P2.15 SATELLITE SEA SURFACE TEMPERATURE (SST) RESEARCH AT NOAA/NESDIS

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1. INTRODUCTION

Remotely sensed sea surface temperatures (SST) derived from the NOAA polar (POES) and geostationary (GOES) satellites continue to be an indispensable resource that directly supports NOAA's missions and strategic goals. Since the inception of satellite oceanography in the 1970s, NOAA/NESDIS has been an international contributor in the advancement of satellite derived global SST methodologies and operational products. These data are required of a number of users (NOAA internal and external), including the NESDIS CoastWatch/OceanWatch and Coral Reef Watch programs, as well as for academic research and numerical forecast model assimilation. Currently at NESDIS, satellite SST research is coordinated within the Oceanic Research and Applications Division (ORAD) SST Science Team at the Office of Research and Applications (ORA). The overarching goal of the science team is oversee and facilitate efficient, end-to-end satellite product development, beginning at the basic research level and continuing through the transition into NOAA operations. To achieve this, ORAD works closely with the NESDIS Office of Satellite Data Processing and Distribution (OSDPD), which assumes responsibility for operational implementation and maintenance. To facilitate cutting-edge research, ORAD also supports tight collaborations within academia, including the Cooperative Institutes at Colorado State University, Oregon State University, University of Maryland and University of Wisconsin-Madison, as well as contracts/grants with the University of Edinburgh and University of Miami. This paper provides an overview of satellite SST research and development conducted at ORAD.

2. THE PRESENT PROGRAM

NOAA/NESDIS is responsible for developing and maintaining operational environmental satellite data products available for public access and distribution. To provide long-term data continuity, ORAD sustains and enhances the current POES and GOES IR SST products. To better serve the user community, the ORAD SST Science Team works to develop and implement SST operational products that meet user requirements in terms of absolute accuracy, precision, geographic coverage, and sampling resolution (spatial and temporal) in near real-time. These user-products include global analyses, CoastWatch/OceanWatch high-resolution coastal SST and Coral Reef Watch monitoring products.

2.1 POES Infrared (IR) SST Products

NESDIS continues to develop and sustain the operational NOAA-16/17 AVHRR/3 SST equations based upon long-established statistical-empirical, multispectral methods. The algorithms include the well-known multichannel SST (MCSST) and non-linear SST (NLSST) algorithms (e.g., Walton *et al.*, 1998; McClain *et al.*, 1985), and the newly implemented experimental aerosol-corrected SST (ACSST) (Nalli and Stowe, 2002). Periodic validation and quality-monitoring of the operational equations are conducted based upon monthly samples of AVHRR-buoy matchups (e.g., Li *et al.*, 2001). The global retrieval precision of AVHRR is currently ≃0.5 K. NESDIS also continues to collaborate with the U.S. Navy under the Shared Processing Agreement. The retrievals form the basis for derived-products, including global analyses and anomaly charts, which are in turn used

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for various user applications. One important application is NOAA's Coral Reef Watch. Figure 1 shows the Degree Heating Weeks chart for 7 September 2002, a product-indicator of prolonged ocean thermal stress (e.g., Liu *et al.*, 2003). This chart, derived from the NOAA AVHRR SST analysis and available in near-real time, indicated a period of high thermal stress at the U.S. Midway Atoll. The thermal stress is also apparent in the SST time-series for Midway shown in Figure 2, where the satellite SSTs (blue line) rose above the coral bleaching threshold for an extended period beginning 1 August through 7 September 2002. Based upon these satellite SST indicators, NESDIS was able to issue a Bleaching Warning to coral reef management authorities on 7 August 2002.

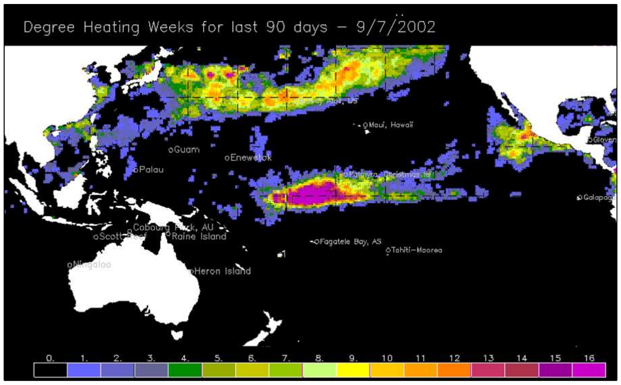


Figure 1: NOAA's Coral Reef Watch Degree Heating Weeks product chart for the 90 day period prior to 7 September 2002.

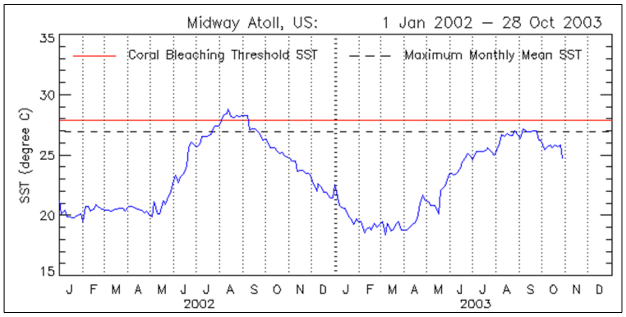


Figure 2: AVHRR SST times series at Midway Atoll, 1 January 2002 through 28 October 2003.

For climate applications, initial Pathfinder AVHRR reprocessing efforts at NESDIS have resulted in the 20 year AVHRR Pathfinder Atmospheres (PATMOS) climatological dataset (Jacobowitz *et al.*, 2003). This data set, which includes aerosol optical depth (AOD) retrieved from AVHRR channel 1 (0.63 μm), has been used to derive a daytime aerosol-corrected SST climatology demonstration product for 1985-2000 (Nalli, 2003). Figure 3 shows zonal-mean monthly climatologies derived the AVHRR PATMOS dataset. The middle plot shows standard MCSST anomalies, whereas the bottom plot shows anomalies derived from the aerosol corrected MCSST (AMCSST). The eruption of Mt. Pinatubo in June 1991 is clearly evident both as elevated AOD in the top plot and as significant MCSST negative bias (< -2.0 K) in the tropics and midlatitudes following the eruption. These aerosol biases are largely reduced or eliminated with the AMCSST (bottom plot). Seasonal to interannual variabilities and trends are apparent, including dust and biomass burning (top plot), and global warming and ENSO (bottom plot). New AVHRR (and GOES) reprocessing efforts are underway at NESDIS that will improve upon known limitations of PATMOS for future iterations toward a stable, climate-quality SST record.

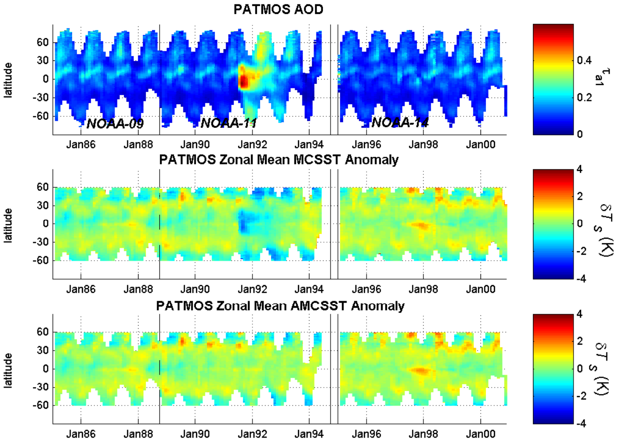


Figure 3: AVHRR PATMOS monthly, zonal-mean climatologies for daytime, ascending node, 1985–2000: (top) channel 1 AOD, (middle) MCSST zonal-mean monthly anomaly, and (bottom) aerosol-corrected MCSST (AMCSST) zonal-mean monthly anomaly. SST anomalies are relative to the NCEP Reynolds OISST 1961–1990 base period.

With the many advances in radiative transfer modeling in recent years, ORAD is moving toward radiative transfer model (RTM)-based skin SST retrievals for AVHRR/3 similar to those used for the ERS Along Track Scanning Radiometer (ATSR) (e.g., Merchant *et al.*, 1999; Merchant and Harris, 1999), and now also GOES (see below). However, difficulties yet to be surmounted in this task for AVHRR include accurate specification of the filter spectral response functions (SRFs) as well as bias correction, RTM refinements and improvements, and finally validation of retrieved skin temperatures against *in situ* buoy bulk-temperature matchups.

Figure 4 shows validation scatterplots of NOAA-17 AVHRR RTM-based SST retrievals against *in situ* buoy matchups. The top two panels show the results using the nominal instrument filter SRFs for split-window (11 and 12μm) and triple window (11, 12 and 3.7μm) retrievals, respectively. The observed error characteristics are dominated by RTM errors that may be due at least in part to errors in specification of the instrument SRFs. However, such comparisons have allowed the development of an initial optimization methodology. Due to the limited number of degrees of freedom, the problem has been constrained to spectral perturbations in the nominal position of the filter functions (i.e., Figure 5). While the results are not independent of validation data, there is the constraint that, since radiative transfer modeling has been employed using a known set of diverse conditions, results should have globally predictable error characteristics. Figure 5 indicates that optimal results (i.e., bias $\simeq$0, gradient 1.0) are obtained for adjustments of about -5 cm^{-1} from the nominal position for both filters, and lie within the region of low standard deviation values. These results are for nighttime data, but a similar outcome is seen for daytime data having a different distribution, thus our confidence in the result is increased. It is likely that calibration errors are the cause of remaining residual bias seen in the triple-window retrieval since here the parameter weightings for the 11 and 12 μm channels are much less than they are in the split-window retrieval, and the implied SRF adjustments (not shown) required to obtain optimal results are significantly greater and unrealistic.

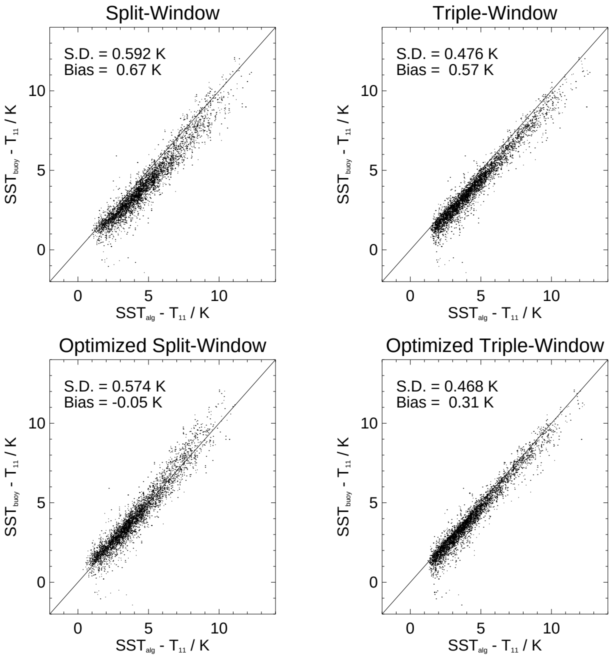


Figure 4: NOAA-17 statistical RTM-based SST retrievals versus *in situ* buoy matchups during nighttime using: (left panels) Split-window (11 and 12μm) equation, and (right panels) triple-window equation (11, 12 and 3.7μm). The top panels show results using the nominal AVHRR SRF without any adjustments. The bottom panels demonstrate that both bias and scatter can be improved by shifting the spectral responses by -5 cm^{-1} as indicated by Figure 5.

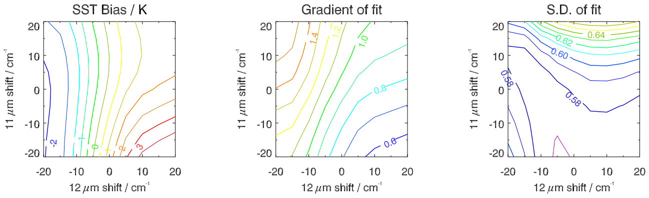


Figure 5: SST retrieval characteristics for radiative transfer based split-window algorithms, calculated using perturbed NOAA-17 instrument spectral response functions, applied to nighttime validation data.

2.2 GOES IR SST Products

SST derived from the GOES geostationary platforms benefit from enhanced temporal sampling frequency (up to once half-hourly versus 4 times per day sampling from two POES satellites). In regions of persistent cloud cover, GOES increases the likelihood of obtaining a clear-sky observation and thus allows the possibility of resolving the diurnal cycle of SST. Although the first operational GOES SST product was based upon a statistical-empirical algorithm similar to that used by AVHRR (Wu *et al.*, 1999), the current operational GOES algorithms are now RTM-based. The rapid transition to RTM-based algorithms was partially motivated by user feedback and by the GOES M-Q design-loss of the 12 μm channel (thereby eliminating the conventional split-window for daytime conditions) (e.g., Maturi *et al.*, 2001). Because there had not been a long-established GOES SST product, the switch to RTM-based retrievals in advance of GOES-12 (-M) was all the more logical. The GOES RTM algorithms use the 3.9 and 11 μm channels (the so-called "dual-window" method) for deriving the correction for atmospheric water vapor. Although the highly-transparent 3.9 μm shortwave IR (SWIR) channel works well for nighttime retrievals, during daytime it is subject to solar contamination. Therefore, the daytime GOES-12

RTM algorithm operates by first screening regions of sunglint and then accounts for diffuse solar contributions in the 3.9 μm channel. The RTM retrieval algorithms for GOES-9/10/12 have been developed by the University of Edinburgh, Scotland under NOAA contract. More recent GOES work at U. Edinburgh now includes the development of a full probabilistic cloud detection method based upon Bayes' theorem (Merchant, 2003). As with POES, NESDIS is responsible for sustaining retrievals for operational GOES-9/10/12 SST products. This includes implementing an improved quality control system for the GOES SST matchup database to remove erroneous buoy outliers.

The GOES SST retrievals are used (along with POES) for NOAA's CoastWatch operational high resolution SST product (e.g., see Figure 6). Composite analysis products from the GOES-9/10/12 are planned for assimilation into the National Weather Service (NWS) forecasting models. Plans for reprocessing GOES data (1994–present), as well as for combining multiple geostationary platforms for global SST, are also in the works.

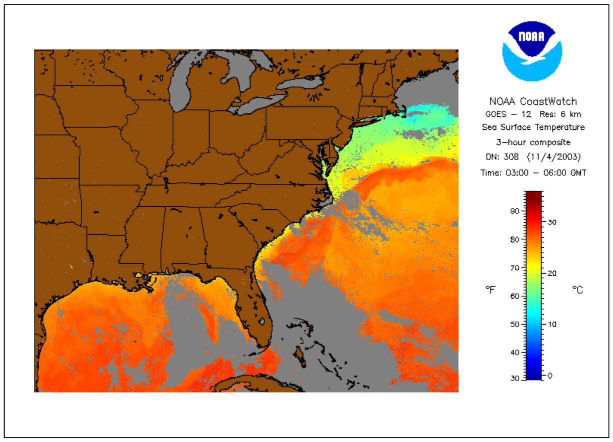


Figure 6: NOAA's CoastWatch SST 6 km operational product derived from GOES-12 for the coastal waters of the Eastern U.S., 03:00–06:00 UTC, 4 November 2003.

Among other things, the GOES SST retrievals have proven to be very useful in resolving SST fronts. SST fronts are often associated with upwelling off the U.S. West Coast, the Loop Current in the Gulf of Mexico, the Gulf Stream in the northwest Atlantic and tidal mixing phenomena in the Gulf of Maine. For example, Legeckis *et al.* (2002) demonstrate the tracking of westward propagating Tropical Instability Waves in the Pacific, the time history of the Loop Current in the Gulf of Mexico, and the formation and precession of cyclonic eddies west of the Hawaiian Islands. A SST frontal probability product (after Mavor and Bisagni, 2001) (e.g., see Figure 7) has been developed based upon GOES SSTs.

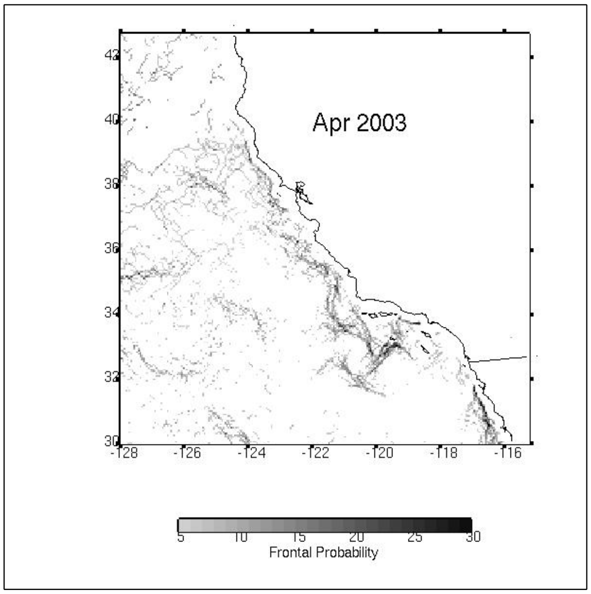


Figure 7: Probability of major frontal boundaries off the California coast using SST derived from GOES-10 for April 2003.

2.3 Microwave (MW) SST Development

Passive microwave (MW)-based retrievals are receiving more attention recently due to the insensitivity of microwaves to clouds, aerosols and water vapor (e.g., Wentz *et al.*, 2000). Recognizing these distinct advantages, ORAD has developed an experimental MW SST retrieval algorithm for the TRMM microwave imager (TMI). The algorithm is based upon a statistical-empirical methodology using observations from the 10 GHz channel (V, H) regressed against NDBC buoys for 2 m s^{-1} windspeed bins (the other channel frequencies are used for wind speed and rain). The TMI correlation of regression against buoys is R^2 >0.9 with rms scatter <1.5 K and bias (TMI minus Buoy) <0.3 K for most windspeed bins <10 m s^{-1}. One reason for the relatively high scatter is that the NDBC buoys are known to occur in regions of high SST gradients, hence improved results may be expected from drifting buoys and the TAO array in the tropical Pacific Ocean. One known disadvantage of MW retrievals is the greater sensitivity to surface roughness changes (i.e., local surface wind speed). Figure 8 shows wind speed variations in retrieved TMI SST against co-located buoy matchups in 2 m s^{-1} windspeed bins.

The experimental, global TMI SST product is still undergoing development but is currently accessible in

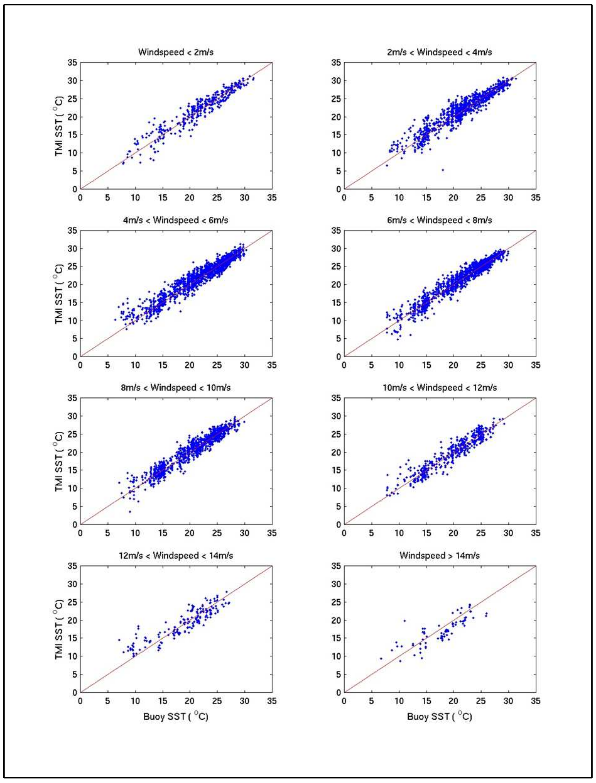
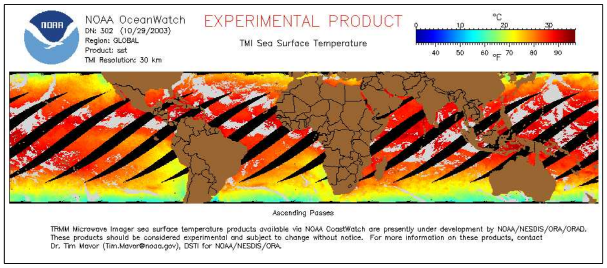


Figure 8: TMI microwave SST scatterplots versus NDBC buoy matchups from January to June 2003 in 2 m s^{-1} windspeed bins.

near real-time as part of NOAA's expanded "OceanWatch" program web page (e.g., Figure 9). Research has also begun on empirical and RTM-based MW retrieval algorithms for use with the improved WindSat instrument. The WindSat/Coriolis mission is a risk-reduction demonstration project in support of the forthcoming National Polar Orbiting Environmental Satellite System (NPOESS) program. The WindSat frequency-array specifications are similar to the future NPOESS Conical Microwave Imager/Sounder (CMIS). The advantages for SST include (1) two spectral channels at 10.7 and 6.8 GHz, the latter providing greater sensitivity to SST <15°C, (2) fore and aft looks that allow a larger observational swath, and (3) polar orbit to allow regional coverage at higher latitudes

2.4 GOES-POES Blended Demonstration Product

An experimental POES/GOES IR blended analysis product has been developed at the Rutherford Appleton Laboratory (RAL) under contract for NESDIS. As of this writing, the demonstration product is expected for delivery to ORAD in late 2003 for validation and implementation into operations. This blended product will eventually replace the 50 km POES SST analysis and will provide a methodology for future multi-instrument, multi-platform SST blending (see below). Note that a blended product is still ultimately contingent upon the accuracy of the component SST retrievals.



TRMM Microwave Imager sea surface temperature products available via NOAA CoastWatch are presently under development by NOAA/NESDIS/ORA/ORAD. These products should be considered experimental and subject to change without notice. For more information on these products, contact Dr. Tim Mavor (Tim.Mavor@noaa.gov), DSTI for NOAA/NESDIS/ORA.

Figure 9: NOAA's OceanWatch TMI microwave SST experimental product (0.25°lat/lon resolution) for 29 October 2003.

2.5 Aqua/Terra

High spatial resolution (≃1.4 km) SST products from the Aqua/Terra Moderate Resolution Imaging Spectroradiometer (MODIS) are provisionally available through NOAA's CoastWatch. In anticipation of future observing systems, ORAD has begun to investigate the potential of hyperspectral SST retrievals from the Aqua Atmospheric IR Sounder (AIRS) instrument. Although AIRS was originally conceived as a sounding instrument and has a relatively large footprint (≃15 km), high spectral resolution has noted advantages for multispectral SST retrieval (e.g., Nalli and Smith, 2003). Furthermore, it is noted that future hyperspectral systems (e.g., GOES-R) are anticipated to have spatial resolution comparable to today's AVHRR.

3. THE FUTURE

While SST retrieval is now considered a "mature" science, the challenge remains for NESDIS to meet stringent user accuracy requirements (on the order of 0.1 K rms) through the use of new instruments and retrieval algorithms. Future SST products from NESDIS will be derived from RTM-based retrieval algorithms to provide a means for more rigorous, systematic and accurate products. This is required to maximize the benefit of including these data into analysis procedures for both the operational and climate research programs. Physical retrieval methods also permit explicit modeling of surface effects. This is an important step for the successful analysis of data from asynoptic observation times.

3.1 Existing Programs

NESDIS will phase out long-established statistical-empirical products in favor of RTM-based algorithms that will optimize accuracy and provide reliable error estimates, including those from residual clouds, aerosols, water vapor, etc. To prepare for this transition, a new POES/AVHRR orbital processing system will be developed to include enhancements over the current system, including (1) implementation of the improved CLAVR-X cloud algorithm, (2) inclusion of ancillary meteorological and oceanographic data for use in radiative transfer modeling, (3) ongoing improvements in the operational AOD products (Ignatov *et al.*, 2004) for aerosol detection and bias-correction (e.g., Ignatov and Nalli, 2002), and (4) replacement of spatial averaging with water vapor smoothing to improve spatial resolution while reducing noise. NESDIS operational SST products will continue beyond NOAA-KLM to the NOAA-N and -N' satellites to be launched in PM afternoon orbits tentatively in 2004 and 2008, respectively. The AM morning satellites MetOp-1 and -2 are slated to be launched and operated by EUMETSAT. Coordination between NOAA and EUMETSAT will be necessary for developing and sustaining SST products from both AM and PM POES platforms.

GOES RTM SST retrievals and cloud mask algorithms, initially developed at U. Edinburgh, will be transferred to NESDIS with appropriate documentation and coordination. An aerosol correction algorithm is also planned using the RTM approach. These algorithms will be applied to the GOES-9/10, MTSAT and MSG, and then merged to derive a geostationary SST analysis product with near global coverage. Retrospective GOES hourly data (from 1994 on) will also be reprocessed to derive a high-resolution GOES SST climatology.

As with the IR products, MW SST products will continue to undergo development, including empirical and RTM-based approaches for optimal results from WindSat. MW retrievals have several advantages over IR, including insensitivity to atmospheric water vapor, aerosol and clouds. They will thus provide a vast improvement in spatial and temporal sampling frequency and may be used to enhance and refine IR based algorithms. However, they have the disadvantages of a smaller signal at a coarser spatial resolution, sensitivity to surface roughness and land contamination in coastal areas. Ultimately, the NESDIS goal will be to develop and implement multi-platform, optimally blended SST products that are able to incorporate the strengths of IR, MW, geostationary and polar orbiting observing systems. This would include the global geostationary and polar satellite constellations and would replace any existing SST analyses (e.g., the 50 km analysis, the NCEP OISST analysis, etc.)

3.2 Improved Validation and Skin-Bulk Effects

The RTM-based retrieval algorithms properly retrieve a surface skin temperature, whereas the conventional statistical-empirical equations are regressed against buoy-measured bulk temperatures at $\simeq$1 m depth. Because the skin and *in situ* bulk temperatures can differ significantly from one another, this presents a new challenge for validation efforts seeking to establish accuracies on the order of 0.1 K. Radiometric, as opposed to *in situ*, ground truth will be necessary for accurate, rigorous validation. One such system, the Calibrated IR In-situ Measurement System (CIRIMS), has been proposed by the University of Washington Applied Physics Lab (A. Jessup 2003, personal communication). It is estimated that at least 10-15 such instruments, distributed in key geographic locations, would be necessary for statistical validation studies. The Marine Atmospheric Emitted Radiance Interferometer (M-AERI) instrument (Minnett *et al.*, 2001) also obtains skin SST of high accuracy ($<$0.1 K absolute), but they are expensive and somewhat impractical to use solely for this purpose. However, it must be recalled M-AERI obtains high resolution IR spectra of the ocean surface and marine atmosphere—such data have already led to important discoveries that have benefited satellite SST retrieval (e.g., Smith *et al.*, 1996). Thus, ORA is currently planning to participate in a number of oceanographic research cruises involving M-AERI and CIRIMS over 2004–2006. NESDIS will also need to invest toward the development of an accurate, radiometric ground-truth system to sustain and enhance the RTM-based retrieval products of the future (e.g., Donlon *et al.*, 2002). Such a validation system will also serve to better characterize and model the skin-bulk temperature profile for optimal numerical model assimilation.

3.3 Satellite SST Climatologies

Because of known limitations in the AVHRR PATMOS and Oceans Pathfinder data sets, additional AVHRR reprocessing iterations are necessary for deriving an SST climatology with optimal accuracy. To resolve the diurnal cycle of SST, GOES data back to 1994 will be reprocessed also. The improved RTM-based retrieval algorithms will be applied to the retrospective data sets, resulting in satellite based SST climatologies useful for inter-annual and long-term climate analyses.

3.4 NPP/NPOESS Era and Beyond

After NOAA-N', the current NOAA POES series will be gradually phased out by the NPOESS program. The NPOESS series will carry a new Visible Infrared Imager Radiometer Suite (VIIRS), an instrument comparable to the Aqua/Terra MODIS. NPOESS will also have a hyperspectral IR instrument, the Cross-track Infrared Sounder (CrIS) as well as the CMIS microwave instrument. These instruments will provide enhanced capabilities for SST retrieval over the current POES/GOES. The NPOESS Preparatory Project (NPP) satellite, scheduled for launch late in 2005, will facilitate the transition from the current NASA Aqua/Terra, and NOAA POES, to the NPOESS era. NESDIS will work to provide independent quality assurance of the NPP SST EDRs developed by the NPP/NPOESS contractor. Likewise, looking beyond GOES M-Q, the GOES-R Hyperspectral Environmental Sounder (HES) and Advanced Baseline Imager (ABI) instruments will provide far more advanced capabilities for SST retrievals from the geostationary platform.

4. SUMMARY

In support of NOAA's mission and strategic goals, NESDIS plays a leading role in the development, implementation and distribution of satellite-derived sea surface temperature (SST) operational products. These data are freely available in the public domain, serving users in the government, academic and private sectors. Within NESDIS, remotely sensed SSTs are critical to the CoastWatch/OceanWatch and Coral Reef Watch programs. NESDIS satellite SST research is coordinated within the ORA/ORAD SST Science Team, with direct collaboration from OSDPD and from academia.

NESDIS satellite SST data products described in this paper are accessible on the world wide web; some URLs are provided below.

Near real-time SST imagery
http://www.osdpd.noaa.gov/PSB/EPS/SST/SST.html

Retrospective SST data
http://www.saa.noaa.gov/cocoon/nsaa/products/welcome

CoastWatch/OceanWatch data
http://coastwatch.noaa.gov/

Coral Reef Watch satellite coral monitoring
http://orbit-net.nesdis.noaa.gov/orad/coral_bleaching_index.html

Monthly GOES frontal probability data
http://manati.nesdis.noaa.gov/tmi/fronts

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