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CSG 15

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD
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Final Project Report

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Project title	Integrated effects of climate change on coastal extreme sea levels		
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Executive summary (maximum 2 sides A4)

The work described here aimed to derive guidance on changes / trends in extreme sea levels from *existing* information.

Contributions to any change in extreme sea levels, as observed at the coast, result from a number of inter-related components. There are published estimates of contributions from the separate elements, and research to improve and refine these is in progress. The intention was to combine these estimates, specifically:

a) global MSL change and observed regional trends
b) regional land movements
c) tidal changes due to increasing sea level
d) changes in extreme storm surge elevations caused by changes in "storminess" with increasing levels of atmospheric CO_2.

The first stages in the work were to review the elements mentioned above, in consultation with external experts, and to assemble estimates (with uncertainties) for UK coasts. Observed trends in sea level were compared against contemporary estimates of the contributing components, providing an indication of the reliability of and uncertainty in estimates derived from combining these elements for past conditions. Future projections could then be attempted using best estimates of components for the next 50-100 years (or approximately the typical lifetime of coastal defence structures).

Long term changes in sea level are monitored by POL using the UK national network of 45 tide gauges, and South Atlantic gauges which are the UK's contribution to the Global Sea Level Observing System (GLOSS). Several UK records are approximately 100 years long and show clear evidence for rising levels, implying 'absolute' sea level trends for the last century of about 1 mm/year, or 10 cm for the century. This is consistent with but at the lower end of the range of uncertainty of 10-20 cm of the estimates of global change by the IPCC. Sea level changes also show a small 'sea level acceleration' component, which is consistent with being the result of an acceleration towards the second half of the 19th century, as well as considerable inter-annual and inter-decadal variability. A 'UK sea level index' provides a useful indicator of these variations.

Long term change in the observed mean sea level at any point is a combination of climate change related sea level variation, sometimes called the *absolute* sea level change, and the effect of land subsidence or uplift. Most land movements are due to long term geological processes such as glacial isostatic adjustment of the Earth following the last ice age or sediment compaction. If we can measure and predict absolute mean sea level and the land movement then the combination of these two factors will provide the *relative* mean sea level change required for coastal defence applications. Land movements around the UK estimated from geological data, show uplift of 1.5mm/year in Scotland and subsidence of 1.5 mm/year in the Thames estuary and 1.4 mm/year in Cornwall. These rates can be compared with predictions from post-glacial rebound models, which compute the deformation of the Earth using the time history of the ice sheets and the inferred viscosity of the Earth's mantle.

New advanced geodetic techniques using GPS and measurement of changes in gravity using an absolute gravimeter (AG) provide methods of directly measuring present day vertical land movements. A long-term monitoring programme is under way to improve estimates and provide local variations.

Future projections must be based on model predictions. Changes in extreme sea level for 2075 were estimated from model projections by combining contributions from MSL, tide, storm surge and land movements. In deriving these estimates, the "best" value available for each component was used. Extreme water levels generally occur as a combination of high water of a spring tide and a storm surge. An increase in mean sea level will, of course, affect extreme levels directly, but changes in the mean level and hence water depth can also influence the tide and surge components e.g. by changing tidal wavelength, and modifying the propagation and dissipation of energy.

For global MSL rise we assumed a value of 50cm for 2100, and 37cm for 2075 from the IPCC mid-range projection. From experiments with a POL model (CS3), mean high water (MHW) levels were found to increase by 40 – 60cm on NW European coasts as a result of a 50cm rise in MSL.

Changes in storm surges and their extremes also result from changes in "storminess". Long (O(10 year)) model hindcast simulations of surges, forced by meteorological data sets from climate GCMs, provide regional storm surge climatologies. Extreme value analysis can be applied to these to estimate extremes. Estimates of change in 50-year surge elevation (S50) were available from POL work in STOWASUS-2100, based on 30-year time slice experiments with the ECHAM4 climate model. For UK coasts changes in S50 are in the range -20 to + 20cm. However, care is required in interpretation of these results, as discussed at length in the paper. Similar estimates from the POL CSX model using forcing from a Hadley Centre regional climate model are quite different from those using ECHAM. Further research is required to understand and resolve these issues.

Changes in absolute and relative extreme sea level between 1990 and 2075 were calculated from the components. For relative values, estimates of the change are between 20 and 60cm for UK coasts, depending on location. Converting these into rates (assumed uniform over the period) gives values between 2 and 7 mm/yr. These can be compared with current guidance (MAFF 2000). Generally, the results agree well on the East Coast of England; but our estimated rates are lower on the South Coast and higher in the Irish Sea and Bristol Channel than currently recommended.

However it is important to be aware that *large uncertainty* attaches to each of these values. In particular:

a) The IPCC TAR projection for global MSL rise from 1990-2100 based on all SRES (Special Report on Emissions Scenarios) scenarios is in the range 9 to 88cm. We have assumed a value of 50cm for 2100, and 37cm for 2075. This latter value is subject to corresponding uncertainty.
b) The effect of MSL rise on tidal conditions depends on the assumed MSL rise and so is subject to corresponding uncertainty.
c) Factors affecting estimates of extreme surge elevation were discussed in section 5. These depend, amongst other things, on predictions of future change in storminess which in turn depend on which climate model and assumptions are made. We showed that recent results from STOWASUS-2100 and the Hadley Centre give very different estimates of future change in S50. These aspects require further research.

d) For land movements, we applied a digitised version of the model results of Lambeck and Johnston (1995). This doesn't account for all mechanisms and gives a smaller range of values than have been derived from observations. It is important, therefore, to continue the monitoring activities and refine both observations and models.
e) Finally, we combined the contributions by simple addition which, given the uncertainties just mentioned is appropriate. However, if the uncertainties can be reduced, interactions among components will be worth considering.

The distributions produced, like all similar estimates, are subject to large uncertainty and must be treated with caution. They are, however, indicative of the type of results that can be produced from model predictions. Reliable quantitative results of this type would be of great value for coastal defence purposes. Further work is required to resolve the aspects of uncertainty, leading to useful quantitative estimates for the UK and other vulnerable coasts.

Footnote:

This report is also available as

Flather, R.A., T.F. Baker, P.L. Woodworth, J.M. Vassie, and D.L. Blackman, 2001. Integrared effects of climate change on coastal extreme sea levels. POL Internal Document No. 140, July 2001, 20pp.

Scientific report (maximum 20 sides A4)

1. Introduction

Current MAFF advice on effects of climate change on sea levels is given in Section 4.6 of MAFF (2000). It is based on trends in mean sea level (MSL) from the 1990 report of the Intergovernmental Panel on Climate Change (IPCC) combined with assumed rates of large-scale land movement in England and Wales from previous research (Shennan 1989). The average predicted sea level rise was 4.5mm/yr over the next 40 to 50 years and, including land movements, the regional rates of relative sea level rise were:

6mm/yr for the E coast south of Flamborough Head and the S coast;
5mm/yr for the South West and Wales; and
4mm/yr for the North West and the E coast north of Flamborough Head.

The possibility that future climate change could have other impacts, e.g. from changing "storminess" – the frequency, duration and severity of storms – was mentioned, but it was not considered possible to quantify its effects for routine application. The general assumption is therefore that trends in extreme sea levels will be the same as those in MSL. Clearly, there may be substantial cost implications if this assumption is not correct. Guidance on and quantitative estimates of changes in extreme sea level round UK coasts resulting from climate change, including indications of uncertainty, would therefore be valuable.

The work described here aims to derive guidance on changes / trends in extreme sea levels from *existing* information.

Contributions to any change in extreme sea levels, as observed at the coast, result from a number of inter-related components. There are published estimates of contributions from the separate elements, and research to improve and refine these is in progress. The intention is to combine these estimates, specifically:

a) global MSL change (IPCC 1996 and 2001) and observed regional trends (Woodworth et al. 1999)
b) regional land movements (Shennan 1989; Ashkenazi et al. 1998; Williams et al. 2001)
c) modelling of tidal changes due to increasing sea level (unpublished POL work)
d) estimates of changes in extreme storm surge elevations caused by changes in "storminess" with increasing levels of atmospheric CO_2 (Flather and Smith 1998; Lowe et al. 2001).
e) improvement in methods and their application to extreme sea levels round the UK (Dixon and Tawn 1997)

The first stages in the work were to review the elements mentioned above, in consultation with external experts, and to assemble estimates (with uncertainties) for UK coasts. Observed trends in sea level were compared against contemporary estimates of the contributing components, providing an indication of the reliability of and uncertainty in estimates derived from combining these elements for past conditions. Future projections can then be attempted using best estimates of components for the next 50-100 years (or approximately the typical lifetime of coastal defence structures).

The paper is organised in sections dealing with the elements listed above. In conclusion, an indication is given of how existing estimates of components might be combined to provide estimates of future extreme sea levels. The resulting estimates are compared with current guidance.

2. Global and regional mean sea level change

Long term changes in sea level are monitored by POL by means of the UK 'A Class Network' of 45 tide gauges, and with the use of data from South Atlantic gauges which are the UK's contribution to the Global Sea Level Observing System (GLOSS) of the Intergovernmental Oceanographic Commission (IOC), (Figure 1).

Several UK records are approximately 100 years or more long (Sheerness being the location of the world's first automatic tide gauge) and show clear evidence for rising levels (Fig. 2).

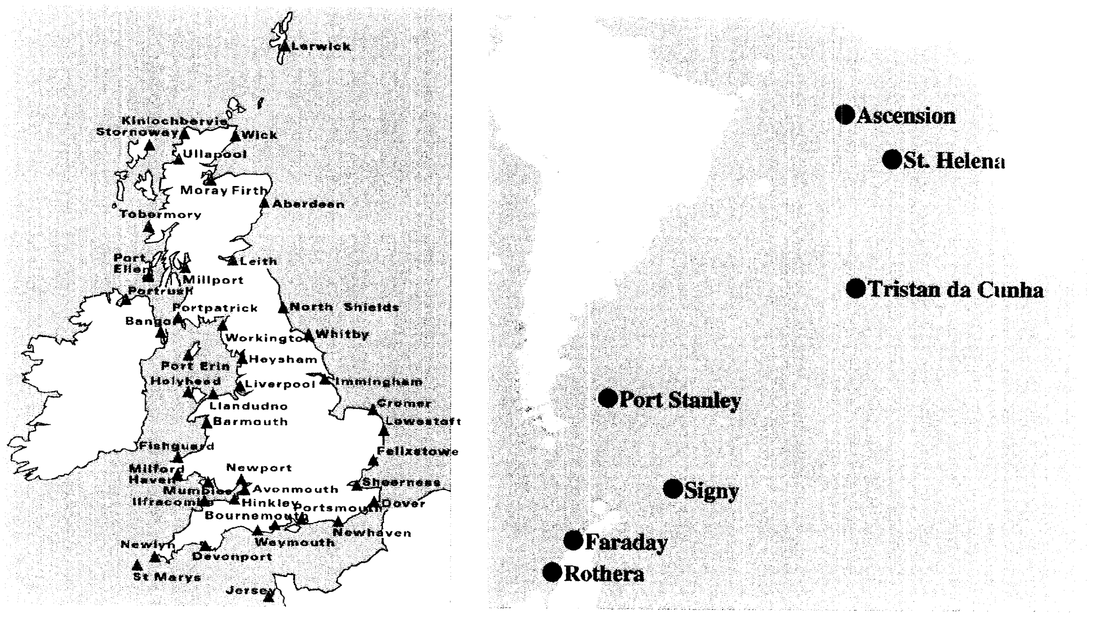

Figure 1: The UK A class tide gauge network (left) and South Atlantic tide gauges operated by POL (red dots, right). Yellow dots are GLOSS sites of other countries.

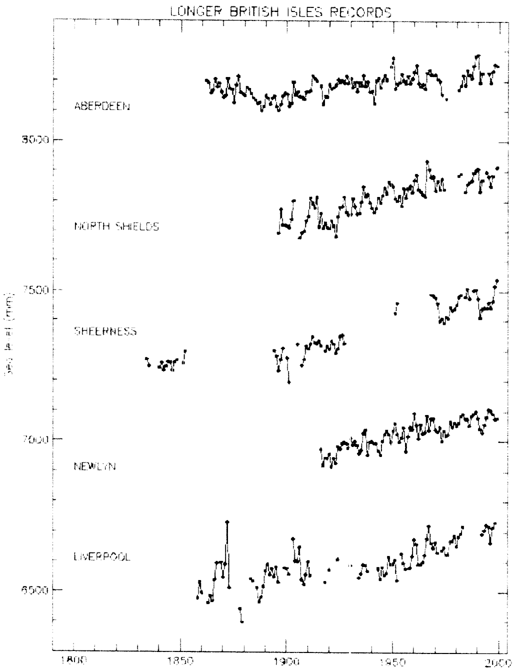

Figure 2: Long term changes in sea level at UK sites with long records.

After comparison to geological data on long term sea level change (which to a great extent provides a measure of local land level changes over the past few thousand years), UK and other North Sea tide gauge data imply 'real' or 'absolute' sea level trends for the last century of approximately 1 mm/year, or 10 cm for the century (see Fig. 3). This value is consistent with, although at the lower end of the range of uncertainty of 10-20 cm of the estimates of global change by the IPCC Third Assessment Report (TAR), (Church et al. 2001). The IPCC TAR suggests that the lower UK and European trends may reflect real regional differences connected to oceanographic changes in the North Atlantic. Recent work on the elastic response of the solid earth to changes in the mass balance of Greenland may go some way to explaining the apparently smaller trends observed in Europe as compared to other regions (Mitrovica et al. 2001).

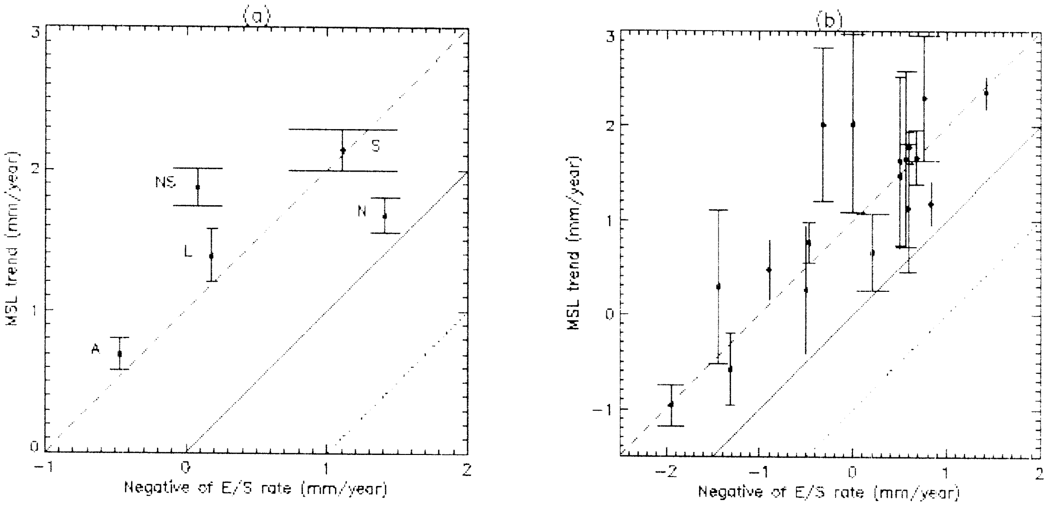

Figure 3: Long term changes in sea level from tide gauges compared with changes from geological data. (a) for long UK records; A = Aberdeen, NS = North Shields, S = Sheerness, N = Newlyn and L = Liverpool. (b) similar plot for the North Sea area. The solid lines correspond to MSL changes equal to the emergence/submergence rate from geology. Points on the dashed line indicate a 'real' MSL trend of +1mm/yr (Woodworth et al. 1999; Shennan and Woodworth 1992).

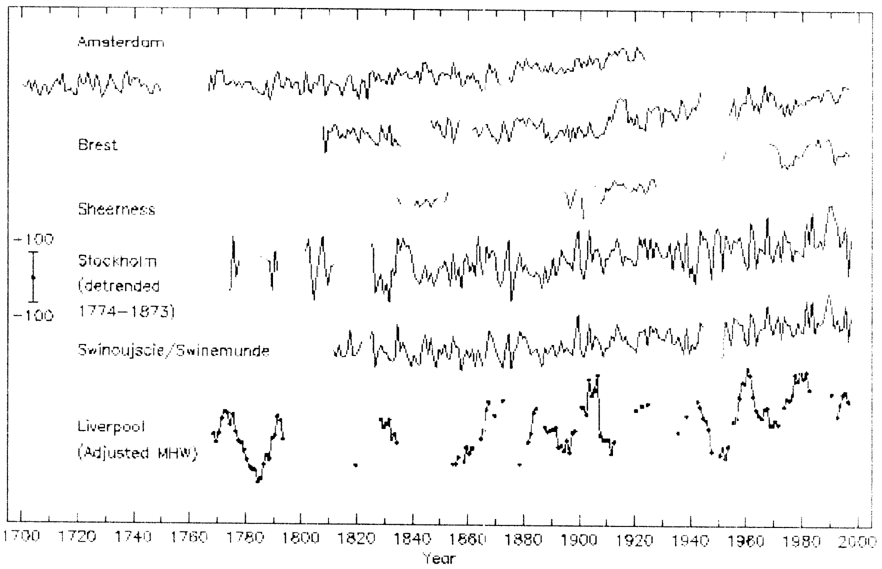

Figure 4: Long term changes in sea level at northern European sites.

An important question is when this apparent rise of sea level began i.e. whether it is a 20th century phenomenon or the continuation of a much longer timescale trend. Fig. 4 shows that the longest records from northern Europe contain a small 'sea level acceleration' component which is consistent with being the result of an acceleration towards the second half of the 19th century.

Sea level changes contain considerable inter-annual and inter-decadal variability in addition to simple trends.

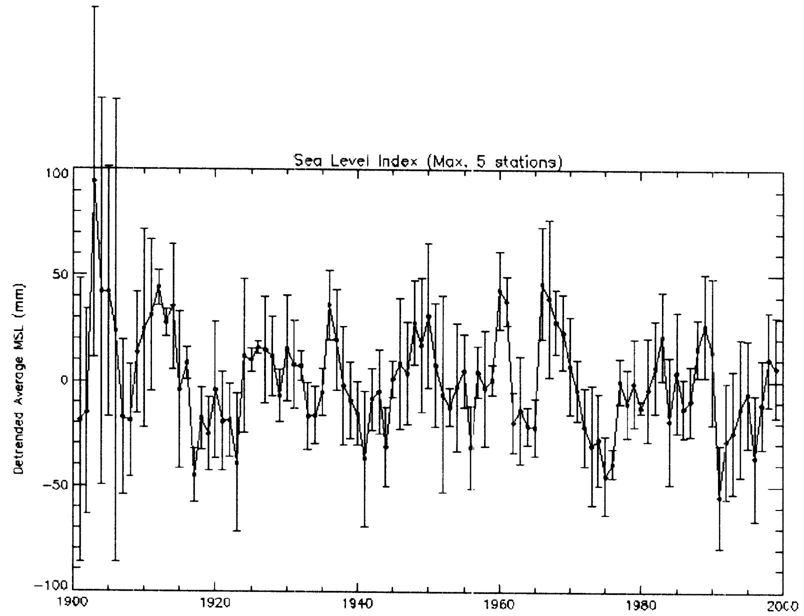

Figure 5: An index of changes in UK-average sea level.

Fig. 5 shows a 'UK sea level index' calculated by averaging data from the long records, each detrended over the period 1921-1990. The year-to-year changes are related to changes in local meteorological forcing (storm surges) and to oceanographic changes in shelf and nearby deep ocean circulation. A more complete understanding of the latter is also important for the determination of more precise boundary conditions for operational tide-surge numerical models.

A truly global data set of deep ocean sea level change is available for the last decade by means of precise satellite radar altimetry, especially that of TOPEX/POSEIDON. This is as yet too short a record to form conclusions on global secular trends and accelerations. However, even in the 'age of altimetry', gauges will continue to be required for application at the coast (where people live) and to provide an ongoing calibration system for the space radars. The UK South Atlantic sites (Fig. 1) are particular important in this role, consisting of state-of-the-art 'B gauges' developed at POL.

3. Regional and local land movements

The long term change in the relative mean sea level at any point around the coast is a combination of two factors. The first is the climate change related sea level variation at that coastal site. This is sometimes called the absolute sea level change. The second is due to the land subsidence or uplift at the coastal site. If we can measure and model (i.e. predict) the spatial variations of the absolute mean sea level and the land movement components around the coast then the combination of these two factors will provide the relative mean sea level change required for coastal defence applications.

Most of the available information on land movements around the UK coast has been obtained from geological data on former shorelines spanning the past 16000 years. By dating these former shorelines and measuring their heights relative to present day mean sea level, the land movements over the last few thousand years can be determined (Shennan 1989). Most of these land movements are due to long term geological processes such as glacial isostatic adjustment of the Earth following the last ice age or sediment compaction. The geological measurements therefore provide information on the present day land movements at various points around the UK coastline. Shennan (private communication 2001) has recently updated his earlier work (Fig. 6) with measurements at a larger number of coastal points. He finds maximum uplifts in Scotland of over 1.5mm/year, near the areas where the former British ice sheet had the maximum thickness. He finds a subsidence of 1.5 mm/year in the Thames estuary and a subsidence of 1.4 mm/year in Cornwall.

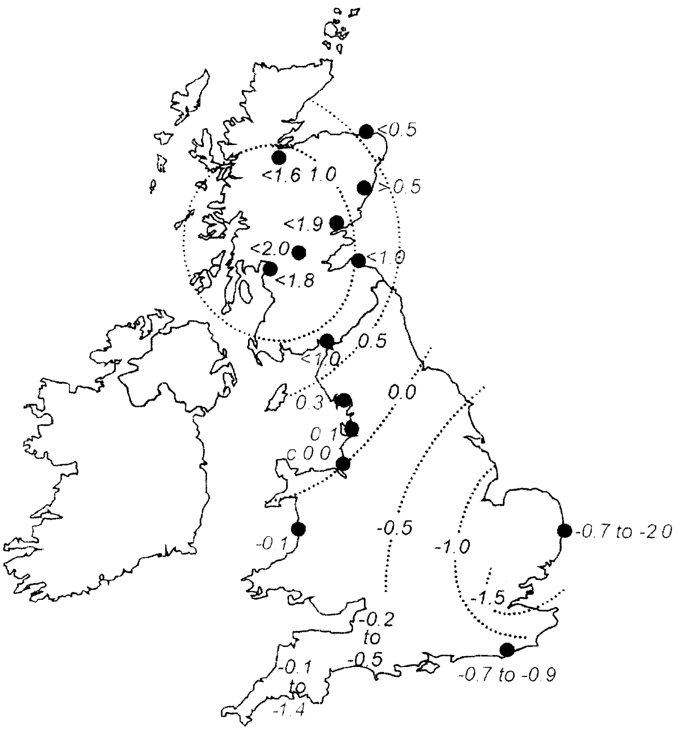

Figure 6: Estimated rates (mm/yr) of crustal movement, after Shennan (1989). Positive values indicate emergence (land rising relative to MSL).

These rates can be compared with the rates predicted by different post-glacial rebound models, which model the deformation of the Earth using the time history of the ice sheets and the inferred viscosity of the Earth's mantle. The model of Lambeck and Johnston (1995) gives a maximum uplift of just over 1mm/year in central Scotland and a subsidence of 1mm/year in Cornwall. The rates from the geological measurements therefore cover a greater range than the post-glacial rebound model. It should be noted that more local processes such as sediment consolidation or water extraction can give an increase in the subsidence in some areas and these processes are, of course, not included in the post-glacial rebound models.

Over the past few years developments of new advanced geodetic techniques have provided methods of directly measuring present day vertical land movements. These techniques are the measurement of the carrier phase of the signals from the Global Positioning System (GPS) of satellites and the measurement of changes in gravity using an absolute gravimeter (AG). For reviews of these techniques and the advances that have been made see Baker (1993) and Neilan et al. (1998). A programme of measurements using these techniques is now in progress at UK tide gauges. Although at least 10 years of measurements are required in order to achieved the required accuracies in the vertical rates, the initial results show that these techniques can now provide valuable information on vertical land movements. The AG measurements are being made by POL (Williams et al. 2001) and measurements at Lerwick began in 1996 and show a subsidence of 3.8±1.6 mm/year. This subsidence is consistent with the post-glacial rebound model of Lambeck and Johnston (1995) which gives a subsidence of 2mm/year for Lerwick. The AG measurements began at Newlyn in 1995 and show an uplift of 1.0±1.4 mm/year. A longer series of measurements is required in order to check the subsidence predicted by the Lambeck and Johnston (1995) model.

A programme of GPS measurements at UK tide gauges has been carried out by the Institute of Engineering Surveying and Space Geodesy (IESSG), University of Nottingham in collaboration with POL over the past few years (Bingley et al., 2001). The programme is now focussed around continuous GPS (CGPS) measurements at 7 UK tide gauges: Newlyn, Portsmouth, Sheerness, Lowestoft, North Shields, Aberdeen and Liverpool. Portsmouth and North Shields are recently installed CGPS stations and the time series of CGPS measurements at the other sites at present only span between 2 and 4 years. The measured vertical rates at present are in the range from −3mm/year (subsidence) to + 2mm/year but with uncertainties of order ±2mm/year. Over the next few years, as these error bars reduce, the land movements at these tide gauges will become much more accurately determined. An important point to note is that these measurement techniques only determine the land movement at the point of the measurement. Any differential local movements e.g. movements in the harbour or subsidence due to water extraction would mean that the land movement at the tide gauge site may differ from the land movements over a wider area. As an example, geodetic levelling measurements over the last 10 years in Sheerness have shown significant differential movements in the dock area. It is clearly important to check the stability of the area in order to ascertain how representative the GPS/tide gauge site is for the surrounding area. Checking the geodetic measurements against geophysical models of land movements also provides a confirmation that the necessarily limited number of measurement points are providing information on the wider scale land movements.

4. Tidal changes due to increasing (mean) sea level

Extreme water levels generally occur as a combination of high water of a spring tide and a storm surge. An increase in mean sea level will, of course, affect extreme levels directly, but changes in the mean level and hence water depth can also influence the tidal component by changing its wavelength, and modifying the propagation and dissipation of tidal energy.

Tides in shelf and coastal seas are their response to oscillations generated primarily in the deep oceans. The response of a shelf sea depends on its size, shape and the water depth. Large tides occur near resonance where a natural mode of oscillation of part of the region has a period close to that of a constituent of the tide. A simple resonant case occurs when the shelf width or length of a basin corresponds to a quarter wavelength of the tide. This is approximately so for the Bay of Fundy, which has the world's largest tidal range, and for the Bristol Channel which has the largest range in NW Europe. Generally, each tidal constituent propagates as a wave forming a linked system, losing energy in shelf seas through dissipation by bottom friction and transferring energy to harmonics and other tidal frequencies through non-linear shallow water processes and interactions.

Changes in water depth due to MSL rise will modify the dynamics of tides. An increase in MSL and hence water depth will increase the tidal wavelength, modifying the system of tidal waves. Both increases and decreases in tidal range may result. E.g. for near-resonant cases, tidal elevations may increase if the system moves closer to resonance or decrease if it moves away from resonance. Increased water depths will also modify bottom friction and hence the dissipation of tidal energy, so changes in general may be more complex.

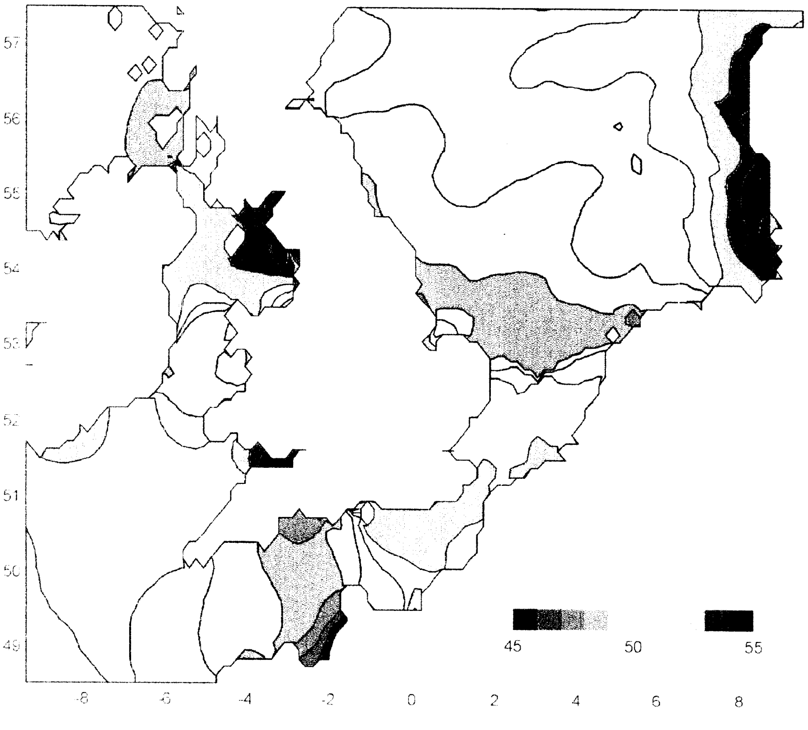

Figure 7: Computed change in mean high water (cm) due to a 50cm rise in MSL

Fig. 7 shows the relative change in mean tidal high water (MHW) due to a 50cm rise in MSL for the NW European Shelf, computed using the POL "CS3" tide-surge model (as used operationally in the UK for storm surge prediction). This shows higher MHW in the German Bight, Skagerrak and Kattegat most probably because of reduced dissipation; more tidal energy reaches the Kattegat from the Atlantic with deeper water. Substantial ($O(10\text{cm})$) increases in MHW also occur in the Bristol Channel and eastern Irish Sea and corresponding decreases in the Gulf of St Malo. These are near resonant areas with large amplitudes for the main M_2 harmonic. So if MSL rises by 50cm, MHW level will increase by 40 – 60cm on NW European coasts.

5. Changes in extreme storm surge elevations

Increased water depth also affects the generation, propagation and dissipation of the storm surge component. In addition, the surge climate can change if the storm climate itself, e.g. storm tracks, intensity and frequency of occurrence, sometimes referred to as "storminess", alters.

In tide–surge dynamics, the met. forcing terms generating storm surges are wind stress / water depth, and horizontal gradient of sea surface atmospheric pressure, ∇P_{msl}. Therefore, wind stress increases in importance in shallow water whereas the pressure gradient term is independent of water depth. Consequently, pressure forcing dominates in the deep ocean, but wind stress in shallow water is most important. Major surges therefore occur in shallow water. Changes in water depth due to MSL rise will consequently modify the dynamics of surges, reducing the effective forcing and hence surge elevations.

Recent studies have aimed at understanding and quantifying changes in the storm surge climatology and in particular in surge extremes. The approach is based on long model hindcast simulations of surges covering periods of order 10 years, forced by suitable meteorological data sets, to provide regional storm surge climatologies in the form of (say) hourly model fields of surge elevation. These can be analysed in the same way as observations to estimate surge extremes. Flather et al. (1998) demonstrated that this approach could produce good estimates of present-day surges and extremes given accurate meteorological data (Reistad and Iden 1995).

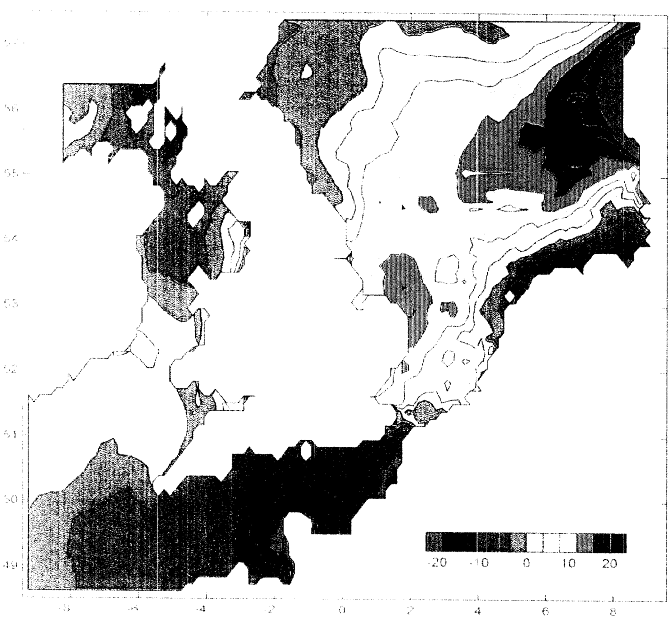

Figure 8: Computed change (cm) in 50-year return period surge elevation from a POL 12km grid model.

Several studies (Flather and Smith 1998; Langenberg et al. 1999; Lowe et al. 2001) using this approach with meteorological data from climate GCMs have attempted to quantify changes in surge extremes with increases in atmospheric CO_2. Two sets of runs are carried out with "control" data representing present day conditions and with data from a "$2\times CO_2$" future climate scenario. Results are analysed to estimate extremes for each set and differences examined. Fig. 8 shows as an example the computed change in 50-year surge elevation (S50) from POL work in STOWASUS-2100 (EU Environment Project ENV4-CT97-0498). This used two 30-year met. data sets from a time slice experiment with the ECHAM4 climate model run by the Danish Meteorological Institute (May 2001; May and Roeckner 2001). The results suggest that S50 might *increase* by about 10cm on the E coast south of Flamborough Head, and on the Lancashire coast, but *decrease* by about 10cm on the S coast.

However, great care is required in interpretation of these results. In particular:

(i) Does the "control" meteorology represent accurately the "present day" storm climate? If not modelled surges and extremes will not be realistic.
(ii) Are estimated changes in, say, 50-year surge (S50) significant? This requires consideration of errors in the extreme estimates and their differences.
(iii) If the changes are significant, are they due to increased CO$_2$? Since extreme estimates depend on the data analysed, we need to check if the change could be due to the natural variability in such estimates; i.e. could the change arise from different samples from the same storm population or inter-annual variability?

These issues have been addressed in some of the above studies and most recently in STOWASUS-2100. Some of the results are summarised in Flather and Williams (2000):

(i) Accuracy of the climate model data depends on its resolution in both space and time. Generally, surges are underestimated, but when high resolution met. data are used, the "control" run produces quite realistic surges. E.g. Lowe et al. (2001) used met. forcing from a high resolution Hadley Centre regional climate model.

(ii) Errors and uncertainty in extreme estimates, have been examined in STOWASUS-2100 (Flather et al. 2001 (in preparation)). Although existing methods (e.g. Tawn 1988), applied to data at a single point, provide reasonable estimates of S50, application to whole model fields with differing surge behaviour in different regions is more problematic. The problems are further highlighted when *differences*, ΔS ("2×CO$_2$" – "control") are calculated. Generally, the uncertainties in extreme value estimates are large, so that confidence in predictions such as shown in Fig. 8 is low. A more robust and consistent analysis approach is needed. Some of the difficulties can be avoided by using studying exceedance percentiles rather than extremes.

(iii) Estimates of natural variability of surge extremes can be derived from analyses of sub-sets of the model data, though unfortunately long (30-year) sub-sets are not independent. Computing the difference between the largest and smallest estimate for each model grid point provides a measure of the natural variability. These can then be compared to the differences between "2×CO$_2$" and "control" results. If the difference, ΔS ("2×CO$_2$" – "control"), is less than the natural variability, ΔS (maximum – minimum), then increasing CO$_2$ may not be the cause. Flather and Smith (1998) found that the natural variability was marginally greater than the estimated change in S5, which could therefore not be attributed to effects of climate change.

Further work is required to address these important issues, refine estimates and reduce the uncertainties. Multiple analyses based on different climate model solutions are also required to check that predictions are consistent. Existing results are not consistent. For example, the prediction from STOWASUS (Fig. 8) suggests a *decrease* in S50 with increased CO_2 on the S coast. Lowe et al. (2001) predict an *increase* using forcing from a different climate model and different analysis approaches (see Fig. 9).

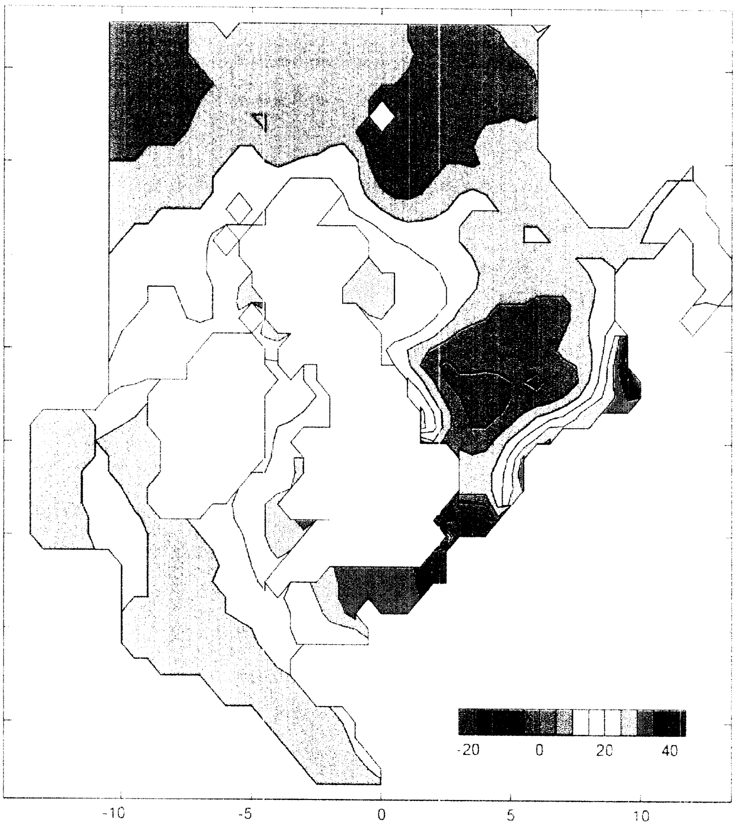

Figure 9: Change in S50 computer using POL CSX (35km) model with forcing from a Hadley Centre regional climate model (based on HADCM2), re-plotted from Lowe et al. (2001).

6. Estimates of changes in extreme sea level

To illustrate the type of results that might be produced from model predictions in the future, we can make estimates of possible change in an extreme total (tide + surge) water level for about 2075. Extreme water levels generally result from the combination of a spring tide and a large storm surge, so combining the estimated change (~37cm) in MSL from the IPCC TAR (Church et al. 2001) with those for MHW (Fig. 7) and for S50 (Fig 8.), we obtain the distribution shown in Fig. 10. Note that this excludes effects of land movement; i.e. it represents the change in *absolute* level (relative to an (assumed constant) geopotential surface).

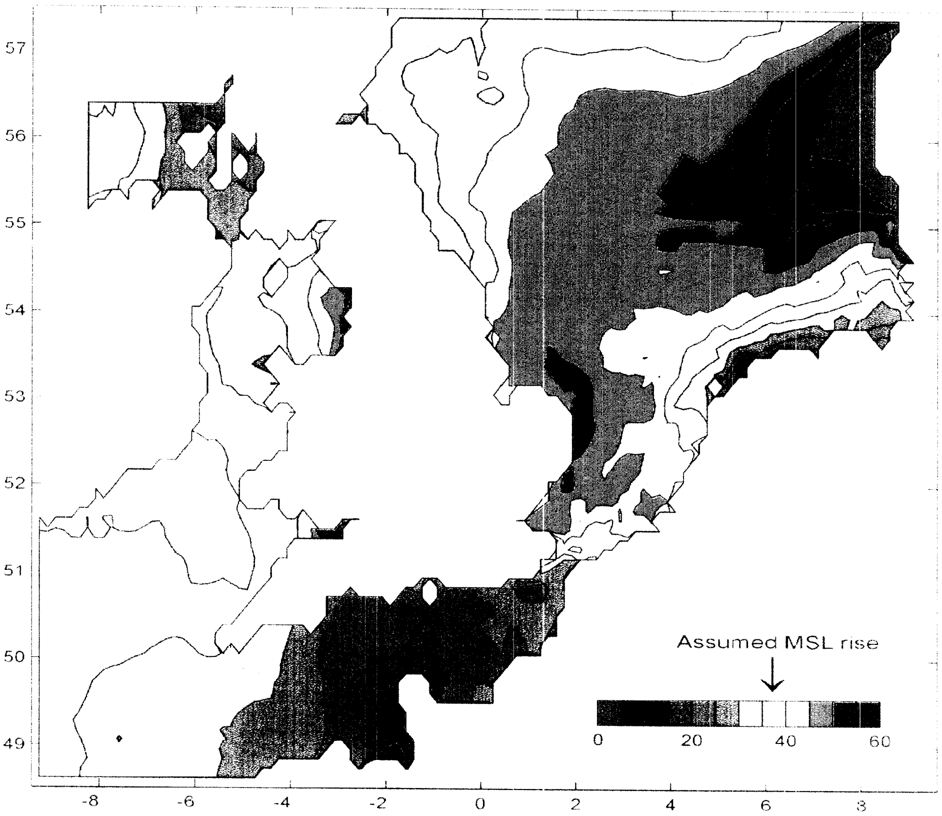

Figure 10: Indicative estimate of the change (cm) in *absolute* "extreme" water level for ~2075 obtained by combining predictions of change in MSL, MHW and S50.

Late in the project, we obtained a digital version of the distribution of land movement rates computed by Lambeck and Johnston (1995) from their post-glacial rebound model. Assuming this rate could be applied between 1990 and our future scenario in 2075, we calculated the corresponding change in land elevation and interpolated it to our model grid. This is shown in Figure 11. As noted in Section 3, this excludes local geological effects and differs in some respects from Shennan's (1989) distribution of land movements.

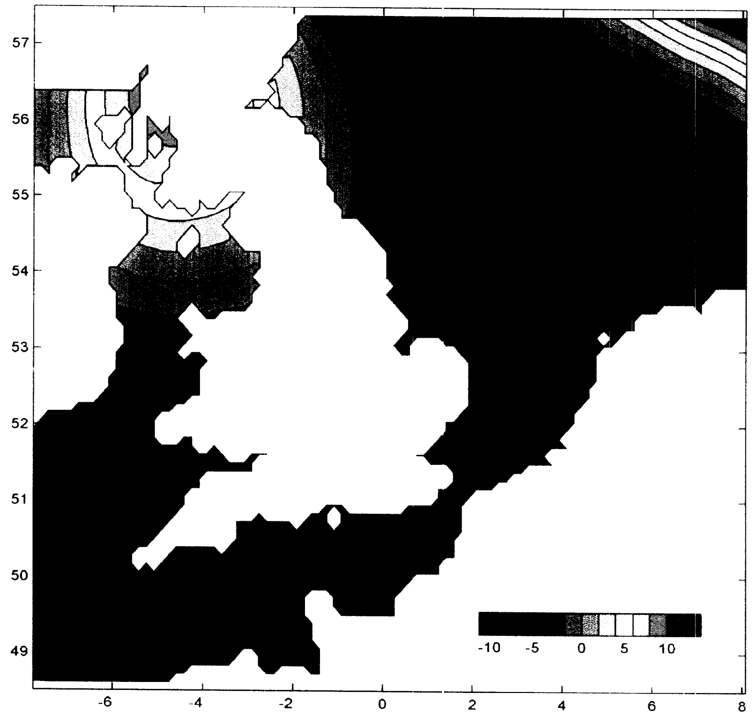

Figure 11: Change in land elevation (cm) by 2075 calculated from the results of Lambeck and Johnston (1995)

Subtracting this from our estimate of change in *absolute* extreme sea level (Fig. 10), we obtain an estimate of the change in extreme sea level *relative to the land*, plotted in Fig. 12.

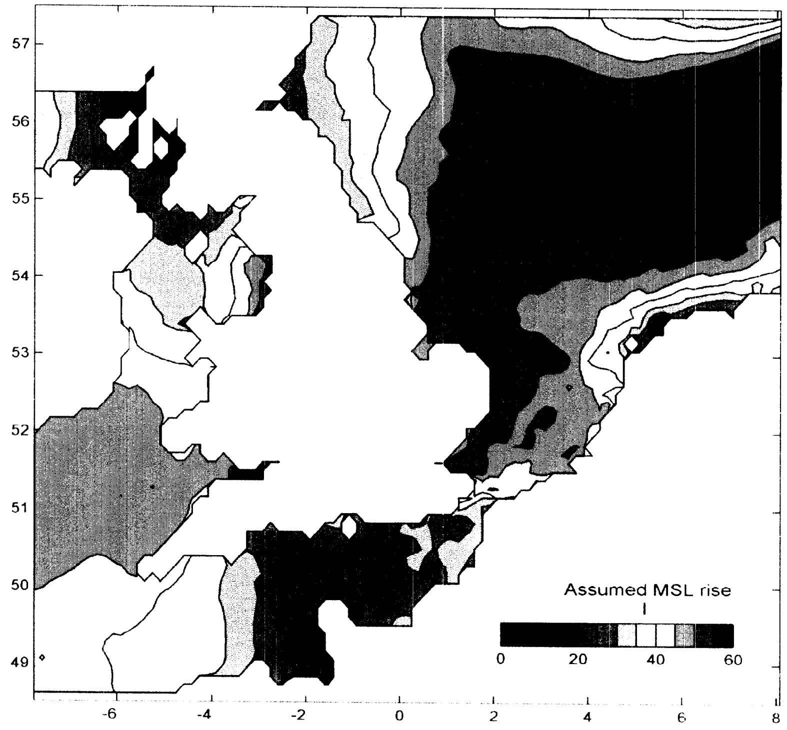

Figure 12: Estimated change (cm) in extreme sea level *relative to the land* for 2075.

It suggests that changes in extreme water levels may exceed those of MSL on some coasts (e.g. +50cm compared with +37cm on the East coast of England, in the Bristol Channel and the Irish Sea), but not on others (e.g. +25 to 30cm compared with the assumed +37cm change in MSL on the South coast).

7. Conclusions – comparison with existing guidance

Finally, assuming that the changes estimated above occur between 1990 and 2075, mean rates of change in *relative* extreme SL over this period can be computed from the distribution in Fig. 12. The result is shown in Fig. 13 with values from current guidance (MAFF 2000) for comparison.

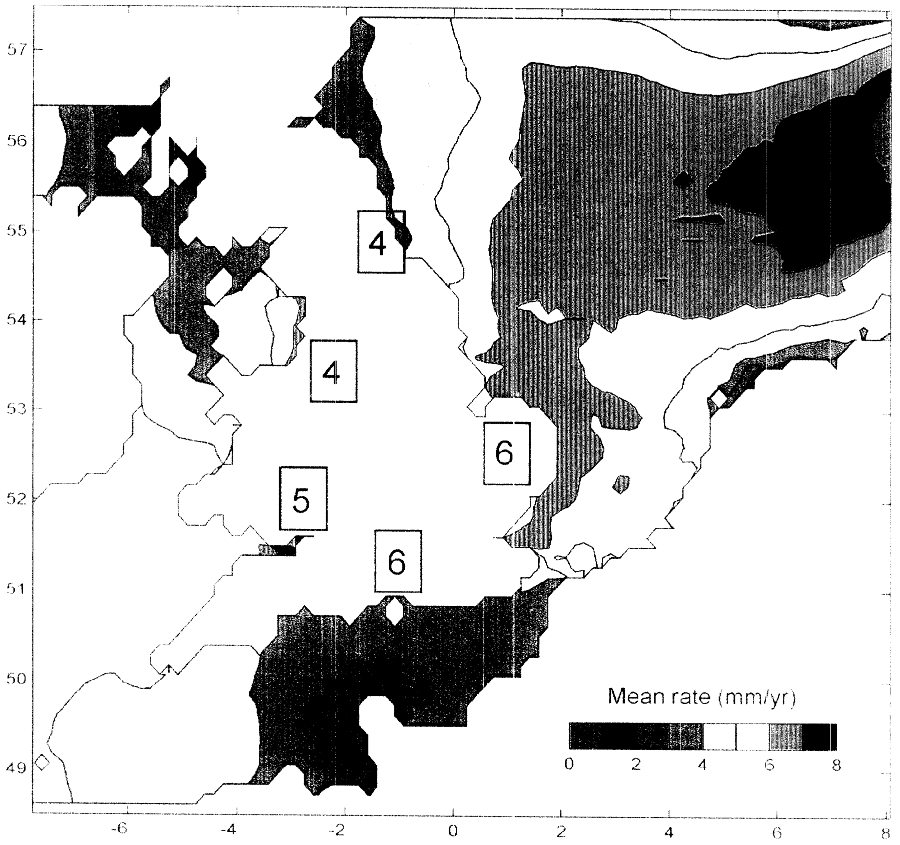

Figure 13: Rate of change (mm/yr) in *relative* extreme SL computed from Fig. 12 assuming the changes occur between 1990 and 2075. Corresponding values from MAFF (2000) are shown in boxes.

Taken at face value, the results agree well with current guidance on the East Coast of England; but give lower estimates on the South Coast and higher estimates in the Irish Sea and Bristol Channel.

Changes in extreme sea level for 2075 were estimated from model projections by combining contributions from MSL, tide, storm surge and land movements. In deriving our new estimate, we have tried to take the "best" value available for each component. However it is important to be aware that *large uncertainty* attaches to each of these values. In particular:

a) The IPCC TAR projection for global MSL rise from 1990-2100 based on all SRES (Special Report on Emissions Scenarios) scenarios is in the range 9 to 88cm, see Church et al. (2001), Gregory (2001). We have assumed a value of 50cm for 2100, and for 37cm 2075. This latter value is subject to corresponding uncertainty.

b) The effect of MSL rise on tidal conditions depends on the assumed MSL rise and so is subject to corresponding uncertainty.

c) Factors affecting estimates of extreme surge elevation were discussed in section 5. These depend, amongst other things, on predictions of future change in storminess which in turn depend on which climate model and assumptions are made. We showed that recent results from STOWASUS-2100 and the Hadley Centre give very different estimates of future change in S50. These aspects require further research.

d) For land movements, we applied a digitised version of the model results of Lambeck and Johnston (1995). This doesn't account for all mechanisms and gives a smaller range of values than have been derived from observations. It is important, therefore, to continue the monitoring activities and refine both observations and models.

e) Finally, we combined the contributions by simple addition which, given the uncertainties just mentioned is appropriate. However, if the uncertainties can be reduced, interactions among components will be worth considering.

Figure 14: Coastal areas of England and Wales with elevation below the 1000-year return period levels computed at POL.

The distributions in Figures 12 and 13, like all similar estimates, are subject to large uncertainty and should be treated with caution. They are, however, indicative of the type of results that can be produced from model predictions. Reliable quantitative results of this type would be of great value for coastal defence purposes. Further work is required to resolve the aspects of uncertainty, leading to useful quantitative estimates for the UK and other vulnerable coasts.

Finally, Fig. 14 shows coastal areas of Great Britain with elevations below the 1000-year return period levels computed at POL. These are (and will be) the main coastal areas affected by sea level changes.

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