Modelling the sea level in the upper Bay of Fundy

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Abstract

A high resolution model of the upper Bay of Fundy was developed to simulate the tides and sea level. The model includes the wetting and drying (inundation) of the extensive tidal flats in Minas Basin. The model reproduces the dominant M2 tidal harmonic with an error of order 0.30 m, and the total water level in Minas Basin with an RMS error of 0.30-0.50 m. Overall the system is capable of simulation with sea level error of 8-11%. The motivation for the model development was the simulation of the land/water interface (instantaneous coastline) to aid in the validation of coastline retrieval algorithms from remotely sensed observations. Qualitative comparison of observed and simulated coastlines showed that the misfit was dominated by errors in the details of the local topography/bathymetry. For example, long narrow features such as dykes are difficult to resolve in a dynamical model but are important for inundation of low lying areas.

1 Introduction

This paper reports on the development of a sea level prediction system for the upper Bay of Fundy (Fig. 1). The motivation is the simulation of the land-water boundary (instantaneous coastline) in the Bay as part of the validation of the land-water boundary extracted from remotely sensed observations (e.g. RADARSAT-1, polarimetric SAR, CASI, Landsat and Ikonos imagery) as described by Deneau (2002) and Milne (2003). This application has two requirements beyond accurate simulation of the sea level: a wetting and drying capability, as the coastline needs to be predicted by the model; and accurate local bathymetry/topography in the area for the comparisons, as small changes in height/depth can lead to large changes in the modelled coastline. The focal region here is Minas Basin, in particular the area around Wolfville, NS.

The dominant feature of the sea level variability in the Bay of Fundy is the M2 tide which varies in amplitude from 3 m at Saint John to over 6 m at the head of Minas Basin. The reason for the large tides is the fact that the natural frequency of oscillation in the Gulf of Maine and Bay of Fundy system is close to that of the M2 tide (Garrett, 1972, 1974). While the M2 tide dominates the sea level level variability, other tidal constituents must be modelled in order to achieve the target accuracy of 0.3-0.5 m in Minas Basin. The N2 and S2 constituents have amplitudes of order 1 m and other semi-diurnals constituents have amplitudes of order 0.1 m. In addition, remotely generated sea level variability that propagates into the Bay can contribute important variability.

The M2 tide in the Gulf of Maine and Bay of Fundy system was modelled successfully by Greenberg (1979) using a series of 4 nested meshes with resolution ranging from 21 km in the Gulf of Maine to 1.6 km in Minas Basin. An accuracy of 0.15 m and 5 degrees in phase was generally achieved in the Bay of Fundy except in Minas Basin where the phases were greater than observed and the amplitudes were too large. The model was extended to include other constituents (N2, S2, O1, K1) by DeWolfe (1986) but the work focused on the potential impacts of tidal power development and a detailed comparison with observations was not reported. Recently, Sankaranarayanan and McCay (2003) modelled 5 tidal constituents (M2, N2, S2, O1, K1) in the Bay of Fundy in support of work in Saint John harbour and achieved errors of less than 0.2 m in amplitude and 7 degrees of phase for M2, except in Minas Basin where the errors increased to 0.3-0.5 m (relative to an amplitude of 4.5-6 m). The errors in N2 (the next largest component) were 0.1 - 0.3 m in Minas Basin (relative to an amplitude of .7- 1 m) with phase errors as large as 20 degrees (roughly a 40 minute error in timing).

In this paper we develop a sea level prediction system for the upper Bay of Fundy. The system includes multiple tidal constituents (M2, N2, S2, O1, K1, plus the four minor semi-diurnals K2, L2, 2N2, Nu2) and uses the Saint John tide gauge record to provide corrections to the open boundary forcing when hindcasting the instantaneous coastline. The system is based on the finite element method so that high resolution can be added where it is required. The model includes wetting and drying of tidal flats so that the instantaneous coastline can be extracted.

The paper is composed as follows. The components of the prediction system are described in Section 2 and the model validation is presented in Section 3. Section 4 briefly describes the spatial variation in dissipation. In Section 5 we compare the simulated and observed instantaneous coastline for two cases and Section 6 provides an error assessment of the five major tidal constituents. The conclusions and suggestions for future model developments are presented in Section 7.

2 The modelling system

2.1 The model

The model, MOG-2D (Carrère and Lyard, 2003), is a two-dimensional model that uses the finite element method to solve the shallow water equations that describe the dynamics of the depth averaged oceanic flow. The model was written by Dave Greenberg (BIO) and Florant Lyard (LEGOS-CNRS). This model is based on the generalized wave equation (Lynch and Werner, 1991; Lynch et al., 1996) using spherical coordinates (Greenberg et al., 1998). It was used successfully for modelling the tides in the northwest Atlantic, including the Bay of Fundy by Dupont et al. (2002).

The wetting and drying of tidal flats was incorporated following the methodology of Greenberg et al. (2003). When the elevation at one node falls under the sea bottom, the nodal velocity is set to zero (but the elevation is still free to move until other constraints come into action). When the elevation at the three vertices of an element fall under the sea bottom, this element is considered dry and counted as an island (or part of one) and not used in the construction of the matrix solving the wave equation problem (i.e., we have basically created a hole in the mesh). When a node falls strictly inside such islands, its associated elevation is temporary frozen. When the water level is rising, it will raise the elevations at the active nodes. When the elevation at one vertex of a dry element rises above the sea bottom, then this element is no longer considered dry and the elevations at the other vertices are free to move again. Once the elevation at all the available nodes is above sea bottom, the water hit the vertical walls of the lateral boundaries of the mesh.

The model uses a quadratic drag law for dissipation and we use the standard drag coefficient for vertically-averaged tidal models, $C_d = 2.5 \times 10^{-3}$.

2.2 The mesh

The model domain covers the upper Bay of Fundy and includes potentially inundated areas with maximum elevation above mean sea level of 20 m (Fig. 1). Three large areas in the Annapolis Basin and around Wolfville and Truro have been especially targeted.

The ocean and land topography were obtained from several sources at differing resolution and coverage. The initial ocean data were obtained from a digital version of CHS chart 4010 - Bay of Fundy (Inner Portion). These were augmented with high resolution multi-beam data in limited areas of Minas Channel and Chignecto Bay. The land topography for the nearshore was obtained from Tim Webster and Robert Maher of the Applied Geomatics Research Group (Centre of Geographic Sciences, Middleton, NS, Canada) and included data from digital versions of land based topographic charts and high density LIDAR data covering the land and some intertidal areas in the Annapolis Basin, and in the vicinity of Wolfville and Truro. Because of the massive amounts of data, severe data pruning was done on individual and combined files to get good resolution without overtaxing computing facilities. The final dataset used close to Wolfville, NS is shown as an example in Fig. 2

The final number of nodes in the mesh is close to 75000 with resolution between 30 m and 5 km (Fig. 3). The time integration is explicit with a time-step of 2 s. An M2 tidal cycle can be computed in 3 hours and 30 minutes on a 1600 Mhz PC (about 3.5 days simulated in one day).

2.3 Tidal boundary conditions

The open boundary runs approximately along a straight line from Digby to Saint John (Fig. 1). The tidal open boundary conditions for the elevation were obtained from the solution of a regional assimilation system following the same procedure as described in

Dupont et al. (2002) and using satellite altimetry data only (harmonic analysis for the tidal constituents at the cross-over points of the Topex/Poseidon data). The domain for this assimilation system is shown in Figure 4 and covers the Gulf of Maine, the Bay of Fundy and most of the Scotian Shelf. The system assimilated tidal harmonic data at 12 Topex/Poseidon cross-over points for 9 tidal constituents (M2, N2, S2, K1, O1, K2, L2, 2N2, Nu2). Each incremental correction required that the forward model be run for 240 days in order to resolve the different constituents in the tidal analysis. The harmonic constituents were then interpolated onto the open boundary nodes of the high resolution model of the upper Bay of Fundy.

2.4 Hindcasting the total water level

For hindcasting the water level for a particular period, we used the hourly sea level at Saint John N.B. to correct the elevation boundary condition. The correction represents any misfit between the modelled and observed sea level at Saint John that can be due to storm surge and modelling errors. The correction is applied uniformly along the boundary. We have tried two different ways of computing the correction. The first one (Correction 1) consists of predicting the elevation at Saint John based on the harmonic solution of the regional assimilation system (9 constituents; see above) and subtracting it from the observed elevation. The second correction (Correction 2) requires an initial run of the high resolution model with no correction and with the open boundary forcing based on the 9 constituents of the regional assimilation system. The correction is then the difference between the observed and simulated elevation at Saint John.

For hindcasting the model is run with the 9 constituent forcing plus the hourly correction. The remaining discrepancy between the simulated and observed elevation at Saint John is generally small, however the model-data misfit does increase away from Saint John.

3 Validation

3.1 The tides

The tidal validation simulation was done using the 5 major constituents (M2, N2, S2, K1, O1) run simultaneously. Table 1 shows the validation for the M2 at the 12 stations common among Greenberg (1979) [additional information extracted from Anomymous (1977)], Sankaranarayanan and McCay (2003), and this study. Overall the amplitude and phase errors are quite small with a mean amplitude error of 0.12 m and a mean phase error of 2.4 degrees. The model underpredicts the amplitude by about 0.2 m in Minas Basin and over predicts the phase by only a few degrees.

The error metric in the last column of Table 1 is the distance in the complex plane between the observed and modelled constituents

$$E = |A_o e^{\imath\phi_o} - A_m e^{\imath\phi_m}| \tag{1}$$

where A_o, ϕ_o are the amplitude and phase of the observed harmonic and A_m, ϕ_m are the amplitude and phase of the modelled harmonic. This error metric, which combines the amplitude and phase errors into a single quantity, will be used as the primary metric for this validation. As an overall error for a single constituent we will use the RMS (root-mean-square) value computed over all the stations (0.26 m for the stations in Table 1). We note that the 2.6° phase error (about 5 minutes) makes a larger contribution to the overall error than the 0.14 m amplitude error.

The new high resolution model has smaller M2 errors than previous models. Using the error metric (1) the RMS error in this model is 0.26 m compared with 0.36 m for Greenberg (1979) and 0.45 m for Sankaranarayanan and McCay (2003). Note that the present model has not been tuned to fit any coastal data[1], whereas the Greenberg model was carefully

[1] The only data used for assimilation was the very coarse set of Topex/Poseidon crossover points in the

tuned for bottom friction and some bathymetric features. The model of Sankaranarayanan and McCay (2003) on the other hand was tuned to fit the elevation record at Saint John with disregard for the rest of the bay.

The comparison of the simulated tides against 29 stations in the Bay of Fundy (Fig 1) is shown in Table 2. The elevation errors for the regional assimilation system (see Section 2.3) and for Dupont et al. (2002) are included for comparison. Figure 5 shows polar plots comparing the observations and the present model results. For M2 the agreement is much better than previously obtained in Dupont et al. (2002); 0.28 m instead of 0.77 m. The improvement likely comes from the improved resolution of the bathymetry. On the other hand the accuracy of N2 degraded (0.26 m instead of 0.19 m). Compared to the regional assimilation system, there is some improvement in M2 by going to higher resolution although we again note the poorer agreement for N2. We will further analyze the M2 and N2 errors in Section 6.

For S2, K1 and O1 the error levels are about the same among the three modelling systems and the errors do not show any obvious patterns (Fig. 5).

3.2 The total water level

For the simulation of the total water level, the nine constituents (M2, N2, S2, K1, O1, K2, L2, 2N2, Nu2) obtained from the regional assimilation system were used. The model prediction is compared against hourly records from the Saint John tide gauge and four subsurface pressure gauges deployed during May 1976 (DeWolfe, 1977): three in Minas Basin (Minas, Economy and Cobequid) and one in Chignecto Bay (Grindstone). The mean values were removed prior to the analysis so that all elevations are relative to mean sea level. Table 3 shows the RMS error of the hourly timeseries at the five stations. Without

regional model. Only two Topex/Poseidon points fall inside the Gulf of Maine (Fig 4).

any correction, the RMS error ranges from 0.2 m at Saint John to 0.6 m at the head of Minas Basin (Cobequid). Correction 1 reduces the error by 0.05-0.08 m. Correction 2 reduces the error by a further 0.03 to 0.1 m, with the largest improvement at Saint John. Hereafter, Correction 1, which does not require running the model twice, will be used. We return to the question of the error in Section 6.

4 Dissipation

One point of interest is the spatial patterns of the energy dissipated in the Bay of Fundy by bottom friction. We computed the averaged value for $\langle |u|^3 \rangle$ from a 32 day run (the 1976 May hindcasting period) with the 9 constituent model. The dissipation by bottom friction in our model is defined as $\rho C_d \langle |u|^3 \rangle$ where $\rho = 1025$ kg m^{-3} is a standard value for sea water density and C_d is the drag coefficient. An arc of very high values occupies Minas Channel at about 50 to 60 W/m^2 where currents are the strongest in the whole bay (Fig. 6). Greenberg (1979), looking at M2 only, found a dissipation of about 100 W/m^2 at about the same location[2]. In the intertidal areas (regions defined as shallower than 6 m), velocities are much less than in Minas Channel and therefore local dissipation rates tend to be much lower. However, one bank in eastern Minas Basin stands out with values just above 10 W/m^2. The other notables features are thin bands of values between 0.2 to 1 W/m^2 located in three river beds in the Wolfville vicinity and along or close to the extreme position of high tides.

[2]As our main goal was to look at the spatial patterns of the dissipation, we have not investigated the reasons for the discrepancy between the models. Nonetheless, both model have similar broad structures. We report here on the smaller scale structures found in our model.

5 Predicting the location of the land/water interface in Minas Basin

5.1 Snapshots

An automatic procedure was designed to produce elevation fields (based on Correction 1) at the exact date and time of the remotely sensed images. However, gaps in the Saint John sea level data needed in the correction method can cause problems. For example, in the five day period leading up to the September 13, 1999 snapshot about 14% of the data was missing and for July 13, 2000 all of the data was missing. In such cases, the data gaps were filled by a timeseries reconstructed from the official tidal constituents at Saint John. For the periods considered, the RMS difference between the reconstructed timeseries and the actual observations (i.e., the nontidal component) varied between 0.10 and 0.22 m. For comparison, the RMS difference between the observed and modelled (with Correction 1) Saint John elevation varied between 0.11 and 0.20 m. Thus the uncertainties associated with missing data are the same order as the hindcasting errors at Saint John and less than the hindcasting errors in Minas Basin (0.3 - 05 m).

The automatic procedure is the following. The model is spun up from rest 5 days prior to the date of interest. The model tidal forcing is ramped up for the first 12 hours from zero to full and is fixed at full forcing for the remaining period of simulation. The model stops at the desired date and time and outputs the elevation field. From this elevation field, the model coastline is defined as the set of points where the water surface meets the bottom. A detailed and quantitative comparison of the simulated coastline and the ones derived from the remotely sensed images is reported by Milne (2003). Below, we will limit ourselves to a qualitative interpretation of the results.

Figure 7 shows the derived coastlines for an image on 13 Sept. 1999. Visually, there is good overall agreement between the modelled and retrieved land/water interface in the western part of the image but the accuracy degrades east of Grand-Pre (see Fig. 2 for locations). Milne (2003) reports that the mean separation between the two coastlines is 141 m, with 14% of the points within 25 m and 37% within 100 m. An important source of discrepancy is local bathymetry. The abrupt reduction in data density east of $64^\circ\ 18'$ W longitude (Fig. 2) and lack of data in the channels between the mainland and Boot Island leads to the model underpredicting the shoreward extent of the land/water interface in this area.

A comparison of the derived coastlines at high tide (Fig. 8) shows that the model overpredicts the inundation of large areas along the rivers beds on the eastern half of the area. This appears to be due to the fact that the dykes, while in the original topography data, are not resolved in the model (with 30 m) resolution. Support for this interpretation is provided by Milne (2003) who reports on a preliminary application of flooding a high resolution (2 m) digital elevation model (DEM) of the Cornwallis River using GIS (Geographical Information System) techniques. He found that the high resolution DEM reduced the mean separation between the derived coastlines from 56 m to 35 m and increased the percentage of points with separation of less than 25 from 44% to 67%.

The comparison between the land/water interface in the model and that retrieved from remotely sensed observations highlights the fact that the model seems qualitatively accurate. The errors are dominated by local problems such as the details of the bathymetry/topography. In particular, the bathymetry (depth below mean sea level) is less well known than the topography (height above mean sea level) and often the two data sets are not referenced to the same vertical datum. On land, the model resolution is not sufficient to resolve important features such as dykes, and this can lead to the artificial flooding of protected lands. .

6 Error Assessment

Figure 9 shows the sea level error (Section 3.2) at the Minas Basin Station when Correction 1 is applied compared to the residual with no correction. The remaining error is dominated by the semidiurnal tidal components (Fig. 10). The fact that semidiurnal error is an order of magnitude larger than the other errors indicates that improvements in the tidal modelling are required to further reduce the error.

The diurnal tidal errors are slightly reduced by Correction 1 (Fig. 10) and further reduced by Correction 2 (not shown). There is however a large increase in the error associated with the M4 tide (period near 6 hrs). The M4 is component is not part of the tidal boundary conditions and the correction method is projecting the M4 from the Saint John record back onto the boundary. The fact that this increases the error suggests that M4 and other high frequency tides should be removed from the Saint John record prior to the correction process [3].

Since the errors in the tidal modelling still dominate the overall error, we decided to further analyze the errors in the five major constituents and investigate whether some form of systematic bias could be found. Figure 11 shows the relative amplitude error and phase difference as a function of the observed amplitude for the five major tidal constituents. Note that the M2 phase and relative amplitude error are independent of amplitude (a proxy for along channel position). This suggests that a simple correction to the amplitude and phase of M2 at the boundary might reduce the M2 errors. The errors for O1, K1, and N2 tend to increase with amplitude. The errors for S2 do not have a pattern. The general bias towards positive amplitude errors for most of the constituents (the error is observed minus

[3] An additional run was done to verify this statement. The energy close to the 6 hour period was removed from the correction prior to the run (otherwise, similar to the run with Correction 2). The 6 hour period spectral peak in the error is then reduced at the level observed with no correction (not shown). The other spectral peaks remained as low as with Correction 2. In terms of RMS error, this translates into a further 2 cm improvement.

modelled) means that the model underestimates the tidal amplitudes. This plus the fact that the relative errors are small at Saint John, suggests that there is too much friction in the model.

We did two experiments with the 5 constituent model where we slightly altered M2 and N2 at the open boundary based on the biases relative to the observed harmonics (Fig. 11). The amplitude of the M2 boundary forcing was uniformly increased by 5 cm and the phase decreased by 2 degrees. The phase of N2 was decreased by 10 degrees and its amplitude was unchanged. Modification of M2 alone leads to a 4 cm improvement in the error metric for M2 and 3 cm for N2. Modification of both M2 and N2 leads to no improvement to M2 and 9 cm improvement for N2. These results highlight the complex dynamical interactions between M2 and N2.

The sensitivity of the model to the value of the bottom friction coefficient, C_d, was investigated by doing two runs using the 5 constituent model where M2 was corrected for its observed bias as done previously. Table 4 shows the effect of decreasing the friction parameter on the elevation error per constituent. M2 tends to degrade while N2 improves. The improvement was not sufficient however to push the N2 error below the value obtained using the solution of the assimilation system for the Northwest Atlantic (Dupont et al., 2002). The other constituents are not very sensitive to changes in C_d. It is not clear at this stage in which direction the evidence points.

A final point about the errors. The very small M2 phase errors in Minas Basin indicate that water is being moved into and out of the Basin at about the correct rates. Therefore the water depths and cross-sectional areas of the main channels, and Minas Basin in particular, must be well represented.

7 Summary and Discussion

The modelling system presented here is capable of accurate simulation of the water level in the Bay of Fundy. The RMS error for the M2 tidal harmonic is less than 0.3 m (relative to tidal amplitude of 3 m at Saint John and over 5-6 m in Minas Basin). The system can also simulate the timeseries of total water level in Minas Basin with an RMS error of 0.3-0.5 m, relative to an RMS signal of 3.6 to 4.5 m. Overall the system is capable of accuracy of 8-11% in Minas Basin.

The system is suitable for a model based tidal prediction system and for the tidal component of an operational water level (storm surge) prediction system for the Bay of Fundy. As well, a system for sediment transport and erosion studies could be created by the addition of a sediment transport module.

The errors are still dominated by the semi-diurnal tides, in particular M2 and N2. Further improvements will require improved simulation of these two components. We have argued that the small phase errors for M2 in Minas Basin indicate that the primary channels are well represented. Thus improvements in the bathymetry may improve the solution locally but are unlikely to improve the global properties of the solutions.

The likely direction for improvement is a careful study of the sensitivity of the model solutions to the value of the drag coefficient, small changes in the boundary conditions, and the details of the cross-channel structure of the tidal boundary conditions. The tight coupling between the M2 and N2 tidal harmonics will complicate attempts to improve the simulations. For example, the nonlinear frictional interactions between M2 and N2 affects the amplitude of the constituents over the nodal modulation cycle (18.6 years; Ku et al. (1985)) and probably over the lunar perigean cycle (28 days; Godin (1988)). In our simulations the frictional coupling is evident in the result that decreasing the drag coefficient leads to improvements in N2 and degradation of M2.

The M2 phase errors in Minas Basin are very small (typically 2 to 4 degrees, or 5 to 10 minutes). Given that error bars are not generally reported in tidal analysis, one wonders whether the model is correct within the uncertainty in the observations. This should be investigated. However, the fact that the model systematically underpredicts the amplitudes and overpredicts the phase lags, suggests that there is room for improvement.

Another potential source of error is the changes in the Bay of Fundy tides over the period of the systematic collection of tidal data (primarily 1950 to 1990; Fig. 12). Godin (1992) estimates that the M2 tide at Saint John is increasing by about 0.07 m per century. This suggests an increase in Minas Basin of about 0.1-0.2 m per century. These changes in M2 tidal amplitude are a result of the regional subsidence and the consequent changes in the resonant system due to increased water depths. A change in the M2 tidal amplitude of 0.03-0.10 m (half the change per century) is not the dominant factor in our overall error of 0.3 m, but it may contribute.

The comparison with the snapshots of the land/water interface shows that the simulation of the instantaneous coastline are primarily limited by the details of the local bathymetry. We also note that the different geoids used for different data sets (e.g. NAD27 versus NAD83) are important, as are differences in vertical datums for the topography (height above the water) and bathymetry (depth below the water).

Long narrow features such as dykes are difficult to model but are important for inundation. One possible way to deal with dykes is through the implementation of specialized dyke elements as has been done by Westernink and Luettich in their model for flooding of New Orleans (Rich Luettich, UNC, pers.comm.). Another possibility is to give up modelling the details of the inundation with a dynamical model. Techniques exist to use the instantaneous water level near the coast to flood a detailed digital elevation model (DEM) with much higher spatial resolution than can be done dynamically. This has been done for flood risk assessment for Charlottetown PEI (O'Reilly et al., 2003) and Truro NS (O'Reilly et al., 2002).

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List of Tables

Stations	Observed		Modelled		Differences		Error (m)
	Ampl.	phase	Ampl.	phase	Ampl.	phase	
Saint John	3.04	98.2	3.00	98.6	0.04	0.3	0.04
St. Martins	3.69	101.6	3.64	103.4	0.04	1.8	0.12
Grindstone Isl.	4.72	107.0	4.60	108.1	0.11	1.0	0.14
Cape d'Or	4.34	102.0	4.27	106.0	0.07	4.0	0.31
Ile Haute	4.15	99.2	4.04	101.8	0.11	2.5	0.21
Margretsville	3.86	92.9	3.85	96.5	0.01	3.6	0.24
Parkers Cove	3.43	89.8	3.28	91.3	0.16	1.5	0.18
Grindstone	4.86	104.4	4.61	108.0	0.25	3.6	0.39
Cumberland Basin	4.74	104.6	4.63	107.2	0.11	2.6	0.24
Minas Basin	5.54	120.8	5.33	122.6	0.20	1.7	0.26
Economy	5.92	125.4	5.71	128.2	0.22	2.8	0.35
Cobequid Bay	6.12	129.3	5.94	132.8	0.18	3.5	0.41
Mean	4.53	–	4.41	–	0.12	2.4	0.24
RMS	4.63	–	4.50	–	0.14	2.6	0.26

Table 1: Observed and modelled amplitude (m) and phase (degrees GMT), and discrepancies (Obs.-Model) for M2. The 'Error' in the last column is the error metric described in the text. The stations are those common among Greenberg (1979), Sankaranarayanan and McCay (2003) and the present study.

Model	M2	N2	S2	K1	O1
present	0.28	0.26	0.12	0.03	0.02
regional	0.32	0.21	0.12	0.02	0.02
NW Atl.	0.77	0.19	0.15	0.03	0.02

Table 2: The RMS elevation error (m) based on the error metric (1) for each tidal constituent for 29 stations in the Bay of Fundy. Stations where the model solution exhibited wetting/drying were excluded from the comparison. The first line corresponds to the present high resolution model, the second line to the present regional assimilation system and the third line corresponds to the northwest Atlantic assimilation system (Dupont et al., 2002).

Correction	Saint John	Minas	Grindstone	Economy	Cobequid
None	0.20	0.42	0.47	0.51	0.58
Corr.1	0.13	0.36	0.41	0.44	0.53
Corr.2	0.03	0.27	0.37	0.38	0.50

Table 3: The RMS timeseries elevation error (m) at five locations using no correction and two different types of correction. The period for comparison extends from May 1 to June 4, 1976.

C_d	M2	N2	S2	K1	O1
2.5×10^{-3}	0.24	0.23	0.12	0.03	0.02
2.0×10^{-3}	0.25	0.21	0.11	0.02	0.02
1.5×10^{-3}	0.40	0.19	0.11	0.03	0.03

Table 4: The RMS elevation error (m), computed as in Table 2, for different values of the bottom friction coefficient (C_d) and using the corrected M2 at the open boundary. The value $C_d = 2.5 \times 10^{-3}$ is the base case.

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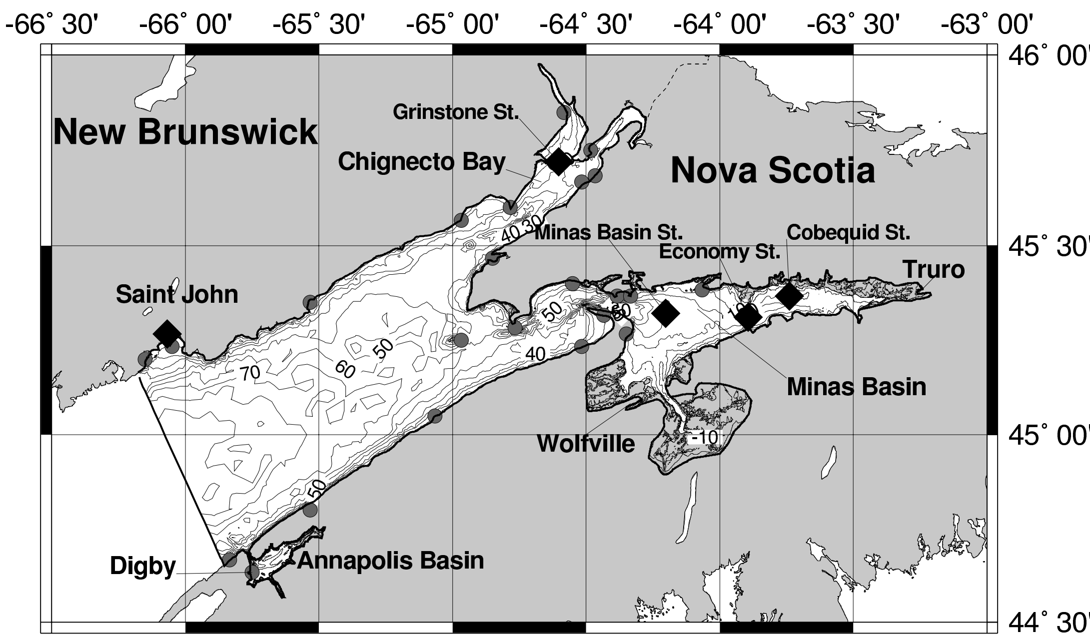
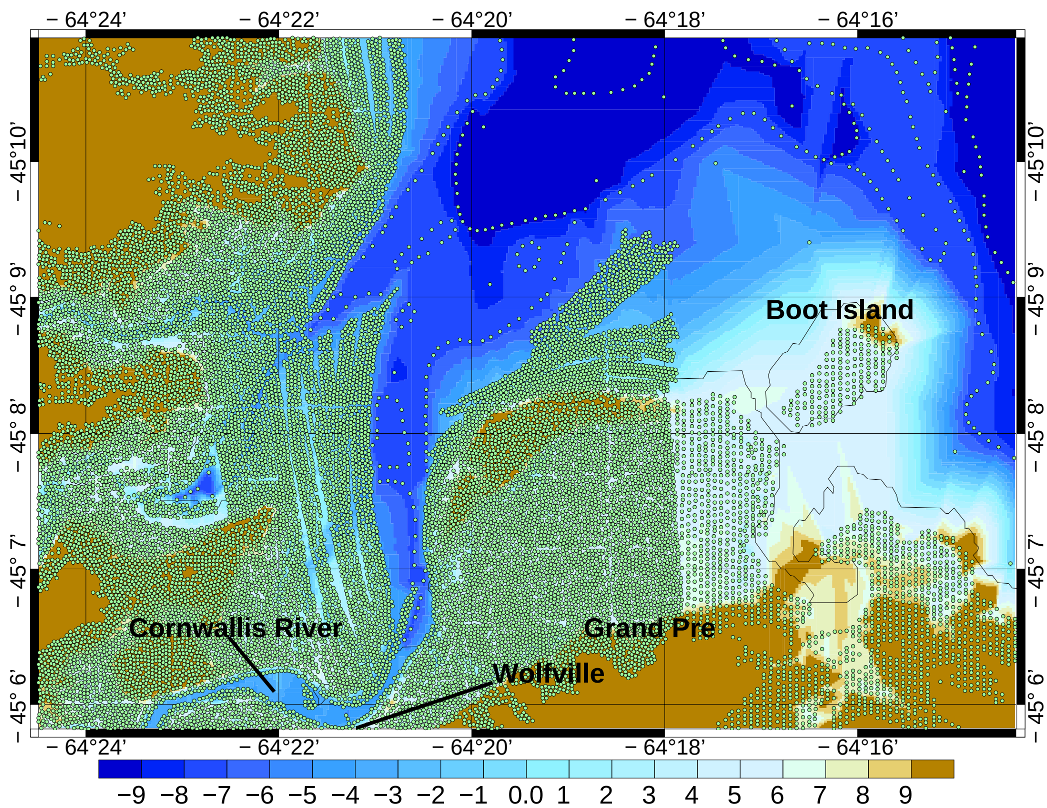


Figure 1: Map of the upper Bay of Fundy showing the locations of the tide gauge stations (grey circles) and the time series stations (black diamonds). The bathymetry is contoured with thin black lines and the computational domain is shown in thicker black lines. Areas below mean sea level are white and areas above mean sea level are grey. Minas Channel is the narrow Channel that connect Minas Basin to the rest of the Bay of Fundy.



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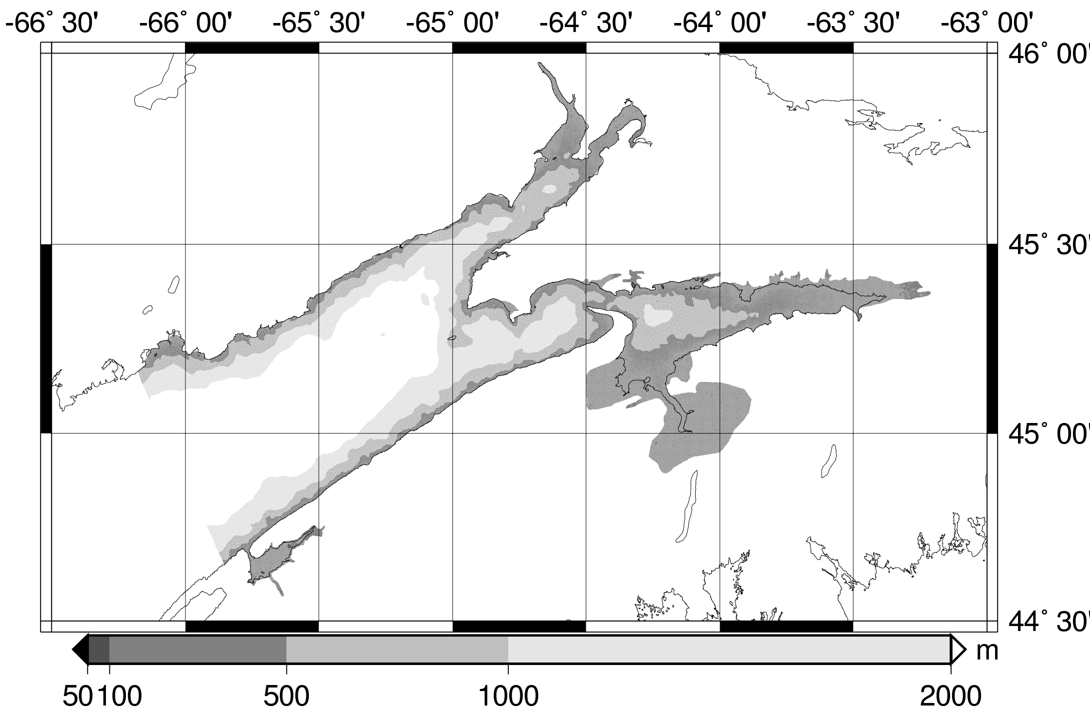

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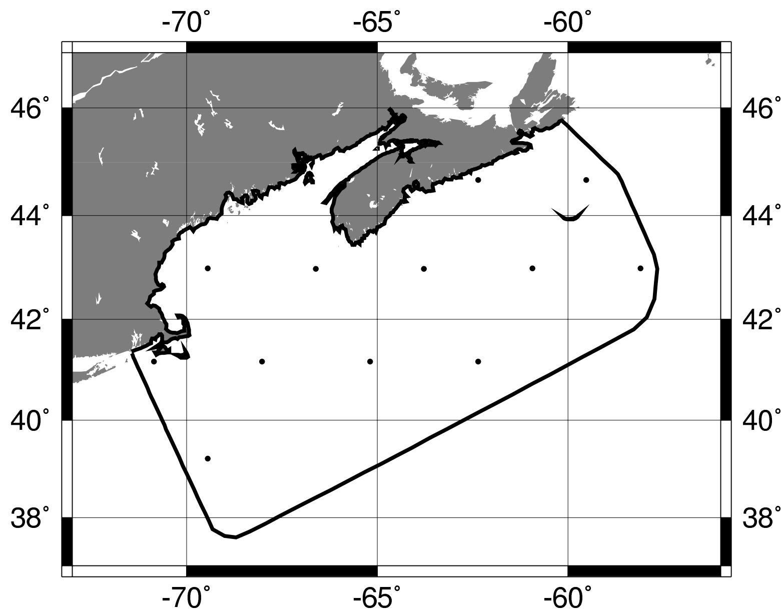
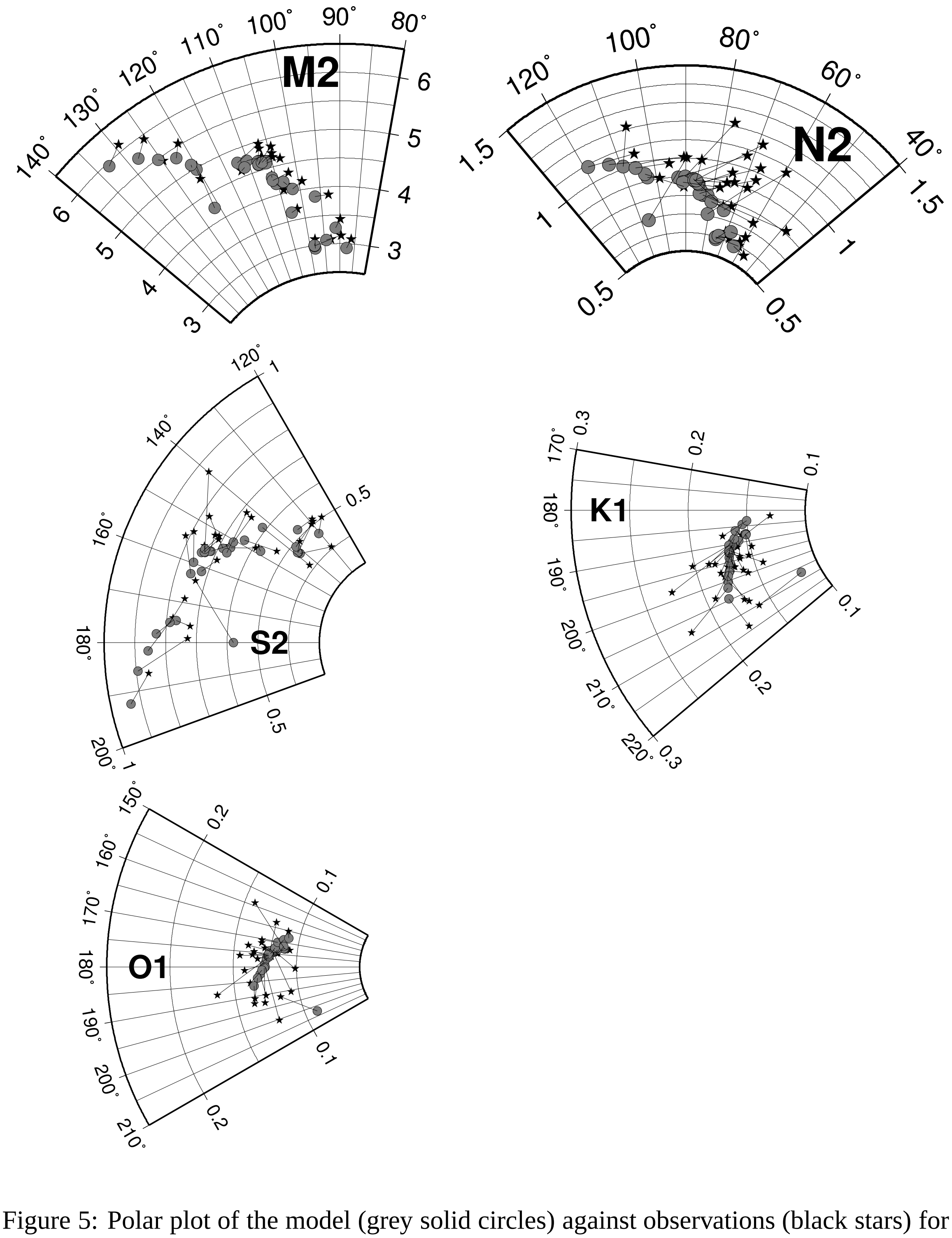


Figure 4: The computational domain used in the assimilation scheme for deriving the tidal boundary conditions for the upper Bay of Fundy model. The Topex/Poseidon cross-over points are shown. These are the locations where tidal harmonics were specified from the analysis of the satellite altimetry.



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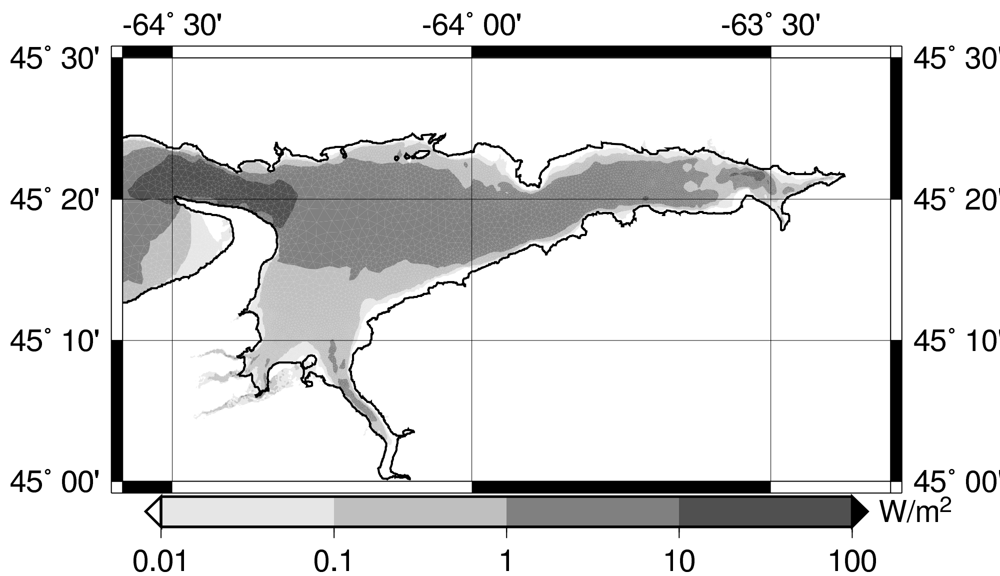

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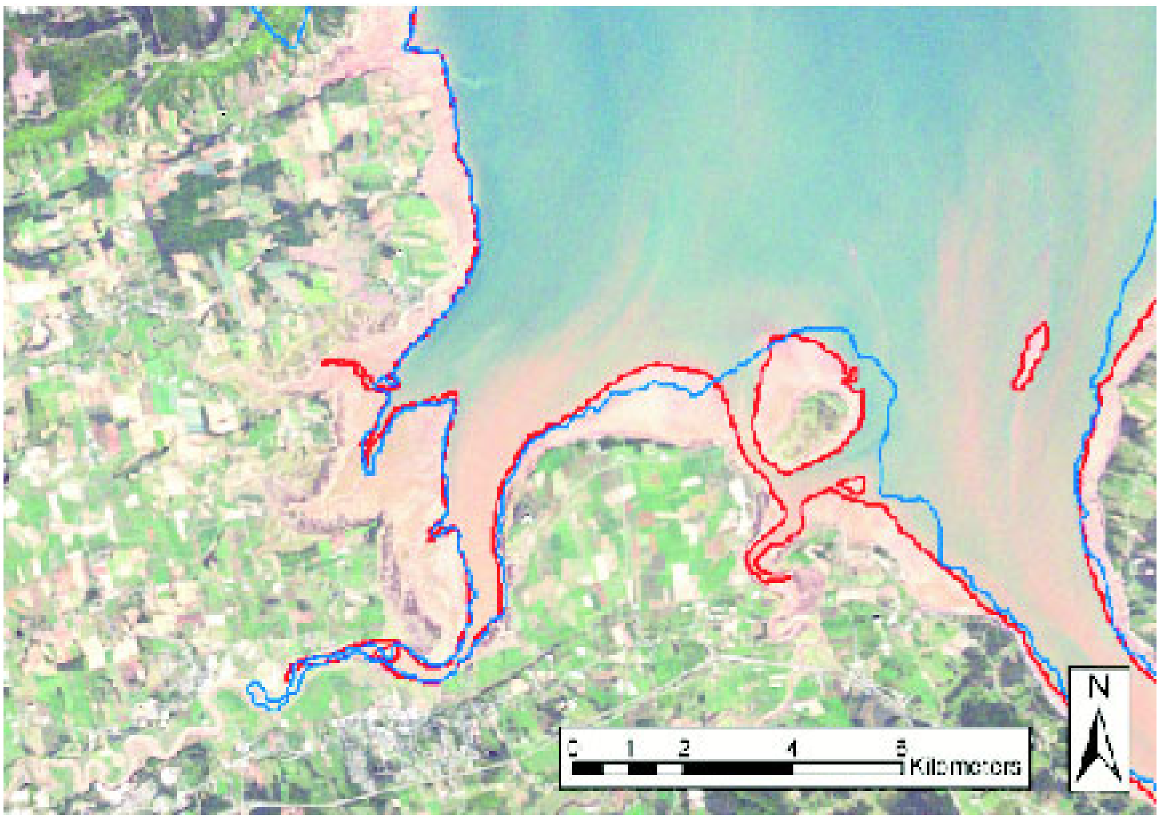


Figure 7: True colour Landsat-7 image of the Wolfville vicinity at 14:54:13 (GMT) on 13 Sept. 1999. The green is vegetation and the sandy brown is exposed tidal flats. The red line is the instantaneous coastline extracted from one of the near infrared bands and the blue line is the coastline extracted from the tidal model. The analysis is reported in Milne (2003). Courtesy of Trevor Milne (AGRG).

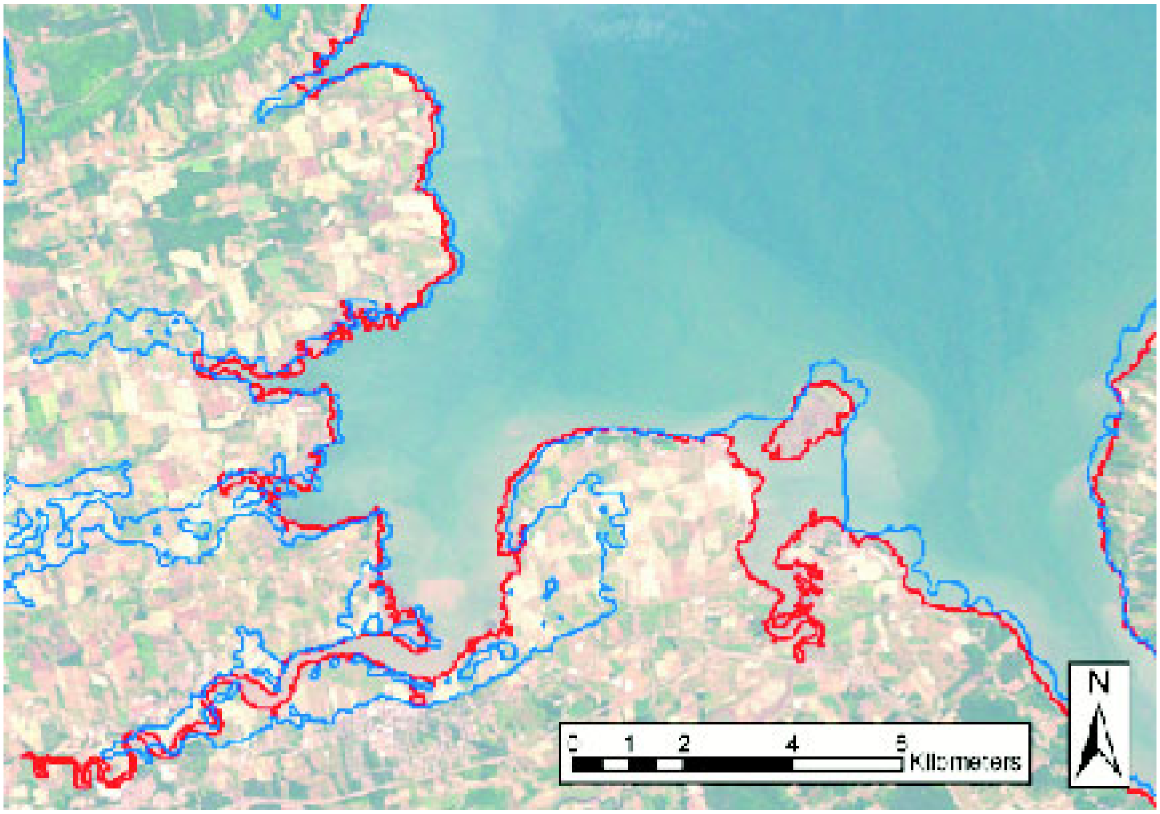
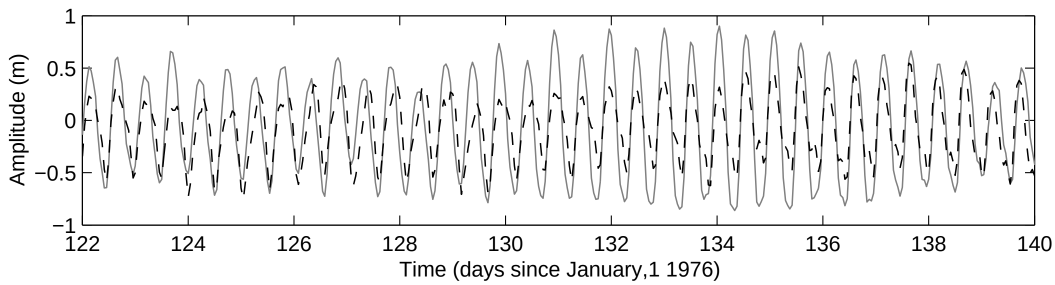


Figure 8: True colour Landsat-7 image of the Wolfville vicinity at 14:52:00 (GMT) on 13 July 2000. The red line is the instantaneous coastline extracted from one of the near infrared bands and the blue line is the coastline extracted from the tidal model. The analysis is reported in Milne (2003). Courtesy of Trevor Milne (AGRG).



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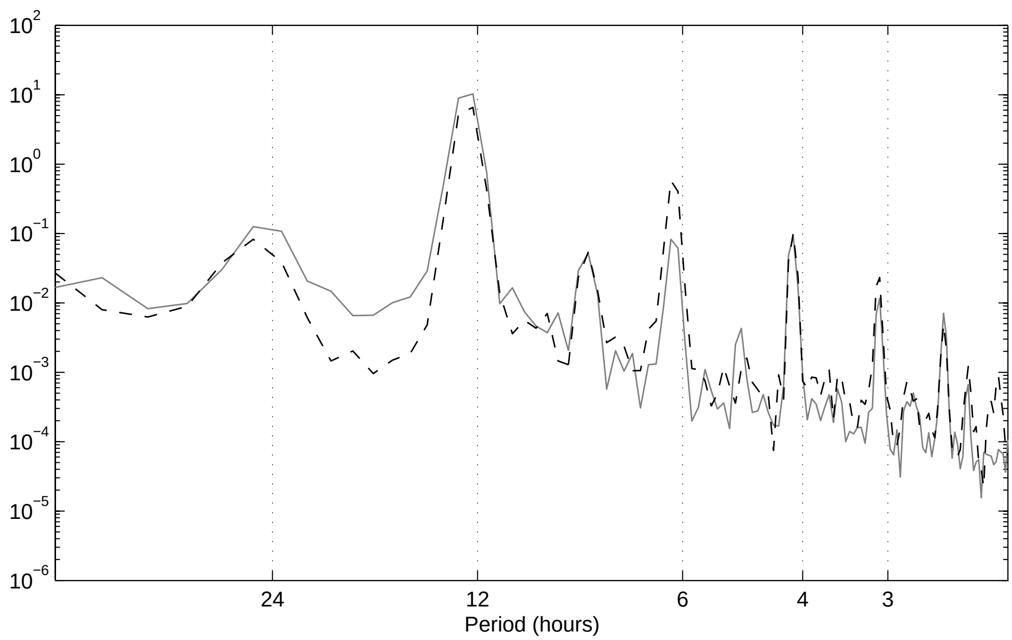

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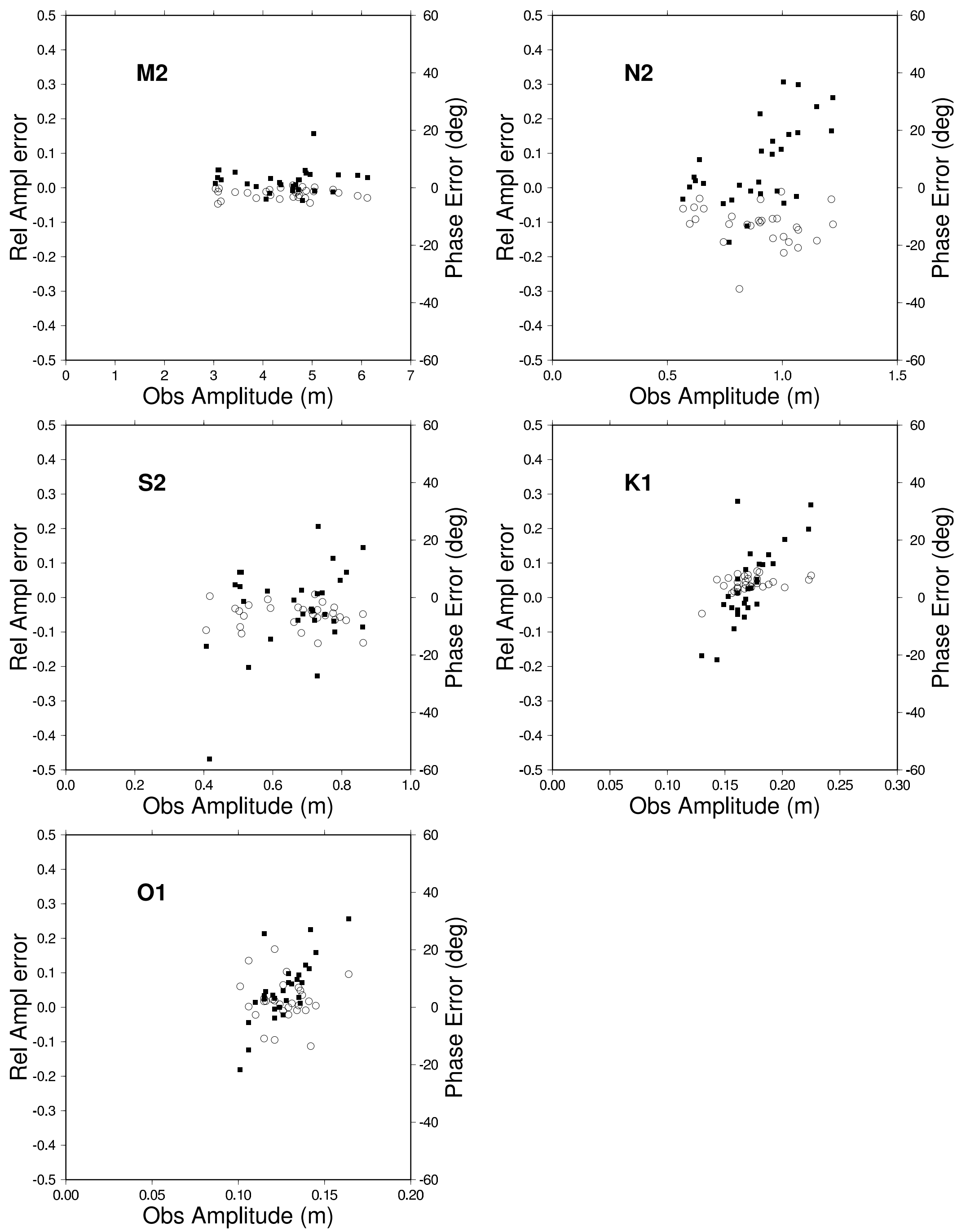

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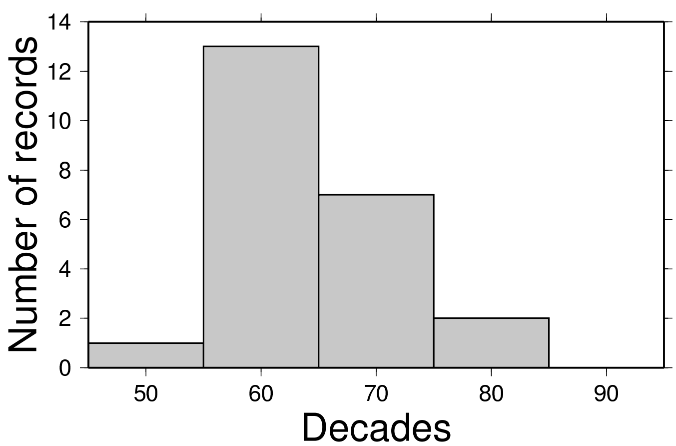

Figure 12: Histogram showing the time history of tidal data collection in the upper Bay of Fundy. The multidecadal records at Saint John and Digby and 4 records with no date in the database are not included.