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Rising sea levels in the English Channel 1900 to 2100

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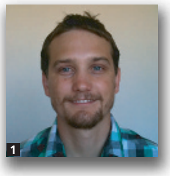
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There is great concern about rising sea levels in the coming century, particularly in terms of extreme sea levels and the increased likelihood of coastal flooding. This is especially true for the south-east coast of England where rising sea levels interact with a growing population and economy. This paper examines how extreme sea levels (excluding waves) have changed through the twentieth century at 16 sites around the English Channel. Extreme sea levels were found to have increased at all 16 sites, but at rates not statistically different from the observed rise in mean sea level. Potential future changes in extreme high sea levels throughout the twenty-first century are estimated for nine UK south coast sites using the 2009 projections from the UK Climate Impacts Programme. For the low, medium and high emissions scenarios (12, 40 and 81 cm total ocean rise, respectively), the exceedence frequency of extreme high sea levels along the south coast would on average increase over the twenty-first century by a factor of 10, 100 and about 1800, respectively. Finally these changes are considered in relation to a large recent surge event in March 2008, which caused significant flooding in the central Channel.

1. Introduction

Around the globe there is great concern about climate-induced sea-level rise in the coming century. Rising sea levels threaten many low-lying and unprotected coastal areas in many ways, including raising extreme sea-level events (Nicholls, 2010). Extreme events can give rise to serious coastal flooding, often resulting in considerable loss of life and major damage to infrastructure and the environment (Lowe *et al.*, 2010). As a society we have become increasingly vulnerable to extreme events as our cities and our patterns of coastal development become more intricate, populated and interdependent (Pugh, 2004).

In England and Wales, approximately £100 billion worth of assets are threatened by coastal flooding today (Hall *et al.*, 2006). According to the national assessment of Evans *et al.* (2004), coastal flood risk could grow substantially through the twenty-first century as rising sea levels and other climate drivers interact with population and economic drivers, particularly in south-east England (Figure 1). In the UK, most attention on extreme sea levels has been focused on the east and west coasts in response to significant flood events, most notably the 1953 storm surge in the southern North Sea (McRobie *et al.*, 2005). The south coast has received much less attention, even though there is significant flood exposure today in areas such as Romney Marsh, Pevensey/Eastbourne, Littlehampton and Poole. In particular, the Solent (Figure 1) has experienced significant flooding over the last 50 years.

The overall aim of the present paper is to examine how extreme sea levels (without waves) are likely to change along the south coast of the UK during the twenty-first century. However, as a first step to considering future conditions, it is important to understand historic changes in extremes to set projected changes in an appropriate context. Knowledge of both the historic and potential future changes in extreme events will help to determine the scale and resources required for improved flood risk management, including upgraded coastal protection (Lowe *et al.*, 2010).

The paper is structured in the following way. First, a brief outline of how different processes combined to cause extreme high sea levels and how the frequency with which these are exceeded can change is given. The paper then examines how extreme sea levels have changed through the twentieth century at 16 sites around the English Channel (Figure 1). Although the focus is on the south coast of the UK, tide records along the northern French coast and on islands within the vicinity are also assessed to examine the Channel as a complete system. Potential future changes in extreme high sea levels throughout the twenty-first century are then estimated, for nine sites along the UK south coast. Finally, these changes are considered in the light of a recent extreme event on 10 March 2008 which caused significant flooding in the central regions of the Channel.

Many of the results presented in this paper have been published elsewhere (Haigh *et al.*, 2009, 2010a, 2010b). The aim here is to summarise the key results of these individual studies taken together and in a broader context, and illustrate their application and implications for coastal flood risk management.

2. Background: the nature of sea-level variations

In the present paper, the term 'sea level' is used to denote the instantaneous height of the sea with respect to a fixed point on land after surface wind waves have been removed. Therefore, at any particular time or location, the observed sea level, can be regarded as the combination of a mean sea level (MSL) component, an astronomical tidal component and a non-tidal residual (Pugh, 2004). The MSL component is the average height of the sea defined over an extended period of time, usually a year. The tidal component is the part of the sea level driven by astronomical forcing due to the varying gravitational attraction of the moon and sun. The non-tidal residual, primarily contains the meteorological contribution to sea level termed the surge. When large storm surges coincide with high water of a spring tide, extreme sea levels arise and can result in serious coastal flooding.

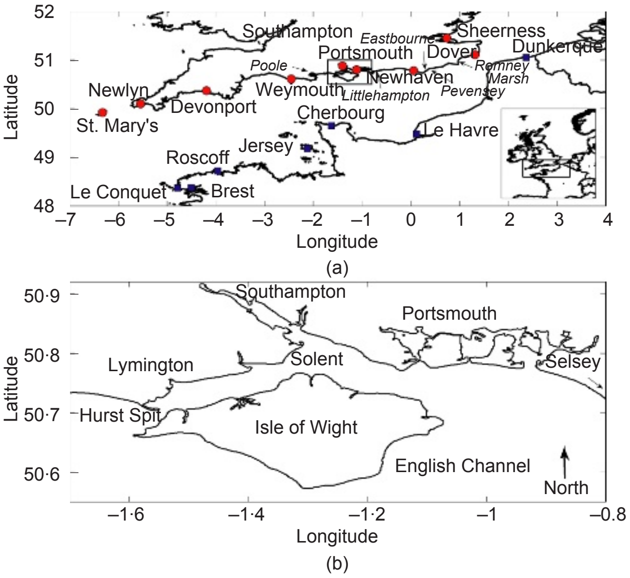

Figure 1. (a) Map of the English Channel with the location of the 16 tide gauges and some selected coastal flood 'hotspots' on the UK side; (b) map of the Solent region

As sea level is the sum of the components outlined above, any changes to these will result in changes to the frequency of occurrence of extreme high sea levels. It is evident from long sea-level observations that MSL is changing. Over the twentieth century, tide-gauge observations show that global MSL on average rose by 17 cm (i.e. 1·7 mm/year) as a result of climate-change-related processes including the melting of land-based ice and the thermal expansion of sea water (Bindoff *et al.*, 2007). Changes in MSL affect extreme sea levels in two ways.

(*a*) Directly: a rise (or fall) in MSL will result in a lower (or higher) surge elevation at high tide being necessary to produce a sea level high enough to cause flooding.
(*b*) Indirectly: changes in MSL alter water depths and hence modify the propagation and dissipation of the astronomical tide and surge components of sea level.

In addition, extreme sea levels can change as a result of variations in the strength and tracks of weather systems which alter the magnitude, duration and intensity of storm surges. Despite the concerns of increased coastal flooding, most of the past studies of sea level changes have concentrated on just examining variations in MSL rather than assessing changes in extreme sea levels (Woodworth and Blackman, 2004).

3. Twentieth century changes in sea level

In this section, historic changes in extreme sea levels are assessed in the English Channel. The focus is on determining the extent to which these past changes were due to direct MSL changes, indirect MSL changes or variations in storminess. In order to determine this, two questions were asked. First, what were the rates of MSL change throughout the twentieth century and the early twenty-first century (to 2007)? Second, were changes in extreme still water levels over the same period significantly different from those observed in MSL?

3.1 Data

The study of historic changes in extreme sea levels is more difficult than research into MSL changes owing to the general lack of access to long, high-frequency and quality-controlled datasets. Records of about 35 years (i.e. about two 18·6 year lunar nodal cycles) are needed to determine accurately changes in extreme levels. Over a period of 18·6 years the declination of the moon, relative to the plane of the sun, varies by about ± 5° and hence changes the magnitude of the astronomical tides over this period. The influence of the lunar nodal cycle can significantly bias trend estimates in shorter datasets. At the start of this study, there were only two tide gauge stations on the UK south coast with records matching these requirements and a further seven sites on the northern French coastline (Figure 2).

In order to increase the length of digital sea-level records for the UK south coast, an extensive data archaeology exercise was undertaken (see Haigh *et al.* (2009)). This added paper-based records and previously unanalysed digital records at St Mary's, Weymouth, Southampton and Newhaven, and the records at Devonport and Portsmouth were extended and corrected for previous errors of interpretation (erroneously high rates of MSL change were previously estimated at both these sites due to datum errors). In total, 173 years of new or corrected data were added to the six sites on the UK south coast (Figure 2). The most significant extension is the new Southampton record, which begins in 1935. It is important to capture these historical paper records to digital format before they are lost. The Southampton record extended here was nearly lost before being digitised and records from the 1920s to 1940 at Newhaven have been lost. All the extended data are freely available to download (www.ivanhaigh.com/Sea-Level).

The French data were obtained from the internet site of the Systéme d'Observation du Niveau des Eaux Littorales (www.sonel.org). The UK data not derived by data archaeology came from the British Oceanographic Data Centre (www.bodc.ac.uk). The final dataset comprises 16 sites (Figure 1), most of which now have 35 years of data (Figure 2). The Jersey and St. Mary's records were included because of their useful locations away from the mainland coasts of England and northern France. The records for Dunkerque and Sheerness were also included to resolve the characteristics of sea level at the boundary of the English Channel and southern North Sea.

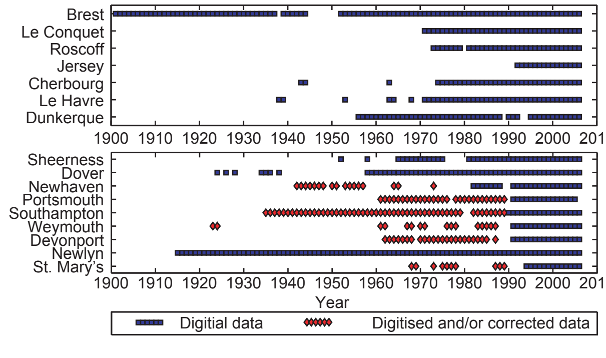

Figure 2. Duration of the sea level records used in this study

3.2 Methods

At each of the study sites, the measured sea-level records were split into MSL, astronomical tide and surge components. Annual MSL values were derived (for years with at least 11 months of measurements with at least 15 days of records for each month) by simply averaging the measured hourly sea-level records for each year. The astronomical tide was predicted using a separate harmonic analysis for each calendar year and the surge component was calculated by subtracting this from the measured record. Trends in each of the three components were then analysed separately before the total extreme sea levels were examined (see Haigh *et al.* (2010a) for more details).

3.3 Changes in mean sea level

At each of the study sites, accurate estimates of rates of MSL change were calculated from the time series of annual MSL shown in Figure 3. Traditionally, rates of change in MSL have been calculated by fitting linear trends to time series of annual MSL. This approach is problematic because of the considerable interdecadal variability present in time series of MSL. This tends to bias estimates of long-term MSL change in records less than 50 years in length, but particularly in records shorter than a few decades. However, part of the interdecadal variability around the UK is coherent across all sites and it can be represented by a

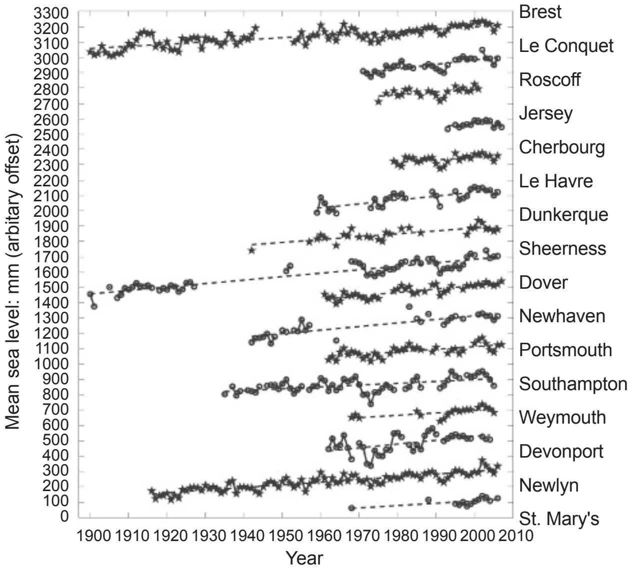

Figure 3. Time series of annual relative mean sea level for data in Figure 2. Note: Annual MSL values were only calculated for years with at least 11 months of measurements with at least 15 days of records for each month. Hence, some data in Figure 2 are excluded

single index derived from a few long records (Haigh *et al.*, 2009; Woodworth *et al.*, 2009). More accurate rates of MSL change were estimated by subtracting the Haigh *et al.* index from the sea-level records prior to fitting linear trends. The MSL trends estimated using this approach are listed in Table 1. They vary by between 0·8 and 2·3 mm/year, depending on location. Trends are lower in the central parts of the Channel, in comparison with the trends at the western and eastern ends, although if the uncertainties are considered none of the rates are statistically different at 95% confidence (i.e. two standard errors).

It is evident from these results that MSL increased across the Channel over the twentieth century. Given concern about human-induced climate change, it is important to assess whether there is evidence for any recent acceleration in this rate of rise. The global rate of MSL rise estimated from altimetry data over the 15 year period from 1993 to 2008 is 3·5 mm/year (Nicholls and Cazenave, 2010) and this considerably exceeds the 1·7 mm/year rate estimated from tide-gauge records for the twentieth century. Taken at face value, this suggests a recent acceleration of global sea-level rise. For the similar period 1992 to 2007, the rates of MSL change for the study sites in the Channel were also considerably higher than those estimated from the complete record lengths at each site. However, following global trends, when compared to trends observed at other 15 year periods since 1900, they were found to be within the envelope of observed change. Figure 4 shows trends in MSL at Newlyn for all overlapping 15 year periods. The recent high rates of sea-level rise for the 15 years centred around 1995 to 2000 are in line with those that have occurred at other times (i.e. mid-1920s and late-1970s). Hence, to date there is no evidence for recent acceleration in sea-level rise in the Channel above twentieth century rates.

Site	MSL trend: mm/year	Rate of vertical land movement: mm/year*
St Mary's	1·72 ± 0·52	−0·32 ± 0·72
Newlyn	1·74 ± 0·06	−0·34 ± 0·26
Devonport	2·07 ± 0·63	−0·67 ± 0·83
Weymouth	1·81 ± 0·28	−0·41 ± 0·48
Southampton	1·30 ± 0·18	0·10 ± 0·38
Portsmouth	1·21 ± 0·27	0·19 ± 0·47
Newhaven	2·27 ± 0·27	−0·87 ± 0·47
Dover	1·93 ± 0·21	−0·53 ± 0·41
Sheerness	2·43 ± 0·09	−1·03 ± 0·29
Dunkerque	1·77 ± 0·27	−0·37 ± 0·47
Le Havre	2·17 ± 0·29	−0·77 ± 0·49
Cherbourg	0·84 ± 0·44	0·56 ± 0·64
Jersey	2·30 ± 1·37	−0·90 ± 1·57
Roscoff	1·25 ± 0·53	0·15 ± 0·73
Le Conquet	1·83 ± 0·37	−0·43 ± 0·57
Brest	1·57 ± 0·08	−0·17 ± 0·28

Uncertainty in the trends corresponds to one standard error (i.e. approx. 68% confidence).
*− indicates subsidence; + indicates uplift.

Table 1. Mean sea-level trends (mm/year) and estimates of rates of vertical land movement (mm/year) around the English Channel

The geological component of changes in MSL needs to be considered. Britain is still responding to the former ice sheet that covered much of it during the last glacial maximum. The result of this is ongoing land uplift in central and western Scotland and subsidence in southern England (Shennan and Horton, 2002). These changes in land movement will continue and will influence future extreme sea levels, so they need to be assessed and included in future MSL projections.

Woodworth *et al.* (2009) estimated that the rate of MSL rise around the UK from oceanographic processes is 1·4 ± 0·2 mm/year. Rates of vertical land movement at each of the study sites in the Channel were estimated by subtracting the relative MSL trends from 1·4 mm/year (both the uncertainty in the relative MSL trend and the estimate of Woodworth *et al.* (2009) were considered). The estimated rates of land movement are listed in Table 1. Current guidance on relative sea-level rise for flood risk assessment is found in Defra (2006a) and Lowe *et al.* (2009); the latter use the data of Bradley *et al.* (2009). The Defra (2006a) guidance is reasonable compared with these observations from an engineering perspective, being a little more conservative in central Channel locations, whereas the data of Bradley *et al.* (2009) appear to be up to about 1 mm/year (or 10 cm/century) too

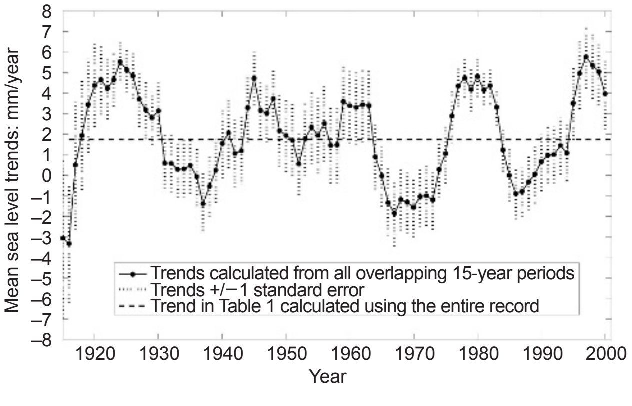

Figure 4. Overlapping 15-year relative mean sea-level trends for Newlyn

high in the western Channel. These discrepancies seem sufficient to warrant further investigation.

3.4 Changes in extreme levels

Having accurately determined rates of change in MSL at the study sides, changes in extreme sea levels over and above these changes in MSL were investigated. The hourly observations for each site and year were ordered in terms of height and these were used to compute various percentile levels. For example, the 99·9th percentile level is the height below which the sea levels remain for 99·9% of the chosen year. These results indicate that extreme high sea levels increased at all of the study sites over their respective record lengths, but at rates not statistically different from that observed in MSL. This is illustrated in Figure 5 for the longest sea-level record on the Channel, which is Brest. Figure 5(a) shows time series computed for 11 percentile levels. The upper five percentiles correspond to high sea levels and the lower five to low sea levels. Each of the percentiles has a significant increasing trend at the 95% confidence level (i.e. two standard errors). The 50th percentile corresponds well to MSL. Figure 5(b) shows the time series after the 50th percentile has been subtracted (i.e. the reduced percentiles). The trends are no longer statistically significant (95% confidence) for any of the percentiles, indicating that the increase observed in high sea levels was a direct result of the increase in MSL. These results imply that the indirect effect of changes in MSL and changes in storm activity were small over the observations.

An assessment of the indirect effect of changes in MSL was undertaken by examining changes in the astronomical tide at each study site. A small (typically $< 0{\cdot}3$ mm/year) increase in mean high water, above that of MSL, and an increase in tidal range (typically $< 0{\cdot}5$ mm/year) at some, but not all sites in the Channel was found. As these changes were small in comparison with observed MSL, they did not significantly increase high sea levels over the last 100 years beyond that associated with MSL. Historic changes in storm activity were assessed by deriving indices from the surge component of the sea-level record at each site. No evidence was found for any systematic increase (or decrease) in storminess over the twentieth century.

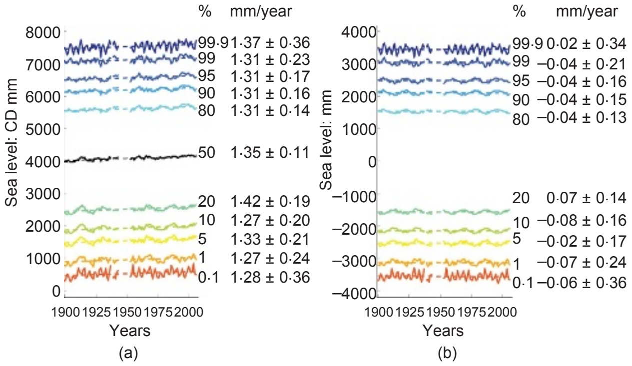

Figure 5. (a) Sea level percentiles and (b) reduced sea level percentiles for Brest with linear trends (dashed lines)

In summary, these results demonstrate that the observed increase in extreme high sea levels over the twentieth century and early part of the twenty-first century was primarily a direct result of the rise in MSL. These findings are consistent with other studies in the English Channel (Araújo, 2006; Araújo and Pugh, 2008; Pirazzoli *et al.*, 2006), other regional studies (see Lowe *et al.* (2010) for a review), and two global assessments (Menendez and Woodworth; 2010; Woodworth and Blackman, 2004).

3.5 Probabilities of extreme sea levels

Increases in extreme high sea levels in terms of return levels and return periods convey information about the changing likelihood (i.e. probability) of rare events. A sea level (i.e. return level) with a return period of 100 years, is the level expected to be exceeded one year in every 100 years, or more precisely, it is the level which will be exceeded in any year with probability 1/100, assuming that the statistics remain unchanged.

Over the last 60 years, six main statistical methods have been developed and refined for estimating probabilities of extreme sea levels (Haigh *et al.*, 2010b). A thorough comparison of four of these methods (the annual maxima method, the *r*-largest method, the joint probability method and the revised joint probability method (RJPM)) was conducted using records from the study sites. The return levels estimated using these methods were also compared with estimates from a fifth method: the spatial revised joint probability method (SRJPM) of Dixon and Tawn (1997). Overall the RJPM was found to perform best around the English Channel and this method is recommended for application wherever possible. The estimates from the SRJPM were found to be significantly larger at most sites; this is due to the comparatively short records originally used to calibrate the model in the English Channel. A major update of the SRJPM method is currently underway, aimed at improving the basic statistical assumptions and using longer records (www.rdextremes.co.uk).

Using the RJPM and the available records at each study site, return levels were estimated relative to the year 1900 and 2010. Although relatively small rises in extreme sea levels were observed over this period, a sea level that had an average likelihood of occurring once every 100 years in 1900, in 2010 had an average likelihood of occurring every 10 to 25 years, depending on the site considered. Further, the return period is continuing to decline around the English Channel, which is an important consideration for flood risk management.

4. Twenty-first century changes in sea level

Having considered historic changes in extreme sea levels in the English Channel, the focus now is on estimating changes over the twenty-first century along the UK south coast for a range of sea-level rise scenarios. It is often assumed that future extreme high sea levels can be estimated by just adding MSL projections to current (i.e. 2010) return levels, calculated from existing records (Araújo and Pugh, 2008). This 'MSL offset method' presupposes that changes in MSL primarily affect extreme levels directly, with no significant indirect effects or changes in storm activity. Based on the results above, this was the case in the English Channel over the last century.

The MSL offset method can be considered in an historic sense; that is, had the projected rate of MSL rise been precisely predicted in 1925, how accurately would extreme sea levels in the year 2000 have been forecast by assuming a constant MSL offset? This was tested directly using the Newlyn and Brest datasets. The data prior to 1925 were used to calculate return levels relative to the year 1925. Then the observed rates of sea-level rise at each site over the period from 1925 to 2000 were added. The estimated return levels for the year 2000 were within 5 cm accuracy of those calculated using the entire records at both sites, showing that changes in extreme sea levels during the twentieth century could have been adequately estimated for engineering purposes based on an offset relative to mean change.

Using the latest sea-level rise projections from the UK Climate Impacts Programme 2009 assessment (UKCP09) (Lowe *et al.*, 2009), the MSL offset method was used to estimate future extreme high levels at the nine UK south coast sites. The UKCP09 sea-level rise projections are based on projections from the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) (Meehl *et al.*, 2007), but take local oceanographic and vertical land movement variations around the UK into account. In this analysis, low, medium and high emissions scenarios were considered to sample a wide range of possible change, corresponding to an absolute (i.e. no vertical land movement) sea-level rise from 1990 to 2100 of 12, 40 and 81 cm, respectively (Figure 6).

Return levels relative to 1990 were estimated at the nine UK south coast sites using the RJPM and all of the available sea-level records. At each site, and for each 10 year period from 1990 to 2100, the return levels were increased by the relevant low, medium and high emission-relative sea-level rise scenarios. Hence, the return period associated with the level in 1990 that had a 100 year return period was computed. This is illustrated for Newlyn and the medium emission scenario in Figure 7. In 1990, an extreme high sea level of 6·5 m is predicted to be exceeded once every 100 years. By 2050, it is projected that this level will be exceeded about every 10 years and by 2100, about three times a year; that is, with sea-level rise, a given water level will be exceeded more and more frequently as progressively less severe conditions are required to achieve that water level.

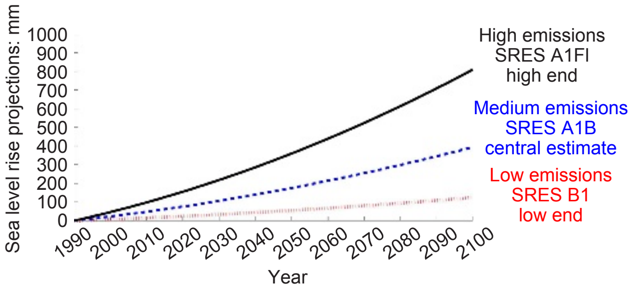

Figure 6. Absolute (i.e. vertical land movement is not included) sea-level rise projections from the UK Climate Impacts Programme 2009 assessment

The results for the nine sites are listed in Tables 2, 3 and 4 for the low, medium and high emission scenarios, respectively. The average reductions in return periods are also listed for each decade in these tables, along with the average factor increase in exceedence frequency (i.e. 100 divided by the reduced average return period). The average reductions in return periods across the nine sites are shown in Figure 8. For the low emissions scenario an extreme high sea level with a return period of 100 years in 1990 reduces to a return period of 10 years by 2100; about a ten-fold increase in exceedence frequency. The low scenario is roughly a continuation of the observed twentieth century MSL rise and illustrates the large changes in return periods of extreme high sea levels that can occur due to what may seem small changes in MSL. For the high emissions scenario, which represents a significant acceleration on twentieth century MSL rates, the same level will have a return

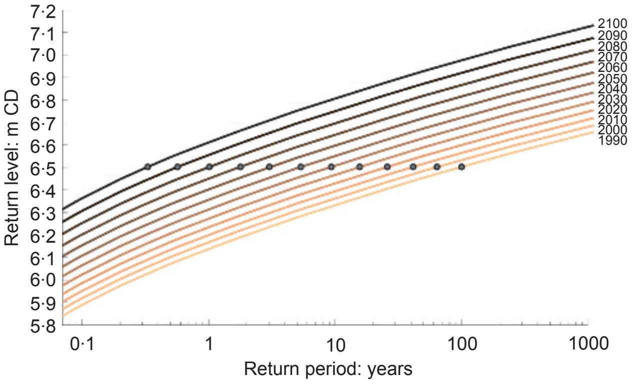

Figure 7. Return period curve at Newlyn in 1990 with the return curve increased every decade by the medium emissions relative sea-level rise scenario

Site	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
St. Mary's	73	54	40	29	21	15	11	8	6	4	3
Newlyn	77	58	44	33	25	19	14	10	7	5	4
Devonport	80	63	49	39	31	24	19	15	11	8	6
Weymouth	79	63	49	37	28	22	17	12	9	7	5
Southampton	84	68	55	45	37	29	24	19	14	11	8
Portsmouth	82	65	52	41	32	25	20	15	11	8	6
Newhaven	87	75	64	54	46	38	31	25	21	17	13
Dover	91	82	73	65	58	51	45	39	34	29	25
Sheerness	90	80	71	62	55	48	42	36	31	27	23
Average	83	67	55	45	37	30	25	20	16	13	10
Factor increase	1·2	1·5	1·8	2·2	2·7	3·3	4·1	5·0	6·3	7·8	9·7

Table 2. Changes to the return periods (years) of the return level with a 100 year return period in 1990 through the twenty-first century for the low emissions relative sea-level rise scenario

period of 20 days by 2100; about a 1800 fold increase in exceedence frequency. There are differences in this reduction of the 100 year return level along the coastline. The largest reduction in return period occurs at the western end of the Channel and the reduction decreases eastwards: the control is geometric with the largest reductions happening where the return period curves are less steep and vice versa.

These estimates only account for changes in extreme high sea levels resulting from the direct increase in MSL over the twenty-first century. Using a modelling approach, Lowe *et al*. (2009) found that the indirect effect of a 3 m increase in water depth on the magnitude of sea level at the outer Thames Estuary was less than 5 cm. Hence, it seems reasonable to assume that indirect MSL effects on extreme high sea levels are likely to remain small for the magnitudes of sea-level rise considered likely in the twenty-first century and can be ignored. The estimates also do not account for the fact that there could be variations in storm activity over the twenty-first century. Recent work suggests that storm tracks over northern Europe may have a tendency to move further south (Lowe *et al*., 2009), which would increase surge

Site	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
St. Mary's	58	33	19	10	6	3	2	*360d*	*307d*	*119d*	*72d*
Newlyn	61	37	22	13	7	4	2	1	*254d*	*142d*	*81d*
Devonport	65	42	27	17	10	6	4	2	1	*237d*	*135d*
Weymouth	63	39	23	14	8	4	2	1	*260d*	*138d*	*76d*
Southampton	68	45	30	19	12	7	4	3	1	*306d*	*173d*
Portsmouth	65	42	26	16	9	5	3	2	*342d*	*190d*	*101d*
Newhaven	75	54	38	26	18	11	7	4	2	1	*299d*
Dover	81	65	51	40	30	22	16	11	8	5	4
Sheerness	80	63	49	37	28	21	15	11	8	5	4
Average	69	47	32	21	14	9	6	4	3	2	1
Factor increase	1·5	2·1	3·2	4·7	7·1	10·7	16	25	38	59	100

Where return periods are < 1 year, the return period is converted to days rather than years and the number is followed by the letter *d* and is in italics.

Table 3. Changes to the return periods (years) of the return level with a 100 year return period in 1990 through the twenty-first century for the medium emissions relative sea-level rise scenario

Site	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
St. Mary's	42	17	7	3	1	*164d*	*75d*	*37d*	*19d*	*11d*	*7d*
Newlyn	44	19	8	3	1	*190d*	*81d*	*37d*	*18d*	*10d*	*5d*
Devonport	48	24	11	5	2	*307d*	*129d*	*57d*	*26d*	*13d*	*7d*
Weymouth	45	19	8	3	1	*168d*	*68d*	*29d*	*13d*	*7d*	*4d*
Southampton	50	25	12	5	2	*354d*	*148d*	*62d*	*26d*	*11d*	*5d*
Portsmouth	47	21	9	4	2	*221d*	*85d*	*33d*	*14d*	*5d*	*5d*
Newhaven	59	32	17	8	4	2	*257d*	*113d*	*54d*	*27d*	*15d*
Dover	69	46	29	18	11	6	3	2	*298d*	*140d*	*65d*
Sheerness	67	44	27	17	10	6	3	2	*320d*	*153d*	*71d*
Average	52	28	14	7	4	2	1	*179d*	*88d*	*42d*	*20d*
Factor increase	1·9	3·6	7·1	13·5	26·5	52	100	204	417	871	1791

Where return periods are < 1 year, the return period is converted to days rather than years and the number is followed by the letter *d* and is in italics.

Table 4. Changes to the return periods (years) of the return level with a 100 year return period in 1990 through the twenty-first century for the high emissions relative sea-level rise scenario

activity in the English Channel and change the shape of the return period curve. However, this requires further investigation, including a more comprehensive sampling of future climatic conditions.

Recently, a number of authors have suggested that the IPCC's AR4 underestimates the range of potential sea-level rise during the twenty-first century (e.g. Grinsted *et al.*, 2010; Rahmstorf and Vermeer, 2009). This is captured in the UKCP09 projections by a very unlikely but physically possible (H++) scenario, which gives an average sea-level rise around the UK of 1·9 m by 2100. This scenario is designed as a limiting case for project appraisal purposes. Under this scenario, the level associated with a 100 year event in 1990 will be exceeded every high tide at all study sites.

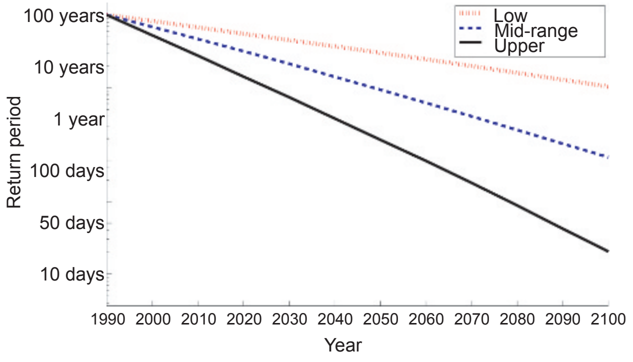

Figure 8. The average UK south coast return periods (years), every 10 years from 1990 to 2100, associated with a return level with a 100 year return period in 1990, for the low, medium and high emissions relative sea-level rise scenarios

5. An example of a recent storm surge event

It is interesting briefly to consider the results from the last two sections in the context of a recent significant storm surge event on the 10 March 2008 (summarised in Table 5). When compared with earlier assessments of surge events (e.g. Henderson and Webber, 1977; Wells *et al.*, 2001), this analysis benefits from a larger observational base, including the French coast.

On the 9 March 2008, a very strong jet stream propagated across the North Atlantic, creating a favourable environment for the development of a deep low depression off south-east Greenland. As this depression moved south-easterly over the North Atlantic, the pressure deepened rapidly from 975 mb at 0600 h on the 9 March to 946 mb 18 h later. The pressure remained very low as the system moved over Ireland, across the Midlands and into the North Sea (Figure 9). The path of the storm was typical of storms that tend to generate large surges in the English Channel (Henderson and Webber, 1977). Interestingly, as early as the 4 March it had been forecast that a deep low depression could be in the vicinity of the British Isles by the 10 March and that a high spring tide was predicted for the same day.

As the event passed over Ireland and England, the low pressure and strong south-west to westerly winds generated a surge of around 1 m in the central regions of the English Channel: skew surge (the difference between predicted and observed high

Site	Sea level: m CD	Astronomical tide: m CD	Skew surge: m	Peak surge height: m	Return period 1990: year	Return period 2008: year
St Mary's	6·43	5·99	0·44	0·64	5	3
Newlyn	6·35	5·80	0·55	0·81	13	9
Devonport	6·34	5·77	0·57	0·82	10	7
Weymouth	3·04	2·33	0·71	1·08	47	29
Southampton	5·60	4·83	0·77	1·20	68	51
Portsmouth	5·50	4·79	0·71	1·09	13	10
Newhaven	7·20	6·78	0·42	0·86	< 1	< 1
Dover	6·21	6·65	−0·44	0·45	< 1	< 1
Le Havre	8·75	8·02	0·73	1·04	3	2
Cherbourg	7·27	6·53	0·74	1·05	15	13
Jersey	12·33	11·58	0·75	1·25	18	11
Roscoff	9·88	9·37	0·51	0·67	7	5
Le Conquet	7·61	7·15	0·46	0·58	1	< 1
Brest	8·03	7·36	0·67	0·67	4	3

Table 5. Levels and associated return periods attained during the storm surge event on the 10 March 2008

water (Horsburgh and Wilson, 2007)) exceeded 0·7 m at six stations (Figure 10(a)). Further east, the surge was much smaller. There was localised flooding in the western and central Channel including Teignmouth (Devon), Flushing (Cornwall), Portsmouth and in several small towns along the Brittany coastline. About 30 people had to be evacuated from a caravan park at Selsey, West Sussex after sea defences were breached. Many residents of the so-called millionaires enclave of Sandbanks (Dorset) were stranded after the road leading to the peninsula was inundated. The flooding was most extensive on the Isle of Wight and in the Channel Islands. In Jersey, according to an unpublished internal report from 2008 by Le Blancq and Searson for the Jersey Meteorological Department, the damage to sea defences was estimated at about half a million pounds. It is also worth noting that newly installed flood defences also worked; in Old Portsmouth new mobile gates avoided flooding in an area that has been repeatedly flooded over the last 50 years.

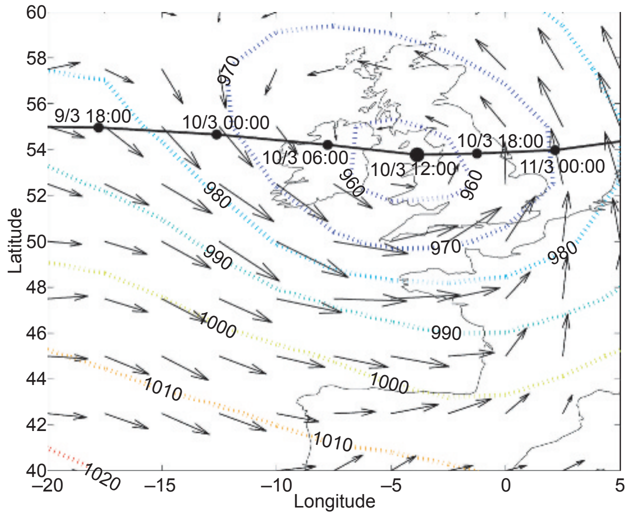

Figure 9. Atmospheric pressure at 1200 h on the 10 March 2008 over the British Isles and the approximate storm track (the arrows indicate wind direction and the dotted contours atmospheric pressure; plot generated using the US National Center for Environmental Prediction global reanalysis data)

The estimated return periods associated with the maximum sea levels are also listed in Table 5, and are shown in Figure 10(b) relative to 2008. The largest return period occurred between Weymouth and Southampton on the UK coast. At Southampton (Figure 11), the sea levels were the highest measured since records began in 1935. While the return period is lower at Portsmouth this represents a small difference in skew surge due to the limited surge heights within the Channel.

Flooding was extensive at Jersey (and also Guernsey), despite the fact that the sea level here only had a return period of 11 years. This highlights that other variables, most importantly waves, are also important, as has been found by the authors in related, as yet unpublished, analyses of flooding in the Solent. It is well known that energetic swell events in the Channel have

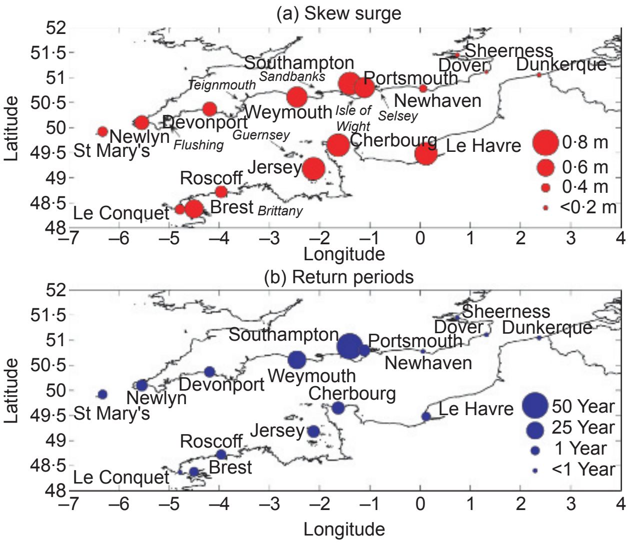

Figure 10. (a) Skew surge and (b) return periods (relative to 2008) associated with maximum sea levels on 10 March 2008

caused widespread flooding combined with high, but not extreme sea levels (Draper and Bownass, 1983). Hence, historic and potential future changes to the wave climate in the English Channel also need to be further investigated.

Looking to 2100, the maximum sea level observed at Southampton during the 10 March 2008 event is projected to be exceeded about every 6 years, three times a year and almost every high water over the spring part of the spring/neap tidal cycle with the low, medium and high UKCP09 emission scenarios, respectively.

Figure 11. Waves overtop the quay wall at Southampton Docks at high tide on 10 March 2008 (Source: Barry Marsh, School of Ocean and Earth Science, University of Southampton)

6. Conclusions and implications for coastal flood management

A recently extended sea level dataset has been used to evaluate changes in mean and extreme sea levels throughout the twentieth and early twenty-first century (to 2007) at 16 sites around the English Channel. Mean and extreme sea levels are rising at similar rates: best estimates vary around the Channel from 0·8 to 2·3 mm/year. While the mean changes may seem small, the return periods of a given sea level occurring have been significantly reduced over the twentieth century and this trend continues. Potential future extreme high sea levels have been estimated at nine sites along the UK south coast. For the UK Climate Impacts Programme's 2009 low, medium and high emissions scenarios (12, 40 and 81 cm total ocean rise, respectively), the exceedence frequency of extreme high sea levels along the south coast would on average increase over the twenty-first century by a factor of 10, 100 and about 1800, respectively. These results illustrate the large changes in return periods of high sea levels that can occur due simply to mean change. Hence, events that are presently considered extreme will become more frequent with time.

Responding to these challenges will be a significant task for flood risk management around the English Channel and by implication, widely around the world's coasts. Here the remarks are restricted to the UK, which is better prepared for these challenges than most countries (Tol *et al.*, 2008). Shoreline management planning accepts that universal protection is not a viable response and is trying to decide where should be protected and where it would be more prudent to allow managed realignment (Defra, 2006b; Leafe *et al.*, 1998). Some of the flood hotspots that have already been mentioned, such as Portsmouth and Pevensey, have received significant investment in better flood defences over the last 10 years, and Portsmouth plans further defence upgrade with sea-level rise being a major factor driving this need. In addition to raising defences, it is also necessary to consider the potential for enhancing flood resilience to manage flood risk under a rising sea level. This could be both retrofitting of existing properties and as an integral element of new properties. Lastly, detection of accelerated sea-level rise is also an important issue, especially if sea-level rise is at the high end of the projected range. This may be first accomplished globally by way of satellite measurements (cf. Nicholls and Cazenave, 2010), but it is important that these results are rapidly translated down to an appropriate scale for adaptation responses, such as the English Channel.

Tide gauge measurements of sea level along the English Channel coast have provided important insights on extreme sea levels, both historically and in the future. In particular, the potential of data archaeology to enhance sea level records useful to flood risk management has been demonstrated. Given that sea levels are rising, it is also important that all these sea-level measurements are continued into the future.

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