esa SP-244
September 1985
ISSN 379-6566

The Use of Satellite Data In Climate Models

Proceedings of a conference held in Alpbach, Austria 10 – 12 June 1985

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Cover: *Marine wind field over the Pacific Ocean derived from Seasat scatterometer data. The vectors show wind direction, with length proportional to wind speed.*
Credit: P. Woiceshyn, Jet Propulsion Laboratory.

Proceedings published by: ESA Scientific & Technical Publications Branch
ESTEC, Noordwijk, The Netherlands

Compiled by: J J Hunt

ISSN 379-6566 Price code E3

Printed in The Netherlands

ASSIMILATION OF MICROWAVE DATA IN ATMOSPHERIC AND WAVE MODELS

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1. The task

The series of microwave satellites planned for operation in the nineties (ERS-1, N-ROSS, TOPEX, MOS-2, ...) will provide a wealth of data on global sea surface topography, surface winds, ocean waves, sea ice, and other fields, opening up important new perspectives for climate research and weather and wave forecasting. In the following I discuss some of the problems we face in using these data effectively for climate or forecasting applications. In particular I wish to address the need for an end-to-end data processing and assimilation system, including algorithms, dynamic data assimilation methods and high resolution models, in order to produce the basic global data sets required for climate research. It turns out that the data processing needs for climate studies are essentially the same as the processing needs for forecasting applications, so that the same system will satisfy both purposes. I discuss also the relation of this end-to-end system, designed for the quasi-real time generation of level III gridded wind and wave fields, with other components of the ground segment, such as the generation of fast delivery (FD) products or the primary archiving facilities (PAFs).

At first sight, the climate and forecasting applications of satellite microwave data appear to pose quite different processing problems. The geophysical fields required for climate research (primarily sea ice, sea surface topography and surface winds - although the generation of wave statistics for off-shore and coastal engineering purposes may also be regarded formally as a climate application) can be produced off-line as 'precision' products, without any time constraints on the data processing cycle. For forecasting applications, on the other hand, the processing of the satellite data, and the imbedding of the processed data into the other data streams which enter into the forecasting operation, must be completed within a few hours of reception of the original satellite sensor data. On closer inspection, however, the formal separation between 'precision' off-line processing and quasi-real-time processing is applicable only for a sub-set of satellite sensors, namely the SAR image data (for sea ice and oceanographic surface features, but excluding waves) and the altimeter sea surface topography data. SAR image processing can be carried out independently of other data, and the precision processing of altimeter mean sea level data requires detailed satellite tracking data and complex orbital reconstitution computations which cannot, and need not, be carried out in quasi-real time. For the wind and wave data, on the other hand, the situation is basically different. In this case a reliable reconstruction of the required global fields cannot be achieved with the satellite sensor data alone because of the unavoidable space-time undersampling of weather scale phenomena by any satellite system consisting of only a small number of satellites, and the inherent ambiguities and inter-dependencies of the various satellite microwave wind-and-wave sensing systems. An optimal reconstruction of the complete global wind and wave fields requires the imbedding of the satellite data in the full set of all available conventional meteorological and wave data, together with the application of sophisticated atmospheric and surface wave models to assimilate the data from different sources in a dynamically consistent manner.

A continuously operating general dynamical data assimilation system requires considerable computer resources and data handling facilities. It can be implemented only at a few well equipped weather centres (e.g. the European Centre for Medium Range Weather Forecasts) which have the necessary experience in the operation of global models and data assimilation systems. The assimilation can also be carried out operationally only on a quasi-real time basis, as part of the regular forecast operation of the centre. A repetition of the analysis at a later time to allow, for example, for a more careful screening of the data, the inclusion of 'late' data, or an improvement of the sensor algorithms, would be very costly and could probably be carried out only for a few selected periods.

2. Wind and wave sensor algorithms

Table 1 lists the microwave sensors to be deployed in planned future ocean satellites which provide data on surface winds or waves. As is evident from the table, a typical property of most sensors is that the information they yield is incomplete or ambiguous. The sensor data must therefore be augmented by independent information to uniquely determine the wind and wave field at a given location. Another characteristic of microwave wind and wave sensor systems is the inter-dependence of the sensor algorithms. For example, wind scatterometer

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Instruments	Measured variable	Sensor data	Potential accuracy	Ambiguities and uncertainties	Additional information required for algorithms
altimeter	significant wave height H_s	return pulse shape	~ 10%	none (no information on spectral distribution)	none
	windspeed U	cross-section	~ 20%	dependence on sea state (no information on wind direction φ)	surface wave spectrum
scatterometer	windspeed U and direction φ	cross-section for 3 look directions	U:~ 10% φ:± 20%	~ 180° directional ambiguity: influence of stability, sea state and other factors on backscatter insufficiently understood	atmospheric stability, surface wave spectrum
SAR (wave mode)	wave spectrum $F(\underset{\sim}{k})$	SAR image spectrum	wave numbers linear domain): 10% spectral transfer function: 20% (?) nonlinear disortion?	nonlinear distortions for short wind seas; transfer function dependent on local wind	wind speed and direction, atmospheric stability

Table 1. Wind and wave microwave sensors of planned ocean satellites

algorithms based on a physically realistic backscattering models require the wave field as input. Conversely, the transformation relation between a SAR image spectrum and the surface wave spectrum depends on the local wind vector. These properties imply that the sensors can be used effectively only in a data assimilation mode, which makes maximal use of the available data (even when this is incomplete or ambiguous), while at the same time providing first quess estimates for the input fields required for the algorithms.

The principal features of microwave wind and wave sensor systems listed in table 1 may be summarized as follows:

2.1 Radar Altimeter.

The significant wave height H_s can be inferred to within about 10% from the return pulse shape. This is one of the very few examples of a microwave measurement which is essentially free from contamination by other fields. (The wave information is, of course, nevertheless incomplete and is useful only if assimilated with additional wave data in a wave model.)

The wind speed U can be inferred from the mean backscatter return, which is inversely proportional to the rms slope of the sea surface. However, the relation between wind speed and rms wave slope is not unique, depending, among other factors, on the state of development of the windsea, the presence of swell and the air-sea temperature difference. A general algorithm including all of these factors has yet to be developed. The sensor yields no information on wind direction.

2.2 Wind scatterometer.

Theoretically, both wind speed U and wind direction φ can be obtained from this instrument by measuring the backscatter cross-section σ^o of a given patch of the ocean for three different look directions. The windspeed is inferred from the empirically determined increase of the backscatter cross-section with windspeed. This is usually approximated by a power law $\sigma^o \sim U^n$, where n typically lies in the range 0.8 - 1.5 for C band and 1.8 - 2.5 for K_u band. The wind direction is derived from the differences in σ^o for the three look directions, making use of the empirically determined azimuthal dependence of the backscattering cross section (cf. Fig. 1).

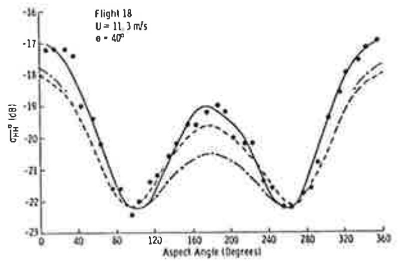


Fig. 1. Azimuthal dependence of backscattering cross-section (HH polarization). Solid line and dots are observations from Moor et al (1978), dashed line and dashed-dotted line are models with empirical ripple directional distribution and theoretical ripple-long wave modulation (from Iwata, 1983)

If only two look directions are available, as in SEASAT, the wind direction can be determined only to within four possible solutions. The addition of one more look direction, as planned for the ERS-1 (one-sided) and N-ROSS (two-sided) scatterometers, theoretically makes the directional determination unique. However, if statistical clutter noise and other signal contaminations are taken into account, a more realistic assessment is that three-look scatterometers will generally reduce the number of directional ambiguities from four to two, the two solutions being separated by approximately 180°. The residual 180° ambiguity is most easily resolved by imbedding the scatterometer wind algorithm in a general data assimilation system which provides a first guess wind vector constructed from all available data with the help of an atmospheric model.

Another reason for a general data assimilation approach to scatterometer data processing is the interpretation of the sensor signal. From our knowledge of radar backscattering from the sea surface, it is rather clear that the empirical scatterometer formula developed for SEASAT of the simple type $\sigma^o = \sigma^o\ (U,\ \Theta,\ \varphi - \varphi_\ell)$, where Θ is the angle of incidence, φ the wind direction and φ_ℓ the scatterometer look direction (cf. Schroeder et al, 1982), cannot capture the essential physics of the backscatter return except for fully developed sea states. While the upwind-crosswind cross-section ratio is essentially determined by the directional distribution of the short backscattering ripples, and is therefore indeed largely governed by the local wind direction, the upwind-downwind asymetry is produced by the hydrodynamic and tilt modulation of the short ripples by the longer waves, and is therefore dependent on the local wave spectrum, $F(\underset{\sim}{k})$. This need not be aligned with the wind. Measurements do indeed indicate a significantly larger scatter of the amplitude and phase of the first harmonic of the azimuthal cross-section dependence (cf. fig. 1), which is a measure of the upwind-downwind asymetry, than the second harmonic, which determines the upwind-crosswind ratio (cf. ESA C-band campaign, 1985). Although smaller than the second harmonic, it is the first harmonic which enables a theoretical unique solution to be extracted from a three-look scatterometer.

In addition to sea state, the stability of the atmospheric boundary layer is believed to have a strong influence on the backscatter cross-section. It is not known whether this effect can be completely absorbed by regarding σ^o as a function of the friction velocity u_* instead of the wind speed at some prescribed height.

A general backscatter model which takes all of these influences into account in a physically consistent manner has yet to be developed (present empirical models do not even satisfy the requirement of dimensional consistency). Since a great deal of backscatter data already exists and additional data are continuously being collected by a number of experimental groups, it can be confidently expected that more satisfactory, physically based backscatter models will be developed in time for the launch of the next generation of ocean satellites. However, these will almost certainly require auxillary input data and can therefore be applied in algorithms only in the context of general date assimilation schemes.

2.3 Synthetic Aperture Radar.

A SAR yields sea surface images whose wavenumber spectra $F_s(\underset{\sim}{k})$, under certain conditions, can be linearly related to the symmetrized surface wave spectrum

$$\hat{F}(\underset{\sim}{k})=\frac{1}{2}(F(\underset{\sim}{k}) + F(-\underset{\sim}{k})) = T(\underset{\sim}{k})F_s(\underset{\sim}{k}) \qquad (1)$$

The transfer function $T(\underset{\sim}{k})$ is determined in part by the kinematics of the large-scale wave field (cf. Alpers et al., 1981, Hasselmann et al., 1985). However, it is also partly dependent on the hydrodynamical interactions between large and small scale ocean waves, which in turn depend on the local wind field. Thus we are faced with the need for a first guess of the unknown wind field to derive the wave spectrum from the SAR spectrum. The ambiguity in wave propagation direction of the "frozen field" wave spectrum $\hat{F}(\underset{\sim}{k})$ also implies that additional information is required to use SAR wave data. Thus a general data assimilation system is again called for.

A further need for data assimilation arises from the problem of nonlinear image distortion (cf. fig 2). This is produced by scatterer motion (velocity bunching) and affects particularly short wavelength windseas generated by weak to moderate wind fields. Without independent information from wave models it is difficult to decide whether a SAR spectrum of the type shown in Fig. 2b, for example, represents a linearly imaged low amplitude swell field or - as was the case in the present numerical simulation - a nonlinearly distorted windsea spectrum. However, with the aid of a first guess wave spectrum from a model and nonlinear inversion methods it should be possible to extract useful information on the wave spectrum also in the nonlinear regime.

3. Data assimilation system

Figure 3 shows a simplified block diagram of the various elements needed for a complete end-to-end wind and wave data assimilation system. Also indicated are the fast delivery (FD) product segment and a primary archiving facility (PAF) (the terms are taken from ESA terminology for the ERS-1 ground segment, but similar facilities are planned for other satellites). The data assimilation system, and most of the elements of the primary archiving facility, should be designed to handle all satellite data. Mutual compatability of the data assimilation system (DAS), FD segment and PAF should be ensured through the use of the same models, data processing methods etc.

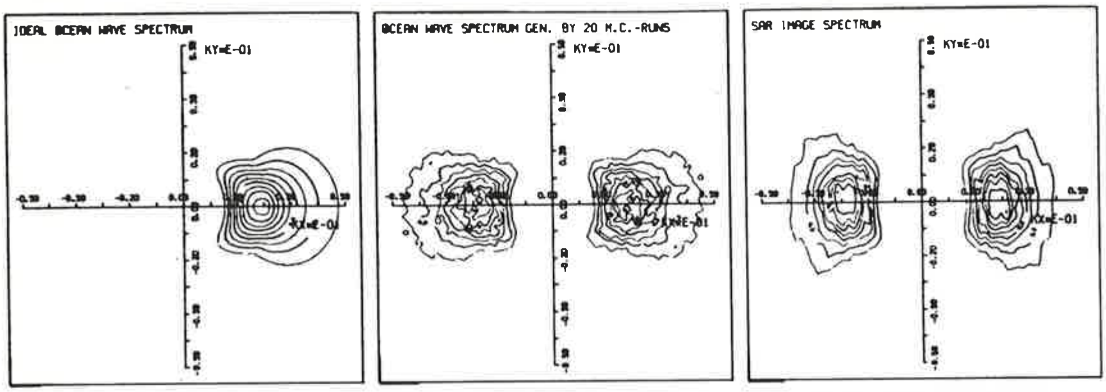
The main difference between FD products and the DAS output is that FD processing is based on individual satellite data only. The sensor algorithms will therefore generally differ from those used in the DAS. The FD and DAS products also differ in output format. The former are limited to the sensor swaths, whereas the latter extend over a global grid. However, FD products will generally be available at higher spatial resolution than the DAS products and are therefore useful not only as a backup, but also for special investigations.

In addition to the archiving of FD and DAS data products, the principal task of a PAF is the validation and improvement of models and algorithms. This can be achieved, for example, through individual field campaigns, continuously operating "sea truth" master stations, and monitoring the FD and DAS output products. Improvements of models and algorithms can then be fed back into the FD and DAS segments.

The individual processing segments and data flow branches of the data assimilation system can be presented in fig. 3 only in broad outline. A more detailed description of data assimilation methods is given for the case of atmospheric models in

MONTE CARLO SIMULATION

a) LINEAR REGIME

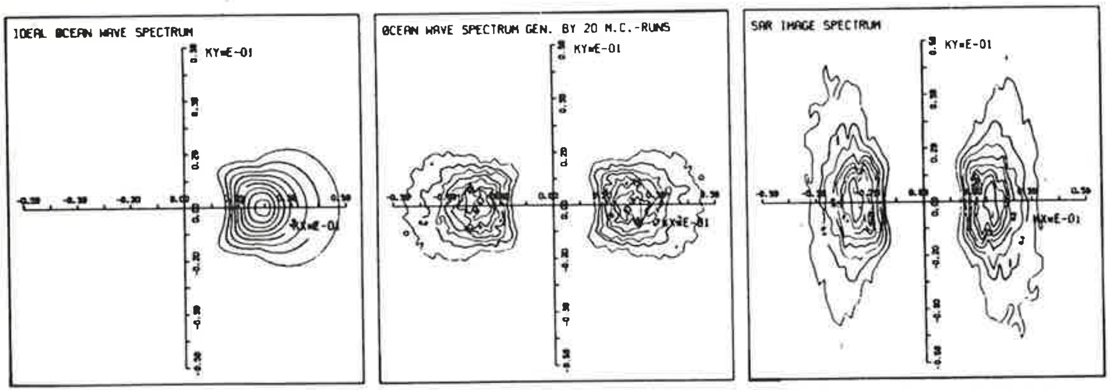


WAVE SPECTRUM

SIMULATED SYMMETRICAL WAVE SPECTRUM

SIMULATED SAR SPECTRUM

b) WEAKLY NONLINEAR REGIME

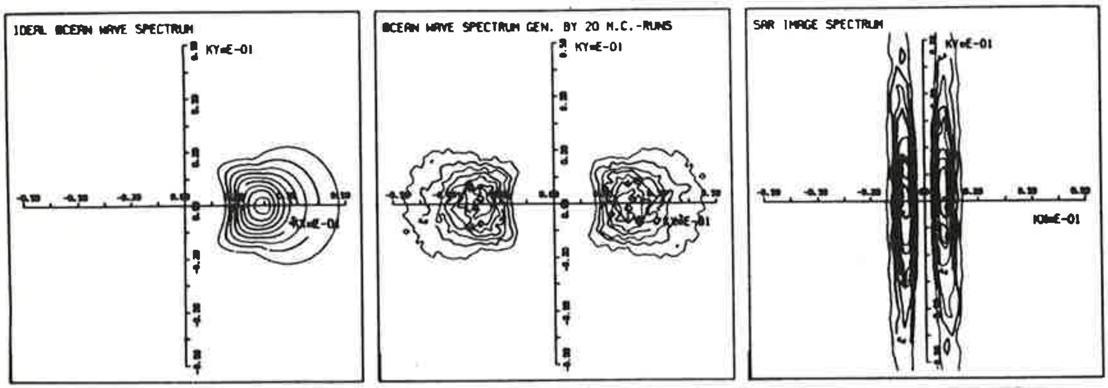


WAVE SPECTRUM

SIMULATED SYMMETRICAL WAVE SPECTRUM

SIMULATED SAR SPECTRUM

c) STRONGLY NONLINEAR REGIME



WAVE SPECTRUM

SIMULATED SYMMETRICAL WAVE SPECTRUM

SIMULATED SAR SPECTRUM

Fig. 2. Simulated mapping of surface wave spectrum into SAR image spectrum in (a) linear, (b) weakly nonlinear and (c) strongly nonlinear domain (from Brüning et al, 1985).

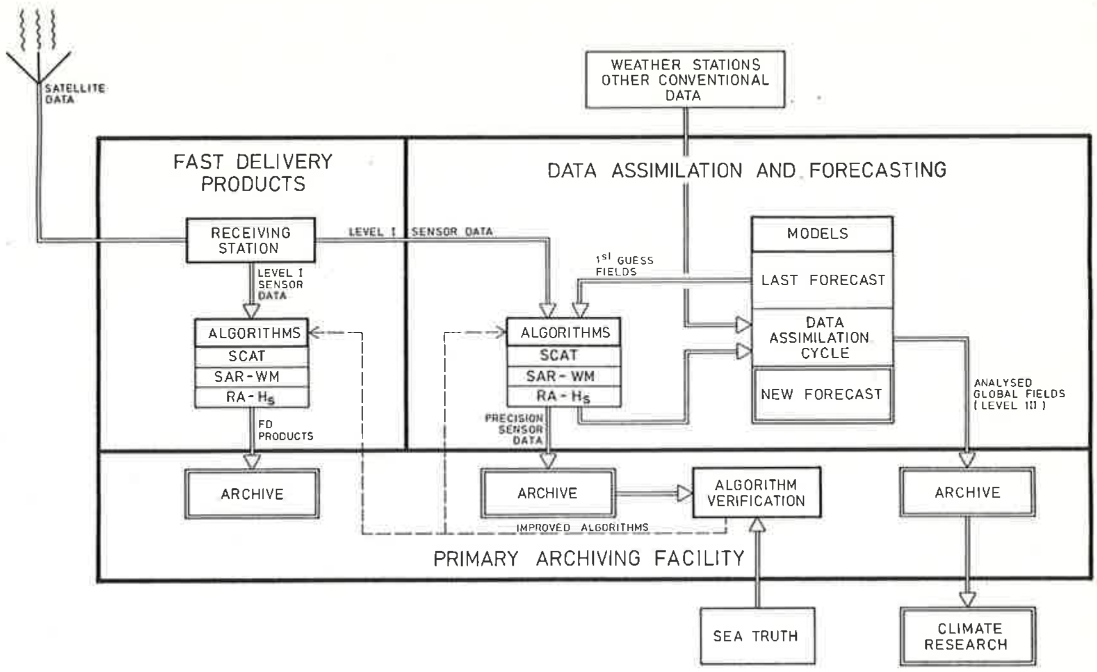


Fig. 3. Ground segment elements required for satellite wind and wave data processing. The end-to-end data assimilation system (DAS) is coupled to the fast delivery (FD) product segment and a primary archiving facility (PAF).

the contribution by L. Bengtsson in this section of the Symposium Proceedings. The extension to wave data and models requires no modification of the basic approach. However, in contrast to the atmospheric problem, where considerable experience in data assimilation has already been gained in the framework of operational weather forecasting, very little work has yet been carried out on wave data assimilation. Thus the incorporation of wind and wave data, with associated models, in a common data assimilation system poses some new technical problems.

The data assimilation system accepts as input calibrated, co-located physical (level I) satellite sensor data, together with standard meteorological observations and other conventional data. It produces two principal outputs: (i) the analysed global fields of surface wind and/or surface stress (as part of the specification of the atmospheric state) and the surface wave spectrum, and (ii) the forecast atmospheric state and wave field (for the basic data assimilation cycle, only short term forecasts are needed, but medium range global forecasts are, of course, produced as the main output of the forecast centre). In addition, the system can produce as intermediate output: (iii) a higher precision version of the FD product, i.e. a high spatial resolution wind and wave field along the satellite sensor swaths, derived from DAS sensor algorithms using the first guess information available from models.

To extend existing data assimilation systems for weather forecasting into general data assimilation systems for satellite surface wind and wave data a number of additional steps are required:

- Wind scatterometers probably provide a closer measure of the surface stress than the near surface wind. Surface stresses are not used as input data in present data assimilation schemes. However, if boundary layer stability data is available, for example from the atmospheric model, surface stress data can be readily converted into equivalent wind data, which can then be assimilated using standard techniques.

- Wave models have not yet been operated in conjunction with atmospheric models in a common data assimilation and forecasting system. It would be useful to gain experience in this area by operating the global third generation wave model currently being developed by the Wave Modeling (WAM) group (cf. Komen, 1984, WAM group, 1985) together with a global atmospheric model, for example, from ECMWF.

- Very little work has been done on the assimilation of wave data in wave models. The assimilation techniques may be expected to differ in various aspects from the corresponding methods used for atmospheric models. For example, the effective region of influence of a wave spectrum measurement is not constant, but depends on the form of the measured spectrum. A wave field update will generally also require some form of wind field update for consistency. A series of numerical experiments using conventional wave observations, SEASAT data and synthetic satellite data would be highly desirable to develop and test wave data assimilation techniques.

- The incorporation of wind and wave sensor algorithms in a general data assimilation scheme requires the modification of existing algorithms in order to exploit the information available from models and other observing systems. In addition, some basic algorithm development is needed to properly include the interactions of wind and waves in the various sensor systems (cf. table 1). Algorithms also need to be developed to extract useful wave spectral information from SAR images in the nonlinear imaging regime.

The scientific community will clearly need to mount a major coordinated research programme in order to accomplish these tasks and implement an operational end-to-end wind and wave data assimilation system in time for the launch of the next generation ocean satellites. It is therefore important that research groups and supporting agencies look beyond the immediate goal of successfully launching and operating the satellites and invest the additional effort required (which still represents only a small fraction of the total costs) to fully realise the great potential of these satellites for climate research and forecasting

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