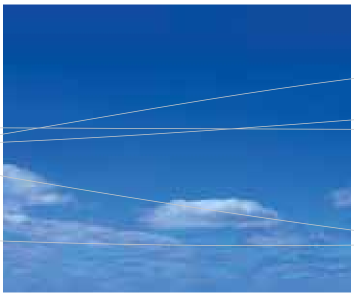

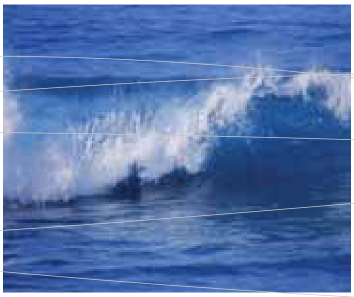

IRISH OCEAN CLIMATE AND ECOSYSTEM STATUS REPORT 2009

Marine Institute
Foras na Mara

This report represents a significant contribution towards achieving the objectives of Sea Change – A Marine Knowledge, Research and Innovation Strategy for Ireland 2007-2013, which presents a national agenda, comprising science, research, innovation and management, aimed at a complete transformation of the Irish maritime economy. Specifically, the report addresses the objectives of the Marine Climate Change Research Programme of Sea Change; in particular the need to increase our understanding of the drivers and regulators of climate so as to improve the accuracy and reliability of predictive models, and to downscale global climate model predictions to the regional/local level in order to refine local impact scenarios. By doing so it strengthens our ability to develop knowledge-based scenarios on climate change impacts on the various marine sectors and include these in all major social, economic and environmental strategies.

Sea Change Casadh na Taoide

NDP National Development Plan Transforming Ireland

SSTI Strategy for Science, Technology and Innovation 2006-2013

ISBN Number: 978-1-902895-40-6
Further copies of this publication, Irish Ocean Climate & Ecosystem Status Report 2009 can be obtained from: Marine Institute, Rinville, Oranmore, Co. Galway, Ireland. Alternatively you can download a pdf version of this report from www.marine.ie
Publication Date: September 2009.

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IRISH OCEAN CLIMATE AND ECOSYSTEM STATUS REPORT 2009

Editors Nolan, G., Gillooly, M. and Whelan, K.

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In Chapter 3, the following acknowledgements are made. The AVHRR Oceans Pathfinder SST data were obtained through the online PO.DAAC Ocean ESIP Tool (POET) at the Physical Oceanography Distributed Active Archive Centre (PO.DAAC), NASA Jet Propulsion Laboratory, Pasadena, CA, USA. Thanks are due to the staff of Met Éireann who have collected and supplied the SST time series from the Malin Head meteorological station.

In the modelling context we would like to acknowledge the following sources. NCEP/NCAR Reanalysis I atmospheric data are provided by Physical Sciences Division, Earth System Research Laboratory, National Oceanic and Atmospheric Administration (NOAA), Boulder, Colorado, from their website at www.esrl.noaa.gov/psd. ECMWF-Interim Reanalysis atmospheric data are obtained from the ECMWF Data Server at http://data.ecmwf.int. The SeaWiFS and MODIS-Aqua chlorophyll data were acquired from http://reason.gsfc.nasa.gov/giovanni, using the GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure (GIOVANNI) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Centre (DISC). Intel is a trademark or registered trademark of Intel Corporation or its subsidiaries in the United States and other countries.

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LIST OF ABBREVIATIONS

AMO	Atlantic Multidecadal Oscillation
AON	Apparently Occupied Nests
AR4	Fourth Assessment Report of IPCC
ASH	Aragonite Saturation Horizon
ATP	Atmospheric Teleconnection Pattern
AVHRR	Advanced Very High Resolution Radar
BFM	Biogeochemical Flux Model
C4I	Climate Change Consortium for Ireland
CCSM	Community Climate System Model
CO_2	Carbon Dioxide
CPR	Continuous Plankton Recorder
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
DON	Dissolved Organic Nitrogen
DSP	Diarrhetic Shellfish Poisoning
EAP	Eastern Atlantic Pattern
EC	European Commission
ECMWF	European Centre for Medium Range Weather Forecasts
EEA	European Environment Agency
EEZ	Exclusive Economic Zone
ERS	European Remote Sensing Satellite
FFD	First Flowering Date
FSBI	Fisheries Society of the British Isles
GCM	Global Climate Model
GCOS	Global Climate Observing System
HAB	Harmful Algal Bloom
HADSST	Hadley Centre Sea Surface Temperature Data Set
ICARUS	Irish Climate Analysis and Research Units
ICES	International Council for the Exploration of the Seas
IPCC	Intergovernmental Panel on Climate Change
ISF	Irish Shelf Front

IUCN	International Union for Conservation of Nature
MATSIS	Method for Assessing the Trophic Status of the Irish Sea Project
MCCP	Marine Climate Change Programme
MSLP	Mean Sea Level Pressure
NAC	North Atlantic Current
NAO	North Atlantic Oscillation
NCAR	National Centre for Atmospheric Research
NCEP	National Centre for Environmental Prediction
NMP	National Phytoplankton Monitoring Programme
NOAA	National Oceanic and Atmospheric Administration
OGCM	Ocean General Circulation Model
ortho-P	Ortho Phosphates
OSPAR	Oslo Paris Convention
PB	Porcupine Bank
PCI	Phytoplankton Colour Index
pCO_2	Partial Pressure CO_2
PN	Particulate Nitrogen
ROMS	Regional Ocean Modeling System
RP	Rockall Plateau
SAHFOS	Sir Alister Hardy Foundation for Ocean Science
SEC	Shelf Edge Current
SRES	Special Report on Emission Scenarios
SST	Sea Surface Temperature
SSTI	Strategy for Science Technology and Innovation
TA	Total Alkalinity
TAR	Third Assessment Report of the IPCC
THC	Thermohaline Circulation
TOC	Total Organic Carbon
TOPEX	Topography Experiment Satellite
TOxN	Total Oxidised Nitrogen

EXECUTIVE SUMMARY

This report has attempted to collate and analyse available marine data sets for Irish waters and to put these data in a climate context where possible. These data sets are collected over varying time scales. The longest data sets extend back to the late 1950s while others have been initiated in the past 5-10 years. In some cases data have been put in a wider context by comparison with international data such as the HADSST sea surface temperature analysis and the Continuous Plankton Recorder (CPR) survey conducted by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS). While the analysis to date has been considerable the brevity of some of the time series means that in 2009 we are relatively poorly equipped to make conclusions as to how climate change will affect Irish waters. This report describes key regulators of ocean climate around Ireland and examines relevant environmental datasets available in 2009. It therefore represents the current status of knowledge regarding the influence of climate on Ireland's marine ecosystems and resources.

Key Findings

This report presents the results from the most comprehensive analysis to date of marine climate change in Irish waters. Using a variety of available datasets from Ireland and elsewhere, the status of Ireland's marine climate is described. The key messages from this research are included overleaf.

Atmosphere

- Atmospheric teleconnection patterns including the North Atlantic Oscillation (NAO) and the Eastern Atlantic Pattern (EAP) are an important influence on ocean conditions around Ireland and elsewhere.
- The trend towards more positive phase NAO conditions over recent decades, associated with a more direct storm track across the Atlantic, has been linked to an increased intensity of winter storms and shifts in temperature and salinity throughout the North Atlantic Ocean.
- The EAP exhibits strong multidecadal variability and has shown a tendency towards more positive values since 1970, with particularly strong and persistent positive values during the 1997-2007 period. The positive phase of the EAP is associated with above average surface air temperatures in Europe throughout the year. It is also associated with above average rainfall over northern Europe and Scandinavia and with below average rainfall across southern Europe.

Oceanography

- The ocean and atmosphere are a coupled system with the ocean responsible for the development of weather phenomena such as wind and rainfall patterns and the atmosphere having a key influence on sea conditions and the structure of the upper ocean.
- The exchanges of heat, gases and momentum across the ocean atmosphere interface are among the key processes regulating Earth's climate.

- The oceans absorbed ~90% of the excess heat input to the Earth system between 1961 and 2003.
- The oceans moderate the global climate through the absorption and storage of heat which is then redistributed gradually in space and time.
- The rate at which sea surface temperature (SST) in the Irish region has increased since 1994 (0.6˚C per decade) is unprecedented in the 150 year observational record.
- The warmest years in the 150 year observational record are 2005, 2006 and 2007.
- Warming of SSTs is superimposed on distinct interannual and multidecadal variability.
- The Atlantic Multidecadal Oscillation (AMO) is the most important component of variability in North Atlantic and Irish SST records.
- Approximately half of the current warm anomaly in Irish SST records can be linked to the current warm phase of the AMO with global warming also contributing.
- There are no clear trends in the large-scale salinity of Irish shelf waters.
- Winter increases in rainfall are linked to freshening of coastal waters.
- Northeast Atlantic wave heights are significantly correlated to the NAO.
- In the southwest of Ireland there has been a positive trend in significant wave height of 0.8 m per decade.
- Model projections of the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES) give a global mean sea level rise of 0.09 m to 0.88 m by 2100 with sea level rising at rates circa 2 to 4 times faster than those of the present day.
- Coastal retreat rates are currently 0.5 to 1.0 m/yr for parts of the Atlantic coast most affected by storms and under sea level rise these rates are expected to increase.
- There is evidence that warming sea temperatures are causing earlier onset and longer duration of shelf sea stratification.
- Variability in the Irish shelf edge current has significant implications for regional ecosystem dynamics and water mass characteristics.
- The shelf edge current is known to be influenced by large-scale atmospheric teleconnection patterns, particularly the North Atlantic Oscillation (NAO).
- An eastward expansion of the subpolar gyre as observed during positive NAO conditions results in relatively cool and saline oceanic waters in the Northeastern Atlantic.

- The gyre transport index indicates a weakening of the North Atlantic Current (NAC) from the mid-1950s through until the early 1970s, with a subsequent strengthening of the NAC until the mid-1990s.
- Paleoclimate evidence exists for a link between the Thermohaline Circulation (THC) and abrupt changes in surface climate over the past 120,000 years.
- Observations suggest significant variability in the THC at interannual to decadal timescales.
- To date no coherent evidence exists for a trend in the strength of the Atlantic THC.

Ocean Chemistry

- The oceans water is becoming acidified (lowering of pH) as a consequence of manmade carbon dioxide emissions in the atmosphere.
- Absorption of anthropogenic carbon dioxide by the oceans has mitigated climate change but lowered the pH of the oceans. This ocean acidification will continue in response to the ongoing carbon dioxide emissions and there is growing concern as to the impact of this rapid change in ocean chemistry on species and ecosystems, especially on calcifying organisms such as deep sea corals. Acidification might be relevant in the highly productive coastal ocean as a consequence of manmade and local discharges of acidifying agents.
- Acidification of seawater at the levels predicted by current carbon dioxide emission rates can completely change the life of many calcifying organisms, from unicellular algae (phytoplankton) to large invertebrates (echinoderms), with unknown consequences for top predators such as fish, birds and mammals. Modification in the availability of nutrients and trace elements, as well as in their potential to be assimilated (speciation) is also expected.
- The median winter values of total oxidized nitrogen and orthophosphates are well below the nutrient thresholds recently indicated by authoritative international environment protection agencies (OSPAR National Eutrophication Assessment Report, 2008). The shelf seas west of Ireland have slightly lower wintertime nutrient concentrations than the Irish Sea reflecting a more oceanic influence on waters ' in the western region.
- Analysis over the 2007-2009 period has allowed us to:
    1. Establish a baseline for the carbonate system variables in Irish waters against which future changes can be measured;
    2. Commence analysing the spatial and seasonal variability of the carbonate system variables in the Northeast Atlantic Ocean for the first time;
    3. Begin to establish whether and under which conditions Irish shelf waters are a source or a sink for carbon dioxide.

Phytoplankton

- Increases in the annual numerical abundance of diatoms and dinoflagellates are evident in all coastal regions since 1998.
- Diatom abundance has increased in numerical abundance earlier in the year since the late 1990s in all coastal regions; an expansion of the growth season.
- An increase in phytoplankton biomass is evident in the northern Celtic Sea, based on Continuous Plankton Recorder (CPR) data, since 2000.
- Total annual abundance of harmful and toxic species varies greatly between years.
- The percentage occurrence of some harmful species during the winter months has increased since 2000.

Zooplankton

- Spatial patterns in the biodiversity of calanoid copepods have changed in response to warming with general movement north of warm water species and retreat of cold water species.
- The seasonal cycle of zooplankton species in the North Sea has altered with a general trend towards a peak in abundance earlier in the year.
- The abundance of a common warm water species *(Calanus helgolandicus)* has increased to the southeast of Ireland.
- A possible phenological shift suggests that production of this species begins earlier in the year.
- In oceanic areas, depth >200 m, gelatinous zooplankton abundance is higher during warm years, which are thought to improve prey availability.
- Gelatinous zooplankton in the Northeast Atlantic show cyclic changes in population sizes that differ between oceanic and shelf areas. However, since 1997 they have been increasing simultaneously in shelf and oceanic waters.

Commercial Fisheries

- The Irish Exclusive Economic Zone (EEZ) supports major fisheries worth €500 million to the international fleets.
- The fishing industry makes a significant contribution to the economic and social fabric of coastal communities.
- Climate change and anthropogenic impacts act in tandem to alter marine ecosystems, such that species responses to climate change cannot be considered in isolation.
- Many, but not all, warm water species, including sprat, anchovy, pilchard and blue-mouth, have increased in abundance to the north of Ireland and in the Celtic Sea.

- Poor cod and lesser spotted dogfish have increased to the north of Ireland and decreased to the south and are suitable candidate climate indicator species.
- In general, the abundance of marine fish has decreased in the Celtic Sea (1999-2007).
- Both Lusitanian (warm water) and boreal (cold water) communities appear stable to the north of Ireland (2002-2007).
- There is some suggestion of an increase in the Lusitanian community to the west of Ireland (2002-2007).
- Climate change may lead to an increase in the Lusitanian fish community. However, fishery effects must be considered and long-term data is required to detect such change.
- Overexploited stocks display stronger responses to climatic fluctuations.
- Climate change may lead to the decline of traditional fisheries (e.g. cod) and the emergence of new fisheries (e.g. boarfish). However, given the high value of many boreal species the economic effect may be negative.
- Natural variability is high in the marine environment and whether or not important changes seen in the gyre circulation are due to global warming or natural variation is unclear.
- Many exotic species are being sighted in Irish and United Kingdom waters. There appears to be an increase in such sightings.
- The increase in the distribution of pipefish may reduce the survival of seabird chicks.

Seabirds

- Annual surveys on one of the largest breeding seabird colonies in Ireland show that the number of guillemots and razorbills has been declining over the last decade.
- Breeding success of some species has become a concern.
- Declines in numbers and breeding failures at such seabird colonies have been linked to climate change. Various studies indicate that changes in sea temperature affect seabirds indirectly through the availability of their preys ('bottom-up control').

Migratory Fish

- Key biological processes in freshwater are controlled by environmental variables, (e.g. temperature, sunlight and rainfall). These play a fundamental role in controlling primary production, food web energetics and critical life stage processes in animals, such as hatching and survival in fish and smoltification and migration in salmonids. Possible changes in Ireland's climate are likely to impact on the growth and survival of many species.

- Diadromous fish species (having both a freshwater and marine element to their life cycle) are an important sentinel species in climate change research. The migrations of these species could have significant implications for understanding a broader set of biogeographical and ecological questions across a wide range of spatial and temporal scales.
- The main three species of Irish diadromous fish have shown a decline in numbers and marine survival over the past three decades, thought to be at least partly related to the interactive effects of changing climatic and oceanic conditions, along with human impacts. Data from the Marine Institute's experimental catchment in Burrishoole, Co. Mayo shows:

  Salmon – declining marine survival since the 1970s.

  Sea trout – stock collapse in 1980s, with adult returns still at a low level.

  European eel – sharp fall in recruitment since the 1980s, in line with similar declines throughout Europe.
- Freshwater temperatures from the Burrishoole catchment have been increasing significantly from the 1970s to the present day. This change is likely to have strong knock on effects on the survival and development of juvenile fish populations.

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INTRODUCTION

Changes in the Earth's climate have been taking place since the planet formed. The climate patterns are controlled by factors such as the relative distance of the Earth from the sun and more localised events such as volcanic eruptions and changes in the make-up of Earth's atmosphere over time. Until the mid 1800s, these changes have typically been in a cyclical nature with a degree of predictability. There is, for example, an even spacing between successive periods when Earth is undergoing glacial conditions (approximately every 100,000 years). Since the 1850s (the post-industrial era) it is widely accepted that the production of fossil fuels from industrial and other processes has increased to an extent that the Earth system is being disturbed beyond what is "normal" in the natural cycle of variability observed over extended periods of time (IPCC 2007). There is now broad acceptance that mankind's activities have impacted on the natural climate cycle of our planet. The impacts are already being seen on land, in the atmosphere and in the oceans.

1.1 THE GLOBAL CONTEXT FOR CHANGES IN IRELAND'S OCEAN ECOSYSTEM

the global picture

'Over the period 1961 to 2003, global ocean temperature has risen by 0.10°C from the surface to a depth of 700 m'.

The Intergovernmental Panel on Climate Change produced a Fourth Assessment Report (IPCC AR4) in 2007 describing among other things, oceanic climate change and sea level (Bindoff *et al.*, 2007). This represents a comprehensive global picture of changes within the ocean and provides useful background to a marine climate change study focussed on Ireland. They key findings of IPCC AR4 are as follows:

- The oceans are warming: Over the period 1961 to 2003, global ocean temperature has risen by 0.10°C from the surface to a depth of 700 m. Global ocean heat content (0 – 3000 m) has increased during the same period, equivalent to absorbing energy at a rate of 0.21 ± 0.04 W m^{-2} globally averaged over the Earth's surface. Two-thirds of this energy is absorbed between the surface ocean and a depth of 700 m. Global ocean heat content observations show considerable interannual and interdecadal variability superimposed on the longer-term trend. Relative to 1961 to 2003, the period 1993 to 2003 has high rates of warming but since 2003 there has been some cooling.
- Large-scale coherent trends of salinity are observed for 1955 to 1998 and are characterised by a global freshening in subpolar latitudes and a salinification of shallower parts of the tropical and subtropical oceans. Freshening is pronounced in the Pacific while increasing salinities prevail over most of the Atlantic and Indian Oceans. Observations do not allow for a reliable estimate of the global average change in salinity in the oceans.
- Key oceanic water masses are changing: however, there is no clear evidence for ocean circulation changes. A weaker pattern of warming in the Gulf Stream and Kuroshio mode waters in the North Atlantic and North Pacific has been observed. Long-term cooling is observed in the North Atlantic subpolar gyre and in the central North Pacific. Since 1995 the upper North Atlantic subpolar gyre has been warming and becoming more saline. It is very *likely* that up to the end of the 20^{th} century the Atlantic meridional overturning circulation has been changing significantly at interannual to decadal time scales. Over the last 50 years, no coherent evidence for a trend in the strength of the meridional overturning circulation has been found.
- Ocean biogeochemistry is changing: The total inorganic carbon content of the oceans has increased by 118 ± 19 GtC between the end of the pre-industrial period (about 1750) and 1994 and continues to increase. It is more *likely than not* that the fraction of emitted carbon dioxide that was taken up by the oceans has decreased, from 42 ± 7% during 1750 to 1994 to 37 ± 7% during 1980 to 2005. This would be consistent with the expected rate at which the oceans can absorb carbon but the uncertainty in this estimate does not allow firm conclusions. The increase in total inorganic carbon caused a decrease in the depth at which calcium carbonate dissolves and also caused a decrease in surface ocean pH by an average

'No coherent evidence for a trend in the strength of the meridional overturning circulation has been found'.

of 0.1 units since 1750. Direct observations of pH at available time series stations for the last 20 years also show trends of decreasing pH at a rate of 0.02 pH units per decade. There is evidence for decreased oxygen concentrations, likely driven by reduced rates of water renewal, in the thermocline (~100 – 1000 m) in most ocean basins from the early 1970s to the late 1990s.

- Global mean sea level has been rising: From 1961 to 2003 the average rate of sea level rise was 1.8 ± 0.5 mm yr^{-1}. For the 20th century, the average rate was 1.7 ± 0.5 mm yr^{-1}, consistent with the TAR estimate of 1 to 2 mm yr^{-1}. There is *high confidence* that the rate of sea level rise has increased between the mid-19th and the mid-20th centuries. Sea level change is highly non-uniform spatially, and in some regions, rates are up to several times the global mean rise, while in other regions sea level is falling. There is evidence for an increase in the occurrence of extreme high water worldwide related to storm surges and variations in extremes during this period are related to the rise in mean sea level and variations in regional climate.
- The rise in global mean sea level is accompanied by considerable decadal variability. For the period 1993 to 2003, the rate of sea level rise is estimated from observations with satellite altimetry as 3.1 ± 0.7 mm yr^{-1}, significantly higher than the average rate. The tide gauge record indicates that similar large rates have occurred in previous 10 year periods since 1950. It is unknown whether the higher rate in 1993 to 2003 is due to decadal variability or an increase in the longer-term trend.
- The patterns of observed changes in global ocean heat content and salinity, sea level, thermal expansion, water mass evolution and biogeochemical parameters described in AR4 are broadly consistent with the observed ocean surface changes and the known characteristics of the large-scale ocean circulation.

'There is high confidence that the rate of sea level rise has increased between the mid-19th and the mid-20th centuries'.

Key to establishing the extent of natural variability in climate and mankind's contribution to changing climate is to have information and data that extend back far enough in time to assess this. Valuable data have been collected from ice and ocean sediment cores that act as a proxy for changes in climate over extended periods. These data show that atmospheric CO_2 levels are at their highest in at least 420,000 years (Petit *et al.*, 1999). CO_2 is a greenhouse gas that traps outgoing terrestrial radiation causing an increase in global air temperatures. Global air temperatures affect many things including the world's oceans.

As an island nation the oceans are critically important in moderating Ireland's weather and climate. The majority of weather systems that affect us day to day come from the adjacent Atlantic Ocean. Changes in Ireland's climate have been examined by the Climate Change Consortium for Ireland (C4I) (Dunne *et al.*, 2008) and by the ICARUS climate team at NUI, Maynooth (Sweeney *et al.*, 2003). Some of the likely

'The aim of this report is to capture the available scientific data from these diverse sources and to identify any apparent trends in Irish marine ecosystems that may be attributed to trends in climate'.

changes include a decrease in frequency of storms but an increase in the intensity of those storms, changes to rainfall patterns over Ireland and increases in surface air temperatures.

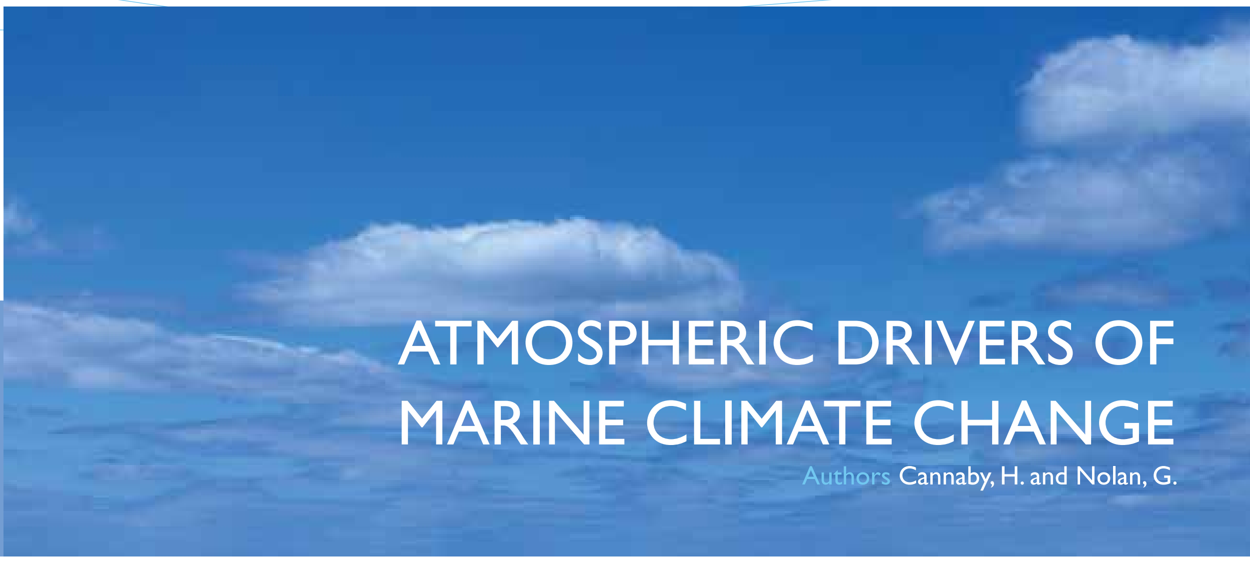
To date there has been very little research on the affects of climate change on the seas around Ireland. It is therefore important to examine and quantify where possible the likely impacts of climate change on the sea and its impact on the various sectors that make up Ireland's maritime economy.

A multi-disciplinary team was recruited at the Marine Institute to examine and analyse the available marine data sets in a climate context. The team comprises oceanographers, plankton ecologists, fisheries scientists, ocean modellers and technicians.

A first step in defining impacts is to look at the current status of Irish waters in a marine climate change context. By comparing existing and historical data sets on oceanography, plankton and productivity, marine fisheries and migratory fish species such as salmon, trout and eels, a picture begins to emerge of Ireland's ocean climate status today. The aim of this report is to capture the available scientific data from these diverse sources and to identify any apparent trends in Irish marine ecosystems that may be attributed to trends in climate. Recent activity in important fields of climate-related research for which Ireland needs to develop expertise and capacity are also highlighted in the report.

This report is intended for policy makers and members of the general public interested in marine climate change. For the majority of findings presented in this status report there is a body of peer reviewed literature that can be found in the bibliography at the back of the report. The report will also inform future analyses of the significance of climate-induced changes for marine resources and industries.

2



ATMOSPHERIC DRIVERS OF MARINE CLIMATE CHANGE

Authors Cannaby, H. and Nolan, G.

KEY POINTS

- » The North Atlantic Oscillation (NAO) represents the most important source of variability in mean sea level pressure (MSLP) over the North Atlantic.

- » When the NAO index shifts from low to high values, wind speeds over the North Atlantic increase by up to 4 m s^{-1} increasing heat fluxes from the ocean to the atmosphere by 150 W m^{-2} over the subpolar region in winter.

- » The Eastern Atlantic Pattern (EAP) describes the second most important source of variability in mean sea level pressure (MSLP) over the North Atlantic.

- » The EAP exhibits strong multidecadal variability and has shown a tendency towards more positive values since 1970, with particularly strong and persistent positive values during the 1997-2007 period. The positive phase of the EAP is associated with above average surface air temperatures in Europe throughout the year with above average rainfall over northern Europe and Scandinavia and with below average rainfall across southern Europe.

2.1 NATURAL VARIABILITY AND CLIMATE INDICES

'The climate that we currently experience is by no means stable in time'.

The climate that we currently experience is by no means stable in time, exhibiting natural modes of variability over interannual to millennial timescales. An understanding of natural variability in the climate system is vital to the interpretation of trends and variability in climate variables and to the assessment of anthropogenic influence on climate.

2.2 ATMOSPHERIC TELECONNECTION PATTERNS (ATPS)

The global climate exhibits a number of recognised oscillatory modes of variability on timescales of years to decades. These oscillatory modes are referred to as atmospheric teleconnection patterns (ATPs). Teleconnections are defined as linkages over great distances of atmospheric and oceanic variables (Barry and Chorley, 2003). ATPs are typically expressed in the atmosphere as an oscillation between high and low pressure centres and drive much of the interannual scale variability in both global and regional climatic conditions. The atmosphere profoundly affects processes that occur in the ocean by altering the rates at which heat, salt and gases are exchanged between the ocean and atmosphere. It is therefore appropriate to provide an atmospheric context for subsequent chapters of this report. The following sections describe the dominant patterns of atmospheric variability in the Northeast Atlantic, the North Atlantic Oscillation (NAO) and the East Atlantic Pattern (EAP).

2.3 NORTH ATLANTIC OSCILLATION (NAO)

'The NAO represents the most important source of variability in mean sea level pressure (MSLP) over the North Atlantic'.

The North Atlantic Oscillation (NAO) describes a north south variation of atmospheric pressure centres between the Arctic low and subtropical Atlantic high pressure system. The NAO represents the most important source of variability in mean sea level pressure (MSLP) over the North Atlantic. The NAO has implications for climate variability throughout the mid and high latitudes of the Northern Hemisphere (Hurrell, 1995; Hurrell *et al.*, 2003). The NAO signal is particularly prevalent during the winter season when the mean atmospheric circulation is strongest. A time series of the Hurrell winter (December – February) NAO index, a record of the pressure difference between the Azores high and the Icelandic low, between 1950 and 2006 is presented in figure 2.1. A positive index indicates a stronger pressure gradient between the two systems.

Interannual to decadal shifts from positive to negative phases of the NAO are associated with large changes in wind speed and direction over the Atlantic. These changes affect heat and moisture transport in the atmosphere and the circulation of the upper ocean (Hurrell *et al.*, 2003; Hurrell and Dickson, 2004). When the NAO index shifts from low to high values, wind speeds over the North Atlantic increase by up to 4 m s^{-1} increasing heat fluxes from the ocean to the atmosphere by 150 W m^{-2} over the subpolar region in winter (Bersch *et al.*, 1999). The trend towards more positive phase NAO conditions over recent decades, associated with a more direct storm track across the Atlantic, has been linked to an increased intensity of winter storms and shifts in temperature and salinity throughout the North Atlantic Ocean.

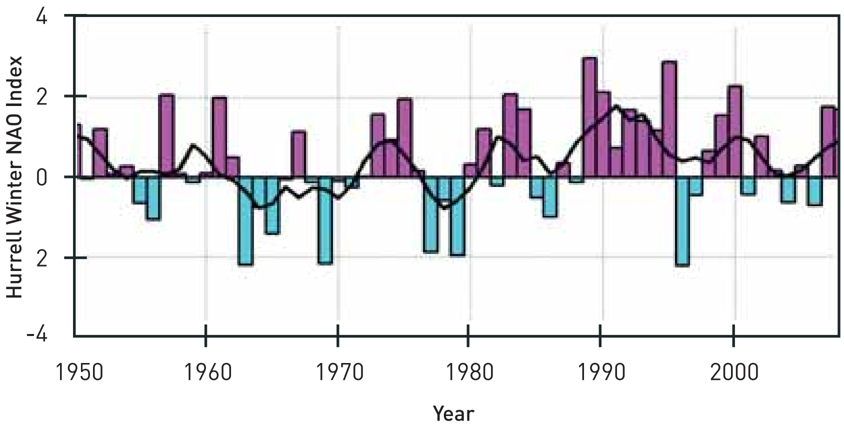


Figure 2.1 Time series of the Hurrell winter (December – February) NAO Index from 1950-2006 (bars), overlain by a 5 year running mean (black line). A positive index indicates a stronger pressure gradient between the two systems.

Skellig Islands, southwest Ireland

2.4 EAST ATLANTIC PATTERN (EAP)

The East Atlantic Pattern (EAP) (Wallace and Gutzler, 1981; Barnston and Livezey, 1987) describes the second most important source of variability in mean sea level pressure (MSLP) over the North Atlantic and is important in all months except from May to August. The EAP is structurally similar to the NAO, consisting of a low pressure centre in the Northeast Atlantic near 55° north, 20°-35° west, and a high pressure centre over north Africa or the Mediterranean Sea. Because the EAP is centred at a lower latitude than the NAO, there is a strong link to subtropical regions (Barnston and Livezey, 1987). The EAP index shown here in figure 2.2 was obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml) and is based on that described by Barnston and Livezey (1987).

'Because the EAP is centred at a lower latitude than the NAO, there is a strong link to subtropical regions'.

The EAP exhibits strong multidecadal variability and has shown a tendency towards more positive values since 1970, with particularly strong and persistent positive values during the 1997-2007 period. The positive phase of the EAP is associated with above average surface air temperatures in Europe throughout the year and below average air temperatures over the southern United States during January to May and in the north central United States during July to October. It is also associated with above average rainfall over northern Europe and Scandinavia and with below average rainfall across southern Europe.

eastern atlantic pattern

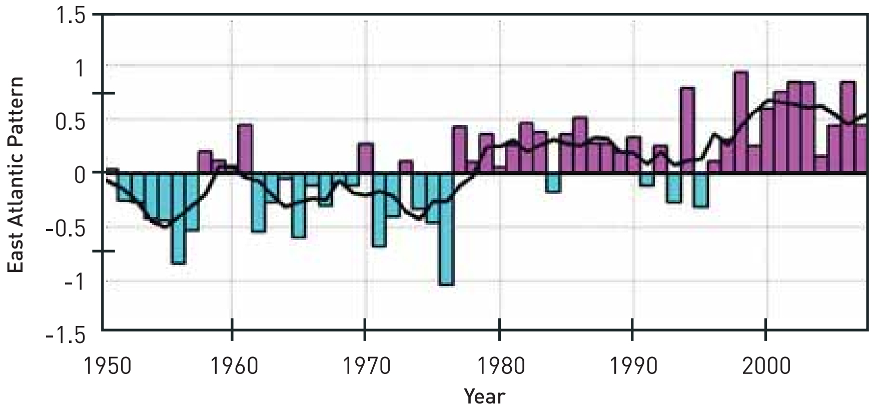


Figure 2.2 Time series of the annual mean EAP from 1950-2006 (bars), overlain by a 5 year running mean (black line). Data are sourced from the NOAA Climate Prediction Centre (www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml).

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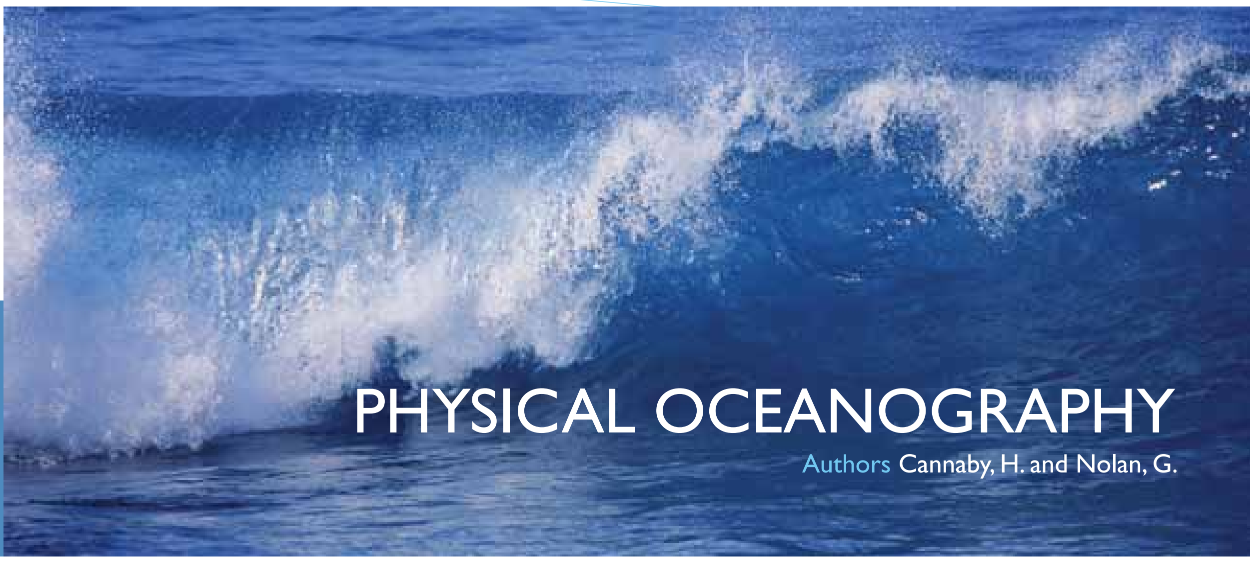

PHYSICAL OCEANOGRAPHY

Authors Cannaby, H. and Nolan, G.

KEY POINTS

- » The rate at which sea surface temperature in the Irish waters has increased since 1994 (0.6˚C per decade) is unprecedented in the 150 year observational record.

- » The warmest years in the 150 year observational record are 2005, 2006 and 2007.

- » Increasing SSTs is super-imposed on distinct interannual and multidecadal variability.

- » Approximately half (0.4°C) of the current warm anomaly in Irish SST records can be linked to the current warm phase of the AMO with global warming contributing the other half (0.4°C).

- » An eastward expansion of the subpolar gyre, as observed during positive North Atlantic Oscillation (NAO) conditions, results in relatively cool and saline oceanic waters in the Northeastern Atlantic.

- » The gyre transport index indicates a weakening of the North Atlantic Current (NAC) from the mid-1950s through until the early 1970s, with a subsequent strengthening of the NAC until the mid-1990s.

- » Paleoclimate evidence exists for a link between the Thermohaline Circulations (THC) and abrupt changes in surface climate over the past 120,000 years.

KEY POINTS continued

- Observations suggest significant variability in the THC at interannual to decadal timescales.
- To date no coherent evidence exists for a trend in the strength of the Atlantic THC over recent decades.
- Variability in the Irish shelf edge current has significant implications for regional ecosystem dynamics and water mass characteristics.
- The shelf edge current is known to be influenced by large scale atmospheric teleconnection patterns, particularly the NAO.
- The Atlantic Multidecadal Oscillation (AMO) is the most important component of variability in North Atlantic and Irish SST records.
- The oceans moderate the global climate through the absorption and storage of heat, which is then redistributed gradually in space and time.
- The oceans absorbed ~90% of the excess heat input to the Earth system between 1961 and 2003.
- There are no clear trends in the large-scale salinity patterns within Irish shelf waters.
- Winter increases in rainfall are linked to freshening of coastal waters.
- Northeast Atlantic wave heights are significantly correlated to the NAO.
- In the southwest of Ireland there has been a positive trend in significant wave height of 0.8 m per decade.
- There is evidence that warming sea temperatures are causing earlier onset and longer duration of shelf sea stratification.

The oceans and the atmosphere are tightly coupled and highly dynamic systems. Heat, freshwater, gases and momentum are exchanged between the ocean and the atmosphere. Interpreting trends and variability in these properties requires an understanding of the complex interactions and feedback linking the ocean atmosphere system. Marine climate variability forms a vital component of climate change research programmes as oceans have a strong influence on the overlying atmosphere.

'Variability and trends in Irish weather patterns and in oceanic conditions around Ireland are influenced by the large-scale currents of the North Atlantic Ocean'.

3.1 OVERVIEW OF NORTH ATLANTIC CIRCULATION PATTERNS

Variability and trends in Irish weather patterns and in oceanic conditions around Ireland are influenced by the large-scale currents of the North Atlantic Ocean. A brief summary of these currents is provided in the following sections.

3.1.1 North Atlantic Gyre Circulation

Circulation in the upper 1000 m of the North Atlantic Ocean is dominated by 2 rotating gyres, the anticyclonic (clockwise) subtropical gyre and the smaller cyclonic (anticlockwise) subpolar gyre. The North Atlantic Current (NAC), an extension of the Gulf Stream flows along the boundary between these two gyres (figure 3.1). The NAC draws relatively warm and saline subtropical waters northeastward across the North Atlantic Ocean. The path of the NAC is highly variable, linked to changes in the mean North Atlantic wind field. As the relative strengths of the subpolar and subtropical gyres change, the path of the NAC is shifted with implications for the water masses at the European shelf edge.

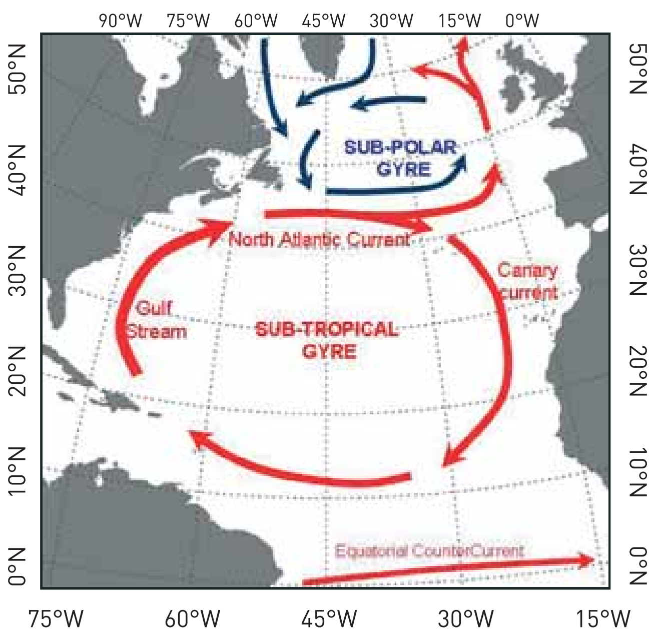

Figure 3.1 A schematic overview of the wind driven gyres which dominate circulation in the upper 1000 m of the North Atlantic Ocean.

'During positive NAO conditions the subpolar gyre increases in strength and the polar front is shifted south eastward.'

The pressure difference between the centres of the subtropical and subpolar gyres can be used to calculate a transport index for the NAC. The gyre-transport index derived by Antov *et al.* (2002) reveals significant interannual variability in NAC (figure 3.2) with a high gyre-transport index indicating a strong circulation and a strong NAC.

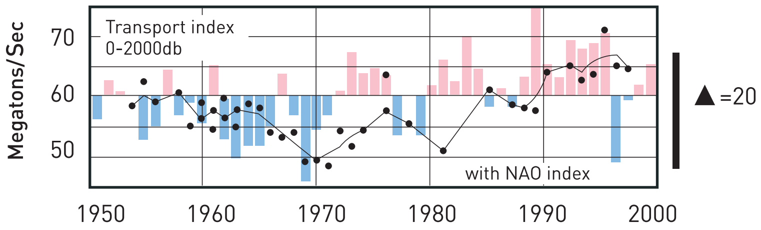

Figure 3.2 Baroclinic mass transport (megatons/sec) flowing eastward between the subpolar and subtropical gyres in the upper 2000 db (black line) and the Hurrell NAO index (pink and blue bars). (Figure from Curry and McCartney 2001).

During positive NAO conditions (see previous chapter for explanation) the subpolar gyre increases in strength and the polar front is shifted southeastward. This results in lower surface salinities in the central subpolar region and an increased volume of subpolar waters reaching the Rockall Trough and adjacent European continental margin. Increased subpolar influence in this region is associated with relatively cool and saline conditions.

3.1.2 Thermohaline Circulation (THC)

CTD Deployment, *R.V. Celtic Explorer*

The North Atlantic Current (NAC) contributes to a net northward transport in the upper 1500 m of the Atlantic Ocean, which forms the upper limb of the Thermohaline Circulation (THC). McCartney *et al.*, (1996) refer to this as the "warm to cold water transformation pipeline" in the North Atlantic whereby warm water gradually loses heat to the atmosphere as it progresses from the subtropics to the subpolar regions. In the Nordic Seas this water becomes heavy enough to sink to the deep ocean, a process referred to as 'deep water formation' where it continues and returns southwards into the Atlantic over the submarine ledges that separate Greenland from Scotland. As a result of the THC the Atlantic is the only ocean where there is a net northward heat transport across the equator and is thus distinguished by relatively warm upper layer temperatures.

The NAC, upon reaching the eastern margins of the Atlantic Ocean, flows northwards following two main routes; through the Rockall Trough, where it undergoes significant mixing with eastern North Atlantic water masses, and through the Iceland Basin, before continuing northwards through the Nordic Seas and eventually reaching the Arctic Ocean (Hátún *et al.*, 2005). The temperature and salinity characteristics of the water masses reaching the Arctic Ocean influence the rate of deep water formation, a driver of the THC circulation. The North Atlantic Ocean has a particularly important role in long term climate studies due to its significance to the global THC.

3.1.3 European Shelf Edge Current (SEC)

The Shelf Edge Current (SEC) flows northward along the European continental margin from Portugal to Norway, with typical current speeds ranging from 10 cm s^{-1} in summer to 30 cm s^{-1} in winter (Pingree and LeCann, 1990). The SEC has an important role in determining oceanic conditions at the Irish shelf edge and has long been recognised as an important transport pathway for passive biota including the eggs and larvae of commercial fish species. The strength and continuity of the SEC fluctuates over seasonal and annual time scales in response to changes in the large scale ocean atmospheric forcing (Pingree, 2002).

'The SEC has an important role in determining oceanic conditions at the Irish shelf edge and has long been recognised as an important transport pathway for passive biota including the eggs and larvae of commercial fish species'.

3.2. THE ATLANTIC MULTIDECADAL OSCILLATION (AMO)

Like the atmosphere, the oceans have recognisable oscillations typically coupled to atmospheric teleconnection patterns. Warmer than usual sea surface temperatures (SSTs) were observed throughout the North Atlantic between 1930 and 1960, and from 1990 to present, with cool periods from 1900 to 1930 and from 1960 to 1990. This decadal scale oscillation in the SST record is commonly referred to as the Atlantic Multidecadal Oscillation (AMO) (Schlesinger and Ramenkutty, 1994; Delworth and Mann, 2000; Kerr, 2000). The pattern of variability associated with the AMO, constructed from North Atlantic mean SSTs is presented in figure 3.3. The AMO, which is most pronounced in the extra-tropical North Atlantic, corresponds to the most significant mode of low frequency variability in Irish SST records (Cannaby and Hüsrevoğlu, 2009) and is also reflected in many other environmental variables. The AMO is linked to changes in weather patterns on both sides of the Atlantic Ocean and is thought to regulate the NAO index.

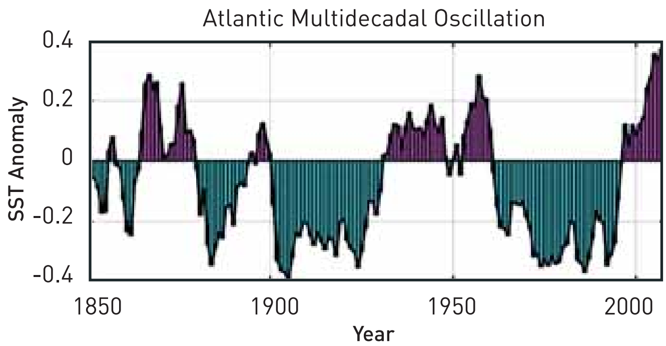

Figure 3.3 Detrended North Atlantic mean SST anomalies illustrating the mode of variability referred to as the Atlantic Multidecadal Oscillation. Detrending was performed through subtraction of a nonlinear global warming trend (Cannaby and Hüsrevoğlu, 2009).

The robustness of this periodicity has been addressed using proxies such as marine sediment cores and tree rings (Grey *et al.*, 2004), and model studies (Delworth and Mann, 2000). Paleoclimate reconstructions spanning four centuries have revealed a 60-110 year period of intermittent warm and cool North Atlantic SSTs. Coupled

'Global mean sea surface temperatures (SSTs) have risen by 0.74°C between 1850 and 2008'.

ocean atmosphere model studies spanning 600 years have revealed an irregular oscillation in both SSTs and the THC, with a time scale of 40-60 years (Delworth and Mann, 2000). The mechanisms forcing the AMO are not yet fully understood, although model studies have suggested a link to the THC. The existence of a mode of variability associated with the AMO in North Atlantic salinity time series adds weight to the hypothesis that the AMO is linked to large scale shifts in the North Atlantic circulation.

3.3 OBSERVED TRENDS AND VARIABILITY

3.3.1 Sea Surface Temperature (SST)

Global Trends: Upper ocean warming has been observed in each of the oceans since the beginning of the observational record in 1850. Global mean sea surface temperatures (SSTs) have risen by 0.74°C between 1850 and 2008. Warming is superimposed on significant interannual to decadal scale variability, and has occurred principally during two main phases, from 1915 to 1945 and since 1975. Warmer SSTs, observed in all oceans during the early 1940s have been related to closely spaced multiple El Nino events (Brönnimann *et al.*, 2004) and a warm phase of the Atlantic multidecadal oscillation (Levitus *et al.*, 2005). The North Atlantic Ocean has exhibited a smaller SST warming trend of 0.49°C over the same period.

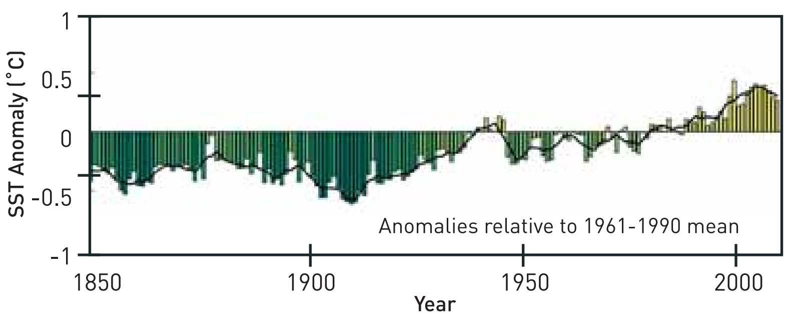

Figure 3.4 Annual mean global SST anomalies (bars), extracted from the HadSST2 dataset (Rayner *et al.*, 2006) and overlain by a 5 year running mean (black line) for the period 1850-2008.

Irish Trends: SST records from the waters surrounding Ireland exhibit a mean warming trend between 1850 and 2008 of 0.3°C. The rate at which warming has occurred since 1994 (0.6°C per decade) is unprecedented in the 158 year observational record, the warmest years in the record being 2005, 2006 and 2007. Warming is superimposed on a distinct multidecadal variability associated with the AMO (figure 3.5). Approximately half of the current warm anomaly in the Irish SST record can be attributed to the current warm phase of the AMO, with the NAO and EAP also playing a smaller role. Additional warming is attributed to an underlying global warming trend (Cannaby and Hüsrevoğlu, 2009).

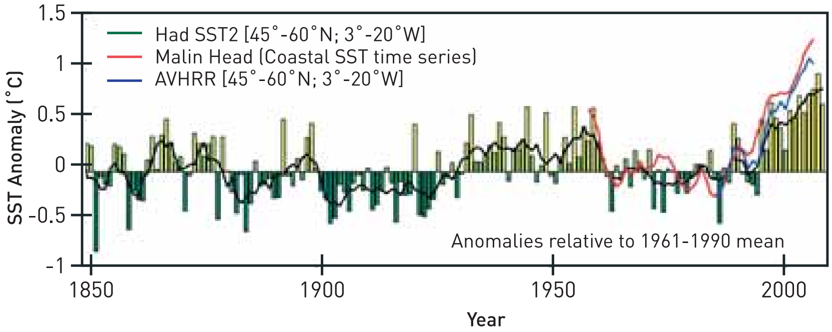

Figure 3.5 Annual mean SST anomalies (green bars), averaged over the region [45°-60°N, 3°-20°W], extracted from the HadSST2 dataset (Rayner *et al.*, 2006) and overlain by a 5 year running mean (black line) for the period 1850-2008. AVHRR satellite derived SST anomalies for the period 1986-2006 are overlain in blue and the Malin Head coastal SST time series from 1958-2006 in red. Anomalies are calculated relative to the 1961-1990 mean for the case of HadSST2 and Malin Head datasets and relative to the time series climatology for the case of the AVHRR dataset (Figure from Cannaby and Hüsrevoğlu, 2009).

'SST records from the waters surrounding Ireland exhibit a mean warming trend between 1850 and 2008 of 0.3°C. The rate at which warming has occurred since 1994 (0.6°C per decade) is unprecedented in the 158 year observational record'.

Warming is evident in the Irish SST record during each month of the year. This is particularly clear when the 2008 monthly mean temperatures at Malin Head are compared to the 1958-2000 monthly means (figure 3.6). Anomalies of annual mean SST derived from AVHRR (figure 3.7) demonstrate that warming has occurred throughout Irish and surrounding waters. The warming trend varies from place to place, however, with the strongest warming trend observed to the southwest of Ireland (Cannaby and Hüsrevoğlu, 2009).

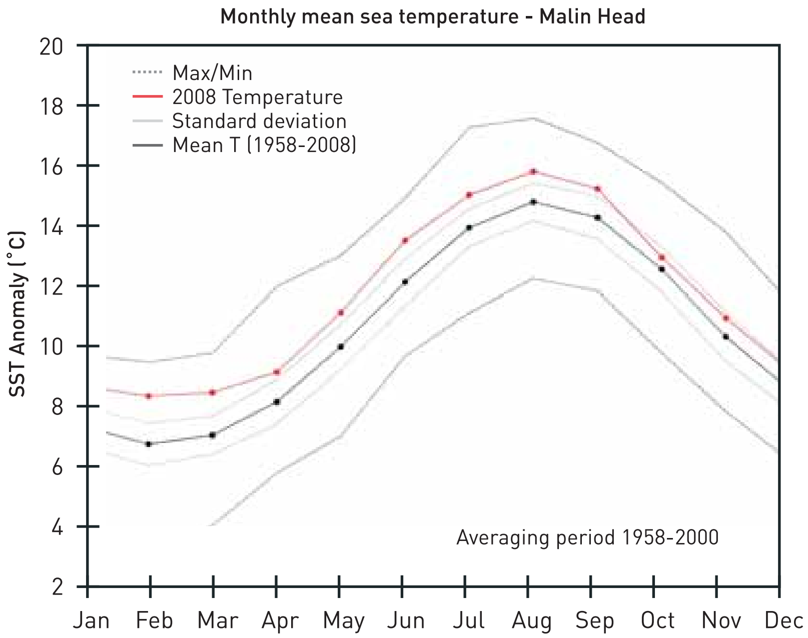

Figure 3.6 Monthly mean sea temperature at Malin Head averaged over the period 1958-2000, showing standard deviations and maximum and minimum temperature ranges. Monthly mean data for 2008 overlain in red emphasises warming throughout the year.

'Close to 90% of the excess heat input to the Earth system over the 1961-2003 period has been absorbed by the oceans'.

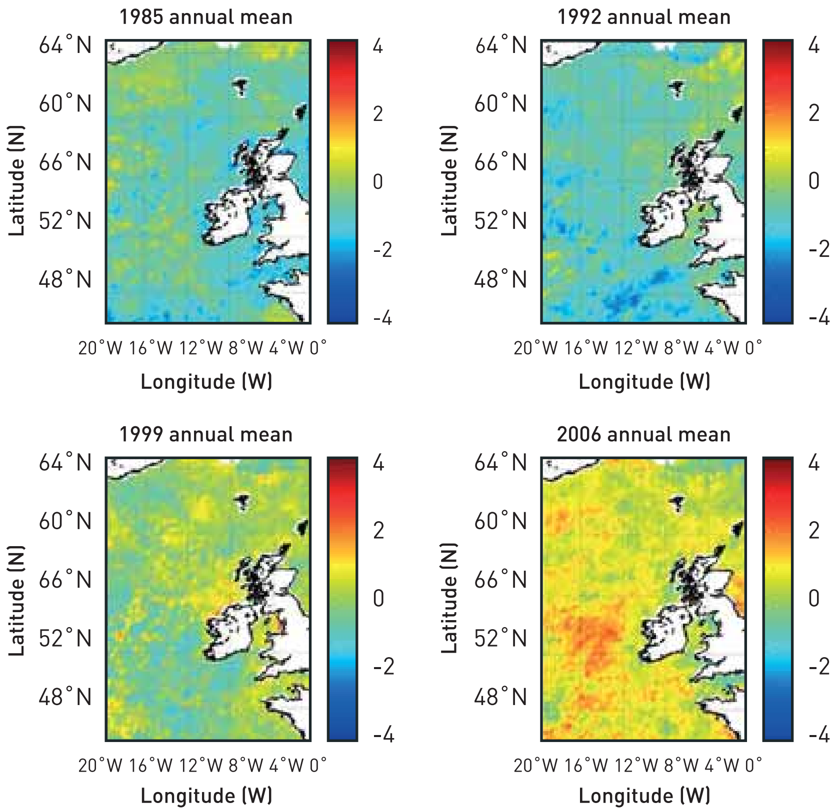

Figure 3.7 Annual mean anomalies of SST (°C) derived from level-3 processed AVHRR satellite data and calculated relative to the 1985 to 2006 climatology. Data are presented at 7 year intervals from 1985 to 2006.

3.3.2 Ocean Heat Content

Close to 90% of the excess heat input to the Earth system over the 1961-2003 period has been absorbed by the oceans (Bindoff *et al*., 2007), emphasising the significance of the oceans in determining the global heat budget. Trends in Atlantic heat content between 1955 and 2003 reveal a warming of the subtropical gyre and a concurrent cooling of the subpolar gyre over this period (Levitus *et al*., 2005; Lozier *et al*., 2008). Subtropical gyre warming extended down to below 1000 m (deeper than anywhere else in the world's oceans) and was particularly pronounced under the Gulf Stream and the North Atlantic Current (Levitus *et al*., 2005). No data are currently available to assess changes in heat content in Irish waters.

3.3.3 Salinity

Global and North Atlantic salinity trends: Estimates of the freshwater content of the global oceans suggest a freshening trend, although the scarcity of data in many regions means uncertainties associated with this trend cannot be quantified (Antov *et al*., 2002). Typically, near surface waters in the more evaporative regions (tropics and sub-tropics) of the worlds oceans are becoming more saline, whilst freshening has been observed at higher latitudes, associated with increased precipitation and run-off, and with increased ice melt, current transport and changes in the THC also contributing in some regions (Hakkinen, 2002). In the Northeast Atlantic and Nordic Seas, the upper ocean freshening trend observed from the 1960s-1990s has since reversed with salinity values in 2004 returning to the pre-1960s peak (Holliday *et al.*, 2008). Interannual variations in upper ocean salinity in the Northeast Atlantic and Nordic Seas show similar patterns of variability to temperature. The low temperature and salinity values observed from the mid-1960s to the mid-1990s and the subsequent anomalously high temperature and salinity values correspond closely to the pattern of variability associated with the AMO. The Arctic Ocean has exhibited a freshening trend over recent years associated with increased river run-off and ice melt. Release of this fresh water from the Arctic Ocean across the Fram Strait and eventually into the sub-polar gyre is expected to influence the rate of deep water formation in the Labrador Sea, with consequences for the THC (Karcher *et al.*, 2005). Intermediate water masses in the central North Atlantic (~900 – 1000 m) have become saltier due to increased Mediterranean outflow. A branch of the Mediterranean outflow is carried northwards by the SEC, with implications for conditions to the west of Ireland.

'In the Northeast Atlantic and Nordic Seas, the upper ocean freshening trend observed from the 1960s-1990s has since reversed with salinity values in 2004 returning to the pre-1960s peak'.

Salinity trends on the Irish shelf: Using the combined archive of salinity data from ICES, the Marine Institute and the World Ocean Database it can be seen that annual mean salinity anomalies on the Irish shelf exhibit a multi-annual variability which, when lagged by 7 years, significantly correlates to the NAO (figure 3.8). No distinct salinity trends exist in deeper waters on the Irish continental shelf (i.e. water depths of ca. 200 m). Surface salinity anomalies on the Irish shelf also show variability from year to year, with evidence of freshening in coastal waters associated with increased winter rainfall. Coastal salinity records are significantly correlated to the Eastern Atlantic Pattern (EAP) (Fennell, 2008).

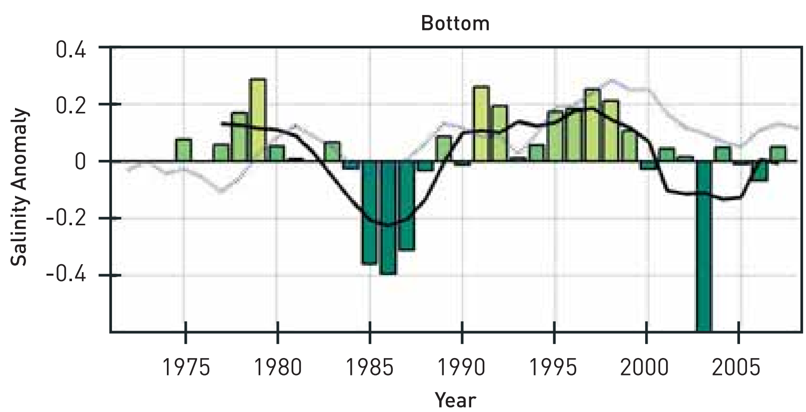

Figure 3.8 Annual mean bottom salinity anomalies on the Irish shelf (bars), overlain by a 5 year running mean (black line). Bottom salinity anomalies are overlain by a 5 year running mean of the NAO advanced 7 years in time (blue dashed). Salinity anomalies are calculated relative to the 1971-2007 climatology, and have been averaged over the region 48-58N, -15-3W.

3.3.4 Sea Level

'Model projections of the IPCC SRES scenarios give a global mean sea level rise of 0.09 m to 0.88 m by 2100, with sea level rising at rates circa 2 to 4 times faster than those of the present day'.

Sea level measurements have not historically been made at the spatial or temporal scales required to directly assess sea level changes around Ireland's coast, though, a network of tide gauges are being developed at present (www.irishtides.ie). There is a heavy reliance on computer model outputs to predict future sea levels as few global long term reference data sets exist. Model projections of the IPCC SRES scenarios give a global mean sea level rise of 0.09 m to 0.88 m by 2100, with sea level rising at rates circa 2 to 4 times faster than those of the present day (Alcamo *et al.*, 2007, EEA, 2004; Meehl *et al.*, 2007). In Europe, regional influences may result in sea level rise being up to 50% higher than these global estimates (Woodworth *et al.*, 2005). The impact of the NAO on winter sea levels provides an additional uncertainty of 0.1 m to 0.2 m to these estimates (Hulme *et al.*, 2002; Tsimplis *et al.*, 2004a). Issues such as sustained melting of Greenland ice and other ice stores under climate warming and feedbacks with the Thermohaline Circulation in the Northeast Atlantic provide additional uncertainty to sea level rise for Europe (Gregory *et al.*, 2004; Levermann *et al.*, 2005; Wigley, 2005; Meehl *et al.*, 2007).

Coastal retreat rates are currently 0.5 to 1.0 m/yr for parts of the Atlantic coast most affected by storms and under sea level rise these rates are expected to increase (Cooper and Pilkey, 2004; Lozano *et al.*, 2004).

3.3.5 Wave Climate

'Increases in the monthly mean significant wave height of up to 0.6 m in the Northeast Atlantic from 1988 to 2002 have been linked to changes in the NAO'.

Increases in significant wave height (the mean height of the highest 1/3 of waves) have been identified in the North Atlantic mid-latitudes based on a 14 year (1988-2002) time series of TOPEX/Poseidon and ERS-1/2 satellite altimetry data (Woolf *et al.*, 2002), with the largest increasing trend of 14 cm per decade in the Northwest Atlantic. The wave climate of the Northeast Atlantic and adjacent shelf regions is strongly seasonal; peaking during the winter months and also exhibits a strong interannual variability that is significantly correlated to the NAO. Increases in the monthly mean significant wave height of up to 0.6 m in the Northeast Atlantic from 1988 to 2002 have been linked to changes in the NAO.

3.3.6 Shelf Sea Stratification and Thermohaline Circulation

Seasonal heating of the shelf seas creates a relatively warm and buoyant surface layer. In deeper regions of the shelf seas, tidal energy is insufficient to mix down the buoyant warm surface layers, creating a seasonally stratified water column. Shallower regions of the shelf seas remain vertically mixed throughout the year. The boundaries between the vertically mixed and stratified regions of the shelf seas, referred to as frontal zones, are associated with density driven currents (figure 3.9) forming important transport pathways in the shelf seas (Hill *et al.*, 2008). Evidence suggests that warming observed in recent decades has resulted in an earlier onset of stratification. This may result in more persistent currents in summer in these frontal regions and changes in the timing of primary and secondary biological production.

'Evidence suggests that warming observed in recent decades has resulted in an earlier onset of stratification'.

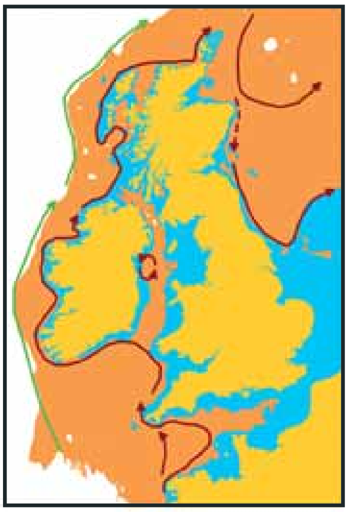

Figure 3.9 Thermohaline circulation in Irish waters showing the coastal density driven circulation (red track) and shelf edge current (green track) (Redrawn from Hill *et al.*, 2008).

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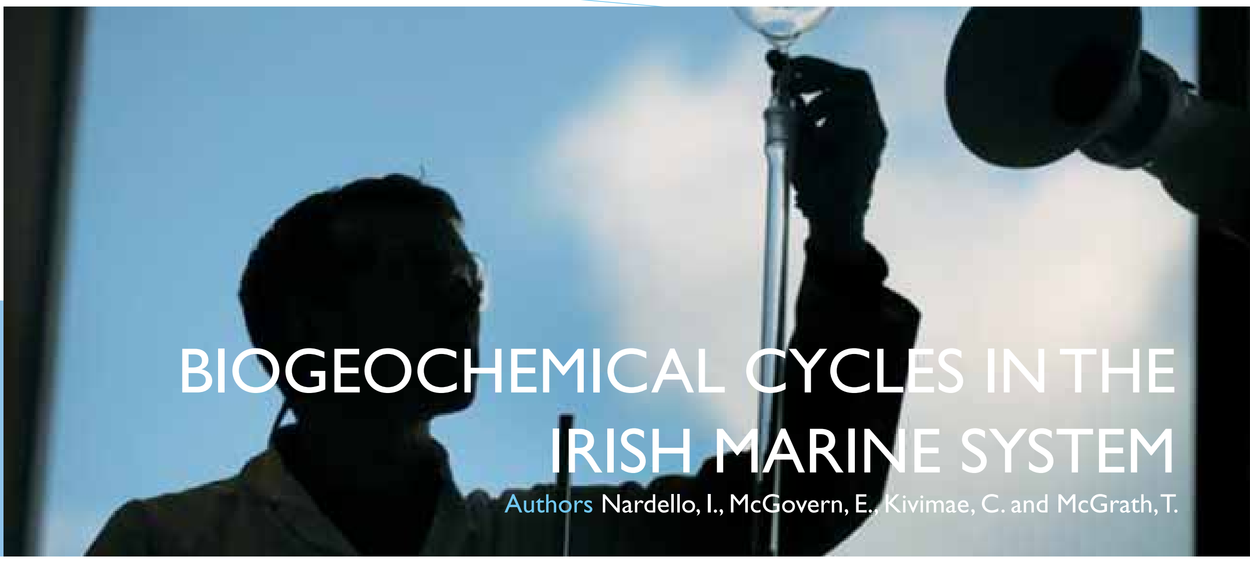


BIOGEOCHEMICAL CYCLES IN THE IRISH MARINE SYSTEM

Authors Nardello, I., McGovern, E., Kivimae, C. and McGrath, T.

KEY POINTS

» Absorption of anthropogenic carbon dioxide by the oceans has mitigated climate change but lowered the pH of the oceans. This ocean acidification will continue in response to the ongoing carbon dioxide emissions and there is growing concern as to the impact of this rapid change in ocean chemistry on species and ecosystems, especially on calcifying organisms such as deep sea corals.

» Temporal trends for winter nutrients concentrations in the western Irish Sea assessed for the period 1990-2000 indicated a significant 20-33% decrease in ortho-phosphate concentration in the western Irish Sea over that period. Trends were less clear for TOxN.

» The shelf seas west of Ireland have slightly lower wintertime nutrient concentrations than the Irish Sea due to freshwater inputs to the Irish Sea.

» Acidification of seawater at the levels predicted by current carbon dioxide emission rates can completely change the life of many calcifying organisms, from unicellular algae (phytoplankton) to large invertebrates (echinoderms), with unknown consequences for top predators such as fish, birds and mammals. Modification in the availability of nutrients and trace elements, as well as in their potential to be assimilated (speciation) is also expected.

the biological pump

4.1 INTRODUCTION

4.1.1 Ecosystem Conditions

Chemical elements such as carbon, nitrogen, phosphorus and silica are constituents of all living organisms (Spencer, 1975; Sarmiento and Gruber, 2006). Unicellular algae at the base of the marine food chain (phytoplankton) transform the inorganic elements through primary production, thus allowing higher trophic levels to directly utilize organic material to build their body structures and extract metabolic energy. It is through this process, called the biological pump, that inorganic carbon is sequestered from the atmosphere and surface seawater into the ocean's depths (Emerson and Hedges, 2008). The activity of phytoplankton accounts for nearly 50% of global primary production, but essential nutrients must be abundant in the sunlit layers of the ocean to support this activity (Falkowski *et al.*, 1998). While carbon is generally abundant, the concentration of nitrogen, phosphorus and silica and other trace elements can be a limiting factor for this fundamental ecological process.

The concentration of carbon and other nutrients in the surface ocean is regulated by the efficiency of the biological pump, and by the physical conditioning of the water column through circulation and mixing. Dissolved inorganic carbon is also controlled in part by the solubility pump, which depends on temperature and salinity of seawater, and on the partial pressure of carbon dioxide (CO_2) in the atmosphere. In the coastal ocean, atmospheric deposition and run-off from land also play an important role in the modification of the biogeochemical and physical conditions of seawater. Human activities and climate change can influence these processes and therefore contribute to altering nutrient availability and their assimilation. Monitoring the biogeochemical properties of the marine environment can provide valuable information on the changes that the marine systems are experiencing in relation to human activities and climate related changes (IPCC, 2007).

4.1.2 Environmental Changes, Human Activities and Reasons for Concerns

The concentration of atmospheric CO_2 has increased from 280 ppm to 380 ppm since the industrial revolution, reaching the highest concentration in the last 420,000 years with a rate of increase unprecedented in the last 20,000 years. According to various authors, half of the manmade CO_2 emitted to the atmosphere since the industrial revolution has been absorbed by the oceans, leading to an average decrease of 0.1 pH units in surface waters. Spatial variability accounts for ± 0.3 units primarily governed by temperature, upwelling, and localized anthropogenic stress.

In recent times, a number of studies from authoritative reports (The Royal Society, 2005; OSPAR, 2006) to scientific journal reviews (Marine Science, Annual review, January 2009; Marine Ecology Progress Series, Theme Session, December 2008), have been raising the concern that the increase in seawater CO_2 concentration in the world's oceans is leading to ocean acidification and representing a major threat for the marine environment,. The IPCC 4th Assessment Report (2007) also highlights decreasing ocean pH as an issue, and concludes that *"the response of marine biota to ocean acidification is not yet clear, both for the physiology of the individual organisms and for the ecosystem functioning as a whole"*.

The studies indicate that the observed decrease in ocean's pH is directly and almost exclusively due to the manmade emissions of carbon dioxide. Feedback mechanisms may reduce the CO_2 uptake by the ocean, due to the reduced buffering capacity at decreasing alkalinity, and decreased solubility at higher temperature. Model forecasts have indicated that with a "business as usual scenario" (IPCC IS92a) there could be a reduction in surface ocean pH of ~0.3 - 0.5 by the end of this century (Orr *et al.*, 2005; McNeill *et al.*, 2006) (Table 4.1). The surface Southern Ocean will begin to become undersaturated in aragonite by 2050, and by 2100 undersaturation could extend to the entire Southern Ocean and subarctic Pacific Ocean (Orr *et al.*, 2005). Aragonite is needed by organisms such as pteropods so they can form shells. In the North Atlantic Ocean the Aragonite Saturation Horizon (ASH), the boundary between surface saturated waters and deeper undersaturated waters, could be 2000 m shallower at a depth of ca. 600 m, while surface waters will remain supersaturated but to a lesser extent. This upward movement of the ASH will limit the part of the water column that organisms relying on aragonite can occupy. Such chemical changes are probably unprecedented in the past 300 million years with the possible exception of rare catastrophic events.

'The response of marine biota to ocean acidification is not yet clear, both for the physiology of the individual organisms and for the ecosystem functioning as a whole'.

Scenario	$[CO_2]_{atm}$	pH	Confidence
Preindustrial	280 [1, 2]	8.2 [3]	High
Today	385 [1, 2]	8.1 [1]	High
2100 ---------------- IPCC IS92A "Business as usual"	788 [4]	7.91 [5]	Medium
2100 ---------------- IPCC 650A "Mitigation"	650 [4]	Shoaling of aragonite saturation horizon by 2000 m to 610 m in the North Atlantic. Lower supersaturation of surface waters. [4]	Medium

Table 4.1. Summary table of the past, present and future scenario relative to atmospheric carbon dioxide concentration ($[CO_2]_{atm}$; values are in parts per million by volume [ppmv]) and seawater acidity level (pH). Numbers in brackets refer to scientific literature: [1] Doney *et al.*, 2009; [2] Solomon *et al.*, 2007; [3] Royal Society, 2005; [4] Orr *et al.*, 2005; [5] McNeil and Matear, 2006.

'Examples of organisms that could be affected by lower supersaturation or undersaturation of carbonate salts include phytoplankton, zooplankton, corals, and echinoderms'.

Examples of organisms that could be affected by lower supersaturation or undersaturation of carbonate salts include phytoplankton (e.g. coccolithophores and foraminifera), zooplankton (e.g. pteropods), corals, and echinoderms (Doney *et al.*, 2009). The potential for marine organisms to acclimatise to such changes in the long term is unknown. The knock-on effects on the marine ecosystem are also unknown. Alteration of pH can certainly influence the equilibrium of chemical compounds, leading to modification in the availability of nutrients and trace elements and in their potential to be assimilated (speciation). Direct physiological responses are also expected.

Volumetric flasks used in laboratory

CAPACITY BUILDING I Ocean Chemistry

Author Nardello, I.

Impacts of Increased Atmospheric CO_2 on Ocean Chemistry and Ecosystem (NUIG and Marine Institute Partnership)

In order to understand the impacts that ocean acidification may have on Irish marine ecosystems, we need to assess the current status of the key variables in the carbonate system in all Irish marine waters, and establish a baseline for organic and inorganic carbon, nutrients and pH, against which future changes can be measured.

The research project "Impacts of increased atmospheric CO_2 on ocean chemistry and ecosystem" was initiated in 2008 through a National University of Ireland in Galway partnership with the Marine Institute, under the Marine Institute's Marine Climate Change Programme funded by the National SSTI.

Sampling Activity

Synoptic observations of the biogeochemical characteristics of seawater pH total alkalinity, total dissolved inorganic carbon, fugacity of carbon dioxide, macro and micronutrients, chlorophyll-a, were started in 2008, in the shallow shelf seas around Ireland as well as in the pelagic area off the Irish shelf (Fig. CB1.1) on board the national research vessels.

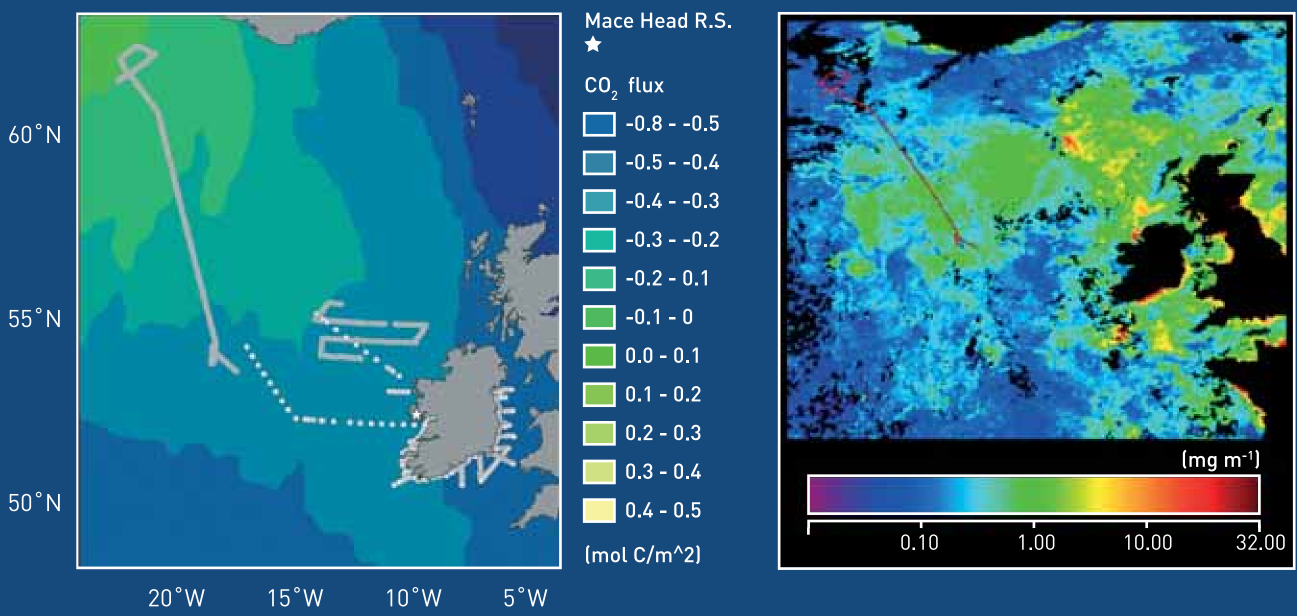


Figure CB1.1 (a) Sampling activities in 2008 relative to the "Impacts of increased atmospheric CO_2 on ocean chemistry and ecosystem" programme. The map shows cruise tracks in the North Atlantic Ocean and monitoring stations on the shelf water for nutrients and carbonate systems variables. The location of the pCO_2 buoy at Mace Head is also represented. In the background, the distribution of the CO_2 flux climatology values (Takahashi *et al.*, 2002; Gurney *et al.*, 2002) show that the oceanic area around Ireland is a moderate carbon sink. (b) On the right, a satellite image from NASA/EOS MODIS_Aqua shows chlorophyll-a concentration in May 2008, at the time a survey cruise was taking place on Research Vessel *Celtic Explorer* (the track is superimposed in red).

The Research Vessel *Celtic Explorer* has been equipped with sensors mounted on a dedicated mast (figure CB1.2a and CB1.2b) to measure air-sea fluxes of carbon dioxide, and with a permanent system to detect seawater concentration of CO_2. In addition, a buoy has been deployed offshore of Mace Head as an observation platform for the measurement of carbon dioxide concentration in seawater (figure CB1.2c). Sensors installed on the Mace Head observation tower will complement the suite of aerosol and other atmospheric measurements with carbon dioxide fluxes.

Ocean's Carbonate System

Dissolved Inorganic Carbon (DIC) / Total Alkalinity (TA) – Seawater samples for dissolved inorganic carbon (DIC) and total alkalinity (TA) were collected during various cruises since the beginning of the programme (May 2008, September 2008 and February 2009). Samples currently being processed will quantify the state and variability of the carbonate system parameters in Irish waters. Water temperature and salinity are the strongest controls on seawater concentration of total dissolved inorganic carbon (DIC) and on total alkalinity (TA) respectively. They vary greatly with depth, latitude and mixing conditions. In the coastal environment, river discharge and land run-off can also significantly alter the biogeochemical conditions of seawater. On the basis of the salinity values measured during our sampling activities (32.8-35.6), total alkalinity values in Irish waters are expected to be found in the range 2200-2345 μmol/Kg (Millero *et al.*, 1998) but processes operating on the Irish continental shelf may alter this picture. For example, precipitation patterns (frequency, intensity, seasonality) affected by climate change can significantly modify the water quality of the coastal systems.

Figure CB1.2 Building capacity in carbon dioxide measurements in the marine environment. (a) Carbon dioxide flux tower on board Research Vessel *Celtic Explorer.* (b) Suite of sensors for CO_2 flux measurement. (c) Carbon dioxide concentration coastal buoy at Mace Head.

CO_2 Fluxes

Fluxes of CO_2 between the Ocean and the Atmosphere

In order to quantify CO_2 fluxes, as well as their relationship to wind speed and biological activity, simultaneous measurements of CO_2 fluxes, the difference in the partial pressure of carbon dioxide between air and seawater (ΔpCO_2; measured in the flux footprint), and biological indicators such as chlorophyll-a concentration are required. This project has enabled such a measurement suite at Mace Head, using the existing CO_2 flux package and the Marine Institute buoy (figure CB1.2c) located in the Mace Head flux footprint. A dedicated flux package has been deployed on the *Celtic Explorer* (figure CB1.2b and CB1.2c) to quantify off-shore fluxes and transfer velocities for CO_2. The new infrastructures on board the national Research Vessel *Celtic Explorer* as well as at Mace Head are still being evaluated.

The pCO_2 measurement network will be analysed for spatial and seasonal trends over a one year period providing an assessment of the seasonal variability and annual average values of pCO_2 in the Northeast Atlantic for the first time.

4.2 NUTRIENTS

'As many of the factors determining nutrient concentration in coastal waters are likely to change as our climate changes (e.g. altered rainfall patterns and the affect on riverine discharges) it is critical that a baseline of nutrient concentrations is available to compare with future values'.

Irish coastal waters – Nutrient concentrations in Irish coastal waters are determined by concentrations in shelf waters (full salinity seawater), nutrient loads associated with freshwater input and land based discharges, atmospheric inputs, and biogeochemical processes such as recycling, biological assimilation or denitrification. Dilution of freshwater inflow and associated nutrient loads in coastal waters can be represented by salinity, although deviations from conservative nutrient mixing patterns can occur due to the combination of multiple land based sources and biogeochemical processes. Land based nutrient inputs to coastal waters reflect natural and anthropogenic sources, including diffuse (e.g. agricultural application of fertiliser) or direct (e.g. municipal waste) discharges, and climatic factors such as rainfall. As many of the factors determining nutrient concentration in coastal waters are likely to change as our climate changes (e.g. altered rainfall patterns and the affect on riverine discharges) it is critical that a baseline of nutrient concentrations is available to compare with future values. Rivers are the primary route for such inputs into coastal waters. Inorganic nitrogen is the limiting nutrient in North Atlantic shelf seas.

The annual cycle of dissolved inorganic nutrients in surface waters of the Irish Sea show maximum concentration in winter and minimum in summer, as is typical of northern European coastal and shelf seas (Gowen *et al.*, 2005). Data from the Interreg-IIIa funded Methods of Assessment of the Trophic Status of the Irish Sea (MATSIS) project shows this seasonal variability of total oxidized nitrogen (ToxN) in stratified waters of the western Irish Sea gyre between Ireland and the Isle of Man (figure 4.1).

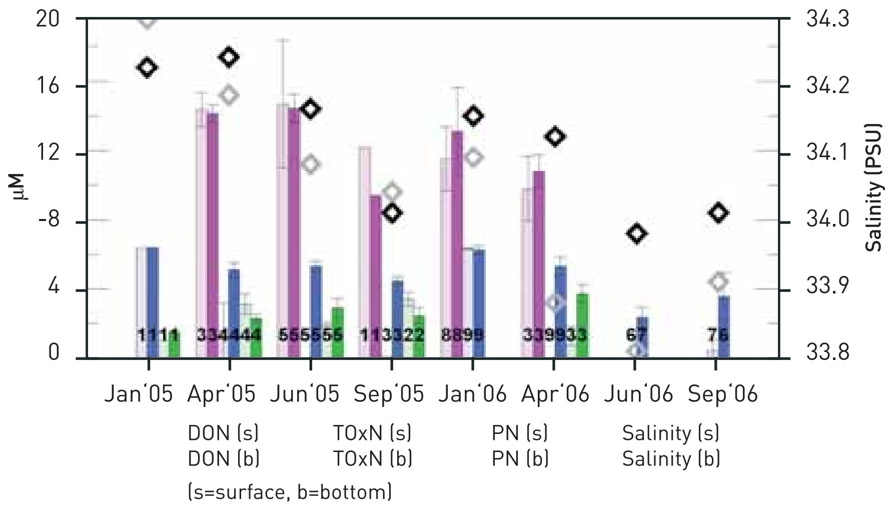


Figure 4.1 Seasonal mean nitrogen concentrations of dissolved organic nitrogen (DON), total oxidized nitrogen (TOxN) and particulate nitrogen (PN) in surface (s) and bottom (b) water at the eastern gyre station in the Irish Sea as determined during MATSIS project 2005 – 2006 surveys. Error bars show standard deviations and numbers of samples analysed are also given as samples were collected during tidal cycles. (No number indicates no samples.) Mean salinity also measured. TOxN concentrations are occasionally low or depleted in surface waters above the thermocline during the growing season, but remain at fairly consistent levels below the thermocline. MATSIS data also indicated an appreciable pool of dissolved organic nitrogen in the Irish Sea but no clear evidence of utilisation of that pool (MATSIS report in prep.).

The Marine Institute has undertaken annual winter nutrient monitoring surveys in the western Irish Sea since 1991. The sampling strategy has evolved over the years to focus on inshore monitoring along with transects to describe nutrient gradients away from the coast (starting in 2003) and extended to the Celtic Sea and the west coast waters over recent years. A baseline composite surface nutrient data set has been compiled for the 2005-2008 period (figure 4.2)

winter nutrients

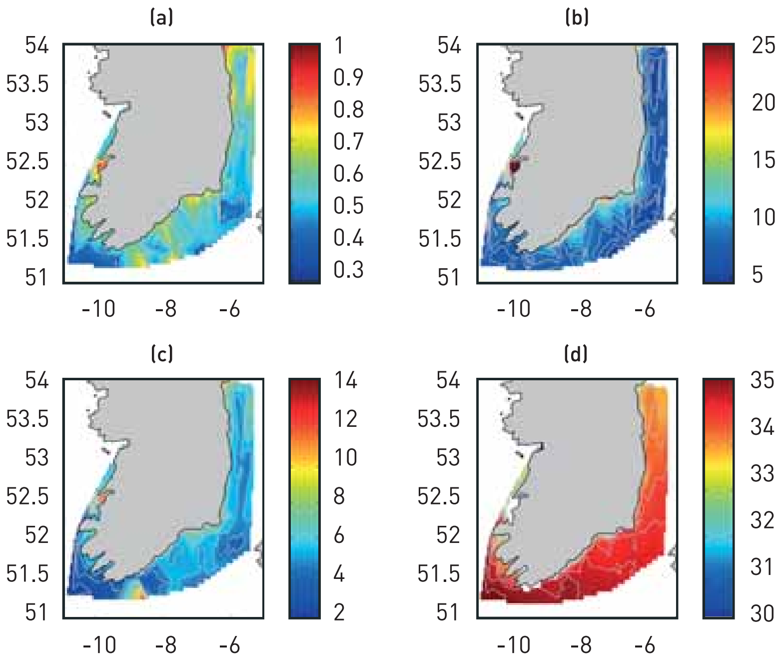


Figure 4.2 Composite surface winter nutrient concentrations for the years 2005-2008 showing nutrient gradients from the coastline and regions of elevated nutrients associated with freshwater inputs and/or limited exchange of seawater; a) phosphate (µM); b) silicate (µM); c) total oxidized nitrogen (TOxN) (µM) d) salinity (PSU).

Figure 4.3 presents plots of winter nutrient concentrations vs. salinity for coastal waters over the same period. The plots suggest different patterns of freshwater inputs to coastal waters in the different areas with lower nutrient concentrations associated with freshwater inputs on the west coast compared with the western Irish Sea, the Celtic Sea and southeast Irish Sea. The bulk of data is at the high end of the salinity range (>32), and small differences in TOxN concentrations at high salinity in the different areas may suggest dentrification in waters moving from the shelf to the Irish Sea. For both inshore coastal and offshore coastal waters, the median winter values of TOxN and ortho-P (figure 4.1) are well below the salinity related nutrient thresholds indicated by the OSPAR eutrophication national assessment criteria (OSPAR National Eutrophication Assessment Report, 2008). Concentrations below these thresholds are considered unlikely to stimulate abnormal/excessive phytoplankton production.

'Temporal trends for winter nutrients assessed for the period 1990-2000 indicated a significant 20-33% decrease in ortho-phosphate concentration in the western Irish Sea'.

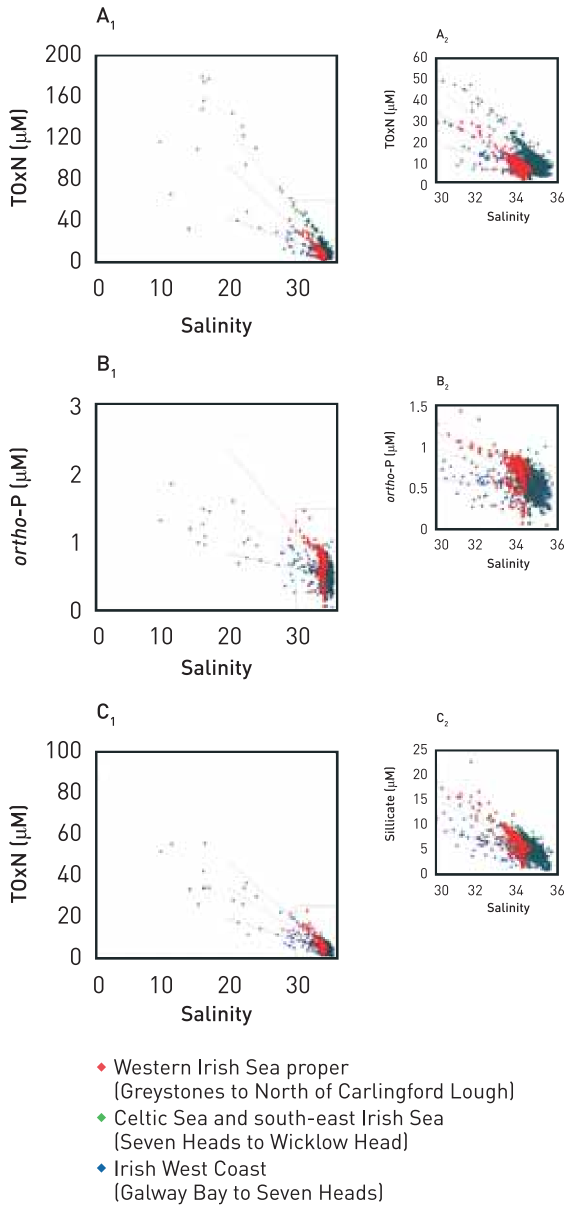


Figure 4.3 Plot of winter nutrient concentrations vs. salinity for Irish coastal waters for 2005-2008 with data defined into three areas. (A) TOxN vs. salinity with regression lines for salinity ≥ 20; (B) ortho-phosphate vs. salinity; (C) silicate vs. salinity and regression lines for salinity ≥ 20. Letters footnoted with 1= full salinity range or 2 = zoomed to salinity 30-36.

Temporal trends for winter nutrients concentrations in the western Irish Sea assessed for the period 1990-2000 (McGovern *et al.*, 2002) indicated a significant 20-33% decrease in ortho-phosphate concentration in the western Irish Sea. Trends were less clear for TOxN (McGovern *et al.*, 2002). Downward trends in phosphates reflect trends in other European seas and may be the result of a reduction in phosphorus loads from sewage and industry to the Irish Sea. A provisional revised examination of annual TOxN concentrations in the Irish Sea proper (1991-2008) and the southwest Irish Sea (1996-2008) shows variable annual nutrient salinity regression slopes indicating interannual variability in freshwater nutrient loadings. At a nominal salinity of 34 this assessment does suggest a downward trend for TOxN in the western Irish sea proper (Mann Kendall $P<0.05$) but not the southwest Irish Sea. A more detailed and robust assessment of nutrient trends and patterns will be undertaken in the coming year to determine if the trend could be an artefact of inconsistent sample coverage, especially in the early years of the programme, and/or non-conservative behaviour in certain years.

West Coast – Since 2006, the Marine Institute Winter Nutrient Monitoring Programme has been sampling coastal waters off the west coast. As in the Irish Sea, in winter the surface water of a number of bays (e.g. Galway Bay and at the mouth of the Shannon Estuary) are enriched with dissolved nutrients relative to the surrounding water. The region southwest of Cork has slightly lower nutrient concentrations than the surrounding water column, representing more oceanic levels of dissolved nutrients. The shelf seas west of Ireland have slightly lower wintertime nutrient concentrations than the Irish Sea. This is because the Irish Sea receives large quantities of freshwater discharge from both the Irish and Welsh coasts, along with large volumes coming in from the Celtic Sea containing nutrients of both oceanic and riverine origin. Also, while salinity off the east coast of Ireland has a median of 33.90 (Gowen *et al.*, 2005), salinity in coastal waters off the west and south coast reaches 35, reflecting a more oceanic influence on waters in this region (figure 4.2d).

Since 2007, winter nutrient data have been collected along transects extending across the shelf edge to the west of Ireland. Vertical profiles of nutrients are presented in figure 4.4. Nutrient concentrations are mixed down to the bottom of the winter mixed layer (c.a 300 m in February 2008). Below this mixed layer, nutrient concentrations gradually increase, reaching the highest concentrations at the seabed, due to remineralisation of sinking organic matter. In the summer, when the thermocline (at c.a 40 m) acts as a barrier for the vertical mixing of nutrient rich waters from greater depths, the concentration of nitrite and silicate in surface water samples is often below detection limit, with TOxN and phosphate concentrations also very low due to the uptake of nutrients by phytoplankton during the growing season. Summertime nutrients concentrations below the thermocline are higher than below the thermocline in winter, between 100-200 m, due to a larger amount of sinking organic material after the spring bloom.

'The shelf seas west of Ireland have slightly lower wintertime nutrient concentrations than the Irish Sea'.

A glass beaker used in laboratory

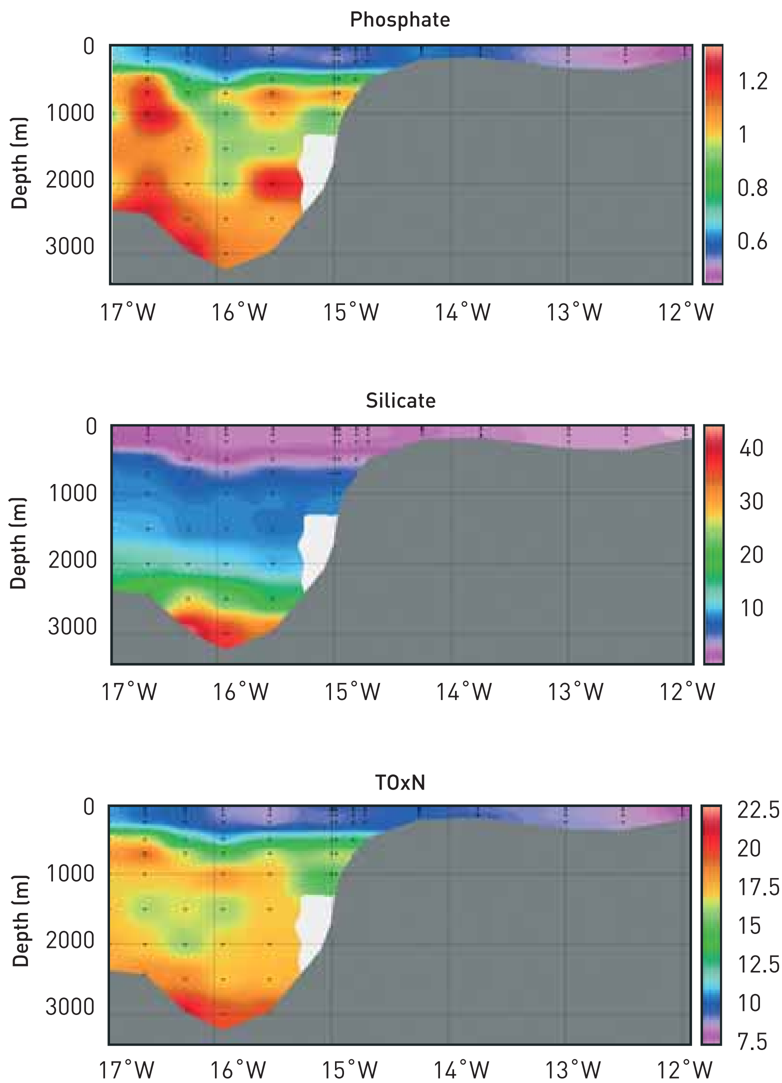
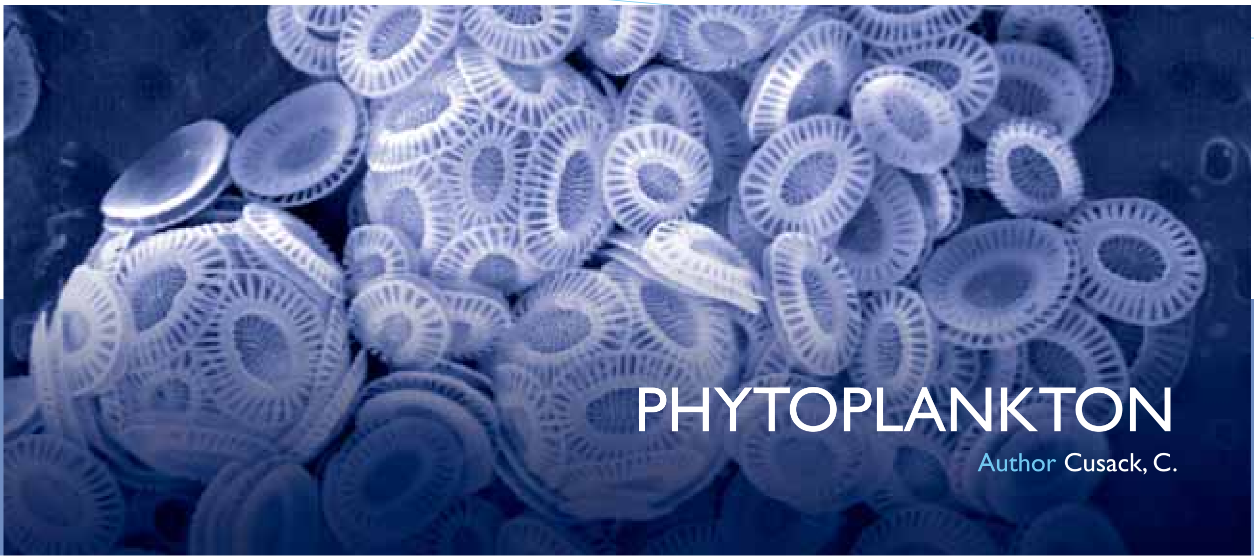


Figure 4.4 Wintertime (2008) vertical distribution of nutrients along an eastwest section off the west coast of Ireland (53° latitude N): a) phosphate; b) silicate; c) total oxidized nitrogen (TOxN).

5



PHYTOPLANKTON

Author Cusack, C.

KEY POINTS

» Increases in the annual numerical abundance of diatoms and dinoflagellates are evident in all coastal regions since 1998.

» Diatom abundance has increased earlier in the year since the late 1990s in all coastal regions; an expansion of the growth season.

» An increase in phytoplankton biomass is evident in the northern Celtic Sea based on CPR data since 2000.

» Total annual abundance of harmful and toxic species varies greatly between years.

» The percentage occurrence of some harmful species during the winter months has increased since 2000.

global photo-synthesis

5.1 INTRODUCTION

At the base of most marine food webs are primary producers called the phytoplankton (usually < 200 μm = 0.0002 m). These unicellular organisms, an important component of the food chain in marine pelagic habitats, are quickly consumed by respiring marine life forms in upper trophic levels (e.g. zooplankton and fish). Phytoplankton are a very sensitive constituent of the marine ecosystem and susceptible to environmental variability including climate change. As the phytoplankton are responsible for an estimated 50% of global photosynthesis (Philippart *et al.*, 2007), any disturbance could result in widespread implications for marine ecosystems and could result in effects that cascade through the food web.

5.2 IMPORTANCE OF PHYTOPLANKTON TO HIGHER TROPHIC LEVELS AND THE GLOBAL CARBON CYCLE

Playing a critical role in marine ecosystems and the carbon cycle, phytoplankton support and limit the biomass of all upper trophic levels. Phytoplankton growth is determined by the supply of inorganic nutrients, light availability, turbulence, predation and the temperature regime. Therefore, depth of the water column and distance from the coast plays a role in determining the nutrient supply crucial to phytoplankton growth (oceanic to coastal sites).

Phytoplankton are represented by different species or functional groups exhibiting unique ecological niches, seasonal patterns and periodic large biomass events, and they respond quickly to physical, chemical and biological fluctuations in their surrounding environment. For example, large cells are abundant in regions with high amounts of inorganic nutrients and sufficient light levels for growth, and growth rates generally increase with higher temperatures.

Changes in global climate can have direct and/or indirect repercussions on phytoplankton productivity and biodiversity, influencing the transfer of carbon through the food web and the overall functionality of the marine ecosystems. Today, c.a 60% of the particulate organic carbon sinking flux are comprised of diatoms, while coccolithophores are responsible for 80% of the particulate inorganic carbon (mostly calcite) flux (Guidry *et al.*, 2007).

Unlike other marine resources such as fish, phytoplankton are not harvested by man, and have relatively short life cycles (days). For these characteristics, the study of these microscopic algae can help us understand the impact of climate on marine ecosystems (Hays *et al.*, 2005). Changes of community structure, alteration of growth rates, and modification of the length of the growing season are all likely impacts of marine climate change on phytoplankton communities. As some of these changes have already been observed in Irish waters, their consequences for higher trophic levels should be investigated as soon as possible.

5.3 PHYTOPLANKTON IN IRISH WATERS

The water circulation patterns around Ireland are complex and play an important role in the transport of phytoplankton (Hill *et al.*, 2008). The properties of the different water masses found off the coast, along with seasonal changes, influence the composition of phytoplankton communities. Ireland is usually categorised as a temperate region and the majority of phytoplankton species recorded in our coastal waters are considered either temperate or cosmopolitan. Warm water species are, however, associated with the European shelf edge current and North Atlantic waters to the west. Although rare, some warm water species have been recorded inshore of the Irish Shelf Front (ISF) (Roden, 1984). The ISF is the boundary that defines two separate water masses; inshore coastal waters from the more saline oceanic Atlantic waters. At the land sea interface a reduction in salinity from land derived fresh water input has an influence on the phytoplankton assemblages found. Close to the coast, on the northwest European continental shelf to the west and south of Ireland, a clockwise coastal current transports phytoplankton populations in a northward direction. Wind driven processes are responsible for the transport of shelf populations into the embayments around the coast. This is particularly noticeable in summer with the development of subsurface bottom density fronts; the associated jet-like currents are considered to be the primary mode of transport at depth of potentially toxic microalgal blooms around the coast. In the open ocean, to the west and southwest of Ireland the European shelf edge or slope current plays an important role in the transport of water masses from the south. The biogeographic limits of phytoplankton are defined by many factors (e.g. nutrient and light availability) with temperature having an important role. Many of the inshore phytoplankton species found in western and southwestern Irish marine waters resemble the flora from the northwest European shelf adjacent to France, Spain and Portugal. There are, however, a number of tropical warm water species that have not yet been recorded in Irish waters (see the section on harmful and toxic microalgae below for details).

'The diversity of phytoplankton in Irish waters is strongly influenced by the complex water circulation patterns of ocean currents'.

The diversity of phytoplankton in Irish waters is strongly influenced by the complex water circulation patterns of ocean currents exhibited offshore where the strength of the poleward movement of water is in part determined by large scale changes in the position of the subtropical gyre. This should, therefore, be taken into consideration when investigating changing patterns of phytoplankton communities overlying the deep ocean west of Ireland.

5.4 PHYTOPLANKTON DATASETS

The first dataset used for phytoplankton analyses in this report came from the National Phytoplankton Monitoring Programme (NMP), Marine Institute (see www.marine.ie/home/services/operational/phytoplankton/). Water samples were collected from aquaculture sites around the coast. The water column remains relatively mixed all year round and diatoms tend to dominate the phytoplankton.

'The data time series summarised here are relatively short and so a cautionary approach must be taken when investigating the effects of climate change'.

Note, very little is known about the phytoplankton composition in the size range < 10 μm and picoplankton > 3 μm in Irish waters. Picoplankton dominate photosynthetic activities in the open ocean where bacterioplankton play a central role in the carbon flux by taking up and remineralising dissolved organic carbon (Hader *et al.*, 1998). It is important to remember that the data time series summarised here (figure 5.1 and 5.2) are relatively short and so a cautionary approach must be taken when investigating the effects of climate change. This in turn highlights the importance of long term monitoring programmes in order to understand how the biological system reacts to external environmental changes including global warming. The second dataset used in this study was the Continuous Plankton Recorder (CPR) data collected by the Sir Alister Hardy Foundation (Plymouth). Phytoplankton Colour Index (PCI) data were used as proxy for elevated phytoplankton biomass. Here, data from the shelf seas to the south and north of Ireland were examined in relation to climate change (figure 5.3).

phyto-
plankton
species

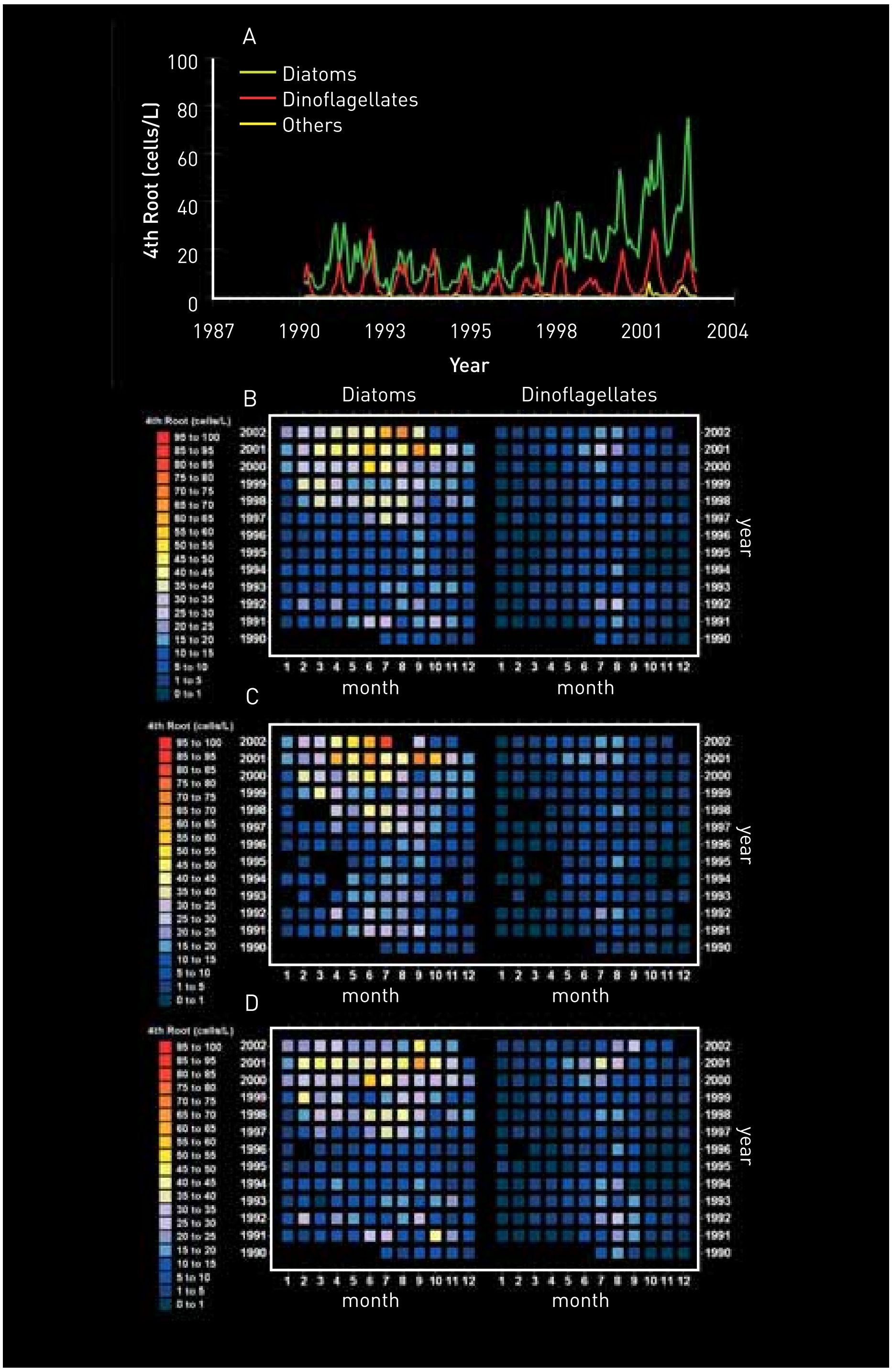


Figure 5.1 Average monthly and yearly abundance of the phytoplankton functional groups, diatoms (Bacillariophyceae) and dinoflagellates (Dinophyceae) in Irish waters from 1990-2002. A + B = all Irish coastal waters, C = west coast and D = southwest coast. Geographic regions to the southwest and west were selected for more detailed investigation since these coastal regions are not as heavily impacted by human activities as the east and south coasts of Ireland (O'Boyle *et al.*, 2008). Plot A. X axis = time; Y-axis = numerical abundance. Plots B-D. X-axis = month; Y-axis = year; colour legend denotes numerical abundance.

Plankton analysis

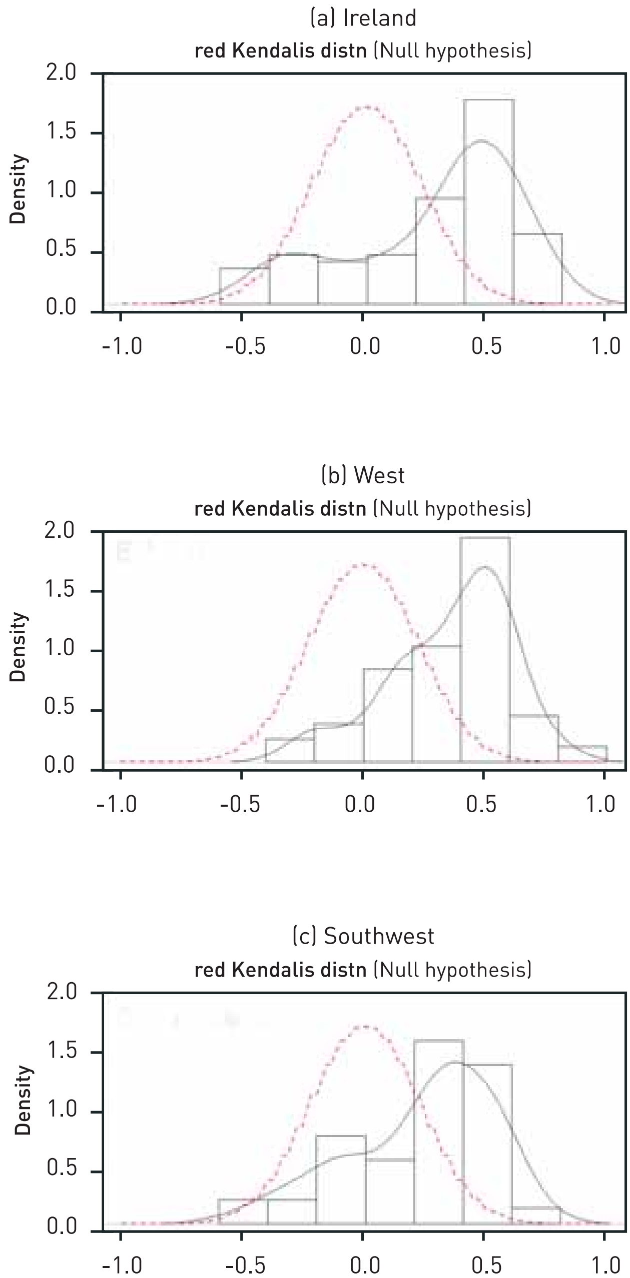


Figure 5.2 True histograms (bars) with Kernel density smoothes (black lines) of Kendall rank coefficients by region for inshore phytoplankton species (all data, west and southwest). In general the phytoplankton community does not show the expected distribution (red line). The shift of the observed histogram to the right (bars and black line relative to the red line) indicates many more species within the community increasing in abundance than would be expected by chance. (p = <0.001) (Source Lynam, Cusack and Stokes unpublished).

5.5 STATUS AND TRENDS OF PHYTOPLANKTON IN IRISH WATERS

phyto-
plankton
trends

The window for optimal growth of phytoplankton in Irish waters is determined primarily by light availability and day length although nutrients also play an important role. The growth season is considered to run from March to September. Of the larger phytoplankton, diatoms tend to dominate Irish inshore marine coastal systems. Diatoms are highly productive, being one of the main contributors to global productivity and nutrient cycling. Diatoms are highly adapted to turbulent environments and exposure to high and low light conditions in the surface mixed layer of ocean and have very efficient CO_2 uptake mechanisms (Falkowski and Knoll, 2007). Dinoflagellates begin to appear at very low concentrations in May, but tend to be most abundant from June to August. Most of the dinoflagellate populations observed inshore are associated with the advection of offshore waters. Coastal phytoplankton exhibit a wide range of environmental tolerances and can endure wide temperature ranges (temperature tolerance) since seasonal and daily sea temperature changes fluctuate greatly.

5.5.1 Coastal Bays

The spatial and temporal variability of inshore diatoms and dinoflagellates (medium sized nanoplankton and microplankton) are presented in figure 5.1 and 5.2. Since the mid-1990s elevated levels of diatoms and dinoflagellates have been found throughout most of the year (compared with the start of the time series). Dinoflagellate growth peaks in July and August in all regions examined while diatoms are most abundant in summer. From 1998-2002 the diatoms increased in numerical abundance earlier in the year. A notable increase in several phytoplankton groups was also observed in Irish waters.

5.5.2 Shelf Sea Phytoplankton

Although there was no clear pattern in the phytoplankton colour index (PCI) from northern waters on the Malin Shelf, an increase in the intensity of colour throughout the year was observed in the northern Celtic Sea since the late 1990s. This extension of the growth season (March-September) became most evident from 2000-2005. This means that an increase in phytoplankton colour was evident in the earlier and later months of the year. A similar finding on land refers to the average date for the First Flowering Date (FFD) of hundreds of British flowering plants; this date has apparently advanced by more than 4 days with many species flowering more then 2 weeks earlier then in the past (Fritters *et al.*, 2002).

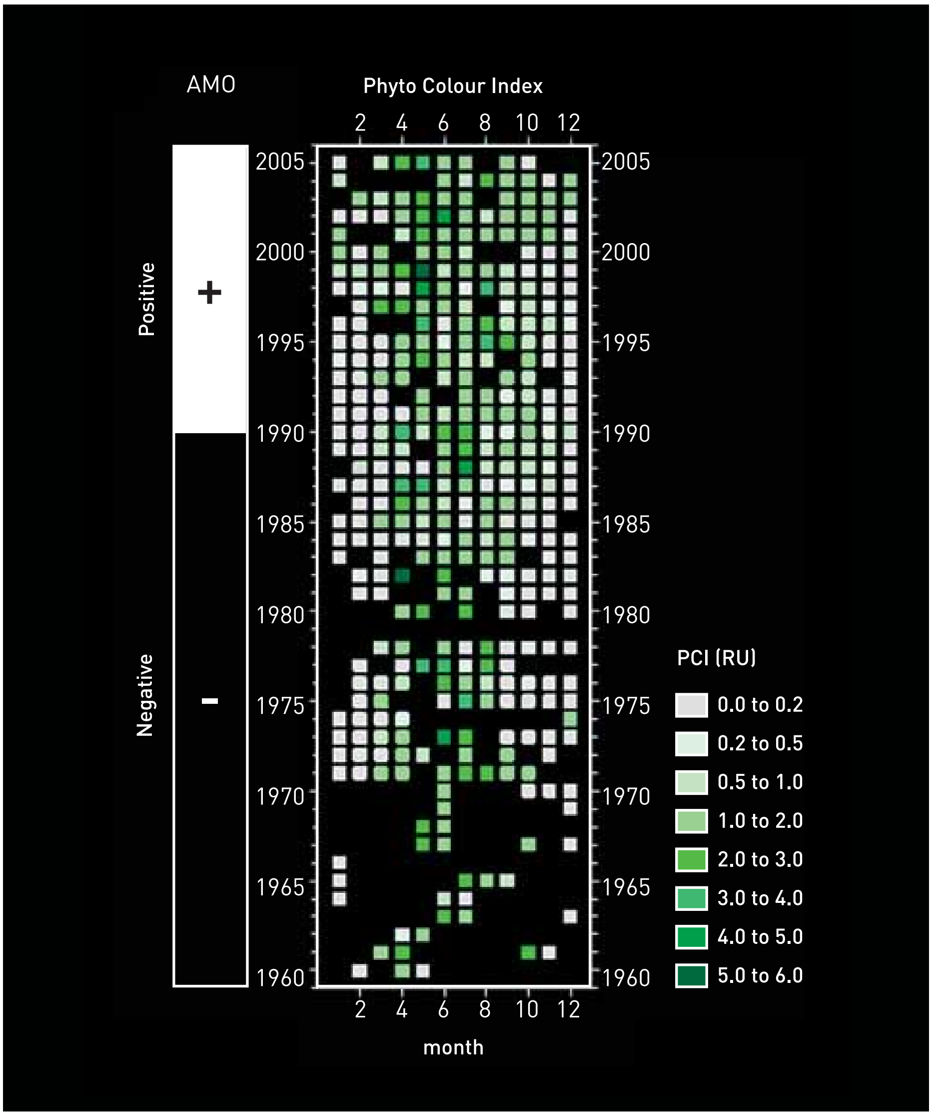
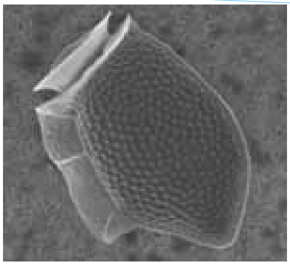


Figure 5.3 Average monthly values for phytoplankton colour (biomass) in the Celtic Sea from 1960-2005. X-axis = month; Y-axis = year; colour legend denotes numerical abundance.

5.5.3 Potentially Toxic and/or Harmful Algal Blooms (HABs)

Hallegraeff (1993) reported that the number of toxic events and HABs are increasing in many pelagic environments worldwide. It is worth pointing out that globally the number of HAB monitoring programmes has also increased. While the increase in HABs has been attributed to human induced water pollution, in some parts of the world human induced changes in climate are considered to be just as important. (Sellner *et al.*, 2003). In Ireland these toxic and harmful events are considered to be mostly natural. In this study, three species which cause harmful algal events in Irish waters *Karenia mikimotoi* (high biomass icthyotoxic spp.), *Dinophysis acuminata* and *D. acuta* (which can give rise to Diarrhetic Shellfish Poisoning (DSP)); these species exhibited large interannual variability. There was no obvious change in the interannual or seasonal variability of the genus *Dinophysis*. Since 2000, the dinoflagellate *Karenia* *mikimotoi*, typically present in bloom concentrations in thin layers in well stratified waters was present in a higher percentage of samples during the winter months (figure 5.4). This indicates that the organism is able to withstand the harsh conditions of winter; winter temperatures have increased in recent years and this is most probably a symptom of these changes. An unusual event that occurred in recent years was a large *Karenia mikimotoi* bloom in 2005 (Silke *et al.*, 2005). What was notable about this bloom was that it occurred in June, 1-2 months earlier than the species usually blooms, its geographic extent all along the western and southwestern coast and its persistence over several months. When the bloom decayed, it caused significant damage to the marine ecosystem all along the west coast of Ireland with mass mortalities of benthic communities (Silke *et al.*, 2005).



Dinophysis acuta

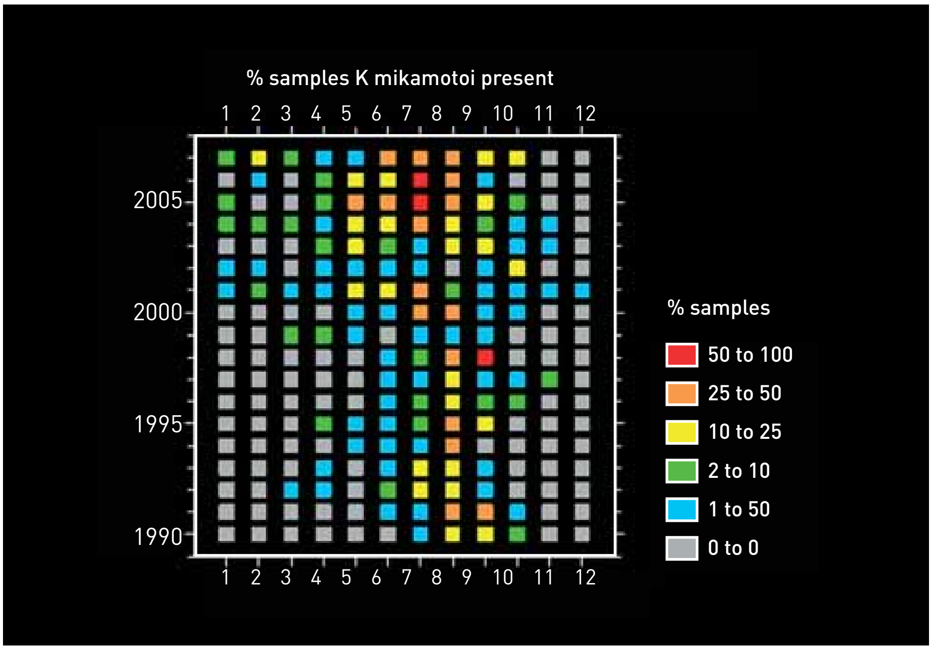


Figure 5.4 Percentage of samples in which *Karenia mikimotoi* was recorded in between 1990–2007 in Irish coastal waters.

The datasets analysed for this study are from short time periods (ranging from 13-46 years); one must bear this in mind when talking about climate change which is a long timescale phenomenon. If current global climate models (GCM) are correct in their predictions, that earlier and prolonged stratification of the water column will occur, then a depletion of surface nutrients in shelf seas is likely to result in a decline in phytoplankton biomass. This type of change will cascade through the food web with many unknown consequences. As most of the toxic and harmful algae recorded in Irish waters prefer stratified waters, it is possible that an increase in the frequency of harmful events will be a symptom of such changes.

6 ZOOPLANKTON

Authors Lynam, C. and Doyle, T.

KEY POINTS

Crustacean zooplankton throughout the North Atlantic

» Spatial patterns in the biodiversity of calanoid copepods have changed in response to warming with general movement north of warm water species and retreat of cold water species.

» The seasonal cycle of zooplankton species in the North Sea has altered with a general trend towards a peak in abundance earlier in the year.

» The rate at which zooplankton are moving poleward is most pronounced over the European shelf edge to the west of Ireland.

Gelatinous zooplankton

» In oceanic areas, depth >200 m, gelatinous zooplankton abundance is higher during warm years, which is thought to improve prey availability.

» Gelatinous zooplankton in the Northeast Atlantic show cyclic changes in population sizes that differ between oceanic and shelf areas. However, since 1997 they have been increasing simultaneously in shelf and oceanic waters.

KEY POINTS continued

Calanus helgolandicus in the Celtic Sea

- The abundance of this common warm water species has increased to the southeast of Ireland.

- A possible phenological shift suggests that production of this species begins earlier in the year.

6.1. INTRODUCTION

Zooplankton are the grazers of the sea, consuming and processing phytoplankton and passing organic matter from the base of the food web to the carnivorous consumers (e.g. fish and seabirds, on higher trophic levels). As such an important link in the food web, any major change in the abundance of zooplankton or shift in their spatial distribution will have consequences that cascade through the marine food web. Due to their sensitivity to temperature and short lifecycles (ranging from days to months), zooplankton are ideally suited to exemplify climate change impacts.

6.2. Crustacean Zooplankton

In the North Atlantic, changes in plankton communities (investigated using Continuous Plankton Recorder (CPR) data, Sir Alister Hardy Foundation for Ocean Science (SAHFOS)) have been associated with warming of the ocean and pressure variations in the atmosphere as measured by the North Atlantic Oscillation index. The clearest response of zooplankton to climate change is the great biogeographical changes in diversity that have been observed in calanoid copepods; crustacean zooplankton species that are a key prey resource for the larvae of many fish species, including cod and herring (Beaugrand *et al.*, 2009) (figure 6.1). The northward movement of copepod assemblages, at an average rate of 23 km per year, reflects the advance of species with warm water preferences and the retreat of a number of cold water species. These biogeographical shifts mirror recent changes in the spatial distribution of many taxonomic groups in terrestrial European ecosystems (Beaugrand *et al.*, 2009 and references therein). However, the observed rates of latitudinal shifts in copepod assemblages are exceptional relative to terrestrial species; for example 65% of non-migratory European butterflies (35 species) studied migrated north over variable periods between 30 and 100 years with a maximal rate of only 5 km per year (Parmesan *et al.*, 1999). The rate at which zooplankton are moving poleward is most pronounced over the European shelf edge to the west of Ireland, and may be partly explained by the additional effect on species migrations of oceanographic variability, namely a contraction of the subpolar gyre and a strengthening of the shelf edge current (see Chapter 3 for explanation of relevant oceanography).

'The northward movement of copepod assemblages, at an average rate of 23 km per year, reflects the advance of species with warm water preferences and the retreat of a number of cold water species'.

Calanus helgolandicus

Phenological changes in annual recursive events, whereby warming alters the timing of life history events, such as the start of the zooplankton production season, have been observed in much the same way that bumblebees (*Bombus* spp.) appear earlier in warmer than usual years. However, the response is not uniform among species; for example, the seasonality of the plankton community in the North Sea has adjusted following warming, but varied in magnitude and direction between different functional groups and trophic levels, leading to potential mismatch between predators and their prey (Edwards and Richardson, 2004). Collectively, however, meroplankton (e.g. *Echinocardium cordatum*) moved forward by 27 days, copepods by 10 days, and non-copepod holozooplankton by 10 days between 1958 and 2002. Temperate marine environments appear particularly vulnerable to such climate-led phenological changes because the recruitment success of many higher trophic levels is highly dependent on the synchronisation with pulsed planktonic production.

'The rapid changes in plankton communities observed over the last few decades in the North Atlantic, related to regional climate changes, have enormous consequences for other trophic levels and biogeochemical processes'.

In the long term, continued warming of the ocean is likely to impact upon zooplankton abundance and spatial distributions. Increasing seawater temperature will accelerate physiological processes, dependent on the species specific characteristics, and continue to alter phenology (the study of organisms as affected by climate, especially dates of seasonal phenomena such as opening of flowers and arrival of migrants). However, the marine ecosystem will respond in numerous interacting ways such that the overall change is difficult to predict with any certainty. Increased acidification of the ocean will also be important, but we are not, as yet, in a position to understand fully the effect on zooplankton in the Northeast Atlantic. However, we can expect detrimental effects on shell and skeleton forming organisms in the long term. Much more research is required linking physical and biogeochemical models to data on plankton biogeographical distributions. The rapid changes in plankton communities observed over the last few decades in the North Atlantic, related to regional climate changes, have enormous consequences for other trophic levels and biogeochemical processes.

cpr data

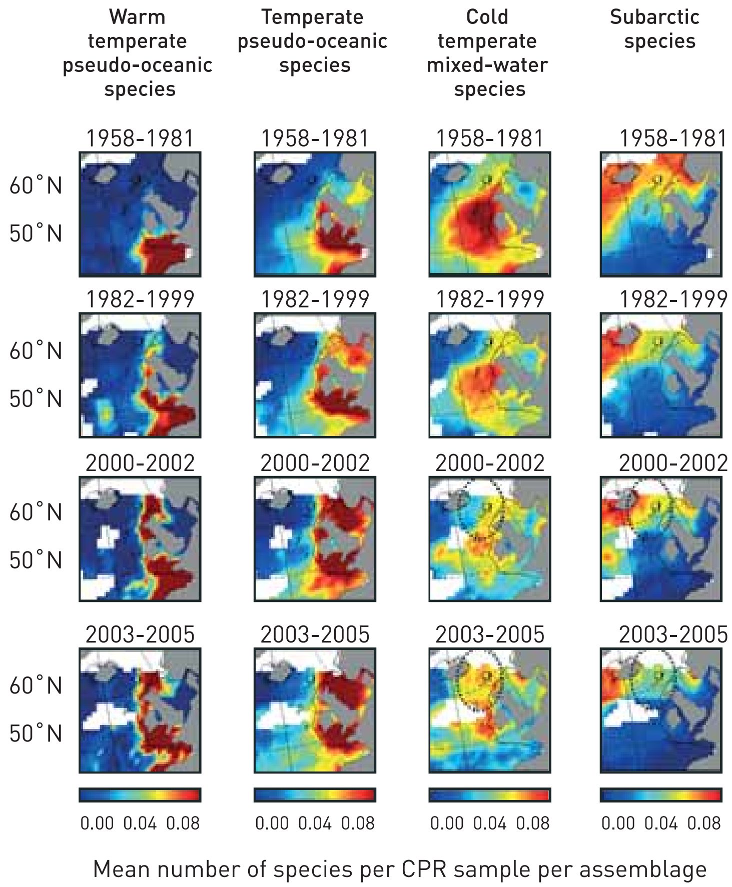


Figure 6.1 Long-term (1958-2005) changes in the mean number of species per assemblage (columns). The period 1958-1981 (row 1) was a period of relative stability and the period 1982-1999 (row 2) was a period of rapid northward shifts. These periods were selected to reduce the number of maps. Average maximum values are rarely superior to row 1 because they include both daylight and dark periods over 2 month periods. Black dotted oval denotes areas where pronounced changes have been observed (Reproduced from Beaugrand *et al.*, 2009).

CASE STUDY

Calanus helgolandicus in Irish waters

Calanus helgolandicus is a copepod with warm water affinity and an important prey for fish species (included by Beaugrand (2009) in the 'temperate pseudo-oceanic species assemblage', figure 6.1). Beaugrand (2009) states that this assemblage is represented in oceanic and neritic water and, prior to the 1980s, the abundance of species within the assemblage was typically highest along shelf edges at latitudes <55°N. In the North Sea, *C. helgolandicus* has increased in abundance, while *C. finmarchicus* (subarctic species assemblage) has decreased (figure 6.1). This shift has had important consequences for North Sea cod *(Gadus morhua)* recruitment due to the current apparent mismatch between the presence of larval cod and the timing of occurrence of potential *Calanus* prey. This is due to the differing seasonality of the two *Calanus* species, resulting in a shift in *Calanus* prey from spring to late summer at a time when larval/juvenile cod feed more on euphausiids and other fish larvae. In Irish waters, *C. helgolandicus* is most abundant in the Celtic Sea and least abundant in the Irish Sea and has a typical preference for medium depth water (25-75 m) (figure 6.2). *C. finmarchicus* is found in highest abundance to the north of Ireland and in particularly low abundance to the southeast of Ireland and in the Irish Sea.

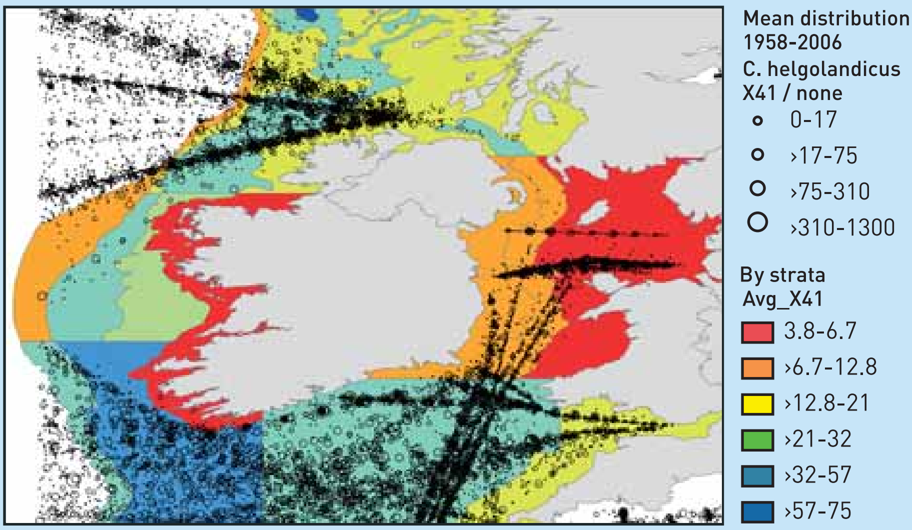


Figure 6.2 Spatial distribution of *C. helgolandicus*, a southern copepod species tolerant of warmer waters by ICES division split by water depth (coastal < 25 m, medium, deep >75 m). Highest mean abundance was found in medium depths to the southwest of Ireland (VIIj) followed by the southeast (VIIg) and the north (VIa), relatively high abundance in coastal waters was only observed in the southeast (VIIg). Black circles show data points from 1958-2006 upon which the mean abundance by water mass is calculated (NB this simple calculation makes no distinction between abundance during day/ night or seasonality of samples).

Beaugrand (2009) (figure 6.1) shows little change in diversity to the south of Ireland in the temperate pseudo-oceanic species assemblage in which *C. helgolandicus* is found. However, the mean annual abundance of this species to the southeast of Ireland (VIIg) does show an increasing trend between 1960 and 2006 and the increase is notably greater during the spring, suggesting that this warm water species may be increasing due to climate warming (figure 6.3).

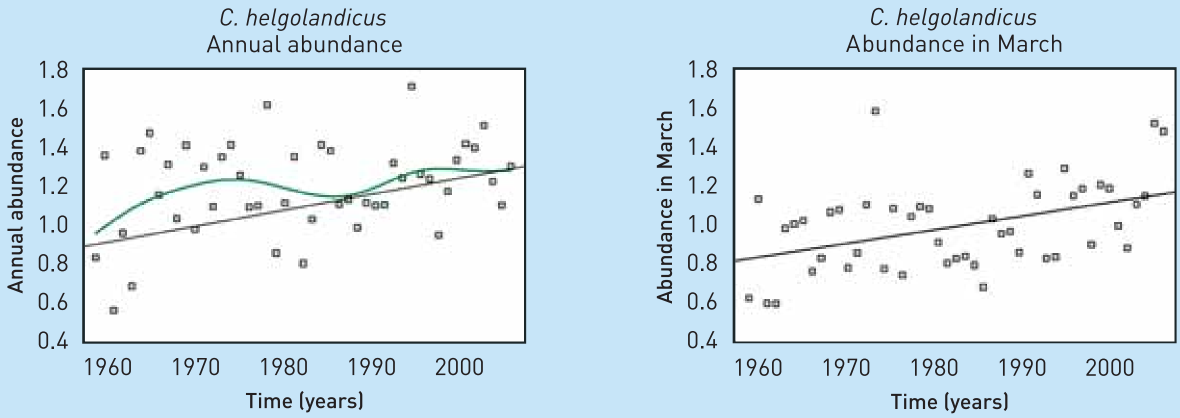


Figure 6.3 Left, mean annual abundance of *Calanus helgolandicus* in the Celtic Sea with smooth trend (green line). Right, mean abundance in March (squares). Black lines show significant ($p < 0.05$) linear trends through abundance values. NB mean values are calculated from measurements once corrected for time of day, seasonality and spatial location using a Generalised Additive Model (see Lynam *et al.,* 2009)

To explore the possibility of phenological change in *C. helgolandicus* abundance, a further model was fitted to the *C. helgolandicus* data incorporating an interaction between year and month as an explanatory variable. A significant fit was found ($p < 0.0001$, $n = 3423$); however, the term only explained 4% of the remaining variability. Nevertheless, an interesting pattern did emerge suggesting a possible weak phenological change towards an earlier presence of *C. helgolandicus* during the spring in the Celtic Sea and an earlier decline during the autumn/winter (figure 6.4).

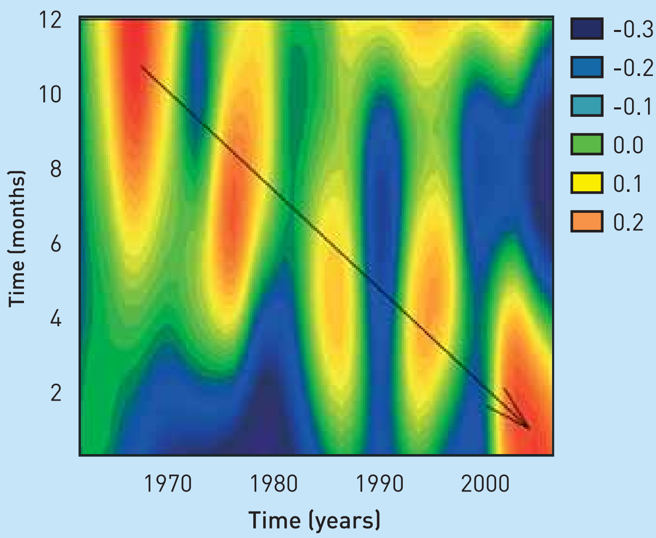


Figure 6.4 A residual pattern in *C. helgolandicus* seasonality, showing abundance anomalies relative to the typical season cycle.

6.3. GELATINOUS ZOOPLANKTON (JELLYFISH)

Gelatinous zooplankton (Cnidaria, Ctenophora and Urochordata) populations may exploit suitable environmental conditions (e.g. a thermal niche or high availability of prey) to rise rapidly in abundance and form extensive aggregations. Due to this great adaptability, gelatinous zooplankton play an important role in our coastal and shelf waters. A growing body of evidence has shown that jellyfish (Cnidaria, Scyphozoa) population abundance is linked to climatic fluctuations (e.g. The North Atlantic Oscillation index has been linked to medusae in the North Sea, Mediterranean Sea, and Chesapeake Bay, an estuary in the United States, while scyphomedusae in Lake Palau, Micronesia have been linked to the El Niño and those in the Bering Sea have been linked to temperature and ice cover (Purcell *et al.*, 2005, Martin *et al.*, 2006, Brodeur *et al.*, 2008)). Although exact mechanisms by which climate may influence medusae are poorly understood, laboratory studies show increasing production of young jellyfish as temperatures warm (Purcell *et al.*, 2005). However, in their natural environment medusae display contrasting responses to interacting climatic and oceanographic effects (Lynam *et al.*, 2005).

'Jellyfish in the Northeast Atlantic show cyclic changes in population sizes However, since 1997 they have been increasing in frequency in CPR samples simultaneously in shelf and oceanic waters'.

Recently, the frequency at which gelatinous tissues and nematocysts (cnidarian stinging cells) are caught in the CPR sampler has been enumerated and used to map the pattern of gelatinous zooplankton abundance across the Northeast Atlantic Ocean (figure 6.5). This combined index shows a clear seasonality, with gelatinous zooplankton uncommon across the region during winter, then increasing along the European continental shelf break during spring, peaking around the Rockall Bank during summer and declining slowly during autumn. In the oceanic area, depth >200 m, gelatinous zooplankton abundance was linked strongly ($p < 0.001$) and positively to SST and total copepod abundance (Gibbons and Richardson, 2009). Jellyfish in the Northeast Atlantic show cyclic changes in population sizes (20 year cycle in oceanic area and 30 year cycle in shelf seas between 1946 and 2005). However, since 1997 they have been increasing in frequency in CPR samples simultaneously in shelf and oceanic waters.

'In their natural environment medusae display contrasting responses to interacting climatic and oceanographic effects'.

'The mauve stinger, a common nuisance in the Mediterranean, has a warm water affinity and is thought to be carried into Irish coastal waters via the shelf edge current and thus potentially linked to the circulation of the sub-polar gyre'.

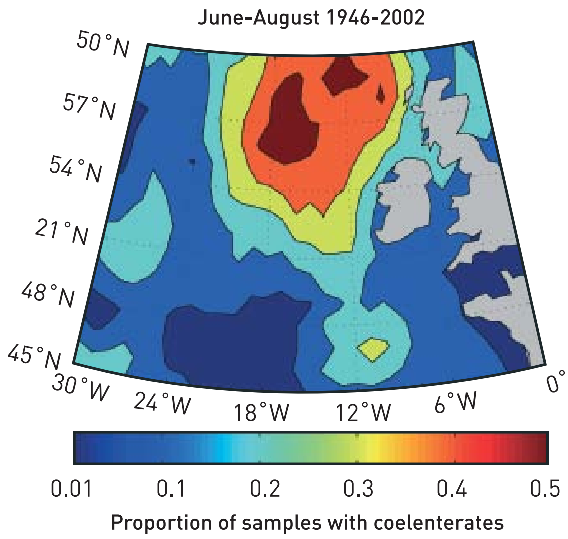


Figure 6.5 Distribution map of the frequency of occurrence of pelagic cnidarians in CPR samples from the Northeast Atlantic in the period June-August, 1946-2005 (adapted from Gibbons and Richardson, 2009).

Recent aerial surveys and ship surveys conducted during 2003-2006 have revealed much about the five coastal species of true jellyfish *(Scyphozoa)* in Irish waters (Doyle *et al.*, 2007). The surveys were initiated to determine the abundance and spatial preferences of migrant Leatherback turtles *(Dermochelys coriacea)* that prey upon medusae. The edible barrel jellyfish *(Rhizostoma octopus)* was found in exceptional aggregations from May to October, comprising tens of thousands of individuals weighing up to 30 kg each, at the entrance of Wexford Harbour and to a lesser extent in the vicinity of the Rosslare ferry port. At times, the barrel jellyfish has been recorded outside the Wexford hotspot, indeed in 1976 it was reported in all Irish coastal waters (O'Conner and McGrath, 1978). Such events raise the question of why populations of barrel jellyfish do not establish themselves in similar estuarine habitats of Ireland. However, contrary to popular opinion, not all jellyfish are at the whim of ocean currents and some have habitat preferences in much the same way as other animals do (Doyle *et al.*, 2007). The lion's mane jellyfish *(Cyanea capillata)* has a clear preference for cooler waters and its distribution reaches north into the Arctic; in the Irish Sea it is only found in large abundances north of the 53° latitude (Doyle *et al.*, 2007). A notable drop in sea bottom temperature during the winter (to below ~8°C) plays a critical role in the successful reproduction of this species. In the southern Irish Sea, and potentially off the south and west coasts of Ireland, the waters may simply be too warm for the lion's mane. With such a clear link with temperature, a coordinated system of recording where this species strands in large numbers may provide a useful indicator of climate change, as its range should contract poleward. In contrast, the oceanic jellyfish, the mauve stinger *(Pelagia noctiluca)*, a common nuisance in the Mediterranean, has a warm water affinity and is thought to be carried into Irish coastal waters via the shelf edge current and thus potentially linked to the circulation of the sub-polar gyre. A fish kill of ~250,000 farmed salmon in November

2007 in Northern Ireland has prompted fears that this species is increasing following climate change. However, an analysis of historical reports and anecdotal sightings reveals that it has previously occurred in Irish and United Kingdom waters at least 25 times in the last century (Doyle *et al.*, 2008) suggesting that this recent event is part of an intermittent cycle. Whether or not the intensity of these mauve stinger blooms is increasing is uncertain but could be expected considering it occurs in the Mediterranean in high abundance following warm, dry periods (Purcell, 2005).

Other gelatinous zooplankton that occur in Irish waters include the hydromedusae, siphonophores, ctenophores, and urochordates (salps, doliolids and larvaceans). Little is known about the broad scale distributions of these groups in Irish waters. One of the largest ever documented gelatinous zooplankton aggregations was that of salps *(Salpa fusiformis)* 10 miles in diameter that occurred off the west coast of Ireland in 1984 (Bathmann, 1988), yet there is little idea of the frequency of such events. There is also concern that the invasive ctenophore *(Mnemiopsis leidyi)* could reach our shores in the near future. The accidental introduction of *Mnemiopsis* into the Black Sea via ballast water perturbed the already highly exploited ecosystem, contributing to widespread reductions in fisheries yield (Purcell, 2005). The spread of *Mnemiopsis* appears to have continued and recently the species has been found in several localities in the North Sea (Boersma *et al.*, 2007). To address the likely impact of climate change on future gelatinous zooplankton occurrence in Irish waters much more detailed information is required at the species level regarding the interacting effects of temperature, rainfall, salinity and currents.

Rhizostoma octopus with G5 tag attached and diver in background, Carmarthen Bay, Wales

7

7 COMMERCIAL FISHERIES

Author Lynam, C.

KEY POINTS

- The Irish EEZ supports major fisheries worth €500 million to the international fleets.
- The fishing industry makes a significant contribution to the economic and social fabric of coastal communities.
- Climate change and anthropogenic impacts act in tandem to alter marine ecosystems, such that species responses to climate change can not be considered in isolation.
- Many, but not all, warm water species, including sprat, anchovy, pilchard and blue-mouth, have increased in abundance to the north of Ireland and in the Celtic Sea.
- The warm water species, poor cod and lesser spotted dogfish have increased to the north of Ireland and decreased to the south and are suitable candidate climate indicator species.
- In general, the abundance of marine fish has decreased in the Celtic Sea (1999-2007) and this is largely due to over exploitation.
- The cold water community of fish appears stable to the north of Ireland (2002-2007).

KEY POINTS continued

» There is evidence of a weak increase in the warm water community to the west and north of Ireland (2002-2007).

» Climate change may lead to an in increase in the warm water fish community. However, fishery effects must be considered and long term datasets are required to detect such change.

» Overexploited stocks display stronger responses to climatic fluctuations.

» Climate change may lead to the decline of traditional fisheries (e.g. cod) and the emergence of new fisheries (e.g. boarfish). However, given the high value of many cold water species the economic effect may be negative. Natural variability is high in the marine environment and whether or not important changes seen in the gyre circulation are due to global warming or natural variation is unclear.

» Many exotic species are being sighted in Irish and United Kingdom waters. There appears to be an increase in such sightings.

» The increase in the distribution of pipefish may reduce the survival of seabird chicks.

7.1. ECONOMIC IMPORTANCE OF FISHERIES

fisheries landings

Marine fisheries are an important economic asset to Ireland and particularly so to the rural economies and communities that they support. In 2004 (last available complete data), an estimated 700,000 tonnes of fish were harvested by the international fleets from the Irish Exclusive Economic Zone (EEZ), with an estimated value of €500 million (Marine Institute, 2008). The waters around Ireland contain major spawning areas for mackerel *(Scomber scombrus)*, horse mackerel *(Trachurus trachurus)*, blue whiting *(Micromesistius poutassou)*, hake *(Merluccius merluccius)* and cod *(Gadus morhua)*. Major fisheries target these species in addition to many others including haddock *(Melanogrammus aeglefinus)*, whiting *(Merlangius merlangus)*, plaice *(Pleuronectes platessa)*, sole *(Solea solea)*, herring *(Clupea harengus)*, sprat *(Sprattus sprattus)* and crustaceans such as Dublin Bay Prawns *(Nephrops)*. Irish landings from the principal stocks show a general trend of increasing value from the early 1980s with a peak in 2001 (figure 7.1). This rise in value of landings is largely due to the increase in the value of landings of mackerel (a threefold rise in value between 1994 and 2007 to approximately €45 million). However, the economic value does not reflect the true state of the system since some stocks are severely depleted (e.g. Celtic Sea herring) or have collapsed (e.g. Irish Sea cod) while others appear to be stable or increasing (e.g. mackerel and horse mackerel).

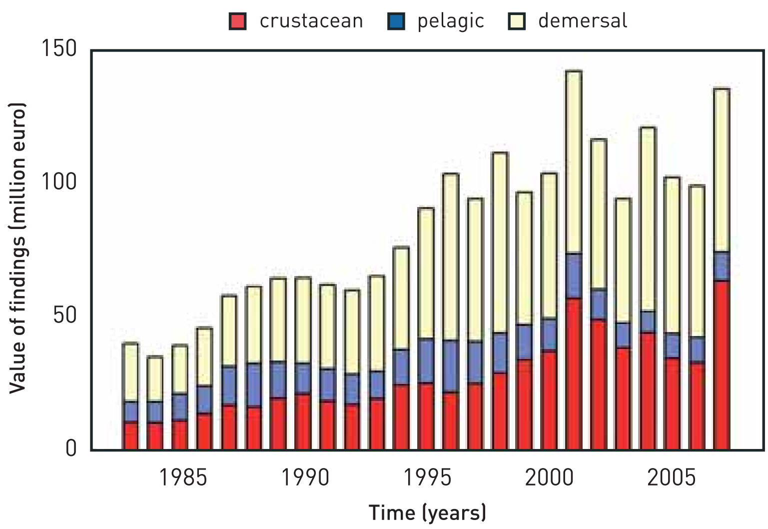


Figure 7.1 The value of landings (million euro), by Irish vessels to all ports, of principal marine species: pelagic fish (blue: herring, mackerel and horse mackerel); demersal fish (white: cod and whiting); and crustaceans (red: Nephrops, lobster and edible crab) (sources: data 1983-2002 from Central Statistics Office and data 2003-2007 from the Sea Fisheries Protection Authority).

7.2. CLIMATE INDICATOR SPECIES

'Both poor cod and lesser spotted dogfish are both well sampled by the Irish Groundfish Survey and these species are thus suitable climate indicator species'.

Marine species at the limits of their biogeographical ranges are expected to respond to climate change by altering their spatial distribution or abundance. While such changes can be detected by scientific study, attributing the particular cause of such a response is of great difficulty. In many cases, the effects of climate change on a species will be confounded with simultaneous impacts from fishing (i.e. depletion of a commercial species or bycatch of a non-commercial species) and ecosystem change, which may result in a 'domino effect' that cascades through the food web via processes of predation and competition. The initial decline in abundance of many commercial fish, such as Atlantic cod in the Celtic or Irish Sea, is due to over fishing. Once overexploited in this way, fish stocks generally become more sensitive to climatic effects and this is most pronounced for those stocks in which few old fish remain (Brander, 2005). Indirectly, exploitation may result in the increase in abundance in some species (e.g. a planktivore, such as herring *(Clupea harengus)*) may rise in abundance if a major predator of fish, (e.g. a piscivore, such as blue-fin tuna *(Thunnus thynnus)*) is overexploited. Rises in abundance might also result through warming, particularly for species that prefer warmer waters, (e.g. john dory *(Zeus faber)* and oceanic sunfish *(Mola mola)*). Thus, a suitable climate indicator species should have three characteristics:

1. a preference for waters generally cooler or warmer than those surrounding Ireland.
2. resilience to fisheries activities.
3. generally well sampled by scientific surveys/observers such that their distributions and abundances are known.

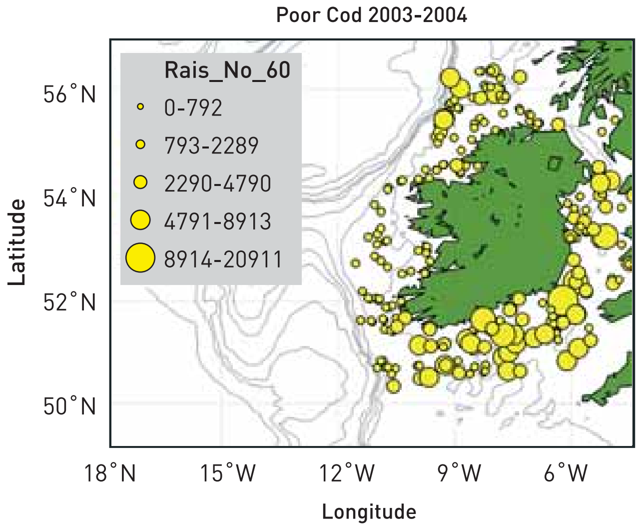
Species that prefer cooler waters than those at our latitudes (50-56°N) are termed 'boreal' species since they will originate from the north, while those that prefer warmer waters are generally called 'Lusitanian' since they favour Iberian waters to the south. Boreal species in our waters that were once common and highly abundant include cod, herring and spurdog (*Squalus Acanthias*, a shark marketed as 'rock salmon'). However, these generally large bodied northern species tend to be valuable and the target of intensive fishing activities. Lusitanian species, such as poor cod *(Trisopterus minutus)*, anchovy *(Engraulis encrasicolus)* and lesser spotted dogfish *(Scyliorhinus canicula)* (figure 7.2) tend to be smaller and less valuable. While anchovy are commercially fished, poor cod are only landed in small numbers by the blue whiting fishery operating in deep waters of the Rockall Trough to the northwest of Ireland. Poor cod juveniles are generally too small to be caught by fisheries targeting other species. In contrast, lesser spotted dogfish are known for their ability to withstand being trawled, such that fishermen are often able to return them to the sea alive. Both poor cod and lesser spotted dogfish are both well sampled by the Irish Groundfish Survey and these species are thus suitable climate indicator species.

Figure 7.2 John dory (left top), poor cod (left bottom) and lesser spotted dogfish (right) caught during the 2008 Irish Groundfish Survey (photographs supplied by D. Stokes, Marine Institute).

'Poor cod and lesser spotted dogfish have both increased in catches to the north of Ireland and decreased to the south'.

Poor cod and lesser spotted dogfish have both increased in catches (g m^{-2}, swept area corrected) to the north of Ireland (VIa) and decreased to the south (VIIg) (figure 7.3). The rise in the north has been accompanied by an increase in the numerical abundance per hour (swept area corrected) of lesser spotted dogfish (length < 23 cm, $R = 0.86$, $n = 5$, $p = 0.06$), indicating that this area might be of increasing suitability for the recruitment of this species. An alternative explanation for the rise in abundance of poor cod and lesser spotted dogfish is that they are benefiting from human exploitation of commercial fish species, such as cod, with which they compete for resources. However, further study into ecosystem responses is required if we are to disentangle the anthropogenic effects from climate impacts. In the case of poor cod, Scottish trawl data (Fisheries Research Services) from 1925 suggest the recent rise in abundance in the North Sea since the mid 1990s has been unprecedented (Beare, 2004). The International Bottom Trawl Survey has also shown long term increases in lesser spotted dogfish in the North Sea (particularly in the north) and to the west of Scotland (north of Ireland) during quarter 1 in the period 2000-2005 when compared to abundances in 1977-1989 (ICES 2008a). Similar increases in abundance were observed to the west of Scotland for john dory *(Zeus faber)* and striped red mullet *(Mullus surmuletus)*, while the following species increased both to the west of Scotland and in the Celtic Sea (south of Ireland, quarter 4, 1990-1999): sprat *(Sprattus sprattus)*, anchovy *(Engraulis encrasicolus)*, pilchard *(Sardina pilchardus)*, blue-mouth *(Helicolenus dactylopterus)* and boarfish *(Capros aper)*, all Lusitanian species. In contrast, herring, a boreal species, showed an increase to the west of Scotland and a decrease in the Celtic Sea.

Net deployment,
R.V. Celtic Explorer



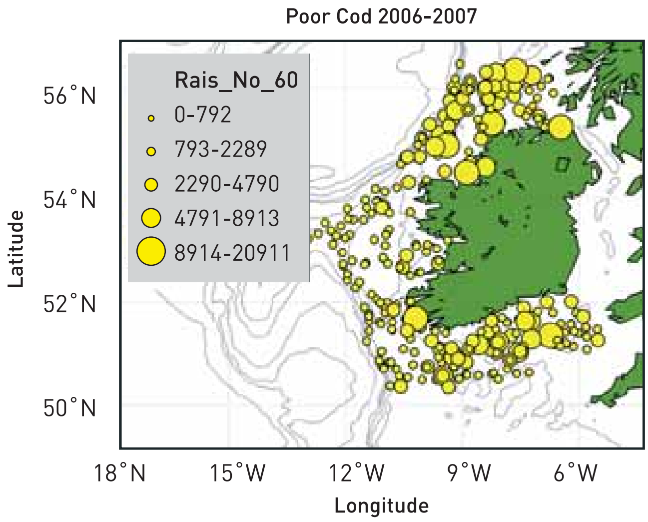


Figure 7.3 The distribution of poor cod for the period 2003-2004 (left) and 2006-2007 (right) from the International Groundfish Survey, where bubble size indicates catch rate (individuals hour-1) and background colour shows mean catch rate by strata (coastal <75 m, medium 75-150 m, deep 150-200 m and slope water > 200 m). NB. The regional sea surface temperature (SST) difference for the above periods (2006-2007 minus 2003-2004) are: north VIa -0.01 °C, west VIIb +0.03 °C, south VIIg +0.24 °C, suggesting little change in the north and west. However, SST in the current decade is much greater than in the previous 2000-2008 minus 1991-1999: north VIa +0.54 °C, west VIIb +0.26 °C, south VIIg +0.20 °C (HadSST2 1x1 dataset).

7.3. COMMUNITY RESPONSES

As an alternative to examining individual species responses to warming, we can examine the entire marine community in order to distinguish potential changes. Here we focus upon the demersal and pelagic species that are sampled by the Irish Groundfish Survey and we group them into communities that represent species with warm water (Lusitanian) or cold water affinities (Boreal) (Lynam *et al.*, in prep). The temporal trends are then evaluated for each of the 60 species and the resulting distribution of the coefficients are compared with that expected by chance, such that we can establish whether or not we are witnessing more or fewer species either increasing or decreasing in the catch than expected (figure 7.4).

'The effect of marine climate change may already be altering the ecosystem to the west and north of Ireland, where stingray, bib, pilchard and anchovy show the greatest increases'.

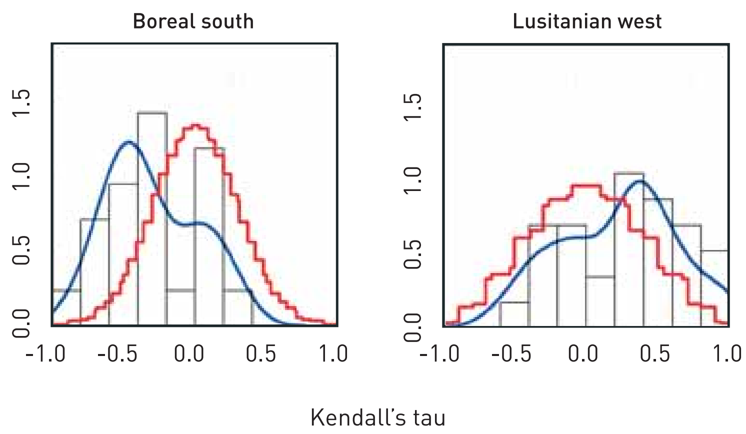


Figure 7.4 True histograms (bars) with smoothes (blue lines) of coefficients (Kendall's tau) by area for species sampled by the Irish Groundfish Survey, split into the boreal community (upper, N = 20 species) in the southern area (ICES division VIIg) and the Lusitanian warm water community (lower, N = 29 species) in the western area (ICES division VIIb). Note that the departure by the Lusitanian species (blue line, lower pane) to the right of the expected distribution (red line) suggests that more species are increasing in abundance than expected by chance, while the departure to the left by the boreal species suggests that the community is declining ($p < 0.01$). The expected distributions differ between regions due to the differing length of time series available (2002-2007 for the west and 1999-2007 for the south) (Lynam *et al.,* in prep).

The entire marine community (as sampled by the Irish Groundfish Survey) in the south (ICES division VIIg) shows generally declining trends largely attributable to fishing ($p < 0.01$) and the decline is greatest in the boreal community ($p = 0.03$, figure 7.4). However in the west and north, the boreal species appear stable while the Lusitanian species are increasing weakly ($p < 0.01$). This suggests that the effect of marine climate change may already be altering the ecosystem to the west and north of Ireland, where stingray *(Dasyatis pastinaca)*, bib *(Trisopterus luscus)*, pilchard *(Sardina pilchardus)* and anchovy *(Engraulis encrasicolus)* show the greatest increases (Kendall's *tau* > 0.8). The possible strengthening of the shelf edge current and changes in the plankton communities might be related to the increases in Lusitanian stocks to the west and north of Ireland (Beaugrand, 2009 and references therein). However, studies of this kind can not attribute cause with effect and must be followed up with further research to determine which factor is responsible for such observations.

'The most economically important stock to Ireland is the wide ranging migratory mackerel and this appears to be stable'.

7.4. MAJOR STOCKS

There are numerous stocks of commercial interest in Irish waters; here we present data on four species in figure 7.5. Celtic Sea cod, a demersal gadoid that feeds upon zooplankton (i.e. a planktivore) in its juvenile stages and upon fish in its adult stage (i.e. a piscivore); herring, a pelagic planktivore; mackerel, a migratory pelagic piscivore; and blue whiting, a migratory pelagic gadoid found in high abundances in deep water (300-400 m but found from shelf to depths of 1000 m) and preys on small crustaceans, fish and cephalopods. Herring and cod are both valuable boreal species, which are at their southern biogeographical limits in Irish waters, and show declines in spawning stock biomass attributable to over exploitation in the 1970s and 1980s. However, the most economically important stock to Ireland is the wide ranging migratory mackerel and this appears to be stable (figure 7.5). Interestingly, landings of migratory blue whiting, used as fish meal in aquaculture, have increased in recent years following a notable increase in the stock that has been linked to warming waters.

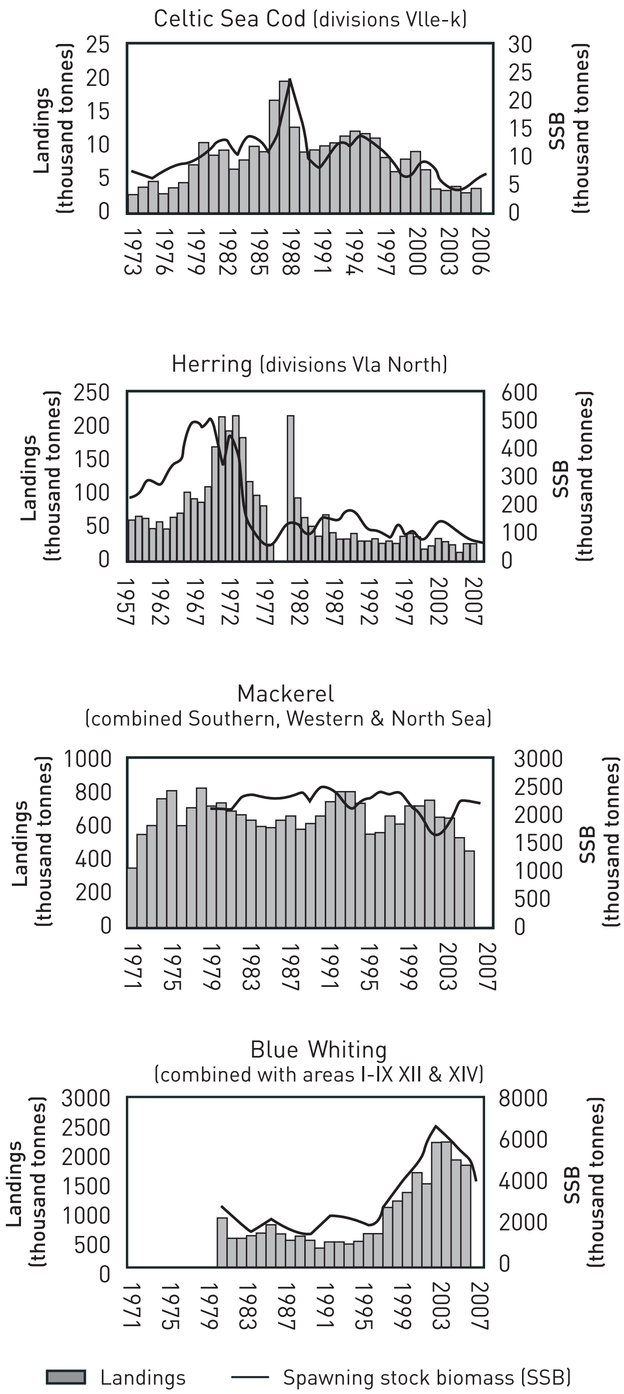


Figure 7.5 Landings of four major commercial species in the region; note different time scales over which reliable data are available (ICES data).

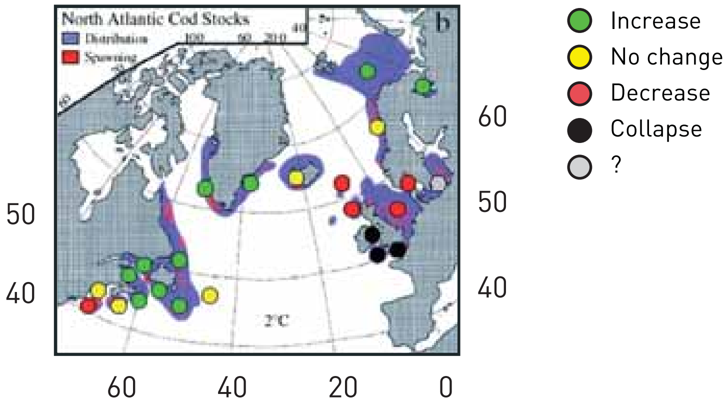
'Boarfish appear to have increased in abundance in recent years and may be benefiting from elevated temperatures'.

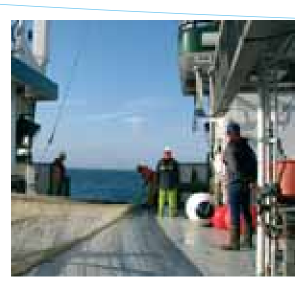
Boarfish *(Capros aper)*

In 2003, a new fishery began targeting boarfish (*Capros aper,* figure 7.6) to the southwest of Ireland; the catch is used as feed for salmon in aquaculture and exported to Australia as crocodile feed. Although an unassessed stock with no management restrictions, boarfish appear to have increased in abundance in recent years and may be benefiting from elevated temperatures (ICES 2008a).

Figure 7.6 Boarfish *(Capros aper)* caught during the Irish Groundfish Survey in November 2008 (photographs supplied by H. Gerritsen, Marine Institute).

It has been predicted that if sea bottom waters rise by a sustained 1˚C then cod in the Celtic Sea, Irish Sea and English Channel will become locally extinct as they might not be able to meet their metabolic costs or compete effectively for prey (Drinkwater 2005, figure 7.7). Under such a scenario, cod in the Irish Sea would also decline in biomass. However, the warm Celtic Sea environment does have some benefits for cod, for example Celtic Sea cod hatch more rapidly (~1 week) than other cod stocks and individuals grow faster and mature earlier than northern stocks. Indeed the recruitment of this stock per unit spawner has not declined as the sea has warmed and this paradox may be explained by an increase in prey availability *(Calanus helgolandicus)* for cod larvae during the spring (Lynam *et al.*, 2009, figures 6.2-6.4). This study highlights how important it is to understand ecosystem responses when attempting to determine the likely impact of climate change and much research is required in this area.





Shooting smolt trawl net, R.V. Celtic Explorer

Figure 7.7 Expected changes in the abundance of the cod stocks with a temperature increase, above current levels of 1°C (Adapted from Drinkwater, 2005).

The spawning stock of blue whiting increased threefold after 1995 (figure 7.5) following increases in sea surface temperature with a three year lag (i.e. The time required for new recruits to contribute to the stock biomass) (Hátún *et al.*, 2009). Like many fish species, the reproductive success of the stock is largely determined during the very early stages of life. The spatial distribution of blue whiting spawners is variable and regulated by the oceanography west of Britain and Ireland (figures 7.8). When the North Atlantic subpolar gyre is strong, spreading cold and fresh water masses east over the Rockall Plateau, the spawning distribution is constrained along the European continental slope and in a southerly position near the Porcupine Bank (Hátún *et al.*, 2005). When the subpolar gyre is weak and conditions are relatively saline and warm, the spawning distribution moves northwards along the slope and especially westwards covering the Rockall Plateau.

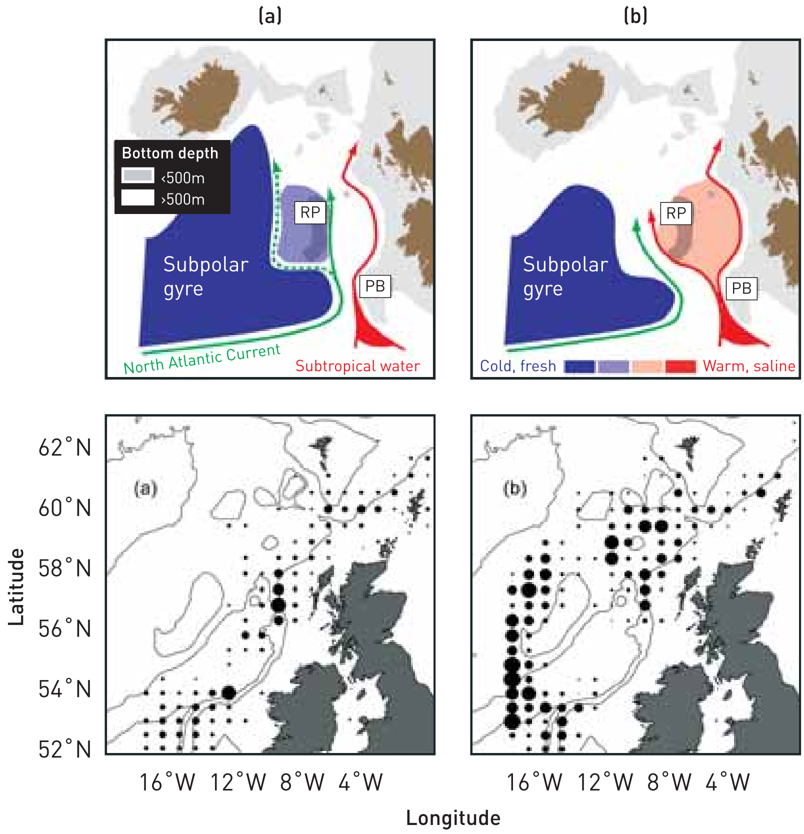


Figure 7.8 Top Simplified illustration of the source flows to the Rockall Region. (a) A strong subpolar gyre results in strong influence of cold subarctic water near the Rockall Plateau. (b) A weak gyre allows warm subtropical water near the plateau. Abbreviations – RP: Rockall Plateau and PB: Porcupine Bank. (Reproduced from Hátún *et al.*, 2009) Bottom Distribution of adult catches of blue whiting reported by the Norwegian fleet, averaged over (a) the low saline and cold years from 1989 to 1996 and (b) the saline and warmer years from 1997 to 2005. The area of each dot is proportional to the amount of blue whiting fished within a 0.5° latitude x 1° longitude rectangle centred on the dot.

7.5. EXOTIC SPECIES AND WIDE RANGING SHIFTS IN BIOGEOGRAPHICAL DISTRIBUTION

Increased sightings in Irish and United Kingdom waters of rare migrant species from more southerly waters include blue-fin tuna *(Thunnus thynnus)*, triggerfish *(Balistes capriscus)*, thresher *(Alopias vulpinus)*, blue sharks *(Prionace glauca)*, ocean sunfish *(Mola mola)* and sailfin dory *(Zenopsis conchifer)* (ICES 2008a and references therein). The increased occurrence of these Lusitanian species could be the result of a northward shift in isotherms linked to global warming and changes in gyre circulation. Since 2003, a massive increase in abundance and distribution of snake pipefish *(Entelerus aequoraeus)* has occurred, which has been linked to increases in sea surface temperature that may allow for increased fecundity of the species (Kirby *et al.*, 2006). The outbreak of snake pipefish in the northern North Sea was much documented for its detrimental effect on seabird breeding success (Harris *et al.*, 2007). However, the species has also been observed in elevated abundance since 2003 in Irish waters in the Irish and Scottish groundfish surveys (figure 7.9). The pipefish have recently extended their distribution from the western slope eastward onto the Malin Shelf (2003) and into the Celtic Sea (2005), but so far none have been caught in the Bay of Biscay in the French groundfish surveys (J.C. Mahe *Pers. Comm.*). The distribution of catches suggest that pipefish breed along the shelf edge in high numbers and spread eastwards onto the shelf from a possible 'hotspot' in abundance to the southwest of Ireland and on the Porcupine Bank, where they are also found in high numbers in Spanish groundfish surveys (F. Velasco *Pers. Comm.*).

'Since 2003, a massive increase in abundance and distribution of snake pipefish has occurred, which has been linked to increases in sea surface temperature that may allow for increased fecundity of the species'.

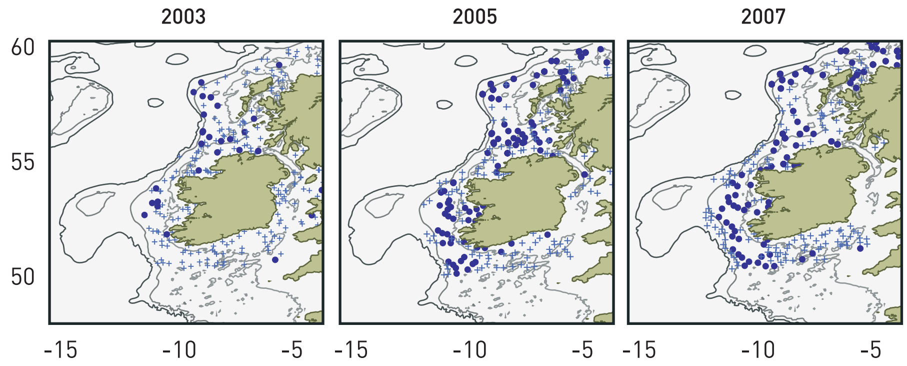


Figure 7.9 Presence (blue circles) and absence (grey crosses) of pipefish in Irish and Scottish groundfish surveys (NB. in 2002 only 3 pipefish were found throughout the surveys) (Data sources: D. Stokes, Marine Institute and D. Beare, E.C. Joint Research Centre, Italy).

8

SEABIRDS

Authors Chivers, L. and Nardello, I.

KEY POINTS

- Annual surveys on one of the largest breeding seabird colonies in Ireland show that the number of guillemots and razorbills has been declining over the last decade.
- Breeding success of some species has become a concern.
- Declines in numbers and breeding failures at such seabird colonies have been linked to climate change. Various studies indicate that the changes in sea temperature affect seabirds indirectly through the availability of their preys ('bottom-up control').

'Whole colony surveys and annual monitoring plot counts show that numbers of seabirds on this island have decreased since 1999'.

A number of recent studies have reported the decline of seabird numbers in the British Isles (Newell *et al.*, 2008; Heubeck *et al.*, 2008; Mavor *et al.*, 2008), and breeding failures at seabird colonies in the United Kingdom (Frederiksen *et al.*, 2007; Mavor *et al.*, 2008; Wanless *et al.*, 2007) and Ireland (A. Lucey, 2008).

Rathlin Island lies off the northeast coast of County Antrim, Northern Ireland. It holds one of the largest breeding seabird colonies in Ireland, with over 100,000 birds. Whole colony surveys (Table 8.1) and annual monitoring plot counts (figure 8.1) show that numbers of seabirds on this island have decreased since 1999.

Species	Count in 1999	Count in 2007	Change (%)
Razorbill *(Alca torda)*	20,860 (N)	10,684 (N)	-48.78%
Guillemot *(Uria aalge)*	95,567 (N)	81,303 (N)	-14.93%
Kittiwake *(Rissa tridactyla)*	9,917 (AON)	9,896 (AON)	-0.21%

Table 8.1 Results from the 1999 and 2007 whole colony surveys of razorbills *(Alca torda)*, guillemots *(Uria aalge)* and kittiwakes *(Rissa tridactyla)* breeding on Rathlin Island (Allen and Mellon, 2007). Counts represent 'number of individuals' (N) for razorbills and guillemots, and number of 'apparently occupied nests' (AON) for kittiwakes.

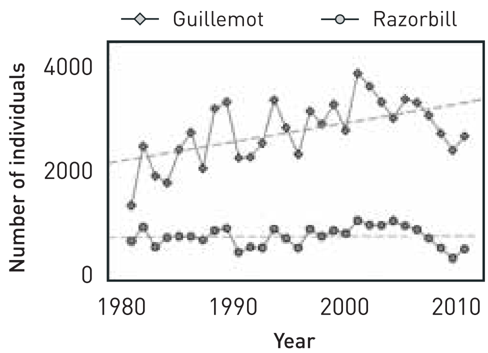


Figure 8.1 Annual counts of total numbers of guillemots (*Uria aalge*; diamonds) and razorbills (*Alca torda*; circles), in three monitoring plots on Rathlin Island, in the period 1980-2008. Concern is rising about the evident decline of both populations over the last decade.

Breeding success of some of these species has also become a concern (figure 8.2). Common guillemots *(Uria aalge)* and black-legged kittiwakes *(Rissa tridactyla)* have suffered complete breeding failure or extremely low breeding success since 2005 (figure 8.2). Although guillemots showed a recovery of breeding success in 2008 (Chivers, 2008), razorbills *(Alca torda)* retained a low productivity rate in 2008. A detailed study in 2008 showed that breeding failure in kittiwakes can be explained by two main reasons: starvation of chicks and predation of chicks. Both these factors can be linked to low food availability, either directly as in the case of starvation, and indirectly because chicks are left alone and vulnerable to predation when both parents are forced to forage (Harris and Wanless, 1990; Wanless and Harris, 1992).

It was also noted that c.a 70% of starved chicks were from two-chick broods (Chivers, 2008). This brood reduction is also consistent with low food supply (Wanless and Harris, 1992).

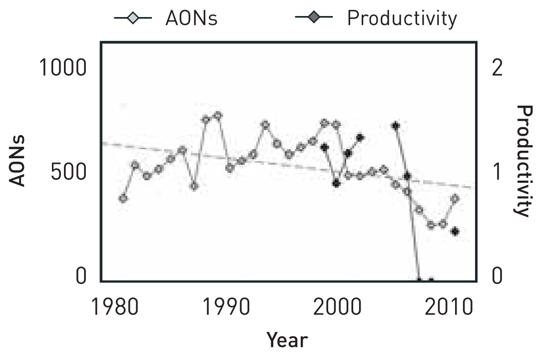


Figure 8.2 Total number of apparently occupied nests (AONs) of kittiwake in three monitoring plots on Rathlin Island, since 1980. The dashed line shows the negative trend of the time series. Productivity of kittiwakes as number of fledged chicks is also shown in the plot for the period 1997-2008.

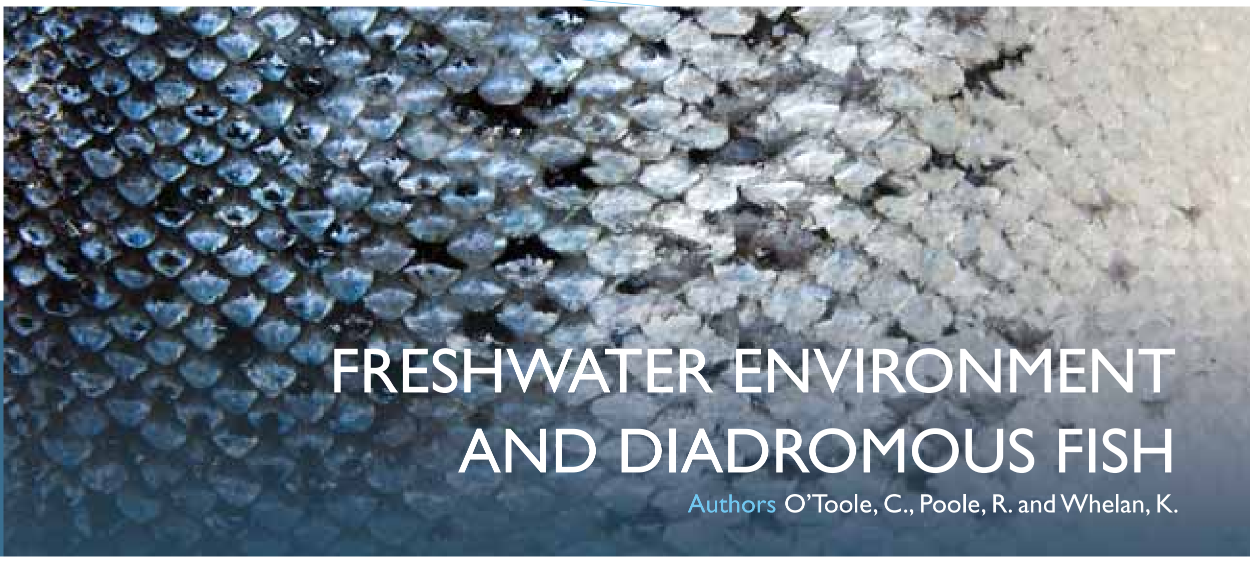
'Common guillemots and black-legged kittiwakes have suffered complete breeding failure or extremely low breeding success since 2005, although guillemots showed a recovery of breeding success in 2008'.

Declines in numbers and breeding failures at seabird colonies such as these have been linked to climate change. Studies have intimated that changes in sea temperature affect seabirds indirectly through their prey, known as 'bottom-up control' (Durant *et al.*, 2003; Frederiksen *et al.*, 2006; Frederiksen *et al.*, 2007; Wanless *et al.* 2007). Research in the North Sea has focused on the main seabird prey species found there, the lesser sandeel *(Ammodytes marinus)*. It has been suggested that climate driven changes in plankton phenology, abundance or species composition affect sandeel abundance and/or quality which, in turn, plays a major role in seabird breeding failure (Frederiksen *et al.*, 2006; Wanless *et al.*, 2007).

Gull with fish

Understanding 'bottom-up control' is critical in predicting how important mid-trophic fish such as sandeels and pipefish, and the predators that depend on them will be affected by future climate change (Frederiksen *et al.*, 2006; Harris *et al.*, 2007). Research initiated in 2008 on Rathlin and other Irish Sea seabird colonies hopes to improve this understanding. Vulnerable areas will be identified and adaptation strategies developed.

9



FRESHWATER ENVIRONMENT AND DIADROMOUS FISH

Authors O'Toole, C., Poole, R. and Whelan, K.

KEY POINTS

» The main three species of Irish diadromous fish have shown a decline in numbers and marine survival over the past three decades, thought to be at least partly related to the interactive effects of changing climatic and oceanic conditions, along with human impacts. Data from the Marine Institute's experimental catchment in Burrishoole, Co. Mayo shows:

Salmon: declining marine survival since the 1970s.

Sea trout: stock collapse in 1980s with adult returns still at a low level.

European eel: sharp fall in recruitment since the 1980s, in line with similar declines throughout Europe.

» Freshwater temperatures from the Burrishoole catchment have been increasing significantly from the 1970s to the present day. This change is likely to have strong knock on effects on the survival and development of juvenile fish populations.

» Diadromous fish species are important indicator species in climate change research. The migrations of these species could have significant implications for understanding a broader set of biogeographical and ecological questions across a wide range of spatial and temporal scales.

9.1 INTRODUCTION

Diadromous fishes migrate between the sea and fresh water to complete their life cycle. Worldwide, there are estimated to be roughly 250 species of diadromous fish. Anadromous species spend most of their lives in the sea and migrate to fresh water to breed (Atlantic salmon *(Salmo salar)*, sea trout *(Salmo trutta)*, shad *(Alosa spp.)*). Catadromous species conversely migrate from fresh waters to the sea to breed (e.g. European eel *(Anguilla anguilla)*, flounder *(Platichthys flesus)*).

Diadromous fish species migrate between freshwater and the ocean and are, therefore, highly sensitive to changes in both environments. They are important indicators in monitoring climate and water related changes. The combination of high resolution environmental and fish data supports an integrated analysis and long term datasets allow the opportunity to observe changes over time, critical in the field of climate change research.

The key eco-physiological processes of the various life stages of these organisms in freshwater, such as hatching and survival in anadromous fish and smoltification and migration in salmonids, are controlled by environmental variables such as temperature, sunlight, day length and rainfall. Other variables, such as water colour, oxygen levels and water flow may also impact on these key processes, for example, by reducing light penetration or increasing drought/flood induced mortality.

Given their high sensitivity to environmental conditions and the large distances that these fish can cover during their migration, diadromous species are particularly vulnerable to changes associated with climate, and these species will be exposed to changes both in freshwater and in the marine environment (Lassalle *et al.*, 2008; FSBI, 2007). Projected changes in rainfall and temperature associated with global warming will likely have serious impacts on the ecology of fresh and transitional waters in Ireland. Ocean climate changes are already known to impact on salmon at sea, largely through the close interaction between growth and survival (Peyronnet *et al.*, 2007); diminishing eel populations may also be the result of changes in the ocean (ICES, 2008).

In Europe, the majority of diadromous fish species are endangered and listed in the Habitats Fauna and Flora Directive, the Bern Convention and the International Union for Conservation of Nature (IUCN) Red List, but current conservation plans do not address climate change issues and consider the distribution range relative to the year 1900 as a reference, even though these species might have undergone a substantial biogeographical distribution shift as a result of global warming.

9.2 IRISH DIADROMOUS FISH SPECIES

Diadromous fish in Ireland are composed of a limited number of species due to factors such as recent glaciation and the island's northerly location. They include Atlantic salmon, sea trout, eel, twaite and allis shad (*Alosa fallax* and *Alosa alosa*), smelt *(Osmerus eperlanus)*, sea and river lamprey (*Petromyzon marinus* and *Lampetra fluviatilis*), along with flounder and some mullet species *(Family Mugilidae)*. Salmon, sea trout and eel support important commercial and/or recreational and tourist fisheries.

'Marine survival and pre-fishery abundance of the Atlantic salmon, has been in steep decline throughout the North Atlantic area over the past three decades'.

9.2.1 Atlantic Salmon *(Salmo salar)*

Marine survival and pre-fishery abundance of the Atlantic salmon, *(Salmo salar)*, has been in steep decline throughout the North Atlantic area over the past three decades. The possible impact of climate change, mainly through increasing sea temperatures, has been studied in relation to the marine growth and survival of salmon. Peyronnet *et al.* (2007) linked marine growth with survival of salmon at sea, particularly during the late summer and early winter periods of the first year at sea. Processes operating at the scale of the Northeast Atlantic may have control over the survival rates of Atlantic salmon, but their effect on interannual variation is suppressed or modulated by other processes, with the freshwater juvenile phase of the life history possibly being important (Peyronnet *et al.*, 2007).

Factors such as increasing temperature, increased or decreased river flow rates, increasing water colour and changes in sediment loading could have possible impacts on the survival and growth of the juvenile stages of Atlantic salmon, further influencing marine survival. Salmon are known to be sensitive to higher than normal temperatures at certain stages in their life cycle, with their optimal growth attained at <15°C and compromised at >20°C. Some Irish lakes have previously recorded summer temperatures of >23°C (Boelens *et al.*, 2005) and stream temperatures >25°C have recently been recorded in the west of Ireland, a maximum that is likely to increase further due to climate change (K. Mc Crann, pers. comm.).

Salmon smolt

Milder winter/spring conditions could lead to salmon smolts migrating outside of the optimal time, possibly leading to poorer marine survival (Crozier and Kennedy, 2003). Byrne *et al.* (2003), however, found that in the Burrishoole catchment, even while smolt numbers were declining from the 1970s to the end of the 1990s, the timing of the smolt run was consistent over that time period. They showed that smolt migration was controlled by temperature and regulated by water level, both factors which are projected to change in the future with probable negative implications for migrating smolts.

9.2.2 Sea Trout *(Salmo trutta)*

Sea trout are widespread in Ireland with the majority of stocks being in the southwest, west and northwest of the country. Sea trout have traditionally been abundant in most short rivers running directly into the sea and in lakes with close proximity to the sea where growth rates are slow and survival difficult. Although

'Between 1988 and 1989, sea trout stocks in the west of Ireland showed stock collapses in the majority of catchments in the midwest as indicated by rod catch statistics and corroborated by trap census in four key west of Ireland fisheries'.

Trout smolt

often associated with salmon, there are many smaller streams and lakes that do not hold many salmon but in which sea trout are numerous.

Between 1988 and 1989, sea trout stocks in the west of Ireland showed stock collapses in the majority of catchments in the midwest as indicated by rod catch statistics and corroborated by trap census in four key west of Ireland fisheries (Gargan *et al.*, 2006, Poole *et al.*, 2006). Sea lice from fish farms were implicated in the collapse, but climatic induced changes in the marine environment may also have played a role in affecting marine survival. Rate of development, generation time and reproductive output of sea lice are all temperature dependent (Tully, 1992) and heavy lice infestation coupled with higher temperatures, particularly in 1989 and 1990, resulted in low survival of sea trout post-smolt (Gargan *et al.*, 2003). It is noteworthy that the lowest marine survival of sea trout occurred following the warmest winter recorded in 1988/89 (figure 9.2). It was also apparent that sea trout and salmon go through a physiologically stressful transition from freshwater to sea water and that this, in conjunction with a new lice burden, can cause additional stress (Poole *et al.*, 2006). Factors influencing the smoltification process and run timing were identified as photoperiod, temperature and water levels all of which could be directly affected by climate change (Gargan *et al.*, 2006). This indicates just how sensitive these migratory stocks can be and it is possible that a rapid rate of climate change could cause significant problems.

9.2.3 Eel *(Anguilla anguilla)*

Since the 1980s, stocks of the European eel *(Anguilla anguilla)*, have been in serious decline, with recruitment decreasing to approximately 1-10% of recruitment observed during the decade of the 1970s, with stronger declines in the more northern and southern parts of the range (Dekker, 2003; ICES, 2008). Several possible causes have been suggested for this decline, including overfishing, habitat reduction, organic chemical contamination, parasites (e.g. *Anguillicola crassus*), and reductions in spawning success and/or larval migration failure due to ocean climate factors (Castonguay *et al.*, 1994; ICES, 2008).

The latest scientific advice from the International Council for the Exploration of the Sea (ICES) concerning European eel was that the stock is outside safe biological limits and that current fisheries are not sustainable. ICES have recommended that a recovery plan be developed for the whole stock of European eel as a matter of urgency and that exploitation and other human activities affecting the stock be reduced to as close to zero as possible. Ireland established a national working group on eel management in 2006, in advance of the agreement of the Regulation (EC) No. 1100/2007 in order to begin the preparatory work required. Approved eel management plans must be implemented on or before the 1st July 2009.

9.3 ENVIRONMENTAL FACTORS AFFECTING DIADROMOUS FISH

As cold blooded animals (ectotherms), fish normally have a body temperature near identical to that of the surrounding water. Their biological functions are critically dependent on temperature and extreme temperatures may be directly lethal to fish, often in combination with drought conditions and low oxygen levels. In contrast, the effects of sub-lethal temperatures influencing processes such as growth and maturation may be far more difficult to predict. The life history stages that will most likely be affected by freshwater temperature changes in salmonids are spawning, hatching and migration. A further level of complexity arises when considering the effects of temperature on the ecosystem as a whole and the implications on fish populations. It is thought that increasing temperatures in both freshwater and the ocean could result in a northward shift of some species, for example salmon, possibly affecting Irish stocks (FSBI, 2007). Climate and ocean changes may negatively affect eels in the spawning and larval migration phases in the ocean leading to global recruitment failure. In Ireland warmer freshwaters are also likely to increase the eel's growth rate, which could have an impact on decreasing the age at migration and changing the sex ratios.

'Since the 1980s, stocks of the European eel, have been in serious decline, with recruitment decreasing to approximately 1-10% of recruitment observed during the decade of the 1970s'.

Changes in rainfall and water flow (e.g. droughts) may impact on migratory salmonid species by restricting their access to natal rivers during periods of low flow. This will impact on timing of migrations to and from the sea and may result in additional mortality due to delayed migrations. High floods due to extreme rainfall events will likely cause erosion and higher levels of sedimentation in rivers and this may impact on spawning success, particularly if gravel spawning beds become damaged or washed away. Low flows (droughts) can lead to juvenile mortalities and isolation of fish. Periods of droughts or flooding will also affect the eel's success in freshwater, affecting both migrations to freshwater of juveniles and seaward migrations of mature adults. A combination of temperature and flow effects can trigger migration effects in diadromous fish. Any alteration to these seasonal patterns could have negative consequences on the timing of migrations and on the fitness of fish to migrate.

In terms of genetic adaptation, it has been shown that adaptive shifts (under genetic control) in the timing of various life stages (e.g. dormancy, migration, development and reproduction) will be required if animals, including diadromous fish species, are to adapt to projected climate change and that these will likely precede other effects. (P. McGinnity, pers. comm.) It is therefore necessary when studying changes in the population size, growth rate, range or any other factor relating to the fish to also look at the environmental variables acting on it.

9.4 COMBINED BIOLOGICAL AND ENVIRONMENTAL MONITORING CASE STUDY

9.4.1 Burrishoole Catchment

The Burrishoole catchment, situated in Newport, Co. Mayo is composed of approximately 55km of rivers and streams and five lakes.

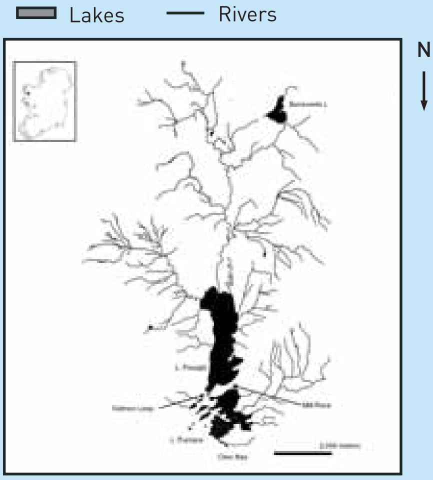


Figure 9.1 Map showing the location of the Burrishoole catchment on the west coast of Ireland and indicating the main lakes and two rivers connecting Loughs Feeagh and Furnace which have full fish trapping facilities.

In figure 9.1 the largest lake is the freshwater Lough Feeagh, which is connected by two outflows to the brackish water tidal Lough Furnace. The Burrishoole discharges into the northeast corner of Clew bay (Whelan *et al.*, 1998). The majority of the catchment is covered in blanket peat. The main land uses in the catchment are forestry and agriculture, largely hillside farming of mountain sheep. Forestry accounts for approximately 19% of land use in the catchment (Ryder *et al.*, in prep). The Marine Institute's facility in Burrishoole, Newport, Co. Mayo is an international index site for diadromous species. The Burrishoole is an important catchment for salmon, trout, char and eels and the stocks have been intensively monitored over the past 50+ years. Fish trapping operations in Burrishoole have the unique advantage of being able to monitor all movements of fish to and from freshwater. The data collected are used by ICES to help gauge the overall status of the Irish stocks of salmon, sea trout and eel on an annual basis. In line with the fish stock monitoring over the past 50 years, a comprehensive monitoring network of instrumentation, including the Met Eireann Weather Station in Furnace, has been established leading to a considerable dataset of environmental variables (Whelan *et al.*, 1998). It is this dataset, along with those from strategically selected catchments around the country, which will form the basis for assessing the future impact of changing climate on riverine and lacustrine habitats and species.

Modelling of climate variables carried out on Lough Feeagh projected changes in the climate including an increase in air temperature in all seasons, increased precipitation in winter and spring and decreased precipitation in the late summer and autumn (Blenckner *et al.*, 2007, Arvola *et al.*, in press). The model indicated increases in stream flow in winter with decreases in the late summer and early autumn. Model runs also indicated a substantial future increase in dissolved organic carbon (DOC) concentration (Jennings *et al.*, in press, Naden *et al.*, in press). These changes could have important implications for the ecology of the lake.

9.5 ENVIRONMENTAL DATA

A long term water temperature data set has been collected since 1959 from the "Mill Race" stream (the outflow from the southern end of Lough Feeagh). Just a hundred metres away a Met Éireann weather station has been recording air temperature and rainfall over the same time period.

The trend in annual average water temperatures in the Burrishoole catchment is positive (figure 9.2) demonstrating an overall increase in average water temperature, in parallel with the air temperature increase ($p<0.001$; data not shown). It is noteworthy that the rate of warming in wintertime (December, January and February) is faster than annual average warming.

Salmonid species in Ireland spawn during the wintertime, and a decrease in temperature appears to trigger the spawning process; the development of eggs as well as the timing of the hatching are also strongly temperature related (Crisp, 1981). Rising winter water temperatures are therefore likely to impact the survival and development of juvenile salmonids.

In agreement with global climate trends, temperature is expected to continue to increase in Ireland in the near future (Dunne *et al.*, 2008), and to pose further threats to the depleted salmonid stocks (figure 9.3). The influence of global climate on the environmental conditions in the Burrishoole catchment emerges from the significant relationships ($R2=0.212$, $p<0.001$) between the North Atlantic Oscillation Index (Hurrell *et al.*, 2003) and winter water temperature in the Burrishoole catchment. (see Chapter 2 for explanation of the North Atlantic Oscillation).

'The trend in annual average water temperatures in the Burrishoole catchment is positive demonstrating an overall increase in average water temperature, in parallel with the air temperature increase'.

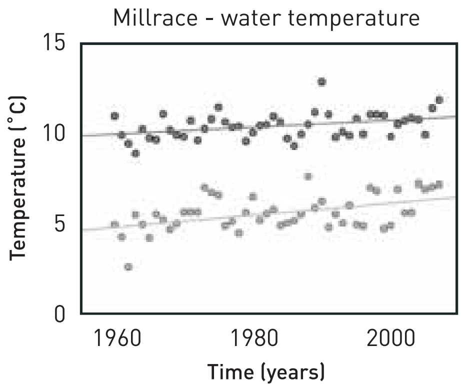


Figure 9.2 Annual average water temperature in the Burrishoole catchment from 1960-2007: year-round (dark grey series); wintertime (light grey series). Trend lines show that wintertime average water temperature is increasing at a faster pace than annual average temperature.

Below the Mill Race Trap Falls - Marine Institute, Newport Facility

9.6 CURRENT STATUS OF MIGRATORY FISH IN THE BURRISHOOLE

'Census returns of returning adult salmon to Burrishoole show a decline in the 1970s with low numbers continuing each year since the 1980s'.

Salmon, sea trout and eel populations have been monitored in the Burrishoole catchment since 1958, with a full census of upstream and downstream migrating fish since 1970. There have been a number of changes to the stock structure and numbers of fish migrating over this time period for all three species but possibly due to different reasons. In many cases, the changes may have been caused or influenced by ocean or climate related factors.

9.6.1 Atlantic Salmon

Census returns of returning adult salmon to Burrishoole show a decline in the 1970s with low numbers continuing each year since the 1980s. The increase in 2007 was as a result of the closure of the high seas drift net fishery. However, it can be seen that present numbers are still below historical returns (figure 9.3). Marine survival of salmon to the coast has been declining (Peyronnet *et al.*, 2007) while survival to the trap (freshwater) has not changed, possibly compensated for by changes in exploitation.

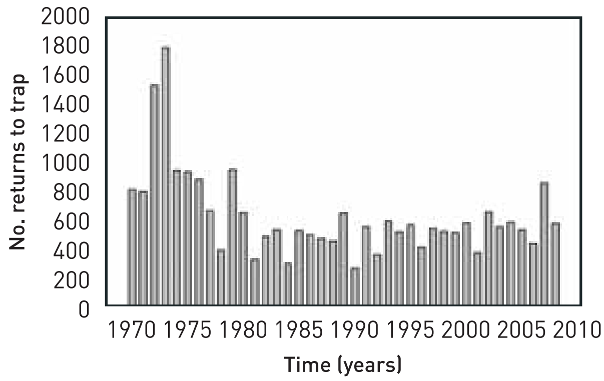


Figure 9.3 Number of returns of adult salmon to the Burrishoole catchment in the period 1970-2008.

9.6.2 Sea Trout

Lough Furnace and Lough Feeagh

In the Burrishoole catchment, there has been considerable annual variation in numbers of returning finnock (0+ sea age adults) with returns historically varying between 11.4% and 32.4% of the smolt output, indicating marine survival is probably affected by a number of factors (Poole *et al.*, 2006). Stocks of returning sea trout collapsed during the period 1989-1990, with sudden strong reduction in marine survival to a finnock return of only 1.5% in 1989 (figure 9.4). This decline is discussed further below. A regime shift in sea trout (finnock) survival was detected using a sequential regime shift detection (Rodinov, 2005) which began in 1987. This corresponded with the development of salmon farming in Clew Bay, warm winter and spring temperatures and higher rates of sea lice on the wild sea trout in Clew Bay being negatively related to marine survival of the trout (Tully, 1992; Gargan *et al.*, 2003). Analysing the pre and post regime shift survivals does not give a significant relationship between mortality rates and NAO.

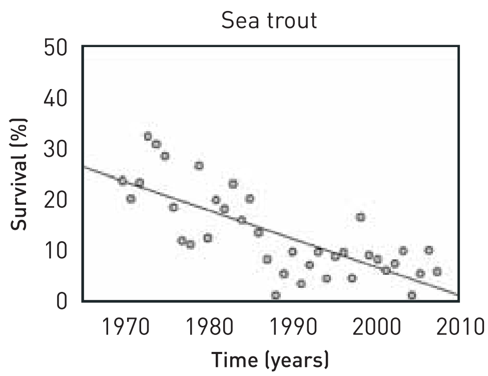


Figure 9.4 (a) Annual percentage return of smolts returning as finnock (0+ sea age) to the Burrishoole traps (taken from Poole *et al.*, 2006).

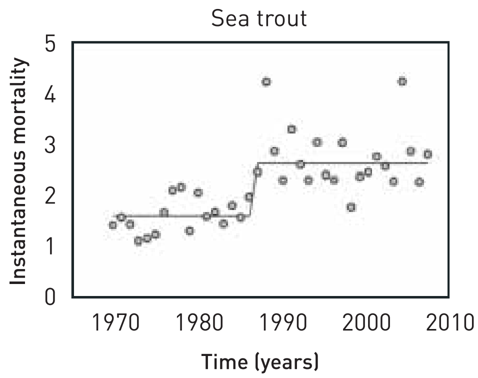


Figure 9.4 (b) Instantaneous mortality rates for finnock showing regime shift in 1988.

9.6.3 Eel

There are no local data for recruitment of glass eel into the Burrishoole. Anecdotal information indicates that recruitment into the catchment has fallen drastically since the early 1980s in line with other areas around Europe. The silver eel migrations in Burrishoole have been studied since 1959 (Piggins, 1985; Poole *et al.*, 1990). Numbers of eels in the annual migrations have decreased (figure 9.5). Total weight of catch has not been affected by the drop in numbers which has been compensated for by a change in sex ratio from 63% males in the 1970s to 32% in the last decade and this has been accompanied by an increase in the size of female eels. A decline in elver recruitment and increasing catchment productivity may be contributory factors in causing these changes (Poole *et al.*, 1990).

'The changes observed in these stocks of migratory fish are thought to be due to a number of complex and sometimes inter-related factors, of which climate change may play an important role'.

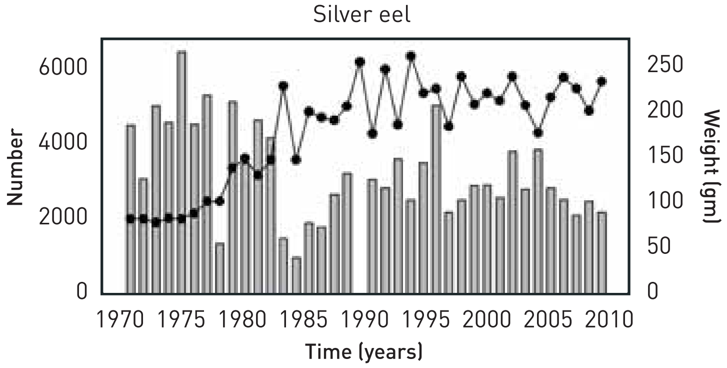


Figure 9.5 Showing the number and average weight of migrating silver eels from Burrishoole 1971-2008.

Overall Changes in Burrishoole: A number of marked changes in the migratory fish stocks in Burrishoole have been observed over the period 1970-2008. Numbers of adult salmon returning to the catchment declined over the period due to a combination of exploitation, environmental degradation and changes in marine survival. Marine survival of sea trout collapsed in the late 1980s leading to a collapse in the spawning stock and a subsequent significant reduction in smolt recruitment. Changes have also been observed in the numbers, sex ratio and size of adult silver eels migrating from the catchment. The changes observed in these stocks of migratory fish are thought to be due to a number of complex and sometimes inter-related factors, of which climate change may play an important role.

CAPACITY BUILDING 2 Ocean Climate Modelling

Author Hüsrevoglu, S.

Ocean Ecosystem Modelling of the Northeast Atlantic

Introduction

Models of ocean ecosystems incorporating biogeochemistry are essential tools for understanding the population dynamics of plankton and fish as well as the mechanisms of nutrient (e.g. nitrogen) and carbon cycling. Ecosystem models span a wide range of complexity, determined by the number of nutrient cycles and species they represent. State of the art in ecosystem modelling is integrating biological models with ocean general circulation models (OGCM), as ecosystem dynamics are tightly coupled to ocean physics. The most common versions of such coupled models are comprised of an ocean circulation model and a lower trophic level biological model, which simulates the interactions between nutrients, phytoplankton, and zooplankton.

Ocean ecosystem modelling research at the Irish Marine Institute has commenced as part of the Marine Climate Change Programme (MCCP), and as of writing of this report, an ocean ecosystem hindcast model implemented for the Northeast Atlantic is in the testing and validation stage. A high performance, 560-CPU parallel cluster featuring Intel Xeon 5450 processors, commissioned in September 2008, is currently used for producing the simulations. A typical hind cast simulation year takes about 48 hours to complete on the Marine Institute high performance cluster.

Study Area

The ocean ecosystem model domain (Figure CB2.1) covers the Northeast Atlantic, including the regions that influence the major hydrographical features of the Irish continental shelf, such as the Shelf Edge Current (SEC). The domain extends from Biscay Bay in the south to the south of Iceland in the north.

The western extent of the domain includes the abyssal waters and the continental slope to the west of Ireland, while the Irish continental shelf, the Celtic Sea and the Irish Sea occupy the eastern part of the domain.

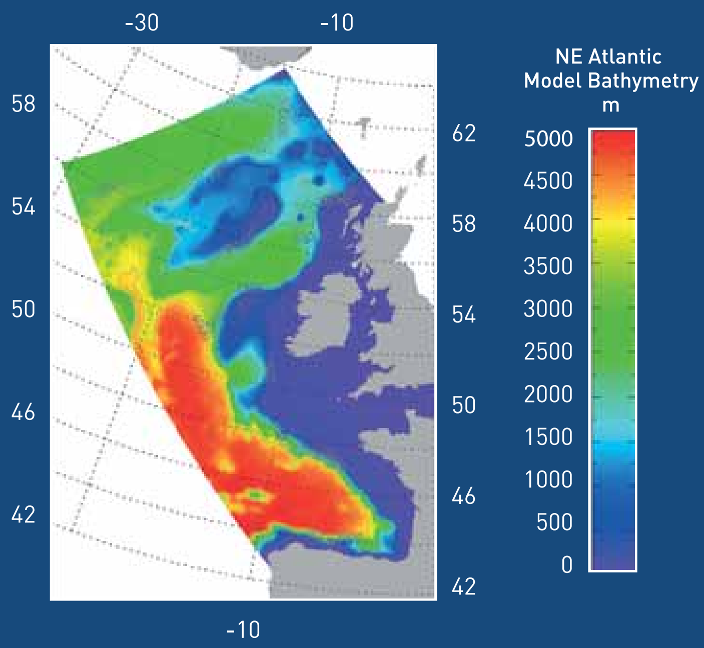


Figure CB2.1 Northeast Atlantic Ocean ecosystem model domain with the bathymetry contours shown.

Northeast Atlantic Ocean Ecosystem Model Description

Physical Model Configuration

The physical model is based on the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005), which is a free surface, hydrostatic ocean circulation model. The resolution of the model is relatively high, with a grid cell area of 25 km^2. The water column is divided into 40 levels, regardless of the bathymetry, and layers are concentrated at the surface and the bottom of the ocean to better represent the dynamics of these highly dynamic boundary layers. The atmosphere is not modelled explicitly, and therefore, atmospheric variables, such as the wind, air temperature, sea level pressure, rainfall, and clouds, are used to drive the model from global reanalysis data sets provided by the European Centre for Medium Range Weather Forecasts (ECMWF) and the National Centres for Environmental Prediction/ National Centre for Atmospheric Research (NCEP/ NCAR). The initial conditions over the whole model domain and the conditions at the domain boundaries are obtained from the global output of one of the Intergovernmental Panel on Climate Change Assessment Report 4 (IPCC AR-4) models, the National Centre for Atmospheric Research-Community Climate System Model (NCAR-CCSM) version 3.0, for the oceanic variables and the World Ocean Atlas 2005 (Boyer *et al.*, 2005) for nutrient fields.

Ecosystem Model Configuration

The ecosystem component of the model framework (figure CB2.2) is a lower trophic level biogeochemical model based on the pelagic nitrogen cycle (Fasham *et al.*, 1990; Fennel *et al.*, 2006). The ecosystem model includes seven variables: phytoplankton, zooplankton, nitrate (NO_3^-), ammonium (NH_4^+), small and large detritus, and chlorophyll. The model also calculates the time evolution of dissolved O_2, partial pressure and surface flux of CO_2 and ocean alkalinity.

2003-2008 Hindcast Simulation

The ocean ecosystem model of the Northeast Atlantic is used to produce a 2003-2008 hindcast simulation of ocean and plankton dynamics of the region. Simulated surface chlorophyll concentration (figure CB2.3), averaged over a region around Ireland produces the spring and autumn bloom cycles with realistic timing when compared to the satellite observations. The magnitudes of the simulated blooms track closely the magnitude of the observed blooms, although, with a negative offset due to the model underestimating the winter phytoplankton standing stock.

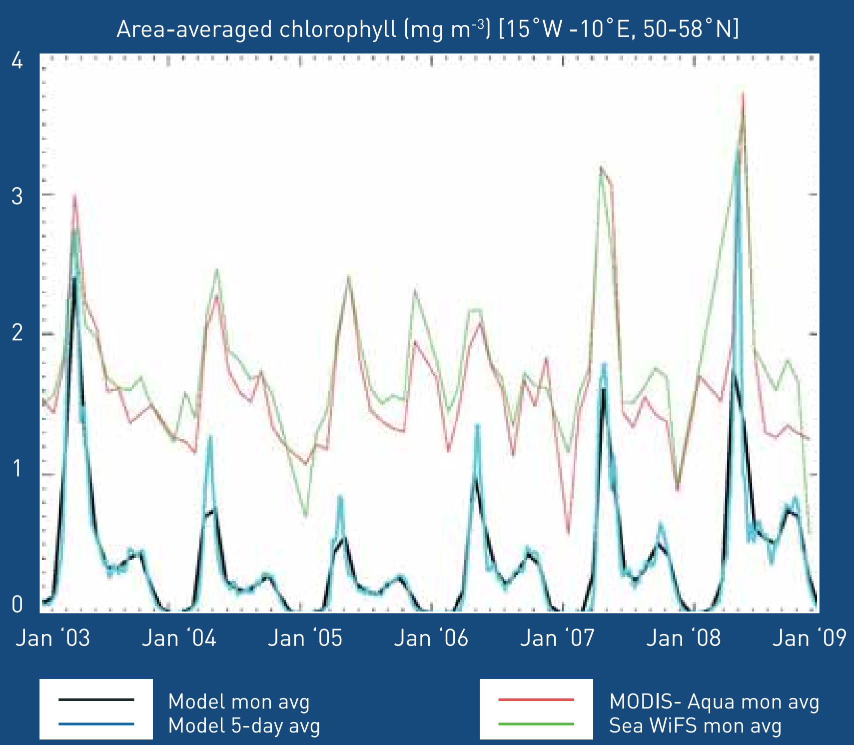


Figure CB2.3 Simulated surface level chlorophyll averaged over the region [15°W-10°E, 50-58°N] and monthly average time series of the same from SeaWiFS and MODIS-Aqua satellites.

Future Work

The model is currently being tuned to produce a simulation that reflects the observations more accurately. The results hence produced will be designated as a control simulation and the tuned model will be used to produce ecosystem related forecasts for the mid and late 21st century in accordance with the IPCC Special Report on Emission Scenarios (SRES) global carbon emission outlook.

More complex ecosystem models (e.g., NEMURO (Kishi *et al.*, 2007), Biogeochemical Flux Model (BFM; Vichi *et al.*, 2007a, b)) that represent multiple nutrient cycles (e.g., phosphate and silicate) and multiple species of phytoplankton and zooplankton will in the future be coupled to the ocean model so that a more detailed picture of the Irish marine ecosystem is obtained from the simulations.

Ultimately, an Earth system modelling approach could be adopted within the Irish marine climate research community, coupling terrestrial, atmospheric and ocean ecosystem models. It may be appropriate to address this with other international partners given the relatively small cohort of Irish climate modellers.

10

RECOMMENDATIONS

This report has attempted to collate and analyse available marine data sets for Irish waters and to put these data in a climate context where possible. These data sets are collected over varying time scales. The longest data sets extend back to the late 1950s while others have been initiated in the past 5-10 years. In some cases data have been put in a wider context by comparison with international data such as the HADSST sea surface temperature analysis and the Continuous Plankton Recorder (CPR) survey conducted by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS). While the analysis to date has been considerable the brevity of some of the time series means that in 2009 we are relatively poorly equipped to make conclusions as to how climate change will affect Irish waters. This report describes key regulators of ocean climate around Ireland and examines relevant environmental datasets available in 2009. It therefore represents the current status of knowledge regarding the influence of climate on Ireland's marine ecosystems and resources.

Improvements in the information base will require:

1. Long term monitoring of essential climate variables is maintained and Ireland contributes as planned to climate monitoring activity planned under the UN Global Climate Observing System (GCOS) (see www.epa.ie/downloads/pubs/research/climate/name,24240,en.html) and the Marine Strategy Framework Directive.
2. Long-term monitoring should be considered in an integrated national sense to represent terrestrial, atmospheric and oceanic measurements.
3. Capacity is retained and strengthened in Irish research groups particularly in:
   - Climate modelling (including multi-species, individual based models, ecosystem and Earth system).
   - Chemical analyses (carbon, nutrients and other chemical variables).
   - Plankton ecology (both phytoplankton and zooplankton).
   - Ageing and genetic techniques.
   - Analysis and interpretation of sediment cores from lakes and oceans.
4. Basic research needs to take place to examine the processes and interactions within ecosystems so that sense can be made of the long-term data and the observed changes within the marine climate system.
5. Research needs to be initiated to increase confidence in estimates of certain climate impacts including sea level rise, ocean acidification, alteration of food webs and downstream affects on coastal communities and to prepare a mitigation and adaptation strategy.
6. The socioeconomic importance of Ireland's marine resources affected by climate change must be better defined (i.e. quantified) so that policymakers can be informed of the full significance of the changes revealed through scientific investigation.
7. Linking marine climate change research in Ireland to major initiatives at the international level is extremely important. Irish researchers should interact with international climate scientists so that technology transfer and capacity building can take place (both ways) and that a flow of research findings exists to and from the Irish marine climate research community.
8. Contributing scientific findings to the Intergovernmental Panel on Climate Change (IPCC) is a necessary and beneficial process that Irish scientists should be involved in.
9. Adaptation measures are best formulated on the basis of robust data.

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