FINAL REPORT

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INFRARED ALGORITHM DEVELOPMENT FOR OCEAN OBSERVATIONS WITH EOS/MODIS

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1 INTRODUCTION

This is final report is a brief summary of the activities over the entire period of performance of this contract, 1990 – 2003. Full details of the progress and problems in each three- and six-month period are discussed in the reports submitted to the MODIS Administrative Support Team, and which are available at http://modis.gsfc.nasa.gov/sci_team/reports/oceans.html. Included in this report is a synopsis of the major results, a complete list of publications and presentations resulting from the research undertaken in this contract, and a discussion of "lessons learned." While these items represent the tangible products of the effort expended in this contract, the main measure of success is the generation of fields of skin sea-surface temperature (SST), that are validated to the level required for their use in many aspects of scientific research, and their increasing acceptance and use by the scientific community.

2 OBJECTIVES

The main objectives of this contract can be summarized as:

- contribute to making MODIS work as a high-accuracy infrared spectroradiometer,
- derive algorithms for accurate skin SST retrievals,
- develop a consistent validation plan, moving beyond the then-existing capabilities
- execute validation plan to demonstrate whether the SST accuracies are being met
- determine the uncertainty characteristics of SST retrievals
- assess the suitability of MODIS SSTs for scientific applications (eg in the Climate Record) by comparison with heritage instruments.

3 LESSONS LEARNED

In this section we discuss the 'lessons learned' during the performance period. While they are necessarily specific to our experience and determined to some degree by the particular characteristics of the MODIS instruments, many of these experiences are directly applicable to other sensors and missions, especially the VIIRS on NPP and NPOESS

3.1 Compromises in instrument design have ramifications

MODIS is a very complex instrument, possibly one of the most complex devices flown on satellites for Earth Observation. Furthermore, it was designed to satisfy a very large a diverse user community. Trying to satisfy the different and sometimes competing or contradictory, requirements of this community leads to compromises that degrade performance for key variables. Some compromises were adopted to reduce costs and others are the consequences of not being able to take advantage of rapid advances in the appropriate technology. Specific examples of MODIS include:

- The proprietary multi-layer coating on the MODIS scan mirror. This is designed to reduce polarization sensitivity and the dependence of the mirror reflectivity on angle of incidence (scan angle) at shorter wavelengths. This coating however, introduces a pronounced reflectivity *vs* scan angle (rvs) in the thermal infrared. This has been a major issue in the quantitative infrared radiometry of the instrument.
- The dynamic range of one of the primary channels of the Terra MODIS used for SST measurements was increased by about a factor of four (in radiance) to accommodate the requirements of the research and applications community measuring the properties of forest fires. The original specification required separate channels with comparable spectral properties but with widely differing dynamic ranges. The consequence of merging these two into one is to lose the increased infrared radiometric sensitivity that MODIS had over heritage instruments provided by 12-bit digitization compared to 10-bit.
- The digitizer design turned out to lead to unreliable representation of the least-significant bit (lsb) resulting in 'hairy histograms' of the digital counts in each channel. Again, the consequence is for compromise the radiometric sensitivity of the radiometry.

3.2 Pre-launch characterization

The complexity of MODIS demands exceptional efforts and diligence in the pre-launch calibration and characterization of the instrument. This must be done piece-wise with the best possible measurement being made on each critical component and sub-assembly, but also at the system level. To meet the ever increasing accuracy requirements of the climate community, the absolute radiometry of MODIS must be close to the 1:1000 level, which is very hard to achieve. The plethora of possible sources of systematic and random measurement uncertainties renders the post-launch resolution of measurement errors a near-impossible task without a confident understanding of how the instrument behaves, based on the pre-launch characterization. Many of the required tests and measurements are expensive in time and resources, and they occur at a time in the instrument development where both of these are at a premium. Requesting launch slippage to allow for more testing is not necessarily a persuasive argument. Nevertheless, having to disentangle the instrumental artifacts post-launch is also an expensive venture, not only in the time and effort involved, but also in the delay in releasing clean data to the user community. There may be additional costs and risks involved in under-taking special spacecraft maneuvers, with potential negative impact on the user communities of other sensors on the satellite.

3.3 MCST-type of organization is important

The importance of the role of the MODIS Characterization Support Team (MCST) cannot be over-emphasized. By acting as an intermediary between the members of the Science Team and the instrument designers, builders and testers, they facilitate the two-way flow of information, proving 'translation' services where needed. They

- monitor instrument development, and report back to the Science Team
- pre-digest test and calibration data to help Science Team understand the results
- respond to suggestions from the Science Team for possible changes in instrument design, testing or operation
- assist the Science Team in understanding the instrument. This is particularly important as the Science Team must understand how changes in instrument design, testing and calibration affect geophysical retrieval algorithms.

3.4 Good two-way communications

Good two-way channels of communication between all interested parties are important. Specifically, the Science Team needs to know of important decisions relating to instrument performance in a timely fashion, and needs to understand how and why these decisions were reached. The Science Team also needs to see that NASA HQ is listening to concerns and taking them seriously. Otherwise, why are they involved?

3.5 Involvement of the Scientific Community

There is a lot of expertise, and people willing to share it, in the broader scientific community. This should be drawn upon in all aspects of instrument specification, design requirements, testing and operation.

3.6 Launch delays can be very disruptive to validation planning

Some activities, such as scheduling ships for the initial validation, have long lead times, and since this involves shared resources, they may not be available when needed. NASA HQ should recognize that too short a post-launch validation period may be difficult to accommodate and this could lead to inadequate validation or unrealistic expectations not being met. Furthermore, uncertainties in launch delays, which are almost inevitable, can also compound these difficulties.

3.7 Discipline oriented groups generally work well

The organization of the MODIS Science Team into Discipline Groups, coming together at periodic Science Team Meetings or interacting in an ad hoc manner when necessary, worked well. Their experiences contributed to solution of problems, which is a positive factor. On the negative side, the lack of cross-discipline information flow can lead to different solutions to same problems (but this is not necessarily always bad)

3.8 Success is dependent on involving the correct mix of people

The success of MODIS is the result of many highly motivated, dedicated and talented people working in teams, often prepared to do extra tasks beyond scope of original proposal and contract. The existence and make-up of these teams, which are a valuable resource to help NASA meet its goals, can be put at risk by budget uncertainties, and poor strategic NASA or Congressional decisions.

4 PROJECT SUMMARY

The work done in this project is summarized under the following main headings:

4.1 Pre-launch analyses of instrument performance

Numerical simulations were undertaken to predict the performance of the MODIS in measuring SST. These included infrared atmospheric radiative transfer simulations to predict the population of brightness temperatures to be measured on orbit in the MODIS channels to be used for the SST retrievals (Bands 20, 22, 23, 31 and 32; see Figure 4 below). These simulated brightness temperatures were used both to derive the coefficients of the optimized retrieval algorithm (see 4.6 below) and also to predict the error characteristics of the retrieved SST fields. Additional studies were done to quantify the consequences of instrumental behavior on the SST retrievals by constructing a realistic error budget. As more of the instrumental behavior became known, as a result of pre-launch tests and characterization (see some examples given in 3.1 above), it became increasingly clear that there was a serious risk that the target accuracies could not be met. This led to a relaxation of the target accuracies from ±0.3K to 'no worse that heritage instruments' (specifically AVHRR). In reality, the accuracy of AVHRR Pathfinder SST measurements was subsequently found to be at the ±0.3K level (see 4.5 below), and the MODIS accuracies are now shown to be approaching this (see 5.4 below).

4.2 Develop high speed internet communications

The growth and impact of the World Wide Web for data transfer and information access has been so rapid and all-pervasive, it is easy to forget that the outset of this project it was largely unknown. The term "Information SuperHighway" had not yet been coined. During the early stages of this project, RSMAS was at the forefront of pioneering approaches for the transfer of large volumes of satellite data that would become necessary after the launch of *Terra*. Three primary networks, Ethernet, FDDI, and ATM were being used to move 100 GB input and 20 GB output. RSMAS enlisted the help of Oregon State University and the Naval Research Laboratory as nodes on this experimental Wide Area Network. This included the early adoption of ATM using DEC Gigaswitch and Fore ASX-100 switches. Heterogeneous computers, DEC 2100 & Alpha 3000 and SGI servers, were used as testbeds for processing data, and SONY optical juke boxes and DEC TL 820 tape library for near line storage. These developments were reported in the computer press in an article by Linda Nicastro in Network Computing, May 1995, which included a two page foldout diagram.

4.3 Develop validation plan

The MODIS-Infrared Sea Surface Temperature Algorithm, Science Data Validation Plan was developed. It discussed the need for, and requirements of, an extensive validation strategy to ensure confidence in the MODIS infrared measurements and derived SST fields. The approach included validation of top-of-the-atmosphere radiances, surface radiances and surface temperatures, using a variety of methods, instruments and platforms, including radiometers on other satellites, high-flying and low-flying aircraft, ships and research platforms. Both highly-focused, intensive measurement campaigns to study the physical processes at the ocean surface and in the atmosphere that influence the MODIS measurements, and long-term global-scale monitoring of the MODIS data were identified as being required. Synergism and collaboration with groups involved in the validation of MODIS ocean color and atmospheric properties derived from EOS instruments was recommended. With the exception of using aircraft, which were costly, this plan was followed though after the launches of the Terra and Aqua.

4.4 Develop validation instrumentation

It was recognized that new instrumentation would have to be developed to provide validation measurements for the MODIS SST fields. There were no instruments available with the required absolute radiometric accuracy that were sufficiently robust to be deployed for extended periods at sea from ships or fixed platforms. The RSMAS group entered into a collaboration with the Space Science and Engineering Center, University of Wisconsin-Madison, to develop a hardened, marine version of the Atmospheric Emitted Radiance Interferometer (AERI) that they had developed for field deployment in the Department of Energy's Atmospheric Radiation Measurements (ARM) program. This device, the Marine-AERI (M-AERI), would have to measure the skin SST of the ocean, using infrared radiometry to provide a like-with-like comparison with the MODIS measurements, be weatherproof, shock mounted, robust, and operate continuously under computer control with self-correction software to survive power supply interruptions. The software would also need to have real-time processing and quality checking capabilities, a capability to recognize rain and spray so that it could suspend measurements, put itself into a safe-hold mode, and resume normal operations when conditions improve, monitor the ships' pitch and role, and acquire and assimilate GPS signals to provide absolute time and accurate geolocation information for each set of measurements. The resultant device fulfilled all of these requirements and has become the benchmark against which other radiometers are measured (see5.3.1 below).

The M-AERI (Minnett et al. 2001) is a Fourier-Transform Infrared (FTIR) Spectro-radiometer that operates in the range of infrared wavelengths from ~3 to ~18μm and measures spectra with a resolution of ~0.5 cm^{-1}. It uses two infrared detectors to achieve this wide spectral range, and these are cooled to ~78^{o}K (close to the boiling point of liquid nitrogen) by a Stirling cycle mechanical cooler to reduce the noise equivalent temperature difference to levels well below 0.1K. The M-AERI includes two internal black-body cavities for accurate real-time calibration. A scan mirror, which is programmed to step through a pre-selected range of angles, directs the field of view from

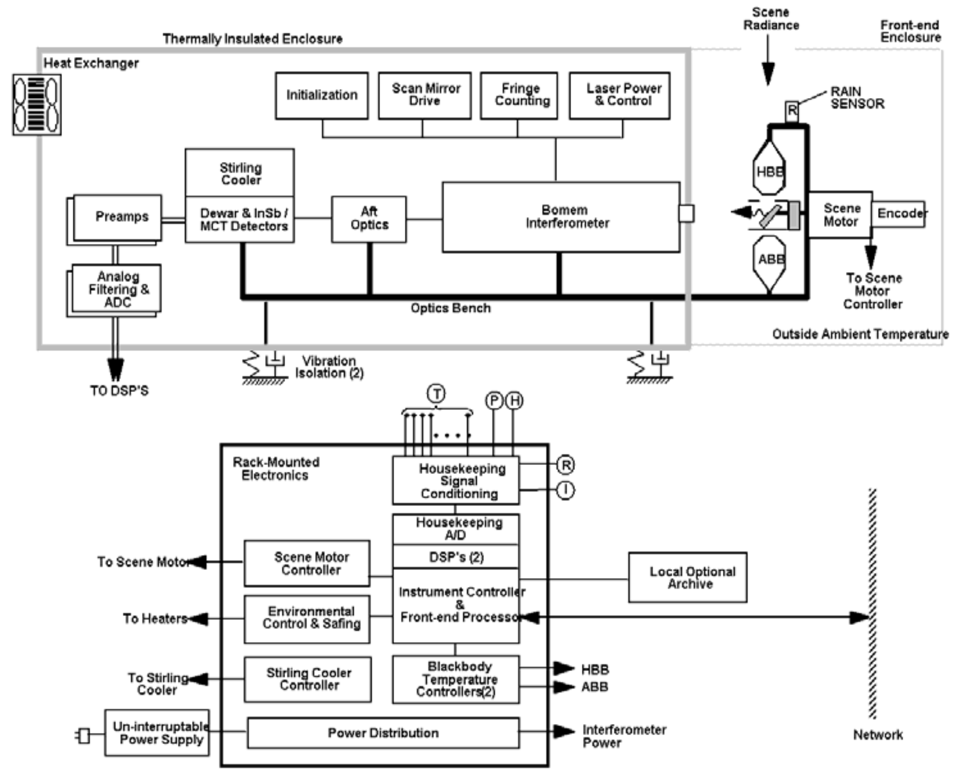


Figure 1. Schematic layout of the M-AERI system. (From Minnett et al, 2001.)

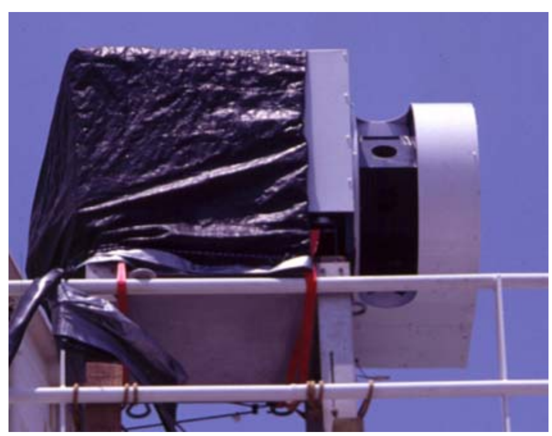


Figure 2. M-AERIs mounted on the Canadian Coast Guard icebreaker *Pierre Radisson* in the Arctic Ocean (left) and on the NOAA Ship *Ronald H. Brown* (right) in the tropical Atlantic Ocean..

the interferometer to either of the black-body calibration targets or to the environment from nadir to zenith. The sea-surface measurement also includes a small component of reflected sky radiance, so the derivation of the skin SST from the M-AERI spectra requires compensation of the reflected sky radiances that are part of the sea-viewing measurement, and of the emission from the atmosphere between the instrument and the sea surface (Smith et al. 1996, Minnett et al. 2001). The interferometer integrates measurements over a pre-selected time interval, usually a few tens of seconds, to obtain a satisfactory signal to noise ratio, and a typical cycle of measurements including two view angles to the atmosphere, one to the ocean, and calibration measurements, takes about five to ten minutes. The M-AERI is equipped with pitch and roll sensors so that the influence of the ship's motion on the measurements can be determined.

The absolute accuracy of the infrared spectra produced by the M-AERI is determined by the effectiveness of the black-body cavities as calibration targets. The absolute accuracy of the spectral measurements of the M-AERI is better than 0.03K (Minnett et al. 2001). The absolute uncertainties of the retrieved skin SST, determined by operating two M-AERI's side-by-side and by comparing M-AERI measurements with those from other well-calibrated radiometers, are less than 0.05K (Minnett et al. 2001; Barton et al. 2004), which are sufficiently small to give confidence in the use of such data in the validation of MODIS SST retrievals.

Three M-AERIs were constructed at SSEC for RSMAS and these have shown themselves to be very robust instruments capable deployment in hostile conditions, such as the extremes of the Arctic Ocean and the Red Sea, and able to maintain their absolute accuracy for months at a time. They have provided at-sea data on 2057 days between March 1996 and December 2003.

4.5 Demonstrate validation strategy

The validation strategy was tested prior to the launch of Terra on measurements form the AVHRR, the MODIS SST heritage instrument. Ocean skin temperature measurements from five of the early M-AERI cruises (Figure 3; see Table 2 for a full list of M-AERI cruises) spanning conditions from the Arctic to the Equatorial Pacific were compared to SSTs derived from AVHRR using the Miami Pathfinder algorithm (Kilpatrick et al. 2001).

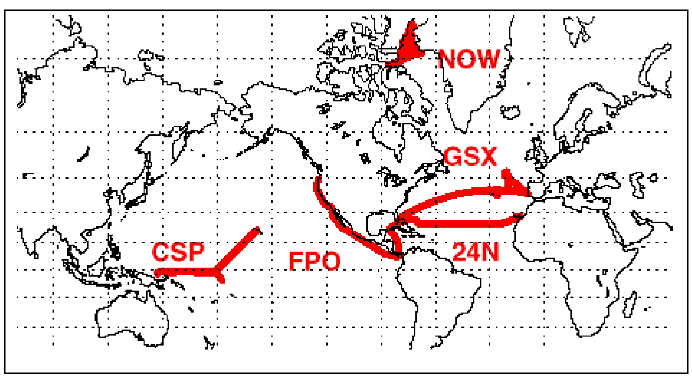


Figure 3. M-AERI cruises used in the AVHRR validation. From Kearns et al, 2000.

Matchups, which are collocated (within 4 km) and coincident (±40 min during the day; ±120 min at night) under cloud-free conditions were compared (Table 1). The average difference between the M-AERI and Pathfinder SSTs was found to be 0.06 ±0.29K from 254 matchups during the low- and mid-latitude cruises; inclusion of 176 more matchups from the Arctic produced an average global difference of 0.13 ±0.37K. The M-AERI to Pathfinder differences compare favorably with the average mid-latitude differences between the M-AERI skin SST and other bulk SST estimates commonly available for these cruises such as the research vessels' thermosalinograph SST (0.12 ±0.17K) and the weekly National Centers for Environmental Prediction optimally interpolated SST analysis (0.41 ±0.58K). While not representative of all possible oceanic and atmospheric regimes, the accuracy of the Pathfinder SST estimates in the conditions sampled by the five cruises is found to be at least twice as good as previously demonstrated. This demonstrated that previous attempts to validate the AVHRR SSTs were too pessimistic (rms of 0.5 - 0.7K; e.g. Strong and McClain 1984), and since they were done using subsurface sea temperatures, were attributing the effects of temperature variability in the uppermost few meters of the water column to uncertainties in radiometric calibration of the satellite measure-ments and to the atmospheric correction algorithm used to derive the SST. These results were published by Kearns et al. 2000.

Table 1. Statistics of the M-AERI to AVHRR Pathfinder comparisons.

Cruise	N	Mean ΔT K	St. Dev. ΔT K
CSP 1996	23	0.16	0.20
24N 1998	16	0.03	0.18
GASEX 1998	168	-0.01	0.25
FPO 1998	47	0.27	0.40
NOW 1998	176	0.24	0.44
Total	430	0.13	0.37
Total (excluding NOW 98)	254	0.06	0.29

4.6 At-launch atmospheric correction algorithm

The form of the MODIS atmospheric correction algorithm is based on that refined over many years, based on the so-called Non-Linear SST (Walton 1988), and modified in the AVHRR SST Pathfinder Project (Kilpatrick et al. 2001):

The algorithm using measurements in the 10-12µm atmospheric window, suitable for both daytime and night-time use, is:

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

where T_n are brightness temperatures measured in the channels at n µm wavelength, T_{sfc} is a 'first guess' estimate of the SST in the area, and z is the satellite zenith angle. The night-time algorithm, using two bands in the 4µm atmospheric window is:

$$SST4 = c_1 + c_2 * T_{3.9} + c_3 * (T_{3.9}-T_{4.0}) + c_4 * (\sec(z)-1) \qquad (2)$$

Note, the coefficients in each expression are different. Other variants of the algorithms are possible. There are two approaches for deriving the coefficients – numerical simulations of the brightness temperature measurements, and collocated and contemporaneous match-ups with in situ measurements. Clearly the second approach can be adopted only after launch, while the numerical simulations can be done prior to launch and be used to study the likely error characteristics of the retrievals.

The success of the numerical simulations depends on several factors and how faithfully these represent the true, environmental conditions. These include the knowledge of the spectroscopy of the atmospheric constituents that interact with the infrared radiation, the spatial and temporal distributions of these (especially water vapor); the atmospheric thermal state, including the air-sea temperature difference, and the surface conditions, specifically the angular and wind-seed dependence of the surface emissivity in the spectral intervals of interest. A very important factor is the completeness of the instrument model, specifically the noise characteristics of the detectors, the reflectivities (angular and spectral) of the optical surfaces, optical cross-talk, relative spectral response of the channels (including out-of-band response), the characteristics of the electronic components (e.g. digitization intervals, and preferences of the digitizers, electronic cross-talk, etc), scattered light sources and paths (which includes the temperature distributions and changes within the instrument and external sources), and the characteristics of the on-board calibration sources (black body calibration target(s), cold space view).

Prior to the launch of the *Terra* MODIS, sets of coefficients for the atmospheric correction algorithms were derived by numerical simulations of the brightness temperatures. The model selected is the line-by-line spectral code developed for the algorithm derivation for the ATSR (Závody et al. 1995), adapted to accommodate the latest version of the water-vapor continuum spectrum (Clough et al. 1989, subsequently revised by Han et al. 1997 and discussed in Merchant et al. 1999), using with improved spectra for atmospheric components from the AFGL data base, and with improved aerosol representation (d'Almeida et al. 1991). The model covers the spectral ranges of 3.5 to 4.2μm and 6.2 to 14.7μm. The input atmospheric profiles, 2790 in number, were derived from the output of the ECMWF data assimilation model at 10^{o} latitude-longitude resolution over the oceans for 12 realizations of the ECMWF model through 1996. Simulations were done for a range of satellite zenith angles, aerosol distributions and air-sea temperature differences. Examples of the simulated MODIS Bands for nadir measurements are shown in Figure 4.

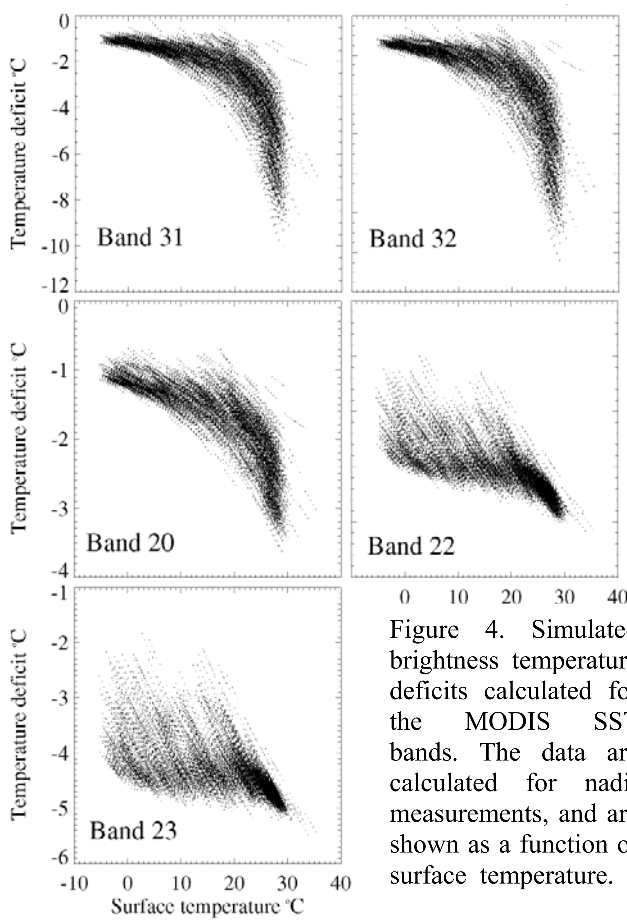


Figure 4. Simulated brightness temperature deficits calculated for the MODIS SST bands. The data are calculated for nadir measurements, and are shown as a function of surface temperature.

4.7 Rapid post-launch validation

Initial verification of the *Terra* MODIS SSTs by comparison with AVHRR SSTs revealed systematic differences that were greater than expected. This caused a reassessment of the approach of deriving the coefficients for the atmospheric correction algorithms, and comparison with AVHRR SSTs was identified as a useful approach that provided self-consistent fields that were comparable to the AVHRR Pathfinder SSTs already validated by comparison with M-AERI data (4.5 above; Kearns et al. 2000). Even now, the error characteristics of the *Terra* and *Aqua* MODIS SST fields derived using atmospheric correction algorithm coefficients obtained by radiative transfer modeling remain not quite as good as those derived using the matchups (Tables 7 and 8 below). This is presumably caused by the effects of unknown sources of uncertainty in the MODIS measurements that are compensated in the empirical, matchup approach.

The AVHRR Pathfinder SST data provided a natural bridge into MODIS with overlap of 3 of the 5 infrared bands. In fact the Pathfinder SST fields were used as an in situ reference SST field for generation of the first set of empirical retrieval equation coefficients and as a comparison and validation test data set that quantified the rvs anomaly in the thermal 10-12µm band and a seasonal/hemispheric bias in the mid-wave 4µm band SST's in the early MODIS Terra SST fields. Subsequent to various instrument tests conducted in conjunction with the MODIS Calibration and Support Team (MCST) that addressed improving calculation of at satellite brightness temperatures, the MODIS SST retrieval equation coefficients were re-derived using the match-up data base and bias corrected using the M-AERI skin temperature measurements. A combination of AVHRR and MODIS thermal SST fields were then used to enhance the mid-wave (SST4) 4µm retrieval equation which eliminated the previously seen seasonal and hemispheric bias. The experience gained through comparing *Terra* MODIS to AVHRR was then transferred directly to *Aqua* MODIS which led to the initial Aqua SST products being declared as valid.

4.8 Revise SST algorithms

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 15,000 matchups between Terra MODIS and buoys and, over 750 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. These coefficients have been derived for MODIS for Aqua and Terra and are used for MODIS SST production. The SST fields generated at both the 11µm and 4µm (night-time) atmospheric windows, have been declared 'validated.'

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

4.9 Sustained validation activities

A series of M-AERI SST validation cruises have been undertaken in the course of this project (Table 2; Figure 5). The reasons behind this sustained effort are twofold: firstly, to sample a wide range of atmospheric and oceanic conditions with a limited number of instruments (and personnel), and secondly, to provide a continuing reference for the uncertainty determination of the MODIS SSTs. The first is required to provide accuracy estimates in as many of the conditions as possible under which the MODIS SSTs are likely to be used in quantitative research in climate-related studies. The second is necessary because of the increasing realization that there are time dependences in the MODIS behavior that can adversely influence the accuracy of the SST retrievals.

Table 2. A summary of the M-AERI validation cruises completed during the performance period of this contract.

#	Project	Area	Ship	Departure		Arrival		Days of data
				Port	Date	Port	Date	
1	CSP1996	Combined Sensor Cruise	NOAA Ship Discoverer	Pago-Pago, Am. Samoa	19960314	Honolulu, HI	19960413	27
2	HiNZ1997	Hawaii-New Zealand Transit	R/V Roger Revelle	Honolulu, HI	19970928	Lyttleton, NZ	19971014	14
3	24N1998	OACES 24 N Section	NOAA S Ronald H. Brown	Miami, FL	19980108	Miami, FL	19980224	25
4	NOW1998	North Water	CCGS Pierre Radisson	Quebec City, Canada	19980316	Nanisivic, Canada	19980728	113
5	GASEX1998	OACES Gasex	NOAA S Ronald H. Brown	Miami, FL	19980502	Miami, FL	19980707	29
6	PANAMA 1998	Panama Transit	NOAA S Ronald H. Brown	Miami, FL	19980712	Newport, OR	19980727	15
7	PACS1998	Pan American Climate Studies	R/V Melville	San Diego, CA	19980908	San Diego, CA	19980929	22
8	SLIP1999	Western Pacific Transect, St. Lawrence Island Polynya	USCGS Polar Sea	Adelaide, Australia	19990301	Seattle, WA	19990511	56
9	NAURU 1999	Equatorial and Western Pacific	R/V Mirai	Yokohama, Japan	19990608	Sikenehama, Japan	19990720	16
10	NOW1999	North Water	CCGS Pierre Radisson	Resolute, Canada	19990824	Quebec City, Canada	19991010	43
11	MODIS1999	Eastern Pacific Gulf of California	R/V Melville	San Diego, CA	19991001	San Diego, CA	19991020	21
12	URANIA 1999	Mediterranean	R/V Urania	Messina, Sicily	19991019	Civitavechhia, Italy	19991109	21
13	EAT1999	Eastern Atlantic Transect	R/V Polarstern	Bermerhaven Germany	19991215	Cape Town, Africa	20000106	13
14	PSTAR2000	Pacific Transect	USCGC Polar Star	Melbourne, Australia	20000304	Seattle, WA	20000501	59
15	URANIA 2000	Gulf of Lions	R/V Urania	Naples, Italy	20000325	Naples, Italy	20000418	22
16	Arctic West, 2000	NE Pacific, Bering Strait, Beaufort Sea	USCGC Polar Star	Seattle, WA	20000727	Seattle, WA	20000921	53
17	PSEA 2000	Pacific Transect	USCGC Polar Sea	Seattle, WA	20001104	Sydney, Australia	20001201	5
18	Royal Caribbean	Caribbean Sea	Explorer of the Seas	Miami, FL	Every Saturday	Miami, FL	Every Saturday	1055 (to end of 2003)

19	GASEX 2001	In equatorial Pacific.	NOAA S Ronald H. Brown	Miami, FL	20010127	Honolulu, HI	20010308	38
20	PSTAR 2001	Pacific Transect	USCGC Polar Sea	Adelaide, Australia	20010309	Seattle, WA	20010501	40
21	ACE-Asia	North western Pacific	NOAA S Ronald H. Brown	Honolulu, HI	20010314	Dutch Harbor	20010503	42
22	Radiometer Workshop	Florida-Bahamas	R/V F.G. Walton-Smith	Miami, FL	20010530	Miami, FL	20010531	2
23	North American Monsoon Expt.	Western Caribbean	R/V Justo Sierra	Tuxpan, Mexico	20010706	Tuxpan, Mexico	20010726	20
24	EWING 01	Eastern Mediterranean, Gulf of Aden, Arabian Sea & across Indian Ocean.	R/V Ewing	Pireus, Greece	20010804	Fremantle, Australia	20011202	94
25	PSTAR 2002	E. Pacific	USCGC Polar Star	Valparaiso, Chile	20020319	Seattle, WA	20020414	22
26	CASES 2002	Arctic	CCGS Pierre Radisson	Resolute, Canada	20020923	Quebec City, Canada	20021018	26
27	URANIA 2002	W. Med	R/V Urania	Naples, Italy	20020929	Livorno, Italy	20021008	10
28	URANIA 2003	W. Med	R/V Urania	Naples, Italy	20030303	La Spezia, Italy	20030426	49
29	HEALY 2003	NE Pacific, Caribbean and NW Atlantic	USCGC Healy	Seattle	20030613	St. John's, Newfoundland, Canada	20030716	33
30	AURORA 2003	Southern Ocean, Australian sector.	RV Aurora Australis	Hobart, Tasmania, Australia	20030911	Hobart, Tasmania, Australia	20031029	49
31	CASES 2003 Leg 1	Canadian Arctic	CCGS Amundsen	Quebec City	20030921	Kugluktuk, NWT, Canada	20031013	23

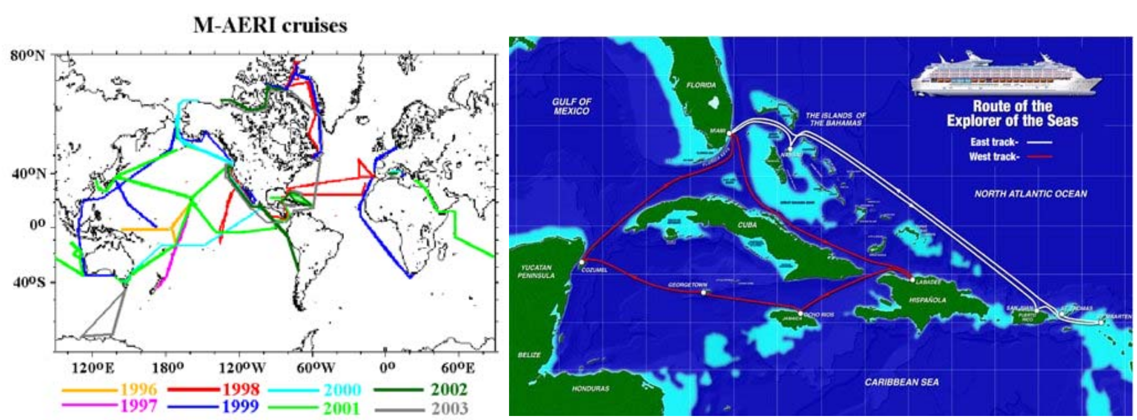


Figure 5. Approximate track-lines of M-AERI cruises undertaken during this project (left), and the repeating track of the Royal Caribbean Cruise Lines ship *Explorer of the Seas,* which completes two circuits starting and ending at the Port of Miami (shown as red and white) on alternate weeks. The *Explorer of the Seas* carries an M-AERI and many other meteorological and oceanographic sensors (See http://www.rsmas.miami.edu/rccl/facilities.html).

4.9.1 Explorer of the Seas

The '*Explorer of the Seas*' is a cruise liner operated by Royal Caribbean International that makes a weekly circuit out of the port of Miami, leaving each Saturday afternoon and returning the following Saturday morning. Since late November 2000 the cruise track has been in the eastern Caribbean. But beginning in spring 2002, a western Caribbean track is done on alternate weeks (Figure 5), Through close collaboration between RSMAS and Royal Caribbean International, the ship has been equipped as a ‘state-of-the-art’ oceanographic and meteorological research vessel (Williams et al. 2002). This involved dedicated laboratory space, with cableways and instrument mounts (including through-hull) being installed at the time of construction. An M-AERI is permanently installed on the ship (Figure 6), and has provided an impressive time-series of measurements (Figure 7) that have contributed to the MODIS SST validation.

Figure 6. The M-AERI on the *Explorer of the Seas.*

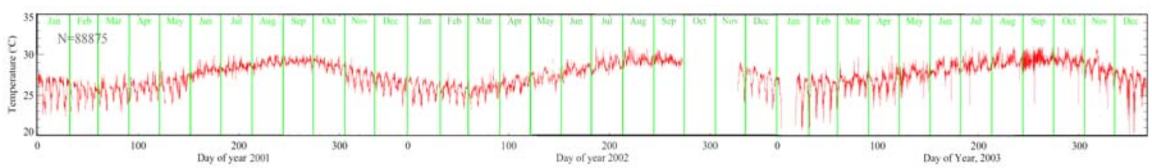


Figure 7. Time series of skin SST measured by the M-AERI on *Explorer of the Seas,* for the years 2001, 2002 and 2003. The gap in late 2002 was caused by instrument failure and in early 2003 by the ship being in dry dock.

5 MAIN TECHNICAL AND SCIENTIFIC RESULTS

5.1 Instrumental artifacts have been reduced to acceptable levels

The initial images derived from the first days of the Terra MODIS data were very exciting and gratifying, but closer analysis of the data over the following weeks reveals many signatures that were systematic of instrumental artifacts, resulting from the use of multiple detectors for each band (detector striping), the use of a two-sided scan mirror (mirror-side striping) and cross-swath effects of the mirror coatings (rvs effects). These artifacts have been corrected in the data from both Terra and Aqua MODIS, but only after a large post-launch investment in time and effort. This effort was led by Drs Robert Evans and Edward Kearns, who worked in close collaboration with members of the MODIS Characterization Support Team (MCST). Had this significant post-launch effort not been necessary, it would have been directed to scientific exploitation of the MODIS data.

5.2 Atmospheric correction algorithms

The atmospheric correction algorithm applied to the 11 and 12 µm measurements is based on the successful algorithms applied to the AVHRR data in the SST Pathfinder project (see 4.6 above, and Kilpatrick et al, 2001). The new bands in the mid-infrared window, which have not been used on earlier radiometers, required a new algorithm (see Eq 2 in 4.6 above). Because the atmosphere is more transmissive than in the thermal infrared, and the transmissivity is less variable, the algorithm is somewhat simpler than that used with the 11 and 12 µm measurements. The SST derived in the 4 µm wavelength atmospheric window, denoted SST4, is subject to significant contamination by reflected solar radiance during the daytime, so its use is limited to the night-time arc of each orbital revolution.

5.3 M-AERI

The development of the M-AERI (see 4.4 above and Minnett et al., 2001) as part of this project is a major success in that is has provided an instrument capable of providing measurements of unprecedented accuracy for the validation of skin SSTs derived from the measurements of MODIS, and other satellite radiometers, and of being used in studies of a range of processes at the ocean interface and in the intervening atmosphere that have a bearing on the SST measurement from space.

5.3.1 IR calibration workshops

The M-AERI was soon recognized by the wider community as the yard-stick again which all other instruments being used for the validation of satellite-derived SSTs should be compared. A mechanism for such a comparison is an international workshop attended by all with such radiometers and the accompanying black-body calibration targets, and by others with an interest in the physics of the measurement or in the outcomes of the comparisons.

The first inter-comparison of infrared radiometers was held at RSMAS during March 1998. This involved several high quality radiometers and some off-the-shelf devices. NIST provided their standard black body target (Fowler 1995) for calibration of each radiometer. Other black bodies available for calibration included a NIST water-bath black-body calibration target provided by the University of Washington, a smaller unit from JPL, the CASOTS black body (Donlon et al. 1999), and a portable unit designed by CSIRO, Australia. Details of the first calibration and inter-comparison can be found at http://www.rsmas.miami.edu/ir/, and Kannenberg 1998.

Following this, a second, more extensive calibration and inter-comparison workshop was conducted at RSMAS during May-June 2001. The aims included an assessment of the relative performance of each instrument as well as ensuring that surface measurements used in satellite product validation are traceable to SI standard units. The experimental campaigns were completed in one week and included laboratory measurements using NIST-certified black-body calibration targets (Fowler 1995), and an inter-comparison of the radiometers on a short cruise on board the R/V *F.G. Walton-Smith* in Gulf Stream waters close to Miami. The NIST EOS Transfer Radiometer (TXR; Rice and Johnson 1996; Rice et al. 2000) was used in the laboratory to characterize several different black

Table 3. Infrared radiometers that participated in the Workshop

Instrument	Institution	Lab.	Sea	P.I.
TXR (Transfer radiometer)	NIST, USA	Yes	No	J. Rice
M-AERI	RSMAS, U. Miami.	No	Yes	P. Minnett
SISTeR	RAL, UK.	Yes	Yes	T. Nightingale
DAR011	CSIRO, Australia.	Yes	Yes	I. Barton
CIRIMS	APL, U. Washington.	No	Yes	A. Jessup
ISAR-5	JRC, EEC.	Yes	Yes	C. Donlon
Nulling radiometers	NASA JPL	Yes	Yes	S. Hook
Tasco (off-the-shelf)	CSIRO, Australia	Yes	Yes	I. Barton

Table 4. Black bodies used for laboratory calibration.

Instrument	Institution	P.I.
NIST-Certified & Designed Black Body Target	RSMAS, U. Miami	P. Minnett
NIST Standard Black Body Target	NIST, USA	C. Johnston
CASOTS black body	JRC, EEC	C. Donlon
Hart Scientific Portable Black Body Target	APL, U. Washington	A. Jessup
JPL Black Body Calibrator	NASA-JPL	S. Hook

Figure 8. The RSMAS Water Bath Black Body Calibration Target being characterized by the NIST TXR (left), and being used to calibrate the DAR011 radiometer (right)

Table 5. Results of the characterization by the NIST TXR of the three Black-Body Calibration Targets. (After Rice et al. 2004)

Quantity	**RSMAS BB**	**JPL BB**	**CASOTS RAL BB**
ε_{BBX}	1.0000	0.9916	0.9905
ε_{BBX} fitting uncertainty	0.0007	0.0008	0.0006
Intercept (W cm^{-2} sr^{-1})	-1.9×10^{-7}	-8.96×10^{-6}	-1.047×10^{-5}
Intercept fitting uncertainty (W cm^{-2} sr^{-1})	8×10^{-7}	9.4×10^{-7}	7.2×10^{-7}

Figure 9. The infrared radiometers mounted on the upper deck of the R/V *Walton Smith*. From the left, when seen from below, these are SISTeR, ISAR, CIRIMS, M-AERI, DAR011, and the hand-held TASCO. The JPL radiometer was mounted on the fore-deck, viewed the sea between the two hulls of the *Walton Smith*, and is not visible in these photographs.

Table 6. Means and standard deviations of the estimated skin SST differences between pairs of radiometers for the entire cruise period. After Barton et al. 2004.

Radiometer Pair	Mean (K)	Std.Dev (K)	N
MAERI-ISAR	0.002	0.135	80
MAERI-SISTeR	0.046	0.066	144
MAERI-JPL	0.007	0.114	148
MAERI-DAR011	-0.008	0.076	149
ISAR-SISTeR	0.038	0.101	79
ISAR-JPL	0.026	0.142	81
ISAR-DAR011	0.007	0.114	80
SISTeR-JPL	-0.048	0.099	144
SISTeR-DAR011	-0.053	0.074	144
JPL-DAR011	-0.014	0.103	148

body calibrators. The Workshop attracted 20 researchers from around the world, and six types of shipboard radiometers, in addition to the M-AERI took part (Tables 3 and 4). Five types of laboratory or field black-body calibration targets were used. The results of these exercises show that these radiometers are sufficiently well calibrated and stable that .they can be deployed independently yet have their measurements combined to supply merged data sets for satellite validation. (Barton et al. 2004; Rice et al. 2004).

5.4 Residual uncertainties in MODIS SSTs

The MODIS SST fields were amongst the first of the Terra and Aqua products to be released to the community as validated retrievals. The MODIS skin temperature retrievals have been validated using ocean skin temperatures measured radiometrically using the Marine – Atmospheric Emitted Radiance Interferometer (M-AERI; see 4.4 above; Smith et al. 1996; Minnett et al. 2001), which is the source of the skin temperature data discussed here, those used by Kearns et al. (2000) to validate the AVHRR Pathfinder SSTs, and those used to investigate the accuracy of the SSTs retrieved by the TRMM VIRS (Minnett 2002). Since the launch of *Terra*, M-AERIs have been deployed on many cruises which cover a wide range of environmental conditions from the Arctic to the Equatorial Pacific Ocean (Figure 5, Table 2). In addition, an M-AERI is permanently installed on the *Explorer of the Seas*, a cruise liner that plies the Caribbean.

Table 7. *Aqua* MODIS SST Buoy & M-AERI Retrieval Statistics.

	Buoy + M-AERI			**Buoy (bulk)**			**M-AERI (skin)**		
	ΔT	ΔT′	n	ΔT	ΔT′	n	ΔT	ΔT′	n
SST (day +night)	-0.053	0.492	14768	-0.054	0.494	14443	-0.034	0.402	325
SST (night)	-0.095	0.451	6557	-0.094	0.454	6381	-0.103	0.370	176
SST (day)	-0.020	0.520	8211	-0.021	0.522	8062	0.048	0.425	149
SST4 (night)	-0.106	0.395	5412	-0.107	0.397	5258	-0.074	0.341	154

Table 8. *Terra* MODIS SST Buoy & M-AERI Retrieval Statistics

	Buoy + M-AERI			**Buoy (bulk)**			**M-AERI (skin)**		
	ΔT	ΔT′	n	ΔT	ΔT′	n	ΔT	ΔT′	n
SST (day +night)	-0.140	0.478	15801	-0.104	0.478	15412	-0.022	0.448	759
SST (night)	-0.081	0.433	6648	-0.081	0.432	6392	-0.062	0.412	457
SST (day)	-0.182	0.504	9153	-0.182	0.503	9020	0.039	0.491	302
SST4 (night)	-0.124	0.370	6222	-0.131	0.370	6001	-0.029	0.363	404

Although the M-AERIs, of which there are only three, provide very accurate skin SSTs, they are too few to provide a convincing validation and so use must be made of the very large data set derived from the array of moored and drifting buoys, as in the Pathfinder project (Kilpatrick et al. 2001). By using night-time comparisons the contributions to the error budget by the diurnal thermocline (see 5.7 below) can be avoided, and the reasonably tight night-time skin-bulk temperature relationship can be exploited. Even though a degradation of the statistics describing the uncertainties ensue (Kearns et al. 2000), the more complete sampling of the range of environmental parameters produces a very valuable data set to study the uncertainty characteristics for the MODIS SST retrievals.

The current residual error estimates for the *Terra* MODIS in Table 8 indicate values that are somewhat larger than earlier ones based on a smaller sample size (Brown et al. 2002). This is to be expected as more of the atmospheric and oceanic variability, the parameter-space of the retrieval, is included in the statistics. This underscores the potential for improving the error characteristics of the retrieved SSTs by developing more robust algorithms that are more capable of accommodating the wide range of global variability. It is noteworthy that the 4µm SSTs for both *Terra* and *Aqua* MODISs (Tables 7 and 8) show smaller residual RMS errors than the 11-12µm SST, demonstrating the smaller sensitivity of the shorter wavelength retrievals to the variability of the clear atmosphere. The residual errors against the M-AERI measurements are smaller than against the buoy temperatures, for both SST products. This is in accordance with the earlier results for AVHRR (Kearns et al. 2000) and highlights the benefits of using radiometrically-determined skin temperature measurements for MODIS SST validation.

5.5 Emissivity dependences

The wind speed dependence of the sea-surface emissivity can be derived from the M-AERI spectral measurements of oceanic and atmospheric infrared emission. Prior results, based on modeling studies (Masuda et al. 1988; Watts et al. 1996 showed a marked

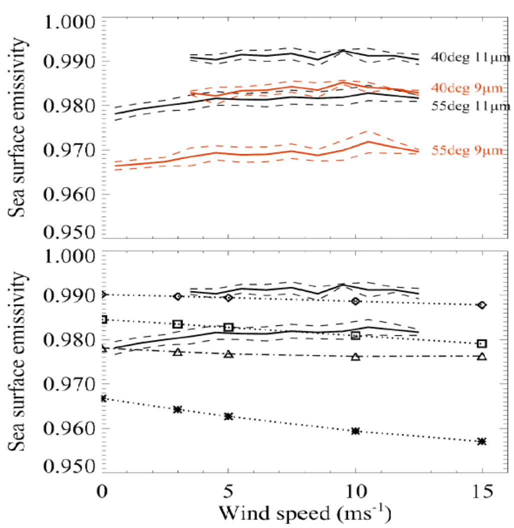


Figure 10. Observed mean (solid lines) and standard deviation (dashed lines) of sea surface emissivity in 1ms^{-1} wind speed bins for 9µm and 11µm at 40° and 55° incidence angles (top). Below, the solid lines are the measured 11µm emissivity for the 40° and 55° views, the dashed line with triangular markers represents values predicted by Watts et al. 1996 for 55° at 11µm (the coefficients given in that paper are valid for 52°-55° viewing angle). The dotted lines are those predicted by Masuda et al. 1988 for 40° (diamonds), 50° (squares) and 60° (asterisks). From: J.A. Hanafin, Ph.D. Thesis, University of Miami, 2002, and Hanafin and Minnett 2004.

dependence of the emissivity on wind speed, but such a dependence is largely absent in the at-sea measurements (Figure 10). This indicates that the contribution to the error budget of validation of the satellite-derived SST has a smaller contribution to uncertainties in the surface wind speed, or surface roughness, is smaller than previously thought. Simulations using the Masuda *et al.* (1988) or Watts *et al.* (1996) dependences may be introducing a systematic wind-speed and zenith angle error.

5.6 Differences between the skin-bulk SSTs

The difference between the skin SST, which is the source of the signal eventually detected by infrared radiometers on spacecraft, and the bulk SST, measured using conventional thermometers at a depth of a meter or more, has been a cause for concern for many years. This concern is both for validating the satellite-derived SSTs (more closely related to the skin temperature) and for applications of satellite-derived SSTs, such as numerical weather forecasting, in which the models have been developed for sub-surface bulk SSTs. It is only with the development of reliable, well-calibrated, ship-borne radiometers, such as the M-AERI and those that participated in the Miami Infrared Radiometer Workshops (see 5.3.1 above) that data of sufficient quality to study the skin-effect has become feasible. What has been found is that the skin-bulk temperature difference is much less variable than previously believed. The M-AERI, night-time data have shown that the skin-bulk temperature differences show only a slight wind-speed dependence and very little dependence on the net heat flux. This lack of heat-flux dependence may be a reflection on the residual uncertain-ties in the heat fluxes calculated from the ship data. The slight wind-speed dependency has been corroborated in data sets taken with some if the radiometers from the Miami Infrared Radiometer Workshop. Figure 11 shows a compilation of the night-time skin effect from many research cruises using a range of ship-based radiometers.

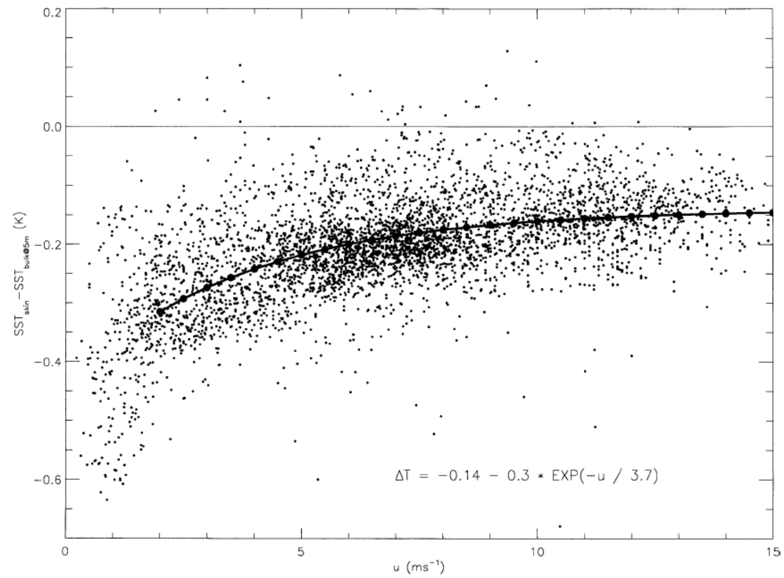


Figure 11. Wind speed dependency of the skin-bulk SST difference. From Donlon et al. 2002.

5.7 Diurnal effects

A major effect in combining SST measurements taken from different satellites with different overpass times is the development, and subsequent decay, of the diurnal thermocline. This results from the absorption of solar radiation in the uppermost few meters of the ocean under conditions of low wind speed. At higher winds, the absorbed energy is mixed by turbulence throughout the deeper ocean surface mixed layer, resulting in a much smaller diurnal range in the skin SST. The deployment of M-AERIs on many research cruises has permitted accurate measurements of the diurnal heating to be made in a wide range of wind speed conditions, and to separate the diurnal from skin layer effects. Under low winds, the amplitude of the diurnal heating can be several degrees, as can be seen in Figure 12, which reveals the dependencies of diurnal heating on surface winds speed, and time of day. As the wind speed increases, the magnitude of the peak temperature decreases, and it occurs later in the afternoon (Minnett 2003).

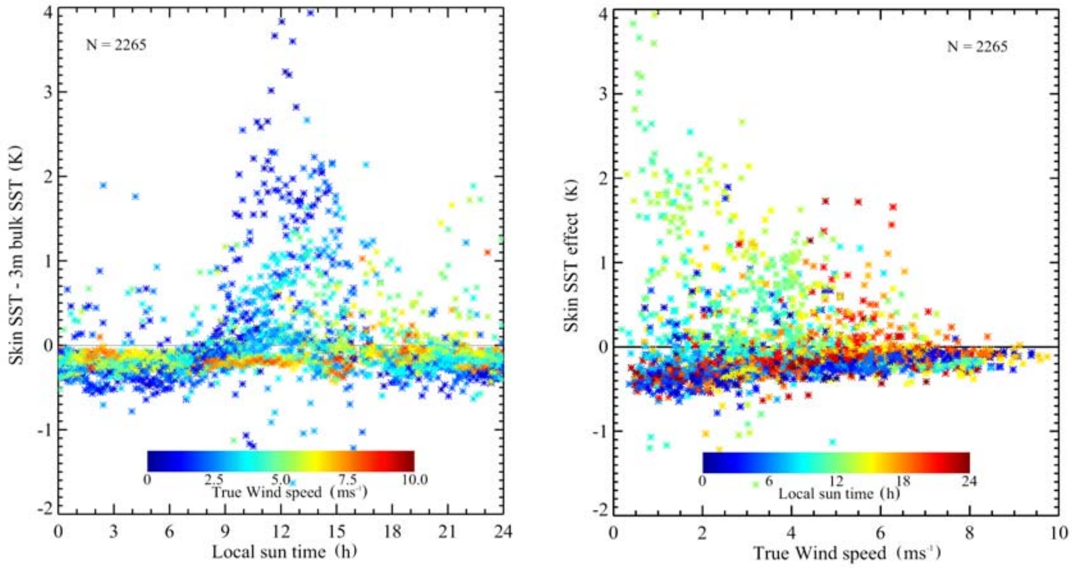


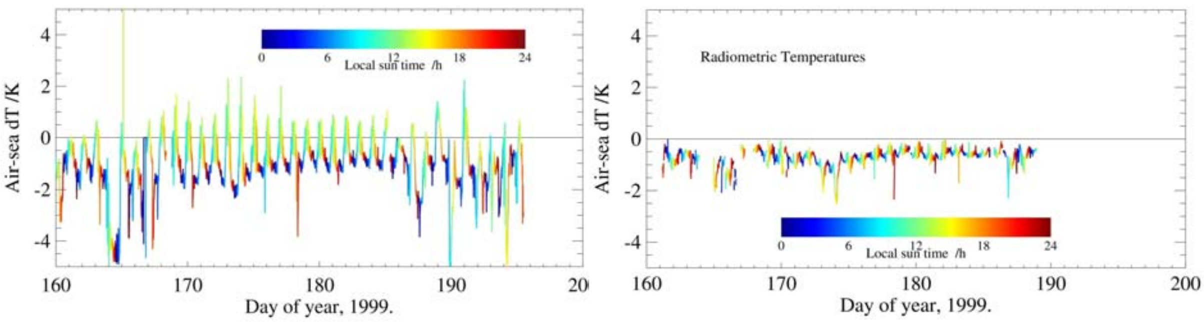
Figure 12. The dependences of the diurnal heating, and surface skin effect, on wind speed and time of day. The same data are plotted on different ordinates in each panel, and were taken during the MOCE-5 cruise of the R/V Melville in the Eastern Pacific Ocean and Gulf of California in October 1999. From Minnett, 2003.

5.8 Air-sea temperature differences

In addition to measurements of the skin SST, M-AERI can be used to make very accurate measurement of the air temperature, at about the height of the instrument (Minnett et al. 2004). When mounted on ships, this provides an accurate measurement of the air-sea temperature difference. Unlike conventional measurements, taken with thermometers in the air and below the water surface, which are susceptible to large errors resulting form a small temperature difference being measured by two sensors with different calibration histories and in two fluids with very different thermal capacity, the radiometric measurement is taken by a single instrument with a single calibration.

The temperature difference between the ocean and the overlying atmospheric boundary layer is an important controlling parameter in the fluxes of heat and gases between the ocean and atmosphere, which are important factors in understanding the climate, and other phenomena and processes, such as marine cloud formation, and their responses to changes in climate. Furthermore the air-sea temperature difference helps to determine the stability of the lower atmospheric boundary layer, and this controls the efficiency of ocean atmosphere coupling, including momentum fluxes.

Analysis of the M-AERI air-sea temperature difference measurements has demonstrated that in the open ocean, the values are much smaller than indicated by the conventional measurements. In particular, the change in sign of the air-sea temperature differences that is found in conventional measurements, especially in the tropics, is absent in the radiometric data. This is illustrated in Figure 13 where measurements taken from the R/V *Mirai* in the Equatorial Pacific Ocean from 6 June to 7 July, 1999. The radiometric measurements of air-sea temperature differences are generally <2K. Air is nearly always cooler than the ocean, with some diurnal fluctuations, especially in clear sky conditions.



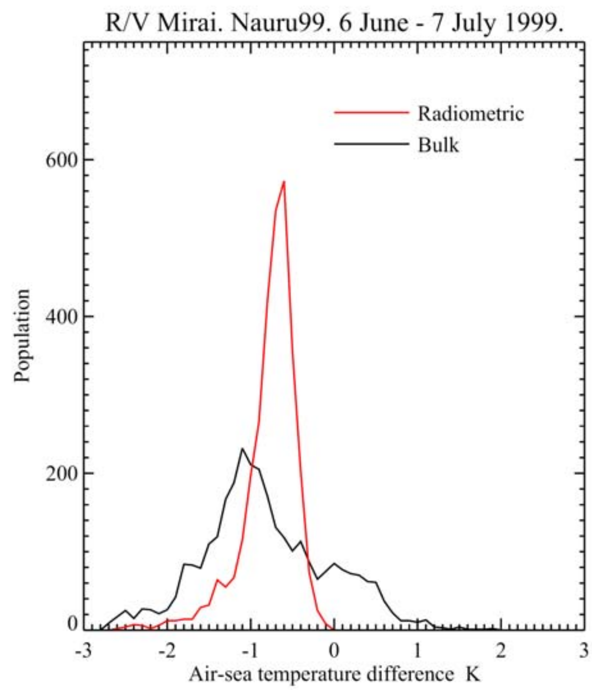


Figure 13. Air sea temperature differences (dT) measured by conventional sensors on the R/V Mirai (top left) and by the M-AERI (top right). The conventional measurements show a strong diurnal signal that is largely absent in the radiometric data. In particular, the reversal in sign found each afternoon in the conventional measurements is absent from the radiometric measurements. The data are shown as histograms (right). Remarkably, the means values are very similar, being -0.772K for the conventional measurements, and -0.721K for the radiometric data, but the standard deviation of the population is much smaller for the radiometric measurements, 0.112K, compared to the conventional ones (0.566K).

These measurements are removed from ship's influence. Significant disparities exist between air-sea temperature differences when measured radiometrically or using traditional bulk sensors. The strong diurnal signal in bulk data, with a change in sign during the afternoon, is absent in the radiometric data. This is mostly due to contamination of the bulk measurements by direct radiative heating of the air thermometer and/or heat-island effects of the ship, and a smaller contribution from failure to sample oceanic diurnal thermocline.

6 FUTURE REQUIREMENTS

To maintain the "validated" status of the MODIS SST fields, it will be necessary to continue an active validation campaign throughout the Aqua and Terra missions. This is because of the time-dependent nature of the instrumental artifacts inserted into the measurements. The validation campaigns should continue to be based on M-AERI and other radiometer measurements, and the much larger data sets provided by the network of drifting buoys. This is necessary for the continued success of the MODIS SST mission.

The data available for SST validation are also useful for algorithm improvements and the MODIS Team should continue to maintain the mechanism for implementing enhanced algorithms to improve the accuracy of the SST fields available to the community. This is most likely to be the case for the SST4 (4µm) SST, which is still essentially an experimental retrieval.
The current requirements for SST fields derived from satellite measurements are summarized in the Strategy and Implementation Plan of the Global Ocean Data Assimilation Experiment (GODAE) High Resolution Sea Surface Temperature Pilot Project (GHRSST-PP). These include estimates of uncertainty for each pixel as well as the absolute SST value.

Looking to the future, the absolute accuracy requirements of the SSTs requested of the user community is certainly going to become more stringent, and already the figure of ±0.1K has been raised in discussions. This goal is beyond current capabilities, but the unprecedented spectral selection of MODIS renders these measurements the best available to explore the strategies for achieving this target uncertainty in future radiometers.

Much of the infrastructure established for the MODIS SST project is directly applicable to the VIIRS on NPP and NPOESS missions. In particular the "lessons learned" should be of relevance to the VIIRS Team. Even though the optical and electronic designs are different, many of problems are solutions encountered in the MODIS development are likely to be duplicated in VIIRS, in concept even if not in exact detail.

7 PUBLICATIONS

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Hanafin, J.A. and P.J. Minnett. Measurements of the infrared emissivity of a wind-roughened sea surface. *Applied Optics.* Submitted..

Minnett, P.J., Infrared interferometric measurements of the air-sea temperature difference. In preparation.

Minnett, P.J., K. Maillet and B. J. Osborne. The temperature of the air in the marine atmospheric boundary layer – measurements using Fourier Transform Infrared Interferometers. In preparation.

7.4 Conference Proceedings

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Barton I.J., and P.J. Minnett, 2001. The Second International Infrared Radiometer Calibration and Intercomparison. Report to the 15th CEOS Plenary Kyoto, Japan, November 6-7, 2001. 16pp.

Minnett, P.J., and B. Ward, Measurements of near-surface ocean temperature variability - Consequences on the validation of AATSR on Envisat. In Proceedings of ERS - ENVISAT Symposium "Looking down to Earth in the New Millennium", European Space Agency. Gothenburg, Sweden, 2000, SP-461. 10pp. Available as CD-ROM from ESA Publications Division, ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands.

Evans, R.H., P.J. Minnett. O.B. Brown, K. Kilpatrick, E.J. Kearns, H. Gordon, K. Voss and M. Abbott. Early Results from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS): Global and Arabian Sea Regional Ocean Color and Thermal Observations. Proceedings of the 5th Pacific Ocean Remote Sensing Conference (PORSEC2000) 5-8 December 2000, Goa, India, Vol, 1, p5.

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Minnett, P.J. and R.O. Knuteson, 1998. Measurements of the Skin Effect and Diurnal Thermocline in the Tropical Western Pacific Ocean. Proceedings of the Seventh Atmospheric Radiation Measurement Science Team Meeting, March 3-7, 1997. US Department of Energy, Office of Energy Research, Environmental Sciences Division. Washington D.C. CONF-970365. January 1998. pp. 289-291.

Knuteson, R.O., F.A. Best, H.B. Howell, P. Minnett, H.E. Revercomb, and W.L. Smith., 1997. High Spectral Resolution Infrared Observations at the Ocean-Atmosphere Interface in the Tropical Western Pacific using a Marine Atmospheric Emitted Radiance Interferometer (MAERI): Applications to SST Validation and Atmospheric Spectroscopy. Proceedings of the Ninth Conference on Atmospheric Radiation, 2-7 February 1997, Long Beach, CA. American Meteorological Soc. Boston, MA. USA.

Smith, W.L., W. Feltz, H.B. Howell, R.O. Knuteson, W.P. Menzel, N.Nalli, H.E. Revercombe, O. Brown, J. Brown, P.J. Minnett and W. McKeown, 1996. Observations of the infrared radiative properties of the ocean - implications for the measurement of sea-surface temperature via satellite remote sensing. Proceedings of the Eighth Conference on Satellite Meteorology and Oceanography. Jan 28 - Feb 2, 1996. Atlanta, Georgia. American Meteorological Soc. Boston, MA. USA. pp 531-535.

8 PRESENTATIONS

8.1 Invited Presentations

Brown, O.B. Ocean Research and Space Systems - Satellite Oceanography: New Challenges. *Marine Technical Society Meeting*, September 26-28 1990.

Brown, O.B. Satellite-Derived Global Sea Surface Temperature Fields: 1982-1989. *OPSAT '90 (Operational Satellites: Sentinels for the Monitoring of Climate and Global Change) Conference*, Washington DC, October 16-19, 1990.

Brown, O.B. Infrared Remote Sensing and AVHRR IR Calibration. NASA/GISS 1991.

Minnett, P.J., Infrared interferometric measurements of the ocean skin temperature. *CASOTS Workshop, Joint Research Centre, Ispra, Italy, 1997.*

Minnett, P.J., R.O. Knuteson and O.B. Brown.. Measurements of near-surface vertical temperature gradients in the Tropical Pacific Ocean. *Fall Meeting of the American Geophysical Union, San Francisco, USA, 1997.*

Minnett, P.J. and J. Hanafin. At-sea measurements of the ocean skin temperature and its response to surface fluxes. 1998. IEEE International Geosciences and Remote Sensing Symposium. Seattle USA May, 1998.

Minnett, P.J., O. B. Brown, R. J. Sikorski, A. Kumar. K. Kilpatrick and A. M. Závody. MODIS SST retrievals – algorithm derivation, error budget and plans for validation. *MODIS Science Team Meeting*, College Park, MD. December 15, 1998.

Minnett, P.J., Applications of infrared hyperspectral measurements made from ships. Institute of Atmospheric Physics, Rome, Italy, June 1999.

Minnett, P.J., J. A. Hanafin and E. J. Kearns. Infrared interferometric measurements of the ocean thermal skin temperature. *IEEE International Geosciences and Remote Sensing Symposium*. Hamburg, Germany. June, 1999.

Evans, R. H., C. Moulin, P. J. Minnett, H. Gordon and V. Banzon. Combined use of visible and infrared channels to identify and correct African dust aerosols. Remote Sensing of the Ocean and Sea Ice, *EOS/SPIE Symposium on Remote Sensing*. Florence, Italy, 23 September, 1999.

Minnett P.J. and R. H. Evans. Comparison of Satellite Retrieved Sea Surface Temperature with the Marine Atmospheric Emitted Radiance Interferometer. *MUBEX Workshop*, Kyoto, Japan. November 1999.

Esaias, W., M. Abbott, J. Campbell, K. Carder, O. Brown, D. Clark, R. Evans, F. Hoge, H. Gordon, P. Minnett. Early MODIS Ocean Data Results. *Spring Meeting of the American Geophysical Union*. Washington, DC. May 30-June 3, 2000.

E. J. Kearns, R. H. Evans, P. J. Minnett, O. B.Brown, K. Kilpatrick, S. Walsh, W. Baringer, J. Brown, and R. Sikorski. New SST and Ocean Color Data from MODIS/Terra: Caveat Emptor? NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL, June 2, 2000.

Brown, O.B., P. J. Minnett, R. H. Evans, E. J. Kearns, and R. J. Sikorski. MODIS Sea-surface temperature. *MODIS Science Team Meeting*, College Park, MD. June 7-8, 2000.

Minnett, P.J. Applications of ship-board infrared interferometry. Department of Atmospheric, Oceanic and Planetary Sciences, University of Oxford, UK. July 5, 2000.

Minnett, P.J. Applications of ship-board infrared interferometry to the validation of the AATSR. Department Space Science, University of Leicester, UK, July 6, 2000.

Minnett, P.J. The Advanced Very High Resolution Radiometer - Two Decades of Applications in Oceanography. *Oceans from Space - Venice 2000.*. Venice, Italy. 9-13 October, 2000

Evans, R. H. and P. J. Minnett. Overview of MODIS Thermal Ocean Observations. *Oceans from Space - Venice 2000.*. Venice, Italy. 9-13 October, 2000

Minnett, P.J., R. H. Evans and O.B. Brown. Prospects for Improved Sea-surface temperatures from MODIS – Superior Accuracy and Refined Applications. *MODIS Science Team Meeting*. Columbia MD, January 24-26, 2001

Evans, R. H., P. J. Minnett, O.B. Brown, H.R. Gordon, K. Kilpatrick and E.Kearns. Results from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS): Global and Arabian Sea Regional Ocean Color and Thermal Observations. *MODIS Science Team Meeting.* Columbia MD, January 24-26, 2001

Brown, O.B., P. J. Minnett, R.H. Evans and E. J. Kearns. Satellite Earth Remote Sensing: The Earth Observing System and the Next Decade. *Oceanology International Americas* 2001, Miami, FL, April 3-5 2001

Minnett, P.J. Cloud masking for MODIS Ocean Color and Sea-Surface Temperature Retrievals. *MODIS Cloud Mask Workshop*, Madison WI, May 8 & 9, 2001

Minnett, P.J Measurements of the Ocean Surface Skin Temperature from the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI). *IEEE International Geosciences and Remote Sensing Symposium*. Sydney, Australia. July 9-13, 2001.

Brown O. B., P. J. Minnett, R. H. Evans and E. J. Kearns. Sea Surface Temperature. *MODIS Ocean Team Meeting*. Baltimore, 17 December, 2001

Brown, O. B., P. J. Minnett, R. H. Evans, E. J. Kearns, V. Banzon, W. Baringer, J. Brown, J. Hanafin, E. Key, K. Kilpatrick, A. Kumar, K. Maillet, M. Szczodrak and S. Walsh. Sea Surface Temperature - MOD 28 Status. *MODIS Science Team Meeting*, Baltimore, 18 December, 2001

Minnett, P.J., Validation of AATSR sea-surface temperatures. *AATSR Commissioning Phase Readiness Review*. Space Research Centre, University of Leicester, UK. 28 January 2002

Minnett, P.J., Use of satellite data to investigate the ocean skin temperature. Department of Physics and Astronomy, University of Leicester, UK. 29 January 2002

Minnett, P.J. Recent results for the Marine-AERI. Department of Atmospheric and Oceanic Sciences, University of Wisconsin – Madison. April 1, 2002.

Minnett, P.J. Spectroradiometric measurements of the sea-surface temperature and air-sea temperature difference. Coastal Studies Seminar, Division of Applied Marine Physics, RSMAS, University of Miami. 23 May, 2002.

Minnett, P.J. Sea-surface temperature - experience gained from MODIS. VIIRS Operational Algorithm Team Meeting, NOAA Science Center, Camp Springs, MD. 7 June 2002.

Minnett, P.J. NPOESS/NPP VIIRS Ocean Measurements: Sea-Surface Temperature. NPOESS Workshop, June 23, 2002, Toronto, Canada.

Minnett, P.J., R.H. Evans, E.J. Kearns and O.B. Brown. Sea-surface temperature measured by the Moderate Resolution Imaging Spectroradiometer (MODIS). *IEEE International Geosciences and Remote Sensing Symposium.* Toronto, Canada. June 24-28, 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 K. 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. 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.

Minnett, P.J. Shipboard measurements for AIRS validation. AIRS Science Team Meeting, Camp Springs, 25–27 February 2003.

Gentemann, C. F. Wentz, P.J. Minnett and C. Donlon. Microwave SST validation and microwave/infrared blending status. CEOS Meeting. Tokyo, Japan. March, 2003.

Minnett, P.J., R. H. Evans, E. J. Kearns, K. Kilpatrick, A. Kumar, W. Baringer, O. B. Brown and W. Esaias. AQUA MODIS Sea Surface Temperatures. Aqua Science Working Group Meeting, NASA Goddard Space Flight Center, Greenbelt, MD, May 28, 2003.

Minnett, P.J., R. H. Evans and K. Kilpatrick. MODIS Oceans Cloud Identification. Aqua Science Working Group Meeting, NASA Goddard Space Flight Center, Greenbelt, MD, May 29, 2003.

Minnett, P.J. Radiometric measurements of air-sea and air-ice temperature differences in the Arctic. IEEE International Geoscience and Remote Sensing Symposium (IGARSS'03), July 21-25, 2003, Toulouse, France.

Minnett, P.J. Remote Sensing of Sea-Surface Temperature: Techniques and Accuracies. 2003 Tyrrhenian International Workshop on Remote Sensing. September 15-18, 2003, Elba, Italy.

8.2 Contributed Presentations

Brown, O.B. Role of Satellite Observations in Global Change. Oceans From Space meeting, Scuola Grande San Giovanni Evangelista, Venice, Italy, May 22-26.

Smith, W.L.,W. Feltz, H.B. Howell, R.O. Knuteson, W.P. Menzel, N.Nalli, H.E. Revercombe, P. J. Minnett, O. Brown, J. Brown, and W. McKeown. Observations of the infrared radiative properties of the ocean - implications for the measurement of sea-surface temperature via satellite remote sensing. Eighth Conference on Satellite Meteorology and Oceanography. Jan 28 - Feb 2, 1996. Atlanta, Georgia.

Knuteson, R.O., P.J. Minnett, F.A. Best, H.B. Howell, H.E. Revercomb, and W.L. Smith, High Spectral Resolution Infrared Observations at the Ocean-Atmosphere Interface in the Tropical Western Pacific using a Marine Atmospheric Emitted Radiance Interferometer (MAERI): Applications to SST Validation and Atmospheric Spectroscopy. Ninth Conference on Atmospheric Radiation, February 1997, Long Beach, CA.

Minnett, P.J. and R.O. Knuteson. Measurements of the skin effect and diurnal thermocline in the Tropical Western Pacific Ocean. Seventh ARM Science Team Meeting, San Antonio, TX, 3-7 March 1997.

Minnett, P.J. and O.B. Brown. MODIS scan mirror issues and SST. EOS PM-1 Spacecraft maneuver meeting. NASA Goddard Space Flight Center, Greenbelt MD, May 1997.

Evans R.H. , P.J. Minnett and J. Vasquez. Pathfinder Retrieval Accuracy and Effects of Water Vapor. Ocean Sciences Meeting of the American Geophysical Union. Boston, U.S.A., 1998.

Sikorski, R.J. and P.J. Minnett. Skin SST and air temperature measurements using a spectral IR interferometer (M-AERI). Spring 1999 Meeting of the AGU. Boston, MA. June 1999.

Minnett, P.J., Validation of satellite-derived ocean skin temperatures using the M-AERI. Along-Track Scanning Radiometer Workshop. European Space Research Institute, Frascati, Italy. June 1999.

Minnett, P.J., E. J. Kearns, J. A. Hanafin, R. H. Evans and O.B. Brown Improved determination of the accuracy of satellite-derived SST fields. Tenth ARM Science Team Meeting, San Antonio, TX, 13-17 March 2000.

Hanafin, J.A. and P.J. Minnett, Thermal profiling of the sea surface skin layer using FTIR measurements. Gas Transfer at Water Surfaces Symposium, Miami Beach, Florida, USA. June 5-8, 2000.

Ward, B. and P.J. Minnett, An autonomous profiler for near surface temperature measurements. Gas Transfer at Water Surfaces Symposium, Miami Beach, Florida, USA. June 5-8, 2000.

Minnett, P.J Radiometric Measurements of the Sea-Surface Skin Temperature and Validation of Infrared Retrievals of Sea-Surface Temperatures From Satellite. Oceans from Space - Venice 2000.. Venice, Italy. 9-13 October, 2000

Minnett, P.J. and B. Ward. Measurements of near-surface ocean temperature variability – consequences on the validation of AATSR on Envisat. ERS – ENVISAT Symposium "Looking down to Earth in the New Millennium" Gothenburg, Sweden. 16-20 October 2000.

Minnett, P.J. Infrared interferometric measurements of the sea-surface temperature in the tropical Pacific Ocean. 5th Pacific Ocean Remote Sensing Conference (PORSEC2000) 5-8 December 2000, Goa, India.

Evans, R.H., P.J. Minnett. O.B. Brown, K. Kilpatrick, E.J. Kearns, H. Gordon, K. Voss and M. Abbott. Early Results form NASA's Moderate Resolution Imaging Spectroradiometer (MODIS): Global and Arabian Sea Regional Ocean Color and Thermal Observations. 5th Pacific Ocean Remote Sensing Conference (PORSEC2000) 5-8 December 2000, Goa, India.

Key, E.L. and P.J. Minnett. Coastal effects on cloud forcing in Arctic polynyas. Gordon Research Conference on Polar Marine Science, Ventura, CA. March 11-16, 2001.

Minnett, P.J., O.B. Brown, B. Albrecht, K. Maillet, R. Kovach, P. Kollias, R.M. Reynolds and S. Cummings. The use of the cruise ship Explorer of the Seas as an instrumented platform for climate-related measurements over the oceans. Part 1. Atmospheric Instruments. Eleventh ARM Science Team Meeting, Atlanta, GA, 19-23 March 2001.

Albrecht, B., P.J. Minnett, O.B. Brown, P. Kollias, K. Maillet, R. Kovach, J. Tenerelli and A. Li. The use of the cruise ship Explorer of the Seas as an instrumented platform for climate-related measurements over the oceans. Part 2. Atmospheric Data. Eleventh ARM Science Team Meeting, Atlanta, GA, 19-23 March 2001.

Minnett, P.J Infrared interferometric measurements of the air-sea temperature difference. Eleventh ARM Science Team Meeting, Atlanta, GA, 19-23 March 2001.

Minnett, P.J., Satellite measurements of sea-surface temperatures – some current issues. Workshop on optimal assimilation of satellite sea surface temperature retrievals. NOAA Science Center, Camp Springs, MD, 24 - 26 April, 2001

Donlon, C.J., P.J. Minnett, I. J. Barton, T. J. Nightingale and C. Gentemann. Sea surface temperature measurements and definitions. WCRP/SCOR Workshop on Intercomparison and Validation of Ocean-Atmosphere Flux Fields, Potomac, MD. May 21-24, 2001.

Hanafin J.A. and P.J. Minnett. Determination of Sea Surface Emissivity and Thermal Skin Layer Depth using Infrared Interferometry. IEEE International Geosciences and Remote Sensing Symposium. Sydney, Australia. July 9-13, 2001. Evans R.H., P.J. Minnett, O.B. Brown, I.L. Barton, E.J. Kearns, K. Kilpatrick, R.J. Sikorski, A. Kumar and A.M. Zavody. Measurements of the Ocean Surface Temperature from the Moderate Resolution Imaging Spectroradiometer (MODIS). IEEE International Geosciences and Remote Sensing Symposium. Sydney, Australia. July 9-13, 2001.

Esaias, W., R.H. Evans, H. R. Gordon, P.J. Minnett, M. Abbott, O.B. Brown, K. Carder, D. Clark, J. Campbell, K. Voss, W. Balch,, K. Kilpatrick, R. Letelier, R. Chen, F. Hoge, E. J. Kearns, R.J. Sikorski, R. Vogel, K. Turpie, K. S. Walsh and J. Brown. MODIS Ocean Product Quality Improvement over the First 16 Months. IEEE International Geosciences and Remote Sensing Symposium. Sydney, Australia. July 9-13, 2001.

Minnett, P.J. Plans for at-sea Aqua validation. AMSR Validation Meeting. GSFC, August 3, 2001

Vogelmann, A.M., P. J. Flatau, P. J. Minnett, M. Szczodrak, K. Markowicz and J. Jafolla. Spectral Radiative Forcing of the ACE-Asia Aerosol Observed During the NOAA Ship R. H. Brown Cruise. Fall Meeting of the AGU, San Francisco, CA, 10-14 December 2001.

Berendes,T., D. Berendes, R. Welch, E. Clothiaux, E. Dutton, P. Minnett and T. Uttal. Validation of a Neural Network Based MODIS Global Cloud Mask Using Ground Based Instruments. 82nd Annual Meeting of the American Meteorological Society, Orlando, FL. 13-17 January 2002.

Minnett, P. J. Radiometric measurements of air-sea temperature difference. AGU Ocean Sciences Meeting, Honolulu, Hawaii, 11-15 February 2002.

Hanafin, J. A. and P. J. Minnett. Measurements of sea surface emissivity and air-sea heat flux during Gasex 2001. AGU Ocean Sciences Meeting, Honolulu, Hawaii, 11-15 February 2002.

Minnett, P.J. Air-Sea Temperature Difference Measured by Ship-Board Infrared Interferometry. Seventh International Conference on Remote Sensing for Marine and Coastal Environments, Miami, Florida, USA, 20 May, 2002.

Hanafin, J. A. and P.J. Minnett. Field measurements of spectral sea surface emissivity. Seventh International Conference on Remote Sensing for Marine and Coastal Environments, Miami, Florida, USA, 20 May, 2002.

Kearns E.J., R.H. Evans, K. Kilpatrick, P.J. Minnett and D.K. Clark. The calibration of MODIS ocean color and sea surface temperature products. Seventh International Conference on Remote Sensing for Marine and Coastal Environments, Miami, Florida, USA, 20 May, 2002.

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.

Minnett, P.J., I.J. Barton and J.P. Rice. The Miami2001 International Infrared Radiometer Intercalibration Workshop. CIMAS Scientific Review, Miami, FL, February 20, 2003.

Minnett, P.J., Shipboard radiometric measurements of some surface meteorological parameters. Center for Ocean-Atmospheric Prediction Studies, Florida State University, Tallahassee, FL, 3-5 March, 2003.

Minnett, P.J., K.A. Maillet and B.J. Osborne. Infrared interferometric measurements of the air-sea temperature difference. XXIII General Assembly of the International Union of Geodesy and Geophysics, June 30-July 11, 2003, Sapporo, Japan.

Gentemann, C.L., P.J. Minnett, C.J. Donlon and G.A. Wick. Diurnal sea-surface temperature modeling with satellite data. XXIII General Assembly of the International Union of Geodesy and Geophysics, June 30-July 11, 2003, Sapporo, Japan.

Evans, R.H., E.J. Kearns. H.R. Gordon, P.J. Minnett, K. Voss and K. Kilpatrick. MODIS ocean color and SST status, calibration and application. IEEE International Geoscience and Remote Sensing Symposium (IGARSS'03), July 21-25, 2003, Toulouse, France.

Noyes, E., B. Mannerings, G. Corlett, J. Remedios, D. Llewellyn-Jones and P. Minnett. Validation of AATSR SST with ship-based measurements from the M-AERI. MERIS and AATSR Calibration and Geophysical Validation Meeting (MAVT-2003). 20-24 October 2003. Frascati, Italy.

Minnett, P.J., R. H. Evans, E. J. Kearns, K. Kilpatrick, K. A. Maillet, A. Kumar, W. Baringer, S. Walsh, E. L. Key, M. Szczodrak & O. B. Brown. Sea surface temperature measurements from the MODerate- resolution Imaging Spectroradiometer (MODIS) on AQUA. AGU Fall Meeting, San Francisco, CA. December 9, 2003.

Maddy, E, W.W. McMillan, P.J. Minnett and H.H. Aumann. Remote sensing of sea surface temperature from ground and sky. AGU Fall Meeting, San Francisco, CA. December 10, 2003.

Minnett, P.J. Diurnal Signals in Air-sea Temperature Signals -- True or False? AGU Ocean Sciences, Portland, Oregon, USA, 26-30 January 2004.

Szczodrak, M., P.J. Minnett, K.A. Maillet and R.A. Jones, Comparative Measurements of Atmospheric Water Vapor Over the Oceans. AGU Ocean Sciences, Portland, Oregon, USA, 26-30 January 2004

Minnett, P J., D.T. Llewellyn-Jones, G.K. Corlett and E.J Noyes. Validating the Sea-Surface Temperatures Derived from the Advanced Along-Track Scanning Radiometer on ENVISAT. AGU Ocean Sciences, Portland, Oregon, USA, 26-30 January 2004

Ward, B. and P.J. Minnett, Observations of cool skin and warm layer temperatures in the Gulf of California. AGU Ocean Sciences, Portland, Oregon, USA, 26-30 January 2004

Ward, B., P. Strutton, P.J. Minnett and I. Nardello, Study of near surface radiant heating from irradiance and temperature profiles in the Mediterranean, AGU Ocean Sciences, Portland, Oregon, USA, 26-30 January 2004.

Williams, E J., E.J. Kearns, B. Albrecht, P.J. Minnett, H.B. Maring, S Cummings and R.M Reynolds, Contributions of the Rosenstiel Labs on Explorer of the Seas to the Southeast Atlantic Coastal Ocean Observing System (SEACOOS), AGU Ocean Sciences, Portland, Oregon, USA, 26-30 January 2004.

9 AWARDS

Jennifer Hanafin was the First Place Winner of Best Student Paper at the International Geoscience and Remote Sensing Symposium, Sydney, Australia, July 2001, for the presentation "Determination of Sea Surface Emissivity and Thermal Skin Layer Depth using Infrared Interferometry" by Hanafin J.A. and P.J. Minnett.

Drs Brown and Minnett have received the following NASA Awards:

- NASA Group Achievement Award, Moderate Resolution Imaging Spectroradiometer (MODIS) Support Team. August 2001.
- NASA Outstanding Teamwork Award – NASA Earth Observing System Aqua satellite, June 2003.
- NASA Group Achievement Award, Aqua Mission Team. August 2003.

10 BUDGET SUMMARY

A summary of the total budget is presented in Table 9. Details of the expenditures have been submitted within each reporting period of the contract. Note that the original contractor estimate was $15,585,855, with the actual total expended being $10,535,000. Thus, the work has been completed at about 32% under the original budget.

Table 9. Summary of Expenditures

Reporting category	**Total expended in $1,000**
Labor costs	3317.05
Fringe benefits	818.06
Materials & supplies	215.23
Travel	297.17
Shipping	174.19
Communications	64.55
Maintenance	238.79
Shiptime	109.44
Computer time	20.43
Consultants	42.33
Subcontracts	1090.10
Captial equipment	1004.41
Direct costs	7391.75
Indirect costs	3143.27
Total costs	10535.02

11 INVESTIGATOR SUPPORT

Table 10 Summary of salary support

	1992			1993											
	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Faculty															
Otis Brown	X	X							X	X	X	X			X
George Halliwell					X	X	X	X					X		
Arthur Mariano															
Peter Minnett															
Res. Associates															
Banzon, Patria															
Baraille, Remy															
Baringer, John															
Bohm, Emanuele															
Brown, James	X	X	X												X
Evans, Peter															
Goni, Gustavo									X	X	X	X	X	X	X
Halliwell, Vicki															
Kilpatrick, Kay															
Kovach, Robin															
Kroger, Aline														X	X
Kumar, Ajoy															
Li, Dalu															
Maillet, Kevin															
Oviedo, Yenia															
Ryan, Edward															
Shenoi, Satheesh															
Sikorski, Richard															
Szczodrak, M.															
Li, Angel															
Splain, Joanie															
Walsh, Sue														X	X
Staff															
Carpenter, Jean								X	X						
Graham, Mark															
Green, Gerry									X	X	X	X	X	X	X
Jones, Robert															
Kolaczynski, R.															
Sanchez, Irmina															
Students															
Forbes, Maria												X	X	X	X
Framinan, Mariana															
Hanafin, Jennifer															
Hargrove, John															
Wilson-Diaz, D.															

	1994											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown	X						X	X	X	X	X	X
George Halliwell			X	X	X	X	X					
Arthur Mariano						X	X	X		X		X
Peter Minnett												
Res. Associates												
Banzon, Patria												
Baraille, Remy												
Baringer, John	X	X	X			X	X	X	X	X	X	X
Bohm, Emanuele												
Brown, James	X	X	X			X						X
Evans, Peter												X
Goni, Gustavo	X	X	X	X	X	X	X	X	X	X	X	X
Halliwell, Vicki												X
Kilpatrick, Kay												
Kovach, Robin												
Kroger, Aline	X	X							X	X		X
Kumar, Ajoy												
Li, Dalu												X
Maillet, Kevin												
Oviedo, Yenia												
Ryan, Edward			X	X	X							
Shenoi, Satheesh										X	X	X
Sikorski, Richard												
Szczodrak, M.												
Li, Angel											X	X
Splain, Joanie											X	
Walsh, Sue	X			X	X						X	
Staff												
Carpenter, Jean							X	X				
Graham, Mark												
Green, Gerry										X	X	X
Jones, Robert												
Kolaczynski, R.												
Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana												
Hanafin, Jennifer												
Hargrove, John												
Wilson-Diaz, D.									X	X	X	X

	1995											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown		X	X	X	X					X		
George Halliwell												
Arthur Mariano	X											
Peter Minnett							X	X				
Res. Associates												
Banzon, Patria												
Baraille, Remy												
Baringer, John	X	X	X					X	X		X	X
Bohm, Emanuele												
Brown, James			X	X	X	X	X	X	X	X		
Evans, Peter								X	X		X	X
Goni, Gustavo								X				
Halliwell, Vicki						X	X	X			X	X
Kilpatrick, Kay												
Kovach, Robin												
Kroger, Aline			X	X	X							
Kumar, Ajoy												
Li, Dalu						X	X	X	X	X		
Maillet, Kevin												
Oviedo, Yenia												
Ryan, Edward												
Shenoi, Satheesh												
Sikorski, Richard												
Szczodrak, M.												
Li, Angel	X	X	X			X	X	X	X	X	X	X
Splain, Joanie												
Walsh, Sue	X	X	X	X	X							
Staff												
Carpenter, Jean												
Graham, Mark												
Green, Gerry	X											
Jones, Robert												
Kolaczynski, R.												
Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana												
Hanafin, Jennifer												
Hargrove, John												
Wilson-Diaz, D.	X	X	X	X	X							

	1996											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown						X	X	X	X	X	X	X
George Halliwell												
Arthur Mariano												
Peter Minnett					X	X	X	X	X			
Res. Associates												
Banzon, Patria												
Baraille, Remy												
Baringer, John						X	X	X	X	X	X	X
Bohm, Emanuele												
Brown, James												
Evans, Peter							X		X			
Goni, Gustavo												
Halliwell, Vicki			X	X	X	X	X	X	X	X	X	
Kilpatrick, Kay												
Kovach, Robin												
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Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana												
Hanafin, Jennifer									X	X	X	X
Hargrove, John												
Wilson-Diaz, D.										X	X	X

	1997											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown	X	X	X	X	X	X	X	X	X	X		
George Halliwell												
Arthur Mariano			X	X	X	X	X	X	X	X	X	X
Peter Minnett			X	X	X	X						
Res. Associates												
Banzon, Patria												
Baraille, Remy												
Baringer, John	X	X	X	X	X	X	X	X	X			
Bohm, Emanuele												
Brown, James				X		X	X	X	X			
Evans, Peter		X	X	X	X	X	X	X				
Goni, Gustavo		X	X	X	X	X	X	X	X		X	X
Halliwell, Vicki												
Kilpatrick, Kay				X								
Kovach, Robin												
Kroger, Aline												
Kumar, Ajoy												
Li, Dalu												
Maillet, Kevin												
Oviedo, Yenia												
Ryan, Edward												
Shenoi, Satheesh												
Sikorski, Richard		X	X	X	X	X	X	X	X	X		
Szczodrak, M.												
Li, Angel	X	X	X	X	X	X	X	X				X
Splain, Joanie				X	X		X					X
Walsh, Sue				X	X	X						
Staff												
Carpenter, Jean												
Graham, Mark												
Green, Gerry												
Jones, Robert								X		X	X	X
Kolaczynski, R.												
Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana								X	X			
Hanafin, Jennifer								X				
Hargrove, John												
Wilson-Diaz, D.								X				

	1998											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown	X	X	X	X	X	X	X	X	X		X	X
George Halliwell												
Arthur Mariano	X	X		X	X	X	X	X	X	X	X	X
Peter Minnett												
Res. Associates												
Banzon, Patria												
Baraille, Remy												
Baringer, John	X	X	X	X	X	X	X	X	X	X	X	X
Bohm, Emanuele						X	X	X				
Brown, James	X	X	X	X		X	X	X	X			
Evans, Peter												
Goni, Gustavo												
Halliwell, Vicki												
Kilpatrick, Kay	X		X	X		X	X	X	X	X	X	X
Kovach, Robin						X	X	X	X		X	X
Kroger, Aline												
Kumar, Ajoy												
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Maillet, Kevin												
Oviedo, Yenia												
Ryan, Edward												
Shenoi, Satheesh												
Sikorski, Richard	X	X	X	X								
Szczodrak, M.												
Li, Angel	X			X								
Splain, Joanie	X	X	X	X		X	X	X	X		X	X
Walsh, Sue	X	X	X	X	X	X	X	X	X		X	X
Staff												
Carpenter, Jean												
Graham, Mark		X	X	X	X	X						
Green, Gerry												
Jones, Robert		X	X	X	X	X						
Kolaczynski, R.			X	X	X	X	X		X	X	X	X
Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana				X						X	X	X
Hanafin, Jennifer												
Hargrove, John										X	X	X
Wilson-Diaz, D.												

	1999											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown	X	X	X	X	X	X	X	X	X	X	X	X
George Halliwell												
Arthur Mariano	X	X	X	X	X	X	X	X	X	X	X	X
Peter Minnett			X	X								
Res. Associates												
Banzon, Patria												
Baraille, Remy			X	X	X	X	X	X	X			
Baringer, John	X	X	X	X	X	X	X	X	X	X	X	X
Bohm, Emanuele												
Brown, James		X	X	X	X	X	X	X	X			
Evans, Peter												
Goni, Gustavo												
Halliwell, Vicki												
Kilpatrick, Kay	X	X	X	X	X	X	X	X	X	X	X	X
Kovach, Robin	X	X	X	X	X	X	X	X	X	X	X	X
Kroger, Aline												
Kumar, Ajoy										X	X	
Li, Dalu												
Maillet, Kevin			X	X	X	X	X	X	X	X	X	X
Oviedo, Yenia												
Ryan, Edward												
Shenoi, Satheesh												
Sikorski, Richard			X	X	X	X						
Szczodrak, M.												
Li, Angel		X	X	X	X	X	X	X	X			
Splain, Joanie	X	X	X	X	X	X	X	X	X	X	X	X
Walsh, Sue	X	X	X	X	X	X	X	X	X	X	X	X
Staff												
Carpenter, Jean												
Graham, Mark												
Green, Gerry												
Jones, Robert	X	X	X	X								
Kolaczynski, R.	X	X	X	X	X	X	X	X	X	X	X	X
Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana	X	X	X	X	X	X	X	X	X	X	X	X
Hanafin, Jennifer												
Hargrove, John									X	X		
Wilson-Diaz, D.												

	2000											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown	X	X	X	X	X					X	X	X
George Halliwell												
Arthur Mariano	X	X	X	X	X	X	X	X				
Peter Minnett			X	X								
Res. Associates												
Banzon, Patria											X	
Baraille, Remy												
Baringer, John	X	X	X	X	X	X	X	X	X	X	X	X
Bohm, Emanuele						X	X	X	X			
Brown, James		X	X	X	X							
Evans, Peter												
Goni, Gustavo												
Halliwell, Vicki												
Kilpatrick, Kay	X	X	X	X	X	X	X	X	X	X	X	X
Kovach, Robin	X	X	X	X	X	X	X	X	X	X	X	X
Kroger, Aline												
Kumar, Ajoy												
Li, Dalu												
Maillet, Kevin	X	X	X	X	X	X	X	X	X	X	X	X
Oviedo, Yenia												
Ryan, Edward												
Shenoi, Satheesh												
Sikorski, Richard			X	X		X				X	X	X
Szczodrak, M.												
Li, Angel		X	X		X	X	X	X	X		X	X
Splain, Joanie	X	X	X	X		X	X	X	X	X	X	X
Walsh, Sue	X	X	X	X	X	X	X	X	X			
Staff												
Carpenter, Jean												
Graham, Mark												
Green, Gerry												
Jones, Robert			X									X
Kolaczynski, R.	X	X	X	X	X	X	X	X	X	X	X	X
Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana	X	X	X	X	X	X	X	X	X	X	X	X
Hanafin, Jennifer												
Hargrove, John				X	X							
Wilson-Diaz, D.												

	2001											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown	X	X	X	X	X	X	X	X	X	X	X	X
George Halliwell												
Arthur Mariano												
Peter Minnett			X	X								
Res. Associates												
Banzon, Patria												
Baraille, Remy												
Baringer, John	X	X	X	X	X	X	X	X	X		X	X
Bohm, Emanuele												
Brown, James												
Evans, Peter												
Goni, Gustavo												
Halliwell, Vicki												
Kilpatrick, Kay		X	X	X	X						X	
Kovach, Robin	X	X	X	X	X	X	X	X				
Kroger, Aline												
Kumar, Ajoy											X	
Li, Dalu												
Maillet, Kevin	X	X	X	X	X	X	X	X	X	X	X	
Oviedo, Yenia												
Ryan, Edward												
Shenoi, Satheesh												
Sikorski, Richard			X	X								
Szczodrak, M.												
Li, Angel	X	X	X	X	X	X	X	X	X			
Splain, Joanie	X	X	X	X	X	X	X	X	X			
Walsh, Sue												
Staff												
Carpenter, Jean												
Graham, Mark												
Green, Gerry												
Jones, Robert												
Kolaczynski, R.	X	X	X	X	X	X	X	X	X	X	X	X
Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana	X	X	X	X	X	X	X		X	X	X	X
Hanafin, Jennifer												
Hargrove, John												
Wilson-Diaz, D.												

	2002											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown	X	X	X	X	X	X	X	X	X	X	X	X
George Halliwell												
Arthur Mariano												
Peter Minnett			X	X	X							
Res. Associates												
Banzon, Patria												
Baraille, Remy												
Baringer, John	X	X	X	X	X	X	X	X	X	X	X	X
Bohm, Emanuele												
Brown, James												
Evans, Peter												
Goni, Gustavo												
Halliwell, Vicki												
Kilpatrick, Kay						X	X	X	X	X	X	X
Kovach, Robin												
Kroger, Aline												
Kumar, Ajoy	X	X	X	X	X	X	X	X	X	X	X	X
Li, Dalu												
Maillet, Kevin					X	X	X	X	X	X	X	X
Oviedo, Yenia												
Ryan, Edward												
Shenoi, Satheesh												
Sikorski, Richard							X					
Szczodrak, M.												
Li, Angel	X	X		X	X	X	X	X	X	X	X	X
Splain, Joanie						X	X	X	X	X	X	X
Walsh, Sue												
Staff												
Carpenter, Jean												
Graham, Mark												
Green, Gerry												
Jones, Robert												
Kolaczynski, R.	X	X	X	X	X	X	X	X	X	X		
Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana	X	X	X	X	X	X	X		X	X	X	X
Hanafin, Jennifer												
Hargrove, John												
Wilson-Diaz, D.												

	2003											
	1	2	3	4	5	6	7	8	9	10	11	12
Faculty												
Otis Brown	X	X	X	X	X	X	X	X	X	X	X	X
George Halliwell												
Arthur Mariano												
Peter Minnett						X	X	X				
Res. Associates												
Banzon, Patria												
Baraille, Remy												
Baringer, John	X	X	X	X	X	X	X	X	X	X	X	X
Bohm, Emanuele												
Brown, James												
Evans, Peter												
Goni, Gustavo												
Halliwell, Vicki												
Kilpatrick, Kay	X	X	X	X	X	X	X	X	X	X	X	X
Kovach, Robin												
Kroger, Aline												
Kumar, Ajoy					X	X	X	X	X	X	X	X
Li, Dalu												
Maillet, Kevin	X	X	X			X	X	X		X	X	X
Oviedo, Yenia	X	X										
Ryan, Edward												
Shenoi, Satheesh												
Sikorski, Richard												
Szczodrak, M.												
Li, Angel					X			X	X	X	X	X
Splain, Joanie	X	X	X	X	X	X	X	X	X	X	X	X
Walsh, Sue												
Staff												
Carpenter, Jean												
Graham, Mark												
Green, Gerry												
Jones, Robert												
Kolaczynski, R.												
Sanchez, Irmina												
Students												
Forbes, Maria												
Framinan, Mariana	X	X	X	X	X	X	X		X	X	X	X
Hanafin, Jennifer												
Hargrove, John												
Wilson-Diaz, D.												

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