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Numerical modelling of storm surges in the Irish Sea and the Isle of Man, and analysis of those factors determining extreme sea levels of the region in a future climate

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ABSTRACT

This report represents the key results from a study into the storm surge climate of the Irish Sea, and with a particular focus on the coastline of the Isle of Man. The project was funded by the Isle of Man Department of Transport, on advice from the Isle of Man Meteorological Office. Much of the work on numerical modelling was performed by Mr John Maskell whilst studying for a PhD under the supervision of Dr Kevin Horsburgh and Dr Alan Davies (both senior scientists at what was formerly the Proudman Oceanographic Laboratory, now the National Oceanography Centre, NOC, Liverpool).

The focus of the project was the use of a relatively novel hydrodynamic model, the Telemac-2D finite element model (FEM) to properly resolve all bays and inlets, and therefore give a more accurate spatial representation of storm surges in these enclosed areas which are sensitive to the direction of wind, and passage of weather systems. Thus the study investigated the utility of such advanced modelling techniques in terms of their forecast accuracy over and above the standard operation forecasting products provided by the UK Coastal Monitoring and Forecasting Service (UKCMF), which is now available to the Isle of Man Met Office (see http://environment-agency.wales.gov.uk/research/policy/116129.aspx for a description of the service). This report acts to advise whether there would be any operational benefit in developing additional fine resolution model tools for the waters surrounding the Isle of Man. In this respect it informs a medium term requirement concerned with the suitability of the present UK operational forecasting suite when faced with highly complex coastal topography.

The report also provides information on the long term climate change implications for storm surge characteristics and development in the Irish Sea, and with focus on the coastline of the Isle of Man. We draw some of this information from the UK Climate Projections 2009 (Lowe et al., 2009) and the Marine Climate Change Information Partnership (MCCIP; http://www.mccip.org.uk/annual-report-card/2010-2011.aspx) supplemented by our further analysis of the storm surge model data from future epochs in the climate models. The project thus considers the long term questions regarding likely flood risk, and key affected locations in future climates. Our results are valuable to government, local government and agencies in the context of designing risk management strategies that may need to evolve in a future climate.

KEYWORDS:

Sea level extremes; storm surges; finite element model

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1. Executive summary

This report summarises the results of a PhD studentship funded by the Isle of Man Department of transport, directed towards understanding the use of advanced numerical computer models in the prediction of storm surge events in the Irish Sea, and the resultant impacts in terms of potential coastal flooding. Storm surges are the sea level response to wind stress and atmospheric pressure gradient. Extreme sea levels (and flood risk) arise from a combination of mean sea level changes, high tides and storm surges. Once a suitable computer model of storm surges in the region has been decided upon, it can be forced with information from global climate models in order to make judgements about coastal flood risk in the future.

By comparison with observed tide gauge data it was found that advanced numerical methods (so-called finite element models) of the region perform comparably but no better than the current suite of operational models used by the UK Coastal Monitoring and Forecasting Service (UKCMF). There is no evidence that increasing the numerical model grid resolution will improve predictive accuracy of the model. The accuracy of storm surge prediction is thus determined mainly by the quality of the meteorological forcing (and the coastal bathymetry in the model). Further experiments with highly resolved wind data (at 4km resolution) were seen to influence certain areas (e.g. Liverpool Bay) but provided no systematic improvement for the Irish Sea as a whole or the coastline of the Isle of Man. From this we can conclude that attempts to infer changes to storm climate for the region can make use of the UKCP09 exercise that coupled the UK operational storm surge modelling suite to regional climate models. We also conclude that for short-term, operational flood warning purposes there would be no benefit in developing highly complex model tools for the Isle of Man coastline. An optimum forecast product would be that provided by UKCMF via the Flood Forecasting Centre (and the operational ensemble is useful for quantifying forecast uncertainties).

Future change to the storm surge climate was investigated using the storm surge projections from the latest UKCP09 report (Lowe et al. 2009). This study reported no significant change to storm surge climate around the majority of the UK (and for most of the Irish Sea). It did point out a small but statistically significant increase in the 50-year return period storm surge for the southwest of the UK. However, our additional analysis of the Bristol Channel (selected because the effect was largest there) finds no significant effects even here. Our analysis focussed on the statistics of surge events rather than attempting to fit a statistical distribution to the data. Section 5 of this report shows no significant changes with time to ensemble mean properties, and that the largest storm surge within a 50 year model time block decreases in the future.

The discrepancy (between our results and UKCP09) probably arises because the variability of modelled storm surges seems to decrease in the future, which affects the statistical model used to determine changes to the surge climate. Our results are consistent with other studies that imply no change in the storm surge climate above natural variability. This in turn implies that changes to future extreme water-levels around our coastline are mainly driven by mean sea level changes. Accounting for predicted mean sea level rises, coastal and risk managers can modify joint probability estimates of tides and surge and (until better information becomes available) should assume that storm surge variability is best derived from the longest high-quality record of observed tide gauge data. Recent, but uncalibrated, estimates of extreme sea level for the Isle of Man coastline are summarised in section 6 of this report. A further series of model experiments, based on the storm surge of February 2002 that caused flooding, investigated whether differences in timing of the weather system with respect to the tide could have changed the severity of the event. We found that the event did represent close to a worst case: had the weather system been advanced by 2 hours then a further 6cm of sea level would have been observed, according to the numerical model.

Observations of mean sea level rise measured at sites around the UK are consistent with the globally averaged figure of 1.8 (± 0.2) mm per year from tide gauge records or approximately 3mm per year from the shorter record of satellite altimetry. It is still unclear whether this recent increase represents acceleration or simply reflects natural variability in the rate. Projections of future sea level rise (from UKCP09) for the UK between the years 1990–2095 are 21–68 cm for London and 7–54 cm for Edinburgh (due to differences in vertical land movement). A very low probability but high impact scenario of 1.9m is estimated for contingency planning purposes.

There is no significant evidence for any observed trend in storm surge frequency or magnitude, or wave climate. Changes to these components of extreme sea level appear to be less important than changes in global mean sea level over the next 100 years.

2. Background: Mean sea level and sea level extremes

Coastal flooding around the UK is responsible for approximately £1 billion of annual insurance losses, and expenditure on coastal defences is approximately £430 million each year. It is estimated that £150 billion of financial assets and about 4 million people are at risk from coastal flooding in the UK. Coastal flooding was also responsible for the worst natural disaster to affect the country in recent history (McRobie et al., 2005): during the night of 31 January 1953, flooding caused the loss of 307 lives in East Anglia (Baxter, 2005) and a further 1836 fatalities in the Netherlands. The most serious threat occurs when higher than average spring tides coincide with extreme storm surge events. Storm surges are the sea level response to wind stress and atmospheric pressure gradient (Pugh, 1987), and they are a critical component of total sea level during coastal flood events. The storm tide is a combination of mean sea level (MSL), tide and storm surge, all of which vary spatially because of bathymetric, topographic and other local scale effects. Global (IPCC, 2007) and local (Woodworth et al., 2009) rises in mean sea level over the coming century will elevate extreme water levels which will increase the risk to coastal properties and infrastructure.

Global mean sea level rise over the last 55 years is estimated to have been 1.8 (± 0.2) mm per year, based upon 177 tide gauges with near global coverage and correcting for vertical land movements. A sparser dataset of tide gauges suggests a similar rate applied over the past century (Church et al., 2008; IPCC, 2007; Holgate and Woodworth, 2004). Since 1992, satellite radar altimetry has suggested a rate of nearer to 3 mm per year (Holgate and Woodworth, 2004; Nerem et al., 2006). Similar rates have been observed in portions of the longer record so it is not yet clear if the higher rate of sea level rise will be sustained into the future. Although there is much variability in the measured values, mean sea levels around the UK mostly exhibit rises that are consistent with the global mean value of 1.8 mm per year (Woodworth et al., 2009).

The most recent projections of future sea level change for the UK are set out in the UK Climate Projections 2009 (Lowe et al., 2009). The methods used to generate sea level projections for the UK use the spread of projections from the most recent IPCC model assessment (IPCC, 2007). Including both scenario uncertainty and climate model uncertainty gives a projected range of sea level rise for the UK over the 21st century of approximately 12 to 76cm. Once land movement is included, slightly larger sea level rise projections are obtained in southern parts of the UK where land is subsiding, and somewhat lower increases in relative sea level for the north. For example, UKCP09 projects relative sea level increases for 1990–2095 of approximately 21–68 cm for London and 7–54 cm for Edinburgh. The full spread of results can be found in Lowe et al. (2009) or downloaded directly from the UKCP interactive user interface (http://ukclimateprojections-ui.defra.gov.uk/ui/admin/login.php).

Proxy records in deep ocean sediments, corals or ice cores from the ice sheets can be used to infer estimates of past sea level changes (e.g. Rohling et al., 2008). These suggest an upper limit of approximately 2.5m sea level rise for maximum global mean sea level rise over the

21st century. Such a large sea level rise requires a degree of ice melt that would in turn affect regional sea levels through the gravitational adjustment of the Earth. If the spatial patterns of adjustment suggested by Tamisea et al. (2001) are adopted then a sensible low probability high impact scenario for contingency planning is estimated as 1.9m. This is consistent with the findings of Pfeffer et al. (2008) who concluded that 21st century sea level rise in excess of 2m appears to be physically impossible on the basis of observed glacial movement.

Extreme sea levels around the UK arise from the combination of high tide, extreme waves and storm surge. Therefore, changes in extreme water level can result from either a change in the local mean sea level or a change in the atmospheric storminess driven components of water level, namely waves and surges. In a global study of tide gauge data since 1975, Woodworth and Blackman (2004) concluded that almost all the trends in extreme high water levels are dominated by changes to mean sea level. For the UK over recent decades there is no compelling observational evidence for trends in either storm surge frequency or magnitude. Recent work by Allan et al. (2008) further suggests that changes in storm frequency over the last several decades of the 20th century is likely to be natural variability.

In the final section of this report we provide further analysis of results from coupled climate-surge model simulations in order to make inference about the future storm surge climate of the Irish Sea. This is deduced by cascading atmospheric information from a global scale general circulation model (GCM) of climate, through a regional climate model (RCM) that can simulate mesoscale meteorological processes, to regional hydrodynamic surge (or wave) models. This methodology has been applied previously to storm surges in the North Sea by Lowe et al. (2001), Woth et al. (2005), and Debernard and Roed (2008). All previous studies have found that centennial changes to extreme water levels are only marginally significant (i.e. are of the same order as the natural climatological variability). The latest storm surge climate projections for the UK (Lowe et al., 2009; Howard et al., 2010) address several deficiencies of previous studies and adopt a perturbed parameter approach, where instead of taking a single estimate for key atmospheric parameters the uncertainty in those parameters is treated explicitly. In our analysis we use the spread from that 11 ensemble member over the full period 1951-2100.

3. Fine resolution numerical modelling in the Irish Sea

3.1 Impact of hydrodynamic model resolution

Storm surges in the Irish and Celtic Seas are caused by the passage of mid-latitude depressions generated by horizontal pressure gradients. The surges experienced on the west coast of Britain are determined by the magnitude and propagation path of these large scale weather systems and are generated by pressure gradients acting on the sea surface and the strong wind stresses associated with them (Pugh, 2004). This is a large scale process as the depressions are often several hundred kilometres in diameter. However, the magnitude and distribution of surges at the coast are often highly dependent on much smaller scale processes. In shallow water regions such as the Eastern Irish Sea the interaction between the tide and surge becomes important and therefore the surge magnitude is partly determined by the wavelength and amplitude of the major tidal constituents (Amin, 1982; Horsburgh and Wilson, 2007). The spatial variability of the wind stress input also becomes important in determining the surge distribution in shallow water regions (Jones and Davies, 1998). At even smaller scales the tide and surge components interact with rapidly changing bathymetry which controls the depth and therefore the influence of the wind stress input and the bed friction on the water column and the propagation speed of shallow water waves. Therefore, to simulate storm surges accurately in shallow water regions a hydrodynamic model needs to have high enough resolution to resolve the processes that determine the surge magnitude and distribution. Since major flooding caused by the 1953 storm surge event in the North Sea and subsequent flooding events on the west coast of Britain in 1976 and 1977 modelling efforts have focussed on the accurate prediction of storm surges in shallow water regions which are at risk from major flooding (Flather and Williams, 2004). Early, storm surge models were based on finite difference models (e.g. Flather, 1976c). These were of a particularly coarse resolution due to limitation in computer power and often failed to fully simulate the magnitude of surge events in shallow water (Flather, 1984). Increases in computational capacity allowed finer grids to be developed and to improve simulated surges in shallow water areas fine resolution grids were nested within shelf wide models so that surge development in shallow water areas could be determined whilst capturing surge generated in far-field regions within the wide area model (e.g. Proctor and Flather, 1989). However, nesting can be problematic at the boundary of the fine grid model where the input of the tide and surge from the coarse area model has to be determined (Jones and Davies, 2004). The development of finite element models with unstructured grids meant that the problems associated with coarse resolution in shallow water and nesting could be overcome due to their ability to have a graded meshing permitting very fine resolution in shallow water areas where the tide and surge show greatest spatial variability and relatively coarse resolution in deep water maintaining a computationally efficient solution (Jones and Davies, 2008).

This report examines whether there is a systematic improvement in the simulated surge in the Eastern Irish Sea using a finite element model (TELEMAC) in comparison to the current operational model (CS3X) which utilises a finite difference method on a regular grid of a much coarser resolution in shallow water. Initially it is determined whether accuracy of surge simulations can be improved by grid enhancement only. However, models eventually become limited by the resolution and accuracy of the input data. Therefore, the influence of increasing the resolution of the bathymetry and the wind stress input on the simulated surge is also examined.

3.1.1 Comparison of TELEMAC with CS3X

TELEMAC (G3AX) was used to carry out a 'season' simulation from 1st October 2007 until March 13th 2008. This period encompasses a typical storm surge 'season', a period when low-pressure systems from the Atlantic propagate across the region more readily causing surge events. No significant surge events were recorded after the 13th of March, so the hindcast simulation was terminated here. The aim of the study was to investigate whether there is any systematic benefit in using a finite element model with enhanced resolution in shallow water areas when forced with a continuous meteorological data set. This could be achieved by comparing the results of the simulation to tide gauge observations and to those of the finite difference operational model (CS3X). The meteorological input into the model was the same in both models and came from the Met Office's NAE weather model. As the meteorological input was the same in both models before spatial interpolation and the surge generated beyond the boundaries of the TELEMAC model was input from the wider area operational model any improvement in simulating the surge could be directly attributed to enhancement in grid resolution.

Monthly residual surge elevations from observations (recorded sea-level minus the harmonically predicted tidal elevations) were compared to residual elevations (predicted sea-level including meteorological forcing minus the predicted tide) predicted by the operational model (CS3X) and Telemac (G3AX) at Workington, Heysham, Liverpool, Llandudno and Port Erin in the Eastern Irish Sea. Monthly time-series of observed and predicted residual elevations were created at each port location (see Appendix 1). The correlation coefficient, mean error, root mean square error (RMSE) and maximum error between the simulated residual elevations and the observed residual elevations for each port location were calculated for each month during the hindcast.

At Workington (Table 1) CS3X and G3AX have similar monthly correlation coefficients with respect to the observed residual elevations with both models having a high correlation coefficient of 0.95 for the full hindcast period (October 2007 to March 13th 2008). There is also no significant difference between the monthly mean errors for both models with both models having a mean error of 0.07m for the full hindcast period. Therefore, both models tend to slightly over predict the observed residual on average. The monthly RMS errors are also similar for both models with an RMS error of 0.11m in CS3X and 0.12m in G3AX for the hind cast period. CS3X has a lower maximum error in October, November, December and March where the maximum error is due to an over prediction by both models except in March where the maximum error in G3AX was caused by an under prediction of the observed residual. G3AX has a lower maximum error in January and February where CS3X over predicted the residual on both occasions of maximum error and G3AX over predicted the residual in January and under predicted the residual in February.

At Heysham (Table 2) CS3X and G3AX have similar monthly correlation coefficients with respect to the observed residual elevations with CS3X having an insignificantly higher correlation coefficient of 0.94 compared to 0.93 in G3AX for the hindcast period. There is also no significant difference between the monthly mean errors with both models slightly over predicting the observed surge on average by 0.01m in CS3X and 0.02m in G3AX. The monthly RMS errors are also similar for both models with an RMS error of 0.10m for both models during the hind cast period. CS3X has a lower maximum error in January and February where the maximum error is due to an over prediction by CS3X and an under prediction by G3AX. G3AX has a lower maximum error in October, December and March where CS3X over predicted the residual on all occasions of maximum error and G3AX over predicted the residual in October and December and under predicted the residual in March. The maximum error in November was the same in both models.

At Liverpool (Table 3) CS3X and G3AX have similar monthly correlation coefficients with respect to the observed residual elevations with CS3X having an insignificantly higher correlation coefficient of 0.93 compared to 0.92 in G3AX for the hindcast period. There is also no significant difference between the monthly mean errors with both models slightly under predicting the observed surge on average by 0.09m in CS3X and 0.08m in G3AX. The monthly RMS errors are also similar for both models with an RMS error of 0.14m for both models during the hindcast period. CS3X has a lower maximum error during every month in hindcast period where both models under predict the observed residual during the time of maximum error except for October and November where G3AX over predicted the residual during the time of maximum error.

At Llandudno (Table 4) CS3X and G3AX have similar monthly correlation coefficients with respect to the observed residual elevations with both models having a correlation coefficient with respect to observations of 0.92 for the hindcast period. There is also no significant difference between the monthly mean errors with both models slightly over predicting the observed surge on average by 0.01m in CS3X and 0.02m in G3AX. The monthly RMS errors are also similar for both models with an RMS error of 0.09m for both models during the hindcast period. CS3X has a lower maximum error during October, November and December where both models over predicted the observed residual during the time of maximum error. G3AX has a lower maximum error during January and March where the residual was over predicted in both models. The maximum error was the same magnitude in both models in February but was due to an over prediction in CS3X and an under prediction in G3AX.

At Port Erin (Table 5) CS3X and G3AX have similar monthly correlation coefficients with respect to the observed residual elevations with both models having a correlation coefficient of 0.95 for the hindcast period. There is also no significant difference between the monthly mean errors with both models slightly under predicting the observed surge on average by 0.02m in CS3X and 0.01m in G3AX. The monthly RMS errors are also similar for both models with an RMS error of 0.07m for both models during the hindcast period. CS3X has a lower maximum error during October, November, February and March with CS3X under predicting the observed residual in October, February and March and over predicting the observed residual during the other months. G3AX has a lower maximum error during December and January with G3AX over predicting the observed residual during October and

November and under predicting the observed residual during the other months during the time of maximum error.

Whilst analysing all the residual elevations for the hindcast period gives a general indication of model performance a significant part of the error or lack of error may be attributed to small meteorological driven sea level changes. These events will have little consequence for coastal flooding even if they were to coincide with the time of local high water. Therefore, to analyse performance from an operational point of view the residuals higher than the 95th percentile elevation observed at each port location for the hindcast period were examined (Table 6).

At Workington the top five percent of observed residuals for the hindcast period were greater than or equal to 0.51m. The correlation with respect to observations is lower for residual elevations greater than the observed 95th percentile residual simulated by both models than if all residual elevations are taken into account with a correlation coefficient of 0.82 in CS3X and 0.81 in G3AX. Based on the mean error it is shown that CS3X tends to over predict the top five percent of residual elevations by 0.07m on average whereas G3AX slightly under predicts top five percent of residual elevations by 0.01m on average. Both models have a similar RMS error, being 0.12m for CS3X and 0.11m for G3AX. The magnitude of the maximum error in CS3X is higher than that in G3AX and can be attributed by an over prediction of the observed residual by 43cm whereas G3AX under predicted the observed residual by 33cm during the time of maximum error.

At Heysham the top five percent of observed residuals for the hindcast period were greater than or equal to 0.56m. The correlation with respect to observations is lower for residual elevations greater than the observed 95th percentile residual simulated by both models than if all residual elevations are taken into account with a correlation coefficient of 0.71 in CS3X and 0.77 in G3AX. Based on the mean error it is shown that CS3X tends to slightly over predict the top five percent of residual elevations by 0.02m on average whereas G3AX slightly under predicts top five percent of residual elevations by 0.07m on average. Both models have a similar RMS error, being 0.16m for CS3X and 0.15m for G3AX. The magnitude of the maximum error in CS3X is lower than that in G3AX and can be attributed to an over prediction of the observed residual by 47cm where as G3AX under predicted the observed residual by 53cm during the time of maximum error.

At Liverpool the top five percent of observed residuals for the hindcast period were greater than or equal to 0.63m. The correlation with respect to observations is lower for residual elevations greater than the observed 95th percentile residual simulated by both models than if all residual elevations are taken into account with a correlation coefficient of 0.85 in CS3X and 0.80 in G3AX. Based on the mean error it is shown that both models tend to under predict the top five percent of observed residuals by 17cm in CS3X and 24cm in G3AX on average. Both models have a relatively high RMS error being 0.22m for CS3X and 0.28m for G3AX. The magnitude of the maximum error is significant in both models and is attributed to an under prediction of the observed residual by 69cm in CS3X and 74cm in G3AX.

At Llandudno the top five percent of observed residuals for the hindcast period were greater than or equal to 0.43m. The correlation with respect to observations is lower for residual elevations greater than the observed 95th percentile residual simulated by both models than if all residual elevations are taken into account with a correlation coefficient of 0.85 in CS3X and 0.86 in G3AX. Based on the mean error it is shown that CS3X tends to slightly over predict the top five percent of residual elevations by 0.02m on average whereas G3AX slightly under predicts top five percent of residual elevations by 0.05m on average. Both models have a similar RMS error being 0.09m for CS3X and 0.10m for G3AX. The magnitude of the maximum error in CS3X is slightly higher than that in G3AX and can be attributed by an over prediction of the observed residual by 26cm where as G3AX under predicted the observed residual by 24cm during the time of maximum error.

At Port Erin the top five percent of observed residuals for the hindcast period were greater than or equal to 0.47m. The correlation with respect to observations is lower for residual elevations greater than the observed 95th percentile residual simulated by both models than if all residual elevations are taken into account with a correlation coefficient of 0.84 in CS3X and 0.83 in G3AX. Based on the mean error it is shown that both models tend to under predict the top five percent of observed residuals by 2cm in CS3X and 8cm in G3AX on average. CS3X has a relatively low RMS error being 0.07m for the period compared to a slightly higher RMS error of 0.11m in G3AX. The maximum error can be attributed to an under prediction of the observed residual in both models by 22cm in CS3X and 33cm in G3AX.

To investigate model performance during the largest residual surge elevations during the hindcast period the top five observed residual elevations at each port location and the corresponding residual elevations simulated by CS3X and G3AX were chosen to represent seasonal extremes. Whereas, the maximum error in the analysis of all residuals and those exceeding the 95th percentile can be often be attributed to phase error, in the analysis of the top five residuals insignificant phase error is ignored to examine model performance in simulating the magnitude of the surge event. For time-series of the top five residual surge elevations at each port location see Appendix 2.

Model performance in both models at simulating the top five surge events at Workington is good with a maximum error of 13cm due to an over prediction in CS3X (Table 7). Both models accurately predicted the largest seasonal event of 1.24m on 31st January where the magnitude of the error was just 3cm in both models. The magnitude of the maximum error is generally less than 10cm in both models. CS3X over predicted the observed residual elevation by between 3cm and 13cm during four of the events and under predicted the fifth event by 5cm. G3AX under predicted the observed residual elevation by between 3cm and 8cm during four of the events and over predicted the fifth event by 2cm.

During the largest seasonal event at Heysham of 1.61m on 12th March both models under predicted the observed residual by 22cm in CS3X and 16cm in G3AX (Table 8). Model performance is good during the other events with the magnitude of the error being approximately 10cm or less with the exception of a residual elevation of 0.98m that occurred on 7th January. Although CS3X under predicted the observed residual by only 1cm during this event, model performance in G3AX was less accurate under predicting the observed residual by 33cm.

Model performance is less accurate during the top five observed residual elevations at Liverpool where both models significantly under predicted the largest seasonal event of 1.93m on the 12th March by 46cm in CS3X and 62cm in G3AX (Table 9). Both models under predict the observed residual elevation during all the top five observed residual by between 17cm and 46cm in CS3X and 13cm and 62cm in G3AX.

Model performance is reasonable at Llandudno where both models over predicted the largest seasonal residual elevation of 1.01m on 31st January by 17cm in CS3X and 13cm in G3AX (Table 10). During the other four events CS3X over predicted the observed residual by 9cm and 23cm on two occasions with no error occurring on one occasion whereas G3AX over predicted the observed residual by 3cm on two occasions and 6cm on another occasion. Both models under predicted the fifth largest event by 6cm in CS3X and 16cm in G3AX.

Model performance at simulating the largest seasonal events at Port Erin is good with CS3X slightly over predicting the largest seasonal event of 0.87m on 10th March by 1cm and G3AX slightly under predicting this event by 2cm (Table 11). CS3X under predicted the observed residual by 7cm and 5cm during two events and over predicted the observed residual by 13cm and 3cm during the final two events. G3AX under predicted the observed residual by 9cm, 11cm and 16cm during three events and over predicted the observed residual by 5cm during the fifth event.

Examining model performance based on the residual elevations gives a good indication of how accurately the meteorological forcing in the model alters the tide in the model in both magnitude and phase. However, it has been shown that due to tide-surge interaction the largest residual elevations will not coincide with high water and are more likely to occur four hours before high water due to phase shift of the tide. It has also been shown that during the largest spring tides the largest residuals are even less likely to occur near to the time of high water (Horsburgh and Wilson, 2007). Therefore, from a coastal flooding point-of-view looking at the peak residual might not be very useful as even a peak residual as high as 2m might not cause coastal flooding if it occurs at mid-tide at a location with a tidal range of 5m. The skew surge is a measure of the extra sea level elevation on top of the height of the predicted high tide during a surge event and is calculated by taking the difference between the maximum water level and the height of the predicted astronomical high water for the time. As a diagnostic it is more beneficial for statistical purposes (Howard et al., 2009) and is utilised in the Dutch operational system (e.g. de Vries at al., 1995) as it is more practical for flood warning than the peak residual which is independent of the tide.

The observed skew surges during every tidal cycle during the hindcast period were calculated and compared to corresponding skew surges simulated by CS3X and G3AX (Table 12).

At Workington both models have a relatively high correlation coefficient of 0.93 between the observed and simulated skew surges for the hindcast period. Mean error shows that both models tend to slightly overestimate the observed skew surge by 4cm on average. Both models have a relatively low RMS error of 0.1m with CS3X having a maximum error of 43cm and G3AX having a maximum error of 34cm.

At Heysham both models have a relatively high correlation coefficient of 0.94 between the observed and simulated skew surges for the hindcast period. Mean error shows that both models tend to slightly underestimate the observed skew surge by 4cm in CS3X and 1cm in G3AX on average. Both models have a relatively low RMS error of 0.09m with CS3X having a maximum error of 24cm and G3AX having a maximum error of 27cm where both models underestimated the observed skew surge during the time of peak error.

At Liverpool both models have a relatively high correlation coefficient between the observed and simulated skew surges for the hindcast period being 0.92 in CS3X and 0.91 in G3AX. Mean error shows that both models tend to underestimate the observed skew surge by 12cm in CS3X and 11cm in G3AX on average. Both models have a slightly higher RMS error of 0.15m at Liverpool compared to the other port locations. CS3X has a maximum error of 40cm and G3AX has a maximum error of 48cm where both models underestimated the observed skew surge during the time of peak error.

At Llandudno both models have relatively high correlation coefficients of 0.90 between the observed and simulated skew surges for the hindcast period. Mean errors are 0.00 in both models showing that there is no bias in over- or underestimating the observed skew surge. Both models have relatively low RMS errors of 0.10m in CS3X and 0.09m in G3AX with a maximum error of 31cm in CS3X and 37cm in G3AX where both models over predicted the observed skew surge during the time of maximum error.

At Port Erin both models have relatively high correlation coefficients of 0.94 in CS3X and 0.93 in G3AX between the observed and simulated skew surges for the hindcast period. Mean error shows that both models tend to slightly underestimate the observed skew surge by 3cm in CS3X and 2cm in G3AX on average. Both models have relatively low RMS errors of 0.09m in CS3X and 0.08m in G3AX with a maximum error of 24cm in CS3X where the model over predicted the observed skew surge and 28cm in G3AX where the model under predicted the observed skew surge during the time of maximum error.

As before in the analysis of the residuals model performance based on simulating observed skew surges great than or equal to the 95th percentile skew surge elevation at each port location was investigated (Table 13).

At Workington the top five percent of observed skew surges were greater than or equal to 0.45m for the hindcast period. G3AX has a higher correlation coefficient of 0.92 than CS3X where the correlation coefficient is 0.86 with respect to observations. The mean error shows that CS3X over predicts the top five percent of observed skew surges by 9cm on average whereas G3AX slightly under predicts the top five percent of observed skew surges by 1cm on average. G3AX has a relatively low RMS error of 0.09m compared to a higher RMS error of 0.14m in CS3X. Both models overestimate the observed skew surge during the time of maximum error by 43cm in CS3X and 24cm in G3AX.

At Heysham the top five percent of observed skew surges were greater than or equal to 0.55m for the hindcast period. G3AX has a higher correlation coefficient of 0.91 than CS3X where the correlation coefficient is 0.80 with respect to observations. The mean error shows that CS3X under predicts the top five percent of observed skew surges by 8cm on average whereas G3AX shows no bias in over- or under predicting the observed skew surges with an error of 0.0m on average. G3AX has a relatively low RMS error of 0.08m compared to a higher RMS error of 0.13m in CS3X. Both models underestimate the observed skew surge during the time of maximum error by 23cm in CS3X and 20cm in G3AX.

At Liverpool the top five percent of observed skew surges were greater than or equal to 0.60m during the hindcast period. Both models have a relatively low correlation coefficient with respect to observations being 0.67 in CS3X and 0.68 in G3AX. The mean error shows that both models tend to under predict the observed skew surge by 17cm in CS3X and 23cm in G3AX on average. Both models have relatively high RMS errors; CS3X having an RMS error or 0.21m and G3AX having an RMS error of 0.26m. Both models underestimate the observed skew surge during the time of maximum error by 36cm in CS3X and 48cm in G3AX.

At Llandudno the top five percent of observed skew surges were greater than or equal to 0.40m for the hindcast period. G3AX has a significantly higher correlation coefficient of 0.81 than CS3X where the correlation coefficient is 0.57 with respect to observations. The mean error shows that CS3X shows no bias in over- or under predicting the observed skew surge with a mean error of 0.0m whereas G3AX tends to under predict the observed skew surge by 4cm on average. Both models have relatively low RMS errors of 0.10m in CS3X and 0.09m in G3AX and underestimate the observed skew surge during the time of maximum error by 23cm in CS3X and 18cm in G3AX.

At Port Erin the top five percent of observed skew surges were greater than or equal to 0.46m for the hindcast period. G3AX has a correlation coefficient of 0.86 compared to 0.84 in

CS3X with respect to observations. The mean error shows that both models tend to slightly under predict the observed skew surge on average by 1cm in CS3X and 7cm in G3AX. Both models have a relatively low RMS error of 0.07m in CS3X and 0.09m in G3AX and underestimate the observed skew surge during the time of maximum error by 20cm.

To investigate model performance during the largest skew surge elevations during the hindcast period the top five observed skew surge elevations at each port location and the corresponding skew surge elevations simulated by CS3X and G3AX were chosen to represent seasonal extremes.

Model performance is generally good at Workington where CS3X over predicted the highest observed skew surge of 1.17m on 31st January by 1cm and G3AX under predicted this event by 4cm (Table 14). CS3X over predicted the observed skew surge by 13cm and 4cm during two events and under predicted the observed skew surge by 10cm during another event. G3AX over predicted the observed skew surge by 4cm during one event and under predicted the observed skew surge by 8cm and 9cm during two other events. During the fifth highest skew surge event the magnitude of the error was relatively higher in both models where CS3X over predicted this event by 43cm and G3AX over predicted the event by 24cm.

At Heysham G3AX accurately predicted the highest observed skew surge event of 1.12m on 12th March over predicting the observed skew surge by 1cm whereas CS3X under predicted this event by 23cm (Table 15). CS3X over predicted one event 10cm and under predicted the remaining three events by 16cm, 4cm and 2cm. G3AX over predicted all the top five observed skew surge events except from one occasion where the error was 0cm. The magnitude of the error was 5cm, 10cm, 7cm for the remaining events.

At Liverpool G3AX accurately predicted the highest observed skew surge event of 1.09m on 29th February under predicting the observed skew surge by 12cm whereas CS3X under predicted this event by 37cm (Table 16). The error was relatively high in the remaining events where both models under predicted the observed skew surge apart from one event where both models under predicted the observed skew surge by 8cm. During the other events CS3X under predicted the observed skew surge by 27cm, 30cm and 22cm whereas G3AX under predicted the observed skew surge by 33cm, 48cm and 39cm.

At Llandudno G3AX accurately predicted the highest observed skew surge event of 0.83m on 29th February under predicting the observed skew surge by 8cm whereas CS3X under predicted this event by 23cm (Table 17). Model performance was reasonably good in both models during the other four events where CS3X had an error of 0.0m on one occasion, under predicted the observed skew surge by 7cm and 9cm on two occasions and over predicted the observed skew surge by 6cm on the remaining occasion. G3AX under predicted the observed skew surge by 3cm, 9cm and 15cm on three occasions and over predicted the observed skew surge by 10cm on the remaining occasion.

At Port Erin both models under predicted the highest observed seasonal skew surge of 0.86m on 29th February by 20cm in CS3X and 18cm in G3AX (Table 18). Model performance was relatively good in both models during the remaining event with CS3X under predicting the observed skew surge by 3cm and 4cm on two occasions and over predicting the observed skew surge by 4cm and 5cm on the remaining two occasions. G3AX under predicted the observed skew surge by 5cm on one occasion and 11cm on two occasions and over predicted the observed skew surge by 3cm during the remaining occasion.

3.1.2 Discussion

Based on the RMS error between all simulated residuals and the tide gauge observations at Workington, Heysham, Liverpool, Llandudno and Port Erin TELEMAC (G3AX) performs as well as the operational model (CS3X) in the Eastern Irish Sea. Both models are accurate at simulating the residuals at Workington, Heysham and Llandudno where correlations coefficients are greater than 0.9 and RMS errors are approximately 10cm. Therefore, simulation of the residuals at these locations is not simply limited by the resolution of the model grid and improvement may be limited by other factors such as the resolution of the bathymetry and the wind stress. The two models also perform well at Port Erin. The deeper water surrounding this port location mean that the surge generation is less dependent on the local wind stress and improved accuracy may be limited by the accuracy of the external surge input and the resolution of the wind stress input that generates surge in areas 'far-field' to this region within the model domain before propagating into the Eastern Irish Sea. Model performance in both models is less accurate at Liverpool. Therefore, the resolution of the model grid is not the main limiting factor in this region and may be due to some unresolved dynamics in the Mersey Estuary region. Tide-surge interaction and accurate representation of the Mersey estuary becomes more important here as the tide interacts with the surge non-linearly through bed friction and the bathymetry. Therefore, the resolution of the bathymetry, representation of the tide in the Mersey and the local wind stress may be limiting factors in accurate surge prediction at Liverpool.

Model performance in simulating the top five percent of observed residual elevations is similar in both models where both models have slightly lower correlation coefficients of approximately 0.80 and higher RMS errors if only the largest five percent of residual surge elevations are taken into account. The main difference in the simulated residuals at some port locations is the bias in the mean error. For example, at Workington CS3X tends to over predict the magnitude of the observed residual whereas G3AX tends to slightly under predict the magnitude on average. Again, model performance is worse at Liverpool in both models with significantly higher RMS errors for the top five percent of residuals and mean errors and maximum errors showing that both models tend to significantly under predict the magnitude of the observed surge. It is evident that both models fail to capture the true extent of the observed residual surge elevations which could be due to the previously discussed limiting factors in this region.

Model performance is good in both models at simulating the seasonal extreme residual elevations represented by the top five observed residual elevations at Workington, Heysham, Llandudno and Port Erin. Again this suggests that at these locations the resolution of the model grid is not the main limiting factor in improving the surge prediction and can be attributed to other factors such as the resolution of the bathymetry and the wind stress input. As is evident in the analysis of the top five percent of residuals both models significantly under predict the magnitude of the observed surge at Liverpool irrespective of any phase difference in the simulated surge peak. Both models significantly under predict the magnitude of the top five residual surge elevations observed at Liverpool in all instances and it is therefore evident that hydrodynamics in the Mersey region are misrepresented in both models.

Model performance in simulating the observed skew surge elevations is good in both models with correlation coefficients with respect to observations greater than 0.9 and RMS errors of 10cm or less at all the port locations except Liverpool. Model performance is slightly worse in both models at Liverpool which is evident in a higher RMS error of 0.15m. It is evident that G3AX performs better than CS3X in simulating the top five percent of observed skew surge elevations with higher correlation coefficients with respect to observations at all port locations and lower RMS errors at Workington, Heysham and Llandudno. Therefore, enhanced grid resolution may allow more accurate prediction of the surge transport propagating into this area which is not evident in the analysis of the residuals where phase shift of the tide may dominated the residual signal. However, improvement is less apparent in simulating the top five observed skew surge elevations where G3AX performs better at Workington and Heysham but there is no significant improvement at the other port locations. Therefore, during the largest events accurate transport of the surge is less dependent on the grid resolution and may become more dependent on the resolution of the local bathymetry and resolution of the wind stress generating the surge.

It is evident that the TELEMAC model's performance is comparable to that of the model used operationally for surge prediction and to provide flood warnings. It was found that based on RMS errors and the prediction of seasonal extremes, TELEMAC performed as well as the operational model using a finite element approach without a need for nested higher resolution models in shallow water regions due to its ability to utilise a graded mesh. However, there is no evidence in this study that increasing the resolution in shallow water regions leads to more accurate surge prediction. It is apparent that increasing the model grid resolution eventually becomes limited by the resolution of the meteorological forcing and bathymetry and that it is essential that the hydrodynamics are accurately simulated in highly non-linear regions such as the Mersey estuary for accurate surge prediction. Other unresolved physics such as wave-current interaction and variable bed roughness may also become important in determining the magnitude and distribution of the surge in shallow water as the grid is refined.

3.2 Increasing the resolution of the forcing meteorology (using Met Office UK4 model)

TELEMAC, based on the G7 grid (high resolution bathymetry in the Mersey region), was used to carry out a hintcast of a typical storm surge season from October 2007 to March 13th 2008 using wind and pressure data from the Met Office UK4 model. The meteorological data is calculated on a grid with an approximate resolution of 4km, therefore providing a threefold increase in the resolution of the forcing data in NAE (~12km). The aim of the study was to investigate whether surge prediction in the Eastern Irish Sea is limited by the resolution of the forcing meteorology on a high resolution grid (G7) by examining any systematic improvement in the simulated surge compared to observations and surge simulated using NAE.

The mean error, correlation coefficient and root mean square error between all observed residual surge elevations and the corresponding residual elevations simulated by TELEMAC using meteorological input from NAE and UK4 was calculated (Table 19). For most port locations both meteorological inputs produce a mean error between the observed and simulated residuals close to zero indicating that there is no significant positive or negative bias in the simulated residuals compared to observations. However, at Liverpool there is a negative bias where the observed residual tends to be underestimated. Residuals simulated using input from NAE tend to have a slightly higher correlation compared to observations than those simulated using input from UK4 with an average correlation across all port locations of 0.92 and 0.91 respectively. The RMS error between residuals simulated using input from UK4 and observations tends to be slightly higher than for residuals simulated using input from NAE with an average across all port locations of 0.12m and 0.11m respectively. The most significant root mean square errors for both meteorological inputs occur at Liverpool using NAE giving an RMS error of 0.16m and UK4 giving an RMS error of 0.15m.

The mean error, correlation coefficient and RMS error between observed residual surge elevations greater than the 95th percentile residual surge elevation at each port location, separated by a least 12 hours, and the corresponding residual elevation simulated by TELEMAC using meteorological input from NAE and UK4 was calculated (Table 20). It is observed that at most port locations the two meteorological inputs give a mean error close to zero so that there is no significant positive of negative bias in the difference in magnitude between the observed and simulated residuals. However, at Liverpool there is a significant negative bias where the observed residual surge tends to be underestimated. Compared to observations, simulated residual elevations from both meteorological inputs generally have correlation coefficients greater than 0.8 at most port locations. Residuals simulated using input from NAE tend to have a slightly higher correlation compared to observations than those simulated using input from UK4 with an average correlation across all Eastern Irish Sea port locations of 0.82 and 0.88 respectively. The RMS error between simulated residuals using input from both meteorological data sets and observations is most significant at Liverpool where both meteorological give a high RMS error of 0.28. The RMS error between residuals simulated using input from UK4 and observations tends to be slightly higher than for residuals simulated using input from NAE with an average across all port locations of 0.15m and 0.13m respectively.

The mean error, correlation coefficient and RMS error between observed skew surges greater than the 95th percentile skew surge height at each port location and the corresponding skew surges simulated by TELEMAC using input from the NAE and UK4 meteorological data sets was calculated (Table 21). At most port locations the mean error is not significantly different from zero. However, at Liverpool there is a significant negative mean error indicating that the model tends to underestimate the top five percent of skew surges at these locations. The correlation coefficients between the observed and simulated skew surge tends to be higher using input from NAE than from UK4, with average correlation coefficients across all port locations of 0.79 and 0.66 respectively. The RMS errors between observed skew surges and skew surges simulated using input from NAE tend to be lower than those simulated using input from UK4 with average RMS errors across all port locations of 0.12m and 0.22m respectively. The most significant root mean square error for both meteorological inputs occurs at Liverpool.

To examine model performance using the two meteorological data sets during the largest seasonal surge events the difference between the simulated surge residuals and observed residuals corresponding to the five highest observed residual elevations at each port location were calculated (Table 22). Forcing the model with UK4 improved model performance during two events at Workington and three events at Heysham. Increases in error were observed between 5cm and 20cm during the other three events at Workington and an increase in error of 12cm and 6cm during the other two events at Heysham. It can be seen that forcing the model with UK4 improved model performance on four occasions at Liverpool, whilst model performance remained the same on the final occasion. Improvement in model performance is more significant at Liverpool than at any other port location with the error being reduced by up to 47cm. At Llandudno forcing the model with UK4 reduced the error on two occasions and increased the error during the other three events. However, the increase in error is generally less than 10cm and represents less than ten percent of total observed residual magnitude.

Overall, forcing the model with the UK4 meteorological data does not significantly reduce the error with error reductions occurring on just over 50% of all the surge events and increasing the error during approximately 44% of all the surge events. Forcing the model with UK4 reduces the error by an average of 11cm during 51% of the events but increases the error by approximately 9cm during 44% of the events. However, improvement is not evenly distributed over all the port locations with ports such as Heysham and Liverpool showing a reduction in error in most of the top five surge residuals and ports such as Workington, Port Erin and Llandudno where the error increased in three out of the top five events. As mentioned previously increases and decreases in the error are generally not very significant and are in the order of 10cm. However, at Liverpool the error is reduced by up to 47cm during the largest observed event and by 23cm on average over the top five observed residual surge events. Therefore, it would appear that input of the higher resolution meteorological data set improves the simulated surge at Liverpool indicating that resolution of the meteorological data is the limiting factor in simulating surge events at this location as opposed to bathymetry.

To investigate the difference in the meteorology that causes this reduction in error at Liverpool four of the top five surge events where input of UK4 reduced the error were examined in more detail. Based on the simulated surge from the period October 2007 to March 2008 it is found that the wind stress accounts for 70% of the simulated surge elevations on average in the Eastern Irish Sea. Therefore, differences in the wind stress during the largest surges observed at Liverpool will be investigated to account for any error reduction when meteorological input from UK4 is included in a simulation.

Figure 1 shows a time series of an observed peak residual of 1.81m that occurred at Liverpool on the 7th January 2008 and the simulated residuals using meteorological input from NAE and UK4. It can be seen that simulations with both meteorological inputs underestimate the magnitude of the observed residual but the error is reduced using forcing from UK4. Although, the timing of the peak residual using UK4 precedes that of the observed residual the error is reduced by 29cm compared to using forcing from NAE. However, the error remains significant with the observed residual under predicted by 42cm. Figure 5 shows the difference in wind stress in the Eastern Irish Sea input from UK4 and NAE during the time of peak wind stress at Liverpool in each data set during this event. It can be seen in the region close to Liverpool at the entrance to the Mersey there is a difference in wind stress of up to $1.8Nm^{-2}$.

Figure 2 is a time series of an observed peak residual of 1.29m that occurred at Liverpool on the 8th January 2008 and the simulated residuals using meteorological input from NAE and UK4. It can be seen the peak residual spike is not simulated using the NAE input, whereas a significant amount of the magnitude is simulated using input from the UK4 data set. However, the simulated peak is much broader and the model fails to capture the true time evolution of the observed residual spike. Meteorological input from UK4 reduces the error by 28cm from 56cm to 28cm. Figure 6 shows the difference in wind stress in the Eastern Irish Sea input from UK4 and NAE during the time of peak wind stress at Liverpool in each data set during this event. It is observed that off the Lancashire coast and in the proximity of Liverpool at the entrance to the Mersey Estuary the wind stresses input from UK4 at the time of peak wind stress at Liverpool are up to $0.8Nm^{-2}$ higher than those input from NAE.

Figure 3 is a time series of an observed peak residual of 1.68m that occurred at Liverpool on the 31st January 2008 and the simulated residuals using meteorological input from NAE and UK4. It is observed that input from NAE does not simulate the time evolution of the peak residual elevation and the magnitude of the peak elevation is underestimated by 39cm. Input from UK4 improves the simulated time evolution of the observed residual elevation with a double spike in the hourly model output that it also observed in the 15-minute tide gauge output. The magnitude of the peak residual is simulated more accurately using input from UK4 reducing the error to 26cm. Figure 7 shows the difference in wind stress in the Eastern Irish Sea input from UK4 and NAE during the time of peak wind stress at Liverpool in each data set during this event. As in previous examples it can be seen that wind stresses input from UK4 are over $0.5Nm^{-2}$ higher than those input from NAE.

Figure 4 is a time series of an observed peak residual of 1.93m that occurred at Liverpool on the 12th March 2008 and the simulated residuals using meteorological input from NAE and UK4. This was the highest residual observed at any port location on the west coast of Britain during the period October 2007 to March 2008. It can be seen that the magnitude of the peak residual using input from NAE is significantly underestimated by 63cm. Input from UK4 improved model performance, significantly decreasing the error in the simulated residual magnitude to 16cm. The difference in the peak wind stresses input from the two meteorological data sets (Figure 8) show that local wind stresses at the entrance to the Mersey in NAE were up $2Nm^{-2}$ lower than those input from UK4 which would have significant impact on the magnitude of the local surge generation.

Forcing the model with a higher resolution wind stress using G7 which includes a detailed description of the Mersey has been shown to significantly decrease the error in the top five residual surge elevation at Liverpool compared to observations. To investigate whether this is due to a combination of high resolution wind forcing and high resolution bathymetry in the Mersey region included in G7 or only due to the meteorology a simulation of a significant surge event that occurred on the 12th March 2008 was carried out forcing the model G3AX, with no detailed description of the Mersey, with the higher resolution meteorological data from UK4. Figure 9 shows that there is no significant difference between the predicted residuals for this significant storm surge event. Therefore, storm surge prediction at Liverpool is not limited by the resolution of the bathymetry within the Mersey Estuary and appears to be mainly dependent on the resolution of the wind stress.

It is known that the largest residuals tend to occur at least four hours before the tidal high water due to phase alteration of the tide causing a tidal advance so that the magnitude of residual elevation has little consequence for coastal flooding (e.g. Horsburgh and Wilson, 2007). The difference between the total water level and the predicted high water (skew surge) is more meaningful in terms of the potential for coastal inundation. To investigate model performance using the two meteorological data sets in simulating the largest seasonal skew surges the difference between the simulated surge residuals and the observed residuals corresponding to the five highest observed skew surges at each port location was calculated (Table 23). At Workington forcing the model with UK4 decreases the error during two events and increasing the error by 11 to 16cm during the other three events. At Port Erin forcing the model with UK4 causes an insignificant decrease in the error between 1 and 6cm during four of the five highest skew surges and increases the error by 17cm during one of the events. At Heysham forcing the model with UK4 increases the error during three events and significantly over estimates the magnitude of the largest observed skew surge during this time period by 75cm. The error is reduced during the other two events by 3 and 8cm. Despite improvement in simulating the largest residuals at Liverpool using UK4, the error in the skew surge prediction is only reduced during two events by 6cm and 12cm. The error is increased during the other three events where the skew surge is significantly over predicted by 65cm and 53 cm and under predicted by 73cm compared to observations. At Llandudno forcing the model with UK4 reduces the error during one event by 4cm but increases the error during the other four events between 9 and 41cm.

3.2.1 Discussion

Comparing the model output to observations at tide gauges it is found that there are no significant differences between the simulated residuals using both meteorological data sets at any of the port locations. Correlation coefficients between all simulated and observed residuals and residuals greater than the 95th percentile residual elevation observed at each port location are slightly higher in general in the model output from the UK4 forced runs. As the UK4 model takes its boundary conditions from the wider area NAE model large scale phase error in depression propagation can lead can be exaggerated in the meteorological input into the surge model from the UK4 model which may cause some of the slightly higher errors in the simulated residuals. The majority of this error may occur during small meteorologically induced sea level changes with no implications for coastal flooding. Therefore, looking at the performance of the model in simulating the top five observed residual elevations at each port location is more indicative to which meteorological input simulates seasonal extremes more accurately. There is no significant difference in error between the top five observed residual and the corresponding simulated residuals using the two meteorological inputs with error reductions occurring on just over 50% of all the surge events and increasing the error during approximately 44% of all the surge events using the UK4 input. The changes in error associated with using the UK4 input are not evenly distributed across all port locations with some port locations showing a general decrease in error and others a general increase so that the input of higher resolution meteorological is not conclusively beneficial. However, at Liverpool it is apparent that the accuracy of the highest simulated residuals is highly dependent on the resolution of the local wind stress. Input of the UK4 meteorological data is beneficial at this location with significant differences in the local wind stress input during the largest surge events and significant reductions in error in the simulated residual. Whilst, it has been found that resolution of the local bathymetry is not a limiting factor, detail of the local wind stress field appears to be the major limiting factor in simulating the residual surge elevations in a 2D depth integrated model in this region. It has been found that increasing the resolution of the bathymetry in the Mersey estuary in combination with increasing the resolution of the wind stress is unnecessary and accuracy at Liverpool is mainly dependent on the wind stress and the associated wind-driven rise in sea level in Liverpool Bay and at the entrance to the Mersey Estuary. However, comparing the top five percent of observed skew surges to the corresponding simulated skew surges, model performance is better using input from NAE based on correlation coefficient and RMS error. Therefore, input of UK4 may be beneficial for improved seasonal extreme residual elevation simulation at Liverpool and at port locations such as Heysham but total water levels at high water are more accurately simulated using input from NAE. At other port locations where surge heights are less dependent on the local wind stress, other factors may be as significant as the wind field resolution such as bathymetry, wave-current interaction and wave set-up.

3.3 Conclusions from the fine resolution modelling study

- The unstructured grid TELEMAC (G3AX) model performs as well as the finite difference operational model (CS3X) using the same meteorological input from the Met Office's NAE model without the need for nested higher resolution models in shallow water regions.
- There is no evidence from this study that simply increasing the resolution of the hydrodynamic model grid in shallow water leads to more accurate surge prediction. The accuracy of storm surge prediction is limited by the resolution of the meteorological input and quality of the bathymetry.
- These factors also limit the accuracy in predicting the highest seasonal skew surges despite improvement in predicting the top five percent of skew surges when the resolution of the model grid is enhanced.
- In some very shallow regions (such as the Mersey) models have to accurately simulate the local hydrodynamics for accurate surge prediction where tide-surge interaction and non-linear dynamics become increasingly important.
- Input of the UK4 (4km wind) meteorological forcing does not systematically improve the simulated skew surges or residuals in the Eastern Irish Sea and its input is not conclusively beneficial.
- Resolution of the wind stress field is a significant limiting factor in the simulation of surge residuals at Liverpool in particular, and input of UK4 significantly improves the simulation of the largest seasonal surge residuals here.

4. Tables and diagrams

Workington									
Month	**Size**	**Corr (CS3X)**	**Corr (G3AX)**	**Mean Err. (CS3X)**	**Mean Err. (G3AX)**	**RMSE (CS3X)**	**RMSE (G3AX)**	**Max Err. (CS3X)**	**Max Err. (G3AX)**
October	744	0.86	0.84	0.05	0.08	0.08	0.10	0.25	0.28
November	720	0.92	0.92	0.13	0.14	0.15	0.16	0.32	0.40
December	744	0.97	0.97	0.11	0.11	0.13	0.13	0.36	0.40
January	744	0.93	0.93	0.06	0.04	0.12	0.10	0.50	0.27
February	696	0.97	0.97	0.00	0.01	0.08	0.07	0.31	-0.27
March (1st - 13th)	312	0.97	0.97	0.02	0.01	0.09	0.09	0.32	-0.33
1st October – 13th March	3960	0.95	0.95	0.07	0.07	0.11	0.12	0.50	0.40

Table 1. Correlation coefficient, mean error, RMS error and maximum error between monthly observed residual elevations and residual elevations simulated by CS3X and G3AX at Workington

Heysham									
Month	**Size**	**Corr (CS3X)**	**Corr (G3AX)**	**Mean Err. (CS3X)**	**Mean Err. (G3AX)**	**RMSE (CS3X)**	**RMSE (G3AX)**	**Max Err. (CS3X)**	**Max Err. (G3AX)**
October	744	0.80	0.78	-0.01	0.02	0.08	0.08	0.37	0.35
November	720	0.91	0.89	0.04	0.07	0.09	0.11	0.37	0.37
December	744	0.95	0.95	0.05	0.05	0.11	0.11	0.47	0.40
January	716	0.92	0.91	0.03	0.00	0.11	0.10	0.43	-0.53
February	696	0.95	0.95	-0.03	-0.03	0.10	0.09	0.33	-0.34
March (1st - 13th)	312	0.95	0.96	-0.02	-0.03	0.12	0.11	0.47	-0.37
1st October – 13th March	3932	0.94	0.93	0.01	0.02	0.10	0.10	0.47	-0.53

Table 2. Correlation coefficient, mean error, RMS error and maximum error between monthly observed residual elevations and residual elevations simulated by CS3X and G3AX at Heysham

Liverpool									
Month	**Size**	**Corr (CS3X)**	**Corr (G3AX)**	**Mean Err. (CS3X)**	**Mean Err. (G3AX)**	**RMSE (CS3X)**	**RMSE (G3AX)**	**Max Err. (CS3X)**	**Max Err. (G3AX)**
October	744	0.78	0.72	-0.08	-0.05	0.11	0.09	-0.32	0.42
November	720	0.91	0.89	-0.03	-0.01	0.08	0.08	-0.26	0.29
December	744	0.95	0.94	-0.04	-0.04	0.10	0.11	-0.37	-0.47
January	744	0.93	0.92	-0.09	-0.11	0.14	0.15	-0.69	-0.74
February	696	0.94	0.94	-0.16	-0.15	0.19	0.18	-0.42	-0.46
March (1st - 13th)	312	0.96	0.95	-0.18	-0.19	0.20	0.22	-0.52	-0.73
1st October – 13th March	3960	0.93	0.92	-0.09	-0.08	0.14	0.14	-0.69	-0.74

Table 3. Correlation coefficient, mean error, RMS error and maximum error between monthly observed residual elevations and residual elevations simulated by CS3X and G3AX at Liverpool.

Llandudno									
Month	Size	Corr (CS3X)	Corr (G3AX)	Mean Err. (CS3X)	Mean Err. (G3AX)	RMSE (CS3X)	RMSE (G3AX)	Max Err. (CS3X)	Max Err. (G3AX)
October	744	0.77	0.74	-0.03	0.01	0.07	0.07	0.21	0.25
November	720	0.88	0.85	0.08	0.10	0.11	0.13	0.41	0.47
December	744	0.94	0.94	0.05	0.05	0.10	0.10	0.47	0.52
January	744	0.93	0.93	0.01	-0.01	0.08	0.08	0.34	0.27
February	696	0.95	0.95	-0.05	-0.04	0.09	0.08	0.29	-0.29
March (1st - 13th)	312	0.96	0.96	0.00	-0.01	0.09	0.09	0.35	0.32
1st October – 13th March	3960	0.92	0.92	0.01	0.02	0.09	0.09	0.47	0.52

Table 4. Correlation coefficient, mean error, RMS error and maximum error between monthly observed residual elevations and residual elevations simulated by CS3X and G3AX at Llandudno.

Port Erin									
Month	Size	Corr (CS3X)	Corr (G3AX)	Mean Err. (CS3X)	Mean Err. (G3AX)	RMSE (CS3X)	RMSE (G3AX)	Max Err. (CS3X)	Max Err. (G3AX)
October	744	0.88	0.86	-0.02	0.02	0.05	0.05	-0.14	0.17
November	720	0.95	0.94	0.04	0.07	0.07	0.08	0.20	0.25
December	744	0.97	0.97	0.01	0.02	0.06	0.06	0.22	-0.18
January	744	0.95	0.96	-0.03	-0.05	0.07	0.07	0.24	-0.22
February	696	0.97	0.97	-0.09	-0.08	0.11	0.09	-0.25	-0.29
March (1st - 13th)	312	0.98	0.97	-0.05	-0.06	0.08	0.09	-0.27	-0.33
1st October – 13th March	3960	0.95	0.95	-0.02	-0.01	0.07	0.07	-0.27	-0.33

Table 5. Correlation coefficient, mean error, RMS error and maximum error between monthly observed residual elevations and residual elevations simulated by CS3X and G3AX at Port Erin.

Residual elevations greater than the 95th percentile residual elevation (Oct 07 -13th Mar 08)										
Port	Size	95th percentile elevation	Corr. (CS3X)	Corr. (G3AX)	Mean Err. (CS3X)	Mean Err. (G3AX)	RMSE (CS3X)	RMSE (G3AX)	Max Err. (CS3X)	Max Err. (G3AX)
Workington	198	0.51	0.82	0.81	0.07	-0.01	0.12	0.11	0.43	-0.33
Heysham	197	0.56	0.71	0.77	0.02	-0.07	0.16	0.15	0.47	-0.53
Liverpool	198	0.63	0.85	0.80	-0.17	-0.24	0.22	0.28	-0.69	-0.74
Llandudno	198	0.43	0.85	0.86	0.02	-0.05	0.09	0.10	0.26	-0.24
Port Erin	198	0.47	0.84	0.83	-0.02	-0.08	0.07	0.11	-0.22	-0.33

Table 6. Correlation coefficient, mean error, RMS error and maximum error between observed residuals greater than the 95th percentile residual surge elevation for the period October 2007 to March 13th 2008 and the corresponding residuals simulated by CS3X and G3AX at Eastern Irish Sea port locations.

Workington – Top five residual elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
10z 31st Jan	1.24	1.27	1.21	0.03	-0.03
6z 10th Mar	1.02	0.97	0.94	-0.05	-0.08
2z 12th Mar	1.01	1.14	0.98	0.13	-0.03
18z 29th Feb	0.99	1.03	1.01	0.04	0.02
7z 9th Jan	0.98	1.05	0.96	0.07	-0.02

Table 7. The error in simulating the top five highest residual surge elevations observed at Workington between October 2007 and March 13th 2008 using CS3X and G3AX.

Heysham – Top five residual elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
5z 12th Mar	1.61	1.39	1.45	-0.22	-0.16
15z 29th Feb	1.20	1.09	1.23	-0.11	0.03
6z 9th Jan	1.13	1.16	1.14	0.03	0.01
17z 8th Dec	1.03	1.13	1.02	0.10	-0.01
5z 7th Jan	1.03	1.02	0.72	-0.01	-0.31

Table 8. The error in simulating the top five highest residual surge elevations observed at Heysham between October 2007 and March 13th 2008 using CS3X and G3AX.

Liverpool – Top five residual elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
5z 12th Mar	1.93	1.47	1.31	-0.46	-0.62
6z 7th Jan	1.63	1.22	1.10	-0.41	-0.53
9z 31st Jan	1.58	1.38	1.44	-0.20	-0.14
23z 29th Feb	1.33	1.16	1.07	-0.17	-0.26
17z 21st Jan	1.26	0.89	1.13	-0.37	-0.13

Table 9. The error in simulating the top five highest residual surge elevations observed at Liverpool between October 2007 and March 13th 2008 using CS3X and G3AX.

Llandudno – Top five residual elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
7z 31st Jan	1.01	1.18	1.14	0.17	0.13
5z 12th Mar	0.91	1.14	0.94	0.23	0.03
16z 29th Feb	0.83	0.83	0.86	0.00	0.03
8z 10th Mar	0.82	0.91	0.88	0.09	0.06
22z 25th Feb	0.82	0.76	0.66	-0.06	-0.16

Table 10. The error in simulating the top five highest residual surge elevations observed at Llandudno between October 2007 and March 13th 2008 using CS3X and G3AX.

Port Erin – Top five residual elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
8z 10th Mar	0.87	0.86	0.85	0.01	-0.02
17z 29th Feb	0.86	0.79	0.77	-0.07	-0.09
11z 13th Jan	0.86	0.81	0.75	-0.05	-0.11
7z 31st Jan	0.84	0.97	0.89	0.13	0.05
6z 12th Mar	0.79	0.82	0.63	0.03	-0.16

Table 11. The error in simulating the top five highest residual surge elevations observed at Port Erin between October 2007 and March 13th 2008 using CS3X and G3AX.

Skew Surges									
Port	Size	Corr. (CS3X)	Corr. (G3AX)	Mean Err. (CS3X)	Mean Err. (G3AX)	RMSE (CS3X)	RMSE (G3AX)	Max Err. (CS3X)	Max Err. (G3AX)
Workington	319	0.93	0.93	0.04	0.04	0.10	0.10	0.43	0.34
Heysham	317	0.94	0.94	-0.04	-0.01	0.09	0.09	-0.24	-0.27
Liverpool	319	0.92	0.91	-0.12	-0.11	0.15	0.15	-0.40	-0.48
Llandudno	319	0.90	0.90	0.00	0.00	0.10	0.09	0.31	0.37
Port Erin	319	0.94	0.93	-0.03	-0.02	0.09	0.08	0.24	-0.28

Table 12. Correlation coefficient, mean error, RMS error and maximum error between observed skew surges for the period October 2007 to March 13th 2008 and the corresponding skew surges simulated by CS3X and G3AX at Eastern Irish Sea port locations.

Skew surges greater than the 95th percentile skew surge elevation (Oct 07 – 13th Mar 08)										
Port	Size	95th percentile elevation	Corr. (CS3X)	Corr. (G3AX)	Mean Err. (CS3X)	Mean Err. (G3AX)	RMSE (CS3X)	RMSE (G3AX)	Max Err. (CS3X)	Max Err. (G3AX)
Workington	16	0.45	0.86	0.92	0.09	-0.01	0.14	0.09	0.43	0.24
Heysham	16	0.55	0.80	0.91	-0.08	0.00	0.13	0.08	-0.23	-0.20
Liverpool	16	0.60	0.67	0.68	-0.17	-0.23	0.21	0.26	-0.36	-0.48
Llandudno	16	0.40	0.57	0.81	0.00	-0.04	0.10	0.09	-0.23	-0.18
Port Erin	16	0.46	0.84	0.86	-0.01	-0.07	0.07	0.09	-0.20	-0.20

Table 13. Correlation coefficient, mean error, RMS error and maximum error between observed skew surges greater than the 95th percentile skew surge elevation for the period October 2007 to March 13th 2008 and the corresponding skew surges simulated by CS3X and G3AX at Eastern Irish Sea port locations.

Workington – Top five skew surge elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
5z 31st Jan	1.17	1.18	1.13	0.01	-0.04
2z 12th Mar	1.01	1.14	0.93	0.13	-0.08
17z 29th Feb	0.96	1.00	1.00	0.04	0.04
14z 13th Jan	0.73	0.63	0.64	-0.10	-0.09
0z 9th Jan	0.70	1.13	0.94	0.43	0.24

Table 14. The error in simulating the top five highest skew surge surge elevations observed at Workington between October 2007 and March 13th 2008 using CS3X and G3AX.

Heysham – Top five skew surge elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
2z 12th Mar	1.12	0.89	1.13	-0.23	0.01
16z 29th Feb	1.10	0.94	1.15	-0.16	0.05
23z 8th Dec	0.78	0.74	0.78	-0.04	0.00
0z 9th Jan	0.74	0.84	0.84	0.10	0.10
19z 18th Jan	0.72	0.70	0.79	-0.02	0.07

Table 15. The error in simulating the top five highest skew surge surge elevations observed at Heysham between October 2007 and March 13th 2008 using CS3X and G3AX.

Liverpool – Top five skew surge elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
16z 29th Feb	1.09	0.72	0.97	-0.37	-0.12
2z 12th Mar	1.09	0.82	0.76	-0.27	-0.33
15z 29th Dec	0.91	0.61	0.43	-0.30	-0.48
5z 31st Jan	0.90	0.82	0.82	-0.08	-0.08
4z 1st Mar	0.87	0.65	0.48	-0.22	-0.39

Table 16. The error in simulating the top five highest skew surge surge elevations observed at Liverpool between October 2007 and March 13th 2008 using CS3X and G3AX.

Llandudno – Top five skew surge elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
16z 29th Feb	0.83	0.60	0.75	-0.23	-0.08
12z 10th Mar	0.59	0.59	0.56	0.00	-0.03
14z 13th Jan	0.59	0.52	0.50	-0.07	-0.09
5z 31st Jan	0.57	0.63	0.67	0.06	0.10
1z 26th Feb	0.57	0.48	0.42	-0.09	-0.15

Table 17. The error in simulating the top five highest skew surge surge elevations observed at Llandudno between October 2007 and March 13th 2008 using CS3X and G3AX.

Port Erin – Top five skew surge elevations 1st October 2007 – 13th March 2008					
Time/Date	Obs	CS3X	G3AX	Err. CS3X	Err. G3AX
17z 29th Feb	0.86	0.66	0.68	-0.20	-0.18
5z 31st Jan	0.76	0.73	0.71	-0.03	-0.05
14z 13th Jan	0.74	0.70	0.63	-0.04	-0.11
2z 12th Mar	0.71	0.75	0.60	0.04	-0.11
9z 3rd Feb	0.69	0.74	0.72	0.05	0.03

Table 18. The error in simulating the top five highest skew surge surge elevations observed at Port Erin between October 2007 and March 13th 2008 using CS3X and G3AX.

Port	Sample size	Mean Err. (NAE) (m)	Mean Err. (UK4) (m)	Corr coeff. (NAE)	Corr coeff. (UK4)	RMS (NAE) (m)	RMS (UK4) (m)
Workington	3912	0.06	0.07	0.94	0.92	0.11	0.13
Port Erin	3912	-0.03	-0.02	0.94	0.93	0.08	0.09
Heysham	3884	0.00	0.03	0.92	0.91	0.11	0.13
Liverpool	3912	-0.10	-0.08	0.90	0.88	0.16	0.15
Llandudno	3912	0.01	0.01	0.90	0.89	0.10	0.11
Average				0.92	0.91	0.11	0.12

Table 19. Correlation coefficient and root mean square error between observed and simulated residual surge elevations using the Met Office NAE and UK4 data sets.

Port	95th %tile residual elev.(m)	Sample size	Mean Err. (NAE) (m)	Mean Err. (UK4) (m)	Corr coeff. (NAE)	Corr coeff. (UK4)	RMS Err. (NAE) (m)	RMS Err. (UK4) (m)
Workington	0.51	31	0.00	0.04	0.93	0.88	0.07	0.11
Port Erin	0.47	22	-0.06	-0.06	0.89	0.79	0.09	0.11
Heysham	0.56	38	-0.02	0.04	0.85	0.81	0.13	0.17
Liverpool	0.63	37	-0.22	-0.18	0.84	0.77	0.28	0.28
Llandudno	0.43	31	-0.02	-0.01	0.90	0.86	0.08	0.09
Average					0.88	0.82	0.13	0.15

Table 20. Correlation and root mean square error between observed peak residuals greater than the 95th percentile residual elevation for each port location over the period October 2007 to March 2008 and the corresponding simulated residuals using meteorological data from the Met Office NAE and UK4 data sets.

Port	95th %tile skew surge (m)	Sample size	Mean Error (m) (NAE)	Mean Error (m) (UK4)	Corr coeff. (NAE)	Corr coeff. (UK4)	RMS (NAE) (m)	RMS (UK4) (m)
Workington	0.45	16	0.04	0.00	0.93	0.82	0.09	0.13
Port Erin	0.46	16	-0.05	-0.09	0.73	0.44	0.10	0.18
Heysham	0.55	16	0.01	0.01	0.94	0.89	0.08	0.25
Liverpool	0.60	16	-0.21	-0.10	0.69	0.63	0.24	0.34
Llandudno	0.40	16	0.01	-0.01	0.66	0.51	0.09	0.20
Average					0.79	0.66	0.12	0.22

Table 21. Correlation coefficient and root mean square error between observed and simulated skew surge elevations greater than the 95th percentile skew surge elevation for each port location using the Met Office NAE and UK4 data sets.

Workington				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
1.27	1.16	1.21	-0.11	-0.06
1.05	1.05	0.99	0.00	-0.06
1.05	1.27	1.07	0.22	0.02
1.03	1.20	1.02	0.17	-0.01
1.00	1.01	0.96	0.01	-0.04
Port Erin				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
0.90	0.62	0.70	-0.28	-0.20
0.88	0.77	0.85	-0.11	-0.03
0.87	0.88	0.90	0.01	0.03
0.86	0.67	0.79	-0.19	-0.07
0.80	0.76	0.68	-0.04	-0.12
Heysham				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
1.66	1.87	1.57	0.21	-0.09
1.20	1.22	1.12	0.02	-0.08
1.14	1.38	0.96	0.24	-0.18
1.07	1.01	1.20	-0.06	0.13
1.06	1.01	0.82	-0.05	-0.24
Liverpool				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
1.93	1.77	1.30	-0.16	-0.63
1.81	1.39	1.10	-0.42	-0.71
1.68	1.42	1.29	-0.26	-0.39
1.34	1.11	1.11	-0.23	-0.23
1.29	1.01	0.73	-0.28	-0.56
Llandudno				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
1.09	1.03	1.08	-0.06	-0.01
0.94	1.14	1.04	0.20	0.10
0.84	0.77	0.62	-0.07	-0.22
0.83	0.74	0.79	-0.09	-0.04
0.83	0.84	0.92	0.01	0.09

Table 22. Difference between the top five observed surge residuals and the corresponding simulated surge residuals using the Met Office NAE and UK4 data sets.

Green	Error reduced using UK4
Red	Error increased using UK4
Blue	No change in error

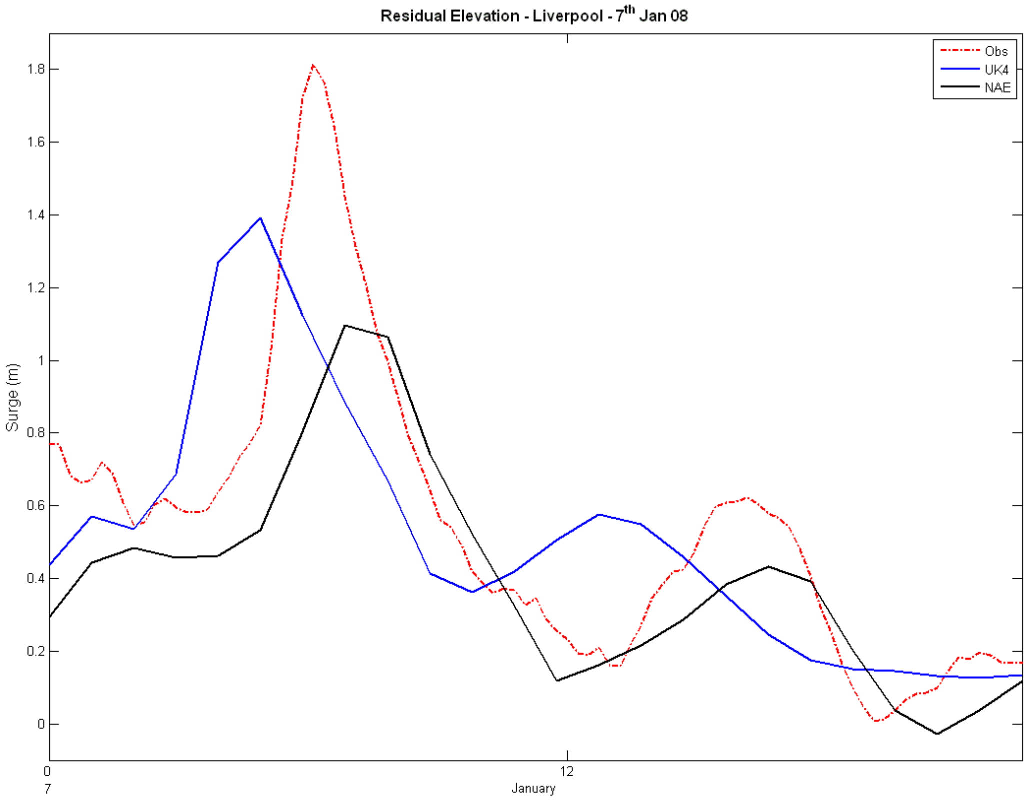

Figure 1. Observed and simulated residual elevations using input from UK4 and NAE at Liverpool 7th January 2008.

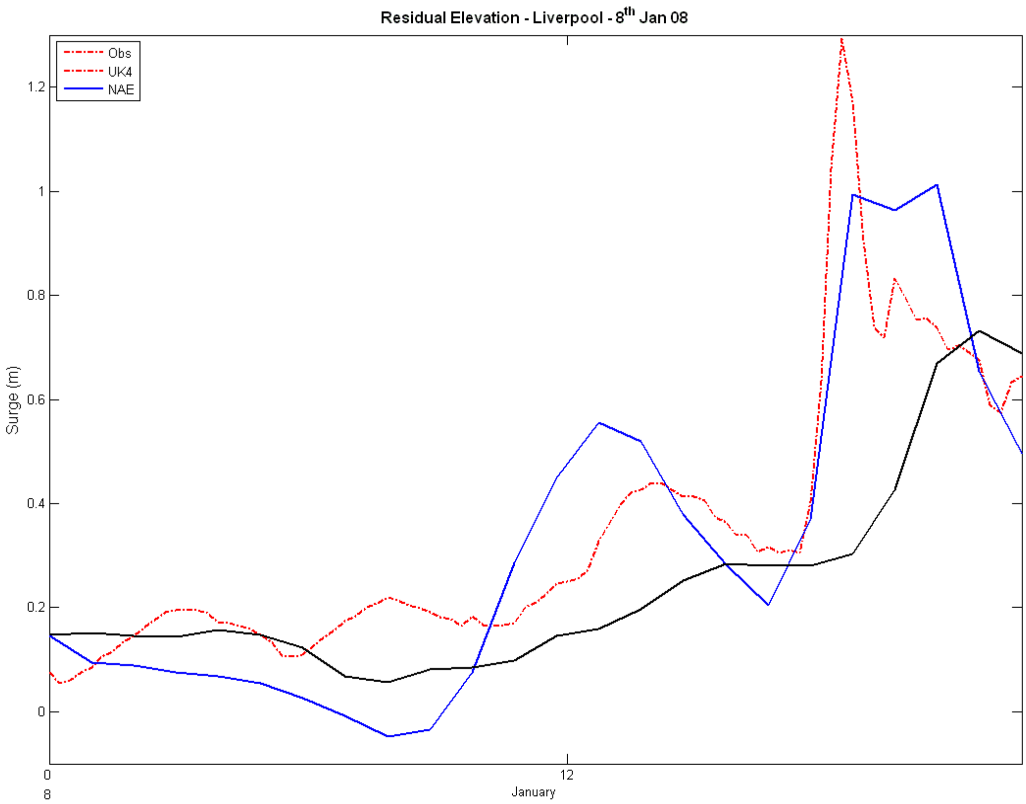

Figure 2. Observed and simulated residual elevations using input from UK4 and NAE at Liverpool 8th January 2008.

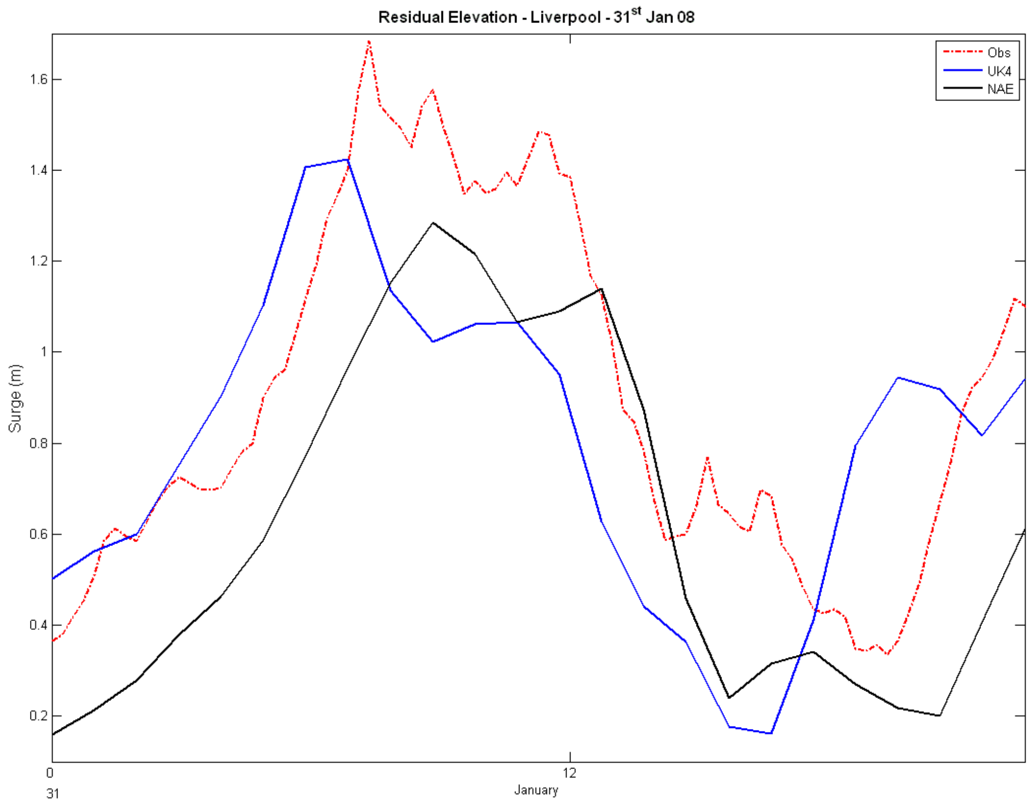

Figure 3. Observed and simulated residual elevations using input from UK4 and NAE at Liverpool 31st January 2008.

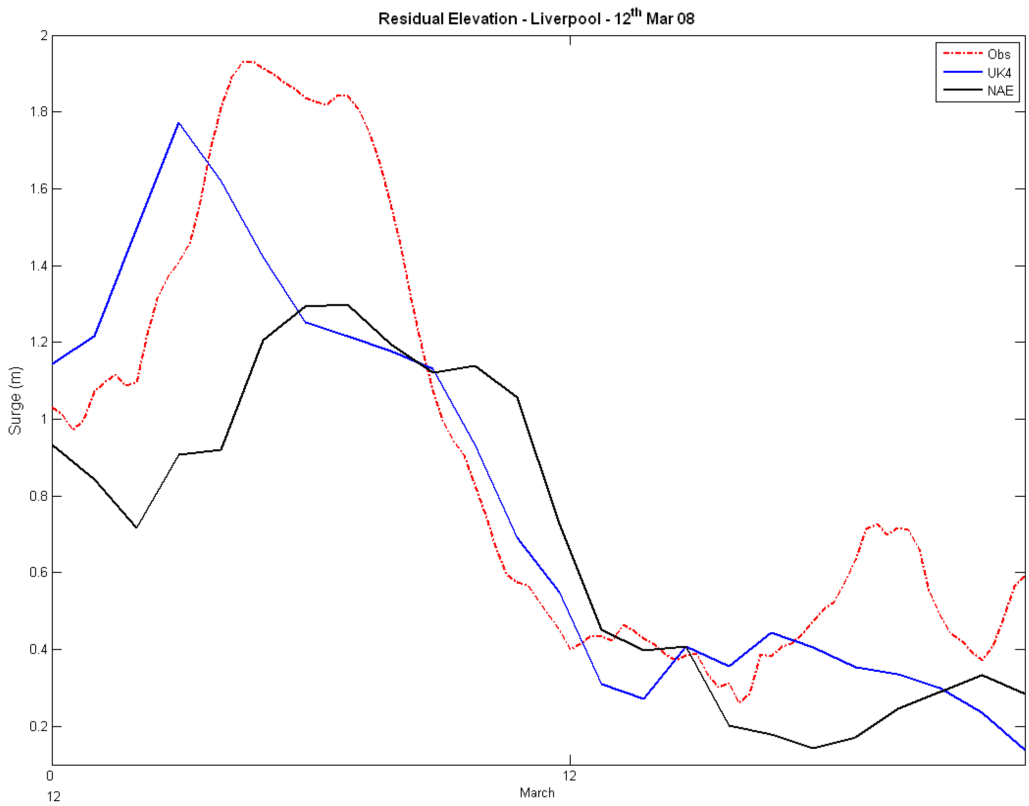

Figure 4. Observed and simulated residual elevations using input from UK4 and NAE at Liverpool 12th March 2008.

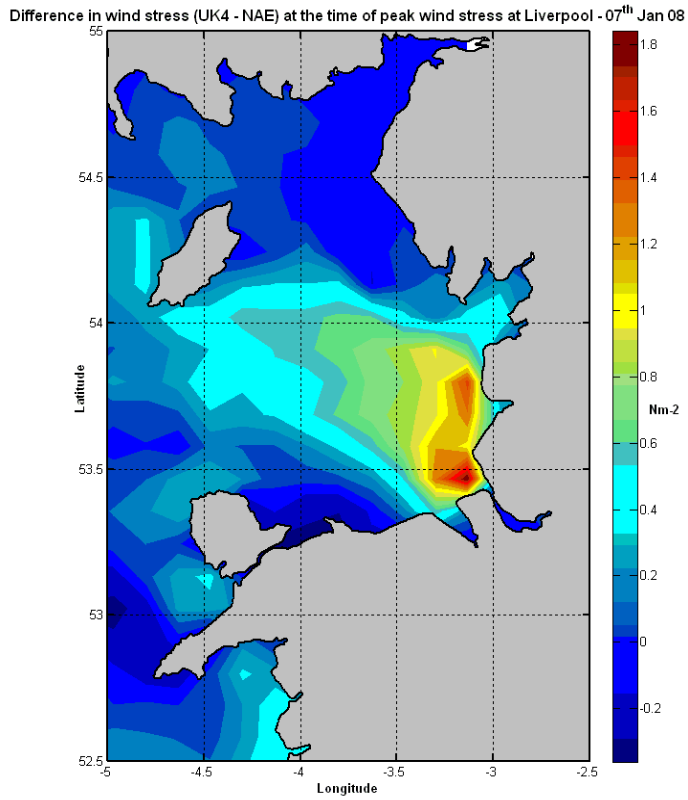

Figure 5. Difference in the wind stress in the Eastern Irish Sea input from UK4 and NAE at the time of peak wind stress at Liverpool 7th January 2008.

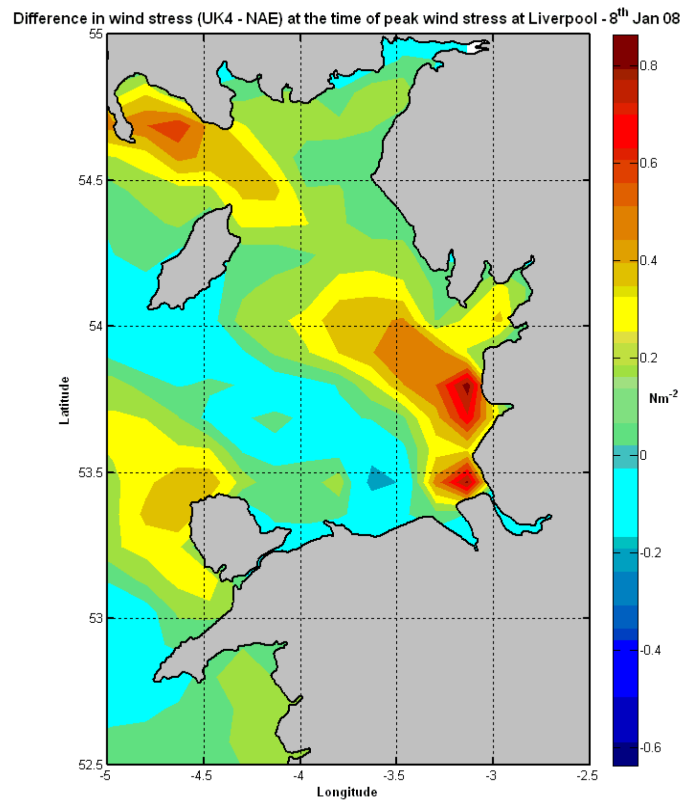

Figure 6. Difference in the wind stress in the Eastern Irish Sea input from UK4 and NAE at the time of peak wind stress at Liverpool 8th January 2008.

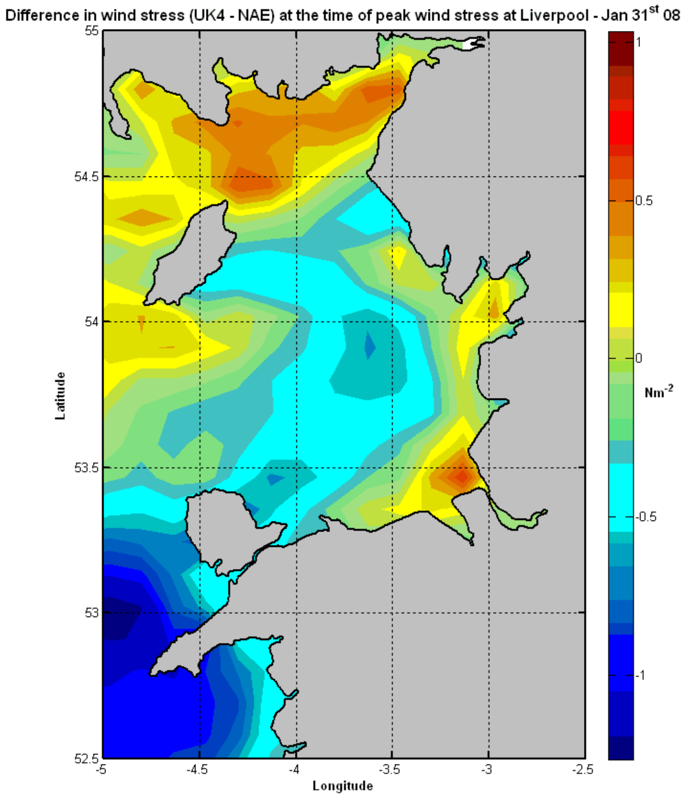

Figure 7. Difference in the wind stress in the Eastern Irish Sea input from UK4 and NAE at the time of peak wind stress at Liverpool 31st January 2008.

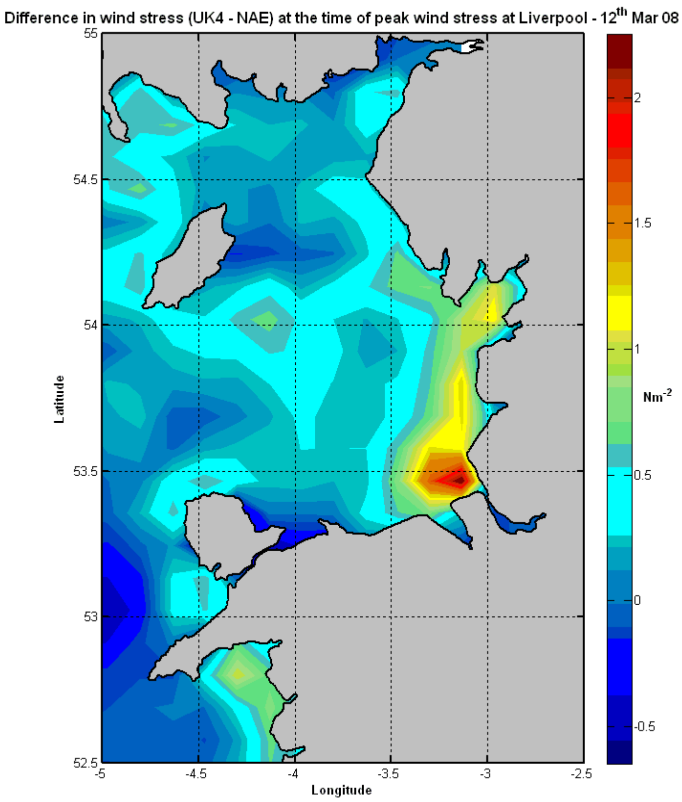

Figure 8. Difference in the wind stress in the Eastern Irish Sea input from UK4 and NAE at the time of peak wind stress at Liverpool 12th March 2008.

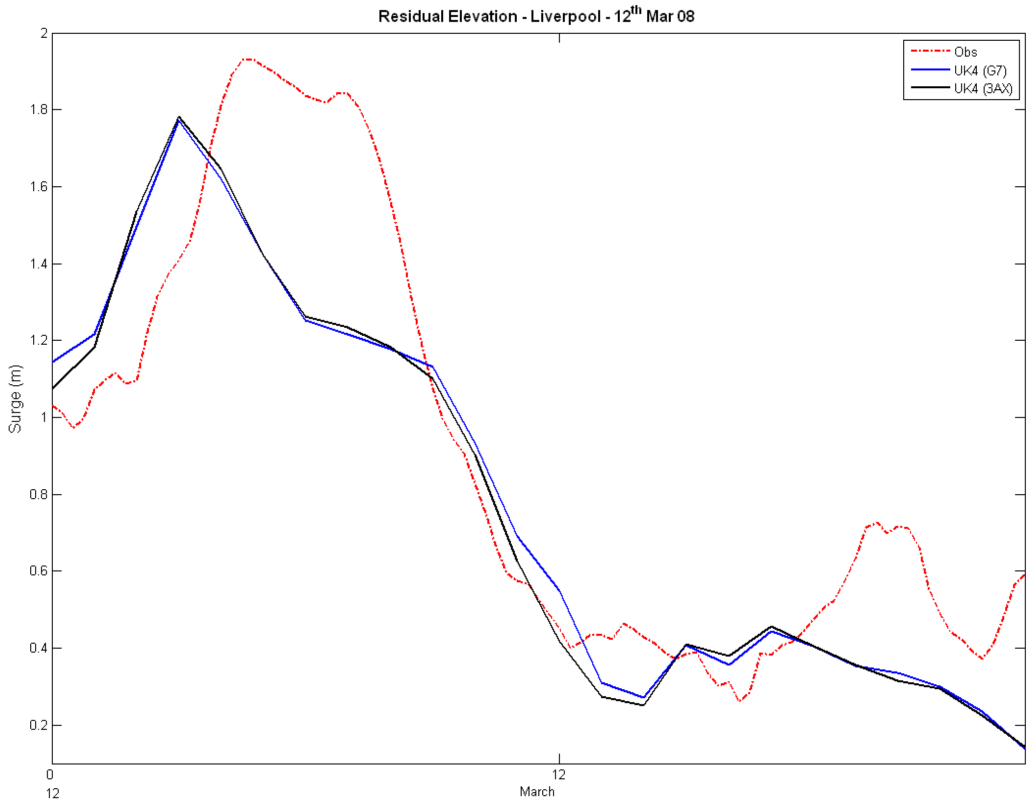

Figure 9. Observed and simulated residual elevations using input from UK4 into G3AX and G7 at Liverpool 12^{th} March 2008.

Workington				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
1.24	1.04	1.15	-0.20	-0.09
1.01	1.01	1.02	-0.00	0.01
0.94	0.83	0.96	-0.11	0.02
0.76	0.88	1.02	0.12	0.26
0.69	0.51	0.71	-0.18	0.02
Port Erin				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
0.89	0.60	0.59	-0.29	-0.30
0.8	0.73	0.67	-0.07	-0.13
0.73	0.50	0.67	-0.23	-0.06
0.71	0.68	0.64	-0.03	-0.07
0.69	0.73	0.74	0.04	0.05
Heysham				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
1.12	1.87	1.19	0.75	0.07
1.07	1.22	1.09	0.15	0.02
0.82	0.85	0.93	0.03	0.11
0.79	0.96	0.86	0.17	0.07
0.73	0.75	0.78	0.02	0.05
Liverpool				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
1.14	1.00	0.88	-0.14	-0.26
1.12	1.77	0.91	0.65	-0.21
0.89	0.46	0.40	-0.43	-0.49
0.88	1.41	0.81	0.53	-0.07
0.87	0.14	0.52	-0.73	-0.35
Llandudno				
Obs (m)	UK4 (m)	NAE (m)	Diff UK4 (m)	Diff NAE (m)
0.83	0.69	0.65	-0.14	-0.18
0.6	0.45	0.54	-0.15	-0.06
0.57	0.35	0.62	-0.22	0.05
0.57	0.99	0.58	0.42	0.01
0.53	1.03	0.67	0.50	0.14

Table 23. Difference between the top five observed skew surges and the corresponding simulated skew surges using the Met Office NAE and UK4 data sets.

(green)	Error reduced using UK4
(red)	Error increased using UK4
(blue)	No change in error

5. Storm surges in a future climate: results from coupled climate models

One possible consequence of climate change is a change in the future frequency of extreme storm surges. This hypothesis is tested by cascading atmospheric information from a global scale general circulation model (GCM) of climate, through a regional climate model (RCM) that can simulate mesoscale meteorological processes, to regional hydrodynamic surge (or wave) models. This methodology has been applied previously to storm surges in the North Sea by Lowe et al. (2001), Hulme et al. (2002), Woth et al. (2005), and Debernard and Roed (2008). All these studies identify certain areas where there is an increase in surge magnitude in future climate scenarios, but there is no agreement over its magnitude or which regions will be affected. Furthermore, the changes to extreme water levels obtained are of the same order as the natural climatological variability.

Lowe et al. (2001) found increases in the 50-year return period value of the non-tidal residual of approximately 20cm over the entire shelf, but no significant increase in the southern North Sea where surges are observed to be at their largest. Woth et al. (2005) found no significant increase in the future surge along the east coast of the UK, whereas Hulme et al. (2002) suggested a positive trend. This lack of consistency led Lowe and Gregory (2005) to conclude that the higher return levels from these studies contain unacceptable uncertainty and lack credible verification. More recently, Debernard and Roed (2008) used a regional climate model to dynamically downscale a combination of different emissions scenarios from three independent GCMs. Their analysis of changes to the wave and surge fields suggested that the most extreme future surges were approximately 3% higher in all future emissions scenarios.

Previous coupled climate-surge modelling studies contain three main methodological drawbacks. The key quantity examined in all previous research on storm surge climate (e.g. Lowe et al., 2001; Hulme et al., 2002) has been the non-tidal residual (i.e. the time series one obtains by subtracting a tidal run from the fully-forced surge model run). Many properties of the residual time series are thus an artefact of small changes to the timing of predicted high water, combined with the fact that wind stress is most effective at generating surge around low water. It is well known that at many locations peak non-tidal residuals are consistently obtained 3-5 hours before tidal high water (Horsburgh and Wilson, 2007). Any extreme value analysis of these maxima would have little scientific or engineering significance. In this new work we focus on the modelled skew surges. Skew surge is simply the difference between the elevation of the predicted astronomical high tide and the nearest experienced high water. It is the preferred surge diagnostic for the Dutch operational system (e.g. de Vries et al., 1995) and is of far greater practical significance than maximum residual.

Climate models remain the only credible tools for making century-scale projections of future climate, yet they cannot provide a single definitive prediction of climate at the end of the 21st century. This is due variously to uncertainty in emissions, uncertainty in the assumptions upon which models are built and because of natural variability. In order to quantify these uncertainties the model runs described here adopted a perturbed parameter ensemble approach (Collins et al., 2006; Murphy et al., 2007). Instead of taking a single estimate for key atmospheric parameters the uncertainty in those parameters is treated explicitly. One interesting finding from Debernard and Roed (2008) was that there is more uncertainty surrounding the choice of GCM than the SRES emissions scenario, a fact that provides a strong argument for an ensemble approach. The spread of results from ensemble studies is useful to decision makers when planning adaptive responses for possible future changes in environmental variables.

The climate model used was the Met Office Hadley Centre global climate model, HadCM3 (Gordon et al., 2000; Pope et al., 2000), which is a general circulation model that has been shown to have skill at simulating the global climate. The atmospheric resolution is 2.5° x 3.75° in the horizontal with 19 vertical layers; the ocean is represented by a 1.25° x 1.25° grid with 20 layers in the vertical. To better represent the mesoscale meteorological processes associated with mid-latitude storms the global climate model provides atmospheric boundary conditions for a regional climate model, HadRM3 at 25km horizontal resolution. Many important physical processes (e.g. cloud formation, convective and diffusive processes) are not resolved by climate models. These processes are parameterised in terms of mathematical relationships between small and large scales so as to emulate their mean effect at the model resolution. This work used a perturbed parameter ensemble (PPE) approach to better describe the uncertainties in model predictions. Rather than use a single best estimate for key parameters, 11 versions of the climate model were run each with different but plausible parameter settings. The choice of parameters was directed by the climatic sensitivity of a large (more than 400 runs) ensemble of a computationally efficient, intermediate complexity climate model with a slab ocean. For full details of the parameters that were perturbed and the sampling strategy see Collins et al. (2006) and Murphy et al. (2007).

Each of the 11 GCM simulations drives a corresponding version of the RCM with equivalent parameter perturbations. The RCM can be considered a dynamically-downscaled version of the PPE global projection, suitable for supplying the wind speed components at 10m and atmospheric pressure at mean sea level required by the hydrodynamic storm surge model. The climate models were spun-up to stable states approximating the pre-industrial climate. Flux corrections were applied during the spin-up to minimize drift and improve the simulation of key features like the European storm track. Historical greenhouse gas and aerosol forcing was then applied between 1860 and the present day, followed by projected values to 2100. The study used the medium emission (SRES A1B) scenario (Nakicenovic et al., 2000). In this, the global mean surface temperature is expected to rise by around 1.7 to 4.4°C during the 21st century as atmospheric carbon dioxide concentrations rise to around 700 ppm. The surge model used was POL CS3X, which is the same model employed for operational coastal flood forecasting in the UK. The tide–surge model covers the entire northwest European continental shelf at 12 km horizontal resolution. Surface boundary conditions are the mean sea level atmospheric pressure and 10 m wind components.

Any assessment of the future storm surge climate of the UK or the northern European coastline is effectively an evaluation of future storminess (although coastal morphology affects tides and surges to a much lesser degree). Impacts studies such as this one depend on the credibility of the synoptic scale atmospheric forcing provided by the climate models. The most up to date assessment of the how the UK climate may change over the 21st century is given in UKCP09 (Murphy et al., 2009). A complete probabilistic projection of surface wind speeds was not provided by Murphy et al. (2009) because wind speed data was not available from many of the IPCC 4AR (IPCC, 2007) climate models. However, limited validation of the surface winds from the 11 member PPE used as forcing in this paper has been performed.

The validation was performed using terrestrial observing stations with data from 1971-2000. Seasonal mean wind speeds over mountainous regions were found to be typically 20% lower than observations, whilst positive biases of about 20% were found across the southern part of the UK. Individual storm events were not considered. The ensemble mean, present day (1971-2000) storm track, as indicated by the wind components at 850 hPa, was located further south than in the ERA40 reanalysis. Systematic biases due to unresolved orography or surface roughness are usual, and do not preclude the RCM data from making useful projections of climatic change. The ensemble mean change (for 2070-2099 relative to 1961-1990) in winter (DJF) surface wind speed showed a 1-6% reduction across most of the UK. The majority of the PPE ensemble members showed a reduction in winter wind speeds over sea regions to the west of the UK (which is key to this report) and in the North Sea. These small predicted reductions **are not statistically significant** when compared to the variability across the 11 member ensemble. This finding is consistent with the recent results of Bengtsson et al. (2009) who report no evidence of any trend in future storminess over the North Atlantic and western Europe.

The storm surge which statistically is expected to occur once every 50 years is defined as the so-called “50 year return level”. In the headline results of UKCP09, Lowe et al. (2009) considered the maximum fitted trend in the ensemble mean for four return periods: 2, 10, 20 and 50 years. For the majority of the UK coastline there were no significant changes to return levels. In the southwest of the UK there was a small but significant trend in the 50-year return level, which implies a change to large storm surges of less than 10cm over the 21st century. This is clearly less significant than either observed or projected rises in global mean sea level rise. The conclusion is that the physical significance of any trends in the storminess-driven component of extreme sea level is small.

5.1 Further analysis of the UKCP09 climate-surge model results for southwest UK

In this final section of the report we probe further into the results from the UKCP09 climate-surge model ensemble and specifically focus on the Bristol Channel: this is the one region of the domain that showed any statistical significance for a possible change in storm surge climate.

Basic statistics were calculated for all skew surges greater than one metre, from the numerical model output for all ensemble members at the model cell closest to the Avonmouth tide gauge. Output from the coupled climate-surge model was divided into three equal time periods (1951-2000; 2001-2049; 2050-2099) to allow a simple comparison of the statistics over time. The ensemble mean values (e.g. the averages of the mean surges within each time period) are summarised in Table 24 below. The results from this simple analysis indicate no significant changes in the mean of large (above 1m) skew surges for future decades. The single largest skew surge obtained actually decreases significantly from 2.68m in the period 1951-2000 to 1.86m in the period 2050-2099. Our complete analysis shows that the range of skew surge heights decreases in the future, with slightly more large events per year but with considerably reduced variability in magnitude.

Table 24. Summary statistics of skew surge in the Bristol Channel for the entire 11-member ensemble for each of the 50-year time periods

	1951-2000	2001-2049	2050-2099
Minimum mean surge across all 11 members (m)	1.12	1.12	1.12
Maximum mean surge across all 11 members (m)	2.68	2.02	1.86
Ensemble mean skew surge (m)	1.18	1.19	1.17
Standard deviation of the ensemble mean (m)	0.05	0.04	0.04
Ensemble maximum number of surges in period	34	41	38
Ensemble mean of the maxima in period (m)	1.64	1.65	1.64

In UKCP09 (Lowe et al., 2009) it was reported that for the majority of the UK coastline there were no significant changes to any storm surge return levels between now and 2100, with the exception of a small but significant increase in the 50-year return period surge in the southwest of the UK (i.e. the Bristol Channel and southern parts of the Irish Sea). The additional analysis we conduct here – based on simple statistics of the actual events rather than a fitted statistical distribution – suggests the opposite. There are no significant changes with time to ensemble mean properties, and the largest skew surge obtained within a 50 year block of the model run actually decreases in the future.

6. Model experiments based on the February 2002 surge event, and uncalibrated extreme value statistics for the Isle of Man coastline

In a series of additional model experiments, we investigated whether differences in timing of the passage of the weather system could have worsened the flooding caused in February 2002, when a surge in the eastern Irish Sea subsequently affected the east coast of the Isle of Man close to high water. These experiments used the UK operational model, CS3X, rather than the finite element model described in section 3. This is because the wind fields for the 2002 event could not be reconfigured to act as input to the unstructured model. Nevertheless, the standard operational model forecast the event fairly accurately so is fit for purpose. The atmospheric forcing was manipulated to be both advanced and retarded by 8 hours. The results are shown in Figure 10 below. The largest residuals would have occurred had the weather system arrived between 4-8 hours earlier. This does not mean that the largest total sea level would have increased, since the tide itself was a major factor in the flooding.

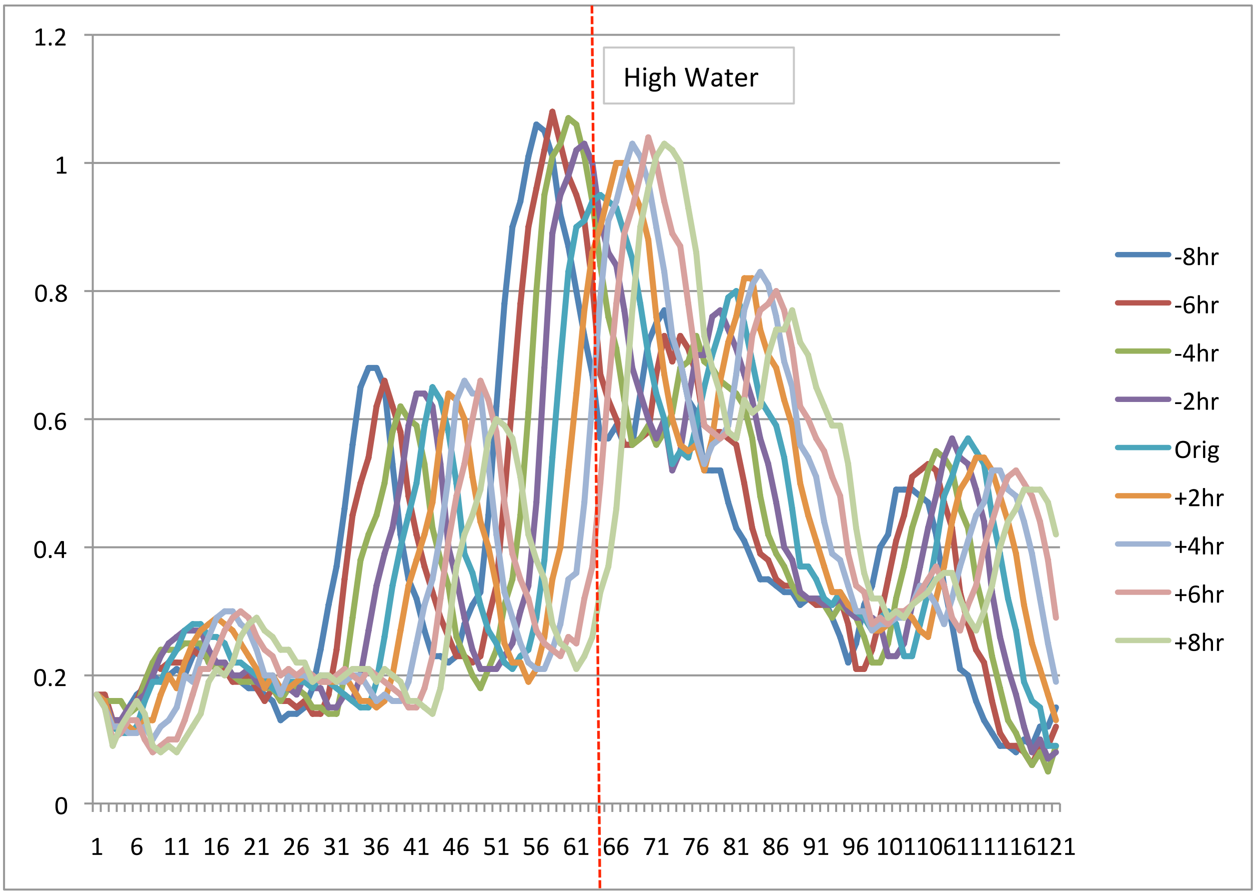

Figure 10. Non-tidal residual at a model cell corresponding to Port Erin; obtained by moving the atmospheric forcing with respect to the tide in the numerical model. The vertical dashed line shows the time of high water. Note that the largest residuals occur in the 6 hours prior to high water.

The total water levels (i.e. the tide plus the storm surge) for the model cell closest to Port Erin are shown in Table 25. According to this model, a two hour advance of the driving meteorology would have increased the total sea level by 6cm (i.e. 3.24 m rather than 3.18 m using the actual timing of the weather system). This small increase is primarily because the surge envelope is moved so as to be more coincident with tidal high water. So although the event in February 2002 was nearly a worst case, a small but significant additional contribution to sea level may be possible if the timing of a similar event in the future allowed the surge to coincide precisely with a larger tide.

Table 25. Maximum total water level around the time of peak surge at model cell corresponding to Port Erin

Relative time of Met Data (hours)	Total Water Level (m)
-8	2.91
-6	3.05
-4	3.19
-2	3.24
0	3.18
+2	3.10
+4	2.88
+6	2.61
+8	2.76

The simple model experiment above illustrates the sensitivity of the total water level, for a single event, to the relative timing of the tide and the causal weather. This has implications for the estimation and interpretation of extreme value statistics for sea levels. Extreme sea levels for the entire UK coastline were recently re-estimated using a joint probability method (Mc Millan et al., 2010). Statistical analysis was performed for all Class A tide gauge sites, using a Generalised Pareto Distribution (GPD) fit to the upper tail of the storm surge distribution. The histograms of tide and storm surge were then combined to give probability estimates at all sites, expressed in levels corresponding to an average return period. Spatial interpolation, needed to give return value estimates in between tide gauge sites, was performed using a numerical model forced by a 45-year meteorological reanalysis (ERA40). Although the project - funded by the UK Environment Agency (SC060064/TR2: Design sea levels) - did not provide information for the Isle of Man, those results were available from the modelling exercise and are summarised in Table 26.

Table 26. Estimated return levels for Isle of Man coastline (corrected to Port Erin)

	Latitude	Longitude	Return Period (years)				
			1	10	100	200	1000
	54.500	-4.417	4.07	4.38	4.67	4.76	4.99
	54.389	-4.583	3.55	3.85	4.10	4.17	4.32
	54.389	-4.250	4.51	4.81	5.11	5.21	5.46
	54.278	-4.750	3.33	3.60	3.84	3.90	4.03
	54.278	-4.250	4.53	4.82	5.11	5.21	5.47
Port Erin	54.167	-4.750	3.32	3.60	3.84	3.90	4.04
	54.167	-4.417	4.30	4.58	4.86	4.95	5.18
	54.056	-4.583	3.87	4.16	4.42	4.50	4.68

It is difficult to interpret the significance of the estimated return levels without considerable further work. Unlike the coastline of the mainland, the Isle of Man does not possess contiguous tide gauges required for the spatial correction of the model results. The results in Table 26 have all been derived from a statistical analysis of the model reanalysis, and then corrected using the tide gauge parameters from Port Erin. This is obviously unrealistic since the parameters of extreme sea level statistics will be affected by orientation to the storm track. There are also issues of model agreement with local datums which should, but have not yet, been taken into account. The point being made here, in the context of the February 2002 experiment, is that small changes in the tide-weather timing will cause small but significant differences in the observed total sea level. These possible outcomes must be taken into consideration by any joint probability technique if the statistical fit to the upper tail of storm surge is to be optimum. This implies that one should use an ensemble of reanalyses when using a hydrodynamic model to derive extreme value statistics for storm surges.

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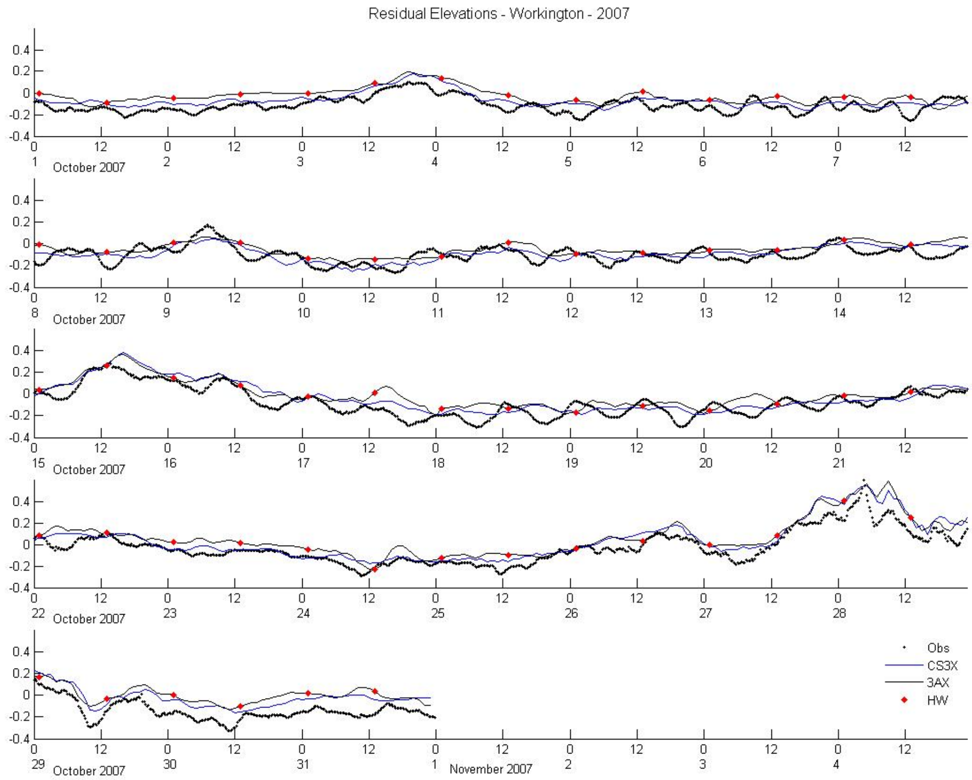
Appendices

Appendix 1



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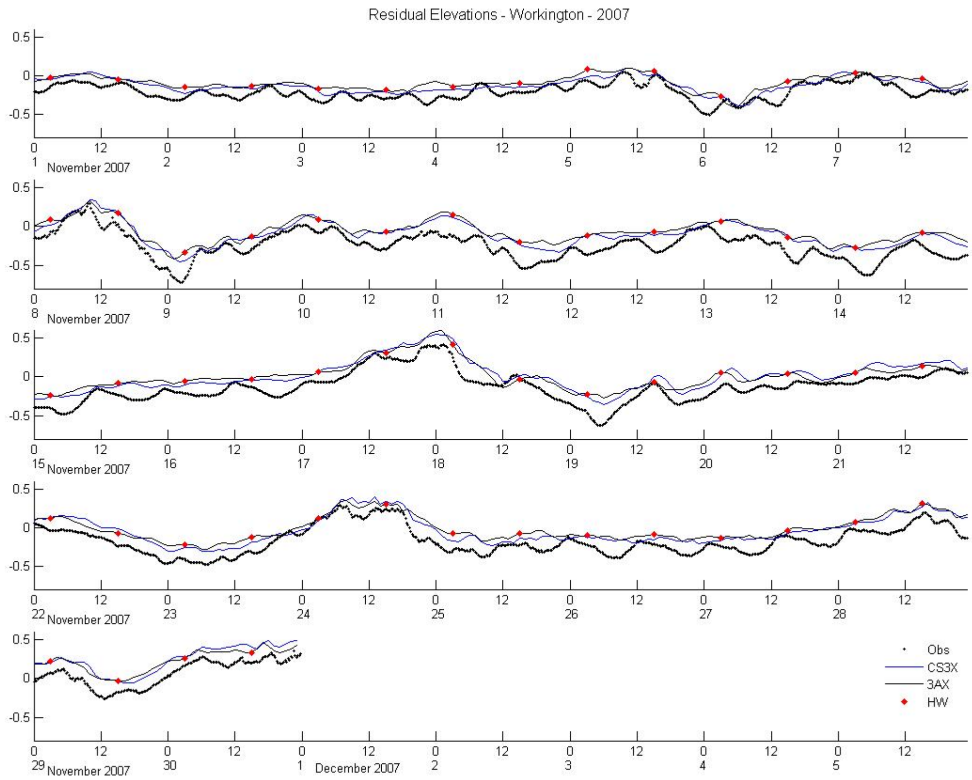

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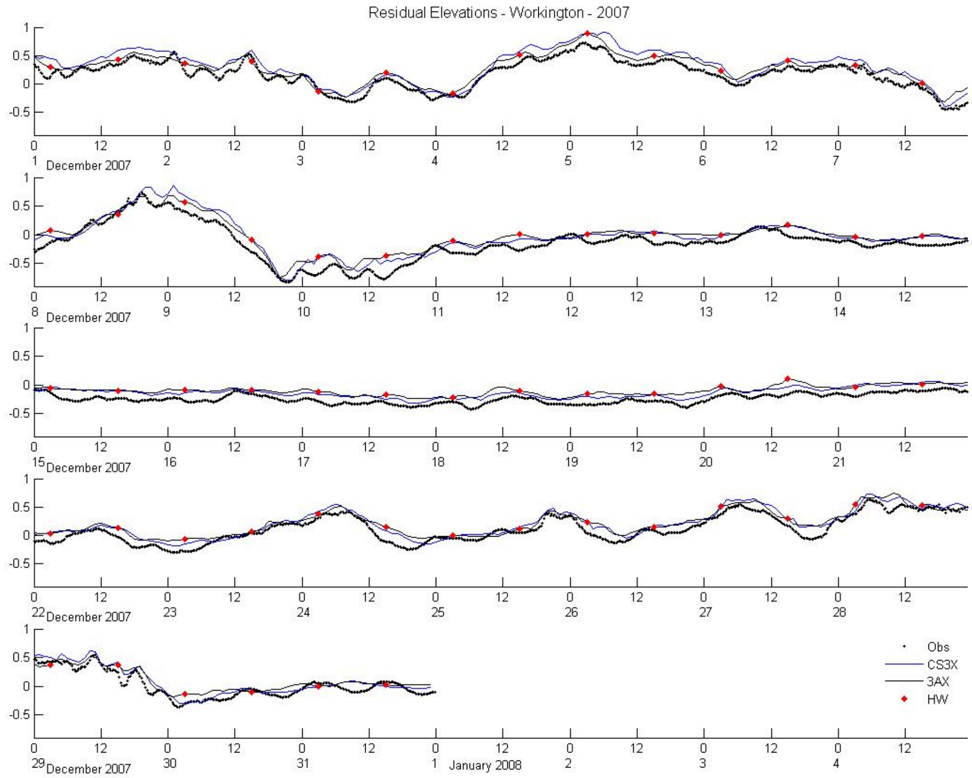
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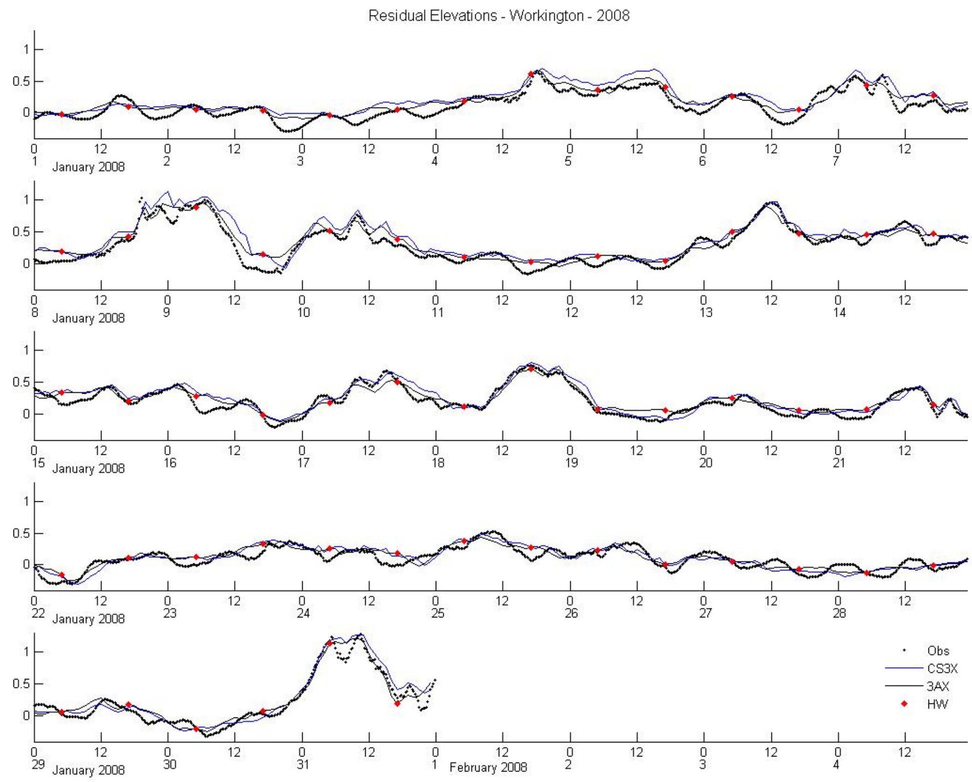
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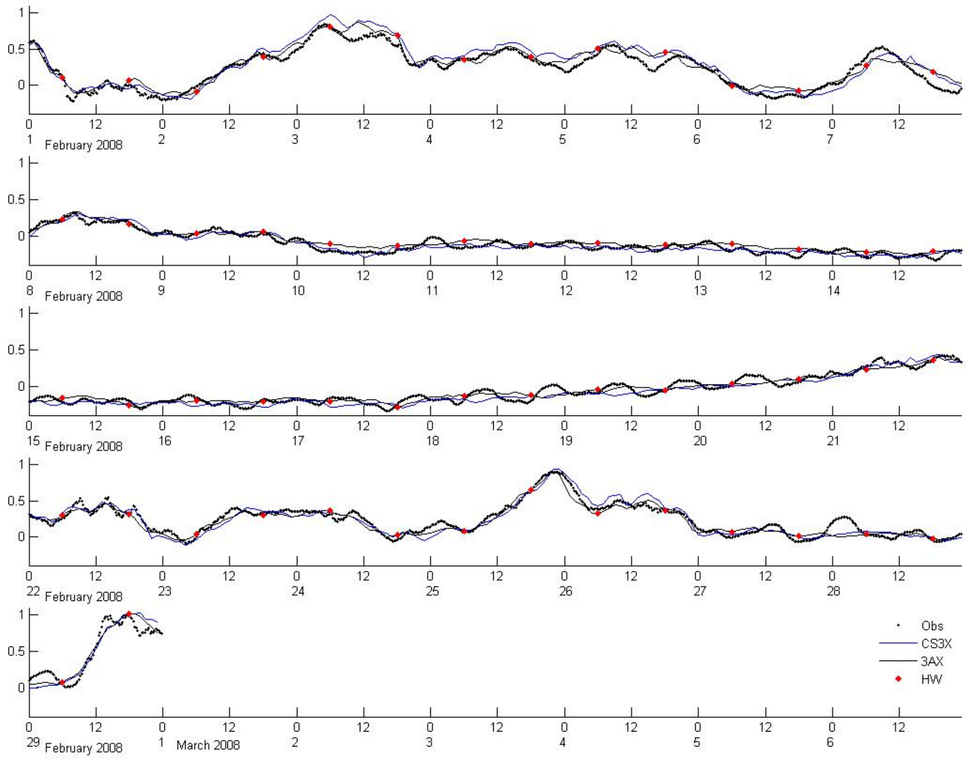

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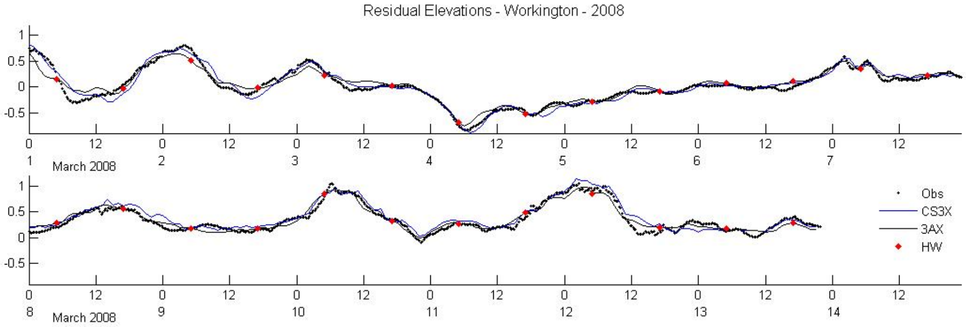

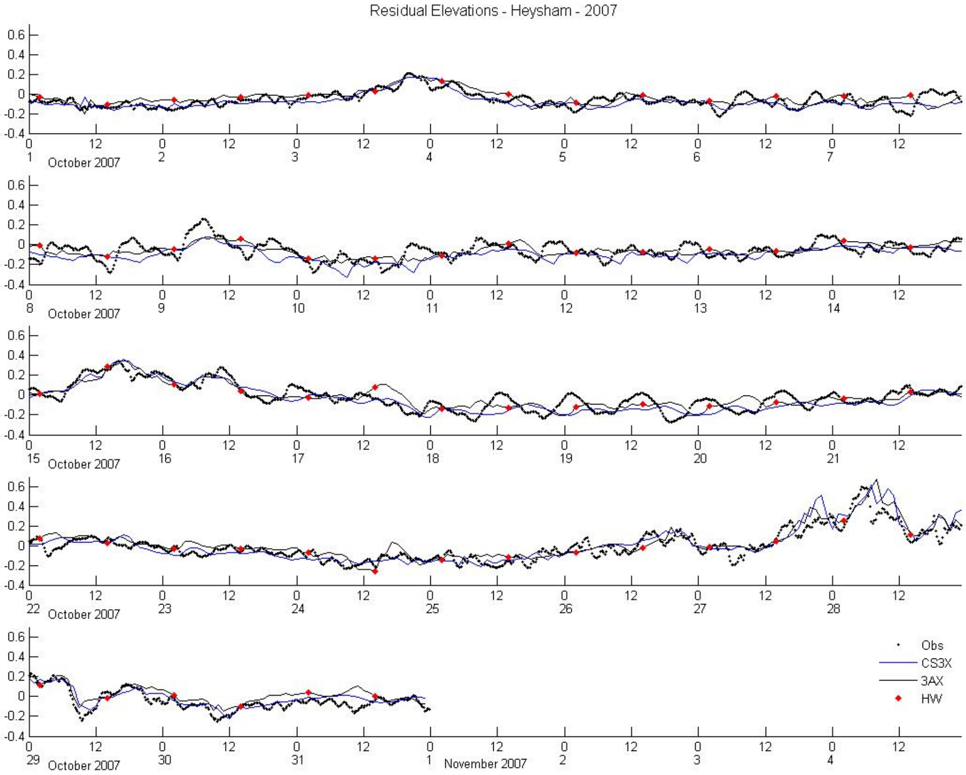
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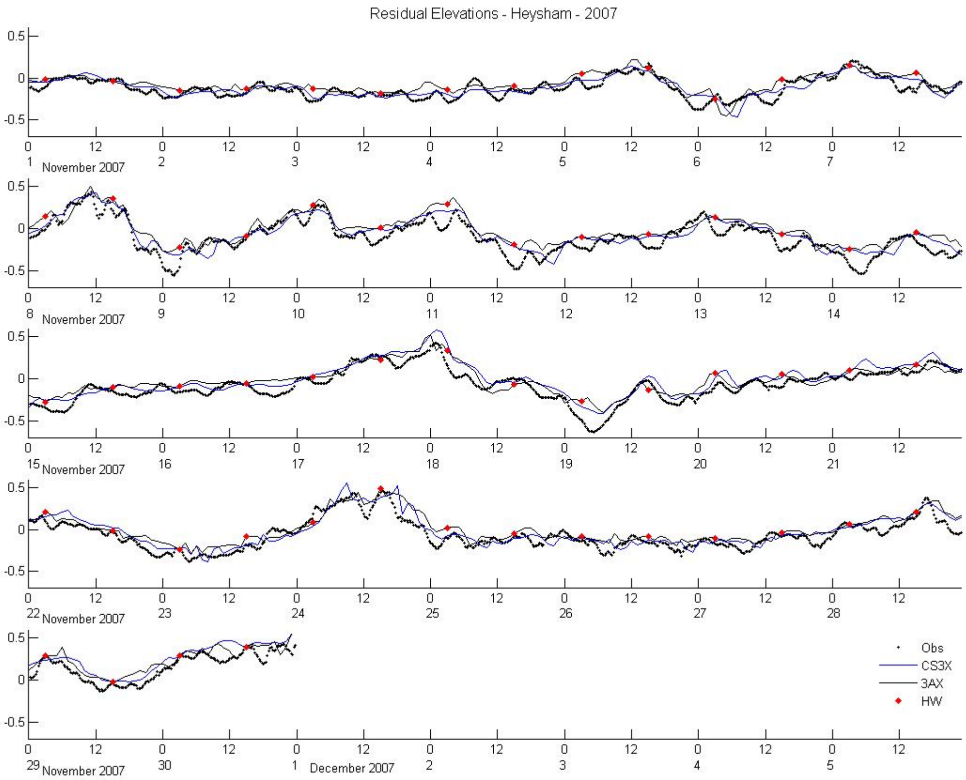
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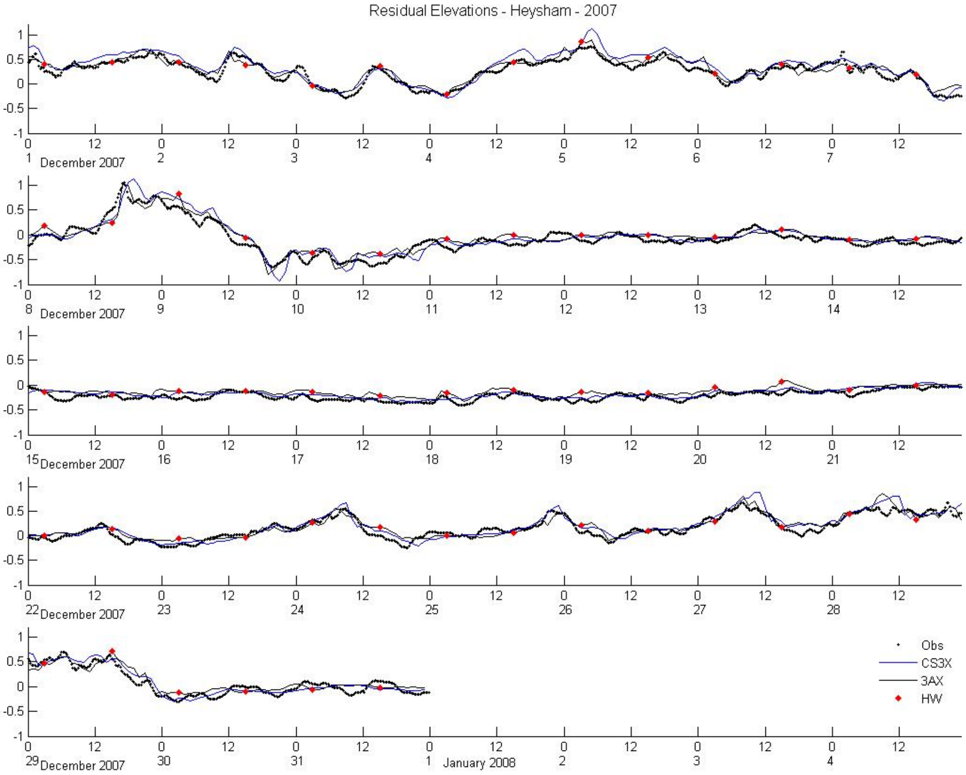
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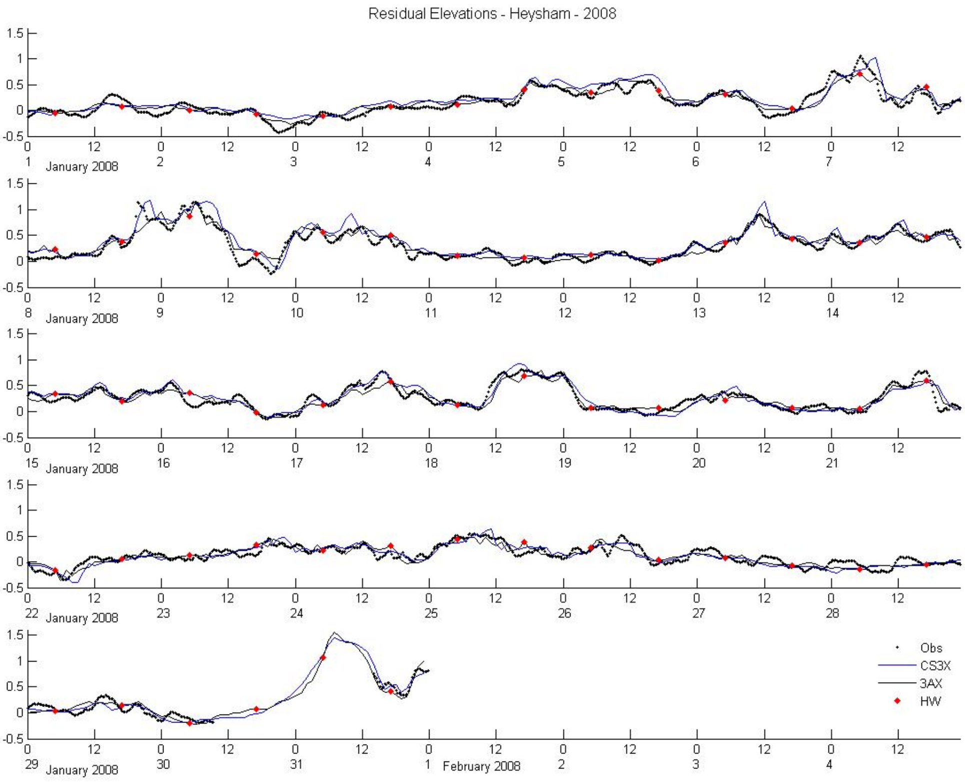
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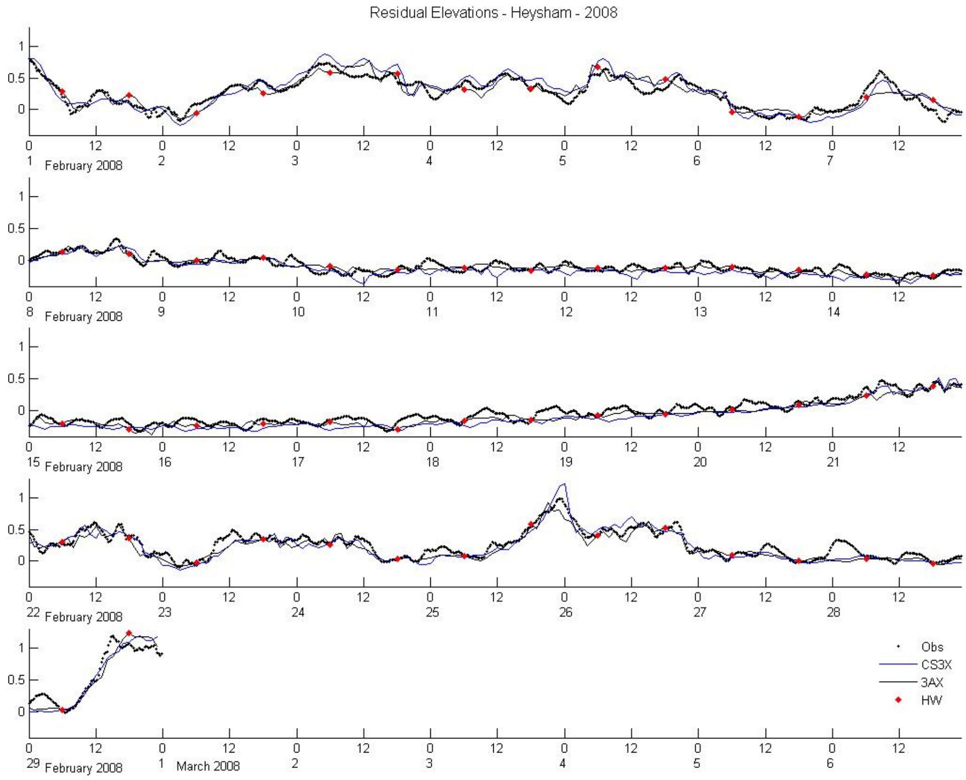
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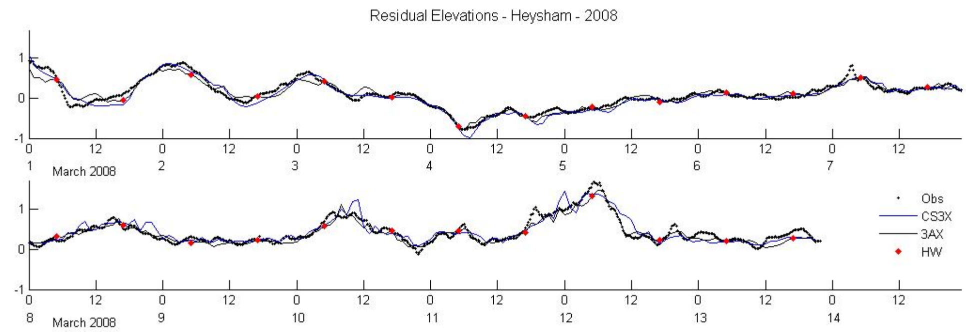
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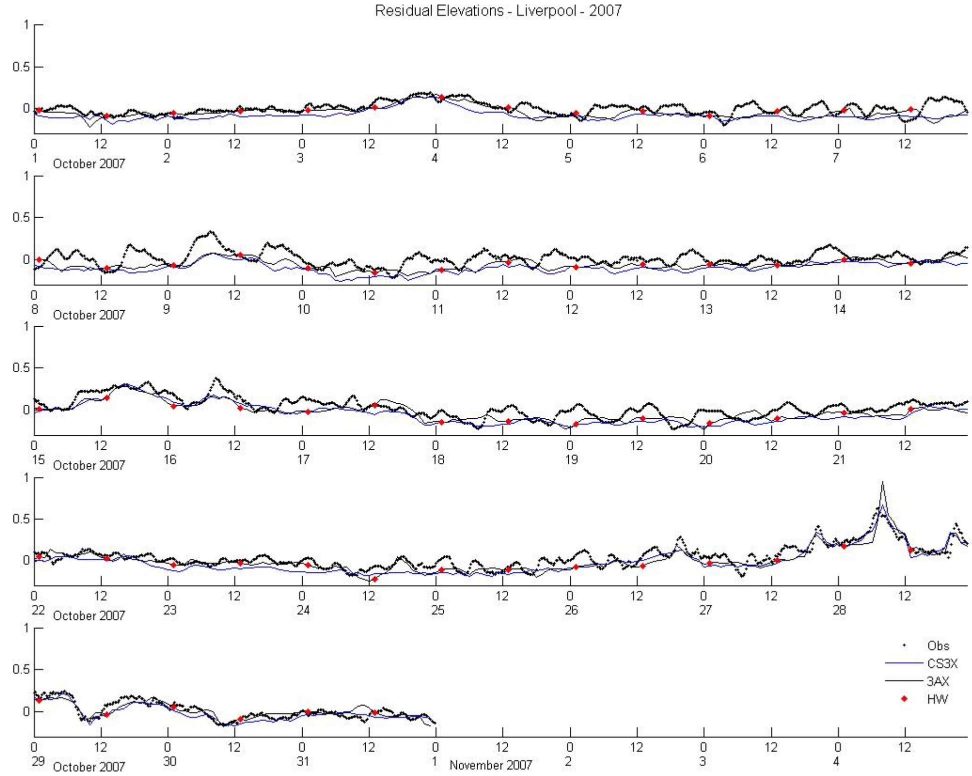
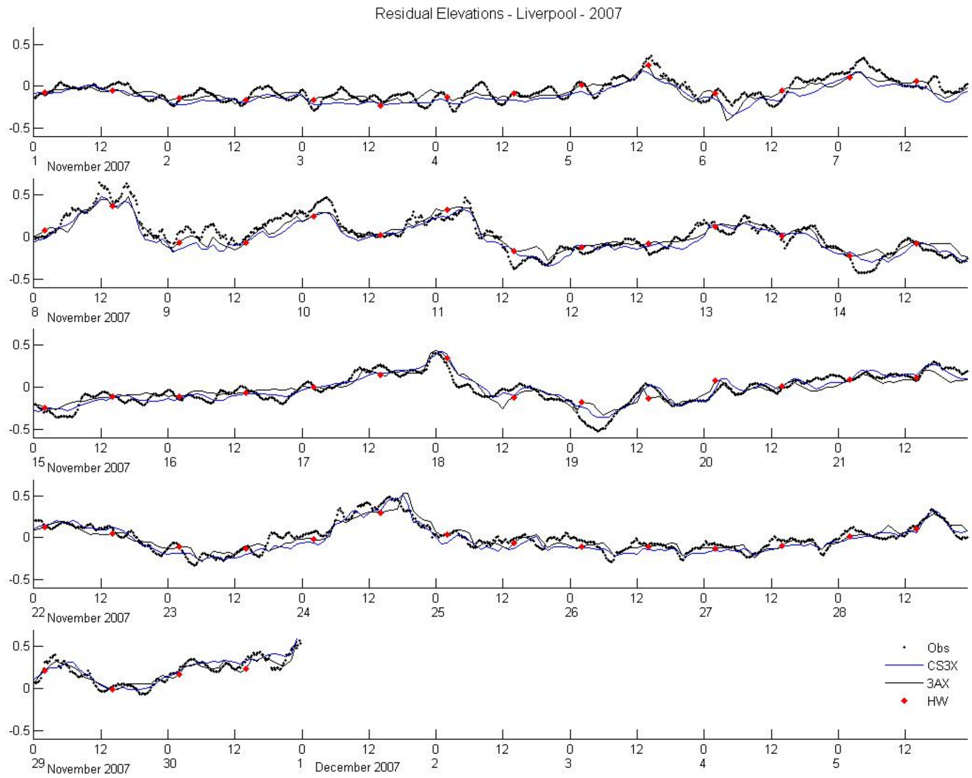
3AX
HW

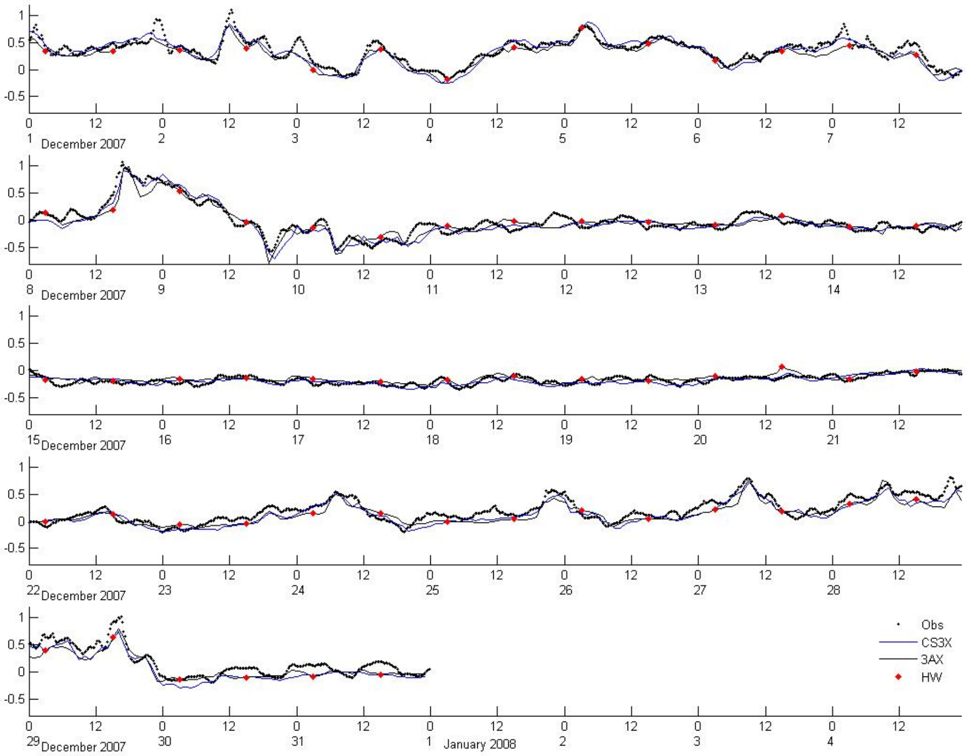


Residual Elevations - Liverpool - 2007
October 2007
November 2007
Obs
CS3X
3AX
HW

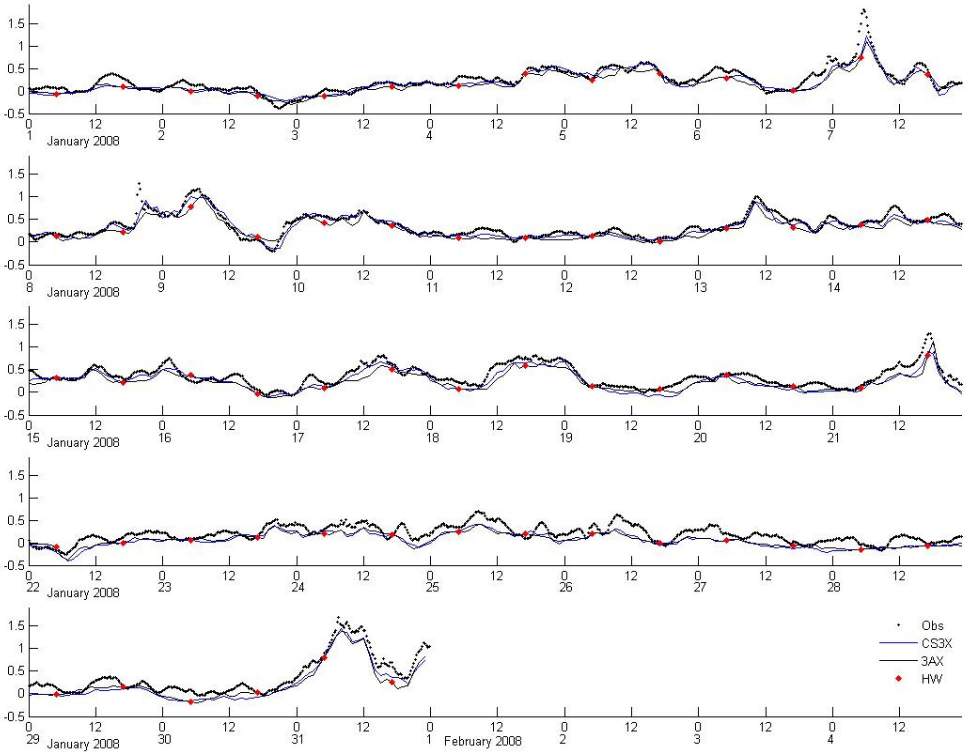


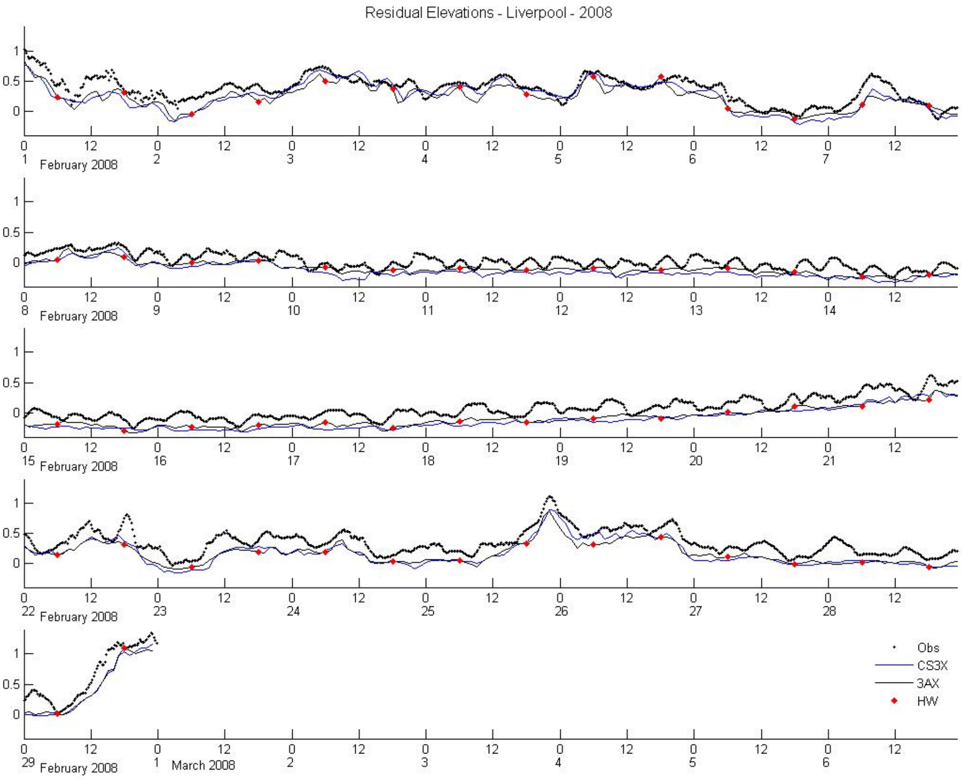
Residual Elevations - Liverpool - 2007
November 2007
December 2007
Obs
CS3X
3AX
HW

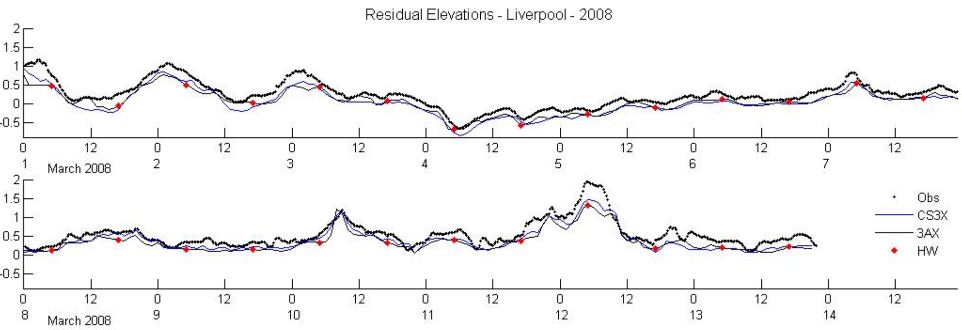
Residual Elevations - Liverpool - 2007

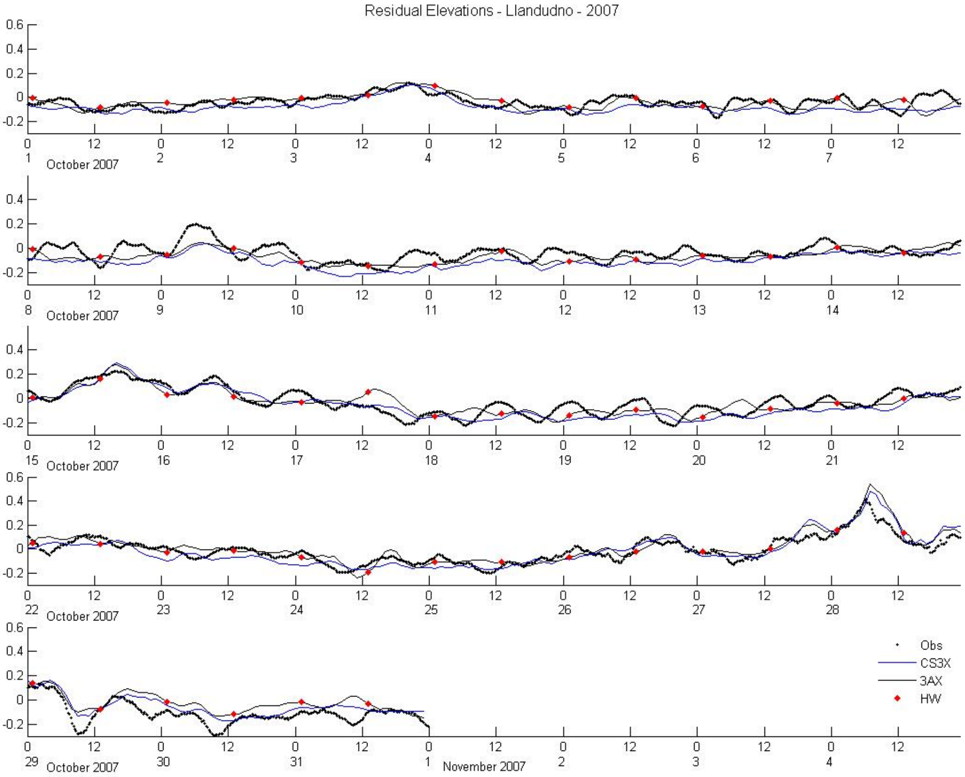


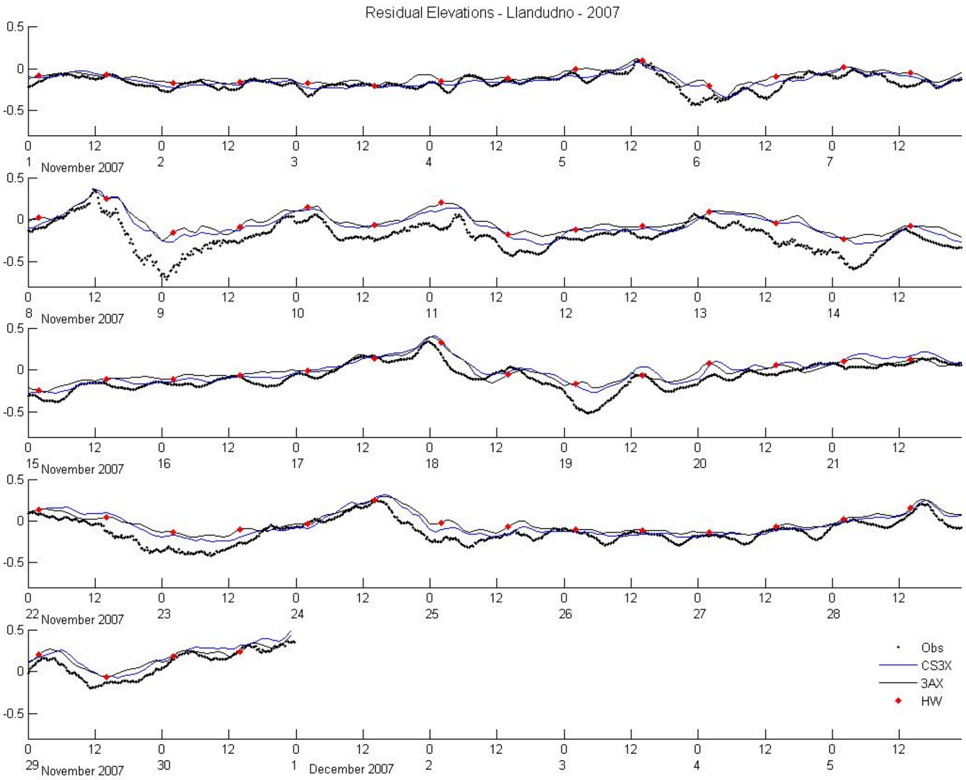
Residual Elevations - Liverpool - 2008

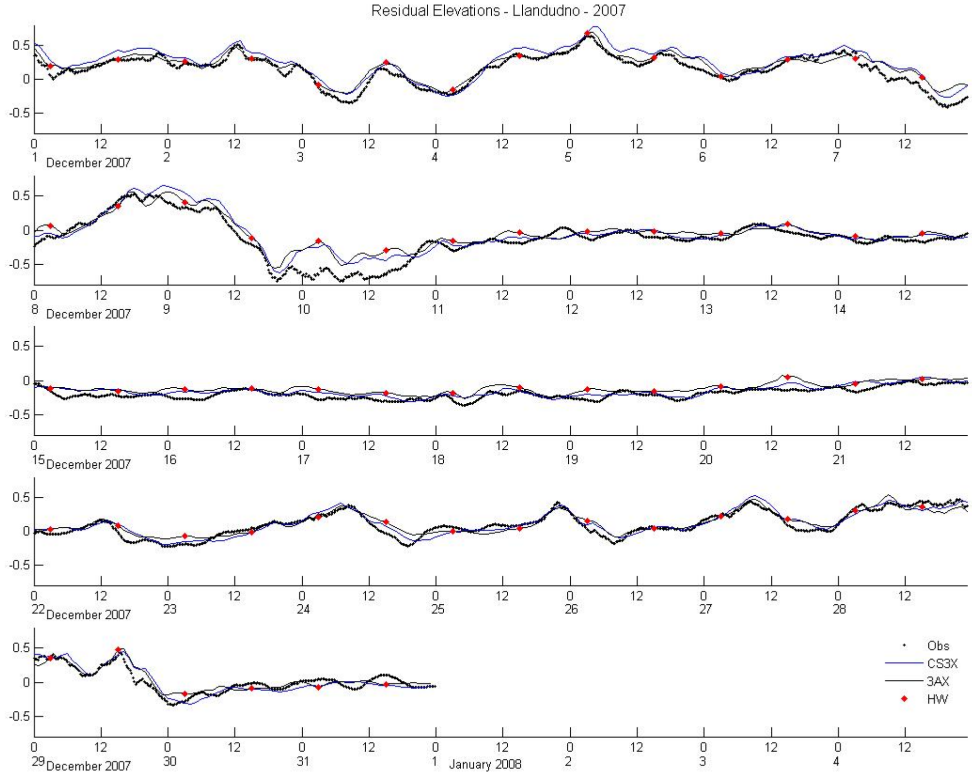



Residual Elevations - Liverpool - 2008
February 2008
March 2008
Obs
CS3X
3AX
HW

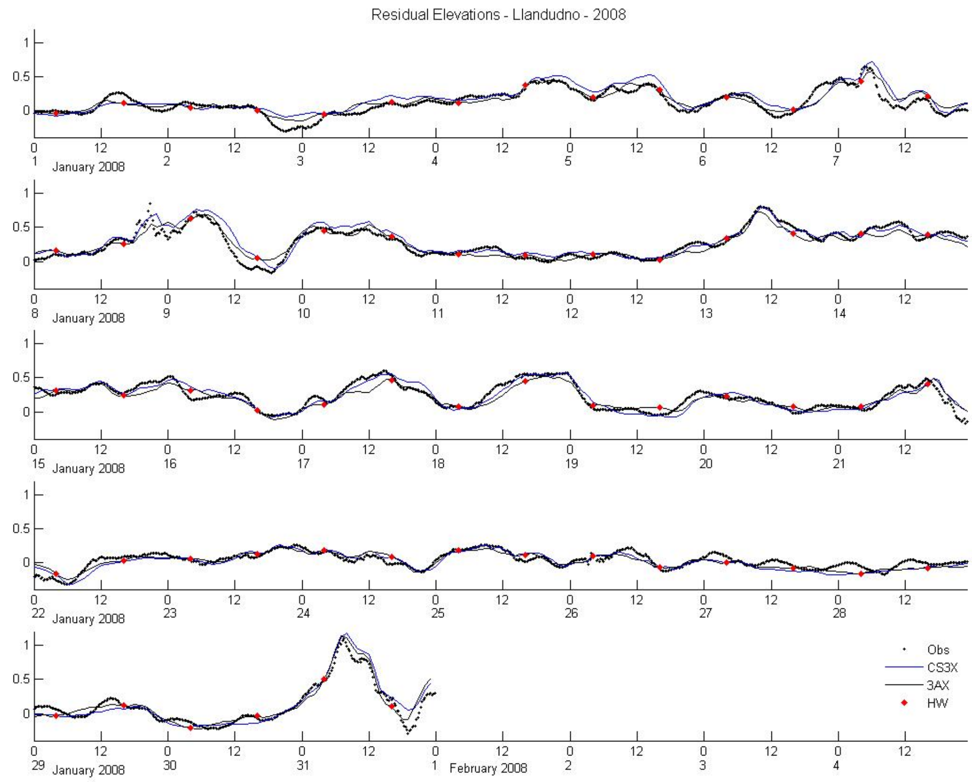

Residual Elevations - Liverpool - 2008
March 2008
Obs
CS3X
3AX
HW


Residual Elevations - Llandudno - 2007
October 2007
November 2007
Obs
CS3X
3AX
HW

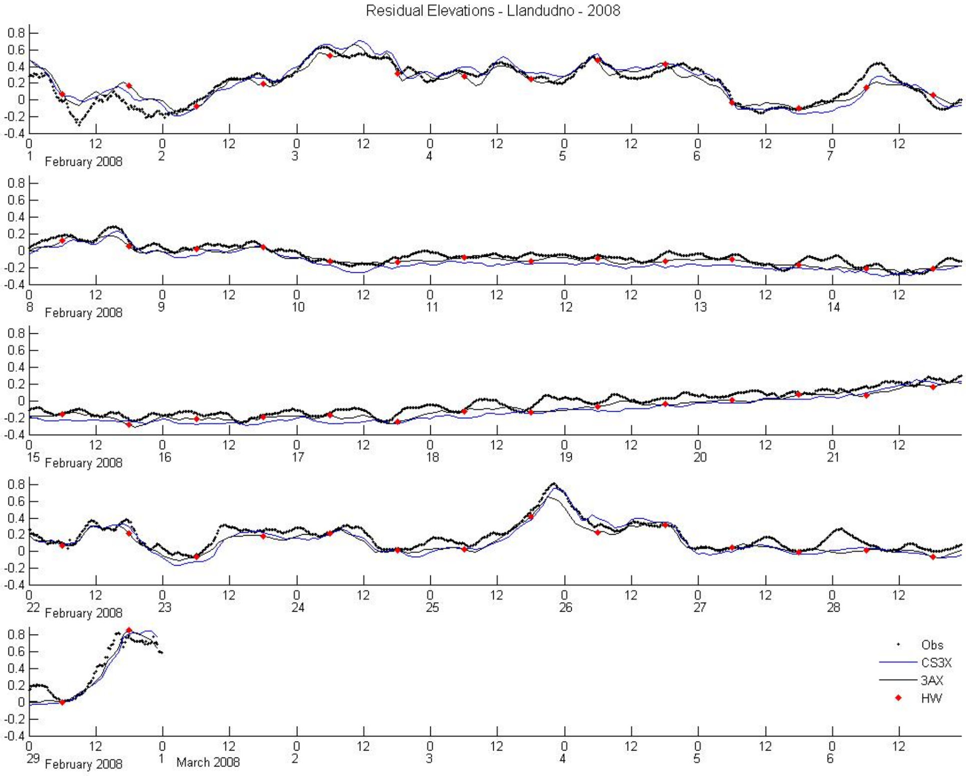

Residual Elevations - Llandudno - 2007
November 2007
December 2007
Obs
CS3X
3AX
HW

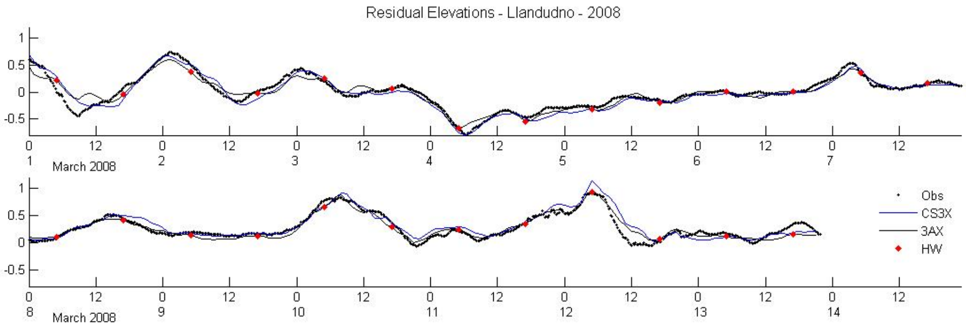


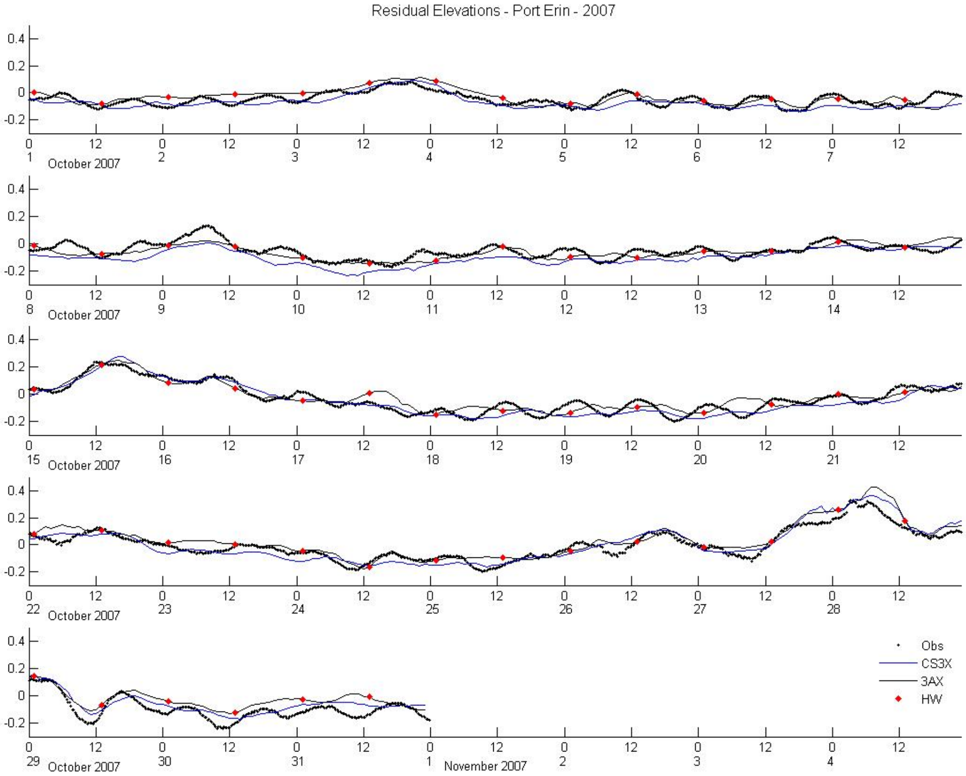
Residual Elevations - Llandudno - 2007
December 2007
January 2008
Obs
CS3X
3AX
HW

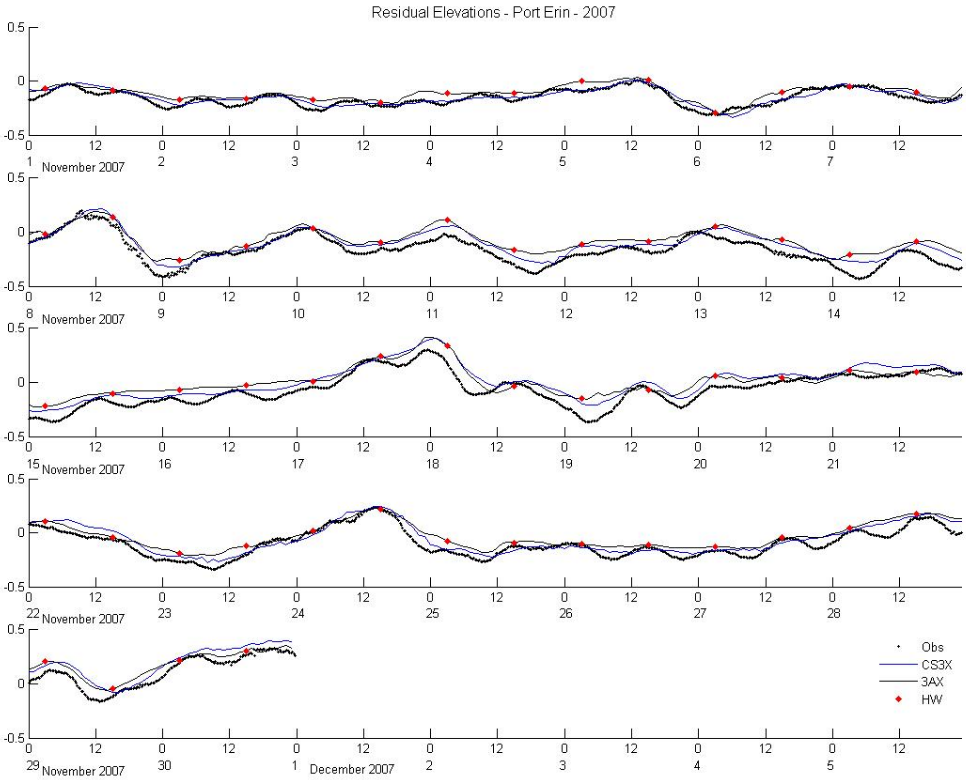


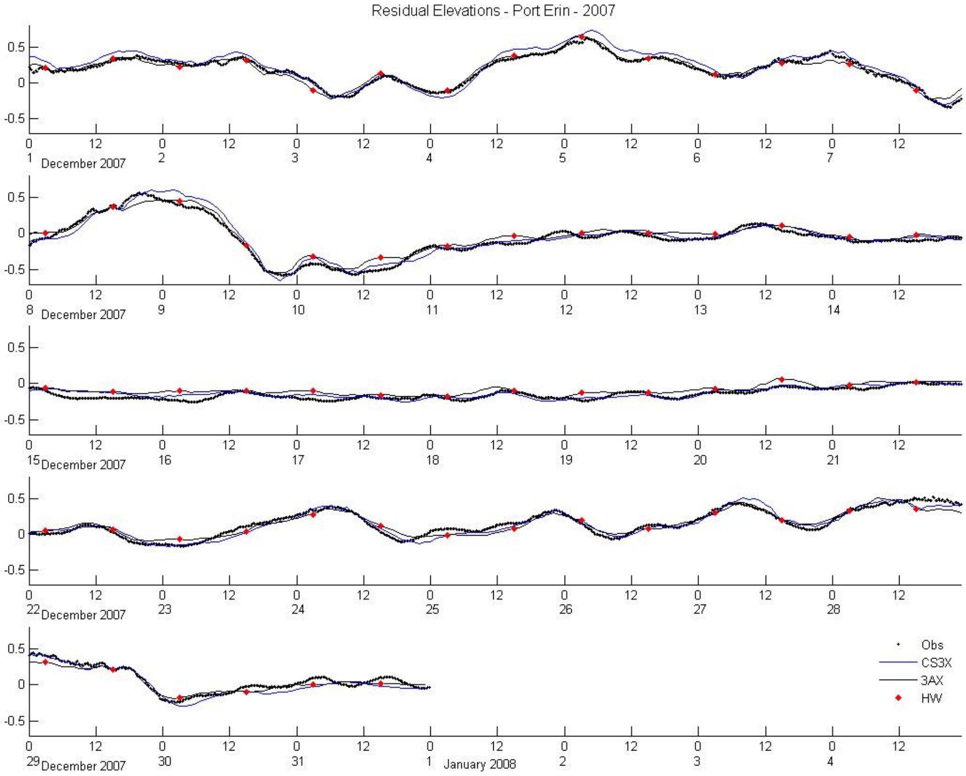
Residual Elevations - Llandudno - 2008
January 2008
February 2008
Obs
CS3X
3AX
HW

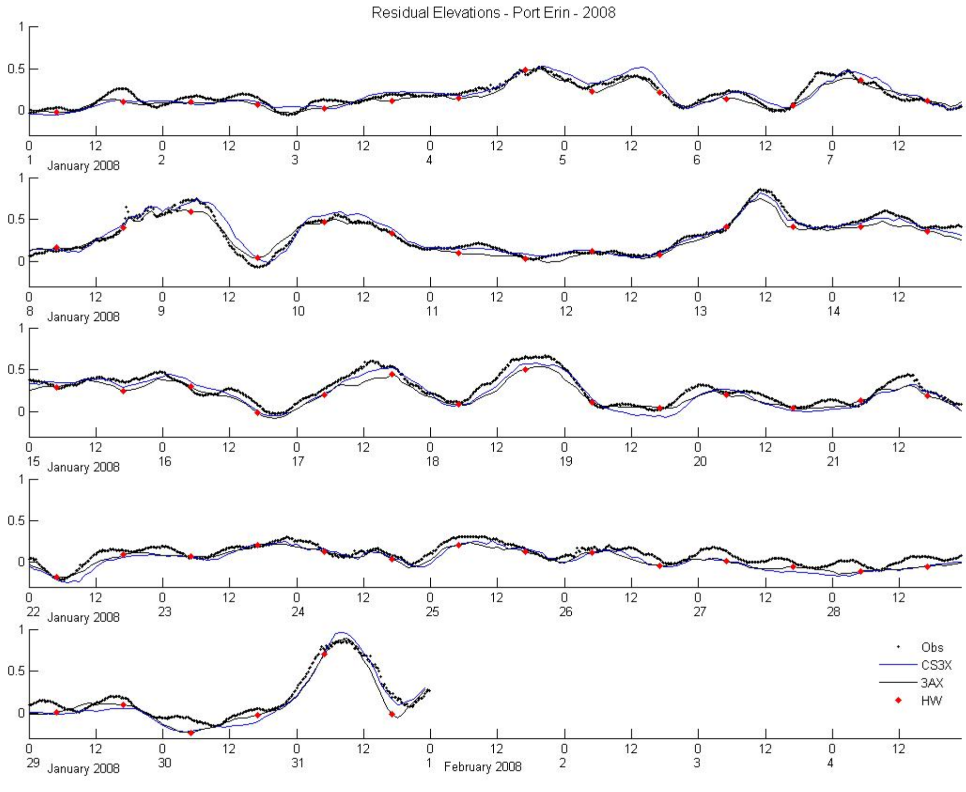

Residual Elevations - Llandudno - 2008
February 2008
March 2008
Obs
CS3X
3AX
HW

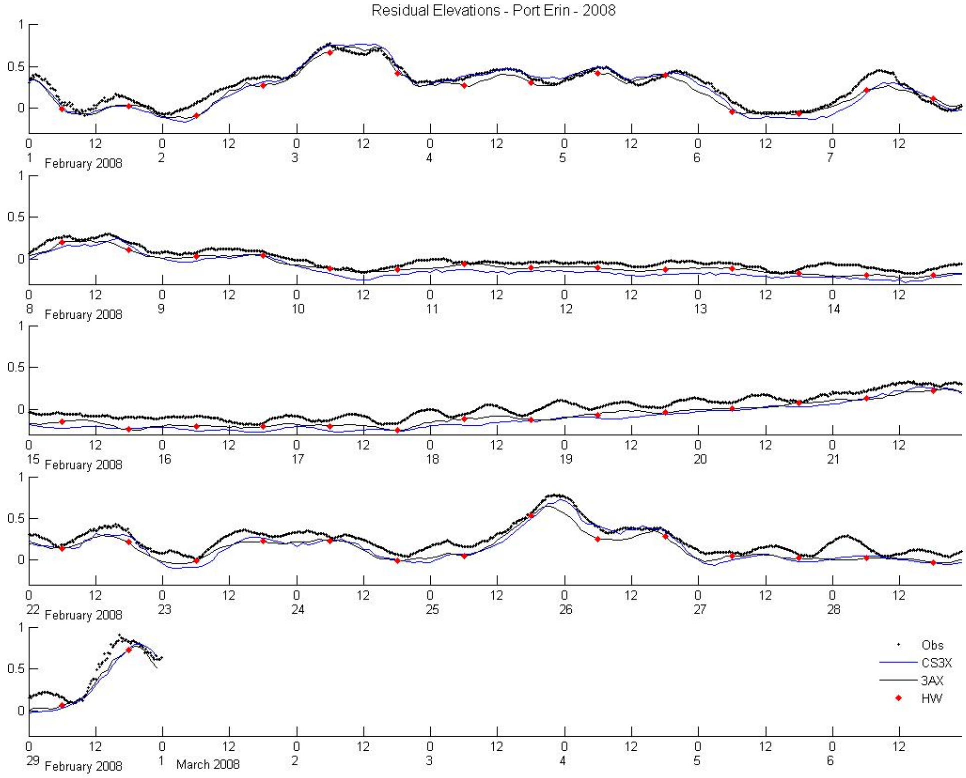

Residual Elevations - Llandudno - 2008
March 2008
Obs
CS3X
3AX
HW

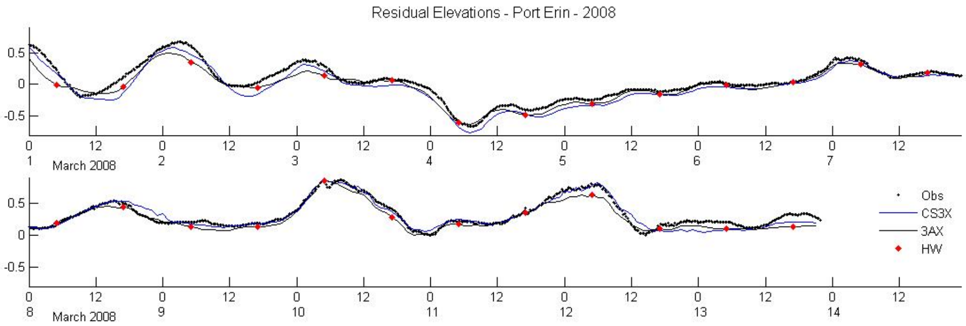

Residual Elevations - Port Erin - 2007
October 2007
November 2007
Obs
CS3X
3AX
HW


Residual Elevations - Port Erin - 2007
November 2007
December 2007
Obs
CS3X
3AX
HW

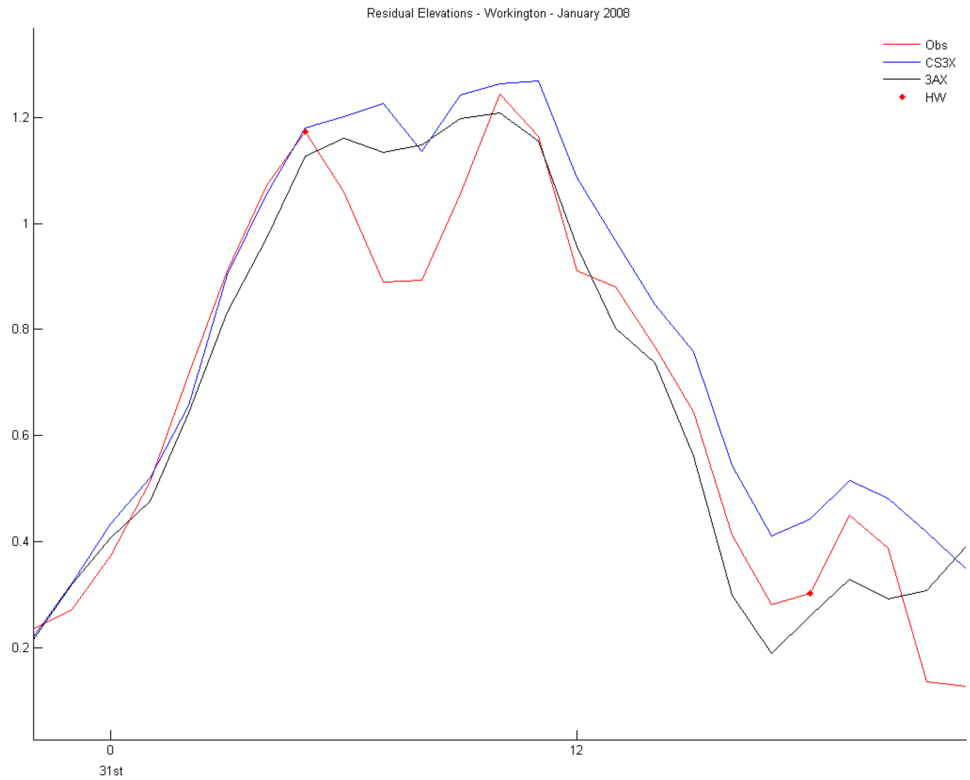

Residual Elevations - Port Erin - 2007
December 2007
January 2008
Obs
CS3X
3AX
HW


Residual Elevations - Port Erin - 2008
January 2008
February 2008
Obs
CS3X
3AX
HW

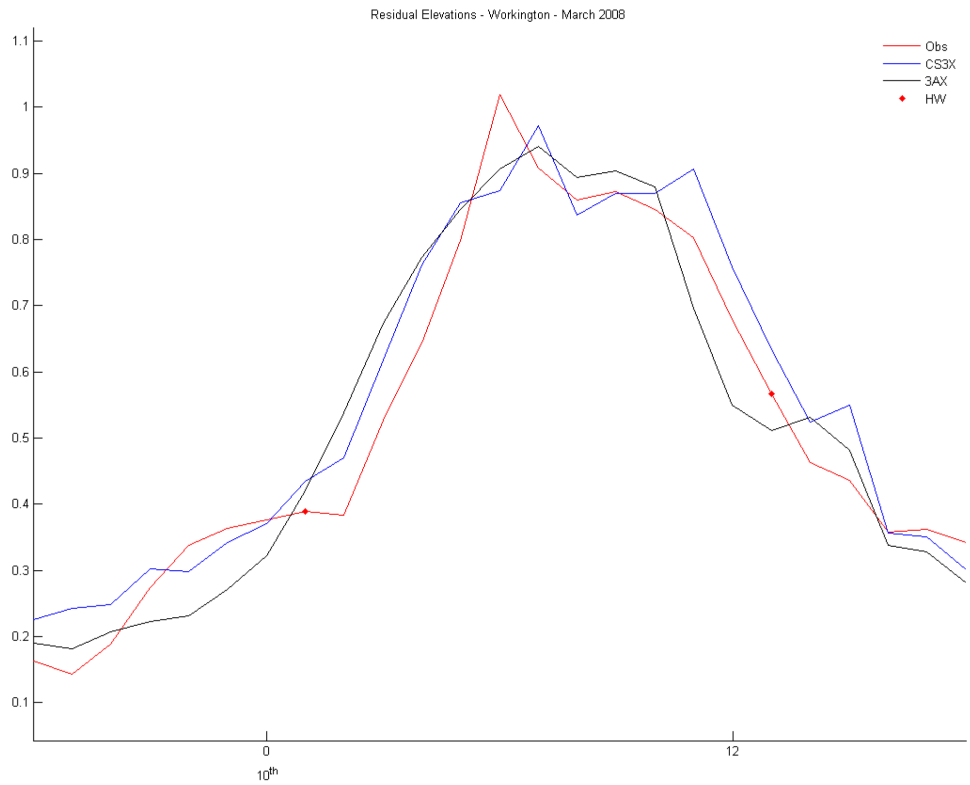

Residual Elevations - Port Erin - 2008
February 2008
March 2008
Obs
CS3X
3AX
HW


Residual Elevations - Port Erin - 2008
March 2008
Obs
CS3X
3AX
HW

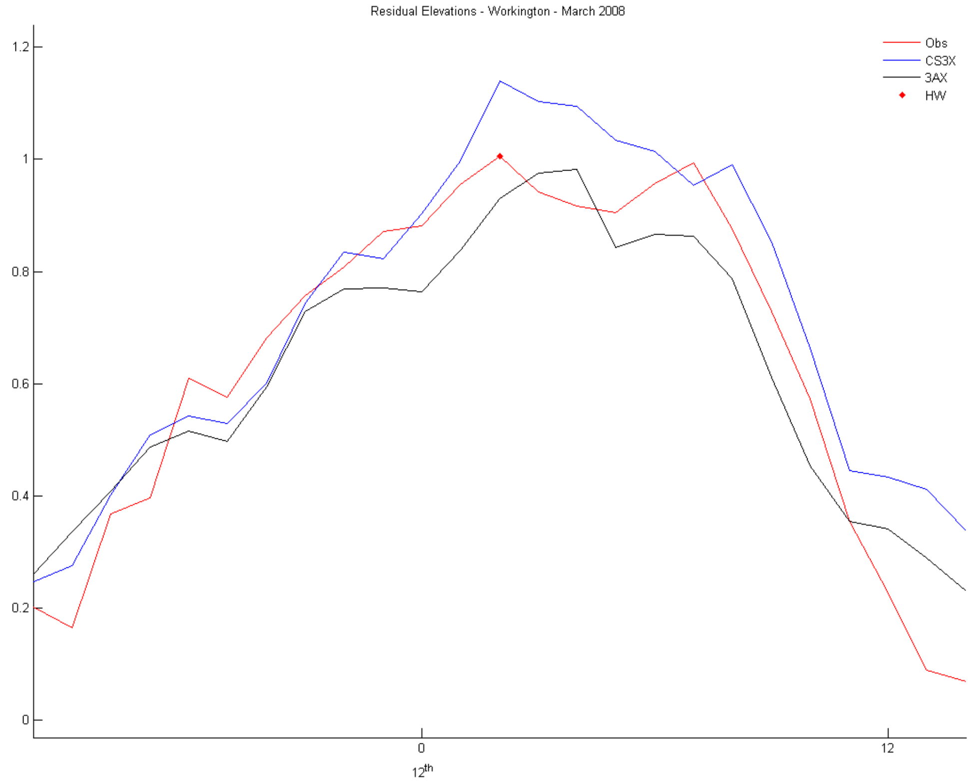
Appendix 2



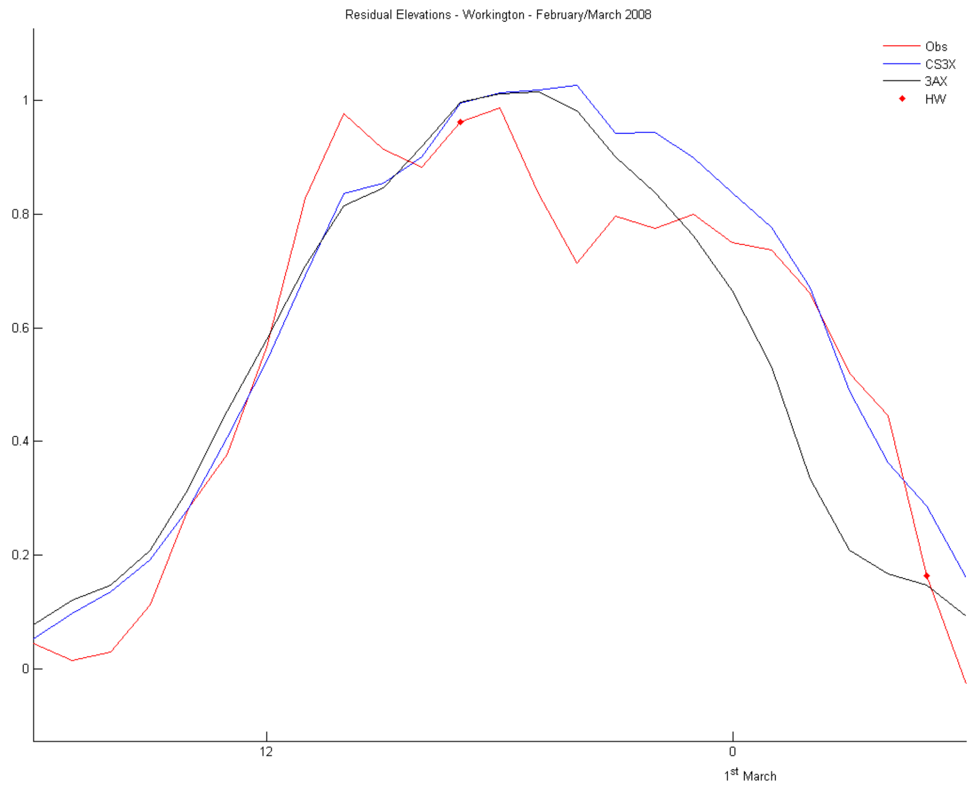
Residual Elevations - Workington - January 2008
Obs
CS3X
3AX
HW
1.2
1
0.8
0.6
0.4
0.2
0
12
31st



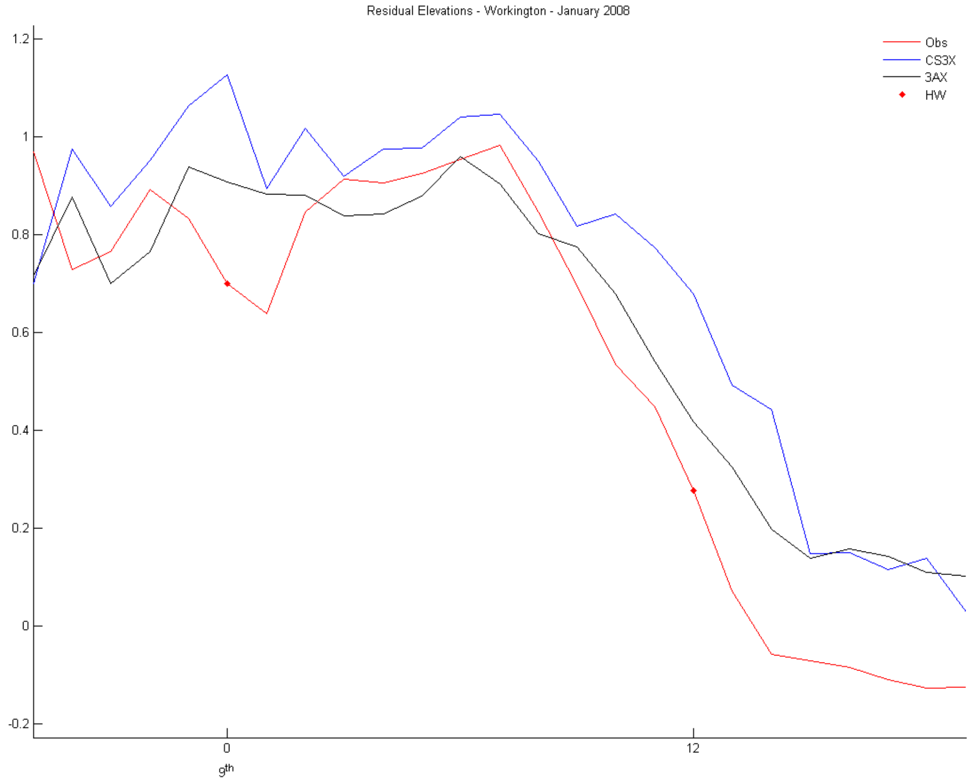
Residual Elevations - Workington - March 2008
Obs
CS3X
3AX
HW
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12
10th

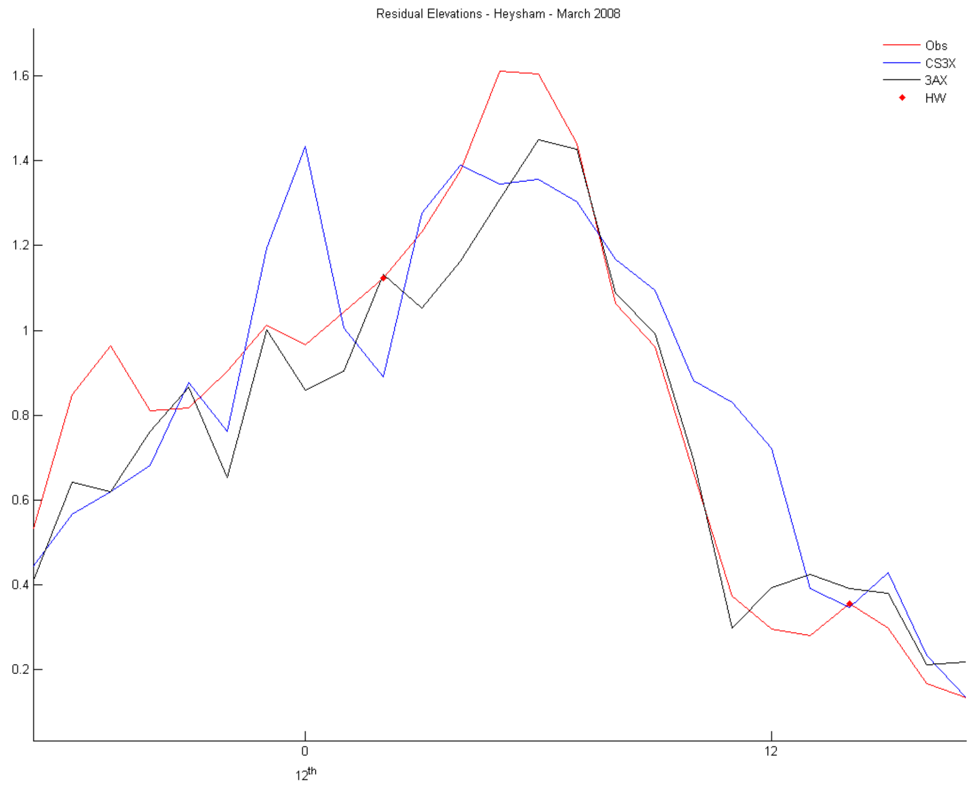


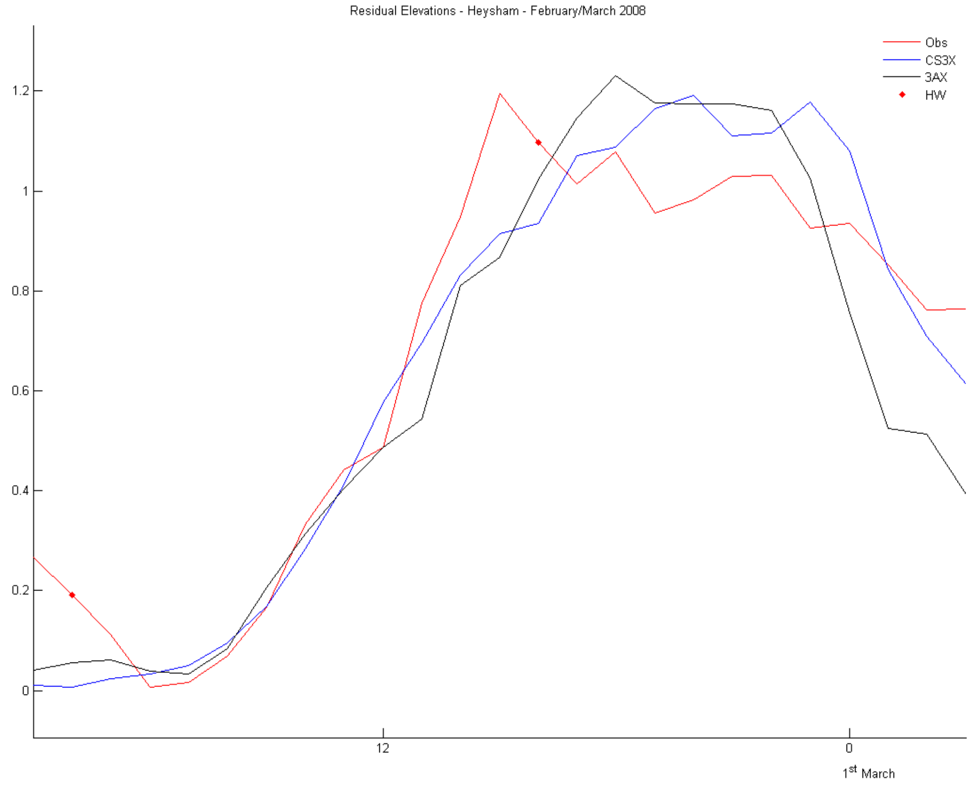
Residual Elevations - Workington - March 2008
Obs
CS3X
3AX
HW
1.2
1
0.8
0.6
0.4
0.2
0
0
12
12th

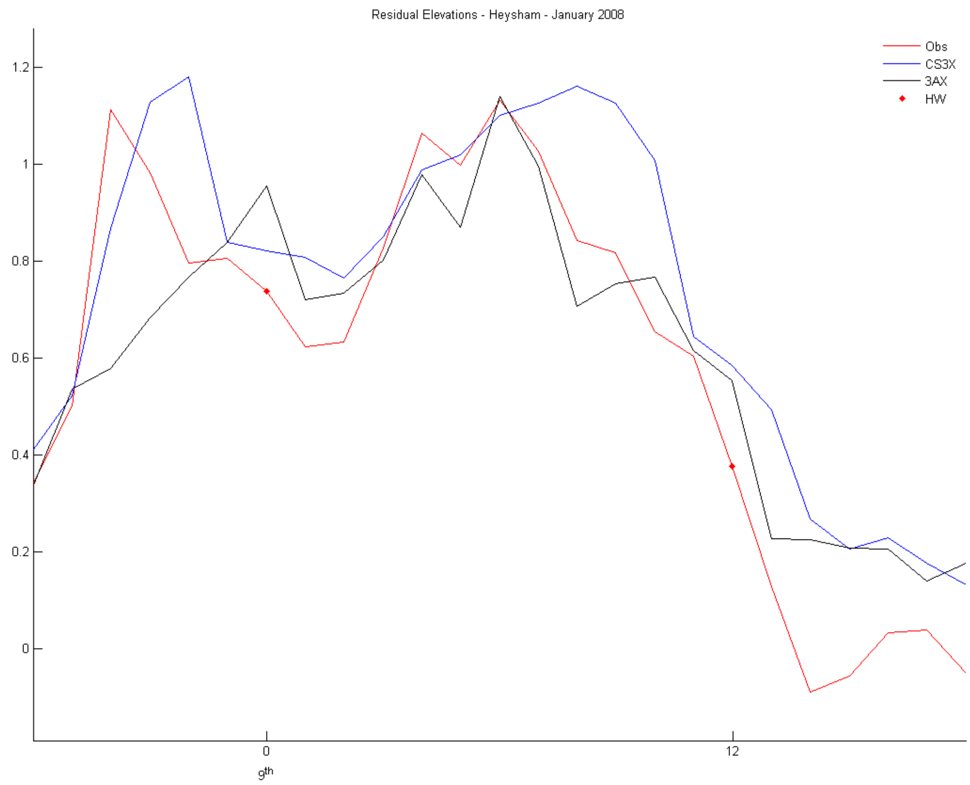


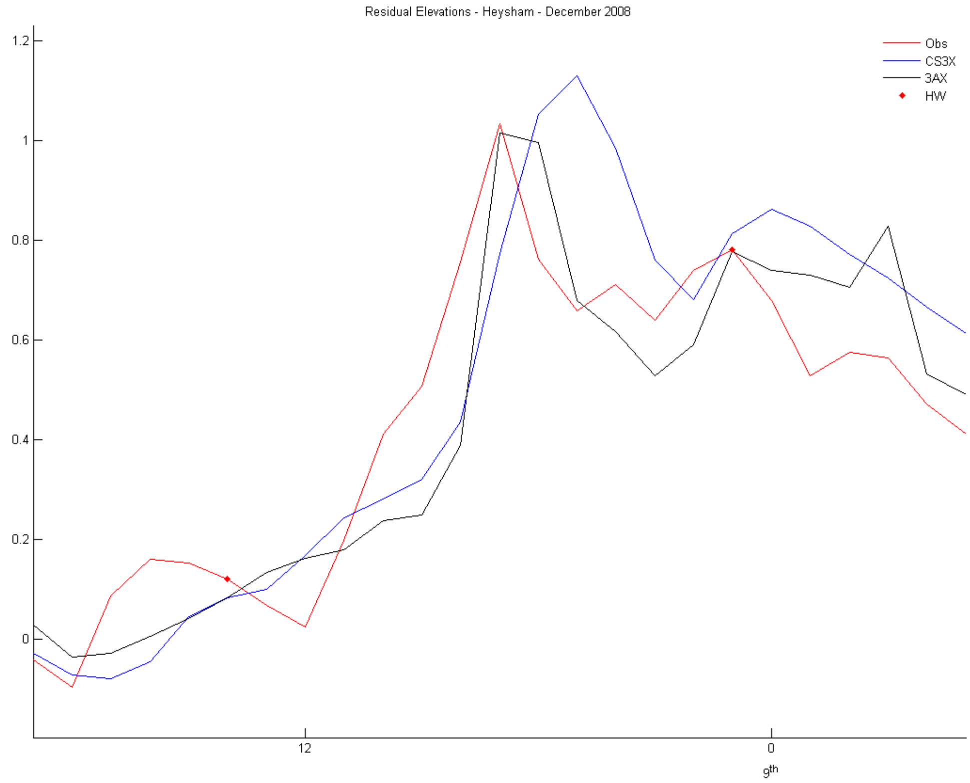
Residual Elevations - Workington - February/March 2008
Obs
CS3X
3AX
HW
1
0.8
0.6
0.4
0.2
0
12
0
1st March

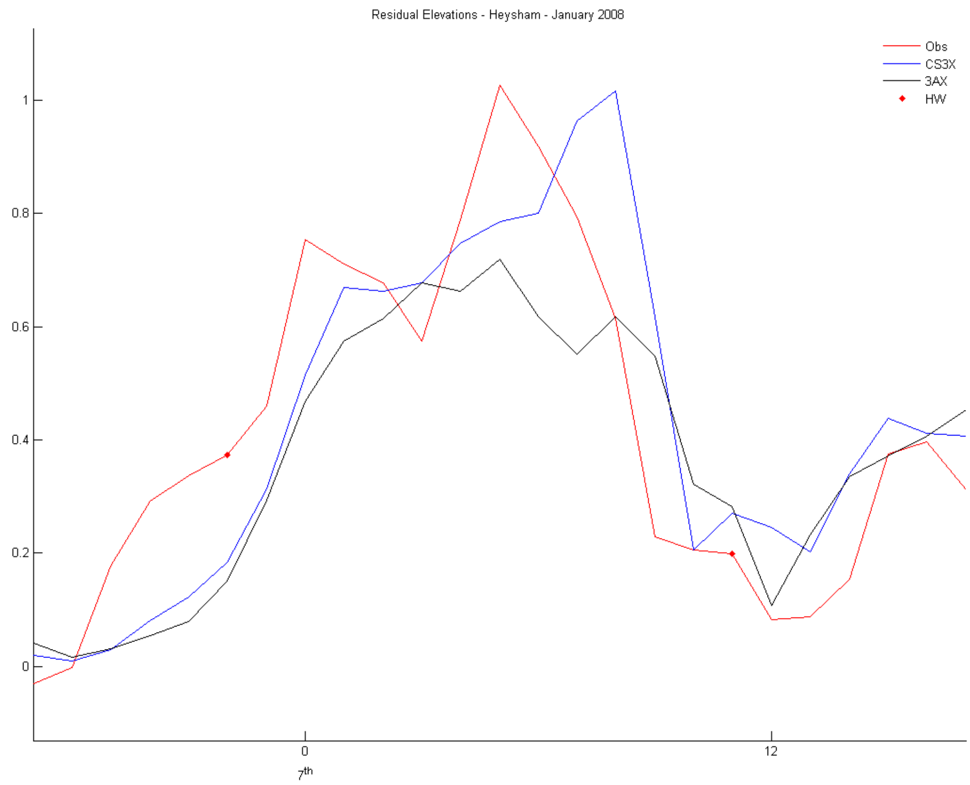

Residual Elevations - Workington - January 2008
Obs
CS3X
3AX
HW
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
12
9th

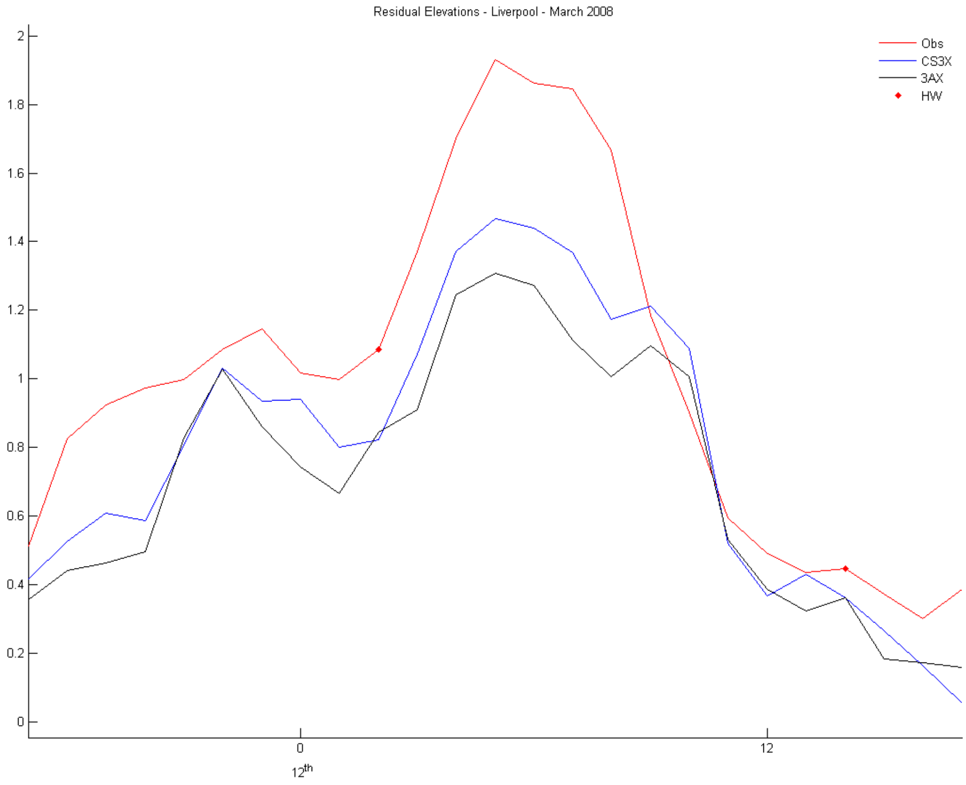

Residual Elevations - Heysham - March 2008
Obs
CS3X
3AX
HW
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
12
12th

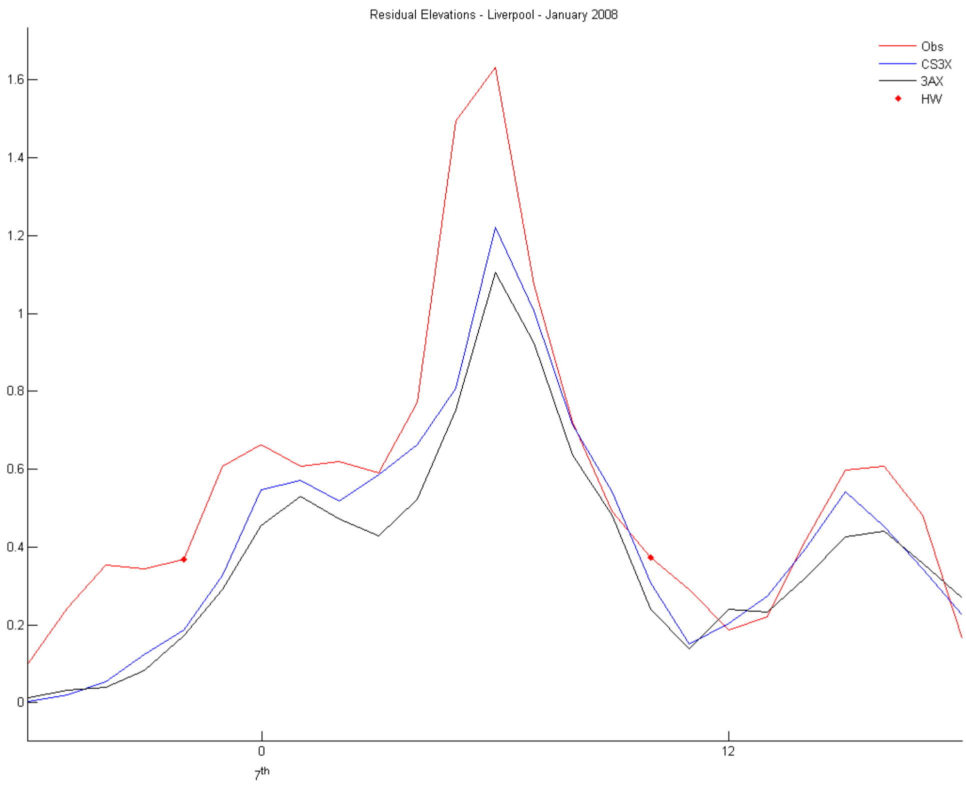

Residual Elevations - Heysham - February/March 2008
Obs
CS3X
3AX
HW
1.2
1
0.8
0.6
0.4
0.2
0
12
0
1st March

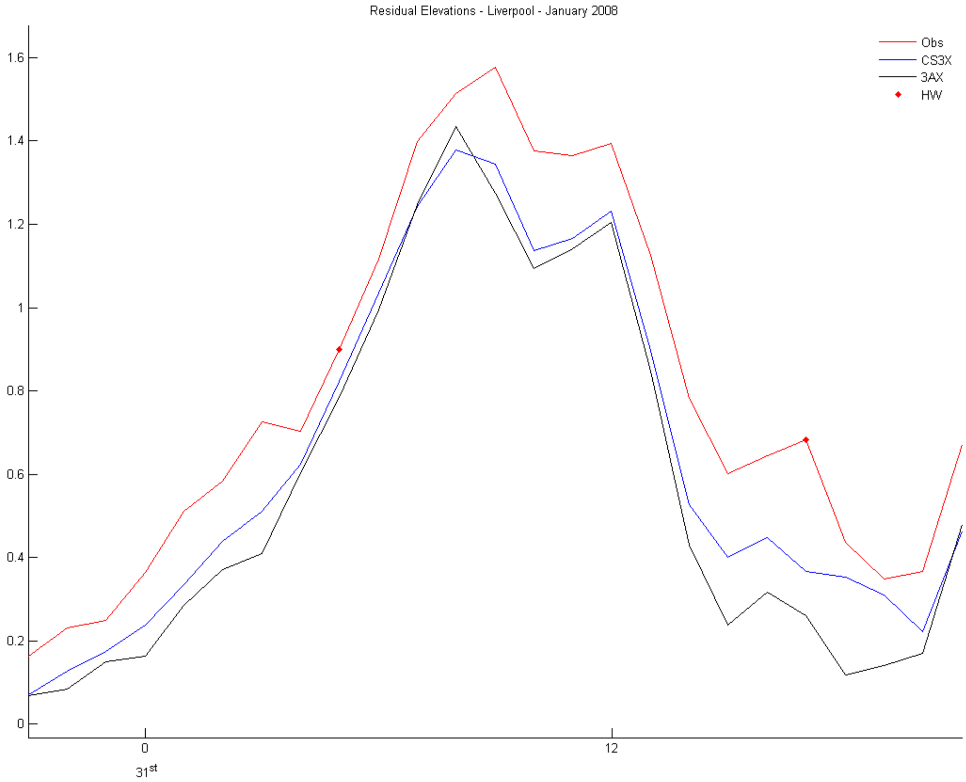

Residual Elevations - Heysham - January 2008
Obs
CS3X
3AX
HW
1.2
1
0.8
0.6
0.4
0.2
0
0
12
9th

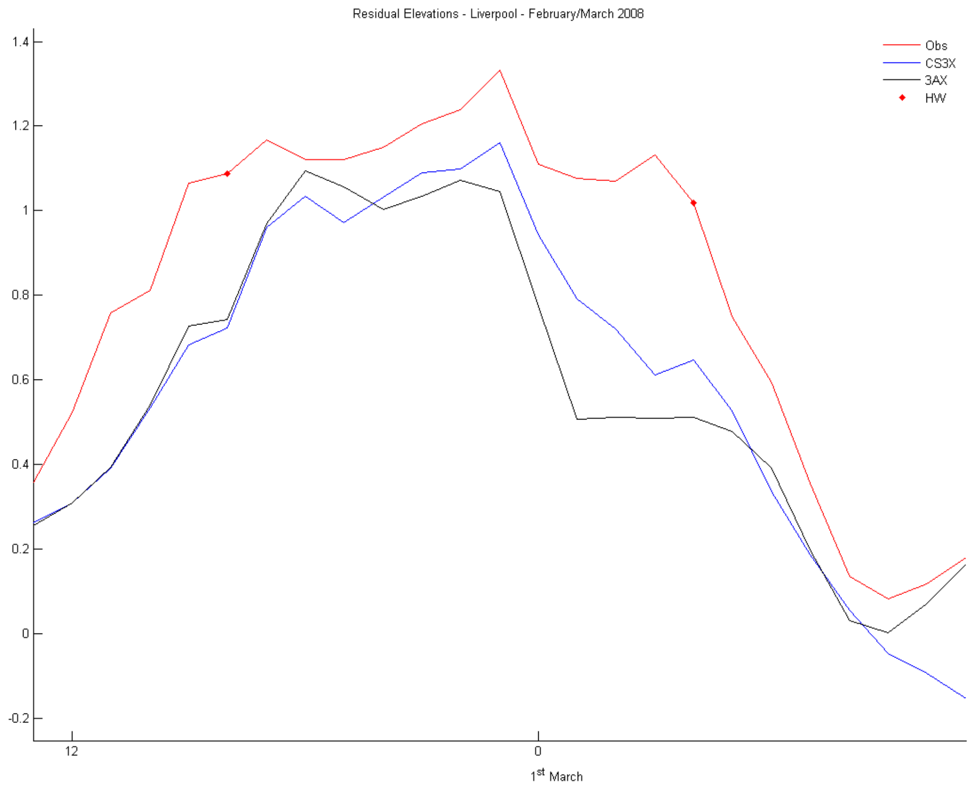

Residual Elevations - Heysham - December 2008
Obs
CS3X
3AX
HW
1.2
1
0.8
0.6
0.4
0.2
0
12
0
9th

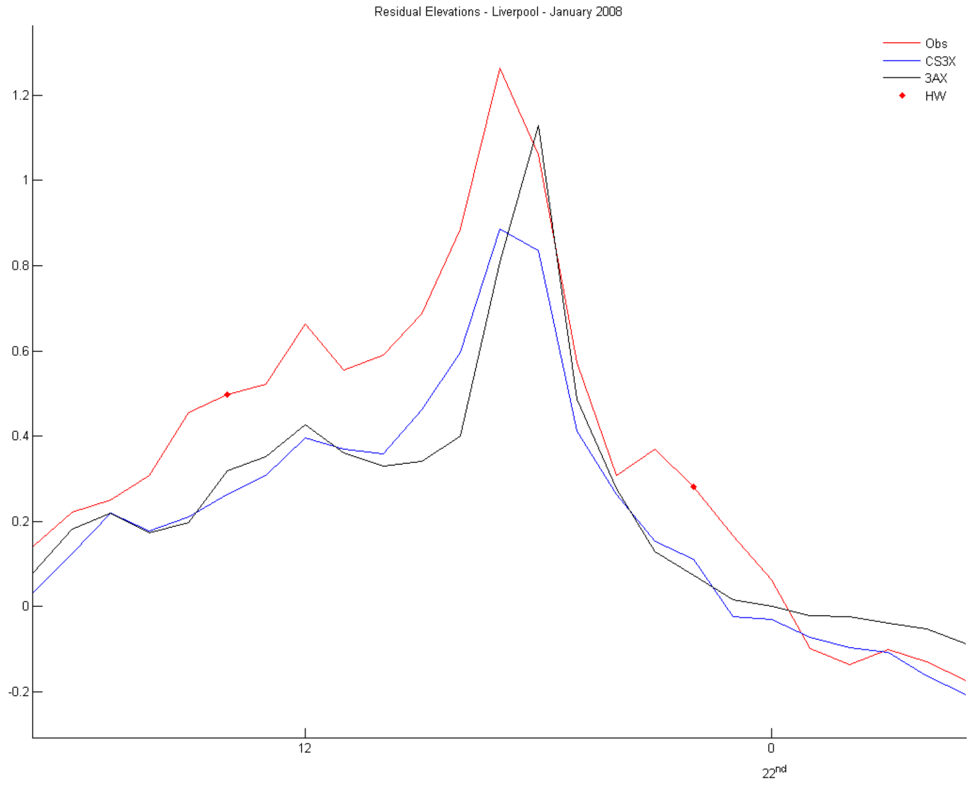

Residual Elevations - Heysham - January 2008
Obs
CS3X
3AX
HW
1
0.8
0.6
0.4
0.2
0
0
12
7th


Residual Elevations - Liverpool - March 2008
Obs
CS3X
3AX
HW
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
12
12th

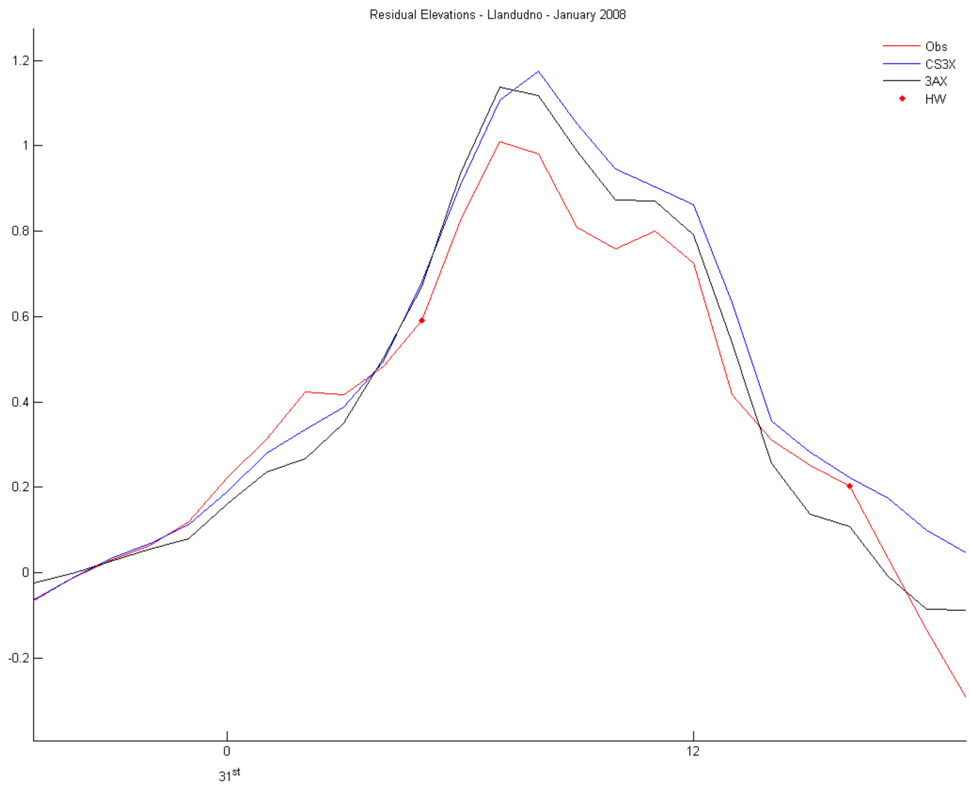

Residual Elevations - Liverpool - January 2008
Obs
CS3X
3AX
HW
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
12
7th


Residual Elevations - Liverpool - January 2008
Obs
CS3X
3AX
HW
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
12
31st

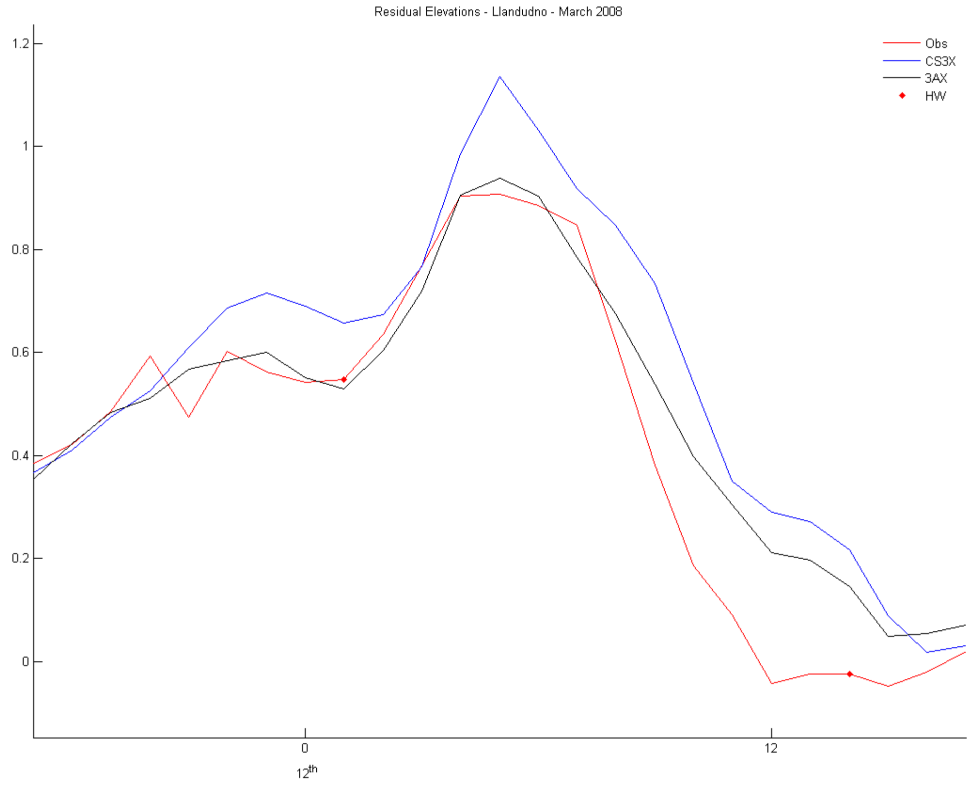

Residual Elevations - Liverpool - February/March 2008
Obs
CS3X
3AX
HW
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
12
0
1st March



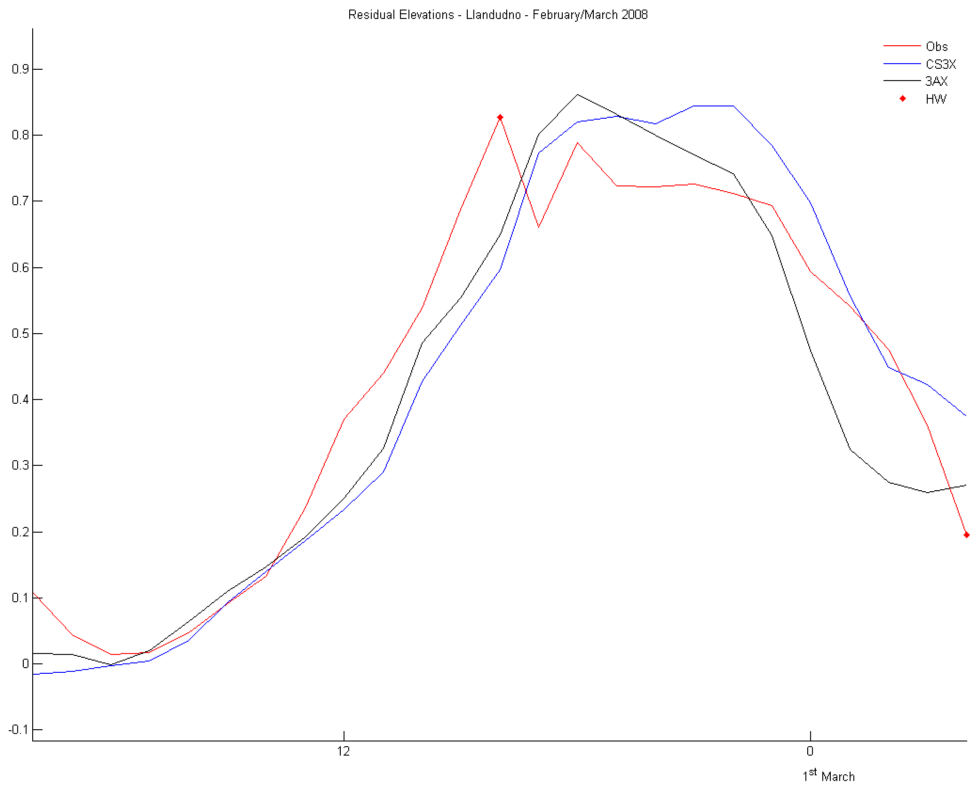
Residual Elevations - Liverpool - January 2008
Obs
CS3X
3AX
HW
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
12
0
22nd



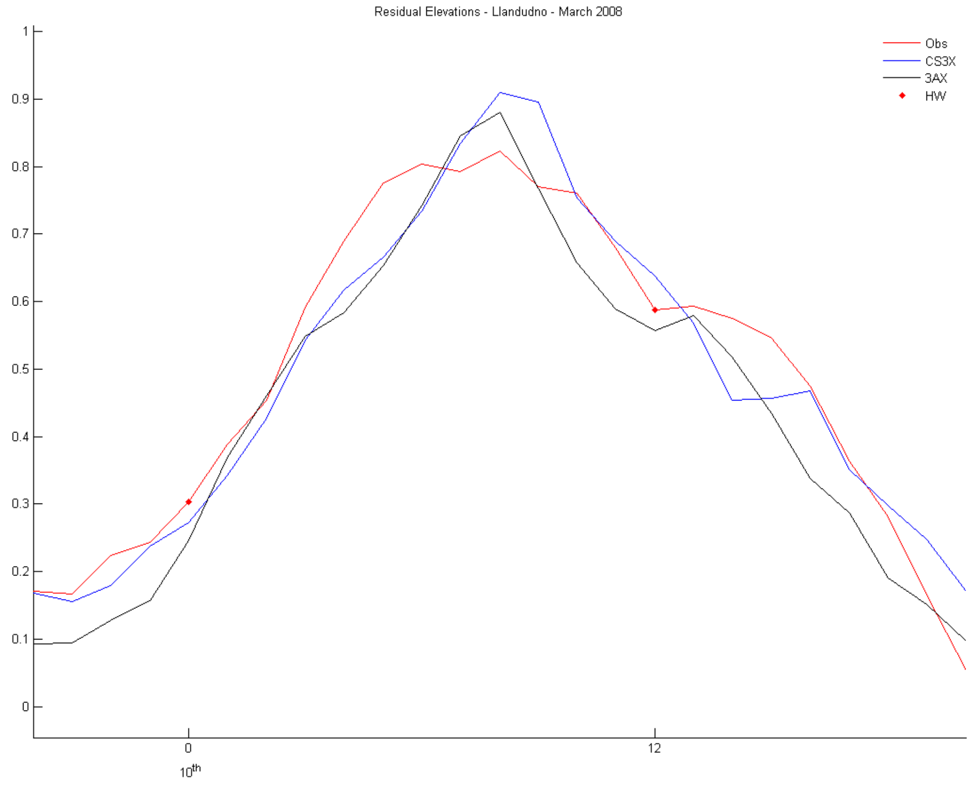
Residual Elevations - Llandudno - January 2008
Obs
CS3X
3AX
HW
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
12
31st

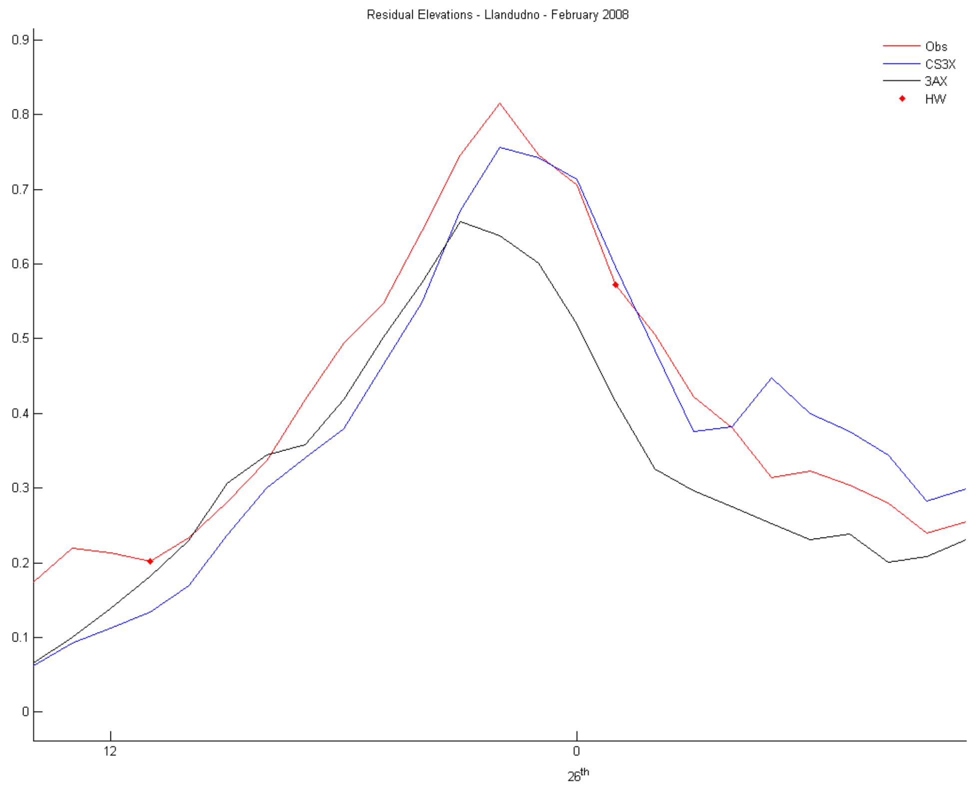


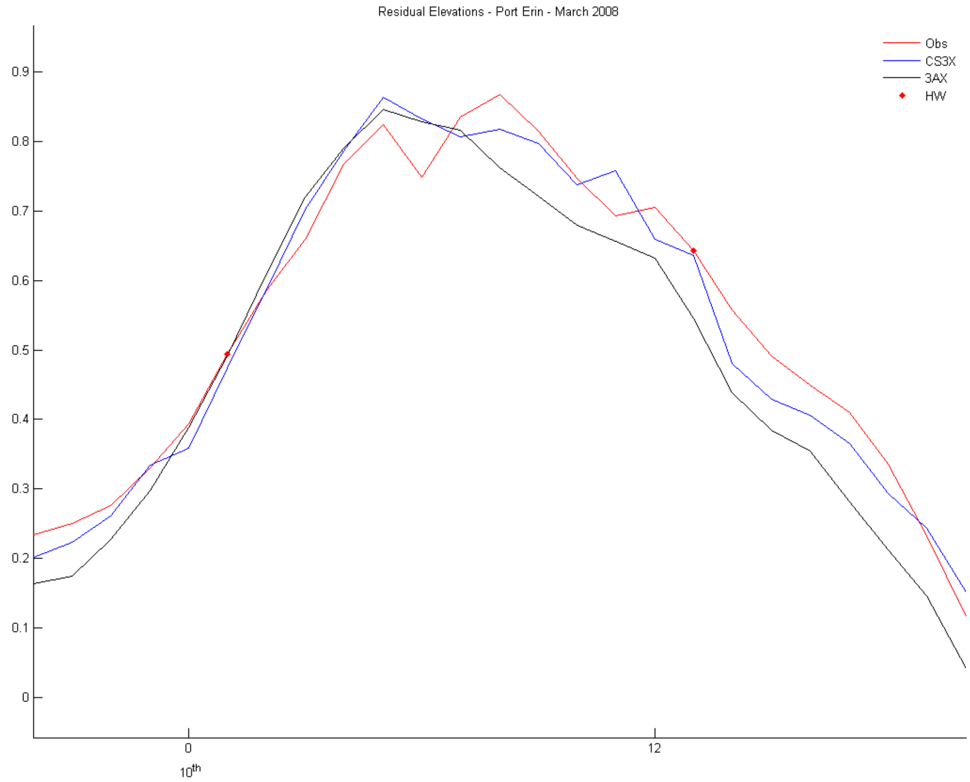
Residual Elevations - Llandudno - March 2008
Obs
CS3X
3AX
HW
1.2
1
0.8
0.6
0.4
0.2
0
0
12
12th

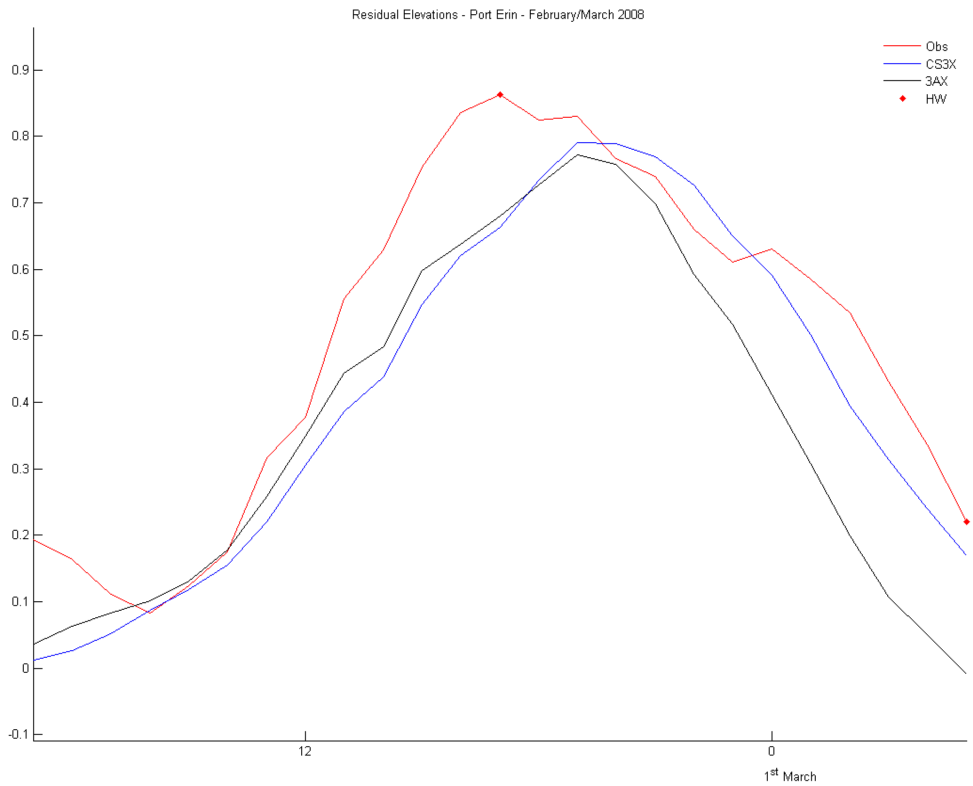


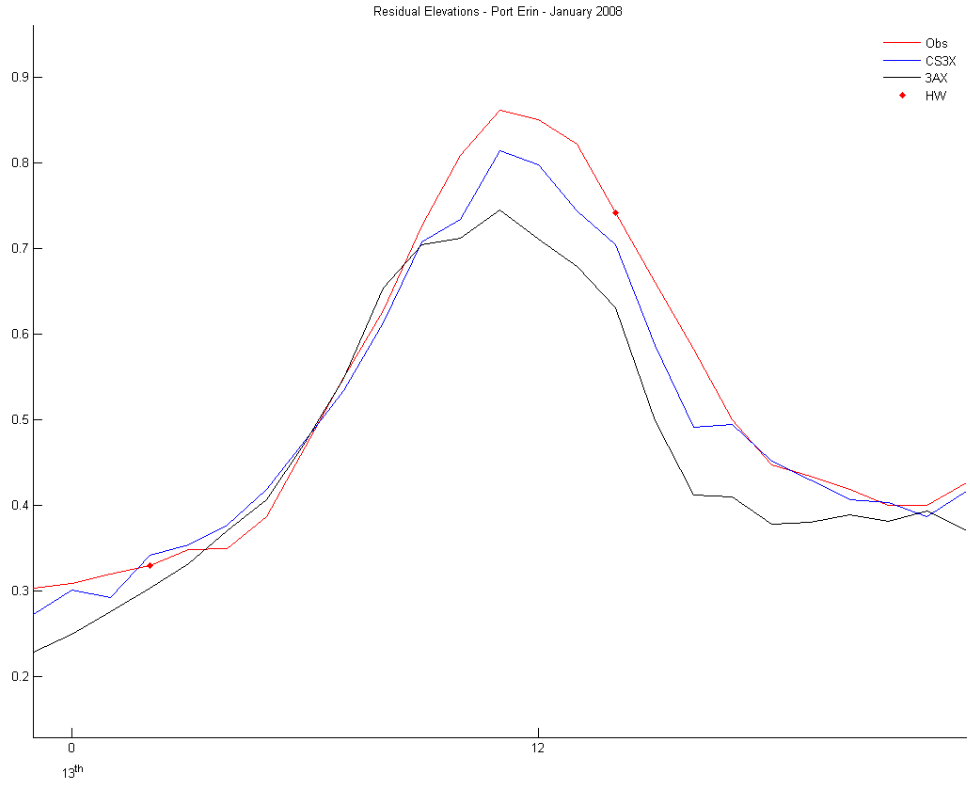
Residual Elevations - Llandudno - February/March 2008
Obs
CS3X
3AX
HW
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
12
0
1st March


Residual Elevations - Llandudno - March 2008
Obs
CS3X
3AX
HW
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
12
10th

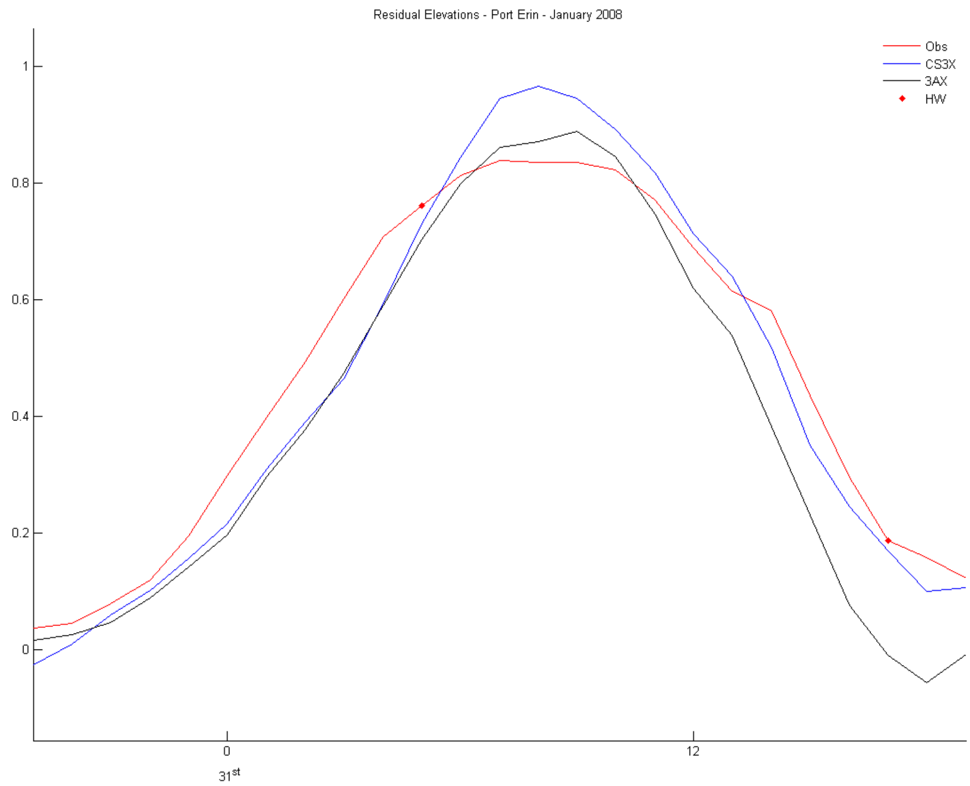

Residual Elevations - Llandudno - February 2008
Obs
CS3X
3AX
HW
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12
0
26th


Residual Elevations - Port Erin - March 2008
Obs
CS3X
3AX
HW
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
12
10th

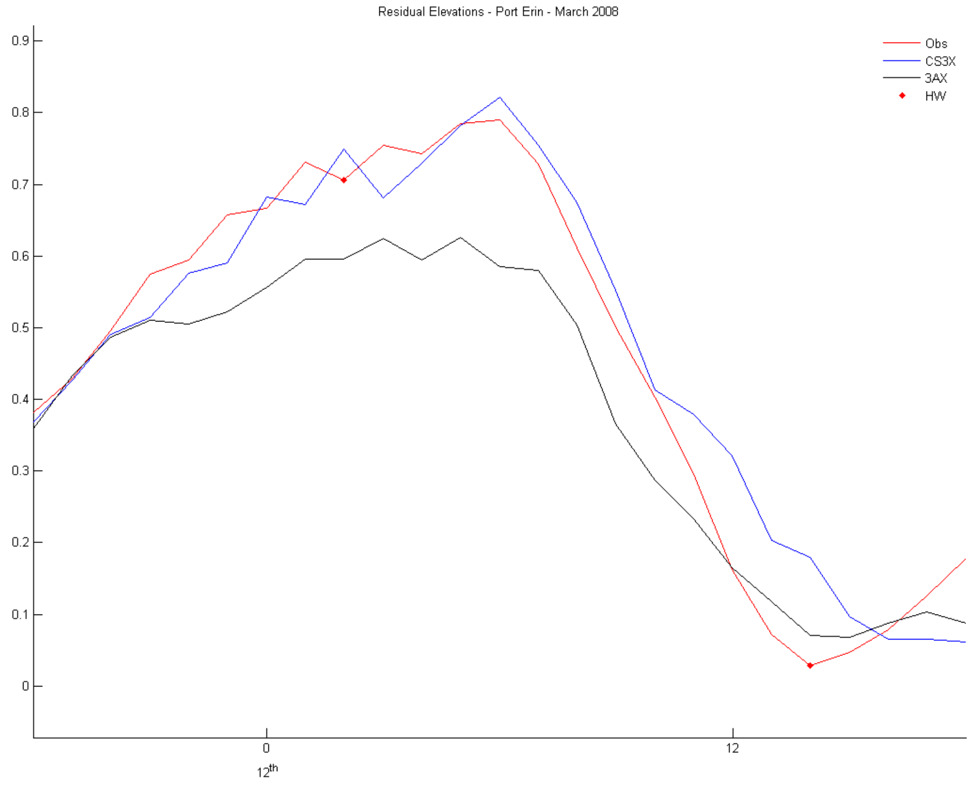

Residual Elevations - Port Erin - February/March 2008
Obs
CS3X
3AX
HW
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
12
0
1st March



Residual Elevations - Port Erin - January 2008
Obs
CS3X
3AX
HW
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
12
13th



Residual Elevations - Port Erin - January 2008
Obs
CS3X
3AX
HW
1
0.8
0.6
0.4
0.2
0
0
12
31st



Residual Elevations - Port Erin - March 2008
Obs
CS3X
3AX
HW
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
12
12th