Numerical simulation of tides and surges in Irish waters

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ABSTRACT. The Regional Ocean Model System (ROMS), driven by ERA-40 forcing fields, has been used to study tides and surges in the Northeast Atlantic Ocean. One experiment focused on hindcasting the tides and surge generated by a storm in early 2002. The ROMS model could simulate the basic tidal characteristic and surge very well, especially in the south Irish Sea. In order to ensure that the model is stable and reliable for decadal scale runs, a longer climate mode simulation was run and evaluated between 1993 and 2001. When compared to the simulation of 2D gravity wave model (MOG2D-G), the ROMS model consistently reproduces the sea level changes in the Irish Sea, and over the waters to the south and west of Ireland. The results show that the ROMS model can robustly and consistently reproduce both tides and storm surge and is a useful tool to study storm surges on short and long timescales.

1. Introduction

During the last century, especially in recent decades, serious flooding events have occurred over coastal ocean areas. Some of these events were accompanied by a significant loss of life and damage to property. The North Sea flood of 1953, for example, affected coastlines of England, the Netherlands, Belgium and France; in the UK an estimated 307 people lost their lives; in Holland the death toll reached 1835.

In Ireland, flooding is associated mainly with heavy rainfall which can lead to enhanced river-flow and over-topping of river banks. However, coastal flooding events are often more serious, particularly those associated with elevated sea levels (variously referred to as storm-surge, tidal surge or sea-surge; in this paper the word *surge* is used to refer to this phenomenon). Surges are temporary increases in sea level above the normal tidal level, caused by reduced atmospheric pressure and/or the action of strong winds on the water surface. The effects may be enhanced locally by the coastal topography [*Wells,* 1997].

Since the surge can pose a serious threat to residents of coastal areas, it is essential to establish a warning or prediction system to minimize the risk to lives and property. Generally, there are two approaches used to establish such a facility. If a long time-series of data is available at a site, a statistical downscaling technique could be applied to study the relationship between the surge and other weather elements (pressure, wind-speed, etc.); once the relationship is established, it is used as a predictive tool. However, this approach is dependent on the assumption that the surge statistics have not altered over the prediction period. Also, long-term records may not be available, particularly over a large area. A widely-used alternative approach is to use a numerical model to simulate the surge.

Flather et al. [1998] showed that numerical storm surge models are capable of generating outputs which have similar characteristics to observed data (e.g. from tidal gauge networks). The model approach also has the advantage of being able to generate information at arbitrary locations and for periods without observations. Two distinct types of ocean model have been developed for this purpose. Over the past thirty years, two-dimensional hydrodynamic tidal models have become well established and have been used to study tides and surges over the European continental shelf area [*Flather et al*., 1991, 1998]. Due to non-linearities, tidal-generated turbulence is the major source of mixing in shallow water environments. The oceanic response to both tidal and meteorological forcing must be adequately represented by the model in order to accurately reproduce the sea level changes due to both forcing and non-linear interactions. The rapid increase in computing capability in recent times has facilitated the use of high-resolution three-dimensional hydrodynamic models for such applications. A number of three-dimensional ocean models have been developed, which are widely used to study currents, tides, surges and other aspects of the ocean [*Davies and Jones*, 1993; *Davies and Lawrence*, 1995; *Jones and Davies*, 2001; *Liu et al.*, 2005; *Li et al.*, 2006].

Previous model studies of the tides and surges in the Irish Sea have been carried out with relatively coarse resolution, or have focused on restricted areas without considering internal wave generation and propagation from the deep ocean to shelf and coastal waters [*Davies and Hall*, 2000a, 2000b]. A configuration of the Regional Ocean Modelling System (ROMS) suitable for regional climate change studies and for an operational forecasting system has been established to run for Irish waters and the Northeast Atlantic. The purpose of this study is to evaluate the performance of this model in generating tides and storm surges over the Northeast Atlantic Ocean in both short and long term simulation. Following a summary of the model set-up in section 2, comparisons with observations and other models are presented for tides in section 3 and for surge in section 4.

2. Method

2.1. Regional ocean model description

The ROMS ocean model used in this study is a three-dimensional, hydrostatic, primitive equation ocean model, originally developed by Rutgers University [Shchepetkin *and McWilliams,* 2005]. This model incorporates a free surface, enabling simulation of surface elevation changes due to tides and surges. The stretched, terrain-following and orthogonal curvilinear coordinate transformations are used in the vertical and horizontal directions respectively. An accurate representation of the baroclinic pressure gradient [*Shchepetkin and Williams,* 2003] was used. The Large-McWilliams-Doney scheme is applied for vertical mixing, which performs well in the open ocean [*Large et al.*, 1994].

Flather et al. [2000a] pointed out that the tides in shelf and coastal seas are responses to oscillations generated primarily in the deep oceans. The model domain should, therefore, be large enough to accommodate the major Atlantic cyclone systems that move over the area, while capturing the shallow-water characteristics of the Irish Sea. The domain was selected which covers the area from the middle of Atlantic Ocean to the North Sea and includes Rockall Trough and the Bay of Biscay (Figure 1). For this study, the model had a horizontal resolution of 4 minutes (about 7km) and 16 vertical levels.

As previously discussed, surges are changes in water level generated by atmospheric forcing, particularly by the drag of the wind on the sea surface and by the variation in surface atmospheric pressure associated with storms. The effects of horizontal surface air pressure gradients were included within the model. In this study, the meteorological forcing data, including the 10-metre u and v component of wind stress, mean sea level pressure, net short-wave and long-wave radiation fluxes, precipitation, evaporation, latent and sensible heat fluxes were taken from the 6-hourly ECMWF 40-year reanalysis datasets (ERA-40) [*Uppala et al.*, 2005]. For the sea surface elevation boundary condition, the Chapman condition and the inverted barometer effect (the change in sea level related to the atmospheric pressure calculated using the hydrostatic assumption) were used. This gives a reasonable approximation to the sea level on the open ocean where the effect of a coastal setup is not felt, and was used as a boundary condition to approximate changes to sea level related to a low pressure system approaching the model domain. A Flather boundary condition [Flather, 1976] was used for the tidal currents and the radiation condition for the momentum, salinity and temperature. Temperature and salinity data were taken from the Word Ocean Atlas 1998 datasets [*Antonov at al.*, 1998; *Boyer et al.*, 1998]. For the tidal forcing, data were derived from the barotropic tidal data assimilation system of Oregon State University (TPXO6.2) [*Egbert and Erofeeva*, 2002]; it includes eight primary (M_2, S_2, N_2, K_2, K_1, O_1, P_1 and Q_1) and two long period (M_f and M_m) harmonic constituents. These data are mainly assimilated from 364 cycles of TOPEX/Poseidon altimeter data.

Because surges are superimposed on the normal astronomical tides generated by variations in the gravitational attraction of the Moon and Sun, the surge height was computed following *Flather* and *Williams* [2000b]:

$$\text{Sea level elevation} = \text{predicted tide level} + \text{storm surge height} \qquad (1)$$

In order to include the effects of interactions due to non-linear dynamical processes in shallow water, two simultaneous simulations were run on separate, but identical, grids. One was driven with all the forcings (tides, inverted barometer effect and wind forcing); the other was driven with tidal forcing only. The surge heights were determined by subtracting the tide-only run from the tide plus meteorological forcing run.

2.2. Storm event experiment

On 1 February, 2002, an intense cyclone formed over the Northwest of Ireland; a central pressure of about 928hPa [*Burt*, 2007] was recorded at 18UTC. This, in combination with strong surface winds and coinciding with high tides, caused serious coastal flooding, particularly along the east and south coasts of Ireland. From Cork to Dublin, hundreds of houses were flooded. The southern counties of Cork and Kerry were worst hit, but western coasts were also affected; in Galway and Mayo wind gusts reached about 40 m/s. This storm was chosen to evaluate the performance of the ROMS model in hindcasting extreme surge events.

The model simulation was run for a total of 45 days from 00 UTC on 1 January, 2002 to 00 UTC on 15 February, 2002. The first 15 days of results were disregarded to allow for model spin-up. The simulated surge for Dublin Bay and Cork Harbor (Figure 2) shows similar time evolution to the UK station data (Figure 8). Unfortunately, observation data were not available at these locations for this period for a quantitative comparison. A strong surge event occurred on 1 February, particularly in Dublin Bay where the surge lasted about 12 hours (much longer than in Cork Harbor). The four spatial distribution maps (Figure 3), at 6-hour intervals from 12 UTC on 1 February, show that in the north Irish Sea there was a continuous strong surge over the 24 hour period, while the south coast experienced two weaker surge events, one at 18 UTC and one at 06 UTC. This is consistent with the mean sea level pressure pattern associated with the storm (not shown).

Harmonic analysis of the sea surface elevation can provide useful insights into the hydrodynamics of the sea and its response to the tidal forcing. The number of tidal components that can be independently determined using harmonic analysis is proportional to the length of the data record. Considering the small contribution of the long term constituents in the short term simulation, one month data is usually sufficient for the analysis of the short-term constituents. In this study, the tidal program VAV [*Ducarme et al.*, 2005,2006], based on the Method of Least Squares (MLS), was used to perform the harmonic analysis. The VAV model applies MLS to the tidal signal taking all theoretical tidal waves and the colored character of the noise into account, giving more accurate results. VAV has different options for ocean tidal data processing; one option is to determine the amplitudes and phases of different groups [*Tamura*, 1987]. In this study, only the diurnal and semi-diurnal constituents were analyzed, due to the limited duration of the run.

For comparison with the simulated tides and surges, data from 4 tide gauges along the UK coast of the Irish Sea for January and February 2002 were used. These four stations are located from south Irish Sea to north Irish Sea (Figure 1).

2.3. Climate mode experiment

One application of this regional ocean model is to assess the effect of climate change on the surge under different climate scenarios over timescales of 10 to 100 years. To assess the stability of the ROMS multi-decadal climate runs, a control run was first carried out in order to evaluate the surge output with the surge from an independent model. The dynamic atmospheric correction (DAC) used in the SSALTO/ DUACS (Segment Sol multimissions d'ALTimétrie, d'Orbitographie et de localisation précise/Data Unification and Altimeter Combination System) processing of altimetric sea level anomalies was used for this purpose [Carrere and Lyard, 2003].

This correction models the oceanic response to both the inverse barometric effect and the effect of wind forcing using a 2D gravity wave model (MOG2D-G). Based on the shallow water continuity and momentum equations, the model is barotropic and non-linear. The resolution increases from 400km in deep water to 20km in shallow water due to finite element discretization. Quadratic bottom friction is included and dissipation due to internal wave generation is parameterized. Pressure and wind forcing are provided by ECMWF fields. Model output is available as an auxiliary product from the SSTALTO/DUACS system at 6-hourly interval on a 0.25°x0.25° global grid.

The ROMS model was run over the Northeast Atlantic domain for the years 1993-2001, with the output from a smaller inner domain (49-55°N and 1-12°W) being saved from the simulations. To compare the ROMS storm surge with the DAC, the mean surge and DAC for the 24 hours corresponding to the date of each sea level anomaly (SLA) weekly product were calculated.

3. Tides simulation

3.1. Temporal variation

Observation data from four stations along the UK side of the Irish Sea were used to validate the model. Table 1 shows the computed harmonic constants of main diurnal and semi-diurnal tidal constituents from the hourly observed and simulated tidal elevation. The simulated tidal heights are in good agreement with the observed for the St. Mary's, Newlyn and Holyhead stations. For Bangor, however, all constituents, except K_1, show significant differences from the observed tidal analysis results.

As a further verification, time series of the simulated surface elevations were compared with matching observations in Figure 4. For St. Mary's and Newlyn (Figure 4a and 4b) the simulated surface elevations are in very good agreement with measured values, except for some peak values at St Mary's that are underestimated in January. A similar pattern is seen at Holyhead, where the high water level was slightly overestimated for the first part of the record (Figure 4c), but simulated low water values were also systematically lower than observed throughout the run by about 30cm. At Bangor (Figure 4d), while the simulation has reproduced the phase of the surface elevation variations well, both the high and low water levels are overestimated. The poor performance of the model here may be due to local effects at Bangor, which is located at the entrance to Belfast Lough, and the inability of the model to resolve this Lough at a spatial resolution of around 7km.

Table 1. Comparison of the harmonic constants from observed and simulated tidal elevation at 4 coastal stations: amplitude (Amp) in cm; phase in degrees

		S.T.Mary		***Newlyn***		***Holyhead***		***Bangor***	
		Amp	***Phase***	***Amp***	***Phase***	***Amp***	***Phase***	***Amp***	***Phase***
M_2	Observation	174.3	142.0	172.2	144.4	181.0	301.6	116.3	330.1
	Simulation	172.0	137.8	183.6	135.4	189.8	294.4	147.5	317.5
S_2	Observation	65.7	184.2	57.9	189.3	59.1	338.7	29.7	14.7
	Simulation	62.2	178.6	65.5	178.6	60.3	330.1	41.1	2.1
K_1	Observation	6.3	117.2	5.8	128.0	14.2	189.5	13.4	199.6
	Simulation	8.0	117.2	7.4	124.5	14.0	170.9	12.9	178.9
Q_1	Observation	4.9	350.4	6.7	352.6	13.0	28.1	13.0	40.7
	Simulation	5.3	359.0	5.4	358.9	9.3	46.6	9.9	62.0

3.2. Spatial variation

The co-amplitude and co-phase of the TPXO6.2 and ROMS simulated semi-diurnal M_2 tides are shown in Figure 5. Both sets of data (Figure 5a and 5b) show that the M_2 constituent propagates counter clockwise around the west coast of Ireland and then along the southern part of the domain, from the Celtic sea into the Irish Sea. Because the Irish Sea is relatively shallow and narrow, the amphidrome here is degenerate, with a virtual amphidromic point displaced over the south east of Ireland.

Comparison of the model simulation in Figures 5b and 6b, with the altimetric data in Figures 5a and 6a for the two main semi-diurnal constituents, reveals good agreement over the entire domain, and very good agreement in the Irish Sea area. For the co-amplitude lines, in particular, only small discrepancies are found for both constituents, located primarily in the English Channel and off the northwest coast of Ireland. Both the magnitude and the spatial pattern of the co-phase lines of both M_2 and S_2 constituents show very good correlation in the Irish Sea. Off the west coast of Ireland the differences extend to a maximum of about 20 degrees.

To assess the relative importance of the diurnal and semi-diurnal tidal constituents, a form factor, F, can be derived from the amplitudes of the harmonic constituents ($H_{\text{constituent}}$):

$$F=\frac{(H_{O_1}+H_{K_1})}{(H_{M_2}+H_{S_2})} \qquad (2)$$

Using the form factor, the tide can be classified into four types: semi-diurnal ($0.0 < F < 0.25$); mixed, mainly semi-diurnal ($0.25 < F < 1.5$); mixed, mainly diurnal ($1.5 < F < 3.0$); and diurnal ($F > 3$). From analysis of the TPXO6.2 data (Figure 7a), F is less than 0.25 over most of the Irish sea except in the North Channel and just off the coasts of Wexford and Wicklow. Even in these two areas, it is still mainly semi-diurnal in nature. The model (Figure 7b) reproduces the spatial pattern of the form factor very well, but overestimates its value in the mixed tide areas, possibly because the resolution of the model is too coarse to resolve local influences. To capture the effects of the complex physical environment in the North Channel in particular on the tides in that area would require much higher spatial and temporal model resolution.

4. Surge simulation

4.1. Temporal variation

Figure 8 shows the simulated and observed surge for (a) St. Mary's, (b) Newlyn, (c) Holyhead and (d) Bangor. The model is clearly reproducing both the magnitude and time of surge events very well in general. Agreement is better at the Newlyn and St. Mary's stations, which are located at Land's End and on the Scilly Isles, respectively, so are less influenced by the topographic and dynamical effects of the semi-enclosed Irish Sea basin. However, some extreme surges, in particular a large event on the 22-23rd January, were underestimated by up to 20cm in the simulation, even at these stations. For Holyhead and Bangor, there is still a high degree of consistency between the modeled and observed time series, but the amplitude of the surge is systematically underestimated at both stations.

One factor may be the use of 6-hourly ERA-40 data to drive the ocean model; this temporal frequency is too low to capture the full effects of fast-moving cyclone systems across the narrow Irish Sea basin. Comparison of the ERA-40 data with synoptic surface observations shows that the ERA-40 wind strengths are biased low, in general, but this bias is particularly evident for the strongest winds. Both of these factors will lead to weaker surges in the simulation compared with the observations.

According to the work of *Lowe et al.* [2001], along the south Irish Sea coast the surge height is dominated by the inverted barometer effect, with the wind forcing providing only 16% of the surge height. In the north Irish Sea, on the other hand, the wind forcing contributes 72% of the surge height. A sensitivity study was carried out in which the ERA-40 winds were modified to provide better agreement with synoptic observations. The results confirmed that issues with the ERA-40 wind fields are the reason that the model performs better in the south Irish Sea.

Table 2. Error statistics of the simulated and observed surge elevation at different stations

	Standard deviation	***RMSE***	***Bias***	***Correlation***
St.Mary's	0.0722	0.0723	-0.0354	0.8546
Newlyn	0.077	0.077	0.003	0.8786
Holyhead	0.1199	0.1409	0.3655	0.9045
Bangor	0.1053	0.1879	0.5139	0.8873

The standard deviation, root-mean-square error (RMSE), the bias of the difference between the observed and the simulated surges and the correlation coefficient are shown in Table 2. The error statistics support the conclusions from visual inspection of the time series. In the north Irish Sea, the simulated surges have a relatively large error compared to the south Irish Sea. The correlation coefficients are very high for all of the stations, however, providing confidence in applying the model to studies of surge climate in the region.

The aim of the control run was to evaluate the surges calculated by the model, while ensuring that the model was still stable following a climate run driven by corresponding forcing fields from different scenario simulations. To evaluate the surge output, both spatial and temporal variability were compared to the DAC product from 1993 to 2001 over the ocean area adjacent to Ireland.

A time series of all data from 1993 to 2001, averaged over the latitude/longitude bins indicated in table 3 is shown in Figure 9. The ROMS model is clearly reproducing sea level anomalies due to both the inverted barometer response and the oceanic response to wind forcing, at least in the southern and western parts of the domain. Time series show very high correlation between both data sets at the south and west locations. The dominance of high-frequency signal in the residuals implies that they are primarily due to differences in the two models. However, the magnitude of the residuals is comparable to the sea level anomaly (Figure 9d) as observed by altimetry over this period, so falls within the level of natural variability of the sea surface.

Table 3. Error statistics of the dynamic atmospheric correction, determined with the MOG2D-G model and the surge generated by the ROMS model.

Area	***Latitude***	***Longitude***	***RMS difference***	R^2	***Bias***
North	56.6-57.1°N	8-9°W	13.0 cm	0.25	4.1cm
West	51.6-52.3°N	10.6-11.6°W	4.4 cm	0.87	4.3cm
South	50-50.6°N	8-9°W	8.1 cm	0.70	-0.4cm

Scatterplots of the ROMS surge against the MOG2D-G DAC (Figure 10) show a clear linear relationship between the output of the two models in the south and west of the domain. Slopes of the (dashed) regression lines shown were (a) 0.37, (b) 0.95 and (c) 0.93.

4.2. Spatial variation

The correlation coefficient and RMS difference fields (Figures 11a and 11b)) show similar features from year to year. High correlations are observed in the southern part of the domain, with values > 0.7 around much of the island, and values > 0.9 off the Southwest coast. The RMS difference fields show a similar pattern, with values of 4-12cm around the coasts and over most of the area, apart from the very north and north-west.

Low correlations and high rms values to the north of the domain indicate a systematic difference between the two models in this area. The consistency of the spatial patterns from year to year points towards a bathymetric effect. This may be due to the bathymetry in the ROMS model having insufficiently high resolution or accuracy in the slope area adjacent to the Erris-Slyne trough to the north-west of the domain. Or it could be due to inconsistencies in the bathymetry used in the two models.

5. Conclusions

Coastal flooding and coastal erosion are issues with serious economic and social impacts. Recent studies have aimed at understanding and quantifying changes in the surge climatology and, in particular, surge extremes. Such studies usually require model simulations extending over many decades. An initial requirement is to validate the capability of the model to realistically reproduce tides and surges and to evaluate whether the model performance is robust over runs of long duration.

In this paper, a regional ocean model was run to simulate a strong tide and surge event over Irish waters in January and February, 2002. The main diurnal and semi-diurnal tidal constituents for the model and for 4 tide gauges along the UK side of the Irish Sea were determined using harmonic analysis. Comparison with tidal components derived from satellite altimeter data (TPXO6.2) showed that the model is reproducing the tidal signal very well. The time series of sea level elevation compared with tide gauge observations also show that the high resolution ROMS model can simulate the tide and the surge very well, especially in the south Irish Sea.

However, due to the a systematic under-prediction of the wind strengths in the ERA-40 data and the coarse temporal frequency (6-hourly), the simulated surge in the north Irish Sea has a relatively large error. In a sensitivity study, the ERA40 winds were modified to provide better agreement with synoptic surface wind observations; the surge simulation was much improved with the modified data, especially the peak values. This highlights the importance of having accurate wind data for driving the model.

To further assess the stability of the ROMS model for climate runs, the model was driven by ERA40 data for a much longer simulation (1993-2001). Compared to the dynamic atmospheric correction from the MOG2D-G model, the model is clearly reproducing sea level anomalies due to both the inverted barometer response and the oceanic response to wind forcing, at least in the southern and western parts of the domain. Time series also show very high correlation between both data sets at the south and west locations. In conclusion, the results from the study have shown that the ROMS model is reliable and of sufficient accuracy for studies of surge climatology in the region.

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Figure captions

Figure 1. The model domain and the depths in metres

Figure 2. The simulated surge at Cork Harbor and Dublin Bay

Figure 3. The simulated surge height at (a) 12UTC, Feb 1st; (b) 18UTC, Feb 1st; (c) 00UTC, Feb 2nd; and (d) 06UTC, Feb 2nd (metres)

Figure 4. The simulated and observed surface elevation at (a) St. Mary's, (B) Newlyn, (c) Holyhead and (d) Bangor

Figure 5. Co-amplitude (solid lines, unit: cm) and co-phase (shaded lines, unit: degree) of the semidiurnal M_2 tidal constituent (a) TPXO6.2 (b) ROMS
Figure 6. Co-amplitude (solid lines, unit: cm) and co-phase (shaded lines, unit: degree) of the semidiurnal S_2 tidal constituent (a) TPXO6.2 (b) ROMS
Figure 7. Tidal form factor derived from (a) TPXO6.2 (b) ROMS main diurnal and semidiurnal components
Figure 8. The simulated and observed surge for (a) St. Mary's, (b) Newlyn, (c) Holyhead and (d) Bangor
Figure 9. Time series of (a) dynamic atmospheric correction, calculated by MOG2D-G model for correction of altimetric sea level anomalies; (b) surge generated by ROMS model; (c) DAC-ROMS residuals; and (d) altimetric sea level anomalies. Data shown are weekly data from the West region (see table 3) from January 1993 to December 2001.
Figure 10. Scatterplots of ROMS surge and DAC for the north, south and west regions defined in table 3.
Figure 11. (a) Correlation coefficient between DAC and ROMS surge calculated for all weekly data between 1993 and 2001 and (b) RMS difference.

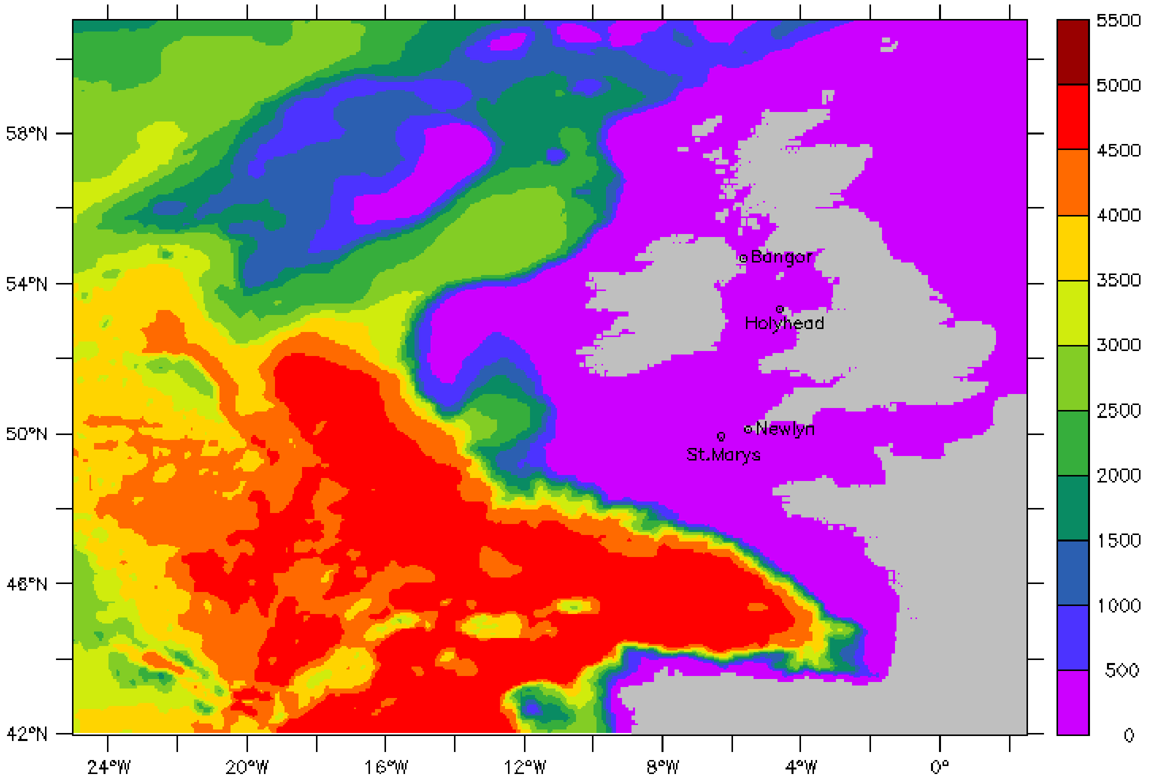


Figure 1. The model domain and the depths in metres

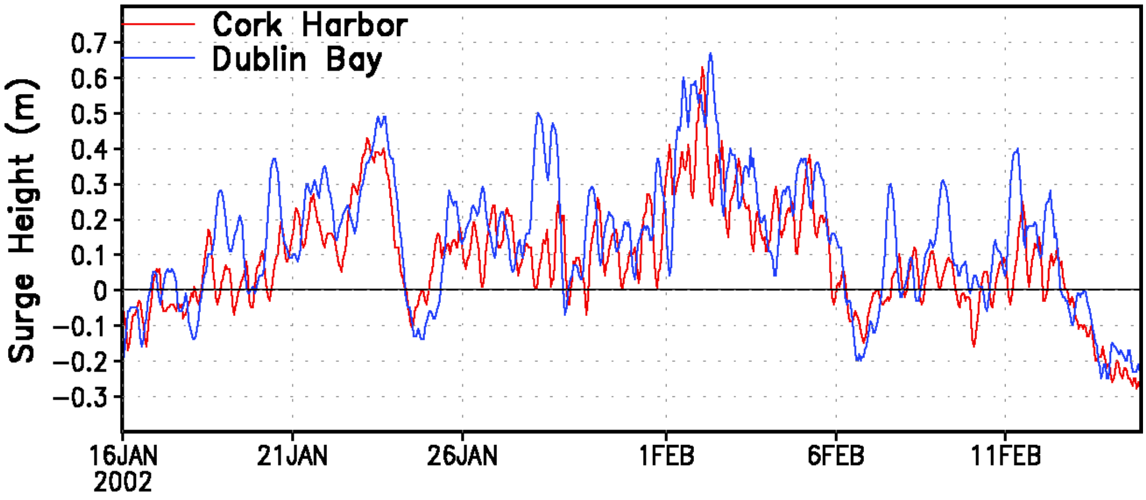


Figure 2. The simulated surge at Cork Harbor and Dublin Bay

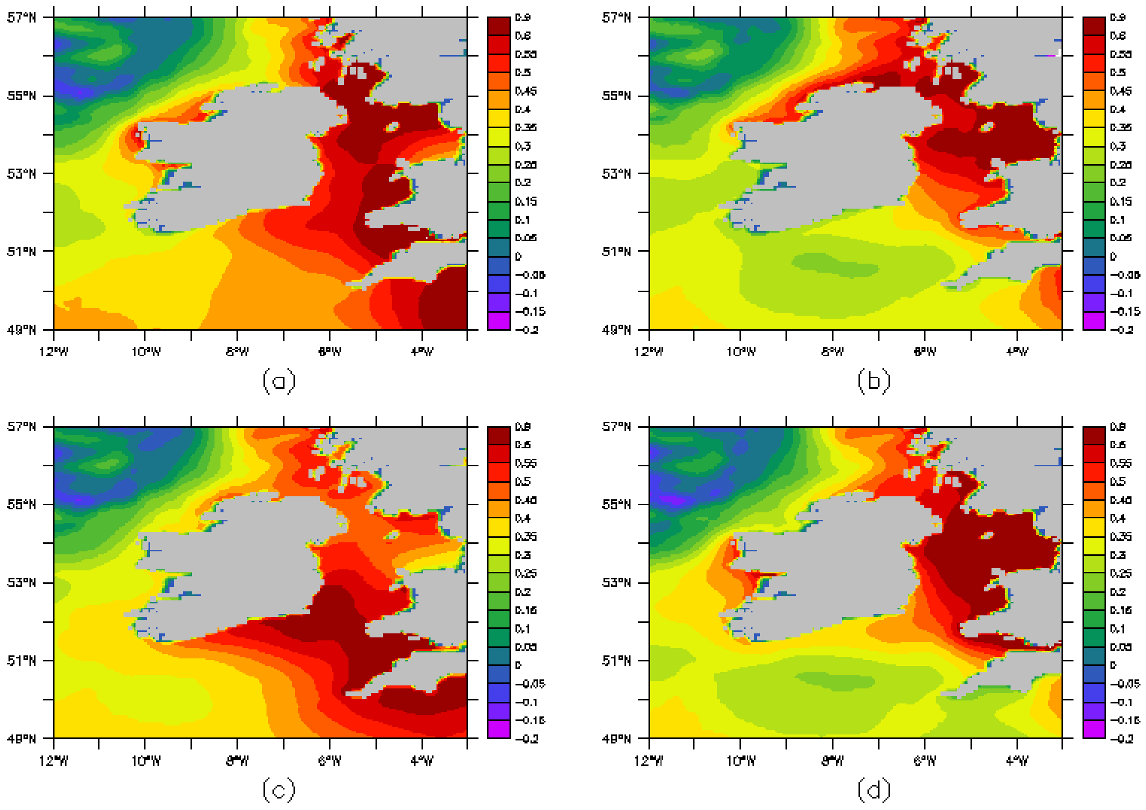
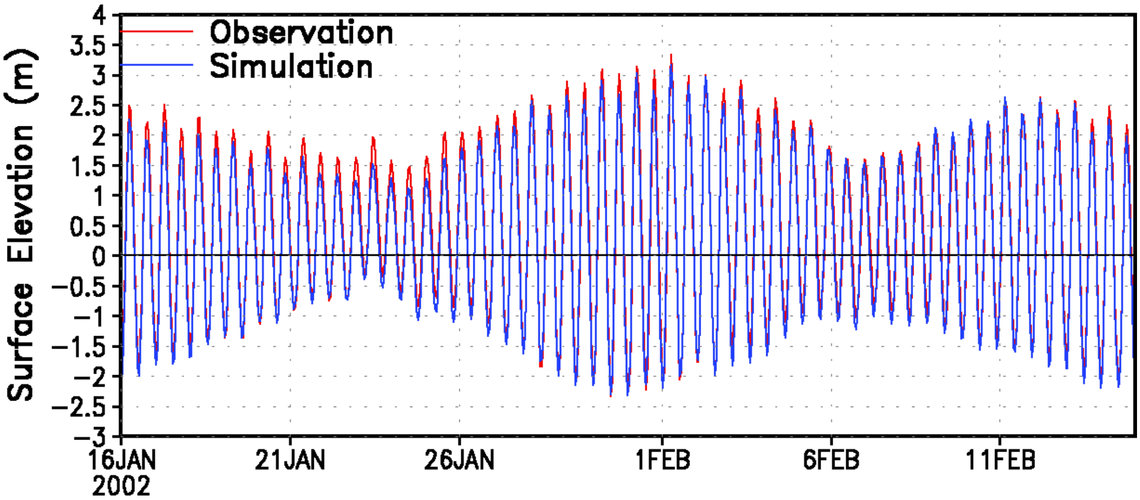
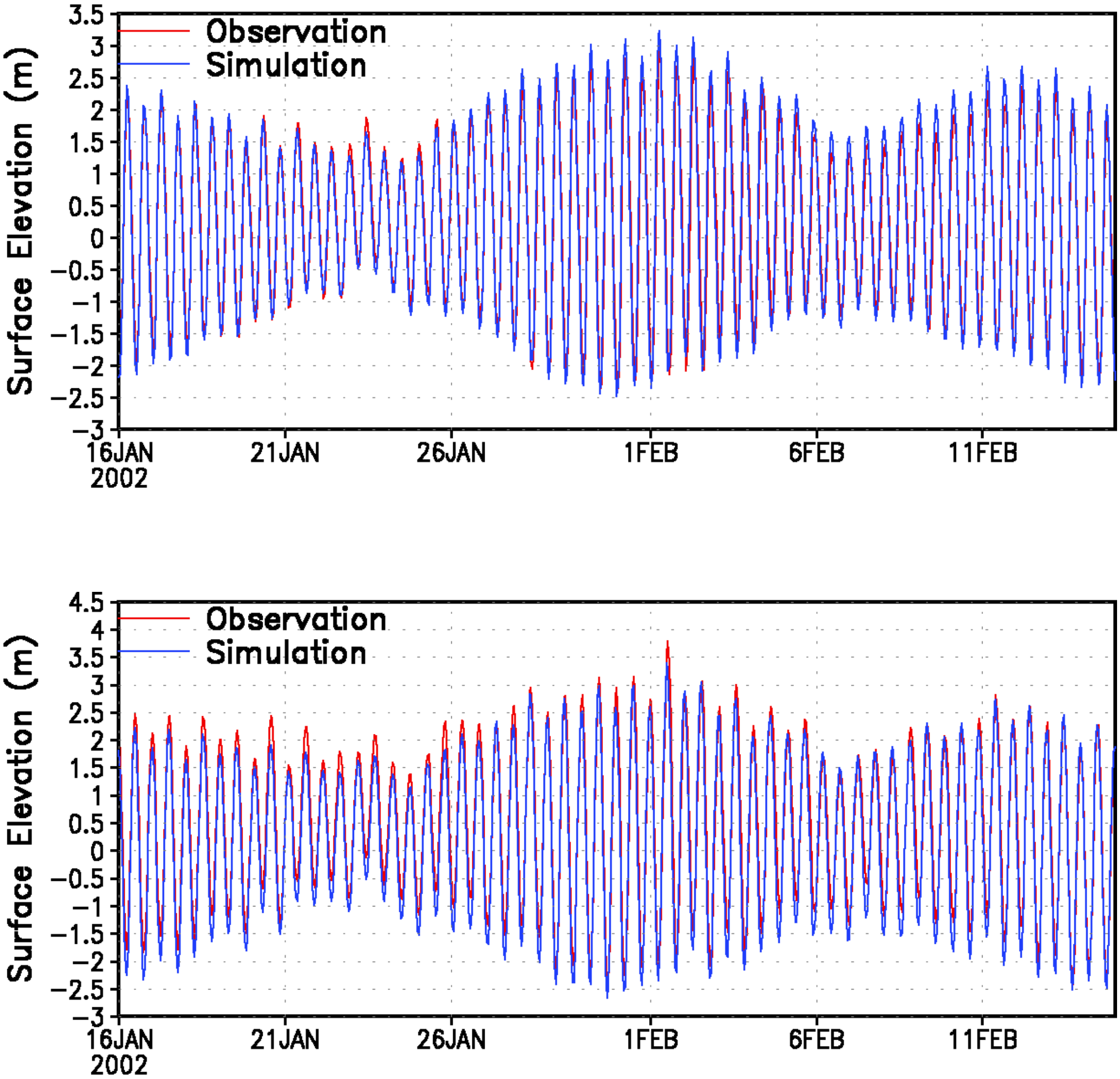


Figure 3. The simulated surge height at (a) 12UTC, Feb 1st; (b) 18UTC, Feb 1st; (c) 00UTC, Feb 2nd; and (d) 06UTC, Feb 2nd (metres)

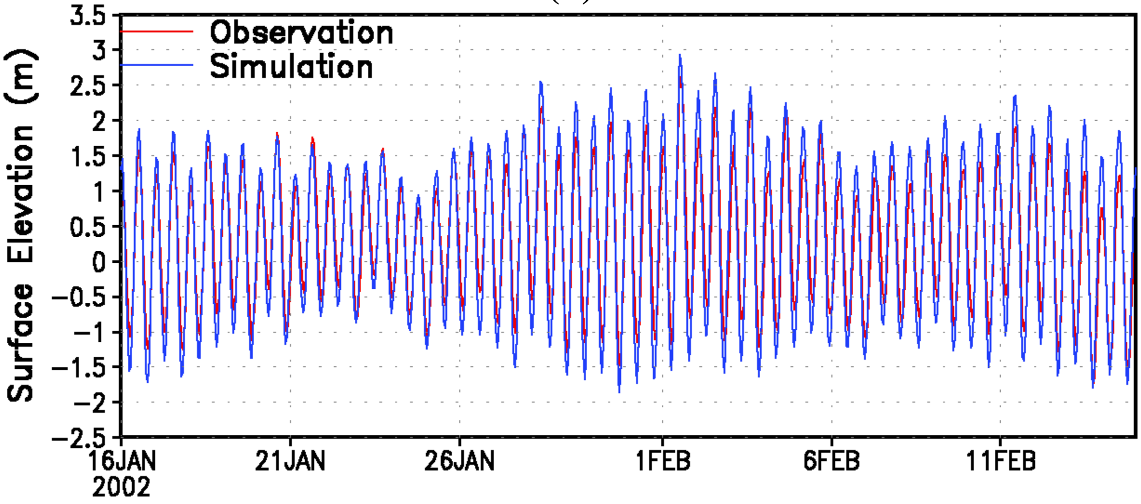

Observation
Simulation
Surface Elevation (m)
4
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
16JAN
2002
21JAN
26JAN
1FEB
6FEB
11FEB

(a)


Observation
Simulation
Surface Elevation (m)
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
16JAN
2002
21JAN
26JAN
1FEB
6FEB
11FEB
Observation
Simulation
Surface Elevation (m)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
16JAN
2002
21JAN
26JAN
1FEB
6FEB
11FEB

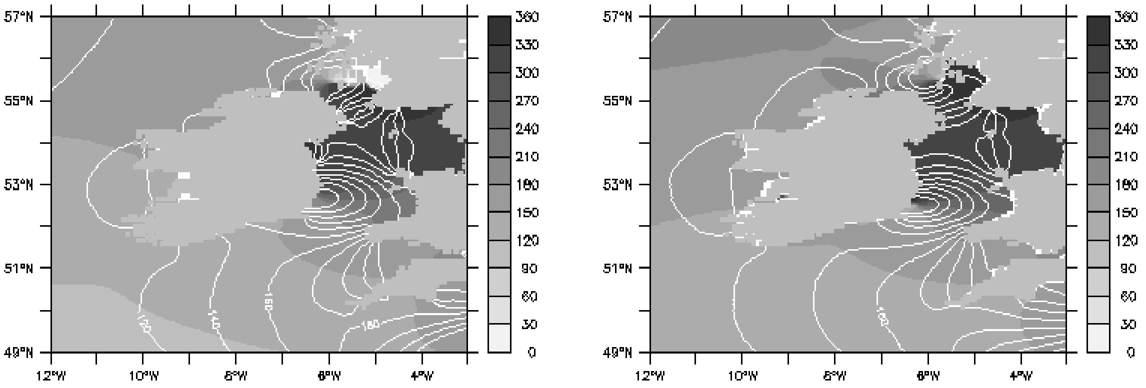
(b)

(c)



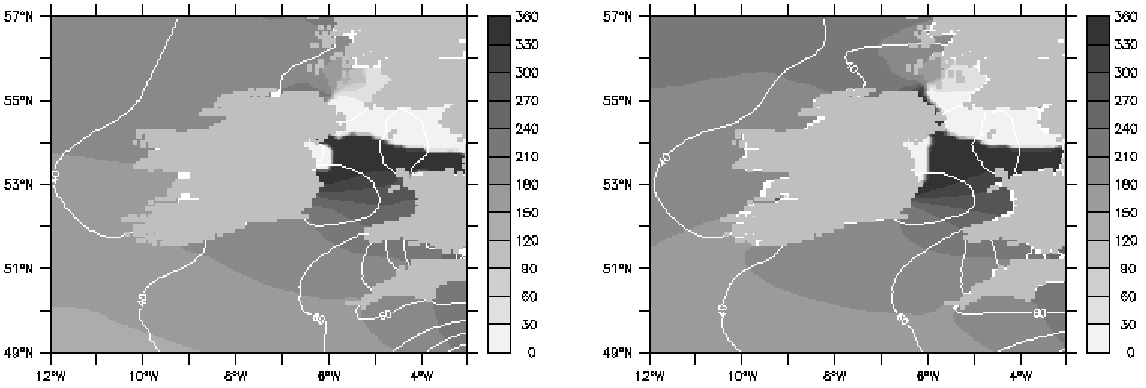
(d)

Figure 4. The simulated and observed surface elevation at (a) St. Mary's, (B) Newlyn, (c) Holyhead and (d) Bangor



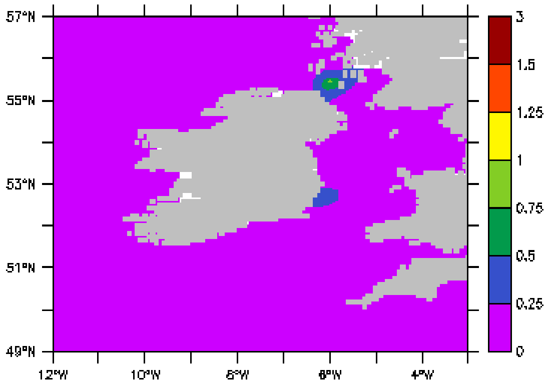
(a) (b)

Figure 5. Co-amplitude (solid lines, unit: cm) and co-phase (shaded lines, unit: degree) of the semidiurnal M_2 tidal constituent (a) TPXO6.2 (b) ROMS



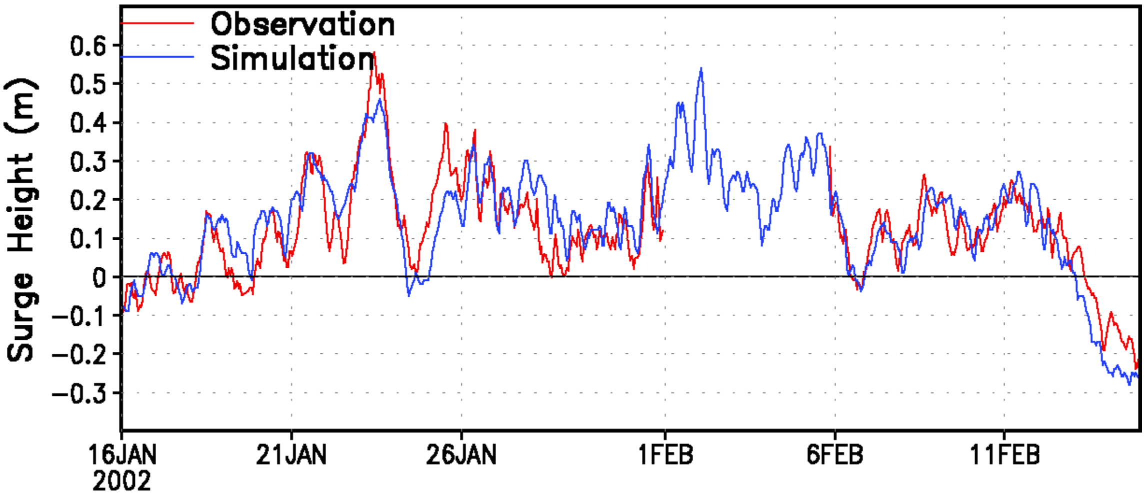
(a) (b)

Figure 6. Co-amplitude (solid lines, unit: cm) and co-phase (shaded lines, unit: degree) of the semidiurnal S_2 tidal constituent (a) TPXO6.2 (b) ROMS

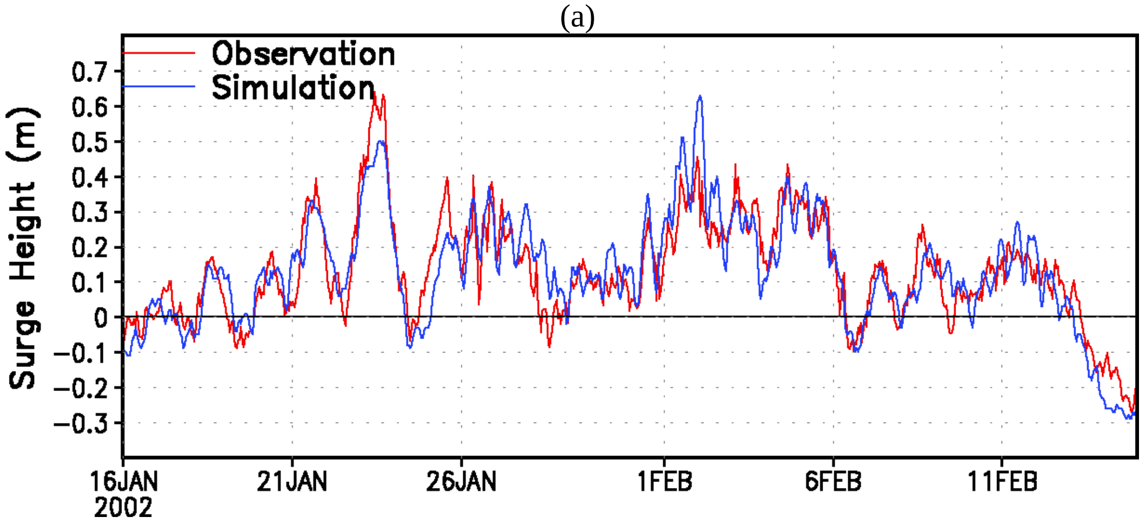


(a) (b)

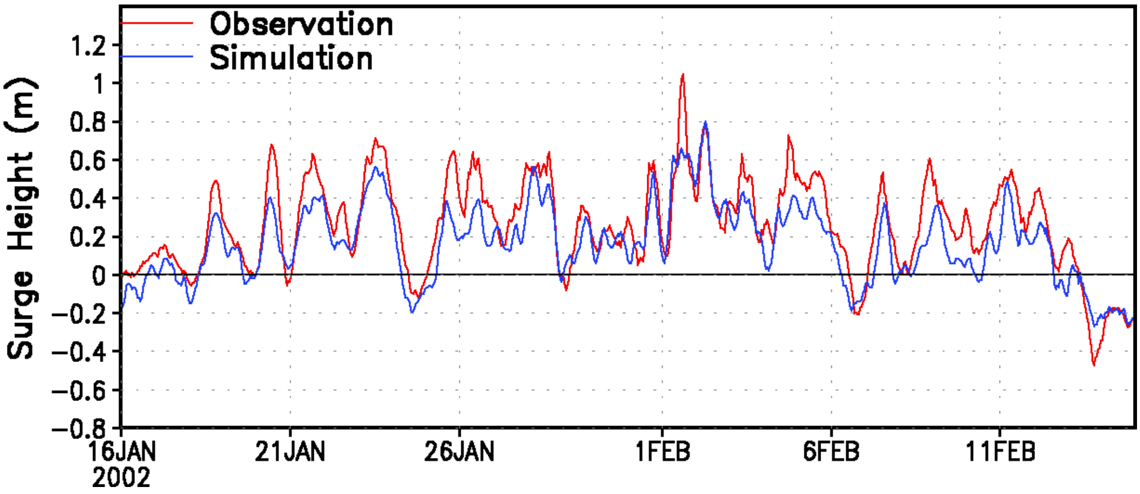
Figure 7. Tidal form factor derived from (a) TPXO6.2 (b) ROMS main diurnal and semidiurnal components



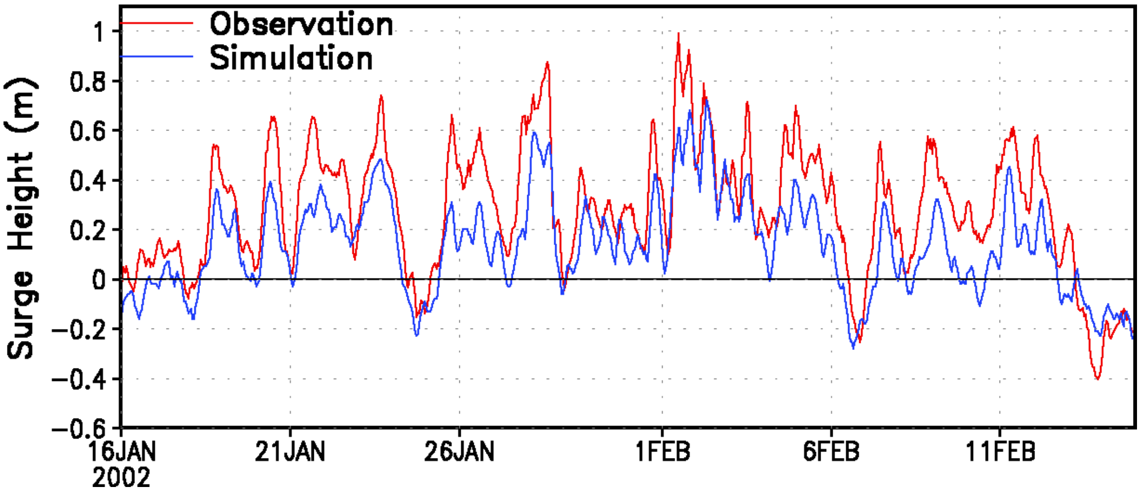
(a)



(b)

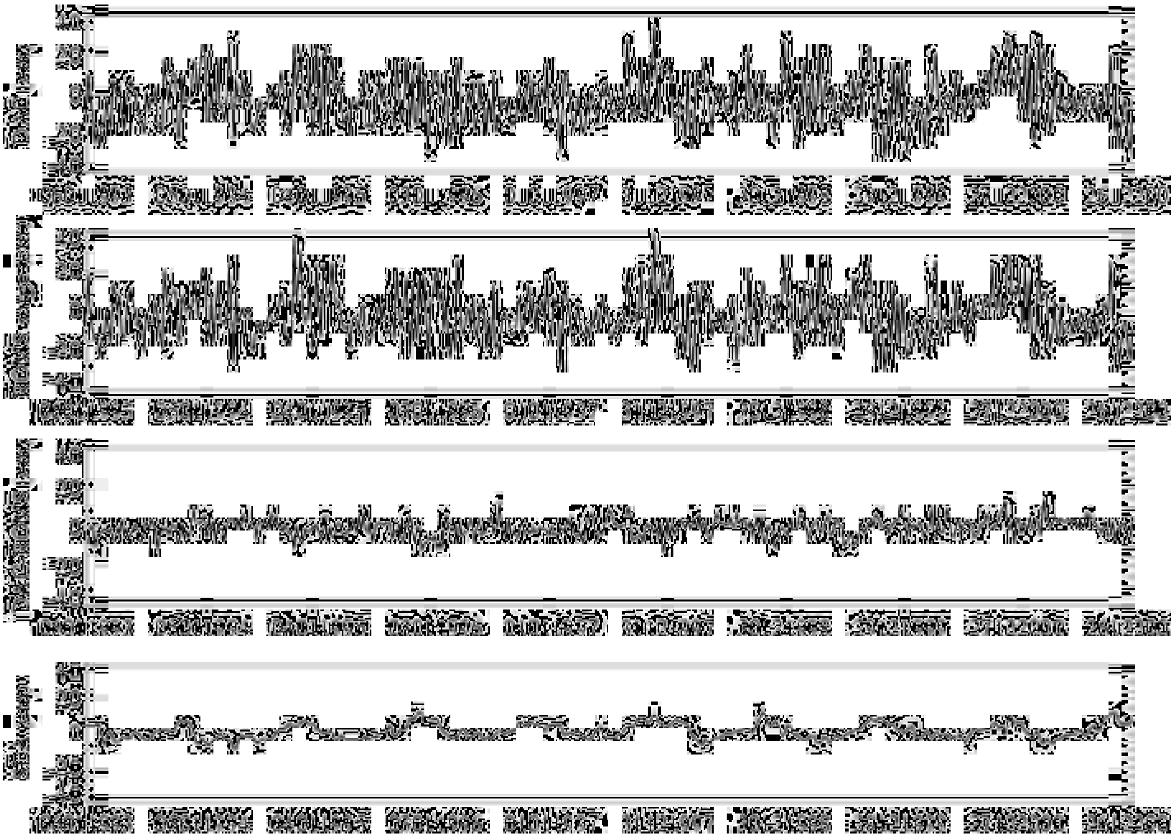


(c)



(d)

Figure 8. The simulated and observed surge for (a) St. Mary's, (b) Newlyn, (c) Holyhead and (d) Bangor



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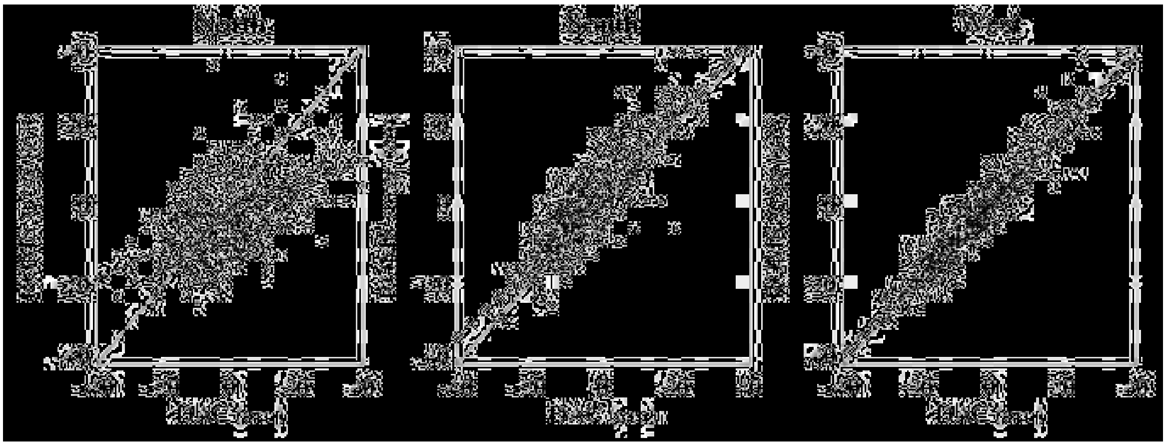
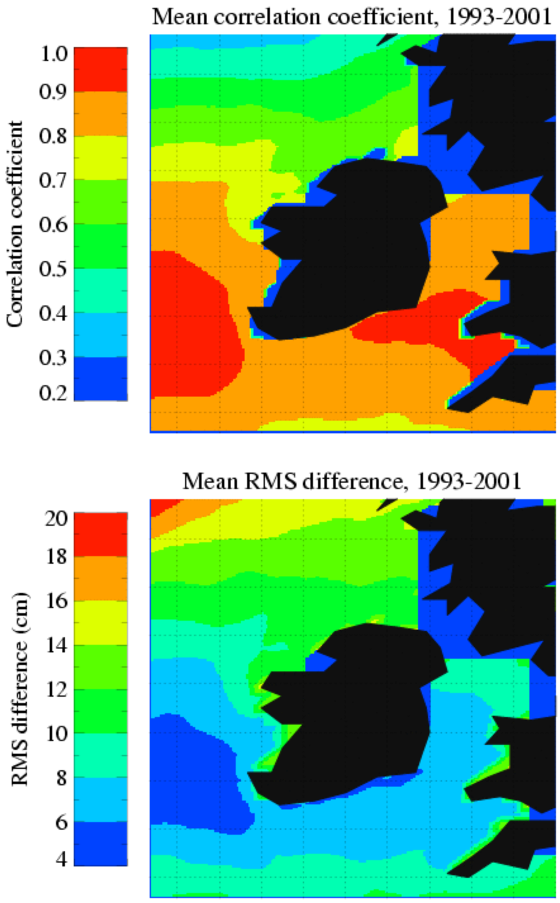


Figure 10. Scatterplots of ROMS surge and DAC for the north, south and west regions defined in table 3.



/media/sda1/val/roms alt sla corr rms plot.ps, printed by J. Hanafin on Fri Feb 16 12:33:02 2007

Figure 11. (a) Correlation coefficient between DAC and ROMS surge calculated for all weekly data between 1993 and 2001 and (b) RMS difference.