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Re-analysis of the December 1981 storm surge event in the Bristol Channel using the current operational tide-surge model suite

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ABSTRACT

The Bristol Channel is an area of complex hydrodynamics which include a very large tidal range, strong currents, extensive inter-tidal areas and river inputs, all of which contribute to make predicting storm surges difficult.

The highest water levels experienced in the Bristol Channel in a century occurred during the storm of 13th December 1981 when severe flooding was experienced along the north Somerset coast. This was due to the passage of a secondary depression which tracked unusually far south for the time of year (Figure 1), producing strong westerly winds in the southern Celtic Sea estimated to be in excess of 30 ms^{-1} (Proctor & Flather, 1989). The meteorological situation was complex and rapidly changing. Also the passage of the storm coincided with tidal high water in the Bristol Channel during a period of spring tides.

At the time of this event, the operational storm surge modelling system comprised solely of the original 35km continental shelf model (CSM) which was implemented in 1978. This is shown in Figure 2. CSM had only two boundary tidal constituents (M_2 and S_2), was forced by an atmospheric model of resolution 100km and produced surge forecasts only twice a day (0000UTC and 1200UTC). This combination of atmospheric and surge forecast models failed to provide adequate warnings of the expected levels in this region. Analysis of the performance (Proctor & Flather, 1989), suggested that the most significant factor was that the direction of the modelled winds was incorrect at the critical time leading up to high water in the Bristol Channel.

The purpose of this study is to quantify any improvement in the forecast that might be achieved if there was a repeat of this event (i.e. how well would the present, much-improved, operational forecasting system deal with a similar weather event). To facilitate this study, the atmospheric model forcing for December 1981 was obtained from reanalyses performed by the European Centre for Medium Range Weather Forecasting (ECMWF).

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Background

The Bristol Channel is an area of complex hydrodynamics which include a very large tidal range, strong currents, extensive inter-tidal areas and river inputs, all of which contribute to make predicting storm surges difficult.

The highest water levels experienced in the Bristol Channel in a century occurred during the storm of 13th December 1981 when severe flooding was experienced along the north Somerset coast. This was due to the passage of a secondary depression which tracked unusually far south for the time of year (Figure 1), producing strong westerly winds in the southern Celtic Sea estimated to be in excess of 30 ms^{-1} (Proctor & Flather, 1989). The meteorological situation was complex and rapidly changing. Also the passage of the storm coincided with tidal high water in the Bristol Channel during a period of spring tides.

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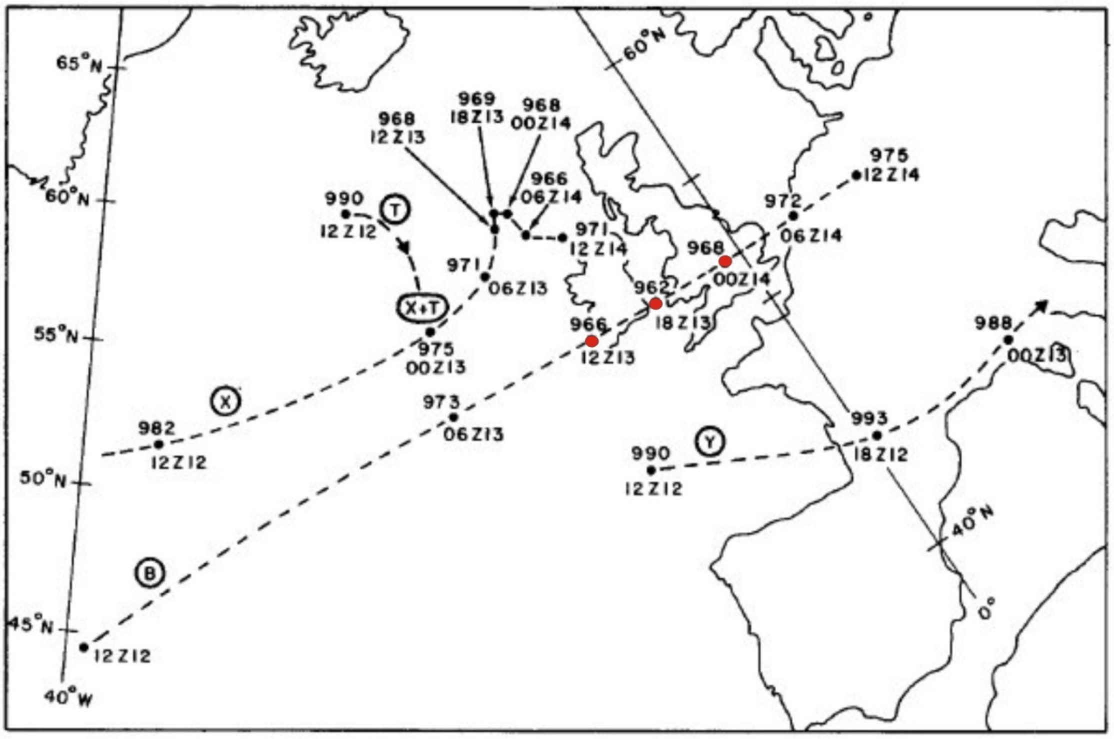

Figure 1: Passage of the secondary depression. The red dots show its position at 1200UTC 13/12, 1800UTC 13/12 and 0000UTC 14/12. (Taken from Proctor & Flather, 1989.)

Introduction

The present operational surge modelling system comprises an extended continental shelf model with three times the resolution of the original model. This is the CS3X model which is 12km resolution and extends to 20°W (Figure 3). Older shelf-scale models were developed primarily for the prediction of east coast surges: their scale was such that they could not resolve the detail of estuaries such as the Severn Estuary. In 1994 a system of one-way nested models was introduced giving high resolution coverage of the Bristol Channel and Severn Estuary (Flather & Smith, 1994). The Bristol Channel model (BCM) has resolution ~4km and the Severn Estuary model has resolution ~1.3km (Figure 4). BCM is forced at the boundary by 26 tidal harmonics plus time series of surge interpolated from the CS3X model. The Severn Estuary model is coupled to a 1D model of the River Severn (together referred to as SRM). SRM uses time series of both tide and surge interpolated from BCM to provide boundary input which accounts better for the tide than harmonics alone (Amin & Flather, 1995).

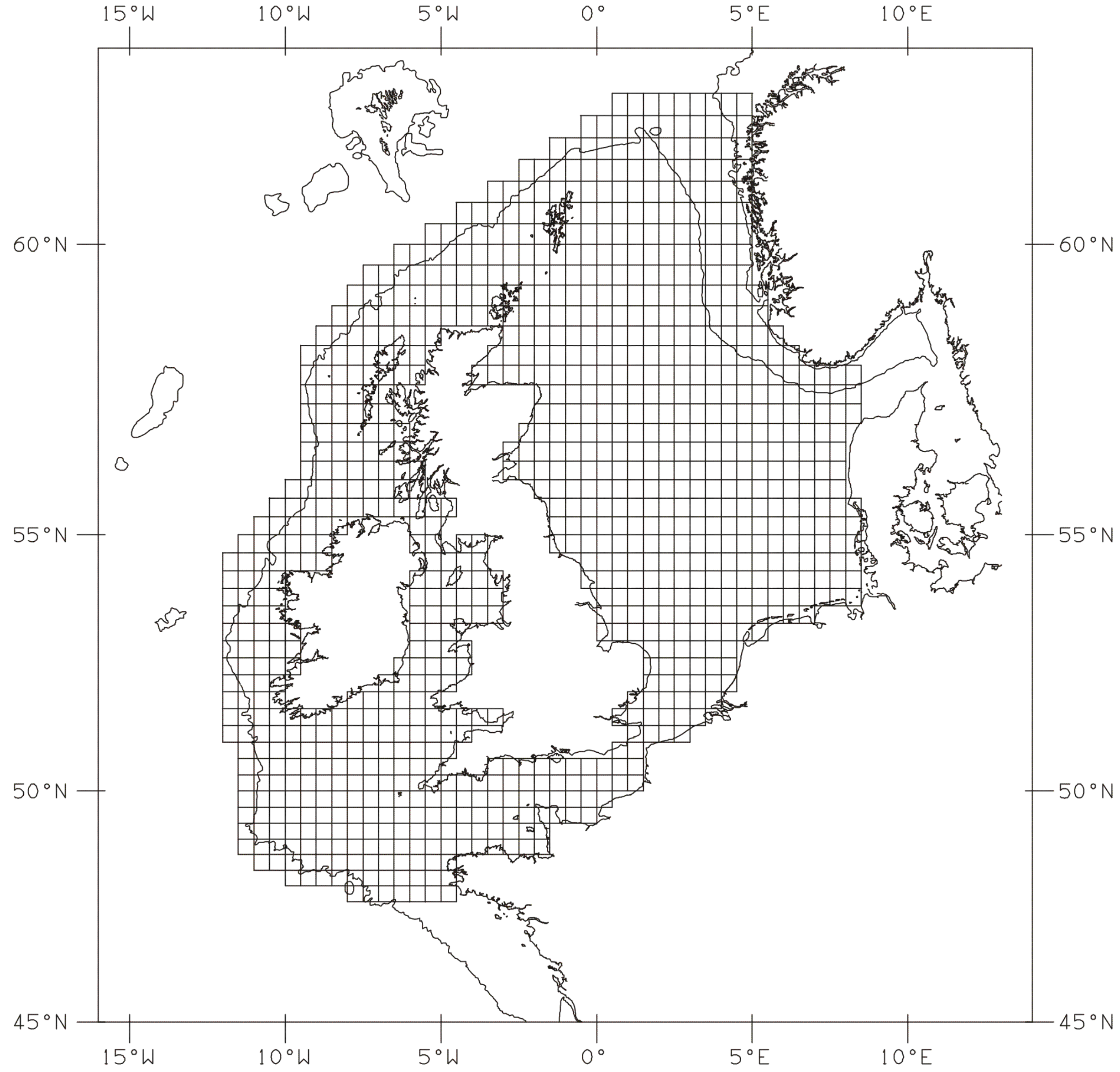

Figure 2: The original 35km Continental Shelf Model (CSM) grid.

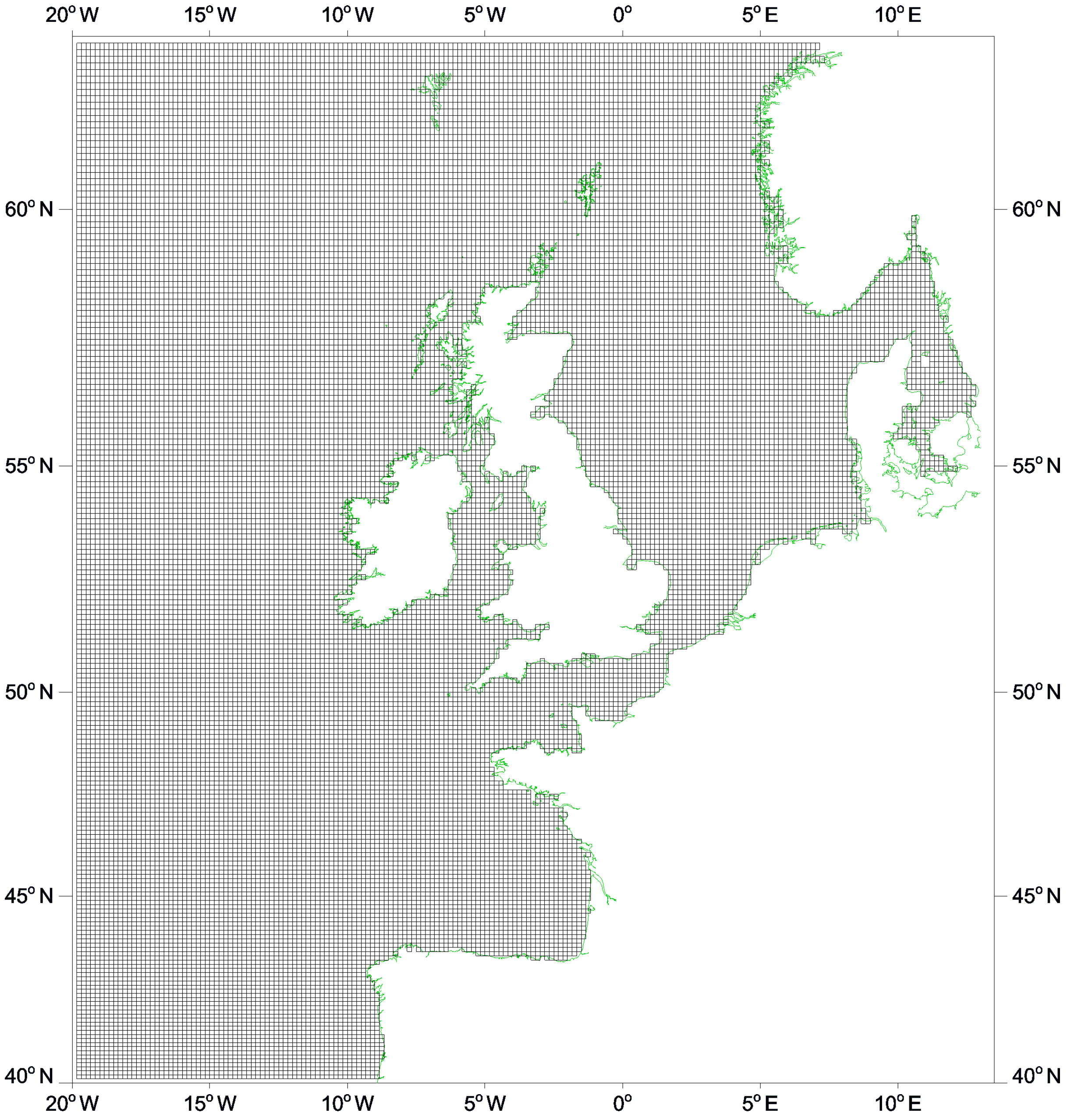

Figure 3: The present 12km CS3X operational model grid.

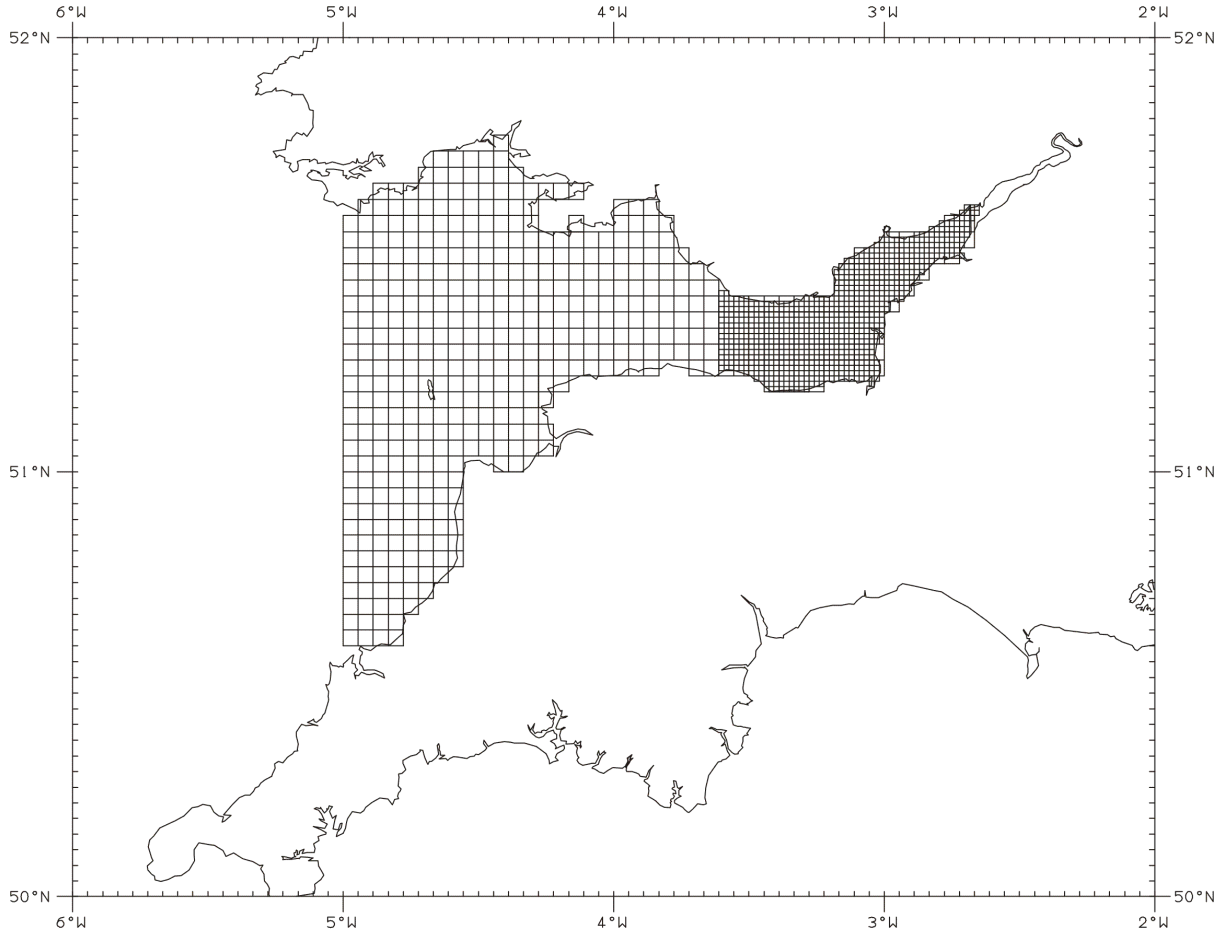

Figure 4: The Bristol Channel suite of models (BCM & SRM).

This study will re-visit the event of December 1981 by running the present suite of models with the best available meteorological forcing to assess how this event would be handled if it had occurred today. For this experiment, we use meteorological forcing from the ERA-Interim Project. ERA-Interim is a reanalysis undertaken by ECMWF which uses an improved (c.f. ERA-40) atmospheric model physics and data assimilation system (ECMWF, 2006-12). In our analysis we compare non-tidal residuals output from the current suite of models with those obtained from the old operational surge model at the time of the event.

Model Runs

Workstation versions of the BCM and SRM were set up for this experiment. The period of interest was selected as a 5-day period: 11-15th December 1981, which encompassed the event on the evening of 13th December.

BCM was run for tide-only from a cold start starting 01/12/1981 for a period of 15 days. This would give ample time for the model to spin-up to provide a re-start condition for a subsequent tide-and-atmosphere forced model run for the period of interest. Storm surge input for the open boundary of BCM was extracted from a 40-year run of CS3X forced by ERA-40 reanalysis meteorological data. This was then linearly interpolated to the open boundary of BCM.

BCM was then run for tide plus surge for 11-15th December 1981 forced by the N-S and E-W components of winds at 10m height and mean sea level pressure at six-hourly intervals derived from the ERA-interim reanalysis dataset. Non-tidal residual elevations were calculated at several Bristol Channel locations by subtracting the tide-only model simulation from that forced by tide and atmosphere. These outputs are shown in Table 1.

The same runs were then carried out with SRM. However for SRM, both the boundary tide and surge input were interpolated from the BCM output arrays prior to the SRM run. Residual elevations for this run are shown in Table 2.

Results

The tables of non-tidal residuals from both models are given below. Note that the output has been cropped to show the 12-hour period of interest from 1200UTC to 2300UTC on 13th December 1981.

```
Storm surge HINDCAST - BCM model
 Data starts at   12 hrs GMT 13/12/1981
 Residual elevations in m.

   Time      Point number  ( I,J = column,row )
   GMT    I =    7     9    15    17    22    26    35    42    38    25    23    21    20    14     7
          J =   30    27    21    16    16    16    16     9     8    10     7     6     7     7     4
             BOSC  BUDE  INST  ILFR  LYNM  PORK  HINK  AVON  NEWP  PAWL  PTAL  SWAN  MUMB  RHOS  TENB

   1200      0.38  0.40  0.39  0.45  0.41  0.35  0.20  0.14  0.42  0.45  0.53  0.61  0.56  0.53  0.68
   1300      0.44L 0.46L 0.41L 0.45L 0.40L 0.35  0.19  0.10  0.44  0.45  0.56L 0.27  0.56L 0.55L 0.68L
   1400      0.60  0.62  0.54  0.54  0.47  0.40L 0.22L 0.13  0.37  0.50L 0.55  0.29  0.57  0.63  0.74
   1500      0.69  0.71  0.72  0.71  0.68  0.58  0.56  0.15  0.54L 0.68  0.79  0.87  0.81  0.77  0.82
   1600      0.68  0.71  0.80  0.84  0.84  0.74  0.71  0.41L 0.78  0.86  0.92  0.99  0.92  0.89  0.91
   1700      0.61  0.64  0.72  0.80  0.84  0.86  0.91  0.66  1.08  0.90  0.87  0.91  0.89  0.84  0.83
   1800      0.54  0.56  0.59  0.66  0.68  0.76  0.88  1.16  1.07  0.77  0.75  0.75  0.76  0.69  0.69
   1900      0.50H 0.51H 0.52H 0.54H 0.54  0.62  0.72  1.74  1.21  0.64  0.63  0.65  0.62  0.59  0.53
   2000      0.44  0.46  0.49  0.50  0.49H 0.55H 0.72H 0.83  0.82  0.57H 0.56H 0.58H 0.55H 0.54H 0.51H
   2100      0.38  0.40  0.46  0.52  0.56  0.54  0.42  0.28H 0.29H 0.65  0.70  0.68  0.65  0.52  0.40
   2200      0.34  0.36  0.40  0.38  0.38  0.35  0.25  0.37  0.24  0.38  0.32  0.26  0.29  0.43  0.40
   2300      0.32  0.33  0.33  0.32  0.34  0.30  0.30  0.34  0.22  0.34  0.36  0.32  0.31  0.25  0.13
```

Table 1: Residual table for BCM ports 1200-2300 UTC 13/12/81.

```
 Storm surge HINDCAST - SRM model
 Data starts at   12 hrs GMT 13/12/1981
 Residual elevations in m.

   Time      Point number  ( I,J = column,row )
   GMT    I =    8    16    26    33    34    37    40    47    50    53    49    44    35    25    20
          J =   33    36    33    32    22    17    16    11    11     2     4     6     8    14    19
             MINE  WATC  HINK  BURN  WEST  YEOR  CLEV  POSH  AVON  BEAC  SUDB  MAGP  NEWP  CARD  BARY

   1200      0.34  0.28  0.27  0.19  0.32  0.29  0.29  0.30  0.29  0.30  0.29  0.32  0.34  0.35  0.35
   1300      0.34  0.27  0.27  0.15  0.31  0.29  0.28  0.27  0.25  0.29  0.28  0.31  0.35  0.37  0.36
   1400      0.39L 0.31L 0.28L 0.12  0.32  0.30  0.25  0.25  0.22  0.25  0.25  0.28  0.40  0.43  0.39L
   1500      0.53  0.47  0.45  0.29L 0.41L 0.35L 0.35L 0.41L 0.33  0.08  0.29  0.21  0.42L 0.59L 0.53
   1600      0.71  0.66  0.64  0.64  0.58  0.57  0.68  0.61  0.76L-0.03L 0.39L 0.27L 0.61  0.72  0.67
   1700      0.82  0.75  0.81  0.74  0.85  0.74  0.73  0.73  0.68  0.81  0.37  1.23  0.84  0.94  0.87
   1800      0.73  0.73  0.82  0.83  0.90  0.92  0.98  1.12  1.09  1.35  1.14  1.40  1.05  0.98  0.87
   1900      0.63  0.64  0.71  0.71  0.87  0.86  0.92  1.08  1.03  1.14  0.84  1.18  0.83  1.07  0.80
   2000      0.53H 0.52H 0.56H 0.52H 0.57  0.63  0.66  0.63  0.58  0.70  0.87  0.72  0.75  0.61  0.64
   2100      0.47  0.47  0.38  0.45  0.44H 0.45H 0.44H 0.47H 0.48H 0.44H 0.42H 0.44H 0.45H 0.45H 0.42H
   2200      0.39  0.36  0.35  0.35  0.30  0.32  0.32  0.32  0.33  0.35  0.32  0.36  0.36  0.35  0.40
   2300      0.35  0.35  0.34  0.39  0.38  0.39  0.36  0.33  0.33  0.36  0.29  0.36  0.35  0.34  0.35
```

Table 2: Residual table for SRM ports 1200–2300 UTC 13/12/81.

We can compare the non-tidal residuals from the models to those observed in December 1981. Hourly observed surge elevations for Ilfracombe and Avonmouth have been extracted from the BODC archive database of processed tide gauge data. For Hinkley Point observed elevations have been derived from old hourly observed water level data files (not in the BODC database) which have had the harmonically predicted tide subtracted from them.

The tables below show the BCM and SRM residual output alongside observations (Ilfracombe is only available from BCM since it is in the outer domain). Additionally for Avonmouth (Table 3) we have included the operational forecast and hindcast that was produced at the time of the event (taken from Proctor and Flather, 1989).

Time 13/12/81	Original Forecast	Original Hindcast	BCM	SRM	OBS
1200	0.19	0.19	0.14	0.29	0.26
1300	0.02	0.10	0.10	0.25	0.36
1400	0.18	0.11	0.13	0.22	0.30
1500	0.41	0.24	0.15	0.33	0.24
1600	0.61	0.33	0.41	0.76	0.44
1700	0.59	0.31	0.66	0.68	0.32
1800	0.63	0.44	1.16	1.09	0.32
1900	0.67	0.59	1.74	1.03	0.21
2000	0.50	0.51	0.83	0.58	1.02
2100	0.39	0.52	0.28	0.48	1.52
2200	0.25	0.46	0.37	0.33	1.79
2300	0.16	0.36	0.34	0.33	n/a

Table 3: Model and observed residual elevations at Avonmouth from 1200-2300UTC 13th December 1981 including the original CSM forecast (start time 1200UTC 13/12/81) and hindcast.

Time 13/12/81	BCM	OBS
12z	0.45	0.83
13z	0.45	0.80
14z	0.54	0.72
15z	0.71	0.56
16z	0.84	0.39
17z	0.80	0.27
18z	0.66	0.45
19z	0.54	0.76
20z	0.50	0.85
21z	0.52	0.91
22z	0.38	1.08
23z	0.32	1.22

Table 4: Model and observed residual elevations at Ilfracombe from 1200-2300UTC 13th December 1981.

Time 13/12/81	BCM	SRM	OBS
1200	0.20	0.27	0.04
1300	0.19	0.27	0.45
1400	0.22	0.28	0.27
1500	0.56	0.45	-0.19
1600	0.71	0.64	-0.11
1700	0.91	0.81	-0.38
1800	0.88	0.88	-0.18
1900	0.72	0.71	0.86
2000	0.72	0.56	1.08
2100	0.42	0.38	1.14
2200	0.25	0.35	1.15
2300	0.30	0.34	n/a

Table 5: Model and observed residual elevations at Hinkley Point from 1200-2300UTC 13th December 1981.

Looking at Tables 3 to 5 we can see that for this event, BCM produced a significantly larger maximum non-tidal residual than SRM at Avonmouth (by 71cm) and also produced a larger value at Hinkley Point (by 10cm). The timing of the modelled surge peaks is similar between BCM and SRM (within 1 hour). The maximum modelled surge occurs at 1600 at Ilfracombe, 1700 or 1800 at Hinkley Point and 1800 or 1900 at Avonmouth (depending on the model). The models predict the peak surge early compared to the observations. The maximum observed surge occurs at 2300 at Ilfracombe (1.22m) and 2200 at Hinkley (1.15m) and Avonmouth (1.79m). (It should be noted that the tide gauge data is unavailable for Avonmouth and Hinkley Point from 2200 onwards which indicates a likely gauge error: this may question the accuracy of some of the data leading up to the gauge fault.)

The original operational forecast output was only available for Avonmouth, and is included in Table 3. We can use this to see how our re-run differs from the original forecast. The CSM forecast for Avonmouth starting at 1200 (which would have given an 11 hour advance warning of the maximum observed peak surge at 2200) gave a peak surge of 0.67m at 1900 (3 hours earlier than observed). The hindcast from the subsequent CSM run showed the peak surge also at 1900 but surprisingly slightly lower (0.59m). The original CSM forecast had under predicted the surge by 1.12m at Avonmouth. Re-run output from BCM and SRM for Avonmouth (Table 3) shows a significant improvement in the magnitude of the surge peak. BCM gives a maximum peak of 1.74m at Avonmouth whereas SRM gives a maximum surge of 1.09m. The BCM value is only 0.05m lower than observed and SRM is worse (0.70m lower).

The surge peak at Avonmouth given by BCM is 1.07m larger than the original operational forecast from CSM. This is only 0.05m lower than the observed value compared this demonstrates a major improvement over the original operational forecast. For other locations, BCM also gives the best predictions for residual elevations compared to observations. Although the accuracy of the peak surge has much improved over the original operational forecast (from CSM), the timing of the peak surge is similar (early at all locations).

We now investigate if there are any issues due to the model tide which may be affecting the timing of the residual. The model tide was extracted for the period of interest at Avonmouth and compared to the harmonically predicted tide. This is shown in Figure 4.

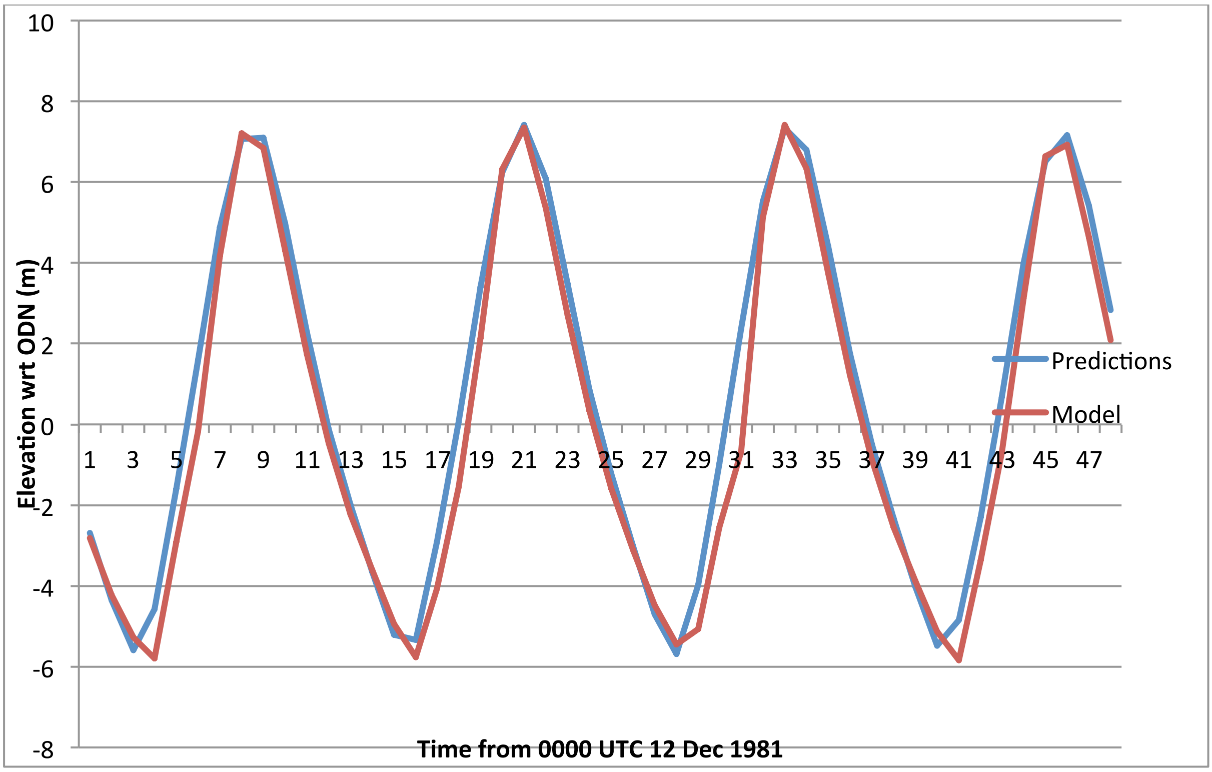

Figure 4: Model v. harmonically predicted tide at Avonmouth for 12-15 Dec 1981.

Figure 4 shows that there are no significant discrepancies between the model and observed tide in terms of phase and elevation, which would account for a timing error in the model residual elevation.

For further clarification, we eliminate the tide completely from the model and run BCM with only meteorological forcing. The result is a purely meteorological response without any tide-surge interaction (shown in Table 6).

Time 13/12/81	BCM (without tide)
1200	0.51
1300	0.50
1400	0.41
1500	0.35
1600	0.61
1700	1.21
1800	1.57
1900	1.25
2000	0.60
2100	0.23
2200	0.28
2300	0.51

Table 6: Elevations for Avonmouth obtained from a BCM run driven solely with meteorological forcing.

Looking at the elevations from the ‘surge-only’ run of BCM in Table 6 shows a peak residual at 1800 which is four hours earlier than observed. This is comparable to the standard residuals in Table 3 which shows BCM peak residual elevation at 1900 (one hour later due to tide-surge interactions). This confirms that the cause of the models giving peak residual elevations several hours before the observed peak is not due to any tide related issues. The likely explanation for the early timing of the peak is that the ERA-Interim forcing is at 6-hourly intervals. The time resolution of the forcing data may not be of high enough frequency enough to resolve the rapidly changing meteorological situation. Figure 2 shows that the secondary depression had taken less than six-hours to pass over the Bristol Channel. Proctor and Flather (1989) discussed the importance of time resolution in the forcing data.

Conclusions

We have re-run the BCM/SRM models for the storm surge event of December 1981 with meteorological forcing from the ERA-Interim reanalysis data. Surges produced by BCM for tide gauge locations are larger than those produced by SRM. Surges at Avonmouth for both BCM and SRM are significantly improved over those produced by the original operational surge model running in 1981. BCM under-predicts the observed value by only 0.05m compared with an original under-prediction of 1.12m. However, timing of the surge peak in BCM and SRM is still too early. The possibility of tidal discrepancies between model and observations has been eliminated. So we conclude that this is likely due to the frequency of the forcing data in the re-analysis dataset which is not high enough to resolve the very rapidly developing nature of the meteorological situation. It is clear from this revisit of the event that the present day operational forecasting system (where both the surge and atmospheric models are significantly better resolved in time and space) would provide an accurate and effective forecast of the storm surge.

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