

## CHAPTER 59

### INTEGRAL CONTROL DATA ASSIMILATION IN WAVE PREDICTIONS

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#### ABSTRACT

In the present study a technique for assimilating observed wave data in numerical wave predictions is developed that exploits (a) the efficiency of a limited number of integral control variables and (b) the effectiveness of variational (model-consistent) assimilation. The formal procedure is independent of the type of control variables and of the wave model. The integral control variables in this study are chosen to represent large-scale errors in the driving wind fields and uncertainties in the wave model. The assimilation technique is validated with observations of the ERS-1 satellite altimeter and two waverider buoys in two consecutive storms in the Norwegian Sea. The assimilation of the observations reduced the errors in the predicted significant wave height at the buoy locations typically from 25% to 15%. The technique is also demonstrated with an simulation of swell prediction in the Indian Ocean based on simulated buoy data and satellite data.

#### INTRODUCTION

Good quality wave forecasts are often required for estimating the workability for coastal and offshore activities. The quality of these forecasts, which are usually based on numerical wave models can be improved by assimilating wave observations (Komen et al., 1994). In simple assimilation techniques (sequential techniques), observed waves are used to correct the model wind and waves locally and instantaneously. The effect is short-lived as the corrections are quickly lost in the uncorrected wind and waves elsewhere in the model. In the more advanced variational assimilation techniques the observed waves are used to correct the entire space-time structure of the wind in detail, which is more effective. This requires very large computer capacity. However, this detail in the corrections is not required for two reasons. First, the wind errors that affect the waves are highly correlated in space and time and second, the waves are an integral effect of the wind in which

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details of the wind are lost. In the present study a variational technique is developed that exploits this correlated and integral character of wind and waves by using integral control variables. It is efficient and seems therefore operationally feasible (e.g., all experiments of the present study were carried out on a personal computer). The technique is validated with an application in the Norwegian Sea and it is demonstrated with simulated data in the Indian Ocean.

## TECHNIQUE

The essence of data assimilation in wave forecasting is that wave observations just prior to the forecast are used to obtain wind fields and wave fields that are as consistent as possible with both the first-guess wind field and the observed waves. The forecast system, including the driving wind fields, thus continuously adapts to the wave observations.

Assimilation techniques for wave forecasting are commonly divided into sequential techniques and variational techniques (e.g., Komen et al., 1994). In the sequential techniques the wave observations are used to correct the wind and the waves at each time level of the model without regard for the previous states of the model. Since the space-time structure of the modelled wave field is not taken into account, the results are not consistent with the dynamics of the wave model. The variational techniques do take the dynamics of the wave model into account. Since the generation, dissipation and propagation of the waves in the entire geographic model domain is thus accounted for, the effect of these techniques is expected to be of longer duration. The most advanced of these techniques is the adjoint technique which determines a very large number of local corrections (in fact, every single wind vector in space and time, e.g., de las Heras, 1994). The variational technique presented here combines (a) the effectiveness of the variational techniques by correcting the driving wind field (consistency with the model dynamics) and (b) the efficiency of the sequential techniques using a relatively small number of corrections (compared with the conventional adjoint techniques). In the present study the chosen control variables are: (1) a shift in time and space of the wind field and (2) a common correction to all wind vectors and (3) a model coefficient representing wave dissipation. These control variables are taken to be constant in time and space during the assimilation period. To improve the subsequent forecast, the assimilated values of the control variables are extrapolated into the forecast.

The assimilation technique optimizes the driving wind field and the corresponding wave field taking into account (a) the differences between the observed and computed waves and (b) the confidence in the driving wind fields and the wave model itself. These aspects are quantified in a cost function  $J$ :

$$J = J^x + J^y \quad (1)$$

where  $J^x$  represents the differences (that need to be minimized) between the observed and the modelled waves and  $J^y$  represents the corrections (that will be

penalized) that are needed in the wind field and the wave model. These differences and corrections are quantified as follows.

- (i) In the following the observed wave field is represented by a set of observed wave parameters such as significant wave height, mean wave frequency etc. Each of these may be observed at different locations and times. They are indicated as  $\chi_i^o$  where subscript  $i$  is the realization index. The modelled waves are similarly represented by the same set of wave parameters  $\chi_i$  at the same locations and times as  $\chi_i^o$ . The penalty is expressed as

$$J^x = \sum_i \sigma_{\chi_i}^{-2} (\chi_i^o - \chi_i)^2 \quad (2)$$

where  $\sigma_{\chi_i}$  is the standard deviation of the error of the wave parameter  $\chi_i$ .

- (ii) The corrections that are required in the driving wind fields and in the wave model can be represented as corrections of a set of control variables such as a shift in the location of a storm or a coefficient in the wave model. Each such control variable is indicated as  $\psi_j$ . Its value prior to the assimilation is indicated as its first-guess value  $\psi_j^f$ . Confidence in these values is expressed by penalizing the corrections that are needed in the assimilation, again with a quadratic measure with the variance of the errors in the control variables as weights:

$$J^\psi = \sum_j \sigma_{\psi_j}^{-2} (\psi_j - \psi_j^f)^2 \quad (3)$$

where  $\sigma_{\psi_j}$  is the standard deviation of the error of the control variable  $\psi_j$  (representing the confidence in the control variable).

The assimilation consists essentially of minimizing the cost function  $J$  which can be interpreted as adjusting the driving wind field and the wave model with a certain penalty, to produce the best-fit wave field. This minimum is estimated with one small perturbation per control variable in the driving wind field and in the wave model. The optimum values of the control variables thus obtained are used to carry out the fully assimilated wave forecast. Details of the method are given in Holthuijsen et al. (1996).

The assimilation is carried out with the original wave model (no adaptations). The computer storage capacity for this technique is therefore equal to that required for one conventional model run. It follows from the above that the number of model runs with the wave model is equal to the number of control variables plus one. The technique is therefore efficient only when a limited number of control variables is considered. This condition is fulfilled if only a few integral control variables are used.

## VALIDATION

The technique is validated in two storms in the Norwegian Sea (1 - 10 March, 1993). For the data assimilation and the verification, observations of the significant wave height (values of up to 7.5 m) from two waverider buoys and from the altimeter of the ERS-1 satellite are used (Fig. 1). The wave model is the second-generation model DOLPHIN-B of Holthuijsen and de Boer (1988). The integral control variables that were chosen for this validation experiment, are the ones mentioned above. They were taken to be constant in time and space (extrapolated into the forecast).

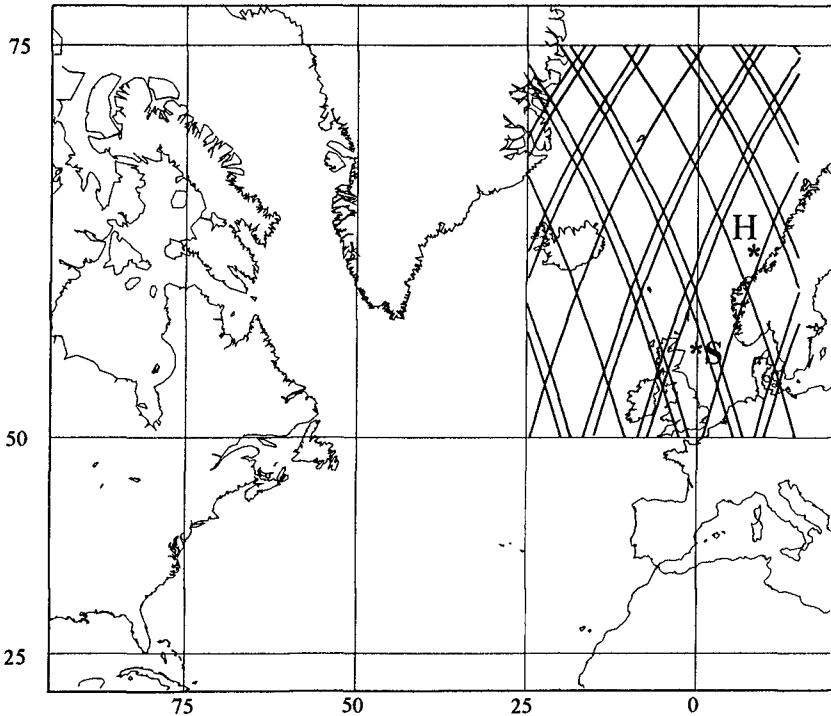


Fig. 1 The area covered by the wave model with the locations SCOTT (S) and HALTENBANKEN (H) and the ERS-1 tracks that were used in this study during the assimilation period 3 - 8 March, 1993.

Several combinations of the buoy and satellite data have been used. The effect is evaluated by comparing the computed significant wave height (before and after assimilation) with the observed significant wave height both in the assimilation period and in the forecast (e.g. Fig. 2 for the HALTENBANKEN location). Table 1 presents some of the results in terms of the scatter index (rms-difference normalized with the mean observed significant wave height). Day 1 - 3 were used as spin-up of the wave model. Day 4 - 8 is the assimilation period. Day 9 - 10 is the forecast period. It is obvious that the agreement between computed and observed

waves improves considerably both in the assimilation period and in the forecast, in particular in the forecast at location SCOTT where the scatter index drops from 37.2% to 12.4% (buoy assimilated) or 17.1% (buoy and satellite assimilated).

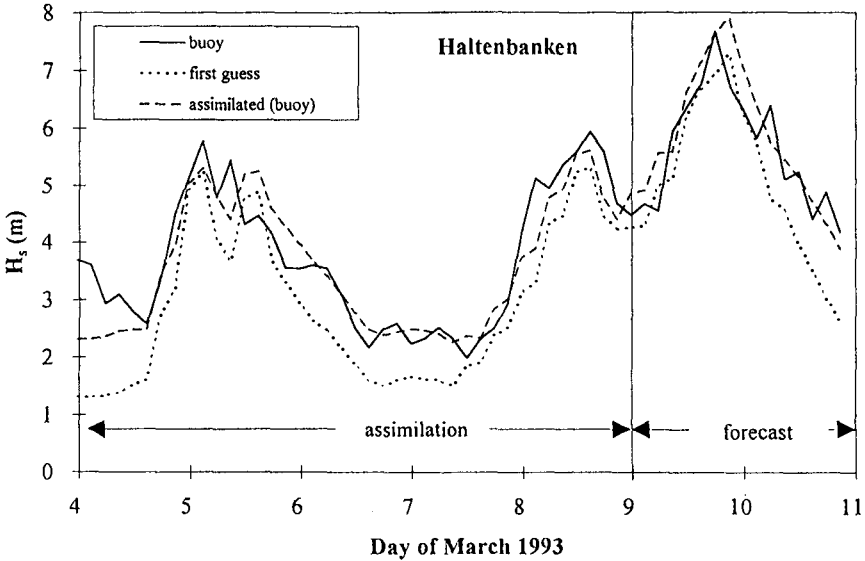


Fig. 2 The observed significant wave height at HALTENBANKEN (waverider buoy) with the first-guess significant wave height and the assimilated significant wave height (HALTENBANK buoy only) in the assimilation period and in the forecast period.

## DEMONSTRATION

The assimilation technique is demonstrated in the Indian Ocean with a simulated swell forecast at a near-shore location (10 km offshore) off Kerala (southern India, Fig. 3). All wave information in this demonstration has been simulated with the wave model. A period has been selected with a storm south of Madagascar that produced high swell conditions off Kerala in July of 1995 (Fig. 3). The aim of the assimilation is to improve the forecast of crossing the 1 m threshold of the swell wave height at the near-shore location. The observed swell wave height (defined as  $H_{swell} = 4 m_{0.1}^{1/2}$  where  $m_{0.1}$  is the variance of frequencies less than 0.1 Hz) is simulated with actual (not simulated) 12-hour wind forecasts of the European Centre for Medium Range Weather Forecasts (ECMWF, Reading, England). The "observed" swell wave heights at the near-shore location are given in Fig. 4. Two cases are considered. In the first case, simulated wave data from one buoy, located 200 km south-west off Kerala are used. In the second case, simulated wave data from the ERS-1 satellite are used. For the assimilation the same control variables are used as in the validation experiment, except the wave dissipation coefficient which is not included (wave physics cannot be inferred from simulated wave data; the value of this coefficient is set at the value obtained in the above validation experiment).

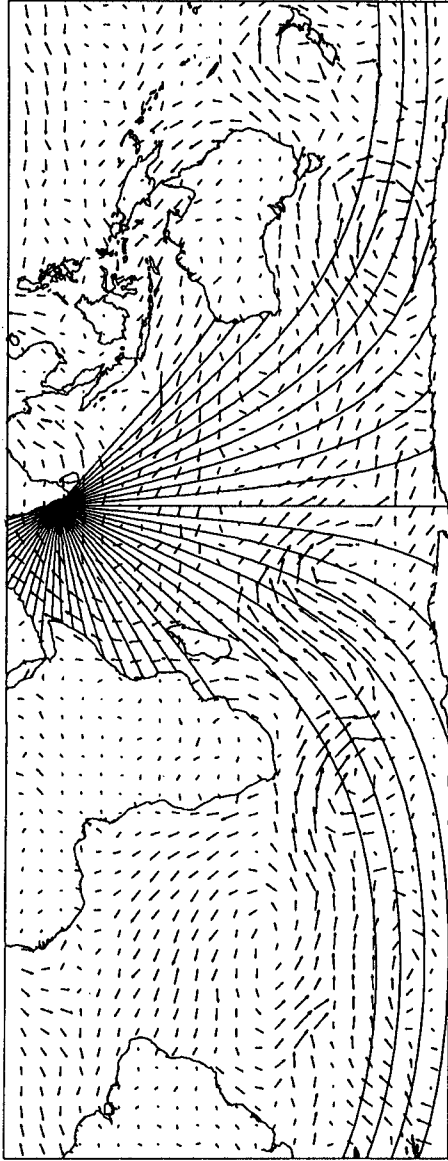


Fig. 3 The area covered by the wave model in the Indian Ocean with the wind field analysis of ECMWF showing the storm south of Madagascar that generated the high swell conditions at Kerala (India). The wave rays indicate great circles along which swell can propagate towards Kerala (the ones shown here are used in the wave model). Note the coinciding directions of wind and swell rays in the storm.

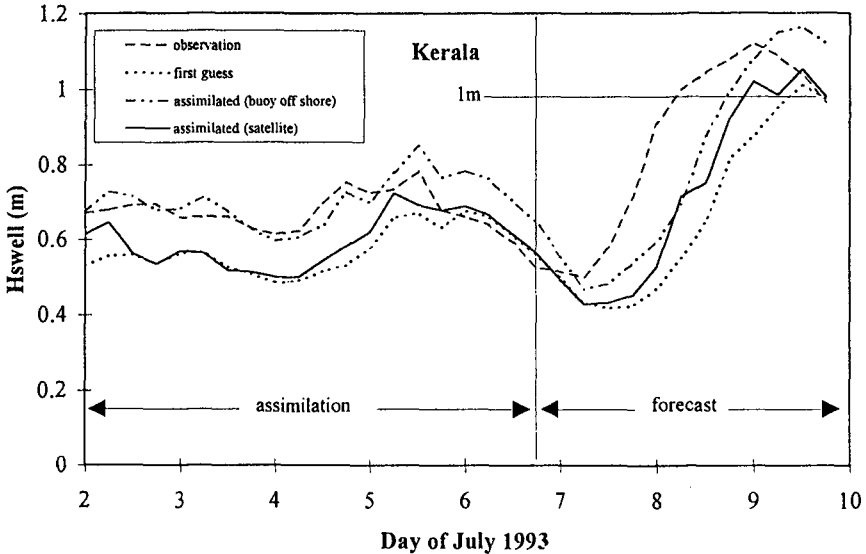


Fig. 4 The "observed" (simulated) swell wave height at the near-shore location off Kerala with the first-guess swell wave height and the assimilated swell wave height (off-shore buoy and satellite) in the assimilation period and in the forecast period.

The first-guess swell wave height (including the first-guess forecast) at the near-shore location is simulated with the wind analyses of ECMWF (to obtain wave fields that are somewhat different from the "observed" wave fields). It is obvious from Fig. 4 that this first-guess, at July 7, 00:00 UTC, predicts the crossing of the 1 m threshold on July 9th more than 24 hours too late. The result of assimilating the off-shore buoy data over a period of 5 days (sampled at 6 hour interval) is to predict the time of threshold-crossing only 9 hours late. This is an improvement of 17 hours. The scatter index of the swell wave height at the near-shore location reduces significantly e.g. in the forecast from 30.9% to 19.2% (Table 2). The satellite data were simulated at the actual tracks of the ERS-1 over a period of 23 days (15 days spin-up, 5 days assimilation and 3 days forecast) with the same wind fields but sampled every 30 min when the satellite was (a) over the Indian Ocean and (b) the observation was on a great circle through the near-shore location off Kerala (so that swell could potentially affect the Kerala location). This resulted in about 6 observations per day, or 88 in total during the 15 day assimilation period (Fig. 5). The effect of assimilating these data on predicting the threshold-crossing is somewhat uncertain as the corrected swell wave height fluctuates around this level (Fig. 4). In terms of the scatter index, the effect is small in the assimilation period but reasonable in the forecast period (Table 2). It is speculated that the poor performance in the assimilation period is due to the fact that 6 observations per day

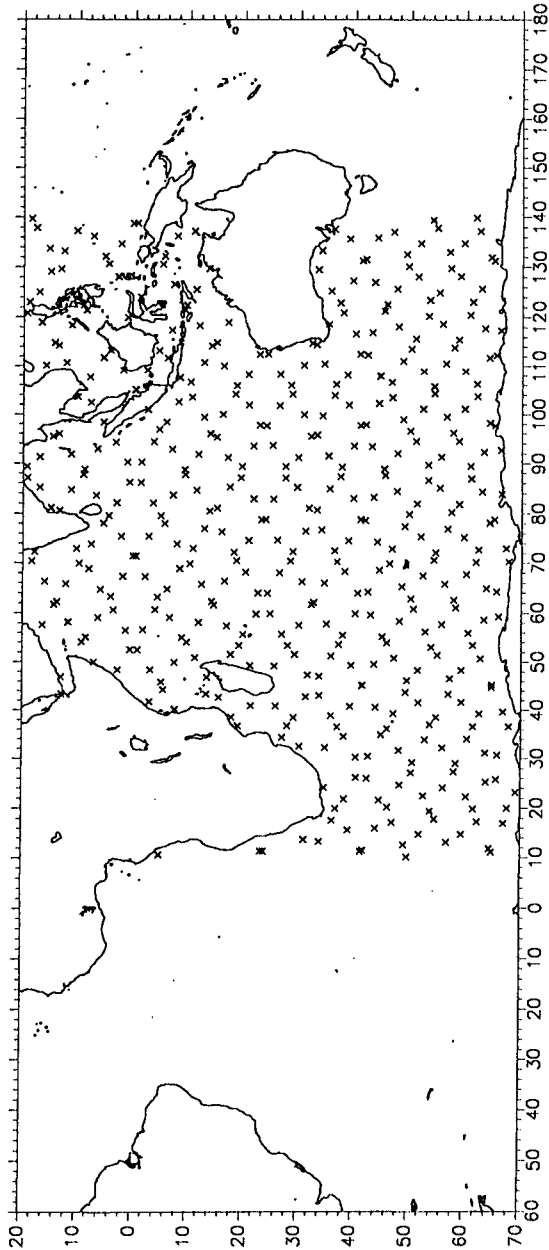


Fig. 5 Locations at which the wave data from the ERS-1 satellite were simulated for the demonstration in the Indian Ocean. The locations are at 30 min interval and on great circles centered at the near-shore location off Kerala (potentially affecting the waves there).



over such a large area is not sufficient to detect and correct rather local (on the scale of the Indian Ocean) errors in the wind field (the timing or location of the storm south of Madagascar that generated the swell).

## CONCLUSIONS

A variational data assimilation technique has been developed based on the notion of integral control variables. It has been shown to be rather effective and efficient in the sense that the forecasts of the significant wave height in the validation experiment improved considerably with only a small fraction of the computer effort that is normally involved in variational techniques. Adding satellite data to the (buoy) assimilation in this validation experiment did not improve the forecasts at the buoy locations. This is possibly due to the fact that the satellite data contribute to the overall improvement of the wave field rather than to the improvement at one particular (buoy) location. The demonstration of the assimilation technique for swell forecasting in the Indian Ocean showed that for satellite data to be effective, more than only a few satellite observations per day are required over such extensive areas as the Indian Ocean.

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scatter index in %	location of forecast	data sets in assimilation	March 1993	
			significant wave height	
			assimilation period	forecast period
ERS-1		<u>first-guess</u>	24.7	26.4
		<u>assimilated</u>		
		altimeter altimeter + buoys	18.3 18.3	25.5 25.4
SCOTT		<u>first-guess</u>	22.0	37.2
		<u>assimilated</u>		
		SCOTT buoy	16.3	12.4
		SCOTT buoy + altimeter HALTENBANKEN buoy	16.0 22.8	17.1 28.0
HALTENBANKEN		<u>first-guess</u>	27.5	17.1
		<u>assimilated</u>		
		HALTENBANKEN buoy	14.5	10.1
		HALTENBANKEN buoy + altimeter SCOTT buoy	19.0 15.2	10.0 13.5

Table 1. Scatter index (= normalized rms-error, see text) between computed and observed significant wave height for the ERS-1 altimeter and two waverider buoys in the Norwegian Sea and the North Sea in the validation experiment.

scatter index in %	location of forecast	data sets in assimilation	July 1995	
			swell wave height	
			assimilation period	forecast period
near-shore		<u>first-guess</u>	18.4	30.9
		<u>assimilated</u>		
		off-shore buoy ERS-1 satellite	9.9 15.4	19.2 23.1

Table 2. Scatter index (= normalized rms-error, see text) between computed and "observed" (simulated) swell wave height at the near-shore location off Kerala (India) using simulated wave data from either an off-shore buoy or the ERS-1 satellite.

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