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Kévin Dubois

Comparison of sea surface height measurements and calculations with the Delft3D-FM model and an analysis of forcing factors

Samanburður á mælingum á sjávarborði og líkanreikningum með Delft3D-FM og greining áhrifaþátta strandflóða

Kévin Dubois, Angel Ruiz-Angulo, Halldór Björnsson, Sigurður Sigurðarson and G. Orri Gröndal*

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A. ABSTRACT

Floods regularly cause damage and disruption to activities in ports or other coastal areas. A recent summary mentioned that there are sources about 84 floods in the second half of the 20th century (Guðrún E. Jóhannssdóttir, 2017) but in an older summary it is stated that about 6 significant floods occur every decade (Páll Imsland and Þorleifur Einarsson, 1991). The frequency of those events and their possible increase under climate change suggest that it is important both to monitor the coastal sea level and to implement computational models to predict probable flooding.

Measurements of sea level have been carried out in several ports around Iceland. The measurements cover different lengths of time and are not overlapping everywhere. From those measurements, the data from seven ports has received particular attention, filling in some small gaps and also correcting the corresponding time shifts. For those stations, the revised data is currently available (Guðjón Scheving Tryggvason, 2016,2017).

The Icelandic Meteorological Office has been working for some time on the installation of the coastal model Delft3D-FM (Deltares, 2020a,b) with the aim of being able to predict coastal floods. The numerical model solves the nonlinear shallow-water equations using finite volume elements in an unstructured mesh (about 500 m resolution along the coast). The model is forced by astronomical tidal forces, winds and pressure fields. The air pressure and winds that the model uses as input data come from the Harmonie forecasting system of the Icelandic Meteorological Office.

The model has already been used to simulate the water level for Reykjavík and compared with tide gauges measurements. The comparison was made both by calculating the tides in Reykjavík directly from the other tidal factors from the recent FES2014 system (Carrere et al. 2017) and using Delft3D-FM to calculate how the tidal wave reached the shore. The results of this comparison show that Delft3D-FM was better able to simulate the maximum sea level than FES2014, which demonstrates the importance of using a regional model to calculate tidal waves in detail. This comparison gives hopes that tides can be simulated elsewhere in the country, though comparison with the Reykjavík station is probably easier than with other stations as this station is the only IOC station in the country, and information from it in international databases such as those on which FES2014 is based.

B. INTRODUCTION

The Icelandic coastline is slightly less than 5000 km, and most of it is vulnerable to sea-level rise and storm surges. Iceland lies in the path of persistent low-pressure systems and frequent wintertime cyclones. In the last century, there were about 6 (to 15) significant (to moderate) coastal flooding events per decade, especially on the South and West coasts of Iceland (Björnsson et al., 2018). Although individual events that have led to significant damage have been reported (e.g. Jóhannesdóttir, 2017; Viggósson et al., 2016; Eydísardóttir, 2015; Geirsdóttir et al., 2014; Sigurðarsson, 2004; Imsland & Einarsson, 1991), no peer reviewed study has examined coastal flooding in general at the coast of Iceland, neither for past nor projected flooding events.

Sea surface height along the coastline has not been well monitored, of about 18 measurement stations only Reykjavik is operated according to IOC standards (Sigurðarsson, 2018). Multiple analysis of ESL statistics from this station yield a 100 year flood of 1.1 to 1.2 m above average spring tide (Jónsson et al., 2017; Elíasson, 1996; Elíasson and Valdimarsson 1993), but statistics for other locations are not available due to lack of data.

Thus, both monitoring and forecasting these events is relevant to the coastal communities. Hydrodynamic models with atmospheric forcing are useful to simulate storm surges, both for operational applications and risk assessments. The aim of this project is to improve knowledge of coastal floods in analysing different storms and comparing them with the new Delft3D-FM coastal model from the Icelandic Meteorological Office (IMO). However, one shortcoming of the model should be mentioned, the model is not a wave model and it does not reproduce water level variations due to waves. This, as will be shown, can impact the model results.

C. METHODOLOGY

At IMO, 4 domains for Iceland have been set up, and the South West domain is our pilot domain, shown in Figure 1. We chose different time periods when relevant storms happened in South-West Iceland: January 2000, December 2011 and February 2016 for different stations where tide gauges data were available: Akranes, Reykjavík, Grindavík, Landeyjahöfn, Þorlákshöfn and Básasker (Vestmannaeyjar).

We used the coastal model Delft3D-FM to simulate the flooding events. The numerical model is forced with hourly surface wind and pressure (IRCA reanalysis) throughout the domain and tidal constituents (FES2014) at the boundaries. The results are compared with the measurements from Vegagerðin's database. Four sets of simulations for each period were carried out to separate the contribution of each component: tide-only, tide and wind-only, tide and pressure-only and the full forced simulation.

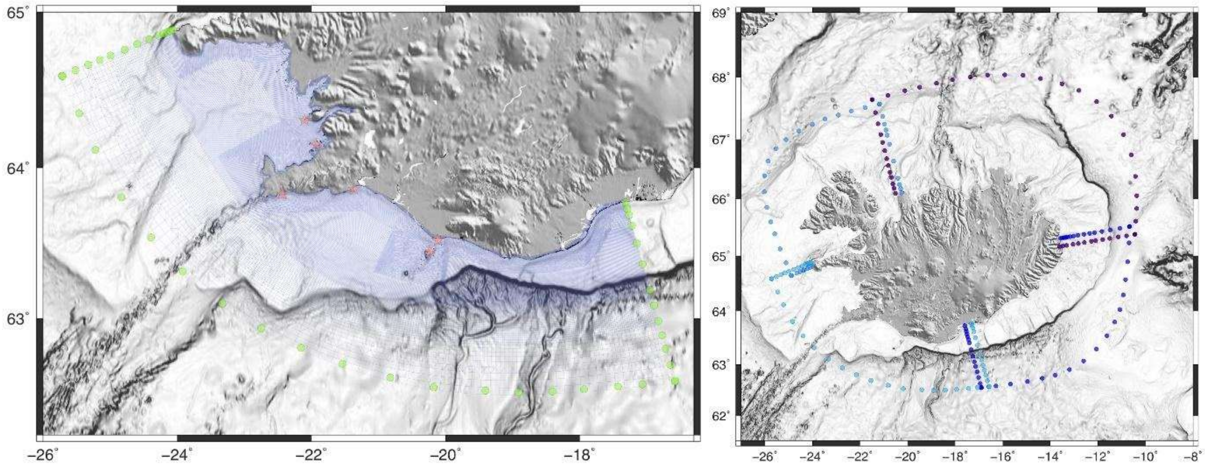


Figure 1. Map of the South West domain of Iceland including the unstructured mesh showing higher resolution at the coast. The stars represent the stations where the comparison was performed.

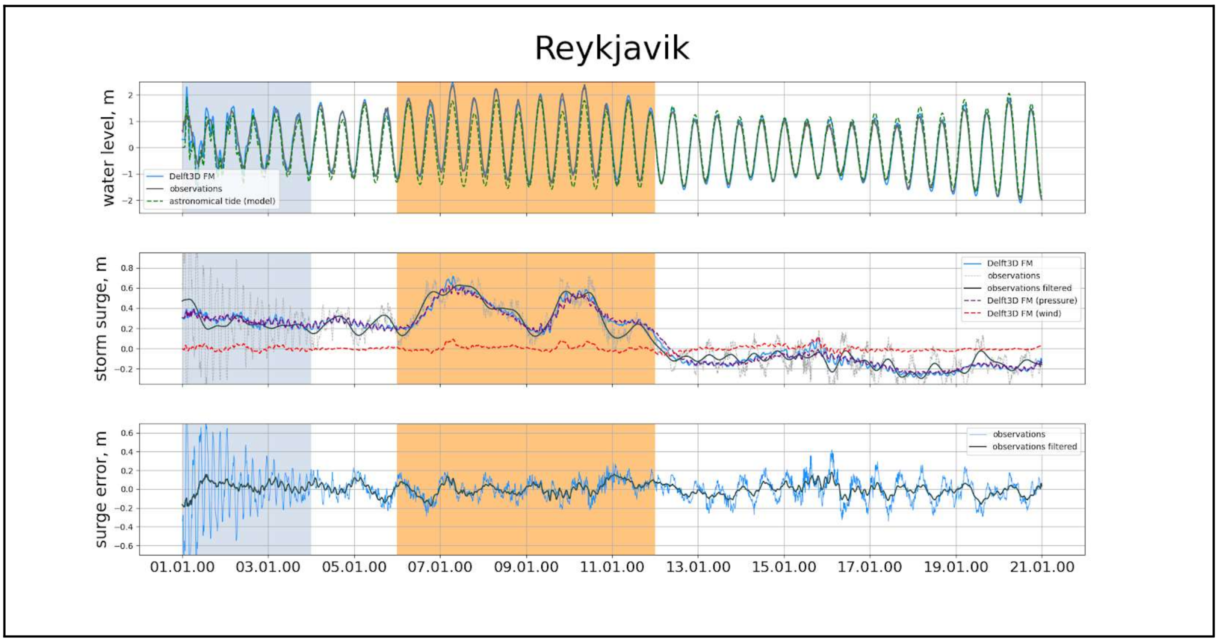
Finally, we compare the model outputs with the observed data at each station to assess the performance of the Delft3D-FM coastal model. More details on the model and grid are given in the appendix.

D. RESULTS AND DISCUSSION

We have successfully performed storm surge simulations for the South West of Iceland. The results are presented in the following figures. For each of the chosen storms, we compared the observations with the resulting simulations at the stations with available tide gauge data. For reasons discussed in more detail below, the high frequency variability in the observations is filtered out with a low-pass filter and the filtered results added to the figures.

For Figures 2-4, the upper panel shows the water level from observations (grey), the tidal model (dashed green) and the Delft3D-FM solution (blue). The middle panel shows the storm surge, resulting from subtracting the full signal from the tidal model, for the observations (grey) and the model full-forced with surface winds and pressure fields (blue) as well as the contribution from each component (wind-only in dashed red and pressure-only in dashed purple). The lower panel shows the residuals between the observations and the model. The period during the first three days of the simulations, highlighted in light grey, corresponds to the model spin-up time, and it is not used for further analysis as it has associated large errors for all stations. The light orange background highlights the active storm period, which is the main objective for this project.

The results for **January 2000** are shown in Figure 2, where we compared at 2 stations showing a very good agreement at Reykjavík station but underestimating the second peak of the storm surge in Grindavík. From the analysis, we performed 4 sets of simulations, which allowed us to separate two components, pressure and wind. The analysis shows that pressure is the main forcing driving the surge, in essence similar to the inverse barometer effect. However, as we mentioned before, we can highlight a high peak in the observation dataset on the 10th of January 2000 in Grindavik which was not reproduced by the model suggesting that the discrepancy could be attributed to the wavefield, trapped waves or local resonant effects. Here, the inclusion of a wave model would be needed to model this.



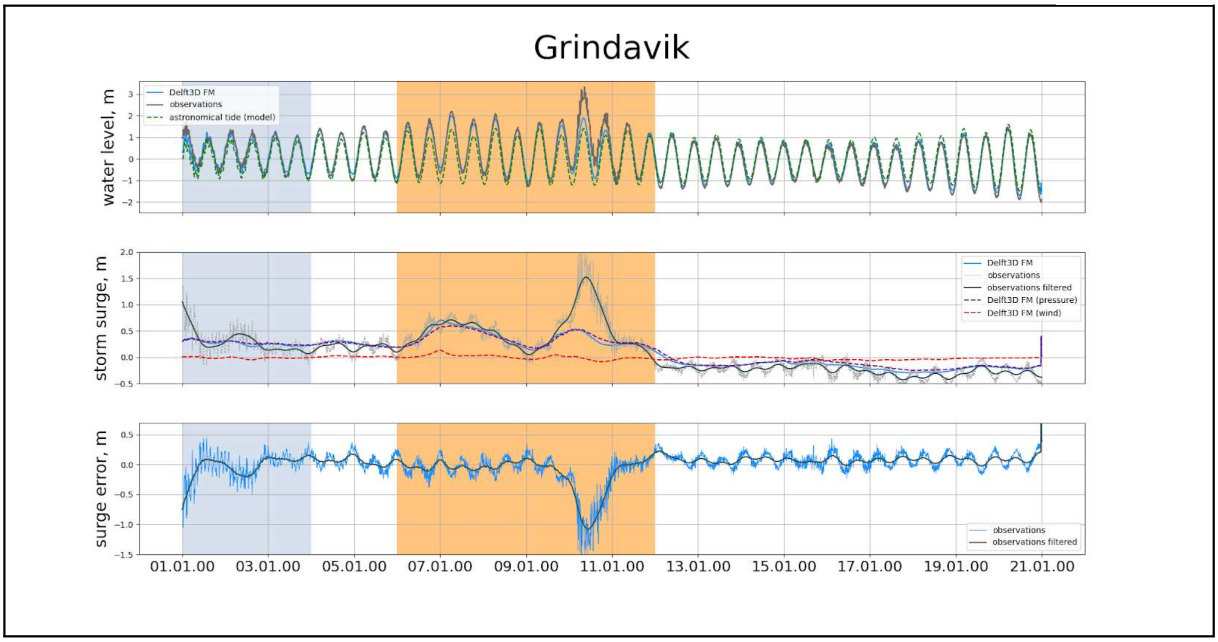
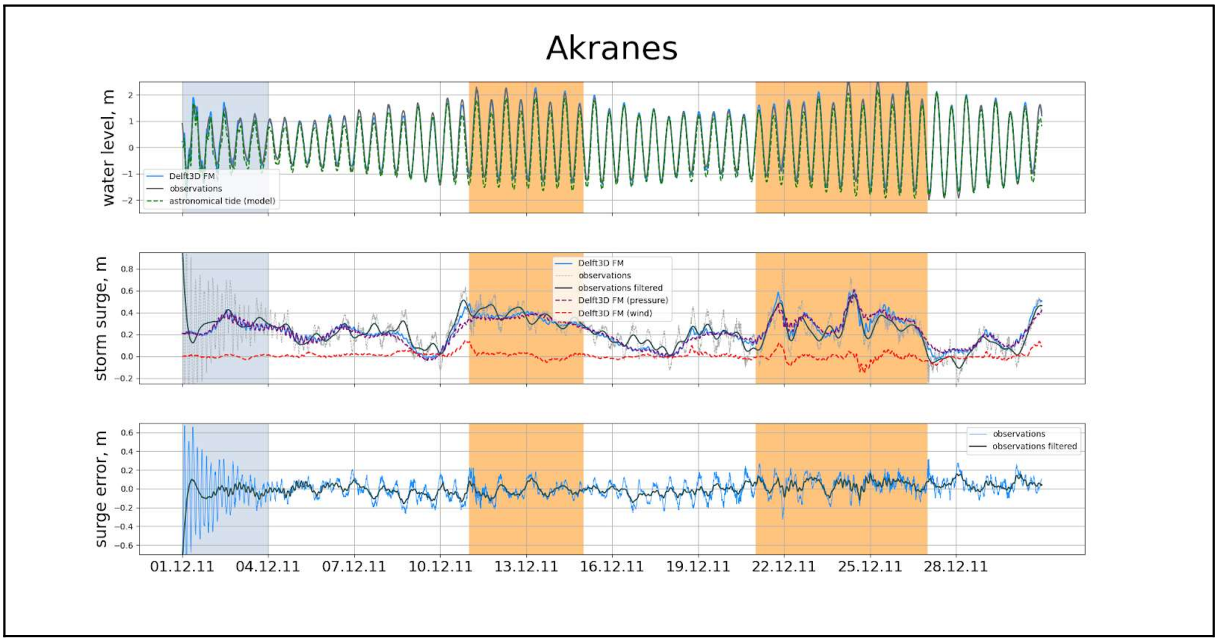
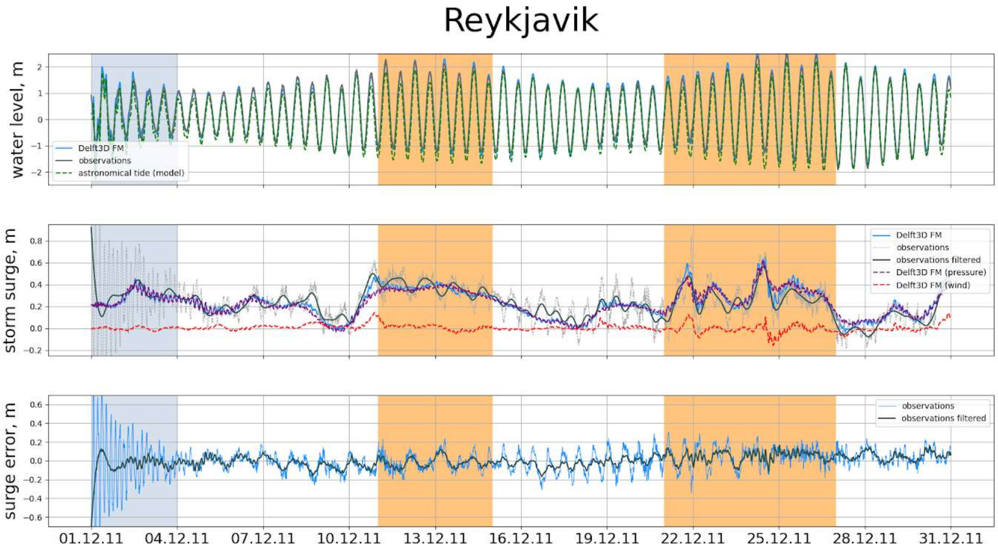


Figure 2. Storm surge: observations and numerical model estimates for **January 2000.** Note the error on January 10th which is most likely due to wave processes not included in Delft3D-FM.

Similarly, the results for **December 2011** are shown in Figure 3, where we compared 6 stations and once more the results show, as before, that pressure is the dominant forcing. However, the peaks of wind sometimes have a significant impact depending on the location, reaching up to 0.3 meters on the total storm surge.




Reykjavik
water level, m
Delft3D FM
observations
astronomical tide (model)
storm surge, m
Delft3D FM
observations
observations filtered
Delft3D FM (pressure)
Delft3D FM (wind)
surge error, m
observations
observations filtered
01.12.11
04.12.11
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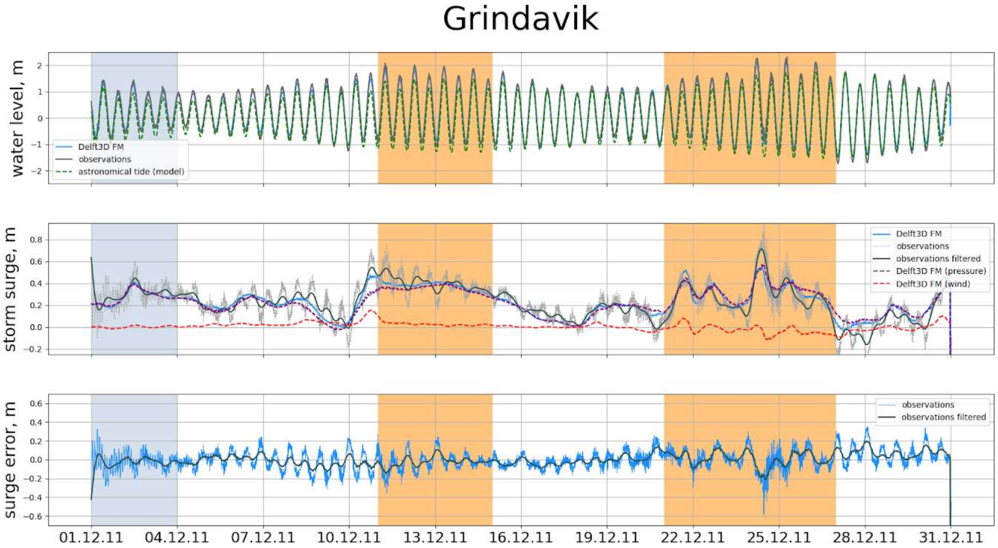
Grindavik
water level, m
Delft3D FM
observations
astronomical tide (model)
storm surge, m
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Delft3D FM (pressure)
Delft3D FM (wind)
surge error, m
observations
observations filtered
01.12.11
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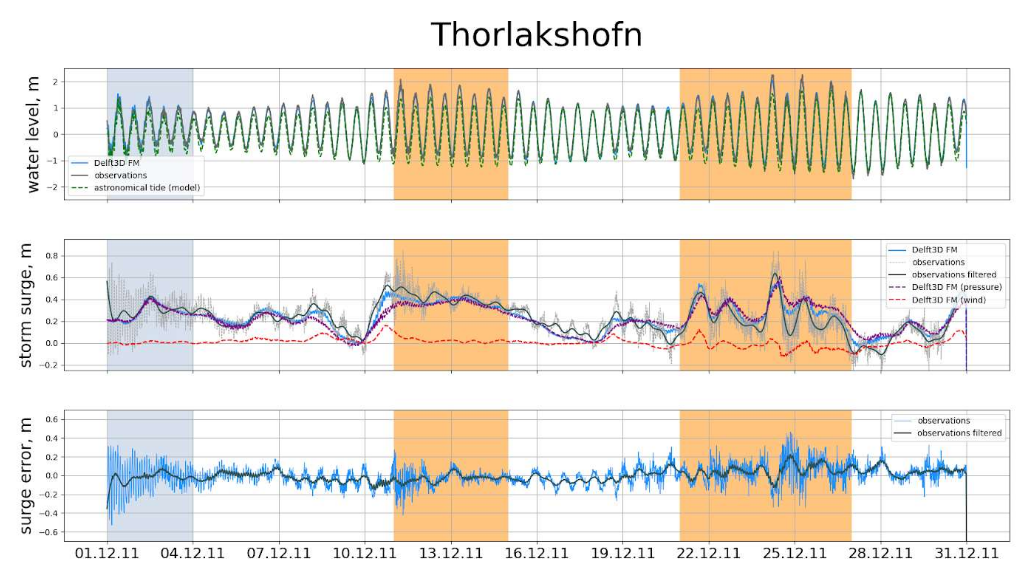
Thorlakshofn
water level, m
2
1
0
−1
−2
Delft3D FM
observations
astronomical tide (model)
storm surge, m
0.8
0.6
0.4
0.2
0.0
−0.2
Delft3D FM
observations
observations filtered
Delft3D FM (pressure)
Delft3D FM (wind)
surge error, m
0.6
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observations
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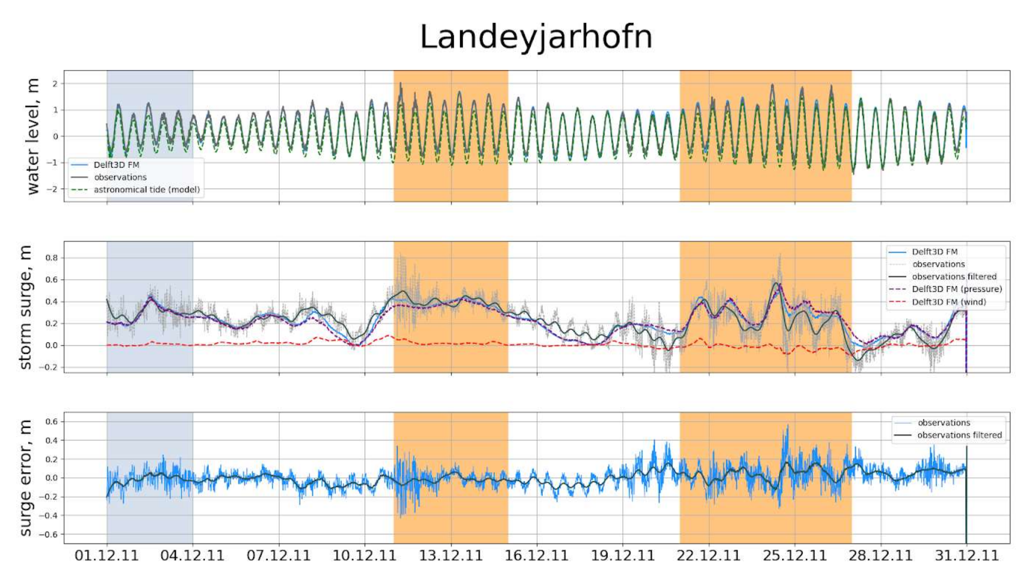
Landeyjarhofn
water level, m
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Delft3D FM
observations
astronomical tide (model)
storm surge, m
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Delft3D FM
observations
observations filtered
Delft3D FM (pressure)
Delft3D FM (wind)
surge error, m
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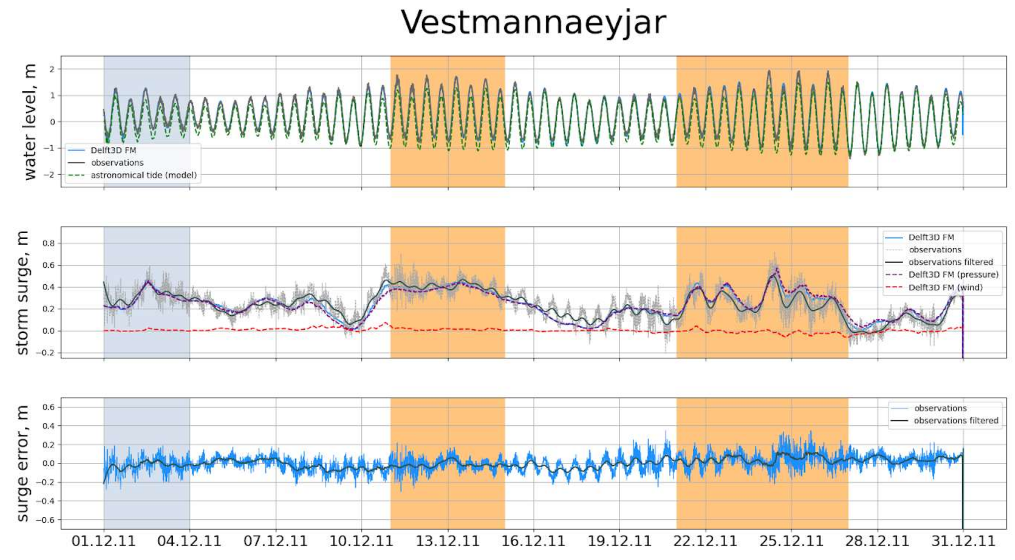
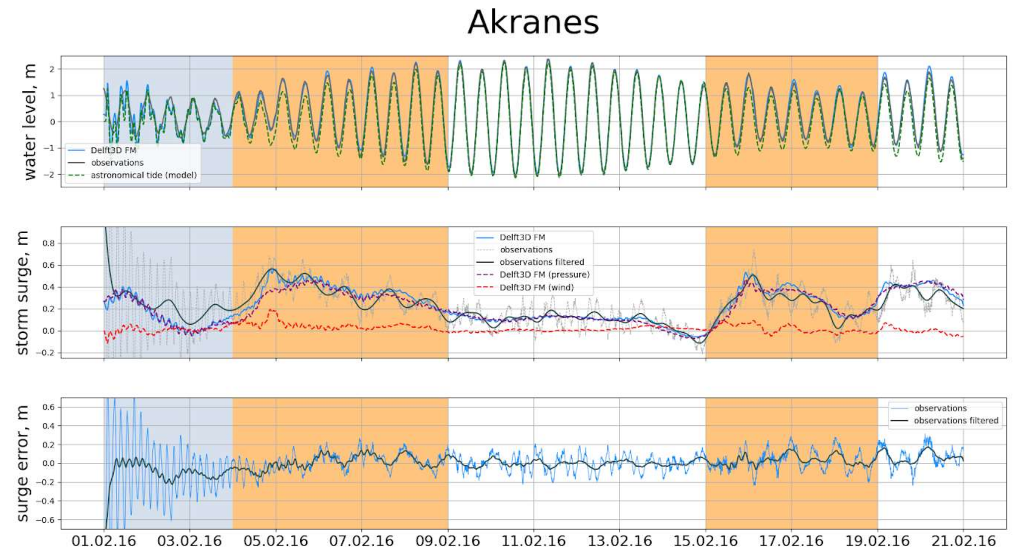
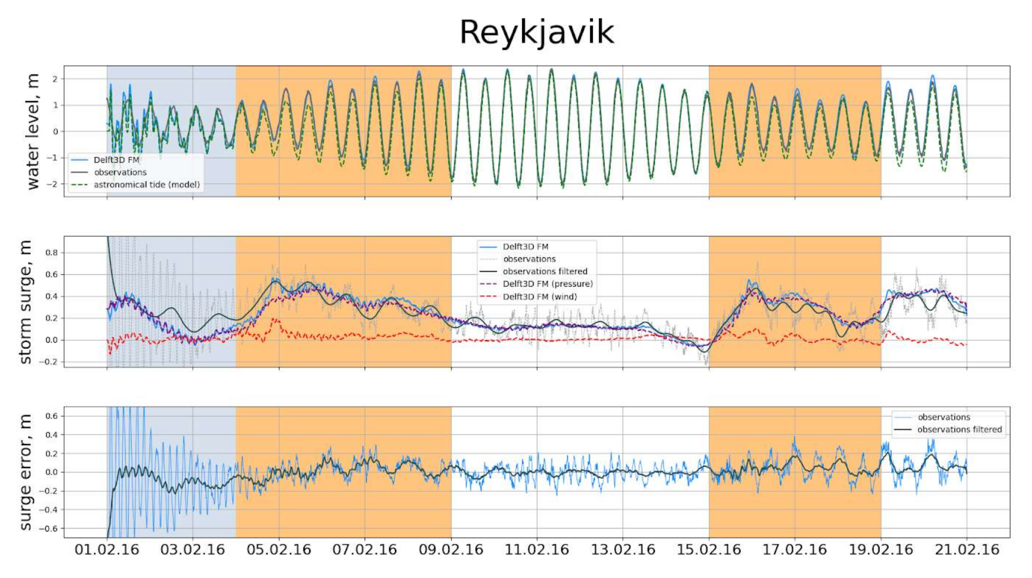


Figure 3. Storm surge: observations and numerical model estimates for **December 2011.**

The last set shown in Figure 4 corresponds to the storm in February 2016 comparing 6 stations. This particular period had two storm events within 12 days, both with modest storm surge. The comparison during this storm is very good for all stations including Grindavík, where we had a large discrepancy in the simulation for January 2000.




Reykjavik
water level, m
Delft3D FM
observations
astronomical tide (model)
storm surge, m
Delft3D FM
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observations filtered
Delft3D FM (pressure)
Delft3D FM (wind)
surge error, m
observations
observations filtered
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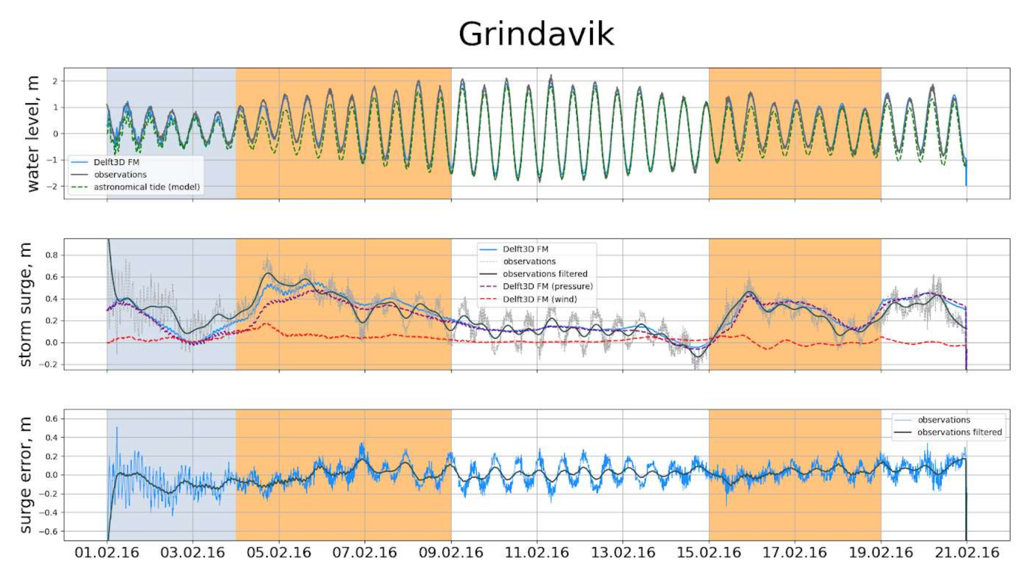
Grindavik
water level, m
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astronomical tide (model)
storm surge, m
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Delft3D FM (wind)
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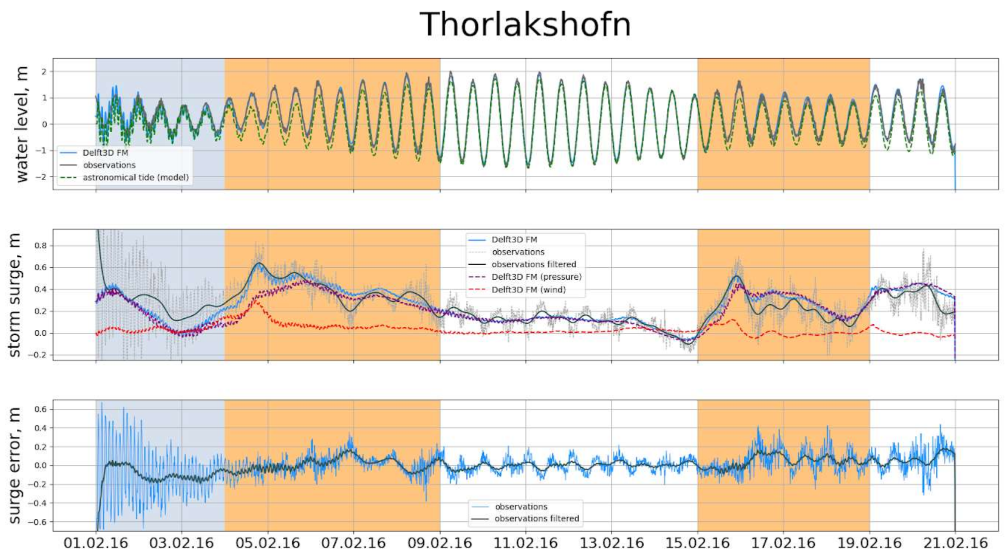
Thorlakshofn
water level, m
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Delft3D FM
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astronomical tide (model)
storm surge, m
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Delft3D FM
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Delft3D FM (pressure)
Delft3D FM (wind)
surge error, m
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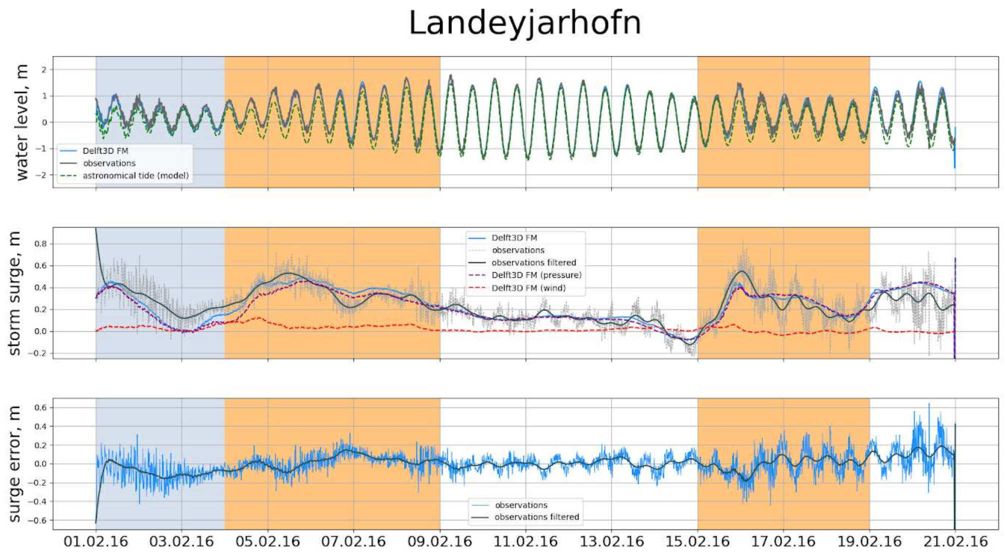
Landeyjarhofn
water level, m
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Delft3D FM
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astronomical tide (model)
storm surge, m
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Delft3D FM
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Delft3D FM (pressure)
Delft3D FM (wind)
surge error, m
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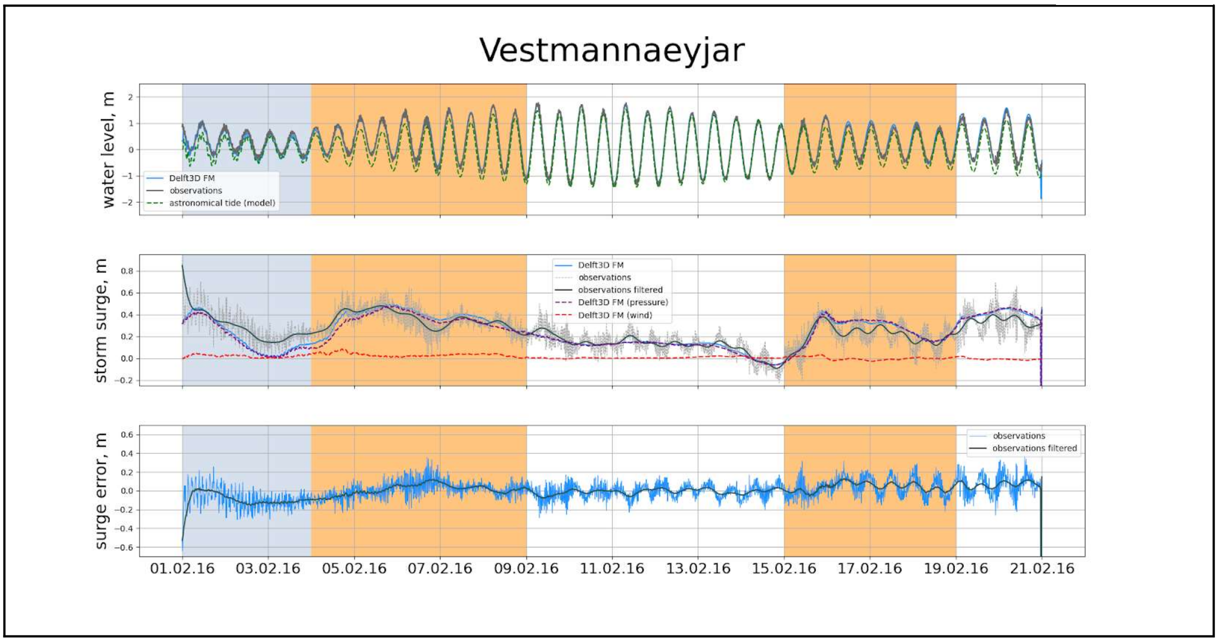

Figure 4. Storm surge: observations and numerical model estimates for **February 2016.**

From the figures 2 to 4, we clearly observe that the numerical model can not reproduce the high frequency variability recorded in the measurements. This variability is mostly associated with waves and wave effects are not included in the model. The model is forced with atmospheric inputs with hourly resolution and it's inability to generate higher frequency variability leads to an automatic filtering of the high frequencies and a mismatch with observations at that frequency scale. By filtering the observations with a Butterworth low-pass filter that eliminates the higher frequencies (see appendix for details), it becomes clear that the low frequency part of the signal is well reproduced by the model.

The overall storm surge estimates are satisfactory, we estimate an error between the model and the observations of around 20 centimetres once the model is past the spin up time. The model gives a good approximation of the sea level height during both calm and stormy weather.

Nevertheless, there is one event where the model did not perform as well as we would like, the 10th of January 2000 in Grindavik. In this case, extremely high water level was measured, equivalent to a 2 meters storm surge water level without the model reproducing more than modest increase in sea level. As the model performed relatively well for the same period in Reykjavik and during all the other simulations, we do believe that other factors, such as the wave setup was dominant in this case. However, to verify this, a wave model would need to be added to the modelling.

In the appendices, we highlight the good correlation (calculated without spin-up time) between the observations and the model with a coefficient of determination r-squared above 98%.

E. CONCLUSION

We have successfully performed storm surge simulations for the South West of Iceland during 3 storm events in the following periods: January 2000, December 2011 and February 2016. The results from the model are compared with the observations at 6 stations showing a relatively good agreement. The numerical model cannot reproduce the high variability observed in the measurements as it is lacking the higher frequency forcing effects due to wave setup, a component that can be significant for some stations. From the analysis, we performed 4 sets of simulations, which allowed us to separate the main components, pressure and wind. From this analysis we conclude that is pressure the main forcing driving the surge, in essence the inverse barometer effect. The spin up time response is very similar for all stations and it is about 3 days. As the overall storm surge estimates are satisfactory the main results of this study shows that the Delft3D-FM model can be used to simulate storm surges in Iceland.

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G. ACKNOWLEDGEMENTS

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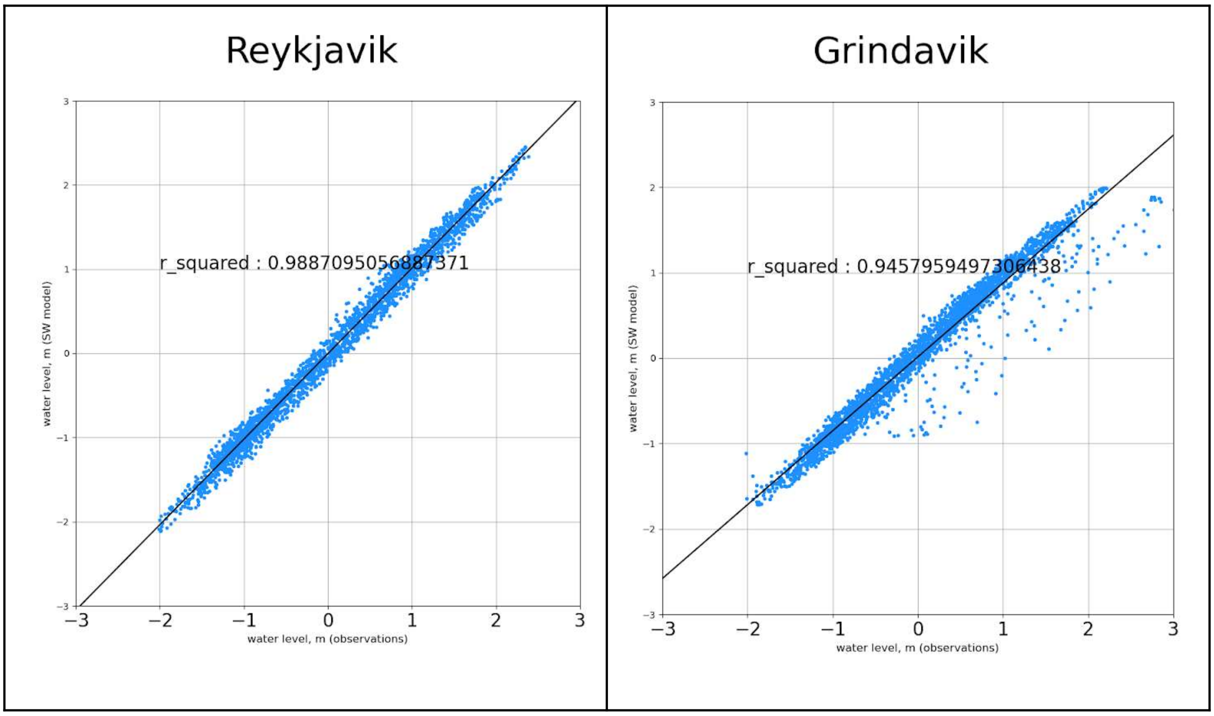
Comparison of observations and simulations

This section is for the storm surge data analysis only. The performance of the model is explored by comparing the low pass filtered observations with the model outputs. Among the limitations of the model are the forcing frequency, which occurs every one hour and this limits the response periods below 1 hr. The following scatter plots show the points from the middle panels of the figures above only after the spin up process but including the post storm period as well. The observations are in the X-axis and the model outputs on the Y-axis.

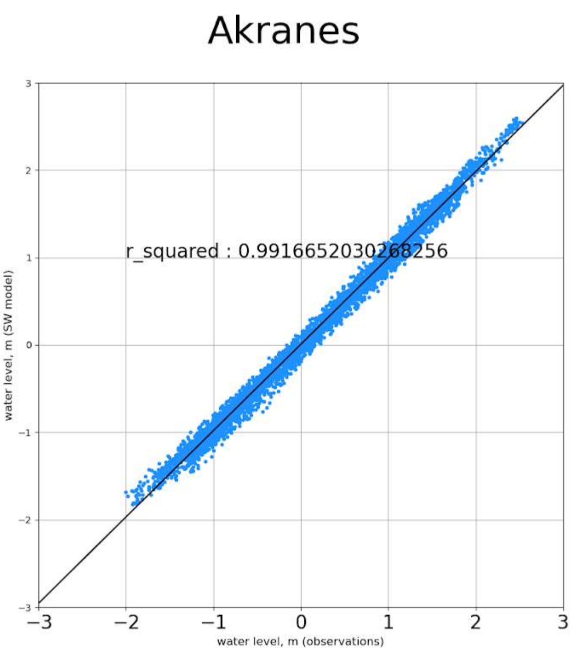
We present 3 sets of plots corresponding to the 3 different storms selected for this study. The performance of the model is satisfactory for most stations. We observe that for Grindavík the model underestimates for a relatively short period of time the storm surge opening several possibilities to explain this as we described in the text above.

January 2000

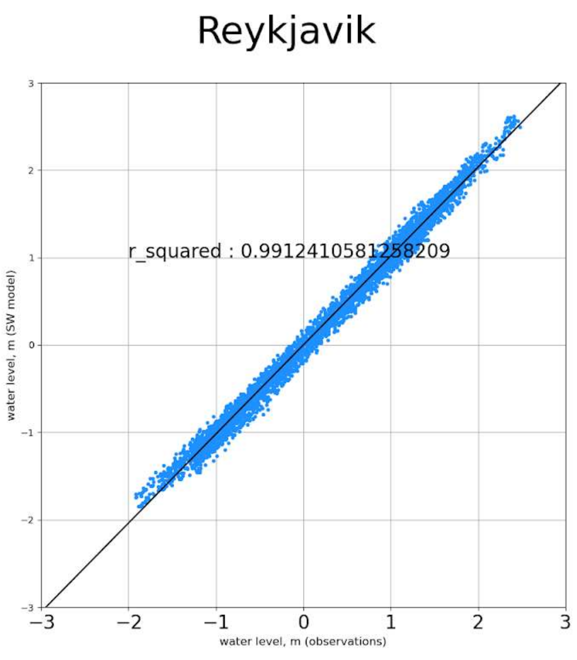


S1. Scattered plots for the comparison of observations (x-axis) and numerical model estimates (y-axis) for January 2000.

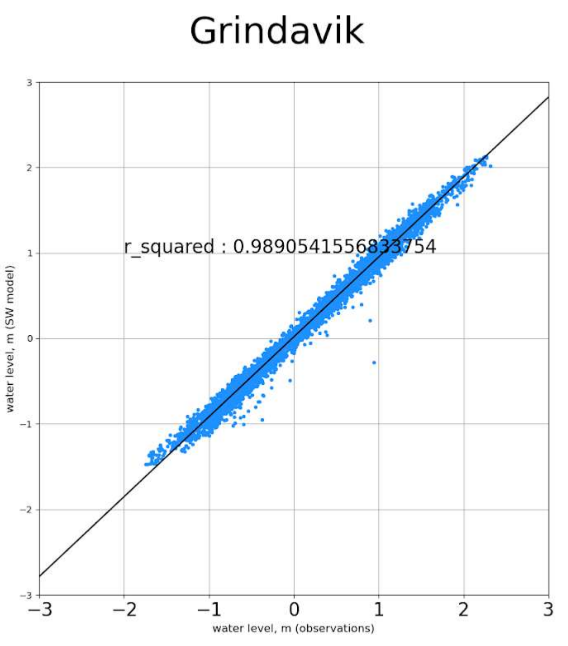
December 2011



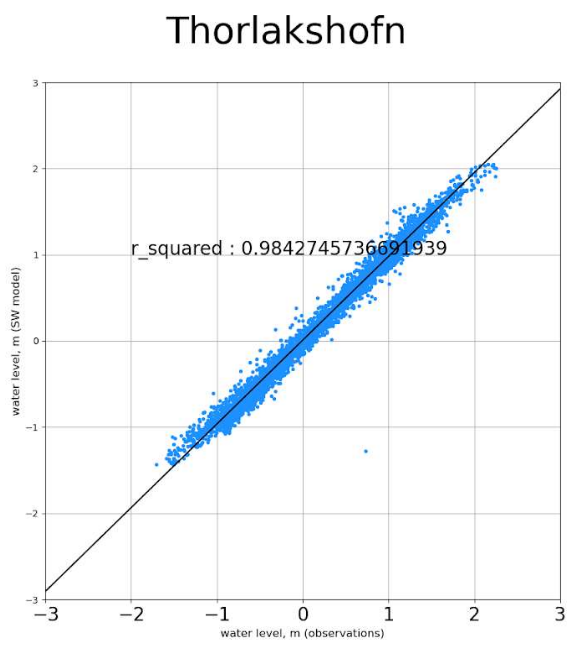
Akranes



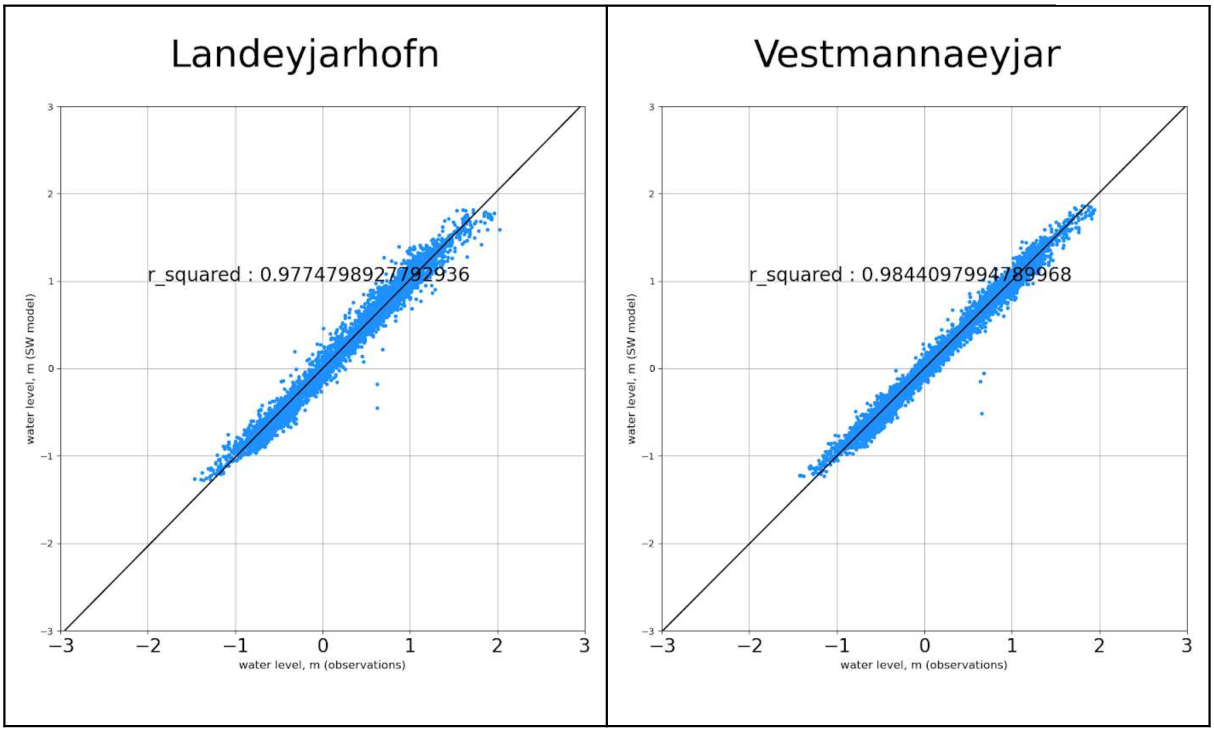
Reykjavik



Grindavik

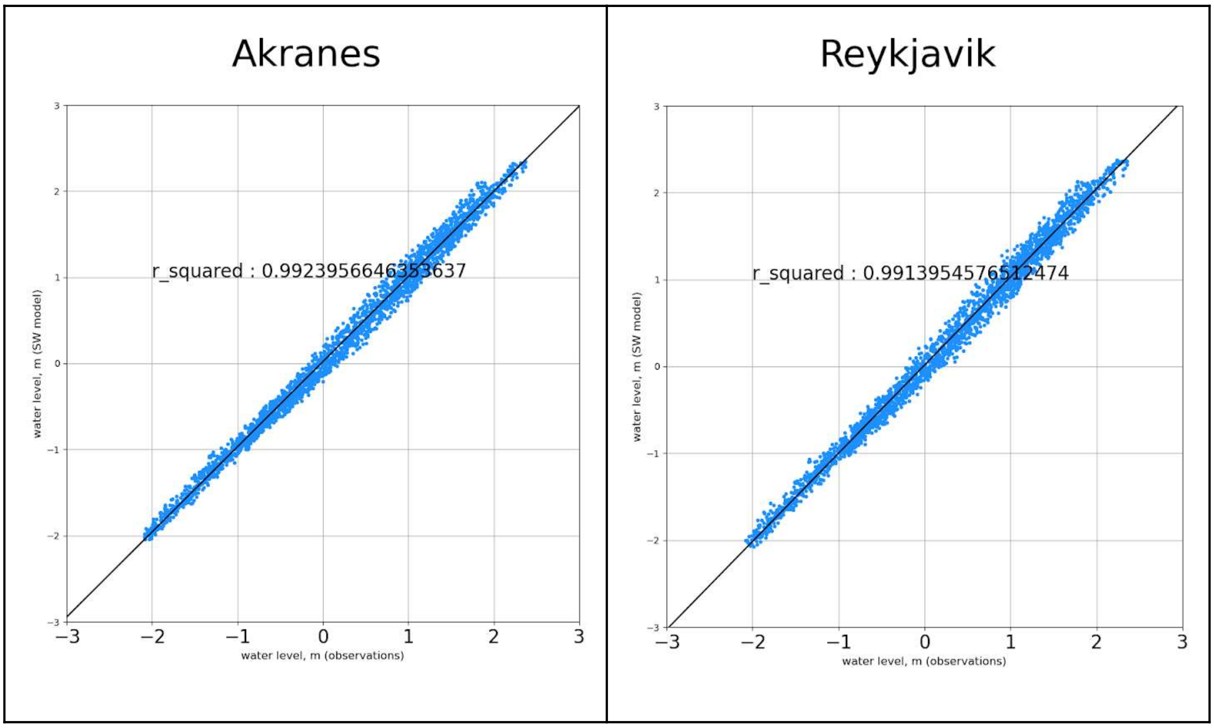


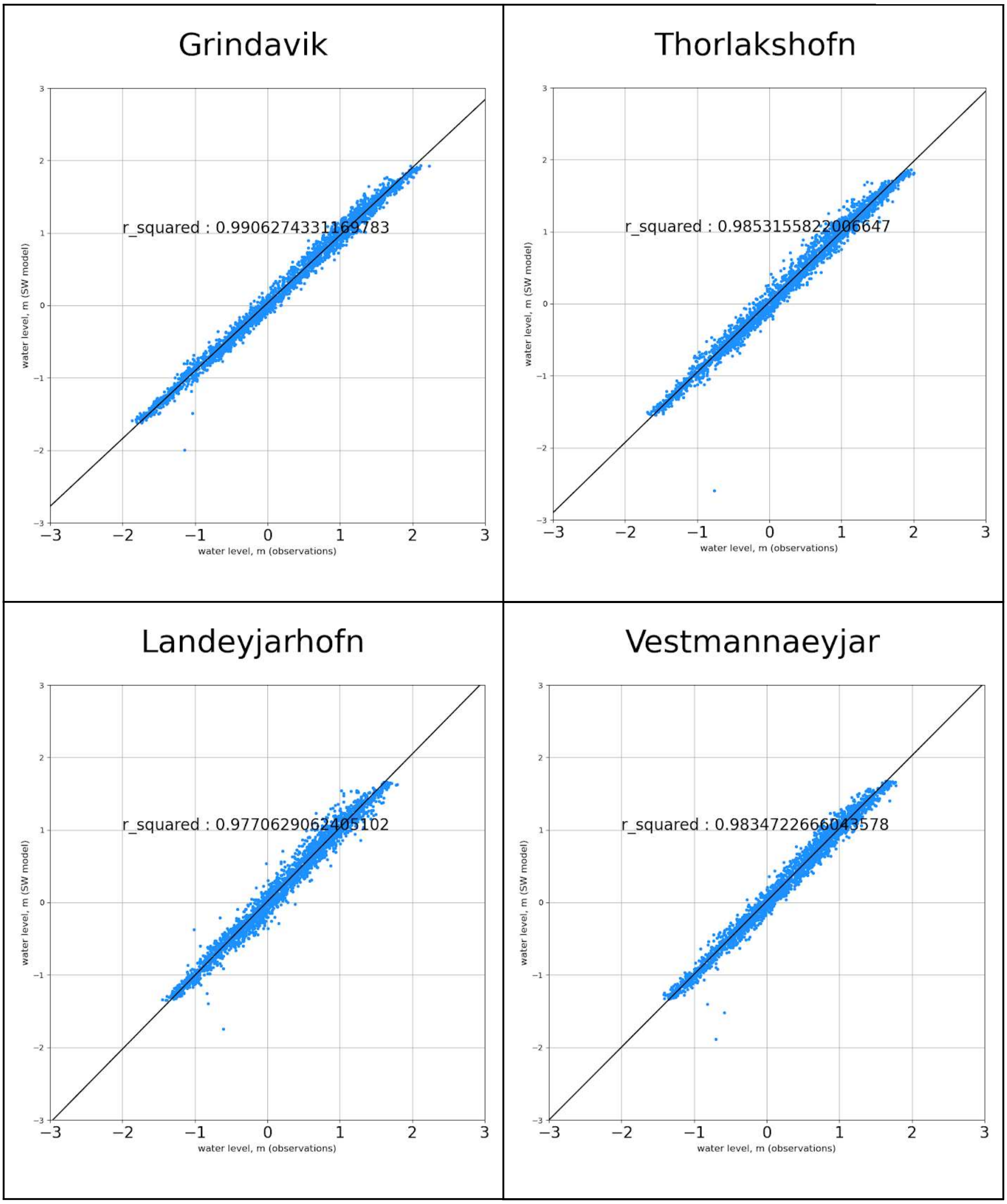
Thorlakshofn



S2. Scattered plots for the comparison of observations (x-axis) and numerical model estimates (y-axis) for December 2011.

February 2016

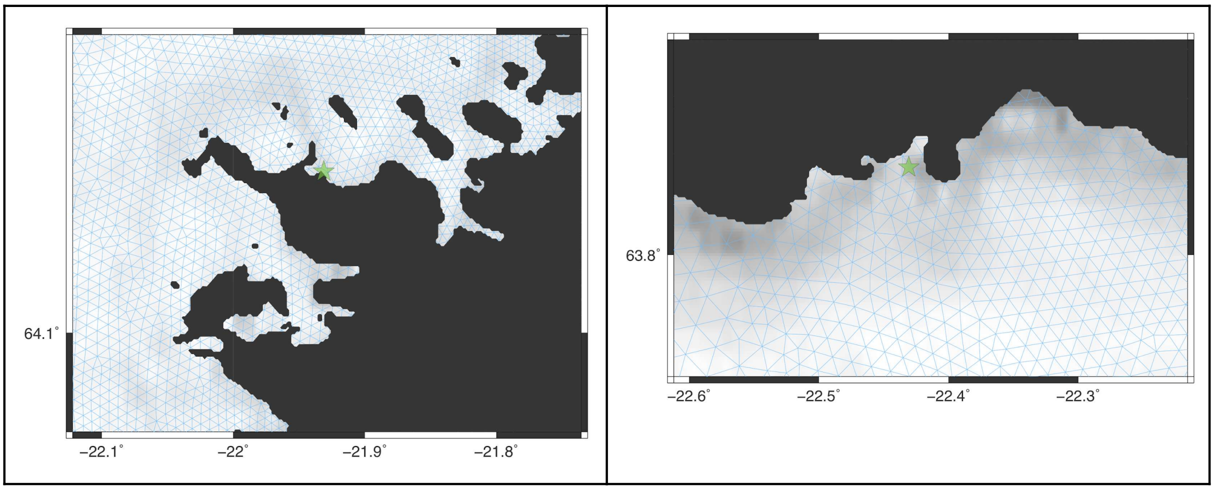




S3. Scattered plots for the comparison of observations (x-axis) and numerical model estimates (y-axis) for February 2016.

Details on the model setup

Figure 1 in the main text shows the grid employed in the simulations. Figure S.4 shows detailed maps zooming in Reykjavík and Grindavík areas, showing the size of the meshes for those two regions. As mentioned previously the mesh size was designed to be about 500m along the coastline. The computational core of Delft3D FM is the D-Flow Flexible Mesh engine for hydrodynamical simulations on unstructured grids (Deltares, 2020). D-Flow solves the 2D and 3D Shallow Water Equations and given the variable mesh size, the time solver also employs an adaptive time step, set to not exceed 70% of the CFL criterion, here 60 seconds.



S4. Left: Map of Reykjavík region with the computational mesh corresponding to this study. Right: Similar plot for the region of Grindavík. The plots also show the location of the computational point used for comparison in this study.

Details on the filter used

The filter used to remove the high frequency variability in the observations is a standard Butterworth (1930) lowpass filter. In the setup here, it was important only to dampen variations faster than a 100 min but to retain slower variations, associated with the surge and the tides. Using a Buttwerworth lowpass filter with a 100 minutes cutoff, Figure S5 shows on the right panel, the power spectral density for the observations in Grindavik in February 2016, showing the tidal components with a large peak at M2 tide and furthermore, showing that the higher frequencies above 100 min (1e-02 1/min) have been removed from the spectrum. The resulting signal from this filter is shown on the right panel (red) comparing it with the original signal including its high frequency content.

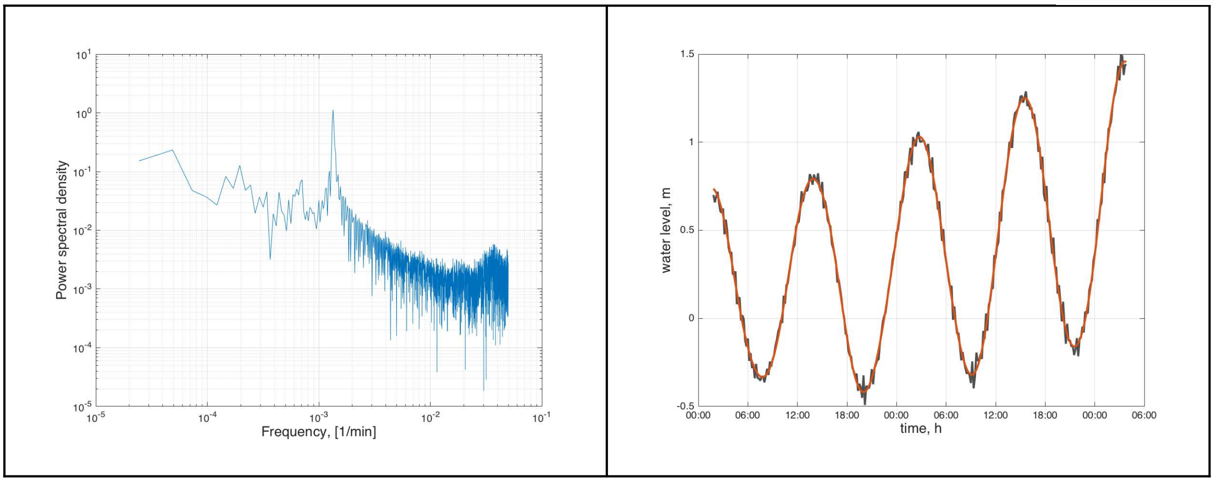


Figure S5. Left: Power spectral density for the water level observations at Grindavík in February 2016, showing the tidal constituents peaks but with the high frequency values removed, above 1e-02 (1/min) corresponding to values below 100 minutes. Right: The resulting signal shown in red and the original signal shown in gray.

Supplementary data

Additionally to this report we have prepared the output data set for each of the events. We generated time series as csv files that we read using Python 3, the plotting scripts are also added to the report package. There are two sets of files, one summarizing the numerical model output and one for the observations. Each csv file corresponds to one station and one event, the files read as follows: model_MonthYear_StationName.csv, and obs_MonthYear_StationName.csv. For example: “model_dec2011_akranes.csv” and “obs_dec2011_akranes.csv”. The description of each file is given in the header of each file.