals, thereby permitting an alternative approach to the conventional multi-channel atmospheric correction algorithms used by MODIS. The AATSR has three channels that match quite well bands 20, 31 and 32 of MODIS. Peter Minnett attended the ENVISAT Validation Symposium at the European Space Research Institute (ESRIN) in Frascati, Italy, in December (with ESA funding).

MODIS SST – Scientific Research

B.8 Study thermal structure of ocean-atmosphere interface.

With funding from ONR a study is underway of the thermal skin layer and subsurface temperature structure in the RSMAS ASIST (Air-Sea Interaction Salt Water Tank). ASIST was designed for studies relevant to air-sea interaction including remote sensing, turbulence, gas transfer, wave dynamics, surface chemistry, spray and aerosol generation, and interfacial thermodynamics. The 15 meter long ASIST is equipped with a wind tunnel (0-30 ms^{-1}), programmable wavemaker, water temperature control, water current control, turbulence and wave instrumentation. The experiments were made of the behavior of the skin layer under a wide range of air sea heat fluxes and wind speeds. This study is in collaboration with Dr B. Ward, now of the Woods Hole Oceanographic Institution, and Dr. M. Donelan of RSMAS.

B.9 Development of optimal skin-SST validation strategy.

During the last week of May, 2001 an international workshop for the comparison and calibration of ship-board infrared radiometers that are being used to validate the skin sea-surface temperatures derived from the measurements of imaging radiometers on earth observation satellites, was held at RSMAS. This included laboratory measurements using the newly developed NIST Transfer Radiometer (TXR), and against NIST-certified black-body calibration targets, and an intercomparison of the radiometers on a short cruise on board the R/V F.G. *Walton-Smith* in local waters around Miami. This was funded by NOAA, ESA and EUMETSAT. The results have been prepared for publication and two papers have been submitted to the Journal of Atmospheric and Oceanic Technology (Barton *et al*., Rice *et al*.); these are detailed in F1 below.

B.10 MODIS Data applications

An important demonstration of the application of MODIS SSTs was undertaken during the Atlantic hurricane season. SST fields are used to forecast the intensity of hurricanes at landfall, and the usual source of this information is the weekly, one-degree spatial resolution fields provided by NCEP. These data are available about one-week after real-time, and sometimes situations develop that require more rapidly-available data. An example of this involves the two hurricanes, *Isidore* and *Lili* that passed through the Gulf of Mexico in September, 2002. *Lili*'s track across the Gulf passed over that of *Isidore*, which had left a cold wake in the SST. *Lili*'s intensity rapidly decreased from Category 4 to Category 2 at landfall, but this was not apparent in time to avoid the evacuation of part of the coast. The reason for the drop in intensity is apparent in SST fields derived by merging those from *Terra* MODIS, *Aqua* MODIS, *Aqua* AMSR and the TRMM TMI (done in conjunction with F. Wentz and C. Gentemann at Remote Sensing Systems Inc), which were being generated at RSMAS on a daily basis with 0.25degree spatial resolution. These were passed to Dr. N. Shay at RSMAS who is working on a research project to improve hurricane forecasts. In collaboration with NOAA researchers, he generated maps of upper ocean heat contact, a much more relevant predictor of hurricane intensity, using a simple upper ocean model with the SST fields and ocean surface topography from satellite altimetry, and this revealed a significant signature of much reduced upper ocean heat content in the track of Hurricane *Isidore*. When Hurricane *Lili* tracked over this wake, the heat available to power the hurricane was much reduced and rapid loss of intensity followed. Had such fields been available to hurricane forecasters in near real-time, the costly coastal evacuation could have been avoided.

With funding from ESA, Peter Minnett attended the Science Team Meeting of the GODAE (Global Ocean Data Assimilation Experiment) High Resolution Sea-Surface Temperature (GHRSST) Pilot Project in Frascati, Italy, in December. The GHRSST objective, to provide global SSTs at a spatial resolution of 10km or better, on a 6-hr time step, requires the merging of SST fields from a wide range of satellite sensors operating both in the infrared and the microwave spectral regions, and the merging of these disparate data sets in a physically meaningful manner is a subject ripe for intense research. Although the mechanism for full US participation in GHRSST is not yet clear, the potential contribution of MODIS SSTs to this is very significant, and desired by the GHRSST international Science Team.

B.11 MODIS cloud cover studies.

The equipment installed on the Explorer of the Seas includes a Total-Sky Imager and Ceilometer to determine the amount and type of cloud cover present at the time of the satellite overpasses. These measurements have multiple applications including the determination of cloud-free conditions when MODIS SSTs are being compared to M-AERI measurements, and as data for validating cloud conditions determined from MODIS. This latter research has been conducted in collaboration with the group at The University of Alabama at Huntsville, and has resulted in a paper by Berendes et al, entitled "Intercomparison of a Neural Network Derived MODIS Cloud Cover Estimate with Surface Instruments" which has been submitted to the Journal of Geophysical Research (see F.1 below).

C. INVESTIGATOR SUPPORT

July	W. Baringer	R. Kolaczynski	R. Sikorski
	O. Brown	A. Kumar	J. Splain
	M. Framinan	A. Li	M. Szczodrak
	K. Kilpatrick	K. Maillet	
August	W. Baringer	R. Kolaczynski	K. Maillet
	O. Brown	A. Kumar	J. Splain
	K. Kilpatrick	A. Li	M. Szczodrak
September	W. Baringer	R. Kolaczynski	J. Splain
	O. Brown	A. Kumar	M. Szczodrak
	M. Framinan	A. Li	
	K. Kilpatrick	K. Maillet	
October	W. Baringer	R. Kolaczynski	J. Splain
	O. Brown	A. Kumar	M. Szczodrak
	M. Framinan	A. Li	
	K. Kilpatrick	K. Maillet	
November	W. Baringer	A. Kumar	J. Splain
	O. Brown	A. Li	M. Szczodrak
	M. Framinan	K. Maillet	
	K. Kilpatrick		
December	W. Baringer	A. Kumar	J. Splain
	O. Brown	A. Li	M. Szczodrak
	M. Framinan	K. Maillet	
	K. Kilpatrick		

D. FUTURE ACTIVITIES

D.1 Algorithms

a. Repair damaged M-AERI, recalibrate and prepare for future validation cruises.
b. Continue to develop and test algorithms on global retrievals.
c. Evaluation of global data assimilation statistics for SST fields.
d. Develop scientifically defensible techniques of merging *Terra* and *Aqua* MODIS data.
e. Develop scientifically defensible techniques of merging infrared and microwave SST fields.
f. Participate in research cruises.
g. Continue radiative transfer modeling to better understand the MODIS SST error characteristics.
h. Continue analysis of research cruise data.
i. Continue to study near-surface temperature structure.
j. Continue planning of validation campaigns.
k. Validation Plan updates (as needed).
l. EOS Science Plan updates (as needed).
m. Continued participation in MODIS Team activities.

D.2 Investigator support

Continue appropriate efforts.

D.3 Presentations and publications.

a. Prepare material for the IGARSS International Symposium in Toulouse in July 2003, IUGG in Sapporo in July 2003, and other symposia as appropriate.
b. Prepare scientific results for publication in the refereed literature.

E. PROBLEMS

Two M-AERIs were damaged in this reporting period, and these are currently being repaired. Although the damage to M-AERI 2, resulting from a storm that hit the *Polar Sea* in the North Pacific Ocean is severe, current assessment indicates that most of it is superficial and relatively easy to repair. The interferometer appears to be functioning, but there remains uncertainty as to whether the optical path will require re-alignment, and this can only be ascertained once the instrument as a whole is sufficiently repaired to allow further diagnostic and calibration measurements to be made. These events have placed an unanticipated fiscal burden, as yet of unknown size, on the project.

F. PUBLICATIONS AND PRESENTATIONS

F.1 Refereed publications:

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: Ship comparisons. *Journal of Atmospheric and Oceanic Technology*. Submitted.

The second calibration and inter-comparison of infrared radiometers (Miami2001) was held at the University of Miami, Rosenstiel School of Marine and Atmospheric Science (RSMAS) during May-June 2001. The radiometers targeted in these two campaigns (laboratory-based and at-sea measurements) are those used to validate the skin sea-surface temperatures and land surface temperatures derived from the measurements of imaging radiometers on earth observation satellites. These satellite instruments include those on currently operational satellites and others that will be launched within two years following the workshop. The experimental campaigns were completed in one week and included laboratory measurements using black-body calibration targets characterized by the National Institute of Standards and Technology (NIST), and an inter-comparison of the radiometers on a short cruise on board the RV F.G. Walton-Smith in Gulf Stream waters off the eastern coast of Florida. This paper reports on the results obtained from the ship-borne measurements. Seven radiometers were mounted alongside each other on the RV Walton Smith for an inter-comparison under sea-going conditions. The ship results confirm that all radiometers are suitable for the validation of land surface temperature, and the majority are able to provide high quality data for the more difficult validation of satellite-derived sea surface temperature, contributing less than 0.1 K to the error budget of the validation. The measurements provided by two prototype instruments developed for ship-of-opportunity use confirmed their potential to provide regular reliable data for satellite-derived SST validation. Four high quality radiometers showed agreements within 0.05 K confirming that these instruments are suitable for detailed studies of the dynamics of air-sea interaction at the ocean surface as well as providing high quality validation data. The data analysis confirms the importance of including an accurate correction for reflected sky radiance when using infrared radiometers to measure SST. The results presented here also show the value of regular inter-comparisons of ground-based instruments that are to be used for the validation of satellite-derived data products - products that will be an essential component of future assessments of climate change and variability.

Berendes, T., D. Berendes, R. Welch, E. Dutton, P.J. Minnett, T. Uttal and E. Clothiaux. Intercomparison of a Neural Network Derived MODIS Cloud Cover Estimate with Surface Instruments, *Journal of Geophysical Research*. Submitted.

A cloud cover "validation" system is developed. Cloud cover estimates are computed from a neural network-based satellite cloud mask. The performance of the satellite cloud mask is evaluated using independent samples from imagery not used in the training process, with cloud classification accuracy greater than 96 %. However, because human analysts may not be able to discern high level thin cirrus and sub-resolution cumulus clouds, it is necessary to intercompare the satellite cloud cover estimates with surface-based instrument data. Two of the instrumented surface sites are operated by the Atmospheric Radiation Measurement (ARM) program. The North Slope of Alaska

(NSA) site and the Southern Great Plains (SGP) site operate several instruments which are used to calculate cloud cover. Additionally, the Explorer of the Seas cruise ship houses several instruments from which cloud cover estimates are computed. At the NSA ARM site, the Whole Sky Imager (WSI) data agrees most closely (83% of the cases agree to within ± 20%) with the satellite cloud mask observations. At the SGP ARM site, the WSI also provides the best match with 76 % agreement. These results suggest that the WSI is an excellent choice for cloud "validation". The primary difficulty with the Micropulse Lidar (MPL) results is that the lidar is far more sensitive to high, thin clouds than is the current satellite cloud mask. Preliminary results using surface instrument data from the Explorer of the Seas cruise ship indicate that the Total Sky Imager (TSI) matches best with 68 % agreement. Each of the instruments has its own strengths and limitations when used to compute cloud cover. The use of multiple instruments and composite data sets such as Active Remote Sensing of Clouds (ARSCL) can provide improved intercomparisons with the satellite derived estimates of cloud cover. Thin, high clouds such as cirrus cause many discrepancies between the satellite mask and surface instruments, but there are indications that aerosols and low clouds, such as fog, are another source.

Hagan, D. and P.J. Minnett, AIRS Radiance Validation Over Ocean from Sea Surface Temperature Measurements. *IEEE Transactions on Geoscience and Remote Sensing*. Accepted.

This paper demonstrates the accuracy of methods and in situ data for early validation of calibrated Earth scene radiances measured by the Atmospheric InfraRed Sounder (AIRS) on the Aqua spacecraft. We describe an approach for validation that relies on comparisons of AIRS radiances with drifting buoy measurements, ship radiometric observations and mapped sea surface temperature products during the first six months after launch. The focus of the validation is on AIRS channel radiances in narrow spectral window regions located between 800-1250 cm^{-1} and between 2500 and 2700 cm^{-1}. Simulated AIRS brightness temperatures are compared to in situ and satellite-based observations of Sea Surface Temperature (SST) co-located in time and space, to demonstrate accuracies that can be achieved in clear atmospheres. An error budget, derived from single channel, single footprint matchups, indicates AIRS can be validated to better than 1% in absolute radiance (equivalent to 0.5 K in brightness temperature, at 300 K and 938 cm^{-1}) during early mission operations. The eventual goal is to validate instrument radiances close to the demonstrated pre-launch calibration accuracy of about 0.4% (equivalent to 0.2 K in brightness temperature, at 300 K and 938 cm^{-1}).

Kumar, A., P. J. Minnett, G. Podestà, and R. H. Evans. Error characteristics of the atmospheric correction algorithms used in retrieval of sea surface temperatures from infrared satellite measurements; global and regional aspects. *Journal of the Atmospheric Sciences*. Accepted

A database of co-temporal and co-located satellite and in situ observation is used to examine the association between brightness temperature differences measured in the thermal infrared channels (T45) of the Advanced Very High Resolution Radiometer (AVHRR) and water vapor (ω) derived form the Special Sensor Microwave Imager (SSM/I). This channel difference is used to estimate the atmospheric correction (due mostly to water vapor absorption) in sea surface temperature (SST) *algorithms. The association between T45 and ω is found to be greatest for tropical latitudes; for mid and high latitudes the association is best during summer. However, the association tends to decrease towards mid and higher latitudes during other periods. SST residual errors (satellite – buoy) show a negative mean in the tropics suggesting undercorrection for water vapor in the tropics. The underestimation is explicitly shown for SST in the high water vapor regimes of the Arabian Sea. In mid and high latitudes, the variability of atmospheric water vapor and air-sea temperature difference contribute to the weaker association between T45 and ω, and results in positive mean SST residual errors. A differential form of SST algorithm that incorporates the use of a "first-guess estimate" that correlates with SST is observed to give least residual errors.*

Minnett, P.J. Radiometric measurements of the sea-surface skin temperature for the validation of measurements from satellites – the competing roles of the diurnal thermocline and the cool skin. *International Journal of Remote Sensing*. Accepted.

It has long been recognized that satellite-borne infrared radiometers measure radiance that is more closely related to the temperature of the skin of the ocean than the sub-surface bulk temperature, but, historically, atmospheric correction algorithm derivation and validation exercises have been conducted using bulk temperatures measured at a depth of a metre or more. A recent validation of sea-surface temperature (SST) fields derived from the Advanced Very High Resolution Radiometer (AVHRR) with skin temperature measurements of the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) revealed a very low mean bias error, much smaller that was expected given the thermal skin effect which acts to cool the surface with respect to subsurface values by several tenths of a degree. This result does not imply the skin effect is not important – its effect is now well documented in many data sets – but that its effect is being partially compensated by diurnal heating effects. The evidence for this is presented and the consequences in terms of validating satellite-derived SSTs and of merging data from sensors with different satellite overpass times are discussed.

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 *Journal of Atmospheric and Oceanic Technology*. Submitted.

The second calibration and inter-comparison of infrared radiometers (Miami2001) was held at the University of Miami, Rosenstiel School of Marine and Atmospheric Science (RSMAS) during May-June 2001. The participants were from several groups involved with the validation of skin sea-surface temperatures and land surface temperatures derived from the measurements of imaging radiometers on earth observation satellites. These satellite instruments include those on currently operational satellites and others that will be launched within two years following the workshop. There were two experimental campaigns carried out during the one week workshop: a set of measurements made by a variety of ship-based radiometers on board the research vessel F.G. Walton-Smith in Gulf Stream waters off the eastern coast of Florida, and a set of laboratory measurements of typical external blackbodies used to calibrate these ship-based radiometers. This paper reports on the results obtained from the laboratory characterization of blackbody sources. A companion paper reports on the at-sea measurements.

Five blackbody sources were intercompared by measurements of their brightness temperature using the National Institute of Standards and Technology (NIST) Thermal-infrared Transfer Radiometer (TXR). Four of these sources are used for calibration of sea-surface temperature radiometers. The fifth was a NIST water bath blackbody used for calibration of the TXR. All blackbodies agreed to better than ±0.1 °C at blackbody temperatures near the ambient room temperature. Some of the blackbodies had reduced effective emissivity relative to the NIST water bath blackbody, and hence they began to disagree at blackbody temperatures far enough away from the ambient room temperature. For these, relative effective emissivity values were determined so that corrections can be applied if they are used in conditions of non-laboratory ambient temperatures.

Vogelmann, A.M., P. J. Flatau, M. Szczodrak, K. M. Markowicz, and P. J. Minnett. Observations of large aerosol greenhouse effects at the surface. *Geophysical Research Letters.* Submitted.

Studies of aerosol effects on the Earth's energy budget usually consider only the cooling effects at short (solar) wavelengths, but we demonstrate that they also have important warming effects at thermal infrared (IR) wavelengths that have rarely been observed and are commonly ignored in climate models. We use high-resolution spectra to obtain the greenhouse effect (IR radiative forcing) at the surface for aerosols encountered in the outflow from northeastern Asia. The spectra were measured by the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) from the NOAA Ship Ronald H. Brown during the Aerosol Characterization Experiment-Asia (ACE-Asia). We show that the surface greenhouse effects are often a few Wm^{-2} *and can reach almost 10* Wm^{-2} *for large aerosol loadings. Thus, even the smaller aerosol IR forcings observed here are comparable to or greater than the 1 to 2* Wm^{-2} *IR surface enhancement from increases in greenhouse gases. These results highlight the importance of aerosol IR forcings which should be included in climate model simulations.*

Ward, B., R. Wanninkhof, P.J. Minnett and M.J. Head.. SkinDeEP: A Profiling Instrument for Upper Decameter Sea Surface Measurements. *Journal of Atmospheric and Oceanic Technology*. Submitted.

The Skin Depth Experimental Profiler (SkinDeEP) is an autonomous, self–contained, hydrodynamic instrument capable of making repeated, high–resolution profiles of temperature and conductivity within the ocean's upper decameter. Autonomous profiling operation is accomplished through SkinDeEP's ability to change its density: positive buoyancy is achieved by pumping air from inside the body of the profiler into an external, neoprene, inflatable sleeve; the instrument sinks when the sleeve is deflated by returning the air to the interior. The sensors are mounted some distance from the top endcap and data are recorded only during the ascending phase of the profile so as to minimize disruption of a naturally occurring scalar structure within the instrument's footprint. Both temperature and conductivity are measured with resolutions in the submillimeter and millimeter range, respectively. Accurate slower sensors are installed for calibration purposes. These data are used to study exchange processes at the air–sea interface, and the structure of the ocean just below.

Williams, E., E. Prager and D. Wilson, 2002. Research Combines with Public Outreach on a Cruise Ship. *EOS* **83**(50): 590, 596.

An innovative partnership among academia, government, and private industry has created a unique opportunity for oceanographic and meteorological research on a cruise ship. The University of Miami's Rosenstiel School of Marine and Atmospheric Science, Royal Caribbean International, the National Oceanic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratories, the National Science Foundation, and the U.S. Office of Naval Research have collaborated to establish two modern laboratories for oceanic and atmospheric research on the 142,000-ton Royal Caribbean ship Explorer of the Seas.

F.2 Conference Proceedings and Data Reports:

Minnett, P. J., I. J. Barton and J. P. Rice. The Miami-2001 Radiometer Intercomparison. Proceedings of the Envisat Validation Workshop, Frascati, December, 2002. ESA Special Publication SP-520. In the press.

Minnett, P. J. and M.C. Edwards, AATSR SST Validation using the M-AERI. Proceedings of the Envisat Validation Workshop, Frascati, December, 2002. ESA Special Publication SP-520. In the press.

F.3 Presentations:

Jessup, A.T, R.A. Fogelberg and P.J. Minnett. Autonomous shipboard infrared radiometer system for *in situ* validation of satellite SST. SPIE Annual Meeting, Seattle, WA, July 8, 2002

Evans, R. H., E. J. Kearns, P. J. Minnett, O. B. Brown, W. Baringer, J. Brown, K. Kilpatrick and S. Walsh. Sea surface temperature measured by the MODerate resolution Imaging Spectroradiometer (MODIS). MODIS Science Team Meeting, Greenbelt MD, July 22-24, 2002.

Evans, R. H. , E. J. Kearns, P. J. Minnett, O. B. Brown, W. Baringer, J. Brown, K. Kilpatrick and S. Walsh. Sea surface temperature measured by the MODerate resolution Imaging Spectroradiometer (MODIS). “Remote Sensing of the Earth's Environment from Terra,” a Workshop at the International Summer School on Atmospheric and Oceanic Science, L'Aquila, Italy, August 25-30, 2002.

Brown, O. B., R. H. Evans, P. J. Minnett, E. J. Kearns and Kay Kilpatrick. Sea surface temperature measured by the MODerate resolution Imaging Spectroradiometer (MODIS). NASA Earth Observing System Investigator Working Group Meeting, Ellicott City, MD. November 18, 2002.

Minnett, P.J. Validation of satellite SST using M-AERI. Third Workshop of the Global Ocean Data Assimilation Experiment High Resolution Sea Surface Temperature Pilot Project. Frascati, Italy, December 4, 2002.

Evans, R.H., O.B. Brown, P.J. Minnett and E.J. Kearns, 2002. A comparison of MODIS AQUA and TERRA SST using MAERI and buoy observations. Third Workshop of the Global Ocean Data Assimilation Experiment High Resolution Sea Surface Temperature Pilot Project. Frascati, Italy, December 4, 2002.

Minnett, P.J. and M.C. Edwards. AATSR SST Validation using the M-AERI. Envisat Validation Workshop, Frascati, Italy, December 12, 2002.

Minnett, P.J., I.J. Barton and J.P. Rice. The Miami-2001 Radiometer Intercomparison. Envisat Validation Workshop, Frascati, Italy, December 12, 2002.