Implications of climate change predictions for flood and coastal defence research

Compiled by P G Samuels

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Summary

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The IPCC reports to be published in 1996 acknowledge for the first time that human activity has affected the global climate in the recent past and the reports set out the current predictions of climate change and their major implications. One area of impact which is important to the UK is the change in flood risk and MAFF wish to consider the implications for flood and coastal defence in terms of both the physical forcing and the response of the defence systems so that an acceptable standard of defence can be maintained. MAFF commissioned HR Wallingford to coordinate a project in collaboration with the Proudman Oceanographic Laboratory, the Institute of Hydrology, the Flood Hazard Research Centre and the University of Southampton to produce a report on the research needs in flood and coastal defence which stem from the work of the IPCC. HR Wallingford convened an expert workshop on 17 November 1995 to promote the discussion of the issues and to identify the research needs.

This report contains the position papers submitted to the workshop and a discussion of the research needs in the flood and coastal defence sector. In all about 10 research topics have been identified falling within two broad themes:

- Project Appraisal and Procedures.
- Past and Future Impact Assessment.

Brainstorming amongst the participants at the workshop was used to facilitate the identification of research needs and the headline topic description of all the topics thus generated (over 100) are contained in an Appendix.

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1 Introduction

1.1 Background

Over the past decade there has been an increasing awareness amongst policy makers, planners and infrastructure designers that changes in the global climate may have important impacts on human society. The IPCC reports to be published in 1996 acknowledge for the first time that human activity has affected the global climate in the recent past and the reports set out the current predictions of climate change and their major implications. One area of impact which is important to the UK is the change in flood risk and MAFF wish to consider the implications for flood and coastal defence in terms of both the physical forcing and the response of the defence systems so that an acceptable standard of defence can be maintained.

1.2 Terms of reference

MAFF commissioned HR Wallingford to coordinate a project in collaboration with the Proudman Oceanographic Laboratory and the Institute of Hydrology together with contributions from recognised national experts to produce a report on the research needs in flood and coastal defence which stem from the work of the IPCC. HR Wallingford were requested to convene an expert workshop to promote the discussion of the issues and to identify the research needs.

The report to the MAFF Flood and Coastal Defence Division will be used as a working document in the formulation of research strategy and priorities over the medium term.

1.3 Approach

Participation at the workshop is by invitation from experts and institutions identified by MAFF. Each institution represented prepared a briefing paper covering their particular area of specialism. These papers set the framework for the discussion at the workshop and form the core component of this report to MAFF. The authors of the papers were invited to submit revised drafts which appear in sections 2 to 7 of this final report. The afternoon of the workshop was given over to a brainstorming session on the research needs and their prioritisation. The discussion of issues and research priorities contained in Section 8.8 have been drawn out from the results of the brainstorming sessions.

2 *Climate change and 1995 international reports: Implications for strategic flood and coastal defence research*

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2.1 Introduction

The Ministry of Agriculture, Fisheries and Food has policy responsibility for flood and coastal defences in England. Priority is placed on provision of adequate and cost-effective flood warning systems, technically, environmentally and economically sound and sustainable flood and coastal defence measures and discouragement of inappropriate development in areas at risk from flooding or coastal erosion. Particular emphasis is placed on the need to work with natural river and coastal processes wherever possible. (MAFF, 1993a)

The Ministry supports this policy through operation of the National Storm Tide Warning Service, the provision of grants for capital works and an ongoing programme of strategic research.

The Inter-governmental Panel on Climate Change (IPCC) reports to be published in early 1996 will set out the current predictions of climate change and their major implications. The implications for flood and coastal defence need to be considered in terms of changes in the physical forcing system acting on defences and the response required to maintain an acceptable standard of protection.

2.2 Background

The IPCC second assessment report now concludes that the balance of evidence suggests that there is a discernible human influence on global climate. This is a major development in international thinking since the first assessment report in 1990. Pursuit of the strategy for Flood and Coastal Defence in a situation of anticipated climate change requires an assessment of predicted long term change in relative sea level. However, it is also becoming increasingly obvious that changes in wave climate and river flood frequency, which depend on assessments of the likely future variability of storm duration, intensity, frequency and direction, may have an even more significant effect.

Relative sea level change depends on global and regional sea level change, large scale earth crust movements and local ground level changes. Recognising that the prediction of local trends in sea level from usually limited tide gauge records is not wholly appropriate, current Ministry policy is to recommend the use of the following regional allowances for net sea level rise based on National Rivers Authority regions. (MAFF, 1993b)

Anglian, Thames, Southern	6mm/year
South Western, Severn	5mm/year
Trent,Welsh, Yorkshire	
North West, Northumbria	4mm/year

These allowances were based on the 1990 IPCC predictions of global sea level rise to 2030, together with large scale land movement estimates over the same period, on the assumption that the average design life for new defences is generally 40 to 50 years. They are intended to be used to test the sensitivity of scheme evaluations and should, if appropriate, be incorporated in the design of defences or used to identify the need to provide the facility for future raising in scheme designs.

Whilst climate change is a significant factor in the long term planning, design and management of flood defences, it is clear that under all current scenarios the additional areas at risk in England and Wales are relatively small. The emphasis of flood defence policy should, therefore, continue to be the maintenance of appropriate defences to all areas where it is technically, economically and environmentally beneficial and sustainable.

'Soft' defences which aim to work with and enhance natural processes are likely to be more resilient to sea level rise and changes in the frequency and severity of storms than hard defences. The ability of natural defences such as beaches and salt marshes to adapt to such changes will depend crucially on factors such as the rate of rise and boundary constraints such as the availability of sediment. Techniques, such as managed set back, contribute to the sustainability of flood defences and will be encouraged where they are the most appropriate river or coastal management response, taking all relevant factors into consideration.

There are few other areas of civil engineering where an appreciation of absolute level independent of local land level changes is so important. When looking at design standards and the economic assessment of coastal and estuarine works, sea level change must be considered in conjunction with long term geological movement. Although the overall effect can be considered as a combined sea level rise allowance, it is important in developing predictions to understand the component elements of such change. Separate assessments should be made of global sea level rise, long term geological movement and local settlement of surface deposits. This will require an investment in monitoring and absolute level determination as well as the development of relevant geological and other models.

Most current hydrological approaches to the design of river flood protection works assume a stationary series of flood event probabilities with time. In a scenario of climate change, techniques for the assessment of large scale change in catchment hydrology, due to both anthropogenic and external forcing changes, will be required.

2.3 Current MAFF funded research

Current flood and coastal defence research sponsored by the Ministry (MAFF, 1995a) includes many areas of process evaluation and model development, which could be of use in predicting specific impacts of climate change, although they are being developed primarily to address current concerns. MAFF also funds, with the Scottish Office, the maintenance of the UK network of A Class Tide Gauges. This work is carried out by the Tide Gauge Inspectorate at the Proudman Oceanographic Laboratory (POL) and the data is banked at the British Oceanographic Data Centre at Bidston.

More specifically related to climate change is the programme of development of differential GPS techniques co-ordinated through POL in collaboration with the Institute of Engineering Surveying and Space Geodesy at the University of Nottingham. Over the last few years this has increased the repeatability of level measurements at a selection of the major tide gauge sites to sub-centimetre levels, raising the prospect of detecting actual ground level changes within a global reference frame over a decadal time scale. In parallel with this, work has also recently started on the measurement of absolute gravity at sites near to some of the primary tide gauges with the intention of obtaining a further independent assessment of crustal movement. Taken together, these should enable the separation of land and sea level changes which should, in the long term, allow the establishment of a national framework of primary levelling stations, to which the levels of tidal flood defences can be related with proper allowance for sea level change.

2.4 Implications for future MAFF funded flood and coastal defence research

In May 1995 MAFF published a Research and Development Implementation Strategy (MAFF, 1995b) for flood and coastal defence research which included a specific section of climate change related work. This noted the need to promote research which would enable the Ministry to honour its strategy commitment to keep under review the guidance on allowances in respect of net sea level change to be used in the design of coastal defence works.

One of the main thrusts of the IPCC impacts assessment in relation to the coast is the need for a strategic approach to coastal planning. For coastal defences, the Ministry has taken a major step forward with the publication of a guide to the production of shoreline management plans (MAFF, 1995c) and the encouragement of plan preparation for all major coastal cells around the country. Such plans are currently in preparation or in the process of being commissioned for almost the whole length of the English coast. The IPCC second assessment report is likely to put less emphasis on strategic catchment planning but this is equally important for river systems when considering potential large scale climate change. A strategic approach is encouraged for the design of all flood defences.

As noted above, the research programme in topics such as long term coastal and river catchment processes and modelling will continue to play a significant role in developing an ability to predict changes and evaluate alternative responses. The results of such work need to be readily available to designers and managers in the form of simulation models or guidelines for design and appraisal.

The need for data is clear, particularly the measurements of absolute trends in both land and sea levels. At a policy level there is also a need for evaluation of the consequences of major climate changes using appropriate economic techniques linked to appropriate technical modelling of scenarios. However, it is anticipated that a much better data set of coastal resources at risk will be available once the current round of shoreline management plans is complete and this should form a useful basis for further analysis specific to the implications of sea level and climate change for coastal defence.

Sustainability is a key issue and work is needed both to refine the definitions and develop the techniques through which sustainable goals can be achieved.

It is likely that new approaches will be required to interpret the spatially and temporally averaged changes predicted by global and regional climate models, to provide related predictions of changes in the relatively short term, and localised fluctuations which influence storm frequency, intensity and duration. The ability to forecast such changes is central to the work on flooding and other hydrological extremes but, in view of its fundamental nature, such work is likely to be well outside the scope of MAFF Flood and coastal defence research funding.

2.5 Conclusions

There is a clear need for research to ensure that flood and coastal defences are designed and managed within a robust framework which can take appropriate account of likely future climate change. The results of this study are intended to provide such a framework, and identify priority areas for strategic research which can build on the scientific work funded by others, and provide improvements in the techniques and understanding available to river and coastal engineers and managers.

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3 Climate change and its impacts - A framework

Contributed by

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3.1 Scope

This note covers four areas:

- the "institutional" *framework*,
- current IPCC and CCIRG *projections*, *uncertainties* in future climates, and
- *impacts and adaptations.*

3.2 The institutional framework

The Intergovernmental Panel on Climate Change (IPCC) was set up by the World Meteorological Organization and United Nations Environment Programme in 1988, to investigate the climate change problem and provide both a review of the scientific state-of-the-art and to formulate appropriate response strategies. The IPCC presented its first assessments between 1990 and 1992, and is currently close to completing the second assessment: the assessment reports should be published in March 1996. Three reports will be published - covering the "science" of climate change, the impacts of change and the social and economic implications - together with a synthesizing summary. Each report consists of a separate chapters, written by groups of experts and reviewed by independent scientists as well as governments and other groups. The IPCC "science" report will assert that recent climatic behaviour is unlikely to be entirely due to natural climatic variability, and will indicate the likely magnitude of change and possible future regional climates.

The Department of the Environment established the Climate Change Impacts Review Group (CCIRG) in 1990, which produced its first assessment of the potential effects of climate change in Britain in 1991, and which will publish its second assessment by May 1996. Individual experts have written individual sector chapters, and these chapters have been reviewed both by the group as a whole and independent experts. The 1996 CCIRG report will include a climate change scenario for the 2050s based on the output from the Hadley Centre transient climate change experiment.

3.3 Current IPCC and CCIRG projections

The IPCC projects an increase in global mean temperature of between 0.15 and 0.33°C per decade, under the "best" emissions scenario, with a sea level rise of between 0.3 and 1.0m by 2100. The IPCC note that the continued presence of sulphate aerosols in the atmosphere would lower these rates of change, although the effects of sulphate aerosols are difficult to simulate and depend on their geographic distribution.

The CCIRG has based its assessment around a scenario derived from the Hadley Centre transient experiment (Murphy, 1995; Murphy & Mitchell, 1995) rescaled to represent conditions in the 2020s and the 2050s according to the best IPCC emissions scenario. Under this climate change scenario, temperature in Britain would by the 2050s be approximately 1.6°C warmer than at present, with the greatest warming in the south. Winter precipitation would increase across Britain, whilst summer precipitation would increase in the north and decrease in the south. The return periods of heavy daily rainfalls would shorten, especially in the north. Sea level rise would be approximately 0.5m by the 2050s in the south, and 0.25m in the north (taking into account crustal movements). The probability of a storm level exceeding a given threshold is likely to increase, although changes in storm tracks are very uncertain.

3.4 Uncertainties in future climates

There are many uncertainties in the estimation of future climates (let alone impacts of these climate changes). Estimates of future emissions of greenhouse gases and atmospheric concentrations are uncertain, depending on assumptions about economic development and the understanding of different sources and sinks. The translation of atmospheric concentrations into global temperature changes is uncertain, with the effects of sulphate aerosols particularly important: they tend to counteract the effects of increased greenhouse gases. Regional climate changes are estimated using global climate models (GCMs). Different models (of a given type) give reasonably similar estimates of changes in temperature, but can give very different indications of changes in *regional* precipitation. This is largely due to the linked problems of limitations in the parameterization of the processes operating in the atmosphere and ocean, and the coarse spatial scale at which GCMs operate: this scale is too coarse for the precise simulation of many important weather features, and makes it difficult to estimate either local changes or changes in extreme climatic conditions (such as heavy rainfall or storms). Many techniques are currently being explored to improve local resolution, and one promising approach uses a high resolution regional climate model nested within a coarse resolution global model (eg Jones *et al*, 1995).

To these "climatic" uncertainties must be added the uncertainties involved in translating climate into effects and impacts on a specific system. In some cases, such as water resources, the models used to translate climate into physical effect are reasonably accurate, and little extra uncertainty is added given that a realistic model of the hydrological process is used. Empirical regression-type models can give very different, and misleading, estimates of change. It will not be possible, for example, to estimate the effects of climate change on flood characteristics using the Flood Studies Report regression equations: these parameterise the internal relationships between current climatic variables, and the sensitivity to change in climate (eg change in average annual rainfall SAAR or flood producing rainfall RSMD) is determined by the magnitudes of the empirical regression coefficients (which themselves are determined by the data used and the number of variables included in the regression model). It will therefore be necessary to apply realistic conceptual models of the flood generation process to estimate the effects of climate change on flood frequencies: these need to be developed. In other cases, for example concerning geomorphological change, transfer models need still more work. Translating the physical *effect* of climate change into a valued *impact* is more complicated still.

3.5 Impacts and adaptations

Many studies have assessed the effects of climate change on natural systems, and inferred impacts on some aspect of society or environmental management. The major flaw with most such assessments is that they overstate the possible impacts by ignoring progressive adaptation to change: they implicitly assume that society or environmental managers will just sit back and watch climate change. In practice, of course, managers and society will progressively adapt to climate change, and the impacts will be lessened. This adaptation, however, will not be without cost, and will most likely be inefficiently implemented (because it will be based on uncertain information). The true "impact" of climate change, therefore, will include the costs (or benefits) of adaptation and the costs (or benefits) of activities and uses which can no longer be supported. Of course, these must be assessed against a changing baseline: changes other than global warming will also be taking place, which may either affect the susceptibility of the system to change or alter its ability to meet its desired targets. In the field of flood defence, for example, a new policy that all urban communities would be protected against the 200-year flood (however defined), brought in without reference to climate change, would have significant implications for the impact of climate change on flood risk in the future. Figure 3.1 (Carter *et al*, 1994) illustrates this general point, comparing three approaches to impact assessment: assuming a constant baseline, assuming a changing baseline and assuming some form of adaptation.

Figure 3.2 shows the stages in the impact assessment methodology advocated by the IPCC (Carter *et al*, 1994). The seven stages are all reasonably self-explanatory, but few published studies have taken such an explicitly structured approach. A coherent structure, with validation where feasible, is essential for the credibility of an impact assessment.

3.6 Conclusions: estimating changes in flood risk and flood management

There have been very few attempts to estimate the effects of climate change on channel stability, riverine flood frequencies and flood management, for two main reasons. Firstly, and most importantly, credible scenarios for changes in those aspects of climate controlling fluvial flooding are very difficult to define: current climate models with their coarse spatial resolution and simplistic parameterisation simulate large-scale features well, but cannot yet be used to estimate changes in short-duration, high intensity events. The increasing use of nested regional models will go some way towards addressing this problem. The second reason for the lack of impact assessments is the limitations in models translating changes in "flood climate" into response (particularly into changes in flood flows and, even more so, channel stability). This area too needs considerable work: the empirical relationships used in engineering applications cannot be used in climate change impact assessments.

It is clear, however, that a relatively small change in flood characteristics can have a major effect on flood risk, and particularly on the frequency with which defined thresholds are crossed. Figure 3.3 shows the frequency of occurrence of the current 10-year flood, with given changes in the mean and coefficient of variation of annual maximum floods, assuming (rather simplistically) that annual maximum floods follow an EV1 distribution (Beran & Arnell, 1995). A small change in mean and CV could lead to very significant changes in the risk of defences being overtopped: the amount of change that would happen under climate change, however, needs to be assessed using credible scenarios and models.

Finally, it is important to emphasise again the difference between a physical effect of climate change and the impact - with implied value - of that change, and to emphasise that progressive adaptation to a range of change stimuli will affect the impact of climate change: the baseline is moving.

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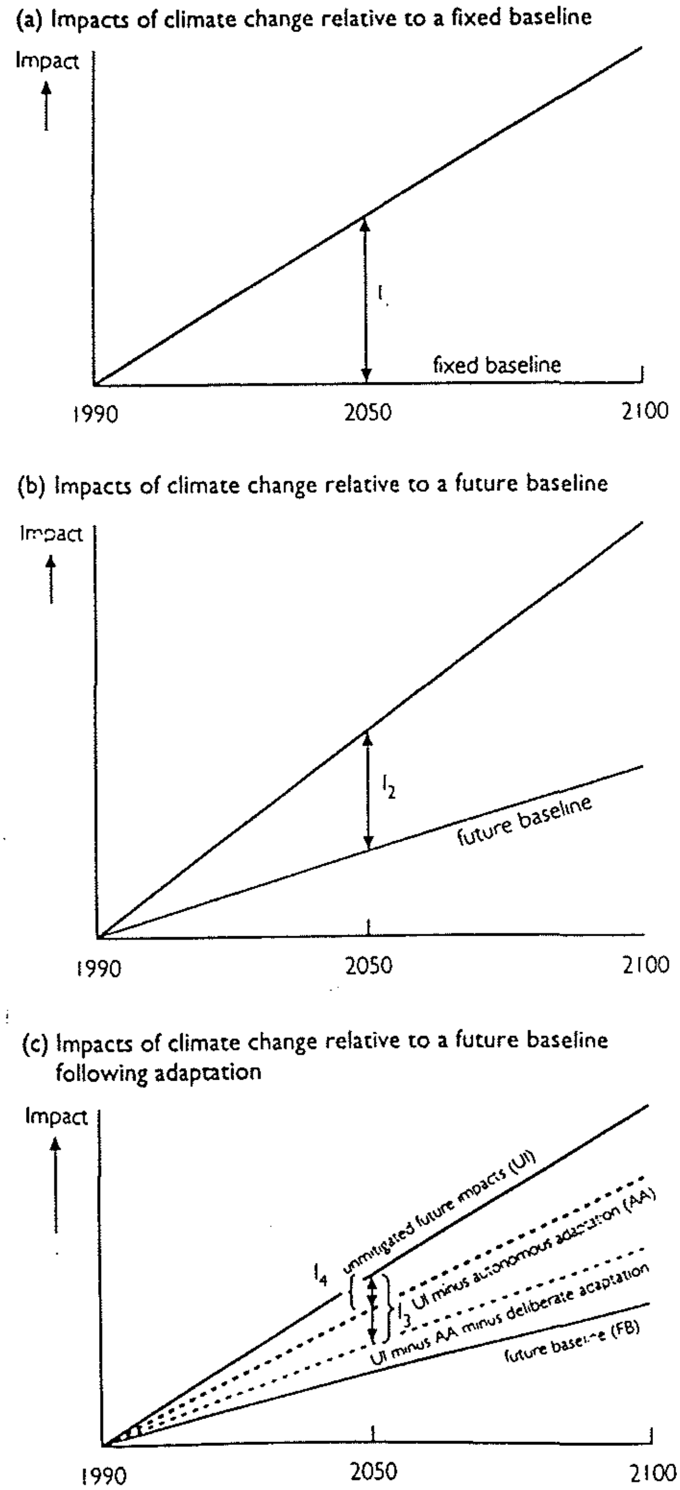

Figure 3.1 Assessment of impacts, with a moving baseline and adaptation (Carter *et al*, 1994)

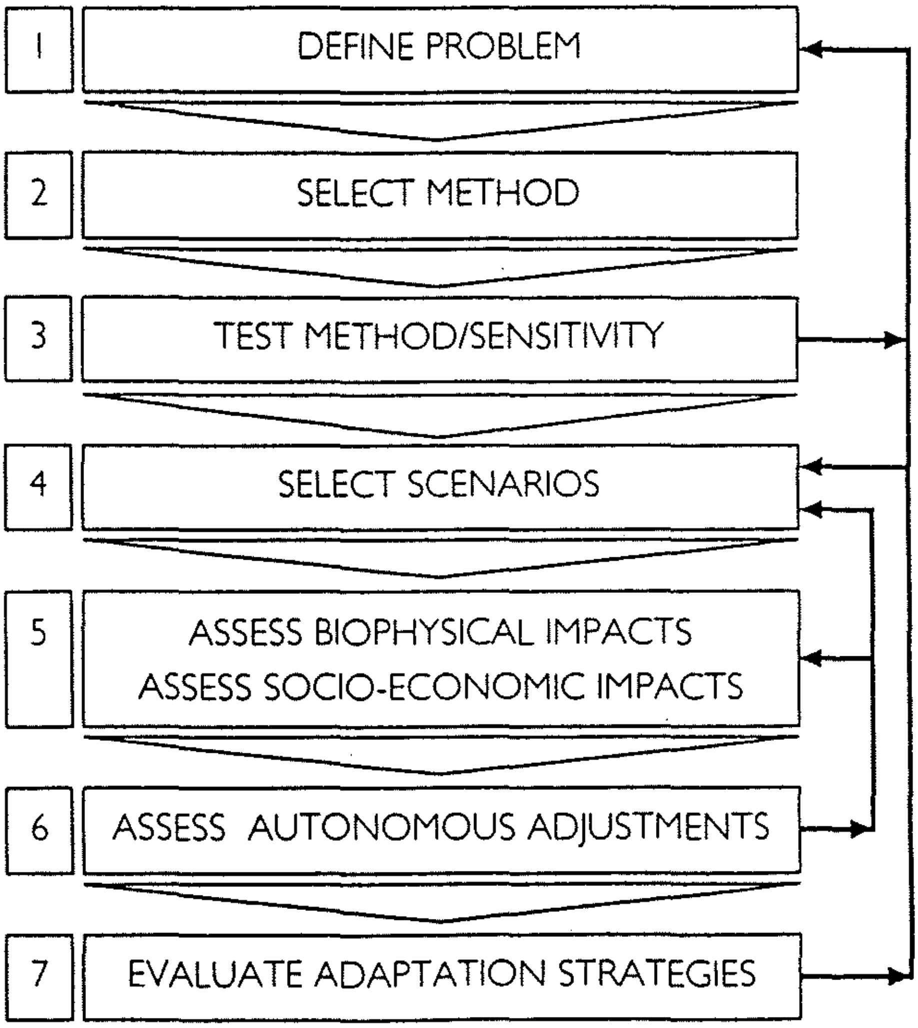

Figure 3.2 Seven steps in an impact assessment (Carter et al, 1994)

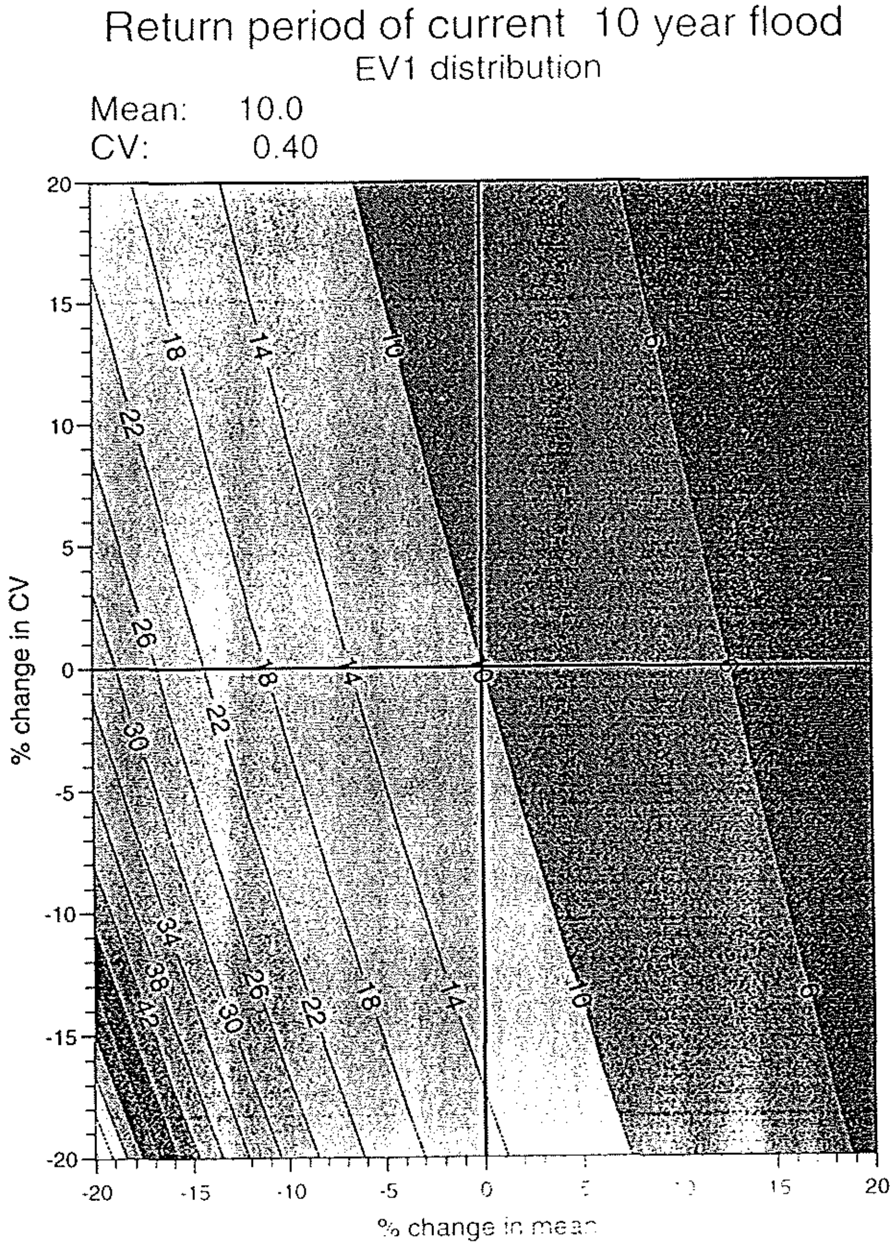

Figure 3.3 **Return period of current 10-year flood, with changes in mean and coefficient of variation of annual maximum floods (Beran & Arnell, 1995)**

4 *Influence of climate change on the offshore wind, wave and tidal conditions*

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4.1 Context

Cyclical variations and trends in metocean parameters during the lifetime of coastal structures could change:

- the water level (mean, tide and/or surge)
- the frequency of severe storms
- the intensity of severe storms.

with possible associated adverse changes in the magnitude and frequency of extreme winds, waves and currents.

4.2 Sea levels

4.2.1 Introduction

'Relative sea level' has two components: that due to changes in actual sea level and that due to vertical movement of the crust; e.g. records in northern Europe over the last 100 years show a downward trend in relative sea level because the crust there is uplifting at a faster rate than the present rise in actual sea level.

Regionally, crustal movements may be due to the effects of plate tectonics or isostasy. The latter is the process by which the crust attains gravitational equilibrium with respect to superimposed forces - due to changes in ice loading, water loading, water loading (particulaly on continental shelves) or sediment loading. Local effects may also include sediment compaction and subsidence.

Any future research needs to carefully consider the relationship between global mean sea level and regional/local sea level; and the relationship between sea level, tides and surges (i.e. the difficulty in separating out components).

4.2.2 Past and present changes

The Second Scientific Assessment of the Intergovernmental Panel on Climate Change (IPCC2) is likely to report that global sea level has risen by between 10 and 25 cm over the past 100 years. As geodynamic models, and measurements, of vertical crustal movements become more reliable, however, this range of uncertainty may well be considerably reduced. There is a fairly consistent 1-2 mm/yr difference between the sea level trend of the past 100 years and that of the last few thousand years from a number of widely separated regions, implying a comparatively recent acceleration in sea level. Studies imply that the acceleration probably began before the 1850's, and also that there is, as yet, no evidence for any acceleration of sea level rise this century as a result of recent global warming.

4.2.3 Future changes

Estimates of future sea level change based on the 'business-as-usual' scenario of greenhouse gas emissions published in 1990 by the IPCC were for a rise in actual sea level of 6mm per year to 2100 AD. IPCC2 is likely to give lower estimates, because estimates of global temperature rise have decreased, but still greater than those that have occurred over the past century. 'Best' estimates and range of sea level rise by 2100 is 23 - 55 - 96cm with constant aerosol emission to the atmosphere and 20 - 49 - 86cm with changing aerosols.

Any change in actual sea level is not expected to be uniform over the globe, but regional details await further development of more realistically coupled atmosphere-ocean models. Nevertheless, some modelling does suggest larger than average changes in the N.E. Atlantic.

4.2.4 Effects of sea level change

Research by POL and RIKZ (the Netherlands) has shown that changes in mean sea level will cause little change in tide and surge elevations (of order few centimetres per metre of sea level rise, unless in locally resonant situations) unless depths are modified by many metres. For example, depth changes of 50cm give a maximum change of order 10cm in tidal range on the European Continental Shelf. Storm surge elevations are likely to decrease as water depth increases.

4.3 Storms

4.3.1 Introduction

The main energy sources for mid-latitude storms are the temperature contrast between the cold polar regions and the warmer sub-tropical conditions and the release of latent heat as water vapour condenses in the warm, poleward moving, ascending air.

4.3.2 Past and present changes

Trends in storm surge activity have been studied for the European Continental Shelf. From analyses of storm surge frequency around the coast of the UK over the past 70 years and at the Hook of Holland and at the German coast over the past few centuries, there is no evidence of a long-term trend in storm surge activity. On the other hand, evidence exists for a trend over the same period in regional winds and air pressures that would result in enhanced German Bight mean sea level (and the surge activity that it reflects). Tide gauge data from the German Bight indicate an increase of storm surge frequency in the area, at least since 1960 and possible before. Local wind data for the Bight itself appear to show no obvious trend over 1950 to 1980, and in spite of large interdecadal variation, very little at all over century time-scales. Clearly, findings will depend on the periods analysed and data spans.

Recent results from the EC ENVIRONMENT project 'WASA' have shown that the storm climate in the near-coastal areas of North west Europe has not systematically worsened in the past century. There is, however, considerable natural variability on the decadal time scale.

4.3.3 *Future changes*

The IPCC2 results are likely to predict an increase in global mean surface temperature relative to the present of 2°C by 2100, with a considerable amplification at high latitudes in winter resulting largely from the seasonal variation of snow and ice cover.

There is qualitative agreement between different models as to the vertical meridional (i.e. north-south) structure of the warming, but longitudinal (i.e. east-west) variations are more model dependent. Most models predict:

A relatively large warming for lower levels at high latitudes, with an implied weakening of low-level baroclinicity at middle latitudes.

A maximum in warming in the tropical upper troposphere with an associated increase in upper-tropospheric horizontal temperature gradients.

A global increase in the water-vapour content due to the increased saturated vapour pressure of the warmer atmosphere.

These features may have competing effects on the behaviour of mid-latitude storms, both in magnitude and track direction, and there is little agreement between models on the changes in storminess that might occur. The UK Met Office models (the 'slab' model and the 'coupled' model) predict an intensification and poleward shift in Northern Hemisphere storms (with the most spectacular change occurring in the eastern Atlantic / western Europe region. The German ECHAM1 coupled model shows a northward shift of North Atlantic cyclones. However, the Canadian CCC slab model suggests no obvious shift in the Northern Hemisphere storm tracks but a slight shortening of the Atlantic tracks suggesting a reduction in storm activity over Europe. Conclusions regarding extreme storm events are even more uncertain.

4.3.4 *Effects of storm changes on levels*

POL and RIKZ have carried out studies examining the sensitivity of changes in tides, surges and total levels to a range of combinations of changing storm intensities, track shifts (and water level changes). The studies showed that significant changes in strom parameters can produce substantial changes in levels, particularly in combination.

4.3.5 *Effects of storm changes and levels on waves and currents*

Wave height depends on wind speed, direction and fetch - all potentially affected by changes in storm intensity, frequency and track. Also, it has been argued that rising sea level will result in less wave damping and higher wave energy. Additionally, wave generation could be enhanced by the associated reduction in bottom friction of greater water depth.

Recent results from 'WASA' have shown that the statistics of the significant wave height in the Northeast Atlantic has undergone a steady increase in the wave height in the last 30 years. An upper bound estimate for this increase amounts to 2-3cm/year for the 50% percentile of the annual wave height distribution and 3-4cm/year for the annual 10% percentile. (Independent analysis by Kushnir, Cardone and Cane supports these estimates.)

The UK Met Office has run its 3° resolution global wave model for 1 year with winds derived from its GCM with 2×CO_2 forcing. There is a very small impact on global wave height means, but regional differences are noticeable - wind speeds are stronger in the North Atlantic and give increases of 0.2 to 0.4m in significant wave height. The WASA project includes running wave models for 20 / 30 years to study the variation over and decadal time scales, and with wind-field outputs from the German GCM for climate change scenarios.

Any changes in tidal currents are unlikely to be significant away from locally resonant areas. Residual currents will be affected by any changes in the wind-driven or thermo-haline driven circulations of the ocean and sea basins.

4.4 Research needs

4.4.1 Data acquisition and analysis

(a) Monitoring of global, regional and local sea levels, using tide gauge and altimeter data.
(b) Comprehensive analysis for trends of existing UK tide gauge data.
(c) Monitoring of coastal and offshore wave data at key locations.

4.4.2 Modelling the hydrodynamics of regional seas

(a) Downscale global models to a resolution suitable for the explanation and prediction of shelf-scale and coastal processes.
(b) Hindcast studies to establish century-scale variations in the frequency and magnitude of surges and waves and their impacts on the coast.

4.4.3 UK land movements

(a) Develop geodetic monitoring programme (GPS + Gravimetry) into operational system.
(b) Effective modelling of the natural (e.g. glacial rebound) and anthropogenic (e.g. sediment consolidation due to land drainage, water extraction) geological processes which cause the land to move.

4.4.4 Modelling effects of climate change at the shoreline

(a) Develop a new generation of models required to assess probable coastal change over temporal and spatial scales of decades to centuries and 10s km.
(b) Investigate effective parameterization of sea-level change as well as storminess, morphodynamics, sediment supply and dispersal, coastal morphology and basement context.

5 *Trends and changes in rainfall patterns, runoff and flow frequencies*

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5.1 Introduction

The recent, unparalleled sequence of rainfall - and temperature - extremes in the UK has led to much discussion about changing climate regimes and the potential impact on water resources (Marsh *et al.* 1994; Arnell and Reynard, 1993). This paper describes some of these recent trends in climatic and hydrological indices and will address three broad themes within this area: current climate change impact studies, trends in rainfall and runoff, and trends in UK flooding. A short description will also be given of climate change impact analyses conducted at the Institute of Hydrology (IH) investigating the potential impact on water resources and flow regimes.

After a summary of the methods and initial results from some climate change impact analyses, the second section will deal with the recent trends in UK rainfall (and temperature) and runoff, particularly focusing on the years since 1988. There will also be a brief description of some of the large-scale patterns in precipitation and runoff anomalies across north west Europe. The third section will review a recent study of UK flood events, which appears to show a clear trend in the occurrence of flooding.

5.2 Climate change impact studies

One of the most significant impacts of future global climate change will be on the hydrological system and hence river flows and water resources. The Institute has been an active member of the UK impacts community for the past six years and was instrumental in setting up the LINK post at the Climatic Research Unit (CRU), funded by the Department of the Environment. This post serves to act as the physical link between the global modelling at the Hadley Centre and the impact community and provides the latter with the relevant and most recent modelling results and scenarios from the UK Met. Office GCM experiments (and a selection of other modelling groups from around the world).

5.2.1 Impact of climate change on water resources

The Institute has undertaken impact analyses in the UK, Europe and eastern and southern Africa. Some of the results from the UK studies will be briefly summarised. The basic methodology follows that recommended by the IPCC and described by Carter et al. (1992). A model describing the hydrological system is developed, calibrated and validated under the current (or some designated baseline) climate conditions. The original climate data are then perturbed according to a set of climate change scenarios. The model is then re-run with the new climate inputs and the resultant hydrological indices can be compared with those from the model run under current conditions (Arnell and Reynard, 1996).

A full description of the assessment of the potential impact of climate change on flow regimes in the UK is found in Arnell and Reynard (1993), but a brief summary of the main findings will be given here. The impact on water resources is dependent on the climate change scenario chosen, given that the current range of scenarios, based on GCM experiments, is large. Figure 1 shows the impact on runoff in 2050 using three Potential Evapotranspiration (PE) scenarios. The LINK rainfall scenario used assumes increased rainfall in all seasons except for the summer in the south and east, with the greatest increase during the winter in the north and west (more than 20% in north west Scotland). There is north-west to south-east gradient throughout the year, with the greater increases in the north and west.

The three PE scenarios represent three alternative methods for calculating change in PE. PE1 results in about a 10% increase in PE allowing only for the increase in temperature. PE2 (the dry scenario) is calculated using scenarios for changes in temperature as well as the other climate variables used in the calculation of Penman PE (radiation, humidity and windspeed). This scenario produced a change in PE of about 30%. An increase in plant water use efficiency in a CO_2 rich environment accounts serves to reduce PE losses through transpiration and taking this into account created the mid-range PE scenario, PE3. The average change under PE3 is about 15%.

Figure 5.1 shows the changes in runoff under these three PE scenarios for Britain. The wettest scenario (PE1 with the smallest increase in PE) would produce a general increase in runoff in the UK throughout the year with the exception of the extreme south and east. The driest scenario (LINK-PE2) would produce a decrease in runoff of 20% to 30% in some places, although runoff still increases in the upland regions to the north and west. The reduction in runoff will be most severe during the summer in the south and east of the country, in the areas with the largest current and projected water resource problems.

The impact of a given climate change will be different depending on the current climate conditions and the catchment characteristics; for instance, the drier south east is more sensitive to change than the more humid north and west, while groundwater resource systems may be better able to cope with a shift in the rainfall regime to one of higher winter and lower summer totals. Figure 5.2 shows the monthly change in runoff for 2050 for six catchments under several scenarios. The main feature is the increase in seasonality in all catchments, particularly the increase in winter runoff in the upland catchments (11001 and 25006) due to the reduction in the amount of snow. Under the wettest scenario, runoff is increased in every month in each catchment. The largest increases occur during the late summer or autumn in the lowland catchments but a little later in the year in the upland catchments (Arnell and Reynard, 1993).

Total snowfall will be reduced by 60-80% and hence the hydrological impact of the spring snowmelt will be greatly reduced, affecting the timing of flows in upland catchments. (11001 and 25006 in Figure 5.2). Future flow regimes may not necessarily be more extreme than the recent anomalous behaviour during the 1980s and 1990s (Arnell and Reynard, 1993; 1996). More important than changes in the mean conditions is a change in the likelihood and severity of extreme events. While some decades, even under the driest scenario, will be less extreme than the 1980s, just a shift in the mean could make the chance of such extreme conditions more likely in the next century. For instance, it has been estimated in 1976 that the summer drought was nationally a 250-year event, whereas this may be reduced to a 50-year event in the middle of the next century (CCIRG, 1991).

5.2.2 *Impacts of climate change on flooding in the UK*

Work is nearing completion on investigating the impacts of both climate and land use change on the flood response of large catchments, as represented by the Severn, Thames and Trent basins (all about 10,000 km^2). The broad framework of the approach is displayed in Figure 5.3. In order to tackle this problem, the advances that have been made are:

- development of a framework for addressing the large catchment problem - this uses a 40 km square grid overlain onto soil, land cover and topography, and a river routing technique which uses the observed river network

- modification of the losses model in a simple one or two store transfer function (IHACRES) so that responses to climate and land use can be worked through

- calibration of the modified model (both losses and time constants) for a wide range of subcatchments in the Severn, Thames and Trent basins

- generalisation of model parameters for 40 km grid squares based on soil, land cover and topographic characteristics

- development and application of climate change scenarios.

The model provides continuous flow series at any point in the large catchment. These are currently being checked over the period 1985-1992 for which additional data on evapotranspiration were purchased from the Met. Office. The model will subsequently be run with 30 years of available daily rainfall data to provide flood frequency estimates for the current climate using peaks-over-threshold (POT) techniques. These will be validated against existing POT data. Scenarios of change will then be applied to the 30 years of record and flood frequency curves under these scenarios derived.

While the large catchment problem is a special case, the continuous simulation approach to flood frequency estimation allows the assessment of the impacts of climate change to be made on any catchment. The essential problems that require more work relate to:

- quantification of the confidence in identified impacts, incorporating the uncertainty in the change and uncertainty in the model structure and its parameter values

- better methods of disaggregating rainfall input, either over space or time, dependent on the data source and the application.

5.3 Trends in rainfall and runoff

In the UK any apparent trend in the long-term climatological or hydrological mean should be treated with extreme caution given the inherent variability of the regimes in the region. However, the hydrological conditions of the last 20 years call into question the stationarity assumption behind many of the water management practices in the UK (Marsh, 1995).

5.3.1 The last 20 years

In terms of temperatures, although recent *individual* years have not proved to be the warmest on record, there has been an unprecedented run of warmer than average years. The last seven years taken as a series are by far the warmest in the Central England temperature record, extending back to 1659 (Manley, 1974). As a result of this sequence of warm years, the evaporation losses, particularly over south and east England, have been unprecedentedly high. Figure 5.4 shows the annual potential evaporation (PE) losses for eastern and southern England since 1960. The higher PE losses have served to make the effective rainfall (rainfall - PE) negative in a region with the highest demand for water in the country (domestic, commercial and agricultural). The obvious implication for this is in the development and reduction (during the autumn and winter) of soil moisture deficits. With higher than average deficits the effective recharge season can be reduced dramatically and if there is also a dry winter (as in the case of 1988/89, 1989/90 and 1990/91) recharge periods can be reduced to a matter of weeks. Figure 5.5 shows the groundwater levels for an observational well in southern England and the low recharge between 1988 and 1994 is striking.

The rainfall regime over the past ten years has been highly variable both spatially and temporally. The annual totals have been dominated by a few very wet winter months. Figure 5.6 shows a five-year running average of the ratio between October to March and April to September rainfall, based on the England and Wales rainfall record (Wigley, 1984). The ratio has been increasing since 1970 and currently the winter rainfall is 12% higher and the summer rainfall 5% lower than the pre-1975 period. The spatial change in rainfall distribution within the UK is even more marked with an enhancement of the north-west/south-east rainfall gradient. A similar ratio approach was taken in Figure 5.7 to display this. The ratio is between rainfall totals for western Scotland (Fort William) and southern England (Kew). As in Figure 6, a clear increase in the ratio is evident from 1970, with the current levels the highest in the 120 year record, Figure 5.8 plots rainfall anomalies against temperature anomalies for winter (December to February) and summer (June-August) quarters. The series used were the Central England temperature and England and Wales rainfall records. The anomalies are expressed as the difference from the 1766-1995 mean for rainfall and from the 1659-1995 mean for temperature. The years since 1976 are highlighted. The winters show a slight trend towards the warm and wet quadrant, but are generally very variable about the mean, although 1990, 1994 and 1995 stand out as particularly mild and wet. The summer in general, however, shows a far greater tendency towards a definite warm/dry and cool/wet split and the recent years cluster in the warm and dry quadrant. The summers of 1976 and 1995 stand as exceptional events. Considering the past 20 summers collectively, rainfall has been 10% below, and temperature 0.6°C above, their respective long-term averages.

A similar approach was taken in Figure 5.9. This compares the long-term rainfall with the long record of Lamb's Weather Types for the UK (Lamb, 1972). Weather Types provide a somewhat subjective description of the synoptic situation over central England. The daily data are made up of a series of classifications such as cyclonic, anticyclonic or westerly. Figure 9 shows the deviation from the 1941-70 mean in the number of anticyclonic days during the summer together with the rainfall difference from the 1941-70 mean, and again 1995 stands alongside 1976.

Consequential effects of these changes in the rainfall and temperature regimes are compounded by the subsequent changes in the PE losses. This accentuates the regional runoff and aquifer recharge patterns across the country (Arnell and Reynard, 1996). The relationship between high and low rainfall events and runoff can be seen in Figure 5.10. This figure illustrates two extreme winters (one wetter than average, one drier). The dry winter of 1971/72 can be seen in rainfall terms with the UK experiencing rainfall up to 40% below the mean and the Low Countries of Europe and Germany with deficits of up to 60%. The regionalised runoff map for the same period shows that for much of Europe the runoff was in the lowest 10% of years and the lowest 30% in the UK. The high pressure from the south dominating during this winter, pushed the depression tracks north over Iceland and Scandinavia, hence the reversed pattern in these regions.

The wet winter of 1979/80 is also shown in Figure 10. Southern Britain recorded rainfall 40% in excess of the mean while north-west Scotland recorded 40% below-average rainfall, with Scandinavia still lower. On the continent the Low Countries and Germany recorded slightly higher rainfall (up to 20% above the mean) while much of France was wetter with up to 60% excess. In terms of runoff, south-east Britain experienced flows in the 70-90 percentile range (only 10% of winters are wetter), as does most of the near continent. Again western Scandinavia (and to some extent Scotland) experience the reverse conditions to the rest of north-west Europe.

5.3.2 The period 1994/95

Figure 5.8 raised 1995 as an exceptional summer event, comparable only with 1976 in the recorded data, but the preceding winter was also worthy of note.

The end of March 1995 saw the end of the wettest 32 month sequence in the England and Wales rainfall series, with extensive flooding during the winter of 1994/95 over large areas of the UK. The water resource position at the end of the winter was, therefore, very healthy. During the spring the Azores high pressure area established itself sufficiently strongly and far enough north to deflect the majority of the North Atlantic depressions north of the UK. This situation remained and indeed strengthened throughout the summer producing a run of exceptionally dry months, culminating in the July and August rainfall totals being only about 15% of average. This made the summer almost as dry as the record driest in 1976. River flows and groundwater levels held up well throughout the spring, but the highest ever demand levels in early summer soon overstressed the water supply distribution networks, particularly in those areas more dependent on surface reservoirs.

5.4 Trends in UK flooding flows

As part of a recent study summarising the variability in the frequency of floods in the UK, evidence was found for an apparent trend in the data. The analysis used the peaks-over-threshold (POT) archive held at the Institute of Hydrology extending back 122 years. Previous work had suggested that the number of floods above a certain threshold was sensitive to the period of record on which the data were calculated (Bayliss, 1994). The new study sought to remove this problem by standardizing thresholds to the 20-year period starting 1 October 1963. This meant that flood data from any number of sites could be combined to investigate flood occurrence at regional or national scales.

The standardization technique was developed (Reed, 1994) so as to obtain 80 peaks in the 20 water years between 1963 and 1982. All stations were ranked according to how closely their records matched this standard period. Of the 857 UK stations on the POT archive, 675 form the fully standardized data set with 178 forming the secondary non-standardized set. Figure 5.11 shows the number of stations operating in each year. Only a few were available before 1930 and the number decreases again after the mid 1980s. The geographic spread provides a good coverage of the UK, but the network is slightly less dense in Scotland.

Figure 5.12 shows the ratio between the mean annual frequency of floods in an individual year and the mean frequency within the standard period. This means that the data for the standard period years 1963-82 (highlighted in bold) tend to fluctuate around 1 (4 events per year). There is an apparent trend evident throughout the record with, perhaps, less variability towards the end of the record also. The confidence intervals are shown and these suggest that more note should be taken of trends post 1950. The recent run of years with an above average number of floods in the UK is particularly worthy of note.

Grew and Werrity (1995) also found a trend to increased frequency and magnitude of flooding in Scotland during the late 1980s and early 1990s. This was matched, statistically, with a changed occurrence of weather types over the same period, particularly cyclonic, westerly and southerly types.

5.5 Acknowledgements

Much of the data for this paper is based on that assembled as part of the national hydrological monitoring programme maintained jointly by the Institute of Hydrology and the British Geological Survey on behalf of the Department of the Environment and the National Rivers Authority (NRA).

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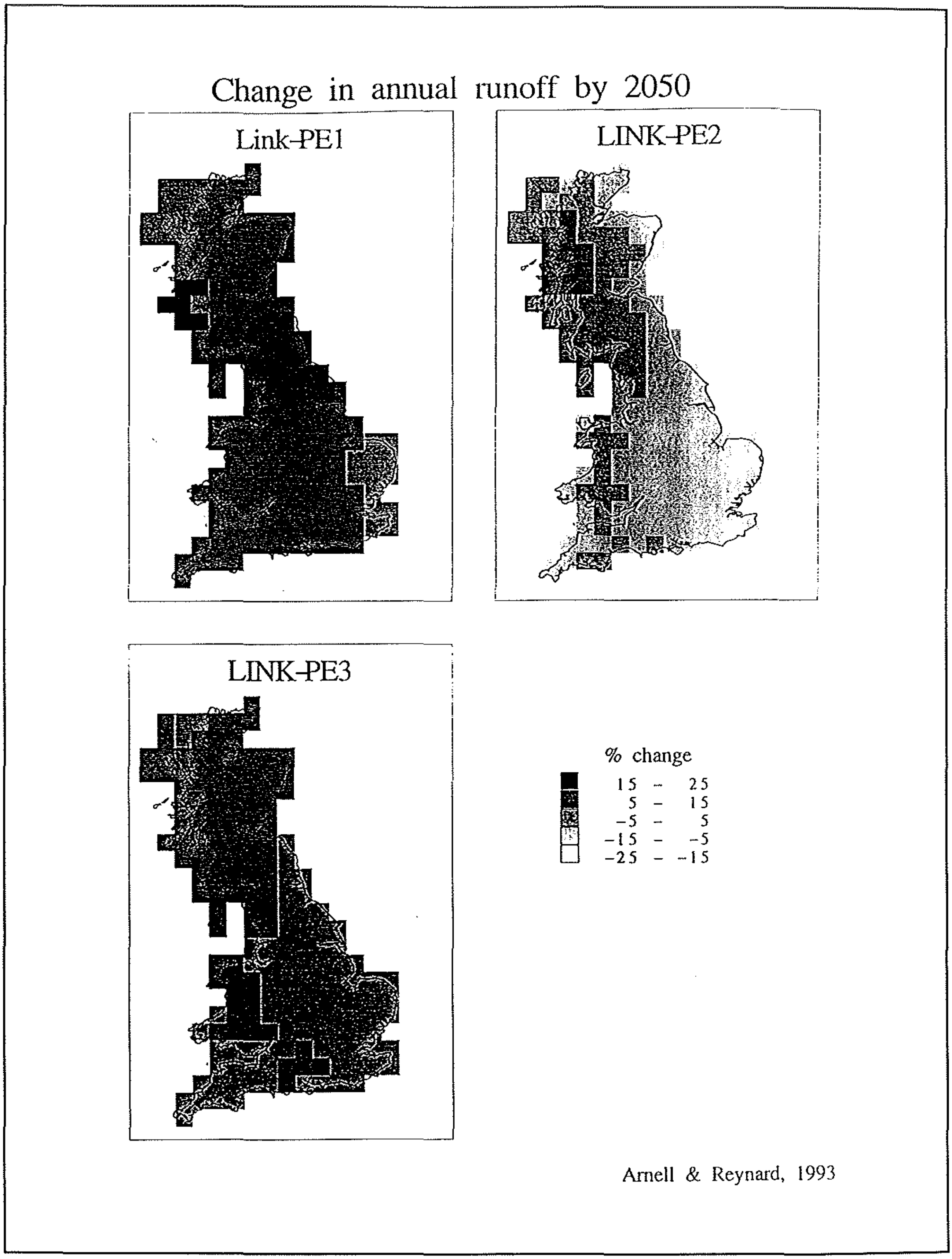

Figure 5.1 Change in average annual runoff for 2050 under three potential evapotranspiration (PE) scenarios

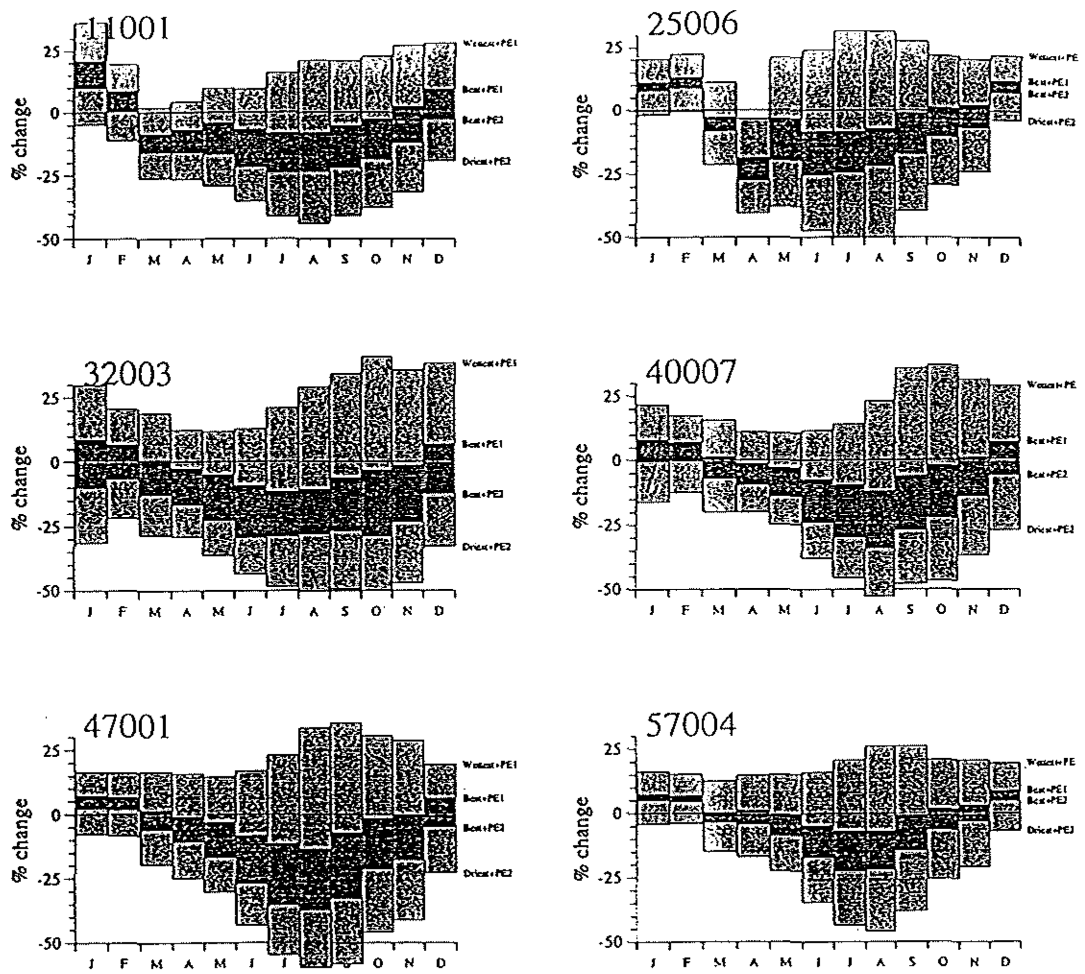

Figure 5.2 Monthly change in runoff for six selected catchments in the UK

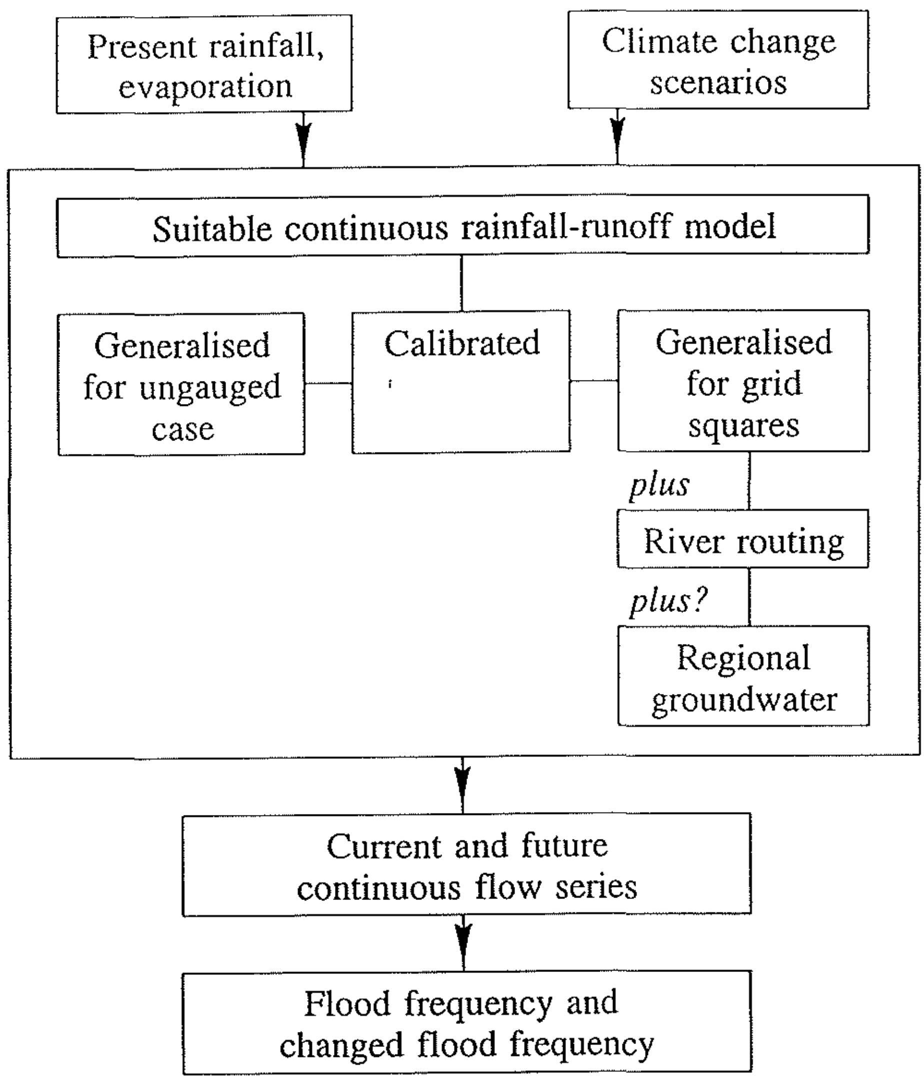

Figure 5.3 Framework for the modelling of large catchments

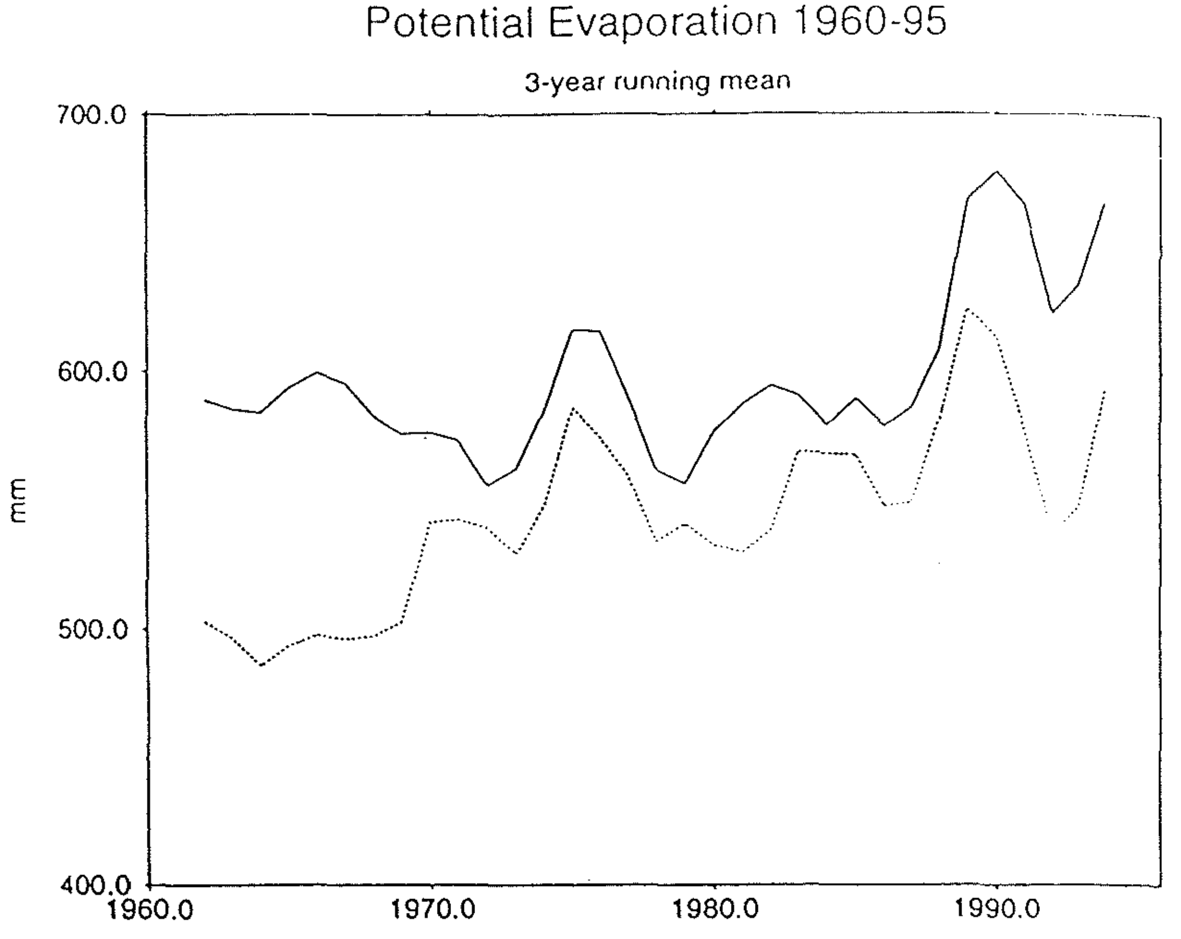

Figure 5.4 Running mean of annual potential evaporation (PE) totals for eastern (solid) and southern (dotted) England

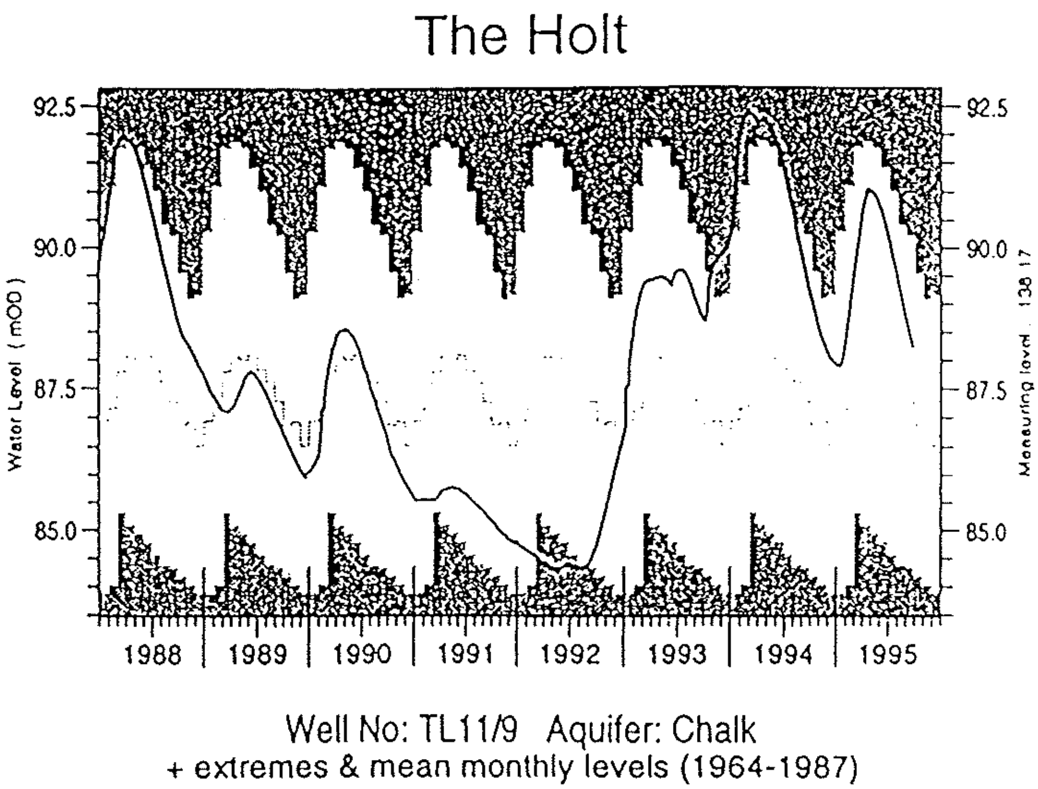

Figure 5.5 1988-95 groundwater levels in the Chalk and Upper Greensand aquifer of southern England

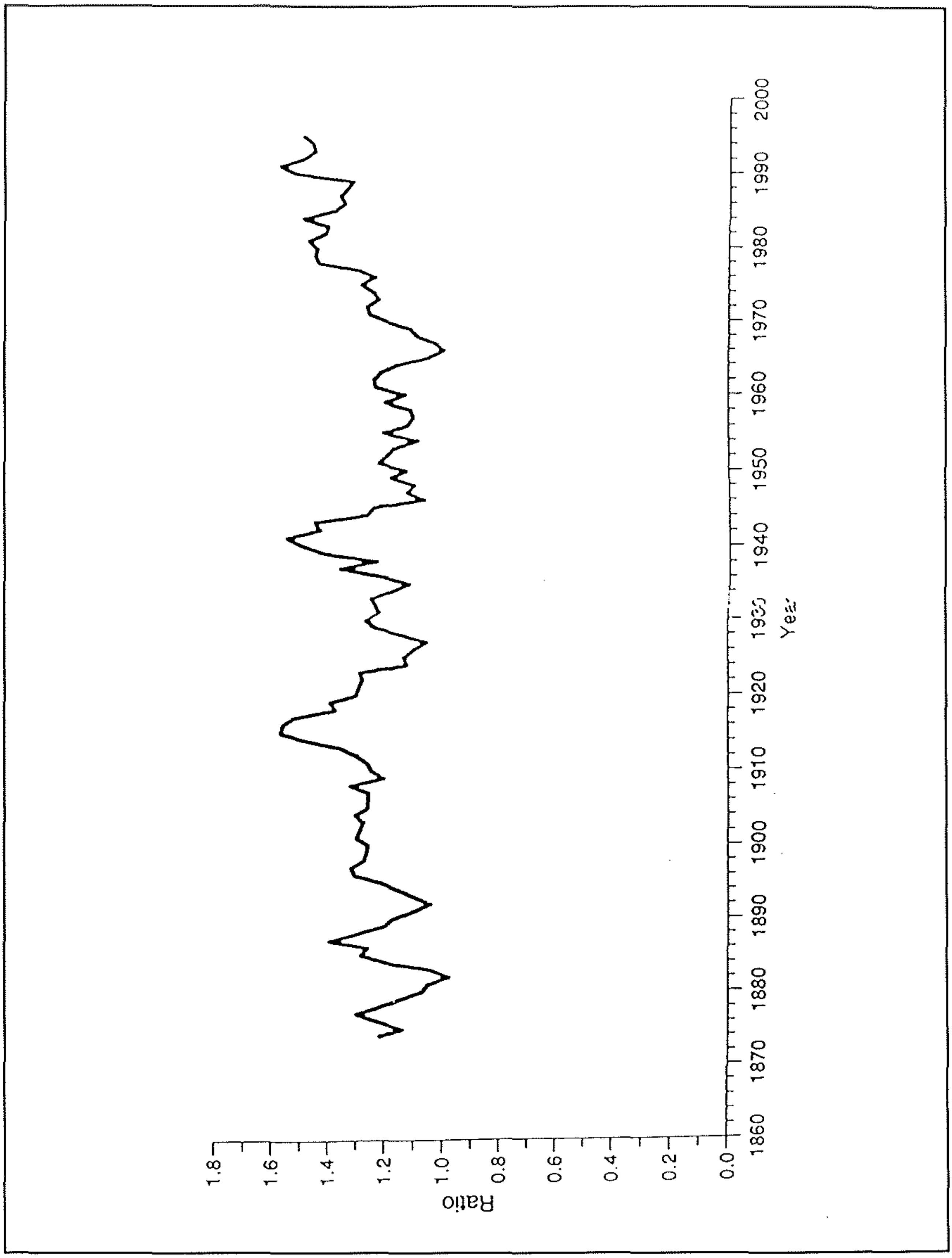

Figure 5.6 Ratio of winter (October-March) to summer (April-September) rainfall for Great Britain - 5-year running mean

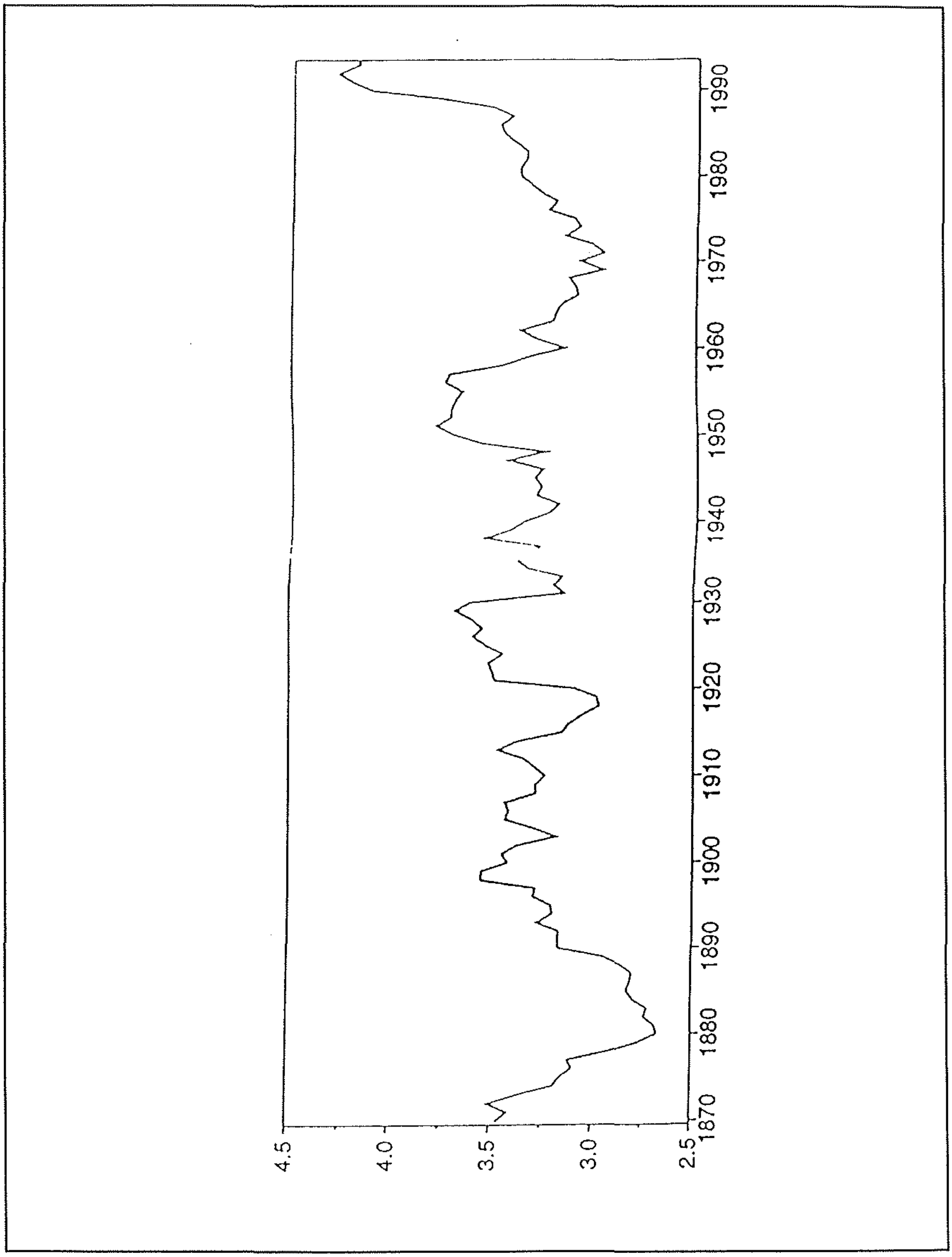

Figure 5.7 Ratio of annual rainfall at Fort William to Kew - 10-year running mean

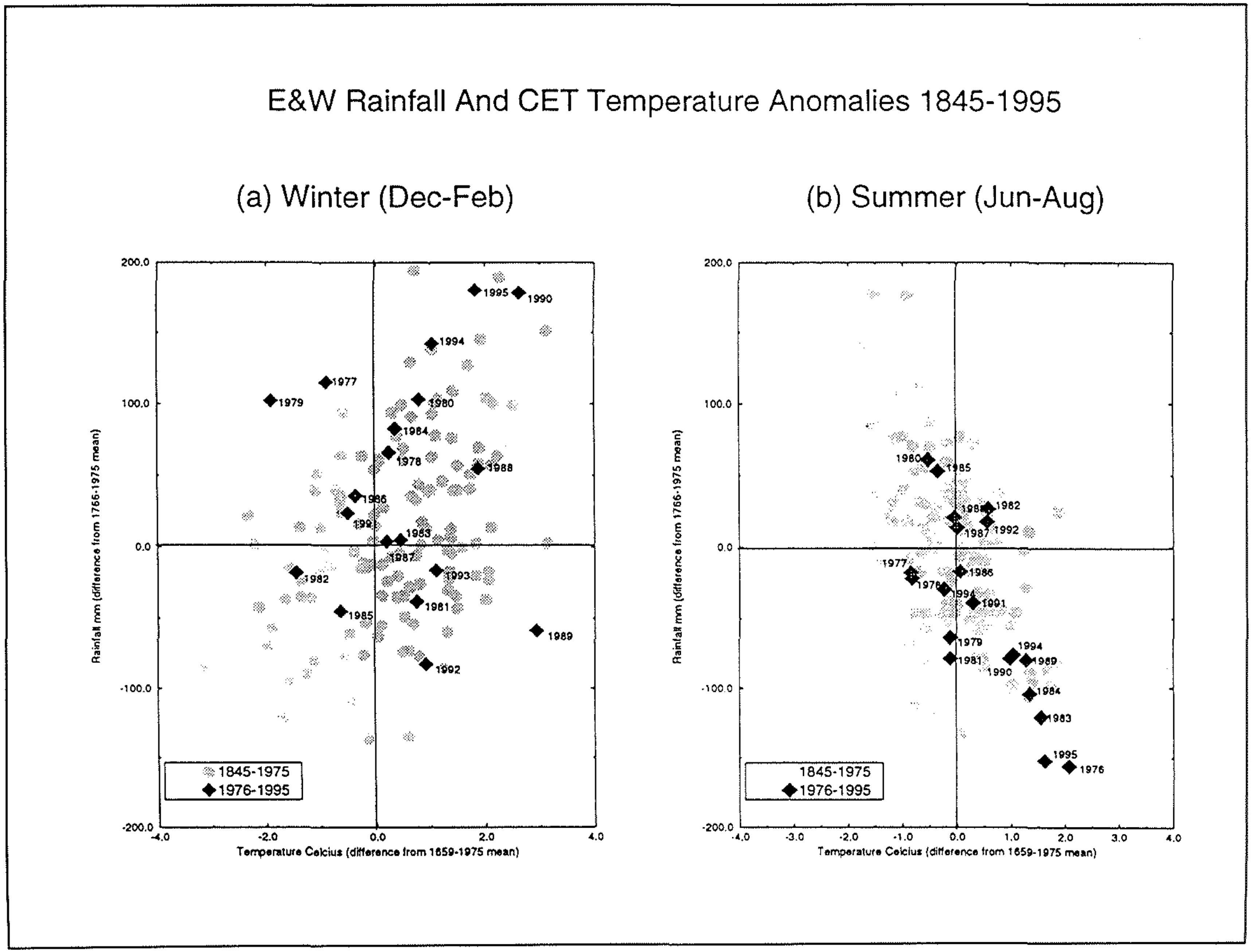

Figure 5.8 Rainfall and temperature anomalies for winter (December-February) and summer (June-August) for England and Wales (1845-1995)

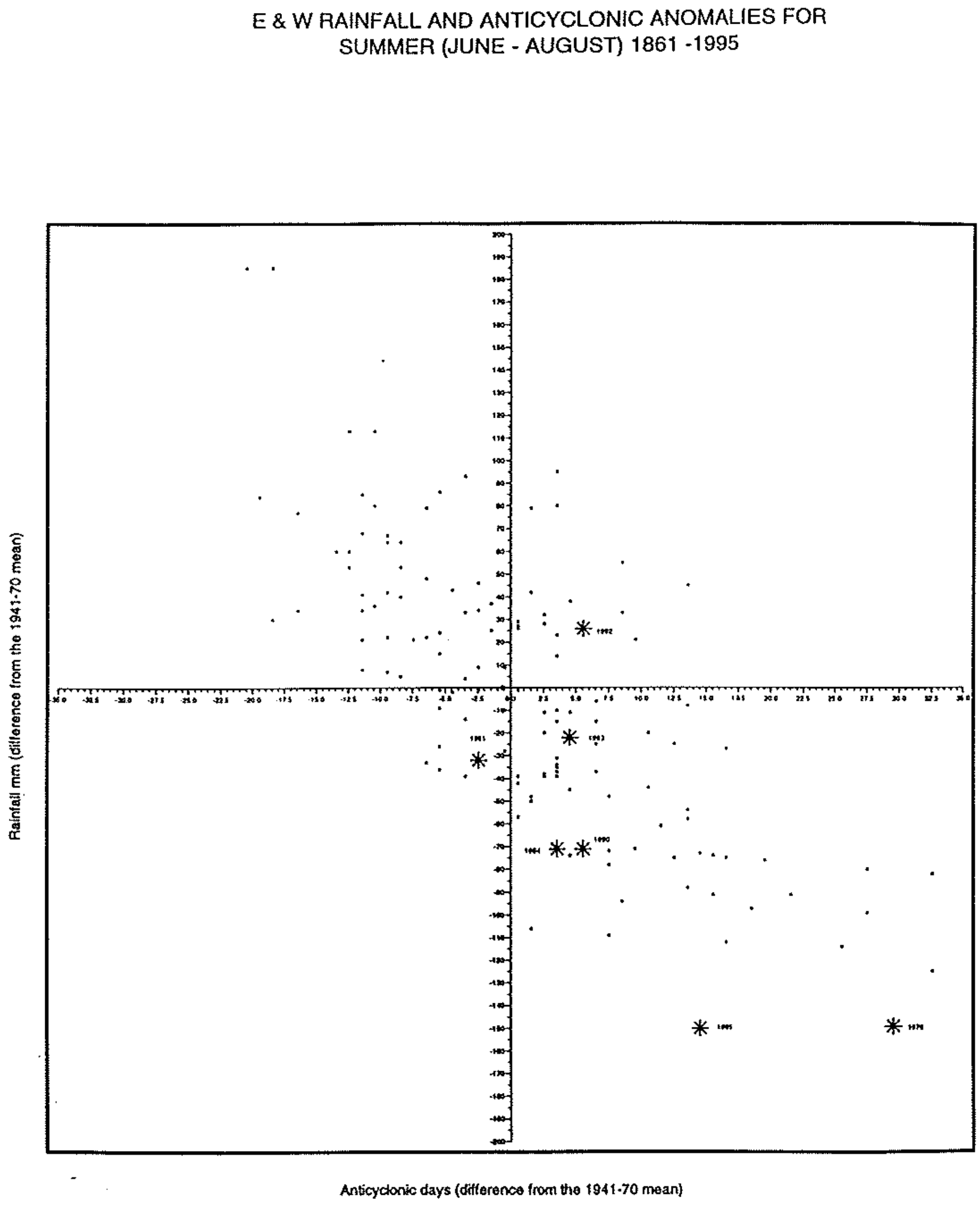

Figure 5.9 Rainfall and weather type anomalies for July and summer (June-August) for England and Wales (1861-1995)

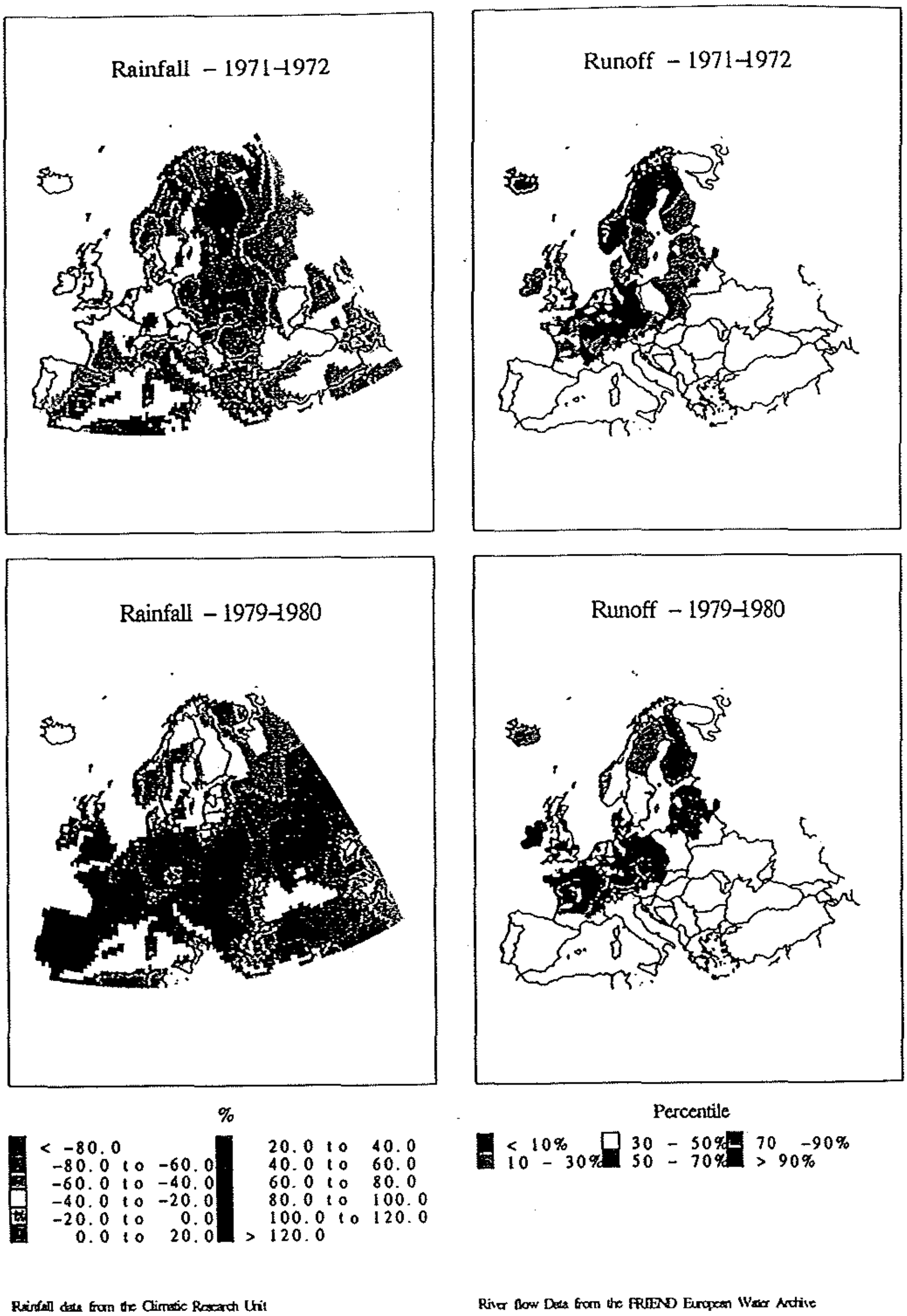

Figure 5.10 Anomalies of rainfall and runoff for north west Europe for the winters of 1971/72 and 1979/80

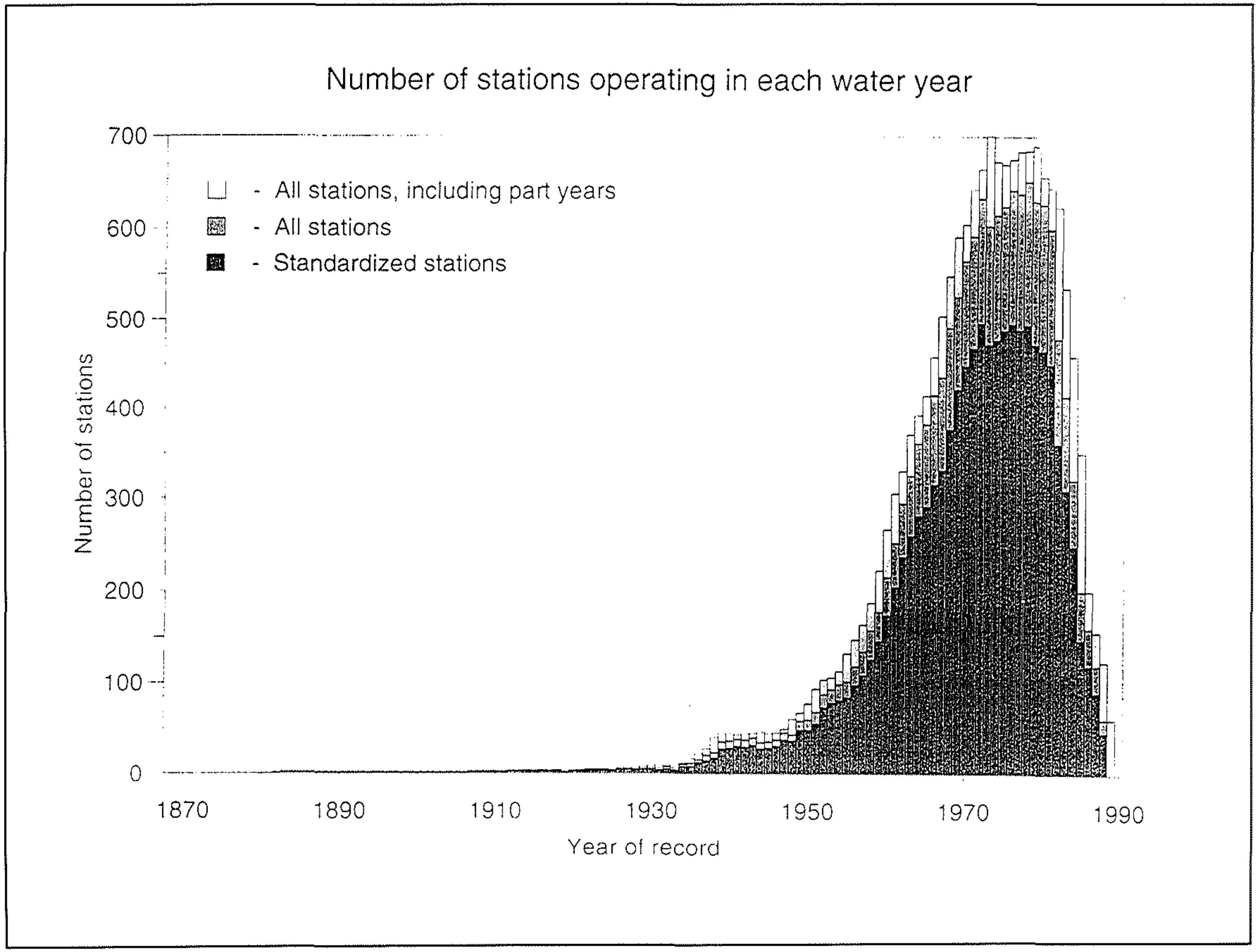

Figure 5.11 Number of stations operating in each water year

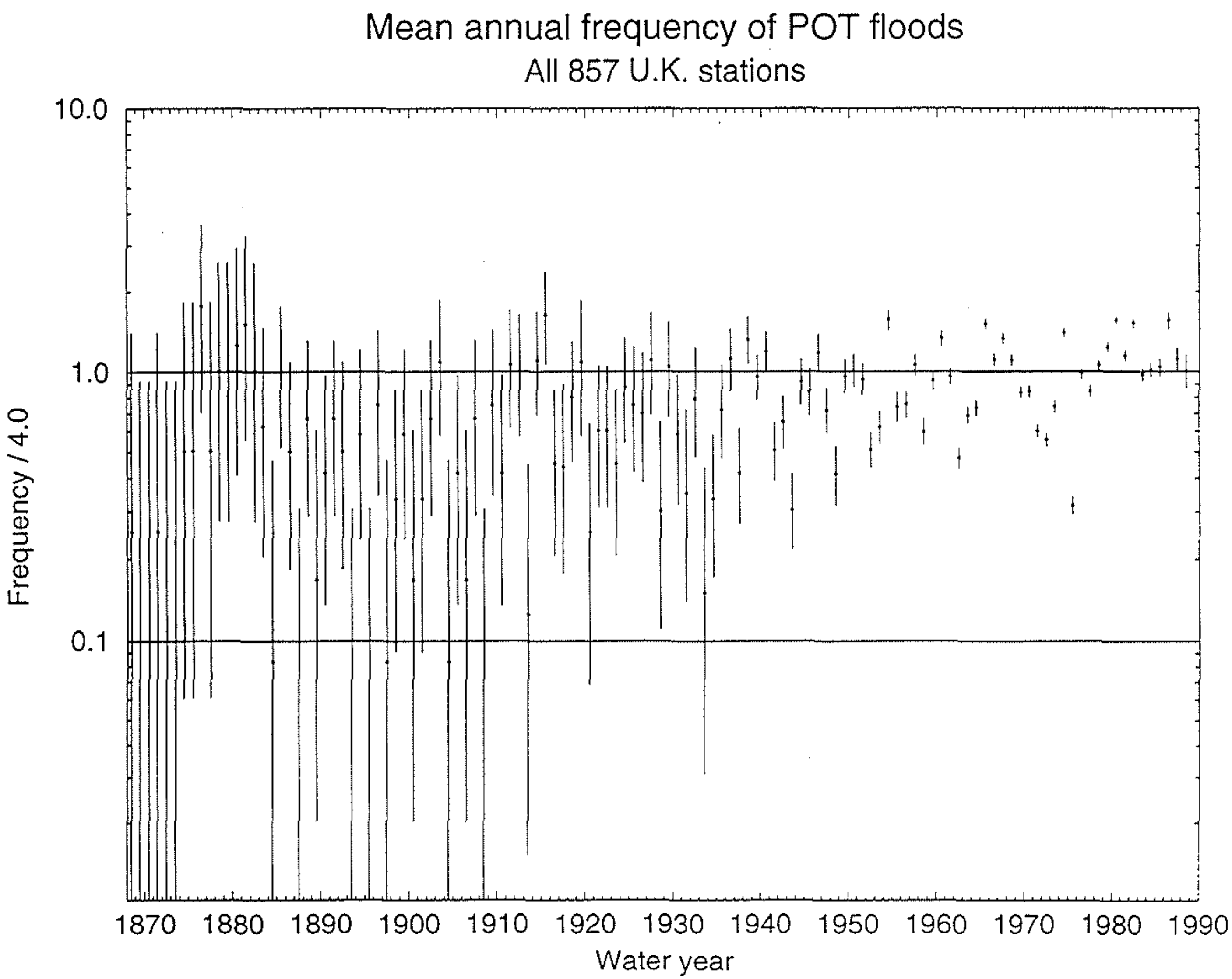

Figure 5.12 Mean annual frequency of POT floods (provisional)

6 Coastal and river responses

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6.1 Background

6.1.1 Context

This working paper has been produced for the workshop on the impacts of climate change which was convened at HR Wallingford on 16 November 1995 to explore the R & D requirements of MAFF to fulfill their River and Coastal defence responsibilities.

6.1.2 Scope

This document considers the possible impacts of global climate change on the risks of flooding around the coast and within river systems. The generation of climate scenarios is not considered nor is the interaction of atmospheric processes which produce the changes to the forcing of river and coastal flood conditions. The paper concentrates on the effects of changes in the physical forcing from the climate (temperature, sea level, wind, precipitation etc) on the river and coastal environment. There are other important impacts within river and coastal systems (eg water resources) which are not included in this discussion document as they do not have a material impact on flood defence. Companion papers from the Proudman Laboratory and IH cover (see sections 4 and 5) changes to sea conditions and river runoff processes.

6.2 Coastal response to climate change

6.2.1 Introduction

A number of the hydraulic and meteorological parameters that are important in determining the responses and development of coasts could be significantly altered by climate change. These are summarised below and are separated into two categories (ie. of Primary and Secondary importance).

<u>Primary</u>	<u>Secondary</u>
Tidal levels (mean and high water)	Rainfall
Tidal currents	Winds (direct influences)
Wave heights and directions	Temperature (of seawater)

In this brief paper, only the responses to the primary parameters are discussed in any degree of detail. A few notes on the effects of changes in the secondary parameters are provided at the very end of this section.

6.2.2 Primary impacts

<u>Effects of changing in tidal level</u>

In the long-term, significant changes in tidal level will inevitably affect the position of the coastline. Much of our knowledge of past sea levels has been deduced from the morphology of the coastal zone (eg. raised beaches, submerged river valleys and cliffs). In the medium-term (eg. 10-50 years), however, the connection between sea level rise and coastal retreat is less certain, depends on the supply (or lack of supply) of sediment and is often masked or overwhelmed by other effects.

In the UK, the effects of an increase in mean tide level are probably quite minor (although low-lying areas requiring a pumped or gravity drainage will be affected within a few decades). It is easier to anticipate the effects of increases in high tide levels (as a result of increases in mean sea level, surges and tidal ranges). The effects include:

- increased incidence of overtopping of "built" defences, in tidal rivers, estuaries and along the open coast, with flooding of low-lying hinterland
- increased overtopping and "roll-back" of beaches, especially barrier beaches
- changes in inter-tidal mud-flats and saltmarshes

Where other effects (eg increased wave conditions, morphology changes) do not complicate matters, it may be sufficient just to raise defences (eg flood-banks in estuaries or tidal rivers), and hence prevent any significant changes in the coastline position. Elsewhere, and especially in estuaries, the changes in morphology that are likely to follow increased tidal levels make the problems of maintaining the present coastline more difficult.

The link between changes in beaches and tidal level changes has received a great deal of attention in recent years. However, the evidence from a study of changes in pocket beach around the coast of England and Wales over the last century or so does not indicate a clear correlation with recorded changes in tidal levels. Other authors have also noted that simple rules linking sea level rise to beach erosion are, at best, of limited applicability. Often there are many more important factors, such as direct human influences on coastal processes, which overwhelm the effects of tidal level changes.

In this context, it is interesting to consider the impacts of the well-known 18.6 year fluctuation in tidal levels produced by the precession of the Moon's orbit. During certain stages of this cycle, the mean tidal ranges can increase considerably (eg by about 20 mm/year at Newlyn), and it can be expected that Spring tidal ranges (and hence highest water levels) will also increase by corresponding amount. This effect lasts for several consecutive years. At such times, the effect on the upper parts of a beach would presumably be much the same as if mean sea level was rising by about half that amount, ie about 10 mm/annum. Therefore, we would presumably expect to see periods of rapid beach erosion, or landward recession at these times (presumably followed about 9 years later by periods of beach accretion as high water levels declined again). We are not aware of any studies into such cyclical changes, nor of any evidence (firm data or anecdotal) to suggest that such morphological fluctuations actually take place. This may therefore be an indication that the effects in the UK of a modest sea level rise may not be as pressing as many people believe.

Effects of changing tidal currents

It can be expected that increases in tidal range will bring about increases in tidal current speeds. It is much less clear that an increase in mean tidal level will have the same effect. Indeed in estuaries where the high water mark already lies against solid defences, there may be a reduction in the inter-tidal volume of the estuary, and hence a reduction in current speeds!

Changes in tidal currents are most likely to be important in estuaries, where they dominate morphological processes. It must be remembered, however, that sediment transport on many beaches around the UK, and in shallow water close to the shore, is also influenced by such currents.

Effects of changes in wave climate

The concept of substantial changes in wave conditions around the globe, as a consequence of climatic change, is often overlooked. In terms of impacts on the coastline of England and Wales, however, this may well be the single most important consequence of a changing climate.

The implications of increased storm wave action on structures such as breakwaters are reasonably straightforward. For example, the size of stable armouring depends on the cube of the design wave height. An increase in extreme wave heights of only 1% each year could, in a decade, lead to a requirement for armour unit weights to be some 38% greater, to achieve the same degree of safety. Such a change would influence the management of our coastline, for example by causing damage to control structures such as groynes or revetments.

Because wave action is the primary "shaker and mover" in beach development, it is not surprising that changes in the wave conditions will also alter beaches. As an example, the profile of a beach behind a detached breakwater tends to steepen as a consequence of the shelter that has been provided. Similarly it has long been observed, and more recently demonstrated by statistical analysis of beach profiles, that beaches in winter (undergoing severe wave activity) tend to have flatter slopes than in summer.

As well as impacts of a change in general wave conditions, an increase in the largest waves (especially if occurring at high tidal levels) will also be important. Barrier beaches such as Chesil will be moved landwards in (only) such events, with material being washed over its crest onto its landward side. The largest waves are also likely to cause dune erosion which may take many months, even years, to repair naturally. Recovery is assisted by the "binding and trapping" effects of vegetation, which itself may be affected by climate change. An increased frequency of such erosive events is therefore likely to result in dune erosion and retreat, which may take decades to restore. It is unfortunate that there are few if any sites monitored around the coast of the UK where the long-term cycle of dune erosion and accretion, or where the episodic retreat of shingle ridges, can be investigated.

It is conceivable, however, that an change in the general level of wave energy may increase the occurrence of more modest waves, and in some circumstances there may even be a decrease the largest wave heights. This could lead to a general steeping of the beach profile and a reduction in dune erosion.

So far, attention has been focused on changes in wave heights and corresponding changes in beach profiles. In most situations, however, the movement of sediment perpendicular to the beach contours (ie cross-shore transport) is a rather minor factor in the long-term evolution of a coastline. The major cause of change is normally the longshore transport of beach material, or more precisely the changes in that transport from point to point along the coast. The longshore transport does depend on the wave height, but more crucially on wave direction. The former influence, in the long term can only increase or decrease the rate at which a coastline is presently eroding or accreting. On many pocket beaches which have adjusted to reach a position of no nett drift, a change in the wave heights will have no effect on the longshore transport.

However, a change in the "average" wave direction will often cause a change in the present trends of erosion and accretion (affecting both rates and patterns). In some recent case studies, it has been found that erosion problems have recently occurred on stretches of coastline which have been stable or accreting for many years. Good examples are provided by East Beach at West Bay, Dorset and Montrose Links in Scotland. At both sites there has been a recent reverse in the nett longshore transport direction, bringing about rapid beach erosion in areas where previously there had been no great problems. In other locations, longshore drift rates have remained in the same direction but have increased substantially over the last 5-10 years. At Seaford, in Sussex, this has directly resulted in greater expenditure than anticipated in artificial recycling of beach material (to counter the effects of longshore movement of shingle). At other sites, beaches have greatly diminished in volume, leading to the need for new coastal defences.

It can be difficult to identify changes in a wave climate by using observed changes in a beach, at least initially, because of the very significant year to year variations in wave "weather". A study by the Climatic Research Unit (University of East Anglia) into storms in the North Sea over the last 150 years or so is of considerable interest in this respect. This shows not only the considerable inter-annual variability in the occurrence of gales (and above), but also a definite negative correlation between their occurrence in consecutive years. That is to say that they showed that a stormy year is likely to be followed by a relatively quiet one. As a result of this type of variability, it may take five to ten years, or more, before a wave climate change can be identified with any certainty.

6.2.3 Secondary impacts

Rainfall

There is a known past variation in the rainfall occurring in the UK. In the southern part of the country, an oscillation of about 40 years period has been postulated. As rainfall increases, a number of effects are likely to occur at the coastline, as follows:

- De-stabilizing of soft coastal cliffs
  Cliff falls are usually caused by a combination of marine erosion, eg undercutting their front face, and geotechnical problems, eg rotational slips. The latter class of effect is increased by greater rainfall, and hence run-off, higher water table levels etc. In the long-term, this will result in beaches receiving fresh supplies of sediment. This benefit, however, may not be much comfort to those living near the cliff edge.

- Increased river flows
  In many parts of the world, rivers still bring large quantities of sand and gravel to the coast, again providing fresh supplies of beach material. In the UK this probably only occurs in Scotland (eg Spey and Findhorn rivers), although estuaries may well be affected (hydrodynamically) by strong river flows, and receive significant inputs of fine-grained sediment (clays and silts).

- Impacts on sand transport
  In locations where a beach is affected by surface water run-off from the land, there are often localised erosion problems, eg around outfall pipes. The frictional resistance of sand is reduced by the water, making it easier to mobilise by waves and currents. Beach drainage systems have been installed in some places in an attempt to reduce this effect. It is likely that increased rainfall will increase beach erosion.

- Impacts on dune building
  Wet sand on the foreshore will be much less easily transported by winds than if it is dry. However, many dune binding grasses suffer in drought conditions, and are generally healthier in wetter climates, thus increasing their capacity to trap and hold sand. It is not clear, therefore, whether increased rainfall would help or be detrimental to dune stability.

<u>Changes in winds</u>
As well as changes in wind conditions altering waves, discussed earlier, there are other direct effects which may affect a coastline:

- Aeolian sand transport
  Strong winds are capable of transporting large quantities of sand, both along the coastline and perpendicular to it. The former effect can add to, or counteract wave induced longshore drift, but tends to take place at higher levels on the beach profile. Onshore transport by wind action typically dominates offshore movement. This is partly because winds blowing over the sea (and hence onshore) are stronger (less affected by friction) than those blowing offshore. Also, onshore winds, created as a result of differential heating of land and sea, tend to occur during the warmest part of the day, and therefore when the sand is driest and most easily moved.

  A change in wind strengths or directions may alter existing patterns of sand transport. It is likely this will be most noticeable by changing dunes.

- Wind induced currents
  Nearshore currents and circulation patterns are often affected by wind action, especially on coastlines which have little tidal range. Even in the UK, flows at different levels in the water column are influenced by wind stresses, with subsequent effects on sediment movement. Strong onshore winds in a storm, for example, will tend to create an "undertow" going seawards near the bed. Changes in wind patterns may therefore affect patterns of sediment transport in shallow water and on beaches, especially for fine sand.

<u>Temperatures</u>
The temperature of seawater has a direct effect on its viscosity, and hence on the capacity of hydrodynamic motions to transport sediment. The amount of material that can be transported as suspended load, in particular, is strongly dependent on the fall velocity of the individual sand particles, which in turn depends on the viscosity of the water. An increase in water temperatures will reduce suspended load transport, and since this is a major factor in offshore movement of beach material during storm conditions, the nett result may be a reduction in beach erosion.

6.3 River response to climate change

6.3.1 *Introduction*

The discussion below assumes that climatic change will influence the size and distribution of flows in rivers, which is discussed in the companion paper. from the Institute of Hydrology (Section 5). There are many potential impacts of climate change on flooding risks in river systems, some of which are the consequence of other changes and adaptations in the catchment. The impacts discussed below will be separated into primary and secondary.

<u>Primary</u>	<u>Secondary</u>
Peak flood flows	Seasonality
Flood volumes	Mean runoff
Tidal Levels	Temperature

In addition there may be adaptations of land-use within the catchment which will alter the vulnerability of the human use of the land to flood risks or change the inputs to the river system.

6.3.2 *Primary impacts*

<u>Peak flood flows</u>

The most direct impact of changes to the typical design flood flow (say 1 in 100 years) will be a change in the water level. Even though mean annual precipitation may remain little changed over the UK, changes in storm intensity, seasonality of precipitation, and type of precipitation will influence the catchment response and are predicted to lead to increased frequency of flood flows. The standards of defence offered by existing flood defence infrastructure will be affected, thus riverside embankments may need to be raised or channels enlarged. A new approach to design will be needed as flood estimates based on historic flow data become inadequate.

An increase in the frequency of high river flows will change the capacity of the river system to transport sediments. If the concept of a formative discharge is accepted in determining the morphology of the natural river channel, then a change of morphology may be expected as the frequency of flood flows increases. In fact the effects on river morphology are likely to be influenced by other factors including:

- the supply of sediments,
- the duration of floods,
- mean water temperature, and
- the frequency of occurrence of catastrophic events.

The changes in river sediment transport may eventually lead to a change in stable plan form but the speed at which such adjustments will take place is uncertain. Increased local scour will occur over shorter time scales (a single major flood event) which may pose a threat in particular to any structure in the river bed.

An increase in high river levels may impact indirectly upon urban storm sewerage systems through changes in the frequency of locking of the outfalls. This may require design changes to the volume of storage within the urban system.

Flood volumes
Any change to the volume frequency relationship in a river will alter the effectiveness of flood defences based upon storage arrangements since for these the design volume of the storage pond depends directly upon the flood volumes at the design frequency. Hence in the long term there may be a need to review the capacity of major flood storage schemes. Any change in the duration of high flows in rivers will change the net sediment transporting capacity and impact upon the river morphology. A less direct impact may arise on dams, where the frequency and volume of flow over the spillways may change or the spillway capacity may need to be increased to reflect increased flood flows. Significant increases in the spillway flows may affect river bed levels downstream of the dam.

Tidal Levels
Flood defence in the tidally influenced reach of a river is usually implemented by the construction of flood embankments or walls. Increases in the extreme tide levels will require these structures to be raised in order to maintain the same standard of flood defence. The fenlands of East Anglia are of particular importance in this respect. Increase in the mean sea level and surge tide levels will push the interaction zone between river and tidal conditions further inland. This will alter the frequency of occurrence of extreme water level changing the regime from fluvial design and changing the patterns of sediment deposition in the upper estuary. This may alter the regime requiring the mean cross-sectional area to increase and therefore pose a threat of bank destabilisation. Another potential impact is upon the frequency and cost of pumping lowland drainage systems into tidally affected watercourses. Adaptation here should be relatively straightforward through possibly resectioning of drains and increasing pumping capacity when the current systems reach the end of their economic life.

A secondary influence of the change in tidal conditions will be on the operation of major barrages and barriers (eg Thames Barrier, Cardiff Bay Barrage). The structures will operate more frequently to exclude the tide from the upper river system and this will alter the impounded level frequency on the landward side of the structure. This may increase the incidence of surface flooding from locking of urban sewerage systems, possibly creating the need for pumping. Also there may be increased sedimentation upstream of such structures in the long term which will require maintenance dredging.

6.3.3 Secondary impacts

Seasonality
Precipitation is likely to be less evenly spread through the year with an increase in the winter flows. The percentage runoff for winter events may increase through the restricted infiltration capacity of the soils. Thus direct surface runoff increases and with it the potential for erosion and thus an increase in catchment sediment yield. Any increase in the sediment yield will affect the channel morphology (see Section 6.3.2). River resistance contains a strongly seasonal element through the growth and decay of vegetation. If the timing of major flood flows changes in relation to the seasonal changes in vegetation cover then there will be an impact upon the frequencies of extreme water levels. Perhaps the most important influence on vegetation and stream ecology will result from the predicted difficulties in water quality in the low flow seasons. These factors could influence particularly the occurrence of "flash" flooding from summer storms.

Mean runoff
Even though mean precipitation is unchanged the mean runoff may change. Any impact upon flood defences is likely to be small, being restricted to possible changes in vegetation conditions and mean sediment transport.

Temperature
Changes to the water temperature will alter its viscosity. This may have several effects including:

- change in the sediment transport capacity,
- change in the effective river resistance through changes in the fluid turbulence, and
- change in the effective river resistance through changes in bed sediment conditions

In addition temperature is an important factor in determining the riverine ecology and temperature changes coupled with poorer water quality in the low flow season could affect riverine vegetation (as discussed above).

6.3.4 Changes and adaptations of land-based systems
The human use of river catchments will develop and adapt to take account of the changing climate. There may be changes in:
- cropping
- irrigation
- surface water resource development
- natural vegetation patterns
- urban drainage practice

All of these have potential feed back into the overall catchment runoff processes.

6.4 Discussion and recommendations
6.4.1 Coastal defence
Existing work on the effects of climate change and its impact on the coastline has largely centred on sea level rise. There has been very little done on the effects of changes (globally) in atmospheric pressures or wind fields, and the subsequent changes in waves and littoral drift. Evidence from the UK, however, suggests that these impacts are likely to dominate changes on "open" coasts, rather than modest changes in tidal levels.

Much more work is needed to predict realistic future wave climate scenarios, to allow planning of coastal defence management in the medium-term future. This will apply to a large variety of coastlines, eg cliffs, beaches and muddy estuarine areas. Some areas may already be defended, whilst others may not be. Where defences already exist, climatic changes may well rapidly reduce both their functional efficiency and residual life. Whatever the coastal type, however, possibly unpopular decisions about the future maintenance of the current shoreline position may be required. This in turn depends on the costs and benefits of defence, which in turn reflects the predicted future marine climate. Assessing this can be partly based on numerical modelling of future atmospheric conditions. In addition, however, it would be worthwhile examining past fluctuations in wind patterns over the UK, to give some guide to natural variability in wave conditions.

Many of the above comments on likely coastal response are rather speculative. This indicates the need for more than just computational modelling. It is therefore suggested that consideration is urgently given to actual measurements of coastal response, as well as of waves and tidal levels. The possibility of long-term monitoring of suitable coastal sites around the UK needs to be investigated, to define its feasibility, content and costs.

6.4.2 River flood defence

Many of the comments in Section on river impacts are speculative and are mostly unquantified. We are not aware of a comprehensive study of the potential impacts of climate change on river flow and sediment processes for UK rivers. It is our expectation that the river flood defence impacts will not emerge as quickly as those around the coast. Already adaptations are being put in place to take account of mean sea level rise when major estuarial embankments are renovated (eg the Middle Level Barrier Bank). Nevertheless, the interactions of the impacts of climate change should be established to "map" the full system involved in river flood defence, of particular importance will be those involving sediment processes and long term adjustment to river morphology.

Within the UK there are likely to be regional differences in the types and importance of impacts of climatic change on flood regime following on from the North, South east differences in predicted changes in mean precipitation There are scale issues which need to be addressed on applying output from GCM predictions to the spatial and temporal scale of response of typical UK river catchments. However, if these are addressed, many of the potential impacts could be examined through testing of scenarios with existing models of river catchment processes (See Section 5.2.2). These catchment models should be capable of being driven by long term precipitation and other climate parameters and contain sufficient soil physics to incorporate changes in percentage runoff.

These scenario tests could be used to indicate sites for maintaining strategic monitoring for river response to climate change. However, given the stochastic nature of precipitation and river flows, monitoring will be a long-term task and will need careful interpretation to assess the causes of any trends in the catchment response.

The appropriate design methodology for flood defences should be reviewed to take account of the uncertainties in future runoff and sediment transport conditions. In particular, it may be necessary to move away from the concept of a design event based upon historic flow data.

The design of flood defence infrastructure should be reviewed to introduce some degree of future-proofing to allow the defence measures to be adapted by later generations if the impacts of climate change become more significant. Care will be needed to ensure that such design changes do not prejudice the performance of the river system over shorter time scales (eg sedimentation of over-sized channels).

7 The implications of climate change for flood and coastal defences: social response and national economic implications

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7.1 Introduction

Climatological information and predictions are now making it clearer that we are experiencing a process of climate change, although the magnitude of that climate change is not yet fully explicit. What is also not clear is the extent of social response to climate change that will be induced by these processes, and the impact that these processes and climate change will have upon the institutions concerned with water management and environmental protection in the United Kingdom.

This paper begins to explore some of these themes of social response and national impacts. This is not unproblematic in that the available detail of regional and local climate change predictions is as yet sparse, and also because there is a degree of speculation that is necessary concerning social processes and their changes consequent upon climate change.

In addition, we must appreciate that social processes and responses are not static at any one time; society is changing continually. It is difficult, moreover, to view the likely impacts of a change to the climate in the years 2025 or 2050 without using the conceptual framework and societal context of the 1990s. That is to say, we may find that the process of adaptation to climate change is much more automatic than we currently believed is likely, given the secular nature of climate change and the dynamic nature of social processes.

Despite these limitations this paper looks at a selected number of impacts of climate change on coastal and river systems. The emphasis here is on the impacts of climate change upon coastal defence and its standards, and on fluvial flooding and its impacts. We have the advantage of some results recently obtained from climate change modelling at the University of Oxford (Environmental Change Unit), which gives more detail about the regional and local impacts of global climate change than hitherto has been available.

7.2 Climate change and social responses

Individuals, groups and society as a whole are changing continually in response to external stimuli. Economic and political forces create pressures for change as instincts for survival dictate shifts in living styles, working patterns and institutional arrangements.

In this respect the 'threat' of climate change is no different from other threats which create the circumstances whereby organisations and individuals could prosper more by adapting their behaviour rather than seeking to maintain the status quo. Individuals will adapt their behaviour so as to minimise the losses that they might incur or maximise the advantage they might reap from that change (Table 7.1). Institutions may change so as to respond to new pressures, for example to different levels of investment or revenue. Government may respond by giving higher priority to the parts of its organisation that might be affected (be it river regulation or coastal zone management).

In this way we should see individuals and the agencies of government as resilient and responsive rather than fragile and vulnerable. Some change will and can be market driven, perhaps through increased or decreased insurance rates for flood damage affecting individual response to increased flood severity. Other responses need to be planned many years ahead (as in the case of new capital investment priorities).

Thus there is no need to think that any new framework is needed to analyse the impacts of climate change than the pursuit of sustainable development to which most governments now subscribe. What will be marginally different is the incorporation of notions and predictions of climate change within other social and environmental change such that this additional element - and the uncertainty inherent in it - is not neglected within the overall scene.

7.3 Coastal impacts: safety and recreational resources

One of the main impacts of climate change at the coast is likely to be through sea level rise. This does not rule out the effects of increased storminess, which will also threaten coastal defences (see Section 6.2.2), but the most obvious long term change is the increased level of the sea as a result of thermal expansion, glacier melting and ice-sheet depletion.

The latest predictions appear to imply that the likely rise in sea level between now and the year 2050 will be no more than approximately 0.5 to 0.75 metres, rather than the more extreme sea level rise predictions of several years ago (Penning-Rowsell and Fordham, 1994, Ch. 2). Nevertheless, locally these more modest sea level rises could have significant impacts at the coast, not least in terms of safety standards and the impacts that they could have on beaches (with the associated consequences for beach recreation and the function of beaches in protecting sea defences).

7.3.1 Warnings, safety and floods at the coast

Whilst not a recent analysis, Figure 7.1 shows the impact that quite modest levels of sea level rise could have on safety standards on the east coast of England (Coker *et al* 1989). What is shown in Figure 7.1 (that part showing the map of eastern England) is the number of times that safety standards have led to warnings being issued against flooding or other impacts from storm surges on the east coast between the years 1972/3 and 1988/9. This information was obtained from The Meteorological Office, which tracks the number of warnings issued by the East Coast Storm Tide Warning Service.

What this analysis shows, interestingly, is how sensitive this process of warning is to sea levels. An increase of only 0.2 metres in average storm surge heights raises the number of warnings issued per year from 112 to 446, a rise of about 300 per cent. The histogram in Figure 7.1 gives the results for Lowestoft, with a 0.5 m sea level rise. It is obviously likely that more extreme increases in sea level will have even greater impact. More detailed analysis is necessary to unravel the local effects of sea level rise on the safety standards and the impact of those effects in economic terms. This research is on-going and should be continued into the future.

7.3.2 Beaches and the impact on recreation

Beaches are highly sensitive to sea level states, and rapid increases in sea level could leave beaches behind, submerged, and result in foreshores depleted of beach material.

Yet these beaches around our coasts are of considerable value. They are valuable, first, for the protection they provide to sea defence works in the form of sea walls behind them, and many of our coastal urban centres are protected in this way, and could be threatened by quite modest increases in sea level resulting in depleted beaches and threatened sea defences. The extra cost of enhancing hard sea defence structures as a result of rapid depletion of beach material in front of them could be significant, although as yet we have no measure of the magnitude of this cost penalty.

What we also have to recognise, of course, is that beaches are also seen as important in terms of the recreational facilities that they provide. Table 7.2 gives the results in aggregate from beach recreation surveys undertaken by Middlesex University and reported in Penning-Rowsell *et al* (1992). What we can see from these results is that the magnitude of the value attributed by people to a day's beach recreation experience is high, and it should be noted of course that these figures have to be grossed up by the very large numbers of people using certain beaches around our coasts at peak times.

It is obvious that if one grosses these figures up over a year, and again over the lifetime of beach replenishment or enhancement works, then very large benefit totals will result. Indeed, much of the research reported by Penning-Rowsell *et al* (1992) indicates that the majority of coastal protection and sea defence works is to be justified in terms of the benefits of protecting beaches, which in turn protect sea defence and coast protection works.

The implications for climate change are that if beaches disappear or are seriously degraded as a result of rapidly increasing sea levels (and the consequent submergence or erosion of beach material) then there could be a considerable societal losses, if recreational patterns continue as they are now into the future (but see below).

7.3.3 Social response and overall national economic implications

The two impacts discussed above are intended to be more than simple illustrations of what could happen at the coast in the light of the IPCC reported changes in sea level consequent upon climate change. It is obvious, however, that there will be a social response during the process of climate change, and therefore the impact will be considerably less than might otherwise be the case if the change were rapid and dramatic.

As far as safety standards are concerned, the social response is likely to be to seek to raise defence standards to anticipate or respond to increased sea levels, or to abandon areas at excessive risk. The former is already happening, and (probably) at marginal increased costs. Comparable results for the Netherlands, where the impact of sea level rise could be much more catastrophic, indicate that the extra cost of raising sea defences in this way is relatively minor in relation to both the benefits obtained and levels of existing gross national product (Penning-Rowsell and Fordham, 1994, Ch. 5).

The situation in Britain is complicated by the fact that the replacement of much sea defence works protecting agricultural land is not likely to be cost-effective in any case. The increase in sea levels will make the recognition of this more dramatic and unanswerable, but it will not alter the economic analysis. Protecting even high grade agricultural land from sea flooding or erosion is in many circumstances not likely to be worthwhile while the current agricultural regime of over production continues. There already needs to be a process of change in expectations with regard to these low lying agricultural areas (principally in Suffolk and Essex), whereby abandonment (or "managed retreat") is practised on a large scale or anticipated in plans to be implemented over the next fifty years.

In similar vein, the nature of beach recreation may well change over the next 50 or 60 years. With increased exposure to ultraviolet radiation threatening increased level of skin cancer it seems unlikely that current or historic levels of beach recreation will continue into the future. Admittedly there will be a short term reaction in terms of more regular and extensive applications of anti-sun lotions, but it is also likely that there will be a more fundamental change in coastal recreation practice, towards indoor recreation experiences (either at the coast or elsewhere) simulating previous outdoor environments and activities.

Thus if southern Britain becomes to resemble southern France or northern Spain in the next 50 years (as indicated could be possible by Clayton *et al* (1995)), then it appears unlikely that we will see the kind of mass beach-based recreation on the south coast of England that has been the case in the past. We are more likely to find many more people frequenting covered swimming facilities and areas where exposure to sunshine is controlled, rather than the 'free and easy' approach that we have adopted in the past.

All this indicates that the process of social change will go on at the same time as climate change occurs, thus complicating the assessment of its full impacts. A national economic impact will nevertheless come from the need for a different pattern of investment in sea defence works, where this can be justified (and more work needs to be done to show whether on balance this leads to a net increase in investment or a net decrease). In any case, however, the level of extra expenditure is unlikely to be serious in terms of the impact on the national economy.

More fundamental could be the impact of a more continental climate on Britain's coastal areas. We may see fewer people travelling abroad for sunshine-based holidays, preferring instead once again to go to Bournemouth or Clacton (or indoor facilities located anywhere), thus making some inroads into the adverse balance of payments of £4.5bn per annum from imported and exported tourism (Department of Transport, 1995). The response of Bournemouth and Clacton is likely to be an increased level of private sector investment, and a beneficial impact therefore on the nation's balance of payments. In terms of the recreation resources provided at the coasts in Britain, the big economic players who can afford major new facilities are likely to be the 'winners', whereas the smaller resorts who cannot adjust in this way may be the 'losers', thus continuing a trend we see today. Much will depend on the process of change in recreational activities over the next 50 - 60 years and these in turn will be affected by personal mobility, the cost of overseas travel, the perceived cost penalties from congested locations, and the nature of the whole leisure marketplace.

The implications for investment in coastal defences is the possibility of modest extra resources being needed to counter the increased threat, although it is just as likely that these needs will not change significantly owing to the reduced need to renew defences for open agricultural land. It is certainly not clear that a dramatically higher level of investment will be needed in the future than in the past, and in that respect the results shown in Figure 7.1 should not be taken as indicating necessarily the need for major new investment programming.

7.4 River management and floods

Relatively little information has been available up until now on the impact of climate change on fluvial flooding. The scale of climate change analysis has been too small (i.e. the areas covered have been too large) for predictions to be made at a catchment level - at least at the size of catchments in Britain - about the impact that climate change may have on fluvial flooding regimes.

Nevertheless, recent results from modelling at the Environmental Change Unit at the University of Oxford have provided some insight into this problem, although these results are still at a European scale (Downing *et al*, 1995).

7.4.1 Rainfall/runoff predictions

Figure 7.2 gives the results for precipitation change between the baseline period of 1961-90 and the year 2050. Figure 7.3 shows similar information for runoff (in effect this is overland flow but is probably a good surrogate for river runoff at this scale). There are some inconsistencies between the two in that the prediction of change in runoff shows a more complex pattern, particularly in the area of northern Germany and northern France, whereas the change in precipitation is a simpler pattern oriented more to latitudinal stratification rather than anything more complex.

Nevertheless, these predictions show quite significant increases in precipitation and runoff for northern Europe, including most of the United Kingdom, and significant decreases in precipitation and runoff in southern Europe. Figure 7.4 gives insight into the seasonality of the precipitation change between the baseline period and the year 2050. This shows that the majority of the increase in precipitation is to be found in winter, whereas in the summer there is a net decrease in precipitation in all areas except the more northerly European regions.

These results have implications for rivers and river management in northern Europe, including the United Kingdom. We can anticipate that those rivers which are most seriously affected by floods generated from precipitation events resulting from Atlantic frontal systems will see an increase in flood severity or frequency (or both). In southern Europe there will be a diminution in flood severity and frequency, except if increased storminess (despite decreased rainfall totals) results in more severe local thunderstorm events creating the kind of southern Europe flood event that can result in catastrophic damage in these areas. We have no details about this storminess or thunderstorm phenomenon.

7.4.2 *Sensitivity of flood-vulnerable areas*

What it is important to recognise, moreover, is that the catchments which are likely to be adversely affected in northern Europe have areas which are highly already sensitive to flood impacts. Table 7.3 gives the results for the lower Thames catchment between Datchet and Teddington, the investigation for which was carried out by Sir William Halcrow and Partners (1992). A change in flood level of just 10 centimetres for the 101 year event increases the event damage by 30.4%, and the capital sum justifiable to spend on flood alleviation to this standard by 50.6%. If the increase in flood severity indicated by Figures 7.2, 7.3, and 7.4 result in marginally increased flood levels of the kind indicated in Table 7.3 then the extra severity of these flood impacts could be quite important. However, one must recognise that there are many uncertainties in these predictions.

An important point also has to be made here is about the type of climate change that we are likely to experience. If it is the major events that are those most affected (i.e. the 50 or 100 year flood), then the impact on the annual average damage figure is likely to be quite small. However, if climate change results in a change in the thresholds of flooding (and therefore the frequency and severity of the 2, 5 and 10 year events), then this will have a major effect on annual average damages and therefore the worthwhileness of flood alleviation investment. It is unclear, yet, which aspect will be the most important, but as far as policy and national economic impacts are concerned this will be much more severe if the smaller and medium sized flood events are increased; the impact of the major events is much less important.

On the other hand, if the major events are increased in severity or frequency (or both) then this could have a significant impact on the insurance industry. If we get many more disastrous floods (comparable to 1947 or 1894 on the Thames) then the impact on the retail insurance industry (and indeed on the more global re-insurance industry) could be significant. And it is likely that the timing of this impact cannot be anticipated because the incidence of these more major flood events cannot be predicted in time.

We do not yet have a regional scale view of these impacts of floods consequent upon climate change in Britain. However, an analysis has been done for the Seine Basin in Northern France which may not be dissimilar to the circumstance in Britain. Tables 7.4 and 7.5 gives these results for the Ile de France area (Garner and Green, 1994), which give a different type of result from those obtained for the lower Thames. The Ile de France results suggest that increases in the severity or frequency of major events will not be very serious; the increased damage potential from quite significant increases in flood levels at the greater flood depths are not large. However, increases in the flood levels near the threshold of flooding are quite significant, and once again these could be the major impacts for climate change that could have serious economic impacts.

7.4.3 *Social response and overall national economic implications*

It is difficult to predict the effect of these changes in fluvial flood frequency, not least because of the uncertainty concerning the climate change results. Nevertheless, if those results are accurate we could see the need for increased levels of investment in fluvial flood protection, if flood protection standards are to be maintained. These changes could be quite significant if climate change alters the frequency and severity of small and medium size flood events; they are likely to be less important if they affect mainly the major events.

However, there may be a process of social adaptation to increased fluvial flood frequency. If areas traditionally relatively free from flooding become regularly flooded then these areas may be abandoned as far as urban development or uses concerned, as the population 'takes to the higher ground'. This process is likely to be relatively episodic, since the incidence of major or even medium sized events is sparse. Nevertheless, it must be recognised that some areas may come to be abandoned rather than protected as a result of increased flood frequency. This will particularly be the case with isolated residential developments rather than major urban centres (which are likely to prove cost effective to protect).

There may be an effect on insurance claims, particularly as more and more people become insured for flood damage (and the trend is in this direction). What we cannot anticipate, however, is the institutional change that climate change may drive. If, for example, water management becomes more precarious in Britain as a result of climate change (or other political processes), then the structure and organisation of river management and flood alleviation may also have to change in parallel. These are the kind of predictions that are difficult to make, but it could be that there is greater emphasis on river management in the future as a result of the dual processes of increased drought and increased flooding, and this could promote a change in institutional arrangements and policy frameworks.

7.5 Assessment: the implications

Climate change will affect the United Kingdom quite significantly in many ways. Probably the most important impacts will be on recreational patterns and behaviour, but these are already changing at the coast. There could well be a massive retreat from coast-based recreation, while at the same time a retreat also from overseas sun-based holidays. The implications would be that coastal resorts as we know them will disappear, as more indoor based recreational patterns will predominate.

Another implication of climate change will be investment in flood alleviation at the coast and for fluvial environments. It is not at all clear that investment will need to rise substantially, since social processes of adaptation may minimise the increased vulnerability. The need for capital expenditure to renew our coastal defences of agricultural land will decline over time, also, and this will affect net investment levels.

What we should be doing is not worrying about the overall national economic effect (which on balance looks to be positive (see Table 7.6)) but promoting the kind of changes in individual behaviour patterns that will safeguard people's health in the new climatic regime.

7.6 References

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Table 7.1 Climate change impacts: social responses

Individual adaption
• Modifying coastal recreation patterns and behaviour • Response to floods: abandoning property; increased insurance; individual flood proofing; etc And: ♦ Individuals within society should be seen as resilient and responsive, not fragile and vulnerable
Institutional policies and policy change
• Flood plain occupance more tightly controlled • Warning systems enhanced (responding to greater uncertainty) • Precautionary approaches taken to the design of fixed investment projects And: ♦ Sustainable development remains the policy framework; dealing with the uncertainty inherent in climate change is the challenge
Institutional change
• River management reorganisation to counter perceived increased threats • Coastal Zone Management changes to respond to changed assumptions about the nature of coastal resources and threats And: ♦ Managing the environment is a political activity and institutional change is one of major vehicles used by governments to respond to external pressures (such as climate change)

Table 7.2 The value of recreational uses of beaches (from Penning-Rowsell et al 1992, Table 4.1a)

Site location and year of study	Value of a day's recreational visit (value of enjoyment measure) [£/day, rounded to nearest £]
Scarborough (1988)	5
Clacton (1988)	10
Dunwich (1988)	7
Filey (1988)	4
Frinton (1988)	10
Hastings (1988)	8
Spurn Head (1988)	7
Bridlington (1989)	6
Clacton (1989)	11
Hunstanton (1989)	9
Morecambe (1989)	6
Herne Bay (1990)	12

Table 7.3 The impact of increasing flood depths by 100mm for the Datchet to Teddington river Thames floodplain

	101 year flood			204 year flood			PMF*
	Properties affected	Event damage (£M)	Capital sum (£M)	Properties affected	Event damage (£M)	Capital sum (£M)	Capital Sum (£M)
A. +10cm	11,576	64.3	34.8	13,578	103.8	41.4	51.1
B. Best estimate	10,447	49.3	23.1	12,435	85.4	30.2	38.1
C. A/B (per cent)	10.8	30.4	50.6	9.2	21.6	37.1	34.1

* Probable Maximum Flood

Table 7.4 Stage/damage results for the Ile de France case study sub-areas (£000s event damages)

Flood depth (m)	Paris V	Ivry	Gournay	Villeneuve-la-Garenne	Geunevillers	Villeneuve-St. Georges	Vitry
0	0	0	0	0	0	0	0
0.5	83	5	1	27	14	32	16
1.0	670	47	7	240	210	240	140
1.5	1,200	160	23	570	1,100	390	440
2.0	1,400	320	51	910	2,000	450	1,500
2.5	1,500	520	80	1,100	2,700	520	5,200
3.0	1,600	918	120	1,300	3,200	850	8,300
3.5	1,600	1,400	140	1,400	4,100	1,100	9,300

Table 7.5 Incremental increase in flood damage with increased flood stage (percent: see Table 4)

Flood depths (m)	Paris V	Ivry	Gournay	Villeneuve-la-Garenne	Geunevillers	Villeneuve-St.Georges	Vitry
A. 1.5 to 2.0	17	100	122	60	82	15	241
B. 2.0 to 2.5	7	63	57	21	35	16	246
C. 2.5 to 3.0	7	76	50	18	19	63	60
D. 3.0 to 3.5	0	53	17	8	28	29	12

Table 7.6 Possible national economic impacts of climate change in coastal and fluvial environments

Negative
Increased investment costs: •Flood alleviation •Coast defence •Port facilities, etc
Positive
Balance of payments gains: •Reduced British tourist outflow •Increased foreign tourist inflow

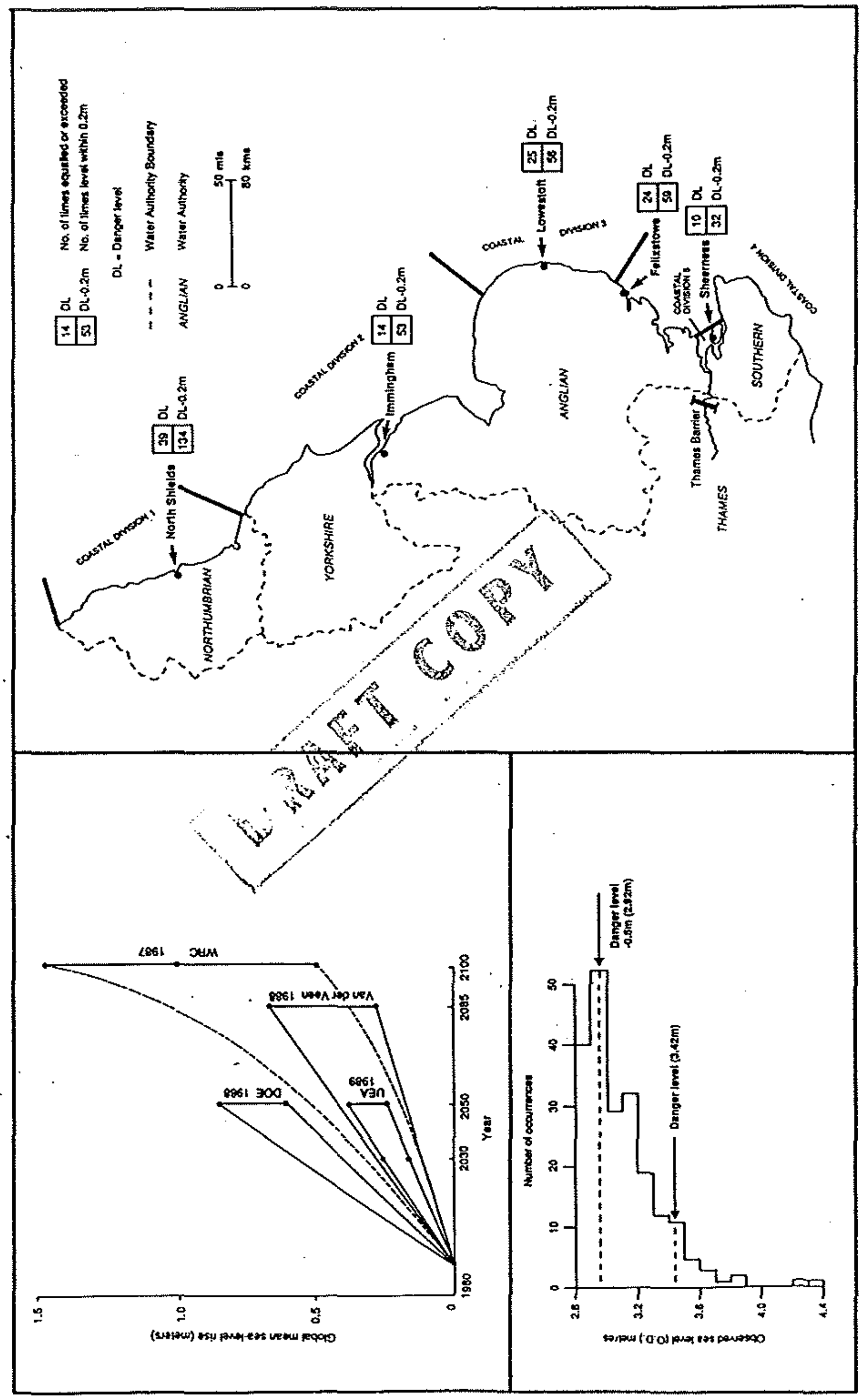
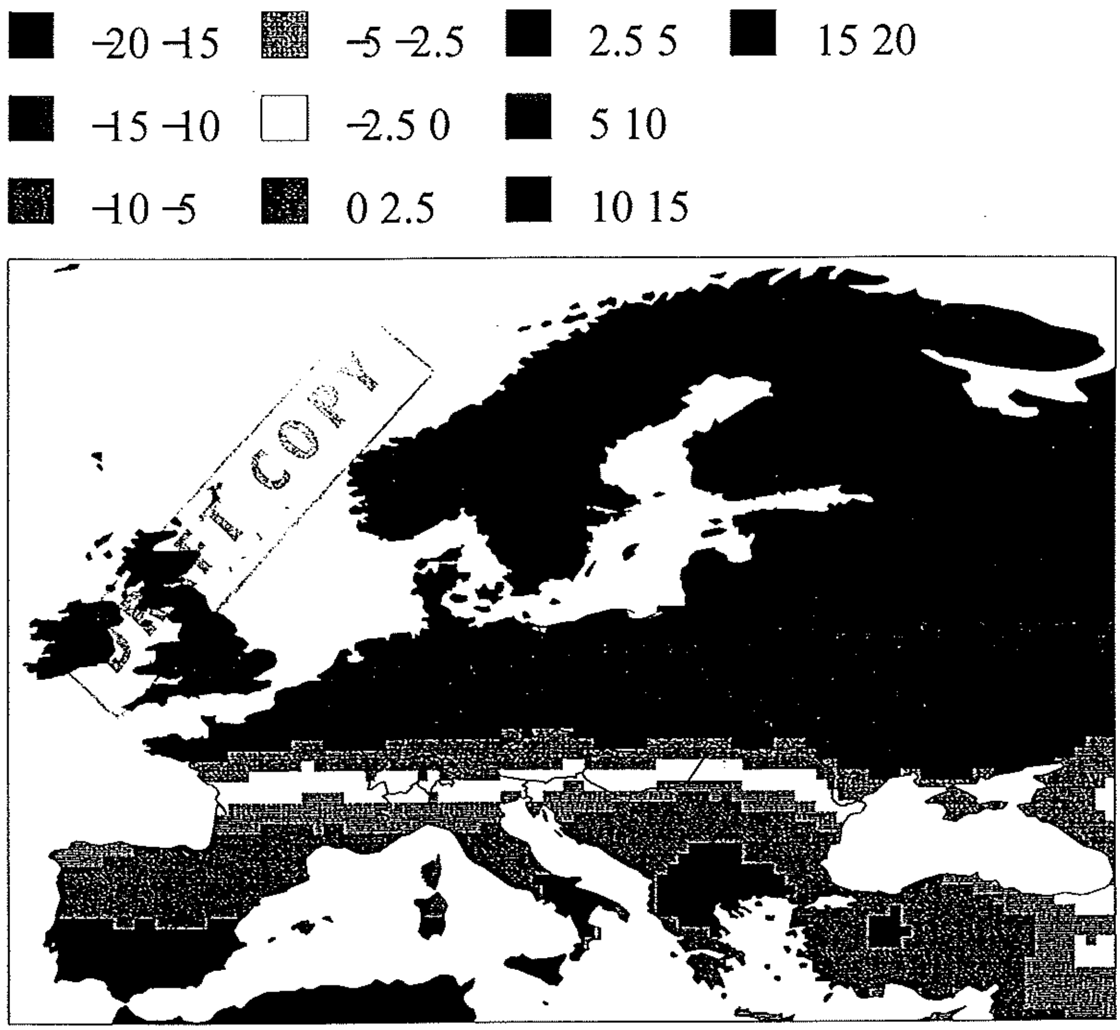


Figure 7.1 Changes in the frequency of East Coast flood warnings as a result of climate change induced sea level rise (from Coker *et al* 1989)



The difference in mean annual precipitation between 1961-90 and the year 2050 (percent)

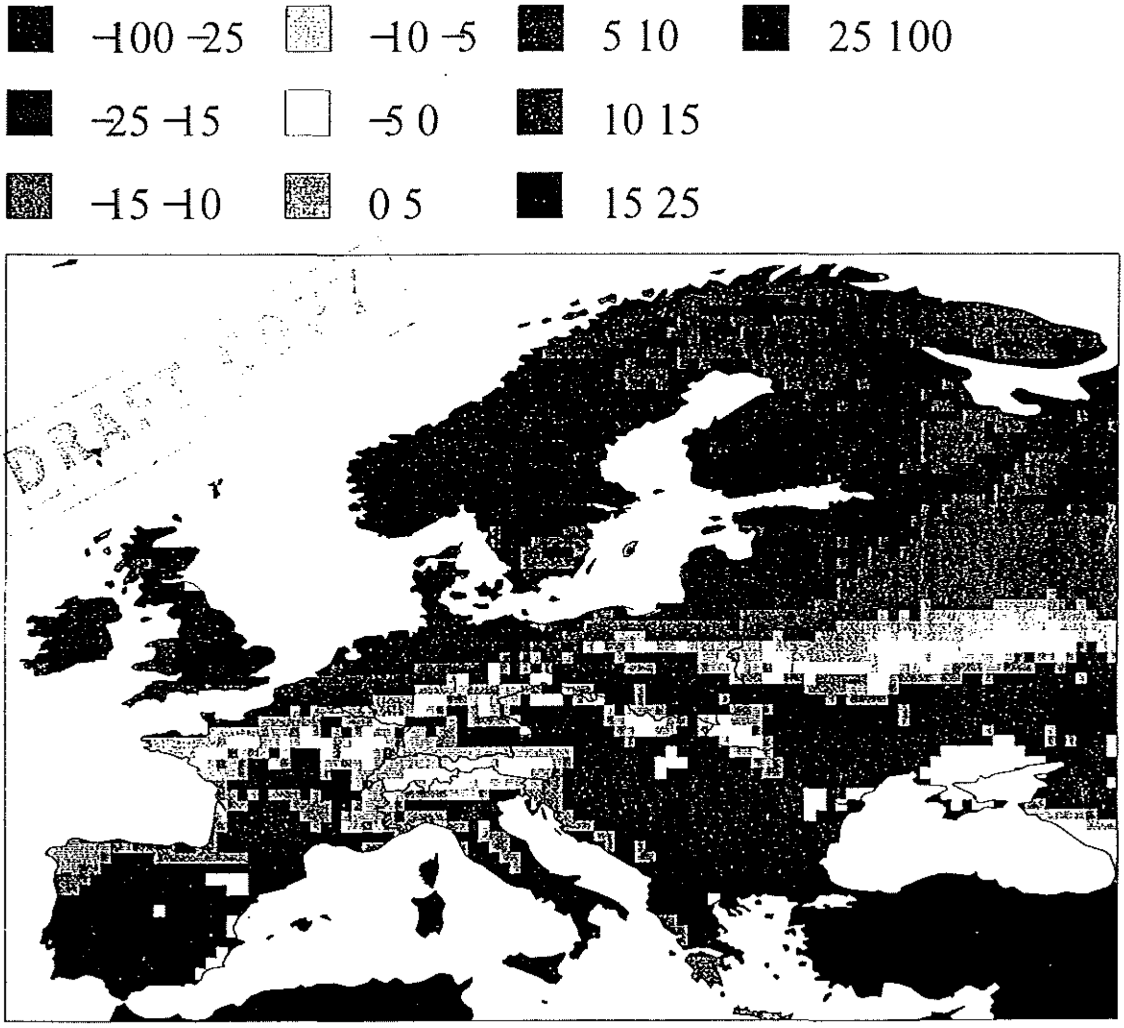
Max: 18.97

Mean: 5.15

Min: -17.01

Prepared by ECU

Figure 7.2



The difference in average runoff between 1961-90 and the year 2050 (percent)

Max: 109.05 Mean: -3.44 Min: -100

Prepared by ECU

Figure 7.3

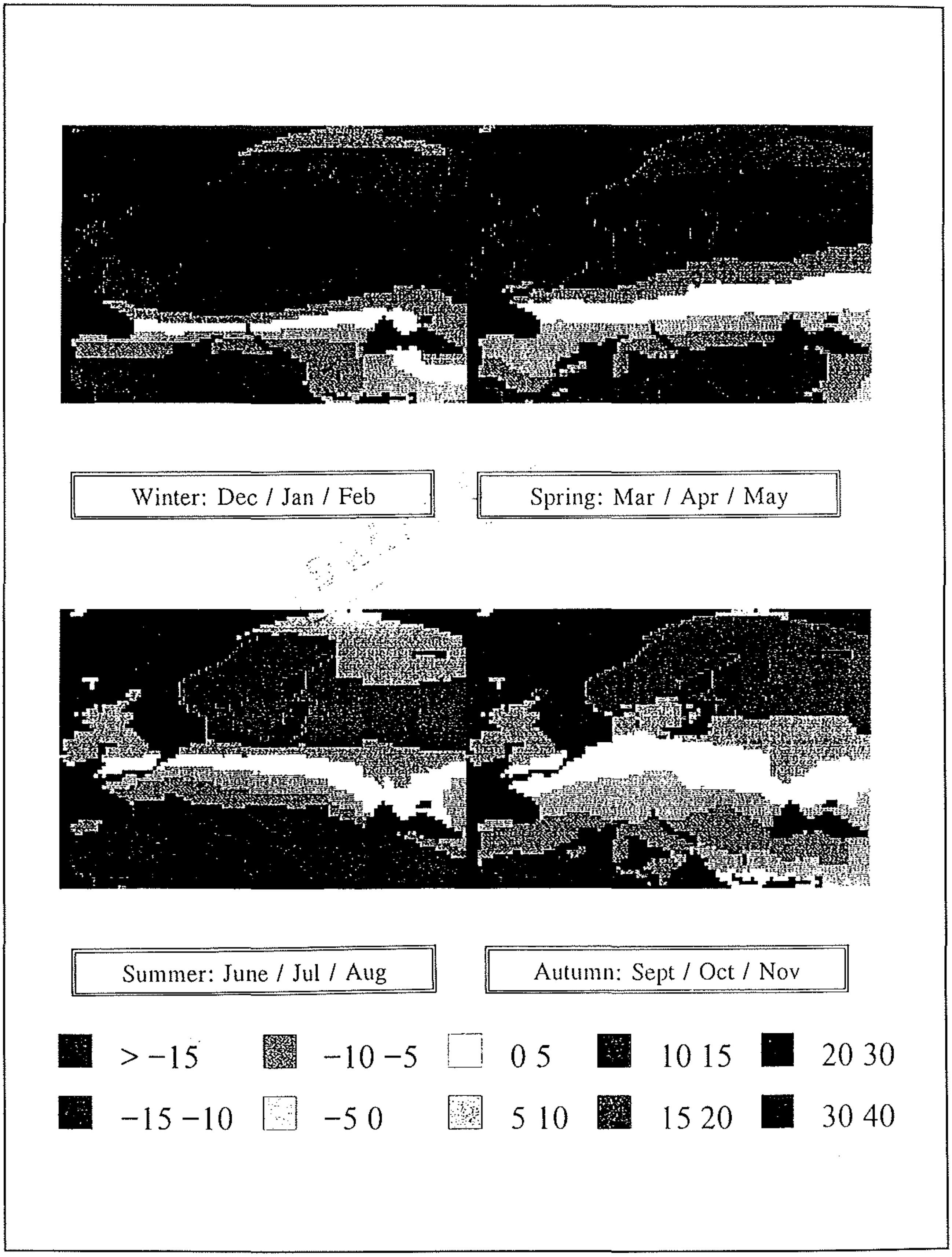


Figure 7.4 The seasonality of the precipitation change between the baseline period and the year 2050

8 Research priorities and discussion

8.1 Process

The participants to the workshop on 16 November 1995 took part in a brainstorming session to identify research needs and priorities. Although some formal structure was imposed on the generation of ideas in the form of topics, opportunity was given to capturing any ideas which could be relevant to the project. After generation, the ideas were sifted for meaning, duplication, and appropriateness. The latter included guidance from the MAFF representatives on any topics which although pertinent lay outside the scope of MAFF Flood and Coastal Defence Division R&D funding. Ranking the ideas within each topic was carried out by asking each person present to chose the most important ideas, with each person having between about 6 to 10 votes depending upon the number of ideas in the topic. There was no cross-reference to the theme papers during the brainstorm and thus it was not guaranteed that the authors picked up the all the topics identified in the texts presented in Sections 2 to 7 above. An attempt has been made to do this in Section 8.7 below.

The raw results of the brainstorming are given in Appendix 2. This consists of the agreed wording of each idea (with any later explanation contained in brackets [....]) and the score for that idea. The list have been divided to show high, medium and low categories. The high category comprises those ideas whose combined score equalled or exceeded one third of the votes cast. The division for the medium category has been set to the next third of the votes cast. Thus in the low category the combined number of votes is at most one third of those cast. The divisions between the categories has been set at a change in the number of votes between ideas. Obviously the voting represents the opinions of those present at the meeting as does the selection of ideas and hence the results of the brainstorming should not be treated with undue rigour. However, it is hoped that the important issues will have been identified.

Several themes may be identified in the results of the brainstorm. These are as follows:

- The need to consider complex systems with interactions rather than individual processes
- The need to support decisions in the context of uncertainty which is difficult to quantify
- The need to make best use of existing information and monitoring of past events
- Risk

8.2 Model development needs

The research needs which are discussed below are taken from the Brainstorming Topic 2, See Appendix 2.

The overall impression of the participants was that the main need for model development lay in systems representation rather than development of individual process models. The key areas for model development identified in the brainstorming are as follows.

Topic C1 Modelling "whole" system

The need is to be able to predict the effects of changes in the climatic forcing and consequent human adaptations on say, river water level and its frequency. It is likely that two or three whole system models might be needed to cover river, estuarine and coastal conditions.

Topic C2 Modelling the decision processes and its resilience to uncertainty

The important factor to capture is when the design of a flood or coastal defence scheme would take a radically different course if the forcing climate data were to be different. The change in course may be forced through technical, economic or environmental effects. A model of the decision process will incorporate a whole system model (Topic C1). A similar topic on coping with uncertainty also scored highly in Brainstorming Topic 4 on Design Methods (See Appendix 2).

Topic C3 River and coastal morphological modelling

Morphological responses to climatic change may be difficult to combat and will depend upon the interaction of several processes. Research is currently in progress on the development of river morphological models associated with the EPSRC Flood Channel Facility programme and for the coast associated with the Coastal Research Facility, CAMELOT and MAST programmes. An important step will be the integration of the results of this existing research with predicted future climatic conditions as a component of a whole system model (See Topic C1).

8.3 Impact assessments

The research needs which are discussed below are taken from the Brainstorming Topic 3, See Appendix 2.

The main thrust of the higher priority topics is the need to evaluate the impacts of climatic change on society as a whole especially for "extreme" events. There is a need to distinguish between natural variability, impacts of changes in land use and the effects of climatic change. This was seen to be a particularly difficult issue to resolve. In one way the overall level of "extreminess" and change from all sources is what is of key importance since this produces the baseline for societal adaptations. However, the contributions from climatic forcing and other anthropogenic changes is important if the adaptations are directed at modifying the incidence of river and coastal flood events.

The following research topics are intended to encapsulate the highest rated topics from the brainstorming session.

Topic C4 Distinguishing the effects of climatic change

An important difficulty in assessing the effects of climatic change is determining what the conditions would be like with stationary climatic conditions but with any other anthropogenic changes still in place. There is of course the possibility that this condition is unrealistic if there is feedback between say changes in land use and the local or regional climatic conditions. However, the effects of climate change must be assessed against some baseline and these baseline conditions may be time dependent, for example the crustal movements affecting relative tide level around the UK coastline discussed in Section 4 above. A further related aspect of this topic is how to interpret the output of GCMs for assessment at the catchment or coastal cell scale which both tend to be smaller than the typical GCM grid scale (technically called down-scaling), See section 3.6.

Topic C5 Assessing extreme conditions

Flood defence infrastructure is typically designed for the "once-in-a-lifetime" or a less frequent event. Hence the prediction of extremes is of particular importance in the current design and assessment methodology in the flood defence sector. The research in this topics should include:

- identification of extreme possibilities - are the conditions which will generate an extreme event in the future qualitatively different from those which have occurred in the (recent) past.
- assessing extreminess - how do the extremes for design purposes compare with the mean and variability of more frequent conditions
- identification of appropriate statistical models and methods to generate the statistics for the future climate and climate impacts, a subject which occurred also in the Brainstorming Topic 4 on Design Methods (See Appendix 2).

Topic C6 Economic and financial aspects

Adapting to the effects of climate change will require use of renewable and non-renewable resources and may require changes in the human use of land. There will be winners and losers from the effects of climate change and the question is how should the impacts and any flood defence mitigations be valued and any necessary changes be financed. The Brainstorming Topic 4 on Design Methods (See Appendix 2) also highlighted the evaluation of future costs and benefits as an important issue. Presumably the implicit assumption is that benefit-cost analysis will continue to be a major tool in project appraisal. Perhaps the implicit concern is that the decision made "today" should also be seen to be correct in the future. Important questions are whether future costs and benefits should be discounted fully and how future generations will value the factors included in the economic assessment. Coupled to this topic are the underlying issues of inter-generational equity, resource auditing and valuation of natural capital which were identified in the Brainstorming Topic 4 on Design Methods (See Appendix 2).

Topic C7 Regional variations

The current indications are that the flood defence impacts of climatic change will vary regionally around the UK both for coastal defence and river flood defence. Hence research should be undertaken to assess the impacts of climatic change regionally in the UK rather than for the country as a whole.

8.4 Design methods

The research needs which are discussed below are taken from the Brainstorming Topic 4, See Appendix 2.

The highest priority topics from the brainstorm did not cover different methods of design but focused on the means of assessment of schemes. As in model development needs the issue of coping with uncertainty in the design process was highlighted (See research topic C2 in Section 8.2 above). Likewise the need was identified to develop the appropriate statistical framework for the design decisions, which is covered in reserach topic C5 in Section 8.3. Amongst the medium scoring topics were possible societal adaptations for providing flood defence - non-structural methods, public participation and information, and insurance needs. These could form a combined research project if later consideration indicates priority for investigating this area of social responses. The other new high scoring topic was as follows.

Topic C8 Total risk assessment

Total risk assessment is already being used in areas outside flood defence and MAFF and the NRA are jointly sponsoring research on this topic for coastal flood defence structures. Risk assessment considers all the possible failure modes of a flood defence system and attaches probabilities to each. It appears to have potential as a robust decision aid in assessing the standard of flood defences in the context of non-stationary climatic forcing. However, the adoption of risk based design and assessment by the river and coastal engineering profession is likely to require institutional and organisation change including investment in human resource development by consultants and the NRA, and a change in the recommended project appraisal procedures.

8.5 Monitoring

The research needs which are discussed below are taken from the Brainstorming Topic 5, See Appendix 2.

Monitoring parameters such as wave climate or river flow will provide a means of establishing whether the frequency of their extremes is changing and so validate or disprove the predictions of impact assessments. However, perhaps the most surprising result of the brainstorming on all topics was that three of the four highest scoring topics under monitoring related to existing information and sites rather than new monitoring sites, methods analysis etc. Perhaps this confirms the discussions earlier in the day of the need to understand developments over the recent past (say 100 years) as a means of detecting the effects of climate change (see for example the recommedation for hindcasting wave conditions in Section 4.4.2 above). Also one other surprising factor identified in the middle third of the voting was the need to record event date information. Perhaps this is a reflection on past generations not realising the future value of information collected for other purposes and losing what later appears as crucial information. A standard for strategic monitoring embracing such factors should be relatively inexpensive to develop and implement. Of all the physical parameters mentioned within the brainstorm, most votes were cast for monitoring of wave conditions and this seems prudent given the sensitivity of coastal defences to relatively small changes in wave climates identified in Section 6.2.2.

Topic C9 Data archiving

Much useful data is not readily available for use in reconstruction of historic conditions since it is held on paper rather than in electronic form. Hence effort should be directed at the computerisation of old records. Also a national data archive should be established (should this replace the archives held at POL, IH, the Met Office, NRA regions etc?). Perhaps an alternative would be knowing who holds what information where and enabling free access (ease and cost) for research purposes at least. Other issues not raised in the discusions but perhaps implied are on the ownership of data (particularly data gathered by publicly funded bodies) and the value to flood defence research of data collected for unrelated purposes - such as wind records at coastguard and RAF stations.

Topic C10 Site selection
Future investment in data collection should be made where the data will yield the maximum information. Criteria need to be developed for site selection for key data types and due emphasis put on maintaining length of record. Homogeneous long-term records are essential in assesing trends in the monitored parameters such as may be produced by climatic change.

8.6 Dissemination

Dissemiation of the research results were covered in Brainstorming Topic 3, See Appendix 2. These have been subsequently categorised as relating to

ease of access
means of access
means of presentation
training and education
institutional and organisational factors

The participants in the workshop acknowledged the importance of dissemination of information from any research on climate change impact assessment and new project design and assessment methodologies. In many respects the issues involved are no different from those which surround the dissemination of current flood defence reserach into professional practice. The topic headlines could be of value to the review currently in progress in the MAFF Flood and Coastal Defence Division on the dissemination of research.

8.7 Discussion of other topics

The research needs which are discussed below are taken from the Brainstorming Topics 1 and 7, See Appendix 2 and from the subject papers in Sections 2 to 7 above. These topics were not subject to the peer voting procedure in the Brainstorming except for those in Topic 1 on impacts not covered in the technical presentations. In hindsight the highest rated topic - change in long duration events is related to research topic C5 on extreme events as is possibly the issue of interannual variability which was also scored highly.

Perhaps the most important issue identified in the Brainstorming Topic 1 was that of changes which were of such severity that adaptation would be difficult or impossible. This is reflected in the topic headlines of rapidity of change, dangerous levels of change and critical thresholds together with the specific example of global water circulation. The latter relates to the linkage between the climate and major ocean currents such as the Gulf Stream which causes the present anomalously warm climate in Northern Europe. The consequences of a change in this benign system of circulation are potentially catastrophic and extend far beyond just flood and coastal defence.

In Section 3.6, the issue is raised of empirical coefficients in engineering design formulae which depend upon the "average" climate and its variability. These will need to be identified and their use monitored. Examples include "no-data" hydrological estimates and the relationship of extremes to the mean of coastal wave heights and sediment transport rates.

The paper from POL (Section 4) identifies several research needs most of which are covered in the topics C1 to C10. However, it is recommended that there is monitoring of global, regional and local sea levels, and comprehensive analysis for trends in existing UK tide data. These topics are perhaps included in the discussion in Section 8.5 but emphasise the need to maintain record length at strategic sites and extract as much information as possible from the historic data which has been collected around the UK.

The paper from HR Wallingford (Section 6) identified that there has been little work done on the effects of changes in atmospheric pressures and wind conditions and the subsequent changes in waves and littoral drift. This again might be covered in a topic concerning learning from the past records. The need to possibly move away from design events based on historic records was also identified, and perhaps this could be incorporated into topic C8 on total risk assessment. Finally, a comment was made on introducing the notion of future proofing into the design of flood defence infrastructure which will allow future generations to adapt the flood defence systems if climatic change is more significant than currently anticipated. Perhaps this could form part of topic C2 on decision and design in the context of uncertainty.

The paper from the Flood Hazard Research Centre (Section 7) identified the need to consider changes to storminess and thunderstorms. This is partly associated with the issue of developing sub-grid scale information from the GCM results and could for part of topic C5 on extreme conditions. The paper also identified the need to consider societal responses to adapt to changed flood risk. These include changes in the organisation and mangement of flood and coastal defence activities and promoting individual behaviour patterns which will safeguard peoples health in a new climatic regime.

8.8 Summary of research needs

Ten topics (C1 to C10) have been identified from the brainstorm together with some others gleaned from the discussion papers. These will need to be organised into a coherent programme and assessment units. The research will require cross-institute cooperation and so will require some form of steering or management group to monitor progress and facilitate communication between the different elements of the programme. The research topics can be divided into two main themes:

Project Appraisal and Procedures

Modelling the decision process and its resilience to uncertainty (Topic C2)
Design in the context of uncertainty (to include future proofing, review of empirical formulae, etc)
Assessing extreme conditions (Topic C5)
Economic and financial aspects (Topic C6)
Total risk assessment (Topic C8)

Past and Future Impact assessment

Modelling whole systems (Topic C1)

River and coastal morphological modelling (Topic C3)
Distinguishing the effects of climatic change (Topic C4)
Regional variations (Topic C7) (but could be included as part of C4)
Data archiving (Topic C9)
Site selection for monitoring (Topic C10)

The next step should be to examine the research currently proposed by other funders (eg Research Councils, NRA, DoE and the EU) to draw up a managed 0programme of complementary projects which will meet the medium and long term policy needs of MAFF and add value to work funded elsewhere.

Appendices

Appendix 1

Workshop participants

Appendix 1 Workshop participants

David Richardson (MAFF)
Tony Polson (MAFF)
John Goudie (MAFF)

Nick Reynard (IH)
Duncan Reed (IH)

Graham Alcock (POL)*
Roger Flather (POL)

Prof Edmund Penning-Rowsell (FHRC)

Nigel Arnell (University of Southampton)

Alan Brampton (HR)
Peter Hawkes (HR)
Paul Samuels (HR)

* invited but unable to attend

Appendix 2

Brainstorming session outputs

Appendix 2 Brainstorming session outputs

Brainstorming Topic 1 - Any Impacts not covered in Technical Presentations

Topic	Score
Higest Rated	
Change in long duration events and their consequences, [eg Chichester, surge duration]	10
Inter-annual variability	8
Rapidity of change	8
Medium Rated	
Critical thresholds	7
Dangerous levels of change	5
Drought impacts on floods/drought and flood periods	5
Lowest Rated	
Links between flooding and conservation	4
Atmospheric pressure	4
Global water circulation	4
Impacts upon flood warning	3
Geological change caused by sea level rise	2
Seismic events	0

Brainstorming Topic 2 - Model development

Topic	Score
Highest Rated	
"What-if" scenarios for complete system - a "super model"	10
River and coastal morphological modelling	9
Modelling the decision process and its resiliance to uncertainty	9
Medium Rated	
Total risk modelling	8
Better techniques for detecting trends and variability	7
Sub grid scale modelling	6
Lowest rated	
Models for flood generation	5
Investigating specific events	5
Models to explain changes in wave direction	4
Responses of individuals to climate change	2
Development mapping	2
Non-linear interactions	2
Better climate models	X
Better resolution	X

X = Outside of remit for MAFF flood defence R&D and thus excluded from the scoring.

Brainstorming Topic 3 - How to use GCM data, scenario testing and impact assessment

Topic	Score
Highest Rated	
Distinguishing land use and climate changes	7
Economic and financial aspects	6
Regional variations	6
Assessing "extreminess"	6
Extreme possibilities	6
Generating statistics for future climate and future impacts	6
Medium Rated	
Sensitivity to prescribed changes	5
Down-scaling	5
How to establish the moving baseline	5
Identification of monitoring sites	5
Lowest Rated	
Impacts or adaptation	3
How to assess credibility [of predictions]	3
Past analogues	3
Hindcasting	3
Distributional effects	2
Source contol of run-off	0
Man's interference with climate affecting GCMs [eg cloud seeding]	x
Disproving GCMs	x
Confidence limits of GCMs	x
Effects of atmospheric pollution controls	x
Anything else forgotten [from GCMs] (eg aerosols in 1990)	x

x = Outside of remit for MAFF Flood Defence R & D and thus excluded from the scoring

Brainstorming Topic 4 - Design Methods

Topic	Score
Highest Rated	
Coping with uncertainty	9
Total risk assessment	7
Evaluation of future benefits and costs	6
Appropriate statistical methods	6
Medium Rated	
Non-structural methods	5
Impacts of flood defence on climate change including energy audit	5
Validation	4
Uniformity [of design standard across UK]	4
Public participation and information	4
Lowest Rated	
Insurance needs	3
Impacts of flood defence on flood levels	3
Failsafe design	2
Resource auditing	2
Active vs passive defence	2
Changes in hydrological regions	2
User acceptance	2
Design standards for urban drainage	2
Intergenerational aspects	2
Valuation of natural capital	2
Defining long-term	2
Scheme maintenance	2

Brainstorming Topic 4 - Design Methods, Continued

Topic	Score
The viability of expert systems	2
Safety factors [eg increase freeboard]	1
Flexibility [of design]	1
Timing of construction	1
Changing standards	1
Post project appraisal	1
Emphasising benefits	0
Role of private sector	0

Brainstorming Topic 5 - Monitoring

Topic	Score
Highest Rated	
Computerising old records [ie digitising paper copies]	8
National data archive	8
Maintaining length of record	7
Site selection	7
Medium Rated	
Waves	5
Event date information	5
Post-scheme monitoring	4
Human response to flooding	4
Lowest Rated	
Beach condition and use	3
Signal and noise	3
Recording storm effects	3
Land movements	3
Remote sensing	3
Actual flood loss assessment	3
Social and recreational changes	3
Accuracy of extremes	2
Data homogeniety	2
Indicator species	1
Height of defences	1
Monitoring river plan form	1
Intergrated event data	1

Brainstorming Topic 5 - Monitoring continued

Topic	Score
Sampling periods	1
International standardisation	1
Selling data for profit	0
Money [to pay] for data collection	0
Habitat migration	0
[Whose] responsibility [to collect data]	0

Brainstorming Topic 6 - Dissemination and access to data

Topic	Category
Freedom of information	E
Public domain data	E
Use World Wide Web	E, M
CD-ROM	E, M
Gossip	M
Software	E, M
Project appraisal guidance notes	M, I
Handbooks	M
Newsletters	M
Conferences and seminars	M, T
Institutional examinations	T
Continuing professional development	T
Teaching	T
Lessons from failures	T
Better presentation of statistical results	P
Data is not information	P
National and local media	P
Professional publicists/lobbyists	P
Consultation	P
Lessons from other disciplines	P
Policy change	I
Educated client	I
Not the lowest priced tender	I

E - Ease of access
M - Means of access
T - Training & Education
I - Institutional / Organisational
P - Means of presentation

Brainstorming Topic 7 - Anthing else missed

Topic	Category
Land instability	F
Demographic change	F
Limited resources	F
Studies of collective risk	A
Integrated assessments	A
Alternative institutional approaches	R
New technologies	R
Partner organisations	M
Technology transfer	M
Choices	V
Quality of life	V

V - Social values
A - Assessment types
R - Alternative responses
M - Methods for research/working
F - Factors & processes