EOS Ocean Validation Plans for 2000-2003 Time Period

Summary of discussion at EOS PM Validation Meeting
April 1, 2, 1998
University of Maryland

A preliminary discussion of planned activities for validation of EOS ocean data products in the time period of the overlapping the EOS PM, Jason-1, and SeaWinds missions was conducted during this meeting. The Jason-1 team was represented by Bruce Haines, SeaWinds was represented by Mike Freilich, the AIRS/AMSU/HSB team was represented by Mous Chahine and Hartmut (George) Aumann, the MODIS sea ice team was represented by Dorothy Hall, the AMSR oceans team was represented by Frank Wentz, the AMSR sea ice team was represented by Don Cavalieri and Joey Comiso, ocean-related EOS IDS investigations were represented by Tim Liu, Peter Niiler, and Mike Freilich, and sea-ice related EOS IDS investigations were represented by Anne Walker. Other participants in the sea ice session included Martti Hallikainen from Finland, Prasad Gogineni from NASA Headquarters, and Claire Parkinson from the EOS PM project.

During the plenary session, overviews of the anticipated validation plans for Jason-1, SeaWinds, and AIRS were provided by Haines, Freilich, and Aumann, respectively. In addition, Niiler discussed the potential for using surface drifting buoys for measuring ocean currents, sea surface temperature, winds and irradiance. Liu discussed some of the scientific applications and accuracy requirements for the ocean parameters. During the splinter session on ocean validation, a short overview of MODIS SST validation plan was presented and Wentz described potential AMSR capabilities for measuring 'all weather' sea surface temperature using some new results from the TRMM TMI. The presentations demonstrated the maturity of the satellite measurements in terms of accuracy, precision and validation.

1. Sea Surface Height

Haines showed that the mean surface height from TOPEX/POSEIDON (T/P) and Jason can be validated at the cm level using data from a fully instrumented oil platform (Harvest) located directly in the path of the repeating satellite ground track off the coast of central California [Christensen et al, 1994]. He also demonstrated that a subset of the global tide gauge network can provide long-term regional, as well as global, validation of the surface height data product. Comparisons between smoothed tide-gauge and T/P sea height measurements show agreement at the 2-cm level [Cheney et al., 1994, see also http://neptune.gsfc.nasa.gov/ocean.html for recent comparisons]. Globally, the "stacked" tide gauge observations can corroborate the T/P-derived estimate of global mean sea level change at the mm/yr level [Mitchum, 1998].

Haines showed how these validation systems successfully detected the effects of a TOPEX algorithm error, discovered nearly four years after launch, that introduced a bias and drift in the sea height measurements. The expression of the error is clearly seen in the validation time series from Harvest and in the global tide gauge analysis (Fig. 1). Recent T/P validation efforts have focused on the on-board radiometer data which are used to correct the altimeter range for the effects of wet tropospheric path delay. These efforts include comparisons with alternative columnar water vapor estimates from both ground-based and other spaceborne radiometers (e.g., SSM/I), as well as radiosondes and terrestrial GPS receivers [e.g., Haines and Bar Sever, 1998]. Results of these efforts have been central to an emerging consensus that the radiometer measurements from T/P are drifting by 0.2 kg m-2 per year in terms of vertically integrated water vapor. This spurious drift implies that estimates of global mean sea level change from T/P are too low by approximately 1.5 mm/yr. A coordinated effort at calibration of water vapor measurements during the EOS PM era was suggested.

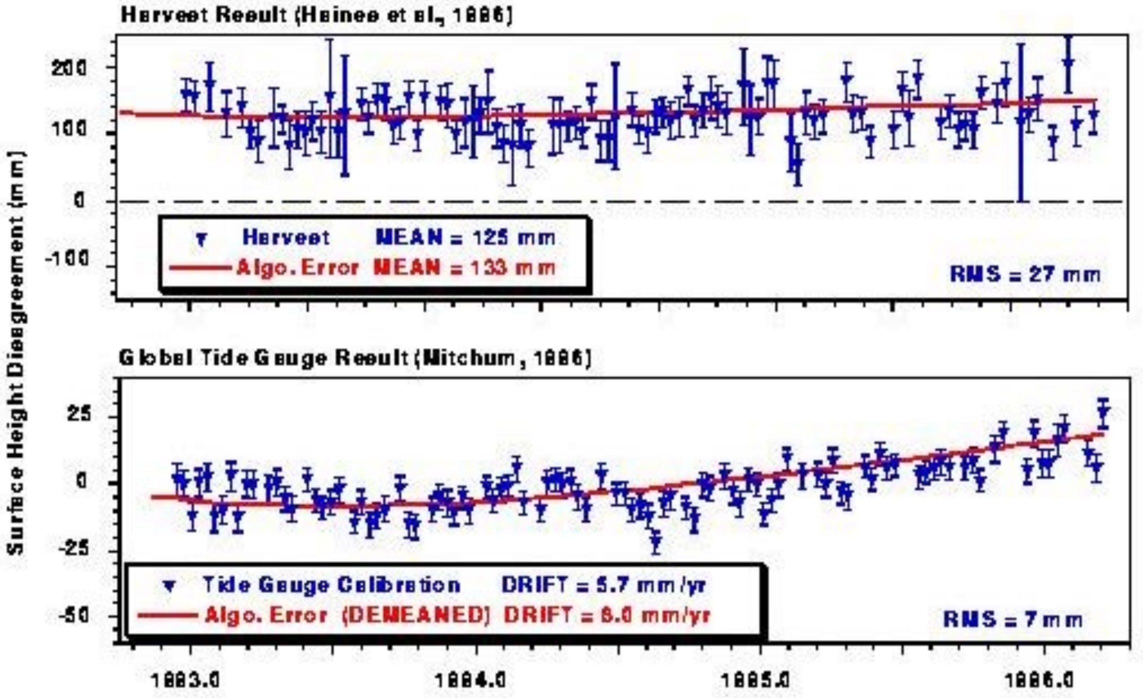

Figure 1: Validation time series of TOPEX sea-surface height measurements based on: a) Measurements from the Chevron Harvest oil platform directly under the satellite track [e.g., Christensen et al., 1994]; b) Measurements from selected tide gauges from the global network. (Lacking collocations with GPS, the tide gauge series cannot determine the absolute bias, i.e., the origin of the ordinate in the bottom panel is arbitrary.) The solid curves denote the effect of a spurious signal introduced in sea height measurements by a TOPEX algorithm error discovered nearly 4 years after launch. The Harvest data accurately detected the bias, while the global tide gauge analysis successfully identified the drift. The combined results provide a remarkably accurate picture of the effects of the algorithm error.

For the Jason era, these systems will again be used for validation. Operations support for the Harvest platform is expected from the Jason project, with funding for analysis through the Jason Science Working Team (SWT). The tide gauge network has been evaluated in a series of recent meetings [Smith, 1997; Neilan et al, 1998] and plans are underway to improve this network for altimeter validation by collocating GPS receivers with select gauges. Some funding for tide gauge network support is currently provided by NASA R&A funding; this may transfer to Jason SWT funding.

Validation of related variables: There are three other variables of interest that can be measured by Jason: 1) surface slope or upper ocean geostrophic current; 2) significant wave height (or upper tercile of surface gravity wave heights distribution within the radar footprint); and 3) wind speed (radar backscatter cross-section). Niiler pointed out some promising preliminary work on using surface drifter measurements of upper ocean velocity for validating sea surface slope/geostrophic currents. This will be pursued further during the Jason era. Significant wave heights and wind speed were not discussed at the meeting. Significant wave heights can be validated with surface buoy observations [e.g., Parke and Morris, 1995]. Validation of surface wind measurements is discussed in the next section.

Coordinated activities: For Jason in the 2000-2003 time frame, the most obvious EOS PM coordinated activity in need of development is water vapor path validation. With a variety of radiometric and sounding measurements of this variable available from both space and ground, a focused cross-instrument sub-team should meet within the next year to outline a strategy for meeting the needs of all instruments. A secondary issue is the potential for measuring surface currents by combining geostrophic flow estimates from Jason with winds derived from QuikSCAT and SeaWinds. A combined group of Jason and QuikSCAT/SeaWinds investigators will be working on this problem. Validation of this effort should be addressed in the EOS PM validation NRA.

Issues, Concerns and Needs: A primary concern for Jason is the longevity of the primary verification site at Harvest, data from which have been collected continuously since 1992. Chevron is the current operator of the platform, and its future is not assured beyond 2000. The Jason project will work with Chevron on this issue, and will explore alternative means for maintaining a permanent validation presence at or near this location. As alluded to previously, precise calibration of potential radiometer drifts at the level required to support global change studies (<1 mm/yr in terms of wet path delay) demands a concerted validation effort spanning analyses of various of ground- and space-based corroborative data sets. Finally, the impact on validation of the differences between in-situ point measurements (e.g., tide gauges) vs. satellite spot averages (e.g., altimeter footprint) requires attention. It should be noted that Jason SWT selection will be announced soon, and investigators with significant validation elements in their programs develop a coordinated Jason validation plan. Ensuring that this validation component for the Jason instrument team obtains enough funding is a concern, and is the subject of on-going discussions.

Accuracy of mapped fields (Level 3): Recent comparisons of surface height estimates from ocean circulation models, including assimilated temperature data, with TOPEX/POSEIDON for the tropical Pacific show that model-based and altimetric measurements are quite comparable. Typical differences of monthly averaged values over 100 to 200 km squares are within 3 cm rms, whereas altimeter validation with tide gauges is at 2 to 3 cm rms in this region. Clearly, an accurate representation of the gridded field is required, as well as its error covariance, in order to provide added value to assimilation systems or to use independently to assess the accuracy in ocean estimates. To date, efforts to validate and assess the accuracy of Level 3 altimeter products has been limited.

Christensen, E. J., et al, 1994: Calibration of TOPEX/Poseidon at Platform Harvest. *J. Geophys. Res.*, **99**, 24465-24485.

Haines, B., and Y. Bar-Sever, 1998: Monitoring the TOPEX radiometer with GPS: Stability of columnar water vapor measurements. submitted to *Geophys. Res. Lett.*

Mitchum, G., 1998: Monitoring the stability of satellite altimeters with tide gauges. *J. Atmos. Oceanic Tech.*, in press.

Neilan, R., P. Van Scoy and P. Woodworth, eds., 1998: Proceedings of the Intl. GPS Service for Geodynamics & Permanent Service for Mean Sea Level Workshop on Methods for Monitoring Sea Level: GPS and Tide Gauge Benchmark Monitoring and GPS Altimeter Calibration, JPL Pub. 97–17, 202 pp.

Parke, M, and C. Morris, 1995: Significant waveheight comparisons between TOPEX and Platform Harvest. Marine Geodesy, 18, 97-104.

Smith, N., ed., 1997: International Sea Level Workshop Final Report, Honolulu, Hawaii, June, 1997, 133 pp., unpublished manuscript, also available on http://www.bom.gov.au/bmrc/mrlr/nrs/oopc/slwkshop.htm.

2. Scatterometer Surface Vector Winds

Freilich discussed the validation plans for QuikSCAT and SeaWinds in the context of the NSCAT experience. Scatterometers acquire direct measurements of global backscatter (ocean, ice and land) from which near-surface vector winds over the ice-free oceans are calculated. Calibration and validation techniques for backscatter and vector winds have been developed, refined, applied, and published in the open literature for the Seasat, ERS-1/2, and NSCAT scatterometer data sets. NSCAT initial backscatter and wind validation was substantially completed within the first three months following instrument activation. Initial QuikSCAT and SeaWinds validation will follow the NSCAT model.

The accuracy of scatterometer radar backscatter cross-section measurements is quantified independently by analyses of data from distributed isotropic, stable land targets (such as the Amazon and Congo rain forests and high latitude tundra areas), analyses of open-ocean data in conjunction with operational surface wind products from ECMWF and NCEP, and directly (although with limited coverage) by measurements from (one or two) specially deployed calibration ground stations. Application of the techniques to Seasat, ERS-1/2, and NSCAT data demonstrate that relative backscatter calibration can be achieved to better than 0.2 dB.

The accuracy of scatterometer wind velocity measurements is quantified primarily through direct comparisons with spatially and temporally collocated conventional surface measurements from operational, open-ocean moored meteorological buoys. Extensive buoy arrays exist in the northern hemisphere extratropics supported by the U.S. National Data Buoy Center (NOAA) and the Japan Meteorological Agency, and in the tropical Pacific (NOAA TAO program). Techniques have been developed and refined for transforming the direct buoy measurements of anemometer-height wind speed and direction to equivalent 10-m neutral stability wind velocity (the variable corresponding to the satellite scatterometer measurements). Extensive development and testing of advanced statistical techniques has taken place and is on-going, to account for the non-negative and non-gaussian characteristics of wind speeds, the circular nature of wind directions, and the presence of errors in both the satellite and the comparison (buoy) measurements. Such detailed analyses are required to identify systematic errors, to quantify random error magnitudes to within a few cm/sec and a few degrees, and to avoid erroneous interpretation of essentially random component errors as systematic speed and direction errors. The NSCAT vector winds were determined to have small (< -0.5 m/s) overall bias, unity gain, random speed rms variability of 1.16 m/s, random direction rms errors of ~14°, and systematic directional bias of ~8° (NSCAT clockwise relative to buoys), over the speed range from ~2-18 m/s. Direction and speed comparisons are consistent with the existence of random component errors of ~1.5 m/s in NSCAT vector winds.

In addition to buoy comparisons, ERS-1/2 and NSCAT data have been compared with wind measurements from research and merchant ships, and specially deployed drifting buoys. Although inaccuracies in merchant ship data are larger than the scatterometer errors, research vessels equipped with IMET packages provide useful (if sparse) comparison data. These can be especially valuable at high southern latitudes where extreme wind conditions are more common and where operational buoy arrays are absent. Drifting buoy comparisons in the Labrador Sea provided unique information on small-scale wind field variability in support of the NSCAT validation campaigns. More indirect, but useful validation information has been obtained (for ERS-1/2 and NSCAT) through comparisons of satellite wind velocity measurements with global and regional predictions of near-surface winds from operational numerical weather prediction forecast/analysis systems, such as NCEP and ECMWF. The support of both NCEP and ECMWF, through provision of global operational analyses in near-real-time made a substantial positive impact on the validation activities of ERS-1/2 and NSCAT, and is planned for the QuikSCAT and SeaWinds missions.

Coordinated Activities: Although microwave scatterometers are the only instruments that can presently measure wind velocity (both speed and direction) under nearly all-weather conditions with useful accuracy, a variety of other active and passive EOS microwave instruments can measure near-surface wind speed. These include multichannel microwave radiometers (such as the NASDA AMSR instrument that will fly on ADEOS-II and EOS PM-1), and altimeters such as Jason. Both the radiometers and altimeters also acquire additional environmental information (such as integrated atmospheric water vapor and surface wave height) that is useful for complete validation of the scatterometer velocity data over the full range of parameters. Indeed, the presence of both AMSR and SeaWinds on the same ADEOS-II spacecraft will allow direct identification of SeaWinds measurements irretrievably contaminated by high rainfall, and correction of other SeaWinds backscatter data contaminated by attenuation from atmospheric water vapor and cloud liquid water. Coordinated active/passive retrieval of a suite of climatically important atmospheric and ocean surface measurements is being pursued by members of several EOS instrument and IDS science teams. Coordinated validation activities will be necessary to quantify the accuracy and covariance of the measurements, as well as to identify systematic errors. EOS (and specifically, ADEOS-II) will present the first opportunities to acquire the required collocated multi-instrument satellite measurements; appropriate validation analysis techniques (accounting explicitly for random errors in all of the satellite measurements) remain to be developed and tested.

Issues, Concerns, and Needs: While validation of the individual ("spot") near-surface satellite vector wind measurements is understood, proven, and planned by (and within the budgets of) the QuikSCAT and SeaWinds instrument projects, three scientifically important validation-related activities must be addressed outside the focused instrument wind validations:

(1) Quantification of the accuracy of spatially and temporally gridded products (Level 3) developed from swath scatterometer (and other instrument) measurements;

(2) Validation of algorithms and multi-instrument backscatter corrections and wind data, especially for joint scatterometer/microwave radiometer retrievals; and

(3) Determination of the effects of subsidiary geophysical quantities (such as non-equilibrium long waves, surface films, and atmospheric surface layer stratification) on the accuracy of the scatterometer measurements.

Of these, validation of the Level 3 products is by far the most important and scientifically challenging, requiring development and analysis of objective algorithms to construct the spatially and temporally interpolated fields from swath-type data (an ongoing activity), and determination of the true variability of near-surface wind velocity over the full range of scientifically relevant space and time scales. To date, neither the real scientific requirements (expressed in terms of random and systematic error magnitudes allowable as a function of scale) nor understanding of the true variability exists. The participation of IDS teams and other non-instrument scientists in the development of proper Level 3 requirements is essential. The development and validation of low-cost drifting buoys, and their dense deployment during initial satellite post-launch validation periods, may allow issues related to small-scale spatial variability to be addressed directly.

In addition to the challenges listed above, acquisition and interpretation of comparison data for extreme wind conditions, both high (> 20 m/s) and low (< 3 m/s) wind speeds, is important for the validation of the satellite measurements over the full range of climatically important conditions. Extreme conditions occur infrequently (and are sampled by satellite instruments even less frequently), and thus acquisition of a statistically valid data set of comparison measurements is difficult. Conventional measurement techniques (e.g., buoy-mounted anemometers and auxiliary meteorological measurements required for the neutral stability transformation) are known to have larger and unique errors at extreme, versus mid-range, wind speeds. Finally, contamination of direct backscatter cross-section (for the active instruments) and brightness temperature (for the passive radiometer instruments) measurements by rainfall is significantly more common at extreme high wind speeds.

2.3 Sea Surface Temperature

The infrared channels of MODIS form a self-calibrating radiometer. By using measurements of cold space and of an on-board black-body calibration target, the infrared measurements from the Earth-scan are calibrated producing radiances in the spectral intervals defined by the system response functions of each channel. These calibrated radiances can be converted to brightness temperatures (i.e., the temperature of a black-body that would give the same channel radiance) at the height of the satellite. To derive an oceanic surface temperature from the calibrated radiances at satellite height (or top-of-atmosphere) brightness temperatures, it is necessary to correct for the effects of the intervening atmosphere. The atmospheric correction is achieved by a combination of coincident measurements from different channels in the spectral intervals where the atmosphere is most transparent and well-suited to oceanic surface temperature measurement. The atmospheric constituent responsible for most of the contamination effect is water vapor, which is highly variable in its distribution, both temporally and spatially.

Several fundamentally different, but complementary, data sets are needed to provide an adequate sampling of the marine atmospheric conditions and sea-surface temperature (SST) that is necessary to validate the MODIS infrared channel measurements and derived SST fields. The validation strategy is two-fold: 1) highly-focused field expeditions using state-of-the-art calibrated spectral radiometers, supported by extensive instrument suites to determine the state of the atmosphere, to understand the atmospheric and oceanic processes that limit the accuracy of the derived SST, and 2) long-time period, global-scale data sets to provide a monitoring capability that would reveal calibration drift and the consequences of sudden or extreme atmospheric events, such as volcanic eruptions, transoceanic transport of terrestrial aerosols, cold-air outbreaks, etc. on the global SST product.

MODIS, and derivative instruments, are expected to be operational for about 15 years beginning with the launch of the AM-1 platform in 1998. Advantage will be taken of field programs that take place during the pre-launch and operational period for MODIS validation exercises. In particular, the DoE ARM (Atmospheric Radiation Measurements) program sites in the Tropical Western Pacific Ocean (TWP) and North Slope of Alaska and Adjacent Arctic Ocean (NSA-AAO) provide a valuable framework for MODIS validation as they provide an unparalleled suite of instruments to determine the state of the atmosphere (Stokes and Schwartz, 1994). These sites will operate for about a decade, beginning in mid-1996 for the TWP and about one year later for the NSA-AAO, at the extreme ranges of atmospheric and oceanic conditions. In addition to these long-term sites, use will be made of supplementary oceanic ARM sites that are intended to be operated on a short-term basis, or intermittently for specific research campaigns. Sites include the eastern North Pacific or Atlantic Oceans (probably the Azores), the Gulf Stream off the eastern U.S.A., and the Bering or Greenland Seas. Opportunities with other oceanic and marine atmospheric campaigns using ships, buoys, fixed platforms, aircraft and island stations will be grasped as funding and resources allow.

Pre-launch campaigns will be used to test strategies, constraints, and to develop the instrumental and computational tools that will be used in the post-launch validation, again as opportunities and funding allow. Examples include the Combined Sensor Program cruise to the Tropical Western Pacific in March-April 1996, the Aerosol Characterization Experiments

(ACE) in the Pacific and Atlantic Oceans, the International North Water Polynya expeditions planned for 1996 and 1997, and various other cruises of opportunity.

Coordinated Activities: Inter-satellite or inter-sensor comparisons can be done on an opportunistic basis throughout the mission. In the first few years of the AM/PM missions, suitable comparison instruments on the EOS platforms are the ASTER, AMSR, and AIRS instruments. Preliminary discussions have started with the ASTER team about cross-validation on the AM-1 platform. Coordinated validation of SST measurements needs to be worked with the AMSR and AIRS teams.

Many other opportunities exist for cross-platform validation. For example, the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA satellites, the Along-Track Scanning Radiometer (ATSR) on the ERS-2 satellite, the Advanced ATSR on the European Polar Platform of the Envisat-1 Mission, and the Global Imager (GLI) on the ADEOS-II satellite should all provide SST observations during the AM/PM missions. These instruments have a 1-km spatial resolution at nadir.

Issues, Concerns, and Needs: Cross-instrument and platform coordination with field observing efforts is complex, at best. There is a near-term need to involve the EOS Validation group in such planning. Current efforts are mainly on an investigator to investigator level.

There are basic instrument characterization concerns in the far infrared with the MODIS instruments. Pre-launch and on-orbit activities are planned to address these concerns and include characterization of digitizer operation, mirror emissivity, and relative spectral responsivity. Knowledge gained from these efforts will be fundamental to the success of subsequent validation activities.

Early processing strategies during the early evolution of EOSDIS currently appear to differ among the EOS instrument teams, i.e., processing load targets are being met by substantially differing approaches. For example, a 25% Level 2 product flow might be met by processing ~2 days per week, or, it could be met a lower resolution surface product (both have been proposed for MODIS on AM-1). Establishing congruent observing strategies for data flows for the far infrared and microwave observing instruments is needed.

2.4 Sea Ice

The two instruments on EOS PM that will produce sea ice products are AMSR and MODIS. For AMSR, the passive-microwave measurements will allow daily calculation of sea ice coverage under almost all weather conditions at a horizontal resolution of about 20 km. The AMSR measurements will extend the time series of passive-microwave sea ice measurements from the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR; October 1978 - August 1987) and the DMSP Special Sensor Microwave Imager (SSMI; starting in July 1987 and on-going). Planned standard AMSR products include sea ice concentration, temperature and snow depth on sea ice. For MODIS, the visible and infrared measurements will allow a much finer (1 km) resolution than the AMSR products, but will be hindered by clouds, thereby limiting determination of the sea ice coverage to cloud-free locations. The planned sea ice product from MODIS will be an indication of the presence or absence of ice in each 1-km cloud-free polar-ocean pixel.

Validation of the sea ice products will include in-situ, aircraft, and especially inter-satellite comparisons. Because the sea ice algorithms being developed for the AMSR are based on those earlier developed for the SMMR and the SSMI, the AMSR sea ice team expects to do pre-launch algorithm validation using SSMI data. To do so, they plan to take advantage of two major field expeditions organized by other groups. Arctic measurements will be obtained in 1998 as part of the Surface Heat Budget of the Arctic Ocean/First ISCCP [International Satellite Cloud Climatology Project] Regional Experiment-3 (SHEBA/FIRE-3). Measurements in the Antarctic will be acquired in 1999 as part of the Antarctic Zonal Experiment (ANZONE). Pre-launch inter-satellite comparisons for validating the derived SSMI sea ice concentrations will be made with NOAA Advanced Very High Resolution Radiometer (AVHRR) and Canadian Radarsat measurements. In the case of MODIS, the first MODIS instrument will be carried on the EOS AM spacecraft. The plan is to validate EOS AM MODIS sea ice measurements with in-situ measurements in the Southern Ocean in January and February 1999 (as part of a funded proposal in response to the 1997 AM-1 Validation NRA) and with measurements from the Landsat Enhanced Thematic Mapper (ETM), the European ERS-2 Synthetic Aperture Radar (SAR) and the Canadian Radarsat.

Once the PM-1 spacecraft is launched, the primary initial validation of the AMSR sea ice products will be through comparisons with the continuing SSMI measurements. There will also be comparisons with the ADEOS II AMSR, expected to be launched in the same time frame as the PM-1 AMSR, and with the ADEOS II Global Imager (GLI). Validation of the PM-1 MODIS sea ice measurements will begin with comparisons to the AM-1 MODIS measurements and the corresponding Landsat ETM, SAR, and Radarsat measurements. The MODIS measurements will then be used to help validate the AMSR measurements.

Coordinated Activities: One potentially important coordinated activity between the MODIS and AMSR sea ice teams was initiated during the Validation Workshop's sea ice working-group session. Dorothy Hall, representing the MODIS sea ice effort, showed an image from the MODIS Airborne Simulator (Fig. 2) that immediately suggested to the passive-microwave sea ice scientists the possibility of using the MODIS sea ice product as validation for the AMSR sea ice concentrations. Although the MODIS product will only be available for clear-sky conditions, it could be an effective correlative measurement for AMSR. Approximately 400 MODIS pixels will constitute one AMSR pixel. Thus, the MODIS presence-of-ice/absence-of-ice indicator will allow MODIS-derived ice concentrations to be calculated for each AMSR pixel to a quarter of a percent.

Issues and Concerns/Needs: The present sea ice validation plan concentrates on validating the sea ice concentration product. The AMSR sea ice temperature and snow depth on sea ice products must also be validated. In the case of snow depths, the working-group consensus was that the best means of validating snow depths would be through aircraft flights with as-yet-undeveloped step-frequency radars and laser altimeters, in conjunction with in-situ surface measurements. In the case of AMSR-derived ice temperatures, comparisons should also be made with in-situ surface measurements and with AVHRR- and MODIS-derived surface temperatures, although these will require the development of appropriate functional relationships between these satellite-derived surface temperatures and the ice temperatures. In view of the current emphasis of the AMSR team members on the validation of the ice concentration product, it is felt that the validation of sea ice temperatures and snow depth on sea ice would be particularly relevant for the planned PM-1 Validation NRA.

Riggs, G. A., D. K. Hall, and S. A. Ackerman, 1998: Sea ice detection with the Moderate Resolution Imaging Spectroradiometer Airborne Simulator (MAS). submitted to *Rem. Sens. of Environ.*

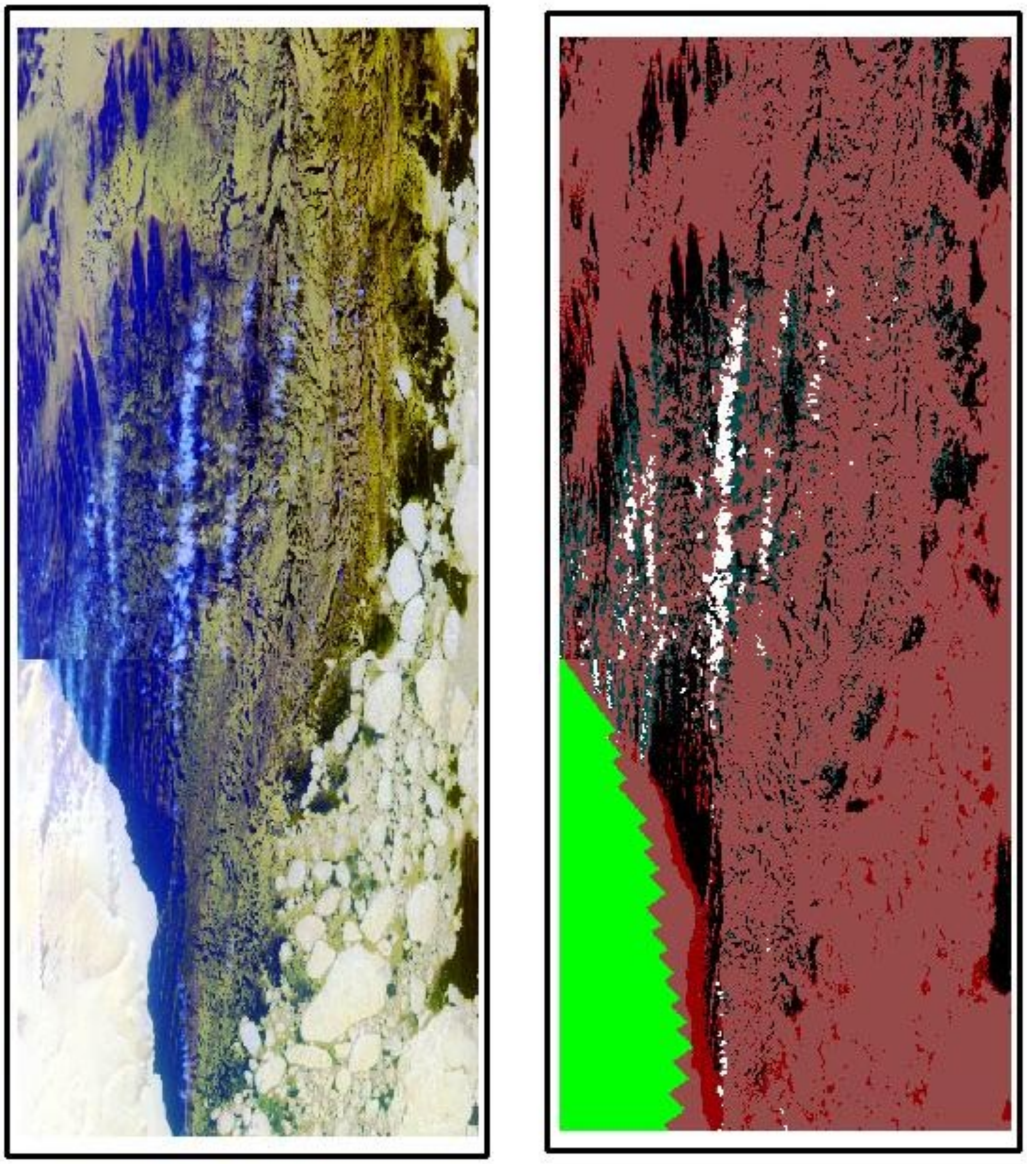

Figure 2: Images illustrating version 2 of the MODIS sea ice algorithm, using data collected by the MODIS Airborne Simulator (MAS) while overflying the Bering Sea on April 8, 1995. On the left is a false-color image of MAS bands 1, 7, and 10. On the right is the derived sea ice coverage, with St. Lawrence Island masked as green, clouds masked as white, and sea ice colored pink where determined by both reflectance and ice surface temperature, red where determined by reflectance only, and dark blue where determined by ice surface temperature only. (From Riggs et al., 1998.)