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Sea level trends and NAO influences: The Bristol Channel/Severn Estuary

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ABSTRACT

Fifteen years, 1993 (earliest available) to 2007 inclusive of monthly mean and extreme (maximum and minimum) sea level data were assessed for four tide gauges located in the Bristol Channel (Mumbles and Ilfracombe) and Severn Estuary (Newport and Hinkley Point). Results showed decreasing maximum sea level trends and increasing minimum sea level trends, resulting in convergence. However, maximum extreme sea levels on the Welsh shoreline (Mumbles and Newport) were higher than corresponding locations on the English coast (Ilfracombe and Hinkley Point). Analysis showed that from 1995 to 1998 inclusive, maximum extreme sea levels were significantly higher at Mumbles ($t = 2.342$; $df = 10$; $p < 0.05$), Newport ($t = 5.034$; $df = 13$; $p < 0.01$) and Hinkley Point ($t = 3.570$; $df = 13$; $p < 0.01$) and were correlated to increased storm frequencies during these years. However, Ilfracombe ($t = 1.472$; $df = 12$; $p > 0.05$) did not demonstrate similar significance, possibly due to tide gauge location and coastal aspect, while tidal influences became more dominant as the tidal prism moved up the estuary. Actual mean sea levels (MSL) at Newport ($t = 2.880$; $df = 14$; $p < 0.05$) and Hinkley Point ($t = 5.282$; $df = 14$; $p < 0.01$) were significantly higher than predicted; at Mumbles ($t = 2.673$; $df = 11$; $p < 0.05$) they were significantly lower than predicted; while Ilfracombe ($t = 1.989$; $df = 13$; $p > 0.05$) once again showed no significant difference. Mumbles is the only location with off-shore sand waves and analysis suggested these as the cause of opposite trends. Sea level variation was strongly correlated to the North Atlantic Oscillation (NAO) Index, especially for maximum extreme sea levels during positive phases ($R^2 = 86\%$), and higher positive or negative NAO Index values resulted in larger sea level ranges. Further analysis showed a rising Bristol Channel and Severn Estuary MSL trend of 2.4 mm yr^{-1} and a 2050 MSL of 0.370 m is projected to inform future management. However, continuous updating and refinement of the sea level datasets will be needed.

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1. Introduction

According to Leatherman (2001), changing sea level has been the driver of shorelines over geological time and is one of the principal determinants of shoreline position. There is a causal relationship among several factors: sea level, sediment supply, wave energy and shoreline position. Sea level rise induces beach erosion or accelerates ongoing shore retreat for several reasons (Leatherman, 1991). First, higher water levels enable waves to break closer to shore. Second, deeper water decreases wave refraction and this increases the capacity for longshore transport. Finally, with higher water levels, wave and current erosion processes act further up the beach profile causing readjustment of that profile. Maintenance of an equilibrium beach/nearshore profile in response to sea level rise requires an upward and landward displacement of the beach in time and space; this typically translates to erosion. Douglas (2001a) recognised the potential of rising water levels to alter ecosystems and habitability in coastal regions, reinforcing views of Schroeder (2000) that it becomes

an issue due to coastal population density, infrastructure and development. Sea level trends for both mean and extreme sea levels in conjunction with assessments of winds and storms, etc., permit identification of coastline consequences (Phillips, 2008). Consequently it is important to assess sea level trends to develop management strategies for mitigating impacts and protecting people.

The Bristol Channel/Severn Estuary (Fig. 1) has one of the highest semi-diurnal tidal ranges in the world (Hashemi et al. 2008) and is an inlet of the Atlantic Ocean on the west coast of Great Britain, separating Wales and Southwest England. Analysis of sea level data by Roberts (1994) suggested that over the last 8 millennia, Bristol Channel Holocene sea level rise was *circa* 16 m from isostatic readjustment. In 1993, four tidal gauges, part of the Permanent Service for Mean Sea Level (PSMSL), were located at Mumbles and Newport on the Welsh coastline and Ilfracombe and Hinkley Point on the English coastline (Fig. 1). Past events have suggested there may be differences between the two sides of the Bristol Channel and Severn Estuary. For example, during the 1607 flood Wales suffered higher flooding levels and inundation in comparison to England (Haslett, 2007). In addition, since at least the 1950s, monitoring has shown an increased frequency of abnormally high tides in the eastern Irish Sea (SBCEG, 1999). This paper therefore assesses sea level trends (mean,

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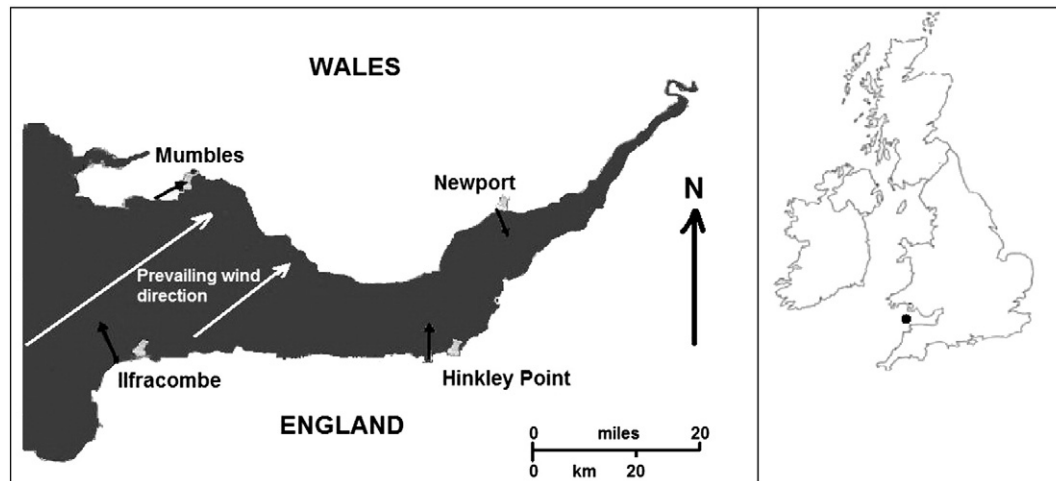


Fig. 1. Tide gauge location and aspect.

maximum extreme and minimum extreme) between 1993 and 2007 at the four locations (Fig. 1). Comparison of sea levels from the two English (Ilfracombe and Hinkley Point) and Welsh (Mumbles and Newport) locations enable identification of similarities and differences between the two coasts, and between the outer channel and inner estuary. Results are assessed alongside other studies and future Bristol Channel/Severn Estuary sea level rise predictions are made. Further evaluation is undertaken on sea level impacts of the North Atlantic Oscillation (NAO) Index.

2. Physical background

The Bristol Channel is exposed to winds and waves from the prevailing south-westerly direction (SBCEG, 1999) while parts of the Severn Estuary, including Newport, are sheltered by land. The boundary of the Bristol Channel and Severn Estuary is approximately mid-way between Mumbles and Newport. Tides are semi-diurnal which dominate its dynamics and near the head (Avonmouth), due to the funnelling effect of the Bristol Channel/Severn Estuary, the tidal range is the second largest in the world (*circa* 15 m). Two factors contribute to this: firstly, the overall dimensions of the Bristol Channel mean that its natural period of oscillation is close to the 12.5 h tidal period, resulting in a strong resonant oscillation; secondly, tidal current speeds generally exceed 1.5 m s^{-1} on spring tides and 0.75 m s^{-1} on neap tides, meaning sections of water can move up to 25 km during a flood or ebb tide. High water at the mouth occurs 1.7 h before high water at Avonmouth. Locally generated waves, which give rise to the largest wave heights at Newport, are uncorrelated with high water levels. This is opposite to the Outer Bristol Channel where swell waves from the west, give rise to the largest wave heights and these are correlated to high water levels (Simm, 1996). The Bristol Channel is exposed to high wind speeds with the strongest winds, predominantly south-westerly, occurring as a result of deep depressions close to the British Isles. However, winds from easterly or north-easterly directions are quite frequent and can have

damaging effects on coastal infrastructure (Phillips, 2008). Human use of the coastal fringe includes all activities defined by Ketchum (1972) and consequently, sea level rise (SLR) and climate change impacts could significantly affect these activities.

3. Methodology

Primary data for this study were taken from tide gauges located at Mumbles, Newport, Ilfracombe and Hinkley Point (Fig. 1; Table 1). Detailed daily records of mean and extreme (maximum and minimum) water levels between 1993 and 2007 were subsequently converted to monthly means. At Mumbles, the Chart Datum reference is 5.000 m below Ordnance Datum (Newlyn), at Newport, 5.810 m below, at Ilfracombe 4.800 m below, and at Hinkley Point, 5.900 m below. Consequently, water level data were adjusted to Ordnance Datum (OD) from which annual mean sea level (MSL) and annual mean maximum and minimum extreme water levels were determined. Standard statistical tests were applied to analyse trends and differences and lack of data availability due to tide gauge problems, for example from 1994 to 1996 inclusive at Mumbles, was considered in all analyses. Linear regression was subsequently used to predict future mean sea levels while mean, maximum and minimum extreme sea levels were analysed alongside NAO Index results, to assess influences.

4. Results

4.1. Analysis of mean sea level trends

Fig. 2, produced from Table 2, shows the fifteen year trends of mean sea levels at Mumbles, Newport, Ilfracombe and Hinkley Point. Monthly results at Mumbles show an opposite trend to the others, and most global models, indicative of reducing mean sea levels. This was given by $y = -0.0041x + 8.3993$, equating to an annual MSL fall of 4.1 mm yr^{-1} . Rising sea level trends at Newport ($y = 0.0079x^{12} - 15.491$), Ilfracombe

Table 1
Tide gauge locations.

	Latitude of measuring point	Longitude of measuring point	Ordnance survey grid reference	Description of site measuring point
Ilfracombe	51° 12' 40.1" N	04° 06' 44.6" W	SS 5264 4786	Measuring points are located on the east face of the new jetty
Hinkley Point	51° 12' 54.9" N	03° 08' 04.1" W	ST 2086 4684	In underwater vented chambers, suspended from a steel pole
Mumbles	51° 34' 12.0" N	03° 58' 31.7" W	SS 6323 8756	Measuring points are mounted on the leg of the RNLI boathouse slipway
Newport	51° 33' 00.0" N	02° 59' 14.8" W	ST 3163 8392	Measuring point at Western entrance to Newport docks

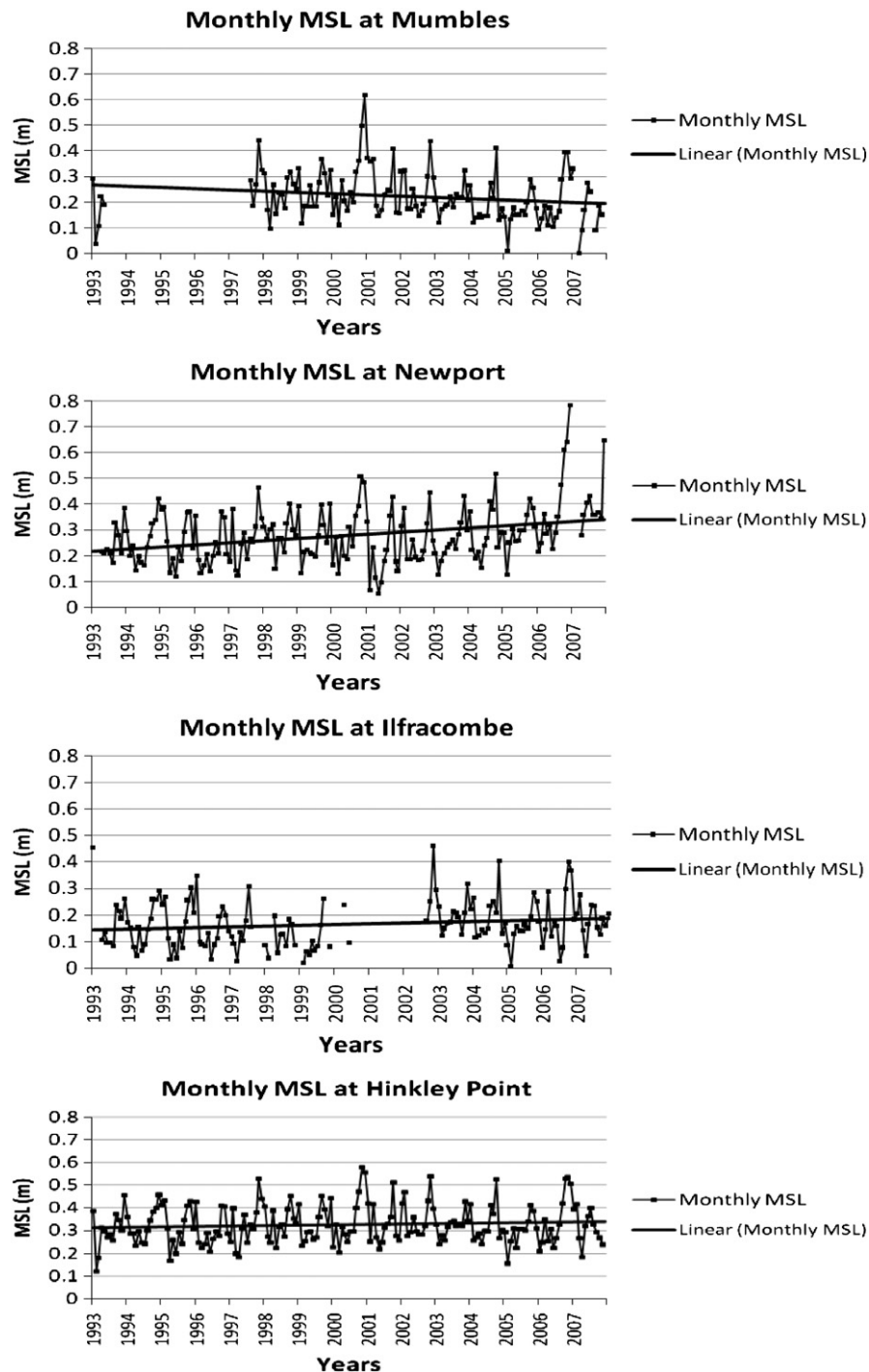


Fig. 2. Fifteen-year MSL trends.

($y = 0.0038x - 7.4297$) and Hinkley Point ($y = 0.0018x - 3.3642$) showed MSL increases of 7.9 mm yr^{-1} , 3.8 mm yr^{-1} and 1.8 mm yr^{-1} respectively (equations in parentheses derived from but not shown in Fig. 2 graphs). Results were further analysed over the fifteen year period with respect to differences between predicted and actual mean sea levels (Table 2). Astronomical mean sea level predictions were converted to OD (Page and Oakley, 2002) at Mumbles (0.275 m), Newport (0.240 m), Ilfracombe (0.150 m) and Hinkley Point (0.300 m) with paired t-tests subsequently applied. Analysis showed actual mean sea levels at Newport ($t = 2.880$; $df = 14$; $p < 0.05$) and Hinkley Point ($t = 5.282$; $df = 14$; $p < 0.01$) were significantly higher than predicted; at Mumbles ($t = 2.673$; $df = 11$; $p < 0.05$) they were significantly lower

than predicted; while at Ilfracombe ($t = 1.989$; $df = 13$; $p > 0.05$) there was no significant difference.

In 1993 and 1998 to 2007 inclusive, annual MSLs at Mumbles were lower than predicted while at Newport this was the case only during 1996 and 2001 (Table 2). At Ilfracombe the annual average MSLs were lower during 1996 to 1999 inclusive, while for Hinkley Point this occurred in 1996 (Table 2). Although no data were available for Mumbles, in 1996 mean sea levels were consistently lower for the fifteen year record in both the Severn Estuary and Bristol Channel. On the English shoreline, Ilfracombe and Hinkley Point demonstrated similar rising trends while on the Welsh side (Mumbles and Newport), trends were opposite. Although studies such as Orford et al. (2006) have

Table 2
Annual mean sea levels.

Year	NAO	MSL N	SD N	MSL HP	SD HP	MSL M	SD M	MSL I	SD I	MSL Bristol Channel /Severn Estuary
1993	0.120	0.249	0.069	0.300	0.090	0.171	0.100	0.188	0.115	0.227
1994	0.510	0.250	0.083	0.321	0.070	N/A	N/A	0.160	0.080	0.244
1995	−0.610	0.262	0.098	0.319	0.091	N/A	N/A	0.162	0.094	0.247
1996	−1.010	0.231	0.083	0.299	0.075	N/A	N/A	0.147	0.085	0.226
1997	−0.180	0.266	0.101	0.330	0.101	0.302	0.094	0.115	0.081	0.253
1998	0.250	0.284	0.062	0.334	0.070	0.232	0.069	0.089	0.054	0.235
1999	0.040	0.269	0.090	0.334	0.077	0.247	0.079	0.079	0.073	0.232
2000	0.035	0.293	0.123	0.352	0.124	0.281	0.150	0.170	0.101	0.274
2001	−0.453	0.200	0.120	0.324	0.088	0.255	0.098	N/A	N/A	0.260
2002	−0.040	0.262	0.088	0.365	0.086	0.247	0.089	0.299	0.120	0.293
2003	−0.303	0.253	0.078	0.322	0.048	0.206	0.047	0.196	0.053	0.244
2004	0.005	0.292	0.107	0.330	0.086	0.194	0.086	0.195	0.085	0.253
2005	−0.254	0.297	0.075	0.301	0.068	0.167	0.069	0.158	0.071	0.231
2006	−0.198	0.402	0.186	0.349	0.012	0.207	0.109	0.194	0.120	0.288
2007	−0.376	0.396	0.104	0.317	0.073	0.170	0.101	0.179	0.060	0.266

Key: NAO North Atlantic Oscillation; N Newport; HP Hinkley Point; M Mumbles; I Ilfracombe.

found decreasing MSLs, Mumbles was the only record to indicate a falling trend (Fig. 2) and influences unique to this location are likely to be the cause. Phillips et al. (2005) analysed tide data between 1993 and 2002 and found annual MSL at Mumbles rose by approximately 5.4 mm yr^{-1} . However, when 2003 to 2007 data (Table 2) was added to the earlier record, sea level changes over these latter years had caused the reversal.

4.2. Analysis of extreme sea level trends

Maximum extreme sea level temporal trends produced from the data of Table 3 show falling water levels at all locations. These are given by: $y = -0.0239x + 52.873$ (Mumbles); $y = -0.0211x + 49.057$ (Newport); $y = -0.0236x + 52.2$ (Ilfracombe) and $y = -0.0209x + 48.255$ (Hinkley Point), effectively an average annual fall of 23.9 mm yr^{-1} , 21.1 mm yr^{-1} , 23.6 mm yr^{-1} and 20.9 mm yr^{-1} respectively. These results agree with the findings of Phillips et al. (2005), who also showed falling maximum extreme sea level trends at Mumbles and Newport. Conversely minimum extreme sea level temporal trends produced from the data of Table 3 show increasing water levels at all locations. These are given by: $y = 0.0263x - 56.975$ (Mumbles); $y = 0.0343x - 74.267$ (Newport); $y = 0.0164x - 37.069$ (Ilfracombe) and $y = 0.0144x - 34.26$ (Hinkley Point), an average annual rise of 26.3 mm yr^{-1} , 34.3 mm yr^{-1} , 16.4 mm yr^{-1} and 14.4 mm yr^{-1} respectively. Therefore, the fifteen year record of mean annual maximum extremes is decreasing while minimum extremes are increasing, indicating convergence and reduced tidal range.

4.3. Analysis of NAO Index influences

The NAO produces approximately 60% of the total sea level pressure variance in the extratropical northern hemisphere and is the main mode of climate variability (Gimeno et al. (2003). Hurrell (1995) characterised its influence over European weather conditions and further work found a statistical relationship between the NAO Index and Northern Hemisphere surface temperatures (Hurrell, 1996). The NAO is dominant in the variation of the North Atlantic winter climate from central North America to Europe, including Northern Asia (Bell and Visbeck, 2009). It is a large scale fluctuation in atmospheric mass between the subtropical high and polar low, and varies from year to year. However, it also has a tendency to remain either positive or negative during intervals lasting several years. In its positive phase, it demonstrates a stronger than usual subtropical high pressure and deeper than normal Icelandic low, resulting in more frequent and stronger northerly Atlantic winter storms. The consequences include: warmer, wetter European winters; colder, dryer northern Canada and Greenland winters; and mild, wet eastern US winter conditions. When the NAO Index is negative, there is a weak subtropical high and a weak Icelandic low. The reduced pressure gradient results in fewer and weaker winter storms which tend to cross on a west–east pathway. Consequently, the Mediterranean is wetter; northern Europe and the US east coast are colder; and Greenland has milder winter temperatures (Bell and Visbeck, 2009).

Table 2 shows the NAO Index and corresponding MSLs for the Bristol Channel/Severn Estuary over the research period. These are plotted in a time series to produce Fig. 3 and results indicate a relationship. Annual mean, maximum and minimum extreme sea levels were subsequently

Table 3
Annual mean minimum and maximum extreme sea levels.

Year	Min Ext N	Min Ext HP	Min Ext M	Min Ext I	Min Ext BC/SE	Max Ext N	Max Ext HP	Max Ext M	Max Ext I	Max Ext BC/SE
1993	−5.768	−5.576	−4.570	−4.429	−5.088	6.822	6.598	5.133	5.291	5.961
1994	−5.793	−5.534	N/A	−4.364	−5.230	7.098	6.648	N/A	5.057	6.268
1995	−5.781	−5.461	N/A	−4.313	−5.185	7.172	6.703	N/A	5.097	6.324
1996	−5.813	−5.522	N/A	−4.407	−5.247	6.98	6.538	N/A	4.969	6.162
1997	−5.802	−5.626	−4.338	−4.480	−5.062	7.132	6.703	5.107	5.157	6.025
1998	−5.687	−5.570	−4.437	−4.452	−5.037	7.111	6.645	5.125	5.007	5.972
1999	−5.638	−5.490	−4.237	−4.425	−4.948	6.907	6.632	4.978	4.824	5.835
2000	−5.625	−5.418	−4.230	−2.792	−4.516	6.886	6.448	4.972	4.328	5.659
2001	−5.564	−5.494	−4.323	N/A	−5.127	6.734	6.418	4.950	N/A	6.034
2002	−5.455	−5.418	−4.318	−4.388	−4.895	6.888	6.557	5.035	5.226	5.927
2003	−5.519	−5.391	−4.273	−4.114	−4.824	6.795	6.424	4.929	4.773	5.730
2004	−5.506	−5.289	−4.246	−4.182	−4.806	6.579	6.249	4.799	4.773	5.600
2005	−5.479	−5.306	−4.265	−4.195	−4.811	6.855	6.379	4.910	4.85	5.749
2006	−5.407	−5.453	−4.386	−4.310	−4.889	6.961	6.464	4.922	4.877	5.806
2007	−5.315	−5.457	−3.894	−4.238	−4.726	6.785	6.493	4.793	4.878	5.737

BC Bristol Channel; SE Severn Estuary; N Newport; HP Hinkley Point; M Mumbles; I Ilfracombe.

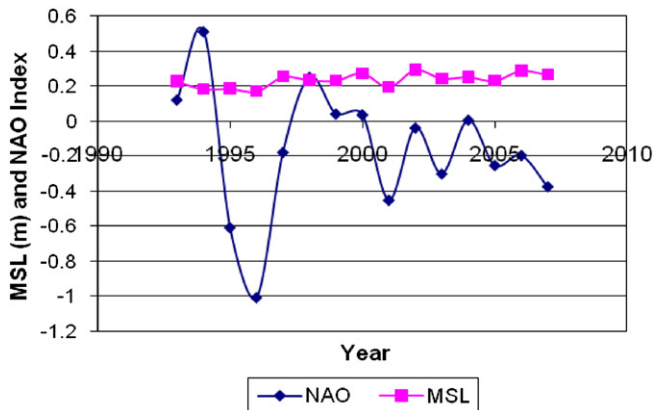
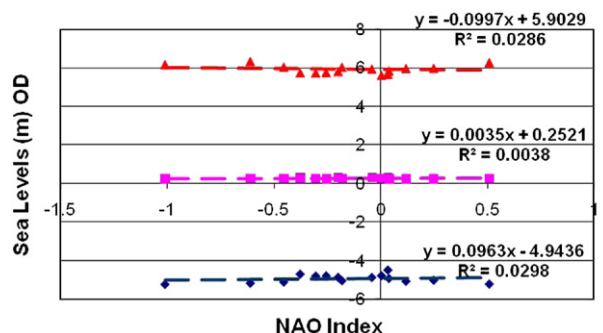
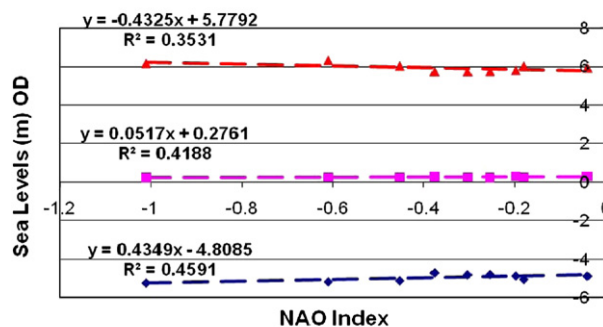


Fig. 3. Temporal variation of MSL and NAO Index.

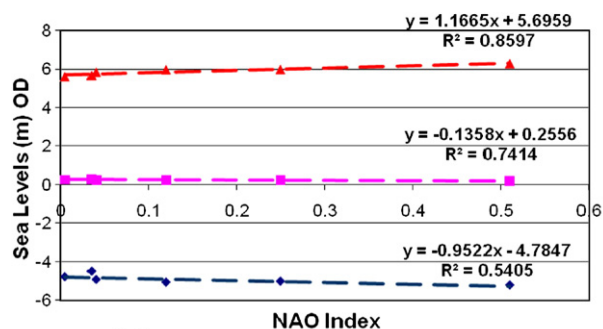
plotted against corresponding NAO values (Fig. 4a), and showed low coefficients of determination, that is, $R^2 = 3\%$ (maximum extreme); 0.4% (mean) and 3% (minimum extreme). However, when corresponding sea levels were plotted separately against both positive and negative NAO



(a) Sea level / NAO index fifteen year trends



(b) Sea level / negative NAO index trends



(c) Sea Level / positive NAO index trends

Fig. 4. Maximum extreme, mean and minimum extreme sea level variations with NAO Index.

years (Tables 2 and 3), results showed significant correlation (Fig. 4b and c). During the nine negative NAO years, coefficients of determination R^2 (Fig. 4b) were 35% (maximum extreme); 42% (mean) and 46% (minimum extreme), while for the six positive years (Fig. 4c), were 86% (maximum extreme); 74% (mean) and 54% (minimum extreme). As the annual NAO Index was determined from monthly results and sea levels from daily records, Fig. 4b and c represented enough data to validate model performance measures, vital for reliable predictions (Healy, 2009). Therefore, NAO Index influences are correlated to the variation of Bristol Channel/Severn Estuary water levels, especially during positive years.

5. Discussion

Over the last century, estimated trends in global sea level have been based on tide gauge records with near global coverage (Woppelmann et al., 2007). These have enabled highly accurate and precise measurements, including identification of local trends and prediction of future sea levels. Emery and Aubrey (1991) further asserted that tide gauges can provide more precise and widespread information about relative sea level change than can be expected from radiocarbon or other kinds of measurements, while Cazenave et al. (1998) indicated that confidence increases as longer time series become available. Long-term tide gauge records show that mean annual sea levels are rising (or the land is sinking) in low and middle latitudes at a median rate of approximately 3 mm yr^{-1} (Emery, 1980) while Douglas (2001a) estimated an average rise of 1.5 mm yr^{-1} over the twentieth century. Although tide gauges are seen by many as very accurate and precise, Nerem (1999) highlighted two main problems using them to estimate global sea levels, i.e., they only measure sea level change relative to a crustal reference point and they have limited spatial distribution. Harvey et al. (2002) reported problems using tide gauges to measure current rates of sea level change, due to geologic, isostatic and anthropogenic effects, while Andersen et al. (2002) described deformation of the ocean basins, melting ice caps and thermal ocean expansion to be among the principal causes. According to Douglas (2001a), eustasy gives an accurate description to within approximately 0.1 mm yr^{-1} for analyses of contemporary sea level rise and argued the rate of relative sea level rise due to glacial isostatic adjustment (GIA) is still about 0.3 mm yr^{-1} . He also suggested that when tide gauge locations are properly selected, the record should maintain internal consistency irrespective of repairs, replacements and technology changes. Douglas (2001b) further argued that although many researchers have used sea level records of 10 to 20 years, this was inadequate and a minimum record of 60 years, and preferably 70 or 80 years, was needed to make reliable predictions. However, as the Bristol Channel/Severn Estuary gauges assessed were established in 1993, only fifteen years of data were available. MSLs and trends were found to be different at the four locations but this is not an unusual occurrence, as both Woodworth (2000) and Douglas (2001a) agreed that sea level varies according to location.

Heyworth and Kidson (1982) highlighted errors in the estimation of tidal levels with large tidal ranges and noted that in these circumstances, distribution of wave energy is as variable as tidal range. However, their analysis of sea level curves suggested that in the last 8000 years, the rate and timing of sea level rise have been comparable over the whole of this region (Heyworth and Kidson, 1982). According to Allen (1991), from an analysis of deposits in active marshes of the inner Severn Estuary, the average rate of sea level rise ranged from 0.4 mm yr^{-1} between the later Roman Period and the Medieval Period to 4.65 mm yr^{-1} since circa 1945. However, Haslett et al. (1998) questioned previous models and found from clay deposition, that relative sea level change had been $0.41\text{--}0.82 \text{ mm yr}^{-1}$. Further Severn Estuary work on saltmarsh accretion rates by Haslett et al. (2001) suggested previous sea level rise rates may be over-estimated, with wider implications of an over-estimation of regional crustal subsidence rates. Therefore, although only based on a

15-year record, mean sea level trends determined in this study agreed with other analyses of Holocene sea level rise.

Both Ilfracombe and Hinkley Point are sheltered from prevailing south-westerly winds while Mumbles and Newport are exposed (Fig. 1). However, as Newport and Hinkley Point lie within the Severn Estuary, these locations are more sheltered. Mumbles was the only bay located tide gauge which directly faces prevailing south-westerly winds, the other locations being more sheltered. It is also the only location where sand waves are present off-shore (Tappin et al., 2004) and Jenkins et al. (2009) noted harbour porpoises using Mumbles as a feeding ground, shoaling fish into the shallower waters. As it is a shallow predominantly muddy sandy bay, this could have impacted on tide gauge readings and sea level variance. Extreme sea level analyses differed from the findings of Jensen and Muddersbach's (2002) work on the German North Sea coastline and Figueiredo da Silva and Duck's (2001) work in the Ria de Aveiro, which both indicated divergence i.e., an increasing tidal range. The final year dataset in those studies was 1999 and highlighted consequences such as increased tidal volume and flow velocity which caused morphological change. Phillips (2008) found extreme sea levels at Penarth, along the same coastline, were significantly higher between 1995 and 1998 inclusive. Following examination of mean annual maximum extreme sea levels (Table 3) an unpaired t-test was applied to compare 1995 to 1998 inclusive with 1993 to 1994 and 1999 to 2007 inclusive at Newport, Ilfracombe and Hinkley Point, making appropriate adjustments for Mumbles due to data unavailability between 1994 and 1996. Consequently, mean annual maximum extreme sea levels in 1997 and 1998 at Mumbles were significantly higher at the 95% confidence level ($t=2.342$; $df=10$; $p<0.05$) than during 1993 and 1999 to 2007 inclusive. For Newport and Hinkley Point annual maximum extreme sea levels between 1995 and 1998 were significantly higher at the 99% confidence level ($t=5.034$; $df=13$; $p<0.01$ – Newport: $t=3.570$; $df=13$; $p<0.01$ – Hinkley Point), compared with 1993 to 1994 and 1999 to 2007 inclusive. However, at Ilfracombe there was no significant difference between mean annual maximum extreme sea levels for these years ($t=1.472$; $df=12$; $p>0.05$).

Adaptation strategies rely on valid data and predictions and to inform future management, a MSL trend for the Bristol Channel/Severn Estuary was determined. Results for the four gauges represent different exposure conditions, location and aspect (Table 1; Fig. 1) and were averaged to obtain an annual Bristol Channel/Severn Estuary MSL (Table 2; Fig. 5). Analysis showed a temporal trend represented by $y=0.0024x-4.6199$ ($R^2=26\%$), which equated to a MSL rise of 2.4 mm yr^{-1} (Fig. 5). To overcome disadvantages of the limited data timescale, results were compared to trends from the Cascais tide gauge. Located near Lisbon with approximately the same exposure conditions as the Bristol Channel/Severn Estuary, Cascais is one of the oldest and most reliable tide gauges in the world (Antunes and Taborda, 2009). Its sea level data are used extensively to predict global sea level trends and over the same fifteen year timeframe, showed a rising MSL trend of

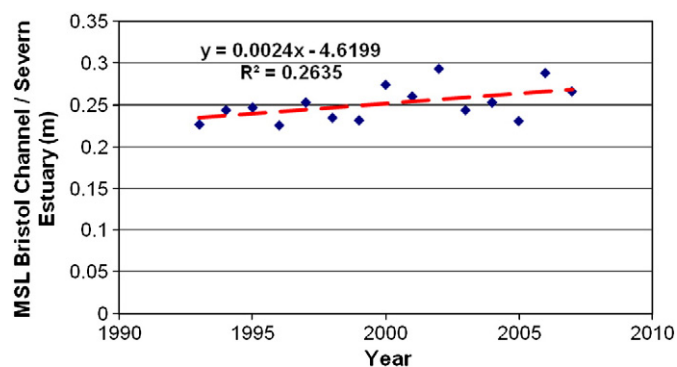


Fig. 5. MSL trend for Bristol Channel/Severn Estuary.

2.1 mm yr^{-1} (Antunes and Taborda, 2009). The 0.3 mm yr^{-1} difference could be explained by channel tidal influences becoming more dominant, as found by Jensen et al. (2003) when researching estuary tidal responses and/or impacts of the large tidal range. Bruun (1962) long ago proposed that long-termed erosion of sandy beaches was a consequence of sea level rise and his model predicted that beaches will erode by 50 to 200 times the rate of increase of sea level (Douglas, 2001b). Therefore, to inform management, a 2050 MSL prediction for the Bristol Channel/Severn Estuary was produced (Fig. 6). Between 1993 and 2007 the MSL range was $0.255 \pm 0.035 \text{ m}$ and is predicted to be 0.370 m by 2050. Although based on a fifteen-year sea level record, similarities with Cascais have justified forecasts. The importance of predictions to inform management is exemplified by Figueiredo da Silva and Duck's (2001) findings which determined that in the Ria de Aveiro, Portugal, a 0.1 m increase in the mean sea level would contribute to an increase in the speed of tidal propagation with up to a 22% increase in the volume of the tidal prism. However, for increased certainty it will be necessary to continually update the sea level record, especially as feasibility studies for the construction of the Severn Barrage are currently ongoing. The proposed site is downstream of both the Newport and Hinkley Point tide gauges and as argued by Phillips (2007), consequences for sea level and coastal evolution will have to be evaluated.

In 2002, MSLs were significantly higher than previous years (Table 2; Fig. 5) when a deep low pressure system in the Atlantic Ocean produced stormy conditions over much of the UK (Met Office, 2008). Similarly, increased maximum extreme sea levels were recorded (Table 3). Consequences included heavy rain and high wind speeds and that year, many UK regions experienced their highest or second highest annual rainfalls, including Pembrokeshire on the Welsh coast. The adverse weather affecting the Bristol Channel caused widespread flooding and damage to coastal infrastructure. The NAO Index in 2002 was negative and with the exception of Ilfracombe, MSL standard deviations were similar (Table 2). Data from Table 3 were again plotted in Excel to produce trend graphs (not shown), with the following results. Maximum extremes in the Bristol Channel (Mumbles and Ilfracombe) showed a decreasing trend of 0.2 mm yr^{-1} while Severn Estuary (Newport and Hinkley Point) sites showed a decreasing trend of 0.1 mm yr^{-1} . Conversely, minimum extremes at all four locations had positive rising trends: 0.1 mm yr^{-1} at Mumbles, Ilfracombe and Hinkley Point and 0.2 mm yr^{-1} at Newport (Table 3). However, the decreasing trends were strongly influenced by significantly higher extreme levels between 1995 and 1998 inclusive, three years of which had a negative NAO Index (Table 2). Over the fifteen years, the Welsh side of the Bristol Channel/Severn Estuary recorded higher maximum extreme and lower minimum extreme sea levels than the English coast (Table 3), equivalent to mean ranges of 12.524 m (Newport), 11.994 m (Hinkley Point), 9.264 m (Mumbles) and 9.157 m (Ilfracombe). This was probably caused by prevailing south-westerly winds having a bigger influence on extreme sea levels along the Welsh coast.

Hurricane activity in 1995 was very high, mainly as a result of favourable conditions including a strong La Niña event. This caused weaker westerly winds and above average sea surface temperatures,

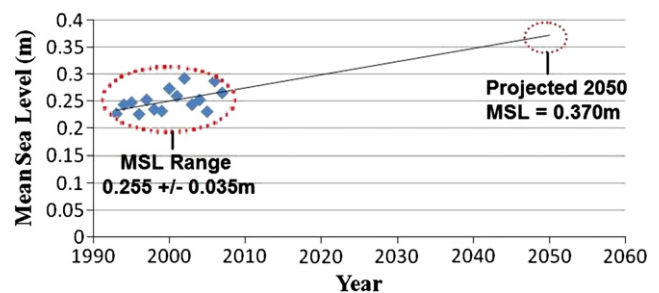


Fig. 6. 2050 MSL prediction for the Bristol Channel/Severn Estuary.

which produced favourable conditions for Atlantic storm activity (Intellicast 2009). During 1995, the Bristol Channel/Severn Estuary experienced severe storms resulting from low pressure, and between 1995 and 1997 all winds included more easterly components. During these years, which included the two largest negative NAO Index values (Table 2), there were significantly more easterly storms than had previously been recorded and major damage was caused to coastal infrastructure, including seawall failure (Phillips, 2008). Furthermore, there was a change in sediment transport and beach formation processes which did not return to previously accepted patterns until the end of 1998 (Phillips and Williams, 2007), when the NAO Index returned to a positive phase.

It is apparent that sea levels in the Bristol Channel/Severn Estuary are significantly influenced by the NAO Index. Fig. 4b and c shows that as the NAO Index increases, either positively or negatively, extreme sea levels increase, while both MSL and minimum extreme sea levels decrease. Therefore, greater numerical positive or negative NAO Index values result in larger sea level ranges. In general, standard deviations during positive NAO years are greater than negative years (Table 2). This is probably due to greater correlation between sea level variation and the more frequent and stronger northerly Atlantic storms. During negative years it has been shown that the weaker west–east weather track has included strong easterly components and as stated by Phillips (2008), coastal processes respond disproportionately when winds do not come from prevailing directions. He further showed that the greatest incidence of easterly storms occurred during 1995 and 1996; years where this study showed the highest recorded negative NAO Index values of -0.610 and -1.010 respectively (Table 2). SLR over the past century has exacerbated impacts of storms and Kevin et al. (2004) suggested storm intensities are becoming worse and more frequent, and this will play an increasingly important role in the morphodynamic evolution of coasts. The MSL trend identified for the Bristol Channel/Severn Estuary and the extrapolated 2050 value should aid management decisions. Greater result confidence was achieved from comparisons with the Cascais dataset together with strong correlations of NAO Index and sea levels. However, it is important that the sea level datasets are continually up-dated to refine predictions and further work is necessary to explain why results at Ilfracombe show no significant changes. Furthermore, a longer sea level dataset will enable influences of the 18.6-year lunar tidal cycle to be assessed. The last one culminated in 2006 and the next one is expected in 2024–2025.

6. Conclusions

Sea level trends (mean, maximum extreme and minimum extreme) between 1993 and 2007 were assessed for four tide gauges located in the Bristol Channel (Mumbles and Ilfracombe) and Severn Estuary (Newport and Hinkley Point). Results over the fifteen years showed decreasing maximum sea level trends and increasing minimum sea level trends, resulting in convergence. However, these trends were strongly influenced by significantly higher extreme levels between 1995 and 1998 inclusive, three years of which had high negative NAO Index values. Maximum extreme sea levels on the Welsh shoreline (Mumbles and Newport) were higher than corresponding locations on the English coast (Ilfracombe and Hinkley Point) and analysis showed that from 1995 to 1998 inclusive, maximum extreme sea levels were significantly higher: Mumbles ($t=2.342$; $df=10$; $p<0.05$), Newport ($t=5.034$; $df=13$; $p<0.01$) and Hinkley Point ($t=3.570$; $df=13$; $p<0.01$). These were correlated to increased storm frequencies during these years, although Ilfracombe ($t=1.472$; $df=12$; $p>0.05$) did not demonstrate similar significance, possibly due to tide gauge location and coastal aspect. Tidal influences were found to be more dominant as the tidal prism moved up the estuary. Actual mean sea levels (MSL) at Newport ($t=2.880$; $df=14$; $p<0.05$) and Hinkley Point ($t=5.282$; $df=14$; $p<0.01$) were significantly higher than predicted; at Mumbles ($t=2.673$; $df=11$; $p<0.05$) they were significantly lower than predicted; while Ilfracombe

($t=1.989$; $df=13$; $p>0.05$) once again showed no significant difference. Mumbles was the only location near off-shore sand waves and these may have been the cause. Sea level variation was strongly correlated to the NAO Index, especially for maximum extreme sea levels during positive phases ($R^2=86\%$). As the NAO Index increased, either positively or negatively, extreme sea levels increased, while both MSL and minimum extreme sea levels decreased. Therefore, higher positive or negative NAO Index values result in larger extreme sea level ranges. Further analysis of the fifteen year dataset showed a rising Bristol Channel/Severn Estuary MSL trend of 2.4 mm yr^{-1} which compared favourably with Cascais (2.1 mm yr^{-1}), a long established sea level dataset. Subsequently, a 2050 MSL of 0.370 m was projected to inform future management, especially with the uncertainty regarding construction of the Severn Barrage. However, continuous updating and refinement of the sea level datasets will be needed.

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