A storm surge model for the coast of Iceland.

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Abstract

An existing tidal simulation model covering the North-Atlantic Ocean around Iceland has been extended to a storm surge model for the coast of Iceland. The model can be run with two types of meteorological forcing, a prescribed circularly symmetrical pressure and wind fields, simulating typical low pressure systems causing extreme conditions along the coast, and pressure and wind fields taken directly from weather forecast models.

Two particular cases have been studied. The first one, a storm that hit Iceland in January 1990 and caused considerable damage along the south- and west-coast of the country, is considered one of the worst storms of this century. The second one, a storm that hit the country in February 1996 during extremely high tides, was considered threatening at the time, but did not cause considerable surge levels. Results from both cases indicate that the model may be used to successfully predict and analyse storm surges along the coast of Iceland.

1 Introduction

Located in the North-Atlantic Ocean between latitudes 63°N and 67°N, Iceland is frequently hit by severe storms, especially during the winter months. On several occasions throughout this century, storm surges and associated extreme wave conditions have caused considerable damage along the coast of the country. The most extensive damage has occurred at low lying areas and in less protected harbours along the south- and west-coast of the country, which are most exposed to surges and extreme wave conditions.

Older historical records indicate, however, that the threat may be more serious than this experience indicates. Estimates for a storm surge event that occurred in the year 1799 show considerably higher sea levels than in any recent events. If these estimates are accurate and if such an event would take place today, serious damage to property and even risk to people would result if action to evacuate certain low lying areas were not taken promptly enough.

Up to now little effort has been put into research on storm surges in Iceland. Attempts have been made to develop statistical models to estimate return periods of storm surges in Reykjavik, the capital of Iceland (Eliasson [1]). The current study is, however, motivated by the need to forecast storm surge events as accurately as possible to minimise risk to property and lives, as well as the need to better understand previous events and the potential of this hazard along the coast of the country.

To serve this purpose, a dynamical model of the ocean and its response to atmospheric forcing has been under development throughout the last year at the University of Iceland. The model is built on top of an existing tidal simulation model of the North-Atlantic Ocean around Iceland. Although still in a preliminary stage of its development, the model has already been used on an experimental basis to forecast storm surges at the coast of Iceland.

2 Model equations

The storm surge model has been developed from an existing tidal simulation model for the North-Atlantic Ocean around Iceland, that has been under development at the University of Iceland for several years (Tomasson & Eliasson [2]). The model is based on the shallow water equations

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}(uH)+\frac{\partial}{\partial y}(vH)=0 \tag{1}$$

expressing conservation of mass (continuity equation), and

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial P_a}{\partial x}-g\frac{\partial}{\partial x}(\eta-\tilde{\eta})+fv-\frac{g}{HC^2}(u^2+v^2)^{1/2}u+\frac{k}{H}W_x|W| \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial P_a}{\partial y}-g\frac{\partial}{\partial y}(\eta-\tilde{\eta})-fu-\frac{g}{HC^2}(u^2+v^2)^{1/2}v+\frac{k}{H}W_y|W| \tag{3}$$

expressing conservation of momentum (momentum equations). Here, g is the gravitational acceleration, C is the Chezy coefficient expressing frictional forces at the bottom, f is the Coriolis parameter, k is a wind stress coefficient and W_x, W_y are wind speeds in the x- and y-directions, respectively, where x and

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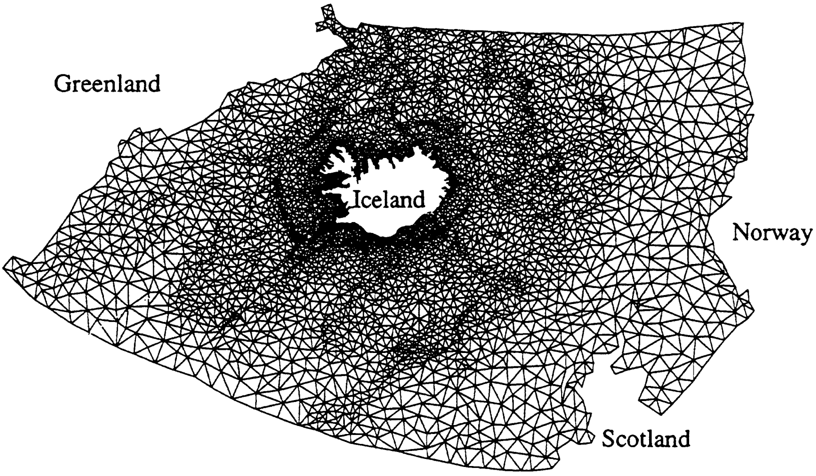

Figure 1: The model area.

y are Cartesian co-ordinates. P_a is the atmospheric pressure and $\tilde{\eta}$ is the equilibrium tide potential, expressing direct influence from the attractive forces of the sun and the moon. η is the surface variation from the mean water level, $H = h + \eta$ is the total water depth, where h is the mean water depth, and u and v are depth averaged velocities in the x- and y-directions, respectively.

The governing equations are approximated numerically using a staggered Galerkin finite element scheme on triangular elements A continuous approximation is used for the water level (η and H), linear within the elements, but piecewise constant approximations are used for the velocities u and v. The momentum equations are discretized in time using a one-step fully implicit approximation and substituted into the continuity equation to form an "integrated" wave equation. This equation is solved for the water level η and subsequently the disretized momentum equations are solved for the velocities u and v.

The model area is shown in Figure 1. It extends from a line between the southern tip of Greenland and the northern part of Ireland in the south to around 70°N in the north, and from the coast of Greenland in the west to the coast of Norway and Scotland in the east, an area covering around 3.3 million km^2 of the ocean. The computational mesh consists of around 5000 nodes and 9500 elements, with the greatest resolution on the shelf and in the coastal areas around Iceland.

The tidal simulations are based on seven tidal components, M_2, S_2, N_2, K_2, K_1, O_1 and Q_1. The computational results for individual components compare relatively well with observations. The mean error for the principal lunar semi-diurnal component, M_2, which is the largest and most important of the tidal

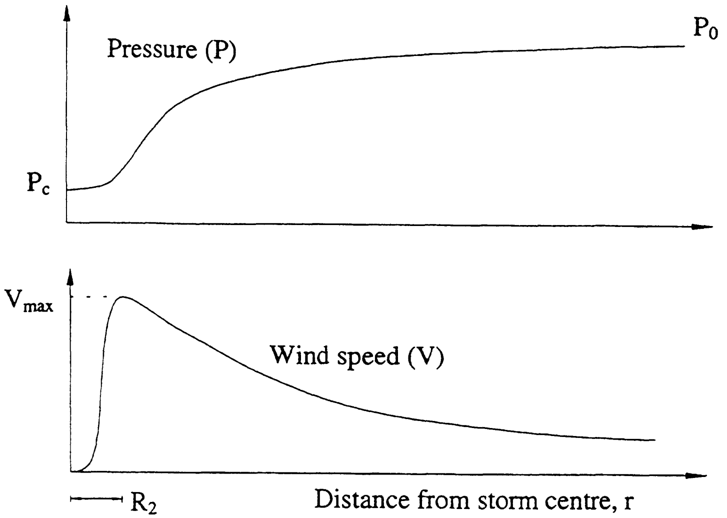

Figure 2: The circularly symmetrical forcing functions

components, is 5.3 cm in amplitude and 4.1° in phase, based on observations at 20 selected stations scattered around the model area. When the model is used to predict actual tidal variations of particular periods in time, an error of up to 20 cm in amplitude and 30 minutes in phase at most, but usually less than 10 cm in amplitude and 15 minutes in phase, is observed (Tomasson, et al. [3]).

The ocean is forced by atmospheric processes through variations in the surface pressure (P_a), and by wind stress at the ocean surface. In the current study, two alternative methods have been tested to describe the atmospheric forcing. In the first method the sea surface pressure distribution and the wind field associated with a particular storm are approximated by circularly symmetrical functions, which are similar to those used in the Hurricane Storm Surge Model from the Federal Emergency Management Agency in USA (Greenhorne & O'Mara Inc. [4]), i.e.

$$P_a(r) = P_c + (P_0 - P_c)e^{-R_1/r} \tag{4}$$

and

$$V_a(r) = \begin{cases} V_{\max} \sin^{5.73}(\pi r / 2R_2) & 0 < r < R_2 \\ V_{\max}\left(1 - 1.3e^{-\left[0.45((r-R_2)/R_2)^{0.55}\right]^{1}}\right) & r > R_2 \end{cases} \tag{5}$$

as shown in Figure 2. Additionally, the wind direction is turned 15° to the left from the direction of the geostrophic wind to simulate frictional effects. Here, V_a is the sea surface wind speed, P_c is the sea surface pressure in the centre of the storm, P_0 is the undisturbed sea surface pressure and r is radial distance from the centre of the storm. The parameters V_{max}, R_1 and R_2 are chosen such that the difference between the pressure and wind speed predicted by the above equations and available observations is minimised.

The other alternative that has been tested is forcing the model with pressure and wind field data taken directly from weather forecast models. The data are taken from 6 hour weather analyses made by the European Centre for Medium range Weather Forecasts (ECMWF) on a 1.125° or 1.5° grid. In the model the imported data are interpolated linearly in space and time to obtain the required pressure and wind field data at any location within the model area and at any time.

3 Simulation of storm surge events

To calibrate a storm surge model like that described above, meteorological data as well as sea level observations from past storms are essential. The meteorological data are readily available from either direct observations or analysis with the aid of computational weather models. Data on sea level variations are on the other hand very limited in Iceland, which makes the calibration more difficult. Up to the year 1992, continuous sea surface records exist only for Reykjavik, from a gauge run by the Harbour of Reykjavik. Since then, a number of gauging stations have been set up all around the country, most of them run by the Icelandic Maritime Administration. However, throughout these years with increased number of gauging stations, only a few minor storm surge events have occurred, but no major ones. In this study we have thus chosen to analyse two events, a major storm that hit the country in January, 1990, causing considerable surge with, however, only one gauging station operating, and a storm that hit in February 1996, causing little surge, but recorded at a number of gauging stations.

3.1 January 1990

The storm that hit Iceland on January 8th and 9th, 1990, is considered one of the worst storms of the century. In less than 48 hours, the storm centre travelled approximately 4500 km from south of Newfoundland to the south-west coast of Iceland, meanwhile deepening to a minimum storm centre pressure of 928 mbar just before hitting the coast of Iceland. During most of this time, wind speed east of the storm centre was at hurricane force. A surface weather map from 18:00 hours, January 8th, is shown in Figure 3.

The storm caused considerable damage in harbours and at low lying areas along the south-west coast of Iceland, although reaching the shore at or near low tide. Associated with the storm surge were extreme wave conditions, with

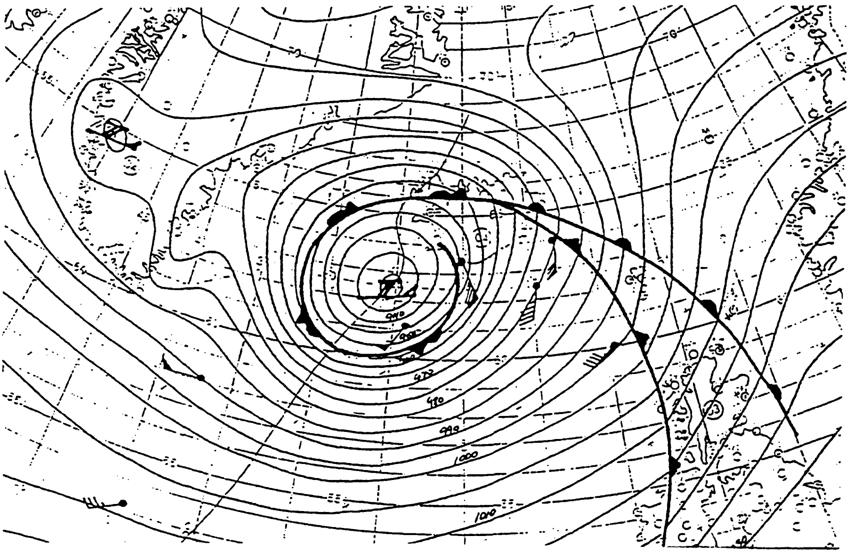

Figure 3: Surface weather map, January 8th, 1990 at 18:00.

the significant wave height just south of Iceland reaching a record high of 16,8 m.

As mentioned earlier, at this time only one sea level recording station was in operation in Iceland, i.e. that in Reykjavik. In Figure 4, the simulated and observed sea level variations in Reykjavik are compared. These simulations are based on the circularly symmetrical atmospheric forcing functions described in §2. The parameters of the forcing functions are taken as

$P_c = 934$ mbar
$P_0 = 1013$ mbar
$R_1 = 354$ km
$R_2 = 354$ km
$V_{max} = 30$ m/s

to match as well as possible the observed wind speed and pressure in Reykjavik throughout the course of the storm. Also shown is the computed tidal variation, i.e. a simulation without the meteorological forcing. The maximum computed surge level occurs at 22:00 hours, Jan 8th, with a deviation from the computed tidal level of around 80 cm. The agreement between the computed and observed sea level is fairly good. Inaccuracy in the underlying tidal simulations explains a considerable part of the phase difference as may be seen clearly from the figure, as well as some of the amplitude difference. A simulation with the atmospheric forcing taken from weather analyses made by

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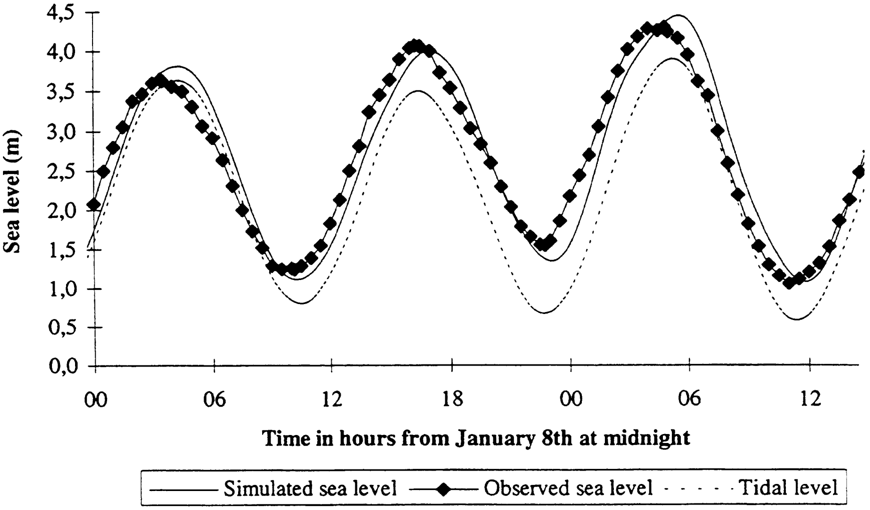

Figure 4: The simulated and observed sea level in Reykjavik January 8th and 9th 1990

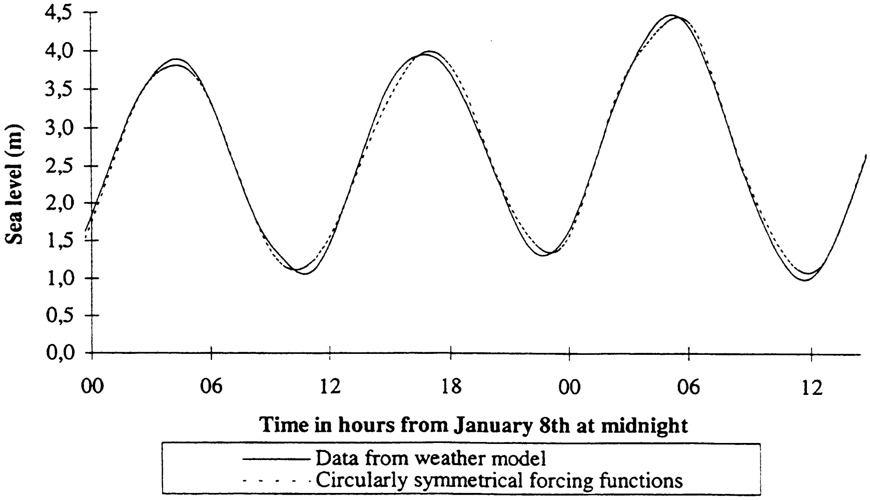

Figure 5: Simulated sea level based on circularly symmetrical forcing functions and data from weather model analysis by ECMWF

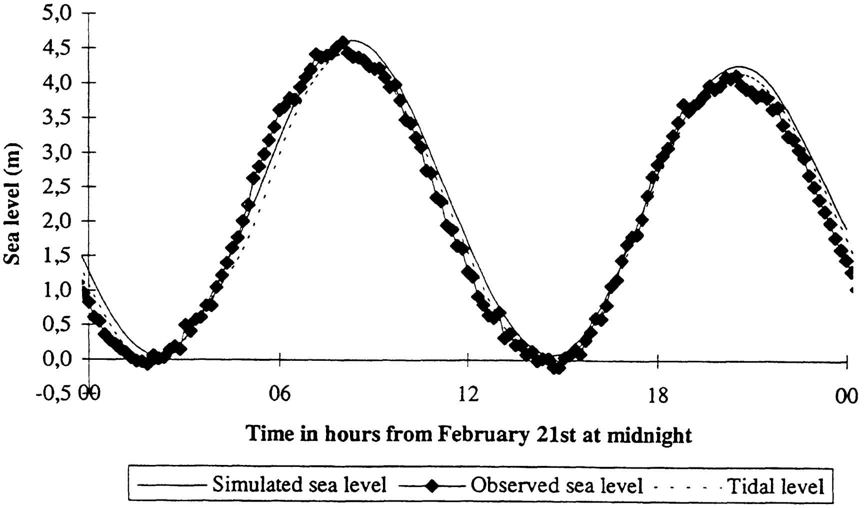

Figure 6: The simulated and observed sea level in Reykjavik February 21st 1996

ECMWF shows little improvement over the simple representation by the circularly symmetric functions, as may be seen in Figure 5.

3.2 February 1996

On February 21st 1996, a day of extremely high astronomical tides, a storm that was considered quite threatening at the time, hit the country. It was, however, different from that described in the previous section in that the storm centre followed a track well west of Greenland up to latitude around 70°N, and then east over Greenland into the North-Atlantic Ocean well north of Iceland. Still, due to an unusually strong high pressure system located to the south of Iceland, a large pressure gradient developed west of the country, causing high wind speeds and bad wave conditions at the west coast.

The observed and simulated sea level variation in Reykjavik is shown in Figure 6 along with the computed tidal variation. The agreement is very good, showing a very small storm surge, both in the observed and computed data. The main reason for the small surge is the great distance of the storm centre from the coast and consequently the relatively high atmospheric pressure at the coast throughout the course of the storm. Damage due to the storm was quite limited in spite of the storm hitting very close to high tide on a day of extreme tidal elevation and a 10-12 m significant wave height just west of the country. The results shown here are based on the circularly symmetrical forcing functions with the following parameters

$P_c = 960$ mbar
$P_0 = 1013$ mbar
$R_1 = 330$ km
$R_2 = 800$ km
$V_{max} = 30$ m/s

Again, results with the atmospheric forcing taken from weather analysis made by ECMWF gave similar results. Comparison with data from other tidal gauges along the west coast gave similar results as well.

4 Discussion

A storm surge model for the coast of Iceland has been set up. The model is based on an earlier tidal simulation model for the North-Atlantic Ocean around Iceland. Although still in an early stage of its development, the model has already been used to forecast storm surges on an experimental basis.

Due to a lack of sea level observations from earlier events, the model has only been tested on two events, a storm that hit the country in January 1990, and a storm that hit in February 1996. Both cases show fairly good agreement between computed and observed sea levels, indicating that the model may be used to successfully predict or analyse storm surges at the coast of the country. However, further calibration of the model is necessary.

Future plans for the model are to run it on an experimental basis in co-operation with the Icelandic Meteorological Office to forecast forthcoming storm surge events. In that way we hope to further develop the model and improve its calibration with time using all available sea level data as soon as they are recorded. Further confidence in the model will hopefully be gained as more and more events are analysed. The final aim of the project is to develop a model that may be used to forecast storm surges on a routine basis, as well as enabling further studies of historical events, to evaluate the potential risk and improve basic understanding of storm surges at the coast of Iceland.

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