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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.

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REPORT OF THE WORKING GROUP ON WIND AND WAVE DATA

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1. PROCESSING AND ASSIMILATION OF WIND AND WAVE DATA - OVERVIEW

The role of the oceans in climate has repeatedly been declared one of the highest priority problems of the World Climate Research Programme. A major advance in this question is expected within the next decade from microwave ocean satellites, which for the first time will provide continuous, global data on the ocean circulation and the surface wind field driving the ocean circulation. The availability of such satellites has provided the basis for the planning of the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean and Global Atmosphere (TOGA) programme within the WCRP.

Working Group A has addressed in particular the problem of reconstructing the surface wind field over the ocean from satellite data. In many aspects this problem is found to be closely intertwined with the task of processing and assimilating satellite surface wave data. Thus the Working Group considered both wind and wave data in conjunction.

Satellite surface wind data will be obtained primarily from microwave scatterometers and altimeters to be flown on ERS-1, N-ROSS, TOPEX and possibly other satellites. Although these all-weather instruments will provide continuous, global coverage, the space-time density of the satellite sensor swaths will nevertheless be insufficient, on their own, to reconstruct the complete space-time history of the global surface wind field with the resolution required for ocean circulation and climate studies. Microwave satellite sensors also suffer from inherent ambiguities in signal interpretation and calibration uncertainties. For these reasons, it is essential that the microwave satellite data are combined with other, conventional data which provide direct or indirect information on the surface wind field (surface pressure observations, ship winds, buoys, etc.). Upper air data (radiosonde stations, meteorological satellites, etc.) also contribute to the definition of the surface wind field through the dynamical interrelations of these data with surface data. Thus the task of reconstructing the surface wind field from satellite data appears as a general data assimilation problem, in which the satellite data is imbedded within the complete set of all available data from the World Weather Watch Global Observing System, the surface wind fields being obtained as one particular output field in the definition of a dynamically consistent complete atmospheric state.

Methods of data assimilation are already widely used operationally in weather forecasting. The methods can be readily adapted to accept satellite wind data, which can be treated in essentially the same way as ship wind data. The assimilation procedure relies on a forecast model for the dynamically consistent interpolation of data from different locations and times. Because of the complexity of the models and the large data handling requirements, a satellite data assimilation method can be implemented effectively only at an operational forecast centre, the assimilation being carried out in quasi-real time within the assimilation cycle of the normal forecasting operation. The reconstruction of surface wind fields from satellite data for climate applications therefore requires the same data processing as the application of the satellite data for weather forecasting.

A similar situation exists with respect to the processing of satellite wave data. Taken alone, the information content and space-time density of satellite wave data, provided by radar altimeters and SAR systems, are insufficient to reconstruct the global wave field reliably. Thus the data must again be assimilated, together with other relevant data, in wave models. This procedure again requires sophisticated models and can be carried out routinely only in quasi-real time as part of a wave forecasting operation. Thus even if the envisaged application of the satellite wave data is not real time (for example, the generation of wave statistics for off-shore engineering design purposes) the availability of the processed wave data will depend on the implementation of a quasi-real time wave forecasting operation with an appropriate wave data assimilation cycle.

Wave data assimilation requires supporting wind data assimilation, since surface winds are needed to drive the wave models used to assimilate the wave data. Conversely, wave data are also potentially useful for wind field reconstructions, since the wind wave spectrum depends very sensitively on the generating wind field. Because of the dynamical interrelationship between wind and wave fields, wind and wave data assimilation schemes for future ocean satellites should be designed as a joint system.

The need for a coupled wind and wave data assimilation approach follows also from the nature of the satellite microwave sensing systems themselves. The received microwave signals are determined by the backscatter from short ripple waves in the 1-10 cm wavelength range (with the exception of the nadir looking radar altimeter, which responds to the rms waveslope). The energy level and directional distribution of the ripples depend both on the local wind speed and direction and on the interaction of the ripples with the longer ocean waves, i.e. on the local sea state. The extraction of reliable wind and wave information from these sensors therefore requires a simultaneous consideration of both fields. The construction of such interactive algorithms can generally be greatly simplified if first guesses of the fields are available. If the sensor algorithms are incorporated in the general data assimilation scheme, these can be provided by models.

In summary, the effective application of satellite wind and wave data for both climate studies and forecasting requires the implementation of a complete, quasi-real time, operational end-to-end system, starting from satellite sensor algorithms operating on the (calibrated and colocated) physical sensor data on the input side, and producing as output continuous, global wind and wave fields with the space-time resolution appropriate to operational high resolution atmospheric and wave forecast models.

The implementation of such a system poses a major challenge to the international scientific community. A significant responsibility naturally rests on European scientists through the commitment to ERS-1. The institutional conditions for carrying out the necessary joint research and development are also favourable in Europe through the establishment of the European Centre for Medium Range Weather Forecasts (ECMWF), which offers a unique combination of operational and research facilities ideally suited for the task. However, the problem is not restricted to ERS-1, and all efforts should be made to implement a system (or systems), in collaboration with scientists from the US, Canada and other nations, which would be able to process all data from all satellites, together with all available conventional data, in a complete global data assimilation system.

The possible structure of such a system, and some of the problems to be faced in implementing the system, are outlined in the position papers and contributing presentations of Working Group A in the appendix. In the following we have attempted to break down the problem into a series of interrelated tasks. The task areas suggested by the Working Group may serve also as a possible framework for the coordination of the various project proposals related to wind and wave data assimilation which are expected to be received by ESA in response to the preliminary ERS-1 Announcement of Opportunity issued in June 1985.

2. TASKS

2.1 Sensor algorithms for wind data

The purpose of this task is to define and implement algorithms for deriving wind data from radar scatterometers (wind speed and direction) and radar altimeters (wind speed only). General backscatter models need to be developed which are applicable for different instruments on different satellites (e.g. both the ERS-1 C-band and N-ROSS K_u-band scatterometers). The dependence on both local wind and local sea state (which cannot generally be regarded as function of the local wind) should be included in the backscatter models. The algorithms should be designed for incorporation in a general data assimilation scheme, so that first estimates of the wind and wave fields can be assumed to be available from models. In this respect the algorithms may differ from those used for the generation of fast delivery (FD) products (task 3), which cannot draw upon model information.

The work in this task needs to be closely coordinated with work tasks 2 (wave algorithms), 3 (FD products), 4 (data assimilation, overall strategy), and 7 (field campaigns, commissioning and validation).

2.2 Sensor algorithms for wave data

The principal wave data available from satellites are significant wave height from radar altimeters and two-dimensional wave spectra (with 180° ambiguities in propagation direction) from SAR images.

The interpretation of SAR images is complicated by the fact that the modulation of the backscattered return of the short ripples by longer waves (which is the mechanism by which a SAR sees long waves) depends on both the local sea state and the wind speed. Furthermore, the imaging mechanism can become strongly nonlinear for windsea spectra at weak and moderate windspeeds. For these reasons the usefulness of SAR wave data is strongly dependent on the incorporation of SAR wave data algorithms in a general data assimilation system in which first guesses of the sea state and wind field are available from models. But wave data assimilation schemes are also required independently for radar altimeter wave data, since significant wave height data alone are of limited value unless augmented by directional and wavelength information.

In contrast to surface wind data, very little experience exists to date in the assimilation of wave data in wave models. The problem differs in some important aspects from the meteorological data assimilation case. Thus pilot projects are urgently needed to develop the proper assimilation methods and define the appropriate interface between sensor algorithms and the data assimilation (cf. task 5). The work of this task is also closely related to tasks 1 (wind algorithm), 3 (FD products), and 7 (field campaigns, commissioning and validation).

2.3 Fast delivery products

In the case of ERS-1, the fast delivery of wind and wave products (within 3 hours after raw data reception) is a contractual requirement of ESA. Similar arrangements presumably apply for satellites of other agencies. This distinguishes the FD product task from other processing and assimilation tasks considered by the Working Group, where the primary responsibility lies with the user community rather than the satellite agency. Nevertheless, the Working Group considers it important that the user community is also involved in the development of FD products through the establishment of a formal user group for this task. Such a task group would provide the necessary interface between the contractual work of ESA and the requirements of the user community. The modellers, in particular, will need FD products as a quick-look back-up for the more sophisticated algorithms to be developed in the framework of a general end-to-end data processing and assimilation system. For this purpose it is important that the FD products are compatible (for example, in terms of the backscattering models used) with the algorithm developed by the user community in tasks 1 and 2. Coordination is also required with the work of task 7 (field campaigns, commissioning and validation).

2.4 Data processing and assimilation - overall system

A more detailed analysis and definition needs to be given of the general end-to-end wind and wave data processing and assimilation system outlined in the papers in the appendix (cf., for example, Hasselmann). The analysis should include data flow requirements and estimates of the computer resources and man years needed for the various tasks within the specified system segments. A broad breakdown of tasks has been carried out by the present Working Group in the context of this report. Further detailed planning of certain segments of the complete system has been carried out by the WAM (Wave Modelling) Group, for example with respect to the development of a global 3rd generation wave model for wave data assimilation and forecasting applications. The purpose of the task group should be to undertake the coordination of the various tasks required to develop and implement the complete end-to-end data processing and assimilation system.

As a first step, the Working Group recommends that ESA initiate a Phase B study of such an end-to-end system, with particular emphasis on the implication of the system on the ground segment envisaged for ERS-1. However, the task group should remain active beyond the completion of the Phase B study and continue to coordinate the development of the system, which represents a pivotal element for the future effective use of ocean satellite data for climate applications and weather and wave forecasting.

2.5 Wave data assimilation

In contrast to the assimilation of wind and other atmospheric data, very little experience exists to date in the assimilation of wave data in wave models. Current operational wave models are driven entirely by the observed or predicted wind field, without updates from wave measurements.

One of the reasons for this situation is that in the past very little wave data has been available with sufficient information to impact the wave models. Although satellites should improve the situation markedly, the wave data will still be far too sparse to reconstruct the global wave field without making use of the wind data and wave models.

Presently the following wave data are available:

1) Conventional data (available in ship-code messages, exchanged on GTS).
   These data are based on visual observations and contain significant wave height, period and direction, in principle separated into wind sea and swell. Coverage is relatively good in time and space. However, the observations are subjective, often unreliable and of low quality. Wind sea and swell are usually poorly distinguished and often even incorrectly assigned.

2) Observations from special platforms and buoys (e.g. COST-43 project).
   These data are not yet exchanged on GTS, but WMO is considering the introduction of a suitable GTS code. Observations provide the one-dimensional wave spectrum and in some cases also the average direction. The data quality is reported to be good, but spatial coverage is very regional and in general sparse.

At the end of this decade, ocean satellites should be providing the following additional wave data:

1) Significant wave height along sub-satellite tracks, with a resolution of 12 km, global coverage (radar altimeters, ERS-1, N-ROSS, TOPEX, ...).

2) SAR image spectra along a track offset 300 km from the sub-satellite track, one spectrum average over a 5 x 10 km ocean patch every 200 km, global coverage (SAR wave mode, ERS-1).

3) SAR image spectra along the entire 100 km SAR swath (SAR full imaging mode, ERS-1). This data is obtainable only within line-of-sight of ERS-1 receiving stations, i.e. in limited regions of the N. Atlantic and N. Pacific, and during the limited full SAR observing periods.

A basic problem in assimilating wave data is that, with the exception of a few sparsely distributed directional wave buoys, wave measurements provided only partial information on the complete sea state (specified by the two-dimensional frequency-direction) which is predicted by wave models at the observation site. The significant wave height obtained from altimeters, for example, defines only the integral of the wave spectrum, while SAR image spectra, although providing in principle a measure of the two-dimensional wave spectrum with good frequency and directional resolution, suffer from ambiguities in wave propagation and amplitude calibration, and from nonlinear imaging distortions.

Open problems exist also in the assignment of 'regions of influence' to individual wave measurements. These depend in general on the type of spectrum: swell from distant storms can be correlated over large areas of the ocean, while local windseas exhibit smaller correlation scales of the same order as the generating wind fields.

To investigate these questions, two initial data assimilation exercises are proposed.

The first project involves hindcasts of the global wave field using the new 3rd generation wave model, recently developed by the WAM Group, for the SEASAT period, summer 1978. As input the global wind fields computed for the Global Weather Experiment can be used or, in an alternative experiment, the wind field derived from the SEASAT scatterometer. An improvement of the hindcast wave field would then be attempted by assimilating the SEASAT SAR wave spectra and altimeter wave height data. The inference of the wave data assimilation on the wind field analysis would also be investigated. All SEASAT products needed for these experiments are available.

As second project a series of simulated ERS-1 data assimilation experiments can be carried out. The simulated 'real data' could be generated, for example, by high resolution models, while the data assimilation experiments would be carried out using lower resolution models.

These experiments should yield the necessary first experience required to design the wave data assimilation segment of the combined wind and wave data assimilation systems (cf. task 4), while at the same time providing a test for the wind and wave algorithms (tasks 1, 2).

2.6 Data assimilation for regional models

The global nature of satellite observations clearly demands the implementation of a global data assimilation system at a central forecasting establishment equipped with high resolution global models and powerful computer facilities. However, in addition there is a need for data assimilation systems tuned to regional applications. These could be limited area forecasting, or high resolution studies of special areas, such as the Mediterranean or the Baltic Sea. Such systems would presumably best be implemented in national forecast centres.

A general data assimilation system developed for global observations can in principle be adapted without significant modification to regional applications. However, there are differences in operation resulting from the shorter assimilation cut-off time normally associated with short term regional forecasting, and the more extensive sources of data available on the regional scale, for example from local buoy networks and platforms. The models themselves will also need to be of higher resolution than the corresponding global models. A good example is the Mediterranean Sea, where the complicated shape of the basin together with the influence of the surrounding mountains (Alps, Pyrenees, Spanish ridges) lead to complex flow patterns and instabilities that can be realistically simulated only by high resolution models.

The higher emphasis on coastal areas in regional applications poses other problems in the interpretation of microwave satellite sensors. Algorithms developed for open ocean conditions are often unreliable in coastal regions, where the sea state is frequently not fully developed and the sea surface is more strongly contaminated by slicks.

The task group addressing these problems will need to interact closely with task groups 4 (overall data assimilation), 5 (wave data assimilation), and 1, 2 (wind and wave algorithms).

2.7 Field campaigns, commissioning and validation

The task of verifying sensor algorithms before satellite launch, testing instrument performance during the satellite commissioning phase and validating and monitoring sensor performance during satellite operation requires a continuous programme of sea truth measurements, supported by remote sensing measurements from aircraft and ocean platforms.

The core validation effort should concentrate on the instruments

- AMI (wind velocity, directional wave spectra),
- RA (wind speed, wave height),
- ATSR (sea surface temperature),

The present programme of C-band measurements for ERS-1 will need to be continued and expanded, the maximum activities occurring during the 3-6 months commissioning and validation phase after launch. A data gathering schedule might be:

major campaigns 1987, 1989 - 1990 commissioning and post launch validation, 1990 further validation and monitoring.

A major limitation in the peak validation activity during the 3-6 months after launch will be the available scientific manpower. To use this efficiently, the overall programme should be designed with this critical validation period in wind.

With regard to the design of the validation programme, it is proposed that

- master stations are implemented at which measurements are made several years before launch during the commissioning phase and throughout the life time of the satellite,
- the master stations should lie close to the ERS-1 ground tracks and be in areas where the entire dynamic range of the sensors may be tested within 3 months,
- airborne microwave instruments are deployed to relate the very accurate measurements made at master stations to larger areas and to sampling conditions comparable with the satellite systems,
- the core validation is chosen in the N.E. Atlantic and Norwegian Sea, a region characterized by
  - o high seas,
  - o closely spaced satellite tracks,
  - o many airports,
  - o proximity of sea ice,
- the position of the 3-day repeat cycle ground tracks should be defined by summer 1986 to enable the timely selection of
  - o master stations, based on studies in prelaunch programmes,
  - o RA transponder sites for calibration with respect to laser stations,
  - o tide guage arrays for wave bias studies,
- higher period repeat cycles be chosen as multiples of 3, so that the master stations lie on satellite tracks also after the initial commissioning phase for further validation and monitoring.