5. Sea Level

1. Key points

i. Introduction

The coastal zone has changed considerably due to growing populations and increasing urbanization. In 1990, 23% of the world's population (1.2 billion people) were living within 100 km distance and 100 m elevation of the coast at densities three times the global average. Society is becoming increasingly vulnerable to sea level extremes as the storm surges of Hurricanes Katrina and Sidr have demonstrated. As UK populations rise, especially in the South-East in general and the Thames Estuary in particular, there are concerns that they are properly protected (www.environment-agency.gov.uk/te2100/). Sea level changes also have environmental consequences, with impacts on intertidal habitats and modifications to groundwater regimes. Rising sea levels imply more flooding and liability to erosion by waves, even if storm intensities do not increase.

ii. How has the assessment been undertaken?

The assessment is drawn from data, from the global and UK tide gauge networks and from international space missions, and from climate modelling. Most findings are available in the scientific literature and have been included in the periodic assessments by the Intergovernmental Panel on Climate Change (IPCC).

iii. Current and likely future status of sea level

Global mean sea level (MSL) is known to have risen by about 120 m between the peak of the last ice age around 20 000 years ago and approximately 6000 years ago. Global sea level rose by about 1.7 mm/y during the 20th century and the few long European records suggest slightly faster sea level rise in the 20th century than in the 19th century (section 4.2.1). After adjusting for land movements, 'absolute' sea level around the UK coast has increased by about 1.4 mm/y during the 20th century; this is slightly lower than the 'global' estimate (section 4.2.2). There were periods during the 20th century when rates were significantly greater or smaller than average. This includes the 1990s which experienced rates of sea level rise between 3 and 4 mm/y (section 4.2.1).

UK sea level records indicate local short-term variations in the height and timing of the ocean tide, but no long-term trends which can be definitely attributed to oceanic rather than local causes. An exception appears to be data set for Newlyn (a particularly long record and 'home' of Ordnance Survey Datum) which shows a long-term increase in mean tidal range. Most UK records do not present evidence for long-term changes in statistics of surges (non-tidal variations from mean sea level), including that from the UK's longest time series (from Liverpool since 1768). Similarly, long-term changes in extreme sea levels do not appear to exhibit significantly different long-term behaviour to that of mean levels (section 4.2.3).

Global sea level is projected to rise in the 21st century by 0.18 to 0.59 m, plus an amount arising from the dynamic instability of ice sheets. Predictions for the UK itself are of comparable magnitude (section 5.1).

iv. What has driven change?

Sea level has varied for the last few million years on timescales of the order of 100 000 years in response to the growth and retreat of the great polar ice sheets. Superimposed on these variations of sea level of the order of ± 100 m are changes of the order of 0.1 to 0.2 m associated with shorter timescale climatic events such as the Little Ice Age. More recently, there has been concern that anthropogenically induced climate change has resulted in enhanced sea level rise. These issues are addressed in detail in the IPCC Scientific Assessments (Church et al., 2001; Bindoff et al., 2007).

v. What are the uncertainties?

The main research uncertainties are concerned with accounting for observed sea level changes, including the present inability of climate models to simulate the magnitudes and timings of sea level changes. Monitoring and modelling need to be enhanced so as to provide greater confidence that sea level changes are understood and that models are capable of predicting future change, thereby contributing to more effective coastal planning and management (e.g. Church et al., 2007).

vi. Forward look

The scientific community is attempting to put in place a coherent monitoring system for sea level (altimetry, space gravity, tide gauges) and related parameters (mass balance of ice sheets and glaciers, temperature and salinity of the ocean, hydrological data sets) which, together with improved modelling, will increase understanding.

2. Introduction

Sea level is the combination of tidal level, surge level, mean sea level, waves and their respective interactions. Any change in mean sea level affects sea level directly but also modifies tide, surge and wave propagation and dissipation by changing the water depth. Increased depth gives longer tidal wavelength and hence the tidal pattern is shifted, resulting in an increase in tidal levels at some locations and a decrease at others. The generation and dissipation of surges partly depends on water depth because the wind-stress effect increases in importance as the depth decreases. Increased depth in coastal waters leads to greater wave energy transmitted to the shoreline.

As the most serious coastal flooding events in the UK are caused by a combination of high tides, surges and waves, any overall long-term increases in tidal level, surge or waves will increase the frequency of coastal flooding, especially if a rise in mean sea level provides a higher ‘base-line’ for them. Rising sea level will tend (1) to reduce the width of beaches and intertidal rocky shores, particularly where high waters are contained by hard structures or rock, and (2) to increase nearshore wave energy and hence coastal erosion.

A rise in sea level can cause the loss of saltmarsh and mudflats, thus having an effect on intertidal ecosystems. Also, the impact of sea level rise on a changing wave climate, and hence on water turbidity, will have an impact in the nearshore environment. For example, stronger currents and less light will generally inhibit biological growth.

2.1 Tidal levels

Tidal levels are the regular motions of the sea generated by astronomical forcing due to the varying gravitational attraction of the Moon and the Sun. UK waters respond strongly to tidal forcing at the Atlantic Ocean boundary and the presence of the British Isles creates a series of more or less separate basins in which the tidal wave, incident from the deep ocean, is reflected and amplified to varying degrees. The general response in UK waters is to amplify semi-diurnal components of the tide; the largest are the M_2 (two tides per lunar day) and S_2 (two tides per solar day) constituents. Irish Sea and Bristol Channel responses are particularly strong; their respective tidal ranges average 8 m and 11.5 m at spring tides (when M_2 and S_2 add constructively).

Animation of surface elevations through a tidal cycle in Liverpool Bay; in UKMAR – OPEG as LivBayElv.gif

Semi-diurnal lunar tides increase and decrease in range over an 18.6 year period (Figure 5.1) because of changes in the lunar declination cycle (i.e. the plane of the moon’s orbit varies relative to the plane of the earth’s orbit around the sun). When the declinations are small the semi-diurnal tides are bigger. The most recent minimum in the amplitude of semi-diurnal tides was in 2006, with the next maximum to be expected in 2015. The theoretical modulations in amplitude are 3.7% about the mean, but in practice because of shallow water effects, around the UK the modulations vary locally and tend to be smaller at around 2%.

2.2 Surge levels

Surge levels are caused by changes in atmospheric pressure and wind stress (the latter proportional to the square of the wind speed), and can result in water levels above (‘positive surge’) or below (‘negative surge’) those of the normal tide. Large positive surges are usually experienced in shallow water areas as the effect of wind-stress increases in importance as depth decreases. The pressure effect is independent of depth. ‘Storm surges’ are generated by major meteorological disturbances, and can result in sea level changes of up to several metres lasting for a few hours to days, depending upon the storm duration, water depth and the extent of the storm.

Animation of surge levels around UK for 8-9 November 2007 storm (surge) event; in UKMAR – OPEG as surge9nov.mpeg.

2.3 Mean sea level

Mean sea level (MSL) is defined as the height of the sea averaged over a period of time, such as a month or year, long enough that short-term fluctuations caused by waves and tides are largely removed. Daily, monthly, seasonal and annual variations in MSL include contributions from tides and surges and are due to changes in atmospheric pressure, wind stress, density and/or water circulation. Around the UK, MSL changes seasonally by approximately 10 cm (range), and is at a maximum in late summer.

Changes in MSL measured by coastal tide gauges contain contributions both from real changes in ocean level and from vertical movements of the land upon which the gauges are situated. Therefore MSL ‘relative’ to the land also depends on local land movements, such as those resulting from local sediment compaction or groundwater extraction, or regional land movements, such as those resulting from ‘glacial isostatic adjustment’ (Figure 5.2). Thus a determination of ‘absolute’ sea level needs to have land movements removed from the measured ‘relative’ MSL signal. Long-term (or ‘secular’) changes in absolute MSL are mainly caused by changes in water volume, such as an increase caused by melting of grounded ice or the thermal expansion of seawater due to heating.

Although small compared to the Fennoscandian and Laurentian ice sheets that covered northern Europe and America respectively during the last ice age, the ice sheet that covered much of the British Isles was large enough for glacial isostatic adjustment processes to have produced contrasting relative MSL changes at different locations (Figure 5.2). Maximum relative land uplift, around 1.6 mm/y, occurs in central and western Scotland and maximum subsidence, around 1.2 mm/y, in southwest England (Shennan and Horton, 2002), although such large rates of subsidence in the south-west are disputed (Gehrels, 2006). Sediment consolidation, arising from compaction as the sediment accumulates and from land drainage, increases the subsidence in areas with thick sequences of Holocene sediments, with an average effect equivalent to an extra ~ 0.2 mm/y land subsidence (Shennan and Horton, 2002).

2.4 Measuring and monitoring sea level

Descriptions of global and national sea level networks can be found at the Permanent Service for Mean Sea Level (PSMSL) (www.pol.ac.uk/psmsl) and Global Sea Level Observing System (GLOSS) (www.gloss-sealevel.org) websites. While methods for monitoring sea level are explained on the PSMSL training web pages. Figure 5.3 shows a sub-set of the locations reporting to PSMSL, Figure 5.4 shows the GLOSS core network and Figure 5.5 shows the UK National (or ‘A-class’) network.

Links to the UK National Network and other monitoring networks and data sets follow here.
Online search interfaces for catalogues and inventories are maintained by the Marine Environmental Data and Information Network (MEDIN) at: www.oceannet.org . This includes a UK tide gauge and sea level catalogue for tide gauges currently operating in the UK:
www.oceannet.org/online_data_by_theme/tide_and_sea_level/tide_tool/.

Many UK monitoring networks are also included in the UK Directory of Marine Observing Systems (www.ukdmos.org).

Other individual links include:

- UK National Tide Gauge Network - www.pol.ac.uk/ntslf/
- Channel Coastal Observatory: Regional Coastal Monitoring Programme www.channelcoast.org
- Irish Sea Observatory http://cobs.pol.ac.uk
- Environment Agency Anglian Region Strategic Coastal Monitoring Programme Shoreline Monitoring Data Catalogue available from EA Anglian Region, Kingfisher House, Goldhay Way, Orton Goldhay, Peterborough PE2 5ZR.
- Permanent Service for Mean Sea Level (PSMSL) www.pol.ac.uk/psmsl/
- Satellite missions www.aviso.oceanobs.com/, http://podaac.jpl.nasa.gov/

3. Progress since *Charting Progress*

Real-time data provision, in addition to the delayed-mode data needed for scientific research, is now becoming increasingly encouraged for several reasons: the data become available to a wide range of new users in ‘operational oceanography’ including coastal protection; faults can be identified faster, leading to more accurate delayed-mode data-sets in the long term. Some sea level stations are now ‘multi-hazard’ sites, with sensors specifically designed for the high rate recording needed for tsunami monitoring. Sensors for tsunami applications have been installed at Lerwick, Holyhead and Newlyn alongside the existing UK National Network gauges.

4. Presentation of the evidence

4.1. Trends in tides and surges

Woodworth et al. (1991) pointed to long-term changes in tidal range at many UK sites. However, it was not easy to identify the causes. One site at which there appeared to be a convincing change in mean tidal range of approximately 0.4 mm/y was Newlyn. Araújo at al. (2002) subsequently studied sea level records from Newlyn, Portsmouth and Dover and showed local short-term variations in amplitude and phase of tidal constituents but no convincing long-term trends. However, in a later analysis concentrating on Newlyn (Araújo and Pugh, 2008), the authors concluded that the main identifiable trends included a 0.17 mm/y change in M_2 amplitude (i.e. half the reported rate in mean tidal range of Woodworth et al., 1991).

Araújo et al. (2002) also showed that there is no evidence of a change in surge levels at Newlyn since the 1920s, Portsmouth since the 1960s or Dover since the 1960s; and that there was no correlation between the Newlyn surge levels and the NAO. Araújo and Pugh (2008) again found no evidence for trends in surge levels (non-tidal residuals) at Newlyn. Analysis of surge statistics from the Liverpool tide gauge data has shown that there were no major long-term changes in surges over the extended period 1768 to 1999 (Woodworth and Blackman, 2002).

4.2. Trends in Mean Sea Level

4.2.1 Global MSL trends

Since the last ice age around 20 000 years ago, MSL has risen worldwide by about 120 m. A consensus seems to have been achieved that the 20th century rise in global sea level was closer to 2 mm/y than 1 mm/y; values around 1.7 mm/y have been obtained recently for the past century (Church and White, 2006) or past half-century (Church et al., 2004; Holgate and Woodworth, 2004). However, the rate of change was far from constant, with an acceleration around 1920-1930, a deceleration after 1960, and a relatively recent acceleration in the 1990s (e.g. Douglas, 2008; Woodworth et al., 2009a). Since the early 1990s, the scientific community has had access to precise radar altimeter data from satellites, notably from the TOPEX/Poseidon and Jason missions. The fast rise in the latter period was observed not only by tide gauges but also by those satellite altimetry missions (Beckley et al., 2007). A longer-term acceleration appears to have taken place between the

18th and 19th centuries into the 20th century, based on the small number of available long European tide gauge records (Woodworth, 1999; Jevrejeva et al., 2008) and on complementary data from saltmarshes (e.g. Gehrels et al., 2006).

MSL is often described as an ‘integrator parameter’, providing an integration of many climate-change related processes, i.e. global warming leading to oceanic thermal expansion, glacier and ice-cap melt, modifications to hydrological exchanges between land and ocean etc. Consequently, if MSL is changing, it points to major changes in one or more of the drivers of that change. Ultimately, anthropogenic climate change appears to be the fundamental issue, although the attribution of the ‘budget’ of sea level rise remains a major research question (Bindoff et al., 2007).

4.2.2 UK MSL Trends

Woodworth et al. (2009b) have recently provided updated tabulations of UK sea level trends. They suggest a pattern of UK sea level change as measured at the coast, comprising effects of land movements and oceanic changes. Vertical land movements are spatially variable (primarily north-south but also locally); they can be inferred from geological (e.g. Shennan and Horton, 2002) or geodetic data (e.g. Teferle et al., 2006, 2009), together with geodynamic modelling (Milne et al., 2006). Sea level variations due to changes in the ocean are largely spatially-coherent. This overall picture is inevitably approximate, but consistency in interpretation of the different data sets (tide gauge, geological, geodetic) appears to have risen as their temporal and spatial coverage has increased.

Figure 5.6 shows the data from the five longest UK MSL records: at Aberdeen, North Shields, Sheerness, Newlyn and Liverpool. The records from Aberdeen and Liverpool are composites from more than one gauge at each site, whereas the others are from gauges where there is a full benchmark datum history, and therefore in the Revised Local Reference (RLR) subset of the PSMSL. All five stations show a positive trend (i.e. an increase) in MSL, relative to the land, as do the majority of the other shorter records (Woodworth et al., 2009b).

The five long time-series can be used to provide a representative sampling of sea level change around the coastline. First, the long-term rate of MSL change can be removed from each record, thereby removing contributions from vertical land movements and (linear) climate-change-associated sea level rise. Then, MSL values from the five records can be averaged to obtain an index of UK interannual and decadal MSL variability, with the index having zero trend by construction, as shown in Figure 5.7a. (The standard deviation of the five values about their mean in any one year is typically 25 mm except for the early years of the 20th century when it is several times larger.)

Finally, a UK-average value for the long-term climate-change component of MSL change, estimated from a comparison of tide gauge and geological rates at a number of UK sites, can be added to make the time series in Figure 5.7b. This average long-term trend is estimated as 1.4 ± 0.2 mm/y which is slightly lower than the 1.7 mm/y consensus value for global sea level change over a similar period.

The 14 cm rise during the 20th century has significantly increased (as much as doubled) the risk of flooding since 1901 at many locations around the UK coastline. In terms of risk, the most affected regions are those (1) where relative land movement due to glacio-isostatic rebound is adverse, such as the south (as opposed to Scotland), or (2) where extreme levels increase only slightly with return period. If sea level rises faster in the 21st century, as suggested by the IPCC Fourth Assessment Report (Meehl et al., 2007), there could be greater risk to the coastal environment and infrastructure.

The interannual changes in the UK sea level index (Figure 5.7a) must be related to changes in local meteorological forcing (storm surges) and to oceanographic changes in shelf and nearby deep-ocean circulation. The 1970s dip exceeds any direct steric effect of the North Atlantic ‘Great Salinity Anomaly’ that passed the UK in that period; it might reflect a change in North Atlantic gyral circulation (Woodworth, 1987) as is also suggested by the opposite (rising) trend of US east-coast sea levels in the early 1970s; such speculation needs to be tested by numerical modelling of the period. The index shows a dip in the early 1990s that is as deep as the 1970s dip and others before. Similar interannual and decadal variability of sea level is observed at stations along the adjacent European coastline (Woodworth et al., 2009b).

4.2.3 Changes in extreme high and low sea levels

Newlyn and Aberdeen are at opposite ends of the UK and have some of the longer data sets of hourly (or 15-minute) sea level data. The small red and blue dots in Figure 5.8a for Newlyn show the time series of annual 99 and 1 percentile levels respectively (i.e. the levels which sea level exceeds 1% and 99% of the time) with the long-term average for each series set to zero. The use of 99 and 1 percentiles is sometimes preferred over the choice of the annual maximum and minimum water levels (i.e. 100 and 0 percentiles respectively) as they provide a description of change in high and low water characteristics without the greater variability inherent in the true extremes.

The long-term rising trend in 99 and 1 percentile is 2.2 and 1.8 mm/y, compared to 2.1 mm/y for median sea level. Trends for the extremes are more difficult to calculate because of the greater variability in their records. Those for high and low extreme levels are 2.2 and 1.3 mm/y. The slightly greater increase in height of high waters compared to low waters is considered to be a consequence of increasing local tidal amplitudes (see Araújo and Pugh, 2008). However, otherwise it is not possible to assign convincingly different long-term behaviour to the extremes than to mean levels. Indeed, Woodworth and Blackman (2004) demonstrated that trends in high water extremes measured over several decades at most locations tend to follow the corresponding trends in mean sea level.

Figure 5.8b shows similar data for Aberdeen, indicating positive trends of 1.9 and 1.3 mm/y for the 99 and 1 percentiles for the period shown, compared to 1.3 mm/y for the median percentile. High and low extremes indicate trends of 3.8 and 0.0 mm/y but are based on very noisy time series.

4.3 Mean sea level and the North Atlantic Oscillation

Winter-mean (December to March) monthly MSL and the NAO Index (Jones et al., 1997) are significantly correlated over much of the NW European shelf (Wakelin et al., 2003). There is a clear spatial pattern in the correlation, with strongly positive (> 0.8) values in the northeast (e.g. German Bight) and strongly negative (< -0.7) in the south (e.g. Western Approaches). This is consistent with a positive NAO Index corresponding to anomalously low (high) atmospheric pressure in the north (south) leading to a hydrostatic increase (decrease) in the sea level due to direct pressure changes (the inverse barometer effect). The sensitivity of the sea level to the NAO is strongest in the southern North Sea, where most of the sensitivity is present also in the non-hydrostatic component of sea level, i.e. that due to changing wind stress. The rest of the North Sea has a correlation of > 0.3; around the north and east coasts of Scotland the correlation exceeds 0.6. For most of the rest of the shelf, the correlations are below the level of significance.

Wakelin et al. (2003) also showed that the relationship varies with time; sea level for the period 1909-1954 shows less correlation with the NAO than that for the period 1955-2000. There was an increase in correlation between the periods 1959-1979 and 1980-2000 for the North Sea. Sea level pressure anomalies related to the NAO were located further eastwards during the latter period (Hilmer and Jung, 2000), thus increasing the associated westerly winds and wind-induced sea level.

4.4 The North Atlantic Oscillation and extreme water levels

The role of the NAO in effecting changes in winter extreme high and low waters and storm surges in UK waters was investigated by Woodworth et al. (2007) with the use of a depth-averaged tide+surge numerical model. Spatial patterns of correlation of extreme high and low waters (extreme still water sea levels) with the NAO index are similar to those of median or mean sea level studied previously (Wakelin et al., 2003). Likewise, spatial patterns of correlations of extreme high and low and median surge with the NAO Index are similar to the corresponding extreme sea level patterns. Suggestions were made as to which properties of surges (frequency, duration, magnitude) are linked most closely to NAO variability. Several climate models suggest higher (more positive) average values of NAO Index during the next 100 years. However, the impact on the UK coastline in terms of increased flood risk should be low (aside from other consequences of climate change such as a global sea level rise) if the existing relationships between extreme high waters and NAO Index are maintained. The shallow waters of the eastern North Sea (i.e. the German Bight) will receive a much greater impact due to the NAO than will the UK.

5. What the evidence tells us about environmental status

Sea level is rising globally and around the UK. Differences in rate as seen at the coast may be caused by land movement and by altered circulation in the coastal or open ocean. Nevertheless, a rise at the coast is found all around the UK. There are periods when rates are significantly larger or smaller than average. The 1990s experienced fast sea level rise of 3 to 4 mm/y.

Tidal constituents (amplitude and phase) show no long-term trends which can be unambiguously assigned to oceanic causes. However, Newlyn appears to be an exception with a long-term increase in mean tidal range. Most UK records do not present evidence for long-term changes in statistics of surges (non-tidal variations from mean level). Thus long-term changes in extreme sea levels largely follow the long-term behaviour of mean levels.

5.1 Projected UK 21st century sea level rise

The following is based on a review of the IPCC Fourth Assessment Report (AR4) by Church et al. (2008) from which more details may be obtained.

The IPCC Third Assessment Report (TAR) of 2001 (Church et al., 2001) projected a global averaged sea level rise of between 0.2 and 0.7 m between 1990 and 2100 using the full range of IPCC greenhouse gas scenarios and a range of climate models. When an additional uncertainty for land-ice changes was included, the full range of projected sea level rise was 0.09 to 0.88 m.

In the subsequent UKCIP02 study, the climate modelling was based on a smaller set of models from the Hadley Centre and only four emissions scenarios (Hulme et al., 2002). Nevertheless, the range of likely global sea level rise (by 2080 in this case) was similar to that proposed by the TAR. The UKCIP study noted that large regional variations in sea level rise predictions exist in all models, and between models, such that predictions could not be provided reliably for the NE Atlantic alone. Consequently, global-average values of sea level rise were employed, modified by estimates of UK vertical land movement.

For the AR4 (Meehl et al., 2007), the range of sea level projections, using a larger range of models, was 0.18 to 0.59 m (90% confidence limits) over the period from 1980-1999 to 2090-2099. The largest contribution was from ocean thermal expansion with the next largest contribution from glaciers and ice caps. However, there is increasing concern about the stability of ice sheets (e.g. see Church et al., 2008, for details). Recognizing this deficiency, the AR4 increased the upper limit of the projected sea level rise by 0.1 to 0.2 m above that projected by the models, implying an overall range of projected sea level rise of 0.18 to 0.79 m. It is unclear what confidence intervals to ascribe to this range given the ice sheet uncertainties. Note that the AR4 also stated that *...larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise*.

While the 2001 and 2007 IPCC projections are somewhat different in how they treat ice- sheet uncertainties and the confidence limits quoted, a comparison (Figure 6 of Church et al., 2008) shows that the ranges of projected rises are similar, except that the lower limit of the projections has been raised from 0.09 m in the TAR to 0.18 m in the AR4.

Despite the additional allowance for ice-sheet uncertainties, a number of scientists remain concerned that the ice-sheet contributions in particular in the AR4 may have been underestimated, and they adopt more of a phenomenological approach to estimating future sea level rise. For example, Rahmstorf (2007) developed a simple statistical model that related 20th century surface-temperature change to 20th century sea level change. Using this relationship and projected surface-temperature increases, he estimated that 21st century sea level rise might exceed the IPCC projections and be as much as 1.4 m. Holgate et al. (2007) raised concerns that Rahmstorf's model is too simplistic and may not adequately represent future change.

Similar conclusions, that the AR4 sea level rise projections may have been underestimated, have been based on analysis of longer-term temperature and sea level information (e.g. Grinsted et al., 2010). Concern remains as to the low physics content of some of these parameterisations. Nevertheless, the concern that the IPCC sea level projections may be biased too low has been reinforced by a comparison of observed and projected sea level rise from 1990 to the present. For this period, observed sea level has been rising more rapidly than the central range of the IPCC (TAR and AR4) model projections and is at the very upper end of the IPCC TAR projections (Holgate and Woodworth, 2004; Rahmstorf et al. 2007), again indicating that one or more of the model contributions to sea level rise may be underestimated.

In the recent UK Climate Projections (UKCP09) marine report (Lowe et al., 2009), sea level rise projections for the UK amounted to approximately 80 cm by 2095 for the London area and high emissions scenarios, and lower values for other areas and scenarios. These findings are not materially different from the earlier studies. However, a useful 'High++' high-end coastal flooding concept was also introduced, which indicated levels (93 to 190 cm) to engineers which lie above best estimates of uncertainty for 21st century sea level rise.

5.2 Status

The summary table (Table 5.1) includes an assessment of trend but not status ('traffic-light') because (1) no accepted criteria apply for sea levels giving significant risk of adverse effects; and (2) the UK (government), or even the EU, cannot itself take measures to improve the status.

Sea level is rising. Changes since pre-industrial times are moderate, O(0.2 m), and have taken place relatively slowly, facilitating adaptation. However, the rate is forecast to increase (as a rise of 0.18 to 0.79 m or perhaps more in the 21st century), making adaptation more difficult (for marine species or as managed by humans). In particular, 'coastal squeeze' – reduction in the aggregate area of beaches and intertidal rocky shores – is likely unless compensatory measures are taken. There is some basis to distinguish between CP2 Regions in that rates are modulated by land movement which increases apparent sea level rise in the south and presently (but probably not in future) nearly negates it in the north-west.

6. Forward look and need for further work

Globally, the observed rate of sea level rise has not been well accounted for by the main contributing factors; thermal expansion of the ocean, melting of land-based ice, hydrological exchanges between land and water and land movements. However, now that the world has much better instrumented monitoring networks, both in space and *in situ*, the discrepancies between observations and understanding of the reasons for sea level change are beginning to decrease. These uncertainties translate to some extent into uncertain projections of future sea level rise. There is scope for looking at the distribution of sea level rise observed from space (altimetry and gravity) in addition to *in situ* methods (tide gauges and geological techniques). These studies are known as 'fingerprinting' and diagnose the origins of sea level change from its spatial variations. Such studies are necessarily complicated by any uneven distribution of measurements, especially by the *in situ* methods.

The distribution of UK tide gauges has been the subject of long consideration and is probably dense enough relative to the scale of sea level variations apart from local land movements. They need to be maintained along with accurate geodetic control (at present with GPS moderated by absolute gravity) to distinguish vertical land movements from geocentric (Earth centred) sea level changes within the tide gauge records.

7. References

Araújo, I., Pugh, D.T. and Collins, M., 2002. Trends in components of sea level around the English Channel. Proceedings of Littoral 2000, Porto, Portugal, September 2002. pp. 1-8.

Araújo, I.B. and Pugh, D.T., 2008. Sea levels at Newlyn 1915-2005: analysis of trends for future flooding risks. J. Coast. Res. 24, 203-212.

Beckley, B.D., Lemoine, F.G., Lutchke, S.B., Ray, R.D. and Zelensky, N.P., 2007. A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits. Geophys. Res. Lett. 34, L14608, doi:10.1029/2007GL030002.

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. Edited by Solomon, S., Qin, D. and Manning, M. Cambridge University Press, pp. 385-432.

Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D. and Woodworth, P.L., 2001. Changes in Sea Level. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P., Dai, X., Maskell, K. and Johnson, C.I. Cambridge University Press, pp. 639-693.

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. J. Climate 17, 2609-2625.

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

Church, J., Wilson, S., Woodworth, P. and Aarup, T., 2007. Understanding sea level rise and variability. Meeting report. EOS, T.. Am. Geophys. Union 88, 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., 2008. Understanding global sea levels: past, present and future. Sustain. Sci. 3, 9-22, doi:10.1007/s11625-008-0042-4.

Douglas, B.C., 2008. Concerning evidence for fingerprints of glacial melting. J. Coast. Res. 24, 218-227, doi:10.2112/06-0748.

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

Gehrels, W.R., Marshall, W.A., Gehrels, M.J., Larsen, G., Kirby, J.R., Eiriksson, J., Heinemeier, J. and Shimmield, T., 2006. Rapid sea-level rise in the North Atlantic Ocean since the first half of the 19th century. The Holocene 16, 948-964.

Grinsted, A., Moore, J.C. and Jevrejeva, S., 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100. Clim. Dynam. 34(4), doi: 10.1007/s00382-008-0507-2.

Hilmer, M. and Jung, T., 2000. Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea ice export. Geophys. Res. Lett. 27, 989-992.

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

Holgate, S., Jevrejeva, S., Woodworth, P. and Brewer, S., 2007. Comment on ‘A semi-empirical approach to projecting future sea-level rise’. Science 317, (5846), 1866b. (28 September 2007). doi:10.1126/science.1140942.

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

Jevrejeva, S., Moore, J.C., Grinsted, A. and Woodworth, P.L., 2008. Recent global sea level acceleration started over 200 years ago? Geophys. Res. Lett. 35, L08715, doi:10.1029/2008GL033611.

Jones, P.D., Jónsson, T. and Wheeler, D., 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. Int. J. Climatol. 17, 1433-1450.

Lowe, J.A., Howard, T., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S. and Bradley, S., 2009. UK Climate Projections science report: Marine and coastal projections. Met Office Hadley Centre, Exeter, UK.

Meehl, G.A., Stocker, T.F., Collins, W., Friedlingstein, P., Gaye, A., Gregory, J., Kitoh, A., Knutti, R., Murphy, J., Noda, A., Raper, S., Watterson, I., Weaver, A. and Zhao, Z.C., 2007. Global climate projections. 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. Edited by Solomon, S., Qin, D. and Manning, M. Cambridge University Press, pp. 747-845.

Milne, G.A., Shennan, I., Youngs, B.A.R., Waugh, A.I., Teferle, F.N., Bingley, R.M., Bassett, S.E., Cuthbert-Brown, C. and Bradley, S.L., 2006. Modelling the glacial isostatic adjustment of the UK region. Philos. T. Roy. Soc. A 364, 931-948. doi:10.1098/rsta.2006.1747.

Pugh, D.T., 2004. Changing sea levels : effects of tides, weather, and climate. Cambridge University Press, xiii+265 pp.

Rahmstorf, S., 2007. A semi-empirical approach to future sea-level rise. Science 315, 368-370.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R., Parker, D.E. and Somerville, R.C.J., 2007. Recent climate observations compared to projections. Science 316, 709. doi: 10.1126/science.1136843.

Shennan, I. and Horton, B., 2002. Holocene land- and sea-level changes in Great Britain. J. Quat. Sci. 17, 511-526.

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. Philos. T. Roy. Soc., 364, 917-930, doi:10.1098/rsta.2006.1746.

Teferle, F.N., Bingley, R.M., Orliac, E.J., Williams, S.D.P., Woodworth, P.L., McLaughlin, D., Baker, T.F., Shennan, I., Milne, G.A., Bradley, S.L. and Hansen, D., 2009. Crustal motions in Great Britain: evidence from continuous GPS, absolute gravity and Holocene sea-level data. Geophys. J. Int. 178, 23-46, doi:10.1111/j.1365-246X.2009.04185.x.

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. Geophys. Res. Lett. 30: 1403, doi: 10.1029/2003GL017041.

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

Woodworth, P.L., Shaw, S.M. and Blackman, D.B., 1991. Secular trends in mean tidal range around the British Isles and along the adjacent European coastline. Geophys. J. Int. 104, 593-610.

Woodworth, P.L., 1999. High waters at Liverpool since 1768: the UK's longest sea level record. Geophys. Res. Lett. 26, 1589-1592.

Woodworth, P.L. and Blackman, D.L., 2002. Changes in extreme high waters at Liverpool since 1768. Int. J. Climatol. 22, 697-714.

Woodworth. P.L. and Blackman, D.L., 2004. Evidence for systematic changes in extreme high waters since the mid-1970s. J. Climate 17, 1190-1197, doi:10.1175/1520-0442.

Woodworth, P.L., Flather, R.A., Williams, J.A., Wakelin, S.L. and Jevrejeva, S., 2007. The dependence of UK extreme sea levels and storm surges on the North Atlantic Oscillation. Cont. Shelf Res. 27, 935-946. doi:10.1016/j.csr.2006.12.007.

Woodworth, P.L., White, N., Jevrejeva, S., Holgate, S., Church, J. and Gehrels, R., 2009a. Evidence for the accelerations of sea level on multi-decade and century timescales. Int. J. Climatol. 29, 777-789, doi:10.1002/joc.1771.

Woodworth, P.L., Teferle, N., Bingley, R., Shennan, I. and Williams, S.D.P., 2009b. Trends in UK mean sea level revisited. Geophys. J. Int. 176, 19-30, doi:10.1111/j.1365-246X.2008.03942.x.

Figure captions

Figure 5.1 Standard deviation in the observed sea level variations at Newlyn, showing the 18.6 year modulations. Standard deviation is larger when the semidiurnal tides have a larger amplitude. Courtesy of David Pugh, from Pugh (2004)

Figure 5.2 Current rate of relative land- and sea-level change in the British Isles in mm/y, showing relative land uplift as positive and relative subsidence as negative. Image is ~900 × 1300 km. Courtesy of the NASA Scientific Data Purchase Program and I. Shennan (Durham).

Figure 5.3 Stations with at least 40 years of consistently-levelled data in the Permanent Service for Mean Sea Level. Source: PSMSL website.

Figure 5.4 Priority sites which make up the core network of the Global Sea Level Observing System. Source: GLOSS website.

Figure 5.5 UK tide gauge network. Source: www.pol.ac.uk/ntslf/ .

Figure 5.6 Mean sea level at Aberdeen, North Shields, Sheerness, Newlyn and Liverpool. Courtesy of Permanent Service for Mean Sea Level.

Figure 5.7 British Isles sea level index. (a) Each record has been de-trended over the period 1921-1990 and the de-trended values averaged. The figure also shows standard deviations of de-trended values about the average. (b) UK-average time-series for long-term climate-change component of MSL change. Source: Woodworth et al. (2009b).

Figure 5.8 The 99 and 1 percentiles of sea level each year at (a) Newlyn and (b) Aberdeen, together with the measured extreme high and low waters. The large red and blue dots show the annual maximum and minimum water levels relative to the long-term means for the 99 and 1 percentiles. Courtesy of NOC

Table 5.1 Summary assessment of trends.

Parameter	**CP2 Region**	**Key factors and impact**	**What the evidence shows**	**Trend**	**Confidence in assessment**	**Forward look**
Sea Level	1-5 (North Sea, Channel, Celtic Sea, Irish Sea)	Climate, geology. Affects local communities (flood risk)	Interannual/decadal MSL-variability superimposed on long-term trends. Changes in extreme sea levels largely follow MSL changes	Rising	High	Faster rise
Sea Level	6-7 (Scottish shelf seas)	Climate, geology. Affects local communities (flood risk)	Interannual/decadal MSL-variability superimposed on long-term trends. Changes in extreme sea levels largely follow MSL changes	Rising slowly	High	Faster rise
Sea Level	8 (adjacent N Atlantic)	Climate		Rising	High	Faster rise