APPLICATION OF REMOTELY SENSED WIND MEASUREMENTS TO OCEAN SURFACE WIND ANALYSIS

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1. INTRODUCTION

Oceanic surface wind data of high quality and high temporal and spatial resolution are required to understand and predict the large scale air-sea interactions which influence both the atmosphere and ocean on short and long time scales. Such observations are needed to drive ocean models and surface wave models, calculate surface fluxes of heat, moisture and momentum, provide initial data and verification data for atmospheric models, validate climate models, and construct surface climatologies. Surface wind stress provides the most important forcing of the ocean circulation, while the fluxes of heat, moisture and momentum across the air-sea boundary are important factors in the formation, movement, and modification of water masses and the intensification of storms near coasts and over the open oceans. In addition, air-sea interaction plays a major role in theories of ENSO and the 50-day oscillation, as well as in the initiation and maintenance of heat waves and drought and other persistent anomalies. Prior to the launch of satellites capable of determining surface wind from space, observations of surface wind velocity were provided primarily by ships and buoys. While these observations are extremely useful, they are limited in coverage and are generally not adequate for global applications.

Beginning with the launch of the DMSP SSM/I F08 satellite, the remote sensing coverage of the global oceans in a 6-hour period increased from 20% in 1987 to nearly 70% in 2004. From 1987 to 2007, over a dozen satellites became operational including both passive microwave sensors and scatterometers. We previously described a variational analysis method (VAM) [1] that was used to combine wind speeds derived from the DMSP SSM/I satellites into a consistent global analysis at 1 x 1 degree resolution [2]. Under the NASA funded REASoN and MEASURES programs, this work was significantly expanded. Cross-calibrated data sets produced by Remote Sensing Systems (RSS) and derived from SSM/I (F08–F15), TRMM TMI, QuikSCAT, SeaWinds and AMSR-E were combined to create a consistent, long-term (1987–2008), global data set of ocean surface winds at high resolution (6 hours, 25 km). Available data from ERS-1, NSCAT, ERS-2, and WindSat were not used initially since these were not cross-calibrated with the RSS data sets used here. The new data products are currently available for interested investigators. Here we summarize the methodology, describe the data assimilated by the VAM, and describe the products available for meteorological and oceanographic applications.

2. METHODOLOGY

The VAM that was previously used for the assimilation of SSM/I wind speeds has been enhanced for the assimilation of data from multiple platforms at high resolution [2]. In prior work, SSM/I wind speeds were treated as a type of scatterometer data. Now we define a microwave ocean surface wind speed observation operator appropriate for SSM/I, TMI, AMSR-E, and other similar instruments. Considering each satellite individually allows us to weight each differently. The weights account for data density and data quality. We also reformulated the dynamical constraint to be the integral of the squared difference between the analysis and background time rate of change of vorticity at the surface. This is to avoid overly smoothing small-scale features in the analysis where the time rate of change of vorticity might be large.

The VAM analysis is defined to be the global grid of vector winds that minimizes the following equation

$$\begin{aligned} J \;=\; & \lambda_{\text{CONV}} J_{\text{CONV}} + \lambda_{\text{SCAT}} J_{\text{SCAT}} + \lambda_{\text{SPD}} J_{\text{SPD}} + \lambda_{\text{VWM}} J_{\text{VWM}} + \\ & \lambda_{\text{LAP}} J_{\text{LAP}} + \lambda_{\text{DIV}} J_{\text{DIV}} + \lambda_{\text{VOR}} J_{\text{VOR}} + \lambda_{\text{DYN}} J_{\text{DYN}} \end{aligned}$$

Here the λ are the weights, and the J are the individual cost function terms defined in Table 1.

Table 1. Observation functions and background constraints used in the VAM.

Term	Expression	Description of constraint
		Observation Function for the
J_{CONV}	$\sum(\mathbf{V}_A - \mathbf{V}_O)^2$	• wind vectors
J_{SCAT}	$\sum(\mathbf{V}_A - \mathbf{V}_O)^2$	• wind vectors
J_{SPD}	$\sum(\lvert\mathbf{V}_A\rvert - \lvert\mathbf{V}_O\rvert)^2$	• wind speeds
		Background Constraints on the
J_{VWM}	$\int(\mathbf{V}_A - \mathbf{V}_B)^2$	• vector wind magnitude
J_{LAP}	$\int[\nabla^2(u_A - u_B)]^2 + \int[\nabla^2(v_A - v_B)]^2$	• Laplacian of the wind components
J_{DIV}	$\int[\nabla^2(\chi_A - \chi_B)]^2$	• divergence
J_{VOR}	$\int[\nabla^2(\psi_A - \psi_B)]^2$	• vorticity
J_{DYN}	$\int(\partial\zeta_A/\partial t - \partial\zeta_B/\partial t)^2$	• vorticity tendency

REASoN and MEASURES products are assimilated at 25-km resolution on a .25 x .25 degree latitude-longitude grid. For comparison a 1 x 1 degree grid was used for the previous SSM/I Pathfinder data set [2]. As spatial resolution is increased, temporal scales must be resolved more accurately. The VAM was modified to perform the analysis at the observation times. This procedure is referred to as the First Guess at the Appropriate Time (FGAT). In areas of overlapping observations from multiple platforms, the linear approximation of the time tendency of the u- and v-components inherent in the FGAT procedure can lead to unrealistic analysis increments. Recognizing that data far from the analysis time is less valuable because of the assumption of linear in time variation of the wind components, the FGAT procedure was enhanced to effectively de-weight the data as the difference between the observation time and the analysis time increases.

3. INPUT DATA AND PRODUCTS

The VAM requires a background (first guess) analysis of gridded u and v winds as an a priori estimate of the wind field. Analysis increments are added to this background to arrive at the final analysis. For this project, two data sets were used as the starting wind field. The 10-meter winds from the ERA-40 Re-analysis were used as a background for the period July 1987 to December 1998. Beginning in 1999, due to the benefits of 4d-VAR assimilation and increased spatial resolution, we made use of the ECMWF Operational analysis. Satellite surface wind data were obtained from RSS. RSS now uses a highly accurate sea-surface emissivity model resulting in much better consistency between wind speed retrievals from microwave radiometers (SSM/I, AMSR, TMI) and those from scatterometers (QuikSCAT and Seawinds). All observations are referenced to a height of 10 meters assuming that the boundary layer over the ocean is neutrally stable. We produce three standard data sets, designated as level 3.0, 3.5 and 2.5. The primary data set, denoted Level 3.0, contains 6-hourly gridded VAM analyses. These analyses are time averaged over 5-day and monthly periods to derive the Level 3.5 data set. Only those grid points containing observations that passed quality control are used in the average to ensure that the time means represent the satellite climatology. Finally, directions from the VAM analyses are assigned to the wind speed observations for each microwave sensor to derive the Level 2.5 data set on the 25-km grid.

4. VALIDATION

To validate our products objectively we examined both the analysis fit to assimilated observations and to independent observations. In general, we expect the VAM to fit the satellite ocean surface wind data better than the ECMWF (or other operational) analyses. This is in part due to the higher spatial resolution of the VAM analyses and also because not all the satellite data were used by ECMWF. It should also be noted that ECMWF used the ERS-1 and ERS-2 winds, which were not used by the VAM. The RMS wind speed fit of the VAM analysis to the assimilated satellite wind speeds is approximately 0.5 m/s for the entire 21-year period. This is a 1-1.5 m/s improvement over the ERA-40 and ECMWF operational backgrounds. The RMS wind speed fit versus Windsat, which was not used in the VAM analysis, is also improved by approximately 1 m/s. Overall, the VAM winds are unbiased relative to the satellite speeds. This is a significant improvement over the background wind field, which has a persistent low wind speed bias. The RMS direction fit of the VAM analysis to the assimilated scatterometer winds (Quikscat and SeaWinds) is approximately 5 degrees which is nearly a 10 degree improvement over the background ECMWF analysis .

5. SUMMARY

We used an enhanced variational analysis method (VAM) to combine the latest RSS cross-calibrated, multi-satellite data sets of ocean surface wind. In this way we uniformly combine all available surface wind speed observations from SSM/I, AMSR-E, and TMI, and all ocean surface wind vector observations from QuikSCAT and SeaWinds with the best ECMWF analyses. The VAM analyses cover the global ocean for the period beginning in 1987 with 6-hour and 25-km resolution. The analyses fit the data used very closely. Comparisons with withheld WindSat observations are also very good. The VAM analyses are used to assign directions to the microwave radiometer wind speed data sets. Pentad and monthly average data sets are also available. The impact of satellite sampling induced by the effect of rain on the microwave instruments is very substantial and must be considered in any analysis based on “satellite-only” data. For most purposes the VAM analyses add substantial value because these fit the microwave surface wind data very closely where such data are available and can improve upon the ECMWF depiction of small scale cyclones in the rain-induced data gaps.

6. REFERENCES

[1] Hoffman, R. N., Leidner, S. M., Henderson, J. M., Atlas, R., Ardizzone, J. V. and Bloom, S. C., “A two-dimensional variational analysis method for NSCAT ambiguity removal: Methodology, sensitivity, and tuning,” *J. Atmos. Oceanic Tech.*, 20, 585–605 (2003).

[2] Atlas, R., Hoffman, R. N., Bloom, S. C., Jusem, J. C. and Ardizzone, J. V., “A multiyear global surface wind velocity data set using SSM/I wind observations,” *Bull. Am. Meteorol. Soc.,* 77, 869-882 (1996).