Three Years of Ocean Products from AMSR-E: Evaluation and Applications

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Abstract— **The Advanced Microwave Scanning Radiometer (AMSR-E) was launched on May 4, 2002, aboard NASA's Aqua spacecraft. Japan Aerospace Exploration Agency (JAXA) provided AMSR-E to NASA as an indispensable part of Aqua's global hydrology mission. Over the oceans, AMSR-E is measuring a number of important geophysical parameters, including sea surface temperature (SST), wind speed, atmospheric water vapor, cloud water, and rain rate. A key feature of AMSR-E is its capability to see through clouds, thereby providing an uninterrupted view of global SST and surface wind fields. The mission accuracy requirements for the suite of ocean products are 0.5°C for SST, 1 m/s for wind speed, 1 mm for water vapor, and 0.02 mm for cloud water. We present a number of validation activities that verify AMSR-E is meeting these mission requirements. Recent science applications of the AMSR-E ocean products are also discussed**

Keywords- AMSR-E, microwave radiometers, sea surface temperature, water vapor, wind speed, cloud water.

I. INTRODUCTION

The AMSR-E ocean products are now being used in a number of scientific applications. Microwave sea-surface temperatures (SST) are an essential part of the Global Ocean Data Assimilation Experiment (GODAE) high-resolution SST pilot project (GHRSST-PP). The Multi-sensor Improved Sea Surface Temperature (MISST) component of GHRSST-PP focuses on producing a multi-satellite global daily high-resolution SST and demonstrating the impact of this improved SST on operational ocean models, numerical weather prediction, and tropical cyclone intensity forecasting.

Another important science application is the generation of decadal time series of the ocean products. The AMSR-E products are being intercalibrated with past datasets to generate climate-quality time series. The water vapor time series is of particular importance because water vapor is the primary greenhouse gas in the atmosphere and is a useful proxy for the air temperature in the lower troposphere. Decadal time series of wind speed are also being produced. Both vapor and winds have been increasing over the last two decades: 1.5%/decade and 0.17 m/s/decade, respectively. This increase in both vapor and wind suggests an acceleration of the Earth's hydrological cycle.

The final science application to be discussed is the determination of the horizontal advection of water vapor. The AMSR-E vapor retrievals in conjunction with retrievals from SSM/I, TMI, and AMSU are being used to track the motion of water-vapor features over the oceans.

II. SST

A. SST Validation

To validate the AMSR-E SST retrievals, we compare them with SST measurements from ocean buoys. Two buoy datasets are used. The first is the near real time (NRT) SST's from the Global Ocean Data Assimilation Experiment (GODAE) Monterey server, which is sponsored by the Office of Naval Research (ONR) and hosted by the Fleet Numerical Meteorology and Oceanography Center (FNMOC). The second dataset is a collection of moored buoys from the National Data Buoy Center (NDBC), the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON), the Pilot Research Moored Array in the Tropical Atlantic (PIRATA), and the Marine Environmental Data Service, a branch of Canada's Federal Department of Fisheries and Oceans. Additional SST validation is done using the weekly 100-km Reynolds optimum interpolated (OI) SST [1] and the daily 50-km Real-Time Global (RTG) SST available from NCEP.

Figure 1 is an example of the locations of the NRT daily SST reports, and Figure 2 shows the mean bias (AMSR-E minus RTG) and standard deviation (STD). To calculate the daily mean bias and STD, we use a 5-day running average, only including NRT data with a probability of error less than 0.70. The 5-day window provides enough data to be a robust estimate of the mean daily bias and STD, but it is still a short enough average to quickly respond to errors.

Table 1 shows the validation statistics for the moored buoys. Very good agreement is obtained in the tropics with the TAO and PIRATA buoy arrays. However, the comparisons with the NDBC and Canadian buoys show larger standard

This work is being supported by the AMSR-E Science Team under a NASA Contract NNG04HZ47C.

deviations, which is partly due to higher spatial/temporal variability in the SST field. To examine this further, a map of the AMSR-E minus buoy mean difference and STD is shown for each buoy in the top panel of Figure 3. The bottom panel shows the mean and STD for Reynolds minus buoy SST. The background field in Figure 3 shows the mean nighttime AMSR-E minus Reynolds SST difference averaged from June, 2002 through September 2004. The Reynolds SST product is calibrated to buoy measurements, and hence the two are not independent. For this reason, the agreement in the tropics is generally very good. However at the higher latitudes, the Reynolds-buoy agreement degrades similar to that seen for AMSR-E. This is additional evidence that the high spatial and temporal variability in the region of NDBC and Canadian buoys is perhaps not well suited for validation of satellite retrievals with low spatial resolution.

Table 2 shows the validation statistics for AMSR-E versus the Reynolds SST and the RTG SST. Although the global biases are very small, Figure 3 shows spatially coherent regional biases of the order of 0.5 C. The RTG analysis is cooler than AMSR-E SSTs in polar regions. We examined RTG SSTs for a number of days and found clear cloud contamination.

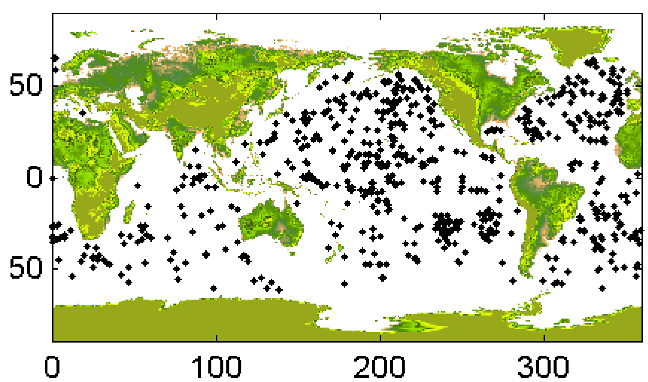

Figure 1. An example showing the location of the NRT daily in situ data collocations for AMSR-E

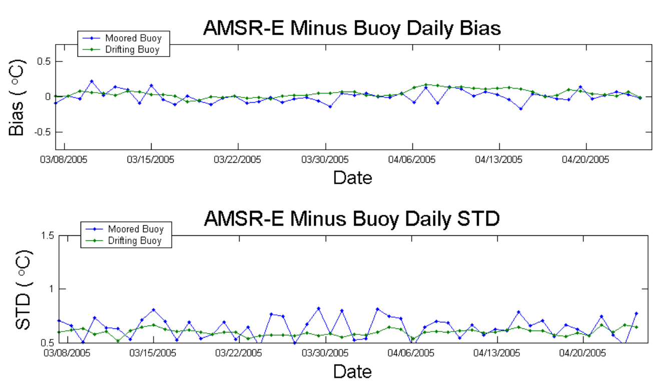

Figure 2. The mean daily bias and standard deviation of AMSR-E SSTs minus NRT SST.

TABLE I. VALIDATION STATISTICS FOR BUOY COMPARISONS

Buoy Array	**Nighttime AMSR-E minus Buoy SST**		
	Collocations	***Mean difference***	***Standard deviation***
TAO/TRITON	16396	-0.03	0.42
PIRATA	1947	-0.02	0.34
NDBC	16672	0.29	0.98
Canadian	3605	0.02	0.93

TABLE II. VALIDATION STATISTICS FOR REYNOLDS AND RTG SST

SST Comparison data	**AMSR-E minus OI SST**	
	Mean difference	***Standard deviation***
AMSR-E Day – Reynolds OI	0.06	0.63
AMSR-E Night – Reynolds OI	-0.12	0.62
AMSR-E Day – RTG OI	0.16	0.60
AMSR-E Night – RTG OI	-0.02	0.62
AMSR-E Day – AMSR-E Night	0.18	0.55

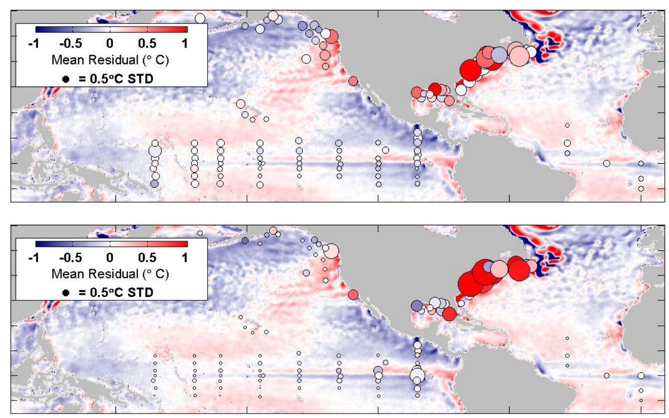

Figure 3. Mean bias (color-code) and STD (size of circle) for each buoy. The background shows the mean difference of AMSR-E nighttime minus Reynolds SSTs averaged from June 2002 through September 2004. The top image shows the mean bias and STD for AMSR-E minus buoy SST and the bottom image shows the mean bias and STD for Reynolds minus buoy SST.

B. Multi-Sensor SST Applications

The near real time operational SST fields currently available do not take advantage of the numerous satellites and different sensors now retrieving SST. These operational fields depend on a single satellite and sensor type, forcing a lower spatial and temporal resolution than what would be possible with a multi-satellite, multi-sensor SST analysis. For example, the NCEP SST field is a weekly 100-km product, and the NOAA RTG SST field is a daily, 50-km analysis based on the same AVHRR data that are used to produce the NCEP SSTs. The higher temporal resolution comes at the cost of a significant increase in uncertainty. Improved global daily SST fields would be useful for a wide range of scientific and operational activities.

With this in mind, we are investigating various methods for combining SST retrievals from different satellite sensors. Four optimum interpolated (OI) microwave (MW) SST fields have been created from the TMI and AMSR-E SSTs. One analysis contains only TMI SSTs, one contains only AMSR-E SSTs, and the third analysis blends the two SSTs. The final product under development includes TMI, AMSR-E, and MODIS SSTs. All fields are produced twice daily in NRT at 25-km resolution. These fields are intended as research for the MISST project, which is a US contribution to GHRSST-PP.

Producing a high quality, multi-sensor SST requires careful intercalibration of different satellite sensors and the calculation of sensor-specific measurement errors that may be a function of environmental conditions. In addition, we are developing techniques for relating and combining measurements at different depths, spatial resolutions, and times of the day. All of this must be implemented in the data fusion methodology. We have focused on the optimal interpolation of microwave SST measurements from space and more recently began including MODIS IR SST retrievals. Figure 4 shows a comparison between the daily 25 km MW OI SST and the (still under-development) daily 10 km MW+IR OI SST.

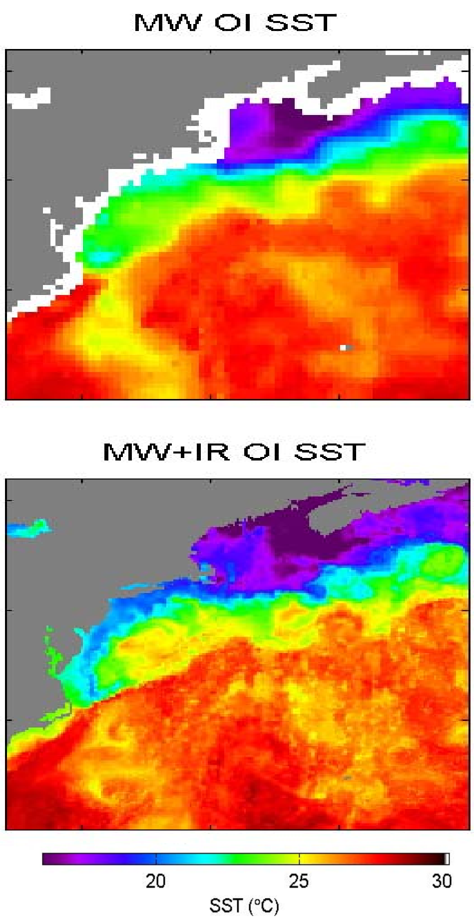

Figure 4. Gulf Stream SSTs on September 21, 2003. The top image shows the MW OI SST, a daily 25km SST that uses AMSR-E and TMI SSTs. The bottom image shows a 10 km optimal interpolation of the AMSR-E and MODIS data for a three-day window centered on September 21, 2003. A hurricane cold wake is visible in both images just below the Gulf Stream.

III. Water Vapor

A. Validation

The AMSR-E water vapor retrievals are validated by comparing them with vapor retrievals from three SSM/I's and from the TRMM microwave imager (TMI). The SSM/I's have been validated directly with radiosondes [2] and serve as our primary reference. We find generally good agreement between the AMSR-E vapor retrievals and those from the SSM/I's and TMI, with the systematic errors being on the order of 0.1 to 0.2 mm. Future plans include a direct comparison of the AMSR-E retrievals with radiosondes.

B. Decadal Climate Time Series

For climate change research, the variability of global water vapor over time is of particular importance because water vapor is the primary greenhouse gas in the atmosphere. It is responsible for 60% of the greenhouse effect, followed by carbon dioxide at 25% and ozone at 8%. Furthermore, the total columnar vapor content is a useful proxy for the air temperature in the lower troposphere. The signal-to-noise characteristics of the water vapor retrieval are considerably better than the more traditional satellite technique for measuring lower tropospheric temperature (i.e., MSU/AMSU). The AMSR-E vapor retrievals are being intercalibrated with past datasets to generate climate-quality time series of total columnar water vapor. Figure 5 shows a global map of the water vapor trend for the last 18 years. Our current estimate of the globally averaged decadal trend of water vapor is an increase of 1.5%/decade.

C. Horizontal Advection of Water Vapor

A new scientific application for the microwave vapor retrievals is under development: the determination of the horizontal advection of water vapor in the atmosphere [3]. There are currently 9 satellite microwave radiometers in low Earth orbit, including AMSR-E, all capable of imaging the total content of water vapor in the atmosphere. This array of satellites includes the SSM/Is, AMSUs, TMI, and AMSR-E.

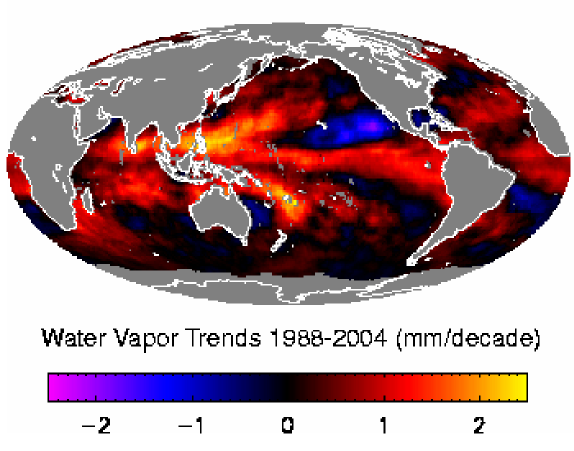

Figure 5. Linear decadal trends of water vapor change computed from satellite microwave radiometers.

With this many satellites in orbit at one time, one can do feature tracking, similar to the feature tracking that is done from geostationary images of cloud motion and upper-level water vapor motion. By tracking the total water vapor content, as opposed to just upper-level vapor, one can determine the horizontal advection of water vapor in the atmosphere. This is a critical term in balancing the precipitation-evaporation (P-E) equation. Coupled with an estimate of evaporation, the determination of the horizontal advection of water vapor provides a new and independent means of estimating monthly precipitation over the oceans.

Figure 6 shows the surface water vapor transport velocities for January 2003. Water vapor transport was calculated from SSM/I (F13, F14, F15), TMI, and AMSR-E water vapor using a very simple feature-tracking algorithm. These satellites gave greater than 90% coverage of the global oceans every 6 hours. No quality control measures have been implement yet. The box in the tropical Pacific was used to calculate water vapor transport out of the tropics (divergence). The divergence was found to match well with bulk-formula evaporation minus TRMM precipitation.

IV. Wind Speed and Cloud Water

A. Introduction

The main focus of this paper is on the AMSR-E SST and vapor retrievals. However, the two other AMSR-E ocean products, wind speed and cloud water, are equally important and we briefly discuss them here.

B. Validation of Wind Speed and Scientific Applications

The AMSR-E wind speed retrievals have undergone extensive validation via comparisons with ocean buoy, satellite scatterometers, and other satellite radiometers. Figure 7 shows a direct comparison of wind speed retrieval for AMSR and the SeaWinds scatterometer. In this case, we use the Midori-2 AMSR rather than AMSR-E because Midori-2 flew both the microwave radiometer and scatterometer. All of our validation studies indicate the AMSR-E wind speed retrieval is meeting or exceeding the mission requirement of 1 m/s accuracy.

The AMSR-E wind speed retrievals are being applied to a number of scientific investigations. Of particular importance is the calculation of evaporation fields over the ocean [4] and ocean mixed layer dynamics. The diurnal variability of SST to a large degree depends on the local wind. Gas exchange across the air-sea interface is also governed by the sea-surface wind speed. And most recently, the detection of decadal-scale variability in the winds is suggesting that winds may be playing a significant role in the acceleration of the Earth's hydrological cycle. Over the last 18 years, satellite wind retrievals have shown a 0.17 m/s/decade strengthening.

C. Validation of Cloud Water and Scienctifc Applicitions

Unlike the other ocean products, there are no reliable in situ data for validation of cloud water. In the absence of in situ, we turn to a statistical validation based on a cloud histogram analysis [2]. Cloud histograms are stratified according to SST, wind, and vapor, and then they are required to be properly aligned. A second type of validation is to identify areas of clear skies using MODIS onboard Aqua. For these clear areas, the AMSR-E cloud retrievals should be near zero. Results indicate that AMSR-E is meeting its 0.02 mm requirement.

AMSR-E cloud retrievals are important in a number of areas. Clouds control the surface energy balance through modulation of longwave and shortwave radiation fluxes. The atmospheric radiation budget requires cloud information as they play a role in latent heating and modulation of solar heating. The AMSR-E cloud retrievals reveal a strong diurnal cycle in the stratus layer over certain ocean regions, which will modulate the local atmospheric boundary layer and the heat balance of the upper layer of the ocean.

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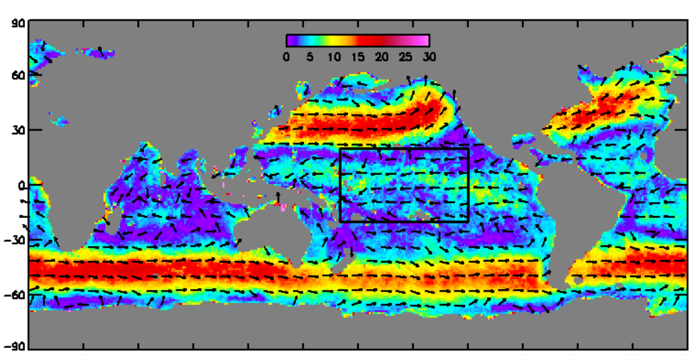

Figure 6. Surface water vapor transport velocities (m/s) for January 2003.

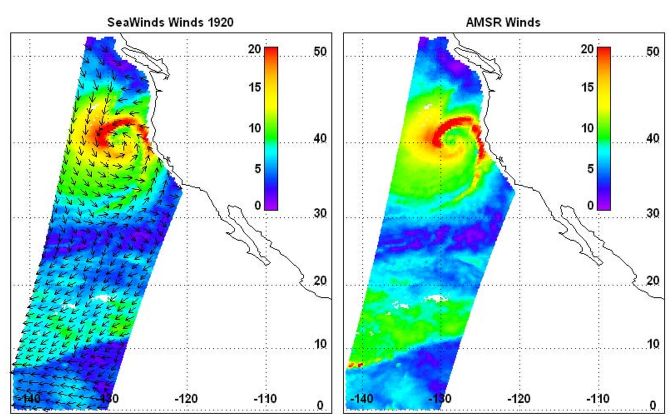

Figure 7. A comparison of the wind speed retrievals from the microwave radiometer AMSR and microwave scatterometer SeaWinds. The rms difference between these two wind estimates is 0.78 m/s.