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Feasibility of improving storm surge forecasts by assimilation of radar altimeter data

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Preface

This note contains the contribution of DELFT HYDRAULICS to the report of the DATUM project for the Netherlands Remote Sensing Board (BCRS).

Contents

1 Introduction

Aim of this note is to assess the feasibility of real-time assimilation of radar altimeter data into the Continental Shelf Model (CSM) to improve storm surge forecasts for the coasts of the Netherlands. Assimilation of radar altimeter data in addition to sea level observations from coastal tide-gauge stations should improve the estimate of the current state of the model, which serves as initial condition for a forecast.

Assimilation of altimeter data in CSM is feasible provided the benefits eventually outweigh the cost of implementation and operation. In practice, available budgets for development and operation will be limited, and benefits from assimilating altimeter data should outweigh the benefits from an improvement of the CSM model or of the currently operational data-assimilation technique requiring an investment of comparable size.

At this stage, it is too early to decide whether this will be the case. As a general guideline, we can assume that even a relatively small improvement of storm surge forecasts is important for the operation of the storm surge barriers by Rijkswaterstaat. Therefore, at this stage, the issue will be to determine whether assimilation of altimeter data in CSM may lead to a significant improvement of storm surge forecasts.

In this Chapter, we will investigate which conditions may restrict or impede a positive impact of assimilation of altimeter data on storm surge forecasts. This results in conclusions, or if the issue is open to question, in recommendations.

The improvement of storm surge forecasts achievable by assimilating altimeter data depends on:

- the data,
- the performance of the assimilation method.

A method for real-time assimilation of data into a storm surge model should become operational, which can assimilate satellite radar altimeter data in addition to conventional tide gauge data. It should be demonstrated that radar altimeter data can have a positive impact on storm surge forecasts and which conditions on radar altimeter data need to be satisfied in order to realize a positive impact. The suitability of satellite radar altimeter data depends on data quality, coverage, timely delivery, and availability of the required data-infrastructure.

2 Suitability of radar altimeter data

The following aspects determine the suitability of satellite radar altimeter data for improving storm surge forecasts:

1 Infrastructure for reception,
2 Timeliness,
3 Coverage in space and time,
4 Data quality.

These aspects are discussed below. For more details on the technical background, see Chapter 2.

1 Infrastructure for reception

Off-line precision data products can be ordered at the EECF (Earthnet ERS-1 Central Facility) at ESRIN, Frascati, Italy. Fast Delivery (FD) altimetry data are disseminated via GTS (Global Telecommunication System) of the World Meteorological Organization which can be accessed by national meteorological offices. KNMI (Royal Netherlands Meteorological Institute) generates storm surge forecasts and has access to GTS data.

2 Timeliness

Requirements with respect to timeliness are that data should be available as soon as possible after collection; the more recently collected, the more valuable data are. We may say that they should be available at least within 12 hours after collection, but preferably sooner.

ERS-1 Fast Delivery altitude data disseminated via GTS are available within a few hours after collection. For precision altimeter data products, the processing takes several weeks. Therefore, only the FD data on GTS are suitable for improving storm surge forecasts.

3 Coverage

Coverage of the Continental Shelf sea by ERS-1 radar altimeter data is still far from optimal for the purpose of storm surge forecasting (see Chapter 4). However, this may improve in the future if altimeter data from other microwave satellites can be used. The planned simultaneous operation of ERS-1 and ERS-2 may be a good opportunity to investigate this aspect. A more important limitation of coverage is that storm surge forecasting requires data collected in storms, but the quality of these data may be insufficient (see below). The coverage of the CSM grid area by the ERS-1 altitude data selected for the DATUM project is rather poor in particular during the storm season (see Chapter 4). However, for the purpose of data-assimilation, the criteria used to select valid data may have been too restrictive, *e.g.* the strict requirements on laser orbit tracking (see Chapter 2; see also below). It will take effort and time to determine criteria on data-quality leading to a proper balance between quality and coverage.

4 Data quality

Satellite radar altitude data are subject to two types of errors: orbit determination errors and errors in the radar altitude measurements. To start with the latter source of errors, the measured return signal is affected by properties of the atmosphere, short sea surface waves and rain. In principle, data of poor quality can be detected and removed, either by ESA (or more generally, by the agency operating the satellite), or as part of the storm surge forecasting procedure. Therefore, the issue is whether, after screening, enough data are left to improve storm surge forecasts.

Absolute requirements on accuracy cannot yet be specified exactly. Even less accurate data may be used, but assigned a lower weight in the data-assimilation procedure. The question then is whether these inaccurate data still have a sufficient impact. A simple rule of thumb for determining whether a positive impact can be expected is that altimeter data should be at least as accurate as CSM first guesses at the locations of altimeter data during storm conditions. Error estimates for CSM-16 forecasts without data-assimilation over September 1992 to May 1993 generated by KNMI have been summarized by Hans de Vries of this institute. Unfortunately, according to De Vries, the sea level data at the offshore stations AUK Alpha and K13a are not completely reliable. Still, the reported root mean square errors of 0-12 h ahead forecasts of high tide surges at these locations are only 0.23 m and 0.15 m, respectively; for almost all coastal stations this error remains below 0.15 m. When focusing on surges of more than 0.80 m only, the reported rms error at AUK from 11 events is 0.54, but as already mentioned, this figure may not be reliable. At most coastal stations in the Netherlands, the rms forecast error of surges above 0.80 m is about 0.25-0.30 m, and about 0.7 m at Wick and Lowestoft. Based on these figures, we can take an rms error of 0.30 m as representative for the forecast error during storm conditions without data assimilation. Suppose that this figure can be reduced by assimilating data from coastal stations to 0.20 m, then errors in the altimetry data should remain below this figure in order to be useful.

As concerns the achievable accuracy, we will focus here on ERS-1 data, but the situation with data from other satellites is probably not very different. The achievable accuracy of altimeter data (without consideration of orbit errors) is different for the FD and precision data products. The precision product is corrected for atmospherical conditions and retracking. For FD data, retracking is not possible because this takes too much time, but the associated error in the altitude measurement remains in the order of 0.05 m. No correction for atmospherical influences is applied to FD data by ESA but estimates of the relevant atmospherical parameters are available in real-time at KNMI, and applying the required corrections is not very difficult. Additional corrections are required for the effect of sea surface waves, using significant wave height data which are also obtained from the radar altimeter. After correction, the remaining error is in the order of 0.1 m for a significant wave height of 8.0 m. Except in the Southern bight of the North Sea, such values occur rather frequently; at least ten times per year on average. This means that during storm conditions, errors due to sea surface waves and possibly also rain will be most restrictive. An extensive comparison of storm surge forecasts and altimeter data collected during the same storms needs to be carried out to assess whether a sufficient number of altimeter data of acceptable quality are available under storm conditions.

Orbit errors over a small area as the North Sea can be represented by only two parameters (bias and tilt). They are quite large for FD data. Correction takes a long time and depends on the availability of laser tracking. Requiring accurate orbit data reduces both the volume of data that is available and conflicts with the requirements on timely delivery. Therefore, we will focus here on the situation that orbits are not accurately known. The orbit errors have rather long wavelengths so, on the grid of CSM, they can be represented by two parameters per orbit (bias and tilt) which can be considered as unknowns in the data assimilation problem. These parameters can be solved for separately, resulting in a modified cost function for the altimeter data along a single track as explained in the appendix. Adopting this approach, of course no information about the mean sea level and mean sea level slope along the ground track can be obtained from the altimeter data, so the extractable information is limited to fluctuations of relatively small wavelength along tracks in predominantly North-South direction. How much this will affect the impact of altimeter data on storm surge forecasts needs to be investigated.

3 Feasibility of data assimilation

Within the constraints of availability and quality of altimeter data, the achievable improvement of storm surge forecasts by assimilation of radar altimeter data depends on the assimilation scheme. The following aspects will be considered:

1 The technical feasibility of assimilation of radar altimeter data,
2 The impact on forecasts,
3 The computational effort.

1 The technical feasibility of assimilation of radar altimeter data

At present, a steady-gain Kalman filter is employed to assimilate tide-gauge data into CSM [*Heemink and Kloosterhuis*, 1990]. This is a sequential method, which means that it updates the state at the current time-level based on observations at the same time-level. It is efficient but assumes that the configuration (locations, sensors) of available observations is the same at each instant. This is not the case for altimeter data. Therefore, an iterative data-assimilation method should be employed which updates unknown model inputs over a certain time-interval preceding the current time-level, using the adjoint model of CSM [*Ten Brummelhuis and Heemink*; 1990]. This requires the following components:

- adjoint model of CSM,
- optimization shell,
- choice of model inputs to be corrected,
- cost function term for altimeter data,
- data-interfaces,
- real-time implementation.

The solution method (adjoint and optimization shell) has already been implemented, but only for calibration of time-invariant parameters such as depth and sea bed roughness [*Ten Brummelhuis and Heemink*; 1990]. In the present project, tests with assimilation of ERS-1 data in CSM will be limited to such invariant parameters. However, real-time assimilation will involve correction of transient model inputs such as disturbances on boundary conditions, atmospheric forcing or "system noise" over a preceding time-interval. The model inputs to be corrected should be chosen based on a detailed error analysis building on the experience with the current data-assimilation method, and on additional experiments. In principle, this choice is independent of the data assimilated. Criterion should be the improvement of surge forecasts. The cost function term which represents the size of the deviation of the CSM output from altimeter observations should reflect the error statistics of altimeter data. As concluded in Section 2.4, the bias and tilt errors of ERS-1 Fast Delivery altimeter data are rather large for the present purpose and cannot be corrected. In the Appendix, a quadratic cost function is derived which neglects tilt and bias errors. The variances of altimeter observations should still be specified; these will most likely depend on the sea state itself. Real-time implementation requires the choice of the length of the interval over which model inputs are corrected; this is a matter of trial and error. Also, a control structure is required for application of an iterative data-assimilation method in the operational forecast cycle, taking care of routing input and output data, temporary storage of results needed for the next cycle, etc.

The modifications and extensions mentioned above will require time and effort, but there is no doubt that they can be realized.

2 The impact on forecasts

The impact of a particular type of sea level observations on forecasts may depend on the number of observations, their weight in the assimilation procedure, and the locations of observations.

The weight of a single observation is determined by the component of the cost function which measures the deviation of the CSM output from this observation (see 1. above). It is derived from the error statistics of the observation. Using a cost function which ignores tilt and bias (see 1. above and the Appendix) will reduce the amount of information extracted from the altimeter data and, as a consequence, the impact of altimeter observations. Numerical experiments will have to provide insight into the size of this reduction.

As we have seen in Section 2.4, the rms errors of the data after subtraction of tilt and bias errors should not be larger than about 0.2 m. Assume that this value is used in the term of the cost function for altimeter observations. Tide gauge data are probably somewhat more accurate, so the weight of a tide gauge measurement will be higher than that of an altimeter measurement. Because tide gauge data are also much more abundant, the total weight of altimeter data will be rather small. This implies that altimeter data will only have a substantial impact if they are complementary to the tide gauge data. In other words, assimilation of altimeter data should give substantial improvements of certain model inputs without influencing the model outputs corresponding to the assimilated tide gauge observations. Whether this will be the case depends on which model inputs are corrected and on the dynamics of the model. If errors in boundary conditions are corrected, then the impact of altimeter data near the boundary may be significant, at least on forecasts for the longer range. Also disturbances in the central part of the North Sea which affect the forecasts for the coast of the Netherlands may be corrected based on the altimeter data. However, if any of these errors has an effect of comparable size on the sea levels along the British East coast, the impact of altimeter data will probably be small. Once it is determined which model inputs will be corrected, numerical experiments with simulated and measured data should be carried out to determine the impact of altimeter data.

3 The computational effort of assimilating altimeter data into the Continental Shelf Model

The CSM model is already operational for storm surge forecasting with a Kalman filter for data-assimilation, which takes very little extra effort compared to a simple forecast run. The new assimilation method based on the adjoint model is expected to increase the computational effort for a forecast run by a factor in the order of twenty, assuming that about ten iterations are needed. This is a crude estimate based on the experience obtained in the present study. An increase in computational load with a factor of 20 is considerable but if assimilation of altimeter data proves to give a significant improvement of forecasts, it may be worth it. On should realize that, at present, storm surge forecasting takes very little effort compared to weather forecasting or wave forecasting. Also, when considering the computational feasibility, it is important to realize that computers are becoming more powerful each year and that costs are rapidly decreasing.

4 Conclusions

1. To improve real-time storm surge forecasts, only Fast Delivery (FD) altimeter data are timely available via GTS. KNMI has access to these data.

2. This FD product is accurate enough only if the effects of orbit tilt and bias errors are eliminated in the data-assimilation procedure. As a consequence, no information about the average sea level and average sea level slope along the track can be obtained.

3. We must find out whether the impact of altimeter data is still sufficient if it cannot provide information about the along-track averages of sea level and sea level slope. Numerical experiments can provide insight.

4. The impact of altimeter data may also be limited by the relative abundance of tide gauge data. Altimeter data may have a significant impact provided they are complementary to these tide gauge data. This can be assessed by numerical experiments using simulated and measured data.

5. Benefits of assimilation of altimeter data for storm surge forecasting are limited to situations in which a pass of ERS-1 coincides with a severe storm causing high set-up at North Sea coasts. However, more microwave satellite missions are planned and the coverage is expected to improve in the future. Of more concern is that, during storms, relatively few data may pass the data quality checks due to the disturbing influences of high waves and rainfall. More insight is needed about the fraction of data retained in these situations and about the prospects for improvement of the suppression of disturbances.

6. Assimilation of altimeter data requires the use of an iterative method for data-assimilation in the Continental Shelf Model. The computational load may increase by a factor of 20 compared to the procedure for assimilation of tide gauge data which is currently operational. It is too early to tell whether this will limit the feasibility.

References

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Appendix

Dealing with orbit errors in the assimilation of altimeter data

Suppose that the satellite orbit is known. Say that the term of the cost functional for the sea level data $y_1,...,y_n$ along a single pass through the CSM grid is quadratic (corresponding to the assumption of Gaussian errors of the sea level data) of the form

$$j = \sum_{i=1,...,n} (\hat{y}_i - y_i)^2 \tag{1}$$

with $\hat{y}_1,...,\hat{y}_n$ the analyses of the sea levels at the same measuring locations computed by CSM.

Now assume instead that the bias and tilt components of the orbit height along the track are unknown. We can incorporate them into the cost functional

$$j = \min_{b_0,b_1} \sum_{i=1,...,n} (\hat{y}_i - y_i + b_0 + b_1 x_i)^2 \tag{2}$$

in which $x_1,...,x_n$ are the along-track distances of the altimeter measurements relative to some point. (2) can be written in the form

$$j = \min_{\boldsymbol{b}} \| \hat{\boldsymbol{y}} - \boldsymbol{y} + \boldsymbol{\Phi b} \|^2 \tag{3}$$

in which $\boldsymbol{b} = (b_0 \; b_1)^T$ and $\boldsymbol{\Phi}$ a matrix with elements

$$\Phi_{i1} = 1 \quad ; \quad \Phi_{i2} = x_i \qquad \text{for } i = 1,...,n .$$

Solving (3) for $\boldsymbol{b}$ results in the following cost functional term for a single pass of the satellite:

$$j = \| [\mathrm{I} + \boldsymbol{\Phi}[\boldsymbol{\Phi}^T \boldsymbol{\Phi}]^{-1} \boldsymbol{\Phi}^T] (\hat{\boldsymbol{y}} - \boldsymbol{y}) \|^2 \tag{4}$$

So the residue $\hat{\boldsymbol{y}} - \boldsymbol{y}$ is simply projected on the subspace orthogonal to the columns of $\boldsymbol{\Phi}$, i.e., effectively only small-wavenumber errors in the CSM forecasts are corrected.

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