UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATCIS

School of Civil Engineering and the Environment

EXTREME SEA LEVELS IN THE ENGLISH CHANNEL
1900 TO 2006

by

Ivan David Haigh

Thesis submitted for the degree of Doctor of Philosophy

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ABSTRACT

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
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Coastal populations are growing at a rapid pace and this is being accompanied by an increased investment in infrastructure at the coastal zone. Combined with this is the concern of enhanced coastal flooding due to rising sea levels and climate change. Hence, it is of utmost practical importance that probabilities of current and future extreme sea level are accurately evaluated so that the changing flood risk can be assessed and defences upgraded where appropriate. This thesis tests the hypothesis that changes in extreme still water level can be approximated by just adding changes in mean sea level to current return levels estimated from measured data, for the English Channel region.

A data archaeology exercise has been undertaken to extend the sea level records along the UK south coast. This exercise increased the sea level data set for this region by 173 years. These new records have been analysed along with existing data to determine rates of change in both mean and extreme sea level, and to estimate probabilities of extreme sea level using four statistical methods: (i) the annual maxima method; (ii) its extension to the r-largest annual events method; (iii) the joint probabilities method; and (iv) the revised joint probabilities method.

Relative mean sea-level trends vary by between 0.8 and 2.3 mm/yr around the Channel over the 20th century. These trends have been estimated using a new approach, in which the coherent part of the sea level variability around the UK is defined as a single index. This is then subtracted from the sea level records prior to fitting trends. The recent high rates of mean sea-level rise observed over the last decade are not unusual on a century scale context. The tidal and non-tidal components of sea level, along with tide-surge interaction, have been separately analysed for trends before analysing variations in extreme sea levels. There is evidence for an increase in extreme sea levels during the 20th century, but at rates not significantly different to that of mean sea level. There is no evidence of a long-term increase in storm count, duration or intensity. The revised joint probabilities method is found to out perform the other statistical methods, in terms of prediction errors.

Results confirm that changes in extreme sea levels during the 20th century can be estimated, to an accuracy of 0.1 m, by simply adding mean sea level changes to return levels estimated from measured data. The return levels should be estimated using the revised joint probabilities method wherever possible.

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DECLARATION OF AUTHORSHIP

I, Ivan David Haigh declare that this thesis entitled ‘Extreme Sea Levels in the English Channel: 1900 to 2006’ and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature from a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this work have been published as:

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LIST OF ABBREVIATIONS

AMM	annual maxima method
AR4	Fourth Assessment Report
BODC	British Oceanographic Data Centre
CD	chart datum
CGPS	continuous Global Positioning System
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EOF	empirical orthogonal function
EPM	exceedance probability method
GEV	generalized extreme value
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
JPM	joint probabilities method
MHW	mean high water
MLW	mean low water
MTL	mean tidal level
MTR	mean tidal range
MSL	mean sea level
NAO	North Atlantic Oscillation
ODN	Ordnance Datum Newlyn
pdf	probability density function
POL	Proudman Oceanography Laboratory
POTM	peaks over thresholds method
PSMSL	Permanent Service for Mean Sea Level
RJPM	revised joint probability method
RLM	r-largest Method
RLR	revised local reference

SE	standard error
SHOM	Service Hydrographique et Océanographique de la Marine
SONEL	Systéme d'Observation du Niveau des Eaux Littorales
SRJPM	the spatial revised joint probability method
TGBM	tide gauge benchmark
WM	Walden method
UK	United Kingdom
UKHO	United Kingdom Hydrographic Office

LIST OF SYMBOLS

e	expected number of observations in each tidal band with no tide-surge interaction
g	acceleration due to gravity
H_t	observed still water level
H_i	amplitude of tidal constituent
I_o	base year
h	water depth
cm	centimetre
km	kilometres
m	metres
mm	millimetres
N	number of tidal constituents
N_i	number of observations observed in each tidal band
nobs	number of observations
p	probability
P	pressure
P_a	atmospheric pressure
r	number of extreme events per year
s	number of hours separating extreme events
S_t	non-tidal residual
t	time
T	return period
X_t	astronomical tide
yr	year
Z_0	mean sea level

z_p	return level
$>$	greater than
$<$	less than
%	percent
$\pm$	plus or minus
$\sum$	sum
$\rightarrow \infty$	tends to infinity
$\aleph$	chi-squared
ρ	sea water density
σ	frequency of tidal constituent
φ	phase of tidal constituent
β	trend parameter in GEV fit
α	intercept in GEV fit

1 INTRODUCTION

1.1 Background and Justification

At the coastal zone, populations are expected to continue to grow rapidly throughout the 21st century along with an increased investment in infrastructure. It is likely that these changes will be accompanied by an increase in extreme high sea levels as a result of rising sea levels and climate change. Therefore, it is of the utmost practical importance that the probabilities of current and future extreme sea level are accurately evaluated so that the changing flood risk can be assessed and defences upgraded where appropriate. This thesis tests the common assumption that changes in extreme high sea level can be accurately determined by adding changes in mean sea level to return levels estimated from measured data, for the English Channel region.

1.1.1 Historic Coastal Flooding

Throughout this thesis, the term 'sea level' is used to denote the instantaneous height of the sea with respect to a fixed point on land after waves have been removed. Therefore, at any specific time or location, the sea level is the sum of a mean level, an astronomical tidal component and a non-tidal residual (Pugh, 1987). The mean sea level (MSL) component is the average height of the sea defined over a year. The tidal component is the response of sea level to astronomical forces. The non-tidal residual or surge component, primarily contains the meteorological contribution to sea level. When large surges coincide with the high water of a spring tide, extreme sea levels result. Such events can be devastating along low-lying, highly populated and developed coastlines, leading to considerable loss of life, billions of pounds worth of damage and drastic changes to coastal landforms.

Northern Europe has a long history of severe storms resulting in coastal flooding. A large North Sea storm occurred in November 1570 and it has been suggested that between 100,000 and 400,000 people were drowned (Lamb, 1991). In 1607, coastal floods in the Bristol Channel caused the greatest loss of life from any sudden onset natural catastrophe in the United Kingdom (UK) during the last 500 years (RMS, 2007). Between 500 and 2000 people were drowned in isolated farms and villages on low-lying coastlines around the Severn Estuary and Bristol Channel. During the great storm of 1703, the lowermost street of houses in the village of Brighthelmstone (today's Brighton) were washed away (RMS, 2003).

In the 20th century, the disasters of coastal flooding in northern Europe were brought to the forefront by the severe storm of 1953 (Rossiter, 1954; McRobie et al., 2005). In southeast England, 307 people were killed and 24,000 people fled their homes (Jonkman and Kelman, 2005). 1,800 lives were lost in the Netherlands (Verlaan et al., 2005). This catastrophic event led to widespread agreement on the necessity of a coordinated response to understanding the risk of future coastal flooding and to provide protection, where possible, against such events (Coles and Tawn, 2005). It was the driving force for the development of storm surge forecasting services (Heaps, 1983), the Delta Plan in the Netherlands (a series of dams, sluices, locks, dikes and storm surge barriers that help to protect 8.5 million inhabitants living below sea level) and the Thames storm surge Barrier in London. Without the Thames Barrier, London's continued existence as Britain's capital and a major world city would be very precarious (Dawson et al., 2005).

The occurrence of considerable coastal flooding arising from these historical extreme storms, most notably the 1953 event, created a demand for the reassessment of flood defence levels (Graff and Blackman, 1978). Since the 1953 event, there has been a large scale upgrading of flood defences around most of the UK at a considerable cost. In each case, some form of statistical analysis has been used to assess suitable design levels (Dixon and Tawn, 1994). These analyses were based on extreme value theory. This is a statistical discipline which uses the concepts of return level and return period to convey information about the likelihood of rare events such as floods. A return level, z_p, with a return period of $T = 1/p$ years, is a high level whose probability of exceedance is p. For example, $z_{0.01}$ is the return 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.

1.1.2 Enhanced Coastal Flooding

In recent decades, a renewed interest in sea-level research has stemmed from concerns relating to climate change, among other factors, and the associated risks of increased coastal flooding. Over the 20th century, tide-gauge observations show that global sea level on average rose by 1.7 ± 0.5 mm/yr (Bindoff et al., 2007). For the 21st century, a global MSL rise of between 18 and 59 cm[1] is one of the more certain consequences of human-induced climate change as shown by the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) (Meehl et al., 2007). Extreme sea levels are almost certain to increase with this expected rise in MSL and could increase further with possible changes in storminess (Hinton et al., 2007). The problem is further amplified in many parts of the world by land subsidence associated with both natural and anthropogenic geological processes, particularly in densely populated coastal deltas and cities (Woodworth et al., 2004). Most of the studies that have assessed changes in either past or future sea level have focused on the variations in MSL rather than in extreme high sea levels, although it is the latter which results in the most impact at the coast (Woodworth and Blackman, 2004).

Society has become increasingly vulnerable to extreme high sea levels over the past century. Profound changes to the coastal zone have occurred due to growing populations and increasing urbanization. In excess of 150 million people live within 1 m of high tide level

[1] larger rises are possible

and a further 100 million live within 5 m of high tide (Anthoff et al., 2006). By 2010, 20 out of 30 mega-cities (population > 8 million) will be on the coast and there are likely to be at least 136 coastal port cities with more than one million people (Nicholls, 1995; Nicholls et al., 2006). Further, billions of pounds are invested in coastal infrastructure (Church et al., 2007).

In England and Wales, approximately £100 billion worth of assets are at risk of coastal flooding today, which is about half of the national flood risk (Hall et al., 2006). Over the 21st Century, some of the largest increases in flood risk in England and Wales are likely to occur along the southern English coastline according to the Foresight analysis (Evans et al. 2004). Large cities such as Plymouth, Poole, Bournemouth, Southampton and especially Portsmouth, are all prone to increasing coastal flooding. Changes in sea level will seriously affect natural barriers such as, the internationally designated Chesil Beach and Hurst Spit, both of which protect neighbouring low lying land. Chesil Beach and Hurst Spit have both been impacted during the 20th century (1979 and 1989, respectively). Therefore, it is imperative that extreme sea levels are accurately evaluated along the UK south coast so that the changing flood risk can be assessed and defences upgraded where appropriate (Coles and Tawn, 2005). In this regard, the majority of sea level research in the UK has concentrated on the east and west coasts. There is a more limited understanding of extreme sea levels in the English Channel. This may reflect the fact that surge levels reached during extreme events have tended to be smaller along the south coast. As a result, the risks were previously assumed to be lower. Further, major flood events have been limited in the English Channel over the last 50 to 60 years, with a few exceptions such as the storm of 14 December 1989 (Wells et al., 2001)

1.1.3 Estimating Future Extreme Sea Levels

With coastal development continuing at a rapid pace, combined with the concern of enhanced coastal flooding, it is fundamental to have accurate estimates of future extreme high sea levels. Three approaches have been used to assess future changes in extreme sea levels, namely: (i) the statistical method, (ii) the dynamic method and (iii) the MSL offset method.

In the statistical approach, relationships between the local surge heights and large-scale driving meteorology are developed from observations or model simulations of the recent past and present day. Next, a projection is made of future large-scale meteorology using a global climate model. Future storm surge characteristics are then determined using the existing statistical relationships (von Storch and Reichardt, 1997; Langenberg et al., 1999). This technique assumes that the relationship between the large-scale variables and the surges, which hold in the present day climate, will remain unchanged in the future (Woodworth et al., 2006).

In the dynamic approach, process-based numerical models are used to simulate sea levels in the past/present day and then future periods. The tide-surge models are driven with pressures and winds from atmospheric climate models for both past/present and future periods (Flather and Smith, 1998; Lowe et al., 2001; Lowe and Gregory, 2005; Woth, 2005; Woth et al., 2005, 2006; Unnikrishnan et al., 2006). When a population of future sea level events has been generated, an assessment of the changes in extreme high sea levels can be made using either a percentile (see Section 4.2) or extreme value analysis (see Section 2.4).

Both methods are complex and require substantial computer resources and access to tide-surge and atmospheric models. Of these two methods, the statistical approach is simpler in that it does not require the further complexity of running a tide-surge model. However, the dynamic approach does not rely on the relationship between past storm behaviour and extreme sea levels continuing into the future.

Both the statistical and dynamic approaches have been used to investigate changes in extreme sea levels across the European shelf. Woodworth et al. (2006) has carried out a detailed review of these studies and therefore a discussion of the results is not given here. Generally, the results of these studies have been unsatisfactory. The spatial extent and magnitude of predicted changes in future extreme sea levels vary significantly depending on which models were used and the time-slices over which the simulations were run.

The third much simpler approach for estimating future extreme sea levels is the MSL offset method. This assumes that future extreme sea level can be approximated by just adding projections of MSL to current return levels estimated using existing sea level records (Araújo and Pugh, 2008). This assumption is illustrated in Figure 1.1 which shows a return period curve for the year 2000 along with the return period curve likely to occur with a 0.2 m rise in sea level. Under present conditions, a 1 in 1,000 year return period event has a level of about 6.45 m. With a 0.2 m rise in MSL, an event of this level will occur about once every 6 years. The aim of this thesis is to test this assumption for the English Channel region (Figure 1.2) over the period 1900 to 2006.

The MSL offset approach raises two important issues: First, estimating future extreme sea levels in this way assumes that changes in extreme sea levels are mainly caused by direct MSL effects (i.e. MSL increasing the baseline). However, increases in MSL alter water depths and so influence extreme levels indirectly by modifying the propagation and dissipation of the astronomical tide and surge components of sea level. In addition, changes in extreme sea level can arise from variations in storm characteristics. Hence, the assumption essentially implies that changes in extreme sea levels are primarily caused by direct variations in MSL and that indirect changes are small and there are no major changes in storminess (i.e. storm track, frequency and intensity).

The second issue is related to the calculation of current return levels. Eight different statistical methods have been developed for estimating probabilities of extreme sea level (Section 2.4). However, there is currently no universally accepted method (Coles and Tawn, 2005). Dixon and Tawn (1994, 1995) compared three of the methods most often used to compute extreme sea levels and showed that the estimated return levels can differ significantly depending on which method is used. Hence, the estimated changes in future extreme still water levels will vary in the MSL offset approach depending on which statistical method is used to estimate current return levels.

In order to address the first issue, the MSL offset approach could be considered in an historical sense; i.e. had a scientist or engineer in 1950 correctly projected the rate of MSL rise between 1950 and 2000, would they have also accurately estimated (to within a certain range) extreme sea levels in the year 2000 by assuming a constant offset as in Figure 1.1? In order to determine this, two questions need to be asked: (i) What were the rates of relative MSL change throughout the 20th century? (ii) Were changes in extreme still water levels throughout the 20th century significantly different from those observed in MSL? In regards to the second issue the important question is: What is the most appropriate statistical method for estimating current return sea levels in the area of interest? This thesis examines these three questions using historic sea level records around the English Channel.

1.2 Aims and Objectives

The aim of this research is to test the hypothesis that changes in extreme high sea level can be determined, to an accuracy of 0.1 m, by simply adding changes in MSL to return levels estimated from measured data, for the English Channel region. When estimating return levels it is practical to work to an overall accuracy of 0.1 m. This is because of both the uncertainties in the statistical methods and the limits to application in real coastal situations (Araújo and Pugh, 2008). In testing the hypothesis the objectives were defined as:

1. **To determine the rates of change in MSL around the English Channel between 1900 and 2006.**

   Method: Carry out a data archaeology exercise to extend the digital sea level observations for the UK south coast. Use this extended data set, alongside existing records, to estimate the rates of relative MSL at tide-gauge sites around the English Channel. Determine the extent to which the changes in MSL are due to vertical land movements or oceanographic processes. Assess whether there is evidence of a recent acceleration in MSL.

2. **To establish whether changes in extreme sea level around the English Channel between 1900 and 2006 were primarily caused by variations in MSL.**

   Method: Split the extended sea level records into tidal and non-tidal components. Separately analyse each component, and the non-linear interactions between them, for significant trends before assessing changes in observed extreme sea levels.

3. **To evaluate which is the most appropriate statistical method for estimating probabilities of extreme high sea levels around the English Channel.**

   Method: Estimate return levels using the different extreme value analysis methods available. Undertake a series of tests to determine how sensitive the different methods are to: (i) the way in which the long-term trends in extreme sea level are handled; (ii) the ratio of the tide to surge variability; and (iii) the frequency, length and completeness of the available sea level data. Assess the performance of each of the methods using prediction errors (i.e. the difference between the estimated return periods of the observed maximum sea level and the corresponding data span).

1.3 Structure of Thesis

This thesis is organised into nine chapters. Chapter 2 describes the nature of sea level variations. It critically reviews the studies that have analysed observed changes in mean and extreme sea level and details the different statistical methods for estimating probabilities of extreme sea level. It also discusses the measurement of sea level and reviews the data sets that are currently available for scientific analysis around the English Channel. The sea level data sets used in the study are outlined in Chapter 3. This includes a data archaeology exercise which was undertaken to extend the sea level record along the UK south coast. Chapter 4 describes the research methodology. This has been undertaken in three main stages each based on one of the study objectives. Stage one is concerned with accurately estimating rates of MSL rise. In stage two the changes in extreme sea level are considered. In stage three the different extreme value analysis methods are evaluated. The results from each of the three stages are described in Chapters 5, 6 and 7, respectively. A summary of the main findings from each stage is given at the end of each of these chapters. A discussion of the results and further synthesis, including recommendations for further work, is given in Chapter 8. Chapter 9 provides the conclusions of this research.

There are also three technical appendices. Appendix A provides a short history of the sites for which data extensions have been made. Appendix B provides additional details relevant to the assessment of MSL trends. Appendix C presents a new test developed to better quantify non-linear interactions that take place at certain locations.

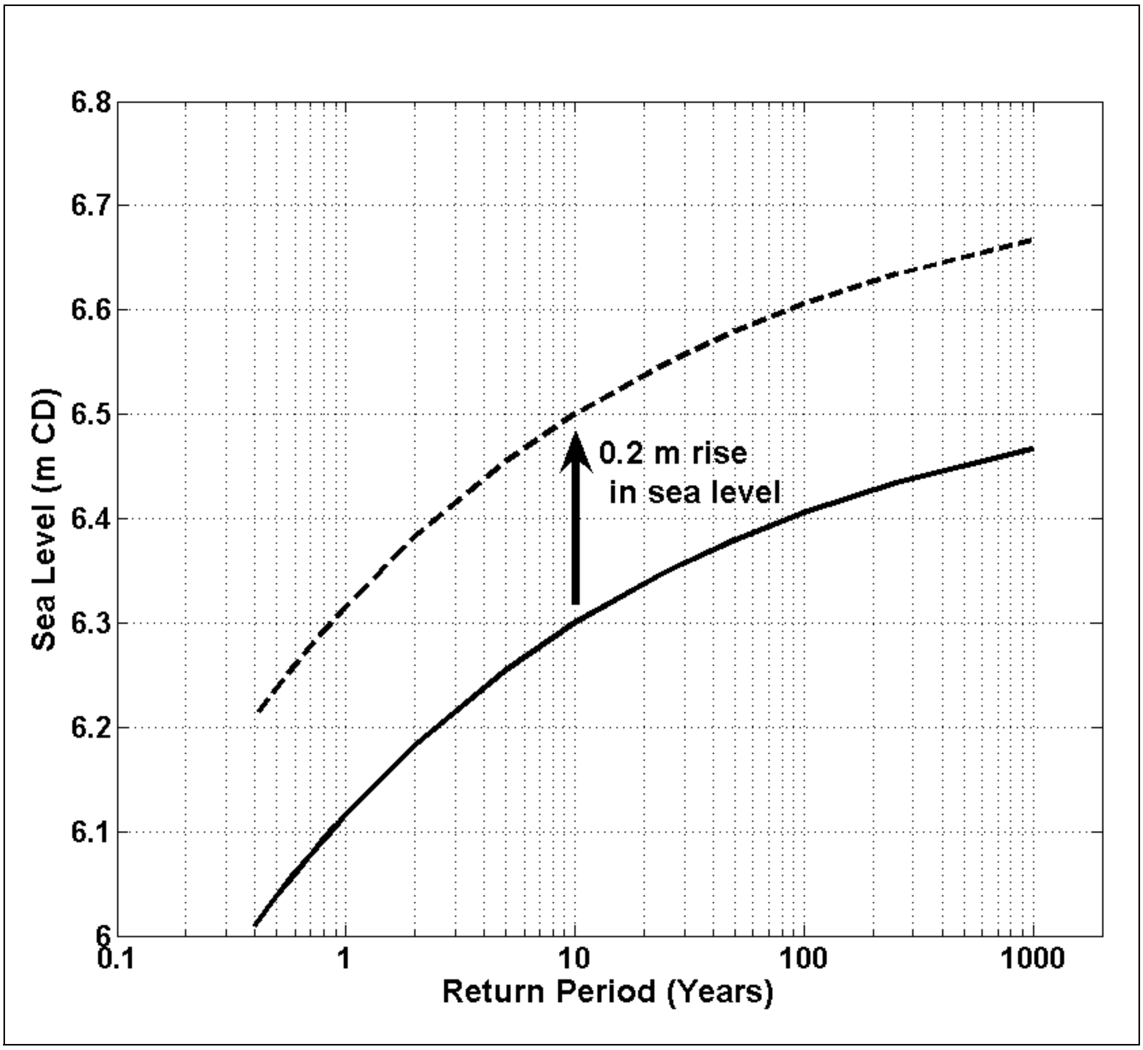


Figure 1.1: Illustrative return period plot showing extreme return levels in the year 2000 (solid line) along with those predicted to occur with a 0.2 m rise in mean sea level (dashed line), at Newlyn.

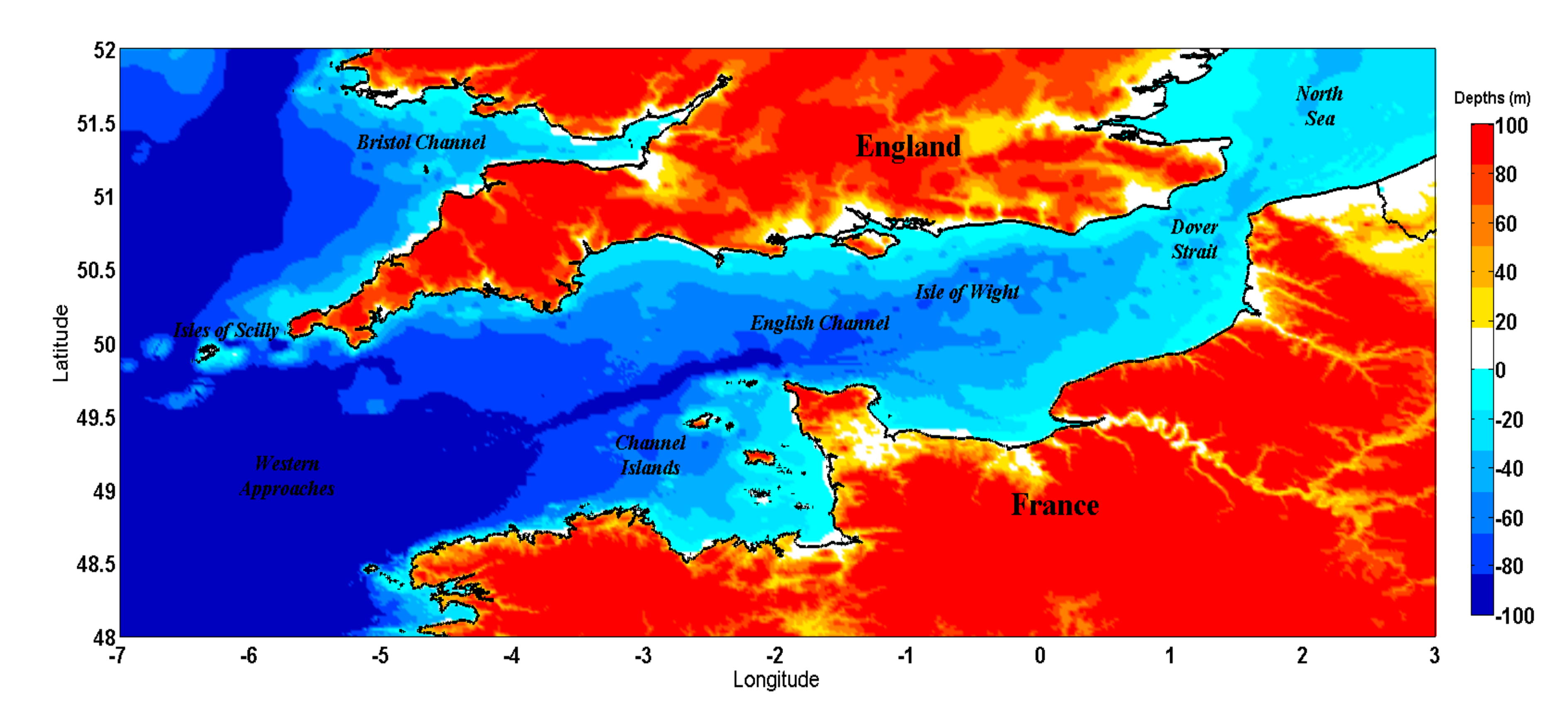


Figure 1.2: The study area (depths are in metres)

2 LITERATURE REVIEW

The study of sea level is of the utmost practical importance and covers many fields of research including: oceanography, meteorology, astronomy, geology and coastal engineering, among others (Woodworth, 2006). This chapter provides a background to sea level science and reviews the relevant literature. It describes the variations in sea level that arise from different physical forces which combine to produce extreme levels (Section 2.1). The studies that have assessed observed changes in mean and extreme sea levels are reviewed (sections 2.2 and 2.3). The different methods for estimating probabilities of extreme sea level are described and discussed (Section 2.4). This chapter also outlines how sea level measurements are made and reviews the data sets that are currently available for English Channel sites (Section 2.5). Finally, the key issues that have previously received little scientific investigation are outlined (Section 2.6). This chapter deals primarily with observed changes in sea level. Future changes are briefly considered in Chapter 8.

2.1 The Nature of Sea Level Variations

At any specific time or location, the observed sea level (H_t) can be described by the sum of three components defined in Equation 2.1 (Pugh, 1987):

$$\boldsymbol{H_t = Z_o + X_t + S_t} \qquad \text{EQ2.1}$$

Where: Z_o is the MSL component, X_t is the astronomical tidal component and S_t the non-tidal residual. At certain locations, non-linear interactions occur between the tidal and non-tidal residual.

The MSL component is the average height of the sea defined over an extended period of time, usually a year (Araújo and Pugh, 2008). Annual MSL values are normally calculated from hourly sea level measurements. The simplest way of calculating annual MSL is to add all the hourly values observed in a year and divide by the total number of hours in a year. More sophisticated methods include the application of low-pass filters (see Pugh, 1987).

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. Study of the astronomical tide is exceedingly well established and the oldest branch of physical oceanography (Cartwright, 1999). The regular periodic tidal variations in sea level are directly related in frequency to periodic geophysical forces (Tawn, 1992). Therefore, the tidal component can be expressed as the sum of a number of harmonic constituents:

$$X_t = \sum_{i=1}^{N} H_i \cos(\sigma_i t + \varphi_i), \qquad \text{EQ2.2}$$

where: H_i is the amplitude, σ_i the frequency and φ_i the phase of each of the i constituents and t is time. N is the number of constituents. H_i and φ_i can be determined by a least squares harmonic analysis (Pugh, 1987). (Equation 1 is written in a simplified form without the complications of the 18.6 year nodal cycle included; see Pugh, 1987). Once the tidal component has been determined, it can then be removed from the observed sea level record to reveal the remaining components.

The non-tidal residual is the part of the sea level which remains once the tide and MSL components have been removed (Pugh and Vassie, 1979). This component primarily contains the meteorological contribution to sea level termed the surge, but may also contain harmonic prediction errors or timing errors. The term ‘storm surge’ is used when excess sea levels are generated by low atmospheric pressure and high wind stress associated with a severe storm. Changes in atmospheric pressure bring about variations in vertical forces acting on the sea surface and are immediately felt at all depths. Wind forcing acts parallel to the sea surface and is transferred down through the water column. The duration and direction of the wind, and the density structure of the water column, determine the depth to which the wind stress forcing is felt (Pugh, 2004). (Throughout the rest of the thesis, the non-tidal residual is referred to as the surge component, assuming that any prediction or timing errors are insignificant).

At certain locations, non-linear interactions occur between the tide and surge components of sea level. It has been recognised for some time that this tends to cause surge maxima to occur most frequently on the rising tide (Doodson, 1929). This process, known as tide-surge interaction, has been most studied in the southern North Sea where it significantly influences extreme sea levels (Rossiter, 1961; Prandle and Wolf, 1978; Wolf, 1978, 1981).

Horsburgh and Wilson (2007) demonstrated that the interaction patterns in the North Sea could be explained by the combined effect of a phase shift of the tidal signal and the modulation of surge production due to water depth. In the southern North Sea, the tendency for large surges to occur about four hours before high water was shown to be primarily because of a phase shift process. If the tide arrives sooner than predicted, and the surge is defined as being the observations minus the predictions, then a surge with the same periodicity as the tide and a maximum on the rising tide is obtained (Figure 2.1). A phase change between the observed sea level and predicted tide can easily be explained. Tides and surges are shallow water waves with phase speeds of $(gh)^{1/2}$. Where h is water depth and g is the acceleration due to gravity. Reduced water depth also will result in a reduced phase speed due to the effects of bottom friction (Wolf, 1981). Positive surges increase the phase speed of the tide and surge as they travel along the coast. Other features of the surge distribution can be explained by the fact that wind stress is more effective at raising the sea surface in shallow water.

At any specific time or location, the unseen MSL, tidal and surge components combine to give the observed total sea level. Extreme sea levels, which are the focus of this thesis, arise when storm surges coincide with high water. The actual magnitude of the surge is usually of secondary importance to the timing of the surge peak. Large surges at low water can occur almost undetected, whereas even relatively moderate surges at the high water of a spring tide could potentially cause flooding. The magnitude of the tidal range is an important factor in relation to extreme sea levels. Where the ratio of the tide range to surge variability is large, the length of time over which a surge can cause an extreme sea level is much shorter than at locations where ratios are small. Sites can be classified as either tide or surge dominant, by calculating the ratio of the tidal range to the surge variability or by calculating the ratio of the tidal variance (or standard deviation) to surge variance (or standard deviation).

This thesis is primarily concerned with observed changes in extreme sea level. As sea level is the sum of the components, outlined above, any changes to these will result in changes to extreme levels. It is evident from long sea level observations that MSL is changing (Section 2.2). Any change in MSL will affect extreme sea level directly by increasing the 'baseline'. However, changes in MSL also affect extremes indirectly by modifying the propagation and dissipation of the astronomical tide and surge components. Further, changes in extreme sea level can arise from variations in the strength and tracks of weather systems which alter the magnitude, duration and intensity of storm surges. Changes in extreme sea level could also arise from variations in tide-surge interaction. Observed changes in MSL and extreme sea level are considered in Sections 2.2 and 2.3, respectively.

2.2 Observed Changes in Mean Sea Level

Traditional estimates of changes in MSL are made relative to a fixed point on land. Consequently, the change in MSL is a measure of the difference between the vertical movements of the sea's surface and of the land itself. Vertical land movements arise from both natural (tectonics, glacial isostatic adjustment, etc.) and anthropogenic (usually subsidence caused by withdrawal of ground fluids and the drainage of susceptible soils) geological processes (Nicholls et al., 2007). Long-term changes in corrected (i.e. land movements removed) sea level are mainly caused by changes in water volume or ocean circulation (Bindoff et al., 2007). Increased water volumes largely result from a range of climate-change related processes including the melting of land-based ice, thermal expansion of sea water and changes in terrestrial hydrological regimes.

Estimates of relative[2] MSL change over the long-term past have been obtained from a variety of geological indicators. These sources reveal that sea level varied by as much as 100 m as major ice sheets grew and shrank during glacial-interglacial cycles (Church et al., 2007). Palaeo data from corals indicate that during the last interglacial period (about 125,000 years ago) sea level was 4 to 6 m above that of present day. Sea level then fell to more than 120 m below the present day level as water became trapped in ice sheets during the last ice age. Levels then rose rapidly until about 6,000 years ago as ice melted, at average rates of 10 mm/yr. Between 6,000 and 2,000 years ago sea level rose more slowly. From ancient fish tanks built by the Romans about 2,000 years ago, it can be deduced that there was little change in sea level from 2,000 years ago until around the start of the 19th century (Lambeck et al., 2004). Estimates from sediment cores collected in salt marshes and from the few long tide-gauge records, reveal that there was an increase in the rate of sea-level rise during the 19th and early 20th century (Gehrels et al., 2006; Woodworth et al., 1999).

Over the past century, more precise estimates of changes in MSL have been made using tide-gauge observations (Section 2.5). Estimates for the 20th century, show that the average global rate of sea-level rise was 1.7 ± 0.5 mm/yr (Bindoff et al., 2007). In spatial terms, the sea level change is highly non-uniform. In some regions the rates are several times that of the global mean rise. In other regions the sea level is falling. This highlights the first major issue related to estimating global rates of MSL change from tide-gauge records. The long tide-gauge records are mostly located along coastlines in the Northern Hemisphere (Woodworth and Player, 2003). Hence, it is difficult to accurately estimate a truly global rate using data measured by tide-gauges only.

A second important issue in determining sea-level trends from tide-gauge records relates to the fact that the vertical movements of the land upon which the gauges are located

[2] The term ‘relative’ MSL change is used to identify that the variations in sea level include the vertical components of both the sea and land.

can be changing spatially as much as the level of the sea itself (Woodworth, 2006). Comparisons of changes in MSL between studies are made difficult by the fact that corrections for vertical land movement are made in different ways. One way of correcting the records for vertical land movements is using models capable of simulating geological processes (Peltier, 2001). Alternatively, rates of vertical land movement can be estimated from geological information near the gauge site (Woodworth et al., 1999). Where possible, the correct scientific approach is to measure vertical movement at the tide-gauge (Woodworth, 2006). With the recent advances in geodetic techniques (Bingley et al., 2007), the scientific community is increasingly turning to this approach (Section 2.5). However, the measured datasets that are currently available are relatively short (< 10 years) and hence the uncertainties associated with the fitted trends tend to be large (>1 mm/yr) (see Bingley et al., 2007).

A third important issue is related to the presence of significant decadal variations in sea level (Holgate, 2007). These variations tend to distort estimates of long term MSL change, particularly in records shorter than a few decades (Douglas, 1991). Pugh (1987) illustrated this by showing that 10-year trends at Newlyn can have different signs depending on the intervals chosen (Figure 2.2). Only a relatively few studies have assessed the importance of record length when estimating MSL trends (Peltier and Tushingham, 1989; Emery and Aubrey, 1991; Douglas 1991, 1992, 1995). These studies generally conclude that at least 40 to 50 years of sea level measurements are required to accurately calculate long-term MSL trends. Further work is required to both understand the causes of the decadal variations in sea level and to assess how shorter records can be better utilised for determining changes in MSL.

In several studies, attempts have been made to remove the meteorological-induced variance in series of annual MSL by: (i) using regression fits, in which sea level was expressed as a function of air pressure (i.e. the inverted barometer effect; Pugh, 1987) recorded at or near the location of the tide-gauge (Rossiter 1972; Woodworth, 1987; Holgate, 2007); (ii) using numerical models (Woodworth et al., 1999, 2009). In this thesis an alternative approach, recently suggested by Woodworth et al. (2009), is used to remove part of the decadal variance. This technique is described below.

Another important issue related to MSL changes has been called the 'enigma of 20th century sea-level rise' (Munk, 2002). This issue is concerned with the fact that the range of possible contributors to 20th century sea level change (i.e. thermal expansion, glacier melt, etc) add up to only 7cm. This is less than half of the observed value. The uncertainties in the contributing terms are large, so that the 7 cm lies within a range of -8 to +22 cm. One could argue that this is consistent with the 17 cm rise of the last century, but this view is not entirely satisfactory (Woodworth, 2006). Increasingly, this issue and the other issues described above are being resolved through wide-scale systematic global measurements of sea level by satellites (Section 2.5). Measurements from satellite altimetry over the period 1993 to 2003 suggest a truly global MSL trend of 3.1 ± 0.7 mm/yr (Cazenave and Nerem, 2004). During this period, the different contributors to sea-level rise sum to 2.83 ± 0.7 mm/yr, which is in much better agreement with the estimate from the altimetry data (Bindoff et al., 2007). The contribution from thermal expansion is 1.6 ± 0.5 mm/yr. The remaining rise is attributed to the melting of glaciers and ice caps.

The central rate of sea-level rise obtained for the recent altimetry data (i.e. 3.1 mm/yr) considerably exceeds the 1.7 mm/yr estimated by tide-gauges for the 20th century (Bindoff et al., 2007). Taken at face value, this suggests a recent acceleration of the global sea level secular trend (Holgate and Woodworth, 2004). The decade over which the satellite measurements were made was at a time when global air and sea temperatures achieved record highs and when high rates of glacier melt were reported (Woodworth, 2006). Accelerations in sea-level rise are particularly difficult to assess due to monthly, yearly and decadal variations linked to climate indices such as the El Niño Southern Oscillation and the North Atlantic Oscillation. Holgate (2007) analysed nine long and nearly continuous tide-gauge sea level records from around the world. He demonstrated that the high decadal rates of change in global MSL observed during the last 20 years of the record were not particularly unusual in the longer context (20th century). Again, this demonstrates that when assessing changes in MSL one needs to carefully consider both the length and period over which the sea level records are measured. Further progress in understanding both long-term global and regional changes in MSL have been made using empirical orthogonal functions, based on combining the tide-gauge and satellite altimetry data (Church et al., 2004a).

Assessments of changes in MSL along the northern French coastline are limited. In contrast, major reviews of changes in MSL around the UK have, on average, been undertaken every decade for the last 30 years (Woodworth 1987; Woodworth et al., 1999; 2009). An important outcome of these studies was the finding that, while the character of sea level variability differs around the UK, part of the variability is coherent between sites. Further, it can be represented by a single index derived from a few long records. In the most recent review, more accurate long-term rates of MSL change were estimated by subtracting this index from time series of annual MSL before fitting trends. What this recent study did not do, was to quantify exactly the extent to which this procedure allows more accurate estimates from shorter records. The rates of MSL change were compared to rates of vertical land movement estimated from geological data and advanced geodetic techniques. Based on this comparison, it was estimated that the rate of sea-level rise around the UK from oceanographic processes only is 1.4 ± 0.2 mm/yr. This value is about 0.3 mm/yr lower than the 1.7 mm/yr global sea level rate for the 20th century. One reason the UK MSL trend was lower than the global-average could be because of the melting of the Greenland ice sheet during the 20th century (Woodworth et al., 2009). The elastic response of the solid earth might have resulted in a redistribution of sea level (i.e. the contribution of the Greenland ice sheet to UK sea level is slightly smaller than that contributed to the global-average).

At the last glacial maximum, the ice sheet that covered much of Britain was large enough for glacial isostatic adjustment processes to produce vastly contrasting relative sea level changes at different locations. Shennan and Horton (2002) estimated rates of vertical land movement around the UK using geological sea level indicators (Figure 2.3). Results imply that maximum land uplift occurs in central and western Scotland (approximately 1.6

mm/yr) and maximum subsidence takes place in southwest England (about 1.2 mm/yr). These vertical land movements tend to result in relative MSL changes at tide-gauges being less than 1.4 mm/yr around Scotland and more than 1.4 mm/yr around southern England (Woodworth et al., 2009).

Gehrels (2006) recently questioned the high rate of subsidence reported for the southwest of England by Shennan and Horton (2002). The author argued that the high rate for the southwest is based on questionable geological data. Further, the rates are based on several assumptions, which if incorrect, lead to over-estimations of the supposed subsidence rate. Interestingly, Woodworth et al. (1999, 2009) suggested that the subsidence rate for the southwest of England might be closer to 0.7 mm/yr, based on the rates of relative MSL change estimated from the tide-gauge data at Newlyn. Clearly, this issue needs to be resolved as current MSL projections for this part of the UK assume higher subsidence estimates (UKCIP, 2005). If these estimates are too high, it may result in needlessly high costs in maintaining appropriate levels of flood defences.

Recent estimates of vertical land movement are available for ten sites around the UK based on advanced geodetic techniques (Section 2.5). These data sets however, only cover short periods (<10 years) and so the uncertainty associated with the trends is large (>1 mm/yr). As the data lengths increase, they will provide an increasingly valuable source of information for the UK.

Table 2.1 lists the published estimates of relative MSL changes for both UK south coast and the northern French sites. The high estimates of MSL have in common that they are based on short data sets. The negative MSL trend at Calais has been attributed to poor data quality (Araújo, 2005). Douglas (1991) suggested that 50 years of records are required to accurately estimate MSL trends. Only Brest and Newlyn have records greater than this length. The most recent estimates at Brest are consistent, at the 95% confidence level (i.e. ±2 standard errors), as are the most recent trend estimates at Newlyn.

The most up to date and accurate MSL trends for the UK south coast have been calculated by Woodworth et al. (2009). The authors only calculated MSL trends at sites with at least 15 complete years of records. Only four sites meet these requirements along the south coast. Two of the four sites, namely Devonport and Portsmouth, contain suspect data (see Section 2.5). Therefore, up to date and accurate estimates of MSL change along the UK south coast are only available for Newlyn and Dover, located at either end of the English Channel.

Pirazzoli et al. (2006) calculated the most recent trends for northern French sites. All but two of these estimates are based on records less than 30 years in length. Further, it appears that the authors included all years of measurements in their analysis. A number of sites that were analysed contain large amounts of missing data (see Table 1 in their paper). Including years with lots of missing data is likely to significantly bias results. The Permanent Service for Mean Sea Level (PSMSL; Section 2.5), only include years that have 11 months of data, with each month required to have at least 15 days of measurements. At Dover, Pirazzol et al. (2006) included the early three years of the Dover data set (1958 to 1960). These years are excluded from Woodworth's et al. (2009) analysis. These years contain datum errors and including them results in the MSL trend being biased downwards.

Clearly there is a need to calculate up to date and accurate estimate of MSL change around the English Channel, as previous assessments have been limited. In particular, a larger number of sites needs to be assessed to improve understanding of the spatial differences in vertical land movements along the UK south coast. It is important to point out that an assessment of changes in mean and extreme sea level at six sites in the Channel (Newlyn, Portsmouth, Dover, Calais, Le Havre and Brest) has been undertaken by Araújo (2005). One of the aims of this present study is to build on the work of Araújo (2005) by applying a wider range of analysis methods to an extended sea level dataset covering a greater number of sites (18) around the Channel.

2.3 Observed Changes in Extreme Sea Level

The last section focused on changes in MSL. While a continued century-scale rise in MSL will threaten many low-lying and unprotected coastal areas, it is the extreme sea level events that will be of more concern from an impacts point of view. Despite these concerns, most of the past studies of sea level changes have concentrated on examining variations in MSL rather than in extreme high sea levels (Woodworth and Blackman, 2004). The IPCC Third Assessment Report emphasized that far more work on all aspects of extreme sea levels is required (Woodworth, 2006).

A study on changes in extreme sea levels is more complex than a study of variations in MSL. This is because any change in MSL affects extreme sea levels both directly and indirectly. Further, changes in extreme sea level can also arise from variations in storminess and changes in the patterns of tide-surge interaction. In addition, there are many more data points for establishing MSL trends than for fitting trends to extremes. For example, annual values of MSL are typically calculated by adding all the hourly values observed in a year and dividing by the total number of hours in a year (i.e. 8760 hours in a none leap year). In contrast, when using a percentile analysis (Section 4.2.4) to assess for changes in extreme sea levels; if trends are fitted to the 99 or 99.9 percentile only the largest 88 or 8 values for each year are considered, respectively. The more extreme the events the fewer data points to assess trends.

A number of studies have investigated past changes in extreme sea levels. Studies for particular locations include: Woodworth and Blackman (2002) at Liverpool (UK), Bromirski et al. (2003) for San Francisco (USA) and Church et al. (2004b) for Australian sites. These studies generally conclude that past changes in extreme sea levels primarily resulted from changes in MSL.

On a regional scale, Zhang et al. (1997, 2000) investigated trends in extreme sea levels at sites along the US east coast and found that there had been no discernible long-term secular trend in storm activity or severity during the past century. Pugh and Maul (1999) concluded that there was no discernible long-term trend over the last century in non-tidal residuals around the UK above the considerable natural sea-level variability. Recently, Marcos et al. (2009) analysed trends in extreme sea level at 73 tide-gauge sites in the Mediterranean from 1940. Results show that the linear trends in extreme sea level are consistent with trends in MSL. Therefore no increase in storminess was evident. Woodworth and Blackman (2004) carried out the only global assessment of changes in extreme sea level using records from 1975 onwards at 141 stations. At most locations, the secular changes and inter-annual variability in extremes were found to be similar to those of MSL.

For sites in the English Channel, assessments of changes in extreme sea level have been undertaken by Araújo (2005), Pirazzoli et al. (2006) and Araújo and Pugh (2008). Araújo (2005) analysed trends in non-tidal residuals and high percentiles of observed sea levels at six sites in the Channel. Increases in extreme sea level were attributed primarily to variations in MSL. Araújo and Pugh (2008) carried out a detailed assessment of the Newlyn record. Small but significant decreases in the non-tidal residual were found, but these were considered to be due to changes in the tide-gauge measuring procedure. Pirazzoli et al. (2006) concluded that the extreme high sea levels had increased on the English side of the Channel in recent decades and less on the French coast. The data lengths used in this study were mostly short (<30 years) and results are almost certainly biased by decadal trends.

Of the studies outlined above, only Zhang et al. (2000) assessed the importance of record length. The authors concluded that between 40 and 50 years of data are required to obtain reliable estimates of the underlying trends in the non-tidal residual. Hence, using short-term data to estimate long-term trends in extreme sea level will produce biased results. Many of the above-mentioned studies analysed data sets that were less than 40 years in length. In particular, the global study of Woodworth and Blackman (2004) is based on sea level records spanning less than 30 years.

The study of extremes is more difficult than research into MSL changes owing to the general lack of access to high frequency and quality-controlled sea level data (Woodworth et al., 2006). Only in recent years are countries beginning to make their raw data freely available for research. Increasingly, these problems are being addressed through: (i) new tide-gauge technology, including real time access to quality-controlled information; (ii) the establishments of national and international sea level networks and programmes; and (iii) web technology that provides data more readily to users.

Most of the previous studies of changes in extreme sea level (outlined above) concluded that extremes have increased primarily as a result of direct changes in MSL. This implies that changes in storminess over the 20th century were small and that changes to the astronomical tide and patterns of tide-surge interaction were insignificant. However, it is important that these changes are evaluated even if they are currently small, as they could give an indication of the types of changes than could be expected with a possible larger change in MSL over the 21st century.

The studies that have used the surge component as a proxy to examine changes in storminess, tended to concentrate only on the magnitude of surges. However, extreme sea levels could also increase if the duration or intensity of storm events increases. Zhang et al. (1997, 2000) assessed how the count, duration and intensity of storm surges changed over the 20th century. This approach could be used to improve understanding of the changes in storminess in the English Channel, beyond that of the previous studies.

An important component in assessing changes in storminess, is determining whether the variability in extremes is dependent upon variations in regional climate, which can be represented by indices such as the North Atlantic Oscillation (NAO) (Woodworth and Blackman, 2004). The NAO is a major mode of atmospheric variability in the North Atlantic, expressed as the difference of atmospheric pressure at sea level between the permanent low-pressure system over Iceland (the Icelandic Low) and the permanent high-pressure system over the Azores (the Azores high) (Hurrell, 1995). The relative positions and strengths of these two systems vary from year to year and this controls the strength and direction of storm tracks across the North Atlantic. When the difference in atmospheric pressure is high between the two systems (i.e. a high NAO index), more storms tend to cross Europe at higher latitudes. When the difference in pressure is low (i.e. a low NAO index), few and weaker storms cross the Atlantic at lower latitudes. Hence, for the English Channel, larger surges are likely to occur when the index is low, as storms will track over the UK at lower latitudes. Several studies have found that there is a weak negative correlation between the NAO index and surges in the English Channel (Wakelin et al., 2003; Woolf et al., 2003; Yan et al., 2004; Tsimplis et al., 2005; Araújo, 2005; Woodworth et al., 2007). The winter NAO index contained a large positive trend in the second half of the 20^{th} century (Woodworth et al., 2007). Therefore, one would expect to see a corresponding reduction in the non-tidal residual over this period. However, no study has, before now (Chapter 6), found evidence of this in the surge component in English Channel sea level records.

Only a relatively few studies have investigated whether the increase in MSL over the last century has altered characteristics of the astronomical tide. Araújo (2005) fitted trends to the main harmonic constituents at six sites in the English Channel. Significant changes were found in the amplitude of the $\mathbf{M_2}$ and $\mathbf{M_4}$ constituents. However, it is difficult to interpret how these changes have altered observed extreme sea levels over the past century. A more appropriate way of assessing whether there is any evidence for an increase in extreme sea levels, apart from MSL changes, is to fit trends to time series of annual mean high and low water. Woodworth et al. (1991) assessed trends in mean tidal range at 13 sites around the British Isles, including Dover and Newlyn in the Channel. The authors found that trends varied by between -1.8 and 1.3 mm/yr depending on location. The English Channel sites had trends of between 0.5 and 1.0 mm/yr. Harris (2004) analysed trends in mean high and low water and mean tidal range at Portsmouth and Newlyn and found trends of similar magnitude. Trends of this magnitude in mean tidal range, imply that these increases should have led to changes in extremes above that of MSL. However, this does not appear to be the case and requires further investigation. Particular care must be taken when analysing trends in the astronomical tide, as changes can also arise when the local bathymetry in the vicinity of the tide-gauge is altered (i.e. though dredging), or from a change in gauge location or technology (Araújo and Pugh, 2008).

No study has quantified whether changes in the non-linear interaction between the tide and surge, have taken place over the last century. Since tide-surge interaction is sensitive to small changes in tidal phase (Section 2.1), changes in MSL could affect the frequency distribution of surges in specific locations (Horsburgh and Wilson, 2007). This in turn could impact on extreme sea levels and alter the calculation of return periods in the methods that separate analyse the tide and surge components of sea level (Section 2.4). Horsburgh and Wilson (2007) concluded that there was no decadal change to the pattern of tide-surge interaction in the southern North Sea by visually comparing their surge histograms (for the period 1993 to 2005) with those of Prandle and Wolf (1978). However, a more quantitative assessment is needed covering the 20th century. A number of approaches[3] have been used to measure the magnitude of tide-surge interaction occurring at a given site. The approaches tend to be based on tidal range and do not distinguish that interaction is different on the flood and ebb phases of the tide. An improved test is needed to assess long-term trends in interaction patterns.

In summary, a much more thorough analysis of changes in extreme sea level is required for the English Channel region. This needs to include an assessment of all the possible factors that could alter extremes and be based on an extended sea level dataset. Further, an analysis should be undertaken to assess the sensitivity of trends to data length.

2.4 Estimating Probabilities of Extreme Sea Level

The aim of this section is to briefly describe the different extreme value analysis methods that can be used to estimate extreme sea levels. There are two types of methods: (i) direct methods, in which the extremes of observed still water level are analysed; and (ii) indirect methods, where the astronomical and surge components of sea level are modelled separately and extremes of sea level are inferred. A full mathematical description of the methods is not given as this is covered in the referenced literature.

[3] These methods are reviewed in Appendix C.

2.4.1 Direct Methods

At the foundation of extreme value theory is the classic annual maxima method (AMM) (Jenkinson, 1953; Gumbel, 1958). This is based on a result from probabilistic extreme value theory which states: if $X_1, X_2, \ldots, X_n$ is a series of independent and identically distributed random variables with $M_n = max\{ X_1, X_2, \ldots, X_n\}$. Then, based on detailed limiting arguments as $n \rightarrow \infty$, the distribution function of M_n can be approximated by a member of the generalized extreme value (GEV) family of distribution functions. The AMM for extreme sea level takes the GEV to be the distribution function of the maximum sea level in each year of observations. For the site of interest, the annual maximum sea level is extracted from observations and is used to estimate the parameters of the GEV distribution. From the estimated distribution, one can obtain the sea levels (i.e. return levels) corresponding to chosen return periods (IOC, 2006). Results are often displayed on a return period plot, where return levels are plotted against return period on a log scale (i.e. Figure 1.1).

Lennon (1963) and Suthons (1963) were the first to use the AMM to map return levels around different parts of the UK. However, both studies were limited by data availability and the range of statistical models and inference techniques that were then available (Coles and Tawn, 2005). Graff (1981) made the next major study of UK sea levels using the AMM. He produced a detailed comprehensive mapping of return levels around the entire UK coastline, exploiting the increase in the number of tide-gauges that had been installed following the 1953 event.

There are two main objections to the AMM. First, the assumptions made in using the AMM are that the hourly sea level heights are: (i) independent; (ii) identically distributed; and that (iii) the number of hours in a year is large enough for the asymptotic approximations to hold (Tawn and Vassie, 1991). Assumptions (i) and (ii) do not hold because sea level is made up of a complex combination of tide-driven (deterministic) and storm-driven (stochastic) components that have strong seasonal patterns. Second, the method is highly inefficient in its use of data (Tawn and Vassie, 1991). This led to the development of two more sophisticated methods which exploit more of the available observations. The first is the peaks over thresholds method (POTM) (Davidson and Smith, 1990). Here the exceedances of some high threshold are fitted to the generalized Pareto distribution. The second is known as the r-largest method (RLM) (Smith, 1986; Tawn, 1988a). This is based on the limiting joint distribution of the *r*-largest values per year. These two approaches exploit more of the available sea level records. However, like the AMM, it is not clear how the parameters of the fitted distributions relate to the tide and surge components of sea level. Further, the methods still require about 10 years of observations in order to estimate extreme sea levels.

To summarize, there are three direct methods for estimating extreme sea levels: (i) the AMM; (ii) the POTM; and (iii) the RLM. The hydrological community adopted the POTM as the standard working approach (NERC, 1975). However, there is only one published example of its application to sea level. This is probably because a separate threshold must be selected for each year and site in the presence of temporal and spatial variability. In contrast, the RLM is robust to temporal and spatial variations as it relies upon a purely relative definition of what constitutes an extreme event (Butler et al., 2007). Therefore, of the three direct methods, only the AMM and RLM are considered further in this study. The RLM is favoured because it exploits more of the data available, but the AMM is included as it can be applied at sites where only annual maxima are available.

2.4.2 Indirect Methods

The joint probabilities method (JPM), Pugh and Vassie (1979, 1980) made an important step in addressing the main limitations of the direct methods. Their approach involves separate analysis of the tide and surge component of sea level, followed by a convolution to obtain the probability distribution of the sum (Coles and Tawn, 2005). In the JPM, separate probability distribution functions (pdf) are calculated for the tidal and surge components of the sea level observations. The pdfs are estimated empirically. As the tidal sequence is deterministic, the probability distribution for all tidal levels can be generated from 18.6 years of tidal predictions. The distribution function of hourly (instantaneous) sea level, is obtained by combining the tide and surge pdfs. The distribution function of the annual maximum can be estimated from this and used to calculate extreme sea levels.

The main advantage of the JPM is that return levels can be estimated from relatively short records (<5 years) because all surge events are taken into account, not just those that lead to extreme levels (Pugh, 1987). The method however, has three main inadequacies. First, it assumes that hourly sea levels are independent, which is false as the tide and surge components exhibit strong temporal dependence. Second, it assumes that the empirical surge distribution is a sufficiently good estimate of the true distribution. Whilst it is acceptable for most of the range, it is restricted near the extremes which is the region of prime interest to these studies (Tawn, 1992). As a result, it does not produce probabilities for sea levels greater than the highest astronomical tide combined with the largest observed surge. Third, confidence intervals cannot be calculated. Further, it is more complex than the direct methods because two forms of dependence must be accounted for, namely; seasonality (larger surges are more prevalent in the winter, whereas larger tides occur at the equinoxes) and tide-surge interaction.

Three additional indirect methods were introduced in the 1980's aimed at resolving the inadequacies of the JPM. The first method, developed by Walden et al. (1982) (hereinafter referred to as WM), involves estimating a pdf of maximum sea level. The main difference is that surge events are represented in terms of duration and intensity, rather than hourly instantaneous levels as in the JPM. The second approach is the exceedance probability method (EPM) (Middleton and Thompson, 1986; Hamon and Middleton, 1989). This involves combining the tide and surge distributions and accounting for dependence in the sea level sequence. The extreme tail of the surge distribution is modelled through the use of a contaminated normal distribution. The third approach is the revised joint probability method (RJPM) (Tawn and Vassie, 1989; Tawn, 1992). Two principle improvements make the revised method more widely applicable than the JPM (IOC, 2006). The first enhancement is related to converting the hourly distribution into annual return periods. The dependence in the hourly tide and surge data is handled using an extremal index derived from the mean overtopping time of a level for each independent storm that exceeds that level. The second modification involves modelling the extreme end of the surge distribution using the RLM. This enables probabilities for levels beyond the existing range of the surge data to be obtained. It also smoothes the tail of the empirical distribution and allows for confidence intervals to be computed.

To summarize, there are four indirect methods for estimating extreme sea levels: (i) the JPM; (ii) the WM; (iii) the EPM; and (iv) the RJPM. A comparison of all of the indirect methods has not been undertaken. However, Tawn and Vassie (1991) demonstrated that the RJPM gives significantly better results than the EPM for longer return periods. This is because the EPM makes artificial assumptions about the joint distribution of the surge and its derivative which restrict and bias the estimated tails of the surge pdf. The only published examples of an application of the WM and EPM to extreme sea levels are by the authors who originally developed the methods. In contrast, the RJPM has been applied more extensively (Tawn and Vassie, 1989, 1991; Tawn, 1992; Dixon and Tawn, 1994, 1995, 1999; Tsimplis and Blackman, 1997). Further, the main spatial models for the UK have been built around the RJPM method (Section 2.4.3). Therefore, of the four indirect methods, only the JPM and RJPM are considered further in this study. The RJPM is the favoured indirect approach. However, the JPM is included as it is the only method that can be used to estimate extreme sea levels from very short records (<5 years).

2.4.3 Spatial Methods

Extreme sea levels along a stretch of coastline are typically generated by the same physical mechanisms (IOC, 2006). The methods outlined in the sections above, ignore this spatial coherence of the sea level process as they are applied independently to data from individual sites. Various spatial extensions of both the direct and indirect methods have been undertaken with the aim of estimating extreme sea-level probabilities at all points along the coastline. These include; simple interpolation of return levels between sites (Dixon et al., 1998); applying the univariate methods to synthetic time series of hourly sea level from numerical models (Flather, 1987; Flather et al., 1998); and bivariate and multivariate extensions of direct methods (Tawn, 1988b; Coles and Tawn 1990, 1991). The first approach gives poor estimates between sites because it ignores the spatial variation in tides. The second approach was restricted in estuaries and tidal inlets because of the coarse resolution of the model (35 km) that was used. This could be improved with higher resolution models. The third approach is limited as spatial models are not particularly well suited to direct methods because the constituents of sea level experience different spatial variations (Dixon and Tawn, 1997). A key advantage of the third approach is that it can utilize sites with extensive sea level observations and augment these with data from sites with shorter records (IOC, 2006).

The most applicable UK spatial model to date, is the spatial revised joint probability method (SRJPM). This was developed as part of a study jointly undertaken by research teams at the Proudman Oceanography Laboratory (POL) and Lancaster University (Dixon and Tawn, 1994, 1995, 1997). The SRJPM extends the RJPM by exploiting knowledge of the spatial variation of the tidal and surge components of the sea level around the UK. The SRJPM has the added advantage that it also incorporates all the types of data available (annual maxima, hourly values and data from the CSX northwest European continental shelf numerical storm surge model) (Flather, 1987). A key output of the study is a set of tables (Tables 8.1 to 8.3 in Dixon and Tawn, 1997) containing return level estimates, relative to the 1 in 1 year return level, for a regular grid around the UK. Estimates of extreme sea level can be made at any location around the UK coast by combining these relative levels (hereinafter referred to as the SRJPM relative return levels) with a 1 in 1 year return level, calculated using one of the univariate methods. Increasingly, this approach is being used to estimate extreme sea-level probabilities around the UK, particularly in studies undertaken on behalf of the UK Environment Agency (Swift, 2003). Spatial models have not yet been developed for the French coast.

2.4.4 Comparison of Methods

Dixon and Tawn (1994, 1995) have undertaken the most detailed comparison of different extreme value analysis methods to date. Prior to this assessment, only limited comparisons of select methods had been undertaken for a few sites (Alcock et al., 1987; Pugh and Vassie, 1979, Tawn and Vassie, 1989, 1991; Tawn, 1992). Dixon and Tawn (1994, 1995) compared the RLM, JPM and RJPM for A-Class tide-gauge sites around the UK. In the first stage of their study (Dixon and Tawn, 1994), estimates of extreme sea level were only made along the UK south coast at Newlyn and Dover. In the second stage of the study, additional sites along the south coast were included, but the lengths of the records at these locations were short (Table 2.2).

A particularly useful component of their study was a sensitivity analysis of the parameters in each method that require an element of subjective choice. It was emphasized that careful parameter selection reduced the uncertainty associated with the estimated extreme sea levels. An important finding of the study was that the direct methods tend to underestimate return levels for return periods of 20 years or more at sites where the surge variation is small in comparison with the variation in high tidal levels. Dixon and Tawn (1999) investigated this further and suggested that the cause of this is the tidal, rather than surge, non-stationarity. A limitation of the study was that the exact ratio of tide to surge variability at which the direct methods start underestimating the long period return level was not established.

A review of the literature highlighted that two important issues have, before now, received little scientific investigation, making a comparison of the different statistical methods difficult. First, sea level records vary considerably in terms of frequency (typically hourly or 15-minute), length (number of years) and completeness (percentage of data available for a given year). It is not clear how these three factors influence the estimated return levels calculated using the different methods. Limited assessments of data length have been undertaken before (i.e. Pugh and Vassie, 1979; Tawn and Vassie, 1979), but a more rigorous investigation is needed.

The second issue is related to the fact that the long-term changes in extreme sea level need to be accounted for in the extreme value methods (Coles, 2001). Trends can either be handled by removing them from the sea level data sets prior to analysis or incorporating them in the different methods (see Dixon and Tawn, 1994 for details). Studies have stressed (see Section 2.2 and 2.3) that between 40 and 50 years of sea level records are required to accurately estimate changes in mean and extreme sea level. Many of the past estimates of extreme sea level are based on shorter sea level records. There is a need to establish, for the English Channel region, which is the best method for handling the long-term trends in sea level and assess how sensitive this is to record length.

Swift (2003) recently reviewed a number of the unpublished engineering studies undertaken on behalf of the UK Environment Agency. It was found that the extreme levels, estimated using the SRJPMrelative return levels, were in good agreement with those estimated by univariate methods along the UK east coast, but were considerably larger along the south coast and parts of the west coast. Swift (2003) demonstrated that the reason for the over prediction at Portsmouth was probably due to the short sea level records that were originally used to calibrate the model at this site (Table 2.2). Clearly, there is a need to understand why the SRJPM over estimates extremes around certain parts of the UK, particularly because this approach is increasingly being used by the Environment Agency for flood risk assessments and to define flood defence design levels.

2.5 Measuring Sea Level

Precise measurements of sea level are required to accurately assess changes in mean and extreme sea level and to estimate probabilities of extreme events. Therefore, it is important to discuss the measurement of sea level and the technical difficulties involved. The measurement of sea level has a long history (Pugh, 1987). Today, sea level is measured using two different methods: tide gauges and satellite altimetry. The research in this thesis is based only on an analysis of sea levels recorded by tide-gauges and hence, a description of this measuring procedure is the primary focus here. However, a brief description of satellite altimetry is important as this technology is defining a new paradigm in studies of MSL change (Nerem and Mitchum, 2001).

2.5.1 Satellite Altimetry

Since 1992, the TOPEX/Poseidon and later Jason satellite programs have provided measurements of sea level every 10 days for 95% of the ice-free ocean (Cazenave and Nerem, 2004). Satellite altimetry data has the advantage of being tied directly to the earth's centre-of-mass. This is particularly relevant in assessing MSL changes (Section 2.2). Unlike tide-gauges, the altimetry data provides an almost global coverage of sea level and does not need to be corrected for vertical land movement, except for a small component due to large-scale deformation of ocean basins from glacial isostatic adjustment (Bindoff et al., 2007). The three current limitations of altimetry data are: (i) the duration of observations is still relatively short; (ii) the satellite altimeters are not able to accurate measure sea level near to the coast; and (iii) the frequency of measurements (10 days) does not allow for changes in extreme sea level to be assessed and for probabilities of extremes to be estimated (this is because there is no guarantee the satellite will be over the correct point on earth to measure the sea level associated with a particular extreme event). Despite these limitations, altimetry data has allowed for significant advances in understanding MSL changes and will be increasingly useful as the data lengths increase and the technology advances.

2.5.2 Tide-Gauges

Tide gauges measure the vertical distance between the average surface of the sea and a fixed level on land. Many different tide gauges have been developed over time, ranging from simple cheap tide poles to sophisticated systems that utilise radar. Most of the measurements of sea level used in this research have been recorded by stilling well float or pressure gauges.

The stilling well float gauge is historically the most common of all the sea level recording systems (IOC, 1985). This type of gauge has been in use since the mid-19th century and is still used in many parts of the world (Pugh, 1987). It consists of a stilling well and recording device (Figure 2.4). The well is a vertical tube of about 1 m in diameter with a hole connected to the sea. The purpose of this is to filter out wave activity. A float moves freely up and down within the well responding to the sea surface movement. The float is connected to a measuring device located above the well. Using a system of pulleys and gears, the movement of the float changes the position of a pen. This pen is situated over a chart mounted on a rotating circular drum. The drum does a complete rotation every 24 hours with the pen charting the tidal signal. Normally, charts are replaced once a week. Hence, a single chart contains seven overlaid traces that represent a week of sea level recordings. Most of the early (pre-1990) sea level records used in this study (Section 3), were measured by float gauges.

A float gauge is a complex system in terms of its structure and operational procedure (Araújo, 2005). As a result, a variety of problems can arise that affect its functioning. For example, the tidal signal can become dampened when there is an obstruction to the inlet of the stilling well (i.e. from a build up of sediment or biological fouling). These and other issues (see IOC, 1985) introduce errors into the measured signal. Further, the charts need to be digitised if the measurements are to be useful for scientific analyses. Errors can be introduced during data digitisation (e.g. erroneously following the wrong part of the trace) (Pugh and Vassie, 1979). Therefore, measurements made using these types of gauges need to be carefully checked before the data is analysed (Section 2.5.2.2).

Recent float gauge installations are less common as they require costly engineering work (IOC, 2006). Increasingly, pressure gauges are being used. These measure subsurface pressure instead of sea level. Hence, knowledge of seawater density and gravitation acceleration is required to make the conversion from pressure to sea level. One of the most commonly used types is the pneumatic bubbler gauge (Figure 2.5). This has been successful used around the world for several decades. The UK National Tide Gauge Network (section 2.5.3) is now based on this technology.

The bubbler system works by releasing compressed air, at a metered rate, along a thin tube to a pressure point fixed underwater. The pressure point is normally a vertical cylinder with a closed top and open bottom. A small ‘bleed hole’ is drilled about half way down the cylinder. Air from the tube enters the cylinder and becomes compressed and pushes down the water inside the chamber. When the water is pushed down to the level of the bleed hole the air bubbles are released through the hole and travel back to the surface. As the surface of the sea varies, the pressure exerted on the pressure point changes. The variation in pressure is transmitted up the tube to a recording instrument. The sea level is calculated according to the law:

$$h = \frac{(p - p_a)}{\rho g}, \qquad \text{EQ2.3}$$

where: h is the height of the sea level above the bleed hole; p is the measured pressure; p_a is atmospheric pressure; ρ is the sea water density; and g is the gravitational acceleration.

2.5.2.1 Datum Control and Levelling

Measurements made by tide-gauges record the relative movement of the sea level with respect to land. Over long periods of time, neither the land nor sea levels are constant (Section 2.2). Therefore, in order to properly understand sea levels, it is necessary to decouple the different sea level and land signals (IOC, 2006). This is attained by: (i) carefully defining tide gauge datums; (ii) local levelling procedures; and (iii) making independent measurements of changes in land levels using geodetic techniques.

Tide-gauges record sea level relative to a fixed point on land called a benchmark. This is a clearly marked point located on a stable surface, such as a building or quay wall. Rather than depending on the stability of a single benchmark, up to five are normally defined. The main benchmark is referred to as the tide gauge benchmark (TGBM). The different benchmarks are connected through high-precision levelling. Ideally, all the benchmarks are tied into a country's national levelling network. The UK national levelling network expresses heights relative to the average level of the sea at Newlyn, during 1915 to 1921. This level is known as Ordnance Datum Newlyn (ODN). As sea level has risen at Newlyn since 1915 (Section 2.2), ODN no longer represents the present average Newlyn sea level (IOC, 2006).

Another important reference level is the tide gauge zero, which is the level for which the gauge would record zero sea level. Normally, the tide gauge zero is the same as chart datum (CD). This is the datum to which the depths on a nautical chart are measured. At many ports, CD is the same as the level of the lowest astronomical tide (Pugh, 1987). The raw sea level data used throughout this thesis have been measured relative to CD.

One of the challenges in constructing long time series of annual MSL at a given site (as has been done in this research, see Chapter 3), is to ensure that measurements collected from different gauges (often with different but geodetically connected TGBMs) are relative to a single level. For this reason, the PSMSL invented the concept of the revised local reference (RLR) datum. The RLR datum at a given site is defined as a simple offset from the TGBM, so that sea level values expressed relative to the RLR datum have numerical values around 7,000 mm. This approximate value was chosen in the late 1960's so that the computers of the time would not have to store negative numbers (IOC, 2006).

It is important, particularly for the study of changes in sea level, that the benchmarks are regularly checked for stability. At poorly maintained sites, the tide-gauge zero is often allowed to wander. As long as the movements are recorded, they can be corrected at a later date. Over the last decade, more accurate fixing of tide gauge benchmarks has been made using modern geodetic techniques. These make use of the satellites of the Global Positioning System (GPS) and those of Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system. Rates of vertical land movement are currently being measured at selected UK tide gauge sites using continuous GPS and absolute gravimetry (see Teferle et al., 2006 and Bingley et al., 2007 for more details).

2.5.2.2 Quality Control of Data

Sea level measurements must be carefully checked before they are ready for scientific analysis. This procedure is known as data reduction (Pugh, 1987). Two approaches tend to be used to check for common errors. First, a value is compared to the values either side to ensure that the difference between them does not diverge by more than a specified tolerance (derived from the data). A value that fails this test can be marked for further scrutiny. Second, the measured sea level is subtracted from the predicted tide to obtain the non-tidal residual. This provides a more sensitive check as the errors tend to be well defined when the residual is plotted (Figure 2.6).

With modern tide-gauge networks, data is often transferred wirelessly directly from the gauge to a data-handling centre. There is an emphasis on the gauges delivering data in near real time (i.e. typically within an hour) (IOC, 2006). The advantage is that it is immediately obvious when problems with a gauge have occurred. Data errors can be immediately flagged and the gauge can be repaired quickly, minimising data loss.

2.5.3 Sea Level Data Currently Available for the English Channel

English Channel sites have two main sea level data sets readily available for scientific analysis and both have been used in this study (Chapter 3). The first is the raw sea level measurements made by tide-gauges. The second is monthly and annual values of MSL derived from the raw data.

Raw (hourly or 15-minute frequency) sea level data is available for eight sites along the UK south coast and at one site on the Channel Islands. These tide-gauges form part of the UK National Tide Gauge Network (Figure 2.7). This network contains 44 gauges and was set up as a result of the severe flooding along the east coast of England in 1953. The data is processed and archived by the British Oceanography Data Centre (BODC) and freely available to download (http://www.bodc.ac.uk/). Raw (hourly) sea level data is readily accessible for nine French sites. These gauges form part of the French national network of gauges operated by the Service Hydrographique et Océanographique de la Marine (SHOM). The data can be obtained from the internet site of the Systéme d'Observation du Niveau des Eaux Littorales (SONEL) (http://www.sonel.org).

Sea levels have been recorded at a number of other sites around the Channel by various port and harbour authorities. These gauges are mainly for operational purposes (i.e. navigation) and so are not generally suitable for rigorous scientific study. Further, the data sets are rarely quality controlled and they must be obtained separately from each owner. Therefore, these records have not been considered in this research, with the exception of Southampton (Chapter 3). The Southampton record has been analysed because it is both long (1935 to present, Section 3.1) and the tide-gauge has been well maintained throughout the duration of the record (Davis, 1980).

Figure 2.8 presents the raw sea level data sets that are currently (as of January 2009) available (from the BODC and SONEL) for the Channel. Other UK sites have also been included for comparison. It is important to emphasise that the Channel contains the two longest (i.e. Newlyn and Brest) raw sea level records that are available for the British Isles and northern France. These have been extensively used throughout this research. Newlyn has the longest continuous high quality raw sea level record for the UK[4] and is one of the best records in the world. The record at Brest is one of the longest sea level data sets in the world

[4] Note: other UK sites have longer MSL records but the raw data is not available.

spanning almost 300 years (Woppelmann et al., 2006). In this research, only the data from 1900 is analysed.

Records spanning at least 40 years are needed to assess changes in extreme sea level (Zhang et al., 2000). In terms of the French data the length is reasonable, and only the Roscoff (34 yrs), St Malo (3 yrs) and Le Conquet (36 yrs) records span less than 40 years. In contrast, only the Dover and Newlyn records, located at either end of the UK south coast, have records meeting the 40 year requirement. The other sites on the UK south coast all have records less than about 20 years.

A database of monthly and annual MSL values is also readily available for English Channel sites. The source of this data is the PSMSL (http://www.pol.ac.uk/psmsl/). The PSMSL was establish in 1933 and is the global data bank for long-term sea level change information from tide-gauges. The data set of the PSMSL contains MSL values[5] for almost 2000 stations around the world. All the data available is known, in PSMSL terminology, as 'Metric Data'. However, only data in the RLR subset can be used to assess trends in MSL as this contains only the sites that have a full benchmark history (Woodworth and Player, 2003). Since the 1970's, most UK data comes from the UK National Tide Gauge Network (Woodworth et al., 1999). French data is supplied by SHOM.

Figure 2.9 shows the 68 RLR annual MSL records that are currently (as of January 2009) available for the UK and the Republic of Ireland, including the English Channel. The UK south coast data set contains fewer years than that available for the northern French coast and the east and west coasts of the UK. It is clear, when comparing Figure 2.8 and Figure 2.9, that the years for which annual MSL values are available do not, in some cases,

[5] Note: the majority of the MSL values held by the PSMSL have been calculated using hourly sea level data. However, some of the earlier values have been estimated by calculating the arithmetic mean of just the heights of high and low waters. This is known as mean tidal range (MTL). It is important to distinguish MTL from MSL. At tide gauge sites in shallow water, MTL may differ significantly from MSL and corrections must be made to account for this.

match the years for which raw sea level observations exist. There are two reasons for this. First, annual MSL values are only included in the PSMSL data bank if 11 months of raw sea level measurements are available for a given year, and each month has at least 15 days of record. Second, prior to the 1970's, a number of different UK organizations supplied MSL data separately to the PSMSL (see Woodworth et al., 1999 Appendix A for details). While the monthly and annual MSL values are held (by the PSMSL) for these earlier data sets, the raw data is often not digitally available or has been lost. For example, the UK Hydrographic Office (UKHO) operated the Devonport and Portsmouth gauges prior to 1992. From 1961 to 1991, the UKHO supplied the PSMSL with monthly and annual values of sea level. In 1992, A-class gauges were installed at both sites as part of the UK National Tide Gauge Network. Only data after 1992 is archived at the BODC. The earlier records are still held by the UKHO but are not in digital format. However, these two records have now been captured as part of this study (Chapter 3).

Woodworth et al. (2009) considered that at least 15 complete years of good quality RLR data are needed to accurately estimate MSL trends. This criterion is currently met at nine sites on the east coast of the UK and at 11 sites on the west coasts of the UK and in the Irish Sea. Nine out of the 10 French MSL records have 15 complete years of data. However, at three of these sites (Calais, Boulonge and Dieppe), the data is suspect (see Chapter 3). Only two sites along the south coast currently contain 15 complete years of good quality data, namely: Newlyn, and Dover. The Devonport and Portsmouth records have more than 15 complete years of data, but the overall quality is poor. The UKHO operated these two gauges to provide sea heights to aid the navigation of Navy vessels rather than for scientific research. Woodworth et al. (1999) argues that the Devonport RLR time series is possibly the worst of the UK records, containing numerous datum shifts and spikes. Similarly, Webber and Walden (1981) cast doubt on the stability of the datum at Portsmouth during the 1960's and 1970's and data errors have led to erroneously high rates of sea-level rise being reported for Portsmouth (as shown in Table 2.1). A thorough investigation of the datum changes that have taken place at these two sites has been carried out in this research (Chapter 3). This exercise highlights the need to replace the values currently held by the PSMSL at these two sites, with more accurate information captured in this study.

In summary, along the French coastline of the English Channel, there are sea level records at six sites that are suitable for the analysis of changes in mean sea level and eight sites with records suitable for examining changes in extreme sea levels. In contrast, along the UK south coast, only the data sets for Newlyn and Dover are suitable for such analyses. As a result, an extensive data archaeology exercise was undertaken as part of this research to extend the hourly sea level record for the UK south coast (Chapter 3).

2.6 Summary

A review of the existing literature provided a guide for the direction and analysis methods that were used for this study. The following are the main issues that were highlighted after the review:

In relation to sea level data:

1. The lack of long records along the UK south coast has hindered the previous assessments of changes in sea level (mean and extreme) and limited the accurate estimation of extreme sea level probabilities. Hence, there is a clear need for an extended UK south coast data set.

In regards to assessing changes in MSL:

1. A new method for calculating more accurate long-term changes in MSL has been proposed by Woodworth et al. (2009). There is a need to; (i) quantify the extent to which this procedure allows more accurate estimates from shorter records; and (ii) use this method on an extended data set to determine improved and up to date rates of MSL around the English Channel.
2. It has been argued that the rate of subsidence reported for the southwest of England by Shennan and Horton (2002) is too high. An extended data set for

the south coast could be used to improve understanding of the broader uplift/subsidence patterns across the region and its contribution to changing extreme sea levels.

3. Further work is also required to evaluate more fully whether the high rates of MSL measured over the last decade are unusual compared to trends observed at other periods in the historical record (i.e. is there evidence for a recent acceleration in sea-level rise). The long sea level records for the English Channel at Newlyn and Brest provide a usefully data set for addressing this.

In regards to assessing changes in extremes:

1. Only a few studies have assessed how the increase in MSL over the 20th century caused indirect changes to the astronomical tide. These studies tended to analyse trends in tidal constituents. It is difficult to understand how these changes altered high water and in turn affected extreme sea levels. An improved understanding could be obtained by fitting trends directly to time series of annual mean high and low water and tidal range.
2. Most of the studies that have used the surge component as a proxy to examine changes in storminess, focused on the changes in magnitude of large surges. Only one study assessed how the count, duration and intensity of storm surges changed over the 20th century (Zhang et al., 1997, 2000). This approach could be applied more widely to improve understanding of the changes in storminess, including in the English Channel.
3. No study has quantifiably assessed whether changes in the non-linear interactions between the surge and tide have taken place over the past century. Further, the interaction tests used in earlier studies to quantify the strength of tide-surge interaction are based on range and therefore do not account for the fact that interaction is different on the ebb and flood phases of the tide.

In regards to estimating probabilities of extreme sea level in the English Channel:

1. Seven univariate methods have been listed. Of these methods, four are considered more suitable for estimating extreme sea levels, namely: (i) the AMM; (ii) the RLM; (iii) the JPM; (iv) the RJPM. There is a need to determine which of these methods is most appropriate for estimating extreme sea levels around the English Channel.
2. There are a number of different ways to account for the long-term trends in sea level in the extreme value analysis methods. There is a need to determine which approach is the most appropriate and assess how sensitive this method is to data length.
3. The direct methods tend to underestimate return levels for return periods of 20 years or more at sites where the surge variation is small in comparison with the variation in high tidal levels. However, the exact ratio of tide to surge variability at which the direct methods start underestimating extreme sea levels has not been established.
4. There is also a need to rigorously assess the sensitivity of the different methods to the frequency, length and completeness of the available sea level data.
5. The most applicable method for estimating return levels at any point around the coastline is the SRJPM. There is a need to understand further why this over-predicts return levels along the south coast of the UK.

In light of the first issue, a data archaeology exercise has been carried out to extend the UK south coast digital sea level record. This is described in Chapter 3. The remainder of the thesis is concerned with analysing this new extended sea level data set in order to address the three study objectives and in particular, each of the related issues outlined above.

Table 2.1: English Channel MSL trends (mm/yr) and standard errors calculated in previous studies. Trends based on records between 30 and 40 years are underlined. Trends based on records of between 40 and 50 years are in italics. Trends based on more than 50 years are in bold. The remaining trends are based on less than 30 years of data.

Site	**Study Number (rates are mm/yr)**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
UK Sites										
Newlyn	*2.2 ± 0.1*	**1.95 ± 0.12**	**1.7**	**1.78 ±0.11**	**1.69 ±0.12**		**1.73 ± 0.13**			**1.70 ± 0.10**
Devonport					<u>3.04 ± 1.01</u>					<u>2.55 ± 0.75</u>
Weymouth									9.8 ± 1.9	
Bournemouth									9.3 ± 1.2	
Southampton		1.06 ± 1.11								
Portsmouth		8.35 ± 0.80			<u>1.45 ± 0.6</u>	1.52 ± 0.56	<u>1.37 ± 0.52</u>		11.1 ± 1.6	<u>1.58 ± 0.44</u>
Newhaven		4.11 ± 1.65							0.6 ± 1.8	
Dover		4.25 ± 0.53			<u>1.94 ± 0.5</u>	2.43 ± 0.39	<u>2.44 ± 0.42</u>		<u>1.6 ± 0.5</u>	<u>2.18 ± 0.26</u>
French Sites										
Brest	**2.1 ± 0.3**		**1.2**				**1.29 ± 0.07**	**1.3 ± 0.15**		
Cherbourg			**1.7**						1.5 ± 0.4	
Le Havre							1.44 ± 0.47		<u>1.8 ± 0.4</u>	
Dieppe									5.3 ± 0.7	
Boulogne									4.4 ± 0.6	
Calais							-1.48 ±1.30		-0.7 ± 0.7	
Dunkerque									<u>2.1 ± 0.5</u>	
1 Rossiter (1972), **2** Graf and Blackman (1978), **3** Pirazzoli (1986), **4** Woodworth (1987), **5** Woodworth et al. (1999), **6** JBA (2003), **7** Araújo (2005), **8** Woppelmann et al. (2006), **9** Pirazzoli et al. (2006), **10** Woodworth et al. (2009)										

Table 2.2: Durations of the data available to Dixon and Tawn (1997) to calibrate the SRJPM relative return levels along the UK south coast.

Site	Duration of record (number of years)
Newlyn	77
Devonport	3
Weymouth	3
Portsmouth	3
Newhaven	8
Dover	31

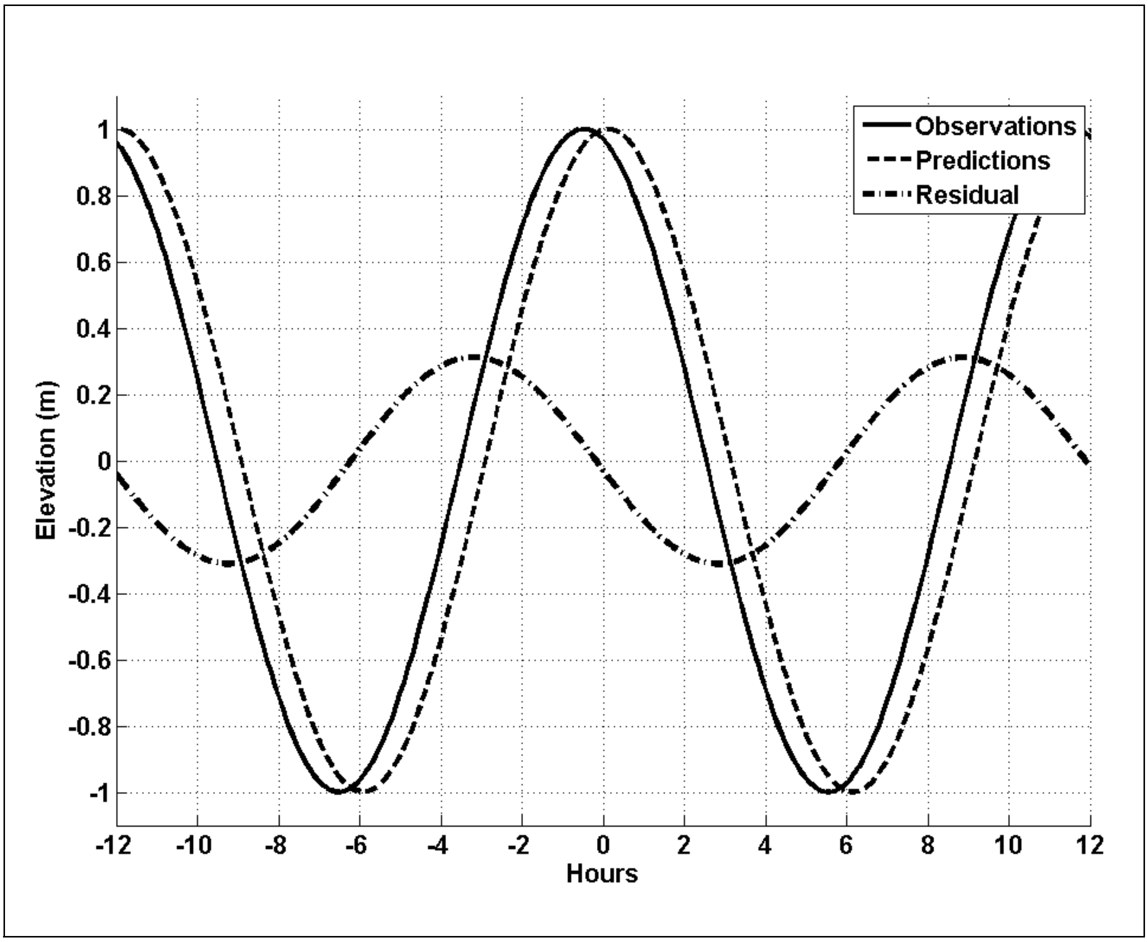


Figure 2.1: Schematic diagram of a sinusoid whose phase shift is altered but whose frequency and amplitude remain unaltered. (Adapted from Horsburgh and Wilson, 2007).

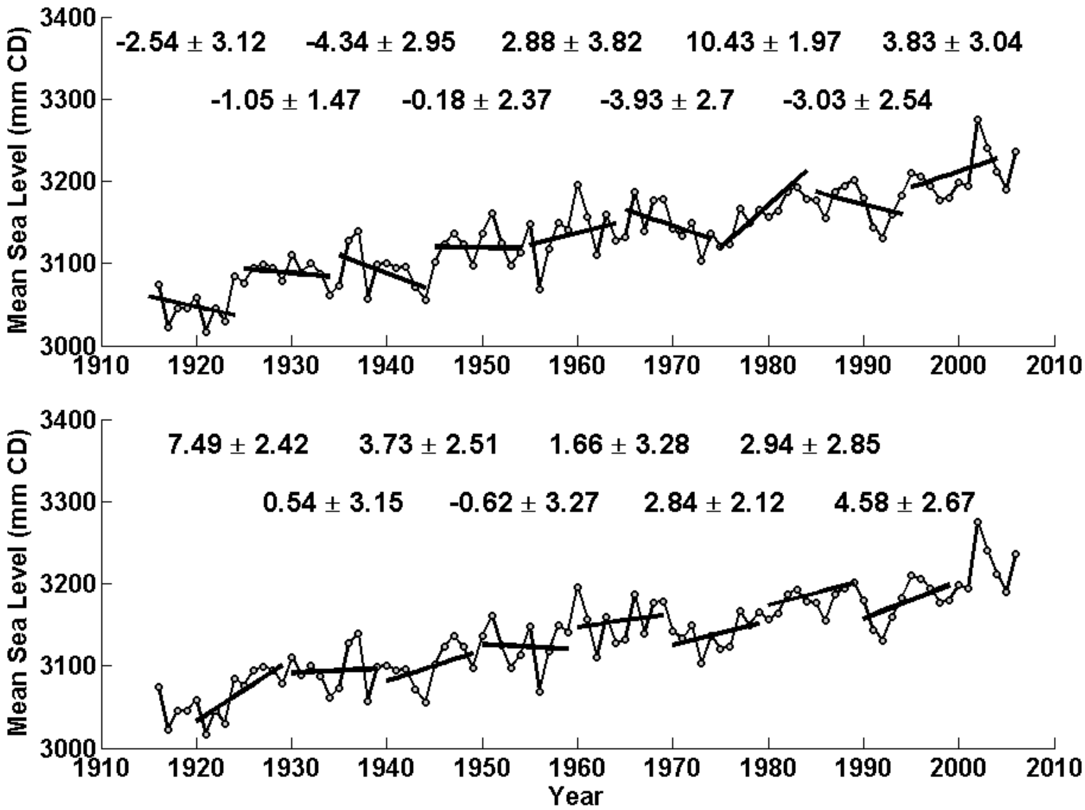


Figure 2.2: Time series of annual mean sea level at Newlyn, taking (a) successive 10-year blocks from 1915; and (b) successive 10-year blocks from 1920. The trends shown are in mm/yr plus or minus the standard error. (Adapted from Pugh, 1987).

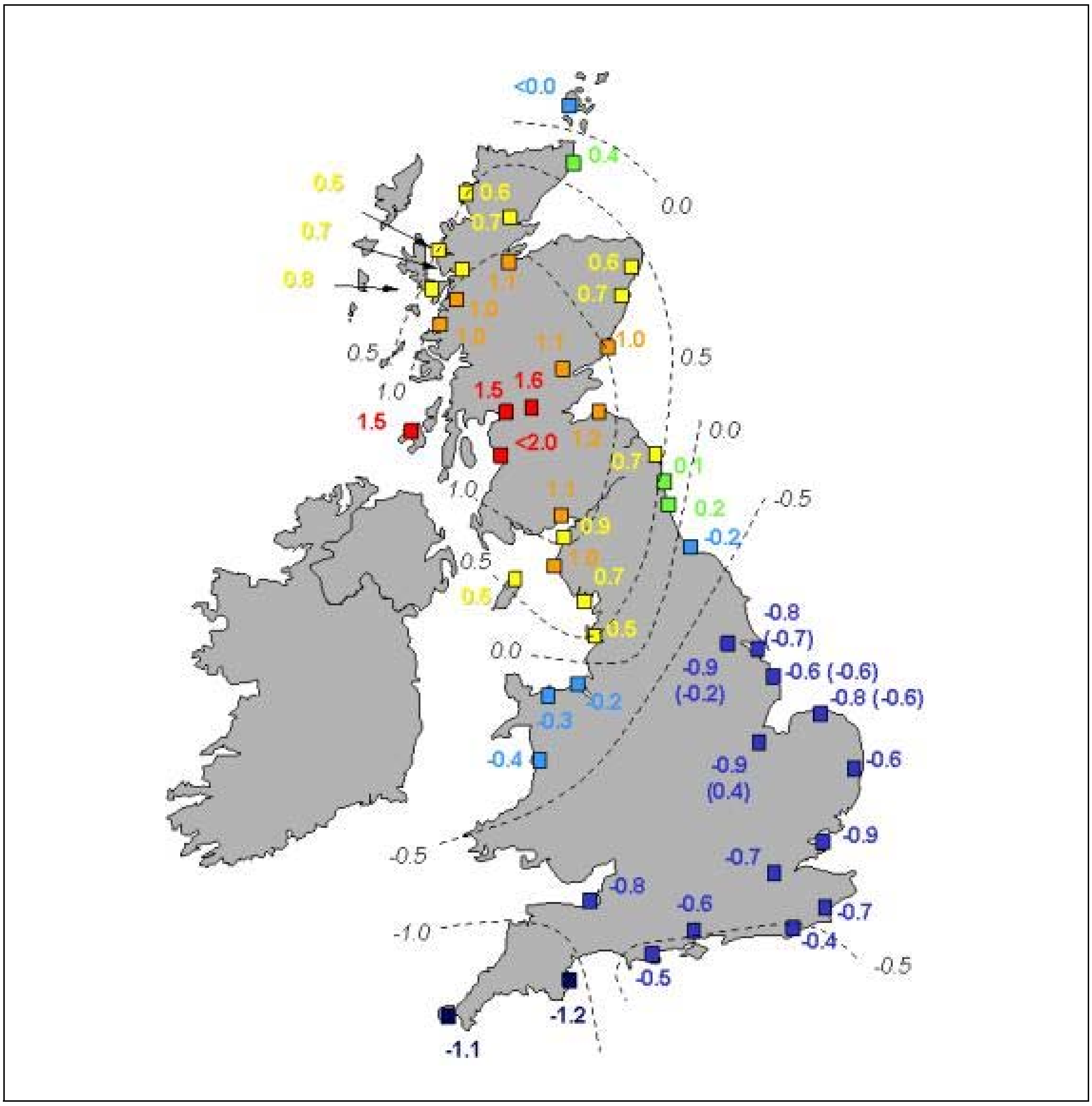


Figure 2.3: Late Holocene mean relative land/sea level changes (mm/yr) in Great Britain, positive values indicate relative land uplift or sea level fall, negative values are relative land subsidence or sea-level rise. Figures in parentheses are the trends that take into account modelled changes in tidal range during the Holocene. Contours are drawn by eye as a summary sketch of the spatial pattern of change. (Source: Shennan and Horton, 2002).

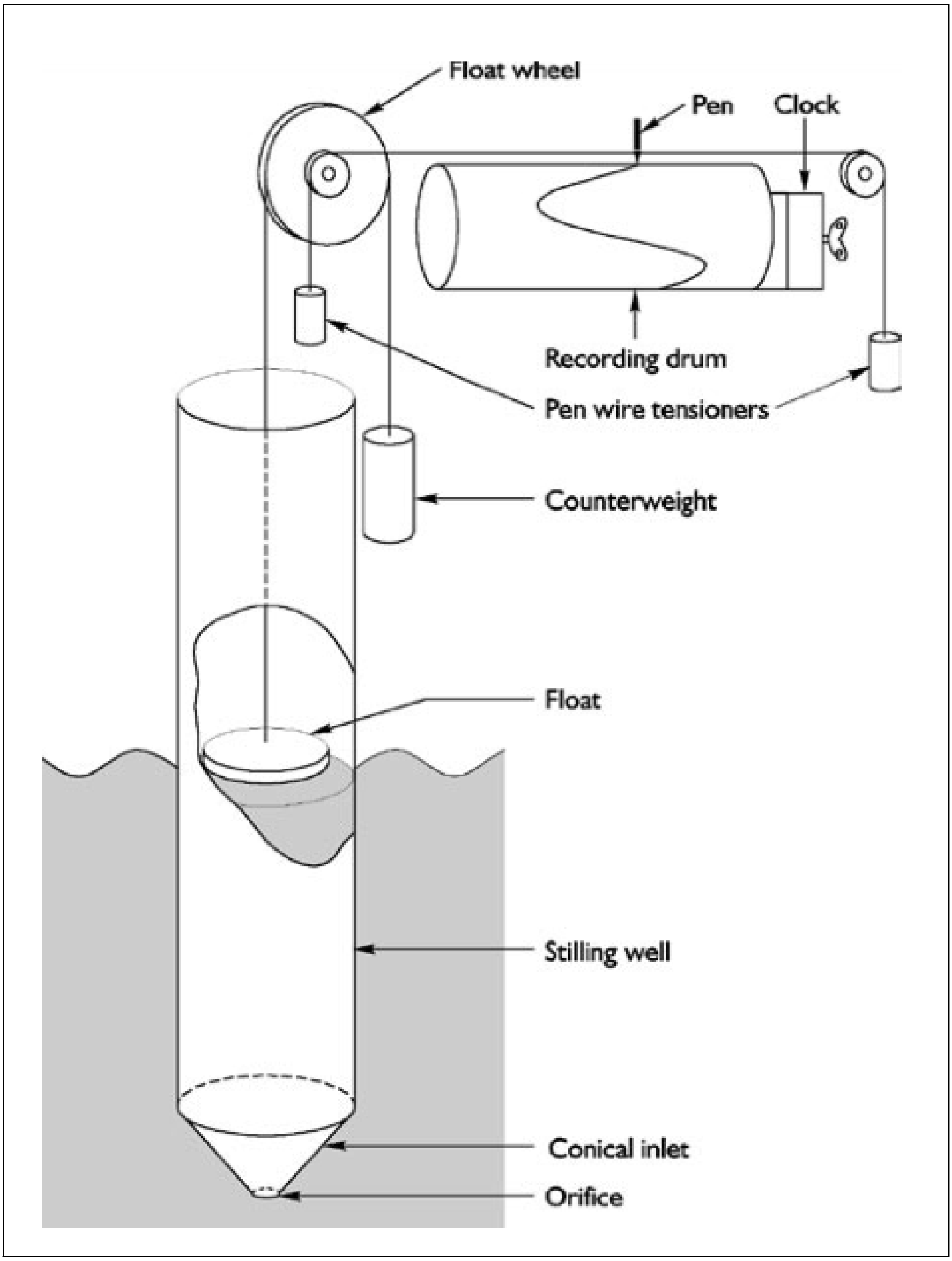


Figure 2.4: Stilling well tide gauge. (Source: IOC, 2006).

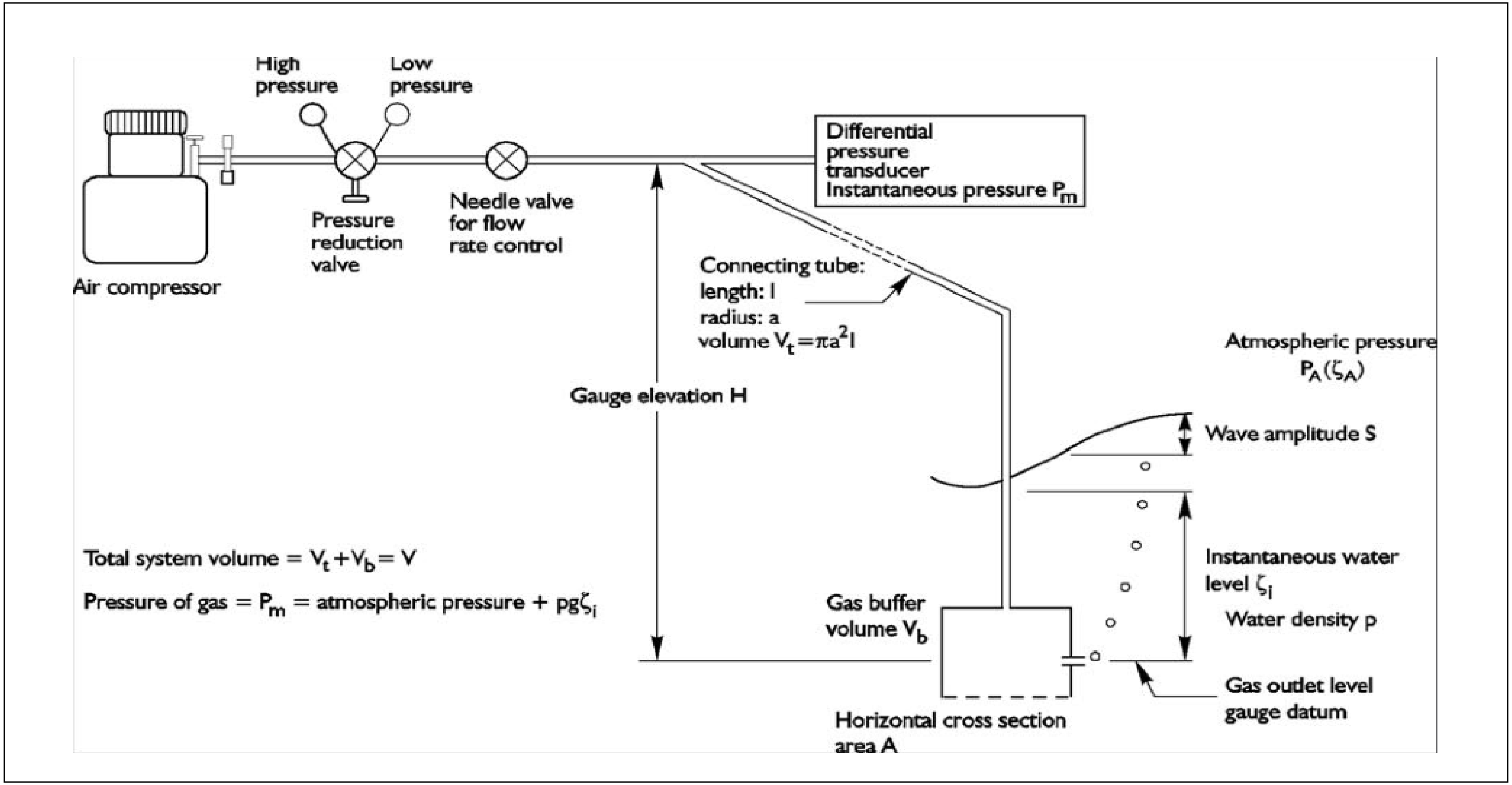


Figure 2.5: Bubbler pressure gauge. (Source: IOC, 2006).

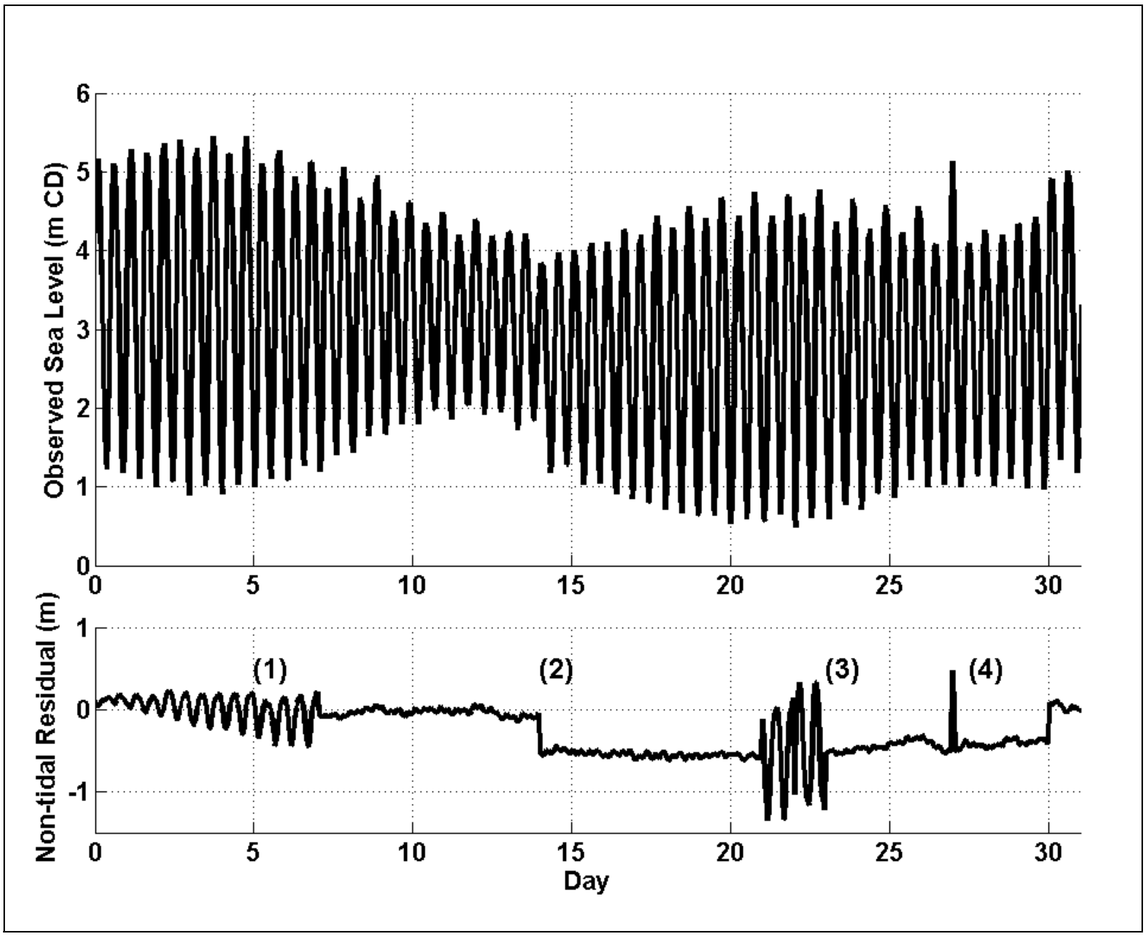


Figure 2.6: Common errors in sea-level data due to; (1) a steady timing gain of 20 minutes over the week, (2) a 0.5m datum shift, (3) wrong identification of tidal trace from chart, and (4) an isolated error of 1m. This is a synthetic data set, the errors have been invented as an illustration. (Adapted from Pugh, 1987).

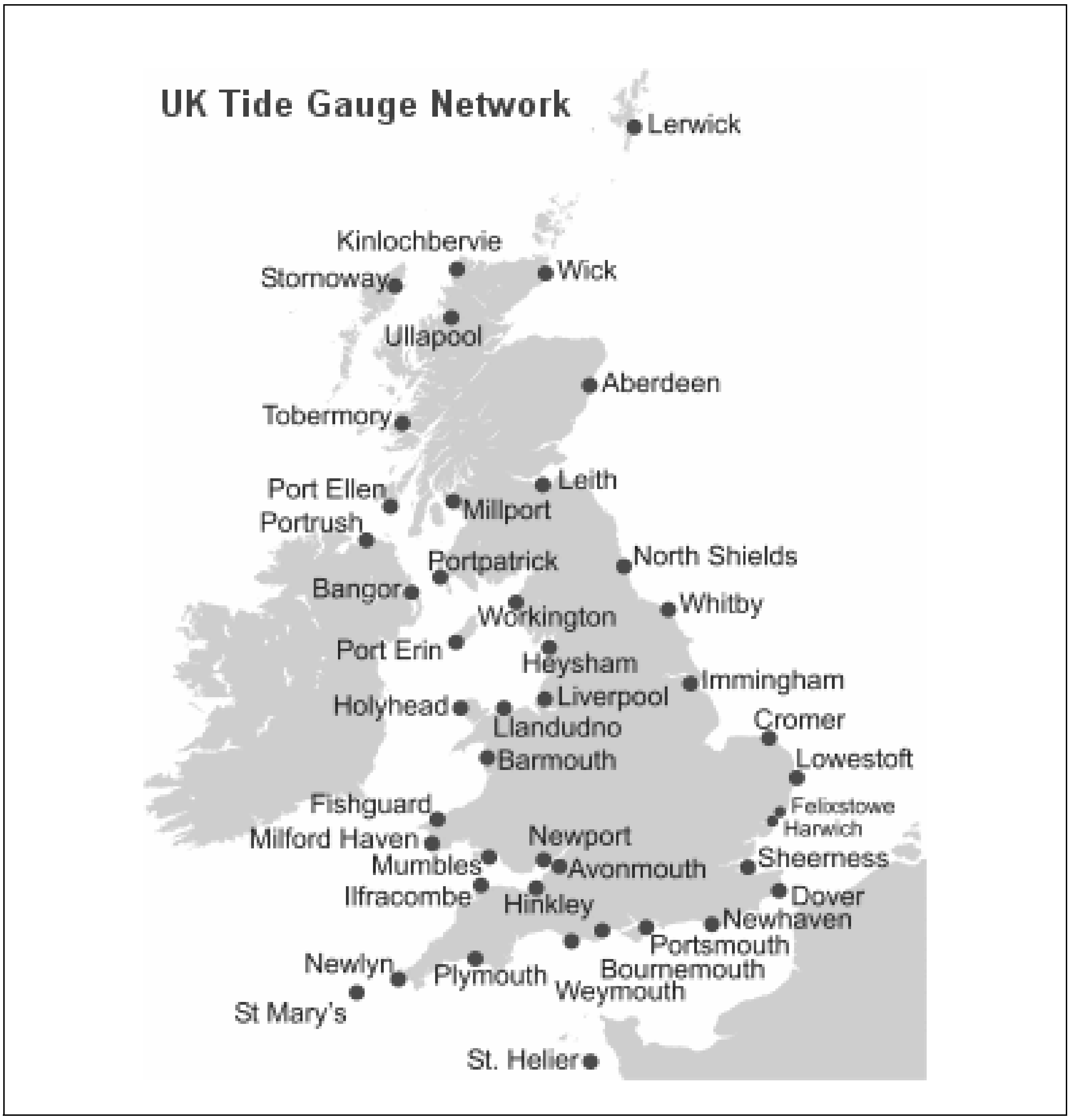


Figure 2.7: The UK National Tide Gauge Network.

(Source: http://www.pol.ac.uk/ntslf/networks.html).

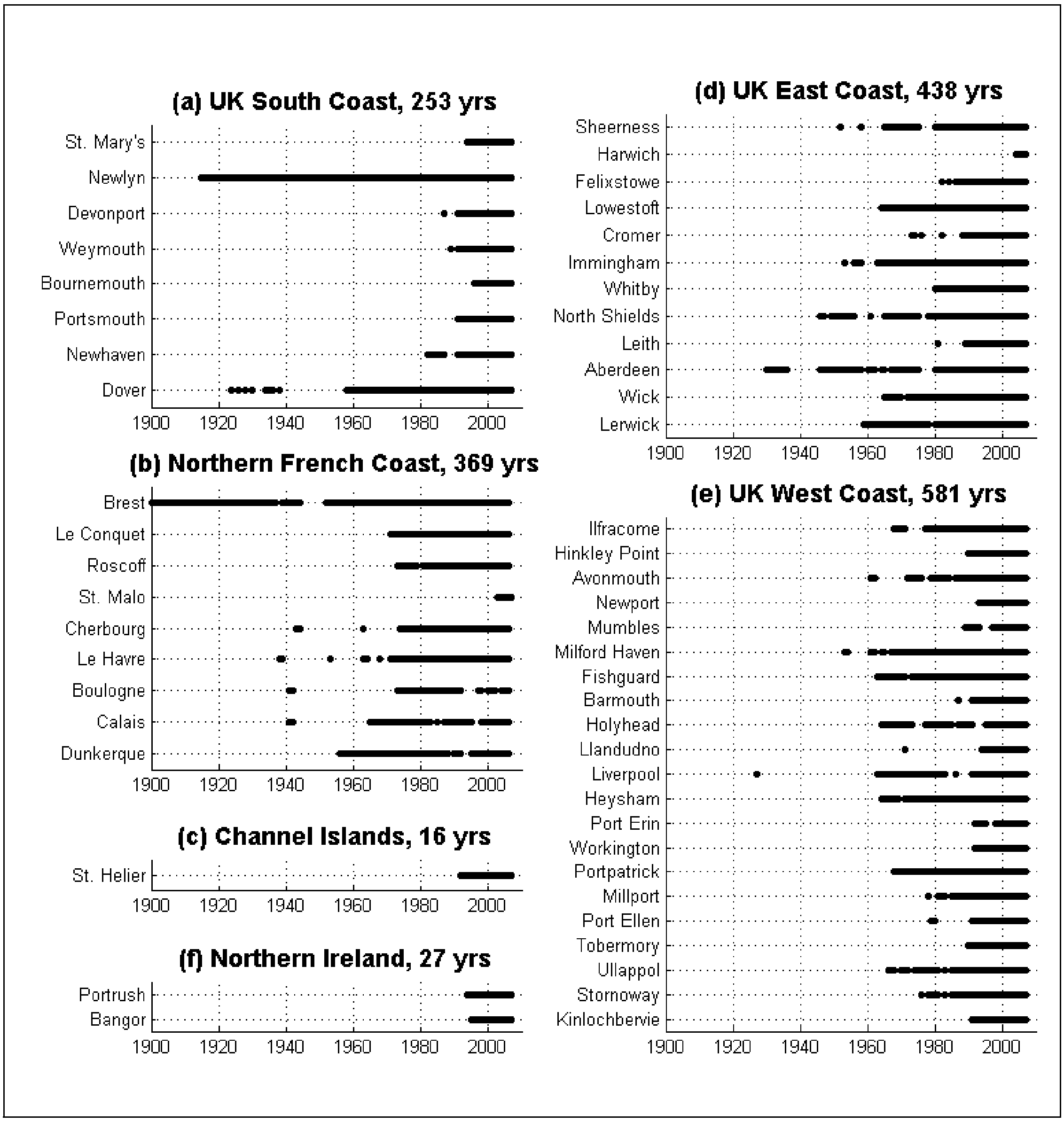


Figure 2.8: Duration of the raw sea level records since 1900 that are available from the internet sites of the British Oceanographic Data Centre and the Systéme d'Observation du Niveau des Eaux Littorales, for; (a) the UK south coast; (b) northern French coast; (c) Channel Islands; (d) UK East coast; (e) UK West coast; (f) Northern Ireland; and (g) the Republic of Ireland. (Downloaded January 2009).

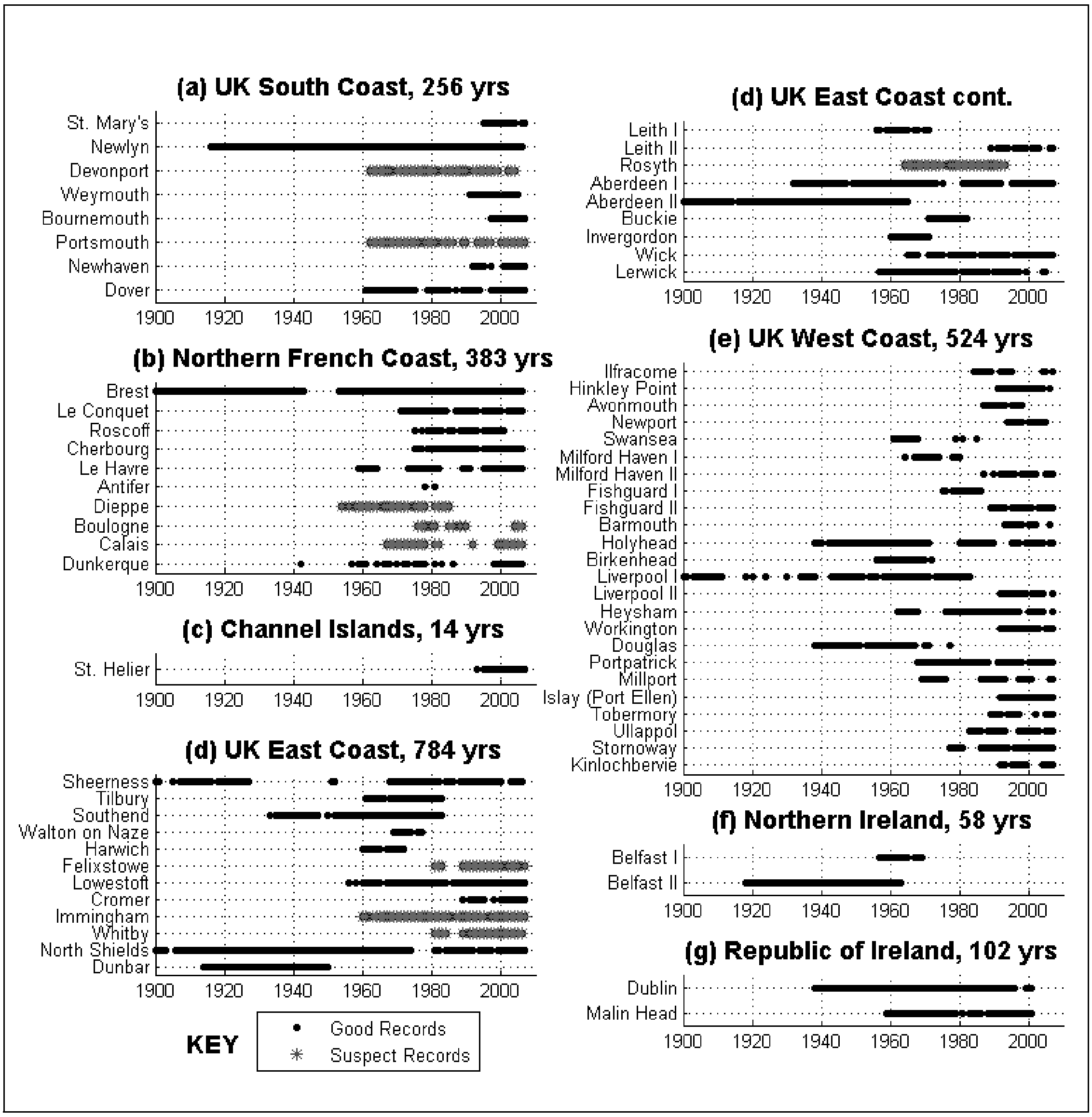


Figure 2.9: Duration of the mean sea level records since 1900 that are available from the Revised Local Reference subset of the Permanent Service for Mean Sea Level for; (a) the UK south coast; (b) northern French coast; (c) Channel Islands; (d) UK East coast; (e) UK west coast; (f) Northern Ireland; and (g) the Republic of Ireland. Good records are plotted as black circles, suspect records as grey stars. Note that data before 1900 is available at Brest, Sheerness, North Shields, Aberdeen and Liverpool. (Downloaded January 2009).

3 DATA SETS

Two different sea level data sets have been used in this research. The first is raw sea level data measured by tide gauges. The frequency of this data is either hourly or 15-minute. This data set has been used at 16 sites in the English Channel and two sites in the southern North Sea to assess observed changes in extreme sea level (Chapter 6) and to estimate probabilities of extreme events (Chapter 7). The second type of data is annual values of MSL which have been derived from the raw sea level measurements. This type of data has been used to assess observed changes in MSL at 55 sites around the British Isles and northern France, although the focus is on the English Channel region (Chapter 5). Particular attention has been given to checking the two sea level data sets for typical errors and datum issues.

3.1 Raw Sea Level Data

A review of the sea level data sets that are readily available (as of January 2009) for the English Channel region, has been described in Section 2.5. This highlighted that there has been, before now, a general lack of long (>40 years) sea level records along the south coast of the UK. As a result, a data archaeology exercise has been undertaken. The focus of this exercise was to capture non-digital hourly or higher frequency data, so that it could be used to assess changes in both mean and extreme sea level and allow for probabilities of extreme sea levels to be estimated. Two previous studies proved particularly useful in identifying potential data holders at the outset of the exercise (Bray et al., 1994; Sharples et al., 2003).

Ten sites (Table 3.1) where substantial data extension was possible were earmarked. Four main data sources were identified:

1. Original paper charts which are time-consuming and expensive to digitise but allow direct access to the raw data (Figure 3.1);
2. A large set of A4 sheets of hand written tabulated hourly sea level heights digitised and held by the UKHO (Figure 3.2);
3. A database of digital hourly records held by the POL, but not available via the BODC; and
4. Readily available data recorded by digital tide gauges (i.e. that available from the BODC or held digitally by the respective Port or Harbour Authorities).

The years available for the four data sources are listed in Table 3.1. Due to financial constraints, the focus was on obtaining a representative spatial spread of records along the coast; these were chosen to be St. Mary's, Devonport, Weymouth, Southampton, Portsmouth and Newhaven. The Portsmouth UKHO tabulated data had been captured previously by staff (including the author) at Associated British Ports Marine Environmental Research (Harris, 2004) and this new data was supplied for use in this study. The Southampton charts were digitised. The remaining tabulated data was manually entered into digital spreadsheets.

Following a careful check of datum changes, the different data sources were combined to produce a single extended record at each site. A short history of sea level measurements for these six sites is given in Appendix A. In total, the exercise adds 173 years of hourly data to the 245 years readily available for the south coast through the BODC and the length of records is now comparable to the UK east coast (Figure 2.8). While this is a significant extension, further significant extensions are possible, such as at Calshot and Poole, and one would hope that all the data in Table 3.1 should be converted eventually to digital form suitable for scientific analysis.

The final data set includes the six sites for which data extensions have been made, along with data for Newlyn, Dover and seven sites along the French coast. The Jersey record has also been included because of its useful location away from the mainland coasts of England and northern France. The records for Sheerness and Dunkerque have been included to better resolve the characteristics of sea level at the boundary of the English Channel and southern North Sea. The recent UK data not derived by data archaeology, came from the BODC and the French data from SONEL. The final raw sea level data set comprises 18 sites listed in Table 3.2. The geographical locations of these sites and data lengths are displayed in Figure 3.3.

The 18 raw sea level records have been converted into the same format and referenced in universal time + 0 hours and CD (Admiralty CD for the UK records and Zéro Hydrographique for the French records). Unless stated, the 15-minute data (Table 3.3) has been subsampled to hourly values. The data has been rigorously checked for common errors, such as data spikes, by applying the two techniques outlined in Section 2.5.2.2 and by comparing records with neighbouring sites. Spurious records have been excluded.

Timing errors were prevalent in large periods of the older Newlyn and Southampton records which were measured using mechanical gauges. These errors typically result from replacing tidal charts on the drum without accurately resetting the drum offset to zero or, as a result of 'backlash' (i.e. despite the pen/clock being set correctly, it may take some minutes for the drum to 'take up the drive') (IOC, 1985). These have been corrected by shifting the data back or forth at ±1 minute intervals to identify the phase shift.

3.2 Mean Sea Level Data

The second data set that has been used in this study is annual values of MSL. The majority of these values have been obtained from the PSMSL. Additional values have been derived from the extended UK south coast data set, described above, by simply averaging the raw sea level records for each year. If a MSL value for a given year was held by the PSMSL, this has been used. The only exception, is in the case of the earlier Devonport and Portsmouth records. Here the PSMSL values have been ignored and the values derived from the extended datasets have been used instead. This is because the early part of the dataset, currently held by the PSMSL, does not correctly account for a number of datum changes that took place at these sites, as described below. The digital capturing of the raw sea level records at these sites, has allowed these two MSL records to be rigorously checked for the first time.

For the six UK south coast sites, annual MSL values have been calculated for the years when the PSMSL criteria is met (i.e. individual years must have at least 11 months of measurements with at least 15 days of records for each month). The early St. Mary's and Weymouth raw records have considerable periods of missing data. As a result, the database of annual sea levels has only been extended (relative to the existing PSMSL data set) by two and five years respectively. However, these limited additional years significantly increase the overall record span[6] (St. Mary's from 12 to 39 years, Weymouth from 15 to 38 years) at the inevitable expense of accommodating gaps in the record. 60 years of the new 70-year Southampton record fulfil the PSMSL requirements. The Newhaven record has been extended by a further 16 years, increasing the record span from 15 to 65 years.

The PSMSL records for the first 26 years of the Devonport and first 25 years of the Portsmouth record have been ignored. Instead, new values have been derived from the extended raw sea level dataset, with one additional year also added to both data sets. The original Portsmouth MSL values supplied to the PSMSL by the UKHO, did not correctly account for two datum changes that took place in the 1960's (Harris, 2004). The Portsmouth PSMSL data set shows a marked step in annual MSL after 1964 (see Figure 2c in Woodworth et al., 1999). CD was redefined on the 1st of January 1965 and again on the 1st of January 1966. When these corrections are made, the step disappears (Figure 3.4). In addition, the zero of the Portsmouth gauge (relative to CD) varied by ±0.05 m between 1961 and 1991. These changes have been corrected by using a list of datum measurements made by the UKHO over this period (these are listed in Walden, 1982). With these corrections, the time series correlation with Newlyn improves from a coefficient of 0.58 to 0.82. Overall, the Portsmouth MSL record has been significantly improved (Figure 3.4).

[6] Note: throughout the thesis the term 'span' is used to describe the number of years between the first and last years in the dataset, not the total number of years available for a given site.

There are only small differences between the new Devonport MSL record and the older one previously supplied to the PSMSL by the UKHO. Maintenance of the gauge was particularly poor in the 1970's, with the zero of the gauge varying by up to 0.5 m. It appears that these changes were correctly accounted for in the earlier data set currently held by the PSMSL. While the MSL record has been slightly improved at Devonport, the overall data quality remains poor in comparison to the other A-Class sites.

In summary, out of the 173 years of hourly sea level captured in the data archaeology exercise, 37 years contain too much missing data to be used to calculate annual MSL values using the PSMSL criteria. Consequently, the exercise extends the data on MSL by an additional 85 annual MSL values along the south coast with a further 51 values improved with new and more accurate information.

Although the focus is on the English Channel, data from the rest of the UK and the Republic of Ireland has also been included to present the results within a wider perspective. The Channel data set includes the six records that have been extended or updated (as described above) in addition to the PSMSL data for Newlyn, Bournemouth, Dover, Jersey and six sites on the French coast (Figure 3.5). The Antifer record on the French coast has been excluded as it only contains two values. The Dieppe data has been excluded as PSMSL documentation suggests there is significant localized subsidence in the vicinity of the gauge. An initial assessment of the French records indicated that there are possibly datum problems with the Calais, Boulogne and the early part (first three years) of the Cherbourg records, so these have also been excluded.

The MSL data for the rest of the UK and the Republic of Ireland has been obtained from the PSMSL. Short histories of many of the sites are described in Woodworth et al. (1999). The two records for Aberdeen have been combined, as have the two records at Liverpool. The Holyhead data before 1959 has been adjusted (as described in Woodworth et al., 1999). The data for Immingham has not been included because it is known to be affected by density changes (Woodworth et al., 2009). The records for Felixstowe, Whitby and Rosyth have been excluded because the PSMSL documentation suggests they are of poor quality (Woodworth et al., 2009). Two records exist for Leith, Milford Haven and Fishguard. Only the later records have been included since it is not possible to combine the later records with the earlier data because a complete datum history is not available for these sites. All data prior to 1900 has been excluded because this has been analysed extensively in earlier studies (Woodworth, 1987; Woodworth et al., 1999).

Most of the MSL records have data only up until 2006 because submission of data to the PSMSL is often a year or two in arrears (Holgate, 2007). The final English Channel and UK data set comprises records from 55 sites whose locations are shown in Figure 3.5.

Table 3.1: Stations with long term digital and non-digital hourly (or higher frequency) sea level data. Underlined text marks the data sets that have been obtained or captured digitally for use in this study. Bold text marks the data sets available from the BODC.

Station	Chart Data (number of years)	Tabulated Hourly Values (number of years)	POL Digital Data (number of years)	Pre-Existing Digital Data (number of years)	Total number of years (range, years)
St. Mary's	1966-1967, 1970-1972, 1974, 1979-1980, 1981-1986 (14)	1987-1989 (3)	1968-1969, 1973,1975, 1977-1978 (6)	**1976, 1994-2006 (14)**	37 (41)
Devonport	1953-1960 (8)	1961-1986, 1988-1990 (29)		**1987, 1991-2006 (17)**	54 (54)
Weymouth	1925-1928, 1963-1966, 1973-1975,1979-1982 (15)	1961-1962, 1967, 1969-1971, 1976, 1983-1987 (12)	1923-1924, 1968, 1977-1978 (5)	**1991-2006 (16)**	48 (84)
Poole	1927-1936, 1947-1948, 1950-1954, 1956-1980 (41)	-	-	1991-2006 (16)	57 (80)
Bournemouth	1974-1990 (17)	-	-	**1996-2006 (11)**	28 (33)
Calshot	1937-1989 (53)	-	-	1991-2006 (16)	69 (70)
Southampton	1935-1950, 1967-1979,1982-1989 (37)	-	1951-1966 (16)	1990-2006 (17)	70 (72)
Portsmouth	1936-1937, 1939-1958 (22)	1961-1990 (30)	-	**1991-2006 (16)**	68 (71)
Shoreham	1950-1970, 1988-1996 (30)	1997-1999 (3)	-	2000-2006 (6)	39 (57)
Newhaven	-	-	1942-1948, 1950-1951, 1953-1957, 1964-1965, 1973, 1988 (18)	**1982-1987, 1991-2006 (22)**	40 (65)

Table 3.2: Details of the final raw sea level data set.

Station Name	Site ID	Location (Degrees, minutes)		Number of years (Spanning)	Range
		Lat.	Long.		
St. Mary's	STM	49° 55' N	06° 19' W	23(39)	1968-2006
Newlyn	NEW	50° 06' N	05° 32' W	92(92)	1915-2006
Devonport	DEV	50° 22' N	04° 11' W	46(46)	1961-2006
Weymouth	WEY	50° 36' N	02° 26' W	33(84)	1923-2006
Southampton	SOU	50° 53' N	01° 23' W	70(72)	1935-2006
Portsmouth	PTM	50° 48' N	01° 06' W	46(46)	1961-2006
Newhaven	NHA	50° 46' N	00° 03' E	40(65)	1942-2006
Dover	DOV	51° 06' N	01° 19' E	57(83)	1924-2006
Sheerness	SHE	51° 26' N	00° 44' E	39(55)	1952-2006
Dunkerque	DUN	51° 03' N	02° 22' E	48(51)	1956-2006
Calais	CAL	50° 58' N	01° 39' E	40(66)	1941-2006
Boulogne	BOU	50° 43' N	01° 34' E	30(66)	1941-2006
Le Havre	LEH	49° 28' N	00° 07' E	42(69)	1938-2006
Cherbourg	CHE	49° 39' N	01° 37' W	36(64)	1943-2006
Jersey	JER	49° 11' N	02° 07' W	15(15)	1992-2006
Roscoff	RCF	48° 43' N	03° 57' W	33(34)	1973-2006
Le Conquet	LEC	48° 22' N	04° 46' W	36(36)	1971-2006
Brest	BST	48° 22' N	04° 30' W	99(107)	1900-2006

Table 3.3: Details of the frequency of the raw sea level data set for each tide-gauge site.

Station Name	Years for which hourly data is available	Years for which 15-minute data is available
St. Mary's	1968-1993	1994-2006
Newlyn	1992-1992	1993-2006
Devonport	1961-1992	1993-2006
Weymouth	1923-1992	1993-2006
Southampton	1951-1966	1935-1950, 1967-2006
Portsmouth	1961-1992	1993-2006
Newhaven	1942-1992	1993-2006
Dover	1924-1992	1993-2006
Sheerness	1952-1992	1993-2006
Dunkerque	1956-2006	-
Calais	1941-2006	-
Boulogne	1941-2006	-
Le Havre	1938-2006	-
Cherbourg	1943-2006	-
Jersey		1992-2006
Roscoff	1973-2006	-
Le Conquet	1971-2006	-
Brest	1900-2006	-

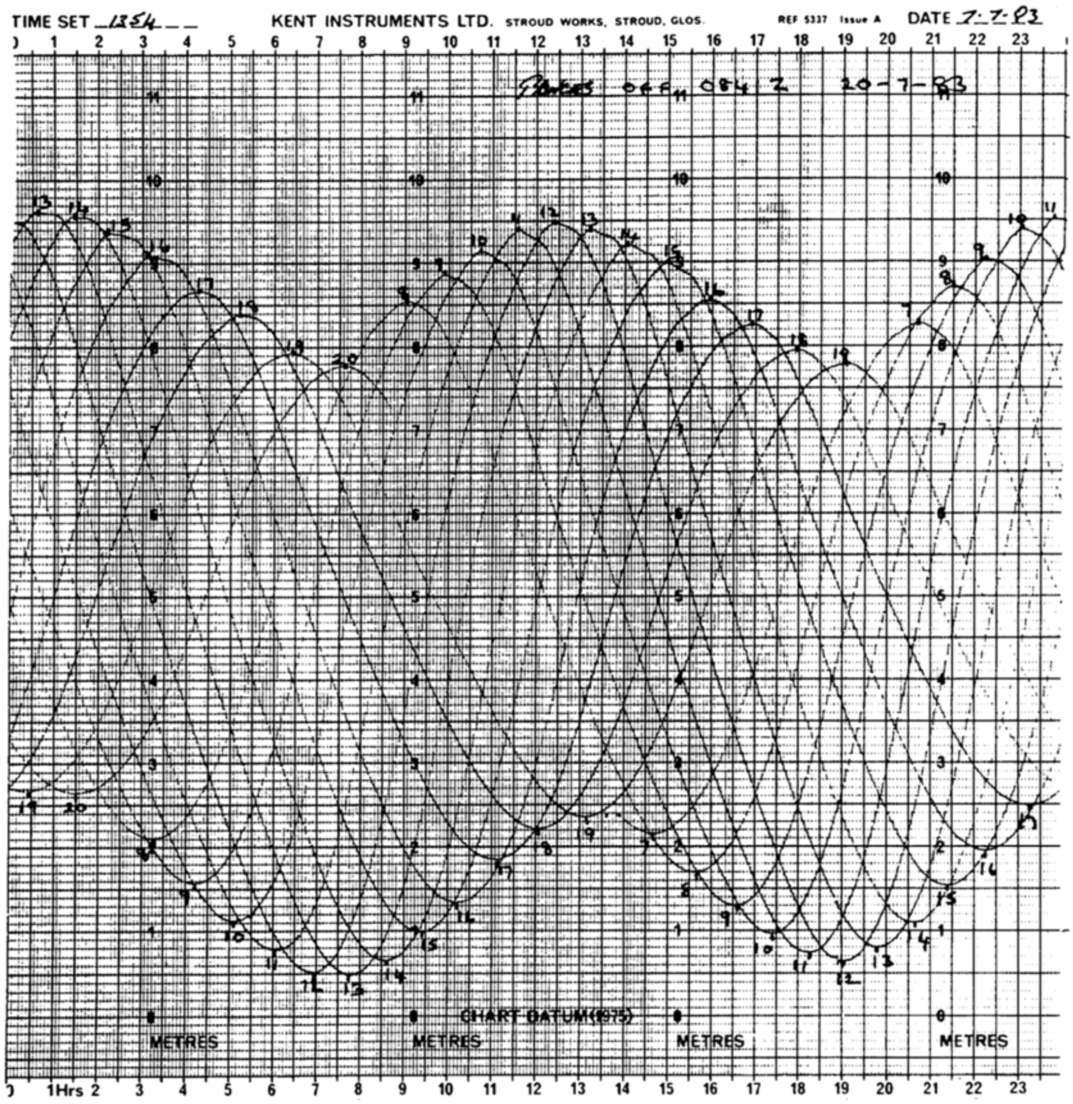
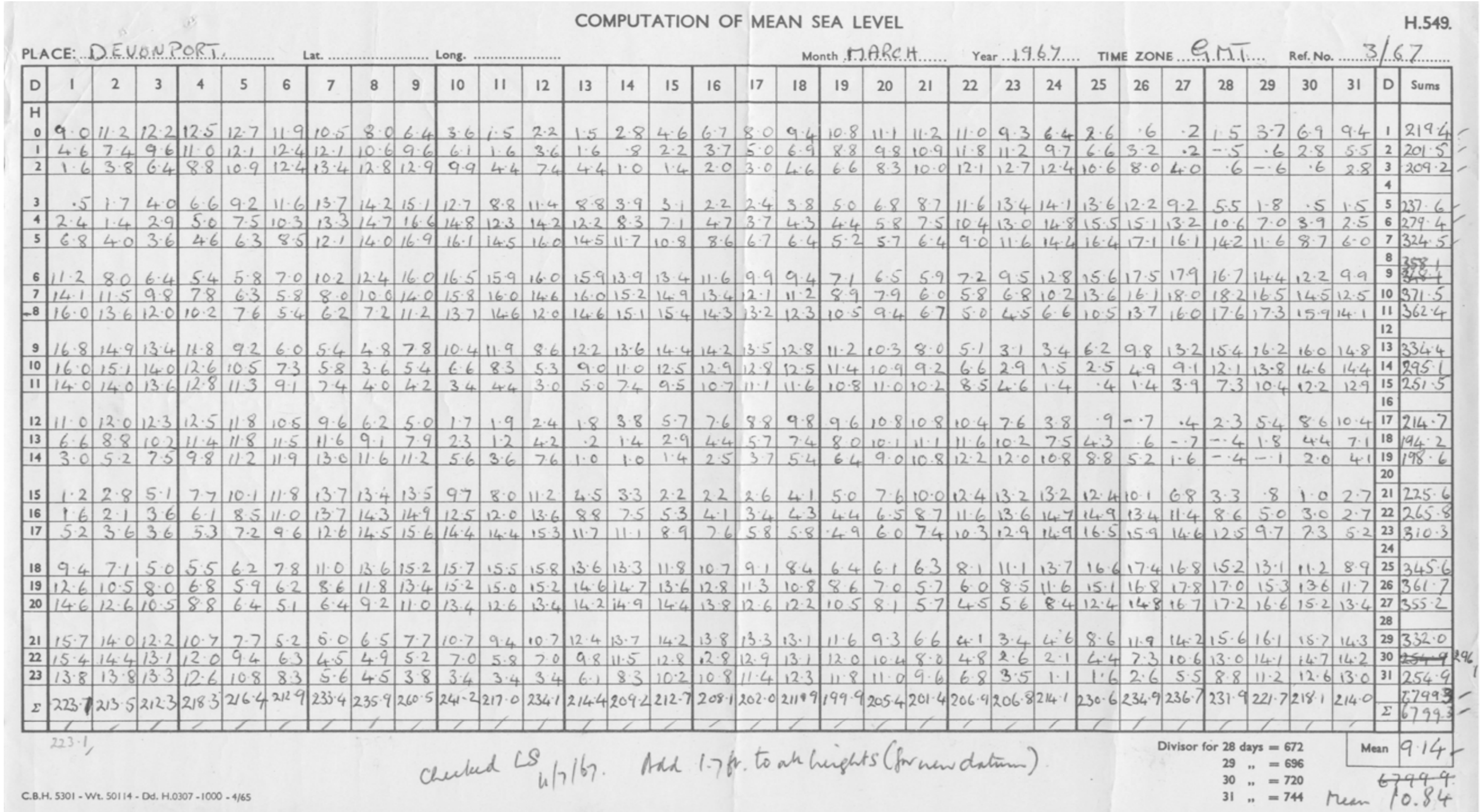


Figure 3.1: Example of a tidal chart record by a mechanical still well float gauge. (Source: IOC, 1985).



COMPUTATION OF MEAN SEA LEVEL H.549.

PLACE: DEVONPORT. Lat. .... Long. .... Month MARCH Year 1967 TIME ZONE G.M.T. Ref. No. 3/67

D H	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	9.0	11.2	12.2	12.5	12.7	11.9	10.5	8.0	6.4	3.6	1.5	2.2	1.5	2.8	4.6	6.7	8.0	9.4	10.8	11.1	11.2	11.0	9.3	6.4	2.6	.6	.2	1.5	3.7	6.9	9.4
1	4.6	7.4	9.6	11.0	12.1	12.4	12.1	10.6	9.6	6.1	1.6	3.6	1.6	.8	2.2	3.7	5.0	6.9	8.8	9.8	10.9	11.8	11.2	9.7	6.6	3.2	.2	-.5	.6	2.8	5.5
2	1.6	3.8	6.4	8.8	10.9	12.4	13.4	12.8	12.9	9.9	4.4	7.4	4.4	1.0	1.4	2.0	3.0	4.6	6.6	8.3	10.0	12.1	12.7	12.4	10.6	8.0	4.0	.6	-.6	.6	2.8
3	.5	1.7	4.0	6.6	9.2	11.6	13.7	14.2	15.1	12.7	8.8	11.4	8.8	3.9	3.1	2.2	2.4	3.8	5.0	6.8	8.7	11.6	13.4	14.1	13.6	12.2	9.2	5.5	1.8	.5	1.5
4	2.4	1.4	2.9	5.0	7.5	10.3	13.3	14.7	16.6	14.8	12.3	14.2	12.2	8.3	7.1	4.7	3.7	4.3	4.4	5.8	7.5	10.4	13.0	14.8	15.5	15.1	13.2	10.6	7.0	3.9	2.5
5	6.8	4.0	3.6	4.6	6.3	8.5	12.1	14.0	16.9	16.1	14.5	16.0	14.5	11.7	10.8	8.6	6.7	6.4	5.2	5.7	6.4	9.0	11.6	14.4	16.4	17.1	16.1	14.2	11.6	8.7	6.0
6	11.2	8.0	6.4	5.4	5.8	7.0	10.2	12.4	16.0	16.5	15.9	16.0	15.9	13.9	13.4	11.6	9.9	9.4	7.1	6.5	5.9	7.2	9.5	12.8	15.6	17.5	17.9	16.7	14.4	12.2	9.9
7	14.1	11.5	9.8	7.8	6.3	5.8	8.0	10.0	14.0	15.8	16.0	14.6	16.0	15.2	14.9	13.4	12.1	11.2	8.9	7.9	6.0	5.8	6.8	10.2	13.6	16.1	18.0	18.2	16.5	14.5	12.5
8	16.0	13.6	12.0	10.2	7.6	5.4	6.2	7.2	11.2	13.7	14.6	12.0	14.6	15.1	15.4	14.3	13.2	12.3	10.5	9.4	6.7	5.0	4.5	6.6	10.5	13.7	16.0	17.6	17.3	15.9	14.1
9	16.8	14.9	13.4	11.8	9.2	6.0	5.4	4.8	7.8	10.4	11.9	8.6	12.2	13.6	14.4	14.2	13.5	12.8	11.2	10.3	8.0	5.1	3.1	3.4	6.2	9.8	13.2	15.4	16.2	16.0	14.8
10	16.0	15.1	14.0	12.6	10.5	7.3	5.8	3.6	5.4	6.6	8.3	5.3	9.0	11.0	12.5	12.9	12.8	12.5	11.4	10.9	9.2	6.6	2.9	1.5	2.5	4.9	9.1	12.1	13.8	14.6	14.4
11	14.0	14.0	13.6	12.8	11.3	9.1	7.4	4.0	4.2	3.4	4.4	3.0	5.0	7.4	9.5	10.7	11.1	11.6	10.8	11.0	10.2	8.5	4.6	1.4	.4	1.4	3.9	7.3	10.4	12.2	12.9
12	11.0	12.0	12.3	12.5	11.8	10.5	9.6	6.2	5.0	1.7	1.9	2.4	1.8	3.8	5.7	7.6	8.8	9.8	9.6	10.8	10.8	10.4	7.6	3.8	.9	-.7	.4	2.3	5.4	8.6	10.4
13	6.6	8.8	10.2	11.4	11.8	11.5	11.6	9.1	7.9	2.3	1.2	4.2	.2	1.4	2.9	4.4	5.7	7.4	8.0	10.1	11.1	11.6	10.2	7.5	4.3	.6	-.7	-.4	1.8	4.4	7.1
14	3.0	5.2	7.5	9.8	11.2	11.9	13.0	11.6	11.2	5.6	3.6	7.6	1.0	1.0	1.4	2.5	3.7	5.4	6.4	9.0	10.8	12.2	12.0	10.8	8.8	5.2	1.6	-.4	-.1	2.0	4.1
15	1.2	2.8	5.1	7.7	10.1	11.8	13.7	13.4	13.5	9.7	8.0	11.2	4.5	3.3	2.2	2.2	2.6	4.1	5.0	7.6	10.0	12.4	13.2	13.2	12.4	10.1	6.8	3.3	.8	1.0	2.7
16	1.6	2.1	3.6	6.1	8.5	11.0	13.7	14.3	14.9	12.5	12.0	13.6	8.8	7.5	5.3	4.1	3.4	4.3	4.4	6.5	8.7	11.6	13.6	14.7	14.9	13.4	11.4	8.6	5.0	3.0	2.7
17	5.2	3.6	3.6	5.3	7.2	9.6	12.6	14.5	15.6	14.4	14.4	15.3	11.7	11.1	8.9	7.6	5.8	5.8	4.9	6.0	7.4	10.3	12.9	14.9	16.5	15.9	14.6	12.5	9.7	7.3	5.2
18	9.4	7.1	5.0	5.5	6.2	7.8	11.0	13.6	15.2	15.7	15.5	15.8	13.6	13.3	11.8	10.7	9.1	8.4	6.4	6.1	6.3	8.1	11.1	13.7	16.6	17.4	16.8	15.2	13.1	11.2	8.9
19	12.6	10.5	8.0	6.8	5.9	6.2	8.6	11.8	13.4	15.2	15.0	15.2	14.6	14.7	13.6	12.8	11.3	10.8	8.6	7.0	5.7	6.0	8.5	11.6	15.1	16.8	17.8	17.0	15.3	13.6	11.7
20	14.6	12.6	10.5	8.8	6.4	5.1	6.4	9.2	11.0	13.4	12.6	13.4	14.2	14.9	14.4	13.8	12.6	12.2	10.5	8.1	5.7	4.5	5.6	8.4	12.4	14.8	16.7	17.2	16.6	15.2	13.4
21	15.7	14.0	12.2	10.7	7.7	5.2	5.0	6.5	7.7	10.7	9.4	10.7	12.4	13.7	14.2	13.8	13.3	13.1	11.6	9.3	6.6	4.1	3.4	4.6	8.6	11.9	14.2	15.6	16.1	15.7	14.3
22	15.4	14.4	13.1	12.0	9.4	6.3	4.5	4.9	5.2	7.0	5.8	7.0	9.8	11.5	12.8	12.8	12.9	13.1	12.0	10.4	8.0	4.8	2.6	2.1	4.4	7.3	10.6	13.0	14.1	14.7	14.2
23	13.8	13.8	13.3	12.6	10.8	8.3	5.6	4.5	3.8	3.4	3.4	3.4	6.1	8.3	10.2	10.8	11.4	12.3	11.8	11.0	9.6	6.8	3.5	1.1	1.6	2.6	5.5	8.8	11.2	12.6	13.0
Σ	223.7	213.5	212.3	218.3	216.4	212.9	233.4	235.9	260.5	241.2	217.0	234.1	214.4	209.2	212.7	208.1	202.0	211.9	199.9	205.4	201.4	206.9	206.8	214.1	230.6	234.9	236.7	231.9	221.7	218.1	214.0
	223.1																														

D	Sums
1	219.4
2	201.5
3	209.2
4	
5	237.6
6	279.4
7	324.5
8	358.1
9	378.4
10	371.5
11	362.4
12	
13	334.4
14	295.1
15	251.5
16	
17	214.7
18	194.2
19	198.6
20	
21	225.6
22	265.8
23	310.3
24	
25	345.6
26	361.7
27	355.2
28	
29	332.0
30	~~254.9~~ 296
31	254.9
	6799.3
Σ	6799.3

Checked LS 4/7/67. Add 1.7 ft. to all heights (for new datum)

Divisor for 28 days = 672
29 „ = 696
30 „ = 720
31 „ = 744

Mean 9.14

~~6799.9~~

Mean 10.84

C.B.H. 5301 - Wt. 50114 - Dd. H.0307 - 1000 - 4/65

Figure 3.2: Example of a month of tabulated hourly sea level values.

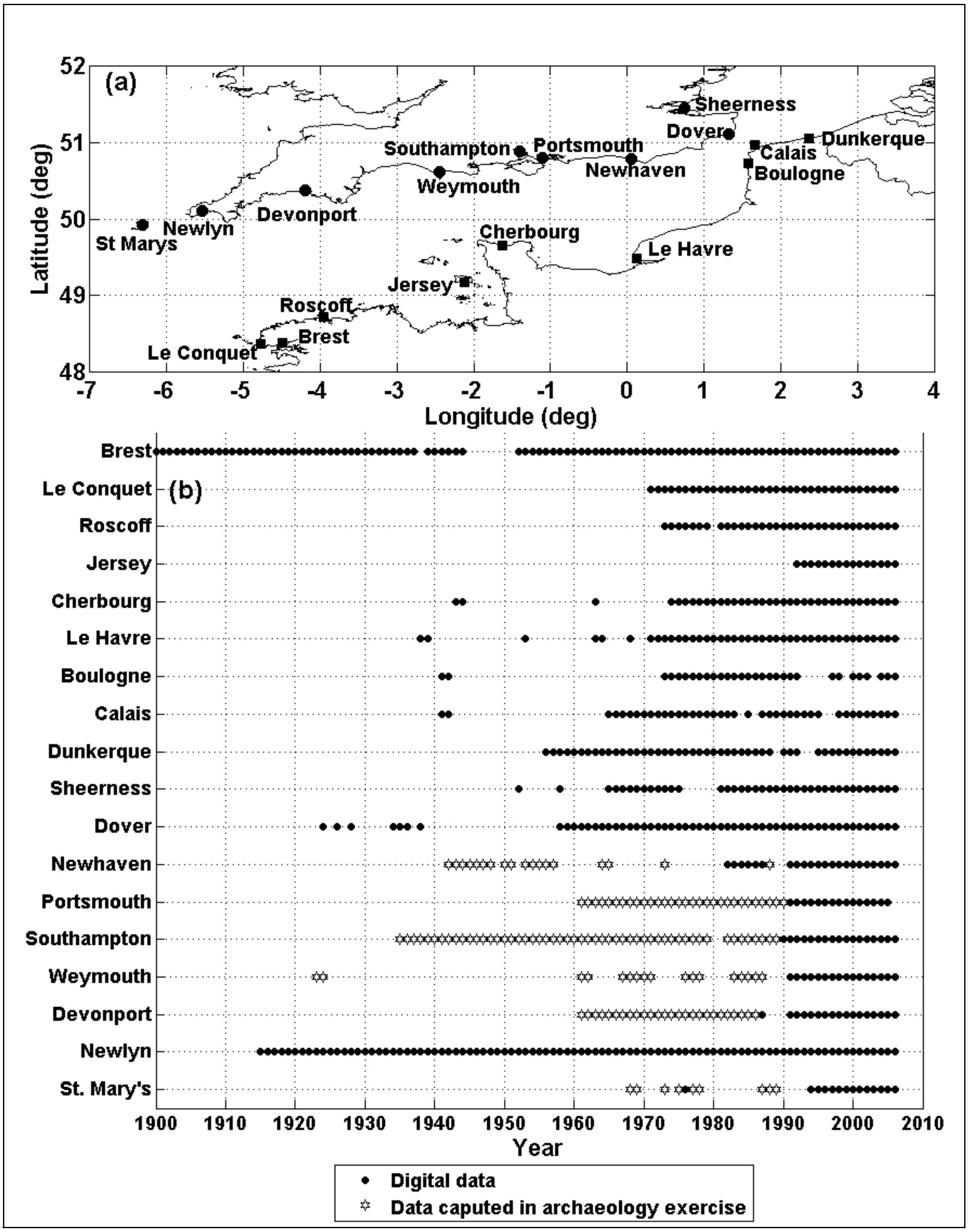


Figure 3.3: (a) Map showing location of the 18 tide-gauges; (b) Duration of the sea level records.

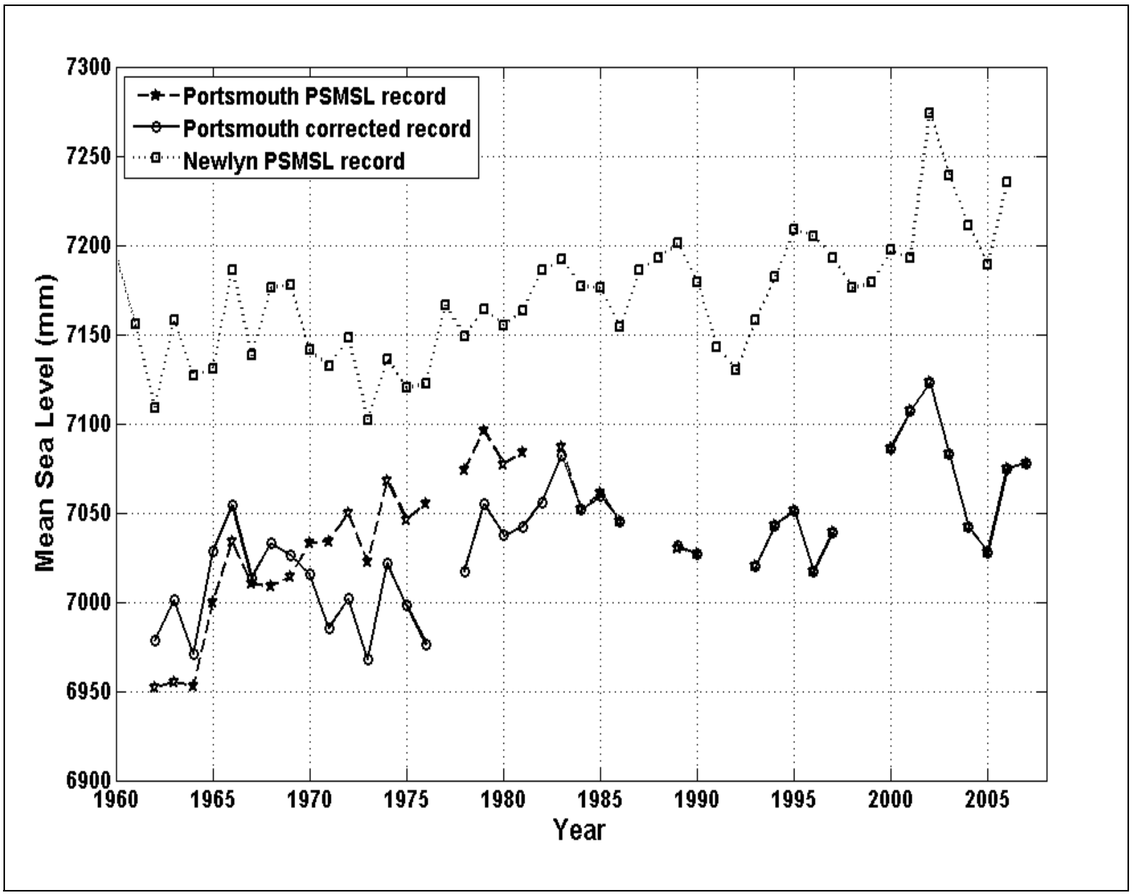


Figure 3.4: A comparison between the PSMSL's time series of annual mean sea level at Portsmouth and Newlyn and the corrected time series of annual mean sea level at Portsmouth.

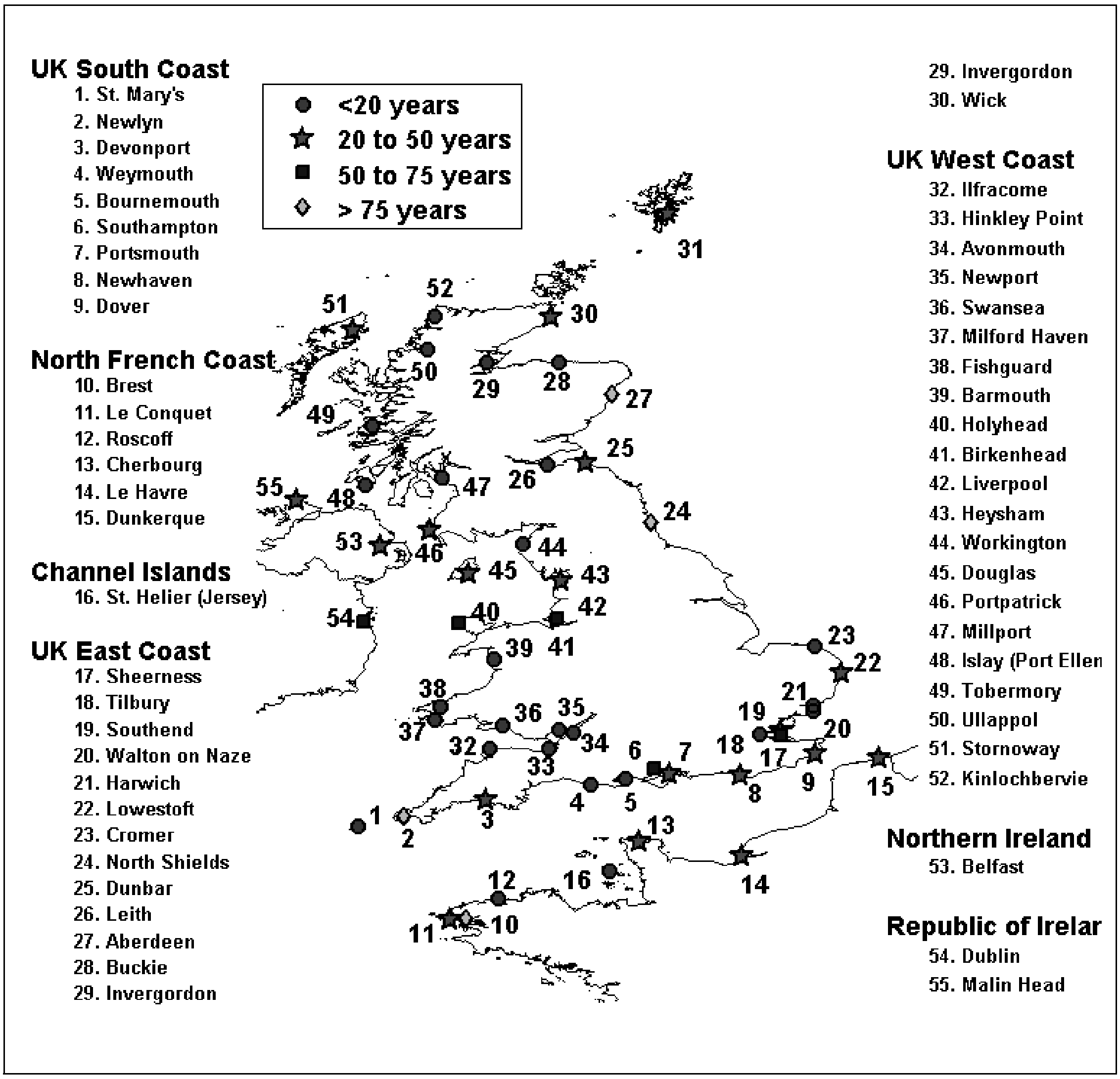


Figure 3.5: Map showing the location of the MSL records. Circles represent sites with less than 20 years of data; stars, sites with between 20 and 50 years of data; squares, sites with 50 to 100 years of data; and diamonds, sites with more than 100 years of data.

4 METHODOLOGY

This study has been undertaken in three main stages. Stage 1 addresses the first study objective: To determine the rates of change in MSL in the English Channel between 1900 and 2006. Stage 2 focuses on the second study objective: To establish whether changes in extreme sea level between 1900 and 2006 were primarily caused directly by variations in MSL. Stage 3 is concerned with the third study objective: To evaluate which is the most appropriate statistical method for estimating probabilities of extreme high sea levels in the Channel. The methodology of each of these three stages of research is described in the follow sections.

4.1 Observed Changes in Mean Sea Level

The first stage of the research has three main components. In the first, rates of relative MSL change are determined around the English Channel. In the second, rates of vertical land movement are estimated and compared with measurements from geological data and advanced geodetic techniques. In the third, the high rates of MSL rise observed around the UK over the last decade are evaluated, to see if they are unusual compared to trends observed at other periods in the historical record. This has been done to evaluate whether there is evidence for any acceleration in sea-level rise over the 20th century. These components are described in the following three sections.

4.1.1 Trends in Mean Sea Level

Traditionally, rates of change in MSL have been calculated by fitting trends to time series of annual MSL using linear regression. However, there have been considerable interdecadal and decadal variations in MSL over the 20th century. These tend to bias estimates of long term MSL change, particularly in records shorter than a few decades (Douglas, 1991). Woodworth et al. (1999) showed, using Empirical Orthogonal Function (EOF) (Preisendorfer, 1988) techniques, that while the character of sea level variability differs around the UK, part of the variability is coherent among sites. Further, it can be represented by a single index derived from a few long records. Woodworth et al. (2009) argued that more accurate long-term rates of MSL change could be computed by subtracting this index from records before fitting trends. In this research, both the traditional and the Woodworth et al. (2009) approaches have been applied. The trends calculated from both methods have been compared in order to quantify the improvement in accuracy gained from the second approach.

The first set of MSL trends has been calculated by fitting trends to the original records using linear regression, with the uncertainty defined as one standard error (SE) (i.e. 68% confidence level). In calculating uncertainties it is assumed that the annual values are not serially correlated. Then, in order to apply the second approach, Woodworth's et al. (1999) EOF analysis has been undertaken and extended to investigate whether the coherent part of the sea level variability around the UK is consistent with that observed along the northern French coast. Following this, a sea level index has been created from the six longest records (Brest, Newlyn, Sheerness, North Shields, Aberdeen and Liverpool) to represent the coherent part of the sea level variability. Finally, a second set of MSL trends has been computed by subtracting this index from each MSL record, with trends fitted to the residual time series using linear regression. A description of the EOF analysis that has been undertaken and the construction of the sea level index are given in Appendix B.

The uncertainties (i.e. SE's), associated with both trend estimates, have been compared at all the study sites in order to quantify the improvement in accuracy gained by removing the coherent part of the sea level variability. In addition, the long and high quality Newlyn record has been detrended (relative to the trend for the entire record length) and trends have been calculated using both approaches for all overlapping 10, 20, 30, up to 90-year periods. Trends for each period were only calculated provided the period was at least 75% compete. The range in MSL trends for each period and each method has then been compared.

4.1.2 Land Movements

The current best regional estimate of sea-level rise around the UK, solely from oceanographic processes, is 1.4 ± 0.2 mm/yr (Woodworth et al., 2009). The second set of MSL trends have been subtracted from 1.4 mm/yr to give an estimate of rates of vertical land movement. The uncertainty in the oceanographic component (±0.2 mm/yr) has been ignored. Hence, it is assumed that all the uncertainty in the MSL trend is associated with vertical land movement. The estimated rates have then been compared to rates of late Holocene sea level change extracted from Shennan and Horton (2002). The SE's associated with these trends are assumed to be 0.2 mm/yr (Woodworth et al., 2009). The rates have also been compared to measurements of vertical land movement from new combinations of continuous Global Positioning System (CGPS) and absolute gravity (Bingley et al., 2007). These comparisons have only been undertaken for UK sites as measurements are not available for the French coastline.

4.1.3 Accelerations in Sea-Level Rise

Trends have first been calculated for all overlapping 10, 25 and 50-year periods, for the longest and most continuous records (Brest, Newlyn, North Shields and Aberdeen), to assure reasonable completeness. Each trend has been subtracted from the trend that had been calculated from the entire record, at each site. Values have then been averaged across the four sites to create a single time series, representative of the regional-average trends. This has been compared to a time series created in the same way, but using data from all 55 sites.

4.2 Observed Changes in Extreme Sea Levels

In the second stage of the study, the raw sea level records at the 18 sites (Figure 3.3) have been split into tidal and non-tidal components. Trends in these components, and the interaction between them, have been assessed separately before the total extreme sea levels are examined[7]. Only years that were at least 75% complete have been included in the analysis.

4.2.1 Astronomical Tide

The tide has been estimated using the PSMSL's harmonic analysis TASK-2000 software package (http://www.pol.ac.uk/psmsl/training/task2k.html) with the standard set of 63 constituents. A separate tidal analysis has been undertaken for each calendar year. Trends have been fitted to the amplitude and phases of the 63 annual tidal constituents. Annual mean high water (MHW) and annual mean low (MLW) tidal elevations (relative to MSL) have been calculated. Along with annual mean tidal ranges (MTR). At each site, the annual mean length of the ebb and flood tide have also been calculated to assess for changes in tidal asymmetry (Figure 4.1).

4.2.2 Surge Component

Changes in historic storm activity can be assessed using a range of different indices based on meteorological or oceanographic data sets (see Zhang et al., 2000 for examples). One approach is to use long records of hourly sea level data as they provide a unique measurement record of extratropical storms affecting the Channel. In this study three indices, derived from the surge component of sea level, have been used as proxies for storminess.

[7] The analysis approach of this stage of the study is an extension of the approach used by Araújo (2005), who assessed changes in sea level at six sites (Newlyn, Portsmouth, Dover, Calais, Le Havre and Brest) around the Channel.

The surge component has been obtained by subtracting the annual MSL and predicted tide from the observed sea level. Following Zhang et al. (2000), three parameters are used to assess changes in storm activity:

1. **Storm count:** the annual number of storm surges above a given threshold;
2. **Storm duration:** the annual number of hours for which the storm surges were above a given threshold; and
3. **Storm intensity:** the annual total area under the storm surge curve and above a given threshold (Figure 4.1).

Indices one and two reflect the number and duration of surges. The third index reflects the surge severity (Zhang et al., 2000), which is a measure of both the surge height and the duration over which the surge occurs. Hence, unlike a typical percentile analysis of surge height, this index can be used to assess for changes in extreme surges that result from changes to both the height and duration of surges. These three indices have been calculated for all surge events above the 95, 99 and 99.9 percentile surge levels at each site. To investigate how extreme surges are affected by regional climate changes, the three indices have been analysed for correlations with the NAO index. The NAO is the major mode of atmospheric variability in the North Atlantic. The NAO index used here is defined as the difference between the normalised sea level pressures at Gibraltar and southwest Iceland (Hurrell, 1995; Jones et al., 1997), and was obtained from the Climatic Research Unit, University of East Anglia[8].

4.2.3 Non-linear Interactions

To check whether there is significant interaction between tides and surges in the English Channel, the timing of the surge peak relative to the nearest high water was recorded for each storm with a surge greater than the 95, 99 and 99.9 percentiles. Frequency histograms have been plotted to determine the distributions of interaction. An improved version of

[8] http://www.cru.uea.ac.uk/cru/data/nao.htm

Dixon and Tawn's (1994) Chi-squared (χ^2) test is used to quantify the level of interaction taking place at each site (see Appendix C for details). The χ^2 test has been calculated for all overlapping 10 year periods to test for changes in tide-surge interaction distributions.

4.2.4 Observed Extreme Sea Levels

Changes in extreme sea levels over and above changes in MSL have been assessed using a percentile analysis. A 'normal year' (i.e. not a leap year) with no data gaps, contains 8760 hourly measurements. These can be ordered in terms of height and can be used to compute percentile levels for the year (Woodworth and Blackman, 2004). Percentile values for the observed sea level are calculated at 11 levels (0.01, 0.1, 1, 5, 10, 50, 80, 90, 95, 99, 99.9). The 50th percentile (the median), corresponds well to MSL. This has been subtracted from each individual percentile for each year to obtain a measure of the distribution of hourly sea levels relative to MSL for that year.

4.3 Estimating Probabilities of Extreme Sea Level

In the third stage of the study, four extreme value analysis methods are evaluated. These are the: (i) AMM; (ii) RLM; (iii) JPM; and (iv) RJPM. This stage of the research has four main components. In the first, the different ways of handling long-term sea level trends are compared. In the second, the ratio of tide to surge variability at which the direct methods underestimate the long period return levels is determined. In the third, tests are undertaken to assess the sensitivity of the four methods to the frequency, length and completeness of the available sea level data. In the final stage, return levels are estimated using SRJPM relative return levels and these are compared to results from the other methods. In the following sections, the setup of the four methods is described (Section 4.3.1) and then the methods used to address each of the four components of this stage are explained (Sections 4.3.2 to 4.3.5).

4.3.1 Method Setup

Parameter estimation has been carried out using maximum likelihood. In the RLM and RJPM there are features that require some element of subjective selection (Dixon and Tawn, 1994). The RLM method requires a choice of the number of extremes per year (r) and what constitute independent extreme events within a year[9]. In regards to the latter, a common approach is to ensure that the r-largest events are at least *s* hours away from each other (Tawn, 1988a). In the RJPM, the above features need to be selected in addition to choosing thresholds for: (i) calculating the extremal indices; and (ii) joining the parametric and non-parametric components of the surge distribution. Rather than arbitrarily adopting single values at the offset, a range of selections has been applied to assess the sensitivity of each parameter. In both the RLM and RJPM eight largest values per year have been used and these have been required to be separated by 30 hours. Thresholds and extremal indices have been calculated at each site using the Dixon and Tawn (1994) approach.

Tide-surge interaction must be accounted for in the JPM and RJPM as it is significant at all but one of the 18 study sites (Section 6.3). Following the approach of Tawn (1988c), the tidal range has been divided into five bands of equal probability (not width) and separate surge distributions have been calculated for each band. For simplicity, seasonality has been ignored as it only has a second order effect on return level estimates for return periods longer than a year (Tawn and Vassie, 1989).

4.3.2 Handling Long-term Trends

The four statistical methods, used in this study, are based on the assumption that the sea level data sets are stationary (Coles, 2001). Therefore, the trends (evident in extreme sea level, Chapter 6) must be accounted for in some way. There are three main approaches to handling these trends:

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[9] It is particularly important to distinguish between independent extreme events in the central region of the English Channel due to the occurrence of double high water.

1. Preprocess the sea level records by the removal of the MSL trend;
2. Fit trends to the actual data sets to which the statistical analysis is applied (i.e. time series of annual maximum sea level, in the case of the AMM; or r-largest sea levels, in the case of the RLM). The sea level records can then be detrended using this information rather than using the MSL trend; or
3. Allow for parameters in the extreme distribution, to which the data is fitted, to vary with time. For example, in the AMM, the location parameter (μ) of the GEV distribution is extended so that $\mu_i = \alpha + \beta(I - i_o)$. Where μ_i varies linearly with year i. The i_o term is a base year, α is the intercept and β the trend parameter (see Dixon and Tawn, 1994 for more details).

In approaches 1 and 2, the trends are included subsequently at the design stage.

There are three important questions: (i) Which of these three approaches is most appropriate for handling the trends in each method? (ii) Do the computed return levels differ, depending on which approach is used? (iii) How sensitive are the approaches to data length. In order to address these questions, return levels have been estimated at each of the 18 sites (Figure 3.3) using these three approaches. Only the first approach can be applied in the JPM, so this has been ignored in this stage of the study. In each case, the base year is the year 2000. The three different approaches have been used to estimate extreme sea levels at Newlyn using all overlapping 10, 20, …., 90 year periods

4.3.3 Ratio of Surge to Tide Variability

Dixon and Tawn (1999) found that the AMM underestimates the long period return levels at sites where the astronomical tidal variations are large relative to the surge variations (i.e. tidally-dominated sites). To determine the precise ratio of tidal to surge variation at which the AMM (and RLM) start underestimating the long period return levels, the astronomical component of sea level at Newlyn has been artificially reduced or increased. This has been done by pre-calculated amounts, so that the ratio of tide to surge becomes: 0.5, 1, 1.5, 2, 3, 5, 7, 10 and 15[10]. The ratio of tide to surge variation has been defined as being the 98% quantile of the astronomical tide (relative to a mean level of 0), divided by the 98% quantile of the surge component[11]. The actual ratio of tide to surge variation at Newlyn is about seven. Therefore, when the ratio of tide to surge is 0.5, the time series is surge dominated. When the ratio is 15, the time series is strongly tidally dominated. Each altered astronomical tidal series has then been combined with the original surge component to produce nine synthetic total sea level records (see Figure 4.2 for an illustration of this process). Extreme sea levels have been estimated (by each of the four statistical methods) for these nine synthetic records.

4.3.4 Data Frequency, Length and Completeness

A series of tests has been undertaken to evaluate how sensitive the four statistical methods are to the frequency, length and completeness of the available sea level data. These tests are described in Tables 4.1 to 4.3. In all these tests, the sea level data has been preprocessed by the removal of the MSL trend. The tests in Table 4.1 have only been undertaken using the records with a frequency of 15-minute (Table 3.3). The tests in Table 4.2 have been carried out using the long Newlyn and Brest records. The tests have also been undertaken using the nine synthetic records described in Section 4.3.3. Tests DC2 and DC3, in Table 4.3, have only been applied using the Newlyn data from 1917 to 1983, as this period is more than

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[10] As shown later, this range of values encompasses the full range found in the UK A Class tide gauges.

[11] Note: this is just one way of defining whether a site is tidal or surge dominant. An alternative ratio could be based on the difference between the variance or standard deviation of the tide and surge components of sea level. In this present study the ratio, defined as being the 98% quantile of the astronomical tide (relative to a mean level of 0), divided by the 98% quantile of the surge component, has been chosen as this is the ratio used by Dixon and Tawn (1999) who first demonstrated that the AMM underestimates the long period return levels at sites where the astronomical tidal variations are large relative to the surge variations (i.e. tidally-dominated sites).

99.9% complete. Hence, this data set can be artificially degraded by removing periods at random, to examine how sensitive the different methods are to incomplete records. These two tests have been repeated using 60, 50, 40, 30, 20 and 10 year subsets of the 67 year period.

4.3.5 Comparison with SRJPM

Extreme sea levels have been calculated for the eight mainland UK south coast sites (i.e. excluding St. Mary's; Figure 3.3) using the SRJPM relative return levels provided by Dixon and Tawn (1997). Return levels have been estimated by adding the SRJPM relative reutnr levels to 1 year return levels, calculated using the RLM. The performance of the five methods (AMM, RLM, JPM, RJPM, SRJPM) has been assessed using prediction errors. This is the difference between the estimated return periods of the observed maximum sea level at each site and the corresponding data span (Dixon and Tawn, 1999).

The extreme sea levels estimated using the SRJPM provided relative return levels, are found to be significantly larger that those derived from the other four methods between Devonport and Newhaven (Chapter 7). Extreme sea levels have also been estimated for the eight south coast sites using just the years that were originally available to Dixon and Tawn (1997) at the time of their analysis (Table 2.2).

Table 4.1: A list of the sensitivity tests that have been undertaken to assess the effects of data frequency (DF) on return level estimates.

Test	Description of Test
DF1	A first set of return levels has been calculated by applying each of the four EVA methods to the data collected at 15-minute intervals.
DF2	A second set of estimates has been made by applying the four methods to the data after it is subsampled to hourly values.
DF3	A third set of estimates was made using just the two direct methods. Here a quadratic interpolation routine has been applied to the data to determine the precise heights of the annual maximum and r-largest sea levels.

Table 4.2: A list of the sensitivity tests that have been undertaken to assess the effects of data length (DL) on return level estimates.

Test	Description of Test
DL1	Initially, extreme sea levels are calculated using just the first 5 years of the data set. Then, the next year in the sequence is added and the extreme levels are calculated again. A further year is added, and so on until the entire time series is used.
DL2	Extreme sea levels are calculated using all overlapping 10, 20, …., 90-year periods in the direct methods in addition to all overlapping 2 and 6 years in the indirect methods.
DL3	Extreme levels are calculated using 10, 20, 30, …, 90 random years of data from the Newlyn record. The test is repeated 1,000 times, using a random generator, to ensure a different set of years is analysed each time.

Table 4.3: A list of the sensitivity tests that have been undertaken to assess the effects of data completeness (DC) on return level estimates.

Test	Description of Test
DC1	Initially, extreme sea levels are estimated using only years that are 100% complete (i.e. no missing data). Then years that are at least 90% complete are used and so on until all years are considered.
DC2	A year is chosen at random and a random month is removed. The extreme levels are then computed. A further month from that year is chosen and removed and another return level estimate made, until only one month remains. Then another year is chosen and 1 month removed at a time until only 1 month remains in that year. The process is repeated until all 67 years have only one month of data. The test is repeated 1,000 times to ensure different years and months are removed each time.
DC3	A year is chosen at random and a random month removed. Then another year is randomly selected and a month removed, until all years have one month removed. The process is repeated until each year has two months missing and so on until all years have 11 months missing. The test is repeated 1,000 times to ensure different years and months are removed each time.

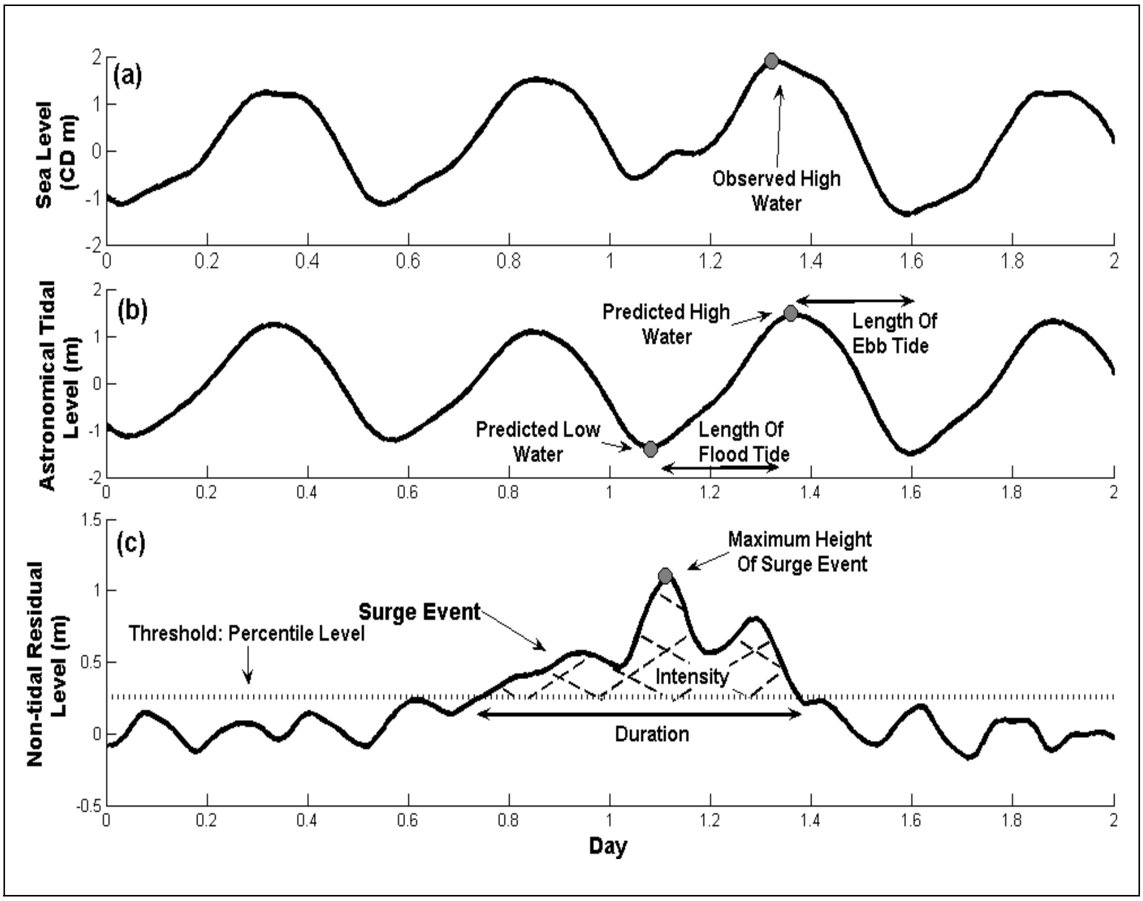

Figure 4.1: (a) Observed sea level, (b) astronomical tidal level and (c) non-tidal residual at Portsmouth during December 2000. The different sea level parameters analysed in this study are indicated.

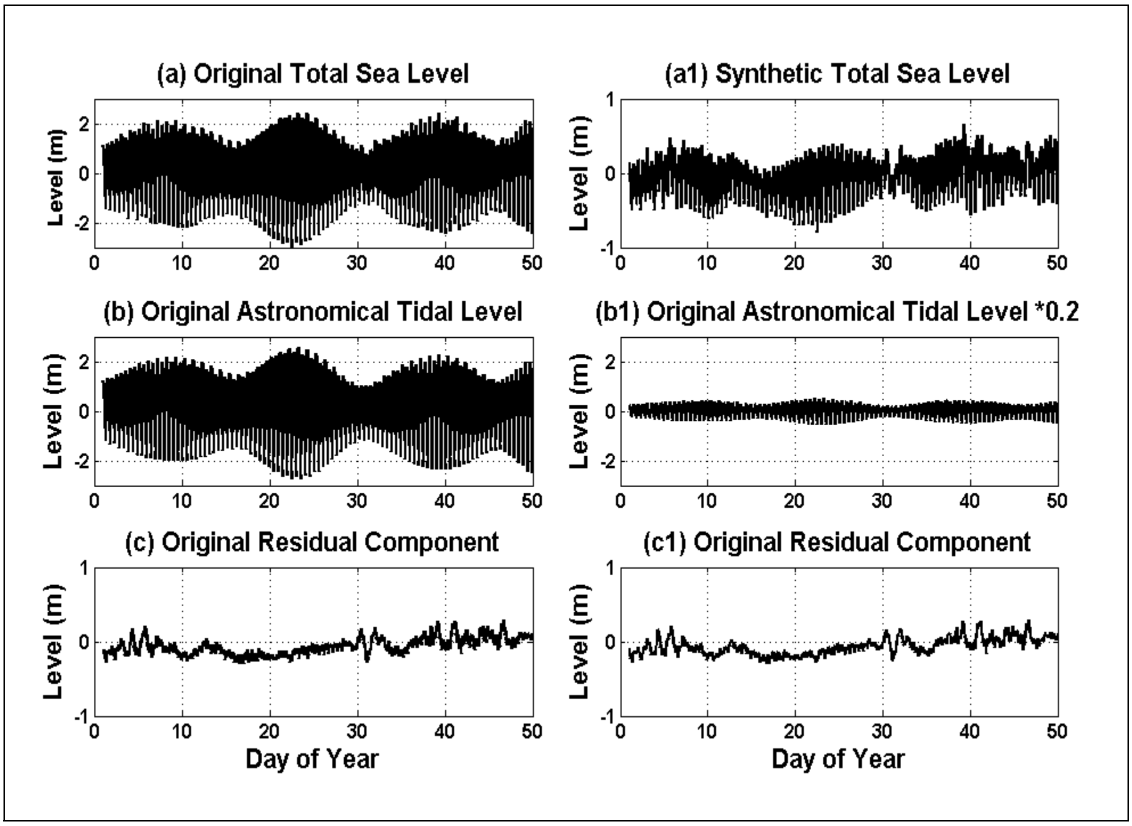

Figure 4.2: (a) Total sea level at Newlyn for the first 50 days of 2006; (b) the predicted tide for this period; (c) the surge component for this period; (a1) the synthetic time series created by combined the modified predicted tide and original surge time series; (b1) predicted tide reduced by a factor of five; (c1) the surge component for this period. This process changes the sea level record from being tidally dominant to surge dominant.

5 OBSERVED CHANGES IN MEAN SEA LEVEL

This chapter describes the results from the first stage of the research. The objective is to determine the rates of change in MSL in the English Channel between 1900 and 2006, including the uncertainties. Trends have been fitted to the time series of annual MSL to determine up to date and accurate estimates of relative MSL change (Section 5.1). Rates of vertical land movement have been estimated and compared with measurements from geological data and advanced geodetic techniques (Section 5.2). An assessment has been undertaken to determine whether there is evidence for any acceleration of sea-level rise during the 20th century (Section 5.3). The main findings are then summarised (Section 5.4).

5.1 Trends in Mean Sea Level

Table 5.1 (column 5) presents the rates of MSL change that have been estimated around the English Channel by fitting linear trends to the original records. Trends for the rest of the UK and Northern Ireland are given in Table 5.2 (column 5). Only sites with records spanning at least 20 years are listed because the SE's from sites with shorter records are large (>1 mm/yr). Time series of annual MSL for these sites are shown in Figure 5.1 and Figure 5.2. Trends for the UK south coast are between about 1.2 and 2.5 mm/yr, with a weighted average of 1.85 mm/yr (weighted by the SE). Trends along the French Channel coast vary between 1.4 and 2.9 mm/yr, with a weighted average of 2.0 mm/yr. There is a reduction in the trends moving from south to north along the east and west UK coasts, consistent with current understanding of the broad uplift of Scotland and subsidence of southern England (Shennon and Horton, 2002).

The trends at all sites in the English Channel are not statistically different at the 95% confidence level[12] from the long and good quality Newlyn record, except at Le Conquet. The trend at Le Conquet is significantly higher than that of Brest, which is initially surprising considering the close proximity of the two sites. However, the trend at Brest, for the same period as the Le Conquet record (1971 to 2006) is 2.95 ± 0.33 mm/yr, which is not significantly different (95% confidence level) to that of Le Conquet.

There is also a significant difference (95% confidence level) between the trends at Sheerness and Southend, which are located on either side of the Thames Estuary. The Southend record contains a smaller and significantly different trend than the Sheerness record over a similar period. A definitive comparison is impeded by the large gaps in the Sheerness record during which most of the Southend data was measured (Woodworth et al., 1999).

A second set of MSL trends has been calculated using the new Woodworth et al. (2009) method, in which the coherent part of the sea level variability is removed from the records prior to fitting linear trends. In order to apply this approach, it is necessary to first demonstrate that the coherent part of the sea level variability around the UK is consistent with that seen along the northern French coast and can be accurately represented by an index derived from a few long records. An extension of Woodworth's et al. (1999) EOF analysis has been undertaken to extract the coherent part of the sea level variability. Results show (Figure 5.3) that the first EOF accounts for 64% of the variance of the five time series that each represents a different region (these regions are: (i) the south coast of the UK, (ii) northern French coast, (iii) UK west coast and Irish Sea, (iv) the UK north North Sea coast (North Shields to Lerwick) and (v) the UK south North Sea coast (Sheerness to Cromer)). The first EOF is weighted almost equally in all five regions and is the only EOF that is statistically significant (95% confidence level). The temporal structure of the first EOF reproduces most of the variability present in each of the five regional time series (Figure

[12] i.e. they are within ±2 SE's of each other

5.4). An index has also been created by averaging the six longest records (Brest, Newlyn, Sheerness, North Shields, Aberdeen and Liverpool). The inclusion of the Brest data results in only very small differences to the five-station index used by Woodworth et al. (2009). The index is significantly (95% confidence level) correlated with all of the MSL records (coefficients are listed in Table 5.1 and Table 5.2, column 6), except at Sheerness. Interestingly, the index is significantly correlated with both the early part of the Sheerness record (i.e. just the data between 1900 to 1927; coefficient: 0.49) and the later part (i.e. just the data between 1951 to 2006; coefficient: 0.74), but not the complete record. This might suggest that there are possible datum issues associated with this MSL time series. A comparison of the index and the temporal structure of the first EOF is shown in Figure 5.5. The two time series show good agreement and are highly correlated (coefficient; 0.93). This demonstrates that the index can be used to accurately represent the coherent part of the sea level variability around the British Isles and northern France.

Table 5.1 and Table 5.2 (column 7) present the linear MSL trends calculated after the coherent part of sea level variability has been removed from the records. Trends along the English Channel are between 0.8 and 2.3 mm/yr. With this new data, there is no difference (at the 95% confidence level) between the trends at all English Channel sites. However, at the 68% confidence level (i.e. ±1 SE), trends are lower in the central Channel (Southampton, Portsmouth and Cherbourg), in comparison with the trends at the western and eastern ends. As data lengths increase, the significance of these trends will become clearer.

After the coherent part of sea level variability has been removed from the records, there is a reduction in SE (Table 5.1 and Table 5.2) at all but three sites; these are Southend, Ullapool and Malin Head. At Malin Head there is a general reduction in MSL after 1990 (Figure 5.2). When a trend is fitted only to the data prior to 1990, the SE reduces to 0.37, after the coherent part of sea level variability has been removed from the record (the SE of the trend fitted to the uncorrected time series is 0.53). The correlation between the index and the MSL record for Malin Head increases from a coefficient of 0.33 for the complete record, to 0.74 for the period prior to 1990. This suggests that the data after 1990 is suspect. There is no obvious reason why no reduction in SE is seen after the coherent part of the sea level variability is removed from the Southend and Ullapool records. This lack of reduction suggests that these records could contain suspect data.

It is interesting to note that the significant differences between the Le Conquet and Brest record are no longer apparent, after the removal of the coherent part of the sea level variability. This highlights the biasing effect that sea level variability can have when calculating trends from data of different lengths and spanning different periods. However, even after the coherent part of the sea level variability has been removed from the records, there is still a significant difference (95% confidence level) between the trends at Sheerness and Southend. This may reflect a difference in vertical land movements on either side of the Thames Estuary (W99), or it indicates that the records at one (or both) of these two sites might be suspect. This difference should be investigated further.

The improvement in accuracy obtained by removing the coherent part of the sea level variability from the records, has been evaluated by comparing the SE's calculated using both the traditional and the Woodworth et al. (2009) approach. Figure 5.6a shows the SE's (one standard error; i.e. 68% confidence level) of the trends fitted to the original data for all 55 sites. Results confirm previous studies (Douglas, 1991; Tsimplis and Spencer, 1997; Woodworth et al., 1999), which demonstrate that 30 and 50 years of records are required to obtain SE to about 0.5 and 0.3 mm/yr, respectively. Figure 5.6b shows the difference in SE after the coherent part of the sea level variability is removed. The reduction in SE can be as large as 1 mm/yr for records spanning less than 20 years. However, even with this level of improvement in accuracy, the SE's calculated from data spanning less than 20 years in length is still larger than 1 mm/yr, in most cases. Hence, this restricts a meaningful analysis of MSL change to records spanning more than 20 years, even after the coherent part of the sea level variability is removed. The reduction in SE for sites spanning at least 50 years is small (< 0.1 mm/yr). Therefore, the main improvement obtained from this new method is for sites spanning 20 to 50 years. As has been discussed previously, not all of the sites show a significant reduction in SE after the coherent part of the sea level variability has been removed. This might suggest that these sites contain suspect data and requires further investigation.

Figure 5.7 shows the trends for all overlapping 10, 20, ... up to 90-year periods for the detrended Newlyn record, before and after the coherent part of the sea level variability has been removed. Douglas (1991) demonstrated that records with 50 years of data were necessary to accurately assess 20th century MSL rates. If trends are fitted to the original records using all 50-year periods, the trends are within ±0.5 mm/yr of the trend calculated using the entire record (91 years). However, with the coherent part of the sea level variability removed, only about 30 years of data are required to estimate trends to this same level of accuracy. Hence, removing the coherent part of the sea level variability essentially reduces the amount of data needed to accurately estimate longer-term trends. While records spanning at least 30 years should ideally be used, findings indicate that the trends with records spanning 20 years are still within a reasonable level of accuracy (±1 mm/yr of the trend calculated using the whole Newlyn record). With less than 20 years of data, the range in trends increases dramatically.

It is interesting that the original trends fitted to all overlapping 70, 80 and 90 year periods are generally less than the trends calculated from the same periods after the coherent part of the sea level variability has been removed (Figure 5.7). The reason for this is because of the general fall in MSL in the 1970's (see Figure 5.5). This consistently downwards biases the trends fitted to longer times series. This again highlights the usefulness of using the index to remove the coherent part of the variability in order to more accurately calculate the underlying long-term trends in MSL.

To summarize, accurate estimates of MSL change have been computed by removing the coherent part of the sea level variability from the records, prior to fitting the trends. The relative MSL trends at each site in the English Channel are between 0.8 and 2.3 mm/yr and are not significantly different at the 95% confidence level. Removal of the coherent part of the sea level variability leads to an improvement in the accuracy of the trends, but still restricts a meaningful analysis of MSL change to sites spanning at least 20 years.

5.2 Land Movements

Land movements also contribute to changes in sea level. Figure 5.8 shows a comparison of the rates of vertical land movement from geological data (Shennan and Horton, 2002) with those estimated from the MSL records (Tables 5.1 and 5.2, column 7) spanning at least 20 years, with an assumption that the sea level change due to the ocean itself was 1.4 mm/yr for the 20th century. The majority of sites show good agreement, confirming the overall pattern of subsidence in southern England and uplift in Scotland. Only the estimates at Newlyn and North Shields differ significantly at the 95% confidence level. Woodworth et al. (1999) suggested that localised subsidence could be taking place at the North Shields gauge, which would explain the difference here. The difference at Newlyn has been previously noted by Woodworth et al. (2009) and is surprising, considering that the Newlyn record is of very high quality. The differences at Newlyn imply that the geological data suggests too much subsidence. Overall, the median estimates from the records along the western and central parts of the south coast also imply that the geological data overestimates the rates of subsidence since 1900 in this region. Along the eastern part of south coast there is good agreement.

Moving eastwards around the coast from Newlyn, Sheerness is the first site at which the vertical rate of land movement is significant different, at the 95% confidence level, from Newlyn. At the 68% confidence level, the subsidence rates for the central part of the UK south coast are lower than the eastern and western regions. Although the magnitudes of the rates are different, this pattern is evident in the Shennan and Horton (2002) estimates. Based on the sea level data analysed here, the highest rate of subsidence around the UK is at Sheerness (i.e. the Thames Estuary) and is not in the southwest of England as suggested by Shennan and Horton (2002).

New measurements of vertical land movement from combinations of CGPS and AG are currently available at eight UK sites (Bingley et al., 2007). The rates estimated from the

MSL records are consistent, at the 95% confidence level, with the new measurements at all locations except Lerwick (Figure 5.9). The rates from the geodetic data are closer to the rates estimated from the MSL records at Newlyn and North Shields, than those from the geological data. This supports the view of localized land subsidence at North Sheilds and further confirms the notion that the geological rates suggest too much submergence at Newlyn and elsewhere in the western and central English Channel.

In summary, the rates of vertical land movement estimated from the sea level record are in general agreement with those measured using advanced geodetic techniques and geological data, around most of the UK. However, the rates estimated from the sea level records imply that the geological data suggests too much subsidence along the western and central parts of the south coast.

5.3 Accelerations in Sea-Level Rise

To test whether the recent high rates of MSL rise around the UK were unusual, compared to trends observed at other periods in the historical record since 1900, trends have been calculated (relative to those for the entire record) for all overlapping 10, 25 and 50-year periods, for the four longest and most complete records. The overlapping decadal trends at these sites show very good agreement (Figure 5.10). The recent high rates of sea-level rise are in line with those that have occurred in the decades centred around 1925, 1945 and 1980. They are smaller than those that occurred around 1910, at Brest and North Shields, so are within natural variability. The good level of agreement among sites further confirms that a large part of the sea level variability around the English Channel and UK is coherent between sites. This justifies the creation of regionally averaged time series. A comparison of the time series averaged from the four long records and that averaged using the data from all 55-study sites is shown in Figure 5.11. The number of records used to calculate each time series is shown in Figure 5.12. The general pattern of variability is captured particularly well using the time series created from only the four longest records. The agreement is better in the first quarter of the 20th century because only a few additional sites are available for this period. On average, the largest negative decadal trends occurred in the decades centred around 1916 and 1970. The largest positive decadal trends occurred around 1910. Decadal trends from 1995 onwards, show that MSL has recently risen by about 5 mm/yr higher than average, but that this is not unusual compared to trends measured during other decades. Recent 20-year trends are higher than average, but again are comparable with trends that have occurred at earlier times. The average 50-year trends for the first half of the 20th century are higher than those of the later part. However, these are not statistically different at the 95% confidence level. The deceleration observed in north European sea level rise during the second half of the 20th century has been known about for some time (Woodworth, 1990).

In summary, the results show that the recent high rates of change in MSL are not unusual compared to those that occurred at other times in the 20th century. Therefore, there is no evidence as yet for any acceleration in sea-level rise over the 20th century in the English Channel.

5.4 Summary

The main findings of this stage of the research are:

- Up to date and accurate estimates of rates of MSL change have been calculated for sites around the English Channel. Relative MSL trends vary between 0.8 and 2.3 mm/yr, depending on location.
- At the 95% confidence level, there is no difference between the trends at all English Channel sites. However, at the 66% confidence level, trends are lower in the central English Channel (Southampton, Portsmouth and Cherbourg), compared with the trends at the western and eastern ends.
- The MSL trends have been estimated using a new approach in which the coherent part of the sea level variability around the English Channel and UK is defined as a single index, which is then subtracted from the sea level records prior to fitting

trends. Removal of the coherent part of the sea level variability allows more precise trends to be calculated from records spanning 30 years. With the traditional approach 50 years is required to obtain the same level of accuracy.

- A meaningful assessment of MSL changes is restricted to sites spanning 20 years or more.
- The MSL trends have been subtracted from regional estimates of sea-level rise from oceanographic process only, in order to approximate rates of vertical land movement. These rates are in generally agreement with those measured using advanced geodetic techniques and geological data around most of the UK. However, the rates estimated from the sea level records imply that the geological data overestimates subsidence along the western and central parts of the UK south coast during the 20th century.
- The highest rate of subsidence around the UK is at Sheerness (Thames Estuary) and not in the southwest of England.
- There is no evidence of any acceleration of sea-level rise in the English Channel during the 20th century.

Table 5.1: Mean sea-level trends for the UK south coast and northern French coast for years with at least 11 months of measurements, with at least 15 days of records for each month. Uncertainty in the trends corresponds to standard errors.

Site No.	Site Name	Number of years (range, years)	Range	Trend (mm/yr)	Correlation coefficient between MSL values and sea level index	Trend (mm/yr) of MSL values minus sea level index
1	St. Mary’s	13 (39)	1968-2006	1.51±0.56	0.34	1.72±0.52
2	Newlyn	91 (91)	1916-2006	1.74±0.10	0.38	1.74±0.06
3	Devonport	38 (43)	1962-2004	2.45±0.68	0.42	2.07±0.63
4	Weymouth	19 (38)	1968-2005	1.58±0.47	0.55	1.81±0.28
6	Southampton	60 (71)	1935-2005	1.19±0.24	0.49	1.30±0.18
7	Portsmouth	39 (46)	1962-2007	1.73 ±0.32	0.63	1.21±0.27
8	Newhaven	30 (65)	1942-2006	2.33±0.28	0.22	2.27±0.27
9	Dover	40 (46)	1961-2007	2.27±0.24	0.54	1.93±0.21
10	Brest	98 (107)	1900-2006	1.41±0.11	0.23	1.57±0.08
11	Le Conquet	32 (36)	1971-2006	2.90±0.44	0.70	1.83±0.37
12	Roscoff	22 (27)	1975-2001	1.74±0.71	0.67	1.25±0.53
13	Cherbourg	27 (28)	1979-2006	1.62±0.57	0.70	0.84±0.44
14	Le Havre	31 (48)	1959-2006	2.53±0.39	0.60	2.17±0.29
15	Dunkerque	28 (65)	1942-2006	1.88±0.30	0.40	1.77±0.27

Table 5.2: Mean sea-level trends for the east and west coast of the UK, Northern Ireland and the Republic of Ireland for years with at least 11 months of measurements, with at least 15 days of records for each month. Uncertainty in trends corresponds to standard errors.

Site No.	Site Name	Number of years (range, years)	Range	Trend (mm/yr)	Correlation coefficient between MSL values and sea level index	Trend (mm/yr) of MSL values minus sea level index
17	Sheerness	60 (107)	1900-2006	2.25±0.12	0.1	2.43±0.09
18	Tilbury	22 (23)	1961-1983	1.58±0.91	0.46	2.29±0.78
19	Southend	47 (51)	1933-1983	1.21±0.23	0.26	1.42±0.24
22	Lowestoft	48 (52)	1956-2007	2.57±0.32	0.56	2.24±0.25
24	North Shields	97 (107)	1900-2007	1.96±0.11	0.26	2.04±0.07
25	Dunbar	37 (37)	1914-1950	0.47±0.31	0.76	0.26±0.22
27	Aberdeen	99 (108)	1900-2007	0.90±0.10	0.43	0.99±0.07
30	Wick	38 (43)	1965-2007	1.38±0.40	0.59	0.94±0.34
31	Lerwick	42 (49)	1957-2005	-0.55±0.32	0.54	-0.22±0.30
40	Holyhead	55 (70)	1938-2007	2.25±0.27	0.37	2.08±0.25
42	Liverpool	71 (108)	1900-2007	1.36±0.20	0.33	1.53±0.16
43	Heysham	29 (36)	1962-1997	0.99±0.59	0.61	1.39±0.42
45	Douglas	32 (40)	1938-1977	0.29±0.67	0.44	0.07±0.61
46	Portpatrick	37 (40)	1968-2007	2.16±0.41	0.69	1.47±0.31
47	Millport	23 (39)	1969-2007	1.07±0.46	0.69	0.06±0.39
50	Ullapool	20 (25)	1983-2007	1.71±0.99	0.44	0.42±0.99
51	Storneway	26 (31)	1977-2007	1.83±0.69	0.74	0.70±0.52
55	Dublin	62 (64)	1938-2001	0.20±0.27	0.52	0.38±0.22
53	Belfast	46 (46)	1918-1963	-0.26±0.34	0.62	-0.48±0.25
54	Malin Head	40 (43)	1959-2001	-1.36±0.53	0.33	-1.06±0.53

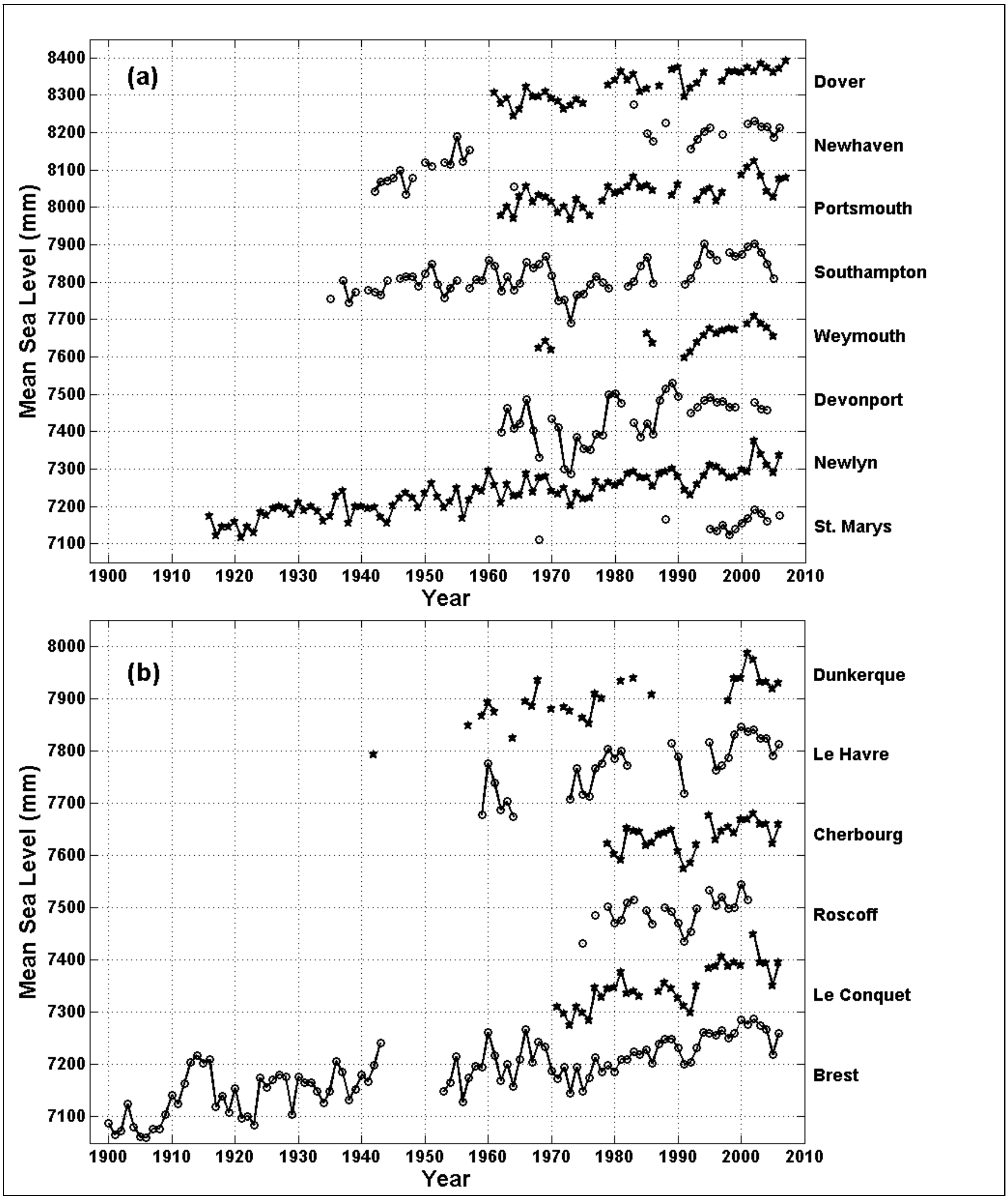

Figure 5.1: Time series of annual mean sea level. The average sea level for each time series has no significance; they have been plotted one above the other with arbitrary offsets for presentation purposes. Subplots: (a) south coast of UK; (b) northern French coast.

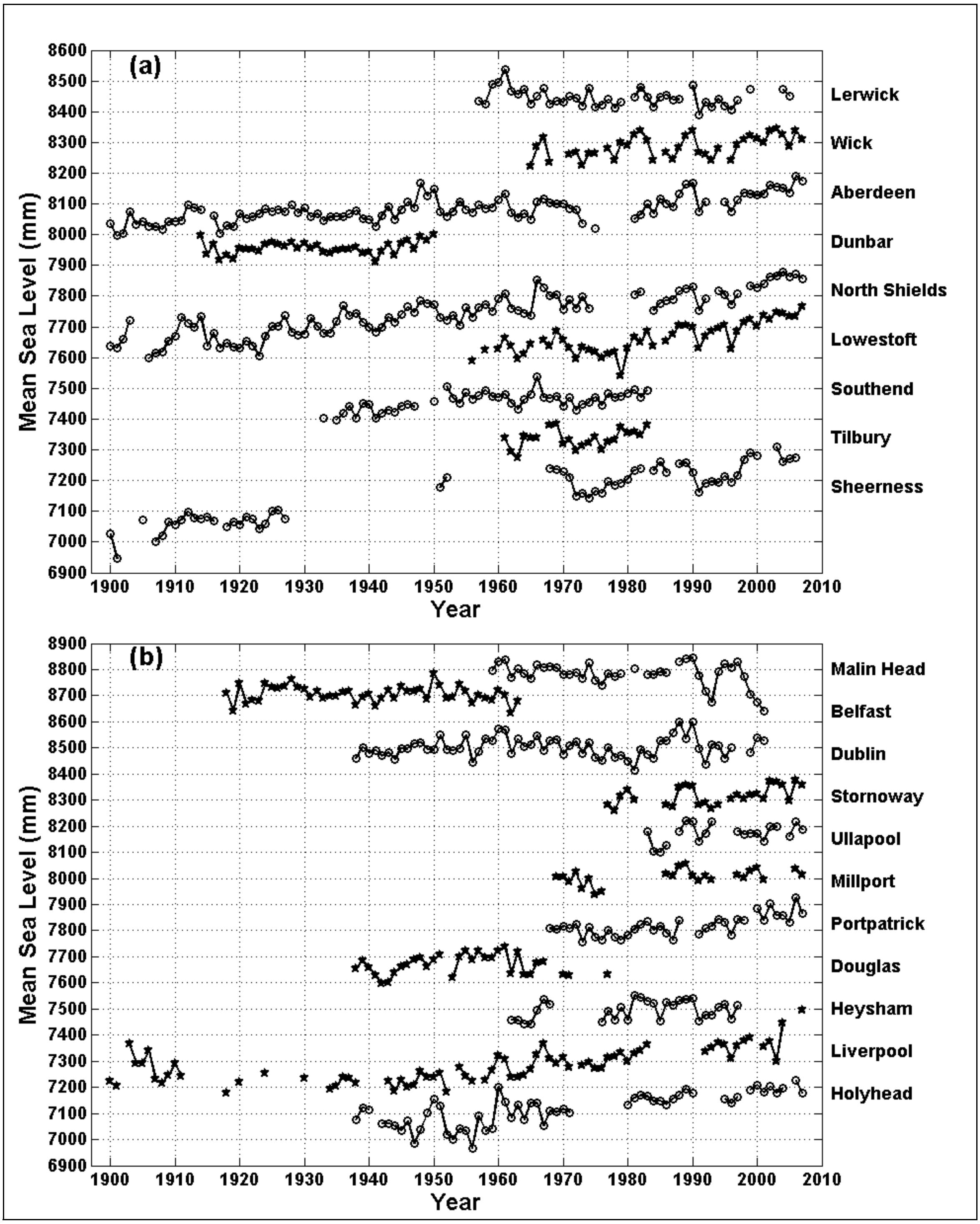

Figure 5.2: Time series of annual mean sea level. The average sea level for each time series has no significance; they have been plotted one above the other with arbitrary offsets for presentation purposes. Subplots: (a) east coast of UK; (b) west coast of UK, Northern Ireland and the Republic of Ireland.

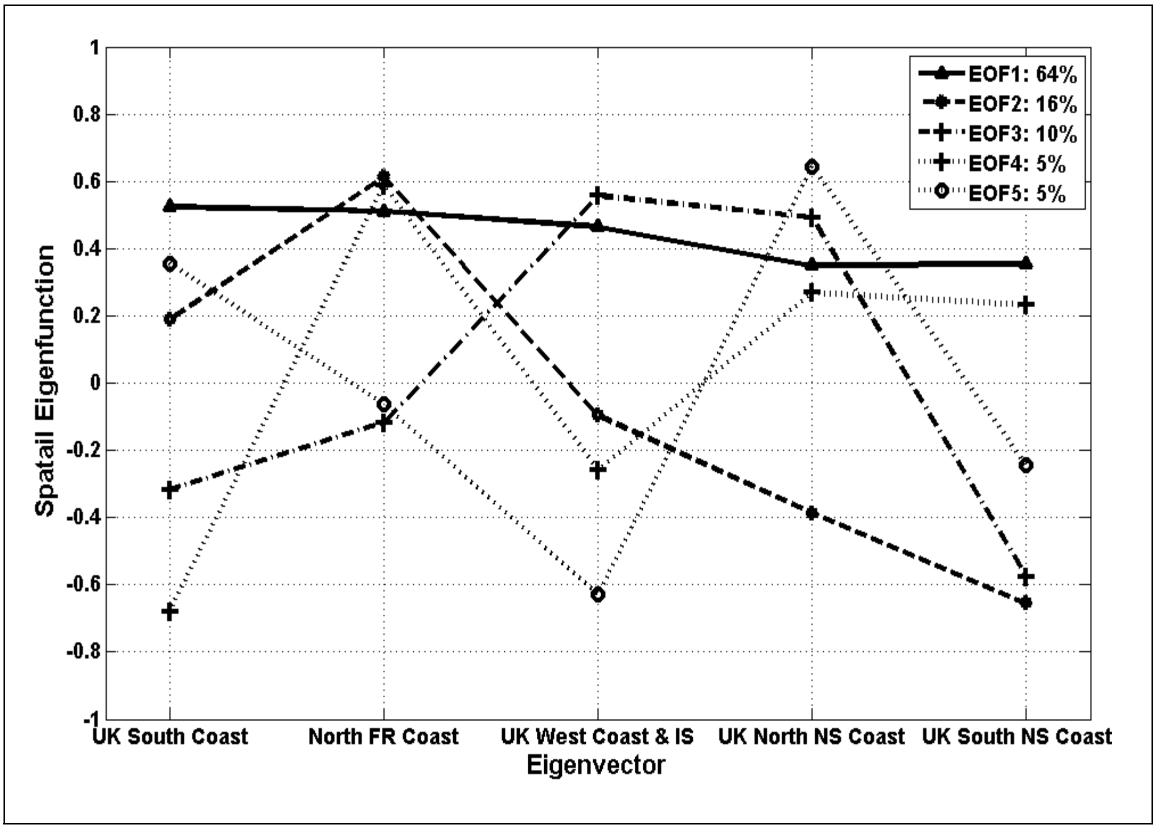

Figure 5.3: Spatial eigenfunctions for the sea level time series representing the south coast of the UK, northern French coast, UK west coast and Irish Sea, the UK north North Sea coast (North Shields to Lerwick) and the UK south North Sea coast (Sheerness to Cromer).

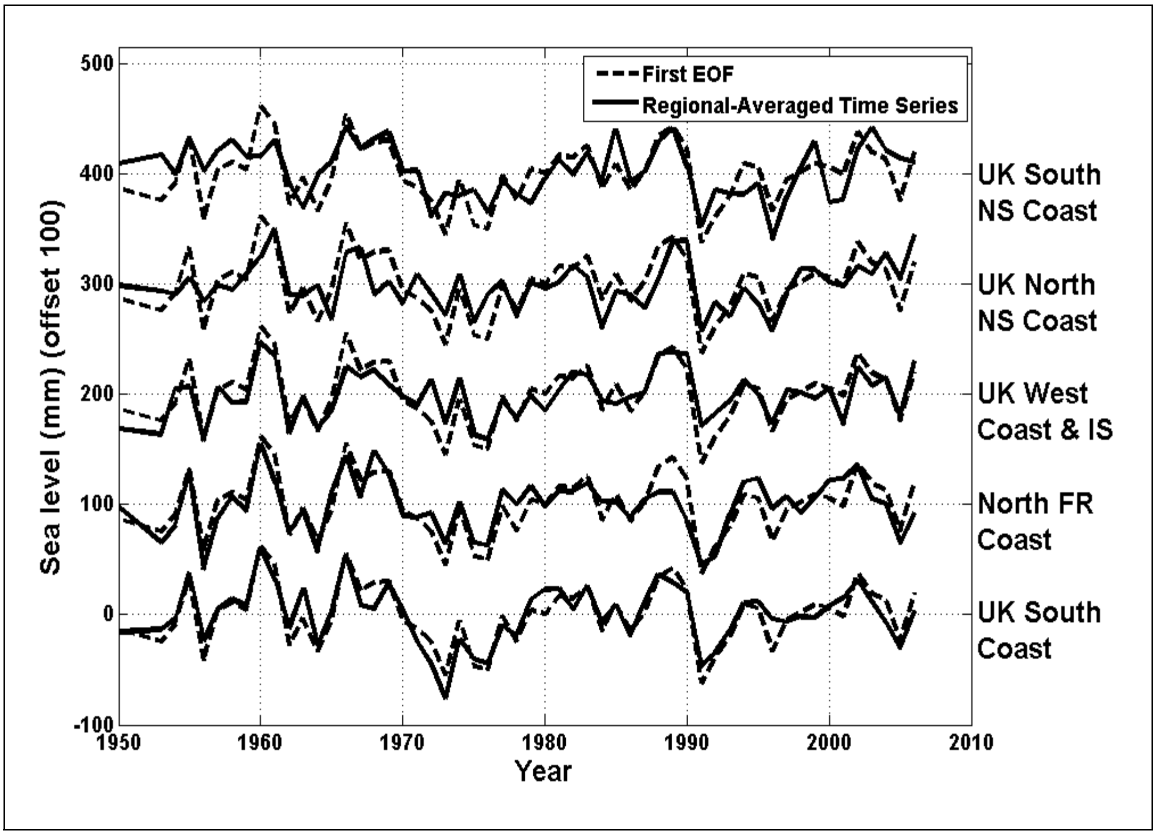

Figure 5.4: Comparison of the time series of the first EOF (dashed line) with those representative of specific stretches of coastlines (solid line). Time series have been offset by 100 mm for plotting purposes.

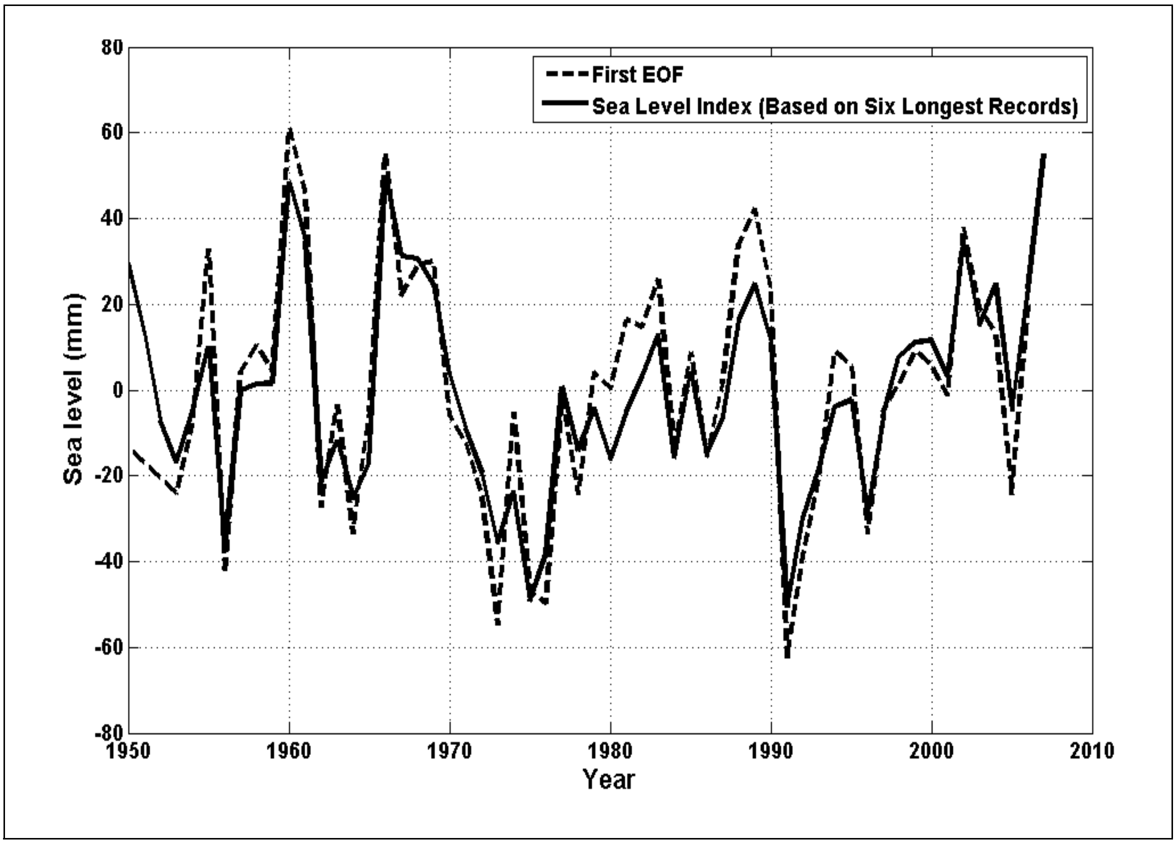

Figure 5.5: Comparison of the time series of the first EOF (dashed line) with the sea level index based on the six long records each detrended over the common period 1916-2006 (solid line).

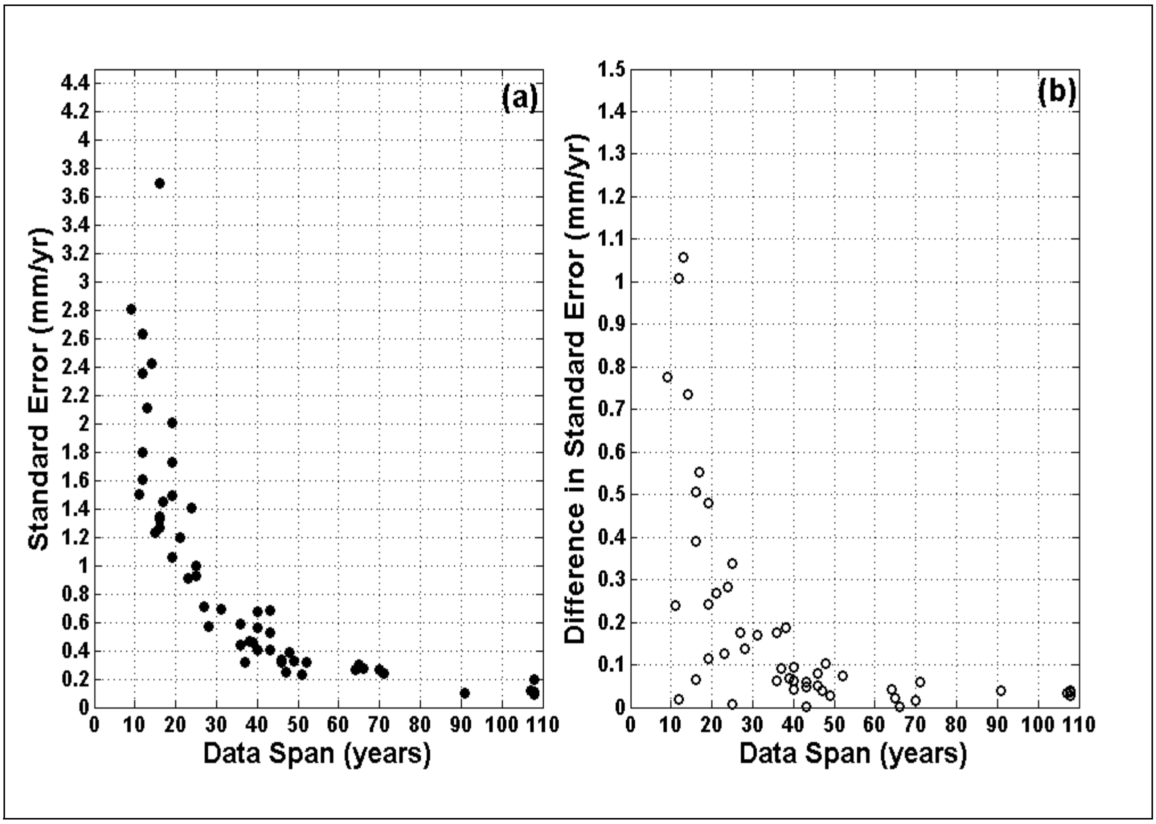

Figure 5.6: Standard errors (one standard error; i.e. 68% confidence level) associated with the mean sea-level trends for all study sites. Subplots: (a) original sea level records, (b) difference between original sea level records and those with the coherent part of the sea level variability removed from records.

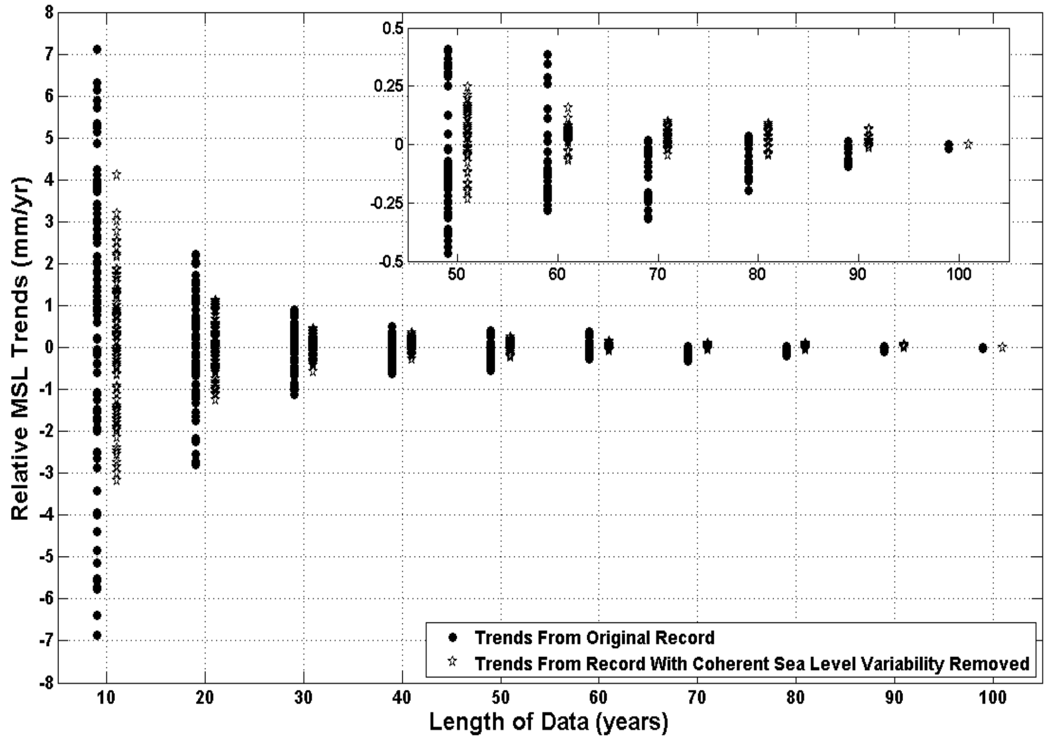

Figure 5.7: All overlapping 10, 20, 30, up to 100 year mean sea-level trends calculated from the detrended Newlyn record. Solid circles show the trends calculated from the original record. Stars show the trends calculated from the records with the coherent part of the sea level variability removed. The plot zooms on the period between 50 and 100 years.

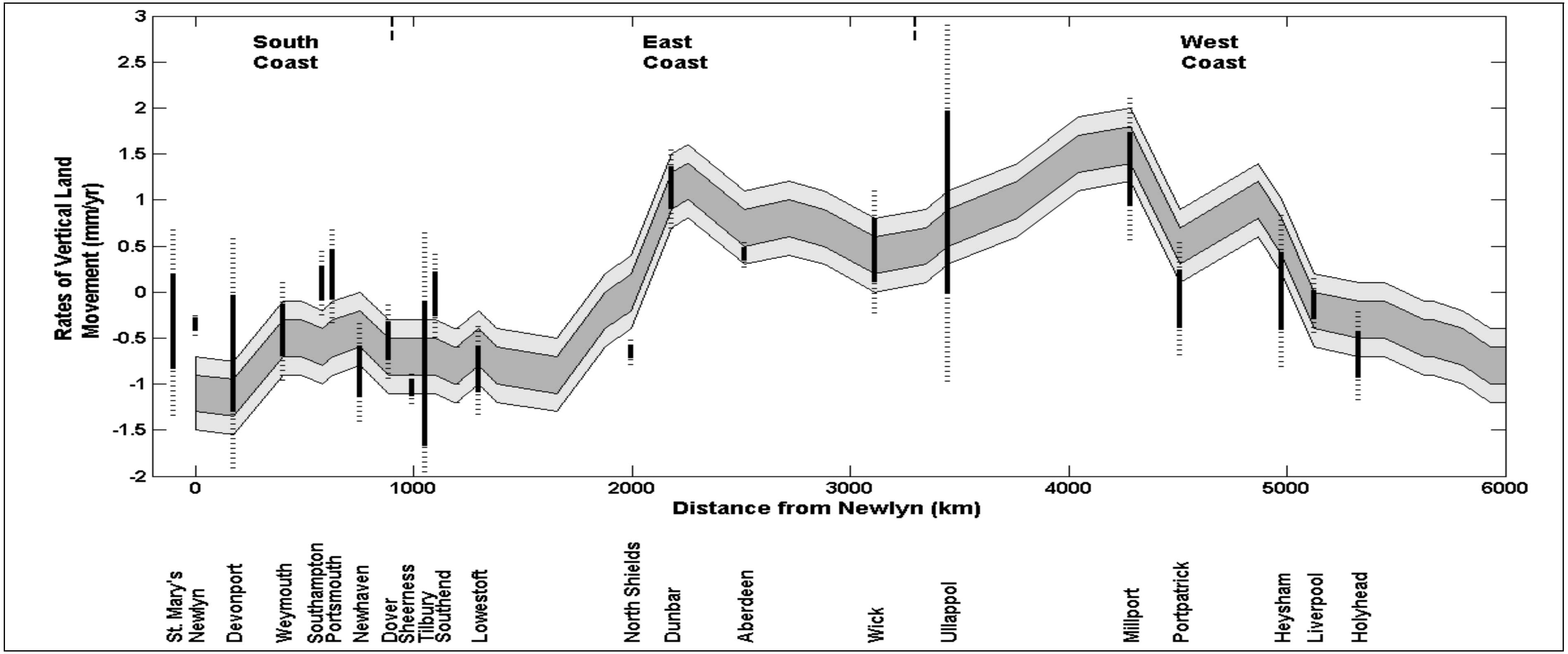

Figure 5.8: A comparison of rates of vertical land movement (+ uplift, - subsidence), plotted against distance around the UK, anticlockwise from Newlyn. The darker and lighter shaded regions indicate the land emergence/submergence rates from Shennan and Horton (2002) ±1 (68% confidence level) and ±2 (95% confidence level) standard errors, respectively. The solid and dashed lines are the rates estimated from the sea level records, subtracted from 1.4 mm/yr and ±1 and ±2 standard errors, respectively.

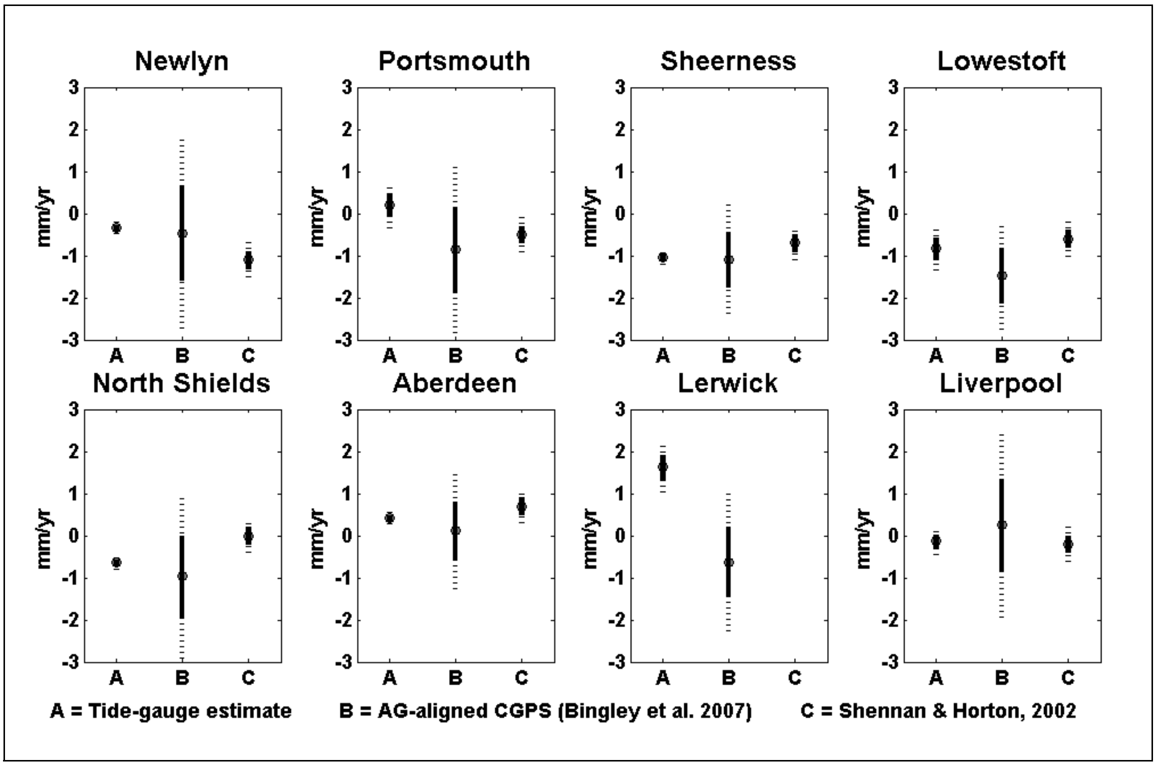

Figure 5.9: Rates of vertical land movement (+ uplift, - subsidence) from (A) sea level estimates, (B) combinations of continuous Global Positioning System and absolute gravity (Bingley et al., 2007) and (C) geological information (Shennan and Horton, 2002). The solid and dashed lines are the rates ±1 and ±2 standard errors, respectively. Note: Geological data is not available for Lerwick.

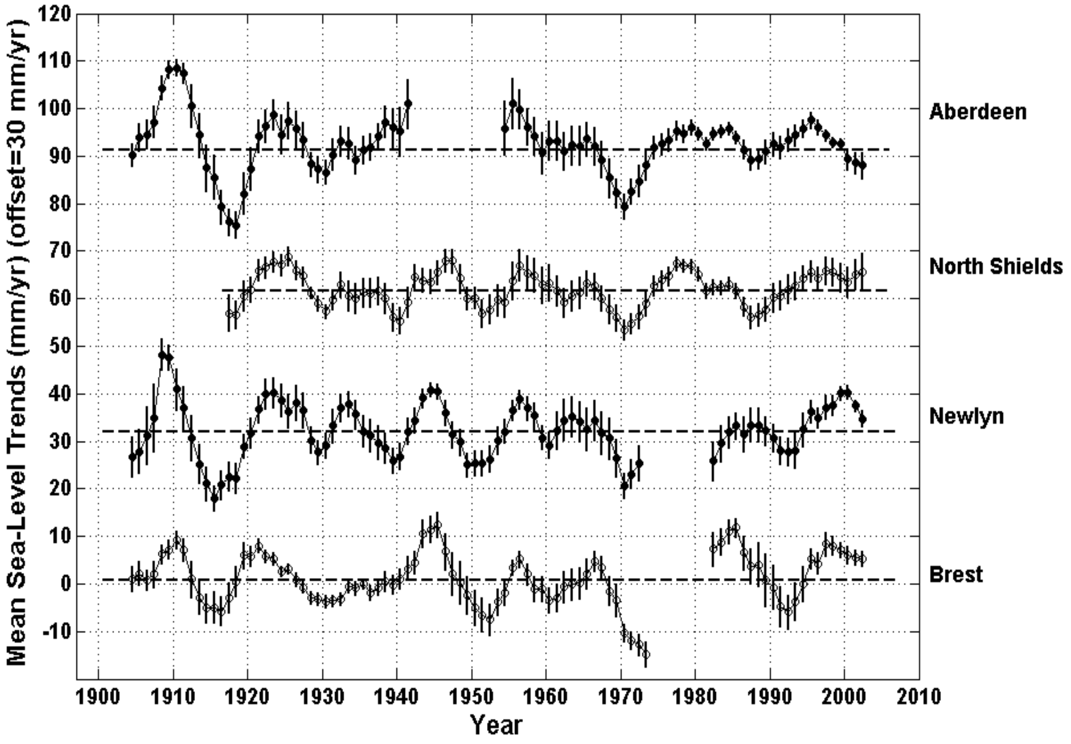

Figure 5.10: Overlapping decadal mean sea-level trends for Brest, Newlyn, North Shields and Aberdeen. Trends for the four sites have been plotted one above the other with arbitrary offsets for presentation purposes. The error bars show ± 1 standard error. The dotted lines represents the trends in Table 5.1 and Table 5.2, calculated using the entire record available for each site.

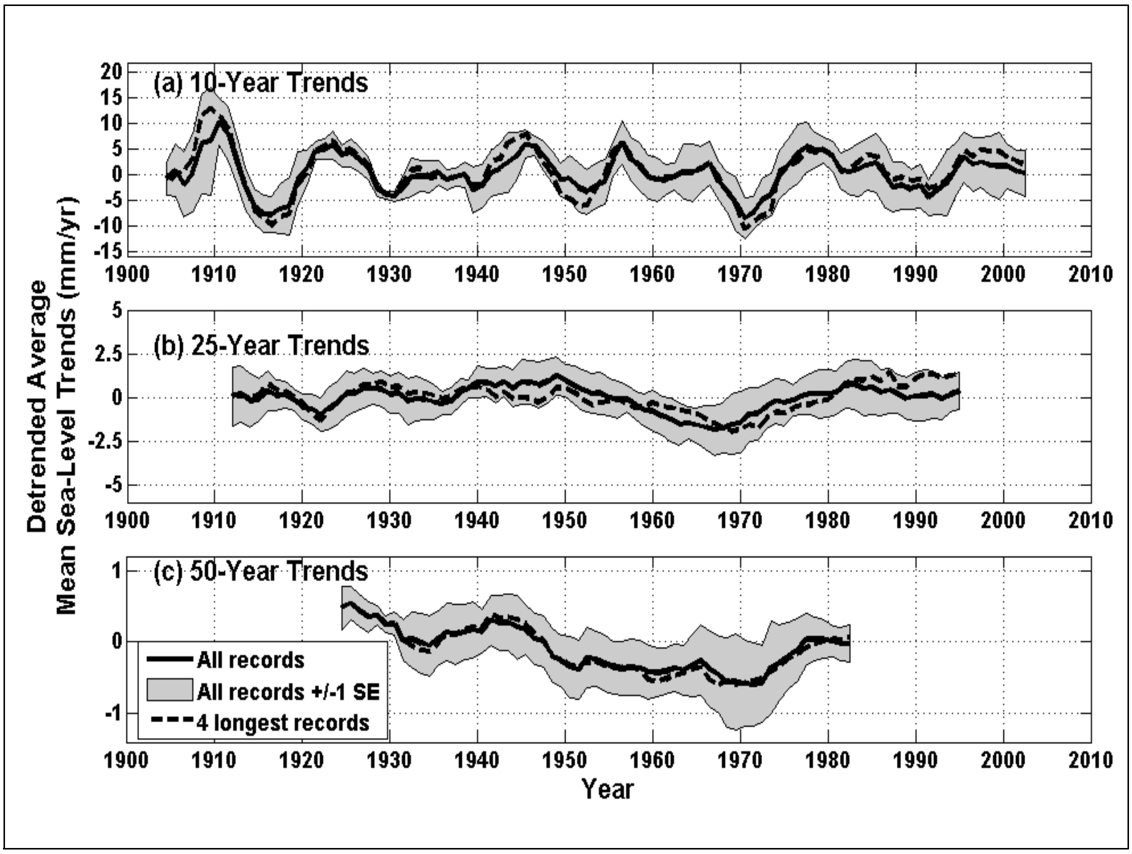

Figure 5.11: Time series of the 10, 25 and 50-year detrended mean sea-level trends, averaged for the four longest and most complete sea level records (dotted line) and for all study sites (solid line). The shaded region indicates ±1 standard deviation for the time series averaged over all study sites.

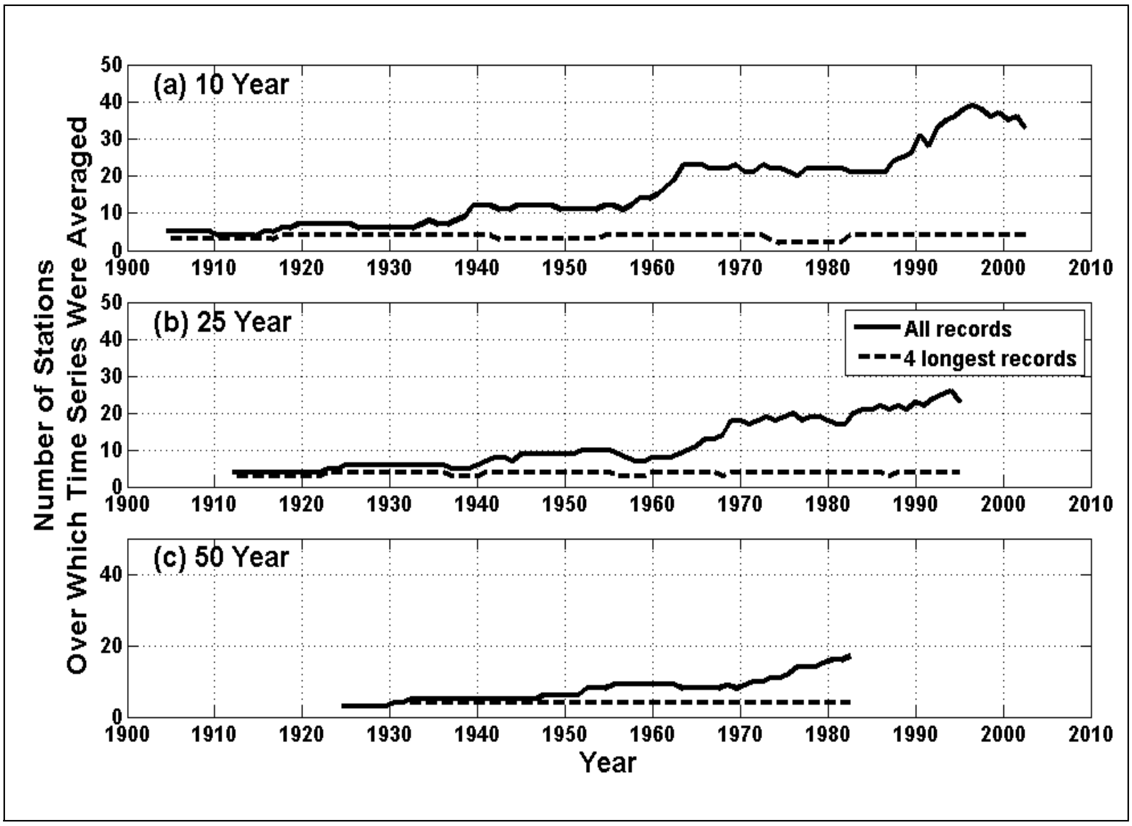

Figure 5.12: Number of sites over which the 10, 25 and 50-year detrended mean sea-level trend time series were averaged for the four longest and most complete records (dotted line) and all the records (solid line).

6 OBSERVED CHANGES IN EXTREME SEA LEVELS

This chapter describes the results of the second stage of the research. Here the objective has been to establish whether changes in extreme sea level between 1900 and 2006 were primarily caused by variations in MSL. Observed changes in the astronomical tide (Section 6.1), non-tidal residual (Section 6.2) and the interactions between them (Section 6.3) have been assessed separately before examining trends in extreme sea levels (Section 6.4). The main findings are then summarised (Section 6.5).

6.1 Astronomical Tide

No consistent English Channel wide increases or decreases were found in the time series of annual amplitude and phase of the 63 harmonic constituents. There is considerable variability from year to year in the time series of which a part can be explained by the 18.6-year nodal cycle. Shallow-water effects leave a residual 18.6-year cycle in the time series despite the fact that the theoretical (equilibrium) nodal cycle is removed in the analysis procedure (Araújo and Pugh, 2008). This variability distorts the fitted trends, particularly over shorter records. The trends in amplitude and phase at Newlyn are consistent with those of Araújo and Pugh (2008) who identified that the stepped changes in phase at this site could be attributed to changes in instrumentation. At other sites, known instrument changes are not evident in the time series, which probably indicates the very high quality of the Newlyn record.

Rather than concentrating on a detailed assessment of the changes in tidal constituents the focus was shifted to examining for changes in annual MHW (relative to

MSL), as changes in this affect extreme sea levels directly. Trends were fitted to annual MHW, MLW and MTR using linear regression with allowance for the 18.6-year nodal cycle. There is a clear seasonal cycle in MHW. Monthly MHW are highest in March and September. During these equinox periods the sun's declination is zero (i.e. over the equator) resulting in larger astronomical tides (Pugh, 1987). At most sites, there is a small increase in MHW and a decrease in MLW resulting in an overall increase in MTR. There are statistically significant trends at Newlyn, Portsmouth, Newhaven, Dunkerque, Calais, Boulogne and Brest at the 95% confidence level. At these sites the increase in MHW is between 0.1 and 0.3 mm/yr and the increase in MTR is between 0.2 and 0.6 mm/yr. To illustrate these findings, annual MHW, MLW and MTR are shown for Portsmouth and Brest (Figure 6.1).

At most sites, there is a statistically significant increase in the length of ebb tide and a decrease in the flood, at the 95% confidence level. Trends are small, in the order of 1 to 5 minutes/century. To illustrate these findings, the annual mean length of ebb and flood tide and the ratio between length of flood and ebb are shown for Portsmouth and Brest (Figure 6.2).

Overall, the evidence suggests that there have only been small indirect changes to the astronomical tide as a result of the increase in MSL throughout the 20th century. In relation to extreme sea levels, the increases in MHW, relative to MSL, of between 0.1 and 0.3 mm/yr is important, but small when compared to the secular MSL trends experienced in the region.

6.2 Surge Component

The three indices (count, duration and intensity) chosen to detect changes in historic storm activity show a clear and coherent seasonal pattern. Storm intensity (greater than the 99 percentile) is highest between November and February and between May and August there is little storm activity (Figure 6.3). Time series of annual total intensity of surges greater than the 99 percentile are shown in Figure 6.4. Like the east coast of the USA (Zhang et al., 2000) there are significant inter-decadal variations in surge activity. These are difficult to quantify because of the different data lengths available and gaps in the record. In some cases common interdecadal trends are apparent between neighbouring sites. Storm intensity is highest at the eastern end of the Channel, reflecting that this area experiences the largest surges.

Trends in the three indices have been fitted using linear regression (Table 6.1). The trends are small and at the majority of sites not statistically significant at the 95% confidence level. There are small significant decreases in storm count at Newlyn, Devonport, Newhaven, Calais and Le Conquet. There are also small and significant decreases in total storm duration at Devonport, Southampton, Newhaven and Calais and a small significant decrease in storm intensity at Newhaven and Calais. There are significant increases in annual duration and intensity at Weymouth. However, the large data gaps present in the record could bias the results. Findings are similar for the 95 and 99.9 percentiles. At each site the annual total duration and intensity have been divided by the storm count to give a measure of mean duration and intensity per storm event. No statistically significant long-term changes were evident in these two time series. These findings contradict the view widely held (i.e. considerable amount of anecdotal evidence, newspaper reports, etc.) that storminess has and continues to increase and suggest that in-fact the opposite has actually occurred. Table 6.1 shows that at a number of sites there has been a reduction in the count, duration and intensity of storms in the English Channel.

Figure 6.5a shows 10-year running means of intensity for storms with surges greater than the 99 percentile, at Brest and Newlyn. Clear decadal patterns are evident and are similar between the two sites. There appears to be a general increase in storm intensity from 1900 to 1955 and a decrease from 1955 to 2000. Intensity is highest in the mid and late 1950's. There are other peaks around the mid 1910's, 1940 and 1980's and troughs around the early 1920's, late 1940's, 1970 and mid 1990's. Figure 6.5b shows 10-year running means of the annual and winter NAO. An inverse relationship between storm intensity and winter NAO is apparent. It is well known that the winter NAO index contained a large positive secular trend in the second half of the 20th century (Woodworth et al., 2007). This coincides with the decrease in storm intensity seen at Newlyn and Brest. The winter NAO has a statistically significant (95% confidence level) but weak negative correlation with the storm intensity at Brest and Newlyn (coefficients: -0.38 and -0.40, respectively). At other sites in the Channel there is also a weak negative correlation between intensity and the Winter NAO. However, there is a stronger positive correlation at Dover, Sheerness, Calais and Dunkerque, consistent with those found by Araújo (2005). Therefore, the relationship appears to change along the Channel reflecting west coast and North Sea behaviours.

In Figure 6.6, the power spectrum is shown for the annual total intensity of storms with surges greater than the 99 percentile at Brest and Newlyn. There are peaks around 2.5, 3.5, 9 and 19 years in the Brest spectrum and peaks around 2, 2.5, 4, 7 and 19 years in the Newlyn spectrum. However, the confidence in the significance of these peaks is not large due to the small number of observations. Overall results suggest that while there are considerable inter-decadal and decadal variations of storminess in the Channel during the 20th century, there is no discernible long-term secular increase in storm activity or severity.

6.3 Non-Linear Interactions

Table 6.2 lists the χ^2 test statistic calculated to quantify the strength of tide-surge interaction in the Channel. There is statistically significant interaction at all sites with the exception of St. Mary's. Interaction is weakest at the western end of the Channel and increases in strength moving from west to east along both the UK and French coastlines. The interaction along the French Channel coast is generally larger than that of the UK south coast, consistent with results from modelling studies (Wells et al., 2001; Haigh, 2004; Haigh et al., 2004). The interaction is strongest at Dover and Calais. The interaction is higher at Southampton than Portsmouth, which is consistent with the findings of Walden et al. (1982). The weak interaction at Weymouth could be due to the relatively small tidal range associated with the degenerate amphidrome in this region.

Figure 6.7 and Figure 6.8 show the frequency of surge events greater than the 95 percentile with respect to the time of the nearest predicted high water, for selected sites. The magnitudes of surge events are indicated using a greyscale subdivision of the histogram bars. At Newlyn and Brest the peaks of surge events do not tend to favour any particularly part of the tidal cycle. Elsewhere in the Channel the results confirm the tendency of surge events to occur most frequently on the rising tide (Rossiter, 1961; Prandle and Wolf, 1978). Interaction distributions at Sheerness are consistent with those of Horsburgh and Wilson (2007) although the distributions shown here are not as detailed because hourly data and not 15 minute data has been used. At Sheerness and Dunkerque the mode is four hours before the nearest high water. Within the Channel, the mode tends to occur two to three hours before high water. Where interaction is strongest the largest surge events do not tend to occur an hour either side of high water.

The χ^2 test statistic has been calculated for all 10-year overlapping periods at each site and trends have been fitted using linear regression. The interaction distributions do vary slightly with time but there are no overall significant long-term trends. This is illustrated in Figure 6.9 which shows the frequency of surge events greater than the 95 percentile for different decades at Dover. There are small differences but the overall interaction distributions are consistent between the five decades.

In summary, results show that tide-surge interaction is important in the Channel and needs to be taken into account in extreme sea-level assessments. There is no evidence for any long-term changes in interaction distributions associated with the 20th century increase in MSL.

6.4 Observed Extreme Sea Level

Changes in extreme high and low sea levels have been investigated using percentile analysis. Figure 6.10a shows the time series of a range of different sea level percentiles along with the trends fitted using linear regression, for Newlyn. The upper 5 percentiles have statistically significant positive trends at the 95% confidence level, with magnitudes greater than the 50^{th} percentile but not significantly greater. The lower percentiles also have statistically significant positive trends at rates less than MSL, but not significantly less. Once the percentile time series are reduced relative to their median values the trends in each of the 10 percentiles are no longer statistically significant at the 95% confidence level (Figure 6.10b). A small residual positive trend remains in the upper percentiles and a negative trend in the lower percentiles suggesting an increase in tidal range. These are not significant at the 95% confidence level.

Results from the other 17 sites in the Channel show similar findings. At all sites there is a statistically significant (95% confidence level) increase in all of the percentile levels analysed. Once the percentiles are reduced relative to their median values the trends in the majority of cases are not statistically significant. Overall, results show that while extreme sea levels in the English Channel have increased significantly over the last 100 years, the increase is primarily a result of the direct rise in MSL. There is evidence for a small increase in extreme levels above that of MSL, but this is masked by the large variability present in extreme percentiles.

6.5 Summary

The main findings of this stage of the research are:

- No consistent English Channel wide increases or decreases were found in the time series of annual amplitude and phase of the 63 harmonic constituents that were analysed.
- There is evidence for a small (0.1 to 0.3 mm/yr) increase in MHW (relative to MSL) and an increase (0.2 to 0.6 mm/yr) in MTR at select sites. However, trends in MHW are considerably smaller than those in MSL and so did not significantly increase extreme sea levels over the last 100 years beyond that associated with the secular MSL rise.

- There is evidence for a small (<5 minutes/century) increase in the length of ebb tide and a decrease in the length of flood tide.
- There is considerable inter-decadal and decadal variability in storm activity in the Channel but no evidence for increased storminess over the 20th century.
- At the two sites with the longest records (Newlyn and Brest) there was a general increase in storm intensity from 1900 to 1955 and a decrease from 1955 to 2000 consistent with the inverse of the winter NAO index.
- Storm intensity is weakly and negative correlated to the winter NAO index throughout most of the English Channel but is strongly positively correlated at the interface with the southern North Sea.
- Tide-surge interaction is strongest at the eastern end of the English Channel.
- There are small decadal changes in the tide-surge interaction distributions but no long-term variations associated with the increase in 20th century MSL.
- There is evidence for an increase in extreme sea levels during the 20th century in the English Channel. This increase is primarily due to the direct rise in MSL.

Table 6.1: Linear regression rates and standard errors for annual count, total duration and total intensity of storms with surges greater than the 99 percentile level. Trends that are statistically significant at the 95% confidence level at indicated in bold.

Station Name	Annual Count (number/yr)	Total Annual Duration (hours/yr)	Total Annual Intensity (m*hours/yr)
St. Mary's	0.035 ± 0.117	1.224 ± 1.224	0.090 ± 0.153
Newlyn	**-0.046 ± 0.015**	-0.152 ± 0.150	-0.008 ± 0.020
Devonport	**-0.230 ± 0.056**	**-0.936 ± 0.456**	-0.093 ± 0.060
Weymouth	0.079 ± 0.049	**0.659 ± 0.264**	**0.075 ± 0.031**
Southampton	-0.059 ± 0.031	**-0.195 ± 0.094**	-0.031 ± 0.018
Portsmouth	0.074 ± 0.053	0.162 ± 0.269	0.044 ± 0.035
Newhaven	**-0.198 ± 0.048**	**-0.733 ± 0.178**	**-0.131 ± 0.027**
Dover	0.010 ± 0.026	0.078 ± 0.167	-0.001 ± 0.044
Sheerness	0.020 ± 0.053	0.069 ± 0.310	0.056 ± 0.118
Dunkerque	0.065 ± 0.044	0.373 ± 0.251	0.052 ± 0.064
Calais	**-0.201 ± 0.052**	**-0.614 ± 0.163**	**-0.108 ± 0.044**
Boulogne	0.107 ± 0.119	0.272 ± 0.438	0.034 ± 0.105
Le Havre	-0.004 ± 0.044	-0.040 ± 0.211	-0.006 ± 0.049
Cherbourg	0.061 ± 0.080	0.481 ± 0.428	0.035 ± 0.056
Jersey	0.400 ± 0.361	1.815 ± 1.497	0.140 ± 0.197
Roscoff	-0.202 ± 0.121	-0.177 ± 0.693	-0.061 ± 0.087
Le Conquet	**-0.207 ± 0.079**	-0.834 ± 0.582	-0.098 ± 0.071
Brest	0.010 ± 0.015	0.043 ± 0.113	0.005 ± 0.015

Table 6.2: Tide-surge interaction χ^2 test statistic for surge events greater than the 95 percentile. χ^2 values greater than 21 are statistically significant at the 95% confidence level and are indicated in bold.

UK South Coast Sites			French Channel Sites		
Station Name	**95 surge percentile (m)**	**χ^2 test statistic**	**Station Name**	**95 surge percentile (m)**	**χ^2 test statistic**
St. Mary's	0.21	13.5	Brest	0.23	**26.9**
Newlyn	0.22	**23.2**	Le Conquet	0.22	**23.9**
Devonport	0.23	**50.1**	Roscoff	0.22	**45.0**
Weymouth	0.22	**30.1**	Jersey	0.26	**58.5**
Southampton	0.30	**55.7**	Cherbourg	0.23	**119.5**
Portsmouth	0.23	**44.1**	Le Havre	0.28	**145.9**
Newhaven	0.25	**92.0**	Boulogne	0.35	**175.4**
Dover	0.30	**203.3**	Calais	0.34	**213.3**
Sheerness	0.35	**143.8**	Dunkerque	0.35	**177.8**

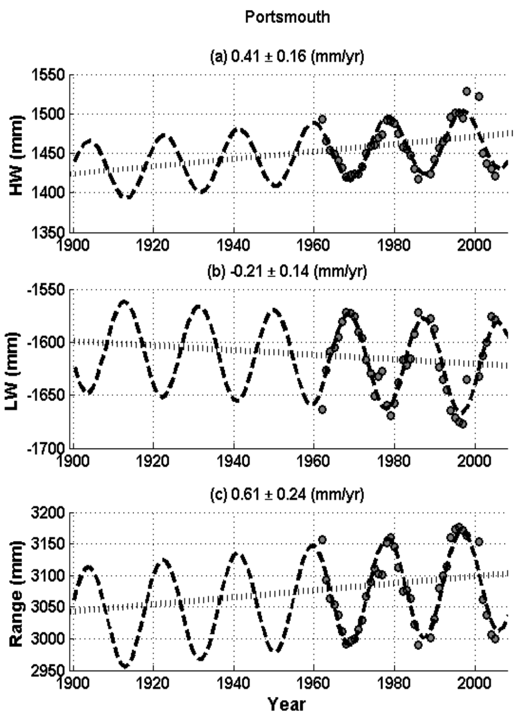

Figure 6.1: (a, d) Annual mean predicted high water, (b, e) low water and (c, f) range with trend fitted with allowance for 18.6-year nodal cycle (dashed line) for Portsmouth (a, b, c) and Brest (d, e, f). The dotted lines show the linear trends.

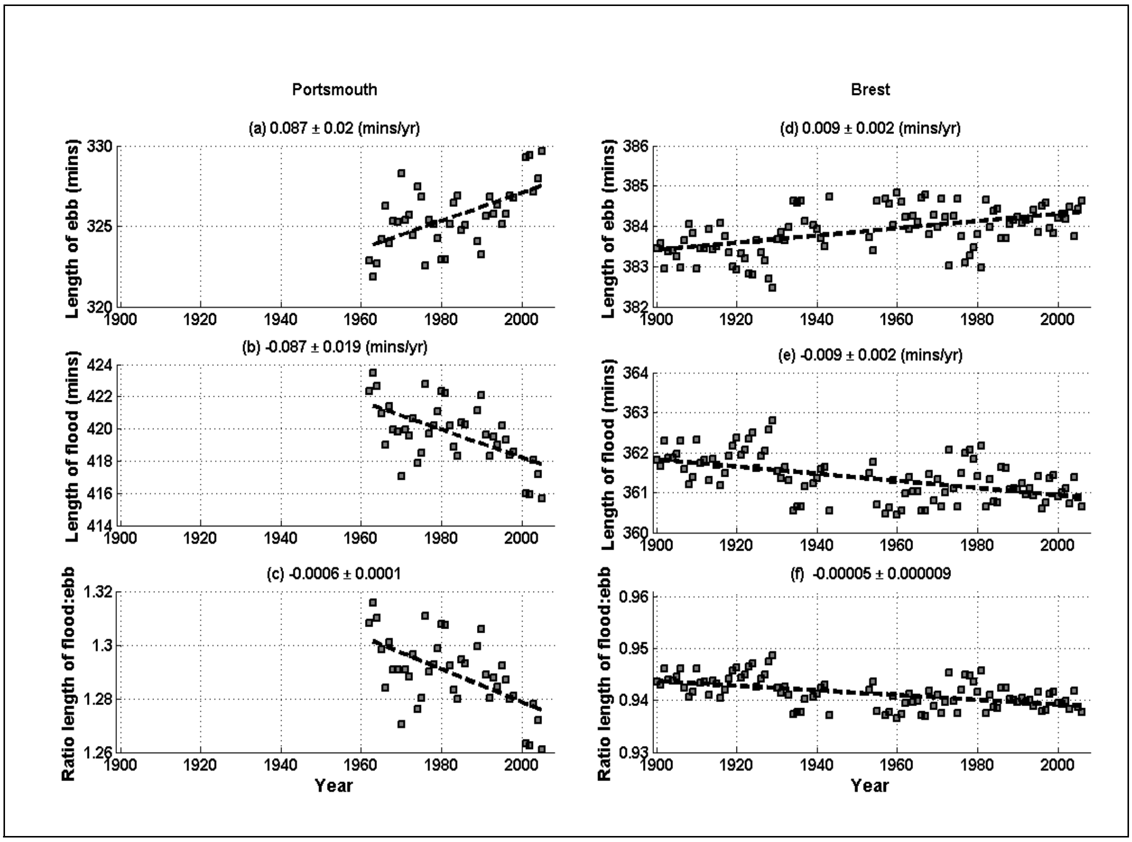

Figure 6.2: (a, d) Annual mean length of ebb tide and (b, e) flood tide and (c, f) ratio of the length of flood to length of ebb tide with linear trend (dashed line) for Portsmouth (a, b, c) and Brest (d, e, f).

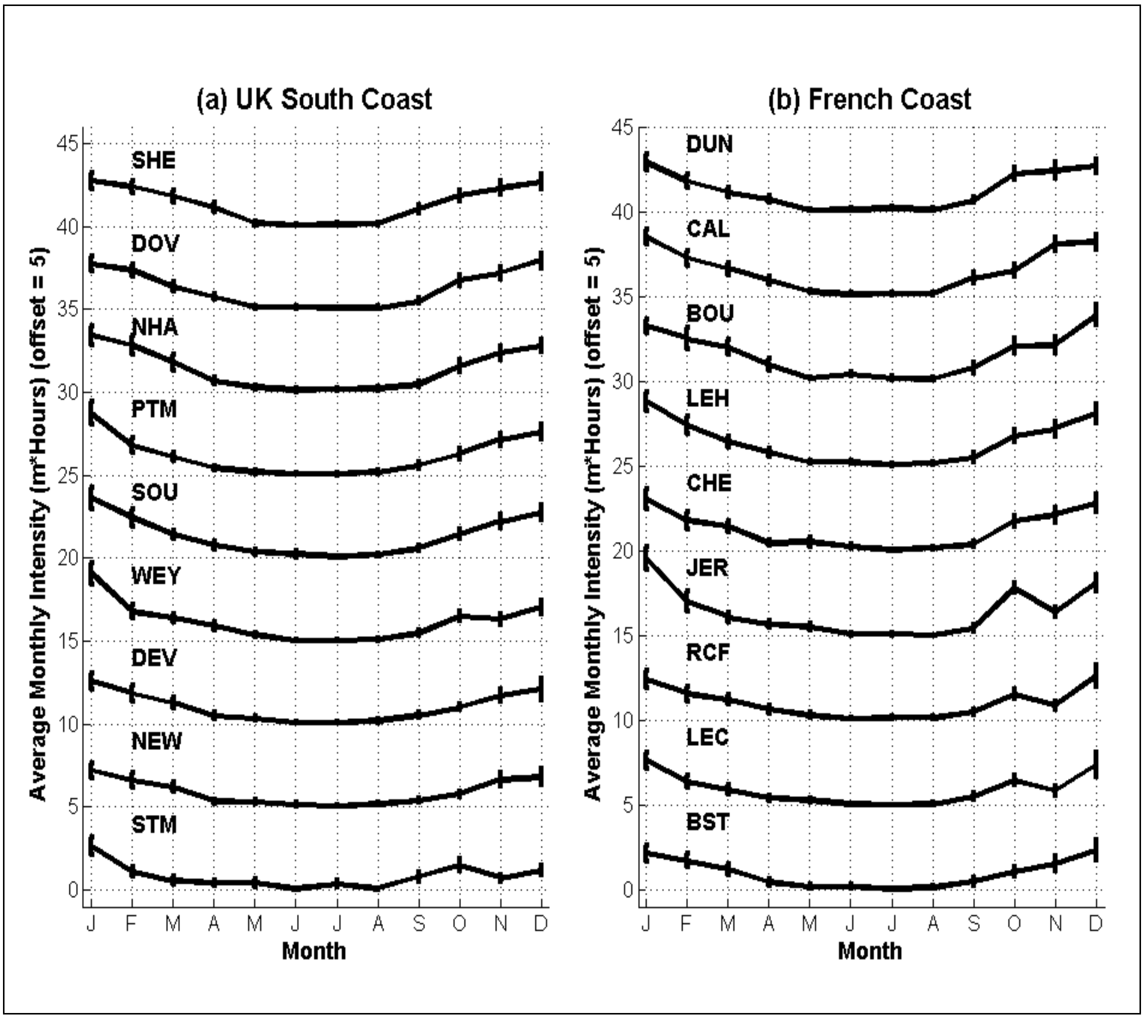

Figure 6.3: Average monthly intensity of storms with surges greater than the 99 percentile level (of the complete record at each site) on (a) UK south coast and (b) northern French coast. Time series are offset by 5.

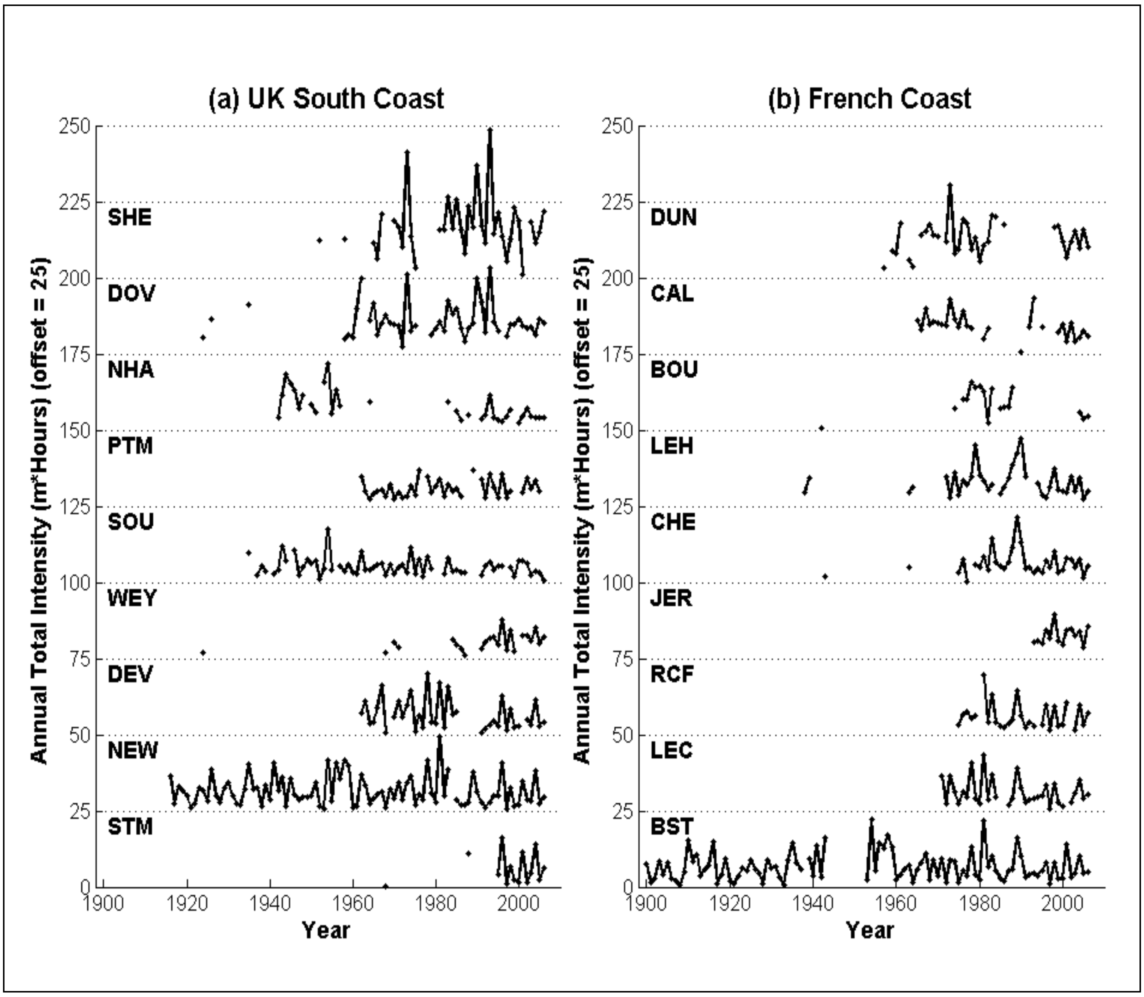

Figure 6.4: Annual intensity of storms with surges greater than the 99 percentile level on (a) UK south coast and (b) northern French coast. Time series are offset by 25.

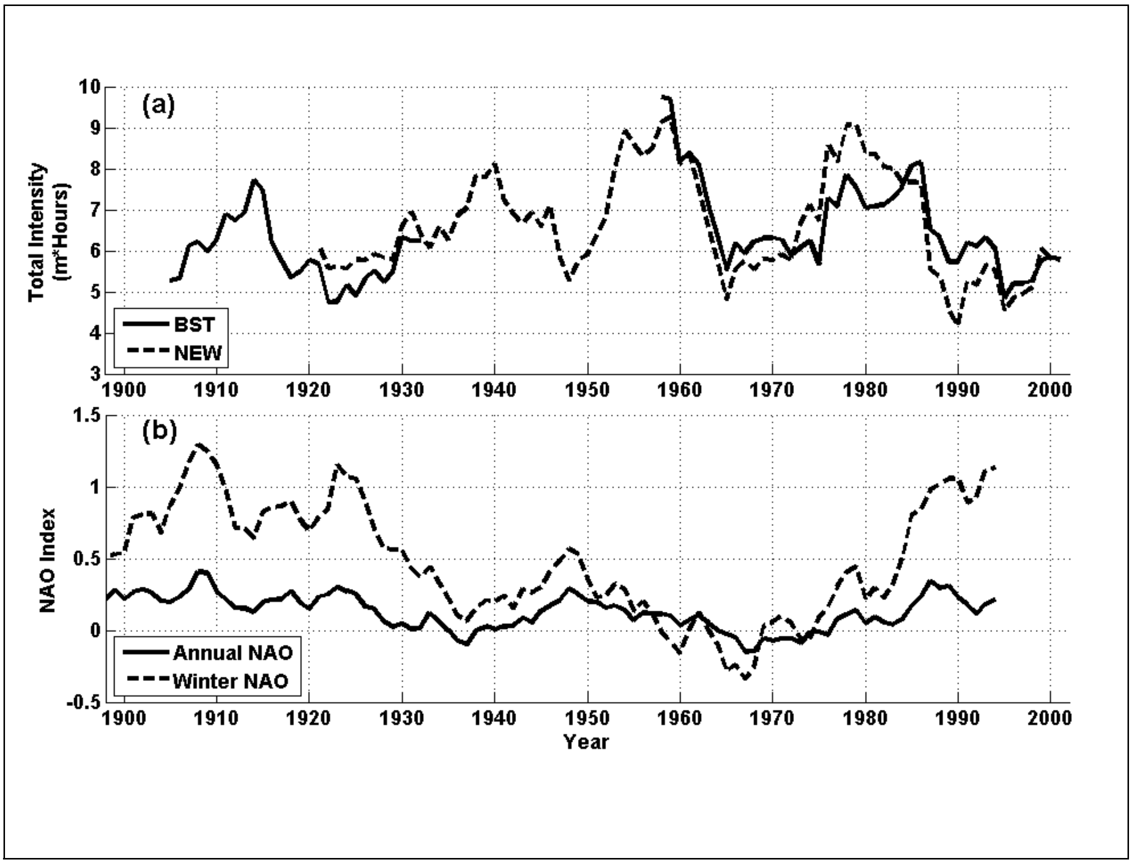

Figure 6.5: (a) 10-year running mean intensity of storms with surges greater than the 99 percentile level at Brest (solid) and Newlyn (dashed); (b) 10-year running mean annual (solid) and winter (dashed) North Atlantic Oscillation index.

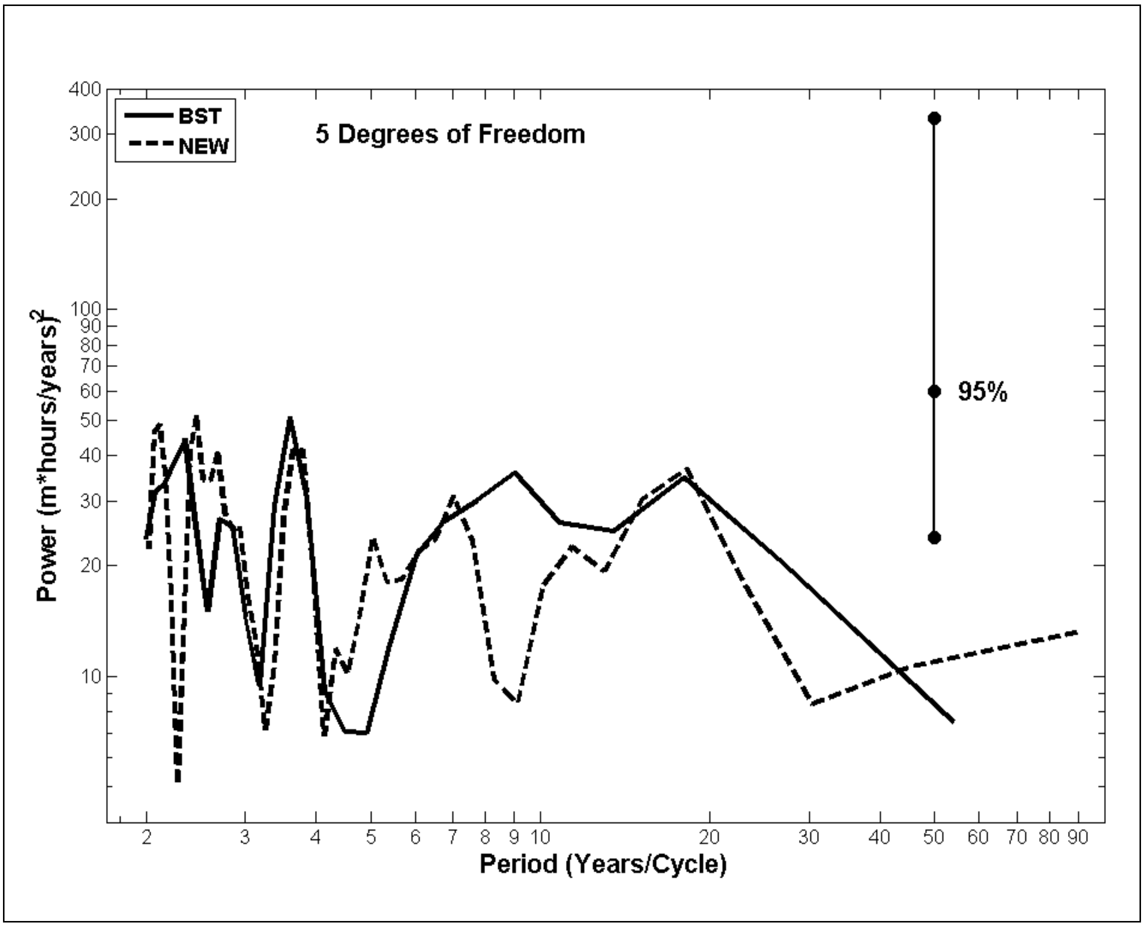

Figure 6.6: Power spectral analysis of the total annual intensity of storms with surges greater than the 99 percentile level at Brest (solid) and Newlyn (dashed).

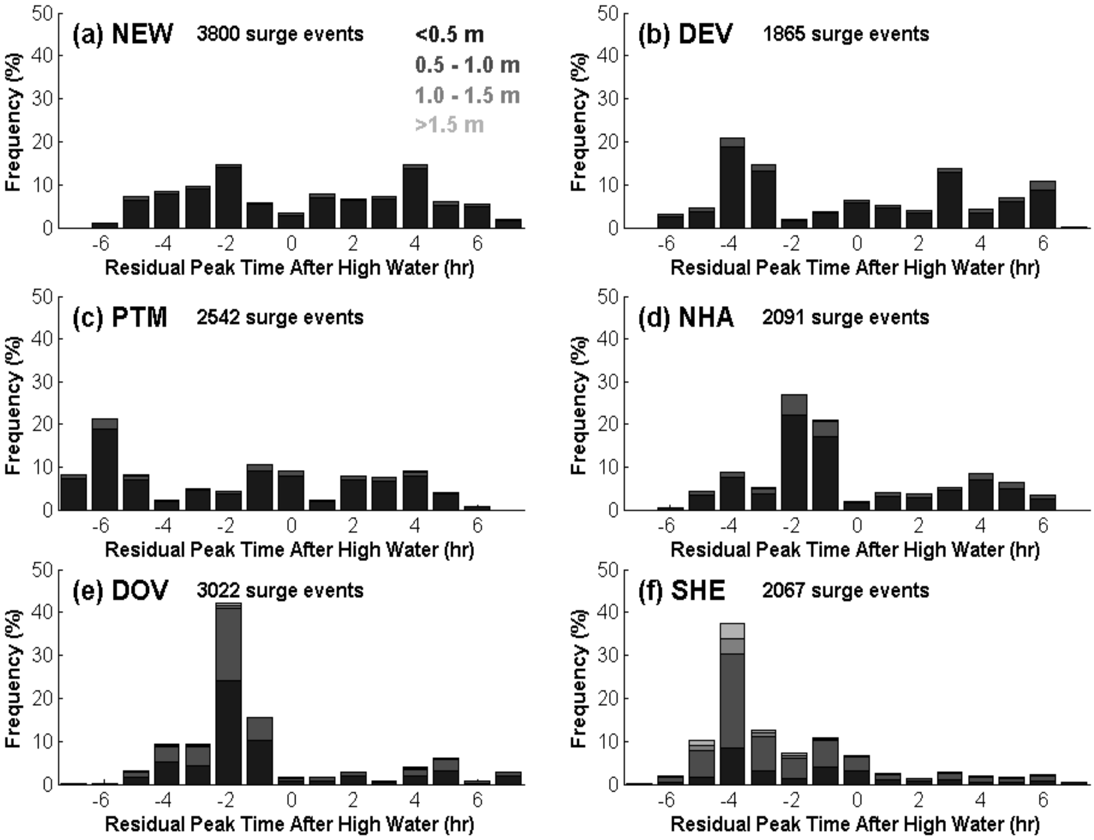

Figure 6.7: Percentage frequency of surge events greater than the 95 percentile level with respect to time of predicted high water for selected UK south coast sites; (a) Newlyn; (b) Devonport; (c) Portsmouth; (d) Newhaven; (e) Dover; (f) Sheerness.

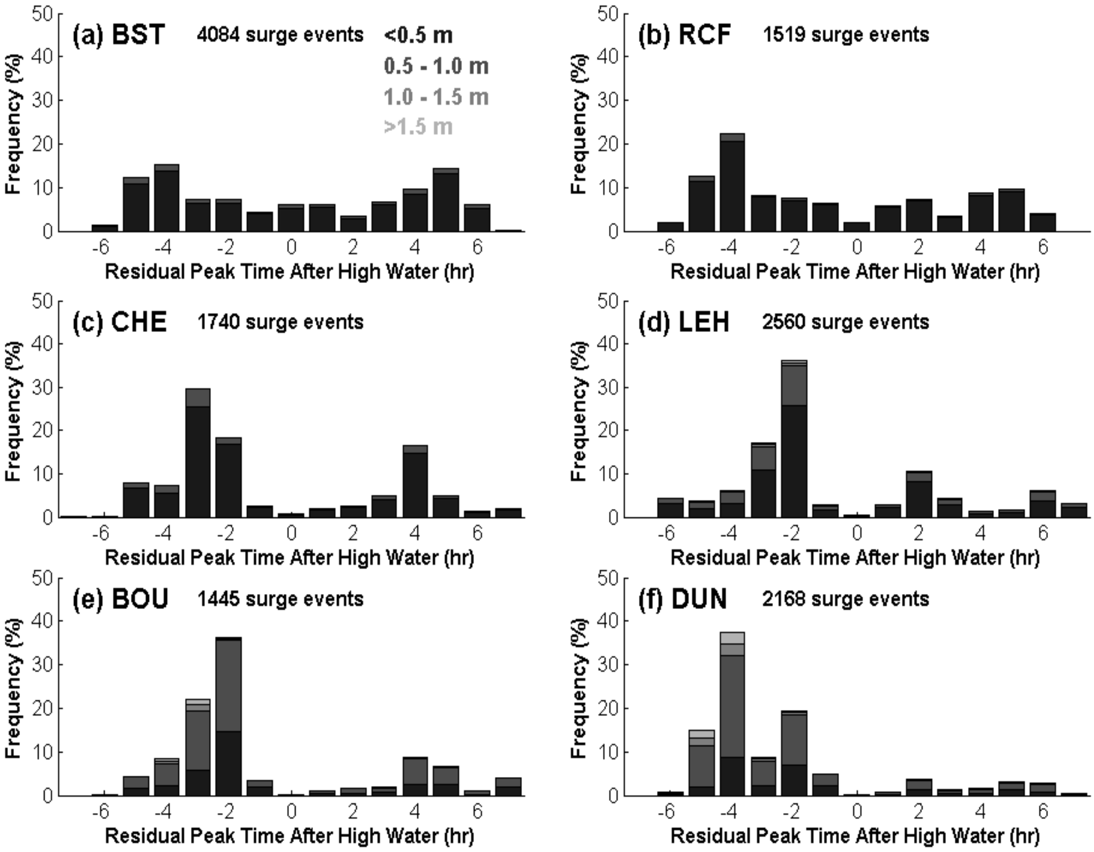

Figure 6.8: Percentage frequency of surge events greater than the 95 percentile level with respect to time of predicted high water for selected French sites; (a) Brest; (b) Roscoff; (c) Cherbourge; (d) Le Havre; (e) Boulogne; (f) Dunkerque.

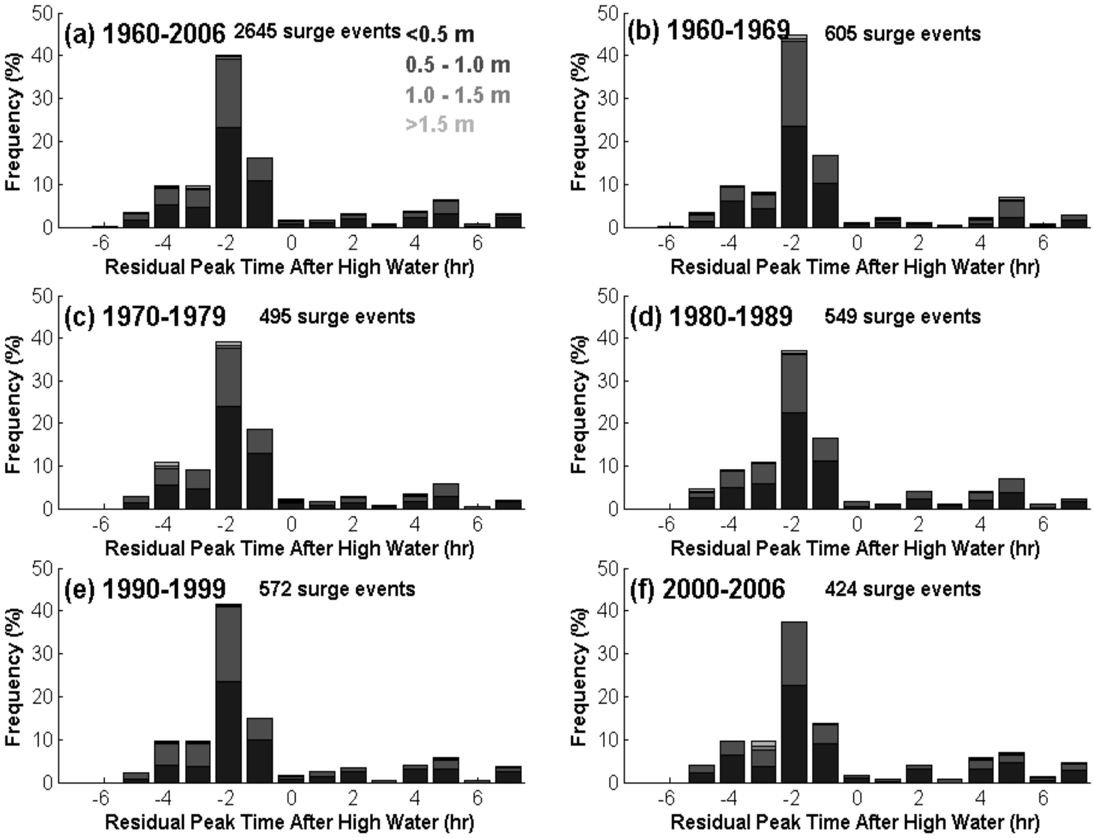

Figure 6.9: Percentage frequency of surge events greater than the 95 percentile with respect to time of predicted high water for different periods at Dover; (a) 1960 to 2006; (b) 1960 to 1969; (c) 1970 to 1979; (d) 1980 to 1989; (e) 1990 to 1999; (f) 2000 to 2006.

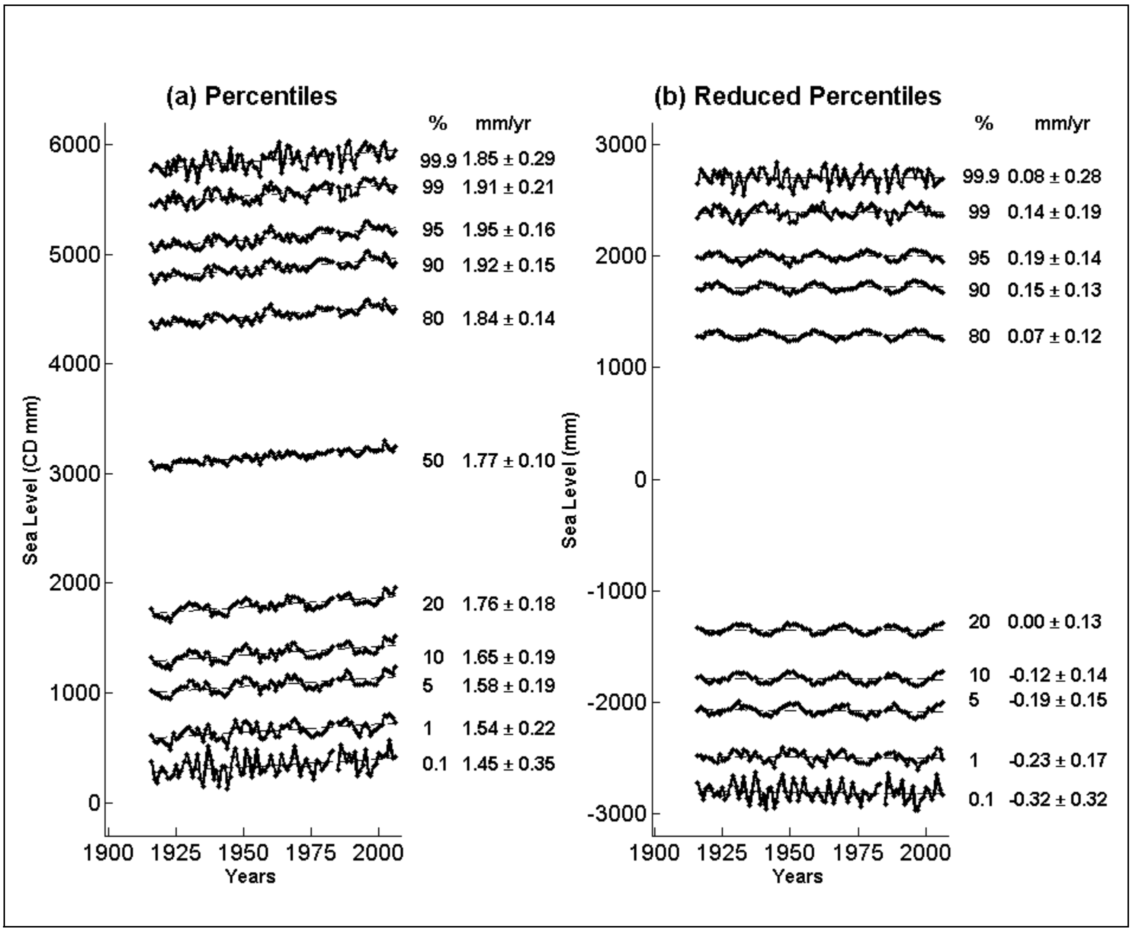

Figure 6.10: (a) Sea level percentiles and (b) reduced sea level percentiles for Newlyn with linear trends (dashed lines).

7 ESTIMATING PROBABILITIES OF EXTREME SEA LEVEL

This chapter describes the results of the third stage of the research. The objective of this stage has been to evaluate which is the most appropriate statistical method for accurately estimating probabilities of extreme high sea levels. Extreme sea levels have been estimated using the: (i) AMM; (ii) RLM; (iii) JPM; and (iv) RJPM. The three ways of handling the long-term trends in sea level have been compared for the different methods (Section 7.1). The sea level record at Newlyn has been artificially altered to determine the ratio of tide to surge variability at which the direct methods start underestimating the long period return levels (Section 7.2). An assessment has been undertaken to evaluate the sensitivity of the four methods to the frequency, length and completeness of the available data (Section 7.3). The performance of each method has been assessed using prediction errors and an investigation has also been carried out to establish why the SRJPM relative return levels overestimate the long period return levels (Section 7.4). The main findings are then summarised (Section 7.5).

7.1 Long-Term Trends

Extreme sea levels have been estimated at the 18 study sites (Figure 3.3) using three different approaches for handling long-term trends (these approaches are described in Section 4.3.2). The results are summarised in Figure 7.1 for the AMM (very similar findings are obtained for the RLM and RJPM). The trends, calculated using the three different approaches, are plotted against record length in Figure 7.1a and are listed in Table 7.1. The range in the 10, 100 and 1,000 year return levels are shown in Figure 7.1b and are listed in Table 7.2. The three trend estimates agree, to within about 0.5 mm, when the sites have at least 50 years of records. Likewise, the difference between the return levels estimated using the three approaches is small for the sites with records longer than 50 years. However, the estimated trends differ by as much as 10 mm/yr and the return levels differ by up to about 0.2 m, at sites with less than 50 years of data. These results demonstrate that the estimated return levels are sensitive to how the long-term trends in extreme sea levels are considered for record lengths of less than 50 years.

Trends and return levels have also been estimated for all overlapping 10, 20, up to 90 year periods for Newlyn. Again, when 50 years of data are used, there is good agreement between the trends and return levels estimated using the three different approaches. Results (not shown) also demonstrate that when less than 50 years of data are used, the trends and return levels differ significantly throughout the year by up to 0.5 m. However, the range in the trends and return levels tends to be smaller when the data has been preprocessed relative to the MSL trend. The main reason for this is illustrated in Figure 7.2. The large variability present in the time series of annual maximum results in a larger range in the fitted decadal trends. This implies that the best method is to remove the trend by preprocessing the data using the MSL trend. This method should be used instead of fitting trends to time series of annual maximum or r-largest sea levels, or by allowing the location parameter in the GEV distribution to vary with time. This is particularly true when the record length at a given site is less than 50 years.

7.2 Ratio of Astronomical Tide to Surge Variability

The Newlyn sea level data set has been modified to produce nine synthetic sea level records. The first record represents a site that is surge dominant. The ninth record represents a site that is strongly tide dominated, and the intermediate records represent sites with intermediate characteristics. A comparison of the return levels that have been estimated (using the AMM, RLM, JPM and RJPM) from these nine time series, is shown Figure 7.3. The statistical methods show good agreement at long return periods when the ratio of tide to surge variability is less than two. The AMM and RLM tend to underestimate the long period return levels, relative to the JPM and RJPM, when the ratio is two or larger. The possible reasons for this are discussed in Section 8.4.

The shapes of the return period curves, estimated from the indirect methods, vary by only small amounts as the tidal dominance increases (Figure 7.3). In contrast, the return period curves for the direct methods flatten off as the tidal dominance increases. The JPM tends to overestimate the short return period levels at tide to surge ratios less than about five. This is because the dependence in the hourly sea level sequence is not taken into account.

In summary, results show that when the ratio of the tide to surge variability at a given site is greater than two, the direct methods will tend to underestimate the long period return levels relative to the estimates from JPM and RJPM. Therefore the direct methods should not be used to estimate extreme sea level at locations where the tidal range is large compared to the magnitude of the surge component[13].

7.3 Data Frequency, Length and Completeness

A series of tests (shown in Tables 4.1 to 4.3) have been undertaken to determine how sensitivity the four methods are to data frequency. A set of extreme sea levels has been estimated using only the 15-minute data that is available (Table 3.3) (Test DF1). A second set of extreme sea levels has been estimating using this 15-minute data after it has been subsampled to hourly values (Test DF2). A third set of extreme sea levels has been estimated (using just the two direct methods) using the exact heights of the annual maximum and r-largest levels (calculated by fitting cubic interpolation routines to the 15-minute data) (Test DF3).

[13] The sites around the UK that exhibit these characteristics are highlighted in Section 8.4.

In the case of the direct methods, there is a negligible difference between the return levels calculated using the 15-minute data and the exact heights. However, the return levels estimated using the subsampled hourly data are 2 cm less than the levels calculated using the 15-minute data. In the indirect methods, there is negligible difference between the return levels estimated using the subsampled hourly data and 15-minute data.

Three tests (Tests DL1, DL2, DL3) have also been undertaken to assess how sensitive the four statistical methods are to data length. Extreme sea levels have been estimated, using each of the four methods, for different data lengths and for different periods. These tests exploit the long records at Newlyn and Brest. Figure 7.4 shows 100 year return levels that have been estimated using all overlapping 2, 6 (just indirect methods), 10, 20, up to 80 year periods, for Newlyn (results are similar for Brest). The instability (i.e. range in estimates) of the estimated return levels increases as the length of the data reduces (Table 7.3; Figure 7.5). This is expected, as the scatter for longer spans of data will be less as the records are not independent (see Figure 7.5). The instability is less for the return levels that have been calculated by the indirect methods. This is because the direct methods use the total sea levels. Therefore, both the variability in the tidal and surge components of sea level is present in the estimate return levels. In the indirect methods, the variation is due only to the variability in the surge component, as the full 18.6 year tidal cycle is included in the analysis (Section 2.4.2).

The range in the 100 year return levels (Table 7.3; Figure 7.5) is to within 0.1 m when at least 37, 26, 9 and 9 years of data are used to calculate return levels using the AMM, RLM, JPM and RJPM, respectively. Dixon and Tawn (1994) suggest that the JPM can be used to estimate return levels from records with less than five years of data. However, these results show that when five years of data are used, the estimated return levels can differ, from the return levels calculated using a much longer record, by more than 0.1 m. About 10 years of records are needed to produce an accurate (i.e. to within 0.1 m) estimate of return levels at Newlyn and Brest.

It has been recognised for some time that the direct methods are unstable to historical outliers (Tawn and Vassie, 1989), as can be seen in Figure 7.6. The return levels, estimated using the direct methods, show a stepped increase when a year, that contains larger sea level than previously recorded, is included in the analysis. Therefore, when using direct methods a careful check must be undertaken to ensure that the periods where measurements are missing do not coincide with particularly extreme events[14]. Tawn and Vassie (1989) demonstrated that the 100-year return level at Lowestoft (calculated using the AMM) reduces by 0.39 m when the 1953 event is excluded from the data set. The indirect methods are more stable against effects of historical outliers because they also account for large surges that occur at times other than high water (Tawn, 1992).

It is important to ensure that the sea level data set includes historical outliers. What is not as well understood is how sensitive the four methods are to data sets with incomplete years that do not contain a particular extreme event. In order to evaluate this, two tests (Test DC2 and DC3) have been undertaken using the Newlyn record between 1917 and 1983. In these tests months are deleted at random to simulate records with different amounts of missing data. In terms of direct methods, results (not shown) indicate that as long as the five largest events over this period are included in the analysis, the results are not particular sensitive to missing data. In terms of indirect methods, results imply that as long as two of the years have no missing data, return levels are to within 0.1 m of that calculated using the complete data set, even when all the other years have only one month of data. Hence, overall the results suggest that the methods are not particularly unstable to missing moderate events.

To summarise this section, results have demonstrated that; Firstly, the four methods are not particularly sensitive to data frequency. In the case of the indirect methods, there is negligible difference between the return levels estimating using the raw 15-minute data and this subsampled to hourly values. In the case of the direct methods, the return levels estimated using the subsampled hourly data are 2 cm less than the levels calculated using the

[14] Large storms have been known to destroy measuring instrumentation.

15-minute data. Secondly, results have shown that the instability of the estimates increase as the length of the data reduces, particularly in the direct methods. In order to estimate 100 year return levels to with an accuracy of 0.1 m (compared to those estimate using the complete record) at Newlyn using the AMM, RLM, JPM and RJPM, requires at least 37, 26, 9 and 9 years of data, respectively. Thirdly, the findings have demonstrated that the direct methods are more unstable to historical outliers than the indirect methods; Finally, it has been shown that the methods are not particular sensitive to missing moderate events.

7.4 Comparison with SRJPM

In this present study, extreme sea levels have been estimated using the AMM, RLM, JPM and RJPM for the 18 study sites using the data periods listed in Table 3.2 and shown in Figure 3.3. These estimates of extreme sea level are shown in Figure 7.7 and Figure 7.8. Return levels have also been estimated using the SRJPM relative return levels for the mainland UK south coast sites (Figure 7.7). The five methods show reasonable agreement at short return periods. At most sites, the RLM estimate are larger than those of the AMM at short return periods and are smaller than those of the AMM at long return periods. At Newhaven, Dover, Sheerness and Dunkerque the AMM estimates are larger than those of the RLM at return periods greater than 100 years. This is probably a result of the larger surges that occur in the North Sea and leak into the Channel through the Straits of Dover. The JPM estimates are consistently larger than the estimates calculated using the AMM, RML and RJPM. The RJPM estimates are similar to the RLM estimates at return periods less than 10 years, but are higher at long return periods. This is expected, as all the English Channel sites are tidally dominated (Section 8.4).

At the sites between Newlyn and Dover, the SRJPM return levels are considerably larger, at long return periods, compared to the estimates from the other statistical methods (Figure 7.7). The SRJPM estimates are in better agreement with the indirect estimates at Newlyn and Dover. At both these sites, Dixon and Tawn (1997) had sea level records of reasonable length with which they calibrated the SRJPM method. However, at the time of their analysis only very short (<10 years) records were available for the other locations along the UK south coast (Table 2.2).

In order to determine if this is the cause of the high SRJPM estimates, return levels have been computed using the four methods and: (i) the entire data set that is currently available at these UK south coast sites (Table 3.2); and (ii) only the years that were originally used to calibrate the SRJPM (Table 2.2). Results are shown in Figure 7.9 for Portsmouth and the RLM. The return levels estimated using the short dataset agree much better with the SRJPM estimates. Return levels have also been estimated using the shorter data set by allowing for a linear trend in the location parameter of the GEV fit (Section 4.3.2). The return levels estimated in this way are larger than the estimates from SRJPM at long return periods. Similar results were obtained for the other methods and sites. Therefore, the over prediction of extreme sea levels by the SRJPM along the south coast is mainly due to the comparatively short data sets originally used to calibrate the model in this area. The new data collected in this study could be used to recalibrate and hence improve the SRJPM relative return levels in the future.

At Sheerness, the SRJPM return levels are also higher (at long return periods) than the estimates from the other methods. A possible cause of this could be that the 12 km hydrodynamic model used by Dixon and Tawn (1997) is too coarse to capture the spatial variations in sea levels around the Thames Estuary.

Finally, the performance of the different methods has been assessed by comparing the difference between the estimated return periods of the observed maximum sea level at each site with the corresponding data span (i.e. prediction errors; Dixon and Tawn, 1999). Results show that at almost all sites, the RJPM has the lowest prediction errors. The RLM has the highest prediction errors at most sites and these are consistently negative, indicating that the methods tend to underestimate the return levels (or overestimate the return periods). The prediction errors for the AMM tend to be slightly smaller than those of the RLM, but are also consistently negative. The prediction errors of the JPM at most sites are consistently positive, indicating that this method overestimates return levels (or underestimates return periods). These results suggest therefore, that of the four statistical methods, the RJPM provides the best estimate of extreme still water levels around the English Channel.

7.5 Summary

The main findings of this stage of the research are:

- The way in which the long-term trend is handled in the different methods can lead to significant differences in the estimated return levels unless, records with at least 50 years of measurements are used.
- Using hourly data results in the return levels being underestimated by about 2 cm in the direct methods (AMM and RLM) compared to 15 minute data. The indirect methods (JPM and RJPM) are insensitive to data frequency.
- Accurate return level estimates, representative of the statistics of the 20^{th} century, should be made using at least 37, 26, 9 and 9 years of data in the AMM, RLM, JPM and RJPM, respectively.
- It has been shown that the direct methods underestimate the long period return levels when the ratio of the 98% quantile of the astronomical tide (relative to a mean level of 0), to the 98% quantile of the surge component, is greater than two.
- Return levels estimated using the SRJPM relative return levels are significantly larger along the UK south coast at long return periods than the other four approaches. The main reason is due to the comparatively short data sets originally used to calibrate the model in this area. Recalibration of the SRJPM relative return levels with longer datasets such as presented in this thesis should significantly improve the SRJPM estimates, allowing further evaluation.
- The return levels calculated by the RJPM have the lowest prediction errors.

Table 7.1: Trends estimated using the three different approaches outlined in Section 4.3.2.

Station Name	Trend in Annual Maximum Sea Level (mm/yr)	Trend in Mean Sea Level (mm/yr)	Trend fitted by allowing location parameter to vary in the GEV distribution (mm/yr)
St. Mary's	9.11	1.20	0.57
Newlyn	2.09	1.77	2.04
Devonport	0.07	1.97	-0.35
Weymouth	8.62	4.09	1.37
Southampton	1.11	1.23	1.63
Portsmouth	1.73	1.69	1.99
Newhaven	3.09	2.41	3.51
Dover	-0.03	1.73	0.68
Sheerness	1.63	1.77	1.75
Dunkerque	-0.21	1.90	0.24
Calais	0.75	-0.03	-0.03
Boulogne	7.06	3.46	-0.40
Le Havre	3.51	1.99	3.64
Cherbourg	0.45	1.46	0.00
Jersey	-5.66	6.30	-1.50
Roscoff	1.54	2.09	-3.64
Le Conquet	2.64	2.91	0.57
Brest	1.35	1.35	0.63

Table 7.2: Range (i.e. maximum return level minus minimum return level) in 10, 100 and 1000 year return levels estimated using the three different approaches outlined in Section 4.3.2.

Station Name	**Range in 10 Year Return Levels (m)**	**Range in 100 Year Return Levels (m)**	**Range in 1000 Year Return Levels (m)**
St. Mary's	0.060	0.087	0.099
Newlyn	0.012	0.009	0.005
Devonport	0.023	0.033	0.037
Weymouth	0.054	0.152	0.219
Southampton	0.009	0.001	0.007
Portsmouth	0.003	0.006	0.010
Newhaven	0.078	0.073	0.064
Dover	0.035	0.057	0.101
Sheerness	0.028	0.029	0.029
Dunkerque	0.043	0.046	0.049
Calais	0.015	0.024	0.031
Boulogne	0.060	0.161	0.217
Le Havre	0.100	0.100	0.099
Cherbourg	0.027	0.034	0.036
Jersey	0.010	0.013	0.021
Roscoff	0.035	0.069	0.095
Le Conquet	0.031	0.048	0.059
Brest	0.028	0.040	0.048

Table 7.3: Range in 100 year return levels for all overlapping 2, 6 (just indirect methods), 10, 20, up to 80-year periods at Newlyn.

Number of Years	Direct Methods AMM	Direct Methods RLM	Indirect Methods JPM	Indirect Methods RLM
2			0.223	0.227
6			0.127	0.126
10	0.425	0.238	0.092	0.100
20	0.228	0.147	0.046	0.044
30	0.147	0.063	0.039	0.024
40	0.080	0.043	0.018	0.019
50	0.056	0.034	0.018	0.011
60	0.029	0.014	0.013	0.009
70	0.020	0.014	0.006	0.005
80	0.019	0.013	0.006	0.003

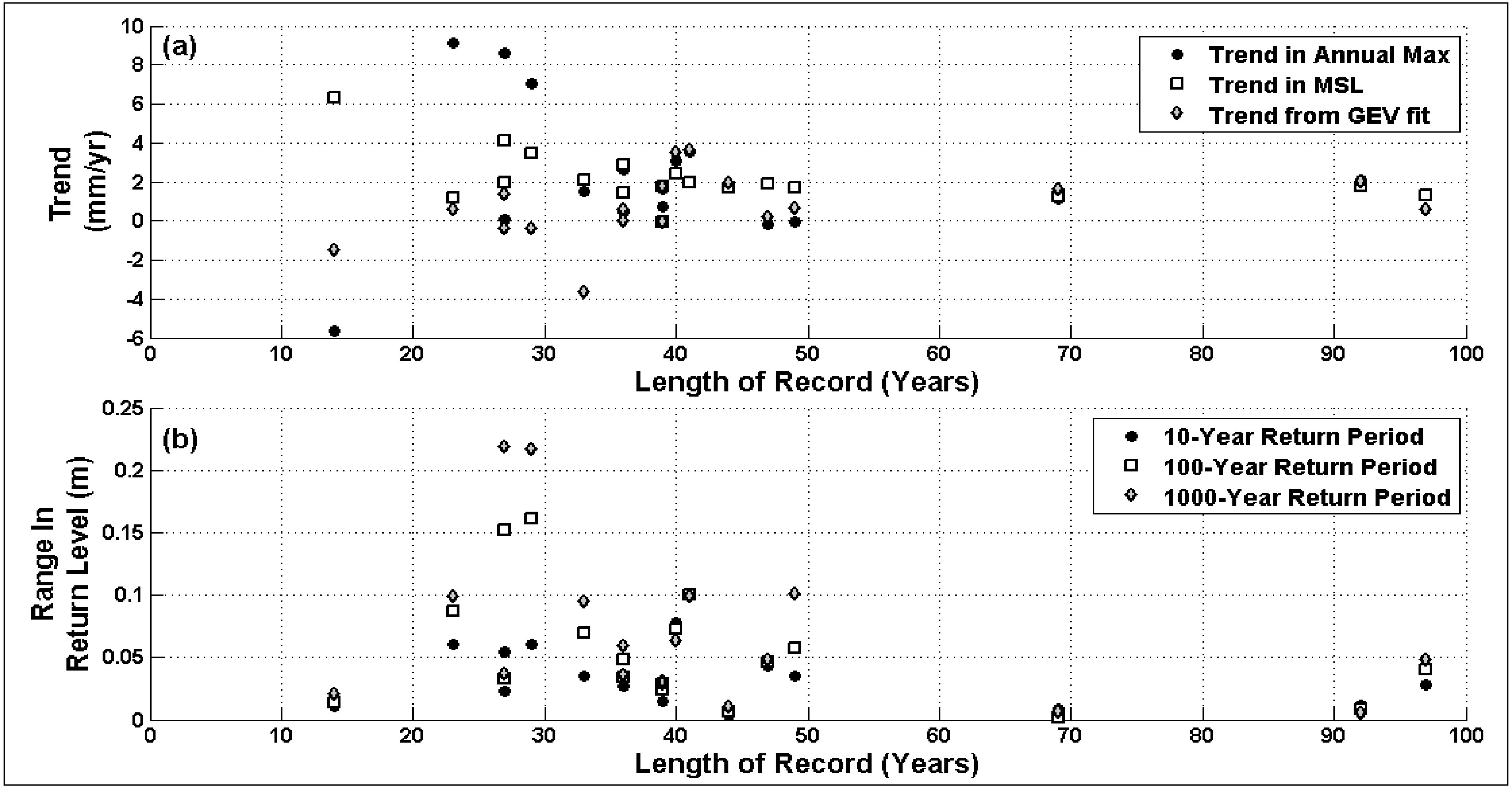

Figure 7.1: (a) Trends calculated using each of the three ways of handling long-term trends; (b) range in the 10, 100 and 1,000-year return levels. Both the trends and ranges in return levels are plotted against the length of the record at each of the 18 sites.

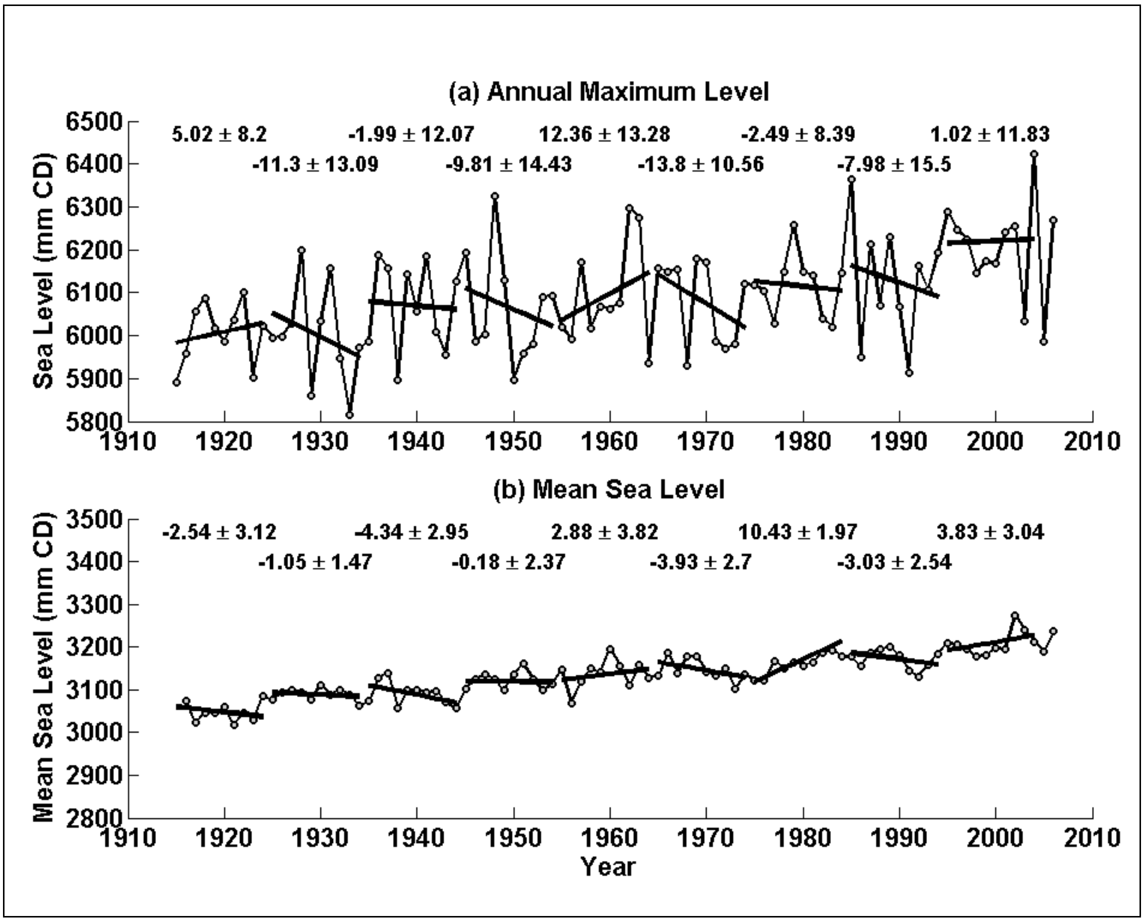

Figure 7.2: (a) Time series of annual maximum sea level and (b) annual mean sea level, at Newlyn. Linear trends have been fitted to different 10-year blocks. The trends are in mm/yr and the uncertainty is expressed as ±1 standard error.

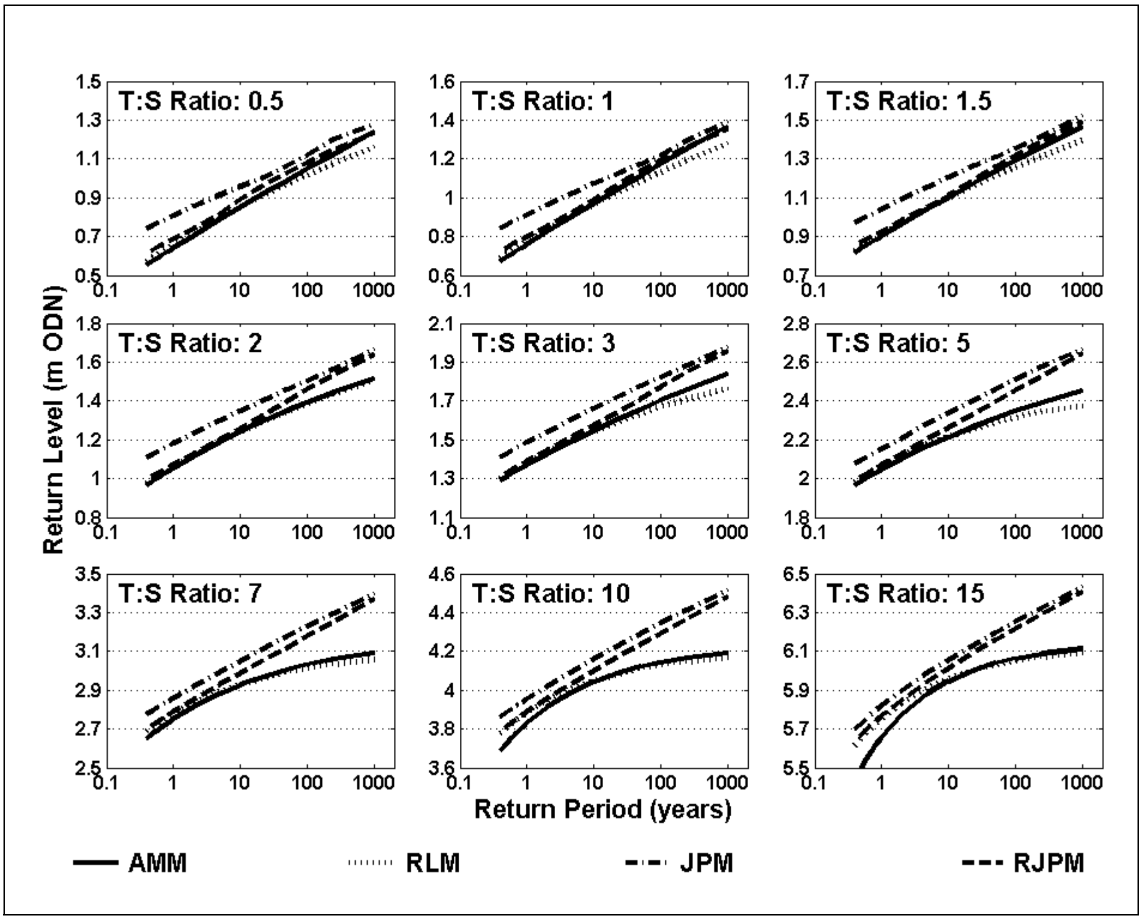

Figure 7.3: Estimates of return levels for 2000 obtained using the AMM (—), RLM (…), JPM (−.−) and RJPM (---) and nine different ratios of tide to surge variability. (Note: for the RLM method 8 largest events per year have been used and these are separated by at least 30 hours).

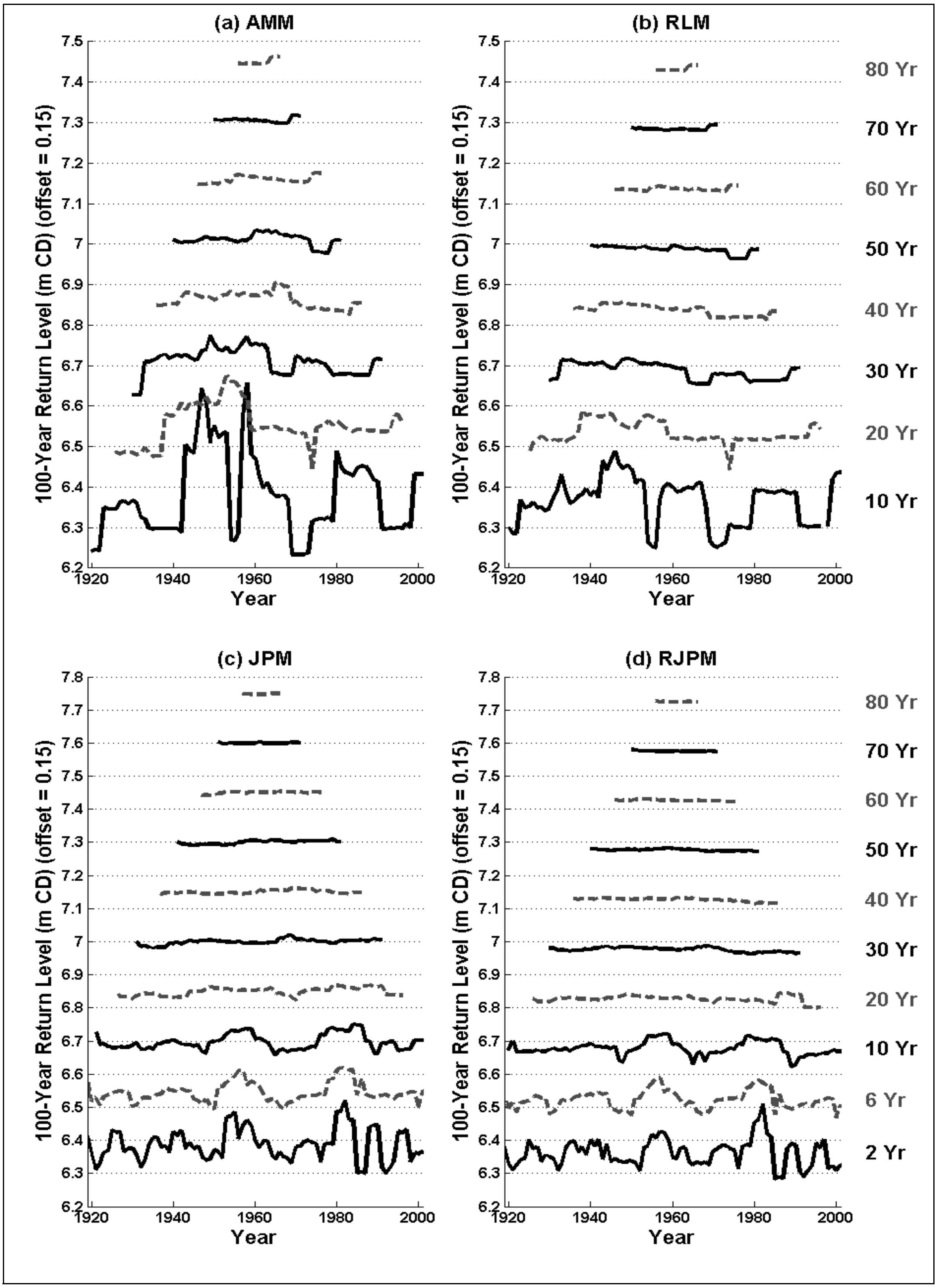

Figure 7.4: 100-year return levels estimated using all overlapping 10, 20, up to 80-year periods for Newlyn; (a) AMM; (b) RLM; (c) JPM; (d); RJPM. For the indirect methods return levels are also shown for all overlapping 2 and 6-year periods. Results have been offset by 0.15 m. Note: for the RLM method 8 largest events per year have been used and these are separated by at least 30 hours.

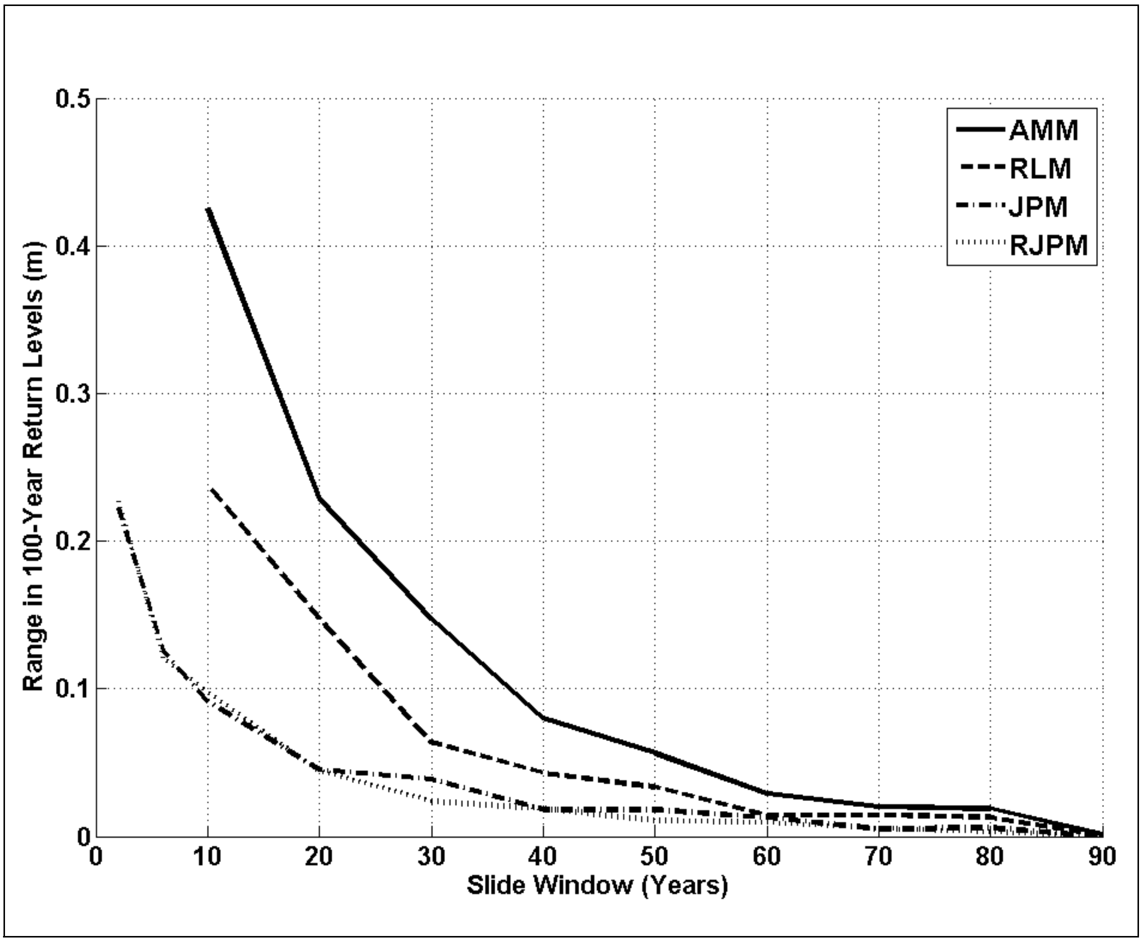

Figure 7.5: Range in the 100-year return levels for all overlapping 2, 6 (just indirect methods), 10, 20, up to 80-year periods for Newlyn.

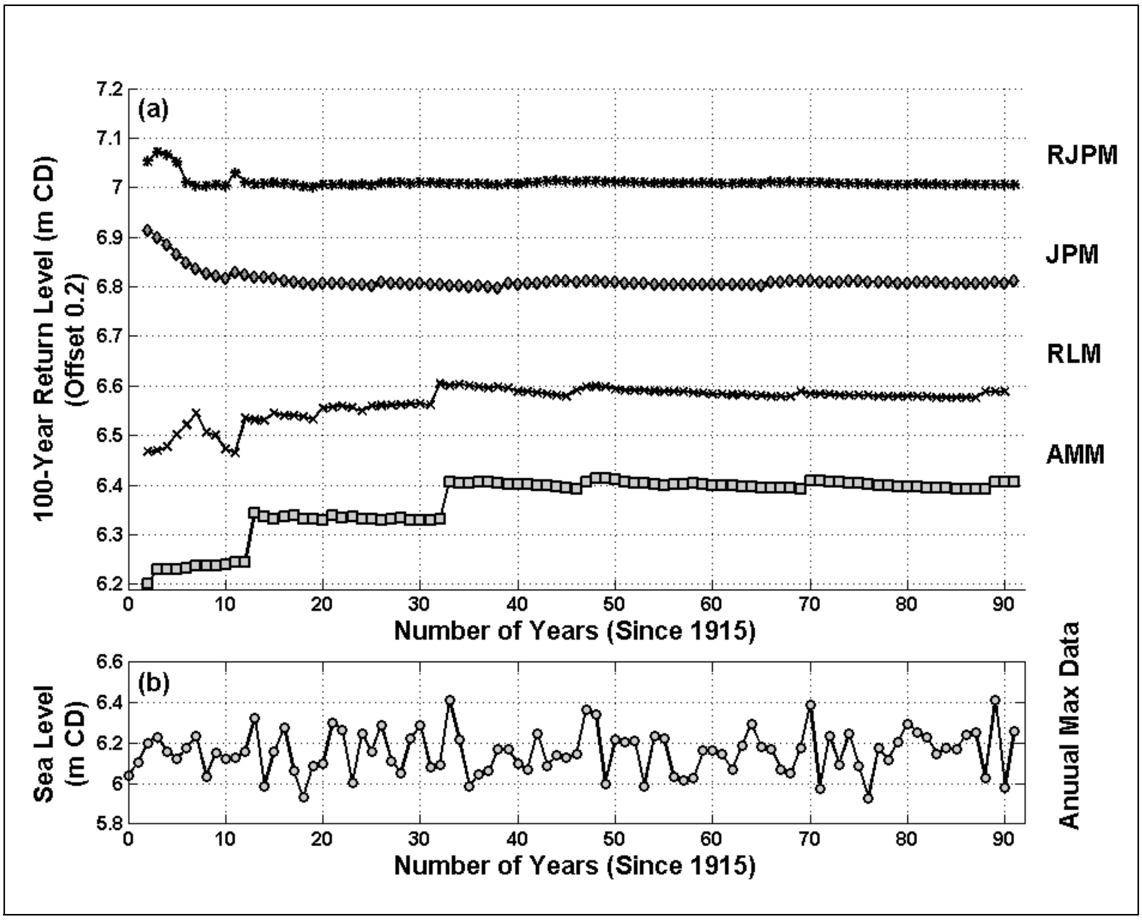

Figure 7.6: (a) 100-year return levels for Newlyn calculated initially using just the first three years of data (1915 to 1917), then the first four years and so on until the entire data set is used (1915 to 2006). The levels are offset by 0.3 m; (b) time series of annual maximum sea level at Newlyn. Note: for the RLM method 8 largest events per year have been used and these are separated by at least 30 hours. In the JPM and RJPM 90 years of astronomical tide are used for each return level estimate.

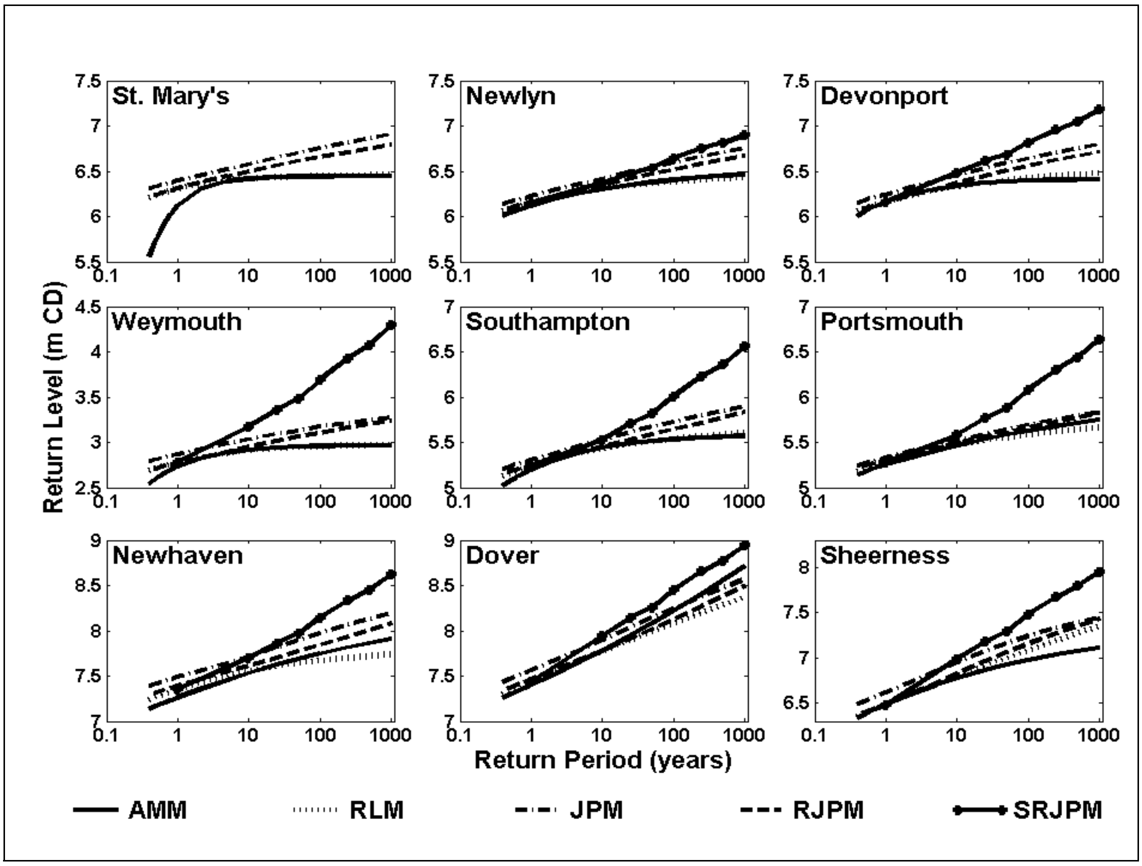

Figure 7.7: Estimates of return levels for 2000 obtained using the AMM (—), RLM (…), JPM (–.–), RJPM (-–-) and SRJPM (•—•) for nine UK south coast sites. Note: (i) the SRJPM estimates are shown for reference; (ii) The data analysed in this thesis do not feed into the SRJPM estimates; (iii) SRJPM estimates are only available for main land UK sites and so are not plotted for St. Mary's; and (iv) for the RLM method 8 largest events per year have been used and these are separated by at least 30 hours).

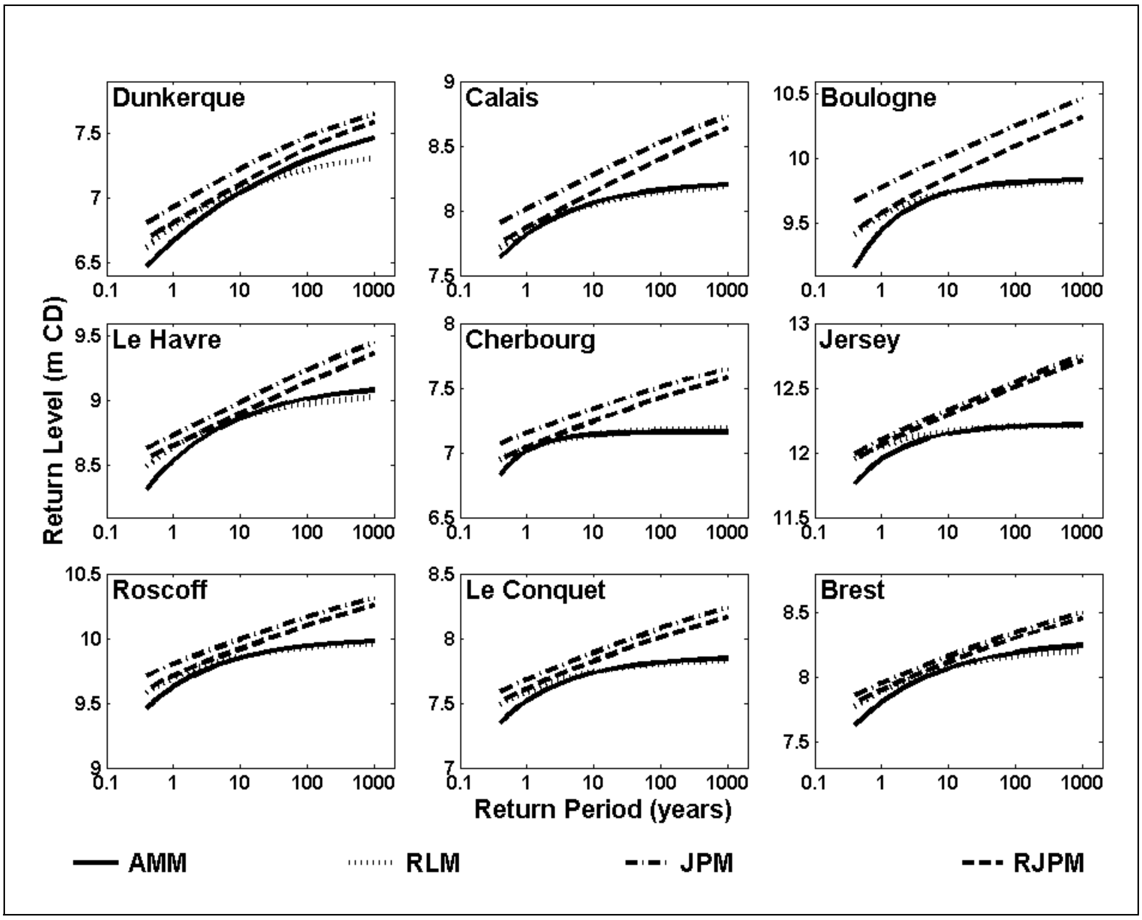

Figure 7.8: Estimates of return levels for 2000 obtained using the AMM (—), RLM (…), JPM (–.–) and RJPM (–––) for nine northern French sites.

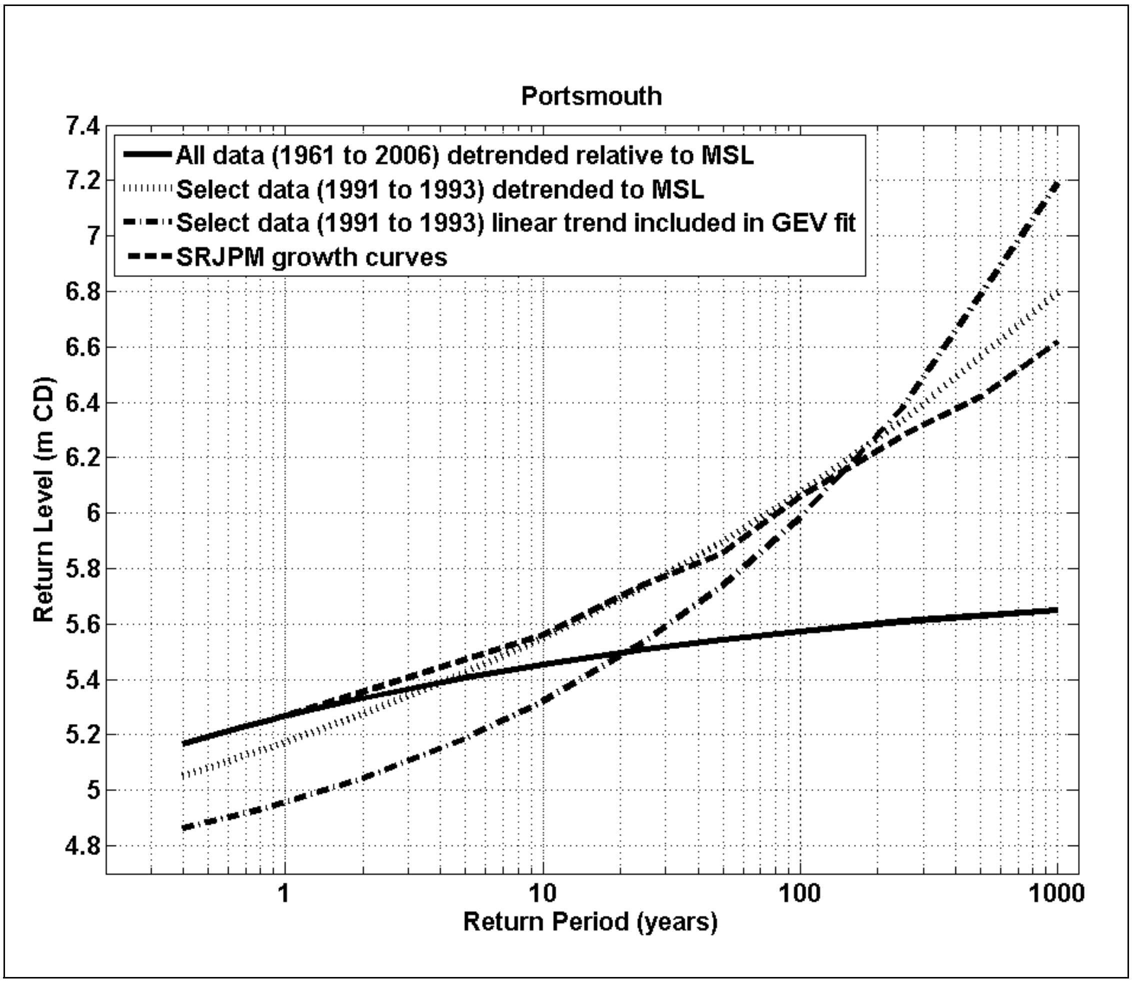

Figure 7.9: Estimates of return levels for 1990 at Portsmouth obtained using the RLM and all the data detrended relative to MSL (—); data from 1991 to 1993 detrended relative to MSL for that period (…); data from 1991 to 1993 with a linear trend included in the location parameter of the GEV fit (–.–); and return levels estimated using the SRJPM relative return levels calibrated on the same data period (1991 to 1993) (–––).

8 DISCUSSION AND SYNTHESIS

The aim of this research has been to test the hypothesis that changes in extreme high sea level can be determined, to an engineering accuracy of 0.1 m, by simply adding changes in MSL to return levels estimated from measured data (Figure 1.1), for the English Channel region. This has been accomplished by undertaking three main stages of research, each addressing a specific objective. The objective of the first stage was to determine the rates of observed changes in MSL in the English Channel. The objective of the second stage was to establish whether changes in extreme sea level throughout the 20th century were significantly different from the rates of MSL change estimated in the first stage. The objective of the third stage was to evaluate which is the most appropriate statistical method for estimating probabilities of extreme high sea levels.

The main results of this research have been described in Chapters 5 to 7. In Chapter 5, it has been established that relative MSL rose in the English Channel by between 0.8 and 2.3 mm/yr, depending on location, for the period 1900 to 2006. Chapter 6 showed that this increase in MSL was accompanied by relatively small (0.1 to 0.3 mm/yr) indirect change to the astronomical tide, but with negligible long-term changes to the patterns of tide-surge interaction. It has also been demonstrated that while there have been decadal changes in storminess there were no significant long-term trends over the past century. In fact, despite the perception (i.e. considerable amount of anecdotal evidence, newspaper reports, etc.) of a recent increase in the frequency of storm events, the evidence from this work suggests a small decrease in storminess in the English Channel over the second half of the 20th century.

Findings demonstrate that extreme sea levels increased throughout the 20th century at all 18 study sites, but at rates not significantly different to that of MSL.

Together, these results verify that past changes in extreme sea levels over the 20th century could have been accurately determined (to within 0.1 m) by simply adding MSL changes to return levels estimated using the available sea level data. To put it another way: If a scientist or engineer in 1950 had correctly projected the rate of MSL rise between 1950 and 2000, they would have accurately estimated extreme sea levels in the year 2000, to within 0.1 m, by adding projections of MSL to return levels estimated using the available sea level records at the time. For changes in extreme sea level throughout the 20th century to be determined to a higher accuracy (<0.05 m), one would have also needed to account for the observed increase in astronomical tidal high water.

Chapter 7 shows that the RJPM produces the most accurate return level estimates for the English Channel. This method has the advantages that it: (i) is not sensitive to data frequency; (ii) is stable to historical outliers; (iii) produces the most accurate estimates of extreme sea levels from relatively short data sets; and (iv) is not sensitive to the ratio of tide to surge variability at a given site. As the MSL offset approach relies on accurate estimates of current return levels, this approach should be used to estimate the current return levels wherever possible. Return levels for 2000, estimated using the RJPM, are listed for the 18 study sites in Table 8.1 for return periods of 1, 10, 25, 50, 100, 250 and 1,000 years.

Table 8.2 shows return levels for Newlyn, calculated using the RJPM. Over the 20th century, relative MSL rose by 1.74 mm/yr at this site (Table 5.1). Table 8.2 presents the return levels for the year 2000, estimated using: (i) the first 10 years of the Newlyn data set (1915 to 1925), with the addition of 75 years of MSL rise, at a rate of 1.74 mm/yr (i.e. about 0.13 m); (ii) the data prior to 1950, with the addition of 50 years of MSL rise (i.e. about 0.09 m); and (iii) using all the available data (1915 to 2006). At one decimal place the return levels are the same. This confirms that, for engineering purposes, changes in extreme sea levels during the 20th century can be adequately estimated based on an offset relative to mean change.

This thesis has focused so far on observed changes in extreme sea level. Results have shown that extreme sea levels increases throughout the 20th century at all study sites, but at rates not significantly different from MSL. It is interesting to now briefly consider 21st century changes for English Channel sites using the MSL offset approach and recent IPCC projections. The IPCC's AR4 predicts that global MSL will rise by between 1.8 mm/yr and 5.9 mm/yr, from 1990 to the 2090s, and larger rises are possible (Meehl et al., 2007). The lower end of the range is approximately consistent with the 1.7 mm/yr global rate of MSL change observed by tide-gauges over the 20th century (Bindoff et al., 2007).

Around the UK, the rate of MSL rise for the past century was 1.4 mm/yr, 0.3 mm/yr less than the global average (Woodworth et al., 2009). If we assume that the rates of MSL rise for the UK are likely to continue to be 0.3 mm/yr below the global average, this would give a projected rate of rise for the 21st century of between 1.5 mm/yr and 5.6 mm/yr. If MSL rises at this lower rate (1.5 mm/yr) over the next 100 years, it is probably reasonable to assume, based on findings in this study, that the indirect changes to the astronomical tide and surge will remain relatively small. Therefore, extreme sea levels in 2100 can be estimated by adding 0.15 m (i.e. 1.5 mm/yr multiplied by 100 years), along with the expected contribution from vertical land movement, to current (i.e. year 2000) return levels calculated from existing sea level records (using the RJPM). In this study, the rate of vertical land subsidence at Newlyn has been estimated to be about 0.4 mm/yr (Section 5.2). Therefore, return levels in 2100 can be estimated by adding 0.19 m (i.e. 0.15 m sea-level rise plus 0.04 m land subsidence) to current return levels (Table 8.3, column 3). At this lower end of the IPCC's projected MSL range, a sea level that is reached once in every 1,000 years today (i.e. year 2000) is predicted to occur about once every 60 years by 2100 at Newlyn.

If MSL accelerates beyond the rates experienced over the 20th century, it is likely that indirect effects will play a greater part in further enhancing extreme levels above that of MSL. With the relatively small MSL increases experienced over the 20th century, changes in predicted high water were about 0.3 mm/yr at some sites. The upper end of the range (0.56 m) is about 3 times higher than that experienced over the last 100 years. Assuming a linear relationship, the increase in predicted high water would be about 0.9 mm/yr with this increase in MSL. Return levels for the year 2100 can then be estimated by adding 0.69 m (i.e. 0.56 m sea-level rise plus 0.04 m land subsidence plus 0.09 m increase in predicted high water) to current return levels (Table 8.3, column 4). At this upper end of the IPCC's projected MSL range, a sea level that is reached once in every 1,000 years today (i.e. year 2000) is predicted to occur about twice a year by 2100 at Newlyn.

Following the same procedure, return periods for the year 2100 have been calculated for the today's (i.e. year 2000) 1 in 1,000 year return levels at all 18 sites (Table 8.4). Return periods have been calculated for both the lower and upper ends of the IPCC's AR4 projected MSL range and by taking into account the rates of vertical land movement estimated at each site (Section 5.2). For a constant MSL offset, the change in return period will depend on the shape of the return period curve and hence will vary within the Channel. At the upper projected MSL rate, today's 1 in 1,000 event will occur more frequently than once a year by 2100 at most sites. This highlights the significant challenges that are likely to be faced by the flood risk management and engineering community over the next 100 years in coastal areas. The largest increases in extreme high sea levels are likely to occur along the western parts of the northern French and southern English coastlines. The frequency of extreme events could further increase significantly with enhanced storminess. Recent work has strongly indicated that storm tracks will have tendency to move further south (Leake et al., 2008), and this will increase storm events in the English Channel.

The main findings of the research will now be discussed in more detail. Section 8.1 briefly discusses the sea level data set that was extended during this research. Sections 8.2, 8.3 and 8.4 discuss the main findings from the three main stages of the research. Recommendations for further research are also provided in Section 8.5.

8.1 Sea Level Data

The data archaeology exercise, described in this thesis (Chapter 3), has increased the hourly sea level record for the UK south coast by 173 years. Hence, rather than the four south coast MSL records considered by W09, eight MSL records are now available, including corrections to two of the records (Devonport and Portsmouth) considered in W09. In 2009, the extended hourly records and derived MSL values will be donated to the BODC and PSMSL, respectively. Further significant data extensions could still be made (such as Poole, Table 3.1) and this should be pursued, especially for studies of extreme sea levels. Several long historical chart records identified in earlier assessments have already been misplaced. This highlights the responsibility that the sea level community has to capture as much past sea level information as possible while it is still available (Woodworth, 2006).

8.2 Observed Changes in Mean Sea Level

The MSL trends estimated in this research for tide-gauge sites in the English Channel are in good agreement with those previously published, when at least 30 years of data are used. The UK south coast trends are not statistically different (95% confidence level) to the recent estimates of Woodworth et al. (2009). The small differences arise from the fact that Woodworth et al. (2009) only used complete years (all 12 months have data for at least 15 days), whereas years with 11 months have been included here. The Newlyn and Dover trends are slightly higher than those of Woodworth et al. (1999) because of the high rate of MSL rise observed over the last 10 years. The trends from the updated Portsmouth and Devonport records are not statistically different (95% confidence level) to those calculated previously by Woodworth et al. (1999). However, the SE's associated with these updated data sets are lower. The Graff and Blackman (1978) and Pirazzoli et al. (2006) rates for the UK south coast are large and have large SE's. Both studies used relatively short data lengths (<15 years). Graff and Blackman (1978) estimates for Portsmouth are large because the record used by the author was relatively short and did not account for the datum changes that took place in the 1960's (Section 3.2). Graff and Blackman (1978) estimates for Dover are significantly (95% confidence level) different to those calculated in this study. The reason for this difference is probably the short data length used by the authors. The Pirazzoli et al. (2006) estimates for the French coast are consistent with those calculated in this study, at the 95% confidence level. The MSL estimates for the French coast in this study are consistent with those calculated by Pirazzoli et al. (2006), while those for Brest are consistent with Woppelmann et al. (2006) and Douglas (2008), all at the 95% confidence level.

A large part of the variability in sea level along both the English and French coastlines of the Channel is coherent and is consistent with that observed around the rest of the UK (Woodworth et al., 1999). As a result, the long Brest record can be used with the five long UK records (Newlyn, Sheerness, North Shields, Aberdeen and Liverpool), to construct a single index that describes a large part of the variability of the British Isles and northern French coastal regions. Woodworth et al. (2009) had two main reservations about their index, derived from just the five longest UK records. Firstly, the similarity between the index and the Liverpool record was weak. Secondly, the index was defined by a different set of stations at different years, due to gaps in each record. The authors pointed out that these reservations could not be major because the index was defined using between three and five stations at all times, except for three early years. As a result the Liverpool data cannot significantly distort the index. The advantage of including the Brest record is that it results in a greater number of stations being used to define the index, further diluting any influence of poor quality data. This idea could be further extended by adding other long European records, if appropriate, as Shennan and Woodworth (1992) have previously done for the North Sea region.

More accurate trends in MSL have been calculated by removing the coherent part of the sea level variability from the records, following the approach of Woodworth et al. (2009). A detailed evaluation of the method has been carried out and shows that much shorter records can be used to accurately calculate longer-term trends in MSL. However, findings suggest that a meaningful analysis of MSL is still restricted to records spanning 20 years or more. 34 of the 55 sites used in this study have records meeting that requirement. These 34 sites are spatially well spread along the south and east coasts of the UK, whereas, along the UK west coast they are clustered around the Irish Sea (Figure 2.9). All of the records for the northern parts of the west Scottish coast and between Holyhead and Newlyn span less than 20 years. With another decade of measurements, 54 of the 55 sites will span at least 20 years. However, current understanding of MSL along the northern parts of the west Scottish coast and between Holyhead and Newlyn is limited and would especially benefit from extensions to sea level records through data archaeology, if data exists for these sites.

This research indicates that Shennon and Horton's (2002) vertical land movement rates overestimate subsidence during the 20^{th} century for the western and central parts of the UK south coast. These earlier results indicate that the highest rates of subsidence in the UK (and hence relatively MSL rise) are in southwest England. However, results from the present research imply that the highest rates of subsidence occur in southeast England. Gehrels (2006) recently put forward the case that Shennon and Horton's (2002) high rate of subsidence for the southwest of the UK is based on questionable geological data and on several assumptions. If these assumptions are incorrect, they lead to over-estimations of the supposed subsidence rate. Prior to this, Woodworth et al. (1999) suggested, based on the Newlyn and Brest sea level trends, that the southwest England subsidence rate might be closer to 0.7 mm/yr. Results from current study, suggests that the rate at Newlyn (supported by St. Mary's) is between 0.2 to 0.5 mm/yr, which is more consistent with recent advanced geodetic measurements (0.46 ± 1.13 mm/yr) (Bingley et al., 2007). The updated data for Portsmouth and new record at Southampton suggest lower subsidence rates and possibly uplift (Figure 5.8). As the geodetic techniques improve and the data lengths increase, they will provide a particularly valuable source of information along the UK south coast.

It has been demonstrated that rates of change in MSL around the English Channel and the UK can be suitably analysed using a few high quality, long and fairly continuous sea level records. This is consistent with Holgate (2007), who showed that the global rate of sea level change could be appropriately studied using nine long records, including Newlyn. The general pattern of decadal MSL change around the English Channel and UK is similar to the mean global decadal rates calculated by Holgate and Woodworth (2004) and Holgate (2007).

The peak in the English Channel and UK decadal MSL trends around 1910 is higher than that calculated by Holgate (2007). The reduced MSL trends in this current study occur earlier (about 1916) than the 'global' mean (about 1925). Differences are expected, as the records used in this current investigation were not corrected for inverse barometer effects, whereas in Holgate's assessment they were, and Holgate (2007) used different stations. Results show that the average rate of MSL rise was higher over the first half of the 20th century than the second, although the difference in rate was not found to be significant. This is consistent with results from studies that analysed the 'global' PSMSL data set (Woodworth, 1990; Douglas, 1992; Holgate, 2007). It has been suggested that this was due to reduced volcanic emissions in the earlier part of the 20th century (Church and White, 2006). Finally, it was found that there is no evidence for systematic acceleration in the rate of MSL rise around the English Channel and that the recent high rates of change in MSL are not unusual compared to those that have occurred at other times in the 20th century. This is again similar to findings on a global scale (Church et al., 2004a; Holgate, 2007).

8.3 Observed Changes in Extreme Sea Level

Only a small number of studies provide examples of changes in extremes at particular locations; Woodworth and Blackman (2002) at Liverpool (UK), Bromirski et al. (2003) for San Francisco (USA), Church et al. (2004b) for Australian sites, and Araújo and Pugh (2008) for Newlyn (UK). On a regional scale Zhang et al. (1997, 2000) investigated trends in extreme sea levels at sites along the US east coast. Woodworth and Blackman (2004) carried out the only global assessment using records from 1975 onwards at 141 stations. The findings from this study for the English Channel are consistent with these other studies in that the secular changes and inter-annual variability in extremes were found to be similar to those of MSL.

There is evidence for small increases in MHW, relative to MSL (0.1 to 0.3 mm/yr), and MTR (0.2 and 0.6 mm/yr) at some locations in the English Channel. These changes are considerably smaller than the secular MSL trends in the region. They are not found to be statistically significant (at the 95% confidence level) in the reduced extreme sea level percentiles, owing to the large variability present in these time series. Woodworth et al. (1991) found that trends in MTR varied by between -1.8 and 1.3 mm/yr around the British Isles and were due primarily to changes in the dominant $\boldsymbol{M_2}$ tidal constituent. Trends varied depending on location but were generally larger (more positive) for larger trends in local MSL. The trends in MTR along the British, Irish, French, Belgium and southern Dutch coasts were less than those reported for the northern Netherlands and the German Bight. Hollebrandse (2005) examined trends in MTR at sites along the Dutch and German coastlines, including an analysis of the Newlyn record. An increase in MTR was found at all stations. At Newlyn the MTR was found to have increased by 0.35 ± 0.09 mm/yr, consistent with the findings presented in this study at the 95% confidence level. Araújo and Pugh (2008) also found an increase in MTR at Newlyn and attributed it to increases in the amplitudes of the $\boldsymbol{M_2}$ and $\boldsymbol{M_4}$ tidal constituents.

The lack of evidence for significant trends in storm activity throughout the 20th century in the English Channel is consistent with previous studies. Pugh and Maul (1999) concluded that there were no discernible long-term trends over the last century in non-tidal residuals around the UK. Bijl et al. (1999) detected no significant increase in storminess over North-West Europe above that of the natural variability. For the French Atlantic coast, Bouligand and Pirazzoli (1999) and Pirazzoli (2000) identified a small decrease in the main factors contributing to surge development in the last 50 years. Pirazzoli et al. (2006) found that surges in the south-easterly parts of the Channel are generally produced by winds from the north-west or south-west. They found that winds from these directions have tended to decrease in frequency and speed over the last 50 years. Along the central UK south coast, they identified that surges are generated by southerly winds which have tended to increase in frequency over the last few decades. The data lengths used at these sites were short and results are almost certainly biased by decadal trends in storm activity. Araújo and Pugh (2008) examined trends in the moments and percentile levels of the non-tidal residual at

Newlyn and and found that large surges have tended to occur less frequently at this site in recent decades. In summary, the results from this study confirms earlier findings. Changes in storminess over the last 100 years have resulted in inter-decadal and decadal variations in extreme sea levels, but have not significantly influenced century scale trends.

A series of recent studies have investigated the relationship between sea level and the NAO index around northwest Europe (Wakelin et al., 2003; Woolf et al., 2003; Yan et al., 2004; Tsimplis et al., 2005; Woodworth et al., 2007). These studies observed a strong positive response in sea level to increasing NAO in the southern North Sea and a slight negative response in the southwest part of the UK, consistent with findings here. Results from this current investigation show that storm intensity was relatively weak in the English Channel at the start and end of the 20th century and highest around the late 1950’s, and is inversely related to changes in winter NAO. One would expect greater storm intensity in the southern North Sea at the start and end of the 20th century because of the stronger positive correlation observed between the NAO and sea levels in this region. The WASA group assessed historic changes in storm activity using an index based on daily geostrophic winds (WASA, 1998). They found that storminess weakened in the North Sea from 1900 to about the mid-1960’s and thereafter increased. The intensity in the late 1990’s was found to be comparable with that at the beginning of the 20th century. These results are interesting as they highlight that the storms generating surges in the English Channel are different to those causing surges in the North Sea. English Channel surges are mainly generated by storms moving over the UK from west to east at latitudes typically around 50° to 52° north (Law, 1975; George and Thomas, 1976; Henderson and Webber, 1977, 1978; Haigh, 2004; Haigh et al., 2004), whereas North Sea surges are generated by storms crossing the UK at higher latitudes. A reduction in the NAO results in fewer and weaker storms crossing the Atlantic at lower latitudes, hence resulting in increases in the storm activity in the Channel while weakening intensity in the southern North Sea. If the NAO index continues to rise in the future and the existing relationships between surges and the NAO are maintained, the storm climate in the North Sea will strengthen while storminess in the English Channel will continue to weaken. Alternatively the inverse will occur with a fall in NAO. Therefore, assessments of future changes in extreme sea levels around the UK must take into account these different storm surge regions.

As previously mentioned, surges in the English Channel tend to result from storms moving over the UK from west to east at lower latitudes. However, large North Sea surges are known to propagate into the Channel from the east (George and Thomas, 1976; Haigh, 2004; Haigh et al., 2004). It is likely that these events cause the reduction evident in the strength of negative correlation of storm intensity to winter NAO from west to east along the Channel coastlines. However, as the storm intensity is negatively correlated to the winter NAO at all sites in the Channel except Dover and Calais, it is clear the North Sea surges are not the dominant surge influence in the Channel. The extreme sea levels from the North Sea are unlikely to be correlated with significant wave action in the Channel as the depression, responsible for generating the surge in the North Sea, move away from the Channel region over northern Europe.

A modified version of Dixon and Tawn's (1994) χ^2 test statistic has been used to quantify the level of tide-surge interaction taking place in the English Channel and to investigate whether there is evidence for long-term changes. Horsburgh and Wilson (2007) concluded that there was no decadal change to the distribution of tide-surge interaction in the North Sea by visually comparing their histograms with those of Prandle and Wolf (1978). Results from this current study suggest that there are small decadal changes in the interaction distributions in the English Channel, but no long-term variations associated with the increases in MSL over the 20th century. This result is advantageous from the perspective of flood risk management. If changes in tide-surge interaction had occured, this would further complicate the mathematical procedure for computing return levels in the joint probability methods (see Dixon and Tawn, 1994 for details). This is the first example of a quantitative assessment of temporal changes in tide-surge interaction. Ideally one would carry out the assessment of long-term trends with 15-minute data as more detailed features of the distributions can be identified (Horsburgh and Wilson, 2007). However, the data lengths of high frequency data that are currently available are too short (Table 3.3).

In this investigation, changes in each of the components of observed sea level have been analysed separately as it allows the inter-decadal and decadal variations in extreme sea level to be understood more clearly. Figure 8.1 shows the variability in the time series of: (i) extreme sea level; (ii) MSL; (iii) MHW (relative to MSL); and (iv) the 95 percentile of the surge at high water at Newlyn. The variability in the extreme sea level and skew surge percentile about the mean is approximately ±0.1 m. It is roughly half this (0.05 m) in the MSL and MHW time series. Correlation between the extreme percentile and the three components are statistically significant at the 95% confidence level (coefficients: MSL variability 0.36; annual MHW 0.57; skew surge 0.25). The low extreme sea levels in the early 1970's and 1990's coincide with periods when MSL rose less than the average rate over the century. The large sea levels around 1960 concur with higher than average MSL rise and when the 18.6-year nodal cycle was at its maximum. The lower extreme sea levels in 1986 and 1987 are due to the lower storm activity around this time and because the nodal cycle was approaching its minimum. This analysis clearly shows the benefit of examining trends in the three components of sea level separately (Araújo and Pugh, 2008).

The presence of decadal variability in the different sea level components and extreme levels raises questions regarding data length. These decadal changes have an aliasing effect when using short records to estimate 20th century changes in sea level(Zhang et al., 2000). Results from the MSL component of the analysis (Chapter 5) indicate that at least 50 years of data are required to estimate 20th century rates in the Channel to within ±1 mm/yr. Following Zhang et al. (2000) trends in storm count, duration and intensity have been computed for all continuous intervals of 10, 20, 30, 40 and 50 years. Figure 8.2 shows the trends in intensity of storms with surges greater than the 99 percentile, at Newlyn. Results suggest that between 40 and 50 years of records are necessary to obtain reliable estimates of 20th century trends in storm activity, consistent with the findings of Zhang et al. (2000). Trends in MHW, MLW and MTR have been computed for all continuous intervals of 10, 20, 30, 40 and 50 years, using linear regression with allowance for the 18.6-year nodal cycle. About 36 years of data (i.e. two nodal cycles) are required to compute century scale trends in these parameters to a reasonable level of accuracy (standard error <0.15 mm/yr). When less than 36 years are used the trends can vary significantly depending on where in the nodal cycle the record begins. Together these results suggest that as a minimum 40 years of sea level records are required for robust estimates of 20th century scale trends in sea level and its components.

8.4 Estimating Probabilities of Extreme Sea Levels

Three different ways of accounting for long-term trends in extreme sea levels have been compared using the AMM, RLM and RJPM. This is the first example of such a comparison. Results demonstrate that when records with less than 50 years of data are used, estimated return levels are sensitive to how the trends in extreme sea levels are handled. Interestingly, Douglas (1991) showed that about 50 years of data are required for robust estimates of century scale trends in mean sea level. Findings also demonstrate that extreme sea level trends are more subject to bias in shorter records, compared to trends in MSL, due to larger variability in the time series of extremes. Hence, the recommendation is that the data be preprocessed by removal of the MSL trend prior to any statistical analysis. Having a standard approach would also make it easier to compare results between different studies.

It has been demonstrated that the direct methods underestimate the long period return levels (relative to the indirect methods) at sites where the astronomical tidal variations are about two times that of the surge variations. It has also been shown that the prediction errors are lowest for the RJPM and are consistently large and negative for the AMM and RLM. Hence, this suggests that bias is in the direct methods, which is consistent with the findings of Dixon and Tawn (1999). The reason for this bias has been explored in detail by Dixon and Tawn (1999). They showed that the reason the direct methods tend to underestimate the long period return levels is most likely due the key assumption in the

AMM and RLM, that the maximum (or r largest values) over a year behaves like a maximum of a stationary process. The sequence of sea level would be approximately stationary and the assumption correct, if the tidal variations and seasonality were negligible compared with the surge variability. However, if the variability of the surge is negligible relative to that of the tide, then because of the deterministic nature of the tide, the maximum sea level over a nodal cycle (i.e. 18.6 years) will be approximately a degenerate random variable equal to the highest astronomical tide (Dixon and Tawn, 1999). When this is the case, the extrapolation to long return periods using the direct methods will be poor. The results of this study are consistent with those of Dixon and Tawn (1999), in that the differences between the indirect methods and direct methods are small for return periods less than 18 years. The results from this current study have shown that this assumption breaks down when the ratio of tide to surge variation is greater than two.

Figure 8.3 shows the ratio of tide to surge variation for all mainland UK A-class tide-gauge sites, calculated using data from the BODC. The ratio is greater than two at all but two mainland UK sites; namely; Lowestoft and Millport. Tawn and Vassie (1989), Tawn (1992) and Dixon and Tawn (1999) all showed that there is good agreement between the AMM and RJPM return level estimates at Lowestoft. None of these studies analysed the Millport record. Results show that the direct methods tend to underestimate the 100-year return level by up to about 0.1 m and the 1,000-year return level by up to 0.2 m, at strong tidally-dominated sites. This is consistent with the magnitude of bias found by Dixon and Tawn (1999) (see Figure 6 in their paper) for most of the UK. It would be interesting to see if this underestimation occurs in diurnal regions.

The return levels obtained from the SRJPM relative return levels are significantly larger at long return periods along most of the UK south coast, compared to the other estimates. The main reason for this over-prediction appears has been shown to be due to the short data sets originally used to calibrate the method. This study has made use of an extensive new digital data set for the south coast, derived from data archaeology. This new data could be used to recalibrate (and hence improve) the SRJPM relative return levels in the future.

Overall the results show that the RJPM out performs the other methods. It is not sensitive to data frequency, it is stable to historical outliers and it produces the most accurate estimates of extreme sea levels from relatively short data sets. Hence, these findings support the case for the RJPM being the standard approach for assessing extreme sea levels. However, it must be stressed, as Dixon and Tawn (1999) have already emphasised, that this method requires high quality data and a more careful statistical analysis, compared to the other methods.

8.5 Further Research

This research suggests a number of different directions for further study. The following list summaries the main points:

1. **Capture remaining non-digital sea level data sets around the English Channel:**
   - At sites along the south coast of the UK, there are still over 200 years of historic charts that have not yet been digitally captured (Table 3.1). Digitising these data sets would make small extensions to the St. Mary's, Devonport, Weymouth and Portsmouth records. Significant extensions would be made for the Bournemouth, Calshot, Shoreham and particularly the Poole record, so the priority should be on capturing this dataset. Similar extensions should be considered for all other UK regions.
2. **Calculation of annual MSL values:**
   - In this study, annual MSL values have only been derived for years with 11 months of data, with at least 15 days of measurement for each month. Using this PSMSL criterion means that the majority of years from the extended St. Mary's and Weymouth data set have not been used to estimate MSL trends. Whilst this criterion

is based on an understanding of the processes driving sea level, it was not originally defined using a quantitative assessment (Woodworth, personal communication). The sea level research community would benefit from a detailed investigation of the effects of missing data on MSL accuracy. This has the potential to increase the number of years available to future studies.

3. **The effects of missing data when calculating trends in sea level:**
    - Missing data can bias trend estimates, particularly in short records. The approach taken in this study and others before it is to only include years, in the analysis of changing extreme sea level, if the amount of missing data for that period is below a given threshold (25% in this study, 25% in Woodworth and Blackman, 2004; 18% in Araújo, 2005). This cut-off, while often based on expert scientific judgement, is rarely quantifiably justified in studies. The sea level community would also benefit from a detailed analysis of this topic.
4. **Extend study to include east and west coastlines of the UK:**
    - All of the analysis techniques used in this study have been automated using Matlab, a powerful numerical computing environment and programming language. These routines could quickly and easily be applied to sea level data measured at other sites along the east and west coasts of the UK.
5. **Process-based numerical modelling:**
    - This study has focused on assessing extreme sea levels at discrete locations. An improved spatial understanding could be obtained using a process-based tide-surge numerical model. The tide -surge model could be driven with meteorological data from the European Centre for Medium-Range Weather Forecasts' ERA-40 reanalysis (Uppala et al., 2006) to simulate storm surges. One could either model single events or alternatively the entire 40 year ERA-40 period (1957-2002). In the latter case, 40-year time series of simulated hourly sea level would be extracted at each grid cell and analysed using extreme value theory. The model could also be

used to assess the influence of large North Sea surge events in the English Channel and improve understanding of tide-surge interaction patterns.

6. **Classify different types of surge events;**

   - The following types of extreme sea level events are provisionally recognised in the English Channel: (i) simple eastward propagating surges and their interaction with river flow in tidal-influence reaches and wind-generated waves (Law, 1975); (ii) residual North Sea surges which influence the eastern English Channel as far as the Solent (George and Thomas, 1976; Haigh et al., 2004); and (iii) composite surge events, for example the December 1989 event lasted much longer than a normal surge event (Wells et al., 2001). Further work would involve classifying each of the largest (say 100) extreme sea level events at each site and examining whether other types of events can be distinguished. In addition, return levels could be calculated separately for each type of event and may be helpful for flood risk management.

7. **Assess possible 21st century changes in extreme still water levels**

   - This study has focused on 20th century changes in extreme sea level. A range of possible 21st century changes could be assessed using a tide-surge numerical model of the English Channel. Different projected MSL changes would be incorporated in the model to determine how much the propagation of astronomical tide and surge is changed relative to the magnitude of the MSL change. In addition, a theoretical storm could be simulated and the influence of changing storm tracks or storm strength examined (i.e. Lowe and Gregory, 2005).

8. **A joint probability analysis of extreme still water levels and waves**

   - This study has not considered waves. Waves become particularly important when sea levels approach the height of flood defences. Hence, although the sea level may not reach the defence crest level, flooding may occur from overtopping by wave action and/or through breaching of the defence. A joint probability analysis could be undertaken of extreme still water levels and waves.

Table 8.1: Return levels for 2000, in metres to chart datum, using the revised joint probabilities methods for return periods of 1, 10, 25, 50, 100, 250, 1,000 years. Note: 95% confidence intervals can be estimated for each return level by adding or subtracting 1.96 times the associated standard error.

Site	**1**	**SE**	**10**	**SE**	**25**	**SE**	**50**	**SE**	**100**	**SE**	**250**	**SE**	**1,000**	**SE**
St. Mary's	6.30	0.014	6.50	0.011	6.57	0.012	6.61	0.012	6.66	0.013	6.71	0.014	6.80	0.015
Newlyn	6.15	0.007	6.35	0.011	6.42	0.013	6.47	0.015	6.52	0.016	6.58	0.019	6.67	0.022
Devonport	6.15	0.014	6.37	0.026	6.44	0.033	6.50	0.039	6.56	0.045	6.62	0.053	6.71	0.063
Weymouth	2.77	0.012	2.95	0.013	3.02	0.014	3.07	0.015	3.11	0.016	3.17	0.017	3.24	0.019
Southampton	5.24	0.010	5.45	0.017	5.53	0.022	5.59	0.025	5.64	0.029	5.72	0.033	5.83	0.039
Portsmouth	5.30	0.012	5.49	0.022	5.56	0.028	5.61	0.034	5.66	0.039	5.72	0.046	5.82	0.057
Newhaven	7.39	0.014	7.61	0.020	7.70	0.023	7.77	0.026	7.84	0.028	7.94	0.032	8.09	0.038
Dover	7.46	0.017	7.78	0.047	7.91	0.067	8.02	0.084	8.12	0.105	8.27	0.134	8.49	0.186
Sheerness	6.49	0.018	6.83	0.053	6.96	0.077	7.06	0.098	7.15	0.122	7.27	0.158	7.43	0.219
Brest	7.90	0.009	8.12	0.010	8.19	0.011	8.25	0.012	8.30	0.013	8.37	0.014	8.45	0.015
Le Conquet	7.61	0.012	7.83	0.014	7.90	0.016	7.96	0.017	8.01	0.019	8.07	0.021	8.16	0.023
Roscoff	9.71	0.014	9.92	0.014	9.99	0.014	10.04	0.015	10.10	0.016	10.16	0.017	10.25	0.018
Jersey	12.06	0.018	12.29	0.015	12.38	0.016	12.44	0.017	12.50	0.018	12.59	0.019	12.71	0.021
Cherbourg	7.04	0.010	7.24	0.010	7.32	0.012	7.37	0.013	7.42	0.014	7.49	0.016	7.58	0.017
Le Havre	8.66	0.016	8.90	0.019	9.00	0.021	9.07	0.022	9.14	0.024	9.23	0.026	9.36	0.029
Boulogne	9.58	0.017	9.86	0.015	9.96	0.016	10.03	0.017	10.10	0.018	10.19	0.019	10.32	0.020
Calais	7.87	0.015	8.14	0.018	8.25	0.021	8.32	0.023	8.40	0.025	8.50	0.028	8.64	0.031
Dunkerque	6.80	0.017	7.11	0.021	7.22	0.022	7.30	0.023	7.38	0.025	7.47	0.027	7.58	0.029

Table 8.2: Return levels for 2000 in metres relative to chart datum at Newlyn.

Return Period	**Return level based on 1925**[15]	**Return level based on 1950**[16]	**Return level calculated using all data**
1	6.125	6.149	6.155
5	6.254	6.290	6.294
10	6.308	6.346	6.350
50	6.420	6.468	6.472
100	6.465	6.512	6.517
250	6.529	6.575	6.581
1,000	6.625	6.658	6.668

Table 8.3: Return levels for 2000 and 2100 in metres relative to chart datum at Newlyn.

Return Period	**Return level for 2000**	**Return level for 2100, low scenario**[17]	**Return level for 2100, high scenario**[18]
1	6.155	6.345	6.845
5	6.294	6.484	6.984
10	6.350	6.540	7.040
50	6.472	6.662	7.162
100	6.517	6.707	7.207
250	6.581	6.771	7.271
1,000	6.668	6.858	7.358

[15] Calculated using data up to 1925 plus 75 years of MSL rise.

[16] Calculated using data up to 1950 plus 50 years of MSL rise.

[17] Calculating by adding 15 cm of sea level rise and 4 cm of land subsidence to the return level for 2000.

[18] Calculating by adding 56 cm of sea level rise, 4 cm of land subsidence and 9 cm increase in the predicted tide to the return level for 2000.

Table 8.4: Return period in 2100 of a 1 in 1,000-year event in 2000 plus projected increases in relative mean sea level.

UK South Coast Sites			French Channel Sites		
Station Name	**Lower End of IPCC's AR4 range**	**Upper End of IPCC's AR4 range**	**Station Name**	**Lower End of IPCC 's AR4 range**	**Upper End of IPCC's AR4 range**
St. Mary's	114	0.3	Brest	82	0.3
Newlyn	59	0.5	Le Conquet	58	0.3
Devonport	48	0.4	Roscoff	133	0.5
Weymouth	38	1.3	Jersey	70	0.5
Southampton	183	0.6	Cherbourg	242	0.6
Portsmouth	149	0.3	Le Havre	95	0.8
Newhaven	122	0.8	Boulogne	610	4.5
Dover	276	10.2	Calais	226	2.7
Sheerness	119	3.7	Dunkerque	118	2.0

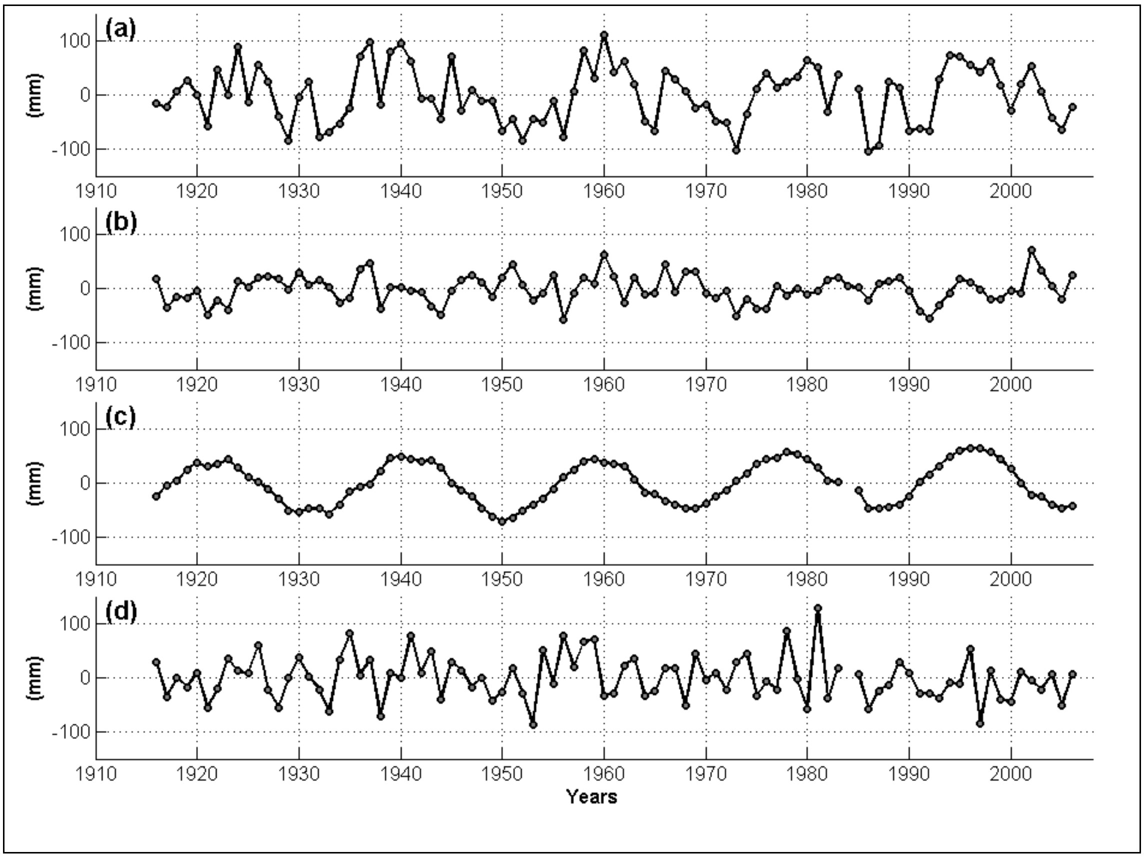

Figure 8.1: (a) 95 percentile level of extreme sea level minus the MSL linear trend; (b) MSL variability about the linear trend; (c) annual mean high water; (d) 95 percentile level of the surge at high water, at Newlyn.

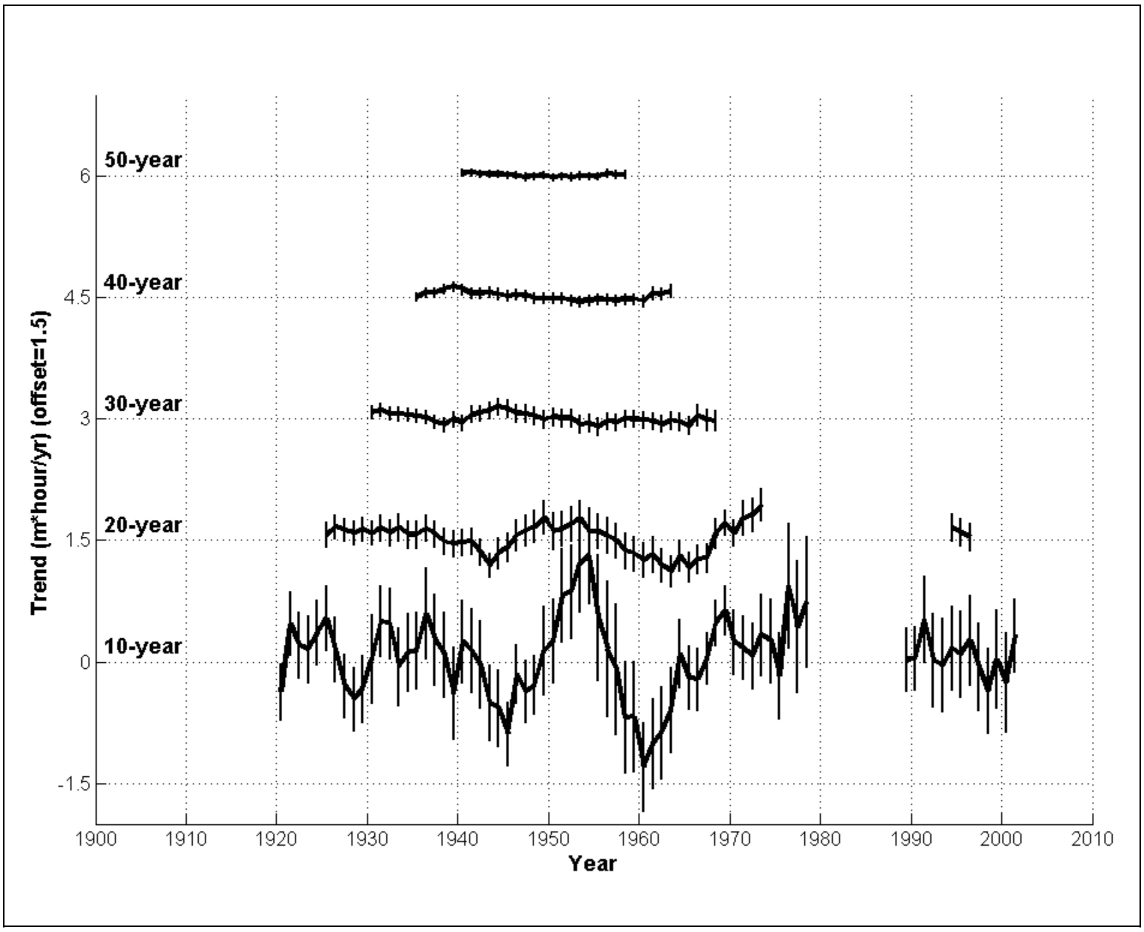

Figure 8.2: Trends of annual storm intensity above the 99 surge percentile level for all continuous intervals of 10, 20, 30, 40 and 50 years in length at Newlyn. Time series are offset by 1.5. The error bars show ±1 standard error.

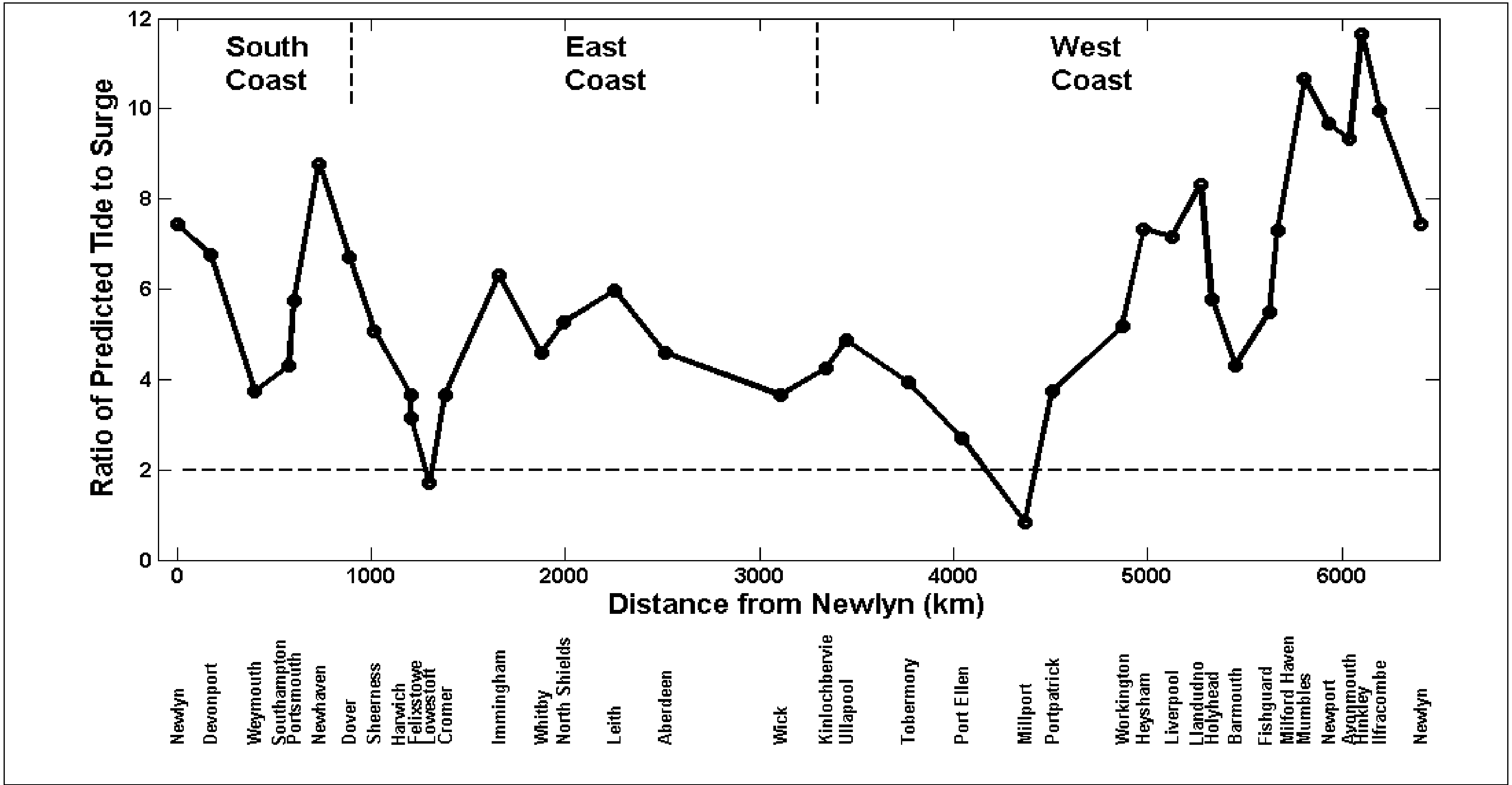

Figure 8.3: Ratio of the 98% quantile of the astronomical tide (relative to a mean level of 0), divided by the 98% quantile of the surge component for all UK mainland A-class sites, plotted against distance anticlockwise around the coast from Newlyn.

9 CONCLUSIONS

In this thesis, the hypothesis that changes in extreme high sea level can be determined, to an engineering accuracy of 0.1 m, by simply adding changes in mean sea level to return levels estimated from measured data (i.e. the mean sea level offset approach), has been tested for the English Channel region. This has been done from a historical perspective using data from 1900 to 2006. The thesis has addressed three objectives: (i) to determine the rates of observed change in mean sea level in the English Channel; (ii) to establish whether changes in extreme sea level throughout the 20th century were primarily caused by variations in mean sea level; and (iii) to evaluate which is the most appropriate statistical method for estimating probabilities of extreme high sea level in the English Channel.

A data archaeology exercise has been undertaken to extend the sea level records along the UK south coast. In total, the exercise increased the sea level record for the UK south coast by 173 years. These new records have been analysed with existing data from the Permanent Service for Mean Sea Level to provide up to date and accurate estimates of rates of mean sea level change along both the French and English coastlines of the English Channel. Relative mean sea level trends vary between 0.8 and 2.3 mm/yr around the Channel, depending on location. These trends have been estimated using a new approach, recently introduced by Woodworth et al. (2009), in which the coherent part of the sea level variability around the English Channel and UK is defined as a single index. This index is subtracted from the sea level records prior to fitting trends. Removal of the coherent part of the sea level variability allows more precise trends to be calculated from records spanning 30 years. With the traditional approach, 50 years of record is required to obtain the same level of accuracy.

Rates of vertical land movement have been estimated from the sea level records and compared to measurements from geological data and advanced geodetic techniques. The geological data appears to overestimate the recent subsidence, especially in southwest England.

There is no evidence of any acceleration of sea-level rise in the English Channel during the 20th century. The recent high rates of change observed in mean sea level are not unusual compared to those that have occurred at other times in the 20th century.

Extreme sea levels increased during the 20th century at all study sites in the English Channel. This increase is primarily due to the direct rise in mean sea level. There is evidence for a small (0.1 to 0.3 mm/yr) increase in mean high water (relative to mean sea level) at select sites. However, trends in mean high water are considerably smaller than those in mean sea level and so did not significantly increase extreme sea levels over the last 100 years beyond that associated with the secular mean sea-level rise.

There is considerable interdecadal and decadal variability in storm activity in the Channel, but no evidence for a systematic change in storminess over the 20th century. Storm intensity is weakly and negative correlated to the winter North Atlantic Oscillation index throughout most of the English Channel, but is strongly positively correlated at the interface with the southern North Sea.

Tide-surge interaction is strongest at the eastern end of the English Channel. There are small decadal changes in the interaction distributions, but no long-term variations associated with the increase in 20th century mean sea level.

An extreme sea level analysis has been undertaken using four methods: (i) the annual maxima method; (ii) its extension to the r-largest annual events method (iii) the joint probabilities method; and (iv) the revised joint probabilities method. It has been demonstrated that unless sea level records with at least 50 years of measurements are used, the way in which the long-term trends is handled in the different methods can lead to significant differences in the estimated return levels. It has also been shown that the direct methods underestimate the long (>20 years) period return levels when the ratio[19] of the astronomical tidal variations to the surge variations, is greater than two.

Return levels estimated using the spatial revised joint probability method relative return levels are significantly larger along the UK south coast at long (>20 years) return periods than the estimates calculated using the other four methods. The main reason for this is due to the comparatively short data sets originally used to calibrate the model in this area. The new data collected in this study could be used to recalibrate and hence improve the SRJPM relative return levels in the future.

The revised joint probabilities method is found to perform best, in terms of prediction errors, at the majority of the sites analysed. Further, this method is: (i) not sensitive to data frequency; (ii) stable to historical outliers; (iii) produces the most accurate estimates of extreme sea levels from relatively short data sets; and (iv) not sensitive to the ratio of tide to surge variability at a given site.

Overall, the results from this research verify that changes in extreme sea levels in the English Channel can be determined, to within an accuracy of 0.1 m over the 20th century, by just adding changes in mean sea level to return levels estimated from measured sea level data. The return levels should be estimated using the revised joint probabilities method wherever possible. In order to determine changes in extreme sea level during the 20th century to a higher accuracy (<0.05 m) would also require that the increase in predicted high water be taken into account. Hence, this thesis concludes that the mean sea level offset approach can be meaningfully applied to estimate extreme sea level scenarios for the 21st century, but with the caveats that the potential rise in sea level is larger and systematic changes in storminess are possible.

This thesis has contributed new insights regarding the study of changes in mean and extreme sea level and for estimating probabilities of extreme sea levels. In particular, this

[19] The ratio of tide to surge variation has been defined as being the 98% quantile of the astronomical tide (relative to a mean level of 0), divided by the 98% quantile of the surge component.

research has:

- Significantly increased the digital sea level record for the south coast of the UK (approximately a 50% increase).
- Used a new procedure (proposed by Woodworth et al., 2009) to improve estimates of long-term changes in mean sea level.
- Quantified the extent to which this new method allows more accurate estimates of change in mean sea level to be calculated from shorter records.
- Developed an improved test, which takes into account the different interaction patterns on the ebb and flood tide, to more accurately determine the level of tide-surge interaction taking place at each site.
- Used this new test to undertake the first quantitative assessment of long-term changes in the patterns of tide-surge interaction.
- Carried out a detailed assessment of the importance of data length in accurately determining trends in sea level and its component parts.
- Comprehensively compared the main extreme value analysis methods for estimating probabilities of extreme still water level.
- For the first time, assessed in detail the sensitivity of these different statistical methods to: (i) the method to consider and remove long-term trends; (ii) the frequency, length and completeness of the available sea level records; and (iii) the ratio of tide to surge variability.
- Been the first to determined the ratio of tide to surge variability at which the direct methods start underestimating the long (>20 years) period return levels.

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APPENDICES

Appendix A: Gauge Histories

In this appendix, short gauge histories are given for the UK south coast sites where data extensions were made. The final data set (up to the end of 2007) is briefly described and the potential for further extensions are outlined. This data has been donated to the BODC. The data can also be downloaded from: http://www.ivanhaigh.com/Sea-Level/Home.html. The web-site also includes additional information for each site, such as datum changes.

St. Mary's

In 1966 a Lea chart recorder float gauge was installed in Hugh Town on St. Mary's Island, which is part of the Isles of Scilly. The gauge and building were lost in a storm in 1989. The new A-Class bubbler system was not installed until 1994, following the redevelopment of the quay. This study has added a further nine years of data (three from the UKHO tabulated data and six from digital POL data) to the existing 14 years of BODC data. The data set now has 24 years, spanning 40 years (1969 – 2007). There are an additional 14 years of chart data archived at the BODC. The final record would have 38 years of data, spanning 42 years (1966 – 2007), if this is digitised.

Devonport

A Lea stilling well gauge, maintained by the UKHO, was in use from 1961. Since March 1991 the gauge has been an A-Class bubbler system operated by POL. This study has added a further 29 years of hourly data (from the UKHO tabulated data) to the 18 years held by the BODC. The record now has 47 years of data, spanning 47 years (1961 – 2007). There is potential to extent the record back a further eight years (to 1953) if the tidal charts archived at the UKHO are digitized. This would give a record of 55 years, spanning 55 years (1953 – 2007).

Weymouth/Portland

Since the 1960's an OTT gauge was used at Weymouth and was operated by the Weymouth and Portland Borough Council. The installation date is uncertain. The gauge ceased recording in 1989 or 1990. The tidal charts have been misplaced. An A-Class bubbler gauge system was installed in 1991 by POL. The first tide gauge was installed at the Portland Naval Base in 1852 and was operational until the 1930's. A Gents system was in use between June 1961 and 1964 and upgraded in 1966. In December 1972 a MUNRO gauge was installed and used until 1987. Tidal charts from 1923 onwards are held by the UKHO. The earlier records have been misplaced. A composite record has been created by combining 17 years from the Portland record (12 years from UKHO tabulated data and five from POL) with the 'A Class' Weymouth data. The record contains 34 years, spanning 85 years (1923 – 2007). The data set could be extended by 15 years if the tidal charts archived at the UKHO are digitised, resulting in a data set of 49 years, spanning 85 (1923 – 2007).

Southampton

A Cary-Porter gauge was installed on the Royal Pier in 1905. This was relocated to Town Quay in 1921 and continued recording sea levels until the 17th November 1986. On the 3rd September 1979 an AGA gauge was installed at 37 Berth Steps, Dock-Head. This measured sea levels until the 19th February 1990. On the 6th Nov 1990 the gauge was replaced with a SONAR SRD system. The chart records prior to 1935 have been misplaced. The complete record was created by combining the 38 years of data digitized from the tidal charts (1935 – 1950, 1976 – 1979, Town Quay; 1982 – 1990, 37 Berth Steps) with the 16 years of digital POL data (1951 – 1966) and the most recent 17 years of digital data (1991 – 2007). The record has 71 years of data, spanning 73 years (1935 – 2007). No further extensions are possible.

Portsmouth

Starting in 1813, systematic records of sea level were undertaken at the Portsmouth Naval Base using a tide board. In 1833 a tide gauge was installed and replaced with a new gauge in 1886. The gauge types are not known. In 1960 a Lea stilling well gauge was installed and replaced in 1997 with a Hydrotide digital recording system. These gauges were/are operated and maintained by the UKHO. In 1991 an A-Class bubbler system was installed by POL, at the same location as the current UKHO gauge. 30 years of data (from the UKHO tabulated data set) have been added to the digital BODC data set, resulting in a record length of 47 years, spanning 47 (1961 – 2007). Potentially 22 more years of data sets could be added, if the tidal charts archived at the UKHO are digitized. This would give a final data set of 69 years, spanning 72 (1936 – 2007).

Newhaven

A Bailey gauge was installed on Newhaven West Pier in 1890. This was replaced in 1941 and again in 1966. The gauge types are not known. Between May 1982 and 1990 an Ott pneumatic system was in operation, with an Aanderaa backup system. Tidal charts for these gauges cannot be traced. In November 1990 POL installed an A-Class Dataring and Bubbler system. In 1991 the Bubbler system was removed due to harbour works and reinstalled in 1992. 18 years of records (from the POL digital data set) have been added. Combining this with the BODC data results in a record length of 41 years, spanning 66 (1942 – 2007). It appears no further data extensions are possible.

Appendix B: EOF Analysis and Sea Level Index

This appendix describes the EOF analysis that has been undertaken in this investigation and the approach used to construct a sea level index. These are based on the ideas of Woodworth et al. (1999) and have been extended to include sea level data from the northern French coast.

EOF Analysis

The MSL records that are available are fragmented and have an unequal spatial distribution. In order to overcome this difficulty, sites have been divided into five groups, each representative of specific stretches of coastline. These are: (i) the south coast of the UK, (ii) northern French coast, (iii) UK west coast and Irish Sea, (iv) the UK north North Sea coast (North Shields to Lerwick) and (v) the UK south North Sea coast (Sheerness to Cromer). The MSL time series for each site were detrended over their whole record lengths and their mean values removed. A single time series for each region was then produced by averaging the residual mean annual values across the sites within each group. An EOF analysis was then performed on the five regional-average time series, for the common period 1953 to 2006. This is shorter than the period Woodworth et al. (1999) analysed (1918 to 1996), because of the gaps in the French records between 1943 and 1953.

Sea Level Index

The six longest and most continuous records (Brest, Newlyn, Sheerness, North Shields, Aberdeen and Liverpool) have been used to construct a 'sea level index'. Each of the six records has been detrended using the common period 1916 to 2006. The detrended MSL values were then averaged across the six sites to create a single time series, representative of the average coherent part of the sea level variability around the English Channel and UK.

References

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Appendix C: Modified Tide-Surge Interaction Test

Two standard methods have tended to be used to identify whether tide-surge interaction is present at a given site. The first involves checking if extreme surge events occur at a particular level (e.g. Walden et al., 1982) or phase (e.g. Prandle and Wolf, 1978) of the tide. In the second method, the probability distributions of the non-tidal residuals are compared for different stages of the tide (e.g. Zhang et al., 2000). Both methods involve considerable subjectivity in their practical application (Bernier and Thompson, 2007).

Dixon and Tawn (1994) suggested an alternative, less subjective approach. This involves splitting the astronomical tidal range into five equi-probable bands. As there are an equal number of non-tidal residual observations with associated astronomical tidal level in each band, the non-tidal observation has an equal probability of falling in any one of the five bands. If the tide and surge were independent processes, the number of surges per tidal band expected to exceed a specific threshold would be the same. However, if interaction is significant the number of surges per tidal band which exceed the threshold would differ. If the threshold is the 99 percentile level of the surge distribution and tide and surge are independent, one would expect *nobs x 0.01 /5 = e* observations above the threshold in each tidal band (*nobs* is the number of hourly observations). If there is interaction, one would observe *Ni (i=1, …., 5)* hourly observations in each of the five bands. Interaction can then be tested for using the following standard Chi-squared (χ^2) test statistic:

$$\chi^2 = \sum_{i=1}^{5} \frac{(N_i - e)^2}{e}. \qquad \text{(EQ.A1)}$$

When the tide and surge are independent the test statistic is small, as the observed number of large surges per tidal band is close to the number expected. The processes are deemed to interact when the value of the test statistic is above the 95% significance level of the test (i.e. $\chi^2_{4,0.95} = 9.5$).

Dixon and Tawn's (1994) test statistic is based on tidal level and does not distinguish that interaction tends to be different on the ebb and flood phases of the tide

(Horsburgh and Wilson, 2007). Hence, the test statistic has been modified in this current study by relating it to tidal phase and not tidal level. The timing of the surge peak relative to the nearest high water is recorded for each surge event greater than the threshold. The tide is now divided into 13 hourly bands between 6.5 hours before and after high water. With no tide-surge interaction the expected number of occurrences in each of the 13 bands becomes *nobs x 0.01 /13*. The statistic is calculated in the same way as before, but summed over the 13 bands. Interaction is deemed to be significant (95% level) if the test statistic is larger than 21 (i.e. $\chi^2_{12,0.95}$).

The two approaches are illustrated in Figure A1. In plot (a) all surge events greater than the 99 percentile are shown plotted against tidal level. In total 472 events are identified that are greater than the 99 percentile. If tide and surge were independent processes one would expect about 94 occurrences in each of the five bands. The plot demonstrates that surge peaks tend to occur most frequently on mid-tidal levels. Plot (b) shows the surge events greater than the 99 percentile plotted against time to the nearest high water. If tide and surge were independent processes there would be about 36 occurrences in each of the 13 bands. The majority of events are seen to occur around four hours before high water.

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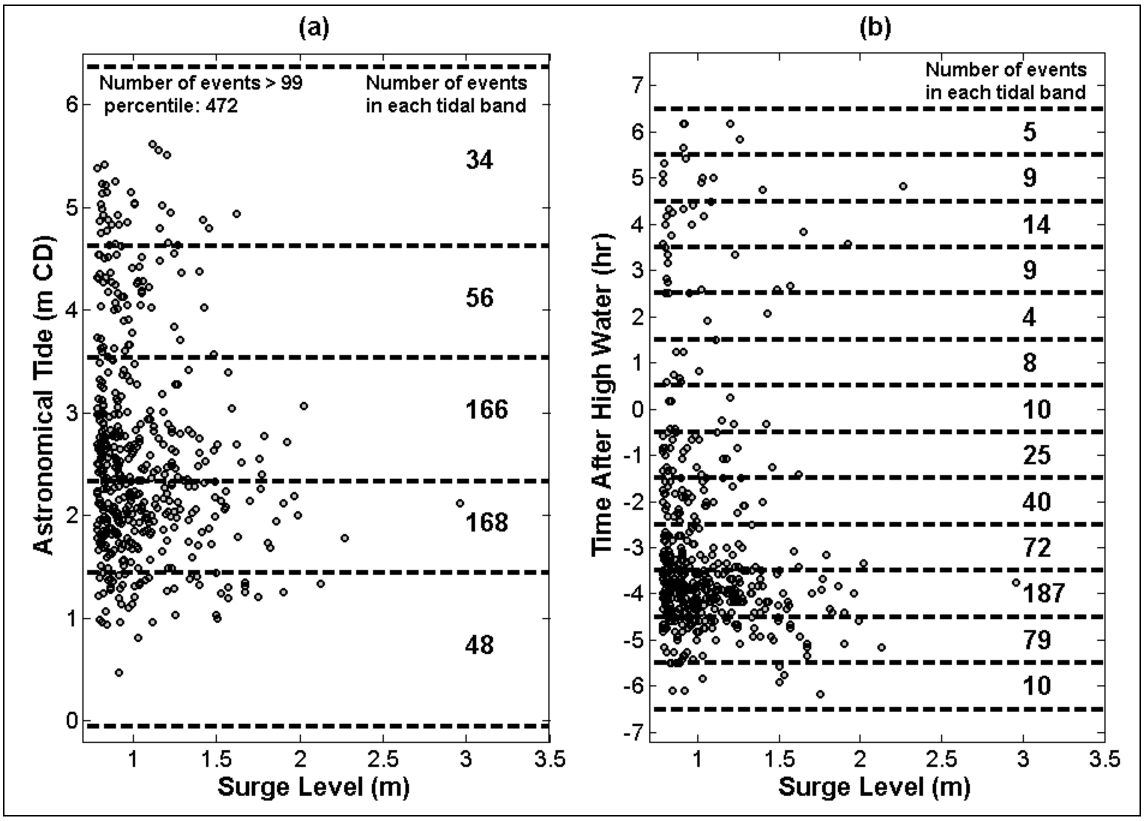

Figure A1: (a) Astronomical tide plotted against surge level; and (b) tidal phase plotted against surge level, for all surge events greater than the 99 percentile level at Sheerness.