Marine Biodiversity and Climate Change

Assessing and Predicting the Influence of Climatic Change Using Intertidal Rocky Shore Biota

Final Report for United Kingdom Funders

N. Mieszkowska*, R. Leaper*, P. Moore*, M. A. Kendall[†], M. T. Burrows[#], D. Lear*, E. Poloczanska[#], K. Hiscock*, P.S. Moschella*, R.C. Thompson[¶], R.J. Herbert[ǂ], D. Laffoley[§], J. Baxter[‡], A. J. Southward* & S. J. Hawkins*

The Marine Biological Association of the U.K.*
Plymouth Marine Laboratory[†]
The Scottish Association for Marine Sciences[#]
University of Plymouth[¶]
Medina Valley Centre, Isle of Wight & Bournemouth University[ǂ]
English Nature[§]
Scottish Natural Heritage[‡]

December 2005

MarClim Research undertaken by:

The Marine Biological Association; The University of Plymouth; Plymouth Marine Laboratory; Scottish Association for Marine Science; UCC University College Cork

MarClim UK was funded by:

Cyngor Cefn Gwlad Cymru Countryside Council for Wales; The Crown Estate; WWF; English Nature; Environment Agency; Joint Nature Conservation Committee; States of Jersey; UK Climate Impacts Programme; Scottish Executive; Natural Environment Research Council; Scottish Natural Heritage; defra Department for Environment Food and Rural Affairs

Marine Biological Association Occasional Publications No. 20

ISSN 0260-2784

MarClim was a multi-partner British and Irish project led by the Marine Biological Association of the U.K. in collaboration with the Plymouth Marine Laboratory, The Scottish Association for Marine Science, The University of Plymouth, University College Cork and a broader network of collaborators. It was funded by the following organisations: Countryside Council for Wales, The Department for Environment Food and Rural Affairs, English Nature, Environment Agency, Joint Nature Conservation Committee, Scottish Executive, Scottish Natural Heritage, The Crown Estates, States of Jersey and WWF, under the umbrella of the UK Climate Impacts Programme (UKCIP). This report summarises the findings of the work undertaken by the British team. A separate report summarising the work conducted by University College Cork (MarClim Ireland) is available at www.mba.ac.uk/marclim. Additional peer and non-peer reviewed publications associated with this project can be obtained from the website and a list of both as well as selected presentations is contained in Appendix 1. MarClim Ireland was funded through a post-doctoral fellowship (PDOC/01/006) October 2002-2005 with the support of the Marine Institute and the Marine RTDI Measure, Productive Sector Operational Programme, National Development Plan 2000–2006.

Contents

1. Executive Summary

In the last 60 years climate change has altered the distribution and abundance of many seashore species. Below is a summary of the findings of this project.

The MarClim project was a four year multi-partner funded project created to investigate the effects of climatic warming on marine biodiversity. In particular the project aimed to use intertidal species, whose abundances had been shown to fluctuate with changes in climatic conditions, as indicator species of likely responses of species not only on rocky shores, but also those found offshore. The project used historic time series data, from in some cases the 1950s onwards, and contemporary data collected as part of the MarClim project (2001-2005), to provide evidence of changes in the abundance, range and population structure of intertidal species and relate these changes to recent rapid climatic warming. In particular quantitative counts of barnacles, limpets and trochids were made as well as semi-quantitative surveys of up to 56 intertidal taxa. Historic and contemporary data informed experiments to understand the mechanisms behind these changes and models to predict future species ranges and abundances.

Main Findings

- Range extensions have occurred at the northern limits of the geographical distributions of typically southern, warm water species *Osilinus lineatus* (toothed topshell), *Gibbula umbilicalis* (flat topshell), *Chthamalus montagui* (Montagu's stellate barnacle), *Chthamalus stellatus* (Poli's stellate barnacle) and *Balanus perforatus* (acorn barnacle) since the mid-1980s in Wales, Northern Ireland and Scotland, including greater penetration around the north of Scotland into the colder North Sea (Section 7).

- Eastward range extensions of the southern species *Osilinus lineatus* (toothed topshell), *Gibbula umbilicalis* (flat topshell), *Patella ulyssiponensis* (china limpet), *Patella depressa* (black-footed limpet), *Melarhaphe neritoides* (small periwinkle), *Actinia fragacea* (strawberry anemone) and *Balanus perforatus* (acorn barnacle) have also occurred since the mid-1980s in the English Channel beyond previous biogeographic boundaries (Section 7).

- The northern species *Alaria esculenta* (dabberlocks) and *Tectura testudinalis* (common tortoiseshell limpet) have shown small retractions in their southern distributional limits and declines in abundance at populations close to these range edges, but the rate of recession is not as fast as the rate of advancement in southern species (Section 7).

- Synchronous increases in abundance have been recorded in populations of southern topshells throughout Britain and northern France since the mid-1980s. These increases are an order of magnitude greater than the inter-annual variation detected, increasing the confidence that these are observations of decadal-scale change rather than the result of anomalous years, providing support that these increases in abundance are climate-related (Section 7).

- Annual reproductive cycles of the southern/lusitanian trochids are commencing earlier in response to milder winters and warmer springs, coupled with increased survival of newly settled recruits exposed to milder, shorter winters on the shore (Section 7).

- The annual reproductive cycles of the southern/lusitanian limpet *Patella depressa* are starting earlier and lasting longer in south-west Britain. In contrast, less than 20% of the population of the northern/boreal limpet, *Patella vulgata*, are reaching gonad development stages at which spawning can occur on some shores in south-west Britain (Section 7).

- Fluctuations of the northern barnacle *Semibalanus balanoides* and the southern *Chthamalus* spp. have been related to climate change, using historical data collected by Southward and advanced statistical methods. These show that there is a direct negative effect of warm springs on survival of *Semibalanus balanoides* which via release from competition has an indirect positive effect on *Chthamalus*. These data have been used for hindcast and forecast modelling using UKCIP climate scenarios. In particular these models have been able to incorporate characteristics such as species mortality, larval supply and competitive interactions to create more biologically realistic predictions of species responses to climate change (Section 8).

- Models using the extensive broadscale resurvey data have been created for all MarClim indicator species to predict changes in their abundance and distribution in response to wave action and sea surface temperature regimes forecast by UKCIP (www.mba.ac.uk/marclim) (Section 9).

Conclusions

The MarClim project has provided strong evidence that recent rapid climate change has resulted in changes in the abundance, population structure and biogeographic ranges of a number of intertidal indicator species (Hawkins *et al*. 2003, Herbert *et al*. 2003, Kendall *et al*. 2004, Mieszkowska 2005, Moore 2005, Southward *et al*. 2005, Mieszkowska *et al*. 2006, Mieszkowska *et al*. in prep), mirroring changes offshore (Beaugrand *et al*. 2002, Genner *et al*. 2004, Richardson and Schoeman 2004, Sims *et al*. 2004, Coombs *et al*. 2005, Perry *et al*. 2005, Southward *et al*. 2005). Experiments have shown that many of the changes in southern/lusitanian species have occurred as a result of increased reproductive output and juvenile survival in response to increased warming. In the case of the northern/boreal limpet, *P. vulgata*, it would appear that decreases in its abundance may be linked to a decrease in this species reproductive output, particularly on shores in south-west Britain. Evidence suggests that species range expansion in response to climatic warming is occurring quicker in marine systems (plankton, fish, as well as intertidal species) than terrestrial systems.

Project Legacy

The MarClim project has fulfilled its aims and in doing so collated extensive long-term time series data on the abundance and distribution of intertidal indicator species around the British Isles. During the project 20 peer-reviewed manuscripts have been published or have been submitted for publication to date (Appendix 2). Many more manuscripts are expected to be published as a result of the data collated and collected as part of the MarClim project. MarClim also disseminated its work by giving over 40 presentations to scientists, policy makers and the general public (Appendix 2).

The MarClim project has collated, undertaken extensive quality assurance measures and created a database of historical quantitative counts for barnacles, limpets and trochids as well as semi-quantitative broadscale data from 4400 sampling occasions at over 1000 locations. During the MarClim project 800 site visits were made to over 470 locations in the UK. An electronic database has been created, to incorporate both the historic and contemporary surveys, to enable long-term availability of the data. All data collated and collected by the MarClim project will be made available via the National Biodiversity Network gateway or by contacting the Marine Environmental Change Network (MECN) co-ordinator (www.mba.ac.uk/MECN).

Eighty sites for which there are long-term records have been designated to form a future monitoring network as part of a wider British marine monitoring programme. The Countryside Council for Wales (CCW) have incorporated MarClim monitoring sites and protocols into their annual marine intertidal survey programme. Future monitoring of rocky shore climate indicator species will continue under the auspices of the Marine Environmental Change Network (MECN).

2. Aims and activities undertaken by the MarClim project

At the outset of the project the main aims of MarClim were:

- To use existing historical information and collect new data on intertidal indicator species from the last 50-100 years to develop and test hypotheses on the impact of climatic change on marine biodiversity in Britain and Ireland.

- To forecast future marine community changes on the basis of the Met Office's Hadley Centre climate change models and the United Kingdom Climate Impacts Partnership's climate change scenarios. The broad range of species known or thought likely to be temperature sensitive were covered.

- To establish low-cost, fit-for-purpose, methodologies and networks to provide subsequent regular updates and track how climate influences the marine biodiversity of Britain and Ireland.

- To provide general contextual time series data to support reporting on the success or otherwise of marine aspects of Biodiversity Action Plans, European initiatives including the Habitats, Birds and Water Framework Directives, and management and monitoring of marine activities and resources, including fisheries and Special Areas of Conservation.

- To evaluate whether the climate indicator species used in this work have a wider contribution to make as part of the sustainability indicators that are needed to underpin the UK sustainable development strategy.

- To disseminate the results widely, and accordingly elucidate the known impact that climate has had on marine biodiversity over the last 100 years, and may have in the future.

- To provide a basis for the development of a proposal for European Commission funding to establish a pan-European network with related aims.

- To assess and report on the likely consequences of the predicted changes in response to climate for society, for commercial and non-commercial users of the marine environment and the policies and frameworks that conserve, manage and protect marine biodiversity. To assess whether any more serious impacts can be ameliorated or mitigated.

MarClim was organised in four phases:

Phase I (April 2001 – August 2001):

- The project specification was refined and end-user liaison established via the MarClim Advisory

Group and discussions with other relevant programmes (MONARCH, Tyndall Centre for Climate Change Research).

- Electronic archiving of MBA and other historical datasets, particularly for fish was started and led to various subsequent publications (Sims *et al*. 2001, Hawkins *et al*. 2002, Hawkins *et al*. 2003, Genner *et al*. 2004, Sims *et al*. 2004, Coombs *et al*. 2005).
- Conference presentations were given and workshops attended to introduce the MarClim project to the research and policy end-user communities.

Phase II (September 2001 – March 2002)

- Relevant intertidal datasets were identified and access granted from their stewards, leading to a central archive held by MarClim (Crisp & Southward broadscale and time-series data, Lewis & Kendall trochid data, Shetland data, Coastal Surveillance Unit intertidal data and Herbert south coast of England data).
- These datasets were archived and appropriate databases designed.
- Fieldwork methods were trialled and a set of standard protocols for resurveys produced (www.mba.ac.uk/marclim).
- Research staff were recruited to the project. All staff were trained and survey techniques cross-calibrated with Kendall, Hawkins and Southward, who had collected much of the historical data using the field survey protocols.
- Initial analyses of historical data were made.

Phase III (April 2002 – March 2004)

- Historical data were analysed to inform re-survey (Herbert *et al*. 2003, Mieszkowska *et al*. 2006).
- Quantitative surveys of barnacles, limpets and trochids and semi-quantitative broadscale surveys of up to 56 indicator species were made at over 470 locations in Britain for which historical data were available.
- Annual quantitative barnacle counts of northern warm-water and southern cold-water species started in the 1950s were continued at over 20 sites in south-west England.
- Time-series of quantitative trochid data were restarted at over 30 sites in England, Wales, Scotland and northern France.
- Annual quantitative counts of limpets started in 1980 were continued at 20 sites in south and south-west Britain.
- Initiation of modelling distributions in relation to temperature and local wave action, and population dynamics of key indicator species (co-supported by NERC small grant to SAMS).
- Further publications were submitted (Herbert *et al*. 2003, Hiscock *et al*. 2004, Kendall *et al*. 2004, Mieszkowska *et al*. 2006)

Phase IV (April 2004 – including extension to October 2005)

- Field surveys were concluded and the monitoring network continued in south-west Britain.
- An electronic archive of historical and resurvey data was completed and re-survey data entered into Marine Recorder.
- Long-term climate change monitoring methodologies and a network were designed for future implementation.
- Models forecasting likely changes in populations of key species and distributions of all MarClim species under scenarios of climate change for the 21st century were completed and trialled.
- Two Ph.Ds associated with the MarClim project were completed (Mieszkowska 2005, Moore 2005)
- MarClim was subsumed with the Marine Environmental Change Network (MECN) in autumn 2005.
- Summary report was written and several publications completed and submitted (Simkanin *et al*. 2005, Southward *et al*. 2005, Mieszkowska *et al*. in review, Moore *et al*. in review, Poloczanska *et al*. in review)
- A major policy paper was completed by the Advisory Group (Laffoley *et al*. 2005)
- Outputs of MarClim were delivered to wider European audiences via invited participation in the European Science Foundation Marine Board Working Group on Climate Change and the European Platform on Biodiversity Strategy Research meeting hosted by Defra and the Scottish Executive as part of the U.K. Presidency of the E.U.

3. A changing climate

There is now compelling evidence to suggest that temperature increases over both land and sea in the northern hemisphere during the 20th century have been greater than during any other century in the last 1000 years.

It is now widely accepted that the planet is currently experiencing a period of rapid climate change, primarily driven by human activities (Oreskes 2004). The global average surface temperature has increased by 0.7°C during the 20th century (Hulme *et al*. 2002). Globally, nine out of the ten warmest years on record were recorded in the decade 1990-2000 and 2003 was the warmest year since instrumental records began in 1860 (Climatic Research Unit news release 16th December 2004). Sea surface temperatures (SST) around the British coastline have increased, with some areas exceeding the global average rise. Data for SST show that in the western English Channel there has been a 1°C rise in SST since 1990, greater than any other change recorded over the past 100 years (Hawkins *et al*. 2003). Similar changes have been recorded in the eastern English Channel (Woehrling *et al*. 2005).

It is difficult to predict how the climate will alter over the coming decades because of uncertainties over the rate of future greenhouse gas emissions and the response of climate to these emissions. Irrespective of the timescale and magnitude of response, some anthropogenically driven climate change is now inevitable. Global climate models (GCMs) predict an acceleration of the current warming trend during the first half of the 21st century as a response to continued anthropogenic emissions; thus the earth is expected to become warmer than at any period during the past 40 million years (Houghton *et al*. 2001). The UK Climate Impacts Programme (UKCIP) in conjunction with the Tyndall Centre for Climate Change Research has produced scenarios of climate change for the UK based on climate modelling work undertaken by the Hadley Centre for Climate Protection and Research at the Meteorological Office. This modelling is based on four different sets of assumptions – or "storylines" – about the key drivers of greenhouse gas emissions and other climate-altering pollutants. The UKCIP02 report (Hulme *et al*. 2002) presents four corresponding scenarios of future climate change for the UK based on: Low, Medium-Low, Medium-High and High-Emissions, for three thirty-year time slices (centred on the 2020s, 2050s and 2080s; Fig.1). The baseline convention for these scenarios is the 30-year period 1961-1990 and scenarios are presented relative to this period (Hulme *et al*. 2002). The scenarios provide a set of four alternative climate futures for the UK based on our understanding of the science of climate change. These include the following:

- An increase in annual average SST is expected under all four emissions scenarios over the next 100 years.
- Southern North Sea and English Channel SST may increase by between 1.5°C under the Low Emissions scenario and 3°C under the High Emissions scenario.
- Irish Sea SST will increase between 0.5°C (Low Emissions) and 2.5°C (High Emissions).
- North-east Atlantic SST will rise between 0.5°C (Low Emissions) and 1.5°C (High Emissions).
- Increases in daily mean wind speeds of between 2% (Low Emissions) to 8% (High Emissions) in the southern North Sea and English Channel during winter and spring are expected by the 2080s.

- Summer and autumn wind speeds are expected to decrease by up to 10% off western Britain by 2080s under the High Emissions scenario.

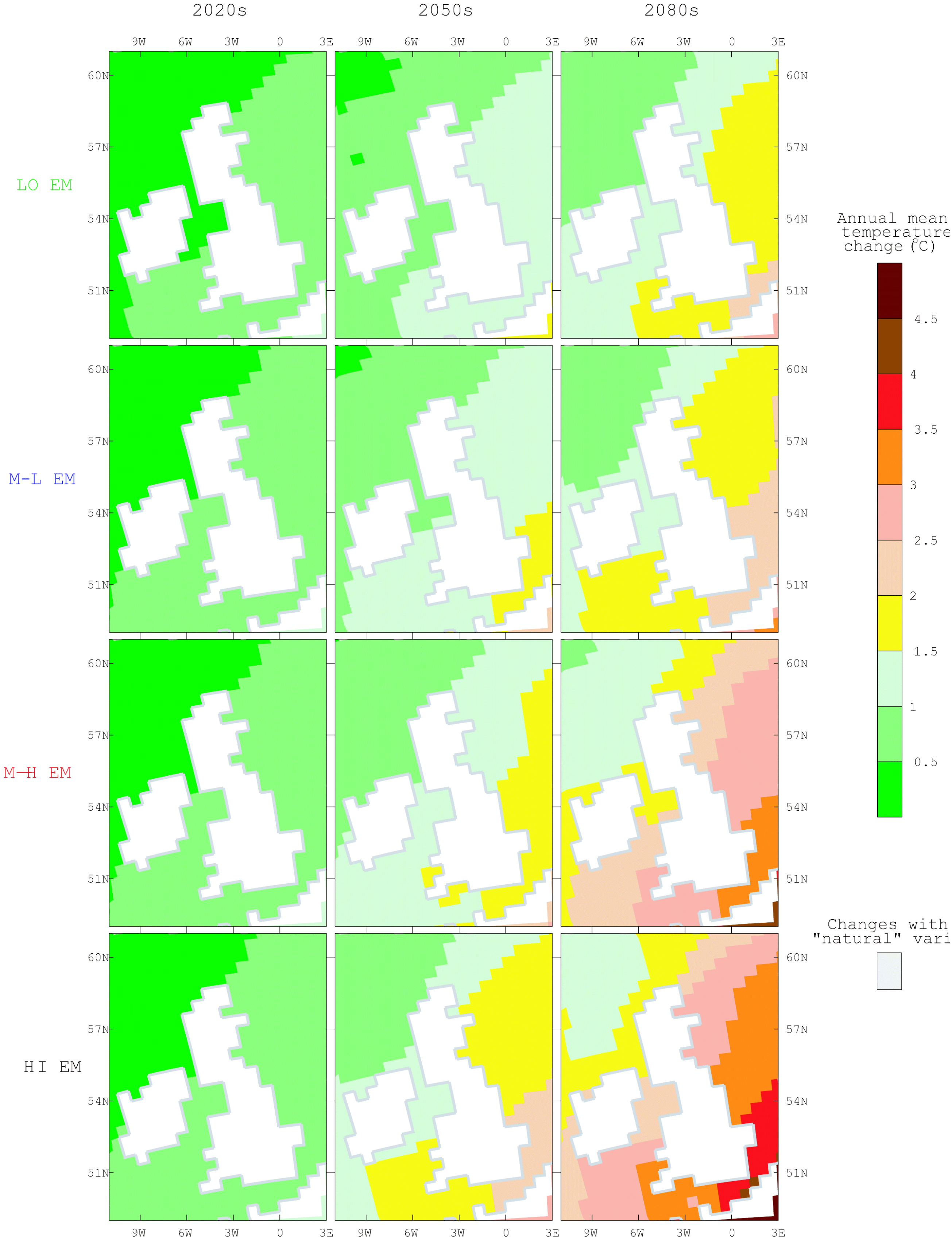


Fig. 1. Changes in average annual sea surface temperature (°C) by the 2020s, 2050s and 2080s, with respect to the model-simulated 1961-90 average. UKCIP02 Climate Change Scenarios (funded by DEFRA, produced by Tyndall and Hadley Centres for UKCIP).

4. Responses of Marine Biodiversity to Climate Change

The MarClim project has assessed the influence of climatic change on rocky shore biota over the last 60 years and forecasts species distributions into the future.

There is increasing concern regarding the impacts of climate change for the conservation and management of marine biodiversity (Fields *et al*. 1993). As climate warming continues a general pole-ward shift in species ranges is expected as species respond to the alteration of suitable 'climate space' they can inhabit (Graham and Grimm 1990, Fields *et al*. 1993, Southward *et al*. 1995, Parmesan 1996, Sagarin *et al*. 1999). Species are likely to respond to rapid temperature increases at different rates due to differences in their metabolism, physiological processes and behaviour (Inouye *et al*. 2000, Réale *et al*. 2003, Sims *et al*. 2004), which will influence adult growth and survival, reproductive output, phenology and recruitment success (Lewis 1996, Walther *et al*. 2002, Herbert *et al*. 2003, Sims *et al*. 2004). Contractions and expansions of geographic range edges will lead to species both being lost from and introduced to assemblages. Such changes will in turn influence the outcomes of species interactions such as competition, facilitation and predation, ultimately altering the structure of communities and marine ecosystem processes (Davis *et al*. 1998, Bertness *et al*. 1999, Case *et al*. 2005, Helmuth *et al*. 2005, Parmesan *et al*. 2005). Climate change could also cause widespread 'local extinction' of species which could lead to global extinctions in those species that are unable to adapt or respond to fluctuations in their physical environment (Grabherr *et al*. 1994, Thomas *et al*. 2004). Thus the effects of climatic variability on the distributions of plants and animals must be measured in order to understand and ultimately forecast changes in marine ecosystems.

As the most readily accessible marine habitat in Britain and Ireland, rocky shores have been the focus of recording species distributions (Stephenson and Stephenson 1972, Lewis 1986, Little and Kitching 1996, Raffaelli and Hawkins 1999), starting with the Victorian passion for the seashore. More formal charting of geographic distributions started in the first half of the 20th century (Moore 1936, Moore and Kitching 1939) with particularly valuable surveys being made in the 1950s (Crisp 1950, Southward 1950, Southward 1951, Southward and Crisp 1952, Southward and Crisp 1954a, Southward and Crisp 1956, Crisp and Southward 1958, Crisp 1964b). Most species are sessile or sedentary and can be surveyed non-destructively. Consequently, some of the best long-term data sets have been acquired for rocky shores – many in Britain and Ireland (Crisp and Chipperfield 1948, Crisp 1950, Southward and Crisp 1952, Southward and Crisp 1954a, 1954b, Southward and Crisp 1956, Crisp and Southward 1958, Southward 1963, Crisp 1964, Southward 1967, 1991, Southward *et al*. 1995). Furthermore, the biology of species and ecological interactions are well known from both laboratory and field manipulative experiments, aiding the interpretation of past change and future forecasts. Britain and Ireland straddle a biogeographic boundary between cold 'northern' boreal waters and warmer 'southern' lusitanian waters (Forbes 1858, Lewis 1964; Fig. 2). As a consequence many intertidal species are either at the northern or southern edge of their biogeographic ranges and will be particularly susceptible to changes in the climate (Southward and Crisp 1954a, Southward 1963, Southward *et al*. 1995, Lewis 1996). Thus the rocky intertidal of Britain and Ireland provides an ideal system for studying the effects of climate in terms of alterations of geographic distribution of species and the mechanisms driving these changes (Southward and Crisp 1954a, Southward and Crisp 1956, Southward 1967, 1991, Southward *et al*. 1995, Genner *et al*. 2004a).

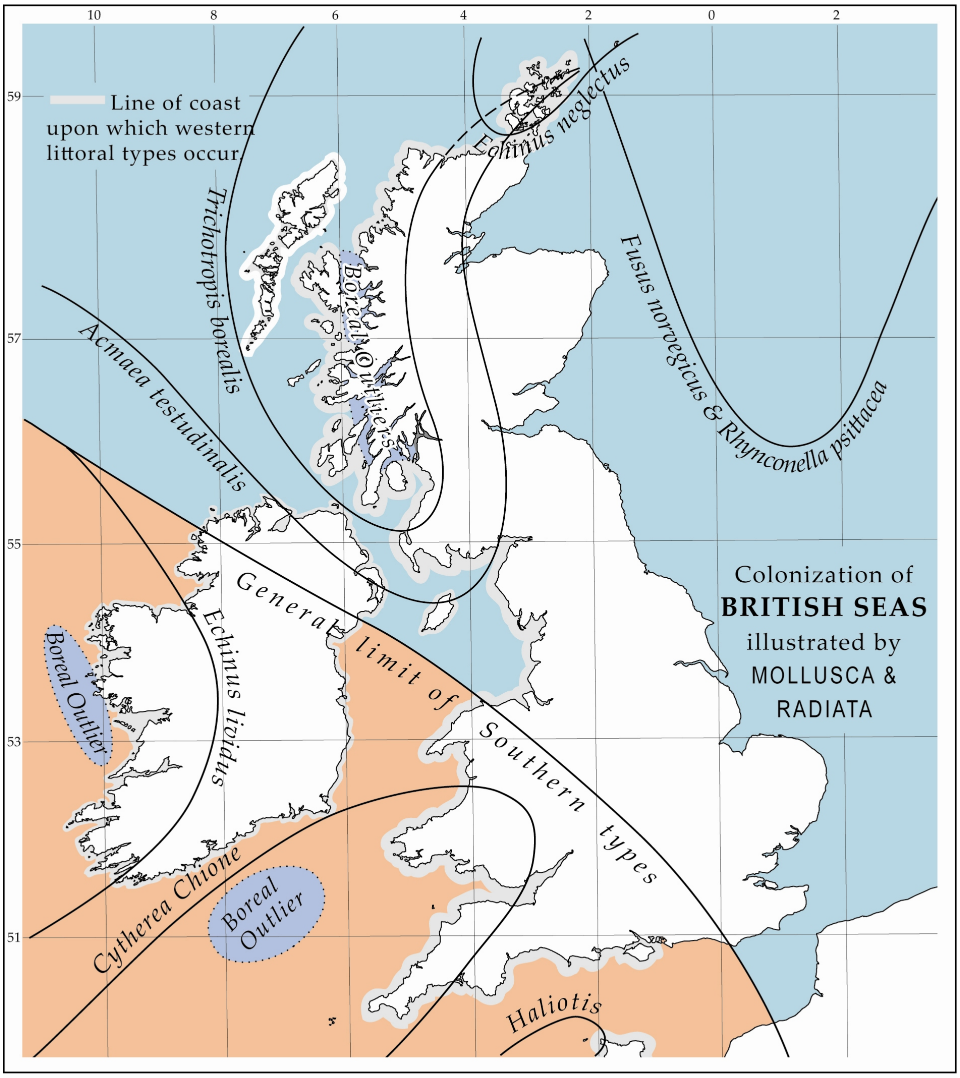


Fig. 2. The biogeographical characteristics of the coast of the British Isles, including the range limits of some species. Redrawn from Forbes 1858 and recently published by Hiscock *et al*. 2004 in Aquatic Conservation. Anglesey is absent from the map as it was in the original publication. *Acaema testudinalis* is now *Tectura testudinalis* (a limpet); *Cytherea chione* is now *Callista chione* (a bivalve mollusc); *Echinus lividus* is now *Paracentrotus lividus* (purple sea urchin); *Fusus norvegicus* is now *Volutopsis norwegicus* (a snail); *Haliotis* is *Haliotis tuberculata* (the ormer); *Rhynconella psittacea* is now *Hemithiris psttacea* (a snail); *Trichotropis borealis* (a snail) retains the same name; *Echinus neglectus* is now *Strongylocentrotus droebachiensis* (a sea urchin).

The MarClim project has investigated the following predictions on the current and future responses of intertidal rocky shore fauna and flora to changes in environmental temperature regimes in Britain:

(1) Northern species will retreat northwards and their abundance will decline; such changes are likely be driven by a reduction in reproductive output and/or decreased juvenile or adult survival during hotter summer periods.
(2) Southern species will expand their range northwards and their abundance will increase. The mechanisms underlying these responses are likely to be an increase in reproductive output and/or juvenile survival during warmer summer periods and milder winters. The extent to which range

extensions can occur will also be dependent on length of larval life stages and presence of rocky shores or artificial substrate beyond existing range edges.

(3) Biological interactions including competition, facilitation and predation will modulate the responses of southern and northern species with implications for community structure and ecosystem functioning.

(4) Changes will be greater than in the last warm period prior to the cold winter of 1962/63.

These predictions have been tested using long-term data series on the abundance and distribution of rocky intertidal species in Britain and Ireland detailed in Section 5, coupled with broadscale resurveys of selected species (Table 1) at key sites between 2001 and 2005 (Fig. 5a). The period for which ecological information exists spans the relatively warm 1950s, the severe winter of 1962-63 and a cool period from the 1970s to the mid 1980s (Fig. 3). Experiments investigating the effects of warming on species reproduction and recruitment of the lusitanian topshells *Osilinus (Monodonta) lineatus* and *Gibbula umbilicalis* have been undertaken to investigate the mechanisms influencing these species increases in range and abundance (Mieszkowska 2005). In parallel, models were constructed on interactions between northern and southern indicator species, focussing on barnacles and validated by comparisons with long-term time series (Poloczanska *et al*. in review; Section 8). Models were also constructed to predict past and current distributions of indicator species and validated against MarClim archived and contemporary data. These models were constructed using UKCIP climate scenarios (Hulme *et al*. 2002) to assess the future distribution of key intertidal species, and the results are detailed in Section 9.

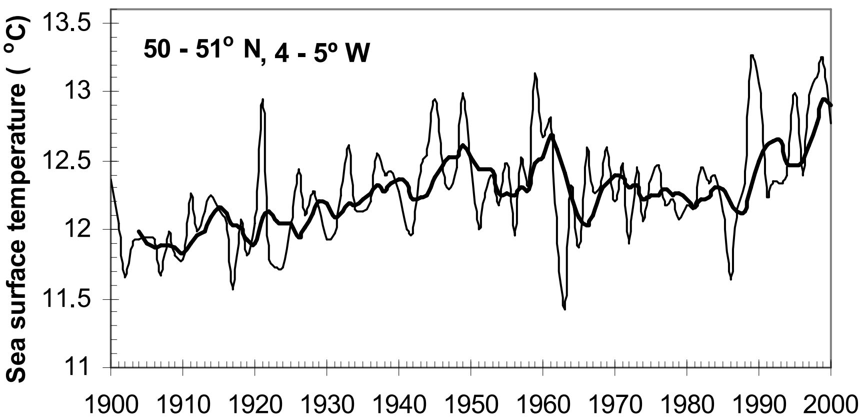


Fig 3. Annual mean sea surface temperature trends from square 50° to 51°N, 4° to 5°W (Hadley Centre for Climate Prediction and Research). Bold line is a five year running mean.

5. The Basis of the MarClim Project: Historic Data

A long history of records from the 1950s to the present day exists for rocky intertidal species distributions.

Broadscale Surveys

Following in the footsteps of the pioneering long-term observations made on both sides of the English Channel (Fischer-Piette 1933, 1936), the subsequent broadscale biogeographic surveys of rocky shores in Britain and Ireland were initiated in the late 1940s and early 1950s. These surveys began with detailed descriptions on the distribution of barnacles (Crisp and Chipperfield 1948, Crisp 1950, Southward 1950, Southward 1951, Southward and Crisp 1952, Southward and Crisp 1954a), but were rapidly extended to include many common intertidal organisms, so that the most important of the various possible abiotic and biotic factors controlling distributions would be revealed (Southward and Crisp 1954b, Crisp and Southward 1958).

The broadscale surveys of French, British and Irish coasts (Fig. 4a for sites in the U.K.), at first focused on the English Channel (Crisp and Southward 1958, Crisp and Fischer-Piette 1959) and around Ireland (Southward and Crisp 1954b). The original aims of the surveys were threefold: (1) to ascertain, as precisely as possible in the field, the environmental requirements of the species chosen; (2) to relate the distribution of each species directly to the physical environment and by looking for a common basis in the various distributions find the major factors responsible, and (3) to provide a reference against which any future changes in distribution might be shown.

During these surveys Denis Crisp and Alan Southward developed a system of categorical abundance estimation for key species that remains in wide use today (Southward and Crisp 1954b). The ACFOR (Abundant, Common, Frequent, Occasional and Rare) abundance scales permitted very rapid assessment of many tens of species in relatively short visits to survey sites. Categories ranged from 'Not found' through 'Rare' to 'Abundant': each class having clearly defined species-specific abundance categories on a semi-logarithmic scale (Appendix 1). A number of survey sites in south and south-west England were re-surveyed on a regular basis using the ACFOR abundance scale by Southward until 1987. The surveys were also extended to other areas of Britain; in particular to sites in Scotland and Wales. Crisp and Southward continued to visit selected sites intermittently until 1987 (Crisp *et al*. 1981), and by 1996 only a very small subset of the original sites were still being surveyed (Southward 1991). It was not until 1997 that more regular surveys were re-started in south-west Britain by Hawkins, primarily to continue the barnacle time series detailed below.

Quantitative Barnacle Time Series

Detailed surveys of the distribution of barnacles were made in Scotland, Wales and south-west England (Fig. 4b; Southward 1950, Southward 1951, Southward and Crisp 1952, Southward and Crisp 1954a, Southward and Crisp 1956). A joint survey between Denis Crisp and Alan Southward was then developed along two lines. (1) Transect surveys at four sites close to Plymouth previously worked by Hilary Moore in 1934. (2)

More-or-less annual (non-transect) surveys at sites in the south-west, with less regular surveys conducted in the rest of Britain and Ireland. The surveys around Plymouth were continued until the mid 1980s, with one site continued until 1998.

Limpet Surveys

Steve Hawkins made quantitative surveys on the boreal limpet *Patella vulgata* and lusitanian limpet *Patella depressa* in Wales and south-west Britain (Fig. 4c). A resurvey of all the Crisp & Southward (Crisp and Southward 1958, unpub) limpet sites in England and Wales were made between 1980 and 1984, with intermittent surveys of a small selection of sites from the mid 1980s onwards.

Coastal Surveillance in the 1970s

Extensive studies of the lusitanian topshell species *Gibbula umbilicalis* and *Osilinus lineatus* were initiated in the 1970s as part of the work by the NERC Rocky Shore Surveillance Group under the leadership of Jack Lewis (Fig. 4c; Kendall and Lewis 1986, Kendall 1987). Data collected by this unit was archived by Kendall following its closure in the mid 1980s. *In situ* counts of topshells were made using replicated timed collections, amongst boulders, underlying gravel and bedrock where juvenile abundance was estimated to be greatest. The basal diameter of each individual in the sample was recorded and the animals returned to the shore.

During the 1960s and 1970s additional long term programmes were prompted by concerns about pollution, especially in relation to the growing oil industry. Thus time series were started at Shetland, Orkney, north Scotland, north-east England and mid Wales. There was a realisation that background, natural variability needed to be measured (Lewis 1976, Lewis 1996). MarClim also collated details of these datasets and is the custodian of data from Scotland and north Wales collected by the Coastal Surveillance Unit at Menai Bridge between 1973 and 1985 (data also collected from 1993-1994 Holt *et al*. 1995). A paper based on the Shetland data collected by the Shetland Oil Terminal Environmental Advisory Group was published showing spatial concordance in changes of abundance in a broad suite of species, including barnacles (Burrows *et al*. 2002). This work showed how barnacles integrate processes over a wide spatial scale.

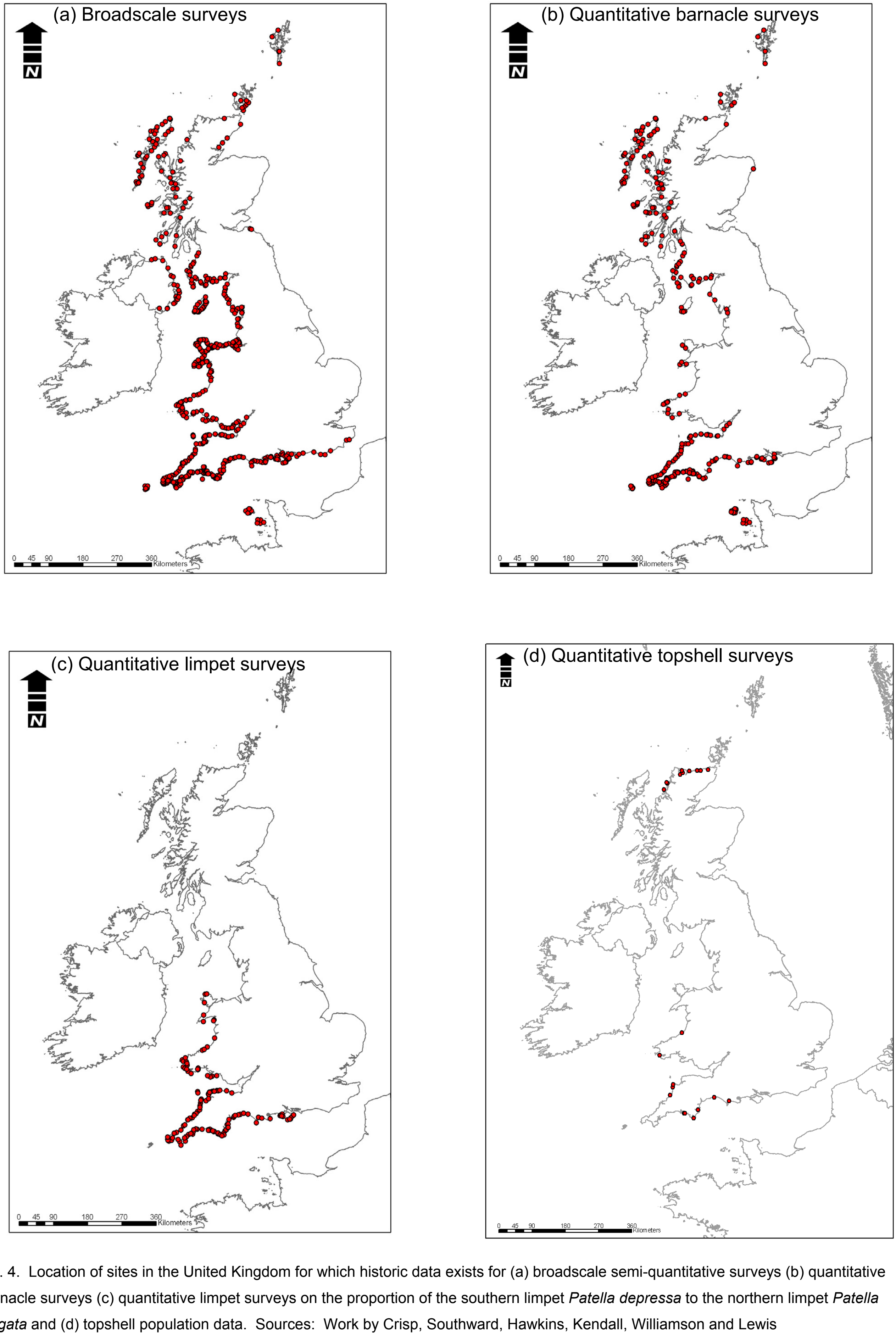


Fig. 4. Location of sites in the United Kingdom for which historic data exists for (a) broadscale semi-quantitative surveys (b) quantitative barnacle surveys (c) quantitative limpet surveys on the proportion of the southern limpet *Patella depressa* to the northern limpet *Patella vulgata* and (d) topshell population data. Sources: Work by Crisp, Southward, Hawkins, Kendall, Williamson and Lewis

6. The Basis of the MarClim Project: Resurvey Data

Historical baselines have been continued under MarClim by way of a large-scale biogeographic resurvey of Britain.

Over a four-year period the biogeographic resurvey of intertidal species for which long-term data exist has been coordinated by two separately funded MarClim programmes. Surveys in Britain, the Isle of Man and Channel Islands have been made by the Marine Biological Association (MBA), in conjunction with the Scottish Association for Marine Science (SAMS), Plymouth Marine Laboratory (PML) and the University of Plymouth (UoP), assisted by selected agency staff. University College Cork (UCC) has surveyed sites in the Republic of Ireland (MarClim Ireland). A joint survey by UCC and the MBA in conjunction with the Department for the Environment (Northern Ireland) was also made in Northern Ireland to allow researchers to cross-calibrate data collection protocols.

The primary objective of both survey programmes was to resurvey locations for which past data were held using the original protocols. The MarClim resurvey included 33 of the species examined in historical broadscale surveys and added a further 23 species thought to be equally sensitive to climate variability in Britain (Table 1). The aims were: (1) to resurvey sites where historical broadscale surveys had been made; (2) to resurvey sites where regular quantitative surveys had occurred to form time-series; (3) to survey additional sites close to and beyond historical recorded range edges and (4) to include sites within or adjacent to areas of designated conservation status. All the resurvey sites were restricted to moderately-exposed and exposed shores of natural substratum except for surveys conducted beyond the recorded range edge of species, where less-exposed shores and artificial substrata were examined. The current abundances of all 56 species were mapped at sites around the British coastline (Fig. 5a to see sites sampled). Based on past records, quantitative surveys of barnacles (northern *Semibalanus balanoides*, southern *Chthamalus montagui* and *Chthamalus stellatus*, and the invasive *Elminius modestus*; Fig. 5b), limpets (relative proportions of northern *Patella vulgata* and southern *Patella depressa*; Fig. 5c) and topshells (southern *Osilinus lineatus* and *Gibbula umbilicalis*; Fig. 5d) were carried out, whilst MarClim Ireland restricted surveys to barnacles and trochids only, due to the absence of *P. depressa* in Ireland. In addition, both survey programmes increased the replication level for quantitative counts used in the historical surveys under the resurvey, to facilitate both modern statistical analyses and to provide a more rigorous baseline for any future comparison. By adopting the same protocols of data collection at locations for which past data are held, MarClim has produced new, but directly comparable, baselines of the distribution and abundance of rocky shore biota in Britain and Ireland (requests for data can be made by contacting the Marine Environmental Change Network (MECN) co-ordinator at www.mba.ac.uk/MECN).

Additional surveys were also made by both teams: MarClim Ireland surveyed a number of locations in addition to those with past records (semi-enclosed bays, sea lochs and harbours) in order to assess the status of *E. modestus* (Allen *et al*. in press). MarClim (SAMS team) quantitatively surveyed a range of locations in western Scotland to examine the effects of the level of limpet grazing on patterns of community structure on both large-scales and in relation to local conditions of wave exposure. The SAMS team supplemented the survey protocols with digital photography of 0.5x0.5m areas at two shore levels, measuring sizes and densities of limpets in each area along with estimates of cover of barnacles, mussels and macroalgae, and counts of other gastropods. Both programmes also trialled digital photography as a modern survey technique for rapidly collecting replicated quantitative data on barnacle population abundance and structure.

Table 1. Temperature-sensitive rocky intertidal species surveyed by MarClim

Species	**Common name**	**Notes on biogeographical distribution**
Codium spp.	Velvet Horn	
Laminaria hyperborea	Tangle	Northern
Laminaria digitata	Oarweed	Northern
Laminaria saccharina	Sugar Kelp	Northern
Laminaria ochroleuca	Golden Oarweed	Southern – northern limit S.W. Britain
Alaria esculenta	Dabberlocks	Northern
Himanthalia elongata	Thongweed	Northern
Sargassum muticum	Wireweed	Invasive
Ascophyllum nodosum	Knotted Wrack	Northern
Pelvetia canaliculata	Channeled Wrack	Northern
Fucus spiralis	Spiral Wrack	Northern
Fucus vesiculosus	Bladder Wrack	Northern
Fucus serratus	Toothed Wrack	Northern
Fucus distichus	Wrack	Northern – southern limit British Isles
Cystoseira spp.	Rainbow Wrack	Southern
Halidrys siliquosa	Sea Oak	Northern
Bifurcaria bifurcata	A Brown Seaweed	Southern
Mastocarpus stellatus	False Irish Moss	Northern
Chondrus crispus	Carrageen	Northern
Lichina pygmaea	Black Lichen	Southern
Halichondria panicea	Breadcrumb Sponge	Ubiquitous
Anemonia viridis	Snakelocks Anemone	Southern
Aulactinia verrucosa	Gem Anemone	Southern
Actinia fragacea	Strawberry Anemone	Southern
Actinia equina	Beadlet Anemone	Ubiquitous
Sabellaria alveolata	Honeycomb Worm	Southern
Sabellaria spinulosa	Ross Worm	Ubiquitous
Chthamalus stellatus	Poli’s Stellate Barnacle	Southern
Chthamalus montagui	Montagu’s Stellate Barnacle	Southern
Semibalanus balanoides	Acorn Barnacle	Northern
Balanus crenatus	Acorn Barnacle	Northern
Balanus perforatus	Volcano Barnacle	Southern
Elminius modestus	Australasian Barnacle	Invasive
Campecopea hirsuta		Southern
Clibanarius erythropus	Red Clawed Hermit Crab	Southern
Haliotis tuberculata	Green Ormer	Southern
Tectura testudinalis	Tortoiseshell Limpet	Northern
Patella vulgata	Common Limpet	Northern
Patella depressa	Black Footed Limpet	Southern
Patella ulyssiponensis	China Limpet	Southern
Gibbula umbilicalis	Flat Topshell	Southern
Gibbula pennanti	Pennant’s Topshell	Southern
Gibbula cineraria	Grey Topshell	Ubiquitous
Osilinus lineatus	Toothed Topshell	Southern
Calliostoma zizyphinum	Painted Topshell	Southern
Littorina littorea	Common Periwinkle	Northern
Littorina saxatilis agg.	Rough Periwinkle	Northern
Littorina neglecta	Obscure Periwinkle	Southern
Melarhaphe neritoides	Small Periwinkle	Southern
Nucella lapillus	Dogwhelk	Northern
Onchidella celtica	Celtic Sea Slug	Southern
Mytilus spp.	Common Mussel	Ubiquitous
Asterias rubens	Common Starfish	Northern
Leptasterias mulleri	Northern Starfish	Northern
Paracentrotus lividus	Purple Sea Urchin	Southern
Strongylocentrotus droebachiensis	Northern Sea Urchin	Northern

Note: Ubiquitous species occur throughout the British Isles

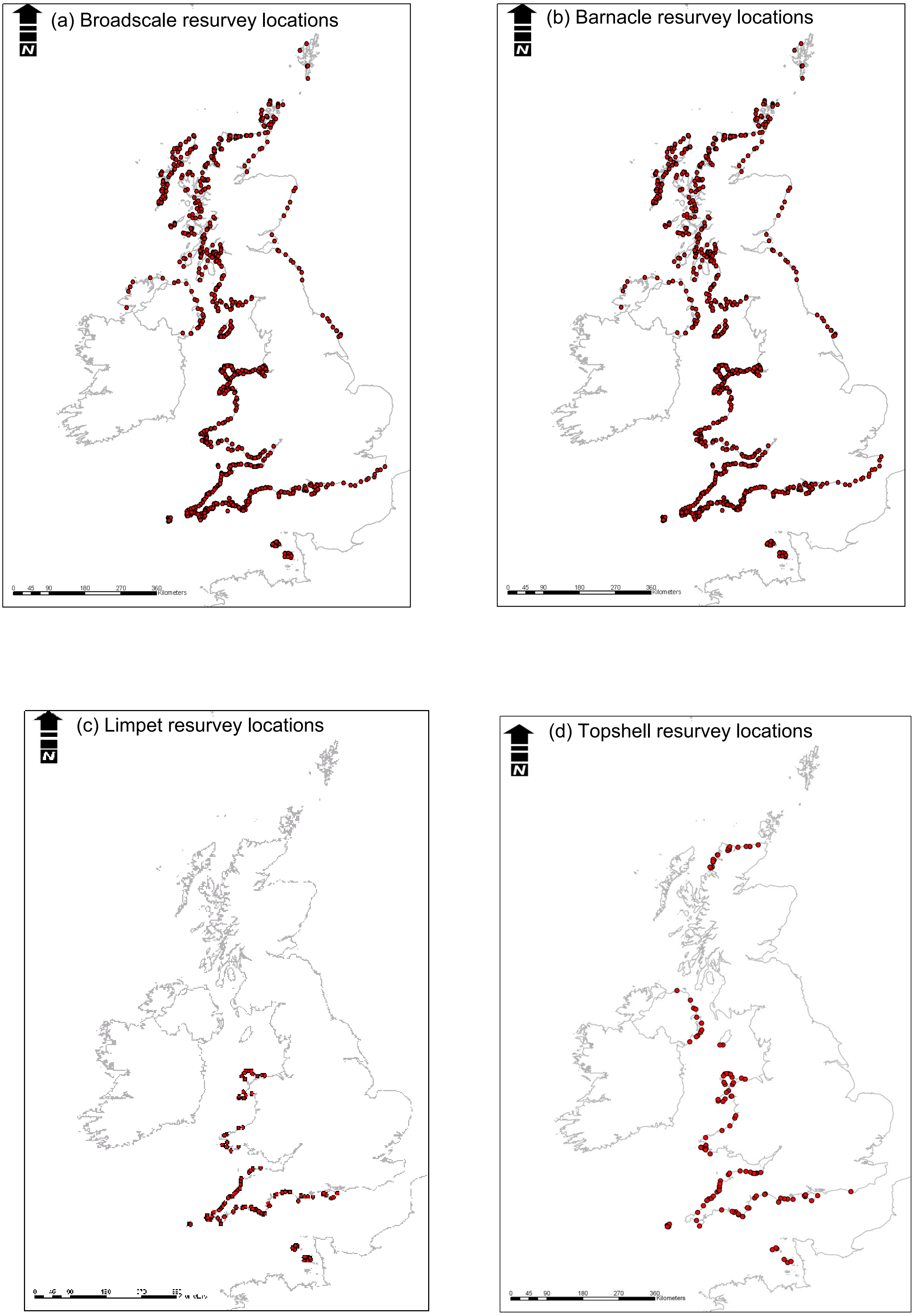


Fig. 5. Location of sites where (a) semi-quantitative broadscale resurvey, (b) quantitative barnacle resurvey (c) quantitative limpet resurvey and (d) topshell population resurveys by the U.K. team were made in 2001-2005. Please note additional surveys are ongoing and these maps represent sites that have been visited up to October 2005.

7. Main Findings: Changes in the Geographic Distribution of Intertidal Species in Response to Climate Change and the Biological Mechanisms Underlying these Changes

MarClim has identified shifts in the geographical limits of species and potential biological mechanisms causing the observed responses of species to climate change.

Southern species advancing

Topshells

Gibbula umbilicalis

In 2002 a breeding population of the flat topshell, *Gibbula umbilicalis* was recorded at Fresgoe, north Scotland (Fig. 6). This was the first time that animals have been recorded at this location despite intensive searches carried out in the 1970s and 1980s. The establishment of the Fresgoe population constitutes a northern range extension of approximately 55km beyond the previous range edge population at Skerray, north Scotland since 1985. Two individuals were also found 80km past Skerray at Murkle Bay in 2003 (Fig. 6), where occasional individuals had been found during previous searches in the 1980s. Since the current period of climate warming began in the late 1980s, populations of *Gibbula umbilicalis* near their northern range limits have shown statistically significant increases in abundance (Fig. 7). Analysis of recruitment and sea surface temperature (SST) data for the 1970s, 1980s and 2000s shows that the increased abundance is likely to be the result of increases in the frequency and strength of recruitment success within populations at and close to the northern range edge in response to warmer temperatures. Winters have become warmer and mean sea temperatures have increased by ~0.5ºC along the north Scotland coastline in the past two decades (Fig. 8). A significant, positive relationship between winter SST and recruitment success in populations close to their range limits in Scotland exists in the 1970s, 1980s and 2000s, with much higher numbers of newly settled juveniles surviving the milder winters during the 2000s in populations close to their northern range edge, resulting in adult breeding populations developing (Mieszkowska *et al*. in review).

The eastern range limit has also extended in the English Channel since the mid 1980s (Fig. 9b) via the colonisation of artificial structures, such as sea defences. The limit was previously set at the Isle of Wight, where there is no clear relationship between population success and sea temperature in the 1970s, 1980s or the 2000s (Mieszkowska *et al*. in review), indicating that this species eastern range limit was set by a lack of suitable rocky substrate beyond the Isle of Wight. Colonisation of sea defences has been rapid; *Gibbula umbilicalis* was not found on sea defences at Elmer in 2001; one or two individuals were found in 2002; occasional individuals were present in 2003 and it had become common by 2004. Breeding populations showing signs of recent recruitment were also found on natural rocky shores east of Brighton in 2004 and 2005 with occasional individuals being found at Beachy Head, showing that artificial structures can act as stepping stones between areas of suitable natural habitat which were previously too distant to allow successful colonisation.

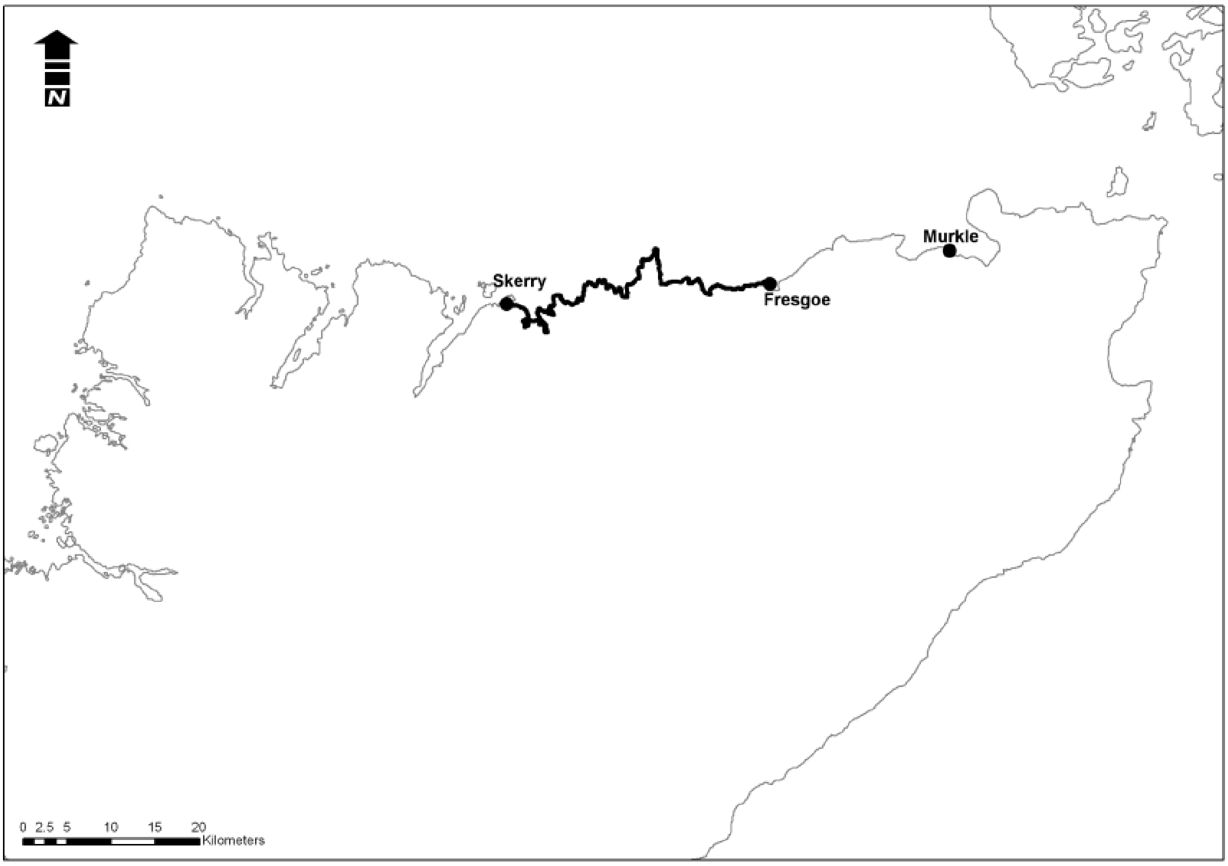


Fig. 6. Extension of the northern range limit of the breeding population of *Gibbula umbilicalis* at Fresgoe in north Scotland between 1985 and 2002 (from Mieszkowska 2005). Two individuals were found at Murkle Bay in 2003.

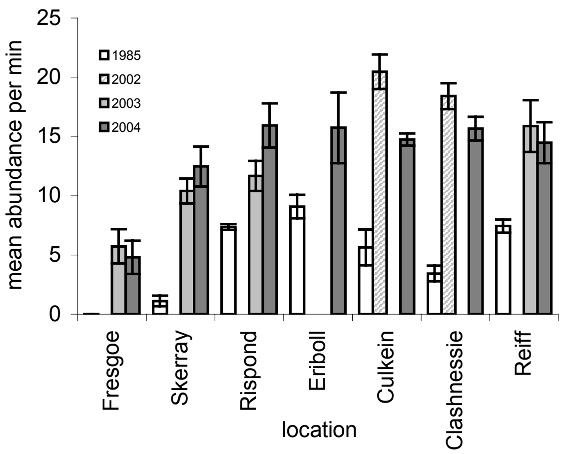


Fig. 7. Abundance of *Gibbula umbilicalis* at sites close to their northern range edge in north-eastern Scotland (from Mieszkowska 2005).

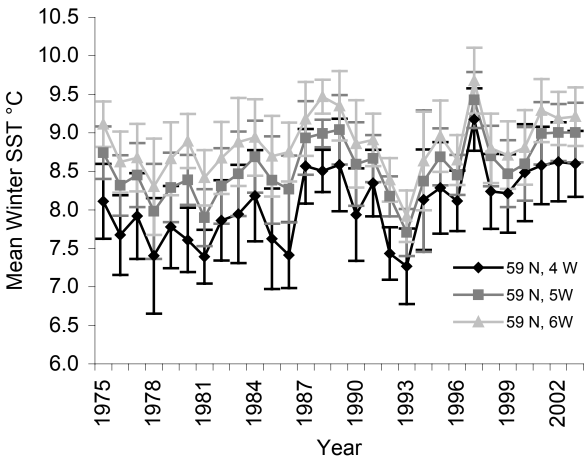


Fig. 8. Mean winter SST (± 1 SE) 1975-2004 for the grid squares at the north-eastern range edge of *G. umbilicalis* on the north coast of Scotland. Data provided by the Hadley Centre, UK Met Office (HadISST, Version 1.1). (from Mieszkowska 2005)

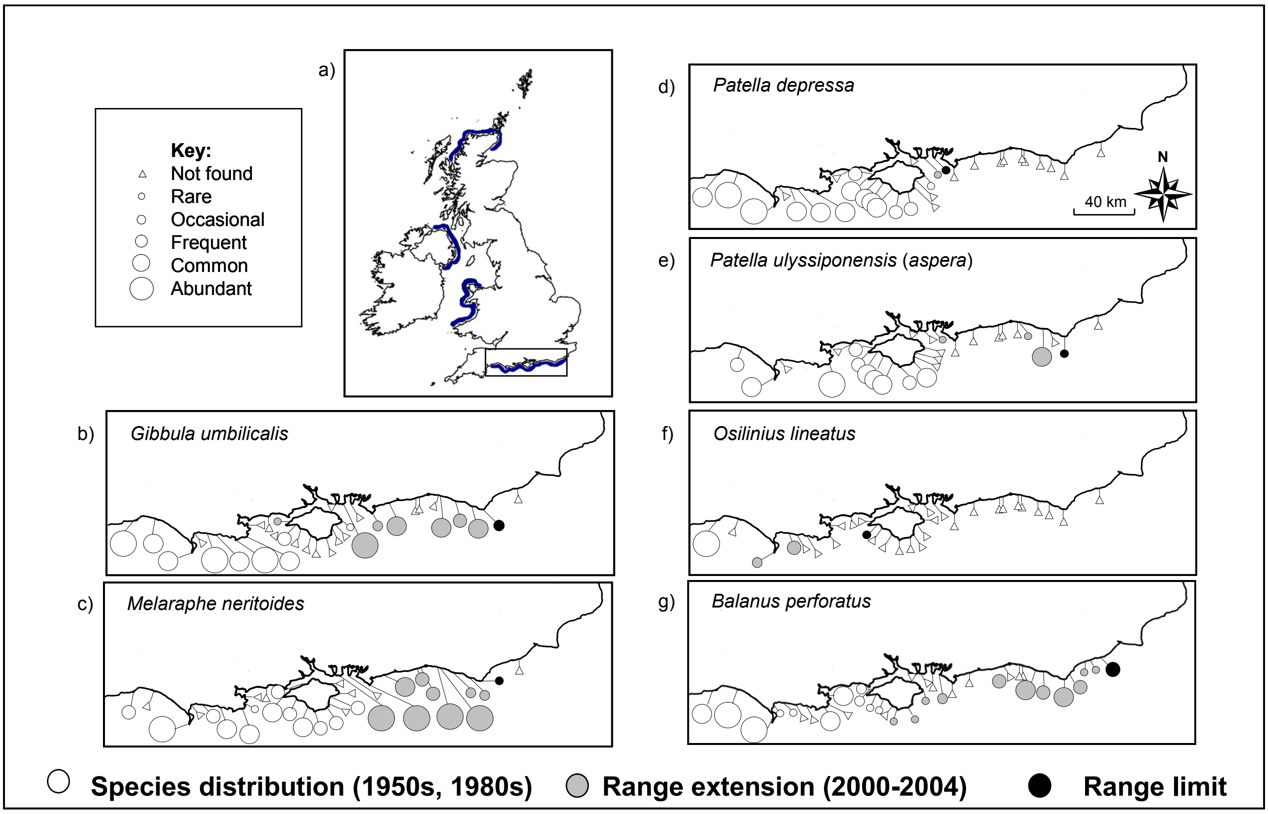


Fig. 9. Abundances and range extensions for six species along the English Channel.

Osilinus lineatus

In the English Channel the previous range limit of *Osilinus lineatus* was located at Lyme Regis (Kendall 1987), with isolated individuals recorded past this point (Hawthorne 1965, Kendall 1987). In 2002, 2003 and 2004 a breeding population was present at Osmington Mills, 55km east of Lyme Regis (Fig. 10). Individuals were also found at Lulworth Cove, and Freshwater Bay on the Isle of Wight, 60km and 120km respectively further east (Fig. 9f). A detailed study of the range edge population in Dorset has been made by local collaborators aided by some MarClim funding.

Populations of the toothed topshell *Osilinus lineatus* were eradicated or reduced in the cold winter of 1962-63 from the northern range edge on Anglesey to the south of the Lleyn Peninsula (Figs. 11, 12; Crisp 1964), and only occasional specimens have since been recorded by Hawkins and co-workers at Rhosneigr, on the south-west coast of Anglesey during the cooler 1980s and early 1990s (Fig. 13). Resurveys as part of MarClim showed that *Osilinus lineatus* had recolonized all sites in north Wales up to Cemlyn Bay, Anglesey, in response to climate warming since the late 1980s, and populations are now present on the Lleyn Peninsula at locations where previous records show apparent absence or only isolated individuals (Fig. 14).

There has also been a significant increase in the abundance of *Osilinus lineatus* at many sites covering four degrees of latitude (approx 450km; Fig. 15), accompanied by an increase in successful recruitment at all locations for which data from the 1980s exist (Mieszkowska 2005). Inter-annual variation in abundance during the 2000s was significantly less than the change in abundance between the 1980s and 2000s, indicating that major decadal-scale increases in population abundance have occurred in response to the decadal-scale changes in climate. Recruitment is still not occurring every year at the northern range edges in north Wales (Fig. 17) although gonads are known to develop (Lewis 1964, Bowman 1986, Williamson *et al*. in press), suggesting that the climate is still not warm enough for successful reproduction or survival of the juvenile cohort in every year.

Warmer or longer summers are likely to increase the period available for reproduction resulting in increased population sizes (Bode *et al*. 1986, Kendall 1987). Any latitudinal cline in the length of the reproductive cycle and spawning periodicity would suggest a correlation with environmental temperature, in this case warming, which decreases along a latitudinal gradient from the tropics to the poles. Preliminary studies on the reproductive output of *Osilinus lineatus* have shown that there is no apparent gradient in timing and periodicity of gonad cycles from populations sampled from their northern range edge to populations at the centre of their range (covering 4.7 degrees of latitude), but reproduction occurs earlier in warmer years such as those experienced in the 2000s (Mieszkowska 2005) and the last warm period in the 1950s (Williams 1964, Williams 1965, Desai 1966). The earlier arrival of juvenile recruits on the shore in warm years provides them with a longer time period to build up metabolic reserves prior to the onset of winter. This may act in conjunction with the increased survival of juveniles that has been observed when experimentally exposed to increased winter temperature (Fig. 16). These results support the conclusions that observed re-colonization and range extensions are being driven by increased survival of juveniles within populations close to range edges, leading to increased numbers of gametes being produced (Mieszkowska 2005).

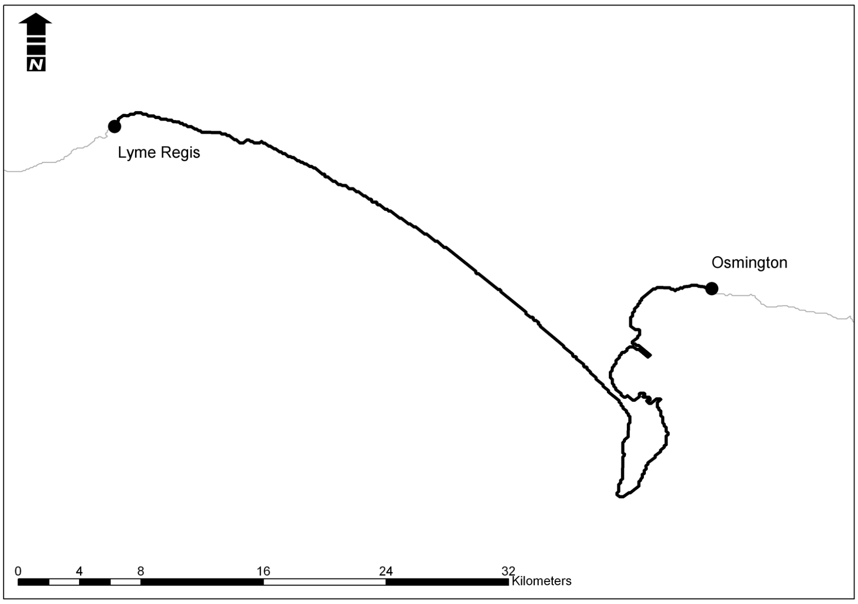


Fig. 10. Eastern range extension (black line) of *Osilinus lineatus* along the English Channel, 1986-2002 (Crisp & Southward 1958, Kendall 1987; from Mieszkowska 2005)

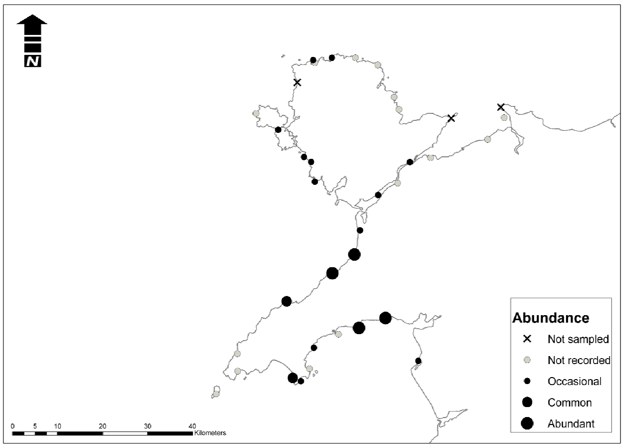


Fig. 11. Abundance of *Osilinus lineatus* at the northern range edge, north Wales in the 1950s (Crisp and Knight-Jones 1954).

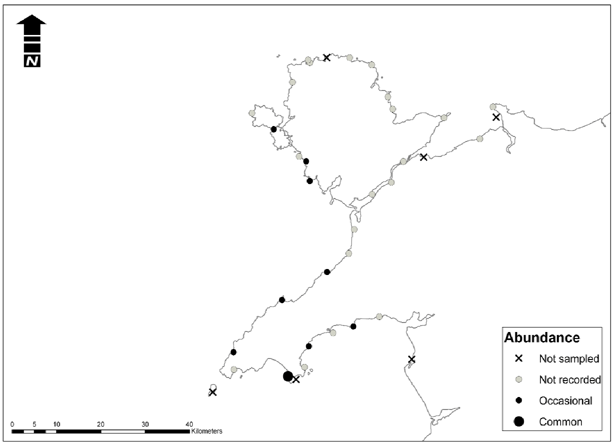


Fig. 12. Abundance of *Osilinus lineatus* at the northern range edge, north Wales in 1964 after the cold winter 1962/63 (Crisp 1964).

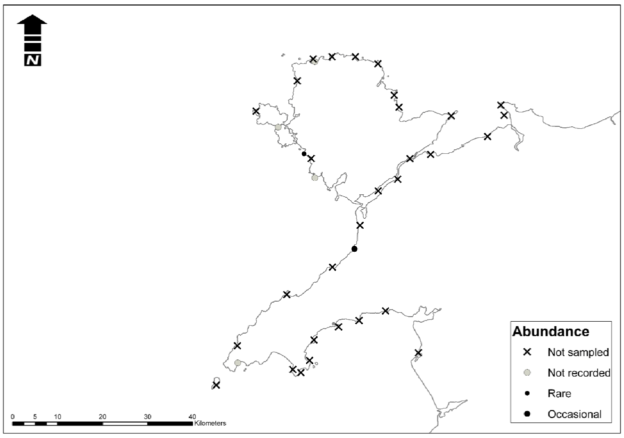


Fig. 13. Abundance of *Osilinus lineatus* at the northern range edge, north Wales in the 1980s (Hawkins unpublished).

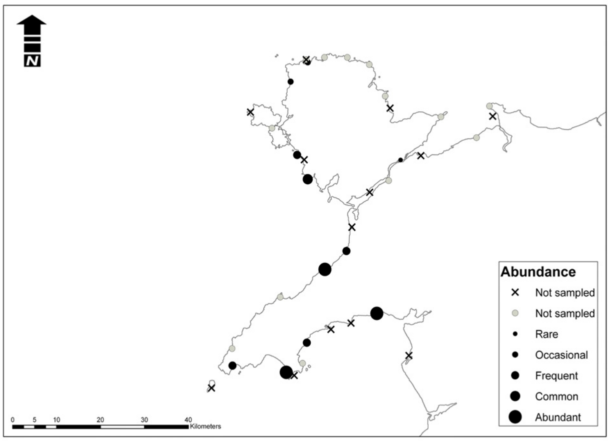


Fig. 14. Abundance of *Osilinus lineatus* at the northern range edge, north Wales in the 2000s (Mieszkowska 2005)

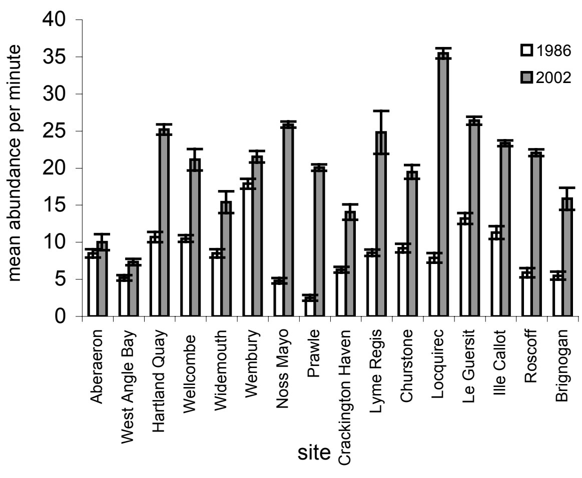


Fig. 15. Abundance of *Osilinus lineatus* at sites close to its northern limits & further south into the range in England & France (± 1SE) (from Mieszkowska, 2005).

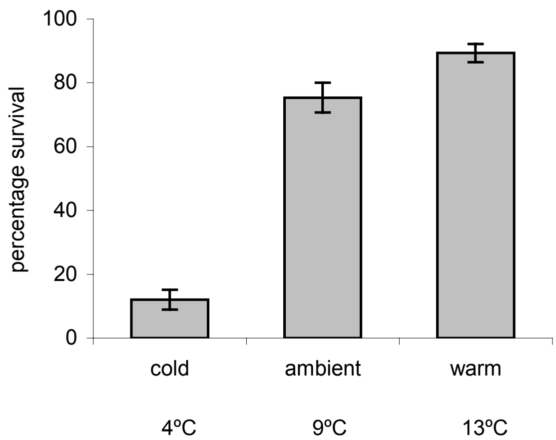


Fig. 16. Survival of *Osilinus lineatus* '0' cohort juveniles exposed to winter sea temperatures (± 1 SE) (from Mieszkowska 2005)

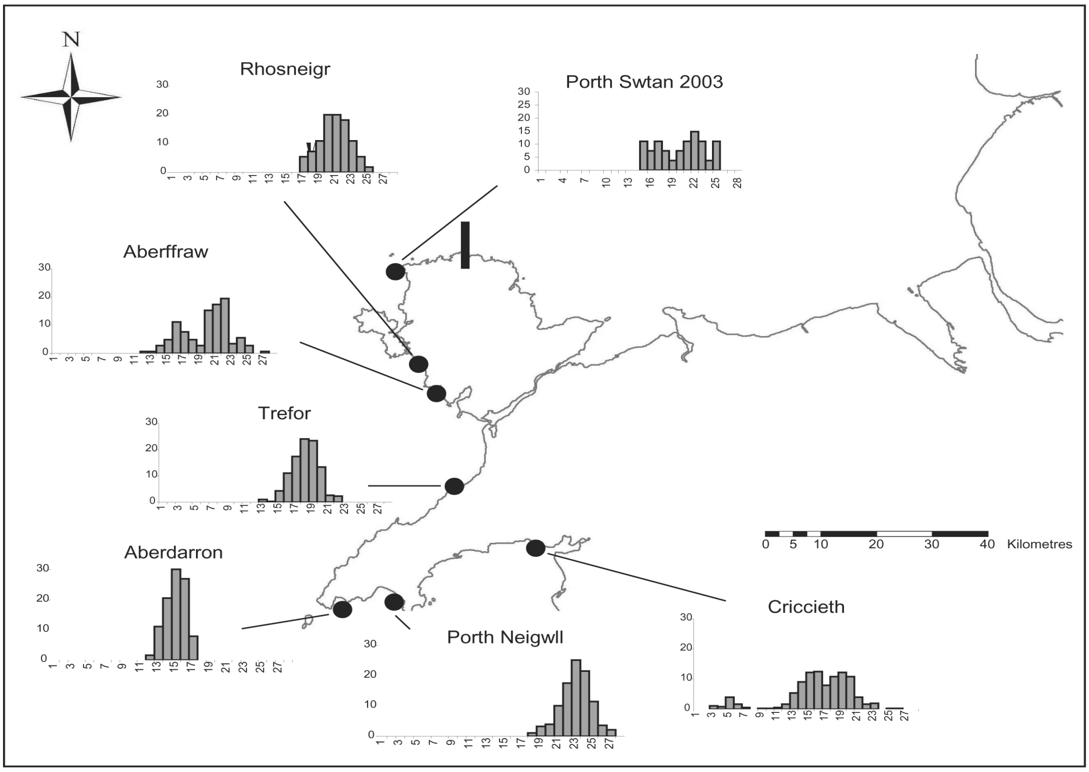


Fig. 17. Population structures of *Osilinus lineatus* at northern range limits in Wales in the 2000s (from Mieszkowska 2005).

Limpets

The southern limpet *Patella depressa* is now much more common at many locations in Britain compared to the cooler early 1980s. This is particularly the case in north Cornwall and Cardigan Bay. In north Wales, numbers have been steadily increasing at sites close to the northern range edges throughout the 2000s, and a breeding population is present at Cricceith, north Wales, where previous surveys in the 1980s and 1990s found only isolated individuals. Elsewhere abundances have not recovered to levels seen in the warm 1950s (Kendall *et al*. 2004). Therefore it would appear that local factors can override climatic influences in this species. Evidence would, however, suggest that more of the *Patella depressa* population is spawning in recent years (Moore 2005). Spawning events for *P. depressa* are happening earlier in the year and for longer periods than previous records suggest, with evidence of gonad redevelopment in south-west Britain (Fig18; Moore 2005). Resurveys show that the eastern range limit in the English Channel of *Patella depressa* has recently extended 30km east from the Isle of Wight to Hayling Island, where a small population has been found on artificial sea defences (Fig. 9d). The range of *Patella ulyssiponensis* has also extended eastwards in the English Channel with a breeding population recorded at Seaford in August 2004, 120km further east than Bembridge, Isle of Wight where only isolated individuals had been found in the 1980s (Fig. 9e). A breeding population has become established at Bembridge since the mid 1990s. A *Patella ulyssiponensis* was also recorded further east at Beachy Head.

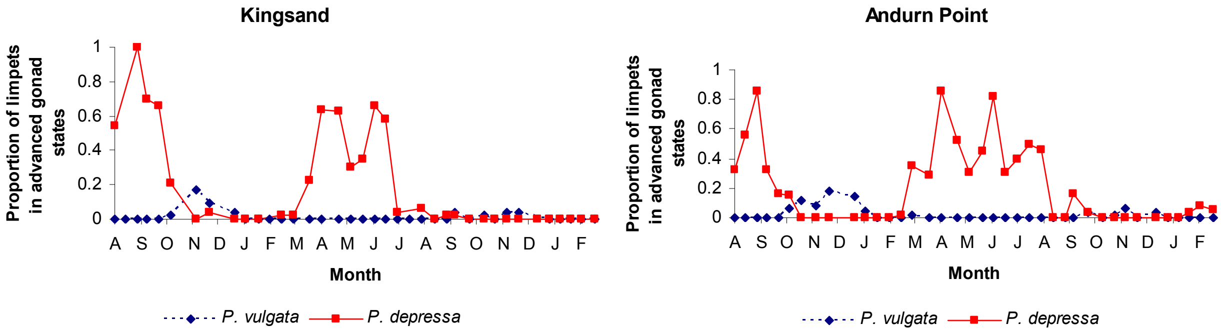


Fig. 18. The proportion of *P. vulgata* and *P. depressa* in advanced gonad states (gonad stages 4 & 5 after Orton *et al*. 1956) for a) Kingsand and b) Andurn Point south-west Britain (from Moore 2005).

Winkles

Melarhaphe neritoides used to only be found as far east as the Isle of Wight. It is now found throughout the eastern English Channel on artificial substrata such as sea walls, piers and sea defences as well as less commonly on chalk cliffs (Fig. 9c). The common factor in the extensions of winkles and limpets along the eastern basin of the English Channel is the colonisation of recently constructed artificial coastal defences. These species have used the structures as stepping stones across areas where unsuitable soft substrata occurs. Although these increases in range have occurred during the current period of climate change, at this stage it cannot be concluded that they are climate-driven.

Barnacles

MarClim resurveys found an increased abundance in northern populations of the warm water barnacles *Chthamalus montagui* and *Chthamalus stellatus* along the Atlantic coastline of northern Scotland since the 1950s. Isolated individuals of both *Chthamalus montagui* and *Chthamalus stellatus* have been found further south along the North Sea coastline of north-east Scotland during each survey year of the 2000s. In 2005 *Chthamalus montagui* was found as far south as Pittenweem in Fife. These range extensions have coincided with warmer Atlantic waters entering the North Sea (Hulme *et al*. 2002).

Infilling of gaps between isolated individuals and breeding populations of both species have also been recorded. In 2003 *Chthamalus montagui* were found on artificial substrata on much of the Wirral coastline, where previously only one or two isolated individuals had been recorded during the 1950s (Southward, pers comm.). In 2004 *Chthamalus stellatus* was recorded for the first time on the Isle of Man, 100km from the next nearest known population in North Wales. Between the 1960s and the 2000s the eastern range limit of *Balanus perforatus* in the English Channel has extended 120km east, with individuals found on artificial substrata at Hastings and subsequently on natural rock at Fairlight Cove and Sandgate, near Hythe in Kent (Herbert *et al*. 2003). There has been an increase in the abundance of *Balanus perforatus* at 18 out of 38 sites resurveyed in the 1990s compared to surveys carried out in the 1950s in the English Channel (Herbert *et al*. 2003). At 17 sites there was no difference in the abundance between surveys, while at three sites there was a decrease in abundance (Herbert *et al*. 2003).

Macroalgae

The most easterly population of the southern brown alga *Bifurcaria bifurcata* has remained near Dartmouth, Devon close to the 6°C winter sea surface isotherms, for the last 100 years (Fischer-Piette 1936, Crisp and

Southward 1958, Lewis 1964). Dubious records do however exist from the 19th century suggesting a more easterly range limit (Harvey 1846-1851, Johnstone and Croall 1860). In 2002 *Bifurcaria bifurcata* was found growing at Portland Bill, Dorset, indicating a possible eastern range extension of approximately 150km. The plants, usually restricted to rock pools near their range limits, were located on open rock on the low shore, a habitat previously only observed to be used by plants in south-west England (Mieszkowska *et al*. in prep).

Northern species retreating

Resurveys by MarClim have found less evidence of a reduction in the ranges of northern species, although some species have not been found on shores where they have been previously recorded.

Algae

Although the absolute range limits of the northern brown alga *Alaria esculenta* have not changed, this species has suffered severe declines in abundance or localised extinctions on shores around the coasts of south-west Britain since previous surveys in the 1950s (Mieszkowska *et al*. in prep). Continued absence from most of these shores was confirmed by the MarClim team between 2001-2004. Transplant experiments failed to re-establish *Alaria esculenta* at sites where it had been recorded in the 1950s (Vance 2004). *Alaria esculenta* has also disappeared from Robin Hood's Bay, Northumberland between the 1980s and the 2000s.

Barnacles

Although the biogeographic range of *Semibalanus balanoides* in Britain has not changed it is less abundant in the 2000s than during the cooler climatic periods of the 1960s and 1970s on shores of south-west England. The southern species of barnacles (*Chthamalus montagui* and *Chthamalus stellatus*) are now more abundant on shores of the south-west than *Semibalanus balanoides*. In recent years there have been more years where *Semibalanus balanoides* settlement has failed on shores in south-west Britain, particularly in 2004 when there was little or no settlement of this species on shores around Plymouth (Moore 2005). Work from further south in its range, in Galicia, suggests it has disappeared from its previous southern limit in Europe (Wethey, pers. comm.)

Limpets

The relative proportions of the northern limpet *Patella vulgata* have reduced in comparison to the southern species of limpet, *Patella depressa,* since the 1980s in south-west Britain. These two species have different bioeographical origins but occupy similar niches on the shore in Britain and northern Europe. In 2004, less than 10% of the *Patella vulgata* population on semi-exposed to exposed shores around Plymouth reached gonad states at which spawning could occur (Fig. 18; Moore 2005). This is in direct contrast to the increase in spawning success of the southern limpet *Patella depressa* in recent years (Fig. 18; Moore 2005). The tortoiseshell limpet *Tectura testudinalis* was not found on the Isle of Man in the 2000s where it had been previously recorded during the 1970s and early 1980s (Hawkins pers. ob.).

There may be various reasons for the apparent lack of northern species range contractions. Many of the northern/boreal species surveyed by the MarClim team reach their range limits slightly further south than Britain and Ireland (Fischer-Piette 1936, 1948, Fischer-Piette and Prenant 1956, Southward *et al*. 1995). Climatic conditions in Britain and Ireland may not yet have reached a threshold beyond which these species will contract their range. In many cases these species will initially respond to increased warming by decreasing in abundance and becoming limited to habitats which provide more amelioration from adverse climatic conditions, such as under macroalgal canopies (Moore in review). The lack of evidence for northern/boreal species ranges being restricted polewards may also be the result of changed climatic conditions affecting the most sensitive stages in a species life history. Such changes may take many years before they become apparent at the population level due to the longevity of many intertidal species. It is likely that northern/boreal populations will become increasingly dominated by adults as mortality of the more susceptible juvenile stages becomes more frequent in warmer conditions (Lewis 1996) and as recruitment fails (Svensson *et al*. 2005).

Table 2. Summary of changes in the range limits of species with northern and southern biogeographic ranges a) Species with southern biogeographic distributions b) Species with northern biogeographic distributions.

a)

Species	Previous Eastern limit	Range Extension	Previous Northern limit	Range Extension	Comments
Gibbula umbilicalis	Isle of Wight	Beachy Head (125km)	Skerray (1985)	Fresgoe (55km)	
Osilinus lineatus	Lyme Regis	Osmington Mills (55km)	Lleyn Peninsula (1964)	North Anglesey (40km)	Isolated individuals as far east as Isle of Wight
Patella depressa	Isle of Wight	Hayling Island (30km)	Porth Oer (1952)	Cricceith (cut back after cold winter 1962/63)	Isolated individuals on Anglesey prior to 1962/3 & 1980s
Patella ulyssiponensis	Isle of Wight	Seaford (120km)		None evident	Northern limit Norway
Chthamalus montagui	Isle of Wight	None evident	Orkney	Pittenweem (140km)	Now Common in Orkney
Chthamalus stellatus	Isle of Wight	None evident	Shetland	Cove Bay, Aberdeenshire (40km)	Now Abundant in Orkney
Balanus perforatus	Isle of Wight	Fairlight Cove, Kent (170km)	South Wales		
Bifurcaria bifurcata	Dartmouth, Devon	Portland Bill (150km)	Wales	Under verification	Previous records incorrect, range being verified

b)

Species	Previous limit	Range Contraction	Previous Southern limit	Range Contraction	Comments
Alaria esculenta	Salcombe	Dodman Point, South Cornwall (120km)	Present in Robin Hood's Bay in 1980s	Not present in Robin Hood's Bay 2004.	Disappeared from much of the western English Channel in 1950s. Did not recover post 1963.
Tectura tessulata			Dublin and Anglesey	Loss of species from south of Isle of Man since 1980s	

Comparison of long time series of population abundance with climatic data can be used to model past and future distributions of key intertidal species in relation to climate.

The MarClim project has constructed population models of competing pairs of northern and southern species of barnacle. Forecasting the response of species to shifts in environmental conditions is important for scoping the impacts of climate change, but predicting how a species will react is complicated by a number of factors. For example, the presence of competing species or fluctuations in the abundance of predator or prey species may all mediate climatic influence. Untangling these factors can be problematic, particularly where there are interactions between several species. However, long-term data sets and a sound knowledge of the underlying biology of the species allow for biologically realistic predictions of species responses to climate change.

In the British Isles, the intertidal zone on open coasts is dominated by one northern (*Semibalanus balanoides*) and two southern (*Chthamalus montagui* and *Chthamalus stellatus*) species of barnacles. *Semibalanus balanoides* is a midshore boreo-arctic species, while the lusitanian *C. montagui* and *C. stellatus* extend further up the intertidal zone. Intertidal barnacles are ideal for an investigation of climatic influence on population dynamics. In the UK all three species reach the edges of their biogeographical distributions, are relatively unimpacted by human activities and their population ecology and interactions with other species are well known. Populations at range edges should be most sensitive to fluctuations in the environment. Indeed, a record of recent changes in relation to environmental variation in the second half of the 20th century is available to MarClim as a long time series of population data (35 years) collected by Alan Southward (see The basis of the MarClim project – Historical data), restarted by Hawkins in 1997.

The historical barnacle time series revealed that during a cold period in the late 1960s and early 1970s *Semibalanus balanoides* increased in numbers while *Chthamalus* spp. decreased (Fig. 19). Two statistical techniques identified environmental sensitivities of key processes of population regulation in barnacle populations. Firstly, general linear models were used to calculate average numbers of barnacles at the mid shore level for each year of the 35-year series. Cross-correlation of the annual abundance of *Semibalanus balanoides,* with monthly time-lagged local sea surface temperature, showed a strong negative association between counts of adults and temperatures in spring of the previous year. Adult counts of barnacles are dominated by the youngest adult age class (1+) so this association suggested a critical period for survival in the first few months after settlement. In contrast high sea surface temperature values were associated with low counts. For the chthamalid species, the strongest association was also with sea temperature the previous spring, but the association was positive indicating that chthamalids are favoured by a warm spring.

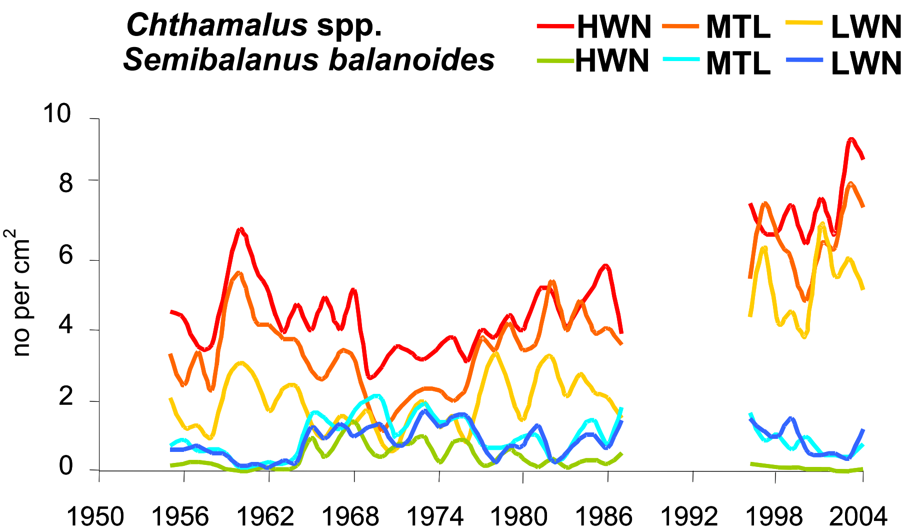


Fig. 19. Long-term changes in northern (*Semibalanus balanoides*) and southern (*Chthamalus* spp) barnacles averaged for several shores on the South coast of Devon & Cornwall (from Southward & Hawkins, unpublished; Southward 1991, Southward *et al*. 1995).

Secondly, the statistical technique of formal path analysis revealed that while temperature may be acting directly on *Semibalanus balanoides*, the climatic influence on *Chthamalus* spp. is probably mediated by the abundance of the competitively superior *Semibalanus balanoides* (Connell 1961). A hierarchy of age-structured population models were constructed to explore whether climate acts directly on each species or if inter-species competition is important. Three levels of model, each of increasing complexity, were developed: (1) temperature influences juvenile *Semibalanus balanoides*; (2) as 1 but with adult numbers influencing *Semibalanus balanoides* recruitment; (3) as 2 but with *Semibalanus balanoides* juveniles competing directly with young *Chthamalus* spp. In models 1 and 2, competition was expressed as simple space pre-emption. Models were assessed to determine the optimal complexity; if a model is too simple, key components driving population regulation may be excluded. The explanatory power of the three models was assessed using an index that combined the goodness of fit of each model to the data with the number of free parameters in the model (AIC: Akaike's Information Criterion). The model with the largest AIC was selected as the best of those considered.

Adding complexity increased the fit of the models. Models started to reproduce the large fluctuations observed in the historical time series for both species once competition was introduced, showing that simple temperature dependent models may be inadequate in explaining changes in population numbers (Fig. 20). The final task for this section of modelling was to run the models forward using temperatures forecast under different emissions scenarios from the UKCIP02 scenarios to determine the probability of extinction of *Semibalanus balanoides* in south-west England over the next 50 years (Fig. 21). MarClim has shown that successful and realistic hindcasts and forecasts can be made of species responses to climatic change if key elements of the biology and ecology of the species are incorporated into models that build on observations of change (Poloczanska *et al*. in review).

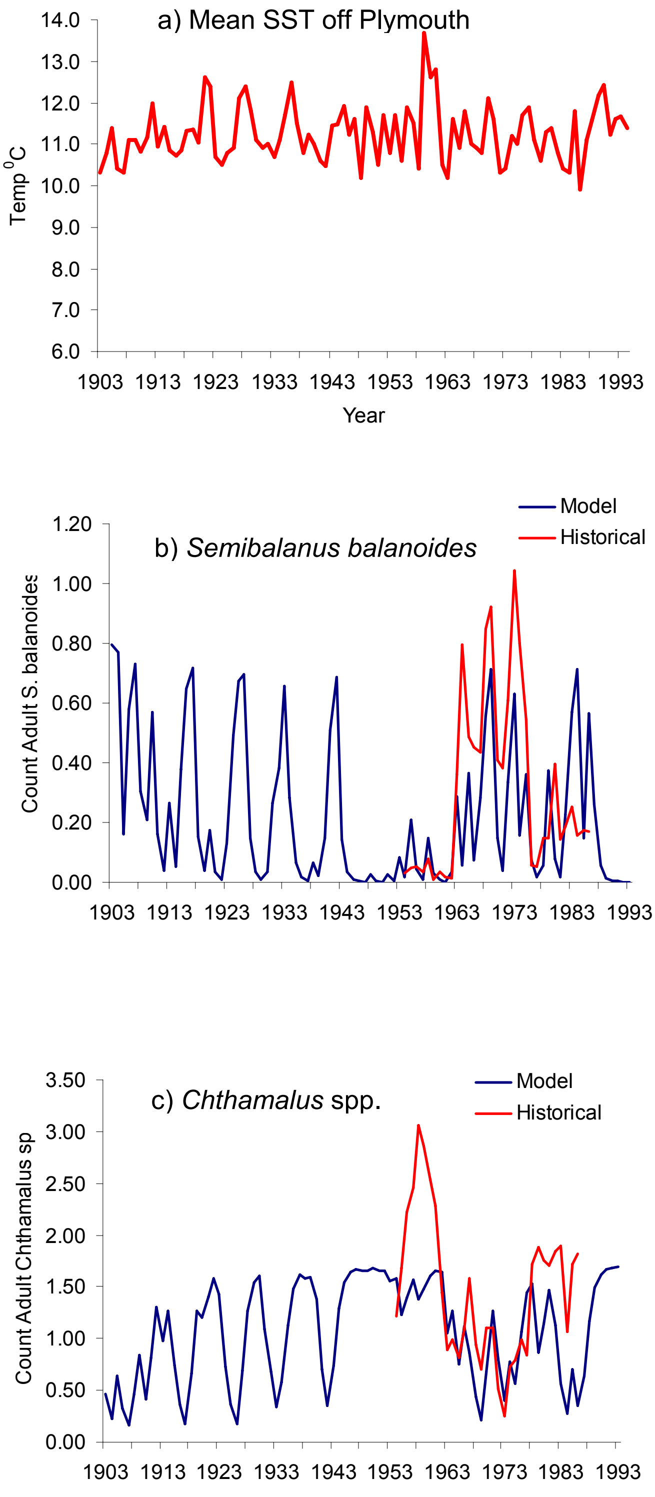


Fig. 20. (a) Annual sea surface temperature (SST) in May from the western English Channel including station E1 [50º 2'N 4º 22'W] off Plymouth Sound (b) and (c) historical counts of adult barnacles from south west England and counts produced by two-species population model with *Semibalanus balanoides* recruitment dependant on SST in May and stock size and with inter-specific competition between juveniles: (b) *Semibalanus balanoides* and (c) *Chthamalus* spp (based on Poloczanska *et al*. in review).

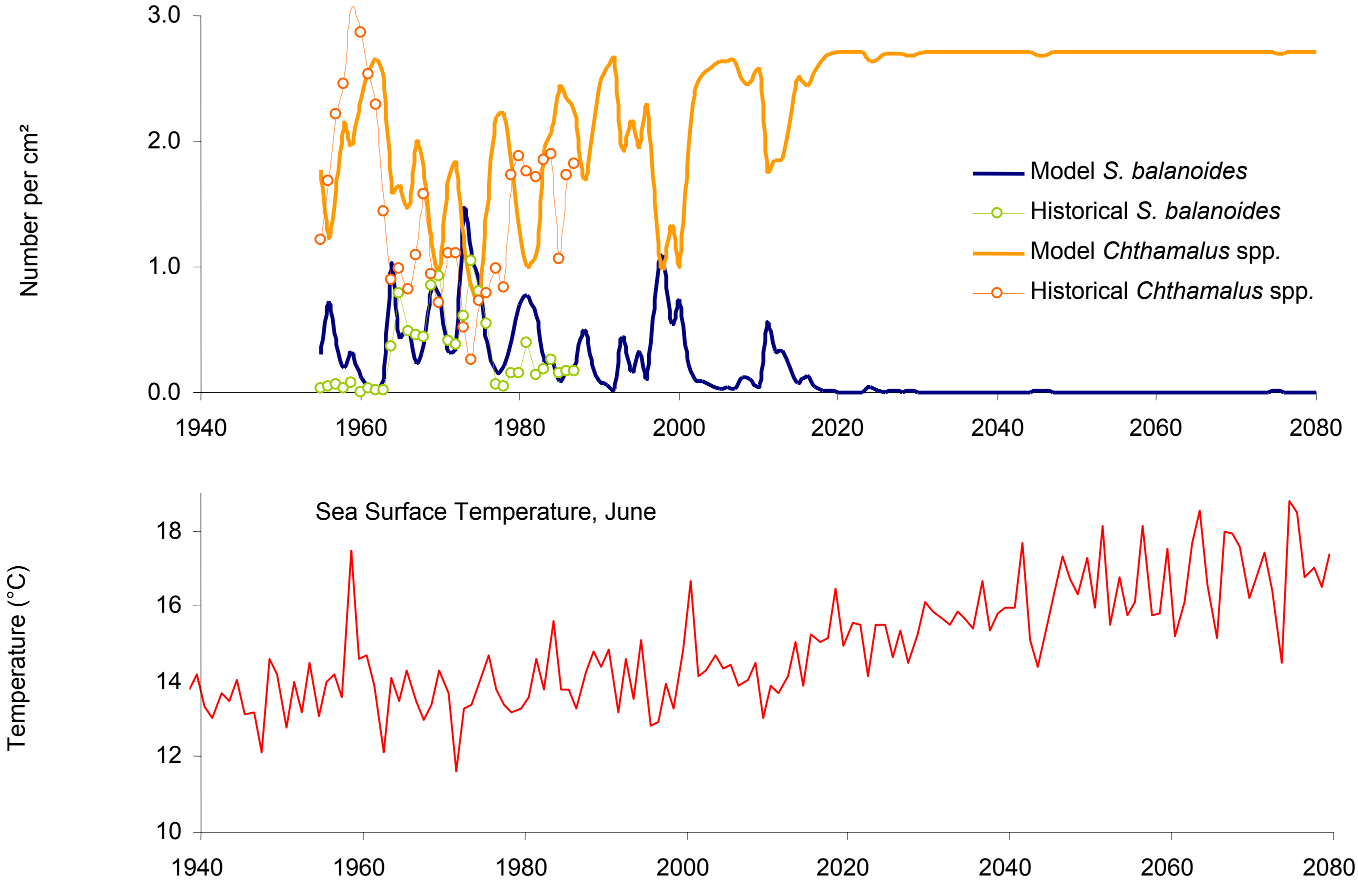


Fig.21. (top) The number of *Semibalanus balanoides* and *Chthamalus* spp. per cm^2 (bottom) Model predictions and observations of fluctuations at high shore levels in SW England (MHWN) from 1940 to 2080, using observed (1940-2003) and projected temperature series generated using the UKCIP02 Medium-High emissions scenario, a linear increase in mean temperature to 2080, and interannual variability as observed from 1900 to 2000 (from Poloczanska *et al*. in review).

Broadscale abundance and environmental data can be used to predict species distributions both now and in the future.

Using the extensive spatial broadscale resurvey data, we have modelled the likelihood of species reaching particular abundance categories at specific locations in the British Isles in relation to environmental variables such as wave action and sea surface temperature. GIS-based models have been developed that estimate wave fetch for 500m grid cells over the entire European coastline (e.g. Fig. 22), whilst sea surface temperature (SST) data have been extracted from the British Atmospheric Data Centre (GOSTA dataset) (Bottomley *et al*. 1990) and from the UKCIP02 scenarios 1961-90 baseline (UKCIP02) (Hulme *et al*. 2002) (Fig. 23). Some climate forecast scenarios predict stormier seas (Hulme *et al*. 2002).

Generalised linear models with cumulative logit link functions have been used to establish statistical relationships between environmental variables and the categorical abundance data for key species. Wave fetch and February SST successfully predict present day distributions for many species (Fig. 24). Where the match is less good the discrepancy between predicted and observed distributions highlights possible hydrographical barriers to dispersal or past historical events during recolonization of the Great Britain and Ireland after the last ice age. For example, the models predict that present day climate is suitable for *Osilinus lineatus* to occur around the west and south coasts of the Outer Hebrides but present day distribution is restricted to south-west England and Wales and around much of the Irish coast. *Osilinus lineatus* may not have made the 'jump' across to the Outer Hebrides from Ireland as conditions warmed after the last glacial maximum, or hydrographical barriers may exist which impede its spread northwards. These models have been extended to include effects of occupancy of neighbouring sites to account for vicariance effects.

It has also been possible to combine these statistical models with future climate change scenarios to forecast species distributions. Sea surface temperature projections for the 2020s, 2050s and 2080s have been incorporated into simulation models based on the statistical models including occupancy to predict likely future changes in species ranges. As an example, given present day relationships between abundance and wave fetch and SST (Fig. 24 top centre) and a 2 to 3°C rise in average February temperatures by the 2080s, the models predict an expansion of the range of the southern barnacle *Chthamalus stellatus* into the entire North Sea wherever suitable rocky habitat is present, a range extension over many 100s of km (Fig. 24 top right). In the same scenario, the northern species of kelp, *Alaria esculenta*, is predicted to retreat from coasts of south-west England and the coasts of western and southern Ireland (Fig. 24 bottom right).

The modelling exercise emphasizes the need to extend the surveys to the east coasts of Scotland and England for which there is little baseline data. This is essential in order to monitor future responses to climate change. Such an approach could also be used to model the outcomes of the NERC RAPID programme which is exploring the consequences of changes in the Atlantic Thermohaline Circulation.

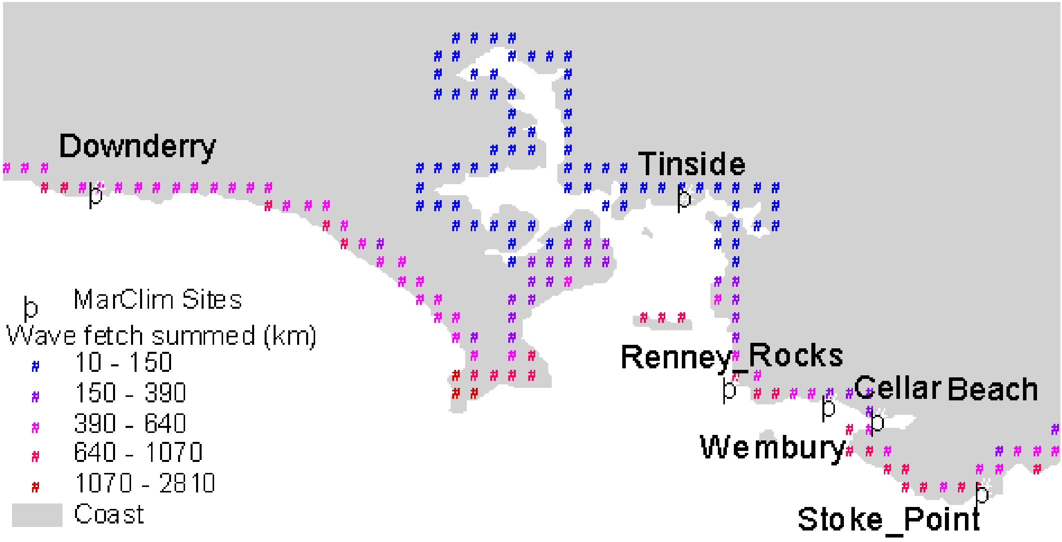


Fig. 22. Local wave exposure for 500m coastal grid squares calculated as the sum of the wave fetch in 16 sectors around each cell. Local wave action is an important predictor of abundance of most rocky shore species and may also vary as climate changes.

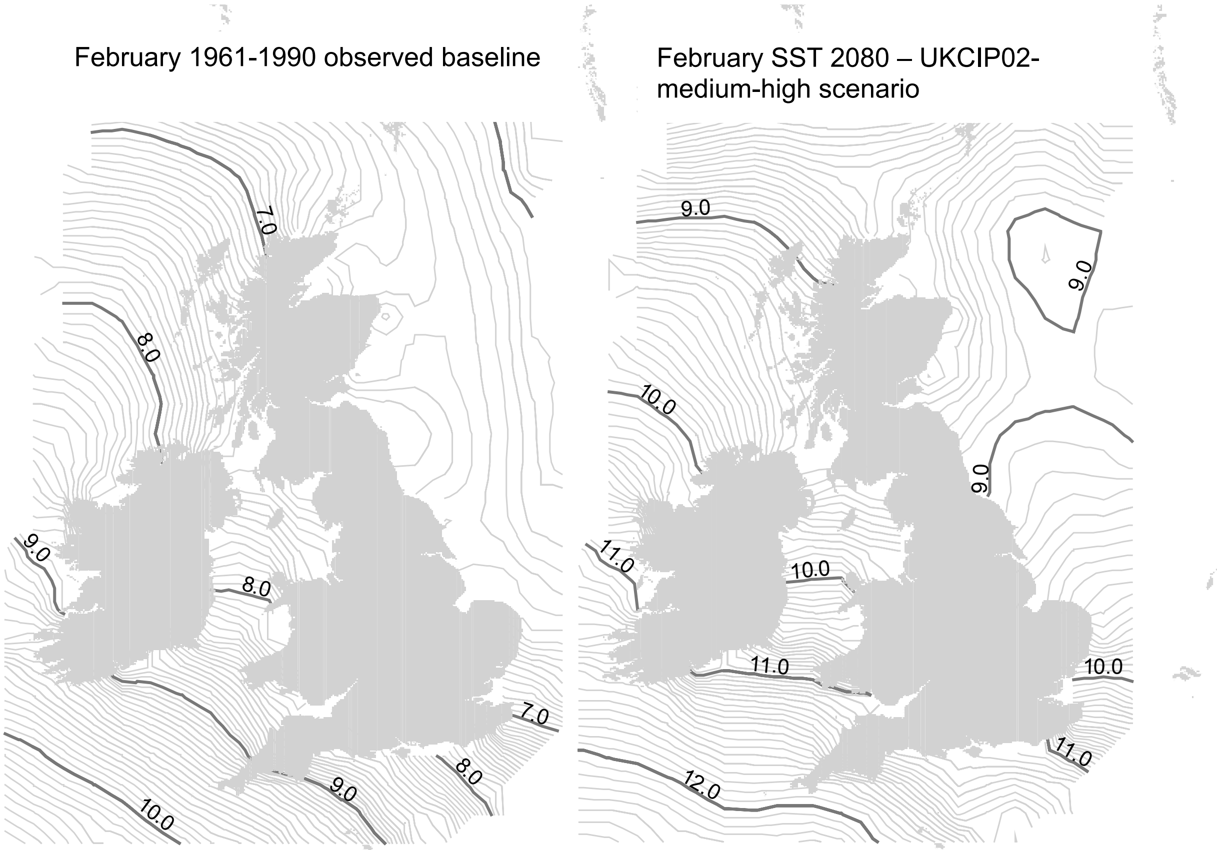
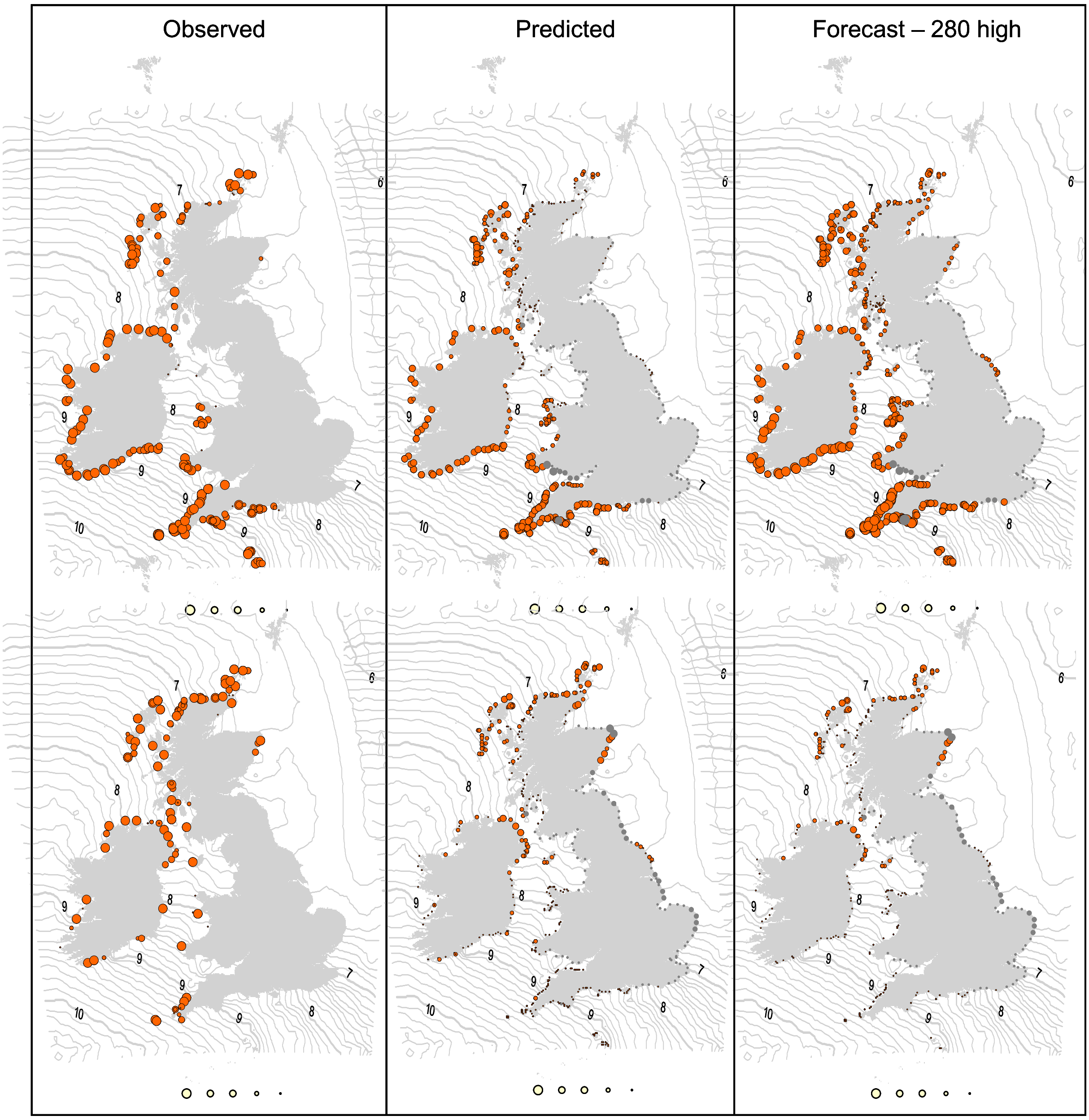


Fig. 23. Sea surface temperature in February (left) for 1961 to 1990, and (right) projected for the 2080s under the UKCIP02 Medium-High emissions scenario, showing a less than 2°C change on western coasts and over 3°C in the North Sea. Data are shown as downscaled isotherms from 50sq km gridded data provided by UKCIP.

a) *Chthamalus stellatus*, a southern barnacle found at wave-exposed sites



b) *Alaria esculenta*, a northern seaweed found at wave-exposed sites

Fig. 24. Observed distributions (left), distributions predicted from statistical models with February temperature and wave exposure (middle), and forecast distributions from models using the UKCIP 2080s high emissions scenario (right). Size of symbols indicates observed or likely abundance categories at each site surveyed between 2002 and 2004, and for simulated sites along un-surveyed coasts (grey circles).

10. Conclusions and Project Legacy

Main Conclusions:

- The MarClim project has demonstrated the importance of the rescue of historical broadscale and quantitative time series, available for rocky shores, in providing a baseline for the previously warm period (the 1950s up to the severe winter of 1962/63) against which to measure responses of biodiversity to current rapid climate change.

- Marine species, including plankton (Beaugrand *et al*. 2002, Beaugrand and Ibanez 2004, Edwards and Richardson 2004, Richardson and Schoeman 2004) and fish (Genner *et al*. 2004, Sims *et al*. 2004, Coombs *et al*. 2005, Perry *et al*. 2005, Southward *et al*. 2005) show rapid responses to alterations in climate. Such changes are also clearly seen and easily quantified for intertidal species (Herbert *et al*. 2003, Hiscock *et al*. 2004, Southward *et al*. 2005, Mieszkowska *et al*. 2006), providing sensitive indicators of environmental change.

- The rate at which the biogeographic limits of southern intertidal species are extending northwards and eastwards towards the colder North Sea is up to 50km per decade (e.g. *Gibbula umbilicalis* has extended its northern range limit along the north-east cost of Scotland by over 55km and by over 125km along the eastern English Channel since the 1980s), far exceeding the global average of 6.1km per decade in terrestrial systems (Parmesan and Yohe 2003, Root *et al*. 2003).

- It is likely that the northward range extensions observed in North Wales and those along the north coast of Scotland down into the North Sea have occurred in response to climatic warming increasing reproductive effort and juvenile survival success allowing these species to establish on suitable habitats.

- It is likely that range extensions along the eastern English Channel have occurred due to a combination of the proliferation of artificial sea defences along this coast providing suitable habitat where none was previously present and greater recruitment success of southern species in response to climatic warming.

- The increased abundance of some southern species, such as trochids, limpets and barnacles, is likely to have been the result of the earlier commencement (and in some cases prolonged) annual reproductive cycles in response to warmer springs, coupled with increased survival of newly settled recruits exposed to milder, shorter winters on the shore. These species may also be out-competing northern equivalents as climatic conditions become more suitable for their survival and less suitable for species with cold water affinities.

- Differential rates of range extensions and contractions are likely to result in a short-term increase in biodiversity on rocky shores close to the biogeographic boundary between cool/boreal and warm/lusitanian waters in Britain. However, as the climate continues to warm biodiversity is likely to return to previous levels as northern cold-water species ranges retract to be replaced by southern warm-water species resulting in different species compositions.

- Only sustained broadscale and long-term decadal observations can separate global environmental change from regional and localised impacts from the intrinsic natural spatial and temporal variability of marine ecosystems. Rocky shores provide an ideal sentinel system to monitor such changes in a cost effective manner.

Project Legacies

- Creation of the MarClim Data Archive as a central repository for historical and resurvey data records over a 60 year period, held in a standardised electronic format with site locations fully geo-referenced using the WGS84 reference frame. This dataset will expanded over time with repeat surveys and monitoring (data can be accessed via the National Biodiversity Network at www.searchnbn.net).

- All original data records have undergone extensive quality assurance checks in conjunction with the original data custodians or their surviving collaborators.

- Historical data for 4400 site visits at over 1000 locations are included in the MarClim electronic database (requests for data can be made by contacting the Marine Environmental Change Network (MECN) co-ordinator at www.mba.ac.uk/MECN).

- Between 2002 and 2004 the MarClim team completed a total over 800 site visits at over 470 individual site locations. Of these resurveys 177 were undertaken at sites for which historical data exist. Targeted work to fill gaps was done at over 40 sites in 2005.

- MarClim has ensured the long-term availability of data by storing all data records in National Biodiversity Network (NBN) format via the Marine Recorder front-end. This information will be made available through the MarClim Website that is maintained by *MarLIN* at the Marine Biological Association (www.mba.ac.uk/marclim).

- MarClim data can be imported to the NBN Gateway for dissemination to the wider scientific community through the Marine Life Information Network (*MarLIN*).

- Sampling protocols have been developed from the original methodology and trialled during the field phase of MarClim. They are available from the project website: www.mba.ac.uk/marclim.

- A fit-for-purpose network of 80 designated sites for which long-term data exists has been designed for future monitoring as part of a wider British marine monitoring programme. The monitoring network documents are available form the project website: www.mba.ac.uk/marclim

- Countryside Council for Wales have incorporated MarClim monitoring sites into their annual marine intertidal survey programme, and have adopted MarClim survey protocols to ensure continuation of the long-term data collection.

- Twenty peer-review manuscripts are published or have been submitted for publication (Appendix 2).

- Over 40 presentations have been made at international scientific conferences and policy orientated meetings and workshops (a selection of these presentations are given in Appendix 2; see the website for a full list).

- Models have been constructed to predict species current distribution patterns and forecast future changes in abundance and distribution based on sea surface temperature and wave action.

- Models of northern and southern barnacle populations have been constructed which broadly match historical datasets and can be used as a general proxy for forecasting other changes in biodiversity.

11. The Implications of Climate Change for Marine Stewardship Policy

This study highlights the scale and scope of climate change impacts on rocky shore biota over the last 60 years and in the future. These changes will need to be matched by changes in marine conservation policy.

The MarClim project has already generated increased awareness of marine climate change issues that has stimulated the production of climate change scenarios for the marine environment, as well as the creation of the Marine Climate Change Impact Partnership (MCCIP), which was officially launched by Elliot Morley (MP) in March 2005. A summary of the key messages is given below with more detail being provided by the accompanying report: *"The MarClim Project, key messages for decision makers and policy advisors, and recommendations for future administrative arrangements and management measures"* (Laffoley *et al*. 2005).

- **British & Irish leadership in assessing the impacts of climate change.** The MarClim database provides a globally unique cover of more than 50 temperature-sensitive seashore species over six decades, across the geographical scale of Britain and Ireland. Used alongside other sources of information, such as the Continuous Plankton Recorder (CPR) run by the Sir Alistair Hardy Foundation for Ocean Science (SAHFOS), this provides Britain and Ireland with a unique opportunity to become world leaders in the understanding of climate change induced trends and impacts on marine ecosystems.

- **The impacts of climate change are real, measurable and growing in extent**. MarClim demonstrates that climate-induced changes are occurring for a variety of intertidal and fish species and that it is a general effect not limited to smaller forms of marine life, such as plankton.

- **Provision of a robust baseline of information**. Whilst there are many other species whose distributions are temperature related, other than data for plankton, none have anywhere near the extensive and robust baseline of MarClim from which to determine future climate change trends and impacts. Results from MarClim, and other work on offshore benthic community datasets, suggest that changes to invertebrate and fish species distributions are also occurring in both coastal and offshore environments, and that these may affect offshore biodiversity as well as species of economic importance for the UK.

- **Offshore waters**. A priority for future study should be to extend the approach of MarClim into offshore waters, and predict the consequences of climate change for key habitats and species of economic and nature conservation importance.

- **The value and necessity of long-term data sets**. MarClim has demonstrated the considerable value of long-term data sets in understanding changes in marine ecosystems and the fundamental importance of a long-term commitment to continued data-collection for analysing climate induced changes in species geographic ranges and abundance.

- **The benefits of a consortium approach with a broad geographic coverage.** The broad geographic coverage enabled by the MarClim consortium, in bringing together relevant agencies and research institutes in the United Kingdom and the Republic of Ireland, has enabled north-south and east-west trends to be validated in a way that a narrower national territorial approach could not have achieved. These lessons are being transmitted to a wider European audience via the European Platform on Biodiversity Strategy Research, the marine board of the European Science Foundation, Climate Change Impacts on Marine Ecosystems working group and via networks developed as part of the E.U. Framework Programme Six of the Marine Biodiversity and Ecosystem Functioning network of excellence.

- **Developing indicators for marine and coastal biodiversity**. Intertidal species studied by MarClim should be included as part of the key indicator set for marine and coastal biodiversity: they are easy and cost effective to measure, are very responsive indicators of climate change signals, and are supported by extensive baseline information geographically dispersed across the islands of Great Britain and Ireland.

- **Factoring in marine climate change into day-to-day business**. The predicted scale and nature of marine climate change impacts needs to be built into how human activities are managed, conservation sites established, monitored, assessed and reported on the status of habitats, species and ecosystems, as well as the structuring of underlying legislation and policies.

- **A national priority for an integrated marine climate impacts monitoring programme**. The underlying monitoring work, which provides information used to understand and predict impacts of climate change, needs to be properly resourced and structured as a core element of a fully integrated programme. Given the importance of tracking climate change impacts and the sensitivity of the United Kingdom and the Republic of Ireland to changes in north Atlantic circulation patterns, developing and funding such an initiative should be seen as a national priority.

- **Future monitoring network**. Continued monitoring of rocky shore indicators of biodiversity responses to climate change should form an integral part of any monitoring network developed via the Marine Environmental Change Network (MECN) programme.

- **Developing streamlined reporting to Government**. The unique value of MarClim data can be increased further by drawing it together with the results of other relevant marine climate change impact projects and programmes (such as SAHFOS for plankton) to provide a streamlined, coordinated and effective reporting framework to deliver key messages *quickly* to Government and the general public on a regular and possibly annual basis – the concept of ‘annual report cards’

12. Literature Cited

Allen, B. M., A. M. Power, R. M. O' Riordan, A. A. Myers, and D. McGrath. in press. Increases in the abundance of the invasive barnacle *Elminius modestus* Darwin in Ireland. *Biology and Environment*.

Beaugrand, G., and F. Ibanez. 2004. Monitoring marine plankton ecosystems. II: Long-term changes in North Sea calanoid copepods in relation to hydro-climatic variability. *Marine Ecology Progress Series* **284**:35-47.

Beaugrand, G., P. C. Reid, F. Ibanez, J. A. Lindley, and M. Edwards. 2002. Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* **296**:1692-1694.

Bertness, M. D., G. H. Leonard, J. M. Levine, and J. F. Bruno. 1999. Climate-driven interactions among rocky intertidal organisms caught between a rock and a hot place. *Oecologia* **120**:446-450.

Bode, A., I. Lombas, and N. Anadon. 1986. Preliminary studies on the reproduction and population dynamics of *Monodonta lineata* and *Gibbula umbilicalis* (Mollusca, Gastropoda) on the central coast of Asturias (N. Spain). *Hydrobiologia* **142**:31-39.

Bottomley, M., C. K. Folland, J. Hsiung, R. E. Newell, K. B. Armitage, and D. E. Parker. 1990. *Global ocean surface temperature atlas "GOSTA"*, Meteorological Office, Bracknell, UK and the Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA.

Bowman, R. S. L., J.R. 1986. Geographical variation in the breeding cycles and recruitment of *Patella* spp. *Hydrobiologia* **142**:41-56.

Burrows, M. T., J. Moore, and B. James. 2002. Spatial scale synchrony of population changes in rocky shore communities in Shetland: implications for monitoring. *Marine Ecology Progress Series* **240**:39-48.

Case, T. J., R. D. Holt, M. A. McPeek, and T. H. Keitt. 2005. The community context of species' borders: ecological and evolutionary perspectives. *Oikos* **108**: 28-46.

Climatic Research Unit news release. 16th December 2004. Another warm year. *in* http://www.cru.uea.ac.uk/cru/press/2004-12-another-warm-year/.

Connell, J. H. 1961. The influence of interspecific competition and other factors on the distribution of the barnacle *Chthamalus stellatus*. *Ecology* **42**:710-723.

Coombs, S. H., N. C. Halliday, A. J. Southward, and S. J. Hawkins. 2005. Distribution and abundance of sardine (*Sardina pilchardus*) eggs in the English Channel from Continuous Plankton Recorder sampling, 1958-1980. *Journal of the Marine Biological Association of the U.K.* **85**:1243-1247.

Crisp, D. J. 1950. Breeding and distribution of *Chthamalus stellatus*. *Nature* **166**:311.

Crisp, D. J. 1964. The effects of the severe winter of 1962-63 on marine life in Britain. *Journal of Animal Ecology* **33**:165-210.

Crisp, D. J., and P. N. J. Chipperfield. 1948. Occurence of *Elminius modestus* (Darwin) in British waters. Nature **161**:64.

Crisp, D. J., and E. Fischer-Piette. 1959. Repartition des principales especes intercotidales de la cote Atlantique Francaise en 1954-1955. *Annales De L Institut Oceanographique* **36**:275-387.

Crisp, D. J., and E. W. Knight-Jones. 1954. *Discontinuities in the distribution of shore animals in North Wales.* Report of the Bardsey Observatory **2**:29-34.

Crisp, D. J., and A. J. Southward. 1958. The distribution of intertidal organisms along the coasts of the English Channel. *Journal of the Marine Biological Association of the U.K.* **37**:157-208.

Crisp, D. J., A. J. Southward, and E. C. Southward. 1981. On the distribution of the intertidal barnacles *Chthamalus stellatus*, *Chthamalus montagui* and *Euraphia depressa*. *Journal of the Marine Biological Association of the U.K.* **61**:359-380.

Davis, A. J., L. S. Jenkinson, J. H. Lawton, B. Shorrocks, and S. Wood. 1998. Making mistakes when predicting shifts in species range in response to global warming. *Nature* **391**:783-786.

Desai, B. N. 1966. The biology of *Monodonta lineata* (da Costa). *Proceedings of the Malocological Society London* **37**:1-17.

Edwards, M., and A. J. Richardson. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* **430**:881-884.

Fields, P. A., J. B. Graham, R. H. Rosenblatt, and G. N. Somero. 1993. Effects of expected global climate change on marine faunas. *Trends in Evolution and Ecology* **8**:361-367.

Fischer-Piette, E. 1933. Le contour géographique des côtes françaises et anglaises de la Manche et la répartition de *Mytilus edulis* et *Balanus perforatus*. *Comptes Rendus de la Société de Biogéographie* **86**:70-72.

Fischer-Piette, E. 1936. Études sur la biogéographie intercôtidale des deux rives de la Manche. *Journal of the Linnean Society, Zoology* **40**:181-272.

Fischer-Piette, E. 1948. Sur les elements de prosperite des Patelles et sur leur specificite. *Journal de Conchyliologie* **88**:45-96.

Fischer-Piette, E., and M. Prenant. 1956. Distribution des Cirripèdes intercôtidaux d'Espagne septentrionale. *Bulletin du Centrre d'Études et de Recherches Scientifiques, Biarritz* **1**:7-19.

Forbes. 1858. *The natural history of Europes seas.* Pages 99-101 *in* A.K. Johnston's Physical Atlas. W & AK Johnston, Edinburgh.

Genner, M. J., D. W. Sims, V. J. Wearmouth, E. J. Southall, A. J. Southward, P. A. Henderson, and S. J. Hawkins. 2004. Regional climatic warming drives long-term community changes of British marine fish. *Proceedings of the Royal Society London, Series B* **271**:655-661.

Grabherr, G., M. Gottfried, and H. Pauli. 1994. Climate effects on mountain plants. *Nature* **369**: 448.

Graham, R. W., and E. C. Grimm. 1990. Effects of global climate change on the patterns of terrestrial biological communities. *Trends in Evolution and Ecology* **5**:289-292.

Harvey, W. H. 1846-1851. *A Manual of the British Algae*. Reeve & Benham, London.

Hawkins, S. J., P. E. Gibbs, N. D. Pope, G. R. Burt, B. S. Chesman, S. Bray, S. V. Proud, S. K. Spencer, A. J. Southward, and W. J. Langston. 2002. Recovery of polluted ecosystems: the case for long-term studies. *Marine Environmental Research* **54**:215-222.

Hawkins, S. J., A. J. Southward, and M. J. Genner. 2003. Detection of environmental change in a marine ecosystem - evidence from the western English Channel. *Science of the Total Environment* **310**:245-256.
Hawthorne, J. B. 1965. The eastern limit of distribution of *Monodonta lineata* (da Costa) in the English Channel. *Journal of Conchology* **25**:348-352.
Helmuth, B., J. G. Kingsolver, and E. Carrington. 2005. Biophysics, physiological ecology and climate change: does mechanism matter? *Annual Review of Physiology* **67**:177-202.
Herbert, R. J. H., S. J. Hawkins, M. Sheader, and A. J. Southward. 2003. Range extension and reproduction of the barnacle *Balanus perforatus* in the eastern English Channel. *Journal of the Marine Biological Association of the U.K.* **83**:73-82.
Hiscock, K., A. J. Southward, I. Tittley, and S. J. Hawkins. 2004. Effects of changing temperature on benthic marine life in Britain and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems* **14**:333-362.
Holt, T. J., D. R. Jones, S. J. Hawkins, and R. G. Hartnoll. 1995. *The sensitivity of marine communities to man-induced change - a scoping report. Countryside Council for Wales* (FC 73-01-96).
Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Eds. 2001. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press,, Cambridge, U.K. & New York, U.S.A.
Hulme, M., G. J. Jenkins, X. Lu, J. R. Turnpenny, T. D. Mitchell, R. G. Jones, J. Lowe, J. M. Murphy, D. Hassell, P. Boorman, R. McDonald, and S. Hill. 2002. *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report.* Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.
Inouye, D. W., B. Barr, K. B. Armitage, and B. D. Inouye. 2000. Climate change is affecting altitudinal migrants and hibernating species. *Proceedings of the National Academy of Sciences, USA* **97**:1630-1633.
Johnstone, W. G., and A. Croall. 1860. *The Nature Printed British Seaweeds*. Bradbury & Evans, London.
Kendall, M. A. 1987. The age and size structure of some Northern populations of the trochid gastropod *Monodonta lineata*. *Journal of Molluscan Studies* **53**:213-222.
Kendall, M. A., M. T. Burrows, A. J. Southward, and S. J. Hawkins. 2004. Predicting the effects of marine climate change on the invertebrate prey of the birds of rocky shores. *Ibis* **146**:40-47.
Kendall, M. A., and J. R. Lewis. 1986. Temporal and spatial patterns in the recruitment of *Gibbula umbilicalis*. *Hydrobiologia* **142**:15-22.
Laffoley, D., J. Baxter, G. O'Sullivan, B. Greenaway, M. Colley, L. Naylor, and J. Hamer. 2005. The MarClim Project: Key messages for decision makers and policy advisors, and recommendations for future administrative arrangements and management measures. *English Nature Research Reports,* No. 671.
Lewis, J. R. 1964. *The Ecology of Rocky Shores*. English Universities Press, London.
Lewis, J. R. 1976. Long-term ecological surveillance: practical realities in the rocky littoral. *Oceanography and Marine Biology Annual Review.* **14**:371-390.
Lewis, J. R. 1986. Latitudinal trends in reproduction, recruitment and population characteristics of some rocky littoral molluscs and cirripedes. *Hydrobiologia* **142**:1-13.
Lewis, J. R. 1996. Coastal benthos and global warming: strategies and problems. *Marine Pollution Bulletin* **32**:698-700.
Little, C., and J. A. Kitching. 1996. *The biology of Rocky Shores*, 1st edition. Oxford University Press, Oxford.
Mieszkowska, N. 2005. *Changes in the biogeographic distribution of the trochid gastropods* Osilinus lineatus *(da Costa) and* Gibbula umbilicalis *(da Costa) in response to global climate change: range dynamics and physiological mechanisms*. PhD. University of Plymouth, Plymouth.
Mieszkowska, N., G. T. Boalch, and S. J. Hawkins. in prep. Changes in the biogeographic range of *Bifurcaria bifurcata* in the English Channel. *Botanica Marina*.
Mieszkowska, N., M. A. Kendall, S. J. Hawkins, R. Leaper, P. Williamson, N. J. Hardman-Mountford, and A. J. Southward. 2006. Changes in the range of some common rocky shore species in Britain - a response to climate change? *Hydrobiologia* **555**:241-251.
Mieszkowska, N., M. A. Kendall, J. R. Lewis, Richardson. A.J., P. Williamson, and S. J. Hawkins. in review. Range expansion of the southern trochid gastropod *Gibbula umbilicalis* during recent climate warming. *Journal of Biogeography*.
Moore, H. B. 1936. The biology of *Balanoides balanoides*. V. Distribution in the Plymouth area. *Journal of the Marine Biological Association of the U.K.* **20**: 701-716.
Moore, H. B., and J. A. Kitching. 1939. The biology of *Chthamalus stellatus* Poli. *Journal of the Marine Biological Association of the U.K.* **23**:521-451.
Moore, P., S. J. Hawkins, and R. C. Thompson. in review. Different behaviours of congeneric species modulate the role of habitat ameliortaion in a changing climate. *Marine Ecology Progress Series*.
Moore, P. J. 2005. *The role of biological interactions in modifying the effects of climate change on intertidal assemblages.* University of Plymouth, Plymouth.
Oreskes, N. 2004. The scientific consensus on climate change. *Science* **306**:1686.
Orton, J. H., A. J. Southward, and J. M. Dodd. 1956. Studies on the biology of limpets. II. The breeding of *Patella vulgata* L. in Britain. *Journal of the Marine Biological Association of the U.K.* **35**:149-176.
Parmesan, C. 1996. Climate and species' range. *Nature* **382**:765-766.
Parmesan, C., S. Gaines, L. Gonzales, D. M. Kaufman, J. Kingsolver, A. T. Peterson, and R. Sagarin. 2005. Empirical perspective on species borders: from traditional biogeography to global change. *Oikos* **108**:58-75.
Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**:37-42.
Perry, A. L., P. J. Low, J. R. Ellis, and J. D. Reynolds. 2005. Climate change and distribution shifts in marine fishes. *Science* **308**:1912-1915.
Poloczanska, E. S., S. J. Hawkins, A. J. Southward, and M. T. Burrows. in review. Modelling intertidal barnacle population response to climate change: Hindcast, forecast and prediction. Global Change Biology.

Raffaelli, D., and S. J. Hawkins. 1999. *Intertidal Ecology*, Second edition edition. Kluwer AcademicPublishers, Dordrecht.

Réale, D., A. G. McAdam, S. Boutin, and D. Berteaux. 2003. Genetic and plastic responses of a northern mammal to climate change. *Proceedings of the Royal Society of London, Series B* **270**:591-596.

Richardson, A. J., and D. S. Schoeman. 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. *Science* **305**:1609-1612.

Root, T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig, and A. Pounds. 2003. Fingerprints of global warming on wild animals and plants. *Nature* **421**:57-60.

Sagarin, R. D., J. P. Barry, S. E. Gilman, and C. H. Baxter. 1999. Climate-related change in an intertidal community over short and long time scales. *Ecological Monographs* **69**:465-490.

Simkanin, C., A.-M. Power, A. A. Myers, D. McGrath, A. Southward, N. Mieszkowska, R. Leaper, and R. M. O'Riordan. 2005. Using historical data to detect temporal changes in the abundances of intertidal species on Irish shores. *Journal of the Marine Biological Association of the U.K.* **85**:1329-1340.

Sims, D. W., M. J. Genner, A. J. Southward, and S. J. Hawkins. 2001. Timing of squid migration reflects North Atlantic climate variability. *Proceedings of the Royal Society of London, Series B: Biological Sciences* **268**:2607-2611.

Sims, D. W., V. J. Wearmouth, M. J. Genner, A. J. Southward, and S. J. Hawkins. 2004. Low-temperature-driven early spawning migration of a temperate marine fish. *Journal of Animal Ecology* **73**:333-341.

Southward, A. J. 1950. Occurrence of *Chthamalus stellatus* in the Isle of Man. *Nature* **165**:408.

Southward, A. J. 1951. Distribution of *Chthamalus stellatus* in the Irish Sea. *Nature* **167**:410-411.

Southward, A. J. 1963. The distribution of some plankton animals in the English Channel and approaches 3 theories about long-term biological changes, including fish. *Journal of the Marine Biological Association, U.K.* **43**:1-29.

Southward, A. J. 1967. Recent changes in abundance of intertidal barnacles in south-west England: a possible effect of climatic deterioration. *Journal of the Marine Biological Association, U.K.* **47**:81-95.

Southward, A. J. 1991. Forty years of changes in species composition and population density of barnacles on a rocky shore near Plymouth. *Journal of the Marine Biological Association, U.K.* **71**:495-513.

Southward, A. J., and D. J. Crisp. 1952. Changes in the distribution of the intertidal barnacles in relation to the environment. *Nature* **170**:416-417.

Southward, A. J., and D. J. Crisp. 1954a. Recent changes in the distribution of the intertidal barnacles *Chthamalus stellatus* Poli and *Balanus balanoides* in the British Isles. *Journal of Animal Ecology* **23**: 163-177.

Southward, A. J., and D. J. Crisp. 1954b. The distribution of certain intertidal animals around the Irish coast. *Proceedings of the Royal Irish Academy* **57**:1-29.

Southward, A. J., and D. J. Crisp. 1956. Fluctuations in the distribution and abundance of intertidal barnacles. *Journal of the Marine Biological Association of the U.K.* **35**:211-229.

Southward, A. J., S. J. Hawkins, and M. T. Burrows. 1995. Seventy years' observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature. *Journal of Thermal Biology* **20**:127-155.

Southward, A. J., O. Langmead, N. J. Hardman-Mountford, J. Aiken, G. T. Boalch, P. R. Dando, M. J. Genner, I. Joint, M. A. Kendall, N. C. Halliday, R. P. Harris, R. Leaper, N. Mieszkowska, R. D. Pingree, A. J. Richardson, D. W. Sims, T. Smith, A. W. Walne, and S. J. Hawkins. 2005. Long-term oceanographic and ecological research in the Western English Channel. *Advances in Marine Biology* **47**:1-105.

Stephenson, T. A., and A. Stephenson. 1972. *Life between tidemarks on rocky shores*. W.H. Freeman, San Francisco.

Svensson, C. J., S. R. Jenkins, S. J. Hawkins, and P. Aberg. 2005. Population resistance to climate change: modelling the effects of low recruitment in open populations. *Oecologia* **142**:117-126.

Thomas, C. D., A. Cameron, R. E. Green, M. Bakkenes, L. J. Beaumont, Y. C. Collingham, B. F. N. Erasmus, M. F. de Siqueria, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. S. van Jaarsveld, G. F. Midgley, L. Miles, M. A. Ortega-Huerta, A. Townsend Peterson, O. L. Phillips, and S. E. Williams. 2004. Extinction risk from climate change. *Nature* **427**:145- 148.

Vance, T. 2004. *Loss of the northern species* Alaria esculenta *from Southwest Britain and the implications for macroalgal succession*. University of Plymouth, Plymouth.

Walther, G. R., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J. C. Beebee, J. M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. *Nature* **416**:389-395.

Williams, E. E. 1964. The growth and distribution of *Gibbula umbilicalis* (da Costa) on a rocky shore in Wales. *Journal of Animal Ecology* **33**.

Williams, E. E. 1965. The growth and distribution of *Monodonta lineata* (da Costa) on a rocky shore in Wales. *Field Studies* **2**:189-198.

Williamson, P., M. A. Kendall, and J. R. Lewis. in press. Transplant experiments for *Osilinus lineatus* (Gastropoda: Trochacea) at the northern limits of its range. *Journal of the Marine Biological Association of the U.K.*

Woehrling, D., A. Lefebvre, G. Le Fevre-Lehorff, and R. Delesmont. 2005. Seasonal and longer term trends in sea temperature along the French North Sea coast 1975 to 2002. *Journal of the Marine Biological Association of the U.K.* **85**:39-48.

Appendix 1. ACFOR abundance categories used by Southward & Crisp (1954b) and by the MarClim project for their broadscale resurveys.

Species	Abundance Category				
	Abundant	**Common**	**Frequent**	**Occasional**	**Rare**
Barnacles					
Chthamalus stellatus, Chthamalus montagui, Semibalanus balanoides, Elminius modestus	More than 1 per cm^2; rocks well covered	0.1-1.0 per cm^2; up to 1/3 of rock space covered	0.01-0.1 per cm^2; individuals never more than 10cm apart	0.0001-0.01 per cm^2; few within 10cm of each other	Less than 1 per m^2; only a few found in 30 min searching
Balanus perforatus	Over 0.1 per cm^2; close groups on most vertical faces, often up to MTL	0.01 to 0.1 per cm^2; adjacent groups, not always above LWN	Less than 0.01 per cm^2; adjacent in crevices	Less than 0.01 per cm^2; rarely adjacent even in crevices	Only a few found in 30 min searching
Limpets					
Patella vulgata, Patella depressa, Patella aspera	Over 50 per m^2 or more than 50% of limpets at certain levels	10-50 per m^2, 10% to 50% at certain levels	1 to 10 per m^2, 1% to 10% at certain levels	Less than 1 per m^2 on average, less than 1% of population	Only a few found in 30 min searching
Topshells					
Osilinus lineatus, Gibbula umbilicalis, Gibbula pennanti	Exceeding 10 per m^2 generally	1-10 per m^2, sometimes very locally over 10 per m^2	Less than 1 per m^2, locally sometimes more	Always less than 1 per m^2	Only a few found in 30 min searching
Periwinkles					
Littorina saxatilis agg., Littorina obtusata/mariae Melaraphe neritoides	Over 1.0 per cm^2 at HW, extending down the midlittoral zone	0.1-1.0 per cm^2, mainly in the supralittoral fringe	Less than 0.1 per cm^2, in crevices		Only a few found in 30 min searching
Littorina littorea	More than 50 per m^2	10 – 50 per m^2	1 – 10 per m^2		Only a few found in 30 min searching
Anemones					
Actinia equina, Actinia fragracea, Anemonia viridis, Bunodactis verrucosa	Many in almost every pool and damp place	Groups in pools and damp places	Isolated specimens in few pools		A small number, usually under 10, found after 30 min searching
Algae					
	>30%	5-30%	<5%	Scattered individuals	Few plants 30 min search

Appendix 2. Publications by the MarClim team 2001-2005 and additional climate research by the MBA and Collaborators.
Direct support by the MarClim project and SNH, MAFF/Defra precursors are asterisked.

Refereed Papers

* Burrows, M.T., Moore, J., & James, B. 2002. Spatial scale synchrony of population changes in rocky shore communities in Shetland: implications for monitoring. *Marine Ecology Progress Series* **240**: 39-48.

* Coombs, S.H., Halliday, N.C., Southward, A.J. & Hawkins, S.J. 2005. Distribution and abundance of sardine (*Sardina pilchardus*) eggs in the English Channel from Continuous Plankton Recorder sampling, 1958-1980. *Journal of the Marine Biological Association of the UK*, **85**: 1243-1247

* Genner, M.J., Sims, D.W., Wearmouth, V.J., Southall, E.J., Southward, A.J., Henderson, P.A. & Hawkins, S.J., 2004. Regional climatic warming drives long-term community changes of British marine fish. *Proceedings of the Royal Society of London, Biological Sciences*, **271**: 655-661.

* Hardman-Mountford, N.J., Allen, J.I., Frost, M.T., Hawkins, S.J., Kendall, M.A., Mieszkowska, N., Richardson, K.A. & Somerfield, P.J. (2005). Diagnostic monitoring of a changing environment: An alternative U.K. perspective. *Marine Pollution Bulletin* **50**: 1463-1471.

* Hawkins, SJ, Southward, A.J. & Genner M.J. (2003). Detection of environmental change in a marine ecosystem-evidence from the western English Channel. *Science of the Total Environment*, **310**: 245-56.

* Hawkins, S.J., Gibbs, P.E., Pope, N.D. Burt, G.R., Chesman, B.S., Bray, S., Proud, S.V., Spence, S.K., Southward, A. J. & Langston, W.J. (2002). Recovery of polluted ecosystems: the case for long-term studies. *Marine Environmental Research*, **54**: 215-222.

* Herbert, R.J.H., Hawkins, S.J., Sheader, M. & Southward, A.J. (2003). Range extension and reproduction of the barnacle *Balanus perforatus* in the eastern English Channel. *Journal of the Marine Biological Association of the UK,* **83**: 73-82.

* Herbert, R.J.H., Southward, A.J., Sheader, M. & Hawkins, S.J. (in press). Influence of recruitment and temperature on distribution of intertidal barnacles in the English Channel. *Journal of the Marine Biological Association of the UK*.

* Hiscock, K., Southward, A.J., Tittley, I. & Hawkins, S.J. (2004). Effect of changing temperature on benthic marine life in Britain and Ireland. *Aquatic Conservation* **14**: 333-362.

* Kendall, M.A., Hawkins, S.J., Burrows, M.T. & Southward, A.J. (2004). Predicting the effects of marine climate change on the invertebrate prey of the birds of rocky shores. *Ibis (Special Edition)* **146**: 40-47.

* Lima, F.P., Queiroz, N., Ribeiro, P.A., Hawkins, S.J. & Santos, A.M. (in press). Geographic expansion of a marine gastropod, *Patella rustica* Linnaeus, 1758, and its relation with unusual climatic events. *Journal of Biogeography*

* Mieszkowska, N, Kendall, M.A., Hawkins, S.J., Leaper, R., Williamson, P., Hardman-Mountford, N.J. & Southward, A.J. (2006). Changes in the range of some common rocky shore species in Britain - a response to climate change? *Hydrobiologia* **555**: 241-251.

* Sims, D.W., Genner, M.J., Southward, A.J. & S.J. Hawkins, 2001. Timing of squid migration reflects North Atlantic climate variability. *Proceedings of the Royal Society of London - Series B* **268**: 2607-2611.

* Sims, D.W., Wearmouth, V.J., Genner, M.J., Southward, A.J. & Hawkins, S.J., 2004. Low-temperature-driven early spawning migration of a temperate marine fish. *Journal of Animal Ecology* **73**: 333-341.

* Southward, A.J., Langmead, O., Hardman-Mountford, N.J., Aiken, J., Boalch, G.T., Dando, P.R., Genner, M.J., Joint, I., Kendall, M.A., Halliday, N.C., Harris, R.P., Leaper, R., Mieszkowska, N., Pingree, R.D., Richardson, A.J., Sims, D.W., Smith, T., Walne, A.W. & Hawkins, S.J. (2005). Long-term oceanographic and ecological research in the western English Channel. *Advances in Marine Biology* **47**: 1-105.

* Simkanin, C.S., Power, A-M., Davenport, J., Myers, A.A. & McGrath, D. (2003). Monitoring intertidal community change in a warming world. *The Irish Scientist 2003 Yearbook* May 2003. Samton Limited.

Svensson, C.J., Jenkins, S.R., Hawkins, S.J. & Aberg, P. (2005). Population resistance to climate change: modelling the effects of low recruitment in open populations. *Oecologia* **142**: 117-126.

* Thompson R.C., Crowe, T.P, & Hawkins, S.J. (2002). Rocky intertidal communities: past environmental changes, present status and predictions for the next 25 years. *Environmental Conservation*. **29**(2): 168-191.

Submitted Papers

* Mieszkowska, N., Kendall, M.A., Lewis, J.R., Richardson, A.J. & Hawkins, S.J. (in review). Range expansion of the southern trochid gastropod *Gibbula umbilicalus* during recent climate warming. *Journal of Biogeography*

* Moore, P., Hawkins, S.J. & Thompson, R.C. (in review). Different behaviours of congeneric species modulate the role of habitat amelioration in a changing climate. *Marine Ecology Progress Series*

* Poloczanska, E.S., Hawkins, S.J., Southward, A.J. & Burrows, M.T. (in review). Modelling intertidal barnacle population response to climate change: Hindcast, forecast and prediction. *Global Change Biology*

In Preparation

Kendall, M.A., Mieszkowska, N., Burrows, M.T., Laffoley, D. & Hawkins, S.J. (in prep). Can we use intertidal species as indicators of climate change. Invited paper to *Marine Pollution Bulletin*.

Mieszkowska, N., Boalch, G.T. & Hawkins, S.J. (in prep). Changes in the biogeographic range of *Bifurcaria bifurcata* in the English Channel.

Moore, P., Hawkins, S.J. & Thompson, R.C. (in prep). Species identity affects the outcome of grazer interactions with canopy forming macroalgae.

Poloczanska, E.S., Hawkins, S.J., Mieszkowska, N, Kendall, M.A., Leaper, R, Southward, A.J., Simkanin, C., Power, A-M. and Burrows, M.T. (in prep). Distributions of intertidal sea anemones around British and Irish coasts: past, present and future?

Theses

Mieszkowska, N. (2005). Changes in the biogeographic distribution of the trochid gastropods *Osilinus lineatus* (da Costa) and *Gibbula umbilicalis* (da Costa) in response to global climate change: range dynamics and physiological mechanisms. Ph.D. Thesis, University of Plymouth. p146

Moore, P.J. (2005). The role of biological interactions in modifying the effects of climate change on intertidal assemblages. Ph.D. Thesis, University of Plymouth. p126

Vance, T. (2004). Loss of the northern species *Alaria esculenta* from Southwest Britain and the implications for macroalgal succession. MRES Thesis, University of Plymouth.

Reports and Semi-popular Publications

Cannell, M., Brown, T., Sparks, T., Marsh, T., Parr, T., George, G., Palutikof, J., Lister, D., Dockerty, T. & Leaper, R. (2003). Review of UK Climate Change Indicators. *DEFRA Contract Report No. EPG 1/1/158.*

Frost, M. T., Leaper, R., Mieszkowska, N., Moschella, P., Murua, J., Smyth, C. & Hawkins, S. J. (2004). Recovery of a Biodiversity Action Plan species in northwest England: possible role of climate change, artificial habitat and water quality amelioration. *Confidential Report to English Nature, The Marine Biological Association.*

Kendall, M. A. (2002). MarClim – Marine Biodiversity and Climate Change. *Report to BIOMARE Newsletter*, p10, Autumn 2002 Issue.

Laffoley, D., Baxter, J., O'Sullivan, G., Greenaway, B., Colley, M., Naylor, L. & Hamer, J. 2005 The MarClim Project: Key messages for decision makers and policy advisors, and recommendations for future administrative arrangements and management measures. *English Nature Research Reports*, No. 671.

Leaper, R. (2003). Intertidal species as indicators responses of biodiversity to rapid climate change in UK marine ecosystems. *Report to the Marine Biological Association Newsletter*, p8, April 2003 Issue.

Mieszkowska, N., (2003). *Osilinus lineatus*. Thick top shell. *Marine Life Information Network: Biology and Sensitivity Key Information Sub-programme* [on-line]. Plymouth: Marine Biological Association of the United Kingdom.

Moore, P., Hawkins, S.J., Hiscock, K. & Southward, A.J. (Winter 2006). A Sea of Change. The Edge – The magazine of CoastNET.

Presentations: Lectures, seminars, workshops and public events

Results from the MarClim project were disseminated via presentations to a broad audience including the wider scientific community, policymakers, stakeholders and the general public. Below is a selected list of presentations given by the MarClim team over the course of the project. A full list of presentations given can be viewed at www.mba.ac.uk/marclim.

P.J. Moore, S.J. Hawkins, M. J. Genner, D. W. Sims, M. Burrows, E. S. Poloczanska, N. Mieszkowska, K. Hiscock & A. J. Southward. 'Climate change – impact on biodiversity and ecosystems'. Devon Living Coasts Conference, Met Office, Exeter, Oct 2005.

S.J. Hawkins, G. Beaugrand, P.C. Reid, M. J. Genner, D. W. Sims, M. Burrows, E. S. Poloczanska, N. Mieszkowska, P.S. Moschella & A. J. Southward. 'Climate Change Impacts on Marine Biodiversity and Ecosystems'. European Platform for Biodiversity Research Strategy, Hosted by DEFRA and the Scottish Executive as part of the UK presidency of the EU, Aviemore, Scotland, Oct 2005

S.J. Hawkins, M. J. Genner, D. W. Sims, M. Burrows, N. Mieszkowska, S. R. Jenkins, R. Leaper, M. Frost, P. S. Moschella, P. Masterson & A. J. Southward. 'The combined influences of global environmental change and regional and local impacts on English Channel ecosystems'. Invited Speaker on section to inform Marine Bill considerations. British Ecological Society Annual Meeting, University of Hertfordshire, Sept 2005.

M.T. Frost, K. Hiscock, N. Mieszkowska & S.J. Hawkins 'Long-term monitoring and data collection projects hosted by the MBA: The UK Marine Environmental Change Network (MECN), Marine Life Information Network for Britain and Ireland (*MarLIN*) and Marine Biodiversity and Climate Change project (MarClim)'. Long Term and Large Scale Management of Marine Biodiversity Information: MarBEF workshop, Helgoland. Mar 2005.

N. Mieszkowska, S.J. Hawkins, M.T. Burrows, M.A. Kendall, R. Leaper, E. S. Poloczanska & A.J. Southward. 'Accounting for climate change in monitoring intertidal communities in Wales'. Invited Speaker. Countryside Council for Wales Marine Monitoring Workshop, Aberystwyth Oct 2004.

N. Mieszkowska, S.J. Hawkins, M.T. Burrows, M.A. Kendall, R. Leaper, E. S. Poloczanska & A.J. Southward. 'MarClim Marine Biodiversity and Climate Change research in Britain'. National Science Foundation (USA) network to co-ordinate research on the North Atlantic (CORONA), Plymouth July 2004.

S.J. Hawkins, M.J. Genner, D.W. Sims & A.J. Southward. 'Climate driven change in the Western English Channel Ecosystem'. Invited presentation. Climate Change and Aquatic Systems: Past, Present & Future. British Ecological Society, Marine Biological Association and Freshwater Biological Association, University of Plymouth, U.K. 21st-23rd July 2004

R. Leaper & A.J. Southward. 'Detecting a signal from noise: retrospective analysis of intertidal communities over a period of major climate fluctuation'. Climate Change and Aquatic Systems: Past, Present & Future. British Ecological Society, Marine Biological Association and Freshwater Biological Association, University of Plymouth, U.K., July 2004

N. Mieszkowska, S.J. Hawkins, R.C. Thompson & M.A. Kendall. 'Is climate change driving increased reproductive success in British trochid gastropods?' Climate Change and Aquatic Systems: Past, Present & Future. British Ecological Society, Marine Biological Association and Freshwater Biological Association, University of Plymouth, U.K., July 2004.

E.S Poloczanska, M.T Burrows & S.J Hawkins. 'Barnacles and Climate Change'. Climate Change and Aquatic Systems: Past, Present & Future. British Ecological Society, Marine Biological Association and Freshwater Biological Association, University of Plymouth, U.K., July 2004

P. Moore, S.J. Hawkins & R.C. Thompson. ‚Ecological complexity places climate envelope in the shade'. Climate Change and Aquatic Systems: Past, Present & Future. British Ecological Society, Marine Biological Association and Freshwater Biological Association, University of Plymouth, U.K., July 2004

S.J. Hawkins, M.J. Genner, D.W. Sims & A.J. Southward. Gaia and Global Change hosted by James Lovelock: 'Changes in marine life in the English Channel in response to climate and fishing pressure'. Invited speaker. Dartington, UK, Jun 2004.

N. Mieszkowska, S.J. Hawkins, M.T. Burrows, M.A. Kendall, R. Leaper & A.J. Southward. 'Application of the Marine Biodiversity and Climate Change Project research to marine policy making'. UKCIP United Kingdom Climate Impacts Programme workshop for marine decision-makers – climate change impacts – what do we need to know? Invited speaker. London, Apr 2004

S.J. Hawkins, N. Hardman-Mountford, D.W. Sims, M.J. Genner & A.J. Southward. 'Long-term changes in the western English Channel by the Marine Biological Association: making the case for time series'. Keynote speaker. International conference hosted at the Linnaean Society on the use of long-term databases for the prediction of ecological change, London, Oct 2003.

N. Mieszkowska, M.A. Kendall & S.J. Hawkins. 'Detecting the effects of climate change on intertidal diversity using long-term datasets'. International conference hosted at the Linnaean Society on the use of long-term databases for the prediction of ecological change, London, Oct 2003.

M.J. Genner, D.W. Sims, V. Wearmouth, E. Southall, S.J. Hawkins & A.J. Southward. 'Climate and fishing drive a century of change in a marine fish community'. International conference hosted at the Linnaean Society on the use of long-term databases for the prediction of ecological change, London, Oct 2003.

R.C. Thompson, T.P. Crowe & S.J. Hawkins. 'Rocky intertidal communities: past environmental changes, present status and predictions for the next 25 years'. International Conference on Environmental Future, Zurich, Switzerland, Mar 2003.

S.J. Hawkins, M.T. Burrows, M.A. Kendall, R. Leaper, N. Mieszkowska, P. Moore, A.J. Southward & R.C. Thompson. 'Climate change and temperate reef ecosystems: integrating space and time'. International Temperate Reefs Symposium. Invited convenor of climate session. Christchurch, New Zealand, Jan 2003.

R. Leaper, M.T. Burrows, M.A. Kendall, N. Mieszkowska, P. Moore & A.J. Southward. 'Can intertidal species be used as indicators of global climate change? Measuring and predicting responses of marine ecosystems in the North East Atlantic'. Invited speaker. International Temperate Reefs Symposium, Christchurch, New Zealand, Jan 2003.

S.J. Hawkins, K. Hiscock, R. Leaper, N. Mieszkowska, M. Kendall, R.C. Thompson, D. Sims, M. Genner, & J. Hill, M.T. Burrows, A.J. Southward. 'The impacts of climate change on marine species and ecosystems around the British Isles and Ireland'. Invited speaker. Marine Conservation Society, Oct 2002

S.J. Hawkins, M.T. Burrows, M.A. Kendall, A.J. Southward & R.C. Thompson. 'Climate change and biodiversity in long-term work by the MBA'. Invited seminar. Tyndall Workshop, University of East Anglia, Oct 2001.

International Working Groups

- S.J. Hawkins Intergovernmental Panel on Climate Change reviewer
- S.J. Hawkins European Science Foundation, Marine Board Working Group on Climate Change Impacts on Marine Ecosystems.

Appendix 3. MarClim Project Deliverables

Summary of Project Progress in Year 1 (April 2001 - June 2002).

	Project Tasks	**Product**
1. Identification & extraction of data	Spreadsheet of all known datasets and stewards	Spreadsheet
	Secure access to priority data sets	Update spreadsheet
2. Archiving databases	Website and database progress	Activity report
3. Analyses of data	Southward, Hawkins & Burrows barnacle datasets – Progress to November 2001	Report
	Crisp and Southward broadscale data – The European geographical distribution of intertidal indicators	Report / maps
	Southward, Lewis SOTEAG, MBA, & Lewis co-workers data – The responses of intertidal indicators: Barnacles, limpets and topshells	Activity report
4. Re-survey	Resurvey of selected sites to test and train team – Progress to October 2001	Activity report
	Preliminary survey of Lewis sites – Progress to November 2001	Activity report
	Resurvey with new MarClim team	
5. Monitoring network	Targeted quantitative sampling at a selection of sites for future low cost monitoring	Activity report
	MarClim sampling protocols	Protocol report
6. Prediction	Impacts of climate change on seabed wildlife in Scotland: Hiscock, K., Southward, A., Tittley, I., Jory, A. & Hawkins, S. 2001. The impact of climate change on subtidal and intertidal benthic species in Scotland. Edinburgh, Scottish Natural Heritage (Survey and Monitoring Series)	Report
8. Communication	Conference papers at University College London – MarClim: Marine Biodiversity and Climate Change	Conference paper
	Conference papers at SAFHOS and Edinburgh – Long term change in the western English Channel	Conference paper
	Moore, P., Hawkins, S.J., Hiscock, K. & Southward, A.J. (Winter 2006). A Sea of Change. The Edge – The magazine of CoastNET.	Semi-popular article
	Herbert, R. J. H., S. J. Hawkins, *et al*. (2003). Range extension and reproduction of the barnacle *Balanus perforatus* in the eastern English Channel. *Journal of the Marine Biological Association of the U.K.* **83**: 73-8	Manuscript
	End of Phase Report (1 & 2)	Final Report
9. Policy application	Draft report of the MarClim policy workshop	Brief report

Summary of Project Progress in Year 2 (July 2002 - June 2003).

Module	Project Tasks	Document
1. Identification & extraction of data	Secure access to priority data sets and assess quality	Update spreadsheet
2. Archiving databases	Data entry	Activity Report
3. Analyses of data	Kendall, M.A., Mieszkowska, N. & Hawkins, S.J (in prep). Long-term changes in the distribution, size, age and longevity of some near-limit populations of Trochid Gastropod *Osilinus lineatus*	Manuscript
	Poloczanska, E.S., Hawkins, S.J., Southward, A.J. and Burrows, M.T. (in review). Modelling intertidal barnacle population response to climate change: hindcast, forecast and prediction. *Global Change Biology*	Manuscript
	MarClim phase 3 update: October 2002 to February 2003	Activity report
4. Re-survey	Resurvey by MarClim team	
	Broadscale re-survey	Activity report
	Re-survey of Kendall and Lewis sites	Activity report
5. Monitoring network	Proposals for establishment of the MarClim monitoring network	Activity report
	MarClim monitoring network: Provisional sampling strategy and standard operational procedures	Activity report
7. Providing data access	Establishment of data access vehicle on the website – awareness report	Awareness report
8. Communication	Herbert, R.J.H., Southward, A.J., Sheader, M. and Hawkins, S.J. (in press). Influence of recruitment and temperature on distribution of intertidal barnacles in the English Channel. *Journal of the Marine Biological Association of the UK*	Manuscript
	Mieszkowska, N., Kendall, M.A., Richardson, A.J., Lewis, J.R. & Hawkins, S.J. (in review) Changes in biogeographic range of the southern trochid gastropod *Gibbula umbilicalis* during the current period of climate warming. *Journal of Biogeography*	Manuscript
	Summary of existing datasets	Link website to *MarLin*

Summary of Project Progress in Year 3 (July 2003 - June 2004).

Module	Project Tasks	Document
2. Archiving databases	Transfer data onto databases and provide metadata	Activity report
3. Analyses of data	Hiscock, K., Southward, A.J., Tittley, I. & Hawkins, S.J. (2004). Effects of changing temperature on benthic marine life in Britain and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems*. **14**: 333-362	Manuscript
	Kendall, M.A., Burrows, M.T., Southward, A.J. & Hawkins, S.J. (2004). Predicting the effects of marine climate change on the invertebrate prey of the birds of rocky shore. *Ibis* **146**(1): 40-47	Manuscript
4. Re-survey	Resurvey by MarClim team	
	Completion of broadscale Crisp and Southward survey – Broadscale re-survey	Activity report
	Kendall & Lewis Trochid re-surveys: Final report	Report
5. Monitoring network	Long-term monitoring network (Oct 2003)	Activity report
	Long-term monitoring network (Dec 2003)	Activity report
8. Communication	Mieszkowska, N., Kendall, M.A., Hawkins, S.J., Leaper, R., Williamson, P., Hardman-Mountford, N.J. & Hawkins, S.J. (2006). Changes in the range of some common rocky shore species in Britain – a response to climate change? *Hydrobiologia*. **555**(1): 241-251	Manuscript
	End of Phase III Report	Final report

Summary of Project Progress in Year 4 (July 2004 - October 2005).

Module	Project Tasks	Document
3. Analyses of data	Southward, Hawkins & Burrows barnacle and limpet datasets	Final report
	Recovery of a biodiversity action plan species in northwest England: possible role of climate change, artificial habitat and water quality amelioration	Final report
5. Monitoring network	Planning future survey and low-cost monitoring	Workshop and report
	Targeted quantitative sampling at a selection of sites	Final report
6. Prediction	Prediction and modelling of climate change impact scenarios	Activity report
8. Communication	Southward, A.J., Langmead, O., Hardman-Mountford, J., Aiken, J., Boalch, G.T., Dando, P.R., Genner, M.J., Joint, I., Kendall, M.A., Halliday, N.C., Harris, R.P., Leaper, R., Mieszkowska, N., Pingree, R.D., Richardson, A.J., Sims, D.W., Smith, T., Walne, A.W. & Hawkins, S.J. (2005). Long-term oceanographic and ecological research in the western English Channel. *Advances in Marine Biology* **47**: 1-105	Manuscript
	Thompson, R.C., Crowe, T.P. & Hawkins, S.J. (2002). Rocky intertidal communities: past environmental changes, present status and predictions for the next 25 years. *Environmental Conservation*. **29**(2): 168-191.	Manuscripts
	Moore, P., Hawkins, S.J. & Thompson, R.J. (in review). The role of biological habitat amelioration in altering the relative responses of congeneric species to climate change. *Marine Ecology Progress Series*	
	Mieszkowska, N., Boalch, G. & Hawkins, S.J. (in prep). Changes in the biogeographic range of *Bifurcaria bifurcata* in the English Channel.	
9. Policy application	Strategic policy issues arising from data and climate change scenarios	Interim report
	Marine climate change indicator species and applications as sustainability indicators	Report
	Implications of predicted changes to marine biota of Britain and Ireland	Final report
	End of Phase IV Report	Final report