23 March 2008

Trends in UK Mean Sea Level Revisited

P.L. Woodworth

Proudman Oceanographic Laboratory, 6 Brownlow Street, Liverpool L3 5DA, UK

Email: plw@pol.ac.uk

F.N. Teferle, R.M. Bingley

Institute of Engineering Surveying and Space Geodesy, University of Nottingham,

University Park, Nottingham NG7 2RD

Email: norman.teferle@nottingham.ac.uk, richard.bingley@nottingham.ac.uk

I. Shennan

Department of Geography, University of Durham, Science Laboratories,

South Road, Durham DH1 3LE, UK

Email: ian.shennan@durham.ac.uk

Accepted date:

Received date:

Summary

This paper presents estimates of rates of mean sea level (MSL) change around the UK based on a larger tide gauge data set and more accurate analysis methods than have been employed so far. The spatial variation of the trend in MSL is found to be similar to that inferred from geological information and from advanced geodetic techniques, which is a similar conclusion to that arrived at in previous, less precise and complete studies. The tide gauge MSL trends for 1901 onwards are estimated to be 1.4 +/- 0.2 mm/year larger than those inferred from geology or geodetic methods, suggesting a regional sea level rise of climate change origin several 1/10s mm/year lower than global estimates for the 20th century. However, UK MSL change cannot be described in terms of a simple linear increase alone but includes variations on interannual and decadal timescales. The possible sources of variation in a 'UK sea level index' are explored. Air pressure is clearly one such possible source but its direct local forcing through the 'inverse barometer' accounts for only one third of the observed variability. A number of larger scale atmospheric and ocean processes must also play important roles, but modelling them satisfactorily and separating the individual contributions presents a major challenge. As regards future regional UK sea level changes, one concludes that there is no basis for major modification to existing projections for the 2080s included in the 2002 UK Climate Impacts Programme studies.

Abbreviated title: Trends in UK Mean Sea Level

Keywords: Sea level change; Global change from geodesy; Atlantic Ocean

1. Introduction

Sea level change is an important scientific topic, closely linked to studies of climate change, solid earth processes and geodetic science. It is of great interest to government and the general public because of the possible impacts of sea level rise on the coast and the associated costs of coastal protection.

This paper provides estimates of long term sea level change as observed in records of the UK National Tide Gauge Network. A major review of changes in UK mean sea level (MSL) was undertaken almost a decade ago by Woodworth et al. (1999). That report concluded that sea level had been rising around our coasts during the 20th century at rates consistent with knowledge of vertical land movements obtained from geological data, together with an additional 1 mm/year. That amount was compatible with, if at the lower end of the range of, the 1-2.5 mm/year estimated for global sea level change by the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (Warrick et al., 1996). That conclusion was unchanged by the modified range for 20th century global sea level change of 1-2 mm/year in the IPCC Third Assessment Report (Church et al., 2001).

Since then, there have been major workshops (e.g. World Climate Research Programme workshop on Sea Level Rise and Variability, Church et al., 2007a), reviews by individual scientists (e.g. Woodworth et al., 2004), and, most recently, the publication of the IPCC

Fourth Assessment Report (Bindoff et al., 2007). A consensus seems to have been achieved that the 20th century rise in global sea level was closer to 2 than 1 mm/year, with values around 1.7 mm/year having been obtained recently for the past century (Church and White, 2006) or past half-century (Church et al., 2004; Holgate and Woodworth, 2004).

As almost a decade has passed since the last major UK investigation of this topic, it is reasonable to examine the evidence for long term sea level change once again from a national perspective. In particular, in the study of Woodworth et al. (1999), the shorter sea level records available were not able to contribute in a major way to the analysis. In the present study, the records are now several years longer and a serious attempt has been made to make more effective use of them. The last decade has also seen great advances in the development of advanced geodetic techniques for measuring vertical land movements at tide gauges (IOC, 2006). These concern primarily the Global Positioning System (GPS) and absolute gravity (AG), or, in the case of the UK, the two techniques used in combination (Teferle et al., 2006).

A main objective of the present investigation is to determine more accurately than before the recent rates of sea level change around the UK coastline. A particularly important component of that investigation is a comparison between tide gauge information and data from geological sources and, in the case of sites with long sea level records, between tide gauge and GPS information. A second objective is to understand more about the reasons for interannual and decadal variability in UK sea level. This is an important topic in itself, but it is also relevant in a discussion of long term sea level trends. The degree to which one is able to model (or understand) the variability determines the accuracy with which long term trends can be computed, and enters ultimately into a consideration of the ability for making useful predictions of future sea level.

2. Data Sets

The UK National Tide Gauge Network is operated by the Proudman Oceanographic Laboratory on behalf of the Environment Agency. It consists of 44 sites, almost all of which nowadays use bubbler pressure gauges as the primary sensors, equipped in many cases with half-tide sensors for datum control (Woodworth et al., 1996). A short history of recording at each site was provided by Woodworth et al. (1999).

All UK data are contributed to the Permanent Service for Mean Sea Level (PSMSL, Woodworth and Player, 2003) and can be inspected and downloaded via www.pol.ac.uk/psmsl. The Revised Local Reference (RLR) section of that data set provides the monthly and annual MSL values, measured with respect to the same local land datum at each station, which are the most suitable for time series analysis. Two RLR records are available from both Aberdeen and Liverpool, and these were combined into composite records for each site. In addition, an early section of the Holyhead RLR record was adjusted for the local difference between MSL and Mean Tide Level as described by Woodworth et al. (1999). The HadSLP2 monthly mean air pressure data set (Allan and Ansell, 2006) was downloaded from the Hadley Centre, UK Met Office (hadobs.metoffice.com/hadslp2), while best estimates of rates of late Holocene sea level change, represented by the negative of the best estimated values of land emergence/submergence, were extracted from Shennan and Horton (2002).

3. Sea Level Trends

Table 1 presents the linear trends in annual MSL in each record for sites with more than 15 complete years of RLR data, a minimum selection criterion as justified by Woodworth et al. (1999). Figure 1 shows their locations. The RLR records from Whitby and Felixstowe were not included in our selection as the PSMSL documentation made clear that they were of poor quality. Only complete years were considered for the station selection criteria, and used for Table 1 for consistency with a similar table in Woodworth et al. (1999), but in the following tables and figures in this report we have also employed annual means computed for years containing only 11 months of data, consistent with normal PSMSL practice. This provides a small increase in the number of station-years available for analysis, at the expense of slightly less precise annual mean values. The gain can be seen by comparing the number of years of data in Tables 1 and 2.

The five longest records are shown in Figure 2(a), while MSL values for each record are shown relative to those at Newlyn in Figure 2(b). The time series in the latter are described to a good approximation in terms of a linear trend, consistent with a general picture of there being an approximately linear vertical land movement signal in each sea level record together with coherent variability due to oceanic and meteorological forcings. The five long records provide a reasonably representative sampling of sea level change around the UK coastline. Woodworth et al. (1999) demonstrated that, while the character of sea level variability differs between locations, part of this variability is coherent between sites. Consequently, records can justifiably be combined into a UK 'sea level index'. An index for 1901 onwards, based on the five long records each detrended over a common period 1921-1990, is shown in Figure 3(a), providing an update to the index presented by Woodworth et al. (1999). Although there are gaps in all records, at least 3 of the 5 stations are represented in the index for all years apart from 1902, 1904 and 1915..

Woodworth et al. (1999) referred to the weak correspondence of the Liverpool time series with the other four records, and this remains the case. Nevertheless, it is one of the longest UK records and cannot be excluded from a UK-average, at the risk of adding more noise than signal to the average. In spite of the simplicity of constructing an index in this way, the resulting time series is almost identical to a second index computed using principal component analysis of both long and short records. The two indices, and their regional subsets, provide convincing evidence (Figures 8-11 of Woodworth et al., 1999) for a large part of the MSL variability around the UK coast being coherent. The UK index closely resembles a separate index for the North Sea/English Channel, based primarily on data from the European coastline (Shennan and Woodworth, 1992) and, as we shall below, it is similar to individual European records from Norway to France. Consequently, we have persevered with the use of the readily-updateable simple 5-station index in the present study, confident that it represents a major part of regional coastal

MSL variability. The index has a zero long term trend by construction. It contains a small 'acceleration' with a quadratic coefficient of 0.0055 ± 0.0028 mm/year^2, comparable to those of the longest records which commence in the mid-19th century (Table 3). It also contains interannual and decadal variability with a root-mean-square (rms) of 24.5 mm.

In previous analyses of MSL trends, in which comparisons are made to rates of sea level change from nearby geological information, the normal procedure has been to emphasise the importance of the longest records. For example, Douglas (1991), Shennan and Woodworth (1992) and Tsimplis and Spencer (1997) determined that typically 50 years of data are usually required to derive a standard error on a linear trend of approximately 0.3 mm/year, and therefore be useful in studies where the trends themselves are of the order of 1-2 mm/year. (Pirazzoli, 1986 arrived at a similar conclusion from qualitative inspection of the records.) Therefore, shorter records have often been discarded or given a lower weight. However, several authors have used Empirical Orthogonal Function (EOF) or 'master station' techniques (Emery and Aubrey, 1991; Woodworth and Jarvis, 1991; Woodworth et al., 1999), and have shown that shorter records can be used to derive relative sea level trends between stations to good accuracy, taking advantage of the fact that any coherent variability is removed when one station record is compared to another.

Therefore, in the present analysis we have made use of the index itself as the 'master', with a trend computed for a record relative to the index being the best estimate of long term change at a site. We have also made use of MSL values for 1955-2006 provided by a tide+surge barotropic numerical model for the NW European continental shelf (Flather et al., 1998), in an attempt to remove some of the higher-frequency variance from the shorter individual records. In the case of such records which commence after 1955, the model annual MSL values are subtracted from the measured MSLs, and the corresponding model average-MSL for the five stations is subtracted from the index.

Table 2 presents the linear trends for each station computed by this method, the flag indicating whether each record has been compared simply to the index (flag 0) or has been adjusted by the numerical model (flag 1). The last column shows the correlation coefficient between each MSL record (before any model correction and trend fitting) and the index. The coefficient is seen to be positive for every station. Of course, a positive correlation is to be expected for the five long records which make up the index. However, the fact that all the others are also positive provides further evidence for part of the variability being similar at each site, and supports the 'master station' approach. The removal of the common variance can be seen to be important. While in some cases there is little improvement, in other cases the standard errors are only a fraction of those obtained by fitting linear trends to the original records in Table 1. The benefit of using the model (flag 1) was a modest one but it did result in a reduction in residual variance about the fitted trend relative to that in the simple comparison to the index (flag 0) for 10 of the 12 records starting in 1955 or later. Therefore, we have chosen to use the flag 1 results for these stations.

Two main reservations can be made about the index as employed here. A first is that, as referred to above and as can be seen from Table 2, the similarity between Liverpool and the index of which it is a component is weak. A second is that, due to gaps in each of the 5 records, the index will have been defined by a different set of stations at different times. Consequently, when a short record is considered, there is a varying possibility of its nearest neighbour long records being included or not in the index, which could affect the apparent strength of correlation of the short record with the index. However, these two reservations cannot be major ones: the similarity of the 5-station time series with other forms of UK and European index means that Liverpool (or bad sections of data in any of the 5 records) cannot result in a significant distortion of it, while the existence of data from 3 of the 5 stations at all times (apart from 3 early years) means that any localised correlations between a short record and a long-record neighbour will be diluted by at least a factor of 3 in the correlation with the index. The complete set of positive correlations, of whatever magnitude, in Table 2 provides reassurance of a reasonable (if inevitably imperfect) procedure.

A validation of these findings can be made by comparison of the trends in MSL to those obtained from geological information near to the tide gauge stations. Such comparisons have been made before but with the use of the MSL trends as observed in the individual records (Shennan and Woodworth, 1992; Woodworth et al., 1999; Shennan and Horton, 2002). Figure 4(a) shows a scatter plot of the MSL trends in Table 1 with the ‘best estimates’ of geological trends by Shennan and Horton (2002) (Table 4). Standard errors for the ‘best estimates’ are not given by Shennan and Horton (2002), so we have used 0.2 mm/year throughout for the present study, based on inspection of the tables in their report.

Evidence for correlation between tide gauge and geological data can be seen in Figure 4 (a). However, the correlation is at first sight less convincing than in studies of North Sea or Scandinavian data (e.g. Shennan and Woodworth, 1992; Milne et al., 2001). The reason for this is that the range of possible sea level trends (or vertical land movements) around the UK is of the order of only 2 mm/year, compared to the 4 and 9 mm/year in the North Sea and Scandinavia respectively, rather than a generally lower accuracy of UK data. Figure 4 (a) has many similarities to Figure 8 of Shennan and Horton (2002), who made use of the measured MSL trends reported in Woodworth et al. (1999). This would suggest that the addition of a decade of new tide gauge information has resulted in little improvement in agreement between the data sets. However, the correlation is improved in Figure 4(b) with the use of the MSL trends from Table 2. Simple correlations between points (ignoring individual errors) of 0.25 and 0.59 are obtained from Figures 4(a) and (b) respectively. This demonstrates that there is a benefit in using the index as a 'master station' in enabling shorter records to be used in analyses of long term change.

In spite of the apparent improvement in agreement between UK tide gauge and geological data sets, there are some reservations to be made. A first is that Figure 4 (b) contains several outliers with the largest from Rosyth and Immingham. Rosyth was a UK Hydrographic Office gauge, the generally poorer quality of which was remarked on by Woodworth et al. (1999). It is no longer operational. The Immingham tide gauge is known to be affected by density changes due to runoff from the Humber. In addition, the choice of geological trend to use for comparison depends critically upon location in the estuary (Shennan and Horton, 2002).

A second reservation is that the Shennan and Horton (2002) data set does not contain geological estimates for the Hebrides, Shetlands or Northern Ireland. Therefore, MSL records from Stornoway, Lerwick and Belfast have not been included in the present analysis. With regard to Lerwick, the small amount of geological information available from the Shetlands and geodynamic models (Hoppe, 1965; Peltier et al., 2002) suggest long term submergence, whereas the tide gauge record (Table 1) suggests significant uplift (especially if one considers a present-day sea level rise of approximately 1.4 mm/year, see below). Consequently, it is unlikely that the Lerwick record would conform to the encouraging picture of Figure 4 (b), even if copious local geological data were available. Stornoway's record will be of great interest when longer: its present trend (Table 1) appears high although it has a large standard error. Belfast offers the greatest potential for further study, with tide gauge charts extending back to the 19^{th} century having been recently rediscovered in an archive.

These reservations aside, the consistency evident between tide gauge and geological data sets supports the overall picture of spatial variation in vertical land movements in the UK (Shennan, 1989; Shennan and Horton, 2004). The distributions of Figures 4 (a,b) also indicate that tide gauge MSL trends are in general larger than those inferred from geological data by 1.34 +/- 0.21 and 1.42 +/- 0.17 mm/year respectively (using weighted averages based on the individual tide gauge trend errors, taken as dominating over geological errors, and with standard errors estimated conservatively from both weighted and unweighted distributions). The latter value, which we consider the most reliable being based on the 'master station' method, is approximately 0.3 mm/year lower than the accepted value for global sea level change during the 20th century referred to above (Church et al., 2001; Bindoff et al., 2007).

Although the shorter records have proved to be useful, there naturally continues to be most interest in the longer ones. Figure 5 (a) presents a scatter plot between the tide gauge trends for the 20th century for the 5 long record stations alone (from Table 1) and their corresponding geological values. One obtains similar conclusions as from Figure 4. The offset is 1.37 +/- 0.24 mm/year, similar to that based on all stations. The most outlying of the five appears to be Newlyn, either because its tide gauge MSL trend is too low or its geological rate suggests too much submergence. This anomaly in the Shennan and Horton (2002) data set has been remarked upon by Gehrels (2006). Figure 5 (b) includes the same MSL data but this time compared to rates of vertical land movement based on a new combination of continuous GPS (CGPS) and AG data (Bingley et al., 2007; Teferle et al., 2008). In this case, the offset is 1.06 +/- 0.16 mm/year (standard error again based on tide gauge errors. This can be increased by 30% if the large CGPS/AG errors are also considered.). Although uncertainties in the combined CGPS/AG land rates are large, the two data sets appear to line up better, especially with regard to Newlyn where the value is closer to that of Gehrels (2006) rather than Shennan and Horton (2002). This is encouraging but it is clear that the strength of the evidence for better line-up comes from one station (Aberdeen). Consequently, this has to be regarded as a preliminary finding with regard to the use of CGPS/AG data.

If one adopts 1.4 +/- 0.2 mm/year from the offsets of Figures 4(b) and 5(a) as the best estimate of the rate of climate-related MSL change during the 20th century (in excess of any late-Holocene long term rate), then this value can be added back to the index to provide an average-UK curve since 1901 (Figure 4(b)). One factor that could be responsible for the lower UK MSL trend than the global-average IPCC values concerns melting of the Greenland ice sheet during the 20th century. The IPCC Third Assessment (Church et al., 2001) considered that Greenland was melting at an average rate of between 0.0 and 0.1 mm/year between 1910-1990 (taking into consideration 20th century effects only). However, this rate has undoubtedly increased in recent years. The IPCC Fourth Assessment (Lemke et al., 2007) suggested that the Greenland ice sheet had lost mass at rates equivalent to 0.05 ± 0.12 mm/year of sea level rise during 1961-2003 and 0.21 ± 0.07 mm/year in 1993-2003. In addition, there are suggestions of an acceleration in the rate (Chen et al., 2006; Rignot and Kanagaratnam, 2006). The elastic response of the solid Earth will have resulted in a redistribution of sea level, and thereby a potentially slightly smaller Greenland contribution to UK sea level than the global-average, depending upon which parts of the ice sheet have lost mass (cf. Figure 1(b) of Mitrovica et al., 2001, see also Plag, 2006 and Mitrovica e al., 2008).

4. Decadal Variability in the Index

The success of the use of the index leads to a reconsideration of the reasons for its temporal variability, and thereby for some of the variability in individual UK records. This is an important topic as low-frequency variability affects both the value of a secular trend and its standard error.

Figure 6 presents a low-pass filtered version of the index, after application of a boxcar filter of full width 5 years. The oscillations are approximately coincident with the (negative of) those in local air pressure, for which we have selected data from the 55N 0E grid point of HadSLP2 as representative of the UK (HadSLP2 has a 5 degree grid; the choice of adjacent grid points makes little difference to this discussion). The correlation coefficients between the two series are 0.43 and 0.51 for the unsmoothed (i.e. annual mean) and smoothed records respectively. For the period after 1930, the correlations increase slightly to 0.47 and 0.61 respectively. Linear regression yields regression coefficients of 9.9 +/- 2.1 and 15.3 +/- 2.6 mm/mbar respectively, suggesting larger departures from the 'inverse barometer' (IB) at lower frequencies, as observed at many locations in the UK, Europe and elsewhere (e.g. Pugh and Thompson, 1986; Mathers and Woodworth, 2001). The departures will arise from forcings (e.g. winds, steric changes and runoff) coherent to some extent with air pressure changes. However, Figure 6 demonstrates that there is variability in the index which is not coincident with that in air pressure (resulting in correlation coefficients less than 1), and yet takes place within a short time of the pressure changes and/or with a variable amplitude. Following Miller and Douglas (2007), one can compute a ratio of the rms values of the index and air pressure smoothed time series, as an indicator of the non-IB, and yet pressure-related, variability in the index. (The pressure-relations would include barotropic wind forcing, and the ocean adjustment to the air pressure and wind forcings over several years.) This yields a ratio of 30.2 mm/mbar, or approximately 3 times the magnitude of the IB response.

A similar conclusion was obtained for 1955 onwards by comparing the index to MSL from the numerical tide+surge model averaged over the 5 station locations: correlation coefficients of 0.50 and 0.45 respectively were obtained, and a ratio of 3.6 for sea level variability in the smoothed time series of the index compared to that in the model. This follows from the fact that the model average sea level will be something like the regional IB response, the modelled sea level changes due to winds over the shelf being more spatially variable (cf. discussion of correlations between modelled MSL values at different ports in section 3.6 of Woodworth et al., 1999). A similar finding was also obtained with the use of a 1° global barotropic model forced by six-hourly European Centre for Medium-Range Weather Forecasts (ECMWF) air pressures and winds for the shorter period 1985-2004 (Hughes and Stepanov, 2004; Stepanov and Hughes 2004). In this case, UK-average model sea level was defined by the average of the Newlyn and Aberdeen information, Liverpool and Sheerness not being well represented in the model grid and North Shields excluded so as not to over-weight the average with North Sea values. Correlation coefficients of 0.41 and 0.61 respectively were obtained, and a ratio of 2.4 for variability in the smoothed time series of the index compared to that of the model.

Similar findings for MSL variability were obtained for Brest, France by Miller and Douglas (2007). They obtained a ratio between the low-pass filtered variability of sea level and local air pressure of 36 mm/mbar but an explanation for the non-IB response in terms of possible forcings was not immediately apparent. (The UK index is too short to allow a comparison of British sea level with distant (i.e. Azores) air pressures on timescales of more than a century, as Miller and Douglas (2007) performed for Brest and Cascais, Portugal. At decadal timescales at least there is no such relationship.) Therefore, the non-IB character of much of the variability observed in the index extends beyond the UK.

A large number of authors have tried to understand the various oceanographic and meteorological forcings responsible for low-frequency UK and European Atlantic coast MSL variability (e.g. Rossiter, 1962; Thompson, 1986). These include steric (density) changes, ocean circulation variability, winds and air pressures (Pugh, 2004). A number have attempted to relate the variability of European MSL to the large scale air pressure field represented by the North Atlantic Oscillation (NAO) (e.g. Wakelin et al., 2003; Woolf et al., 2003; Tsimplis et al., 2005; Tsimplis et al., 2006; Miller and Douglas, 2007; Kolker and Hameed, 2007). However, to our knowledge, such studies have not provided evidence for coherent UK or European-coastline variability such as we require. A complicating factor is that the time series of many meteorological forcing terms are highly correlated. For example, river runoff is known to be responsible for MSL variability in many parts of the world on seasonal and longer timescales (e.g. Meade and Emery, 1971; Tsimplis and Woodworth, 1994; Wang et al., 1997; Huenicke and Zorita, 2006), and is a contributor to density change on the NW European continental shelf (Reid et al., 1988). Therefore, one might expect runoff (or its proxy in rainfall) to be a potential forcing of UK MSL also, although it might be less plausible for relatively open-ocean sites such as Newlyn than it would be for sites in river estuaries such as Sheerness. Rainfall and air pressure changes in the UK are highly correlated on interannual timescales (Woodworth, 1985). Consequently, it is not surprising that a UK rain time series computed from spatially-averaged normalized variability for 1914-2005 obtained from the UK Met Office (www.metoffice.gov.uk/research/hadleycentre/obsdata/ukcip/, see Perry and Hollis, 2005 for details of rainfall data set construction) yields positive correlation coefficients with the sea level index (0.41 and 0.54 for unsmoothed and smoothed records respectively). However, a positive correlation does not confirm runoff (or any other shelf parameter) as a significant forcing factor for MSL. The best approach with regard to the role of runoff will be through advanced numerical modelling of shelf processes which are just beginning (e.g. Young and Holt, 2007).

Nevertheless, one probably has to search for processes with larger spatial scales than the shelf, given that the decadal variability in the UK index has similarities to that in many other records along the European Atlantic coastline (Thompson, 1980; Woodworth, 1987). Figure 7 shows some of the longer European records, together with the UK index, each detrended over the period 1921-1990 and low-pass filtered as above. The coherent variability between most of them is evident, correlation coefficients between the UK index and other stations being (north to south): 0.56, 0.33, 0.61, 0.29 (or 0.69 for data from 1915), 0.05 and 0.53. (A coefficient of 0.28 would be considered significant at 95% confidence level given 50 years of data assuming no serial corelation.) Even the one with no apparent correlation (La Coruña) does have similarities to the UK index for parts of its records (cf. Thompson, 1980; the La Coruña record is discussed in detail by Marcos et al., 2005).

Thompson (1986) described a simple model of change in zonal (trans-Atlantic) sea level gradient, such that sea level on the European coast would be proportional to the integral of [distance times Ekman pumping], with distance measured eastwards from the western boundary. The distance term gives greater weight to Ekman pumping on the eastern boundary, which again implies an approximate relationship to (the negative of) local air pressure, and gives another example of correlated variables. Thompson (1986) explained that this process contributes to a greater extent at lower frequencies and is capable of simulating part of the drop in Newlyn MSL during the 1970s (Figure 10 of Thompson, 1986).

Such physics is nowadays included in ocean and climate models. For example, Hill et al. (2007) employed the Massachusetts Institute of Technology (MIT) 1° resolution general circulation model (Marshall et al., 1997), which includes daily oceanic heat and freshwater fluxes as well as meteorological forcings, to study MSL variability at tide gauge sites worldwide over the period 1958-1997. The model time series for Newlyn is shown in Figure 8, demonstrating the drop in the 1970s and, owing partly to the IB response, a drop in the early 1990s. Correlation coefficients with the index are 0.64 and 0.63 for unsmoothed and smoothed records respectively, with a ratio of 1.1 for variability in the smoothed time series of the index compared to that of the model. Although it is not possible at present to extend the modelling through the whole period of the index, it confirms that ocean circulation change is probably the main source of its low-frequency variability, and that ocean modelling offers the best possibility for its further understanding.

Whatever the reasons for variability in the index in Figure 3(a), it is intriguing that it contains several features in common with sea level records from elsewhere in the world. These include a reduction in the rate of sea level change, or deceleration, after 1960 (e.g. Woodworth et al., 2008; Douglas, 2008). During the 1990s, many locations experienced high rates of sea level change (Holgate and Woodworth, 2004), and this can be seen to have been the case also around the UK coastline.

5. Conclusions

This report has summarized current knowledge of change in MSL around the UK coastline. It has made use of a larger number of shorter sea level records than has been employed so far, in order to maximize the amount of available information, and has been based on an improved method for determination of UK sea level trends. The changes observed are consistent with findings of previous analyses, although they are more precise. They suggest a pattern of UK coastal sea level change composed of spatially-variable (primarily north-south) local vertical land movements, which can be inferred from either geological (e.g. Shennan and Horton, 2004) or geodetic data (Teferle et al., 2008) together with geodynamic modelling (Bradley et al., 2008), superimposed upon which are sea level variations due to changes in the ocean, a large part of which are spatially-coherent component. This overall picture is inevitably an approximate one, but it is gratifying that the consistency in interpretation of the different data sets (tide gauge, geological, geodetic) appears to have risen as their temporal and spatial-coverage has increased. The comparison of tide gauge, geological and geodetic trends provides an estimate of 1.4 +/-0.2 mm/year for the climate-related secular change in UK MSL since 1901 (in excess of any late-Holocene long term rate).

Some progress has also been made in understanding the reasons for variability of UK MSL on interannual and decadal timescales. An inability to account adequately for decadal variability results in greater uncertainty in the calculation of long term sea level trends. It is also a topic of interest in its own right. It has been demonstrated that much of it is related to air pressure change. However, it is not a simple relationship such as that implied by the local IB model or even by the shelf response to air pressures and winds. One finds a UK-average response to air pressure approximately three times that of the IB model. The large scale air pressure and wind fields (e.g. as represented by the NAO) undoubtedly play a role in producing this response, as must the ocean circulation adjustment to those forcings. The modelling of four decades of ocean circulation change by Hill et al. (2007) has indicated the most encouraging direction for such work. It would be highly desirable for the ocean modelling to be taken further back to the start of the 20th century should the required data sets of model forcing become available. In addition, more local contributors to MSL variability such as runoff cannot as yet be excluded, and require study from runs of advanced shelf models (e.g. Young and Holt, 2007).

The validity of the simple model of a regionally-coherent sea level signal of ocean origin superimposed on a spatial pattern of local vertical land movement is important, in that it provides the most straightforward means for developing scenarios of future sea level change around the UK and their possible impacts (cf. Hulme et al., 2002; Tsimplis et al., 2005). Projections for 21st century UK sea level change have in most studies been assumed to be similar to the global projections, and will necessarily remain so until fuller understanding of regional deviations from global-averages is obtained from improved atmosphere-ocean general circulation models. Therefore, given that global projections in the two recent IPCC Assessments are similar, if Fourth Assessment values are increased to allow for the dynamic response of the Greenland and Antarctic ice sheets to warming (Church et al., 2008), then conclusions on future change in sea level around the UK, such as those for the 2080s by the UK Climate Impacts Programme (Hulme et al., 2002: typically several 10 cm in low emission scenarios, typically 75 cm in a high emission scenario) would be essentially unchanged.

Acknowledgements

We thank Emma Hill, Rui Ponte, Jim Davis and Detlef Stammer for the MIT model data set, Jane Williams for help with the Proudman Oceanographic Laboratory (POL) tide+surge model data, and Vladimir Stepanov for the POL global barotropic model information. Two reviewers provided excellent comments on a draft of this paper.

References

Allan, R. and Ansell, T. 2006. A new globally complete monthly historical mean sea level pressure data set (HadSLP2): 1850-2004. Journal of Climate, 19(22), 5816-5842.

Bindoff, N., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C., Talley, L. and Unnikrishnan, A. 2007. Observations: oceanic climate change and sea level. In Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. S. Solomon, D. Qin, and M. Manning). Cambridge University Press. United Kingdom and New York, NY, USA.

Bingley, R.M., Teferle, F.N., Orliac, E.J., Dodson, A.H., Williams, S.D.P., Blackman, D.L., Baker, T.F., Riedmann, M., Haynes, M., Aldiss, D.T., Burke, H.C., Chacksfield, B.C. and Tragheim, D. 2007. Absolute fixing of tide gauge benchmarks and land levels: measuring changes in land and sea levels around the coast of Great Britain and along the Thames Estuary using GPS, absolute gravimetry, persistent scatterer interferometry and tide gauges. Defra/Environment Agency Joint R&D Flood and Coastal Erosison Risk Management Programme R&D Technical Report FD2319/TR, May 2007.

Bradley, S.L., Milne, G.A., Teferle, F.N., Bingley, R.M. and Orliac, E.J. 2008. Glacial isostatic adjustment of the British Isles: new constraints from GPS measurements of crustal motion. Geophysical Journal International (submitted).

Chen, J.L., Wilson, C.R. and Tapley, B.D. 2006. Satellite gravity measurements confirm accelerated melting of Greenland Ice Sheet. Geophysical Research Letters 313: 1958-1960

Church, J.A., J.M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M.T. Nhuan, D. Qin, and P.L. Woodworth, 2001. Changes in sea level. In Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson, eds. Cambridge University Press, Cambridge, 881pp.

Church, J.A., White, N.J., Coleman, R., Lambeck, K. and Mitrovica, J.X. 2004. Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. Journal of Climate, 17, 2609–262.

Church, J. A. and White, N. J. 2006. A 20th century acceleration in global sea-level rise. Geophysical Research Letters, 33, L01602, doi:10.1029/2005GL024826.

Church, J., Wilson, S., Woodworth, P. and Aarup, T. 2007a. Understanding sea level rise and variability. Meeting report. EOS, Transactions of the American Geophysical Union, 88(4), 23 January 2007, p43.

Church, J.A., White, N.J., Aarup, T., Wilson, W.S., Woodworth, P.L., Domingues, C.M., Hunter, J.R. and Lambeck, K. 2007b. Understanding global sea levels: past, present and future. Sustainability Science, doi:10.1007/s11625-008-0042-4.

Douglas, B.C. 1991. Global sea level rise. Journal of Geophysical Research, 96(C4), 6981-6992.

Douglas, B.C. 2008. Concerning evidence for fingerprints of glacial melting. Journal of Coastal Research, doi:10.2112/06-0748.

Emery, K.O. and Aubrey, D.G. 1991. Sea levels, land levels, and tide gauges. New York: Springer-Verlag. 237pp.

Flather, R.A., Smith, J.A., Richards, J.D., Bell, C. and Blackman, D.L., 1998. Direct estimates of extreme storm surge elevations from a 40-year numerical model simulation and from observations. The Global Atmosphere and Ocean System 6, 165-176.

Gehrels, R. 2006. Sea-level rise and coastal subsidence in southwest England. Reports and Transactions of the Devonshire Association, 138, 25-42.

Holgate, S.J. and Woodworth, P.L. 2004. Evidence for enhanced coastal sea level rise during the 1990s. Geophysical Research Letters, 31, L07305, doi:10.1029/2004GL019626.

Hoppe, G. 1965. Submarine peat in the Shetland Islands. Geografiska Annaler, A, 47, 195-203.

Huenicke, B. and Zorita, E. 2006. Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century. Tellus, A,58, 141-153. doi:10.1111/j.1600-0870.2006.00157.x.

Hughes, C.W. and Stepanov, V.N. 2004. Ocean dynamics associated with rapid J2 fluctuations: Importance of circumpolar modes and identification of a coherent Arctic mode. Journal of Geophysical Research, 109, C06002, doi:10.1029/2003JC002176.

Hulme, M., G. Jenkins, X. Lu, J.R. Turnpenny, T.D. Mitchell, R.G. Jones, J. Lowe, J.M. Murphy, D. Hassell, P. Boorman, R. McDonald, and S. Hill, 2002. Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, 120pp.

IOC, 2006. Manual on sea-level measurement and interpretation. Volume 4 - An update to 2006. (eds. Aarup, T., Merrifield, M., Perez, B., Vassie, I and Woodworth, P.). Intergovernmental Oceanographic Commission Manuals and Guides No. 14. IOC, Paris, 80pp.

Kolker, A.S. and Hameed, S. 2007. Meteorologically driven trends in sea level rise. Geophysical Research Letters, 34, L23616, doi:10.1029/2007GL031814.

Lemke, P., Ren, J., Alley, R., Allison, I., Carrasco, J., Flato, G., Fujii, Y , Kaser, G., Mote, P., Thomas, R. and Zhang, T. (2007). Chapter 4: Observations: Changes in Snow, Ice and Frozen Ground. In Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M.C. Marquis, K. Averyt, M. Tignor and H.L. Miller). Intergovernmental Panel on Climate Change, Cambridge and New York.

Marcos, M., Gomis, D., Monserrat, S., Álvarez-Fanjul, E., Pérez, B., García-Lafuente, J. 2005. Consistency of long sea-level time series in the northern coast of Spain. Journal of Geophysical Research, 110, C03008, doi:10.1029/2004JC002522.

Marshall, J., Adcroft, A., Hill, C., Perlman, L. and Heisey, C. 1997. A finite-volume, incompressible Navier-Stokes model for studies of the ocean on parallel computers. Journal of Geophysical Research, 102, 5733-5766.

Mathers, E.L. and Woodworth, P.L. 2001. Departures from the local inverse barometer model observed in altimeter and tide gauge data and in a global barotropic numerical model. Journal of Geophysical Research, 106(C4), 6957-6972, doi:10.1029/2000JC000241.

Meade, R.H. and Emery, K.O. 1971. Sea level as affected by river runoff, Eastern United States. Science, 173, 425-428.

Miller, L. and Douglas, B.C. 2007. Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise. Geophysical Research Letters, 34, L16602, doi:10.1029/GL030862.

Milne, G.A., Davis, J.L., Mitrovica, J.X., Scherneck, H.-G., Johansson, J.M., Vermeer, M. and Koivula, H. 2001. Space-geodetic constraints on glacial isostatic adjustment in Fennoscandia. Science, 291, 2381-2385. doi:10.1126/science.1057022.

Mitrovica, J.X., Tamisiea, M.E., Davis, J.L. and Milne, G.A. 2001. Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. Nature, 409, 1026-1029.

Mitrovica, J.X., Tamisiea, M.E., Ivins, E.R., Vermeersen, L.L.A., Milne, G.A. and Lambeck, K. 2008. Surface mass loading on a dynamic Earth: complexity and contamination in the geodetic analysis of global sea level trends. Chapter to be published in, Understanding sea-level rise and variability (eds. J.A. Church, P.L. Woodworth, T. Aarup and S. Wilson) by Blackwells (London).

Peltier, W.R., Shennan, I., Drummond, R. and Horton, B.P. 2002. On the post-glacial isostatic adjustment of the British Isles and the shallow visco-elastic structure of the Earth. Geophysical Journal International, 148, 443-475.

Perry, M. and Hollis, D. 2005. The generation of monthly gridded datasets for a range of climatic variables over the UK. International Journal of Climatology, 25, 1041-1054.

Pirazzoli. P.A. 1986. Secular trends of relative sea-level (RSL) changes indicated by tide gauge records. Journal of Coastal Research, SI 1, 1-26.

Plag, H.-P. 2006. Recent relative sea-level trends: an attempt to quantify the forcing factors. Philosophical Transactions of the Royal Society of London, A, 364, 821-844.

Pugh, D.T. and Thompson, K.R. 1986. The subtidal behavious of the Celtic Sea - I. Sea level and bottom pressures. Continental Shelf Research, 5, 239-319.

Pugh, D.T. 2004. Changing sea levels. Effects of tides, weather and climate. Cambridge: Cambridge University Press, 280pp.

Reid, P.C., Taylor, A.H., Stephens, J.A. 1988. The hydrography and hydrographic balances of the North Sea. In: Salomons, W.; Bayne, B.L.; Duursma, E.K.; Forstner, U., (editors). Pollution of the North Sea: an assessment. p.3-19. Berlin: Springer-Verlag.

Rignot, E. and Kanagaratnam, P. 2005. Changes in the velocity structure of the Greenland Ice Sheet. Science, 311, 986-990.

Rossiter, J.R. 1962. Long-term variations in sea-level. Chapter 16 in, The Sea (ed. N.M. Hill), 590-610. New York: Interscience.

Shennan, I., 1989. Holocene crustal movements and sea-level changes in Great Britain. Journal of Quaternary Science, 4, 77-89.

Shennan, I. and Horton, B. 2002. Holocene land- and sea-level changes in Great Britain. Journal of Quaternary Science, 17, 511-526, doi:10.1002/jqs.710.

Shennan, I. and Woodworth, P.L. 1992. A comparison of late Holocene and twentieth century sea-level trends from the UK and North Sea region. Geophysical Journal International, 109, 96-105.

Stepanov, V.N. and Hughes, C.W. 2004. The parameterization of ocean self-attraction and loading in numerical models of the ocean circulation. Journal of Geophysical Research, 109, C03037, doi:10.1029/2003JC002034.

Teferle, F.N., Bingley, R.M., Williams, S.D.P., Baker, T.F. and Dodson, A.H. 2006. Using continuous GPS and absolute gravity to separate vertical land movements and changes in sea-level at tide-gauges in the UK. Philosophical Transactions of the Royal Society, 364, 917-930, doi:10.1098/rsta.2006.1746.

Teferle, F.N., Bingley, R.M., Williams, S.D.P., Shennan, I., Woodworth, P.L., Milne, G.A., Orliac, E.J., Bradley, S.L. and Baker, T.F. 2008. Crustal motions in Great Britain: evidence from absolute gravity, continuous GPS and geological information. Geophysical Journal International (submitted).

Thompson, K.R. 1980. An analysis of British monthly mean sea level. Geophysical Journal of the Royal Astronomical Society, 63, 57-73.

Thompson, K.R., 1986. North Atlantic sea-level and circulation. Geophysical Journal of the Royal Astronomical Society, 87, 15-32.

Tsimplis, M.N. and Woodworth, P.L. 1994. The global distribution of the seasonal sea level cycle calculated from coastal tide gauge data. Journal of Geophysical Research, 99(C8), 16031-16039.

Tsimplis, M.N. and Spencer, N.E. 1997. Collection and analysis of monthly mean sea level data in the Mediterranean and the Black Sea. Journal of Coastal Research, 13, 534-544.

Tsimplis M.N., Woolf, D.K., Osborn, T.J., Wakelin, S., Wolf, J., Flather, R., Shaw, A.G.P., Woodworth, P., Challenor, P., Blackman, D., Pert, F., Yan, Z. and Jevrejeva, S. 2005. Towards a vulnerability assessment of the UK and northern European coasts: the role of regional climate variability. Philosophical Transactions of the Royal Society of London, 363, 1329-1358, doi:10.1098/rsta.2005.1571.

Tsimplis, M.N., Shaw, A.G.P., Flather, R.A. and Woolf, D.K. 2006. The influence of the North Atlantic Oscillation on the sea-level around the northern European coasts reconsidered: the thermosteric effects. Philosophical Transactions of the Royal Society of London, A, 364, 845-856.

Wakelin, S.L., Woodworth, P.L. Flather, R.A. and Williams, J.A. 2003. Sea-level dependence on the NAO over the NW European Continental Shelf, Geophysical Research Letters, 30(7), 1403, doi:10.1029/2003GL017041, 2003.

Wang J, Cheng, R.T., and Smith, P.C. 1997. Seasonal sea-level variations in San Francisco Bay in response to atmospheric forcing, 1980. Estuarine, Coastal and Shelf Science, 45, 39-52.

Warrick, R.A., Le Provost, C., Meier, M.F., Oerlemans, J. and Woodworth, P.L. 1996. Lead authors of Chapter 7 (Changes in sea level) of Climate Change 1995. The science of climate change. Contribution of working group I to the second assessment report of the

Intergovernmental Panel on Climate Change, eds. J.T.Houghton, L.G.Meira Filho, B.A.Callander, N.Harris, A.Kattenberg and K.Maskell. Cambridge: Cambridge University Press. 572pp.

Woodworth, P.L. 1985. The interannual correlation between sea level air pressure and rainfall in the British Isles - North Sea region. Weather, 40, 285-292.

Woodworth, P.L. 1987. Trends in UK mean sea level. Marine Geodesy, 11, 57-87.

Woodworth, P.L. and Jarvis, J. 1991. A feasibility study of the use of short historical and short modern tide gauge records to investigate long term sea level changes in the British Isles. Proudman Oceanographic Laboratory Internal Document No.23, 32pp. and figures.

Woodworth, P.L. and Player, R. 2003. The Permanent Service for Mean Sea Level: an update to the 21st century. Journal of Coastal Research, 19, 287-295.

Woodworth, P.L., Vassie, J.M., Spencer, R. and Smith, D.E. 1996. Precise datum control for pressure tide gauges. Marine Geodesy, 19(1), 1-20.

Woodworth, P.L., Gregory, J.M. and Nicholls, R.J. 2004. Long term sea level changes and their impacts. pp.715-753 (chapter 18) in The Sea, Volume 13, edited by A.R. Robinson and K.H. Brink. Harvard University Press.

Woodworth, P.L., Jevrejeva, S., Holgate, S., Church, J., White, N. and Gehrels, R. 2008. Evidence for the accelerations of sea level on multi-decade and century timescales. International Journal of Climatology (in press).

Woolf, D.K., Shaw, A.G.P. and Tsimplis, M.N. 2003. The influence of the North Atlantic Oscillation on sea level variability in the North Atlantic Region. The Global Atmosphere and Ocean System, 9(4), 145-167.

Young, E.F. and Holt, J.T. 2007. Prediction and analysis of long-term variability of temperature and salinity in the Irish Sea. Journal of Geophysical Research, 112, C01008, doi:10.1029/2005JC003386.

Figure Captions

1. Map indicating the tide gauge stations in Table 1. (R: Rosyth, T: Tilbury, S: Southend and Sheerness on the north and south sides of the Thames estuary, respectively, HH: Holyhead, L: Liverpool, H: Heysham, D: Douglas, PP: Portpatrick, M: Millport, B: Belfast.)

2 (a) Long UK records of annual MSL. The Aberdeen and Liverpool time series are composites as described by Woodworth et al. (1999). The North Shields, Sheerness and Newlyn records are from the PSMSL RLR data set. Each record has been offset for presentation purposes. (b) MSL values for the records of (a) relative to MSL at Newlyn, Cornwall.

3. (a) A UK sea level index for the period 1901 onwards computed from MSL data from five stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool). Each record has been detrended over the period 1921-1990 and the detrended values averaged. Standard deviations of detrended values about the average are shown by the error bars. (b) As for (a) but with a best estimate of 1.4 mm/year added back to the index to provide an average UK time series for climate-related MSL change.

4. (a) Measured trends in MSL for 1901 onwards for the stations in Table 1 compared with the (negative of) emergence/submergence rate obtained from nearby geological information (Shennan and Horton, 2002). (b) Trends in MSL derived by the 'master

station' method (Table 2) compared to the same geological information. The solid, dashed and dotted lines indicate offsets between data sets of zero and ±1 mm/year.

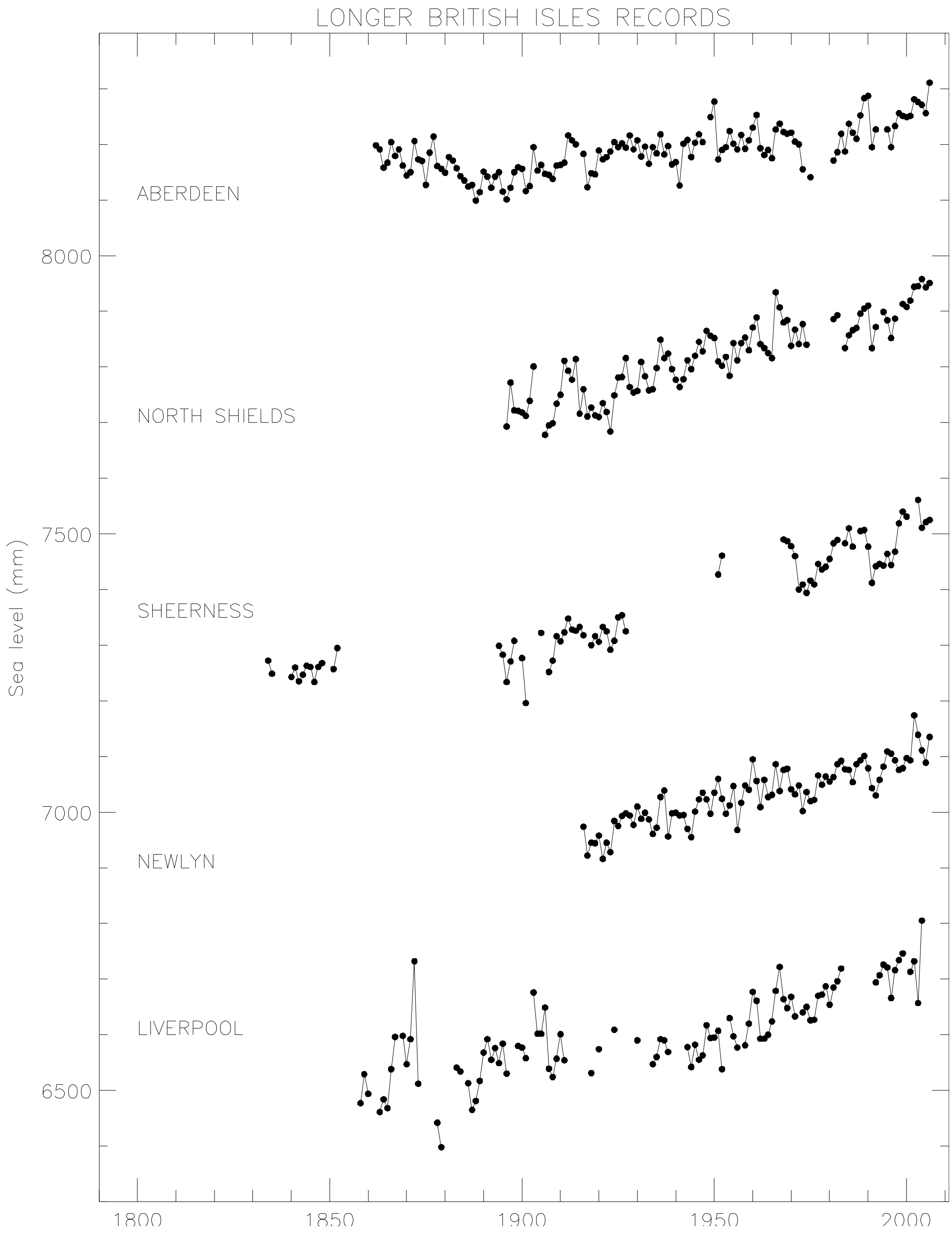
5. (a) Measured trends in MSL for 1901 onwards for the 5 longest records compared to geological information. (b) Measured trends in MSL compared to the corresponding information from GPS and AG. (N: Newlyn, S: Sheerness, L: Liverpool, NS: North Shields, A: Aberdeen.) The solid, dashed and dotted lines indicate offsets between data sets of zero and ±1 mm/year.

6. A low-pass filtered version of the sea level index compared with (the negative of) representative UK air pressure. The air pressure time series has been scaled to have the same root-mean-square variability as the index.

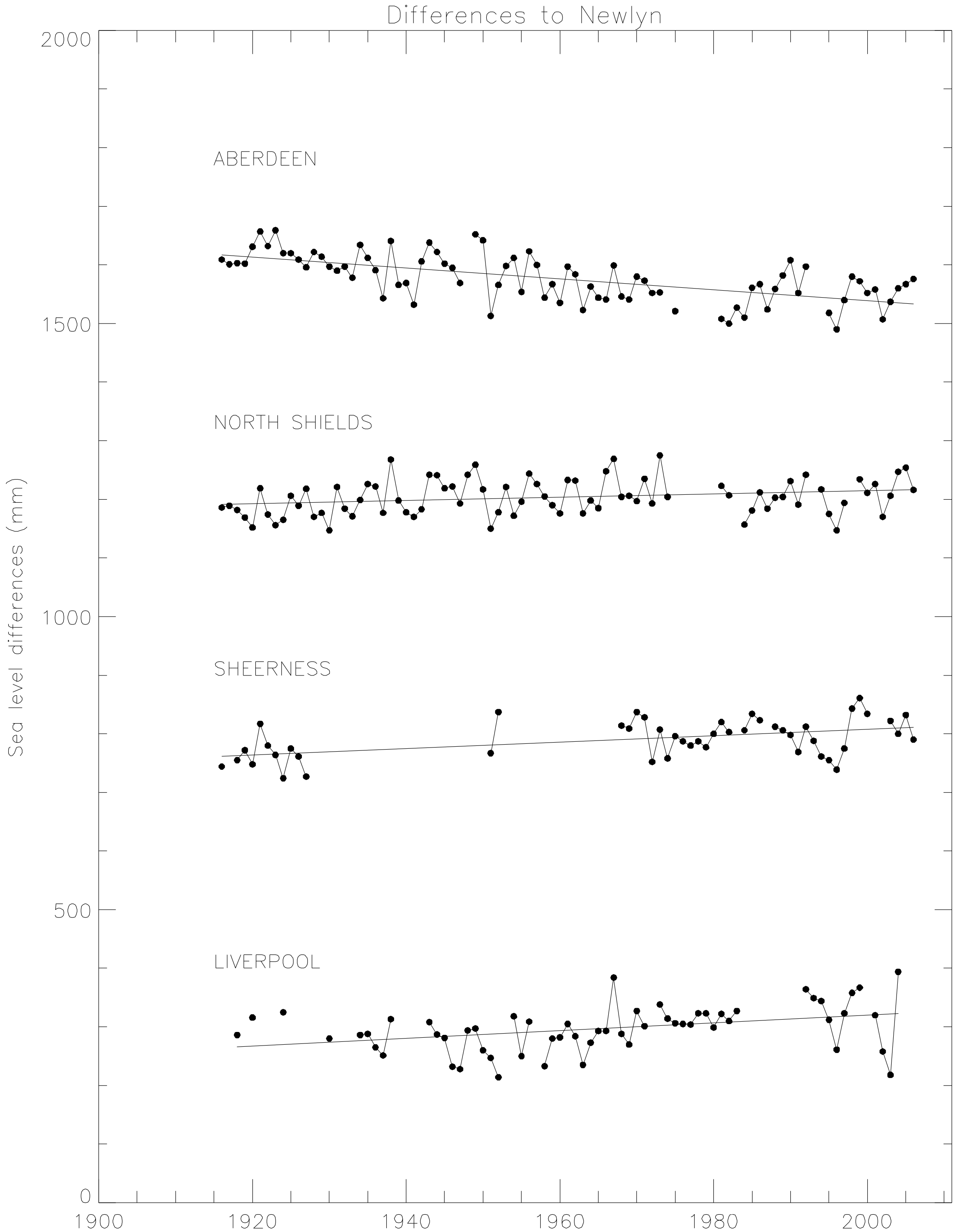
7. Selected MSL records from the European coastline (Stavanger, Norway; Esbjerg, Denmark; Ostende, Belgium; Brest, France; La Coruña, Spain; Cascais, Portugal) together with the UK index. Each record has been detrended over the period 1921-1990, low-pass filtered with a 5 year boxcar filter, and offset for presentation purposes.

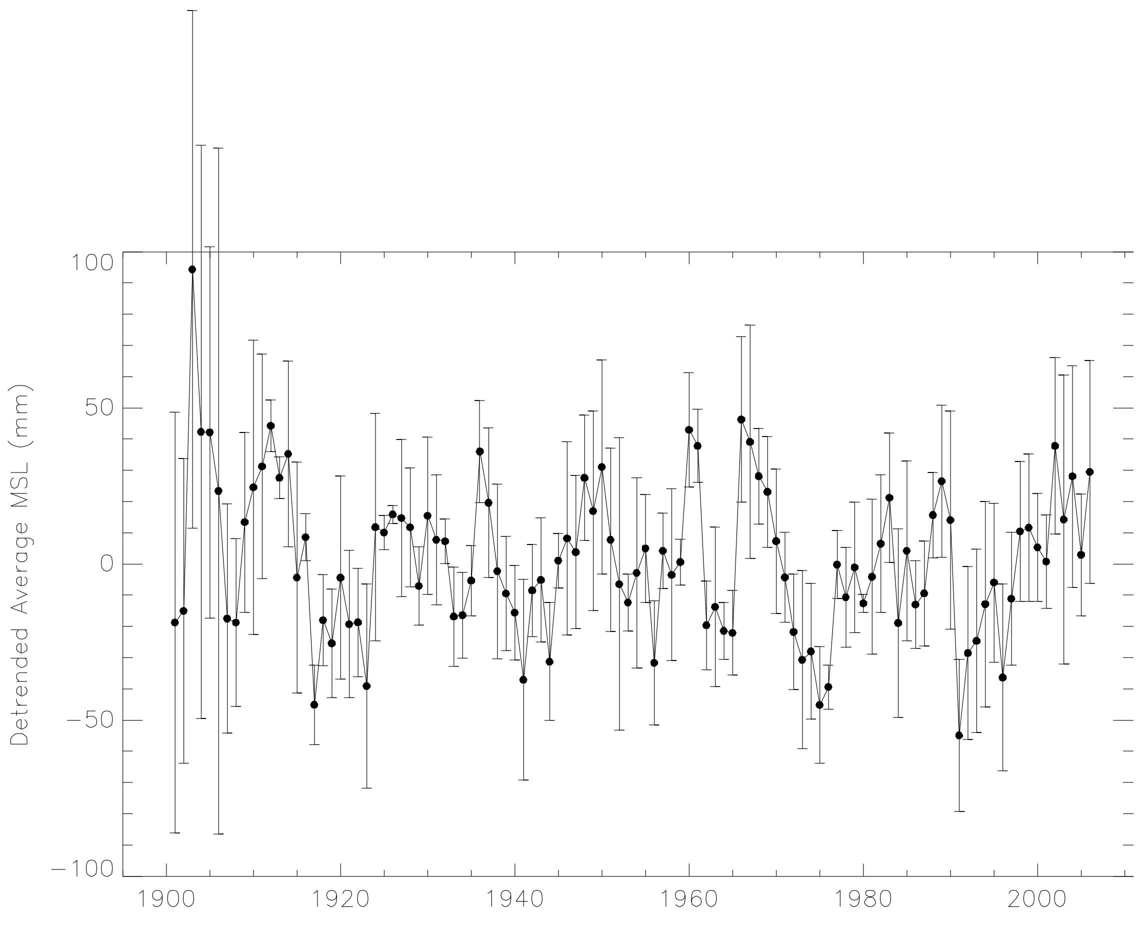
8. MSL changes at Newlyn from the ocean model study of Hill et al. (2007). The solid line shows the overall contribution from both ocean circulation and IB, while the dashed line shows the ocean circulation contribution only. The ordinate contains an arbitrary model offset.


10˚W
5˚W
0˚
5˚E
60˚N
55˚N
50˚N
Lerwick
Stornoway
Wick
Ullapool
Aberdeen
Dunbar
R
M
PP
North Shields
B
D
H
Immingham
HH
L
Lowestoft
T
S
Dover
Portsmouth
Devonport
Newlyn

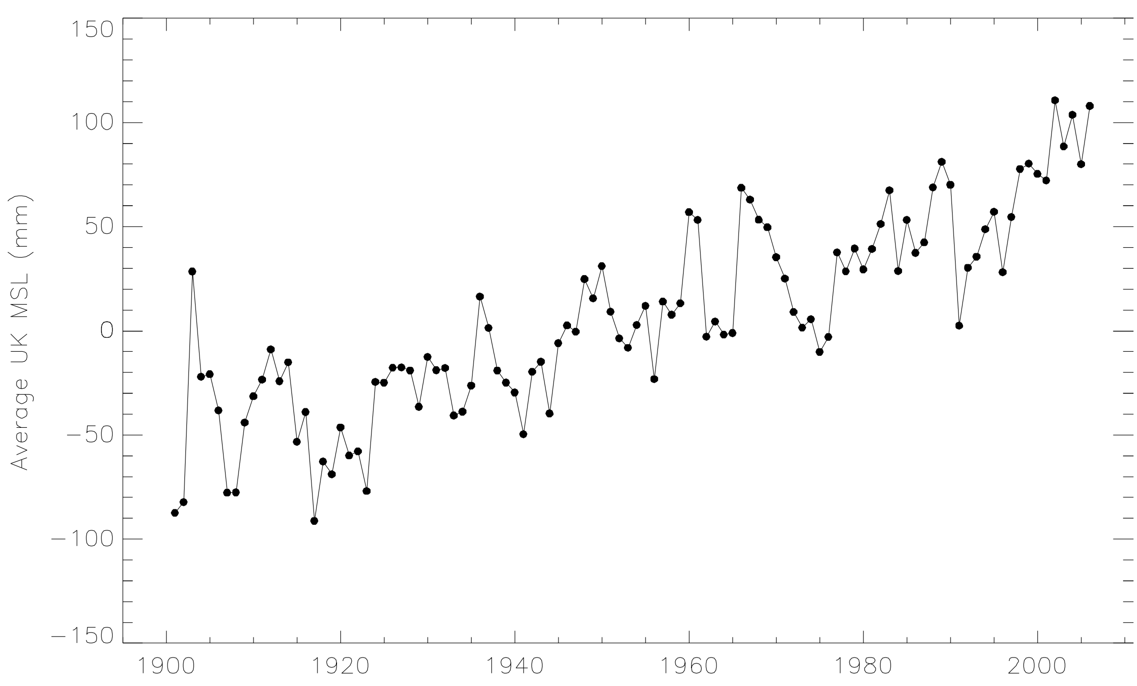


LONGER BRITISH ISLES RECORDS
ABERDEEN
NORTH SHIELDS
SHEERNESS
NEWLYN
LIVERPOOL
Sea level (mm)
8000
7500
7000
6500
1800
1850
1900
1950
2000

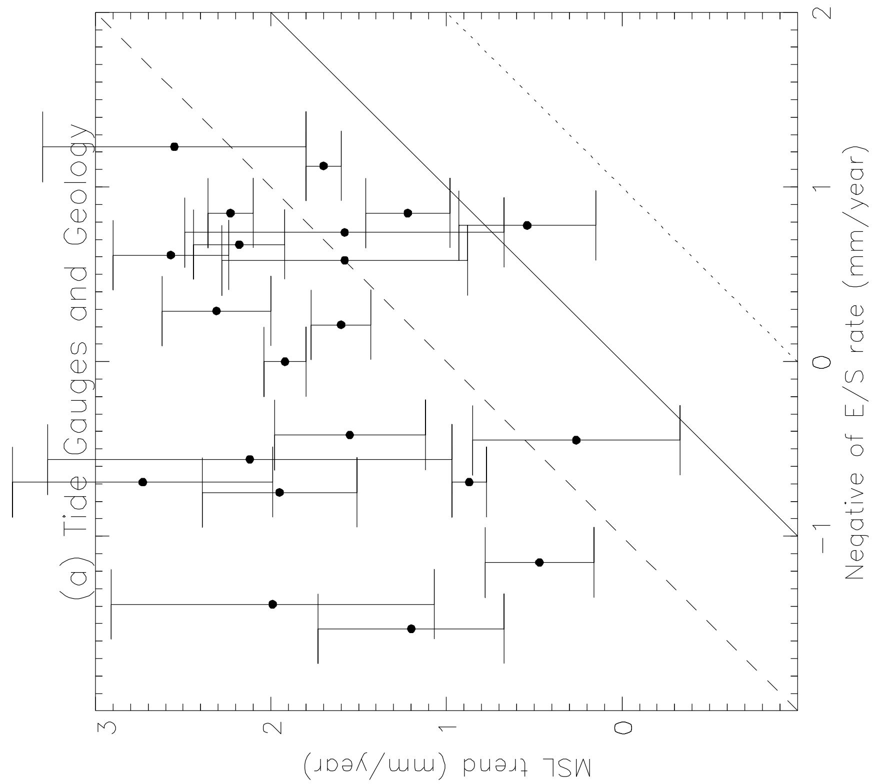

Differences to Newlyn
ABERDEEN
NORTH SHIELDS
SHEERNESS
LIVERPOOL
Sea level differences (mm)
2000
1500
1000
500
0
1900
1920
1940
1960
1980
2000

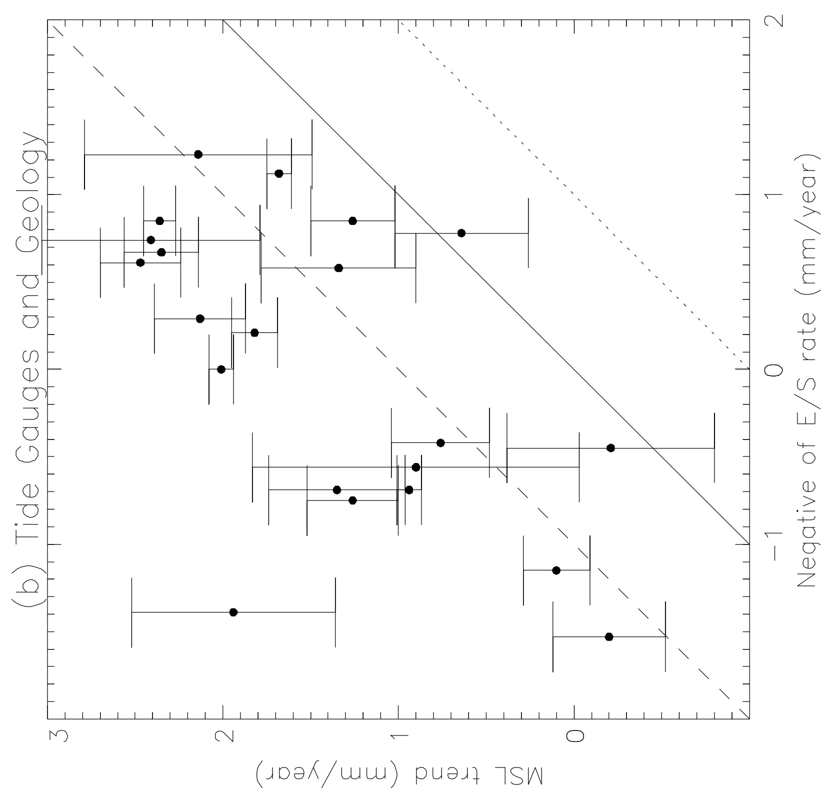

Detrended Average MSL (mm)
100
50
0
−50
−100
1900
1920
1940
1960
1980
2000

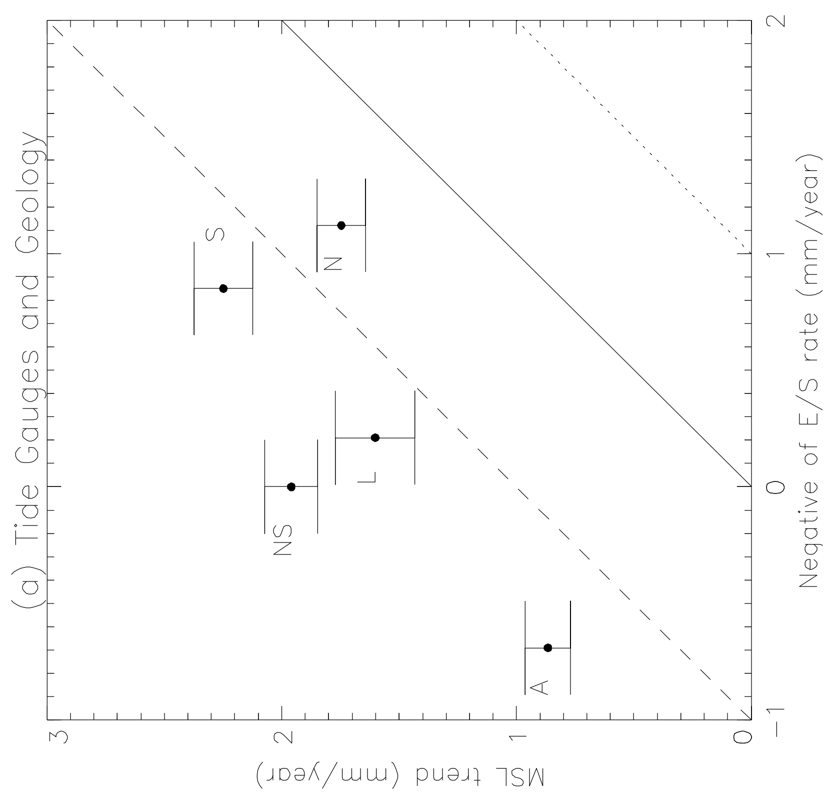
(a)

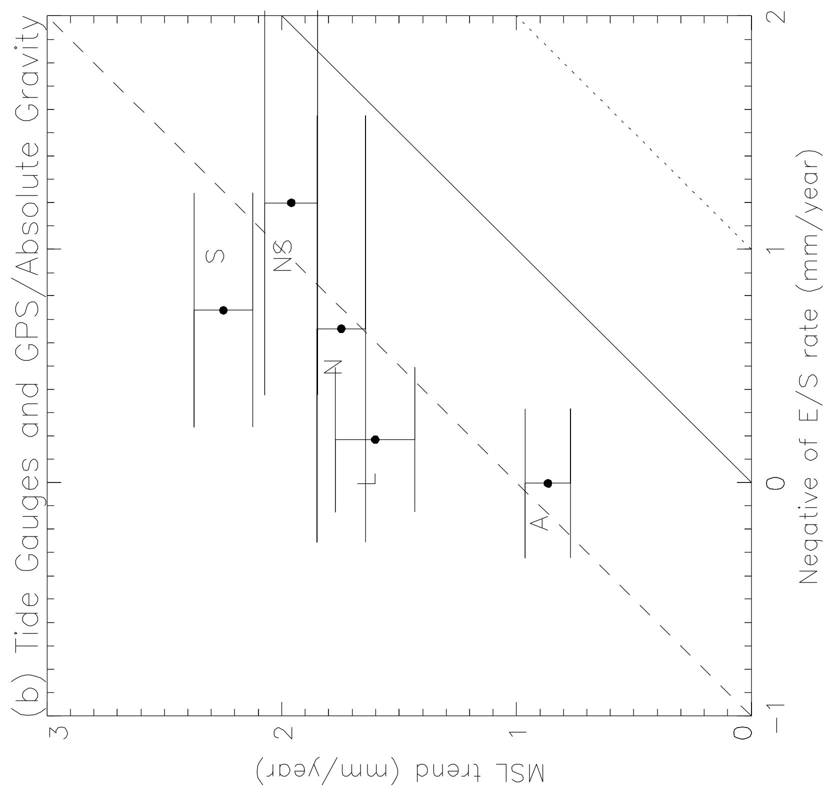

Average UK MSL (mm)
150
100
50
0
−50
−100
−150
1900
1920
1940
1960
1980
2000

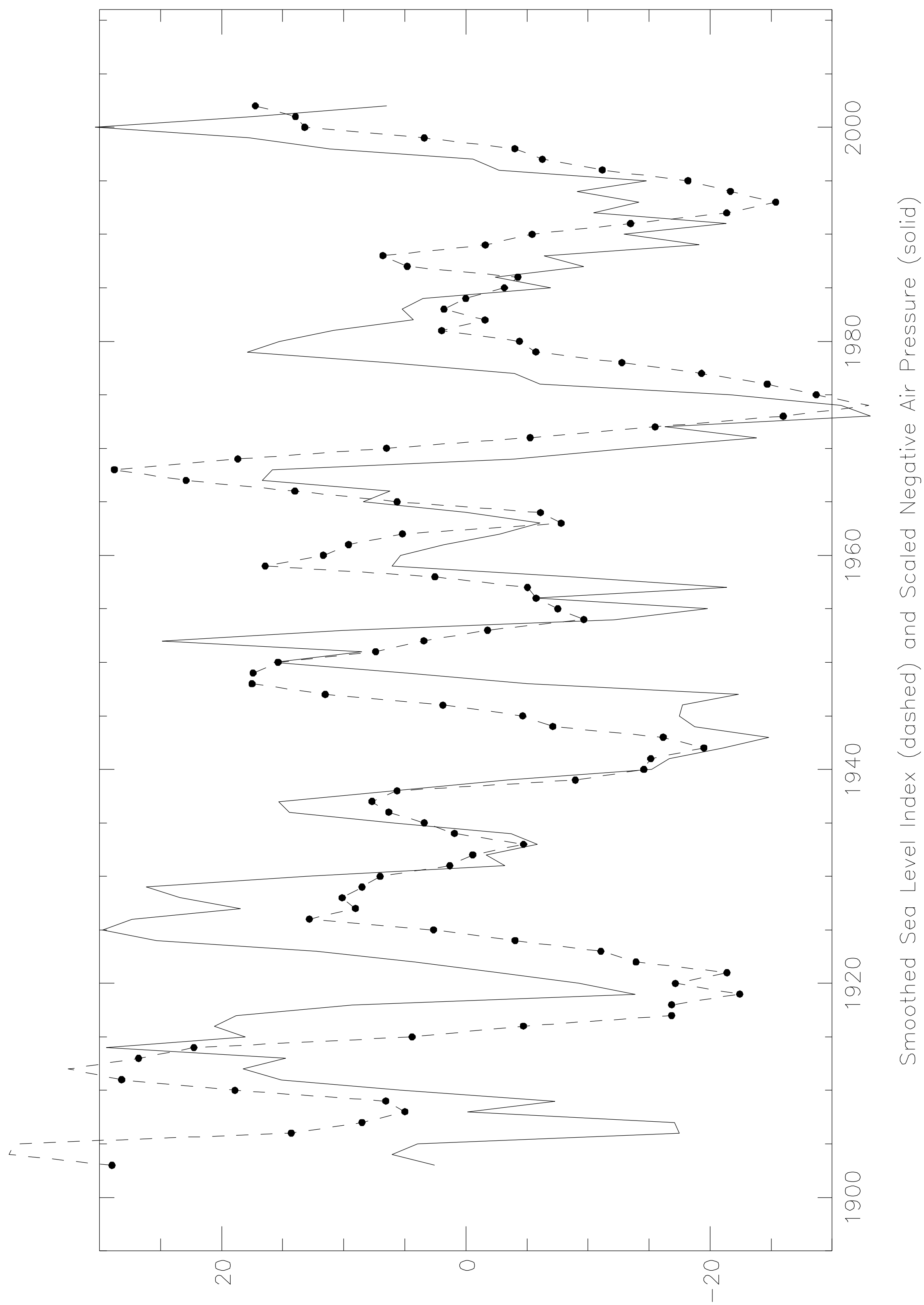
(b)

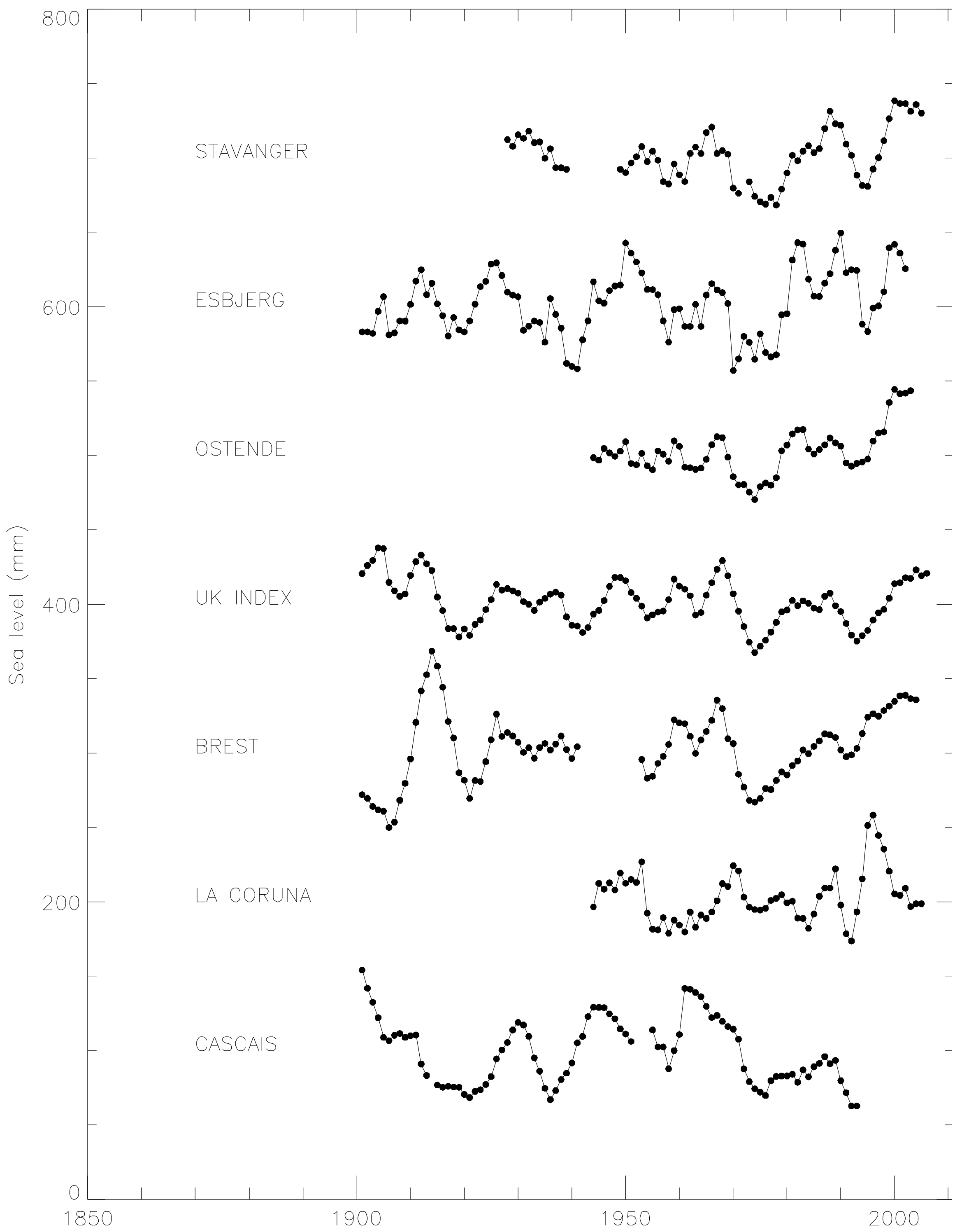

(a) Tide Gauges and Geology
Negative of E/S rate (mm/year)
MSL trend (mm/year)
−1
0
1
2
3
2
1
0

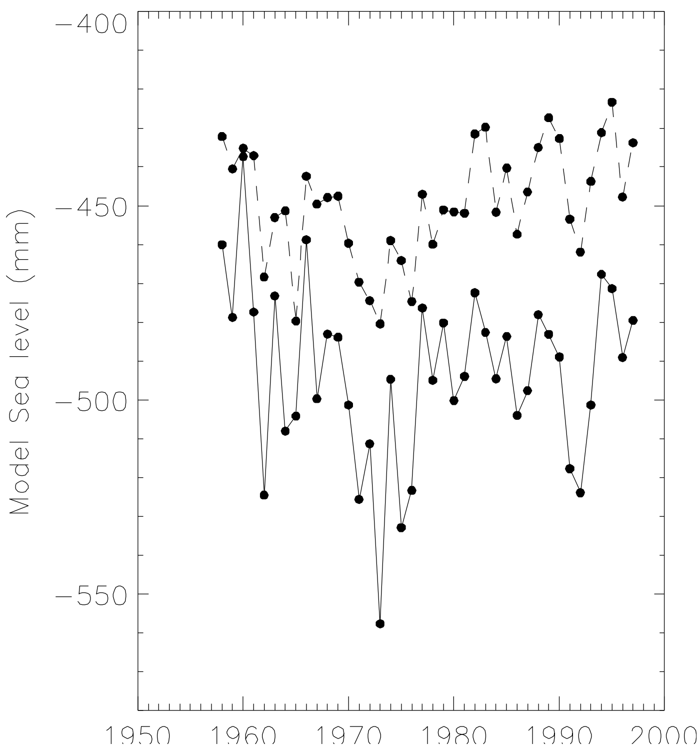

(b) Tide Gauges and Geology
Negative of E/S rate (mm/year)
MSL trend (mm/year)
−1
0
1
2
3
2
1
0


(a) Tide Gauges and Geology
MSL trend (mm/year)
Negative of E/S rate (mm/year)
A
NS
L
S
N


(b) Tide Gauges and GPS/Absolute Gravity
MSL trend (mm/year)
Negative of E/S rate (mm/year)
A
L
N
NS
S


Smoothed Sea Level Index (dashed) and Scaled Negative Air Pressure (solid)
Smoothed Sea Level Index (mm)
1900
1920
1940
1960
1980
2000
20
0
−20


STAVANGER
ESBJERG
OSTENDE
UK INDEX
BREST
LA CORUNA
CASCAIS
Sea level (mm)
800
600
400
200
0
1850
1900
1950
2000



Model Sea level (mm)
−400
−450
−500
−550
1950
1960
1970
1980
1990
2000