IRISH OCEAN CLIMATE AND ECOSYSTEM

STATUS REPORT
2023

Foras na Mara
Marine Institute

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CONTENTS

EXECUTIVE SUMMARY

Photo credit: Tomasz Szumski

EXECUTIVE SUMMARY

This report is intended to summarise the current trends in Ireland's ocean climate. Use has been made of archived marine data held by a range of organisations to elucidate some of the key trends observed in phenomena such as atmospheric changes, ocean warming, sea level rise, acidification, plankton and fish distributions and abundance, and seabirds. The report aims to summarise the key findings and recommendations in each of these areas as a guide to climate adaptation policy and for the public. It builds on the previous *Ocean Climate & Ecosystem Status Report* published in 2010.

The report examines the recently published literature in each of the topic areas and combines this in many cases with analysis of new data sets including long-term time series to identify trends in essential ocean variables in Irish waters. In some cases, model projections of the likely future state of the atmosphere and ocean are presented under different climate emission scenarios.

MAIN FINDINGS

The ocean is important to Ireland and its citizens with many livelihoods and activities supported from the marine sectors including fisheries, aquaculture, ocean energy, shipping, tourism and leisure. About 40% of the population live within 5 km of the coast. It is critical to understand how our ocean is being affected by climate change and the implications this may have on how the ocean is used by humans.

The Intergovernmental Panel On Climate Change (6th Assessment Report) has found that CO_2 in the atmosphere continues to rise, that surface land and ocean temperatures are warmer, Arctic sea ice has decreased, the upper 700 m of the ocean have warmed, oceans have become more acidic and have seen a decrease in oxygen levels, and that sea levels have risen. Other observed changes in our ocean include a perturbation of nutrient cycles, changes in biogeography of organisms ranging from phytoplankton to marine mammals, ocean warming impacting fisheries catches, increasingly stressed coastal ecosystems and changes in the nature and extent of harmful algal blooms.

The changes observed around Ireland in many cases mirror those observed at regional and global scale and are presented in this report.

ATMOSPHERIC DRIVERS OF MARINE CLIMATE

The ocean and atmosphere are intricately linked elements of the Earth system with changing dynamics in the atmosphere having a direct effect on oceans and their ecosystems. The North Atlantic Oscillation (NAO) is the leading mode of climate variability in the North Atlantic. A positive NAO leads to warm, wet and stormy weather over northern Europe. Other important atmospheric modes are the East Atlantic (EA) and Scandinavian (SCA) patterns. The EA (in its positive phase) is associated with decreased precipitation and above-average temperatures in winter in Ireland. The SCA pattern exhibits similar effects to the EA pattern in winter. It is more appropriate to use a combined analysis of the NAO-EA and NAO-SCA rather than analysing the NAO on its own in future studies examining atmospheric drivers of marine processes.

RECOMMENDATIONS FOR ATMOSPHERIC DRIVERS OF MARINE CLIMATE

1. Future research examining modes of atmospheric variability should extend beyond analysis of the NAO alone with an emphasis on connecting to changes in ocean and ecosystem processes.
2. Enhance organisational cooperation between domains e.g. atmosphere, biosphere, oceanic etc. earth system.
3. Ocean initialisation should be included in future analyses due to its importance in predicting particular periods, such as the extreme mid-1990s positive phase of the NAO (missed in uninitialised models).

PHYSICAL OCEANOGRAPHY

The Atlantic Meridional Overturning Circulation (AMOC) or Gulf Stream system is key to Ireland's mild climate. This system is predicted to decline due to climate change. Irish waters have warmed since the 1980s, with 2007 temperatures over 0.8°C above the 1960–1990 average. Recent years have seen a cooling trend of -0.3°C/decade. Sea surface temperatures remain 0.4°C warmer in the 21st century relative to 1960–1990. Sea levels continue to rise with larger sea level rise observed in Cork and Dublin compared to global estimates.

RECOMMENDATIONS FOR PHYSICAL OCEANOGRAPHY

1. Enhance coordinated observations of ocean circulation and heat content in Irish waters to understand whether recent cooling trends are part of an anthropogenically-forced, long-term decline in the AMOC or are associated with natural variability.
2. Continue research of regional and local variations in sea level change, given the striking differences already observed in Irish cities. Understanding the drivers of these differences are key to accurate regional projections of sea level rise and is crucial for effective climate adaptation.

OCEAN CHEMISTRY

The ocean takes up over a quarter of anthropogenic CO_2 emissions each year and understanding the magnitude, variability and limitations of the ocean as a carbon sink is critical to climate science.

This CO_2 uptake is altering seawater chemistry, a phenomenon referred to as "Ocean Acidification". Irish offshore waters have become more acidic with an overall reduction in pH of 0.02 units per decade. The reduction in pH is also evident in deeper waters (1500–2000 m) when 2010 is compared to the 1990s.

Ocean acidification also results in reduced calcium carbonate saturation states, which impacts the ability of organisms to form shells and skeletons. The aragonite saturation horizon (ASH), which is the depth below which unprotected aragonitic calcium carbonate tends to dissolve, has become shallower. As this continues over the course of this century, benthic ecosystems on the shelf slopes will be at risk.

Short-term pH variations in biologically productive coastal waters can be much larger than the observed signal in the open ocean. In coastal embayments the carbonate system may also be strongly influenced by local catchment geology.

Recent measurements of atmospheric and surface ocean CO_2 on board the national research vessels indicates that Irish coastal waters act as a CO_2 sink in spring and summer, while in autumn these waters often act as a CO_2 source to the atmosphere.

There is no clear trend in dissolved winter nutrient concentrations in the western Irish Sea, the area with most consistent sampling over the last two decades.

RECOMMENDATIONS FOR OCEAN CHEMISTRY

1. Undertake a sustained high quality observing programme for essential biogeochemical climate variables to monitor changing ocean conditions and the impacts of climate change.
2. Assess the trends and variability of ocean acidification in Irish waters at various scales and support targeted OA monitoring and research to better understand the risks to local shellfish aquaculture from ocean acidification and other climate stressors.
3. Continue CO_2 measurements on research vessels and other platforms to better constrain the carbon budget and the role of the continental shelf as a seasonal CO_2 sink/source.
4. Maximise the impact of national data collection and research by contributing to international activities and data centres that support regional and global assessments of ocean climate change (e.g. ICOS, Surface Ocean CO_2 Atlas, reporting to IOC-UN SDG 14.3 Ocean Acidification).

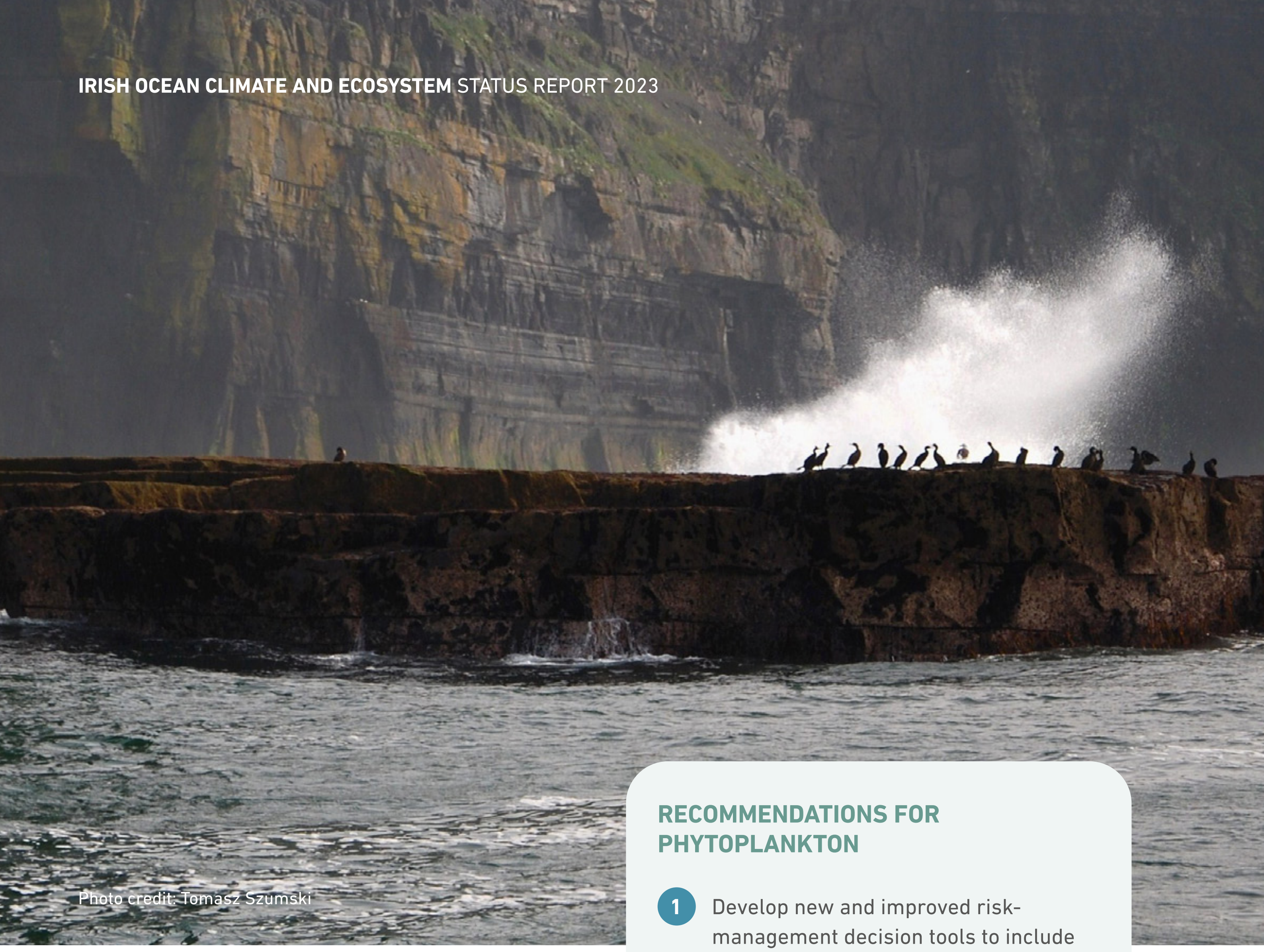

Photo credit: Tomasz Szumski

PHYTOPLANKTON

Phytoplankton are the base of the marine food chain and include several harmful algal species that impact the seafood sector and potentially humans. An expansion of the phytoplankton growth season has been observed for some species in Irish waters. Diatom cell abundance has increased nationally while many dinoflagellates have declined in terms of monthly cell abundance. Significant regional variation in some of the trends is observed (see chapter 5). *Alexandrium* species has increased from June to August and their geographic range has extended around the south west coast in recent years. *Karenia mikimotoi* blooms appear to occur slightly later in the year when comparing the most recent decade with 2001 to 2010.

RECOMMENDATIONS FOR PHYTOPLANKTON

1. Develop new and improved risk-management decision tools to include an operational Harmful Algal Bloom (HAB) forecast system and biophysical models (including the development of HAB seasonal forecasts and HAB and phytoplankton community climate predictions) that can provide support to the seafood sector adaptation plan.
2. Establish a long-term climate network of sentinel sites (collecting biological, chemical and physical data) to detect invasive plankton species and novel/emerging biotoxins produced by these species.
3. Develop appropriate spatial scale models to estimate the future likely change in biological processes, e.g., prevalence of harmful algae.
4. Extend phytoplankton sampling offshore to improve knowledge of plankton shelf dynamics, and augment the existing alert system (HABs).

COMMERCIAL FISHERIES

There are many significant commercial fisheries in the Irish Exclusive Economic Zone (EEZ) with stock trajectories varying by species. Declines in over-exploited stocks may be exacerbated by climate change. Disentangling climate effects from other pressures including fishing remains a challenge. There is evidence of increasing Lusitanian (warm water) species to the south of Ireland which may allow for new fishing opportunities e.g. boarfish and anchovy. Increases in some species may be more due to natural long-term fluctuations in abundance, e.g. snake pipefish. It is imperative that new and existing fishing opportunities are managed effectively and sustainably.

RECOMMENDATIONS FOR COMMERCIAL FISHERIES

1. Continue research into the best methods of incorporating ecosystem parameters into current fishery management programmes.
2. Long-term scientific monitoring of fish stocks in the Irish EEZ should be maintained to continue monitoring the stocks health status and to allow further research into the potential impacts of climate change on fisheries.
3. Develop methods to further interrogate data with respect to climate-forcing.
4. Novel fishing opportunities created by species distribution shifts must be managed correctly to ensure a sustainable yield. International cooperation on the management of fish stocks is vital to manage not only novel stocks, but current stocks undergoing distribution shifts.

SEABIRDS

Half of seabird species globally have declining population trends. Eighty-nine percent of seabirds affected by climate change are also affected by other threats e.g. overfishing, incidental capture, hunting/trapping and disturbance. Similar to fisheries, it is difficult to disentangle the precise effects of each threat on the seabird population. Northward shifts in the copepod prey of sandeels have been observed with important implications for the diet of many seabird species. Sea level rise is likely to impact populations such as Little Terns and Ringed Plover that nest on coastal beaches. Wrecks of seabirds due to storms cause starvation in extreme cases. More than 50,000 seabird wrecks (mortalities) were observed in 2013/2014 on the coastline of Europe.

RECOMMENDATIONS FOR SEABIRDS

1. Increase resources dedicated to research on climate change in relation to seabirds, such as targeted long-term dietary and productivity studies.
2. Enhance research on the interactions between climate change and other pressures/threats to seabirds.
3. Adopt the use of regional sentinel sites with a suite of indicator species for annual study; Black-legged Kittiwake is used as an indicator species in Britain.
4. Identify conservation concerns and actions regarding other pressures and threats such as disturbance, over-fishing, bycatch, predation and habitat loss, and implement appropriate measures that may help alleviate some of the pressures arising from climate change.
5. Investigate the impact of climate change on non-breeding species in Ireland, such as wintering birds or passage migrants.
6. Collaborate with international partners to protect flyways of passage migrants, as well as breeding seabirds in Ireland that overwinter in different countries.
7. Develop a standardised recording protocol for beached birds to assess seabird mortality and frequency of wrecks.
8. Develop and resource improved seabird data sharing and data management mechanisms to enable and support national and international scientific and management collaborations.

LAND OCEAN AQUATIC CONTINUUM (LOAC)

Ireland's land mass is connected with the surrounding ocean, and the terrestrial and ocean environments should be studied in tandem.

The Marine Institute Burrishoole catchment provides an ideal natural laboratory for such research. Comparison of CO_2 levels in Lough Feeagh and Lough Furnace show that Lough Furnace emits far less CO_2 than Lough Feeagh and can be a net sink of CO_2 at certain times of the year. Regional inputs of nutrients and carbon from watersheds should be coupled with scenarios of global CO_2 emissions to assess local impacts on coastal ecosystems.

The return of Atlantic Salmon after one winter at sea have declined from almost 1,800 in 1973 to 279 in 2014, below the conservation limit for the Burrishoole catchment. Reduced returns have been correlated with increased water temperatures and decreased abundance of plankton. The average run of sea trout smolts from Burrishoole has declined from 4,100 fish before 1990 to circa 250 fish in recent years. The number of silver European eels migrating from Burrishoole has also halved.

In the south and southeast of Ireland, decreases in total nitrogen and total phosphorus inputs from Irish rivers have been observed between the 1990s and 2014, with slight increases in both nutrients since 2014.

RECOMMENDATIONS FOR THE LAND OCEAN AQUATIC CONTINUUM (LOAC)

1. It is critical that key long-term datasets, which capture disruption signals along the LOAC, are maintained and financially supported. Examples are:
   - Lough Feeagh (Mill Race) water temperature
   - Diadromous fish stocks as sentinel species
   - Greenhouse gas emissions along the aquatic continuum
   - Irish Reference Network (IRN) of hydrometric stations
   - Riverine Inputs and Direct Discharges (RID) programme
2. Modelling exercises using future climate projections are an essential decision support tool and should be used in future catchment management plans.
3. Assessment of future impacts of climate change for Ireland requires that monitoring and research of rivers, lakes and transitional waters are considered simultaneously.
4. Anthropogenic pressures, that reduce the resilience of sensitive habitats and species to climate change, must be reduced to ensure the conservation of Ireland's biodiversity.
5. Nature-based solutions should be included in climate change mitigation plans.

REGIONAL & LOCAL DOWNSCALED MODELS

While this report is primarily focused on the current state of the ocean, one chapter is dedicated to summarising some of the key marine climate projections for the 21st century. Significant wave heights are projected to decrease, particularly for summer and winter. Mean sea level for the Irish coast is projected to increase by between 25 cm and 0.8 m depending on the greenhouse gas emissions trajectory considered. Sea surface and near bottom temperatures for southwest Ireland are projected to increase by 0.1°C to 0.3°C. Some earlier projections for the Irish Sea suggest increases of 1.9°C to 3.0°C. Stratification of the Celtic Sea water column and the western Irish Sea gyre are projected to strengthen. Projections of the salinity off southwest Ireland suggest a freshening trend by 2035. Net primary productivity is projected to decrease by 0.135% per annum by the mid-21st century under a pessimistic (RCP8.5) scenario.

RECOMMENDATIONS FOR REGIONAL & LOCAL DOWNSCALED MODELS

1. Ensure historical climate runs are bias-corrected before proceeding with future projections to reduce uncertainties.
2. Develop biogeochemical climate models to meet stakeholder requirements.

Photo credit: Tomasz Szumski

MARINE INFRASTRUCTURE & PROGRAMMES FOR ESSENTIAL OCEAN VARIABLE MONITORING

The Essential Ocean Variables (EOVs) that form the basis for many of the chapters in this report are collected by an array of marine infrastructures and monitoring programmes in Irish waters. Marine infrastructure include marine platforms or observatories and land based specialised equipment and laboratories. These infrastructures are key to gathering long-term evidence in a changing climate and require specialised training, knowledge and skill to operate to ensure they are operated correctly.

RECOMMENDATIONS FOR MARINE INFRASTRUCTURE & PROGRAMMES FOR ESSENTIAL OCEAN VARIABLE MONITORING

1. Ensure essential ocean variables relevant to Irish waters are measured sustainably and meet international requirements for climate monitoring.
2. Maintain existing infrastructure, critical for decision-makers (e.g. IMDBON, tide gauges, pCO_2 systems).
3. Build capacity (expertise and equipment) for essential ocean variables in gap areas (e.g. zooplankton, marine carbonate chemistry) and ensure sentinel sites are established and maintained.
4. Advance pilot projects that have already provided valuable scientific information for decision makers.

CHAPTER 1

INTRODUCTION

Photo credit: Jonathan White

1.1 WHY IS MARINE CLIMATE CHANGE IMPORTANT FOR IRELAND?

Ireland is an island nation on the fringes of the North Atlantic Ocean. Ireland's territorial waters are many times the size of the land territory. This marine territory supports livelihoods in many sectors including fisheries, aquaculture, ocean energy, shipping, tourism and leisure among others. Our ocean territory also delivers ecosystem services in the form of carbon sequestration, oxygen production, provision of habitats for plant and animal species, and moderation of the weather and climate. We have observed changes in our ocean since measurements became available to study key ocean phenomena. Irish waters have warmed and have become more acidic. There have been shifts in the distribution and abundance of key plankton, fish and seabird species, and sea level rise is observed for much of the Irish coast.

Much of our population (~40%) lives within 5 km of the coast and many of our citizens will be at the forefront of climate change adaptation in the coming years. As our ocean changes, we will need robust solutions to the threats posed by climate change. Our seas have the potential to mitigate some of the effects of climate change by storing carbon, providing nature-based solutions to coastal erosion and sea level rise, and continuing to provide sources of protein for humans through commercial fisheries and aquaculture. Significant opportunities exist to develop offshore renewable energies, (e.g., wind, wave and tidal power). The challenge is to transition from carbon intensive marine activities to those with higher mitigation potential. It is critical that through education, Irish citizens understand climate change in the marine domain and how it may affect their livelihoods and quality of life.

1.2 CLIMATE CHANGE IN A GLOBAL CONTEXT

The ocean is part of the wider Earth system that also includes our atmosphere, terrestrial biosphere and cryosphere (ice influenced area). The Intergovernmental Panel on Climate Change (IPCC) recently produced a sixth assessment report (AR6) outlining the physical science basis for climate change observed to date in the Earth system (Masson-Delmotte *et al.*, 2021). The major changes within our ocean outlined in IPCC 2021 include:

- Increasing atmospheric concentrations of CO_2 (annual averages of 410 ppm in 2019), much of which ends up in the surface oceans.
- Warmer global surface temperatures on land and over the ocean when comparing the 2011–2020 period to 1850–1900.
- Decreases of 40% in Arctic sea ice in September and 10% in March when comparing 1979–1988 to 2010–2019.
- Warming of the upper 700 m of the global ocean since the 1970s.
- An increase in ocean acidification and a decrease in oxygen levels in the upper ocean since the mid-20th century.
- Global mean sea level has increased by 0.2 metres between 1901 and 2018 with a marked acceleration in the rate of sea level change between 2006 and 2018.

The IPCC Special Report on Ocean and Cryosphere (Bindoff *et al.*, 2019) identified key changes in ocean ecosystems associated with a changing climate. The report notes that:

- Open ocean nutrient cycles are being perturbed with regionally varying impacts on primary producers.
- Ocean warming has led to changes in biogeography of organisms, ranging from phytoplankton to marine mammals.
- Fisheries catches are already impacted by the effects of warming and changing primary production in some regions.
- The combined effects of ocean warming, sea level rise and non-climatic pressures from human activities on land are stressing coastal ecosystems.
- The occurrence of harmful algal blooms has changed in some coastal areas since the 1980s with implications for food provisioning, tourism, the economy and human health.

Photo credit: Tomasz Szumski

The focus of the IPCC climate efforts is primarily at the global and regional scale. Climate decision-makers however often need scientific evidence at national or local scale to inform climate adaptation and mitigation policies and planning. The Environmental Protection Agency published "*The Status of Ireland's Climate 2020*" (Cámaro García and Dwyer, 2021) to compile national and local changes in Ireland's climate for the atmosphere, ocean and terrestrial spheres. The key ocean findings from this report were that:

- Sea level around Ireland has risen by 2–3 mm per year since the early 1990s.
- Sea surface temperatures on Ireland's north coast (Malin Head) were 0.47°C higher over the last 10 years compared with 1981–2010.
- Irish surface ocean waters have become more acidic between 1991 and 2013.
- Harmful algal species have expanded their growth season since 1990 and are now present throughout the year in Irish waters.

1.3 POLICY DRIVERS FOR CLIMATE OBSERVATIONS AND ANALYSIS

As a party to the UN Framework Convention on Climate Change (UNFCCC), and the Paris Agreement, Ireland committed to carrying out climate observations and to establish a national committee for the Global Climate Observing System (GCOS). The National Adaptation Framework and Climate and Low Carbon Development (Amendment) Bill 2021 requires individual economic sectors and local authorities to regularly produce and update adaptation plans for their sector or by local authority area.

Ireland has set ambitious targets in terms of climate action including an annual reduction in greenhouse gas emissions. Government policy emphasises the need for fit-for-purpose climate adaptation and mitigation actions, both at sectoral and local authority level. Among the key climate threats to Irish marine sectors are rising sea levels, ocean warming (and consequent changes of key fish species distributions), ocean acidification (with impacts on aquaculture) and coastal inundation (with impacts particularly at ports, critical infrastructure and urban areas).

Other policy considerations include the OSPAR North East Atlantic Environment Strategy 2020–2030, Marine Strategy Framework Directive (MSFD), National Marine Planning Framework, Offshore Renewable Energy Development Plan (OREDP), and the designation of Marine Protected Areas (MPAs) in the coming years.

The Maritime Area Planning (MAP) Act and the National Marine Planning Framework (NMPF) are important policy developments that support the sustainable development of Ireland's marine and coastal waters, the protection of marine biodiversity and climate change mitigation. The MAP Act and the NMPF recognise the need for Ireland to take into consideration long-term changes due to climate change.

New cross-government structures are being established as part of Project Ireland 2040 where there may be a substantial investment target for all-island cooperation.

A report by the National Economic and Social Committee (NESC) to the Department of the Taoiseach, Shared Island: Shared Opportunity, has recommended "*greater cognisance of the connected nature of the climate crisis and biodiversity emergency for the island of Ireland, and reflect this in a programme of coordination and joint action*". Specifically, the report recommends that a number of opportunities are explored for future collaboration on key all-island climate and biodiversity concerns, which include: marine and coastal impacts of climate change – strengthening cooperation, and expanding knowledge sharing.

1.4 RATIONALE

This report is intended to summarise the current trends in Ireland's ocean climate. Use has been made of archived marine data held by many organisations to elucidate some of the key trends observed in phenomena connected to atmospheric changes, ocean warming, sea level rise, acidification, plankton and fish distributions and abundance, and seabird population trends. The report aims to summarise the key findings in each of these areas as a guide to climate adaptation policy and to the public. It builds on the previous *Ocean Climate and Ecosystem Status Report* published in 2010.

1.5 STRUCTURE OF THE REPORT

The report first considers changes in atmospheric patterns over Ireland and the adjacent Atlantic. It then examines changes in the physical oceanography of the region, e.g., ocean heat content and sea level rise. The changing chemistry of our oceans is examined in chapter 4, while changes in marine phytoplankton are presented in chapter 5. Observed trends in the distribution and abundance of fish species are examined in chapter 6, and observations of key seabird species are discussed in chapter 7. Chapter 8 explores trends from the land ocean aquatic continuum with emphasis on the Burrishoole catchment in Co. Mayo. An insight into ocean climate modelling and marine climate projections to date is provided in chapter 9, while the infrastructures that underpin the collection of marine climate data are included in the final chapter of the report.

1.6 CONTRIBUTORS TO THE REPORT

This report represents a collaboration between marine researchers within the Marine Institute and many others based in Ireland's higher education institutes and public bodies. The Marine Institute has established a climate services team to bring expertise from a wide range of disciplines together. The report also includes authors from Met Éireann, Maynooth University, the University of Galway, the Atlantic Technological University, National Parks and Wildlife, Birdwatch Ireland, Trinity College Dublin, University College Dublin, Inland Fisheries Ireland, the National Water Forum, the Environmental Protection Agency, and the Dundalk Institute of Technology.

1.7 ANTICIPATED AUDIENCE FOR THE REPORT

This report is for the scientific community, the public and policy makers who require evidence for climate change adaptation at a local, regional or national level, and it contributes to adaptation plans at sectoral and local authority level. The report is accompanied by a summary for policy makers and web resources available at www.marine.ie.

Photo credit: Coast Monkey

CHAPTER 2

ATMOSPHERIC DRIVERS OF MARINE CLIMATE

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Photo credit: Tomasz Szumski

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2.1 INTRODUCTION

The ocean and the atmosphere are a tightly coupled system, with heat, momentum and mass (including gases, aerosols, sea spray, and water vapour) continuously exchanged between the two. Heat transfer from the ocean to the atmosphere provides one of the main energy sources for atmospheric motion. Atmospheric circulation, in turn, affects oceanic circulation, with surface winds generating ocean waves and currents. The ocean also serves as the Earth's largest reservoir of moisture and is a core component of the hydrological cycle. Globally, evaporation exceeds precipitation over the ocean, allowing for moisture to be transported by the atmosphere onto land. The transfer of heat and moisture from the ocean to the atmosphere influences weather and climate patterns globally. This is particularly true of Ireland's climate, which is dominated by the influence of the Atlantic Ocean.

This chapter provides an overview of the dominant modes of large-scale atmospheric variability in the North Atlantic and their influence on Ireland's climate. Section 2.2 introduces the three main modes, namely the North Atlantic Oscillation, the East Atlantic pattern and the Scandinavian pattern. Sections 2.2.1, 2.2.2 and 2.2.3 describe the patterns in detail and their influence on Ireland's climate. Finally, Section 2.2.4 describes the combined effects of the three main modes and details how a combined analysis more appropriately describes European winter climate variability.

The NAO positive phase results in warm, wet, stormy weather over northern Europe and cool, dry weather over southern Europe.

These patterns are reversed during negative phases of the NAO.

2.2 CLIMATE VARIABILITY AND ATMOSPHERIC MODES

An understanding of natural variability in the climate system is vital for the correct interpretation of climate trends and variability. Climate variability in the North Atlantic can be analysed in several ways. This chapter focuses on the dominant modes of large-scale atmospheric variability in the region – namely the North Atlantic Oscillation (NAO), the East Atlantic pattern (EA) and the Scandinavian pattern (SCA) – as these patterns are referenced throughout the report. Complementary approaches which analyse climate variability in the region in terms of the position and strength of the North Atlantic jet (e.g. Woolings *et al.*, 2010; Hallam *et al.*, 2022) shows a 3° northward shift (from 44° to 47°) in winter between 1871-2011 (0.2° per decade). The northward shift means the average jet position, and associated storm track, is now closer to Ireland in winter. Jet speed also increased over the period 1871-2011 by 10 mph (8%) to 132 mph on average in winter (Hallam *et al.*, 2022). Regional weather regimes (e.g. Ferranti *et al.*, 2015), are not considered here for the sake of brevity.

The NAO is the leading mode of climate variability in the North Atlantic.

Historically, large-scale modes of atmospheric variability have been defined as the difference in normalised mean sea level pressure at locations corresponding to their centres of action. The NAO, for example, is defined in this way as the pressure difference between the Azores High and Icelandic Low (Hurrell, 1995; Jones *et al.*, 1997). A more common approach today is to compute the leading empirical orthogonal functions (EOFs) of mean sea level pressure anomalies in the North Atlantic region. EOF analysis is a widely used method for decomposing a dataset into its weighted principal components or orthogonal patterns. The first EOF is defined as the pattern that accounts for the most variability in the dataset, the second EOF is the pattern that accounts for second highest, and so on.

This chapter focuses on the influence of the NAO, EA and SCA on Ireland's climate for the winter months of December, January and February (DJF), taking its lead from the key studies referenced here (e.g. Comas-Bru and McDermott, 2014; Zubiate *et al.*, 2017; Comas-Bru and Hernández, 2018). To the best of the author's knowledge, similar studies for summer, spring and autumn have not yet been performed. Results for these seasons could be incorporated into future editions of this report should they become available.

As the leading mode of variability in the North Atlantic, the NAO corresponds to the first EOF of winter monthly mean sea level pressure anomalies in the North Atlantic region (Comas-Bru and McDermott, 2014; Zubiate *et al.*, 2017; Comas-Bru and Hernández, 2018). The second leading EOF is typically the EA pattern, with the third EOF the SCA pattern. Figure 2.1 shows all three patterns as calculated by Comas-Bru and McDermott (2014) using the 20CRv2 global dataset (Compo *et al.*, 2011). The NAO accounts for 37.3% of the relative variance in this analysis, while the EA and SCA account for 17.7% and 14.4%, respectively. A detailed description of each mode is given in the following three sections (Sections 2.2.1 – 2.2.3).

Caution must be exercised when defining indices in this way to ensure that the polarity of each mode is consistent with the climatic effects described in the literature (Hurrell, 1995; Wanner *et al.*, 2001; CPC 2012). The approach of Comas-Bru and McDermott (2014) is followed here, where the signs of each eigenvector have been fixed so that the northern pole of the NAO is negative and the main centres of action of the EA and the SCA are positive for a positive phase of the NAO. This results in a definition of the EA which differs from that used in the previous edition of this report (Nolan *et al.*, 2010) and from that presented in Moore *et al.* (2013), but which agrees with several recent studies (Wallace and Gutzler, 1981; Moore and Renfrew, 2012; Comas-Bru and McDermott, 2014) and has been chosen to be consistent with the results presented here.

The temporal variability of each pattern can be obtained by projecting spatiotemporal data onto the EOF-defined pattern (Moore *et al.*, 2013; Wang *et al.*, 2012). In this way, indices for each pattern are obtained, referred to here as the NAO index (NAOI), the EA index (EAI) and the SCA index (SCAI). Figure 2.1 shows a time series of each index plotted alongside its corresponding EOF-derived pattern. To assess the relationship between the three identified modes of North Atlantic variability and the climate of western Europe, correlation distribution maps between winter precipitation and temperature and the NAOI, EAI and SCAI were computed by Comas-Bru and McDermott (2014) and are shown in Figure 2.2.

Climate models exhibit some predictive skill for the NAO in winter out to near-decadal timescales.

2.2.1 THE NORTH ATLANTIC OSCILLATION

The NAO is the leading mode of variability in the North Atlantic and refers to the redistribution of atmospheric mass between the Arctic and the subtropical Atlantic (Hurrell, 1995; Hurrell *et al.*, 2009). Changes in the phase of the NAO correspond to changes in the strength and position of a semi-permanent dipole over the North Atlantic, characterised by a low-pressure system located approximately over Iceland and a high-pressure system located approximately over the Azores, as shown in Figure 2.1. The NAO exerts a strong influence on air temperature, precipitation and wind patterns over the North Atlantic sector during winter (Hurrell, 1995; Wanner *et al.*, 2001; Hurrell *et al.*, 2009; Comas-Bru and McDermott, 2014; Zubiate *et al.*, 2017).

Variations in the amplitude and phase of the NAO manifest themselves in changes to the position and extent of the jet stream and the North Atlantic storm track. A positive phase of the NAO corresponds to a deeper Icelandic low and stronger Azores high, with a resulting increased pressure gradient over the North Atlantic (Hurrell *et al.*, 2009). This shifts the storm track to a more northerly orientation, resulting in warm, wet, stormy weather over northern Europe and cool, dry weather over southern Europe (Figures 2.2(a) and (b)). There is also an associated increase in the frequency and intensity of midlatitude cyclones (Hurrell *et al.*, 2009; Pinto *et al.*, 2009) and increased wave heights (Gallagher *et al.*, 2016; Gleeson *et al.*, 2019).

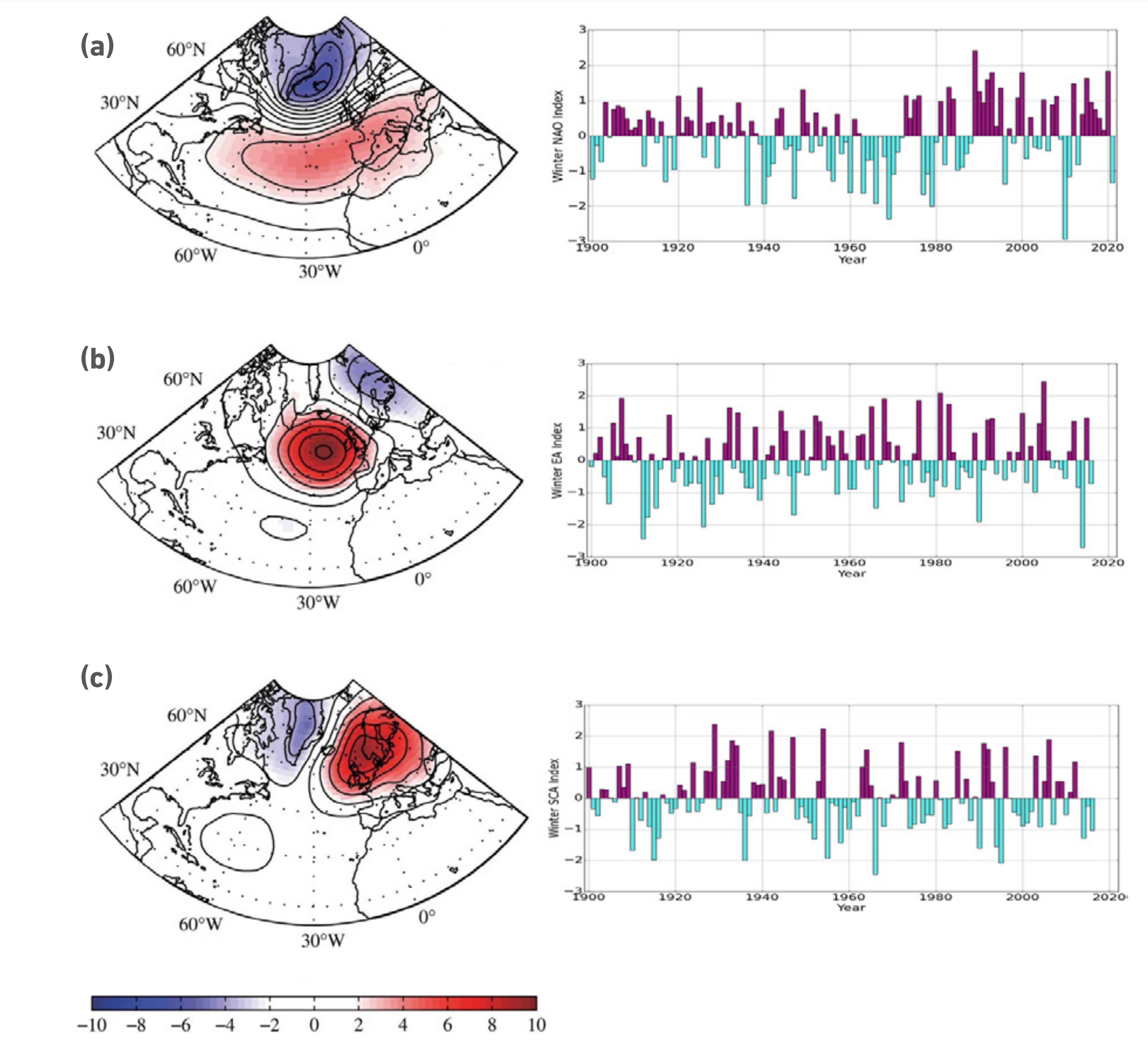

Figure 2.1 The three leading modes of atmospheric variability in the North Atlantic. From Comas-Bru and McDermott (2014).

(a) The North Atlantic Oscillation (NAO), corresponding to the first eigenvector of winter (DJF) monthly MSLP anomalies (mb) for the North Atlantic (1872-2009) and accounting for 37.3% of the total variance, calculated using the 20CRv2 dataset (Compo *et al.*, 2011). The Euro-Atlantic plot in the left-hand panel is taken from Figure 2(a) of Comas-Bru and McDermott (2014). The NAO time-series in the right-hand panel is the winter (DJF) Hurrell NAO index (1900-2021), retrieved from: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based.

(b) The East Atlantic pattern (EA), corresponding to the second eigenvector of winter (DJF) monthly MSLP (mb) for the North Atlantic (1872-2009) and accounting for 17.7% of the total variance. The Euro-Atlantic plot in the left-hand panel is taken from Figure 2(b) of Comas-Bru and McDermott (2014). The EA index in the right-hand panel is taken from Comas-Bru and Hernández (2018), retrieved from: https://doi.pangaea.de/10.1594/PANGAEA.892768

(c) The Scandinavian pattern (SCA), corresponding to the third eigenvector of winter (DJF) monthly MSLP (mb) for the North Atlantic (1872-2009) and accounting for 14.4% of the total variance. The Euro-Atlantic plot in the left-hand panel is taken from Figure 2(c) of Comas-Bru and McDermott (2014). The SCA index in the right-hand panel is taken from Comas-Bru and Hernández (2018).

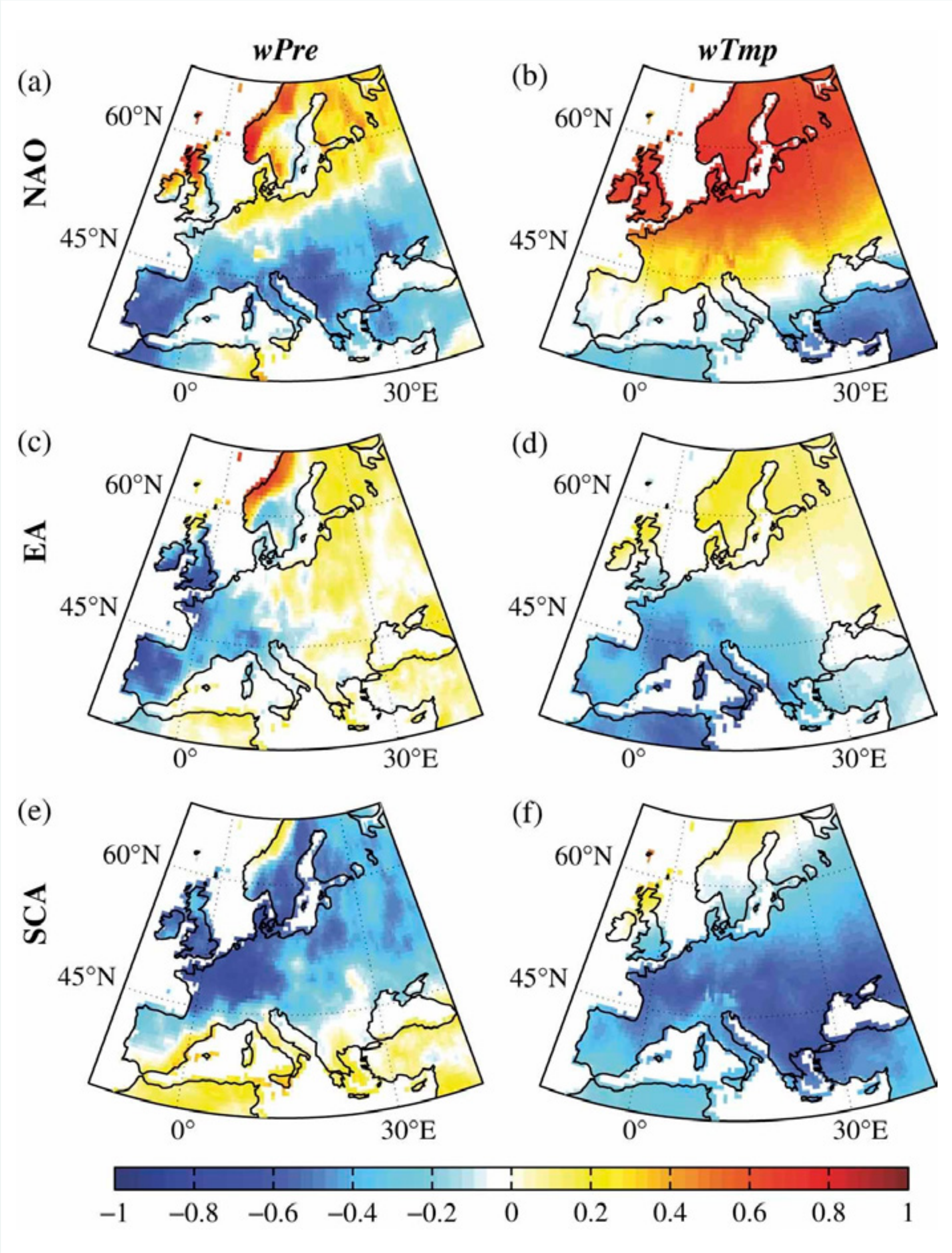

Figure 2.2 Correlation distribution maps between the winter precipitation and temperature (*wPre* and *wTmp*) datasets and the NAO ((a) and (b)), for DJF between 1902-2009, calculated using the CRU-TS3.1 dataset and EOF-based indices. From Comas-Bru and McDermott (2014). Similar correlation distribution maps for ((c) and (d)) EA and ((e) and (f)) SCA. Positive correlations are shown in red and negative correlations are shown in blue (see colour bar).

A negative phase of the NAO corresponds to a shallower Icelandic low and weaker Azores high, that results in a decreased pressure gradient over the North Atlantic and Europe (Hurrell *et al.*, 2009). This phase results in a shift in the storm track to a more zonal (east-west) direction, that weakens the westerlies over Europe compared with the positive NAO phase. This results in colder, drier, calmer conditions over northern Europe and warm, wet weather over southern Europe (Figures 2.2(a) and (b)). The reduced pressure gradient is also associated with a decrease in the frequency and intensity of midlatitude cyclones in the region (Pinto *et al.*, 2009), as well as reduced wave heights (Gallagher *et al.*, 2016; Gleeson *et al.*, 2019).

Most climate projections show a positive trend in the NAO in the 21st century combined with a north-eastward shift in its centres of action.

A timeseries of the winter Hurrell NAO index (Hurrell, 1995; Hurrell *et al.*, 2009) from 1900 to 2021 is shown in Figure 2.1(a). The NAO exhibits strong multidecadal variability; positive NAO winters dominate the period 1900–1940, while negative NAO winters dominate from 1940 to 1980. Positive NAO winters are more frequent from 1980 to 2020; however, this period also includes the exceptionally negative NAO winter of 2010, the lowest on record.

The East Atlantic pattern (EA) is the second mode of variability in the North Atlantic.

It has been shown that the NAO can be dynamically interpreted in terms of planetary wave breaking (PWB; Benedict *et al.*, 2004; Rivière and Orlanski, 2007; Woollings *et al.*, 2008), defined as the large-scale, irreversible overturning of potential vorticity contours near the tropopause (Hoskins *et al.*, 1985). Recent studies have examined the relationship of PWB in the North Atlantic to European windstorms. Hanley and Caballero (2012) found that 22 of the top 25 most destructive historical windstorms over western continental Europe were preceded by cyclonic and anti-cyclonic wave breaking over the North Atlantic, that is associated with an eastward shift of the NAO dipole. This results in an intensified, zonally-orientated jet, which favours the intensification of windstorms and steers them towards Europe (Hanley and Caballero 2012; Messori and Caballero 2015; Messori *et al.*, 2016).

Several recent ground-breaking studies have revealed that climate models exhibit some predictive skill for the winter NAO out to near-decadal timescales (Athanasiadis *et al.*, 2020; Dunstone *et al.*, 2016; Scaife *et al.*, 2014; Smith *et al.*, 2020). This is feasible only with extremely large multi-model ensembles, however, and considerable post-processing is needed to overcome the low signal-to-noise ratio. The results of Smith *et al.* (2020) suggest that the NAO predictability is composed of two components: one from initialisation of the ocean, and the other from external forcing. Klavans *et al.* (2021) performed a similar analysis using an uninitialised ensemble, showing comparable predictive skill. Their work highlights the potential importance of ocean initialisation in predicting particular periods, such as the extreme mid-1990s positive phase of the NAO, which is missed in uninitialised models.

Most climate projections show a positive trend in the NAO with increasing greenhouse gas concentrations in the atmosphere (Bacer *et al.*, 2016). Stephenson *et al.* (2006) found a positive increase in the NAO index in winter with increasing atmospheric CO_2 in 13 of the 18 CMIP2 models studied. Gillett and Fyfe (2013) examined 37 CMIP5 RCP4.5 model runs and found an increase on average in the NAO index between 1860 and 2100. Fabiano *et al.* (2021) investigated the response of the NAO index in 19 CMIP6 models under a range of future scenarios, showing an increase in NAO+ frequency and persistence during the second half of the 21st century for all scenarios considered, with the largest changes for the SSP3–7.0 and SSP5–8.5 scenarios. A north-eastward shift in the NAO centres of action has also been reported in several future climate studies (Ulbrich and Christoph, 1999; Hu and Wu, 2004; Bacer *et al.*, 2016).

Recent studies report a negative trend in the EA pattern in 21st century climate projections.

Photo credit: Tomasz Szumski

The EA positive phase is associated with decreased precipitation and above-average temperatures in winter in Ireland.

The reverse is true during negative phases, which are associated with stronger winds and larger waves off the west coast of Ireland.

2.2.2 THE EAST ATLANTIC PATTERN

The East Atlantic (EA) pattern is usually the second mode of climate variability in the North Atlantic. It was first described by Wallace and Gutzler (1981) as anomalously high 500 mb height anomalies over the subtropical North Atlantic and Eastern Europe when in positive mode. Like the NAO, this pattern is most prominent during the winter months (Barnston and Livezey, 1987). As noted in Section 2.2, the EA pattern presented here differs from that presented in Moore *et al*. (2013) and in the previous edition of this report (Nolan *et al*., 2010). It is, however, in agreement with a number of recent studies (Wallace and Gutzler, 1981; Moore and Renfrew, 2012; Comas-Bru and McDermott, 2014) and has been chosen to be consistent with the results presented in Section 2.2.4.

In its positive phase, the EA has an area of positive MSLP anomaly over the eastern North Atlantic and a more diffuse low MSLP anomaly over northeast Europe, as shown in Figure 2.1. The EA in its positive phase is associated with decreased winter precipitation in Ireland and the UK, and with above-average winter temperatures in Ireland, the UK and Scandinavia (Figure 2.2(c) and (d)). Greater precipitation and below-average temperatures are observed in Ireland and the UK during negative EA phases (Figures 2.2(c) and (d)). The anticyclonic ridge associated with the positive EA phase weakens flow over western and central Europe, leading to reduced wind speeds in those regions during winter (Zubiate *et al*., 2017). In its negative phase, the EA is associated with stronger winds and larger waves off the west coast of Ireland (Gleeson *et al*., 2019), and is known to contribute to northwest swells in the Bay of Biscay (Izaguirre *et al*., 2010).

The Scandinavian pattern (SCA) is the third mode of variability in the North Atlantic. It is associated with broadly similar climatic effects as the EA in winter in Ireland.

A timeseries of the winter EA index (Comas-Bru and Hernández, 2018) from 1900 to 2016 is shown in Figure 2.1(b). Unlike the winter NAO index, the winter EA index does not clearly exhibit strong multidecadal variability over this period. The response of the EA to increasing greenhouse gas concentrations in the atmosphere was recently investigated by Cusinato *et al.* (2021) in a CMIP6 multi-model ensemble, showing a negative 21st century trend (they report a positive trend but for an EA with reversed polarity compared with the pattern defined here) for the SSP5–8.5 future scenario considered. Fabiano *et al.* (2021) reported a decrease in the frequency and persistence of the Atlantic Ridge weather regime – a pattern similar to the positive phase of the EA – in all scenarios for a 19-member CMIP6 ensemble.

2.2.3 THE SCANDINAVIAN PATTERN

The Scandinavian pattern (SCA) is typically the third mode of climate variability in the North Atlantic. It corresponds to the Eurasia-1 pattern (Barnston and Livezey, 1987), and is characterised by positive MSLP anomalies over Scandinavia and a more diffuse negative MSLP centre over Greenland (Vautard, 1990; Cassou, 2008), as shown in Figure 2.1. As with the NAO and EA, the focus here will be on the SCA during the meteorological winter months.

The SCA in its positive phase is associated with broadly similar climatic effects over Europe as the EA in its positive phase: reduced winter precipitation in Ireland and the UK, and above-average winter temperatures in Ireland, the UK and Scandinavia (Figures 2.2(e) and (f)). These effects are reversed for the negative phase of the SCA. The SCA in its positive phase is associated with an anticyclone over northwestern Europe, which acts to redirect incoming low-pressure systems from the Atlantic. This leads to a reduction of wind speeds in northwestern Europe, in particular over Ireland and the UK (Comas-Bru and McDermott, 2014; van der Wiel *et al*., 2019). The SCA is known to be negatively correlated with significant wave heights in the North Atlantic during the extended winter months, in particular north of Ireland and the UK (Trigo *et al*., 2008).

A timeseries of the winter SCA index (Comas-Bru and Hernández, 2018) from 1900–2016 is shown in Figure 2.1(c). Like the winter EA index, the winter SCA index does not clearly exhibit strong multidecadal variability over this period. The response of the SCA to increasing greenhouse gas concentrations in the atmosphere was recently investigated by Cusinato *et al*. (2021) in a CMIP6 multi-model ensemble, with no clear 21st century trend reported for the SSP5–8.5 scenario considered. Fabiano *et al*. (2021) reported a decrease in the frequency of the Scandinavian Blocking weather regime – a pattern similar to the positive phase of the SCA as defined here – in a 19-member CMIP6 ensemble, with the signal most robust for the SSP3–7.0 and SSP 5–8.5 scenarios.

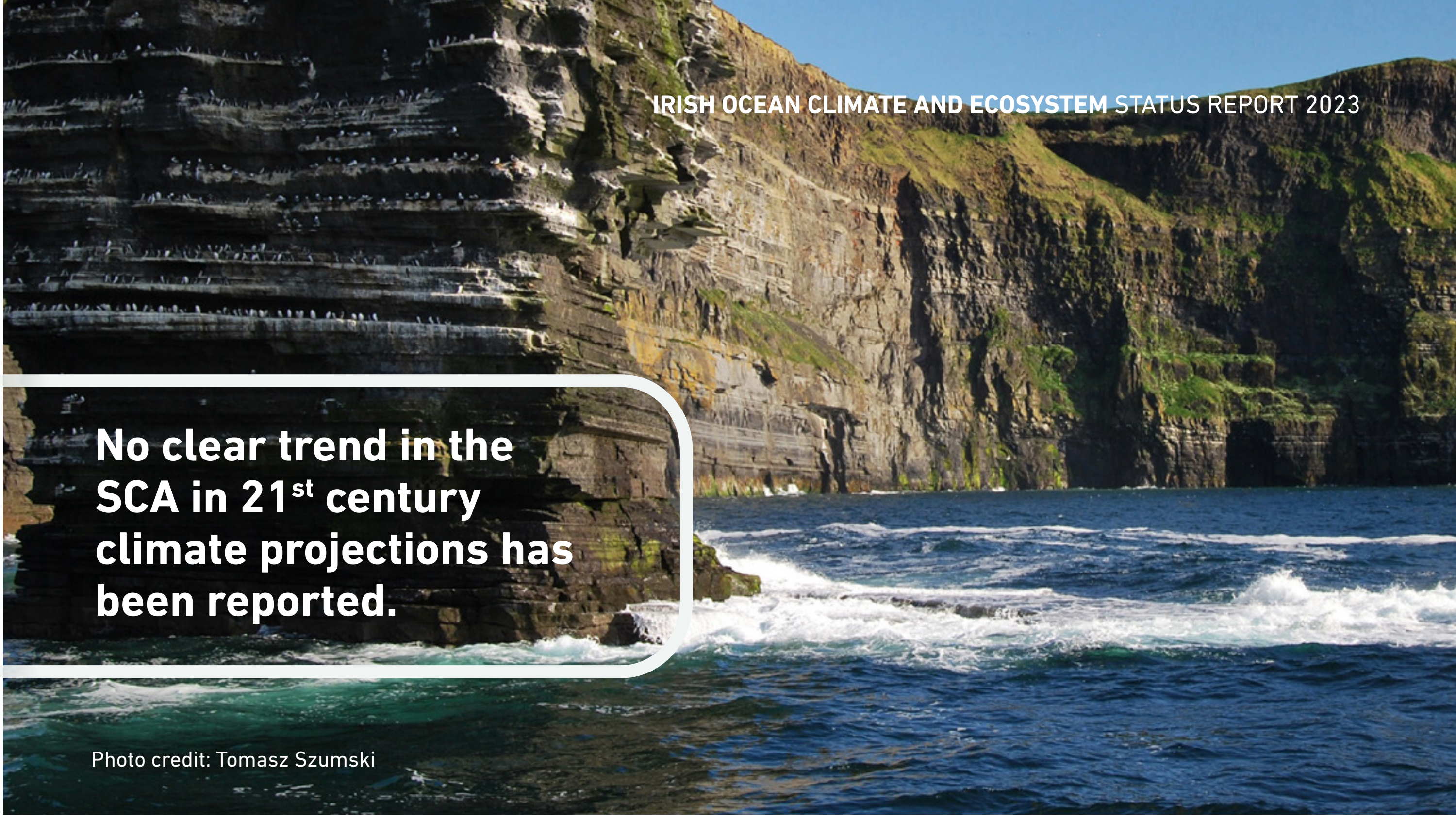

Photo credit: Tomasz Szumski

2.2.4 COMBINED EFFECTS OF THE NAO, EA AND SCA

Recent publications (Moore *et al.*, 2013; Comas-Bru and McDermott, 2014; Zubiate *et al.*, 2017) have highlighted how the EA and SCA patterns can modulate the geographical position of the NAO dipole. Comas-Bru and McDermott (2014) demonstrated that a combined NAO-EA and NAO-SCA analysis more appropriately describes European winter climate variability. They show that the NAO centres of action migrate to the northeast when the NAO and the EA have the same sign, with a migration to the southwest during phases of opposite sign. The NAO centres of action move in an anticlockwise manner when the NAO and SCA have the same sign, with a clockwise rotation during phases of opposite sign.

Comas-Bru and McDermott (2014) demonstrated that migrations of the southern NAO pole exert a detectable influence on Irish and UK precipitation patterns when the NAO and EA have the same sign (Figure 2.3). Their study also indicates that much of the interannual variability in the UK north–south winter precipitation gradient originally attributed to interannual and interdecadal variations in the NAO (Wilby *et al.*, 1997; Murphy and Washington, 2001) appears to be influenced by these combinations of the NAO and EA. They show an accentuation of the UK north-south gradient during concomitant positive EA and NAO winters, with a damping during winters of opposite phase, while wetter conditions are found overall in the UK during negative EA years (Figure 2.3). Winters of opposite NAO and EA phases are associated with the largest changes in winter precipitation in Ireland. A combination of NAO+/EA- is associated with wetter winters in Ireland, while a combination of NAO-/EA+ is associated with drier winters (Figure 2.3).

A combined NAO-EA and NAO-SCA analysis more appropriately describes European winter climate variability.

Zubiate *et al.* (2017) studied the relationship between wind speeds over western Europe and combined phases of the NAO, EA and SCA. They show that when the NAO and EA are simultaneously in either positive or negative states, wind speed anomalies over Ireland are damped compared with NAO positive or negative phases (Figure 2.4). Likewise, when the NAO and EA patterns present opposite signs, wind speed anomalies are enhanced in the mid-Atlantic and Ireland. When the NAO and SCA indices have the same sign, wind speed anomalies are weak

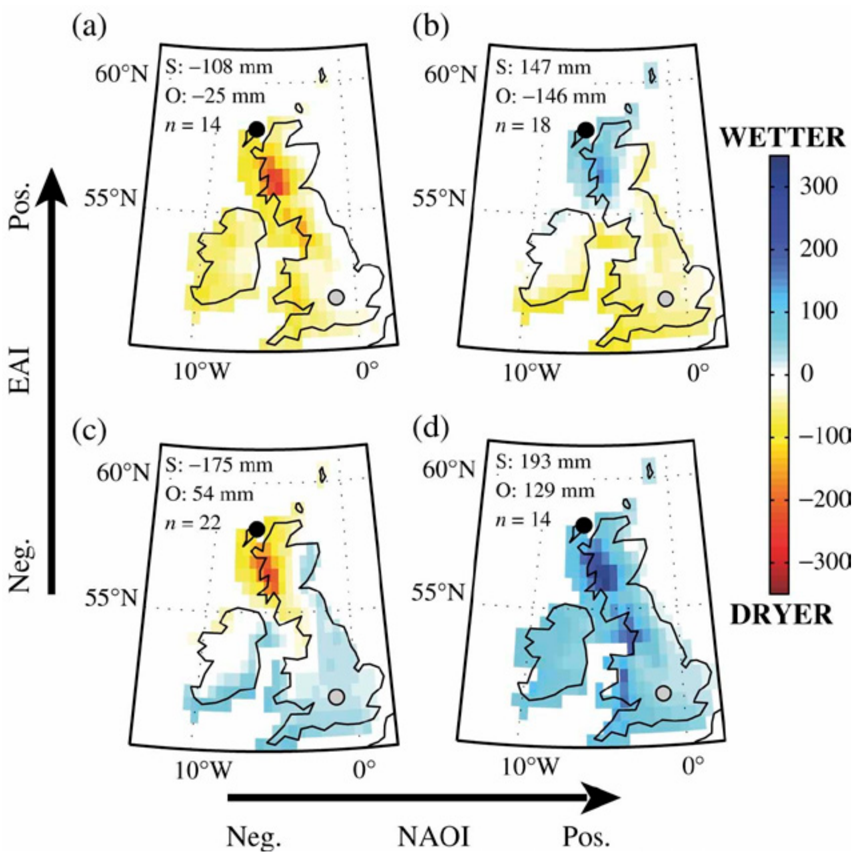

Figure 2.3 Mean DJF precipitation anomalies (in mm) from the long-term 20CRv2 dataset mean in the UK and Ireland for (a) negative North Atlantic Oscillation Index (NAOI) and positive East Atlantic Index (EAI), (b) negative NAOI and EAI, (c) positive NAOI and EAI and (d) positive NAOI and negative EAI. From Comas-Bru and McDermott (2014).

overall in Europe, except for Northern Ireland and western Scotland in the negative NAO case. When the NAO and SCA patterns exhibit opposite sign phases, enhanced anomalies are observed in Ireland, Great Britain, southern Scandinavia, Germany and Denmark. For Ireland and the UK, the strongest positive wind speed anomalies are present when the NAO is in a positive phase combined with either a negative EA or negative SCA phase, as shown in Figure 2.4.

Gleeson *et al*. (2019) found that the 20-year return levels of significant wave heights are largest when the NAO is in a strong positive phase and the EA and SCA are in strong negative phases. They also found that when the NAO is in a positive phase, the SCA enhances the westerly winds over the Atlantic, which in turn has a positive impact on wave heights off the west coast of Ireland. Overall, they found that the +, −, − patterns for the NAO, EA and SCA, respectively, are associated with the largest significant wave heights.

A combination of positive NAO and negative EA is associated with wetter winters in Ireland, while negative NAO and positive EA is associated with drier winters.

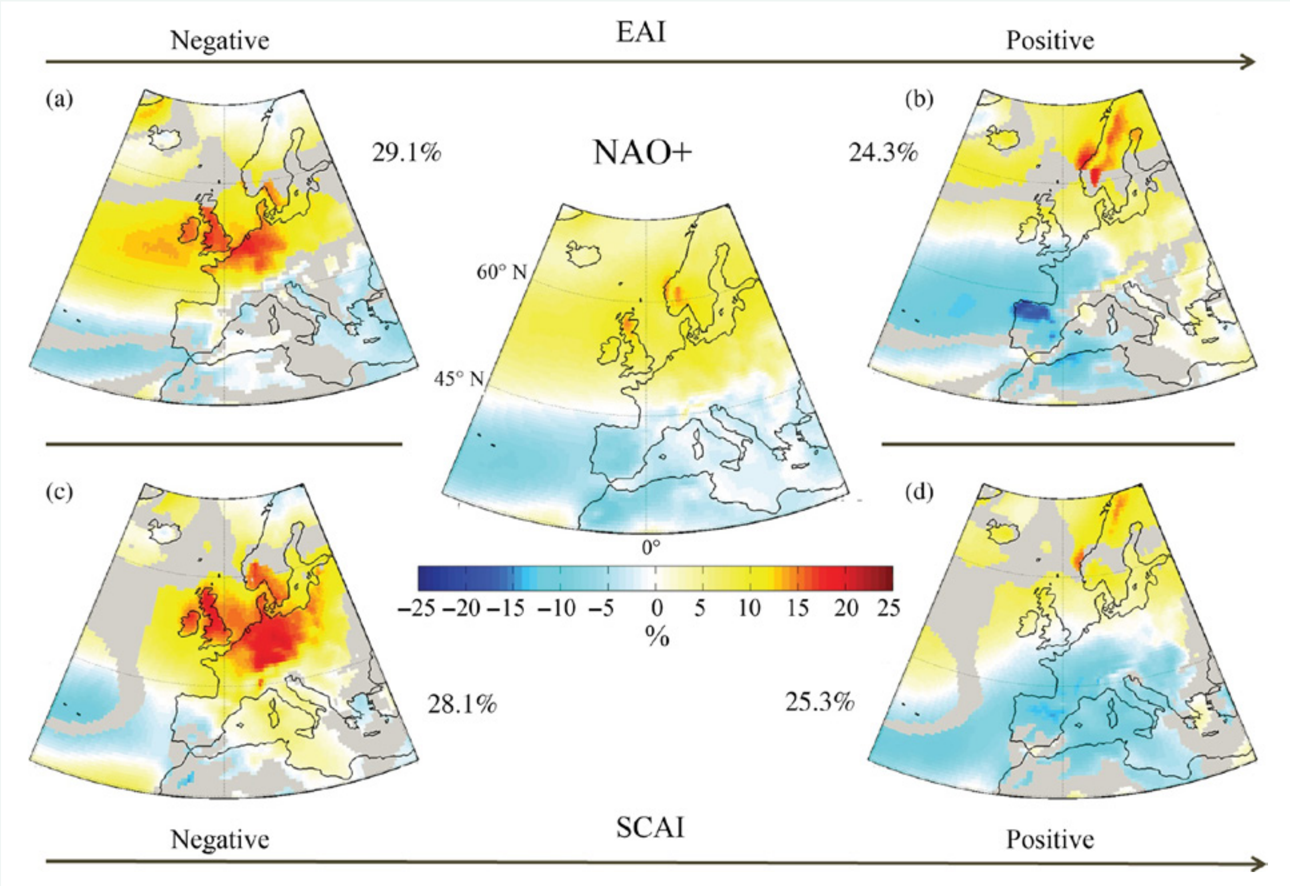

Figure 2.4 Wind speed anomalies for NAO+ winter months (1979–2013) for: NAO+ alone (central figure), (a) NAO+/EA- combined, (b) NAO+/EA+ combined, (c) NAO+/SCA- combined, and (d) NAO+/SCA+ combined. From Zubiate *et al*. (2017).

A recent study by Mellado-Cano *et al*. (2019) demonstrated that the variability of the North Atlantic eddy-driven atmospheric jet stream can be largely described using a combination of the NAO and EA. Their results indicate that winter NAO and EA have significant complementary fingerprints in the North Atlantic jet stream on seasonal time scales extending previous studies based on daily diagnostics (e.g., Woollings *et al*., 2010). They show that the jet speed is more affected by the NAO, with the EA acting on the same direction, while the NAO and EA are of comparable importance but have opposite effects in terms of jet latitude. As such, the largest departures in jet speed (latitude) tend to occur in winters with equal signed (opposite) phases of the NAO and EA.

The strongest positive wind speed anomalies over Ireland are present when the NAO is in a positive phase combined with either a negative EA or negative SCA phase.

Photo credit: Caroline Cusack

The variability of the North Atlantic eddy-driven jet stream can be largely described using a combination of the NAO and EA.

2.3 RECOMMENDATIONS

1. Future research examining modes of atmospheric variability should extend beyond analysis of the NAO alone with an emphasis on connecting to changes in ocean and ecosystem processes.
2. Enhance organisational cooperation between domains e.g. atmosphere, biosphere, oceanic etc. earth system.
3. Ocean initialisation should be included in future analyses due to its importance in predicting particular periods, such as the extreme mid-1990s positive phase of the NAO (missed in uninitialised models).

Significant wave heights off the west coast of Ireland are largest when the NAO is positive and the EA and SCA are both negative.

CHAPTER 3

PHYSICAL OCEANOGRAPHY

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Photo credit: Tomasz Szumski

3.1 NORTH ATLANTIC CIRCULATION

Circulation of the North Atlantic offshore of Ireland is dominated by the subpolar gyre circulation and the Atlantic Meridional Overturning Circulation (Figure 3.1(a)). Closer to the Irish shelf, the European Slope Current delineates the separation between the open Atlantic and the shelf seas, although the path of the Slope Current near Goban Spur is still debated (orange dashed line in Figure 3.1). The shelf seas around Ireland are home to a system of coastal currents (Figure 3.1(b))

3.1.1 NORTH ATLANTIC GYRE CIRCULATION

The North Atlantic consists of two gyres: the subtropical gyre, with warm western branches of the Gulf Stream recirculating through the Azores current, and the subpolar gyre with warm eastern inflow from a branch of the North Atlantic Current and cooler currents through the Iceland, Irminger, and Labrador Seas (Figure 3.1(a)).

A major mode of variability in the subpolar gyre is an expansion of the gyre associated with cool periods, and a contraction of the gyre during warmer periods. Cool periods in the Atlantic are associated with drier summers in northwest Europe and beyond; warmer periods are associated with increased hurricane frequency (Sutton *et al.*, 2018). This was first described by Häkkinen and Rhines (2004) who showed the contraction of the subpolar gyre was co-incident with a rapid warming in the mid-1990s. Satellite-derived indices for subpolar gyre strength show that the subpolar gyre is in a cool, expanded state in recent years, consistent with observed cooling (Hátún and Chafik, 2018).

In the subtropical gyre, an expected change is a poleward expansion of the gyre due to the northward shift of the western boundary current, the Gulf Stream, in response to a poleward shift of the prevailing winds (Yang *et al.*, 2016). Direct observations do not show this clearly, with the Gulf Stream extension showing a broadening rather than a poleward shift (Andres 2016).

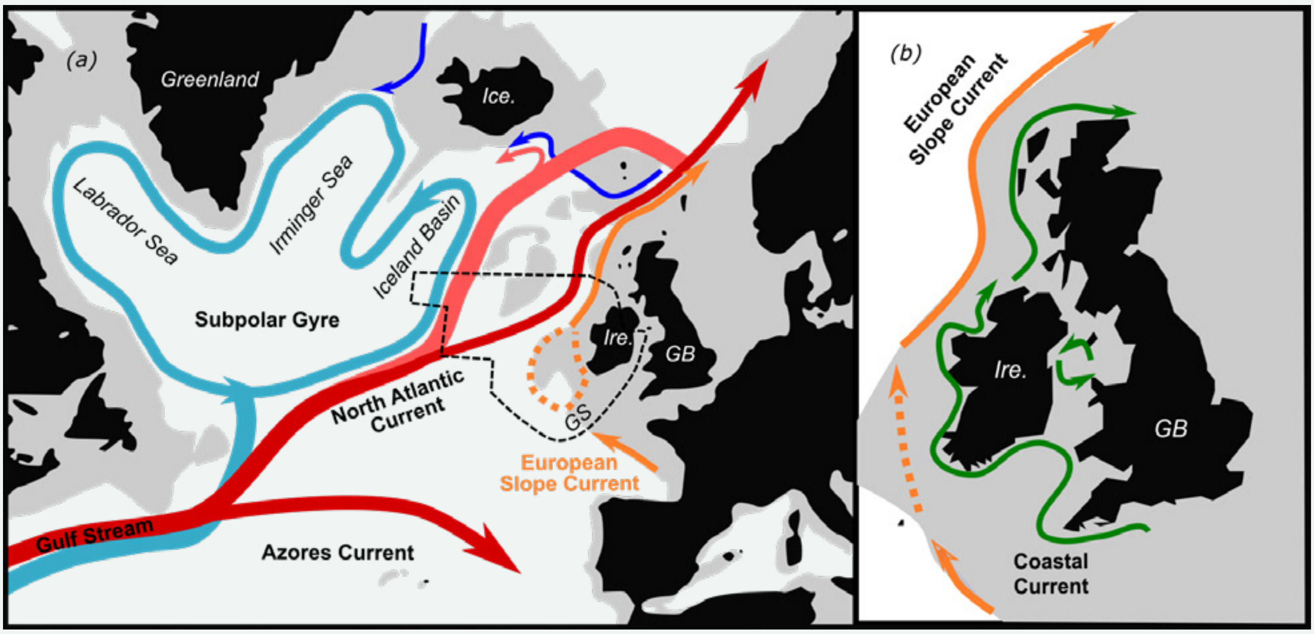


Figure 3.1 (a) Circulation of the North Atlantic showing the main ocean currents (bold text) and geographic features (italics). Warm currents, such as the Gulf Stream and North Atlantic Current, are shown in red. Cold currents, such as those of the subpolar gyre, are shown in blue (b) Slope (orange) and coastal (green) circulation around Britain and Ireland modified from Hill *et al.* (2008). Dashed orange line in (a) denotes the disputed path of the Slope Current near Goban Spur (GS). Dashed black line in (a) denotes the so-called 'Real Map of Ireland'—the limits of Irish waters used for calculations in Figure 3.3 Grey shaded areas indicate the continental shelf (depth < 200 m).

3.1.2 ATLANTIC MERIDIONAL OVERTURNING CIRCULATION

The Atlantic Meridional Overturning Circulation (AMOC) is a system of ocean currents, including the Gulf Stream (the AMOC is sometimes referred to as the Gulf Stream System), which transports warm, shallow water northwards and returns, cold deep water to the south. The AMOC is a major factor in the maintenance of Ireland's mild climate (McCarthy *et al.*, 2015), with Ireland potentially 10°C cooler if the AMOC were to collapse (Jackson *et al.*, 2015). A collapse of the AMOC is not considered a likely scenario (Masson-Delmotte *et al.*, 2021). However, a decline in the 21st century due to anthropogenic climate change is *very likely* (Masson-Delmotte *et al.*, 2021). The trajectory of the AMOC in the 21st century is one of the largest sources of future uncertainty in climate models (Bellomo *et al.*, 2018).

Prior to about the 1980s, AMOC estimates rely on proxy data such as sea surface temperature (SST) or changes in fossilised plankton distribution in marine cores (Figure 3.2, lower three lines). Taken on the centennial timescales, proxy reconstructions indicate that the AMOC is weaker now than it has been in 1000 years, showing two clear points of slowdown: one in the late 19th century and one in the mid-20th century (Caesar *et al.*, 2021). The mid-20th century decline is not simulated by climate models (Menary *et al.*, 2020). The question remains whether the proxies themselves could be in conflict (Kilbourne *et al.*, 2022) or whether the unconstrained climate models are capable of reproducing the observed variability (Bonnet *et al.*, 2021).

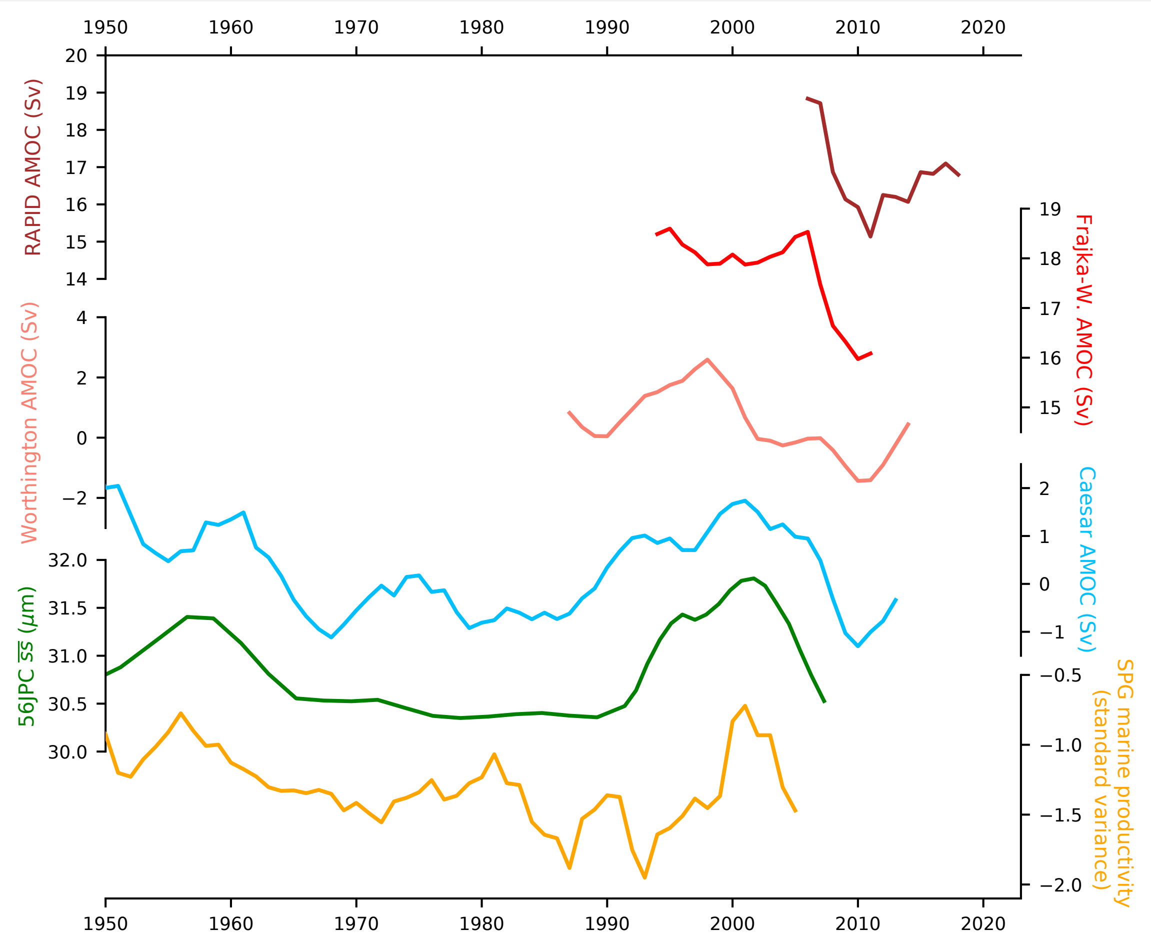


Figure 3.2 Figure taken from (Caesar *et al.*, 2022) showing AMOC evolution since the mid-20th century. The top three lines are AMOC estimates based on high-quality hydrographic or satellite data. The lower three lines are proxy-based data. A mid-20th century decline, centered on 1960 is seen in the proxy data. All proxies show a strengthening of the AMOC through the 1990s and a weakening through to around 2010.

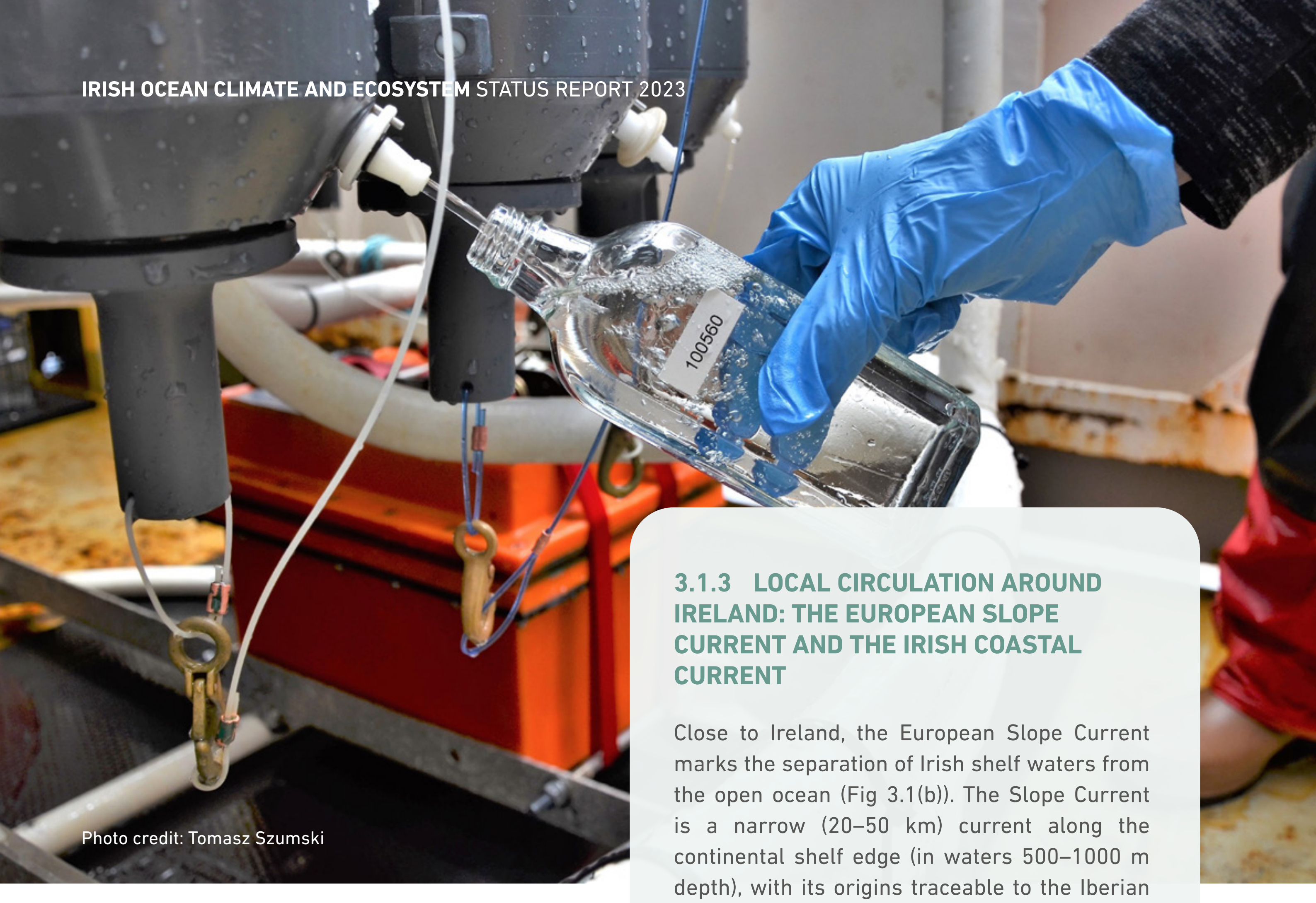


Photo credit: Tomasz Szumski

Reconstructions of the AMOC based on hydrographic data span a shorter time, with the longest reconstruction stretching from the 1980s (Figure 3.2, upper three lines). These show no evidence of a long-term decline in AMOC strength (Worthington *et al*., 2021; Fu *et al*., 2017). Direct observations from modern AMOC observing systems, such as the RAPID project, showed a decline from the mid-2000s but a recovery since around 2010 (Moat *et al*., 2020). None of these observations are necessarily in conflict, given their different timespan but their lack of agreement does show the difficulties in interpreting observed AMOC change.

3.1.3 LOCAL CIRCULATION AROUND IRELAND: THE EUROPEAN SLOPE CURRENT AND THE IRISH COASTAL CURRENT

Close to Ireland, the European Slope Current marks the separation of Irish shelf waters from the open ocean (Fig 3.1(b)). The Slope Current is a narrow (20–50 km) current along the continental shelf edge (in waters 500–1000 m depth), with its origins traceable to the Iberian Peninsula and extending all the way around the European shelf towards Scandinavia. The concept of a single continuous slope current is an oversimplification. For example, there is a known seasonal reversal of the current south of the Goban Spur, that is not replicated farther north (Porter *et al*., 2018). The strength of the Slope Current ranges from 1–2 Sv near Goban Spur up to 5–8 Sv in the Faroe-Shetland Channel (Xu *et al*., 2015) (1Sv=1 million cubic metres per second). The Slope Current has notable seasonality in general, being stronger in winter than summer—a seasonality that is exaggerated to the north, with the strong winter flow being associated with bringing heat and material to higher latitudes (Xu *et al*., 2015). North of the Porcupine Bank, the Slope Current is forced by the wider Atlantic, with a particular role for the North Atlantic Current (Marsh *et al*., 2017). Questions remain about the pathways of the Slope Current southwest of Ireland, with competing pathways suggesting offshore (Moritz *et al*., 2021) and onshore (Xu *et al*., 2015) pathways (Figure 3.1(b)).

Closer to the coast, the Irish coastal current winds its way around Ireland (Figure 3.1(b)). It is influenced by wind, tides, and thermohaline factors, which can each dominate at different times. For example, in a long-term study of the coastal circulation west of Scotland, Jones *et al.* (2018) noted times the longest-term variations were likely of thermohaline origin but that large contrasts existed if easterly or westerly wind forcing was the dominant factor. In summer, warm or salty bottom fronts contribute to a thermohaline driven circulation in addition to the regular tidal mixing factors (Hill *et al.*, 2008). The summertime coastal circulation is important to the transport of harmful algal material around the Irish coast and towards the important aquaculture regions of the southwest coast (Raine, 2014).

Irish waters warmed strongly from the 1980s to the mid-2000s, with the highest annual sea surface temperatures recorded in 2007 at over 0.8°C above the 1960–1990 average. Recent years have seen a cooling trend of over -0.3°C/decade, linked by some to a decline in the AMOC.

3.2 HEAT AND FRESHWATER

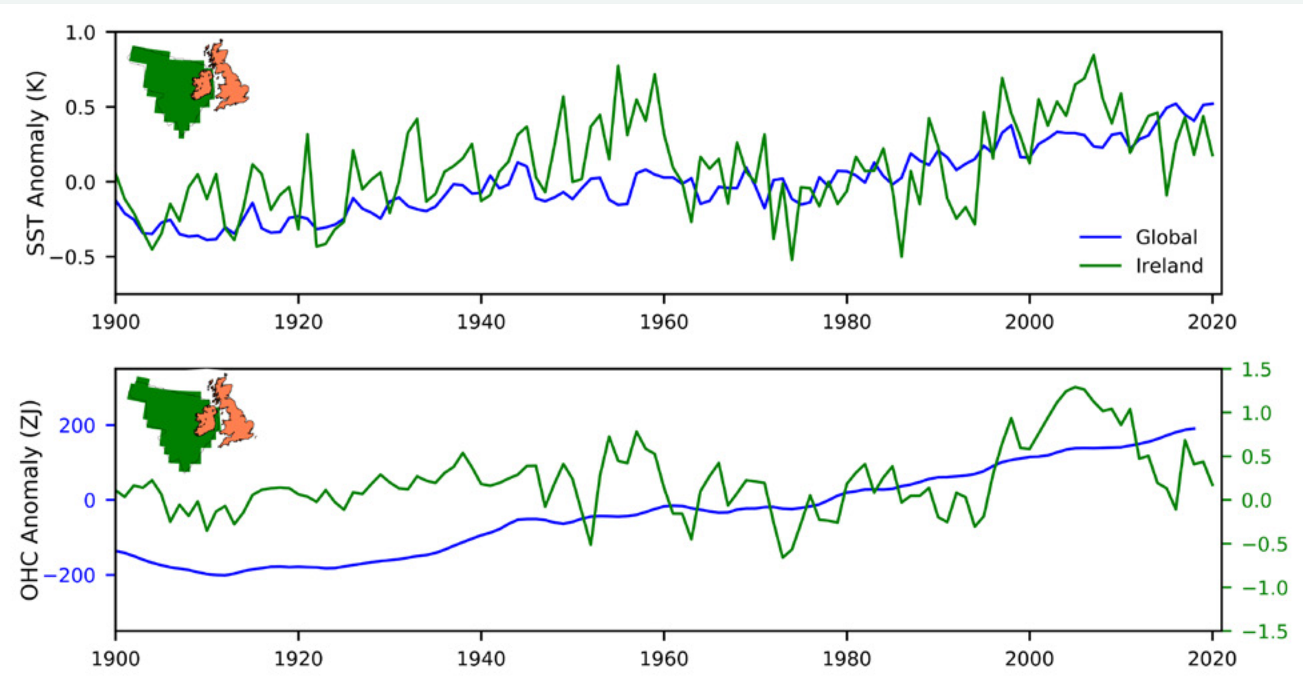


Figure 3.3 (top) Global (blue) and Irish waters (green) sea surface temperature anomaly. (bottom) Global (blue) and Irish waters (green) ocean heat content. Anomalies are calculated relative to the period 1960–1990. Inset hightlights in green the 'Real Map of Ireland'—the limits of Irish waters used here.

3.2.1 SEA SURFACE TEMPERATURE AND OCEAN HEAT CONTENT

Globally sea surface temperature (SST) and ocean heat content (OHC) are rising due to anthropogenic climate change (Masson-Delmotte *et al.*, 2021). In fact, OHC—the sum of the heat energy stored in the ocean—has taken over 90% of the excess heat trapped in the climate system due to anthropogenic climate change (Masson-Delmotte *et al.*, 2021). The same patterns are evident in Irish SST and OHC but with notable periods of deviation from the long-term trend (Figure 3.3). Anomalies are shown relative to the period 1960–1990. Specifically, Irish SST and OHC experienced warm periods from the 1940s to the late 1950s, and from the mid-1990s to the mid-2000s. The highest SSTs in Irish waters occurred in 2007, averaging over 0.8°C warmer than 1960–1990, and the highest heat content occurred in 2005. Cool periods interceded these warm periods. Through the 1970s and 1980s, a cooler period persisted with record low SST anomalies in Irish waters of -0.5°C occurring in 1974 and 1986. This decadal variability is well-known in the North Atlantic, most famously in the Atlantic Multidecadal Variability (AMV)—sometimes referred to as the Atlantic Multidecadal Oscillation. The drivers of AMV are disputed. External (to the ocean) forcing has been cited as dominant through volcanic or anthropogenic forcing (Mann *et al.*, 2020) or through anthropogenic aerosols (Booth *et al.*, 2012). An alternative perspective however, is that AMV is an internal oscillation linked with variations in the AMOC (Zhang *et al.*, 2019).

In recent years, Irish waters have been cooling. Since 2007, SSTs in Irish waters have cooled at a rate of -0.3°C/decade. The Atlantic SST south of Iceland exhibited record low temperatures in 2015. This cold anomaly has been linked with atmospheric heat loss (Josey *et al.*, 2018) or linked to a slowdown in the AMOC that occurred around 2009/10 (Bryden *et al.*, 2020). This cold anomaly had a direct impact on Irish waters with the coolest SST values in the 21^{st} century occurring. Land temperatures in Ireland were also lower than average in 2015 because of the cool ocean—an almost unique record in a year that showed the highest global temperatures on record. Despite this recent cooling, SSTs in Irish waters are 0.4°C warmer in the 21^{st} century, relative to 1960–1990.

The Atlantic Meridional Overturning Circulation (AMOC) or Gulf Stream System is key to Ireland's mild climate but is predicted to decline due to climate change, with some proxies indicating this may already have begun.

Photo credit: Christine Loughlin

3.2.2 SALINITY

Salinity in the ocean is frequently interpreted as an indicator for changes in the global hydrographic cycle with the precept that 'the wet gets wetter and the dry gets drier' translates to ocean salinity as the fresh areas get fresher—regions where precipitation dominates over evaporation—and the salty areas get saltier—regions where evaporation dominates (Masson-Delmotte *et al.*, 2021). In the subpolar gyre however the precipitation-evaporation exchange does not dominate the observed salinity changes. For example, in recent years, the eastern subpolar Atlantic has seen its freshest values in 120 years (Holliday *et al.*, 2020). This freshening was a result of a wind-driven change to ocean circulation where fresh waters from the western subpolar gyre were imported to the eastern basin.

3.2.3 SHELF SEAFLOOR PROPERTIES AND STRATIFICATION

Seafloor temperature and salinity are key quantities for fisheries and benthic ecosystems. Information on how the near seafloor is changing is however limited. A climatology compiled by Berx and Hughes (2009) is shown in Figure 3.4. Distribution of temperature follows a meridional (north-south) gradient with warmer temperatures to the south and colder to the north. Salinity reflects the competing influence of salty Atlantic waters and on shelf freshwater. The climatology of (Berx and Hughes 2009) provides a snapshot of seafloor conditions. Investigations of bottom temperature and salinity west of Ireland using the EN4 (https://www.metoffice.gov.uk/hadobs/en4/) found that cooler and fresher conditions occurred when Atlantic climate indices such as the NAO and AMOC were positive (Johnson *et al.*, 2020). Both studies are limited—temporally in the former study and spatially in the latter study (EN4 is a 1° product).

To address these gaps in our understanding, the NEOClime Product will provide 50-year climatology of temperature and salinity over the last half century (1971–2020), for the northwestern European continental region, encompassing the Celtic Sea, the continental margin west of Ireland and Scotland and the North Sea. NEOClime is co-developed between the Marine Institute and Marine Scotland Science and builds, in scope and

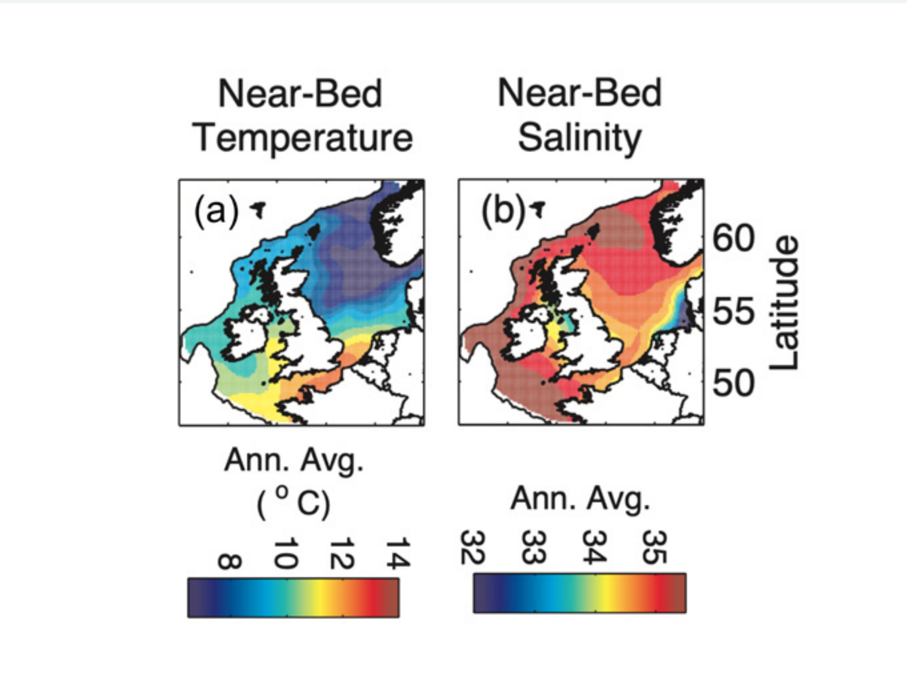


Figure 3.4 (a) Seafloor temperature and (b) salinity from (Berx and Hughes 2009).

methodology, on a previous product by Marine Scotland Science for the ICES standard 30-year climatology of 1971–2000 (Berx and Hughes, 2009).

Shelf stratification is another key quantity for ecosystems. Stratification occurs when less dense water lies above more dense water. Typical seasonal stratification occurs when a surface warmed layer lies on top of deeper, colder water during summer months. This type of stratification is key to ecosystems as it is a barrier to the replenishment of nutrients to the sunlit zone. Factors that act against stratification are tidal and wind-driven mixing. A trend towards earlier stratification has been noted in the European Shelf (Sharples *et al*., 2020), and stronger stratification has been noted in the western Irish Sea (Young and Holt 2007). Future projections are for earlier stratification by one week by the end of the century and stronger stratification. Both of these projections are based on projections of future warming. Where wind-driven factors are important, stratification projections are less confident due to lack of confidence in future wind projections (Sharples *et al*., 2020).

Sea levels continue to rise around Ireland. Larger local sea level rise has been observed in Cork and Dublin, with recent rates of relative sea level rise being twice the global average in Dublin.

3.3 SEA LEVEL

Sea level is a combination of mean sea level (the averaged sea level over a period, typically a month or a year), tides, storm surges, and waves.

3.3.1 MEAN SEA LEVEL

Sea levels around Ireland remained relatively constant from 5000 years ago until the anthropogenic influences began to cause global sea levels to rise in the 20th century (Kopp *et al*., 2016). Rising global temperature impacts sea level through thermosteric expansion of the water column and when land ice (glaciers, ice sheets, etc.) melts. While the former dominated sea level rise through the 20th century, the latter is set to dominate in the coming centuries to millennia (Masson-Delmotte *et al*., 2021).

In Ireland, mean sea level trends are in line with global trends (Cámaro García *et al*., 2021), with a number of important regional caveats. Prior to the early 1990s, observational evidence for sea-level rise is reliant on coastal tide gauge data. Ireland has a historical geographical bias in the location of these gauges, with long-term observations being confined northeast of an axis from Dublin to Malin Head. Sea-level rise from Dublin and Belfast was reported at <1 mm/year prior to the 1990s (Carter 1982; Woodworth *et al*., 1999), not dissimilar for recently revised global rates of rise for the same period (Dangendorf *et al*., 2017). Since the 1990s, satellites have shown increased rates of global mean sea level rise of 3 mm/year (Nerem *et al*., 2018). A comprehensive all-Ireland tide gauge network was established in the 2000s but is shorter than the necessary 40 years (Hogarth *et al*., 2021) for assessing mean sea level trends. Data archaeology (digitisation and observational-based statistical modelling) has successfully supplemented observations. In Cork, Pugh *et al*., (2021) found a 40 cm rise in mean sea level since 1842, equivalent to 2.2 mm/year, larger than would be expected from a combination of regional mean sea level rise and Glacial Isostatic Adjustment alone. A statistical reconstruction of recent trends in Dublin showed double the rates of global rise since 1997 (Shoari Nejad *et al*., 2022). Investigation into the regional differences in rates of sea level rise around Ireland is ongoing work. A new project, Retro, funded by the Marine Institute will contribute to this understanding through data archaeology southwest of the Dublin-Malin axis and offer a better picture of Irish sea level rise.

Local factors that need to be considered to understand Irish mean sea level deviations from regional trends include Glacial Isostatic Adjustment, local land level change, proximity to the Greenland Ice Sheet, and ocean circulation changes. For example, Figure 3.5 shows future projections for Cork from Palmer *et al.* (2018) relative to the global projections. Cork has a lower rate of relative sea-level rise than global estimates, primarily due to Ireland's proximity to the Greenland Ice Sheet. A complexity of the impacts of melting of Greenland Ice Sheet is that locations sufficiently close to Greenland, including Ireland, will experience a relative sea level fall due to the resultant change in the Earth's gravitational field. This relationship means that melting of the Antarctic ice sheet leads to greater than average sea level rise in regions far from Antarctica, including Ireland. Sea level rise in Ireland is projected to be 15–20% higher than global average rates in a scenario of the west Antarctic Ice Sheet alone melting (Mitrovica *et al.*, 2011). And in future scenarios dominated by Antarctic melt, Ireland's sea level rise is greater than the global average.

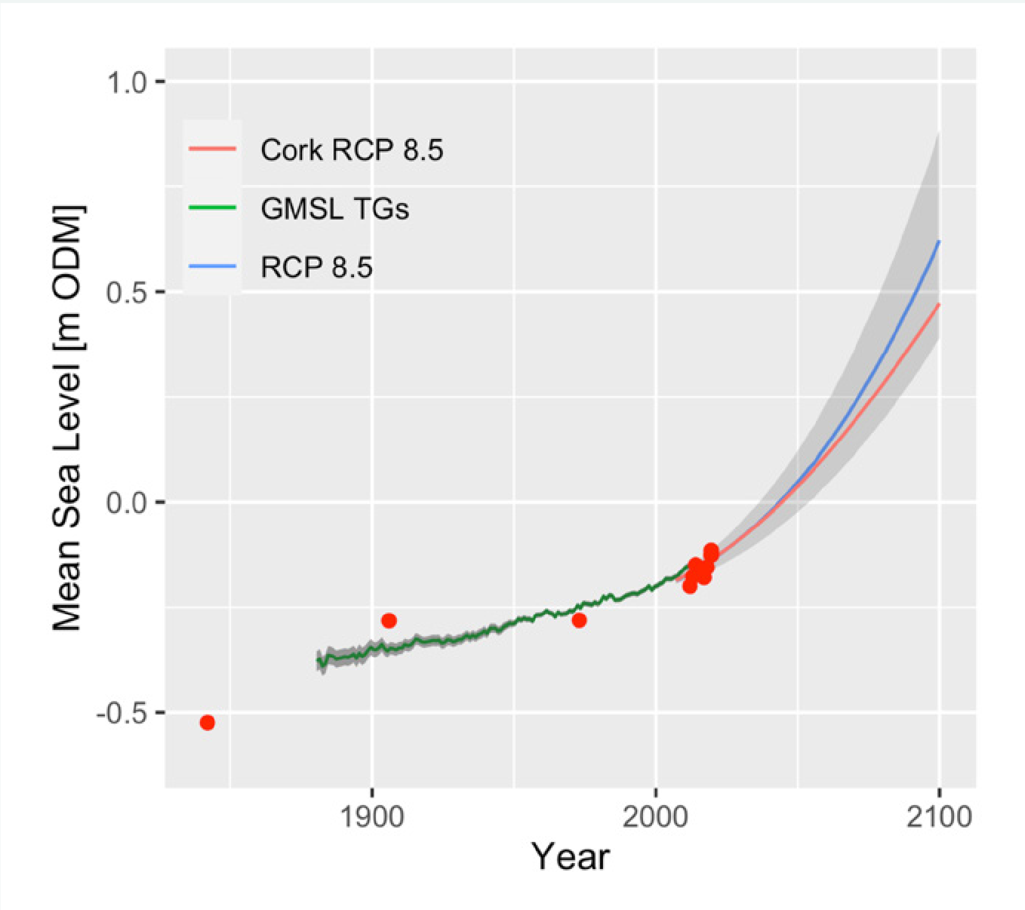


Figure 3.5 Mean sea level estimates from the Cork region from Pugh *et al.* (2021) (red dots) with future projections from UK Climate Projections (Palmer *et al.*, 2018) for Cork (red line). Observed global mean sea level (GMSL) rise through the 20th century (green line) from Church and White (2011) and future projections under RCP8.5 (blue line) from (IPCC 2019).

3.3.2 TIDES

Astronomical tides are driven by the regular transit of the sun and the moon. These drivers are not likely to change on any human timescale. Real tides, however, propagate as shallow water waves and are subject to the changing depth of water. The largest factor in this is modification of channels through dredging. Interest is growing in how sea level rise is potentially changing tides globally (Haigh *et al.*, 2020; Idier *et al.*, 2017) however, studies of tidal change in Ireland have not found changes to tidal parameters (Pugh *et al.*, 2021).

3.3.3 WAVE CLIMATE AND EXTREME SEA LEVELS

Significant variation in wave and wind climate is evident due to complicated geomorphology of the Irish coast (Gallagher *et al.*, 2014). Due to its location in the Northeast Atlantic, Ireland possesses one of the highest wave energy climates in the world (Tiron *et al.*, 2015). Ireland has a long history of large waves, from storm waves to destructive freak waves recorded in a variety of sources (O'Brien *et al.*, 2013).

Studies on future wave climate show an overall decrease in significant wave height around Ireland (Gallagher *et al.*, 2016; Tiron *et al.*, 2015). Tiron *et al.* (2015) compared the 30 year (2031–2060) wave climate projection with a 29 year (1981 to 2009) historical run and revealed annual decreases in both mean significant wave height and storm wave heights for the North Atlantic in general and Ireland in particular, and a decrease of maximum significant wave height in winter. Gallagher *et al.*, (2016) looked at future wave projection and found an overall decrease in annual and mean significant wave height around Ireland with largest decrease in summer.

Strong correlation between the North Atlantic Oscillation (NAO) and wave height, wave period and wave direction was found by Gallagher *et al.* (2014) from a 34 year (1979–2012) wave hindcast performed for Ireland. In addition to this, Gleeson *et al.* (2017) showed a strong correlation (>0.7) between NAO and significant wave height to the west and northwest of Ireland.

Extreme sea levels including waves and storm surges pose an ever-increasing threat to coastal communities due to changing patterns of storminess and rising mean sea levels. The coastal cities of Dublin and Galway have seen notable wave overtopping events in recent years. In February 2002, the coincidence of high astronomical tides and a storm surge led to a wave overtopping event in Clontarf, Co. Dublin when numerous houses and businesses were flooded. Subsequent improvement of flood defences in the Dublin area (Cooke *et al.*, 2005) meant that higher sea levels in 2014 resulted in less flooding and stands as a benchmark for adaptation measures in response to rising seas and extreme sea levels.

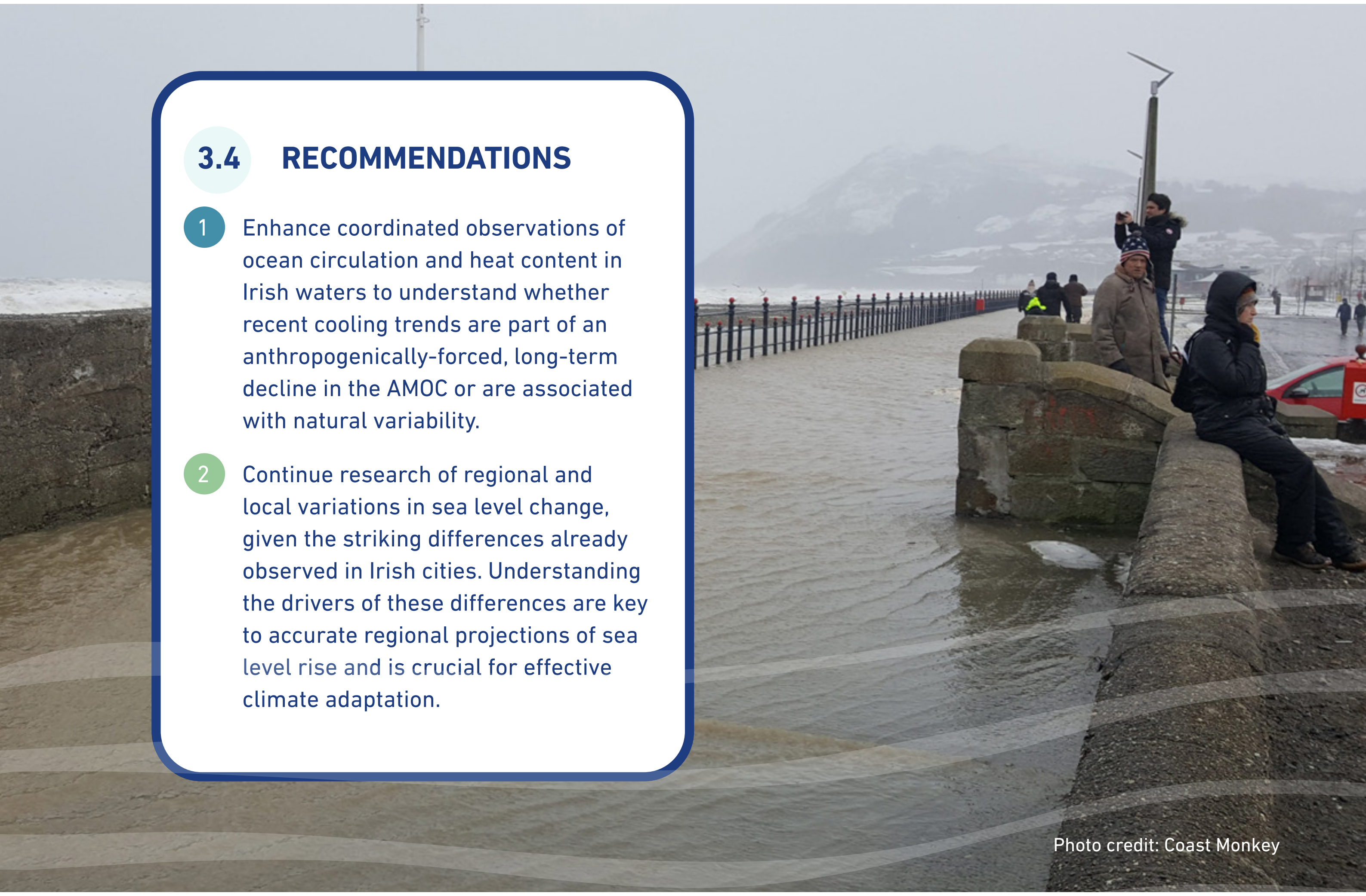
Ireland is vulnerable to changing extreme sea levels due to its location on the edge of the Atlantic, close to the mean position of the North Atlantic storm track. Storminess is closely associated with the NAO, which has been positive (increased storminess) in recent years. Future projections of storminess remain uncertain in climate projections (Masson-Delmotte *et al.*, 2021).


Photo credit: Coast Monkey

3.4 RECOMMENDATIONS

1. Enhance coordinated observations of ocean circulation and heat content in Irish waters to understand whether recent cooling trends are part of an anthropogenically-forced, long-term decline in the AMOC or are associated with natural variability.

2. Continue research of regional and local variations in sea level change, given the striking differences already observed in Irish cities. Understanding the drivers of these differences are key to accurate regional projections of sea level rise and is crucial for effective climate adaptation.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CHAPTER 4

OCEAN CHEMISTRY

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Photo credit: Tomasz Szumski

4.1 INTRODUCTION

Carbon dioxide (CO_2) emissions to the atmosphere have increased inexorably since the industrial revolution, due to fossil fuel combustion, cement production and land-use change. This has resulted in an average global atmospheric partial pressure of CO_2 of ~ 415.7 +/- 0.2 ppm in 2021, which is 149% of preindustrial levels (WMO 2022). Today's atmospheric CO_2 levels would likely be much higher, had the oceans not absorbed about one quarter to one third of the total anthropogenic CO_2 emissions (IPCC, 2019; Bindoff *et al.*, 2019). Increasing carbon dioxide in the Earth's atmosphere results in changes to ocean chemistry, which impact marine life. The uptake of CO_2 in the oceans has caused the ocean to become more acidic due to the increase of protons (H^+ ions) as a result of reactions of CO_2 with the surrounding seawater. This change is measured using the (logarithmic) pH scale and the process is known as ocean acidification (OA).

Carbonate chemistry in off-shore waters west of the Irish shelf has been measured across the southern Rockall Trough since 2009, showing a high variability on both spatial and seasonal scales, but with an overall reduction in pH of ~0.02 units per decade.

Not only is the pH of seawater decreasing with ocean acidification, the carbonate ion concentration (CO_3^{2-}) is decreasing at the same time, which particularly affects calcifying organisms. The two most common forms of calcium carbonate used by calcifying organisms to produce their shells and skeletons are aragonite and calcite. Calcifying organisms such as bivalves and corals will find it particularly difficult to build their protective hard parts when CO_3^{2-} is diminishing. In addition, the ocean depths below which aragonite and calcite tend to dissolve is getting shallower. The aragonite saturation horizon (ASH) has already shoaled by 80–400 m in the North Atlantic since pre-industrial times (Feely *et al.*, 2004; Tanhua *et al.*, 2007) and is projected to rise further from 2600 m to as shallow as 200 m depth by the end of the century (Orr *et al.*, 2005). Benthic deep-sea ecosystems such as cold-water coral reefs that currently live in supersaturated waters with respect to aragonite are projected to be exposed to aragonite undersaturation by the end of the century due to OA (about 70% of known habitats, Guinotte *et al.*, 2006; Zheng and Cao, 2015).

Atmospheric CO_2 concentrations are increasing at a rate 8–15 times faster than anytime during the past 60 million years (Zeebe *et al.*, 2009) and higher than in at least the last 800,000 years as documented from Antarctic ice core records (Petit *et al.*, 1999; Luthi *et al.*, 2008). Projected CO_2 concentrations of these emission scenarios, denoted as 'Representative Concentration Pathways' (RCPs), range from ~420 to over 900 ppm (RCPs 2.6 to 8.5; IPCC, 2019). Model simulations project a further decrease of surface ocean pH of 0.1 – 0.3 pH units to occur by 2100 under different emission scenarios, with a corresponding increase in ocean acidity (IPCC, 2019). Ocean acidification proceeds at a rate probably unprecedented in Earth's history (Honisch *et al.*, 2012; Zeebe, 2012). There is now a UN Sustainable Development Goal for marine acidity – SDG 14.3.1 – Average marine acidity (pH) measured at an agreed suite of representative stations.

As an island situated in the North Atlantic Ocean, Ireland is an ideal site for oceanic and atmospheric baseline monitoring. The North Atlantic is one of the most intense ocean sinks for atmospheric CO_2 in the Northern Hemisphere (Gruber *et al.*, 2002), and is therefore an important area to monitor CO_2 fluxes. Estimates of CO_2 fluxes, however, come with a high uncertainty due to substantial variability in dissolved inorganic carbon concentrations driven by natural oceanic processes and lack of long-term time series observations. Few continuous data are available so far and there are only a few stations for long-term monitoring of biogeochemical properties. In addition to model-based projections, data from field observations (sampling/monitoring) are therefore urgently needed. Ní Longphuirt *et al.* (2010) published a marine foresight report detailing the emerging threat that ocean acidification poses. A baseline for key parameters of the carbonate chemistry and nutrients to identify the current status of the carbonate system and detect future changes in Irish marine waters was established to understand the impacts of ocean acidification on Irish marine ecosystems.

4.1.1 EVOLUTION OF SAMPLING ACTIVITIES

The Marine Institute commenced the Annual Ocean Climate Survey in 2006 collecting samples across the western Irish shelf and the Rockall Trough with the focus on physical oceanography by CTD (conductivity, temperature, depth profiler) environmental data collection (Figure 4.1). This is now carried out annually on the *RV Celtic Explorer* from the Irish shelf west of Ireland (53°N) to Rockall Bank (54°N) to monitor ocean change in the North Atlantic (Figure 4.1).

A series of collaborative projects between University of Galway and the Marine Institute on ocean acidification began with a baseline study from 2008 to 2012 (O'Dowd *et al.*, 2011, McGrath *et al.*, 2012a, b). In 2009, water samples were collected for the first time for ocean chemistry analysis along the Ocean Climate Survey transect including samples for OA analysis.

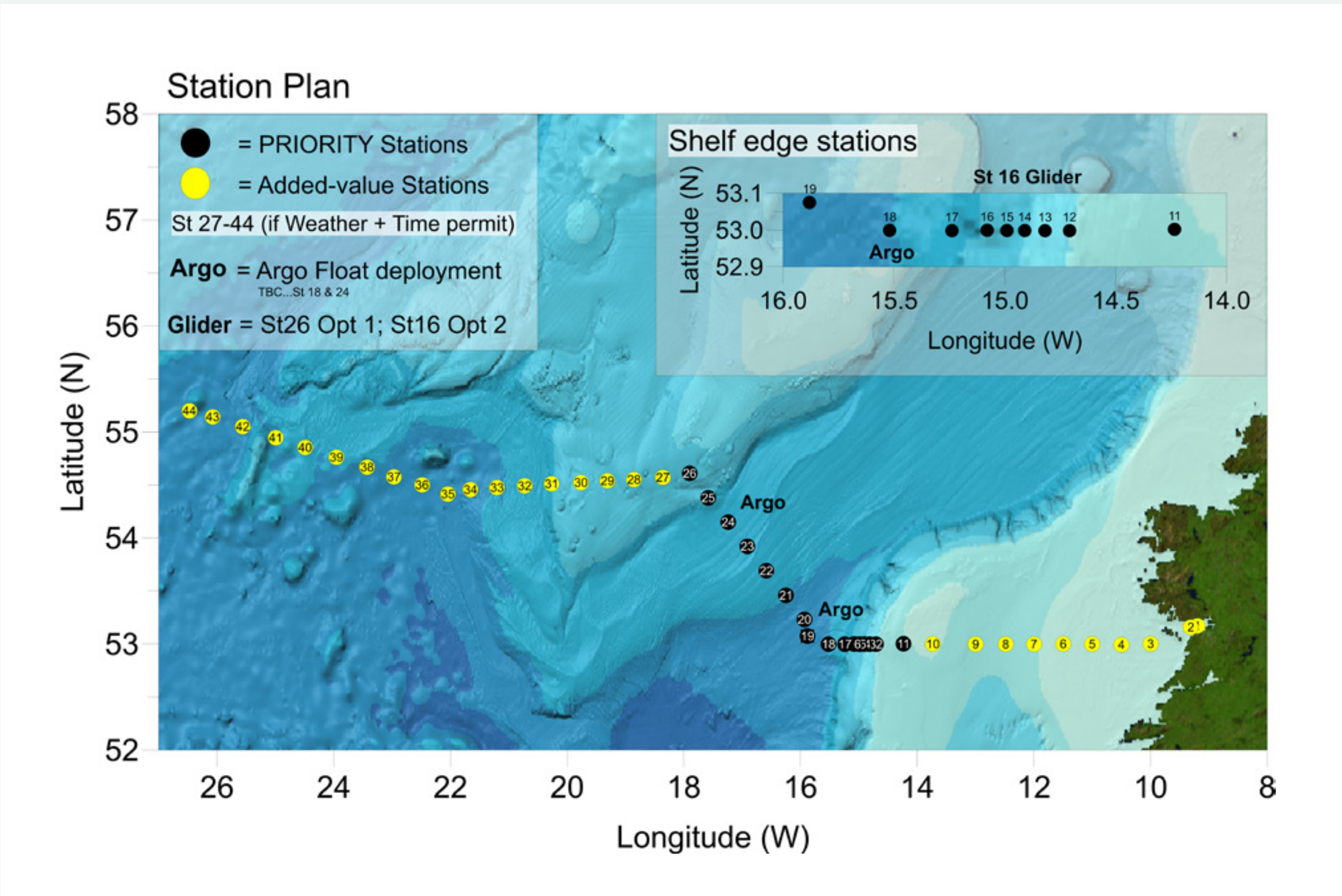

Figure 4.1 Station plan of 'Ocean Climate Survey' carried out near-annually either in winter or summer since 2009, subject to change depending on weather conditions. Map from Marine Institute Ocean Climate Survey cruise reports (Caroline Cusack).

Figure 4.2 shows the evolution of sampling activities since the Ocean Climate Survey commenced. Ocean chemistry parameters measured include total alkalinity (A_T) and dissolved inorganic carbon (C_T) as well as dissolved inorganic nutrients (nitrate, nitrite, phosphate, silicate). The inorganic carbon parameters C_T and A_T enable accurate calculation of other parameters of the carbonate system of seawater, including seawater pH, and the pCO_2, bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) concentrations. On the Irish shelf, water samples for marine chemistry analysis are usually collected at the surface and at the bottom of the water column at each station. In the deeper stations in the Rockall Trough, samples are collected every 200 – 300 m throughout the water column. Other parameters are included for water sampling, for instance, in 2019, chlorofluorocarbon (CFC) samples were added (Figure 4.2). CFC data are used as transient tracers to estimate the age of a water parcel, as concentrations can indicate the time span since the water parcel was last in contact with the atmosphere. Together with other parameters, this gives insights on how quickly deep waters formed in the Arctic regions are reaching the Rockall Trough.

The reduction in pH is also evident in deeper water depths between 1500–2000 m in the Rockall Trough with a similarly strong decreasing trend of 0.03 units in 2010 when compared to data from the WOCE (World Ocean Circulation Experiment) surveys in the 1990s.

The most recent project (VOCAB, 2017–2021) included the collection of samples and data from shelf and nearshore waters as well as underway pCO_2 data in shelf waters (Cave *et al.*, 2019, 2021; Gallagher, 2018; Pérez Anta, 2018; McGrath *et al.*, 2019; McAleer, 2021).

Complementing the off-shore and shelf survey, an annual Winter Environmental Survey on board the RV *Celtic Voyager* is carried out in coastal waters around the entire island of Ireland. It began collecting samples for dissolved inorganic nutrients in 1991 in the Irish Sea as part of the NORSAP project on the RV *Lough Beltra*. This was

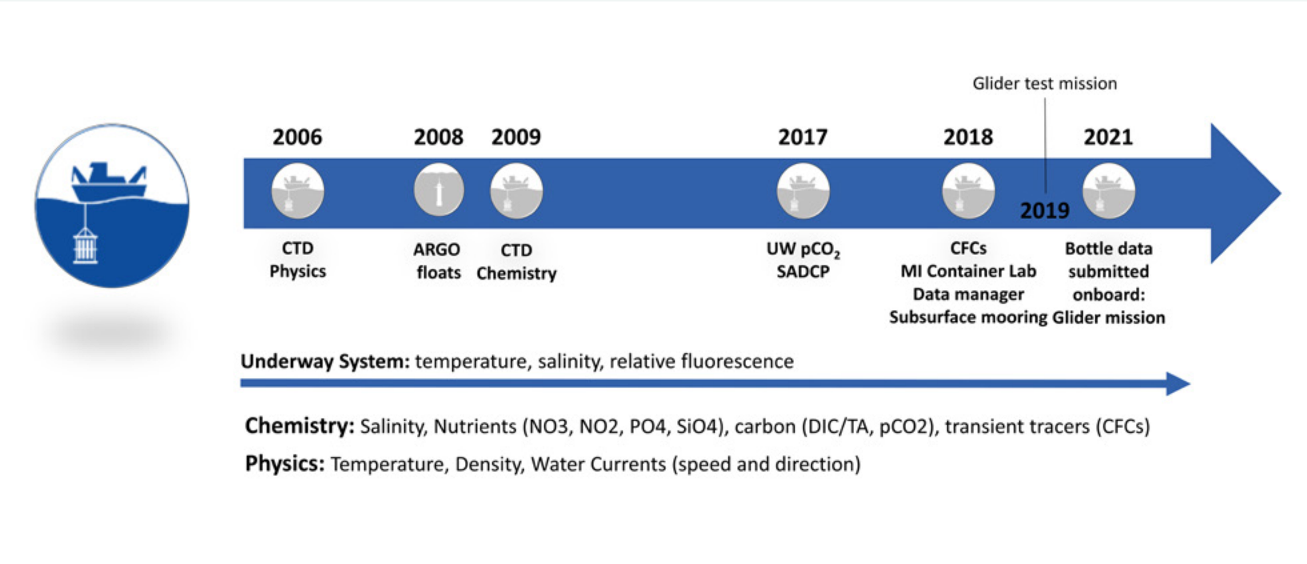

Figure 4.2 Evolution of the Ocean Climate Survey activities since it started in 2006. Graphic from Cruise Report of the Ocean Climate Survey 2021 (CE21003).

Photo credit: Tomasz Szumski

extended over subsequent years and first included OA parameters in 2011. The surveys are in support of international commitments that Ireland has regarding eutrophication and water quality monitoring (e.g. OSPAR Coordinated Environmental Monitoring Programme and European Water Framework and Marine Strategy Framework Directives).

In addition, underway surface ocean and atmospheric pCO_2 measurements began on board the RV *Celtic Explorer* in 2017 as part of the GO-SHIP transect (McGovern *et al.*, 2017, Sloyan *et al.*, 2019, Arruda *et al.*, 2020) and a pCO_2 system on RV *Celtic Voyager* collected seasonal pCO_2 data around Ireland in 2020. The new Irish research vessel *Tom Crean*, commissioned in 2022, will also collect underway pCO_2 data. Irish researchers also collaborated on the UK Shelf Seas Biogeochemistry programme (Hartman *et al.*, 2019), that collected nutrient and carbonate data across the northwest European shelf including the Irish Sea and Celtic Sea over an 18-month period in 2014–15.

4.2 CARBONATE CHEMISTRY

4.2.1 NATURAL VARIABILITY AND TRENDS IN OFF-SHORE WATERS

Anthropogenic CO_2 is not only evident in the surface ocean; resulting increased carbon concentrations in the ocean have also been detected in 2500 m water depth and are believed to have reached at least 5000 m in the North Atlantic (Tanhua *et al.*, 2007). In the Rockall Trough, McGrath *et al.* (2012a) observed an increase in anthropogenic carbon in 2009 and 2010 compared to data from the WOCE (World Ocean Circulation Experiment) surveys in the 1990s. It shows that the pH has not only decreased in subsurface waters (upper ~ 200 – 500 m) in the Rockall Trough by 0.04 units, but also in deeper water depths between 1500 – 2000 m where the Labrador Sea Water (LSW) is usually found, with a similarly strong trend of 0.03 units (Figure 4.3).

The aragonite saturation horizon (ASH), the depth below which undersaturation with respect to aragonite occurs, driving dissolution of shells and skeletons unprotected by organic tissue, has become shallower over the last decade in the Rockall Trough, approaching 2000 m water depth in summer compared to over 2500 m in winter in previous years.

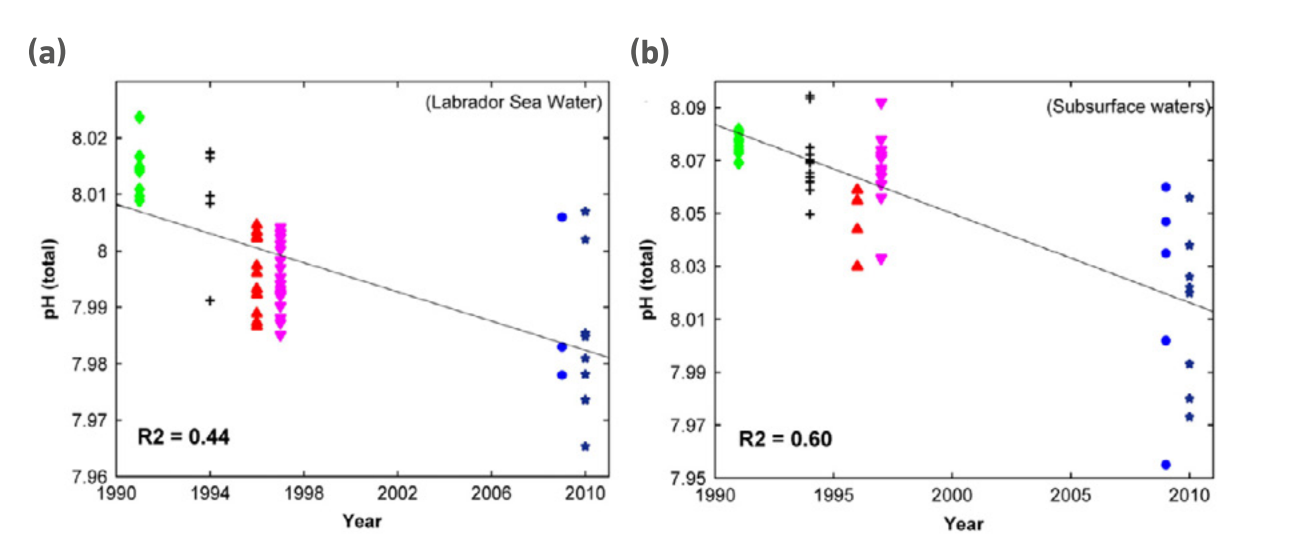

Figure 4.3 pH values calculated using *in situ* dissolved inorganic carbon (C_T) and total alkalinity (A_T) measurements between (a) 1500 and 2000 m (Labrador Sea Water) and (b) subsurface waters (upper 400 m) across different transects of the southern Rockall Trough between 1991 and 2010. From McGrath *et al*. (2012a).

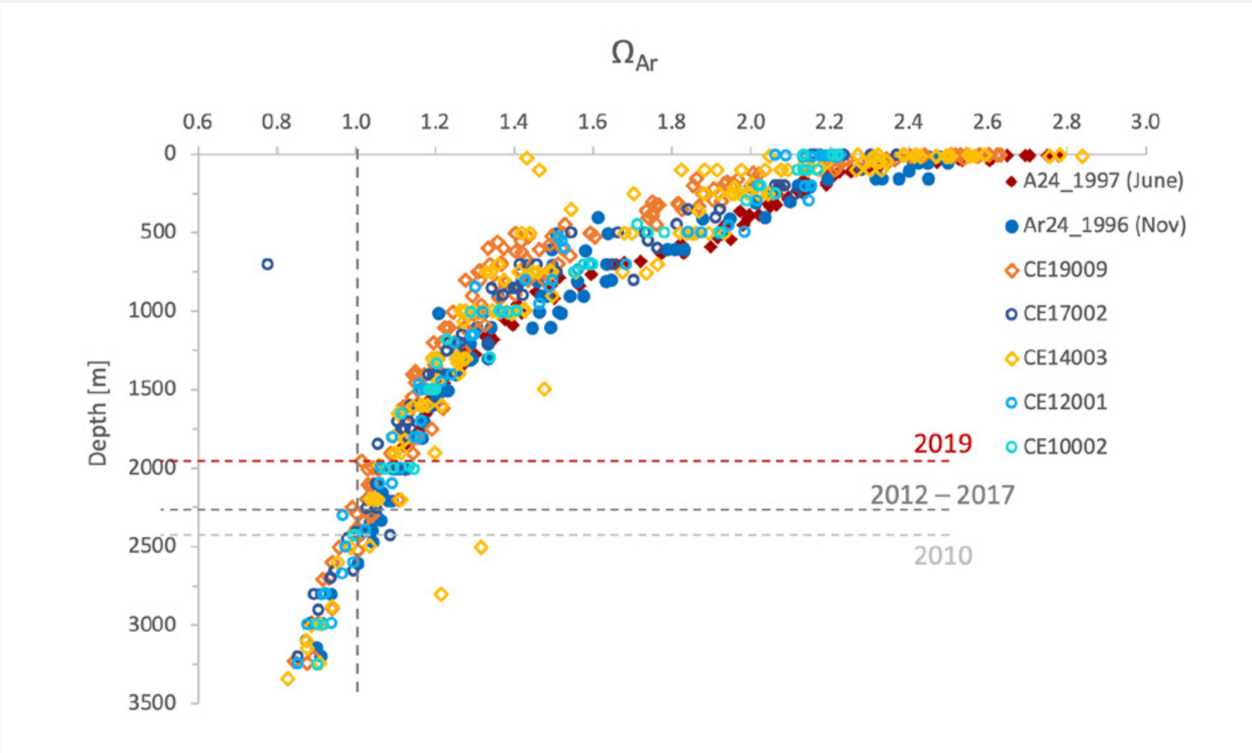

Figure 4.4 Aragonite saturation (Ω_{Ar}) with depth (in metres) from several RV *Celtic Explorer* surveys over the last ten years compared to previous WOCE surveys (summer 1997 and winter 1996). Orange colours indicate summer surveys, winter surveys are blue symbols. The vertical dashed line indicates the Aragonite saturation horizon of Ω_{Ar}=1 and horizontal dashed lines indicate at which depths Ω_{Ar}=1 is apparent first in the data collected during the different surveys (preliminary data).

A study carried out in canyons along the Irish shelf edge (Case Study - Rockall Trough Carbonate Chemistry Intercomparison) shows that cold-water coral ecosystems in canyons at the northern Irish shelf edge experience different carbonate chemistry and nutrient conditions during the same season from those living at the southern shelf edge (Porcupine Bank) in the Rockall Trough. While the southern canyons are influenced by warm, salty and high alkalinity Mediterranean water that enters the Rockall Trough from the south, northern canyons do not see these same signals. Therefore, organisms living in the northern Rockall Trough area may experience conditions close to their tolerance limits sooner than ecosystems in the south, if aragonite saturation states become unfavourable for organisms to grow their calcium carbonate shells (e.g. bivalves) or skeletons (e.g. corals).

Photo credit: Coast Monkey

CASE STUDY

ROCKALL TROUGH CARBONATE CHEMISTRY INTERCOMPARISON

Comparison of the carbonate chemistry, i.e. the total alkalinity, dissolved inorganic carbon, pH, and aragonite saturation (Ω_{Ar}) in canyons north and south of the shelf edge in the eastern Rockall Trough (see map in Figure CS4.1 and data from collected water samples in Figure CS4.2) underlines the potential of ocean chemistry data being used to identify water masses in the ocean as highlighted by McGrath *et al.* (2012a). The influence of Mediterranean water on total alkalinity can clearly be distinguished in the southern canyons with significantly higher values than seen in the northern Rockall Trough (red circle in upper left panel of Figure CS4.2).

The aragonite saturation values at the deepest stations (Figure CS4.2) confirm the observed trend of shoaling of the aragonite saturation horizon (ASH) in the Rockall Trough seen in the data from the Ocean Climate Survey (Figure 4.4). Values close to the ASH (Ω_{Ar}=1) are already found at around 1700 m in the canyons.

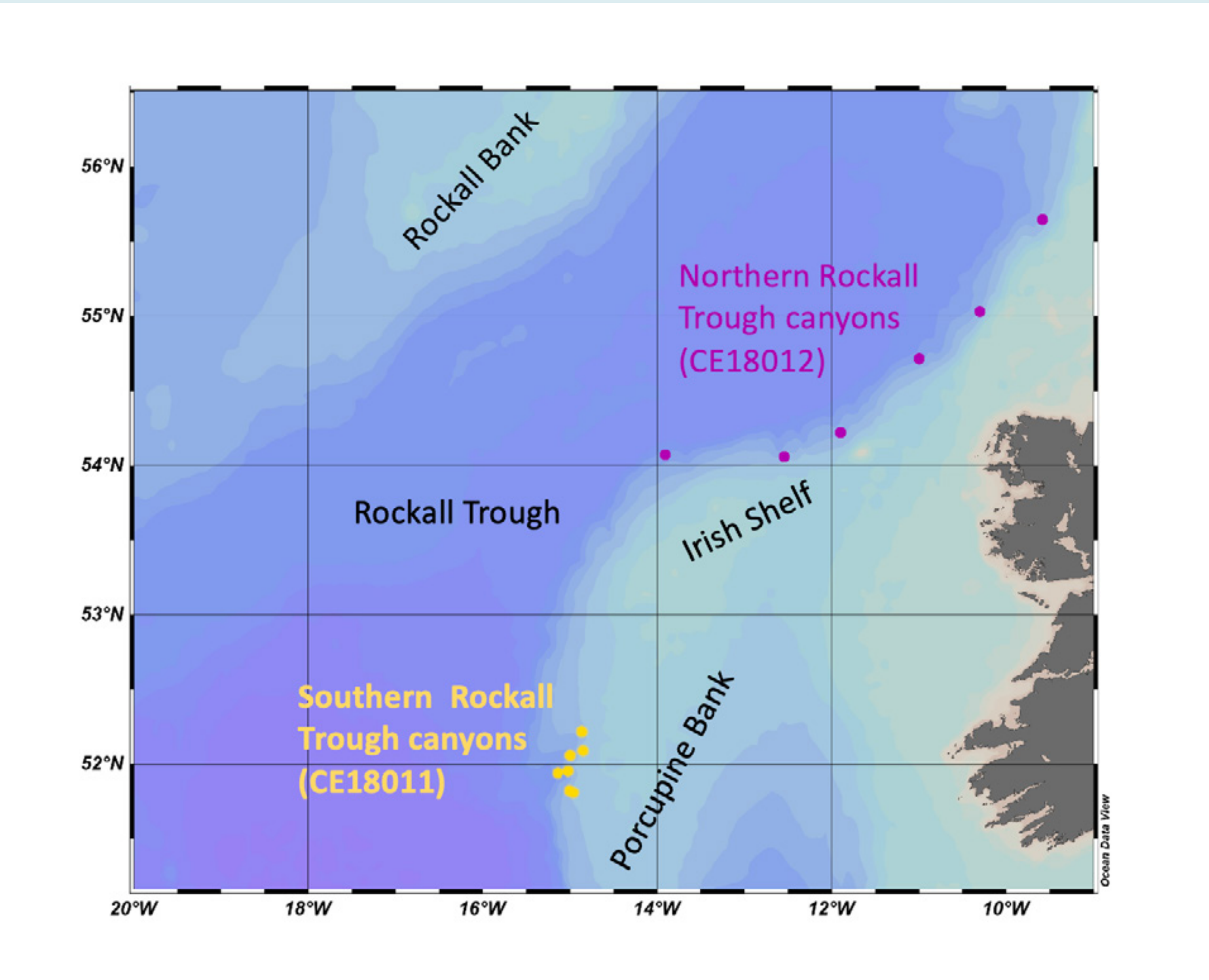

Figure CS4.1 Map of stations along the Irish shelf edge north and south of the Rockall Trough, where water samples were collected in canyons to analyse water chemistry at various depths.

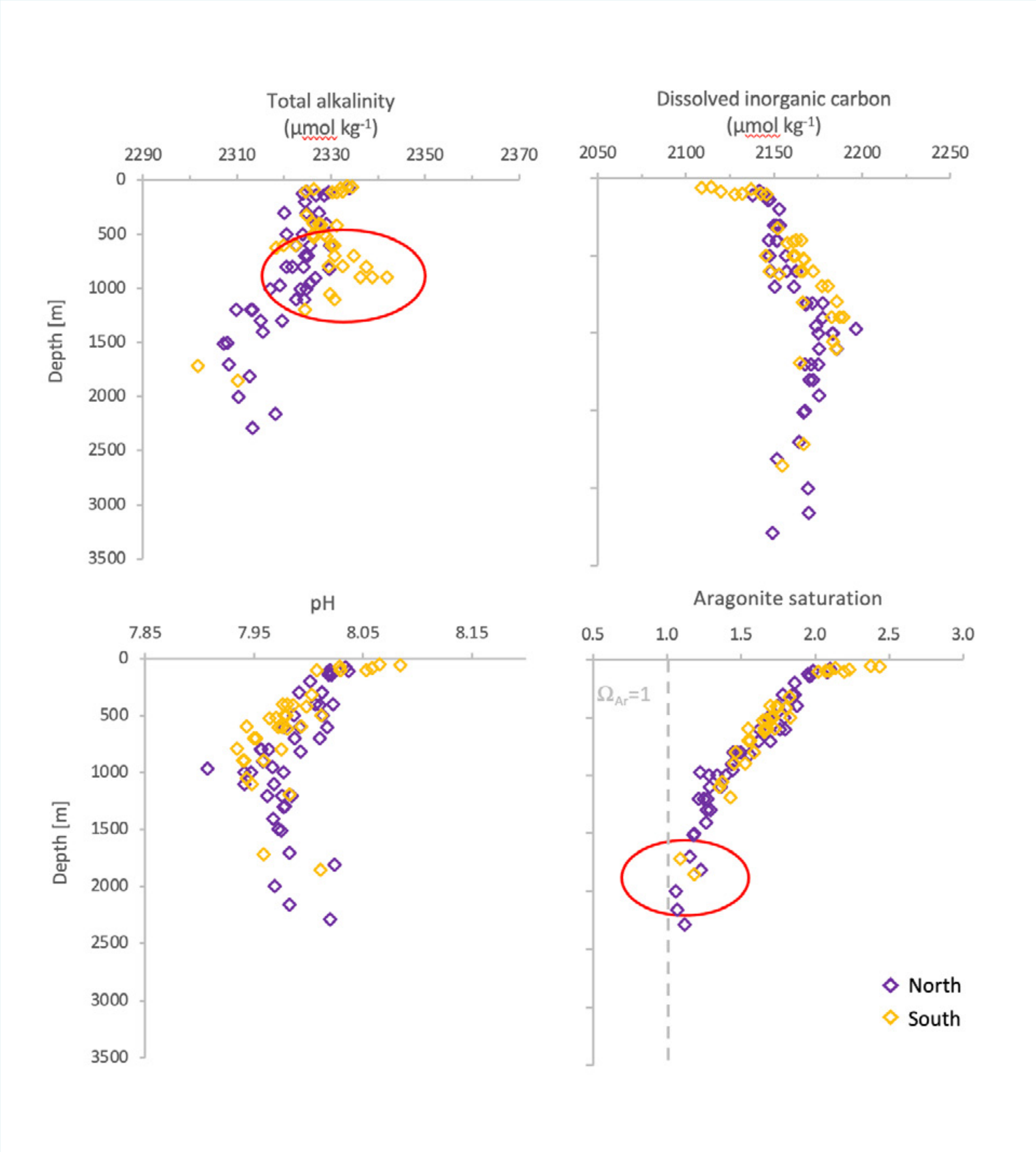

Figure CS4.2 Vertical profiles of the carbonate chemistry parameters total alkalinity (upper left panel), dissolved inorganic carbon (upper right panel), seawater pH (bottom left panel), and aragonite saturation (Ω_{Ar}, bottom right panel) in canyons on the Porcupine Bank at southern entrance of the Rockall Trough (RV *Celtic Explorer* survey CE18011, Figure CS4.1) and along the northern flank of the Irish Shelf in the Rockall Trough (RV *Celtic Explorer* survey CE18012, Figure CS4.1). Data are part of a study that is being prepared for publication.

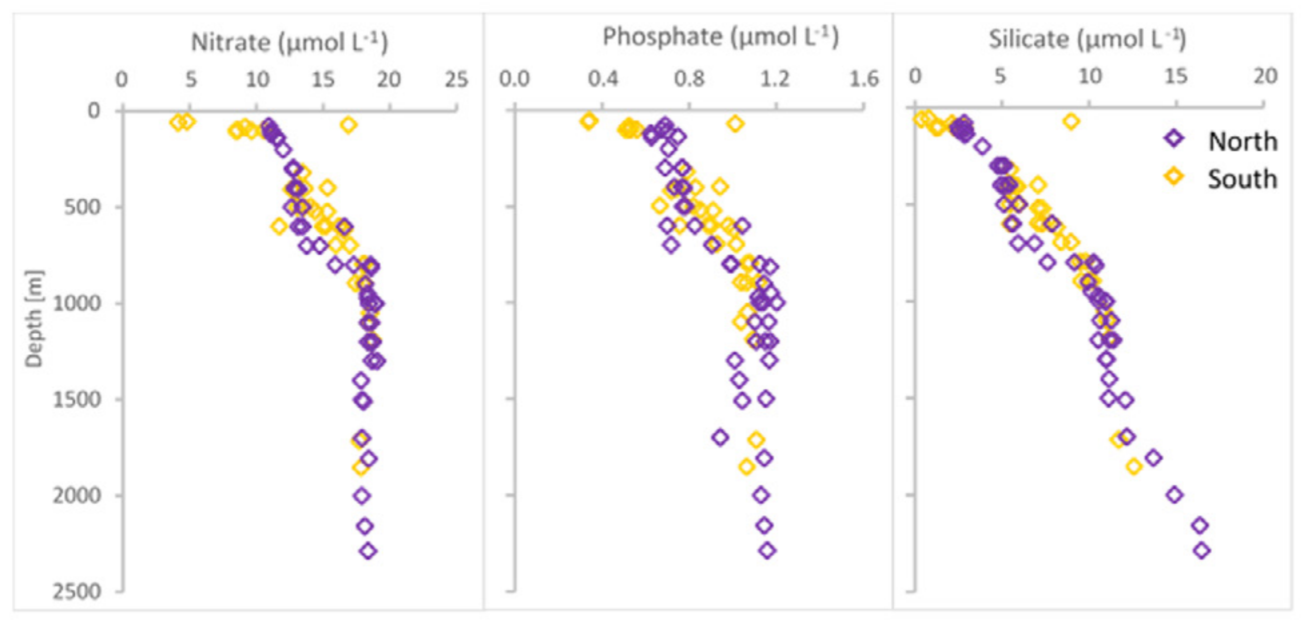

Figure CS4.3 Vertical profiles of the dissolved inorganic nutrients, nitrate (analysed as total oxidised nitrogen), phosphate and silicate in µmol L^{-1} through the water column in canyons north and south along the Irish shelf edge in the Rockall Trough west of Ireland. Data are part of a study that is being prepared for publication (Büscher *et al.*, In Prep).

Dissolved inorganic nutrients can be indicative of water masses in addition to physical properties and carbonate chemistry (compare McGrath *et al.*, 2012b). In this case study we see higher nitrate concentrations and other nutrients associated with the influence of Mediterranean water in the southern canyons (yellow) between 500 and 900 m, which is not seen in the northern canyons (purple) (Figure CS4.3).

In some estuarine and near-shore waters with freshwater inputs, organisms may feel the effects of acidification earlier than in others that are better buffered due to underlying catchment geology.

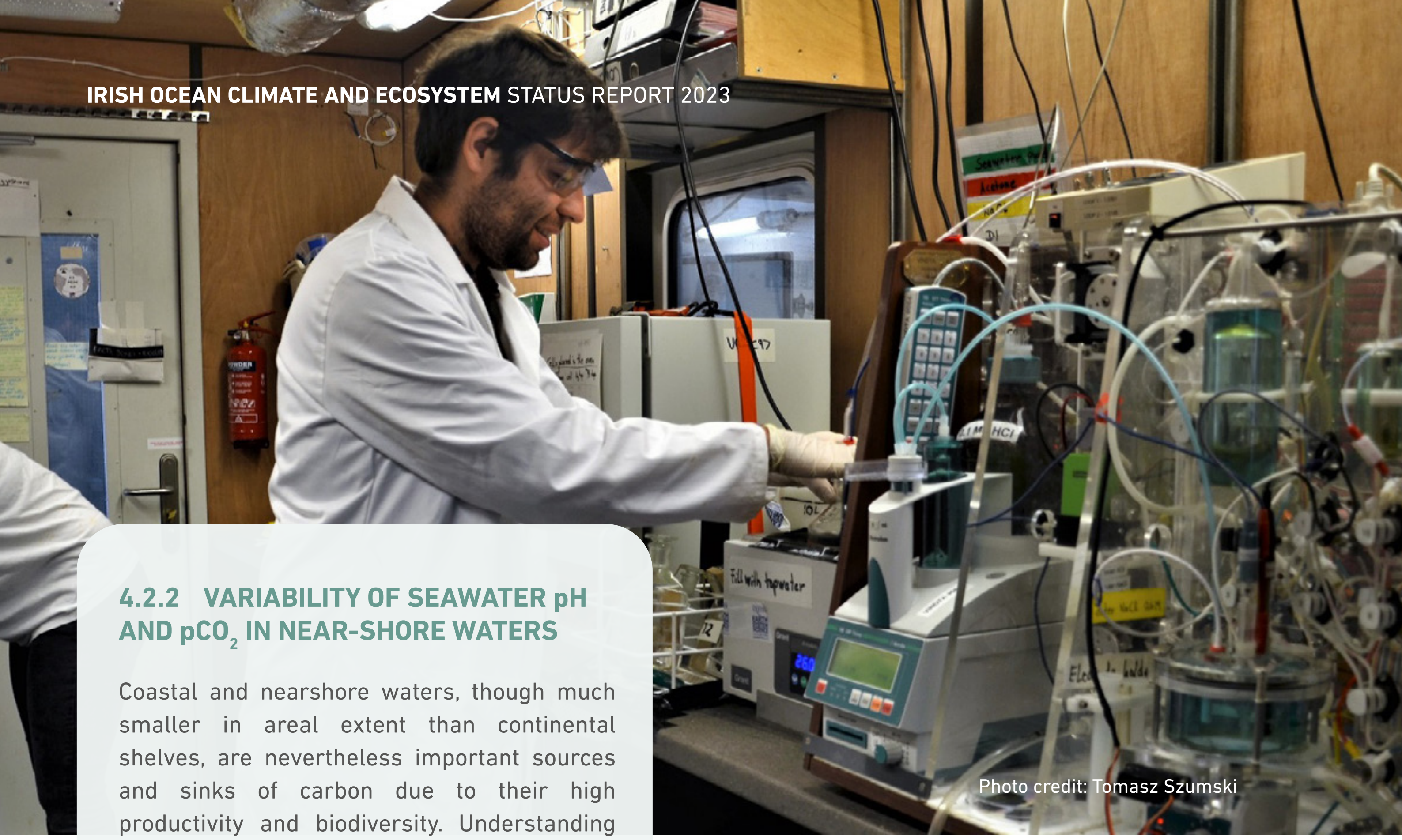

Photo credit: Tomasz Szumski

4.2.2 VARIABILITY OF SEAWATER pH AND pCO_2 IN NEAR-SHORE WATERS

Coastal and nearshore waters, though much smaller in areal extent than continental shelves, are nevertheless important sources and sinks of carbon due to their high productivity and biodiversity. Understanding the effects of ocean acidification in these areas is of high importance, since coastal waters are nurseries for many commercial fish and shellfish species, and host aquaculture. Moreover, coastal waters are susceptible to land-based activities, as variable inputs of nutrients and organic matter are discharged to coastal waters from human activities.

The natural variability of primary production and recycling of organic material in coastal waters, the variable land-based inputs, and seasonal changes in water temperature, together drive the local uptake and release of CO_2. A further source is the oxidation of methane from shallow sediment sources (e.g. Jordan *et al.*, 2019). The CO_2 itself leads to a reduction in the pH of the seawater due to the release of protons during the reaction by which also the proportion of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) is altered. In addition, pH affects the reactions of many other substances in seawater including nutrients and trace metals, which all influence the organisms living in the sea. Therefore, changes in the carbonate chemistry affects many biological processes, so pH changes have knock-on effects across whole ecosystems, particularly in coastal areas.

4.2.2.1 pH measurements in Irish coastal waters

Nearshore waters are much more complex and variable than the open shelf, and each bay and estuary has different physical, chemical, geological and biological characteristics. High frequency (every 15 minutes) *in situ* measurements of pH have been made over periods of months in selected coastal waters largely unaffected by freshwater input to establish both the diurnal and seasonal variability of pH in inshore waters (Cave *et al.*, 2019, 2021 and unpublished data). Sampling was carried out in several contrasting bays and estuaries to establish the variability in carbonate parameters (McGrath *et al.*, 2016, 2019). Key findings in respect of ocean acidification in Irish coastal waters are outlined below.

The underlying geology of Irish bays and river catchments has a profound effect on the carbonate chemistry of rivers and groundwater (Bloomfield, 2018), and a knock-on effect on the aragonite saturation and the pH of estuarine waters and coastal embayments (McGrath *et al.*, 2016, 2019). Lowering pH tends to lead to an increase in the concentration of dissolved trace metals, stimulating a response from both phytoplankton (e.g. Kim *et al.*, 2016) and seaweeds (e.g. Murray *et al.*, 2013). In some cases, this may be beneficial, in others it will cause toxicity. In some Irish coastal waters, which have underlying volcanic or sandstone geology (promoting acidity) and where the limited river input has low pH, such as Bantry Bay, organisms may feel the effects of ocean acidification earlier than in other coastal areas, that are better buffered. Aragonite saturation varies seasonally and is lowest in all the bays in winter (Ω_{Ar}=1.6 to 1.9, highest in Waterford harbour due to high calcium inputs from the river Suir) (Figure 4.5). Wexford has by far the highest spring and summer saturation, (Ω_{Ar} > 4.5 in summer), driven by high primary productivity, with Waterford and Bantry being lower and similar to each other, but higher than Kinvara. The bays with limestone catchments (Kinvara and Waterford) are a source of CO_2 to the atmosphere year-round, despite the effects of primary production, whereas the non-limestone areas (Bantry and Wexford) are a CO_2 sink in spring and summer (after McGrath *et al.*, 2019). The boxes in the map in Figure 4.5 indicate the degree of high aragonite saturation (High), medium (Med), or low in aragonite (Low) in the different meteorological seasons in different areas around Ireland. Research indicates that some shellfish species grown in low-pH waters may confer resilience to low pH onto their offspring (Lim *et al.*, 2021). Commercial shellfish growers should consider the acidification status of the waters where they source their seed from.

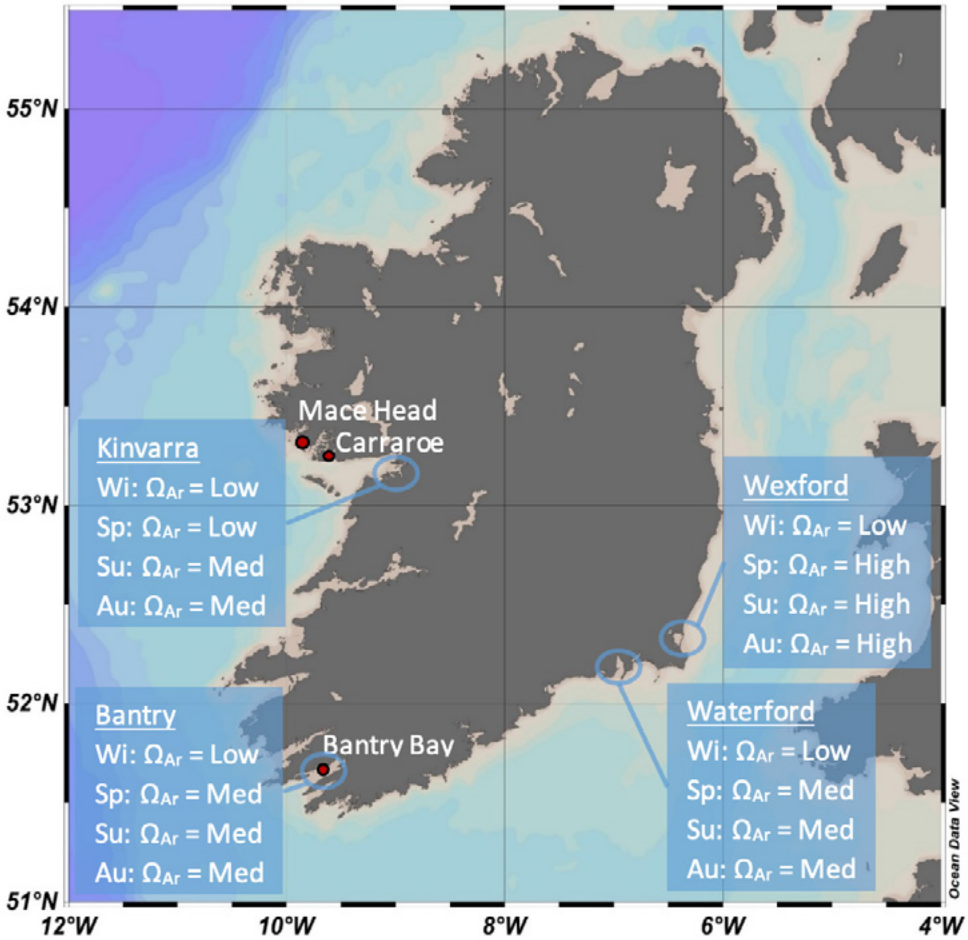

Figure 4.5 Levels of aragonite saturation (Ω_{Ar}=High, Med (medium) and Low) at environmentally contrasting coastal areas around Ireland during the four meteorological seasons: Winter (December to February, Wi), Spring (March to May, Sp), Summer (June to August, Su), Autumn (September to November, Au).

The measured long-term rate of pH decline in the open ocean is of the order of 0.02 pH units per decade, such as found in Irish offshore surface waters of the Rockall Trough (McGrath *et al.*, 2012a). In contrast, pH in productive coastal ecosystem habitats where macroalgae flourish, varies as much as 0.2 pH units over a 24-hour cycle (Cave *et al.*, 2019 and unpublished data). This is ten times the variability on a daily basis than the decadal change in the open ocean. For example, kelp beds at Carraroe drive a clear local diurnal signal in pH, with photosynthesis driving it up and respiration driving it down, whereas Bantry pH is lower overall and influenced by more variable photosynthesis, with respiration and decomposition of faecal material from shellfish aquaculture (Figure 4.6). These sites were chosen for their limited salinity variation (which would affect pH) as both are away from freshwater influence (Cave *et al.*, unpublished). It is clear therefore that organisms in some coastal water habitats are acclimatised to a much wider pH range than others.

In estuarine waters, the daily interaction between river and seawater, and the effects of spring and neap tides and seasonal increases in river discharge, may combine to give highly variable pH. Our ability to perceive any long-term trend in pH in such waters as well as long-term effects of pH shifts beyond natural variability on organisms living in such waters is obscured by this natural variability and it may be necessary to use sentinel organisms, ideally in near-pristine waters, to warn us if low pH is becoming a threat.

4.2.2.2 Sources and sinks of CO_2 in coastal waters

Shelf seas have an important role in the global carbon cycle, disproportionate to their areal extent (Cai *et al.*, 2006; Chen *et al.*, 2009). The Northwest European Shelf Seas (NWES) are seasonally and spatially heterogeneous in both carbonate chemistry and nutrient biogeochemistry (Hartman *et al.*, 2019). This NWES region absorbs between ~ 14.4 – 39.6 Tg carbon (1 Tg=10^6 metric tonnes) from the atmosphere annually, but off-shelf transport and shelf burial are poorly constrained (Legge *et al.*, 2020). Kitidis *et al.* (2019) reported a net influx of atmospheric CO_2 of 26.2 ± 4.7 Tg C yr^{-1} in 2015 dominated by winter influx due to strong winds. Burial was estimated as a small carbon sink (1.3 ± 3.1 Tg C yr^{-1}) and the majority of riverine C-inputs were removed by estuarine CO_2 discharge. Acidification and temperature changes are likely to impact on future shelf carbon stocks. Partial pressure of CO_2 (pCO_2) data can be collected either from fixed stations in coastal areas e.g. Case Study - Mace Head Pilot Oceanographic Observatory, or from ship-based underway systems.

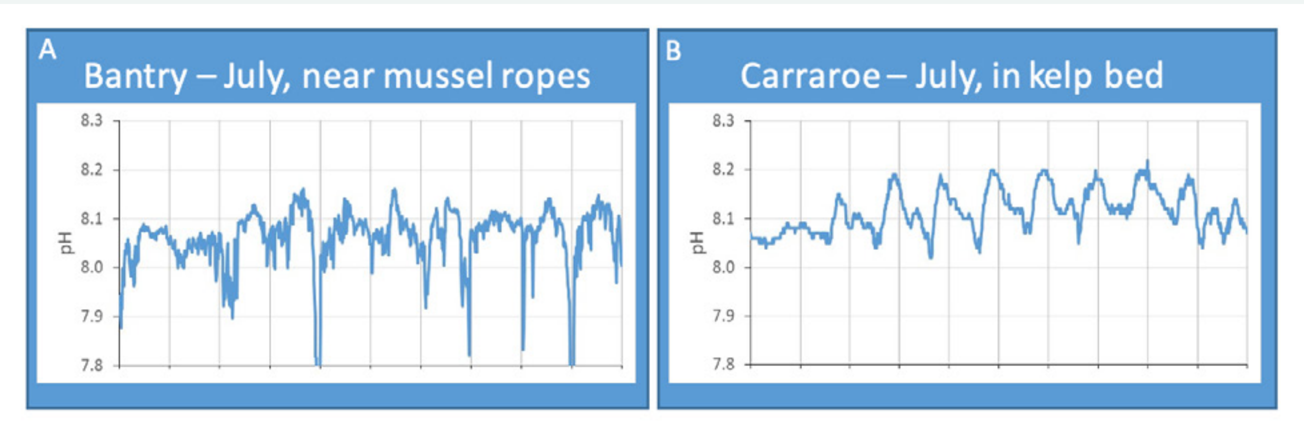

Figure 4.6 High resolution *in situ* pH measurements (every 15 minutes) in seawater in summer in (a) Bantry Bay, Co. Kerry and (b) Carraroe, Co. Galway **over 10 days in summer.** Each vertical grid line represents 24 hours.

High frequency pCO_2 data are routinely collected since 2017 on surveys by the RV *Celtic Explorer* using an autonomous underway pCO_2 measuring system, quality checked and reported to the Surface Ocean Carbon Atlas (SOCAT, www.socat.info), a widely used dataset in regional and climate research (Bakker *et al*., 2016), as are pCO_2 data by UK research vessels in Irish and UK waters. The RV *Celtic Voyager* collected pCO_2 data gathered by autonomous underway pCO_2 measurements throughout 2020, allowing the first delineation of source and sink areas in coastal waters around Ireland at different seasons (McAleer, 2021). These data will be submitted to SOCAT for its next iteration. The areas as shown in Figure 4.7, north (a), east (b), south (c), and west (d) of Ireland, were chosen according to their different environmental influences, with area A encompassing the Malin – Hebrides shelf; area B semi-enclosed Irish Sea, area C enclosing the Celtic Sea and area D with the strongest influence from the North Atlantic and the River Shannon. Net fluxes of CO_2 were calculated for the four meteorological Irish seasons as depicted (Figure 4.7).

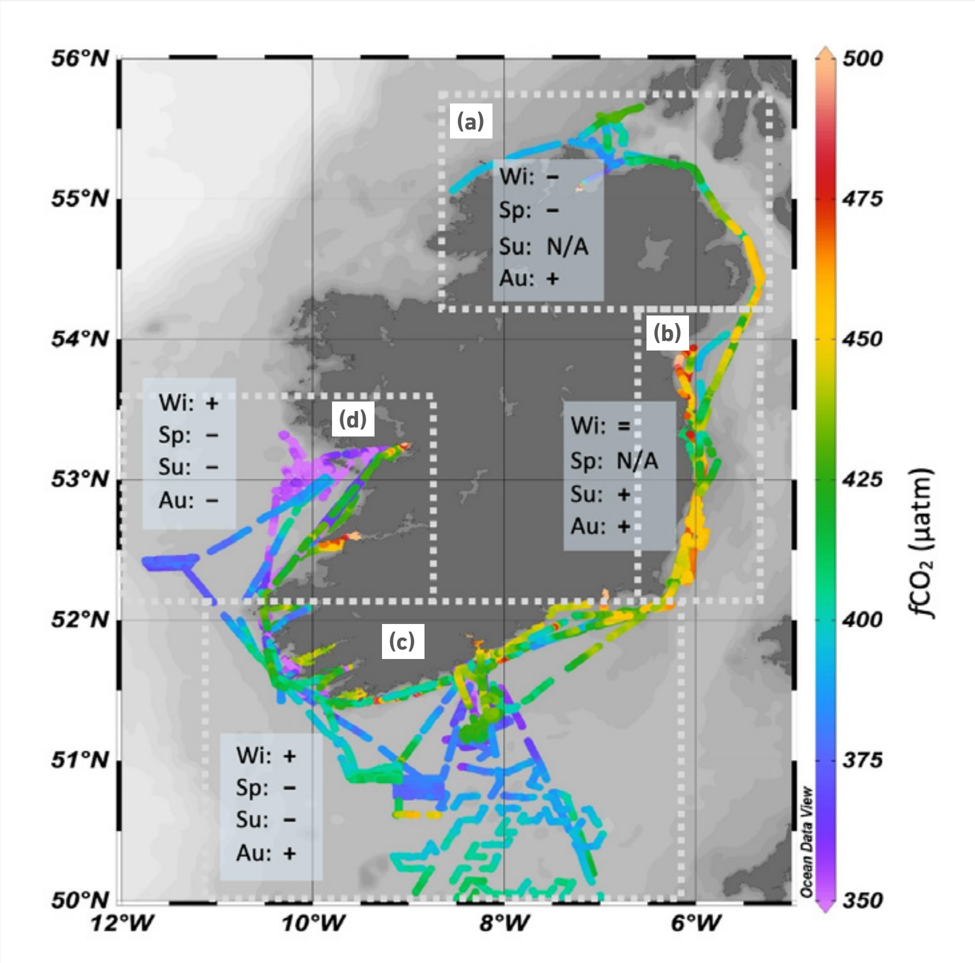

Figure 4.7 Map of the cruise track of the RV *Celtic Voyager* in 2020 during which pCO_2 data from the autonomous underway pCO_2 system installed on board were recorded. The colour code indicates the surface seawater pCO_2 levels represented as fCO_2 (which is the pCO_2 corrected for non-ideal behaviour of CO_2 gas, compare Bakker *et al*., 2016; www.socat.info) in µatm. For calculations, Irish coastal areas were subdivided in north (a), east (b), south (c) and west (d) coasts and information in the boxes indicate whether waters close to the coast were a net CO_2 source (+), sink (-) or at equilibrium (=) to the atmosphere in Winter (Wi), Spring (Sp), Summer (Su) or Autumn (Au). N/A denotes no data available for this season in the area. Data in this study were mostly gathered close to the coast on passage legs between ports. Modified from McAleer, 2021.

Measuring pCO_2 in surface waters from underway systems, which sample every few minutes, gives a first order view of whether a given area of the shelf is acting as a source or a sink at the time of measurement. Sampling for total alkalinity (TA), dissolved inorganic carbon (DIC), dissolved oxygen (DO), nutrients and chlorophyll in sub-surface waters at different seasons allows us to calculate the autotrophic/heterotrophic status of these waters at different depths and to integrate throughout the water column to establish whether the shelf area is a net source or sink at different seasons. Such data can improve the parameterisation of carbon in global carbon budgets (e.g. Borges *et al*., 2005; Ward *et al*., 2020).

Waters to the west and north of Ireland mostly appear to act as a sink of CO_2 across all seasons based on observations of pCO_2 from 2017 to 2020 on *RV Celtic Explorer* (Figure 4.8). In contrast, the Celtic Sea appears to act as a source of CO_2 to the atmosphere in autumn and winter, similar to observations in McAleer (2021) from the *RV Celtic Voyager* underway system.

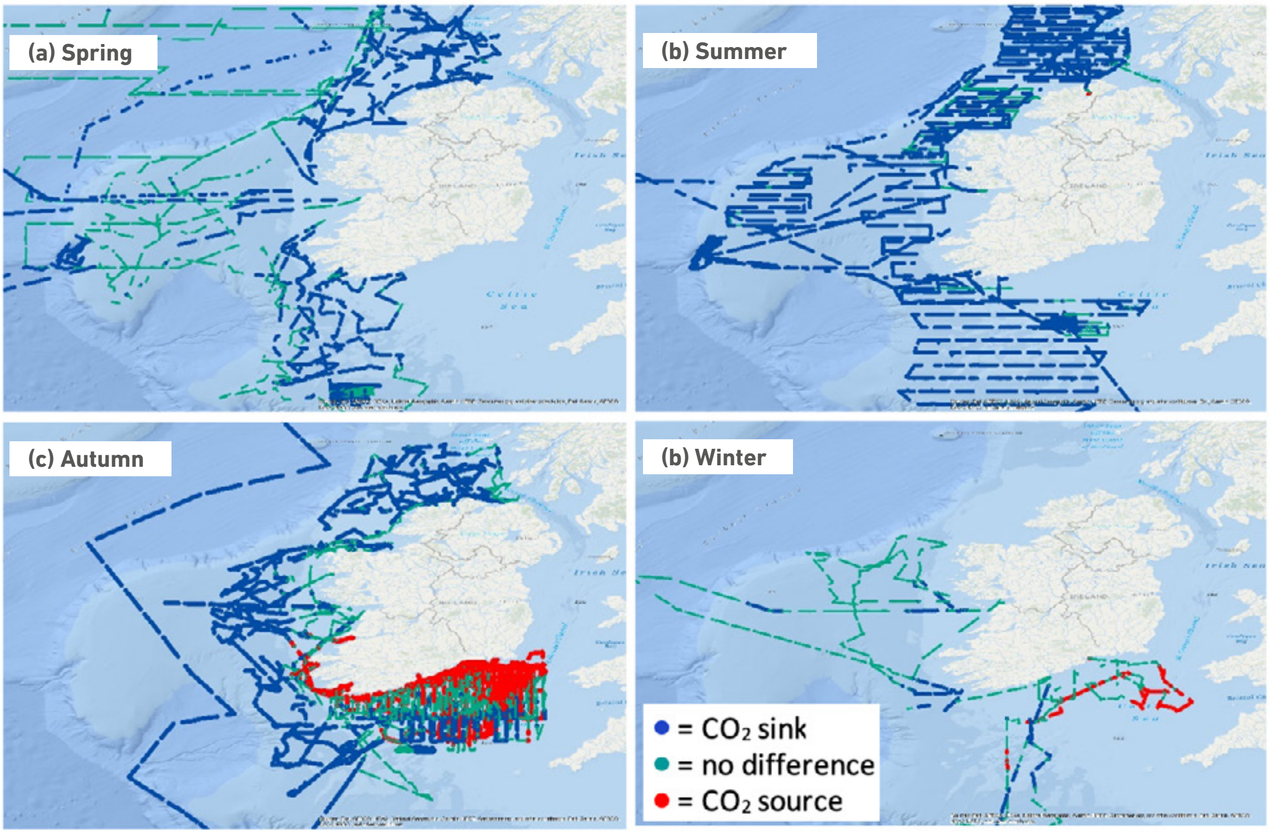

Figure 4.8 Indicative seasonal variation in ΔCO_2 (surface ocean CO_2 minus atmospheric CO_2) from May 2017 to July 2020 on RV *Celtic Explorer* surveys. Both surface ocean (-5 m) and atmospheric CO_2 were measured underway by General Oceanics GO-8050 pCO_2 system with LiCOR 7000 detector. Different colours indicate whether the ocean around Ireland acted as net CO_2 sink (blue), CO_2 source (red) or no appreciable difference (± 20ppm) was found (green) for the four Irish meteorological seasons (a) spring (43906 observations), (b) summer (62900 observations), (c) autumn (49097 observations), and (d) winter (9525 observations).

CASE STUDY

MACE HEAD PILOT OCEANOGRAPHIC OBSERVATORY

The Marine Institute has operated a pilot coastal oceanographic observatory, west of Mace Head since June 2018 to monitor a suite of essential ocean variables and to investigate processes driving change and variability. The location of the buoy is close to the Mace Head Global Atmospheric Watch station (Figure CS4.4), whose long-term time series can provide high accuracy data for climate studies, particularly carbon fluxes.

The Mace Head Observatory is equipped with an array of sensors measuring real-time temperature, salinity, dissolved oxygen (DO), pCO_2, pH and nitrate. As well as sensor measurements, frequent water sampling and laboratory analyses for many essential climate variables is undertaken, specifically DO, dissolved inorganic carbon, total alkalinity, dissolved inorganic nutrients and salinity to provide additional parameters and to ensure the accuracy of the semi-continuous sensor data with the intention of adding biological parameters. The data collected

Figure CS4.4 Mace Head Observatory at the west coast of Ireland, measuring real-time data of temperature, salinity, dissolved oxygen, pH, pCO_2, and nitrate.

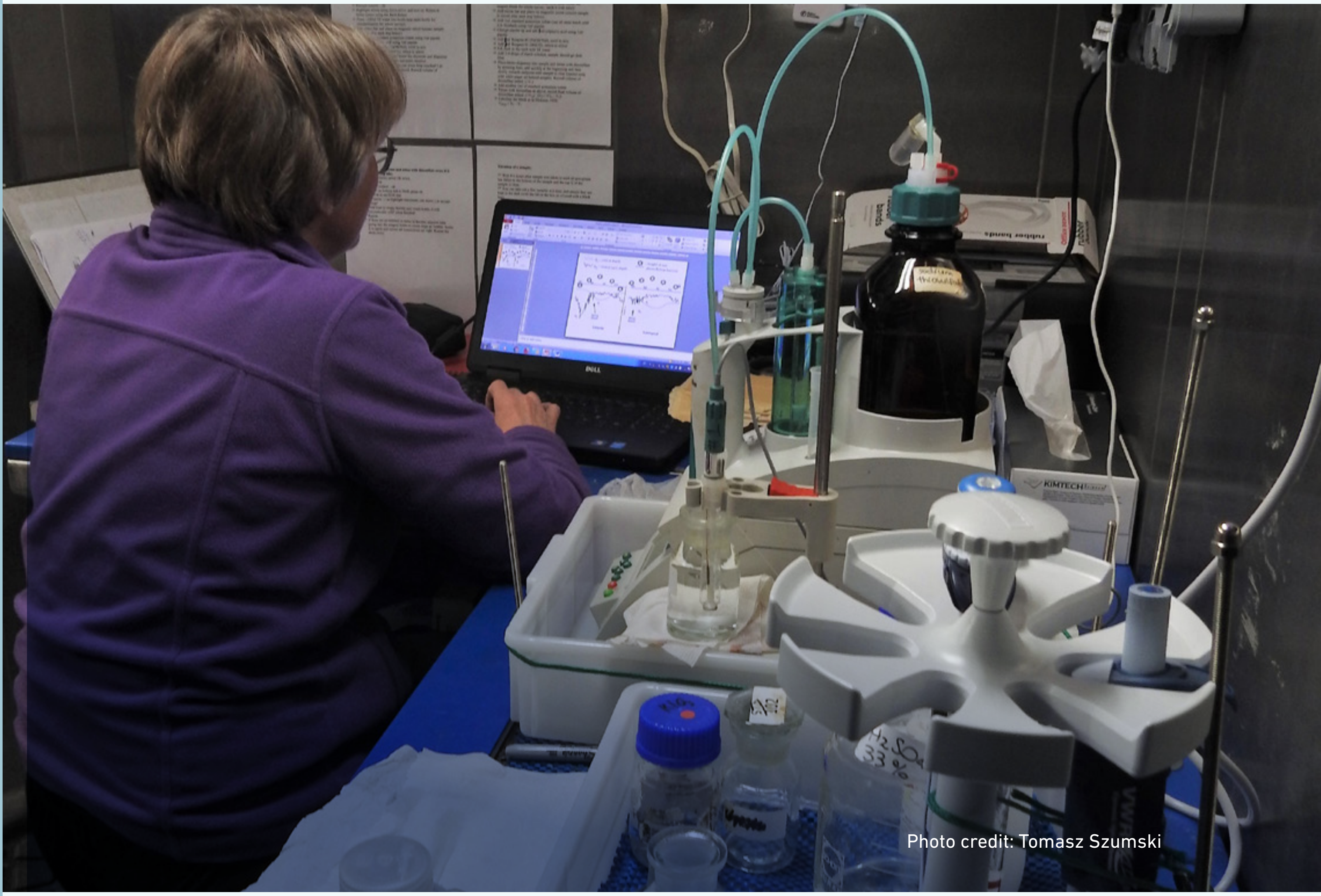

Photo credit: Tomasz Szumski

are providing a picture of baseline variability on various time scales for an integrated set of essential climate variables in a coastal ecosystem. This sentinel site will generate a long-term time series against which to monitor impacts of climate change on Irish coastal and shelf waters. The mooring was established as part of a network of oceanographic moorings under the Interreg VA funded COMPASS project (Collaborative Oceanography for Monitoring Marine Protected Areas and Species)[1] between the Marine Institute, Agri-Food and Biosciences Institute Northern Ireland, the Scottish Association for Marine Science and Marine Scotland Science.

Atmospheric CO_2 continues to rise inexorably as a result of emissions from human activity. Atmospheric CO_2 concentrations have been measured at Mace Head since 1991 and track concentrations measured at Mauna Loa, Hawai'i, the station with the longest atmospheric CO_2 time-series. Seawater pCO_2 in coastal waters as measured at the Mace Head oceanographic observatory shows high variability and a strong seasonal signal with lowest pCO_2 associated with biological uptake in spring (Figure CS4.5(b)). Biological fixation of CO_2 from seawater in spring-summer drives CO_2 drawdown from the atmosphere and coastal waters are a sink for CO_2. In winter coastal waters are no longer a sink and may even be a source of CO_2 to the atmosphere. Coastal observatory measuring multiple essential ocean/climate variables in an integrated manner enables the study of interrelationships between atmospheric and coastal physical, biological and chemical processes over time.

[1]https://compass-oceanscience.eu/ This project is supported by the European Union's INTERREG VA funding programme to the value of €6.3 million. INTERREG VA is managed by the Special EU Programmes Body.

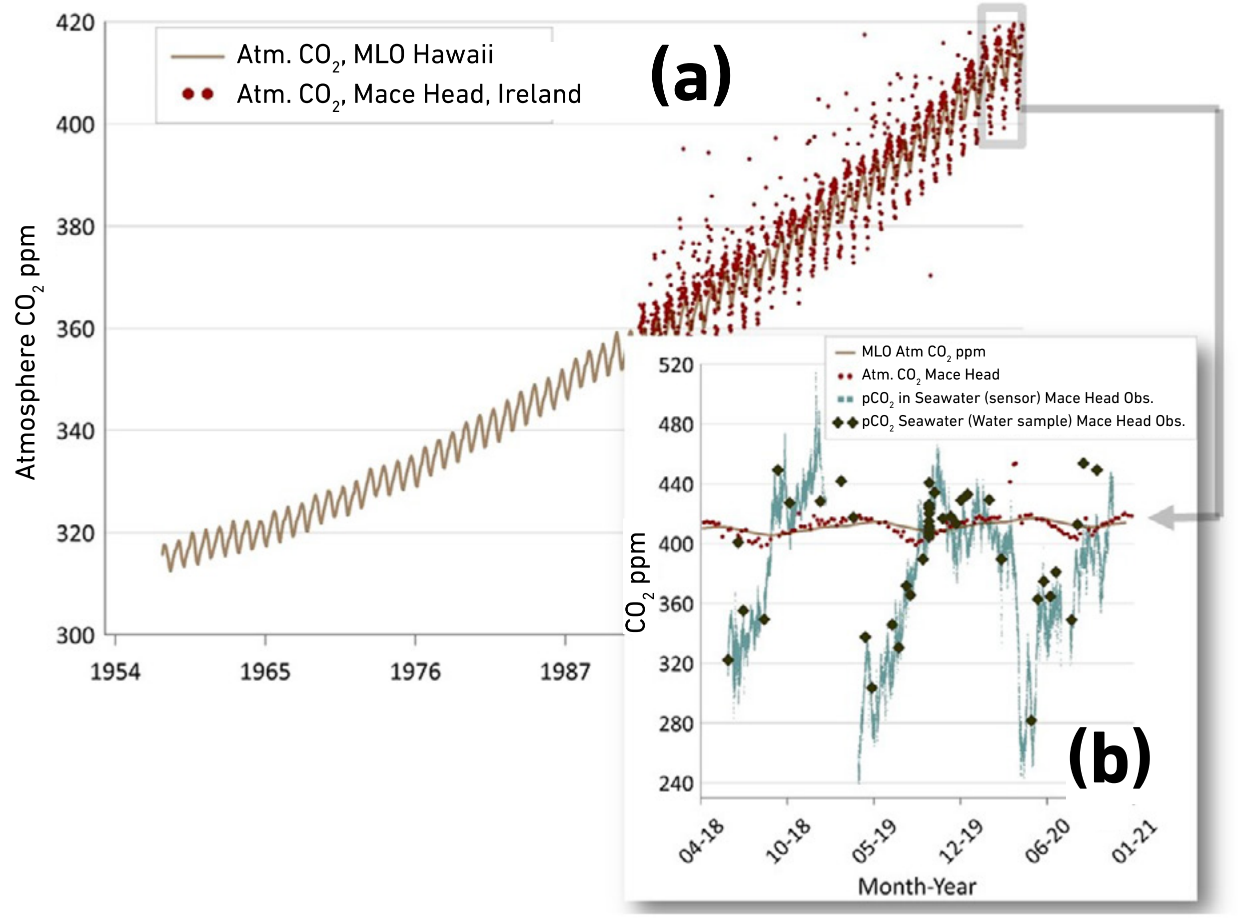

Figure CS4.5 (a) Atmospheric CO_2 concentration (ppm) at the Mauna Loa Observatory (MLO) in Hawaii (brown) for over 60 years and at NUI Galway's Mace Head Observatory in Ireland since 1993 (red) indicating a similar annually increasing trend. The inset (b) shows an excerpt of these data from recent years plus measurements of CO_2 in coastal seawater at the Mace Head Coastal Observatory (as partial pressure of CO_2, measured directly using sensors and also calculated from water sampling for the full carbonate system) between 2018 and 2020.

The variability of pH in productive coastal ecosystem habitats where macroalgae flourish, is of the order of 0.2 pH units over a 24-hour cycle. This is considerably higher on a daily basis than the decadal change in the open ocean. Additional long-term changes in carbonate chemistry and nutrient concentrations in addition to the daily variability may eventually shift the organisms' tolerances beyond their limits.

4.3 NUTRIENTS

4.3.1 NUTRIENTS AND CLIMATE CHANGE

Dissolved inorganic nutrients are essential for plant growth and depleted concentrations in surface waters can limit primary productivity. There is no clear overall trend in dissolved winter nutrients in the western Irish Sea, the area in Irish waters with most consistent sampling over the last 20 years. Climate models project reduced nutrient supply to the surface ocean in the late 21st century in part due to reduced vertical mixing.

Nutrients, specifically dissolved inorganic nitrogen, phosphate and silicate, are essential to primary productivity and when depleted can limit plant growth. IPCC notes that in response to ocean warming and increased stratification, open ocean nutrient cycles are being perturbed and there is high confidence that this is having a regionally variable impact on primary producers (Bindoff *et al.*, 2019). Climate models predict nitrate concentrations in the upper 100 m are very likely to decline under both high and low emission scenarios by 2081–2100 relative to 2006–2015 in response to increased stratification (Kwiatkowski *et al.*, 2020, Bindoff *et al.*, 2019).

Nutrient concentrations in Irish coastal waters are determined by concentrations in shelf waters, nutrient loads associated with freshwater input and land-based discharges, atmospheric inputs and biogeochemical processes such as recycling, biological assimilation or denitrification (Nolan *et al.*, 2010). Excess nutrients can cause eutrophication. Measures through European Directives and the OSPAR Commission address marine eutrophication through controlling sources and inputs of nutrients. Marine eutrophication problems in Ireland are limited to certain nearshore areas and embayments (Ní Longphuirt *et al.*, 2020). The impact of climate change, i.e. potentially prolonged stratification and changing rainfall patterns, are likely to influence the concentration and distribution of nutrients in Irish coastal waters. By the end of the century the annual mean stratification of the top 200 m (averaged between 60°S – 60°N relative to the 1986–2005 period) is projected to increase in the very likely range of 1–9% and 12 – 30% for RCP2.6 and RCP8.5, respectively (Bindoff *et al.*, 2019). More rain and increased flooding during winter months due to climate change are expected to enhance nutrient enrichment through increased freshwater input and run-off from land (Painting *et al.*, 2013). Climate models predict that areas with high precipitation will become even wetter in the future, especially in the Northern Hemisphere (Bindoff *et al.*, 2019). Higher net precipitation increases river discharge, supplying more nutrients and freshwater to the sea. Consequently, eutrophication is accelerated due to the increased nutrient supply and primary production. Met Éireann predicts decreases in mean annual, spring and summer precipitation amounts by mid-century. Frequencies of heavy precipitation events however show notable increases of approximately 20% during the winter and autumn months (https://www.met.ie/climate/climate-change).

4.3.2 WINTER NUTRIENT CONCENTRATIONS IN IRISH WATERS

The measurement of dissolved inorganic nutrients in Irish waters is carried out by the Marine Institute on two annual multidisciplinary surveys. Parameters measured are nitrate (measured as total oxidised nitrogen (TOxN), which is the sum of nitrate + nitrite, but where nitrite concentrations are generally very low and thus TOxN is referred to as 'nitrate' throughout the document and in plots), nitrite, phosphate and silicate. Sampling is primarily undertaken in winter when biological activity is at a minimum and vertical mixing is greatest. The surveys complement transitional and coastal water quality monitoring undertaken by the Environmental Protection Agency. The extent of the sampling activity in coastal and off-shore waters for the period 2000–2019 is shown in Figure 4.9.

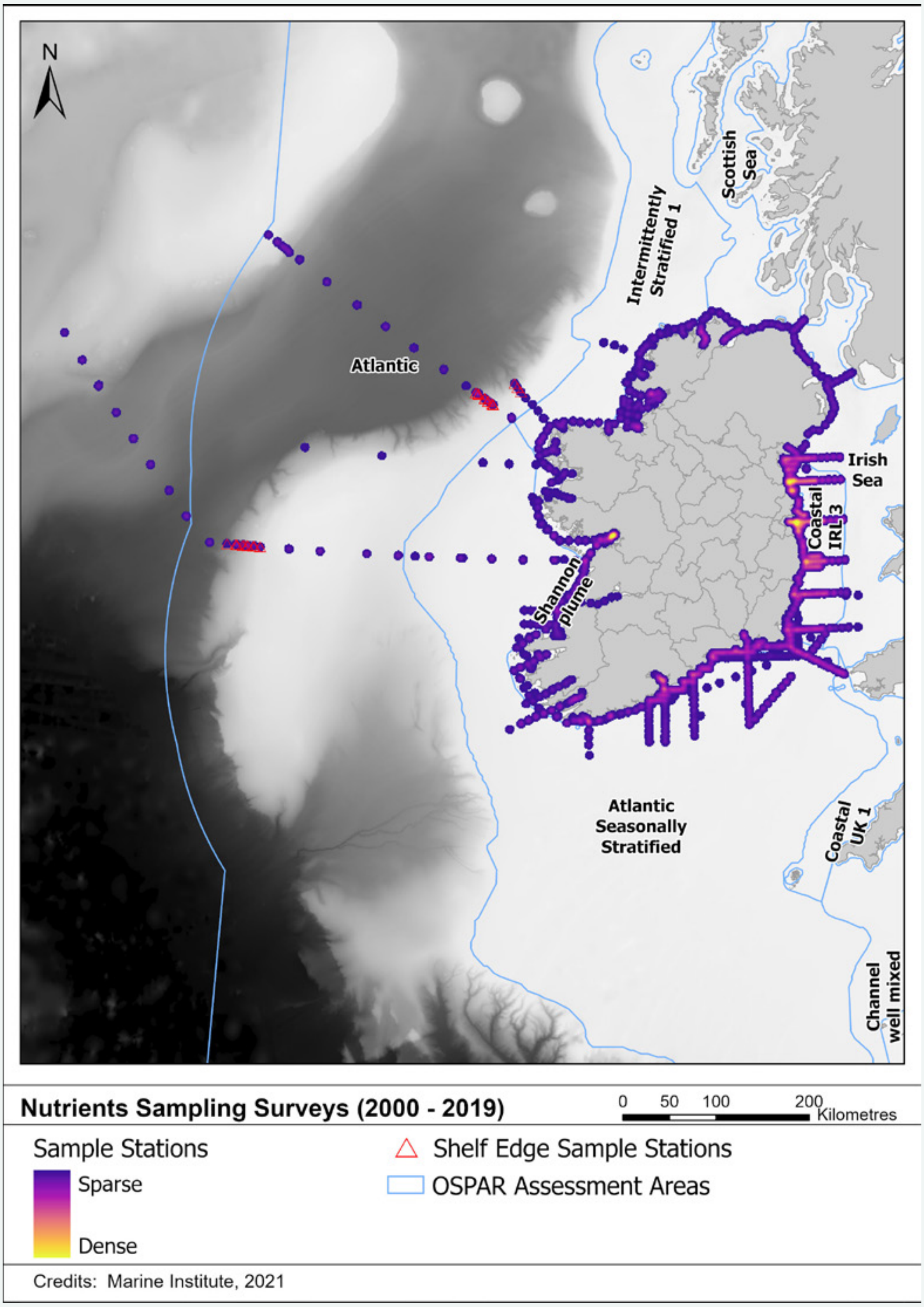

Figure 4.9 Stations with salinity >33, sampled for winter surface (<10 m) dissolved inorganic nutrients during oceanographic surveys between 2000 and 2019. Sampling intensity (Dense=high sampling intensity, Sparse=low sampling intensity) is also indicated showing increased sampling activity on east and southeast coasts.

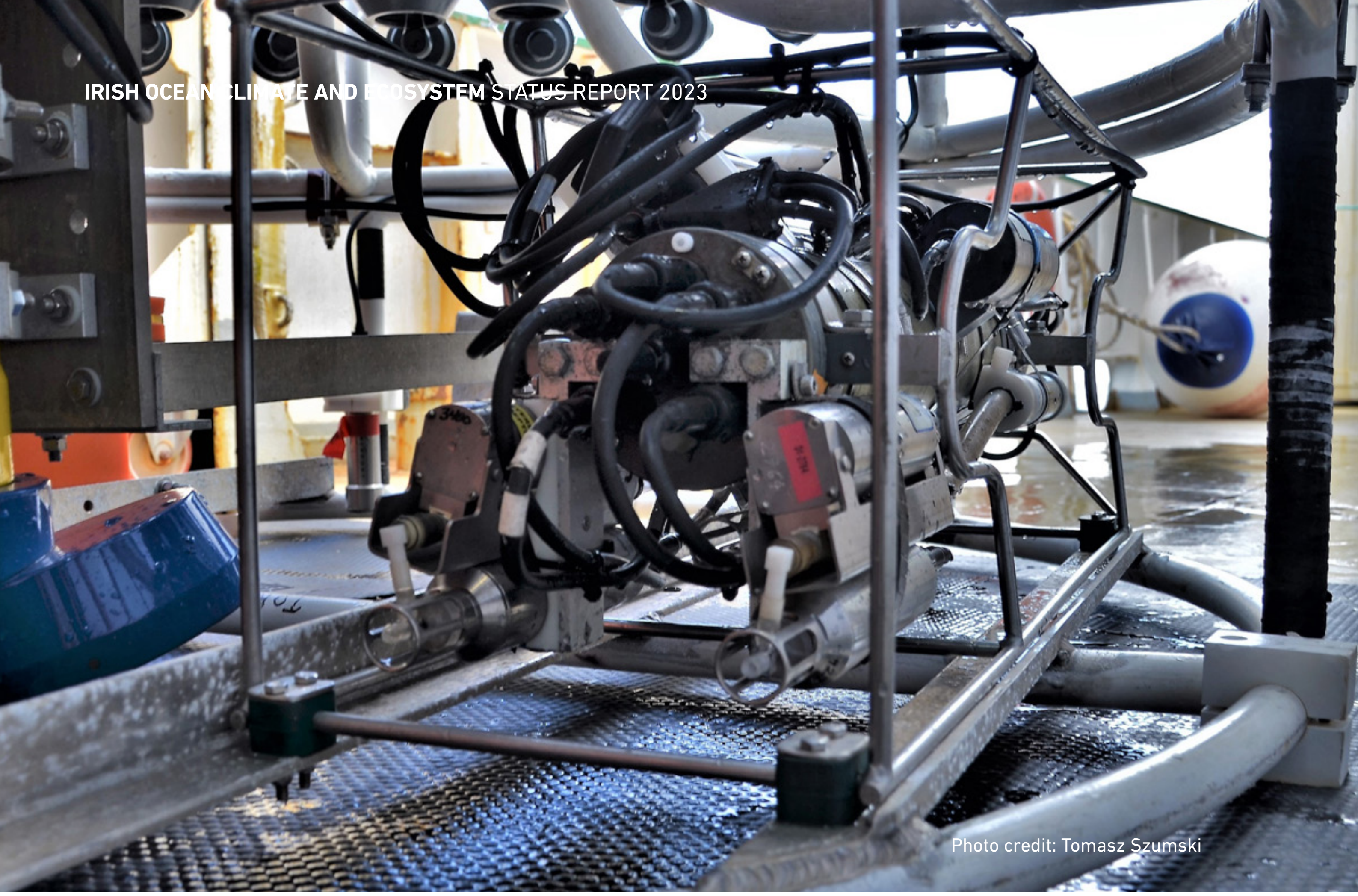

Photo credit: Tomasz Szumski

Figure 4.9 also shows assessment areas defined by OSPAR based on depth, natural features/boundaries, stratification, salinity and phytoplankton dynamics. These assessment areas will be used in the fourth application of the OSPAR Comprehensive Procedure for the assessment of eutrophication status.

In Figure 4.10 the spatial distribution of surface nutrients in Irish coastal waters for 2015–2019 are shown with nutrient concentration gradients extending from the coastline and indicating regions of elevated nutrients associated with freshwater inputs.

As expected, due to freshwater inputs, salinity values were generally lower in near-shore environments such as Dublin Bay, Dundalk Bay, Carlingford Lough and the Waterford Estuary. Higher nutrient concentrations (particularly nitrate (TOxN) and phosphate) in these areas are likely to be related to enhanced nutrient inputs from agriculture, sewage treatment plants and industrial activity.

Winter nutrient concentrations at the land-ocean continuum tend to reflect the freshwater-seawater mixing gradient as indicated by the salinity.

Distinct areas are evident from nutrient–salinity correlations. Over a wide salinity range, nutrient values decrease with increasing salinity. High salinity shelf edge and Atlantic surface waters have higher nitrate concentrations than high salinity waters of the coastal (Irish Sea) and Atlantic seasonally stratified areas. This indicates that the background seawater concentrations in the latter waters are lower than at the shelf edge. This may reflect denitrification processes in the shelf seas (Hydes *et al*., 1999). The median nitrate concentration for the coastal area (Irish Sea) is 8.53 µM compared to 10.5 µM for the shelf edge (despite lower salinity of the Irish Sea). There is a linear relationship between salinity and silicate. Temperature and salinity data have been used to identify water masses present in the Rockall Trough, and have been combined with nutrients (nitrate, nitrite, phosphate, silicate) and oxygen data to outline the chemical characteristics of each of the water masses (McGrath *et al*., 2012b).

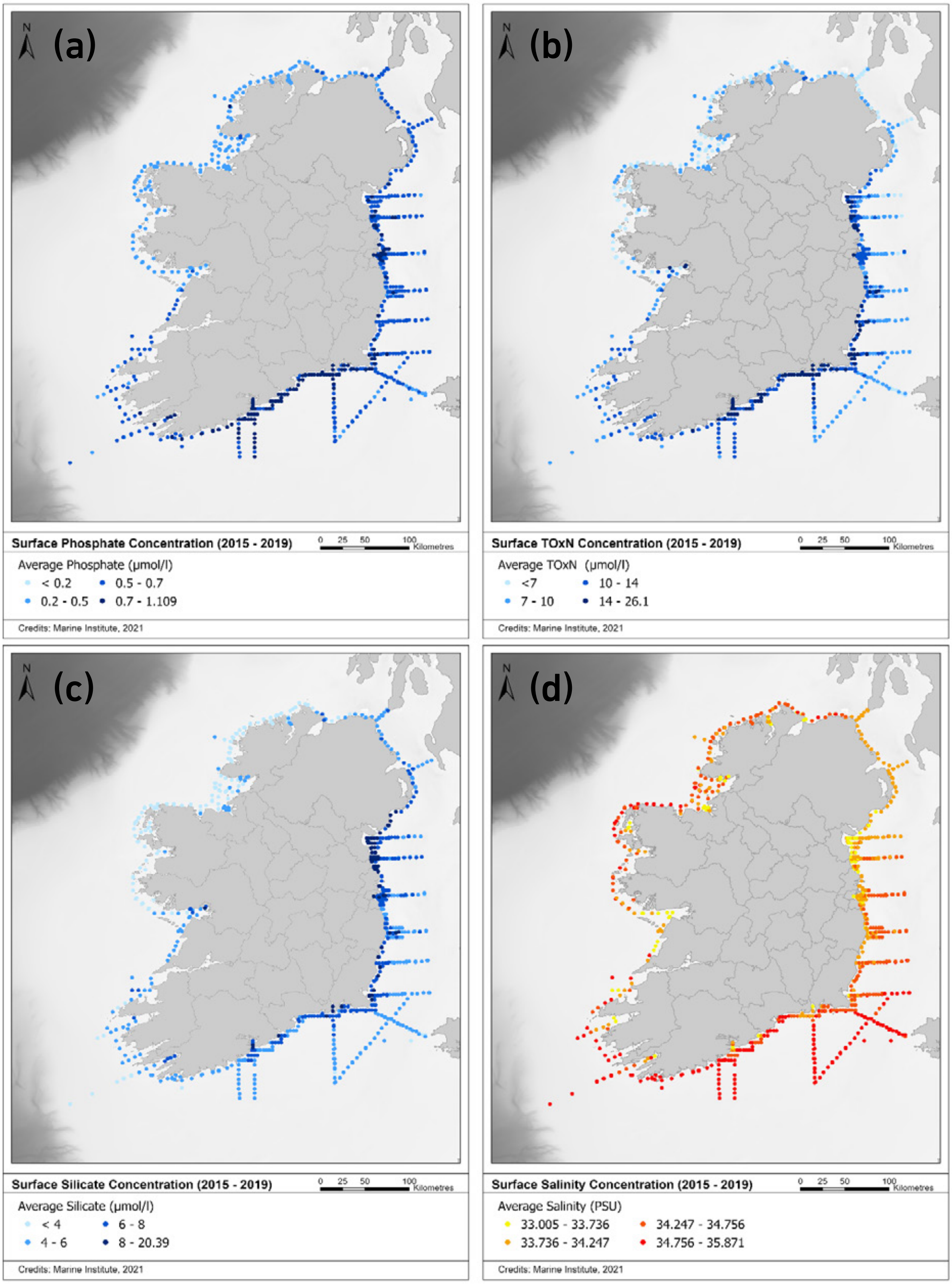

Figure 4.10 Surface winter nutrients concentrations between 2015–2019 for Phosphate (a), Nitrate (TOxN) (b), Silicate (c) and Salinity (>33) for the same time period (d).

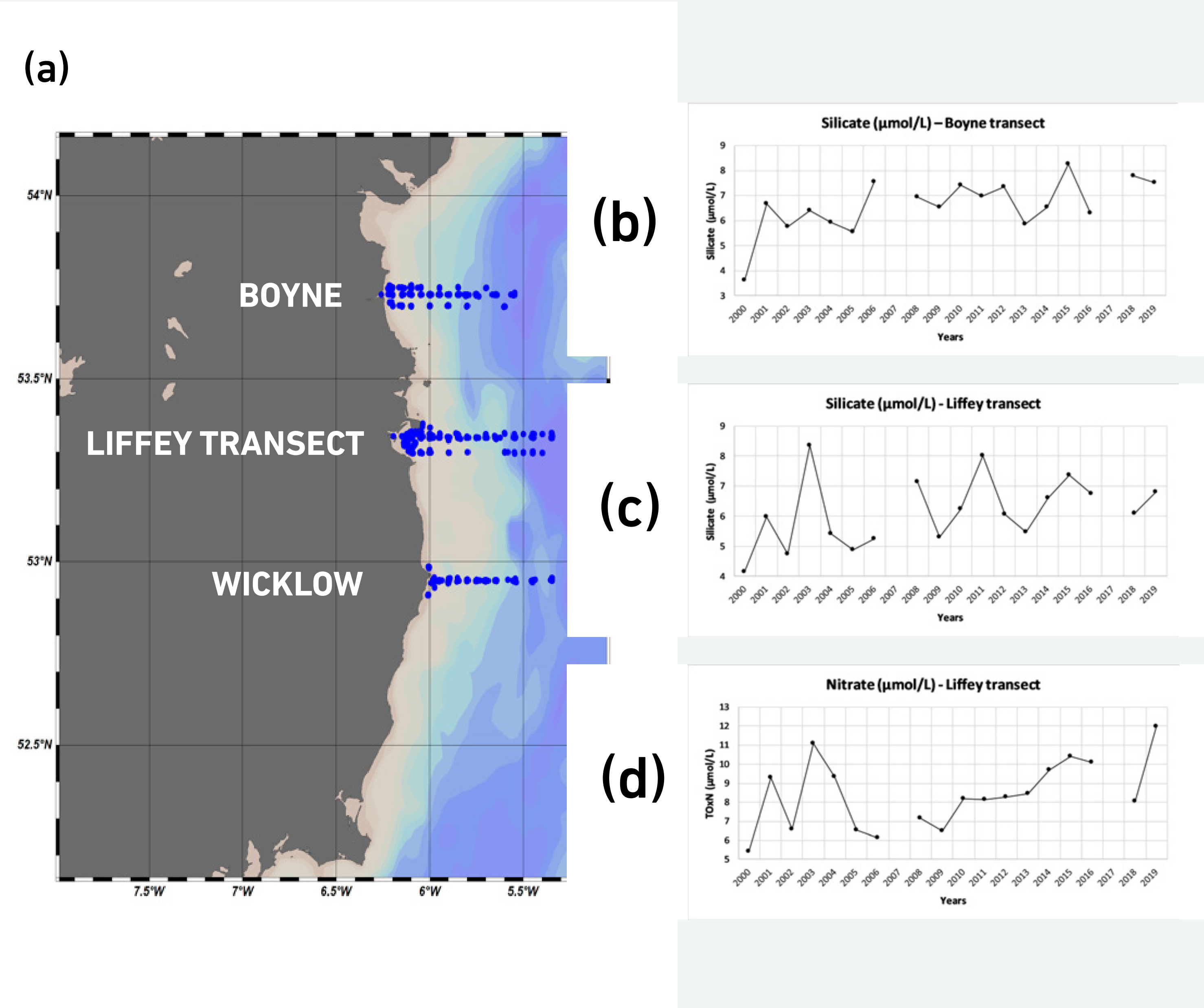

Figure 4.11 (a) Irish Sea sampling transects for which trends were assessed between 2000 and 2019 for the dissolved inorganic nutrients nitrate (total oxidized nitrogen, TOxN), nitrite, phosphate, and silicate. Shown are three examples with significant increasing trend in nutrient concentration, which was the case for (b) silicate at the Boyne and at the (c) Liffey transect and for (d) nitrate (TOxN) at the Liffey transect.

4.3.3 TREND ANALYSIS FOR THE WESTERN IRISH SEA

An initial assessment of temporal trends in surface winter dissolved inorganic nutrient concentrations for salinity >33 in the western Irish Sea comprising three transects (Figure 4.11) was conducted using non-parametric Mann–Kendall tests. The selected region reflects areas where most consistent year-on-year sampling coverage is available. No significant trend was apparent ($p>0.05$) for winter nutrient concentrations, although significant upwards trends were determined for silicate in the Boyne and Liffey transects and for nitrate in the Liffey transect ($p<0.05$) when assessed separately (Figure 4.11). Further work is required to assess nutrient trends in Irish waters.

4.4 RECOMMENDATIONS

1. Undertake a sustained high quality observing programme for essential biogeochemical climate variables to monitor changing ocean conditions and the impacts of climate change.
2. Assess the trends and variability of ocean acidification in Irish waters at various scales and support targeted OA monitoring and research to better understand the risks to local shellfish aquaculture from ocean acidification and other climate stressors.
3. Continue CO_2 measurements on research vessels and other platforms to better constrain the carbon budget and the role of the continental shelf as a seasonal CO_2 sink/source.
4. Maximise the impact of national data collection and research by contributing to international activities and data centres that support regional and global assessments of ocean climate change (e.g. ICOS, Surface Ocean CO_2 Atlas, reporting to IOC-UN SDG 14.3 Ocean Acidification).

CHAPTER 5

PHYTOPLANKTON

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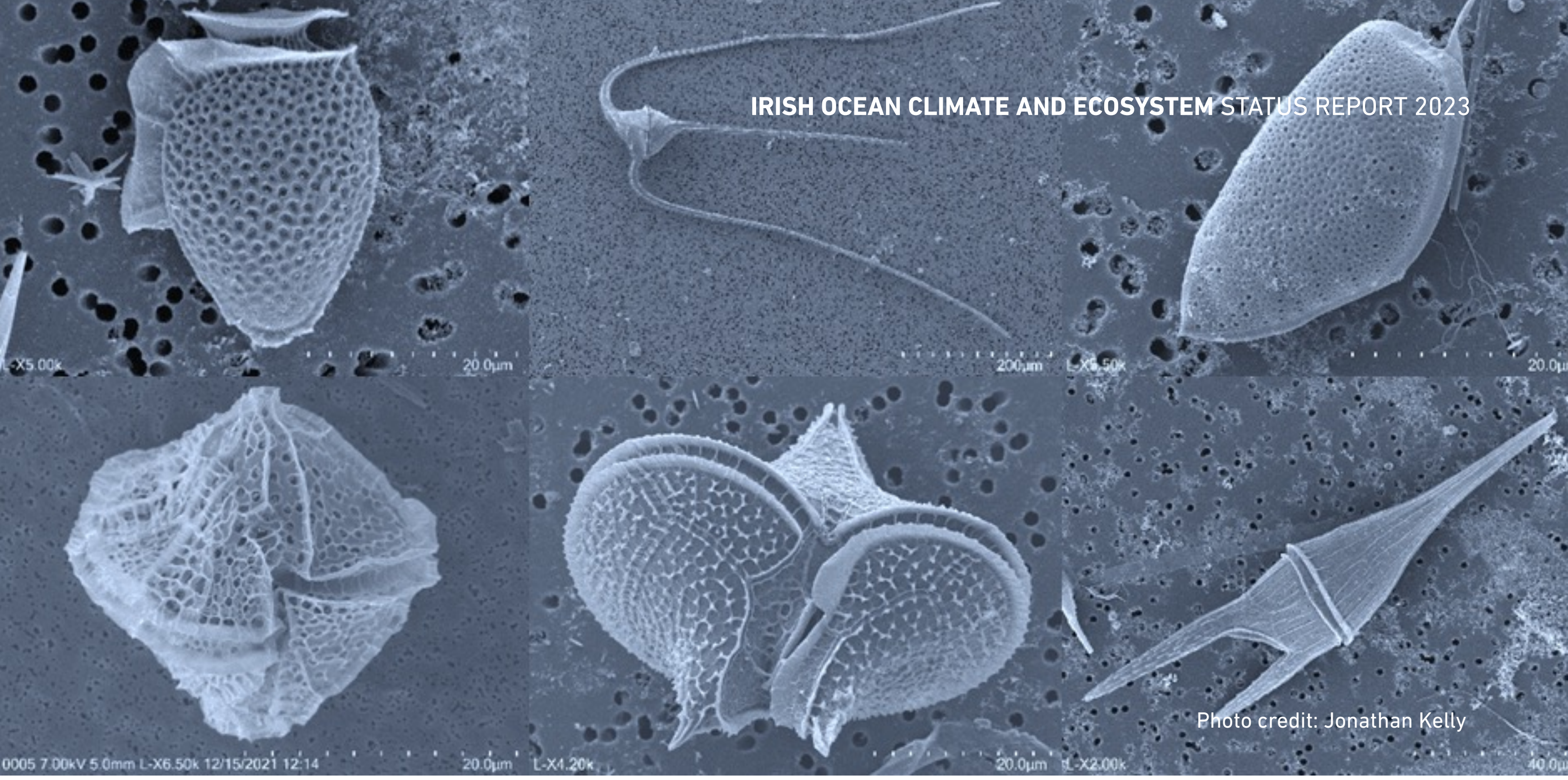
[1] Marine Institute

Photo credit: Catherine Jordan and Michelle Tomlinson



5.1 INTRODUCTION

Marine phytoplankton are responsible for c. 50% of the primary production on Earth. These microscopic unicellular plant-like organisms are an important food source that sustains marine life and benefits humans who depend on seafood as their primary source of protein. Phytoplankton can be thought of as sensitive indicators of climate change, where changes in community composition can affect and alter marine ecosystems.

A phytoplankton group known as harmful algae with ~200 species know globally. Harmful algae are broadly split into two sub-groups; toxin and non-toxin producing species that can cause harmful effects to marine ecosystems and/or cause seafood safety issues. Toxins produced include Phycotoxins (which can cause harm and impact human health if contaminated shellfish are consumed) and Icthyotoxins (responsible for fish kills). Non-toxin producing high biomass phytoplankton bloom species can result in negative marine ecosystem effects including anoxia, water discolouration, mucilage, and mechanical damage to fish gills.

This chapter presents the observed national and regional phytoplankton results (composition, abundance and peak growth from a seasonal and annual perspective) with data collated from the Marine Institute's National Monitoring Programme for Phytoplankton from 2001 to 2020.

The impacts of climate change on the seafood sector through Harmful Algal Bloom (HAB) events are expected to occur more frequently. An expansion of the phytoplankton growth season (for some species) has already been observed. Changing environmental conditions driven in part by climate change can result in multiple environmental stressors influencing HABs.

5.2 STATUS AND TRENDS OF PHYTOPLANKTON – A GLOBAL PERSPECTIVE

The IOC–UNESCO Global Harmful Algal Bloom Status Report (Hallegraeff *et al.*, 2021a) concluded that the perceived idea that HAB trends and events are increasing globally is unsupported by meta–analyses. For a true assessment, research is required at a regional basis focused on individual species and associated biotoxins. This conclusion was also reached after an intensive review of international datasets (Hallegraeff *et al.*, 2021b) showing there are no statistically significant trends of increasing distribution and abundances of HAB species. Increased awareness, technology

Monthly cell abundance of diatoms has increased throughout the year nationally, with noticeable increases between October to January, outside the expected growth season.

and monitoring efforts have resulted in increased reports of HAB events, rather than due to increases in the actual occurrence of HAB events.

Climate change impacts on HAB species are of a global concern with many unknowns and scientific questions on how phytoplankton and HAB species will adapt to future changes in the marine environment (Wells *et al*., 2021). Physical and biogeochemical changes that influence water column stratification, temperature, ocean acidification, and salinity could lead to changes in phytoplankton distributional ranges and an extension of the growth season in some regions (Edwards *et al*., 2020). In a world with an increasing human population and a demand for increased global food production from aquaculture, there is uncertainty around climate change impacts on shellfish species settlement and growth, the carrying capacity of bays and physical processes such as flooding, coastal erosion and storms affecting coastal and intertidal habitats.

It is generally concluded that more comprehensive time series data are required, on environmental parameters surrounding HAB events, to improve HAB modelling and predictive forecasts (Wells *et al*., 2020). Such datasets are essential to improve our understanding of the observed effects and changes in phytoplankton communities and HAB events attributed to climate change.

5.3 STATUS AND TRENDS OF PHYTOPLANKTON IN IRISH WATERS

The phytoplankton community composition in Irish coastal waters is influenced by ocean current circulation patterns and seasonal changes of light availability, nutrients, salinity, temperature and other variables. Inshore marine areas, remain relatively well mixed in winter with intermittent water column stratification due to freshwater runoff from land. In the warmer months, thermal stratification influences phytoplankton growth from March to September. Offshore, in shelf waters, the transport of phytoplankton is associated with the Irish Coastal Current with bottom density fronts playing an important role for the development and transport of blooms in summer and autumn. The transport of phytoplankton and HABs into the bays of southwest Ireland are primarily driven by wind. For a detailed review on the biophysical drivers of HABs in Irish waters please refer to Raine (2014).

Results presented here indicate a noticeable extension of the growth season and an increased average abundance of some phytoplankton in the last decade. In addition, the previous *Irish Ocean Climate & Ecosystem Status report* (Nolan *et al*., 2010) observed that during the growth season there was an increased phytoplankton abundance (particularly for diatoms) in the early months of the year (from 1998 to 2002), a trend that is also observed in this review. The dinoflagellate group are typically at their highest cell densities from June to August, with the growth season commencing in May and continuing through to August on an annual basis.

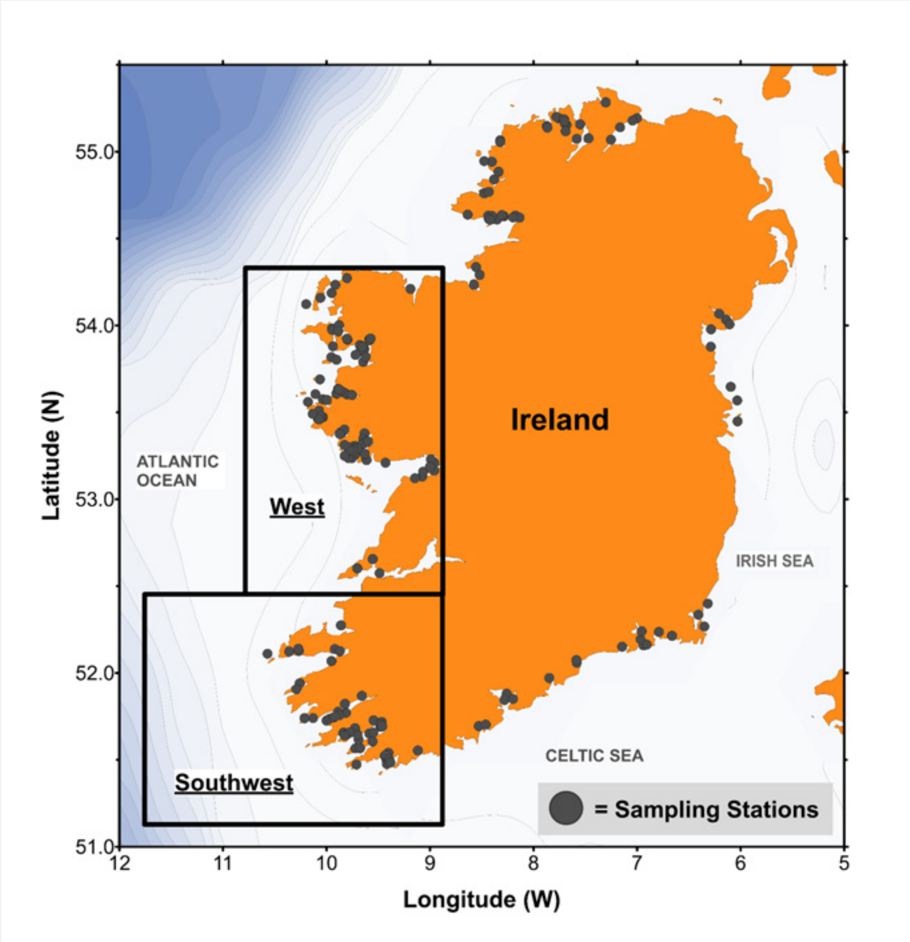


Figure 5.1 Map of aquaculture site locations in Ireland where *in situ* water samples are collected, represented by grey circles. The west and southwest regions are specific focus areas in this review and are defined by the boxes in the map.

5.4 PHYTOPLANKTON DATASETS

The Irish National Monitoring Programme (NMP) for Phytoplankton commenced in the mid–1980s and was setup to identify and enumerate phytoplankton species (with a particular emphasis on harmful algae) in coastal areas where licensed finfish and shellfish aquaculture operations take place. In the early 2000s, the programme was improved and expanded, and from 2014 onwards, circa 70 samples were collected and analysed weekly in actively harvesting production areas.

Since 2003, phytoplankton data are stored in the Marine Institute's Harmful Algal Blooms (HABs) database (Microsoft SQL Server) with all NMP data publicly available at https://webapps.marine.ie/habs. Prior to this, the Marine Institute's Phytobase (Microsoft Access) database was used to store phytoplankton data.

Phytoplankton data (average monthly cell abundance) used in this chapter covers the time period from 2003 to 2020 for three main phytoplankton groups: diatoms, dinoflagellates and 'all community' species. For the HAB species detailed in this review, a slightly expanded dataset from 2001 to 2020 was used. For both data sets, results were compiled into three areas, referred to as the 'whole Ireland' where all NMP coastal site data was included, and for two specific regions where intensified aquaculture production activities occur, i.e., the "west" and the "southwest" (Figure 5.1).

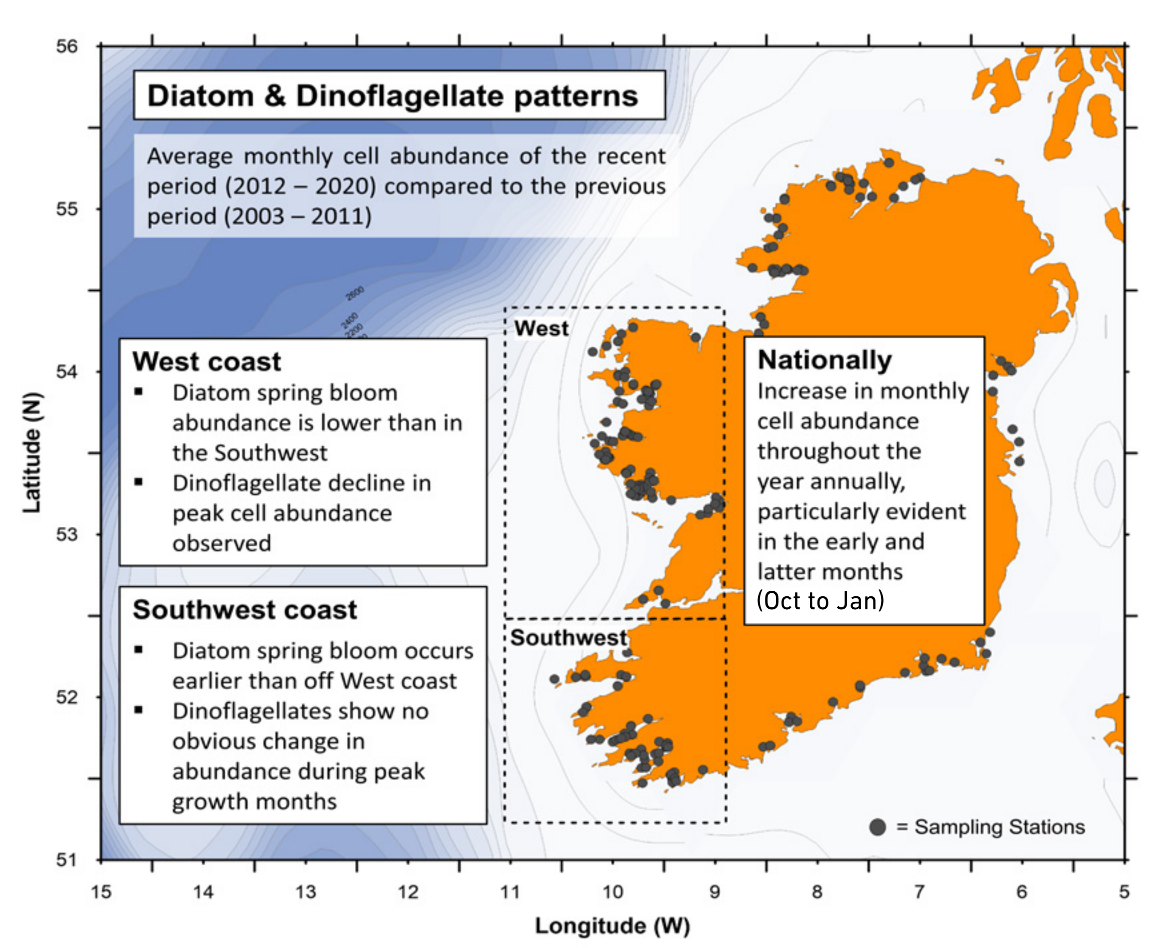


Figure 5.2 Overview of the key observations and changes observed for Diatom and Dinoflagellate average monthly cell abundance and occurrence from 2003 to 2020

Additional phytoplankton abundance datasets for Irish coastal and estuarine waters exist. These programmes include (a) the annual offshore phytoplankton oceanographic survey and (b) the Water Framework Directive (WFD) monitoring programme that began in 2011. The Environmental Protection Agency and the Marine Institute are responsible for WFD phytoplankton monitoring, one of the many parameters used in the assessment of water quality. Due to different consistencies in timeframes, sampling protocols and analytical methodologies, data from the two programmes mentioned above are excluded from the current review.

5.5 PHYTOPLANKTON IN COASTAL BAYS

The key observations and changes observed for diatom and dinoflagellate average monthly cell abundance and occurrence from 2003 to 2020, with comparisons between the two time periods 2003–2011 and 2012–2020 are presented in Figure 5.2.

In coastal waters, phytoplankton are relatively abundant throughout the year from February to October. Diatom blooms occur in both spring and autumn, and as expected, spring bloom abundances are higher than those observed in autumn. From a national perspective, the overall observation for the total phytoplankton community

Photo credit: Andrew Downes

was an increased cell abundance on a monthly basis throughout the year for the period 2012–2020 when compared to 2003–2011 (Figure 5.3(a)). While high phytoplankton productivity is expected at inshore coastal sites throughout the growth season (March to September), the recent elevated levels of phytoplankton in late autumn and winter (October to January) is surprising.

The recent monthly average cell abundance increase throughout the year is particularly noticeable off the west coast of Ireland. For the period 2012–2020, average cell concentrations were higher and the growth season extended in the latter part of the year.

Since 2008, phytoplankton average numerical abundance has increased in winter. Off the southwest coast (Figure 5.3(b)), from 2003 to 2011 the highest average cell concentration was in June; however, this was not observed in the recent period, 2012–2020. The overall observations from the west and nationally, 2012–2020 show a higher average cell abundance with a more prolonged growth period throughout the year. Of interest in the southwest, was a change from a bi–modal seasonal distribution (2003–2011) to a tri–modal distribution (2012–2020).

For diatoms, nationally, there were increases of average cell abundances throughout the year in the recent period (2012–2020) when compared to the period 2003–2011 (Figure 5.3(c)). The spring bloom duration increased from March to April (2003–2011) to March to May (2012–2020). Slightly different patterns emerge in the west and southwest regions, e.g., the spring bloom off the southwest coast occurs earlier in the year by approximately one month. Spring bloom cell abundances are also lower in the west when compared to the southwest, and this is particularly evident in the 2012–2020 period (Figure 5.3(d)).

For dinoflagellates, nationally, average cell abundance for the time period 2003–2011 increased from May with maximum abundances in July and August while the maximum for the period 2012–2020 were confined to August (Figure 5.3(e)). In recent years (2012–2020), dinoflagellates have shown an increased abundance in the early and latter months of the year. Slightly different geographic patterns are observed in both periods regionally. For the period 2003–2011 dinoflagellate bloom peak (cell maximum abundance) was in July, while it was August in the southwest. For the period 2012–2020 the bloom peak in both the west and southwest was lower than that observed in 2003–2011 (Figure 5.3(f)).

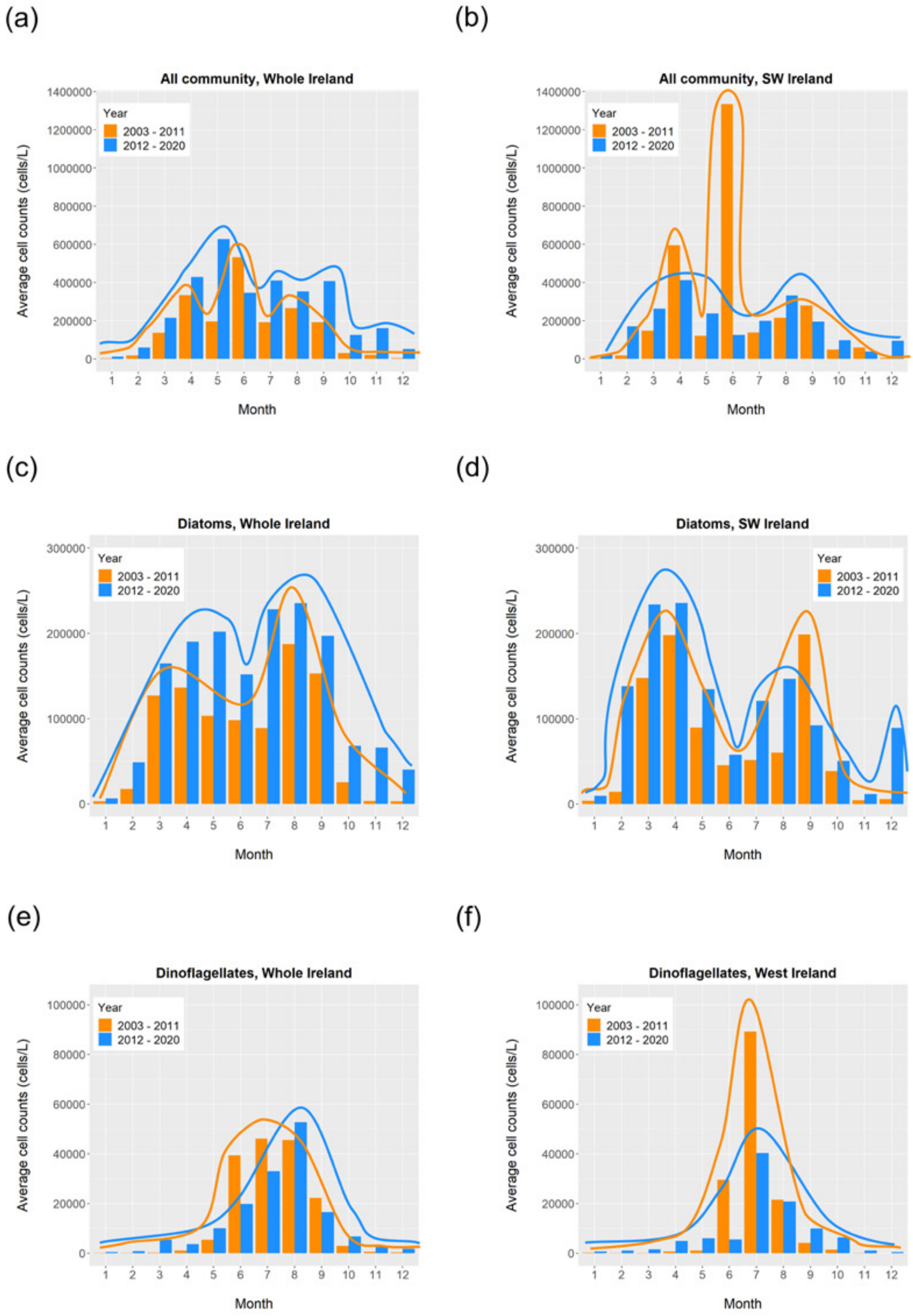


Figure 5.3 Average monthly cell counts (cells/L) for two time periods, 2003–2011 (orange) and 2012–2020 (blue). X–axis=month; Y–axis=numerical abundance. Phytoplankton community (a) whole Ireland and (b) southwest Ireland. Diatoms (c) whole Ireland and (d) southwest Ireland. Dinoflagellates (e) whole Ireland and (f) west Ireland. *Orange/Blue distribution lines are free hand drawn and are for visual purposes only to demonstrate seasonal changes in abundance between the two time periods and not statistically derived.*

5.6 POTENTIALLY TOXIC AND/OR HARMFUL ALGAL BLOOMS (HABS)

In this study, five phytoplankton taxa, each with the potential to cause a harmful algal event are examined over two decades between 2001 and 2010 and 2011 and 2020 (see Figures 5.4 – 5.8). These taxa include *Dinophysis acuminata*, *Dinophysis acuta, Karenia mikimotoi, Alexandrium* species and *Pseudo–nitzschia* species from the "*P. seriata*" complex. The HAB taxa exhibited large inter–annual variability.

5.6.1 *DINOPHYSIS* SPECIES

Dinophysis acuminata and *Dinophysis acuta* are usually present as low biomass blooms that produce Diarrhetic Shellfish Toxins. An overview of key observations for *Dinophysis* species average monthly cell abundance in the recent decade (2011–2020) compared to the previous decade (2001–2010) are presented in Figure 5.4.

The most abundant *Dinophysis* species in Irish coastal waters, responsible for Diarrhetic Shellfish Toxins in Irish shellfish, are *D. acuminata* and *D. acuta*. Nationally, there was relatively little change in the overall average monthly *Dinophysis* cell abundances. Regionally, however, changes were

An overall decrease in average monthly cell abundance was observed for both *Dinophysis acuta* and *Dinophysis acuminata* off the west coast of Ireland. In the southwest, a general increase in abundance was observed with *D. acuta* maximum abundance peaking later in the year.

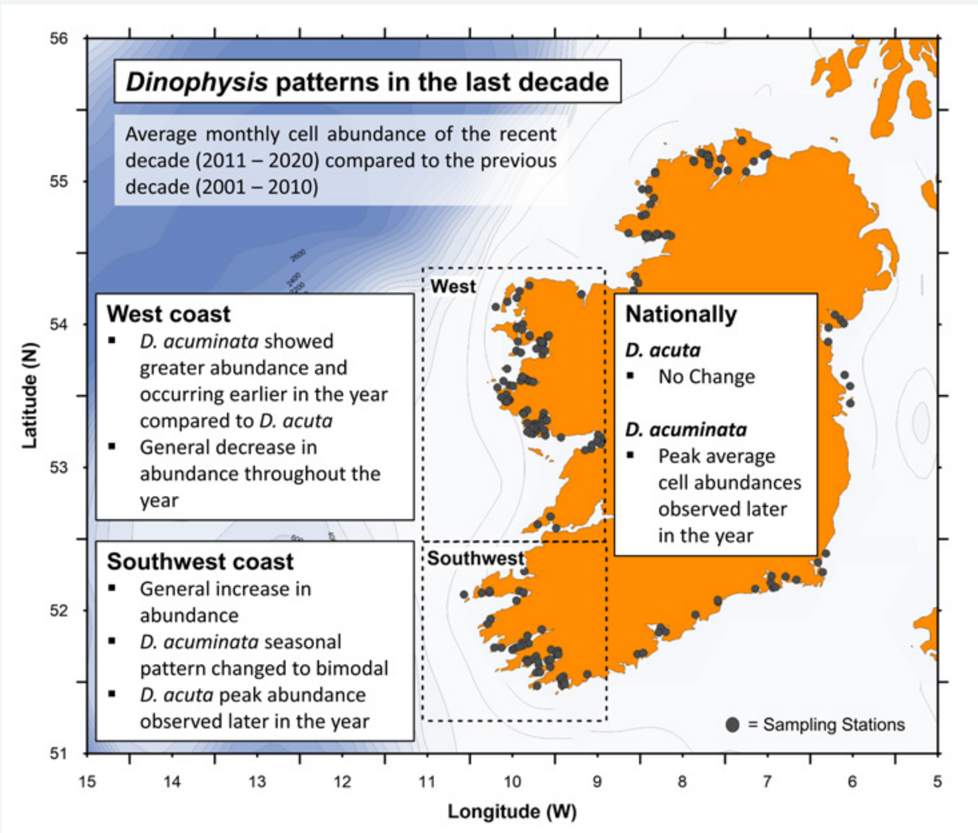


Figure 5.4 Changes observed for *Dinophysis* species between the period 2003 and 2011 and 2012 and 2020.

observed in the timing of blooms and average monthly cell abundances. In the west, there was a decrease in the average monthly cell abundance for both *D. acuta* and *D. acuminata* during 2011–2020 when compared to 2001–2010. Both *Dinophysis* species are clearly more abundant at aquaculture sites located in southwest Ireland when compared to sites in the west and when combined with the results of sites nationally around the coastline of Ireland. In the southwest, the average monthly cell abundances of *D. acuminata* increased with the maximum abundance occurring earlier in the year (June) in the recent decade (2011–2020) when compared to previous decade (2001–2010; Figure 5.5(a)). For *D. acuta* during 2011–2020, the peak abundance was in September compared to August during 2001–2010 (Figure 5.5(b)). Such changes could have an impact on the timing and length of toxin related shellfish harvesting closures.

5.6.2 *KARENIA MIKIMOTOI*

Karenia mikimotoi is a high biomass bloom forming icthyotoxic (produces chemicals harmful to fish) species that has a negative impact on caged fish and benthic communities. Historically (e.g. in 2005 and 2012) this species formed persistent and geographically extensive large blooms that had devastating effects on Irish marine ecosystems and resulted in extensive mortalities of fish and benthic organisms off the southwest and west coasts of Ireland.

Karenia mikimotoi, has shown a noticeable presence throughout the year, including the winter months since 2000 (Figure 5.6(a)). Average monthly cell abundance of this dinoflagellate in the recent decade (2011–2020) shows this organism is more prevalent than in the previous decade (2001–2010). Blooms (maximum average cell abundance) are occurring later in the year (July to September) with a maximum peak average cell

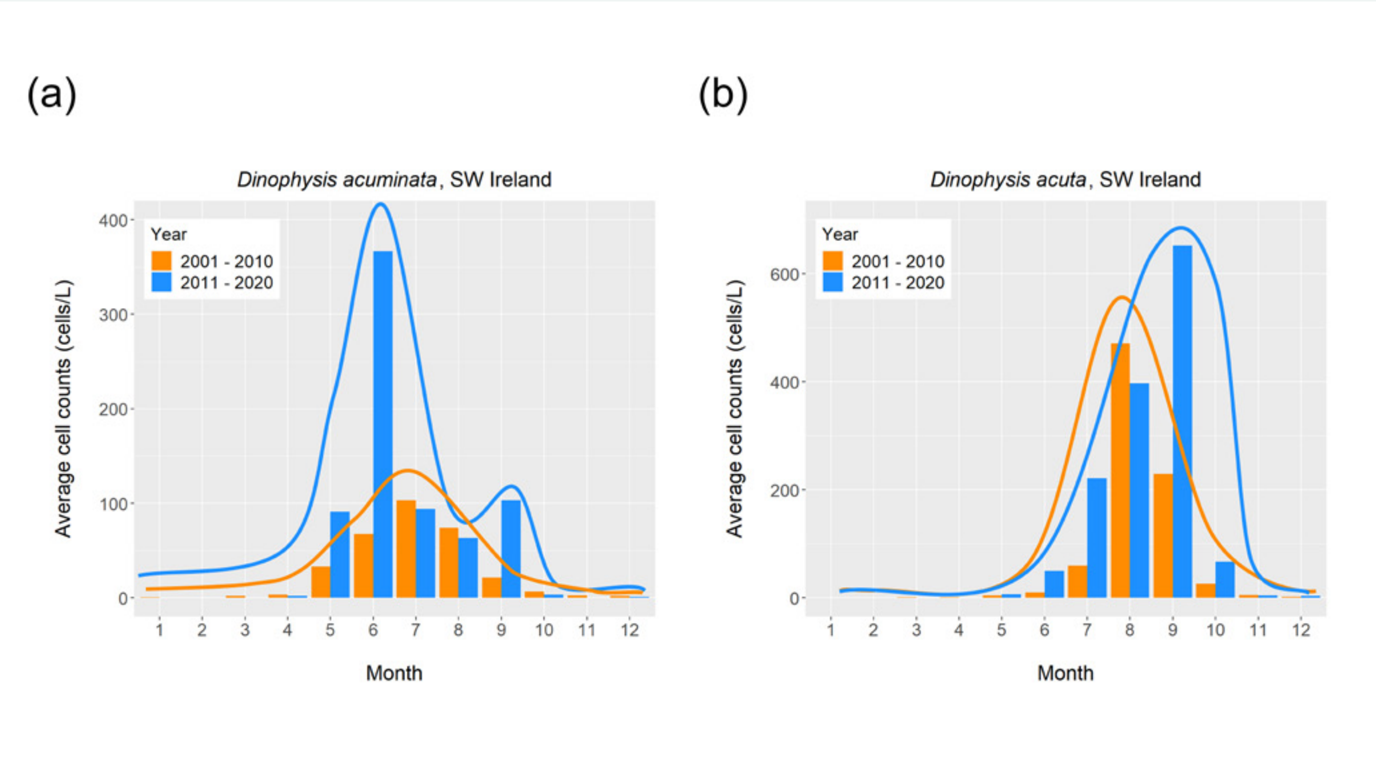


Figure 5.5 Average monthly cell counts (cells/L) for two time periods, 2001–2010 (orange) and 2011–2020 (blue). X–axis=month; Y–axis=numerical abundance. *Dinophysis* species in southwest Ireland (a) *D. acuminata* and (b) *D. acuta. Orange/Blue distribution lines are free hand drawn and are for visual purposes only to demonstrate seasonal changes in abundance between the two time periods and not statistically derived.*

abundance in July compared to June in the previous decade. This pattern is also visible in the west coast region (Figure 5.6(b)) and in the national dataset examined. Maximum average cell abundance off the southwest coast in August/September were higher than in the west (Figure 5.6(b) and 5.6(c)).

5.6.3 *PSEUDO-NITZSCHIA* SPECIES

Pseudo–nitzschia species from the "*P. seriata*" complex represent a mix of difficult to identify species, some of which produce Amnesic Shellfish Toxins. In the recent decade, the abundance of diatoms in the "*P. seriata*" complex have declined with a significant decline observed off the west coast. Nationally, blooms in spring and autumn for the period 2001–2010 are not as obvious in the most recent decade 2011–2020, where average cell abundance is consistent from April to September.

5.6.4 *ALEXANDRIUM* SPECIES

Some *Alexandrium* species cause a serious illness in humans if shellfish contaminated with Paralytic Shellfish Toxins (PST) are consumed resulting in the human syndrome referred to as Paralytic Shellfish Poisoning (PSP).

***Karenia mikimotoi* was more abundant in recent years (2011-2020) with blooms occurring later in the year (July to September), and maximum cell abundance is occurring in late July in the most recent decade compared to June in the previous decade (2001-2010) both nationally and in the southwest.**

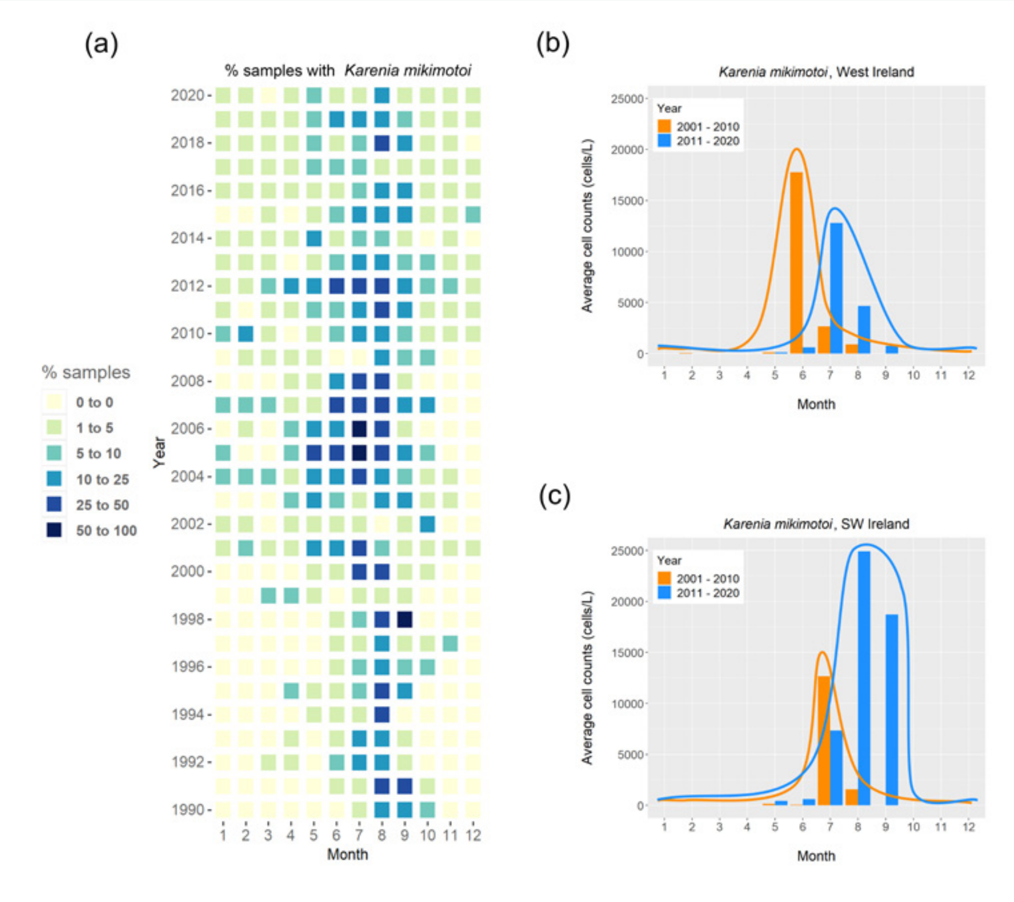


Figure 5.6 (a) Percentage of samples with *Karenia mikimotoi* cell counts (cells/L) observed from 1990 to 2020, X–axis=month; Y–axis=% of samples. Average monthly *K. mikimotoi* cell counts (cells/L); (b) west coast Ireland and (c) southwest coast of Ireland; for two time periods, 2001–2010 (orange) and 2011–2020 (blue). X–axis=month; Y–axis=numerical abundance. *Orange/Blue distribution lines are free hand drawn and are for visual purposes only to demonstrate seasonal changes in abundance between the two time periods and not statistically derived.*

Monthly cell abundance of *Alexandrium* species has increased from June to August, with a noticeable shift in the cell abundance pattern. Substantial increases in cell abundance are now observed, particularly in the southwest since 2018. Paralytic Shellfish Toxins were reported above EU regulatory levels in shellfish from the southwest for the first time in 2018, and this is now observed annually.

Alexandrium cell abundances between 2001 and 2020 were examined in this review. Key observations between two decades 2001–2010 and 2011–2020 are presented in Figure 5.7.

The geographic distribution and abundance of *Alexandrium* has changed in recent years off southwest Ireland (Figure 5.8(a)). Historically, PSTs above regulatory levels were confined to one location on the south coast, however, since 2018, PSTs above EU regulatory levels in shellfish have occurred on a near annual basis at one additional location off the southwest. This increased risk for potential Paralytic Shellfish Poisoning events is a concern to the shellfish industry and regulatory authorities. To address this, a recently funded project called PSPSafe (2021–2025) by the Department of Agriculture, Food and the Marine is working to determine the geographical extent of this issue (distribution of PSTs and associated *Alexandrium* species diversity).

Nationally, the bloom frequency and abundance of *Alexandrium* has increased in the recent decade (2011–2020). In the west, small decadal average cell abundance increases occurred in June and July (Figure 5.8(b)). In the southwest, significant increases in cell abundance occurred in the last decade between June and August, where blooms peaked in August (Figure 5.8(c)). The significant cell abundance increases off southwest Ireland include both toxic and non–toxic *Alexandrium* species, with larger bloom densities observed since 2018.

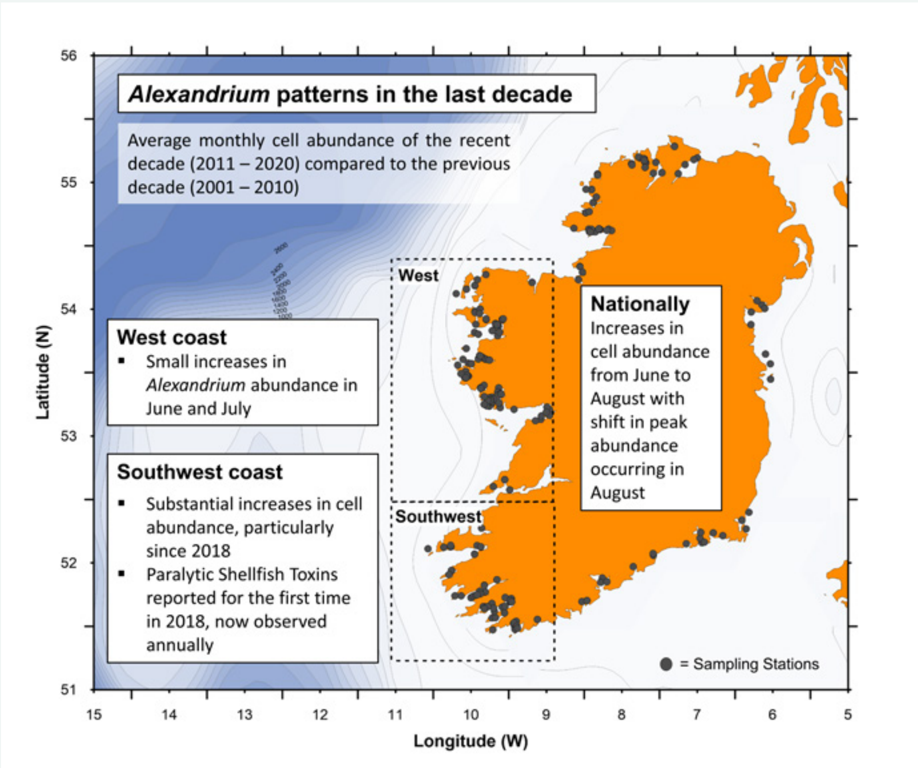


Figure 5.7 Changes observed for *Alexandrium* between the period 2003 and 2011 and 2012 and 2020.

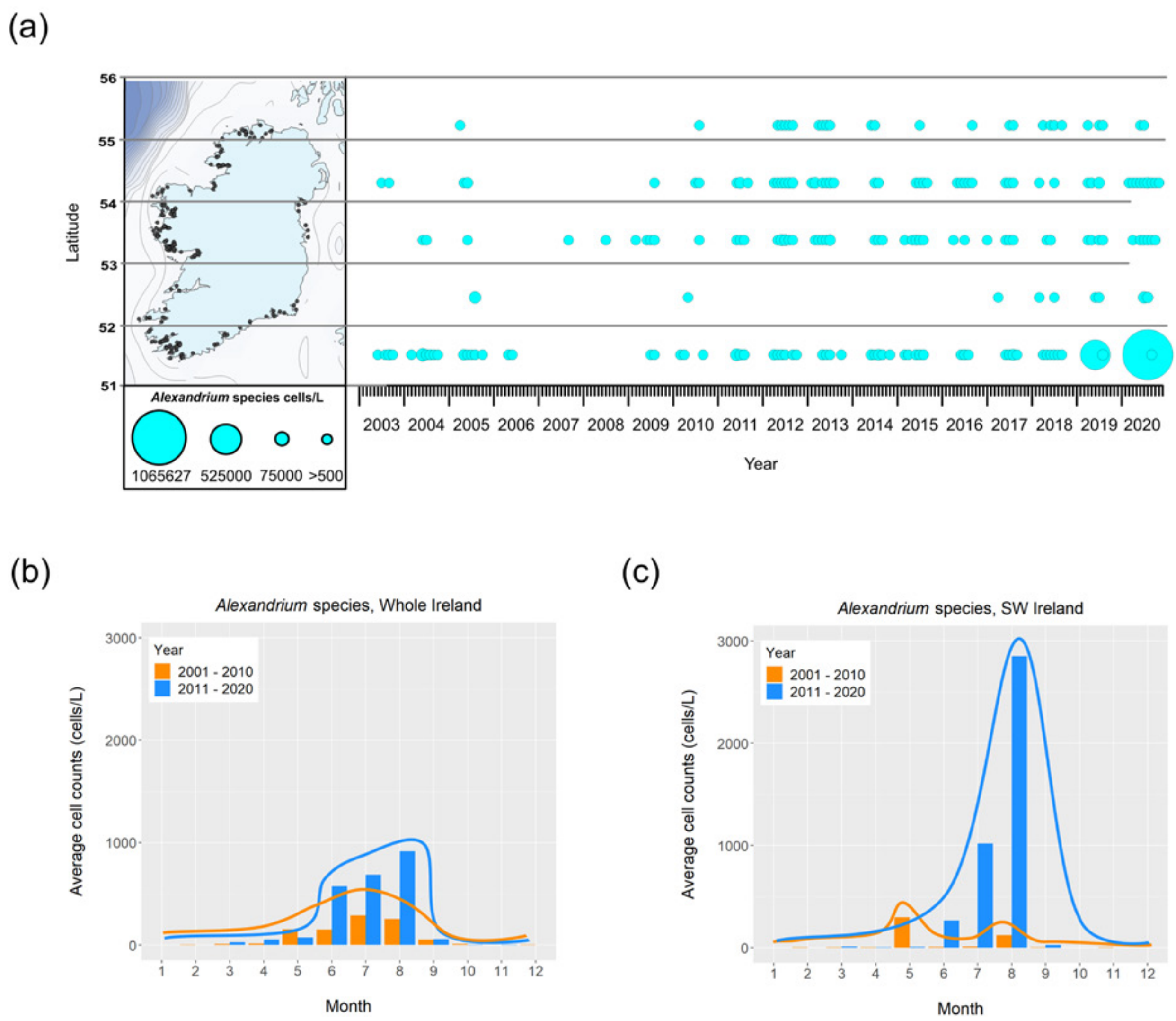


Figure 5.8 *Alexandrium* abundances and distributional patterns off the Irish coast. (a) Temporal and spatial distribution of *Alexandrium* species cells counts (>500 cells/L) from 2003 to 2021 where the X–axis=month/year and Y–axis=Latitude. Average monthly *Alexandrium* species cell counts (cells/L), (b) whole Ireland and (c) southwest coast of Ireland; for two time periods, 2001–2010 (orange) and 2011–2020 (blue). X–axis=month; Y–axis=numerical abundance. *Orange/Blue distribution lines are free hand drawn and are for visual purposes only to demonstrate seasonal changes in abundance between the two time periods and not statistically derived.*

CASE STUDY

HARMFUL ALGAL BLOOM SPECIES IN IRELAND – FUTURE PREDICTIONS

ESTIMATING HARMFUL ALGAL BLOOMS IN A FUTURE OCEAN – CASE STUDY TO DEVELOP HAB CLIMATE SERVICE (PROTOTYPE)

A downscaled Irish ocean climate model was developed in 2020 (Nagy *et al.*, 2021; Chapter 9). Using data from this numerical model combined with the National Monitoring Programme HAB data, a machine learning approach was carried out to estimate future distributions and occurrences of key Harmful Algal Bloom (HAB) taxa in Irish waters.

Most HAB taxa examined showed a slight probability of presence increase in spring, summer and autumn, and an increased bloom period in the contemporary/future ocean (2017–2035) when compared to the recent past ocean (1997–2016). The abundance model for *Dinophysis acuminata* showed similar trends. However, "*Pseudo–nitzschia seriata*" complex was an exception and only showed an increased presence in spring.

The climate service application (Figure CS5.1) was developed for *Dinophysis acuminata*. Abundance estimates in the application allows the user to view the modelled estimates under "recent past ocean conditions" (i.e. 1997–2016) and "contemporary/ future ocean conditions" (i.e. 2017–2035). An option is available to view the difference between the two time periods and to watch the distributional changes with time.

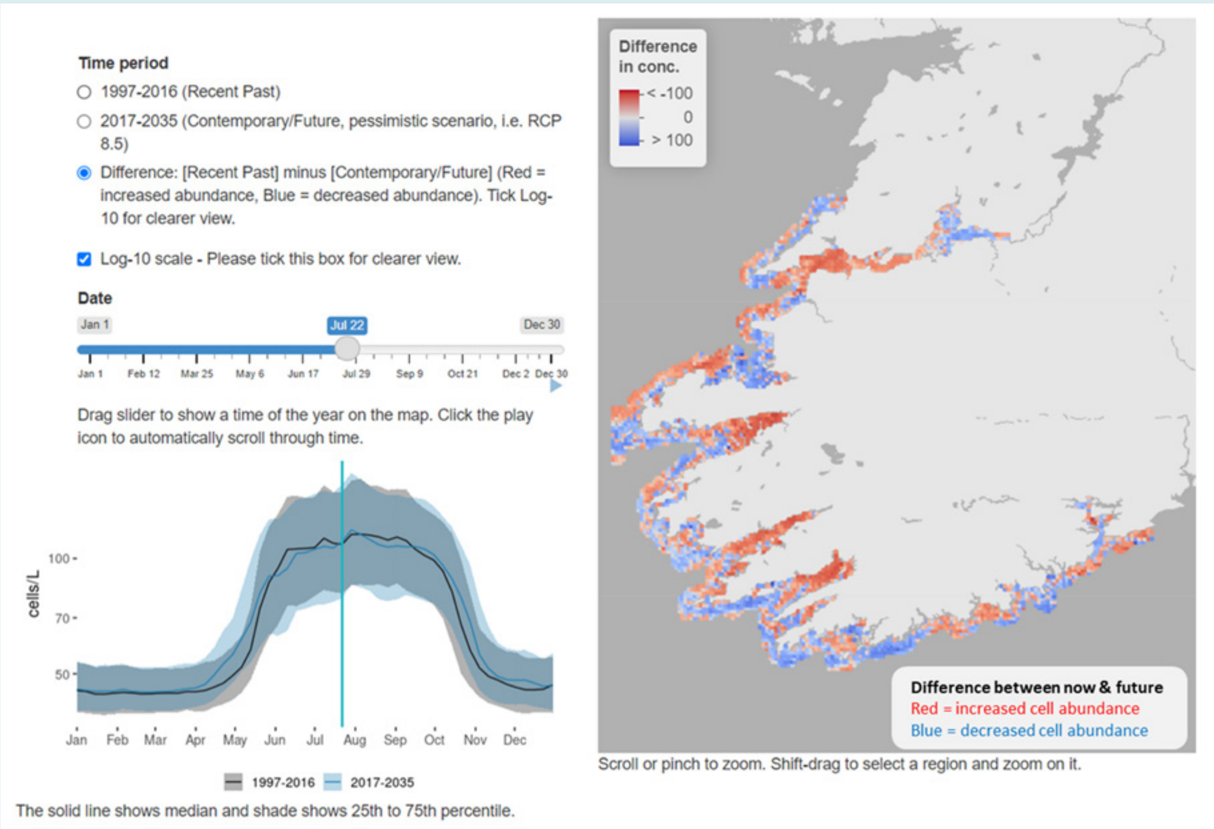


Figure CS5.1 Harmful Algal Bloom Climate Service with applications developed for *Dinophysis acuminata* presence probability and abundance estimates. The applications are also available for *Dinophysis acuta* presence and abundance, *Karenia mikimotoi* presence, "*Pseudo-nitzschia seriata*" complex presence and abundance, and *Alexandrium* species presence.

Photo credit: Caroline Cusack

5.7 RECOMMENDATIONS

1. Develop new and improved risk-management decision tools to include an operational HAB forecast system and biophysical models (including the development of HAB seasonal forecasts and HAB and phytoplankton community climate predictions) that can provide support to the seafood sector adaptation plan.
2. Establish a long-term climate network of sentinel sites (collecting biological, chemical and physical data) to detect invasive plankton species and novel/emerging biotoxins produced by these species.
3. Develop appropriate spatial scale models to estimate the future likely change in biological processes, e.g., prevalence of harmful algae.
4. Extend phytoplankton sampling offshore to improve knowledge of plankton shelf dynamics, and augment the existing alert system (HABs).

CHAPTER 6

COMMERCIAL FISHERIES

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Photo credit: Jonathan White

6.1 INTRODUCTION

Fish are a key component of marine ecosystems contributing to food webs as both consumers and prey items. As such they interact closely with their biological, physical and chemical environments. These interactions make them particularly vulnerable to potential impacts of climate change. Sea-surface temperatures in the Northeast Atlantic have risen by between 0.1 and 0.5°C per decade in the past century (Pinnegar *et al*., 2017). A detailed climate risk assessment carried out across the European marine fisheries sector placed Irish fisheries in the categories of low-medium risk (Payne *et al*., 2021). As warming is expected to continue, however, more detailed information is required to truly understand the effects of climate change on our marine fish communities.

Around €382M worth of quota fish and shellfish species are caught in the Irish EEZ annually.

This chapter provides an overview of commercial fish stocks in Irish marine waters and highlights a range of stocks, including (a) stocks of economic importance such as Atlantic mackerel, (b) potential stocks such as European anchovy and (c) historically important stocks such as cod. Potential impacts of climate change on fish communities are investigated here. Where there is little information on Irish stocks, we present information from geographically adjacent stocks to identify potential effects on Irish stocks arising from climate change. It can be difficult to disentangle climate change effects from anthropogenic activities most notably the effects of fishing. We present possible methodologies for detecting climate change including a simple community analysis approach and the use of indicator species.

Important commercial species by value include Atlantic mackerel (*Scomber scombrus*), Norway lobster (*Nephrops norvegicus*), monkfish (*Lophius spp.*) and horse mackerel (*Trachurus trachurus*).

6.2 ECONOMIC IMPORTANCE OF IRISH FISHERIES

Marine fishing is of significant importance to the Irish economy with an average number of 500 fishing vessels active daily within Irelands Exclusive Economic Zone (EEZ) (Gerritsen and Kelly, 2019). Ireland has some of the most biologically sensitive and important sea areas in EU waters with major spawning areas of Atlantic mackerel (*Scomber scombrus*), horse mackerel (*Trachurus trachurus*), blue whiting (*Micromesistius poutassou*), hake (*Merluccius merluccius*) and cod (*Gadus morhua*). Ireland's marine territory is approximately 500,000 km^2 (Government of Ireland, 2020) (Figure 6.1). Ireland's fishing waters are part of the FAO (Food and Agriculture Organization of the United Nations) Northeast Atlantic major fishing area 27 (FAO, 2021) and is further subdivided into ICES (International Council for the Exploration of the Sea) fishing areas (Figure 6.1). Fisheries stocks in Irish waters come under the remit of the EU Common Fisheries Policy (CFP) (EU 380/2013). Except for inshore fisheries, the CFP is enforced through total allowable catches (TAC) with a catch limit set for a particular fishery generally for a year or a fishing season. Around €382M worth of quota species are caught in the Irish EEZ annually (€254M by foreign vessels and €128M by Irish vessels). Irish vessels catch

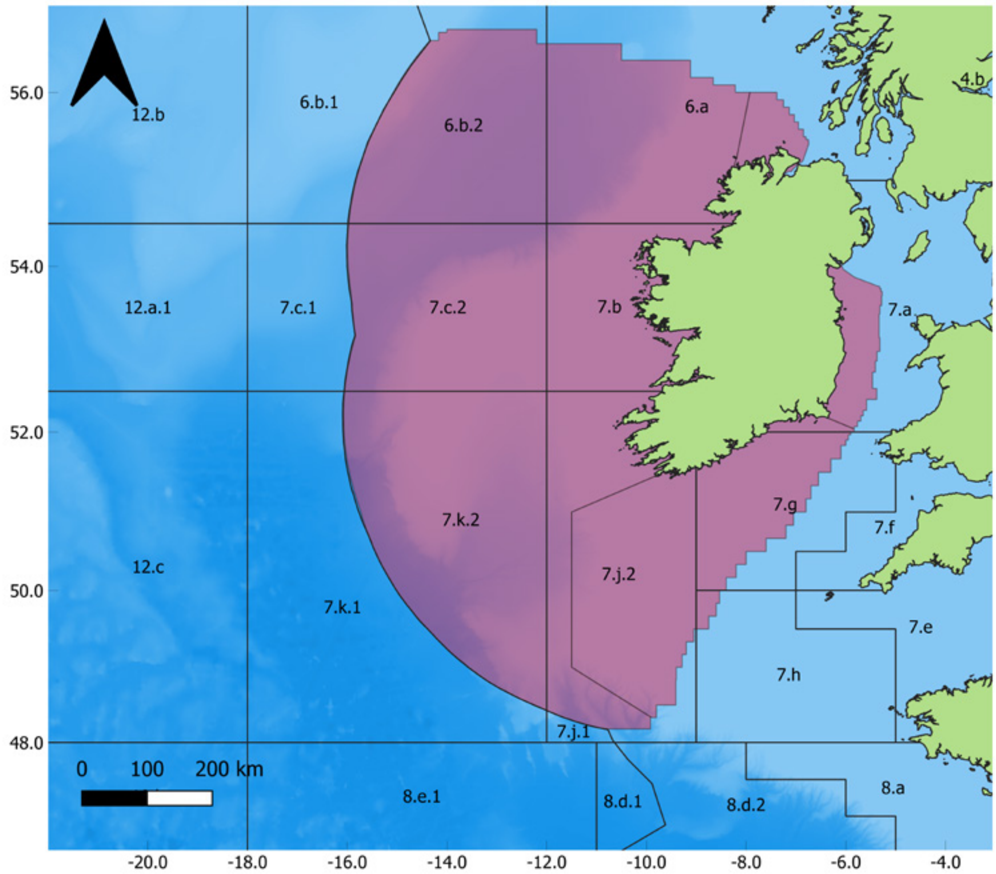

Figure 6.1 Marine waters surrounding Ireland, showing ICES fishing areas and subdivisions and Ireland's exclusive economic zone (EEZ) highlighted in purple.

around €250M worth of quota species annually (Department of Agriculture Food and the Marine, 2022). Figure 6.2 shows (a) live weight in thousand tonnes and (b) values of landings (million euros) of marine species into Irish ports from 1973 to 2020. The value of landings has shown an increasing trend since records began. This general upward trend is also evident after values were adjusted for inflation (Figure 6.2(c)). In 2019, four species; Atlantic mackerel, Norway lobster (*Nephrops norvegicus*), monkfish (*Lophius spp.*) and horse mackerel accounted for 60% of the landed value of fish into Irish ports by Irish vessels with Atlantic mackerel and Norway lobster making up approximately 50% (€118M) of this value (Central Statistics Office, 2020).

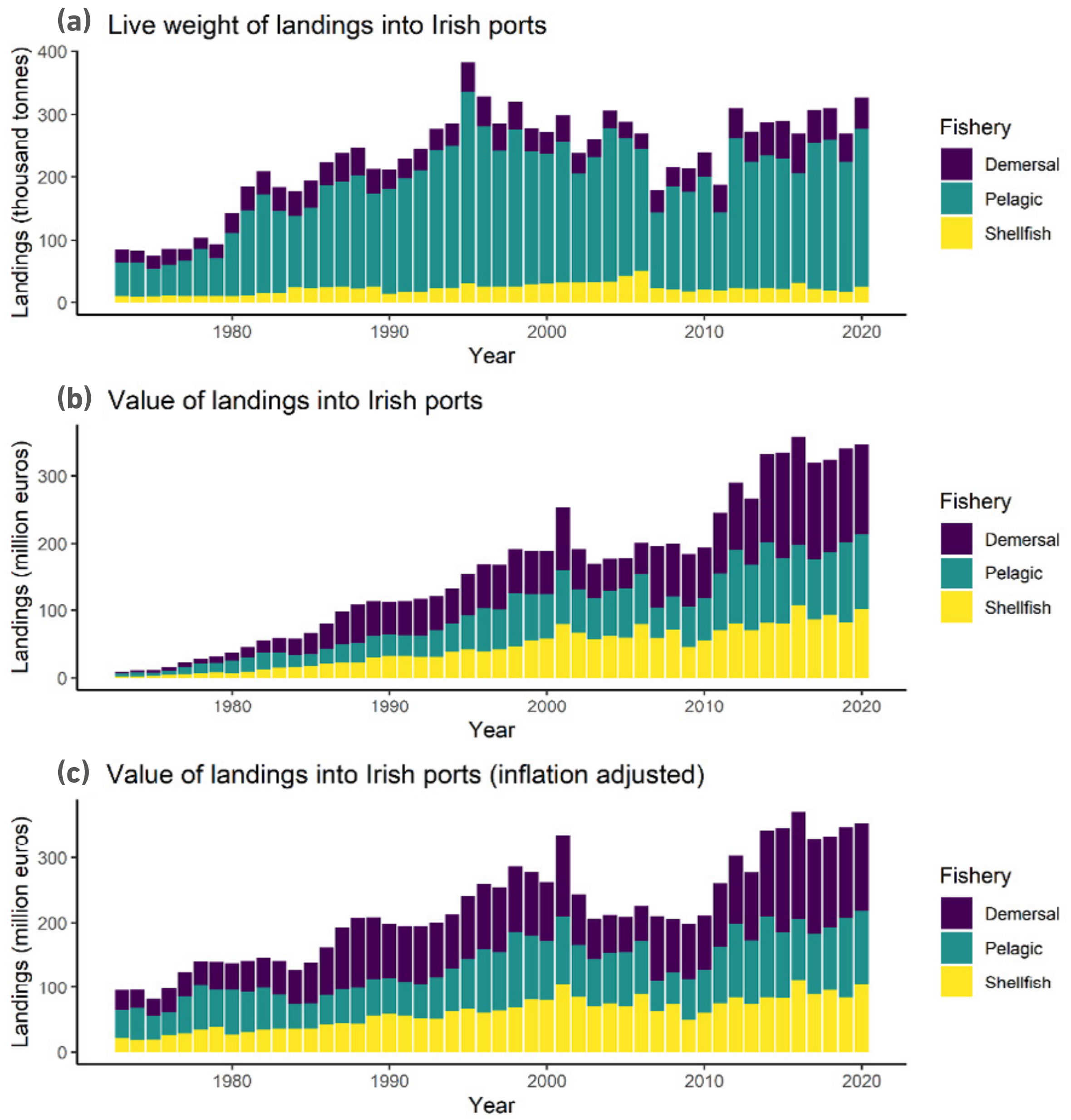

Figure 6.2 Landings into Irish ports of marine species (pelagic, demersal and shellfish[1]) (a) live weights of landings (thousand tonnes), (b) value of landings (million Euros) and (c) value of landings (million Euros) after adjustment for inflation. Data sources: 1973-2004: https://data.gov.ie/dataset/ata04-sea-fish-landings, 2005-2020: https://www.cso.ie/en/statistics/environmentstatistics/fishlandings[2], inflation rates taken from https://visual.cso.ie/?body=entity/cpicalculator.

[1]For further information on species groupings of Irish Commercial fish, please refer to the Appendix 2 in Anon. Atlas of the commercial Fisheries around Ireland, 2009.

[2]Data collected from the Sea Fisheries Protection Authority (SFPA). The SFPA Statistics Unit is responsible for collating all sea-fisheries data, particularly domestic and foreign landings by Irish vessels. Data for Irish fishing vessels of 10 m or longer was obtained from logbooks. Fishing vessels of less than <10 m are not generally required to complete a fishing logbook; landing statistics were gathered using sales notes and gatherers documents. Aquaculture and angling data are not included in this dataset.

6.3 CLIMATE EFFECTS ON FISH COMMUNITIES

Climate change is already affecting marine taxa through changes in ranges, abundance, productivity, mortality, maturity and growth (Pinnegar *et al.*, 2017: Rijnsdorp *et al.*, 2010). Climate models predict that the impact of climate change will differ between geographic areas. In Irish waters, climate change is projected to cause changes in wave height, sea surface temperature (SST), near bottom temperature (NBT), salinity and primary productivity (Chapter 9, this report). Impacts to fish communities will vary not only between geographic areas, but also between species. How a fish species responds to climate change will depend on their ability to adapt (Rijnsdorp *et al.*, 2010). Climate change may impact all stages of the fish lifecycle including (i) size and location of suitable habitat; (ii) retention of eggs and larvae; (iii) match in timing of the fish larvae and their food; (iv) connectivity between habitats of successive life stages; (v) growth; and (vi) predation mortality (Rijnsdorp *et al.*, 2010).

There is a mixture of stock trajectories within the Irish EEZ, with some stocks rebuilding well following overexploitation by fisheries. Average overall fishing mortality rates have declined in the Celtic Seas ecoregion since around the year 2000 with subsequent increases in spawning stock biomasses. Some stocks remain at levels of exploitation above current scientific advice. Declines in over-exploited fish stocks may be exacerbated by climate change.

6.3.1 RECRUITMENT/PRODUCTIVITY

The number of young fish recruited to a stock is dependent on egg production along with survival rates from eggs to juveniles. Fish eggs and spawning adults are particularly vulnerable to environmental processes most notably warming due to climate change (Dahlke *et al.*, 2020). Recruitment can be difficult to predict, with spawning behaviour and environmental conditions all influencing recruitment rates (Brosset *et al.*, 2020). Climate change can affect recruitment through changes to the physical environment or through fluctuations in the abundance and range of prey items such as zooplankton (Brunel and Boucher, 2007). In the North Sea declines in recruitment of cod has been linked to warming induced declines in zooplankton prey species (Brander, 2010). Changes in recruitment may lead to range shifts due to the decreased recruitment success of populations at the southernmost edge of their ranges (Rijnsdorp *et al.*, 2009). A study of 40 fish stocks in the Northeast Atlantic demonstrated that a long-term decline in recruitment was linked to warming SST (Brunel and Boucher, 2007). Conversely warming at the poleward edges of a population range may allow spawning areas to expand northwards.

6.3.2 DISTRIBUTION SHIFTS

A common population response to ocean warming involves the changing distribution of marine fish toward cooler waters and thus frequently poleward. The SST and NBT off southwest Ireland are projected to increase in the next couple of decades (Nagy *et al.*, 2021). Simpson *et al.* (2011) analysed fish species in the Northeast Atlantic and found that 50 common species responded to warming waters by changing distribution and abundance, with smaller bodied warm-water Lusitanian species increasing in abundance while cold-water Boreal large bodied species decreased (Rijnsdorp *et al.*, 2010). This may be a response to recruitment variations and to changes in suitable habitats. Atlantic mackerel is an example of highly publicised commercial fish stock that has expanded its range in the past decade. From the mid-2000s summer feeding populations expanded westward towards south Iceland and east Greenland and northward toward Svalbard (Olafsdottir *et al.*, 2019). The range expansion of the population can be attributed to several factors including an increased stock size, changes in zooplankton biomass and increasing ocean temperatures providing favourable conditions for fish (Overholtz *et al.*, 2011; Kvaavik *et al.*, 2020; Payne *et al.*, 2022). While expansion of a stock's range can provide novel opportunities for fisheries it can also lead to management challenges particularly for stocks like Atlantic mackerel that span several management areas. The range expansion of Atlantic mackerel allowed for the fisheries from Iceland, Faroe Islands and Greenland to begin exploiting the stock (Baudron *et al.*, 2020). Disputes over quota allocations between countries led to the so-called "mackerel wars" in the early 2010s. This study highlights the need for forecasting models that could potentially predict changes in fish distribution. Payne *et al.*, (2022) demonstrated that decadal-scale climate prediction can be applied to the habitat distribution of three fish species (mackerel, blue whiting and blue fin tuna). The study showed that the current conflicts between the European Union, Faroe Islands, Norway and Iceland over Atlantic mackerel fishing quotas (Spijkers and Boonstra, 2017) could have been foreseen using predictive models (Payne *et al.*, 2022).

While fish may experience northward range shifts with the advent of warming waters, there is some evidence that certain species may change their distribution vertically in the water column. Atlantic cod off the Norwegian Skagerrak coast were shown to select shallower vegetated habitats with better feeding opportunities at cooler temperatures while at higher temperatures they showed a preference for non-vegetated rocky bottoms and sand habitats that provided deeper, colder conditions (Freitas *et al.*, 2016; Freitas *et al.*, 2021). With increasing sea temperatures, species may be forced to inhabit deeper habitats with suboptimal feeding conditions as a trade-off for favourable temperature conditions (Freitas *et al.*, 2016). The availability of habitats at suitable depths may constrain the adaptability of demersal fish in particular (Rutterford *et al.*, 2015). As there is commonly a decoupling between SST and NBT, either due to lateral current flow or seasonal stratification (Rheuban *et al.*, 2017), it is vital to understand the projected spatial and temporal variability of the water column for future management of fisheries (Rheuban *et al.*, 2017).

Disentangling long-term fishing effects from the impacts of climate change is difficult. Climate change cannot be examined in isolation of these effects.

6.3.3 BODY SIZE AND GROWTH

As oceans warm they will also experience deoxygenation which can have consequences for fish metabolism and physiology. Marine fish as ectotherms are expected to develop faster but reach smaller adult body sizes due to the interactive effects of temperature and oxygen availability (Ohlberger *et al.*, 2011). Evidence of body size changes has already been noted in certain fish species found in Irish waters. Decreases in size at age for herring in the Celtic Seas ecoregion was noted since the mid-1980s (Lynch, 2011). Lyashevska *et al.*, (2020) related this decline in adult size to increases in sea surface temperature during the first growing season. Negative relationships between growth and temperature were noted in other fish stocks including haddock in the North Sea (Baudron *et al.*, 2011) and Mediterranean fish populations (Shapiro Goldberg *et al.*, 2019). Declines in growth can also be attributed to food availability, density dependant and fishing effects (van Walraven *et al.*, 2010; Lyashevska *et al.*, 2020).

Warming waters may allow for new fishing opportunities (e.g. boarfish and anchovy), but it is imperative that new opportunities are managed effectively and sustainably.

CASE STUDY

THE CASE OF SNAKE PIPEFISH (*ENTELERUS AEQUORAEUS*)

Increases in rare migrant species from more southerly waters is one of the expected outcomes of warming waters, however, scientists and policy makers must be careful not to attribute all unexpected changes in distributions to climate change. The increase of snake pipefish (*Entelerus aequoraeus*) in the North Sea in 2003 and subsequently in Irish waters was attributed at the time to rising sea surface temperatures facilitating increased fecundity of the species (Kirby *et al.*, 2007). Since 2008 however, numbers of this species have declined in the Irish Groundfish Survey (IGFS) despite a continuing upward trend in sea surface temperature (SST) (Figure CS6.1). This decline in abundance was seen throughout its geographic range (Heath *et al.*, 2012). There is some anecdotal evidence of mass mortality events of this species in the Atlantic Ocean and North Sea previously (Brongersma-Sanders, 1957). Whether these mass mortality events were linked to previous population explosions is unknown. Natural fluctuations in fish populations, such as snake pipefish, highlight the importance of long-term monitoring if we are to accurately model the impacts of climate change on marine ecosystems.

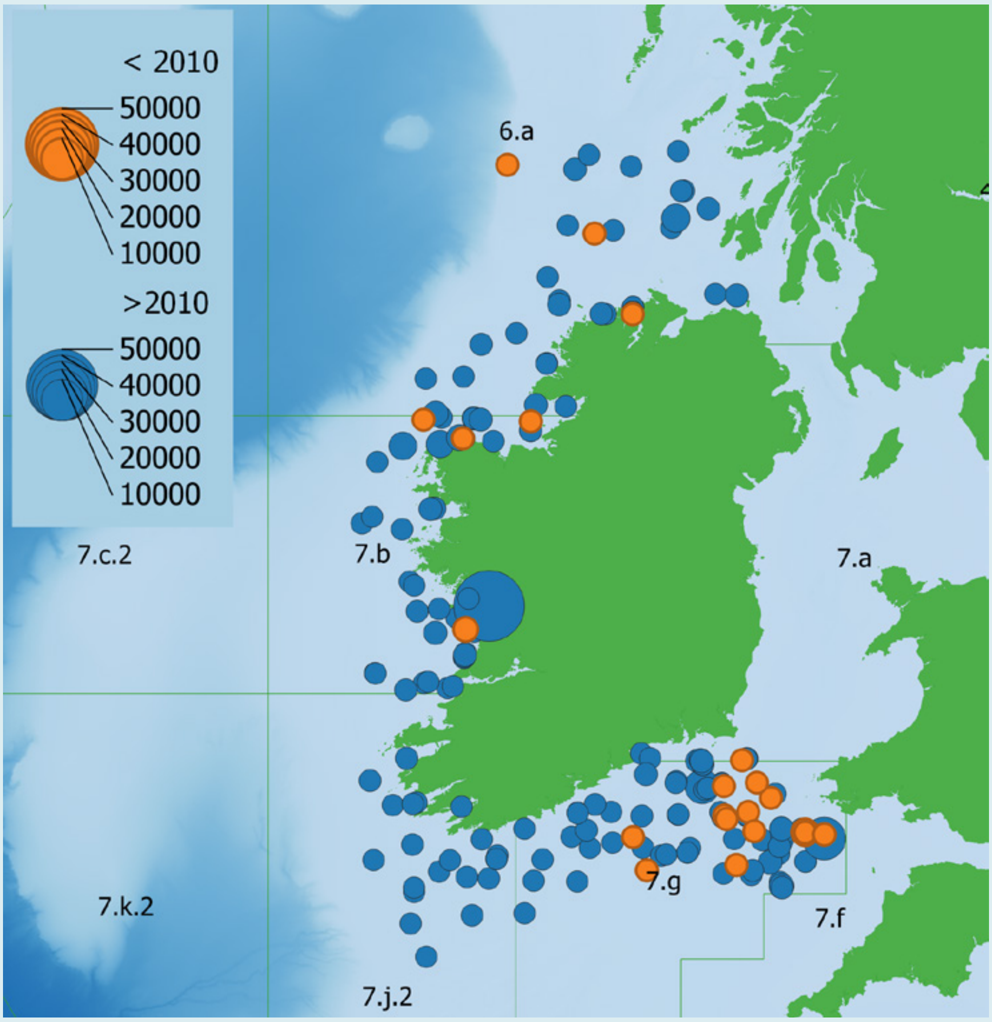

Figure CS6.1 The distribution (no/km^2) of Snake Pipefish (*Trisopterus minutus*) from the Irish Groundfish Survey from 2003–2008 (orange circles) and 2009–2020 (blue circles).

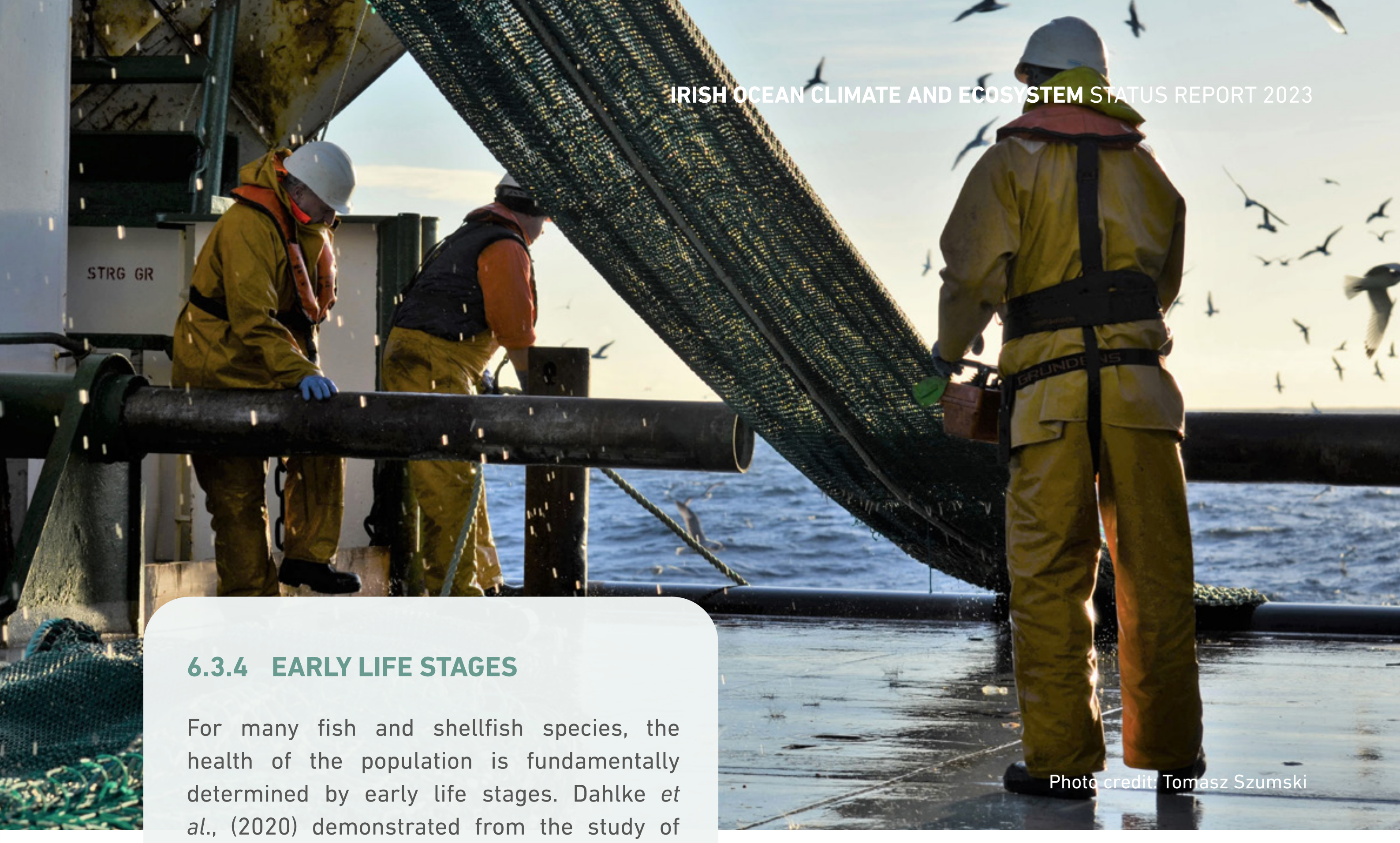

Photo credit: Tomasz Szumski

6.3.4 EARLY LIFE STAGES

For many fish and shellfish species, the health of the population is fundamentally determined by early life stages. Dahlke *et al.*, (2020) demonstrated from the study of 694 marine and freshwater fish species that spawning adults and embryos have narrower thermal tolerance ranges than other life stages. They hypothesised that the "thermal bottlenecks" may define the vulnerability of fish to thermal changes caused by climate change. Physiology and growth rates of larvae are also affected by environmental temperatures (McGeady *et al.*, 2021). McGeady *et al.* (2021) modelled larval transport of the Norway lobster (*Nephrops norvegicus*) in the Irish Sea and, demonstrated that embryo incubation and release of larvae occurred 17.2 days earlier in the period of 2000–2010 than in 1982–1995. The 17.2 day earlier release time accompanied a 0.9°C increase in surface water temperature coinciding with the incubation period (McGeady *et al.*, 2021).

Oceanographic environments are complex with many physical and biological interactions. This can make it difficult to estimate the effects of parameters on early life stages, demonstrated particularly when examining the abundance of the mesopelagic gadoid blue whiting (*Micromesistius poutassou*). Stocks of blue whiting in the Northeast Atlantic show fluctuations in abundance over time. Payne *et al.* (2012) postulated several hypotheses to explain the variations in abundance including large mackerel feeding on blue whiting pre-recruits and variations in the physical environment affecting the food type available to larvae. When the sub-polar gyre (See Chapter 3 of this report for more information) is strong (large in size), cold fresh water spreads east over the Rockall plateau limiting blue whiting spawning to a narrow area along the European continental slope and to the south of the Porcupine Bank (Hátún *et al.*, 2009). When the gyre is weak (constricted) blue whiting spawning spreads northwards and westwards along the continental slope over the Rockall plateau (Hátún *et al.*, 2009). Spawning of blue whiting appears limited to a salinity window of 35.3 to 35.5 (Miesner and Payne, 2018). Weak gyre conditions are associated with more saline, warm water conditions (Hátún *et al.*, 2009). Spatial overlap between blue whiting pre-recruits and their mackerel predators may be regulated by the sub-polar gyre (Payne *et al.*, 2012). Mackerel spawning distribution is limited to the continental shelf edge during March to April and covers more of the blue whiting spawning area from April to May (ICES, 2011). In years with strong gyres, the spatial overlap between spawning distribution of both species is limited, restricting opportunities for mackerel to prey on blue whiting. Hydrographic surveys have indicated that the Northeast Atlantic is currently in a period of freshening (González-Pola *et al.*, 2020) constricting the habitat typically associated with blue whiting. Future climate model projections, up to 2035, estimate that surface and bottom waters off southwest Ireland will continue to freshen (Nagy *et al.*, 2021).

6.4 STATUS OF MAJOR STOCKS

Overall, fishing mortality rates have declined in the Celtic Seas ecoregion since around the year 2000 with subsequent increases in spawning stock biomasses on average (ICES, 2021a). Forty-seven percent of stocks are fished below F_{MSY}, but not all stocks are currently fished at fishing mortality rates commensurate with long-term maximum sustainable yield (MSY), with 15% fished above this rate and 37% with unknown or not defined exploitation rates in 2021 (Marine Institute, 2021). While overexploitation was significantly addressed within the region, there are stocks that are still overfished. The effects of climate change on a stock will depend not only on the biology and ability to adapt to change, but also on the current stock status. The health of stocks is monitored through implementation of the CFP and collection of data under the data collection framework (DCF) Directive (EC 665/2008; 2010/93/EU). Data collected from these programmes also feeds into the EU Marine Strategy Framework Directive (MSFD) (2008/56/EC), which was instigated in 2008 in an effort to protect the marine environment across Europe (Marine Strategy Framework Directive, 2008). The Directive requires Member States to take appropriate action to maintain or achieve Good Ecological Status (GES) by 2020. In terms of commercial fisheries, it aims to restore and maintain populations of harvested species to levels that can produce the MSY and minimise wider impacts of fishing on the ecosystem (Department of Housing Planning and Local Government, 2019). In the latest assessment, GES was achieved for five of the eleven qualitative descriptors used to assess the quality of marine waters. Commercial fisheries are covered under Descriptor 3 – Commercially Exploited Fish and Shellfish and GES was not fully achieved. A total of 34 stocks (18%) have achieved GES, while the environmental status of 99 stocks (60%) is currently unknown. GES was not achieved for 44 of the remaining stocks (Department of Housing, Local Government and Heritage, 2021).

Ireland's position in the Northeast Atlantic supports a wide variety of fish stocks with varying biogeographic affinities (Lusitanian/Boreal/Atlantic). Depending on the life history of the population, potential impacts of climate change can be very different. Due to this diverse nature of marine habitats in Irish waters, numerous stocks of importance are exploited by vessels from more than one country. International cooperation is required to accurately access the health of these stocks. Most scientific assessments and advice for stocks in Irish waters is delivered by the International Council for the Exploration of the Sea (ICES). ICES provides scientific advice to governments and international regulatory bodies that manage fisheries stock assessments. ICES stock assessment data is presented for six stocks found in Irish or adjacent waters with a mixture of biogeographical affinities (Table 6.1, Figure 6.3). Example stocks are highlighted with respect to their biogeography, life history, fisheries and climate vulnerability.

For future management of demersal fisheries such as hake, cod, whiting and haddock, it is vital to understand the projected spatial and temporal variability of both sea surface temperatures and near bottom temperatures.

6.4.1 HERRING AND COD

Herring and cod are cold water (boreal) species and are at the southern limit of their range. Both species demonstrate overall declines in spawning stock biomass (SSB) over their respective time series. This can be attributed to overexploitation in the 1970s and 1980s (Cook *et al*., 1997; Cushing, 2001; Kelly *et al*., 2006). Fishing pressure on the Celtic Sea cod stock is above the reference points FMSY, Fpa, and Flim and spawning-stock biomass is below MSY $B_{trigger}$, B_{pa}, and B_{lim} (ICES, 2021b). Since 2017, cod SSB was below B_{lim} indicating that recruitment has a high likelihood of being "impaired". Forecasting models using a range of projected climate change scenarios predicted declines in abundance of Atlantic cod in the Celtic Seas (Maltby *et al*., 2020).

Historically, herring was one of the most important pelagic species caught by Irish fisheries. Stock collapses in the Celtic Seas ecoregion in the 1970s and early 2000s led to catches dropping from over 150,000 tonnes in the 1970s to present levels of less than 2,000 tonnes. Current assessments of herring stocks in the Celtic Sea and west of Scotland categorise SSB levels to be at the lowest levels seen since the time series began in the 1950s (ICES, 2021c). For 2022, ICES recommendations is for a zero catch where a precautionary approach applies (ICES, 2021c). Herring and cod are highly susceptible to potential ocean warming. As noted in section 6.3.3, herring in the Celtic Seas ecoregion show steady decreases in size at a given fish age from the mid-1980s, which can be partially explained by rising sea temperatures (Lyashevska, *et al*., 2020). This decline in size may lead to an increased vulnerability of herring in the Celtic Seas ecoregion which is already at the southern limit of its range.

6.4.2 ATLANTIC MACKEREL AND BLUE WHITING

Atlantic mackerel (*Scomber scombrus*) in the Northeast Atlantic is a migratory, widely distributed pelagic schooling fish. Atlantic mackerel stocks in the Northeast Atlantic are relatively stable with fishing mortality approximately at F_{MSY} and SSB greater than $MSY\ B_{trigger}$ (ICES, 2021d). From 2010-2019, the value of Atlantic mackerel catches landed into Irish ports amounted to an average of approximately €46M making it the most economically important stock to Ireland. While Atlantic mackerel stocks appear stable, changes in migration and spawning patterns have been evident over the last decade (Astthorsson *et al*., 2012; Bruge *et al*., 2016). Since 2007, large numbers of Atlantic mackerel were observed in the waters around Iceland allowing for the development of a direct fishery in the Icelandic Exclusive Economic Zone (Astthorsson *et al*., 2012; Bruge *et al*., 2016).

Table 6.1 Common characteristics of six stocks from Irish and adjacent waters.

Common Name	Latin Name	Habitat	Biogeographical affinity	Fish Stock Code	Stock Location
Cod	*Gadus morhua*	Demersal	Boreal	cod.27.7e-k	Celtic Sea and west of Scotland
Herring	*Clupea harengus*	Pelagic (Benthopelagic)	Boreal	her.27.6a7bc	Celtic Sea and west of Scotland
Atlantic mackerel	*Scomber scombrus*	Pelagic (Epipelagic)	Atlantic/ Migratory	mac.27.nea	Northeast Atlantic and adjacent waters
Blue whiting	*Micromesistius poutassou*	Pelagic (Mesopelagic)	Atlantic/ Migratory	whb.27.1-91214	Northeast Atlantic and adjacent waters
European hake	*Merluccius merluccius*	Demersal	Lusitanian	hke.27.3a46-8abd	Northern stock (Greater North Sea, Celtic Seas, and the northern Bay of Biscay)
European anchovy	*Engraulis encrasicolus*	Pelagic	Lusitanian	ane.27.8	Atlantic Iberian waters

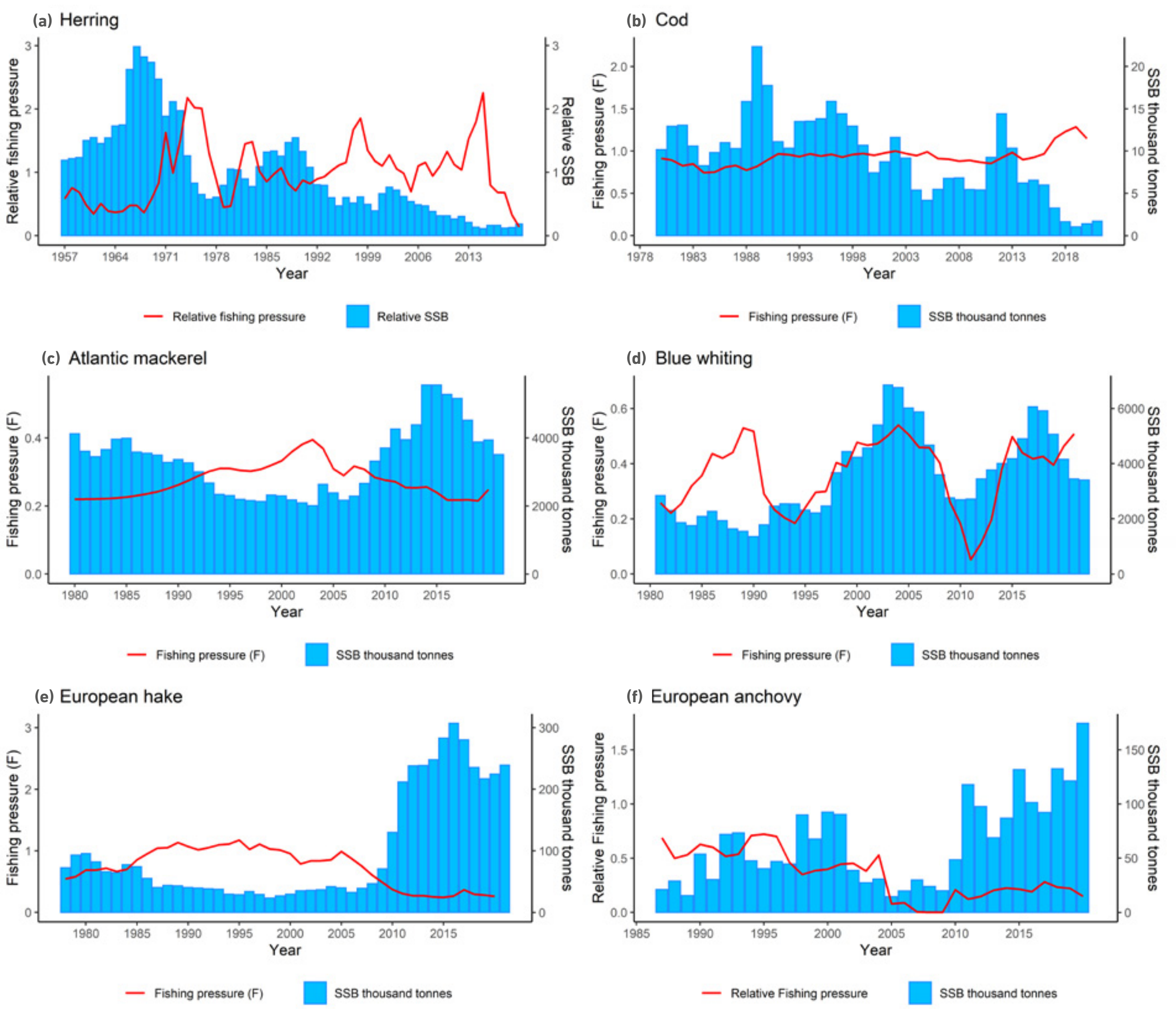

Figure 6.3 Fishing pressure F (blue bars) and spawning stock biomass SSB (red line) of six commercial species in Irish and adjacent waters (data source: http://standardgraphs.ices.dk/stockList.aspx), (a) Herring (*Clupea harengus*), Celtic Sea and west of Scotland stock, (b) Cod (*Gadus morhua*), Celtic Sea and west of Scotland, (c) Atlantic mackerel (*Scomber scombrus*), northeast Atlantic and adjacent waters, (d) Blue whiting (*Micromesistius poutassou*), northeast Atlantic and adjacent waters, (e) European hake (*Merluccius merluccius*), northern stock (Greater North Sea, Celtic Seas, and the northern Bay of Biscay), and (f) European anchovy (*Engraulis encrasicolus*), Atlantic Iberian waters. Note: the different timescales over which the data is available. Fishing pressure in graphs (a) and (f) and SSB in graph (a) are expressed as relative to mean over assessment period.

Blue whiting (*Micromesistius poutassou*) is a pelagic gadoid fish closely related to cod, haddock and hake. Found over the continental slope and shelf to more than 1000 m, it is more commonly found at depths of 300–400 m. Estimates of the spawning stock of blue whiting in the Northeast Atlantic is carried out by the annual international blue whiting spawning stock survey that targets spawning and post-spawning fish. The 2022 survey estimated that the total stock biomass (TSB) of blue whiting in the area was 2.7 million tonnes, representing a 15% increase in biomass from the previous survey (Marine Institute, 2022). While in recent years blue whiting SSB has declined from a high of approximately 6.2 million tonnes in 2018 (Figure 6.3(d)), the stock size remains above B_{lim}. A 4% increase in SSB was noted in 2022 compared to 2021 however, the fishing pressure on the stock remains above F_{MSY} and F_{lim} (ICES, 2022).

There is some evidence of increases in warm water (Lusitanian) species to the south of Ireland (2003-2020). Increased abundance of European anchovy has been noted in both scientific surveys and commercial catches.

6.4.3 EUROPEAN HAKE AND EUROPEAN ANCHOVY

Hake and anchovy are considered Lusitanian (warm water) species. Under a warming ocean scenario, it is expected that Lusitanian species will expand poleward (see Section 6.3.2). Figure 6.3(e) shows fishing pressure and landings from the northern stock of European hake; in general, there is a rising trend in SSB from the mid-2000s to present. In 2009 a recovery plan, was implemented by the European Commission to improve northern hake stocks in European Union waters. This has led to a decrease in fishing mortality and an increase in SSB (Figure 6.3(f)). Increases in hake are mostly attributed to implementation of a more sustainable exploitation regime (Baudron and Fernandes, 2015). However, an increase in suitable habitats due to warming may allow further expansion of this species.

While not yet a major stock in Irish waters, recent evidence indicates that European anchovy may be increasing in numbers. There is no stock assessment data for the European anchovy in Irish waters, however, data from the 2020 Celtic Sea herring acoustic survey indicated high densities of anchovy from Helvick to Waterford harbour within 10 nmi of the coast (O'Donnell *et al.*, 2020). Higher densities of anchovy have also been noted in the groundfish survey carried out in Irish waters annually (Figure 6.4). European anchovy is a pelagic species that forms large schools. and there is some evidence of anchovy increasingly being caught in commercial fishery catches (Siggins, 2020). Figure 6.3(f) presents data from the Atlantic Iberian European anchovy stock to the south of Ireland. The SSB has increased in the last decade. European anchovy has been observed in increasing quantities in northern European and Baltic waters (Alheit *et al.*, 2012). As a small pelagic clupeoid fish, anchovy can respond quickly to changes in climate and can often be used as an indicator of ecosystem change (Lehodey *et al.*, 2006; Checkley *et al.*, 2009; Alheit and Bakun, 2010). To date there is no indication of anchovy spawning in Irish waters. The expansion of anchovy into the Baltic Sea in the mid-1990s has been attributed to a combination of global warming, strengthening of the North Atlantic Oscillation (NAO), the positive phase of the Atlantic Multidecadal Oscillation (AMO) and sub-polar gyre contraction (Alheit *et al.*, 2012). With water temperatures set to continue increasing in the waters surrounding Ireland (Chapter 9, this report) it is reasonable to assume that an increased presence of fish species with southern biogeographic affinities may occur. It is thought that historical changes in the distribution and abundance of these species occurred in response to changes in NAO, AMO and the Subpolar Gyre. Further research is needed to identify what the added effect of climate change will have on these variations and how fisheries managers can respond to maintain sustainable populations.

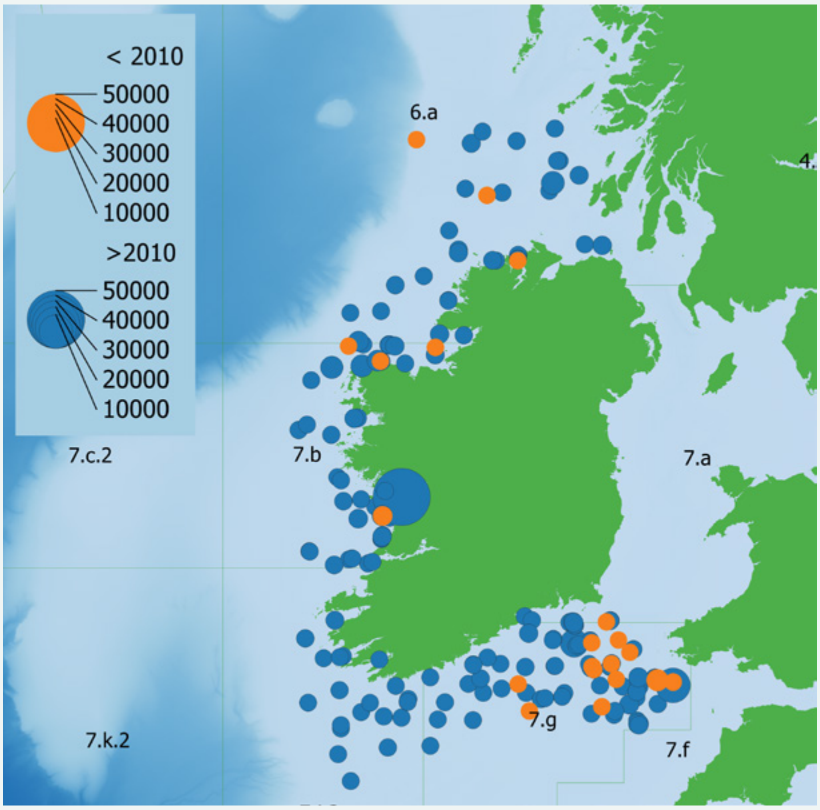

Figure 6.4 The distribution (no/km^2) of European anchovy (*Engraulis encrasicolus*) from the Irish Groundfish Survey from 2003–2009 (orange circles) and 2010–2020 (blue circles).

6.4.4 POTENTIAL FOR NOVEL FISHERIES

As the abundance of warm-water species increase in Irish waters, they may become a viable option for exploitation by fisheries. While we have yet to see any significant exploitation of the European anchovy by vessels in Irish waters, other novel fisheries have developed in the last decade. Elevated numbers of boarfish (*Capros aper*) in the early 2000s led to the development of new pelagic trawl fishery targeting this species. Boarfish are small deep bodied fish, growing up to 23 cm in length but are typically smaller up to an average of 12.9 cm (White *et al*., 2011). They are a mesopelagic shoaling species often associated with the continental shelf edge, an area of high productivity (O'Donnell *et al*., 2012). As a Lusitanian species, elevated water temperatures may be contributing to its increased numbers in more northerly waters (Coad *et al*., 2014). The boarfish fishery is conducted in shelf waters to the south and southwest of Ireland and northern Biscay (ICES, 2021e).

It is important that any novel fishery that arises from distributional shifts are managed sustainably. The boarfish fishery was unrestricted until 2010 with a total catch of 144,047 tonnes reported that year. The biomass rapidly declined in subsequent years, with a TAC of 33,000 tonnes implemented from 2011 in ICES Subareas 6, 7 and 8. In 2020, Ireland took 14,666 tonnes out of a total catch of 15,649 tonnes (ICES, 2021e). Any exploitation of potential new stocks (e.g. European anchovy) should be approached with caution, allowing for development of effective management strategies. This will ensure species are exploited at a level that will maintain a maximum sustainable yield (MSY) while still contributing to the Irish fishing industry and economy.

Photo credit: Jonathan White

6.5 ASSESSING CLIMATE IMPACTS IN IRISH WATERS

Perhaps the biggest challenge to determining climate change impacts on fish species is disentangling the simultaneous pressure of fishing (ter Hofstede and Rijnsdorp, 2011). Declines in species abundance such as cod and herring in the Celtic Seas ecoregion can be attributed to fishing making it difficult to extract information on the effects of climate change on these stocks. Additionally, an over-exploited stock may be more sensitive to further environmental perturbations (Minto *et al.*, 2008) making them more sensitive to climate change effects.

6.5.1 CLIMATE INDICATOR SPECIES

To investigate climate change effects, Nolan *et al.* (2010) suggested using climate indicator species defining them as species with the following 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.

A potential species fitting these criteria is the Lusitanian species poor cod (*Trisopterus minutus*). Poor cod are caught regularly in the Irish Groundfish Survey (IGFS), a fisheries independent scientific survey carried out annually as part of the International Beam Trawl Survey. Poor cod increased in density (number per km^2) to the north of Ireland (VIa) from 2003 to 2010. However, abundance declined from 2011 to 2020 (Figure 6.5). These decreases have been mirrored in other areas to the south of Ireland (VIIj and VIIg). Further research is required to investigate whether the fluctuations in potential indicator fish species can be related to climate change.

6.5.2 COMMUNITY RESPONSE

Likely climate change effects on Irish fish stocks have already been demonstrated in various studies mostly focusing on individual stocks and species (Lyashevska, *et al.*, 2020; McGeady *et al.*, 2021). In order to examine the fish community as whole and following the methods of Lynam *et al.* (2010) we took a community level approach to examine the effect of ocean warming on fish communities in Irish waters. Fish sampled by the IGFS from 2003 to 2020 were grouped by their biogeographic affinity for warmer (Lusitanian) or cooler (Boreal) waters. The temporal trends were evaluated for each species using a Mann–Kendall test with

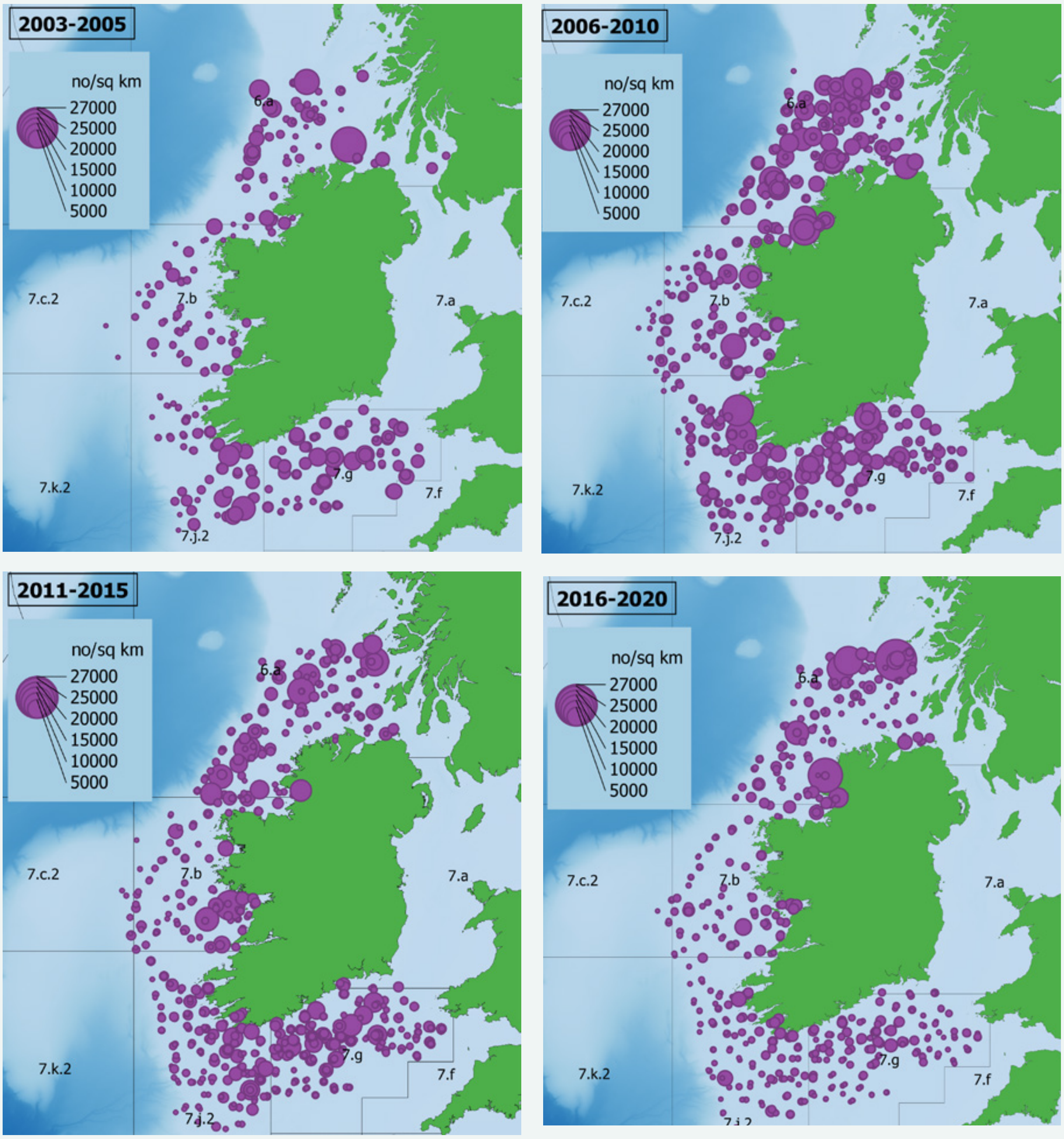

Figure 6.5 The distribution of poor cod (*Trisopterus minutus)*, (2003–2020) from the Irish Groundfish Survey, where bubble size indicates density in numbers per km^2.

the resulting distribution of tau coefficients (correlation between relative abundance and time) compared to a null distribution. Deviation from the expected null distribution allows inference on whether taxonomic groups are increasing or decreasing overall in different areas (Figure 6.6). Previous analysis of IGFS data showed Boreal taxa were significantly decreasing in the south while Lusitanian species were increasing in the north and west (Lynam *et al*., 2010). The current analysis updates the time series adding in the IGFS data from 2008 to 2020. In the updated analysis no significant increasing or decreasing trends were noted in the Boreal communities. The Lusitanian communities in the southeast (ICES division 7g) and southwest (ICES division 7j) showed significantly increasing trends ($p < 0.001$*). While it is difficult to assign changing fish distributions to climate change, increases in Lusitanian species such as anchovy (*Engraulis encrasicolus*) may indicate a response to warming waters. Therefore, although individual species such as anchovy show changes in distribution, there is little evidence at the community level for a broad-scale expansion of warm-water Lusitanian species or a contraction of cold-water Boreal species in the Celtic Seas ecoregion. Further study is needed to analyse these changes in distribution. In particular, it is important that future studies investigate the effects of climate in conjunction with fishing effort. This research was carried out under the ClimFish project ("Impacts of Climate Change on Commercial Fish Stocks in Irish Waters"), a collaboration between the Marine and Freshwater Research Centre at the Atlantic Technological University, Galway and the Marine Institute. The project is carried out with the support of the Marine Institute and is funded under the Marine Research Programme by the Irish Government.

Increases in some species may be due to natural long-term fluctuations in abundance (e.g. snake pipefish). This highlights the value of historical documentation and long-term datasets that monitor beyond commercial stocks.

MANN–KENDALL TEST

A Mann–Kendall Test is used to determine whether a time series has a monotonic upward or downward trend. The null hypothesis for this test is that there is no trend. For the time series $x_1, .., x_n$, the MK Test uses the following statistic:

$$s = \sum_{i=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_i)$$

Note that if $S > 0$ then later observations in the time series tend to be larger than those that appear earlier in the time series, while the reverse is true if $S < 0$.

* p values from analyses were corrected for multiple tests using a post-hoc Bonferroni correction.

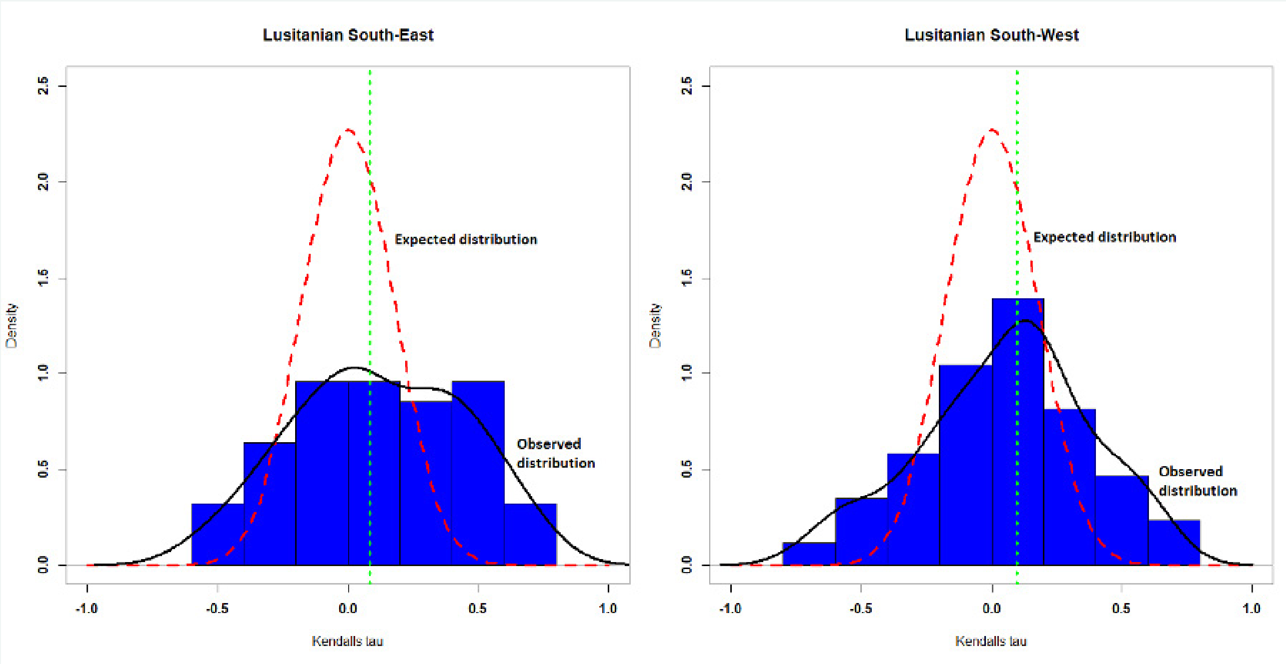

Figure 6.6 Observed histograms (blue bars) with smoother (black lines) of coefficients (Kendall's tau) by area for Lusitanian (warm water species) taxa sampled by the Irish Groundfish Survey, in the southern areas (ICES division 7g and 7j). The red dashed line represents the expected distribution while the green dashed line is the median value of all the observed values. The departure of species to the right of the expected distribution suggests more species are increasing in abundance than expected by chance.

6.6 FISHERIES MANAGEMENT IN A CHANGING CLIMATE

For many fish stocks in Irish waters the primary driver of abundance trends continues to be exploitation by fishing (Kempf *et al.*, 2022). With continued sea warming however, the effects of climate change will likely become more evident. A well-managed fishery will be more resilient to climate change than a degraded stock (Pinnegar *et al.*, 2017). Global climate change poses a significant challenge to fisheries management with models indicating a likely global decline in marine production (Tittensor *et al.*, 2021). However, the regional effects of climate change are less clear (Bahri *et al.*, 2021). An adaptive approach to fisheries management is critical to maintain fish stocks in an uncertain changing environment (Bahri *et al.*, 2021). Current fisheries management is largely based around single species stock assessments and the use of reference points to promote fisheries yields at sustainable levels. Reference points are commonly defined using the Maximum Sustainable Yield (MSY) approach, but, this approach does not commonly allow for fluctuations in ecological processes (FAO, 1995). With the advent of potential ecosystem shifts associated with climate change, a more holistic approach to fisheries management may be needed. In recent years, there has been a move towards implementing an Ecosystem Approach to Fisheries Management (EAFM) in combination with the traditional stock assessment methods (Howell *et al.*, 2021). An ecosystem model of the Irish Sea identified negative correlations between the North Atlantic Oscillation winter index (NAOw) and large zooplankton abundance, and between the Atlantic Multidecadal Oscillation (AMO) and the recruitment of cod (*Gadus morhua*) and whiting

(*Merlangius merlangus*) (Bentley *et al.*, 2020). Knowledge of such ecosystem interactions may highlight potential impacts of climate change. Further development of ecosystem models within Irish waters will support fisheries management. The complexity of ecosystem models is sometimes difficult to translate into targeted management decisions for fisheries. Bentley *et al.* (2021) postulated the use of a F_{eco} value which uses ecosystem indicators to provide ecosystem-based fishing mortality reference points within ICES F_{MSY} ranges. Silvar-Viladomiu *et al.* (2022) postulated the potential use of Peterman's productivity method (PPM) due to its ability to track temporal change of recruitment productivity via the stock-recruitment (SR) relationship (Peterman *et al.*, 2000; Minto *et al.*, 2014; Perälä *et al.*, 2017). These approaches allow the incorporation of ecosystem understanding into existing single species management plans, implementing the first step towards a more ecosystem approach to fisheries management.

The complexity of ecosystem models is sometimes difficult to translate into targeted management decisions for fisheries, however, further development of ecosystem models within Irish waters will support fisheries management. Knowledge of such ecosystem interactions may highlight potential impacts of climate change.

6.7 RECOMMENDATIONS

1. Continue research into the best methods of incorporating ecosystem parameters into current fishery management programmes.
2. Long-term scientific monitoring of fish stocks in the Irish EEZ should be maintained to continue monitoring the stocks health status and to allow further research into the potential impacts of climate change on fisheries.
3. Develop methods to further interrogate data with respect to climate-forcing.
4. Novel fishing opportunities created by species distribution shifts must be managed correctly to ensure a sustainable yield. International cooperation on the management of fish stocks is vital to manage not only novel stocks, but current stocks undergoing distribution shifts.

CHAPTER 7

SEABIRDS

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Cormorant (*Phalacrocorax carbo*).
Photo credit: Brian Burke

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Approximately half of seabird species globally have declining population trends.

Kittiwake (*Rissa tridactyla*).
Photo credit: Andrew Power

7.1 SEABIRDS AS SENTINELS

Ireland's coastal features and oceanographic conditions provide ideal breeding and feeding conditions for seabirds (Lloyd *et al.*, 1991) and as a result, Ireland is home to seabird colonies of international importance (Lloyd *et al.*, 1991). "Seabird" is not a strict definition, but generally refers to bird species that travel into marine environments to obtain food (Furness and Monaghan, 1987). Wading birds, divers, grebes, sea ducks, herons and fish-eating birds of prey are not normally described as seabirds. Seabirds are comparatively easier to study than other marine, long-lived, higher-trophic level species, such as cetaceans, as they are easily visible at sea and breed in terrestrial environments (Dias *et al.*, 2019). They often breed in large colonies at the same location, allowing for efficient data collection over long time scales (Velarde *et al.*, 2019). Given their abundance, wide distribution, high dispersal ability and trophic positions, seabirds are a key component of marine ecosystems globally. As a result of these factors, seabirds have been widely used to reflect, or, infer diverse aspects of the health of marine environments (Furness and Camphuysen, 1997; Mallory *et al.*, 2010) including the state of fish populations, the occurrence of pollution, as well as climate change.

7.2 SEABIRD DEMOGRAPHICS

Seabirds are one of the most threatened groups of birds globally (Dias *et al.*, 2019). Approximately half of all seabird species have declining population trends (BirdLife International, 2021a, 2021b). Climate change, alongside pressures brought about by invasive species and incidental bycatch, has been identified as one of the leading threats to seabirds. Eighty-nine percent of seabirds impacted by climate change are also affected by other threats such as overfishing, hunting/trapping and disturbance. All have been identified as key threats to seabirds worldwide (Dias *et al.*, 2019). High mortality of adult seabirds was recorded in colonies across Europe, North America, and Africa in 2022 due to highly pathogenic avian influenza (HPAI) (Kuiken and Cromie, 2022). These recent outbreaks further demonstrate the myriad of threats seabirds face.

There are 24 seabird species breeding in Ireland. Recent population estimates of seabird species that breed in Ireland suggests that 68% have increased, 21% to have decreased and 11% showed more static trends (Cummins *et al.*, 2019). It should be noted, however, that this study did not include burrow-nesting seabirds which are among the most challenging to survey accurately. Only one Irish seabird species is currently green-listed nationally (i.e. in good conservation status): the Great-Black Backed Gull (*Larus marinus*) (Gilbert *et al.*, 2021) while four species are red-listed (i.e. having highest conservation priority): Leach's Petrel (*Hydrobates pelagicus*), Black-legged

Northern Fulmar (*Fulmarus glacialis*).
Photo credit: Brian Burke

Kittiwake (*Rissa tridactyla*), Razorbill (*Alca torda*) and Puffin (*Fratercula arctica*) (see Table 7.1). On a European level the most threatened species in Ireland are Northern Fulmar (*Fulmarus glacialis*), Black-legged Kittiwake and Puffin (Table 7.1). All seabird species in Ireland also breed in other countries, with narrow and wide breeding distributions described. Seabird species that breed in Ireland have been widely studied across their global range.

89% of seabirds impacted by climate change are also affected by other threats such as overfishing, incidental capture (bycatch), hunting/trapping and disturbance. It is difficult to estimate the impact of climate change on Irish seabird populations given the myriad of threats they currently face, plus historical and current gaps in population monitoring.

7.3 CLIMATE CHANGE AND SEABIRDS

There is very little research to date on the impact of climate change on seabirds in Ireland, and it is difficult to estimate this given the myriad of other existing pressures and threats they currently face on land and at sea. Climate change, however, has been highlighted as a significant threat (Cummins *et al*., 2019). Climate change has also been attributed as one of the primary causes of seabird declines in Britain (Mitchell *et al*., 2020) and it should be considered a contributing factor to the decline in Ireland as well. Ireland and Britain are at the southern limit for most breeding species of seabird in the Northeast Atlantic (Mitchell *et al*., 2020). Therefore, seabird species historically and currently breeding in Ireland are particularly vulnerable to increasing temperatures brought about by climate change, as their ranges may contract in response to changing environmental conditions. Climate change can disrupt seabirds in numerous different ways. Most seabird species breeding in Ireland are migratory to some extent and are vulnerable to the negative impacts of climate change in their breeding grounds as well as in their wintering quarters. There are two main processes by which climate change can impact seabirds: 1) indirect negative stressors as a result to changes in food supply; 2) direct stressors such as mortality from extreme weather and habitat loss due to sea level rise (please see chapters 2 and 3 of this report).

Razorbill (*Alca torda*).
Photo credit: Andrew Power

7.4 FOOD SUPPLY

Seabirds are long-lived, higher trophic level organisms with high dispersal ability and complex migration strategies. Prey availability at different locations throughout the year is an important factor in seabird behaviour and distribution (Dunn *et al*., 2020). Warming waters is causing a shift in the community structure and abundance of potential prey item for seabirds (Beaugrand *et al*., 2008; Luczak *et al*., 2012). Feeding strategies are complex and can vary markedly between species, colonies and even between individuals of the same species. Therefore, it is difficult to interpret the impact of climate change on different seabird species as impacts may be species or site specific. Generalist species, species that can feed throughout the water column, and scavenger species are considered less sensitive to changes in prey availability as they are more adaptable to shifting environmental conditions. Conversely, more specialist seabird species that rely on specific prey species or have specialised feeding behaviours are thought to be the most at risk from changes in food supply due to climate change. Seabirds in Ireland fit into two broad categories, water-column feeders and surface feeders (Table 7.1). According to Oslo Paris Convention for the Protection of the Marine Environment of the Northeast Atlantic (OSPAR) assessments of seabird populations in the Northeast Atlantic, water-column feeders are faring better than surface-feeders (Mitchell *et al*., 2020).

Seabird populations in the North Atlantic are predicted to shift northward following prey (Beaugrand *et al*., 2008). Warming waters in Britain have resulted in northward shifts of copepod prey of sandeels (*Ammodytes* spp.) (Beaugrand *et al*., 2008; Tarling *et al*., 2022), some of the most ecologically important fish species in the Northeast Atlantic and a critically important dietary component for many seabird species breeding in Ireland (Lindegren *et al*., 2018). Rising sea surface temperature (SST) has been linked to reduced adult survival rates and lower breeding success of several seabird species in Britain including Kittiwake, Fulmar, Puffin, Arctic Tern (*Sterna paradise*), Shag (*Phalacrocorax aristotelis*) and Guillemot (*Uria aalge*) (Burthe *et al*., 2014; Cook *et al*., 2014; Reed *et al*., 2015). Rising SST has also been linked to reduced biomass of sandeels (Carroll *et al*., 2017). This has been most notably linked to declines in Kittiwakes in Britain. The breeding success of Kittiwakes in the Celtic Sea, including Irish colonies, however, did not have a negative relationship with SST (Lauria *et al*., 2013). It has been speculated that Kittiwakes in the Irish Sea are more dependent on other small

Warming waters in Britain have resulted in northward shifts of copepod prey of sandeels, which are an important dietary component for many seabird species that also breed in Ireland.

fish species (Mitchell *et al.*, 2020). Other factors, such as water column stratification, are considered important factors in Kittiwake colony productivity (Carroll *et al.*, 2015). Ocean water column stratification, bringing about vertical changes in sea water density, is likely to become stronger due to climate change (Yamaguchi and Suga, 2019). Stratification increases light availability in the ocean surface waters and may increase plankton growth, encouraging capelin (*Mallotus villosus*) and other fish to feed closer to the surface (Buren *et al.*, 2014). Early stratification can result in a mismatch between peak prey availability and the breeding season of seabirds (Burthe *et al.*, 2012). Biomass of suitable prey species may be present in sufficient abundances in the water column, but not in desirable or accessible locations for seabirds, and in this regard surface feeding seabirds may be particularly vulnerable to such stratification.

The differing impacts of climate change on Kittiwakes between colonies exemplifies the challenges associated with climate change research on seabirds. Not only does the change in the abundance and composition of lower trophic level organisms impact seabirds, but the timing of key life history events for these prey species is also significant. There is growing concern that seabird species are not adapting their breeding seasons in response to changes in peak abundance of prey, which is essential for good productivity. Fish species becoming more abundant in the food web, a result of climate change, may not have energy values sufficient for breeding seabirds to successfully feed and fledge chicks. Snake pipefish (*Entelurus aequoreus*) have been shown to have among the lowest energy values of fish eaten by seabirds (Harris *et al.*, 2008) and there were concerns that seabird population declines in Britain during the early 2000s were a result of changes in food supply, including a significant increase in pipefish populations in the Northeast Atlantic (van Damme and Couperus, 2008). As well as being nutritionally poor for seabirds, young seabirds can also choke on pipefish (Harris *et al.*, 2006). While it is likely that the pipefish population has subsequently crashed it illustrates the sensitivity of seabirds to changes in food supply (Heath *et al.*, 2012; Anderson *et al.*, 2014). (See Case Study on Snake Pipefish in Chapter 6 of this report).

Rockabill Island in the Irish Sea is an internationally important breeding site for Roseate Terns (*Sterna dougallii*) but also has populations of Common Tern (*Sterna hirundo*), Arctic Tern, Kittiwake and Black Guillemot (*Cepphus grille*). During the breeding season, the site is continuously wardened and each year feeding studies are conducted on Roseate Terns to determine the prey species being provided to chicks. Roseate Terns are surface feeders and sensitive to changes in food supply, and so the long-term acquisition of data from Rockabill could be used to help track shifts in prey base. Annual reports from this conservation project have highlighted years where species such as snake pipefish have been more prevalent in tern diet (McKeon *et al.*, 2017). Detailed information on productivity and breeding success is also collected for Rockabill, demonstrating its potential as a sentinel site for climate change in the wider Irish Sea.

The primary concern around a shifting prey base for seabirds is that the new food supply will not meet the energy requirements to maintain adult survival and breeding success. Secondary impacts of a change in diet should also be considered. As a result of dietary change in response to climate change, seabirds may be exposed to new or different concentrations and profiles of chemical pollutants (Kalia *et al.*, 2021). Persistent organic pollutants (POPs) can have lethal and sublethal impacts (Bustnes *et al.*, 2015). Additionally, changes in prey availability may alter exposure or transmission rates of parasite-borne disease amongst seabirds.

Table 7.1: Conservation status of seabird species breeding in Ireland on a national (Colhoun and Cummins, 2013) and European level (BirdLife International, 2021a) and their potential vulnerability to climate change. Four main criteria were used to assess vulnerability: 1) feeding guild, is the species a generalist or surface-feeder; 2) reliance on sandeels; 3) vulnerability to weather events in winter and; 4) vulnerability to weather events during the breeding season. Vulnerability, Not=0, low=1, moderate=2, high=3. It should be noted that this table is intended as an indication of the potential vulnerability of seabirds and more research is required to adequately assess each species. Red text (R)=red listed, amber text (A)=amber listed, green text (G)=green listed. European Red List uses IUCN criteria, LC=least concern, NT=near threatened, VU=vulnerable, EN=endangered.

Species	Feeding guild	Birds of Conservation Concern in Ireland (BOCCI) 2020-2026	European Red List of Birds (BirdLife International) 2021	Vulnerability to climate change
Northern Fulmar (*Fulmarus glacialis)*	Surface feeder	A	VU	1
Manx Shearwater (*Puffinus puffinus)*	Surface feeder	A	LC	2
Storm Petrel (*Hydrobates pelagicus)*	Surface feeder	A	LC	2-3
Leach's Petrel (*Oceanodroma leucorhoa)*	Surface feeder	R	NT	0-1
Northern Gannet (*Morus bassanus)*	Water column feeder	A	LC	0-1
Cormorant (*Phalacrocorax carbo)*	Water column feeder	A	LC	2
Shag *(Phalacrocorax aristotelis)*	Water column feeder	A	LC	2
Great Skua (*Stercorarius skua)*	Surface feeder	A	LC	0-1
Kittiwake (*Rissa tridactyla)*	Surface feeder	R	VU	2
Black-headed Gull (*Chroicocephalus ridibundus)*	Surface feeder	A	LC	1
Mediterranean Gull (*Ichthyaetus melano-cephalus)*	Surface feeder	A	LC	1
Common Gull (*Larus canus)*	Surface feeder	A	LC	1
Lesser black-backed Gull (*Larus fuscus)*	Surface feeder	A	LC	1
Herring Gull (*Larus argentatus)*	Surface feeder	A	LC	1
Great Black-backed Gull (*Larus marinus)*	Surface feeder	G	LC	1
Little Tern (*Sternula albifrons)*	Surface feeder	A	LC	3
Sandwich Tern (*Sterna sandvicensis)*	Surface feeder	A	LC	2
Common Tern (*Sterna hirundo)*	Surface feeder	A	LC	2
Arctic Tern (*Sterna paradisea)*	Surface feeder	A	LC	2
Roseate Tern (*Sterna dougallii)*	Water column feeder	A	LC	2
Common Guillemot (*Uria aalge)*	Water column feeder	A	LC	1
Razorbill (*Alca torda)*	Water column feeder	R	LC	1
Black Guillemot (*Cepphus grylle)*	Water column feeder	A	LC	1-2
Puffin (*Fratercula arctica)*	Water column feeder	R	EN	2

Common Guillemot (*Uria aalge*)
Photo credit: Brian Burke

7.5 WEATHER EVENTS

Wrecks or mass mortalities of seabirds can be caused by adverse weather conditions. The number and strength of cyclones (storms) in the North Atlantic have increased significantly in the past 50 years (IPCC, 2014). Models predict the frequency of strong cyclones will continue to increase with climate change (IPCC, 2014). Additionally, climate change is predicted to shift cyclone tracks, increasing the frequency of storms in western European waters (Tamarin-Brodsky and Kaspi, 2017; Wolf *et al*., 2020). Seabird mortality during cyclones is likely caused by starvation, as seabirds cannot effectively find prey in these extreme conditions (Clairbaux *et al*., 2021). Storms in 2013/2014 resulted in mortalities of over 50,000 seabirds on the coastline of Europe (Morley *et al*., 2016). Several seabird species exposed to cyclones in the North Atlantic could be especially vulnerable to shifting climatic conditions in winter months (Clairbaux *et al*., 2021). Seabird species breeding in Ireland identified as vulnerable include Guillemot, Puffin and Kittiwake; the latter two species are currently red-listed in Ireland. Stormy conditions not only affect adult survival in winter months, but can cause delayed breeding seasons (Mitchell *et al*., 2020).

Populations of Little Terns may be the most vulnerable to sea level rise, as well as species that nest on coastal beaches such as Ringed Plover.

Climate change may also negatively impact the foraging success of seabirds during the breeding season by making prey more difficult to detect, particularly for diving species (Darby *et al*., 2022). Biologging data of Manx Shearwaters in Ireland has shown that high turbidity (less clear water) may constrain foraging ability (Darby *et al*., 2022). Summer storms can reduce the breeding success of seabirds by chilling eggs and killing chicks (Newton, 1998). The impact of extreme weather on the breeding success of seabirds varies amongst species due to differences in their ecology and life history. Seabirds nesting directly on exposed beaches, such as the Little Tern (*Sternula albifrons*) can be highly vulnerable to storms washing away entire colonies. For example, in 2012, 86% of Little Tern nests (226 eggs, 91 nests) were washed

Seabird mortality during storms is likely caused by starvation, as seabirds cannot effectively find prey in these extreme conditions. Storms in 2013/2014 resulted in wrecks (mortalities) of over 50,000 seabirds on the coastline of Europe.

away by summer storms in Kilcoole, Co. Wicklow (Keogh *et al*., 2012). No chicks hatched from the remaining eggs at this site due to predation, human disturbance and abandonment, and it is speculated that the reduced population was more vulnerable to these threats (Keogh *et al*., 2012). Thus climate change may not act alone but can also exacerbate the impact of other pressures, and this feature (i.e. cumulative pressures or threats) must be considered when evaluating the risk to seabird populations arising from climate change.

Little Terns may be the most vulnerable to sea level rise (Mitchell *et al*., 2020) as well as other species that nest on coastal beaches such as Ringed Plover (*Charadrius hiaticula*). Storm Petrels (*Hydrobates pelagicus*) at several Irish colonies can nest close to the shore and may also be at risk due to their exposed location. Colonies of cliff nesting seabird species in exposed areas are also highly vulnerable to storms. Razorbill, Shags, Kittiwakes and Guillemot nesting in exposed areas had failure rates between 10 and 30% as a result of a summer storm in the North Sea (Newell *et al*., 2015). Increased or more intense rainfall from summer storms may also have an impact on Puffins and Manx Shearwaters (*Puffinus puffinus*) by flooding their burrows.

7.6 CONCLUSION

Climate change is already having a clear impact on seabird populations worldwide (Crick, 2004; Dias et al., 2019; Sydeman et al., 2015, 2012); however, information on the impacts of climate change in relation to seabird species breeding in Ireland is limited. Given the international importance of Ireland to many seabird populations in Europe and the North Atlantic, and the location of Ireland at the southern range limit of several species, it is important that effective conservation strategies, informed by appropriate research and scientific evidence, are developed and implemented. The pressures and impacts on seabirds brought about by climate change are complex and multi-faceted, and a holistic evidence-based approach should be adopted to research and conserve seabird species in this country.

7.7 RECOMMENDATIONS

1. Increase resources dedicated to research on climate change in relation to seabirds, such as targeted long-term dietary and productivity studies.
2. Enhance research on the interactions between climate change and other pressures/threats to seabirds.
3. Adopt the use of regional sentinel sites with a suite of indicator species for annual study; Black-legged Kittiwake is used as an indicator species in Britain.
4. Identify conservation concerns and actions regarding other pressures and threats such as disturbance, over-fishing, bycatch, predation and habitat loss, and implement appropriate measures that may help alleviate some of the pressures arising from climate change.
5. Investigate the impact of climate change on non-breeding species in Ireland, such as wintering birds or passage migrants.
6. Collaborate with international partners to protect flyways of passage migrants, as well as breeding seabirds in Ireland that overwinter in different countries.
7. Develop a standardised recording protocol for beached birds to assess seabird mortality and frequency of wrecks.
8. Develop and resource improved seabird data sharing and data management mechanisms to enable and support national and international scientific and management collaborations.

CHAPTER 8

LAND OCEAN AQUATIC CONTINUUM

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Photo credit: Mary Dillane

8.1 INTRODUCTION

Ireland is particularly influenced by the ocean as it is a small land mass bordering a large ocean (McCarthy *et al.*, 2015). The terrestrial ecosystems of Ireland are strongly coupled to variability in the ocean, particularly in terms of hydrology. Previous chapters have outlined the changes occurring in the atmosphere and oceans surrounding the country, and in this chapter, we consider how these changes are likely to impact our terrestrial ecosystems and aquatic processes. Initially coined to refer to the changing biogeochemistry of nitrogen, phosphorus and silica from land to ocean by Billen *et al*. (1991), the Land Ocean Aquatic Continuum (LOAC) concept encapsulates the transition zone between terrestrial ecosystems and the open ocean and has been used to describe a series of biogeochemically and physically active systems that process carbon and other nutrients as these elements move from upland soils to the open ocean (see Xenopoulos *et al.*, 2017 for overview). The LOAC concept recognises that changes in the transport and transformation of elements, as well as ecological functions, occur along this aquatic continuum, and that these changes are tightly coupled with the hydrological cycle.

Rainfall (particularly in winter) and the frequency of heavy rainfall events are increasing.

The hydrological cycle of Ireland is characterised by relatively short transport distances and rapid response times to precipitation. As the crow flies, there is no point in Ireland more than 100 km from the sea, and although the longest aquatic continuum (the Shannon) is 360 km from source to sea, the majority of Irish rivers are less than 30 km in length (Kelly-Quinn *et al.*, 2020). Many drain the mountainous regions in the coastal counties, and respond to rainfall events in a matter of hours. The shape of the country, with its central depression, lends itself to an accumulation of water in ponds and lakes, and their surrounding wetlands. A recent inventory enumerated 12,205 lakes in Ireland, and highlighted the importance of lakes as hotspots for biochemical processing (Dalton, 2018).

Given the coupled nature of Ireland's land mass with the surrounding ocean, it is necessary to consider changes in the terrestrial environment in tandem with any review of ocean variables. The climatic conditions that are driven by Atlantic Ocean circulation, and the linked multidecadal oscillations in atmospheric teleconnections, influence a diverse range of ecosystem processes across the island. Here, we describe some of these processes along the aquatic continuum from upland headwater ecosystems to the ocean (hydrology, nutrient transport, carbon dynamics and ecology) that are impacted by climate change. Land use change in Ireland affects freshwater and coastal habitats and there may be substantial interactions between this and climate change. Agricultural eutrophication, land drainage, urbanisation, waste water treatment inadequacies and afforestation all have a role in shaping the current situation. Where monitoring occurs, 47.0% of rivers, 49.5% of lakes and 62.0% of transitional waters, are classified as either moderate or worse ecological status (O'Boyle *et al.*, 2019). Adaptation to climate change will only be successful if a full awareness of interacting stressors is considered.

8.2 HYDROCLIMATE AND HYDROLOGY

The moderating influence of the Gulf stream and the North Atlantic current on Ireland's weather is well documented, with long-term records emphasising the dominant characteristics as "moist and equable" (Sweeney, 2014). Excessive air temperatures, such as those recorded on mainland Europe, are not yet a feature of our weather, and this pattern is carried through to freshwater aquatic habitats, where the water temperature of our lakes and rivers is also moderated. Comparisons of decadal lake surface temperatures across eight lakes in Europe indicate that Lough

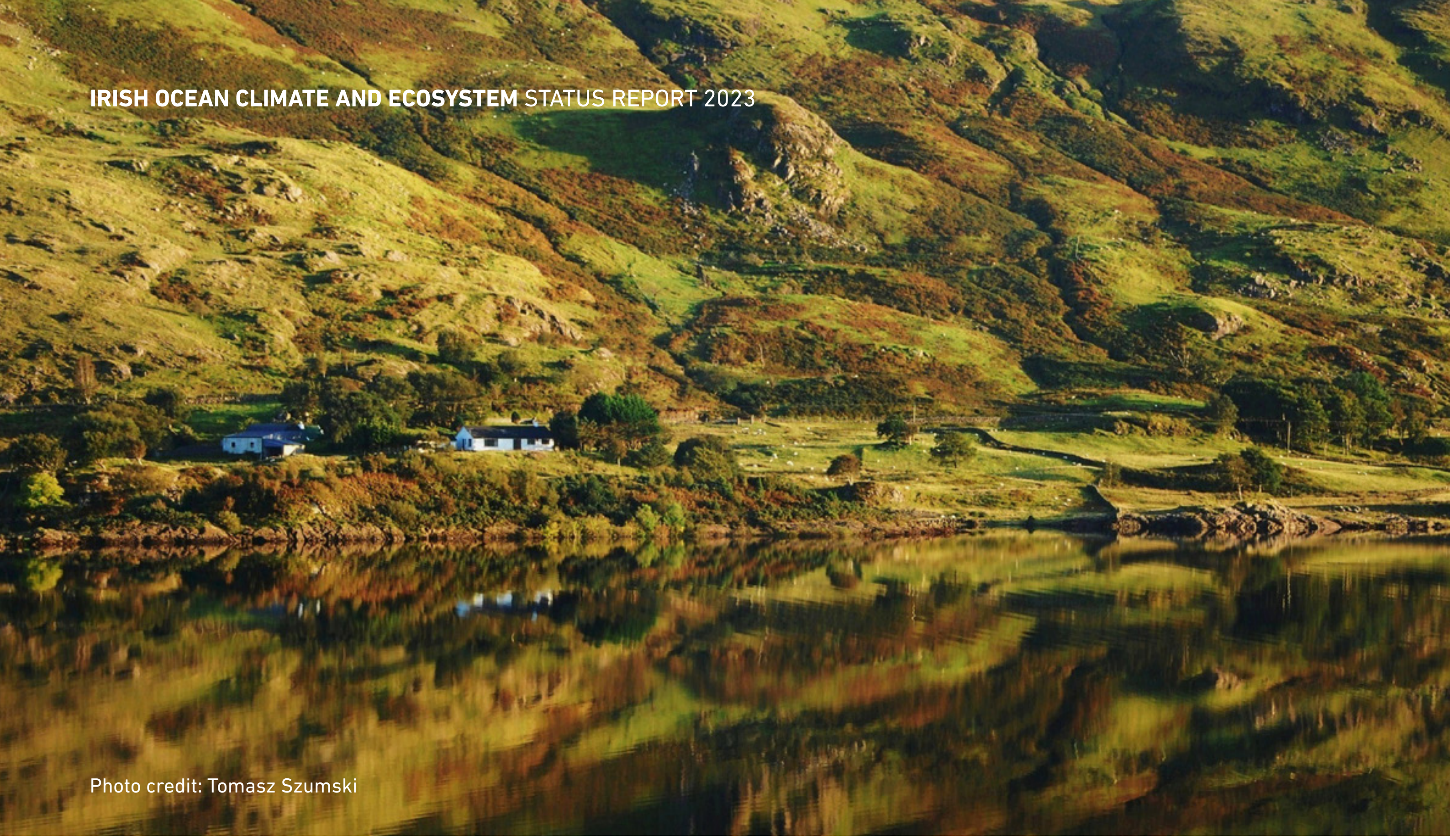

Photo credit: Tomasz Szumski

Feeagh, Co. Mayo has experienced less warming in summer than other lakes (Dokulil *et al*., 2021) with warming winter temperatures more apparent (Woolway *et al*., 2019). Future projections of winter water temperatures are a cause for concern for the species that rely on cool water temperatures for survival and reproduction, such as Arctic charr (Kelly *et al*., 2020b). Despite Ireland's moderate oceanic climate, heat waves are becoming more common (Cámaro García and Dwyer, 2021), and in the summer of 2021, surface waters of Lough Feeagh heated to 23.8°C, a value that had not previously been recorded in the 60 year dataset of water temperatures maintained by the Marine Institute (Figure 8.1).

The adjacent Atlantic Ocean delivers significant heat and moisture to Ireland and strongly influences changes in rainfall and hydrology. Analysis of gridded precipitation observations from Met Éireann for the period 1941 to present, indicate increasing trends in annual precipitation totals since the 1980s (Cámaro García and Dwyer, 2021). Given the large interdecadal variability of Irish precipitation, analysis of long-term records is critical to identify robust changes. Noone *et al*. (2016) developed a quality-assured precipitation series for the island dating back to 1850. Their results show winter rainfall is increasing, while summer rainfall is decreasing. Prior to this, Murphy *et al*. (2018) developed a 300-year precipitation series for the island, confirming the findings of Noone *et al*. (2016) and showing that recent decades are the wettest in the entire series.

Changes in extreme precipitation are driven by thermodynamic (warmer atmosphere) and dynamic (circulation) changes. In general, warming increases the water holding capacity of the atmosphere following the Clausius-Clapeyron (CC) relation, which results in increases in extreme precipitation at the global scale (around 6–7% per degree of warming near the Earth's surface). Harrigan (2016), in an analysis of daily precipitation records from the 1950s onwards, found increases in precipitation intensity consistent with expectations of a warming atmosphere, particularly in the east and southeast of the island in summer. Cámaro García *et al*. (2021) found increasing trends in the length of wet spells across the island over the period 1961 to present. Ryan *et al*. (2021, 2022) evaluated changes in precipitation extremes for daily observational records extending to early 20th century and found significant increasing trends in rainfall intensity, again predominant in the east and southeast,

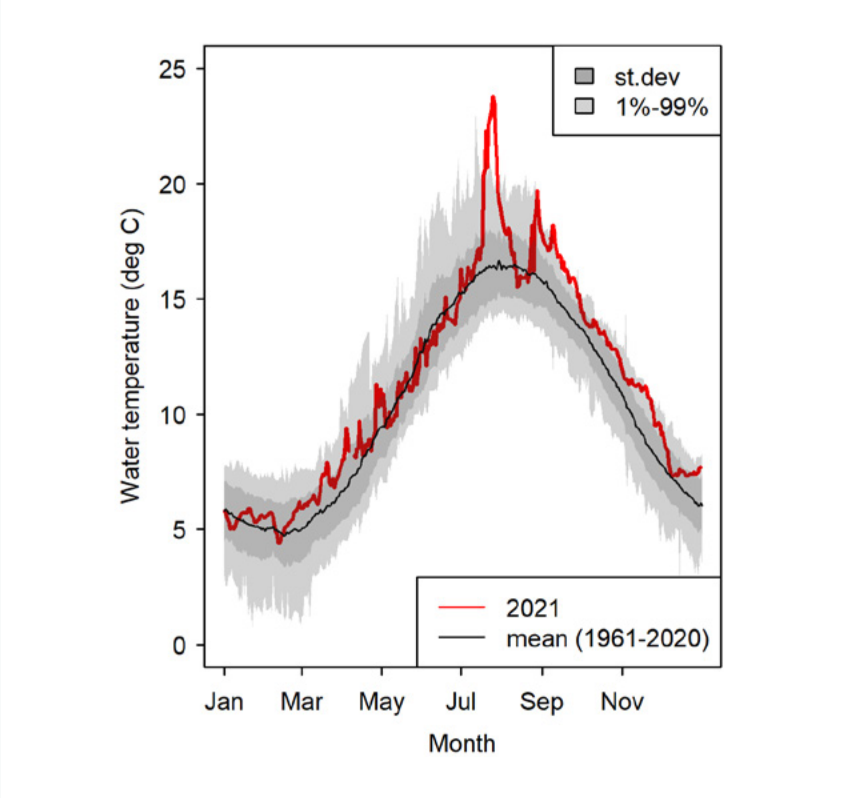

Figure 8.1 Lough Feeagh surface water temperature, 1961–2021. Red line indicates 2021, black line is the mean daily values recorded between 1961 and 2020.

while the contribution of heavy and extreme precipitation events to annual totals was also found to be increasing. Such heavy rainfall events can lead to prolonged disturbance of freshwater and coastal ecosystems, as described for Storm Desmond over Co. Mayo (Case Study - The impacts of storm Desmond on the Burrishoole catchment, Co. Mayo). Few studies have evaluated changes in meteorological drought in Ireland. One exception is Vicente-Serrano *et al*. (2021) who evaluated long-term variability and trends in meteorological droughts for western Europe over the period 1851–2018, including stations quality assured by Noone *et al*. (2016). Trends towards an increasing magnitude of summer drought conditions were found for Ireland and Britain over the period analysed. In an assessment of reconstructed river flows for Irish catchments, a tendency towards shorter, more intense meteorological and hydrological summer droughts over the past century was identified (O'Connor *et al*., 2022b).

River discharge can be impacted by climate variability and change as well as land-use change, abstractions and discharges (Slater *et al*., 2021). Moreover, river flow records tend to be shorter than those for precipitation. To address this, Murphy *et al*. (2013) developed an Irish Reference Network (IRN) of hydrometric stations across the island for climate change monitoring that attempts to minimize such confounding factors. An analysis of the updated network is provided in Cámaro García *et al*. (2021). Over the period 1972–2017, high flows (those exceeding 10% of the time) show significant increasing trends in magnitude, except for some stations in the southeast of the country, where non-significant decreases are evident. European scale studies that include records for Ireland also indicate changes in the timing (Blöschl *et al*., 2017) and increased magnitude (Blöschl *et al*., 2019) of floods consistent with expectations of wetter winters from climate model simulations. In

Occurrences of high discharges in rivers are increasing with some evidence for shorter more intense summer droughts.

addition, Hodgkins *et al*. (2017) found significant increases in major flood occurrence for 50-year floods over the period 1961–2010 for medium size catchments (100–1000 km^2), particularly in temperate regions of Europe (such as Ireland).

Low flows (flow magnitude exceeded 90% of the time) in catchments contained in the Irish Reference Network over the period 1972–2017 show increasing trends, however, this is likely an artefact of record length, with the dry 1970s at the start of the record. Low flow discharge over the period 1992–2017 shows decreasing trends in parts of the southeast and few significant increasing trends. Significant drought events in 2018 and 2020 are likely to have strengthened this decreasing trend. Given short record lengths, however, along with large variability, trends in low flow magnitude are highly dependent on the period used for analysis. O'Connor *et al*. (2022a) evaluated trends in reconstructed annual, seasonal and monthly mean flows for Irish catchments for the period 1900–2016 to better understand the long-term pattern of behaviour. They found significant increasing trends in annual mean flows for western catchments. In winter, significant increasing trends dominate catchments on the western seaboard, with significant decreasing trends in the southeast. Few significant trends are found in spring and summer mean flows, while autumn shows significant increasing trends in northern catchments. Considerable global scientific effort is now being focused on the ecology of drying rivers (e.g. Keller *et al*., 2020), but as yet, it would appear that this is not particularly a cause for concern in Ireland.

CASE STUDY

THE IMPACTS OF STORM DESMOND ON THE BURRISHOOLE CATCHMENT, CO. MAYO.

The frequency and severity of storm category weather events during winter 2015/16 in Ireland and Britain was considered exceptional, peaking with the extratropical cyclone Storm Desmond during 4^{th}–6^{th} December 2015. Rainfall during Desmond broke the 24-hour and 48-hour British rainfall records and multiple rivers throughout Ireland and Britain recorded highest ever peak discharge. Desmond was caused by enhanced horizontal water vapour transport from the Atlantic Ocean, with the plume of moist air generating an 'atmospheric river,' and causing extreme precipitation along mountainous western Irish and British coastlines. These intense rainfall events can impact freshwater ecosystems by transporting large quantities of sediment and terrestrial matter into streams and lakes, altering physical and biogeochemical environments. The large volumes of river discharge can also impact downstream coastal zones. For example, during Storm Desmond the lagoonal estuary Lough Furnace in Co. Mayo received the largest volume of freshwater input on record (since 1976) resulting in fundamental changes to the salinity balance and estuarine circulation, with effects lingering for several months post-storm (Kelly *et al.*, 2020a). In addition, a 20-fold increase was estimated in the volume of seaward flowing low salinity water between Lough Furnace and the adjacent coastal waters of Clew Bay. Such a severe hydroclimatic event, which originated through ocean-atmosphere interactions and had impacts spanning the full catchment-to-coast continuum, exemplifies the intrinsic interactions between atmospheric, terrestrial, coastal and oceanic domains.

Figure CS8.1 Flooding at the north shore of Lough Feeagh, Co. Mayo, during Storm Desmond, December 2015.

8.3 NUTRIENTS AND PRIMARY PRODUCTIVITY

The hydrological cycle described above drives the processing and transport of nutrients (phosphorus, nitrogen and micronutrients such as iron, potassium and manganese) from terrestrial stores, leading to strong correlations between oceanic conditions and nutrient export. For example, the intensity of the North Atlantic Oscillation (NAO) (see Chapter 2 for detailed explanation of the NAO) has been linked to large shifts in baseline nutrient concentrations in agricultural catchments, which, in combination with episodic weather events and changing land use practices, has considerable implications for water quality (Mellander and Jordan, 2021). A positive relationship was observed between winter nitrate concentrations in two lakes in southwest Ireland and the latitudinal position of the Gulf Stream in the previous spring (Jennings and Allott, 2006). This variability has implications for the primary productivity in terrestrial and aquatic habitats. A positive winter NAO is related to early onset of the terrestrial growing season across Ireland and Great Britain (Craig and Allan, 2021), while variability in particular phytoplankton groups (such as diatoms) in White Lake, Co. Tyrone can be linked to the NAO index (Anderson *et al.*, 2012). In Co. Kerry, an inverse relationship was found between winter chlorophyll in Lough Leane and the NAO (Jennings *et al.*, 2000), with higher chlorophyll (indicative of phytoplankton biomass) being recorded in years when the winter NAO was negative.

As part of the Oslo Paris Convention for the Protection of the Marine Environment of the Northeast Atlantic (OSPAR), a Riverine Inputs and Direct Discharges (RID) programme has been in operation since 1990 to assess the annual inputs of nutrients and other substances to the marine environment from inland waters. Monthly samples are taken at 19 rivers around the country at the freshwater/saline interface. Loads of total phosphorus (TP) and total nitrogen (TN) show clear trends related to catchment activities since monitoring began (Figure 8.2). Inputs of both TN and TP were highest at the beginning of the time series but better wastewater treatment infrastructure and changes in farming practices produced substantial and significant decreases in the inputs of these nutrients. While significant decreases across the full time series are clear, upward trends are becoming apparent in recent years. The most substantial increases come from the rivers along the south and southeast coasts showing the largest increase in nutrients entering the marine environment (Trodd and O'Boyle, 2021). The reduction in TP has been much greater than any reduction in nitrogen compounds. This can influence the ratios of nutrients reaching the sea. Recent research indicates that the ratio of nitrogen to phosphorus loads being transported to transitional waters has increased significantly (O'Boyle *et al.*, 2017). This is a result of the greater overall reduction in phosphorus relative to nitrogen. It is likely that changes in agricultural practices and in particular the reduction in the use of inorganic phosphorus fertilizer may account for the largest reduction in riverine phosphorus loads (O'Boyle *et al.*, 2017). This imbalance can have implications for primary producers and the food webs that they support (Burson *et al.*, 2016). While climate factors are also likely to be a contributor, the inherent variability at the land-sea interface make this difficult to distinguish. Nevertheless, catchment management plans (aimed at reducing nutrient losses from terrestrial sources) must be future-proofed for the changing hydrological patterns described in the previous section.

Increased nutrients are draining off agricultural catchments to the sea causing an increased risk of phytoplankton and macroalgal booms.

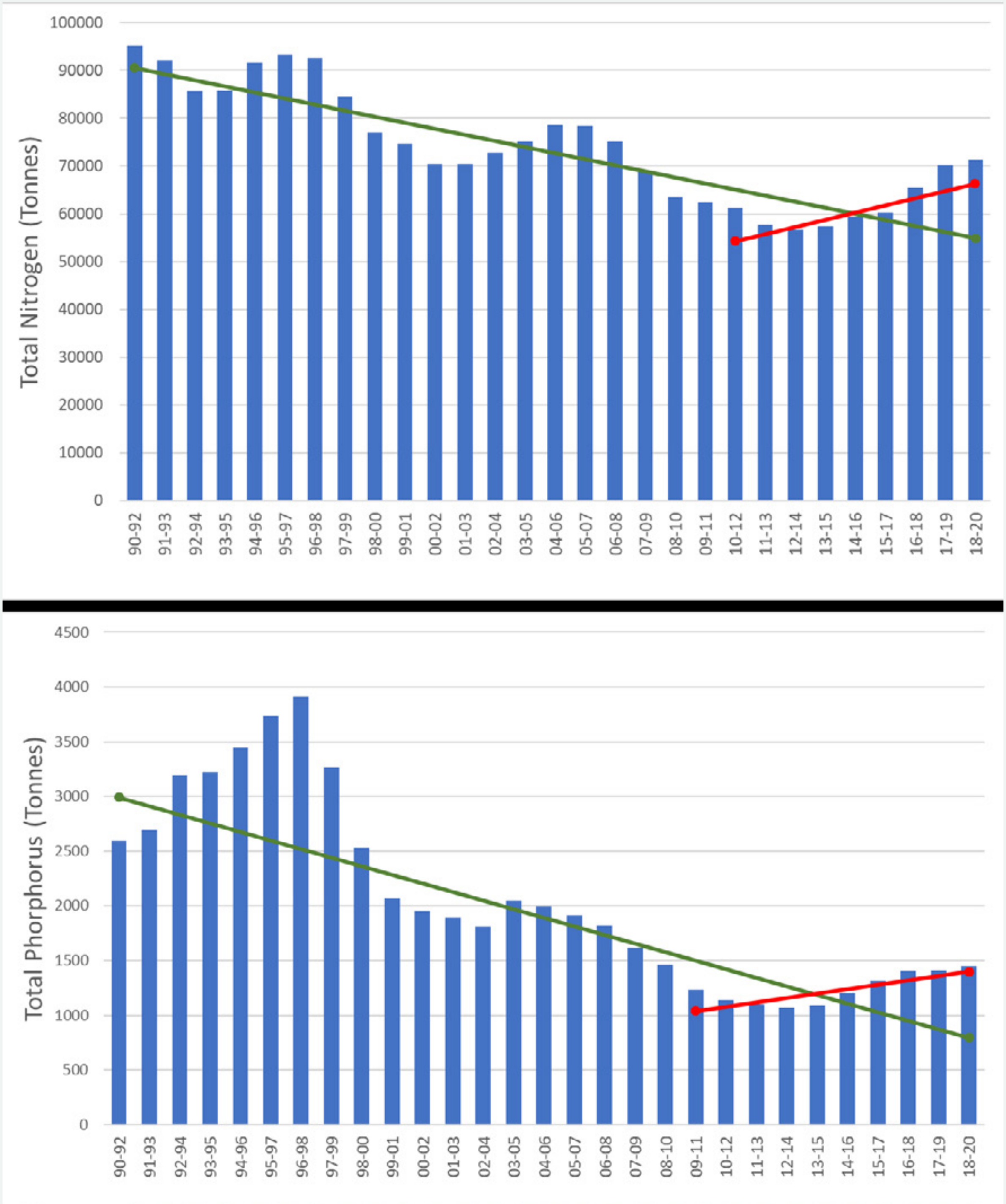

Figure 8.2 Flow normalized inputs of TN (top) and TP (bottom) to marine environment (three-year average period from 1990–1992 to 2018–2020). Green lines show significant downward trends and red lines show significant upward trend (Mann–kendall test).

Photo credit: Tomasz Szumski

8.4 CARBON

The LOAC (Land Ocean Aquatic Continuum) plays a key role in the global carbon cycle, transporting, processing and storing organic carbon (OC) from source to sea (Weyhenmeyer and Conley, 2017). A significant fraction of this lateral carbon flux is entirely "natural" and is thus a legacy of the pre-industrial component of carbon cycle. Changes in environmental conditions and land-use however, have caused an increase in the lateral transport of carbon along the LOAC – a perturbation that is relevant for the global carbon budget (Friedlingstein *et al.*, 2020). Movement of carbon from the extensive terrestrial stores in Ireland's bogs to inland waters is controlled by soil temperature and precipitation (Jennings *et al.*, 2010, 2020) and has a markedly seasonal pattern (Doyle *et al.*, 2019).

Understanding the potential sinks and sources for OC along the LOAC is crucial for adaptation measures designed to limit the amount of carbon loss from terrestrial sources. An OC budget for Lough Feeagh, an oligotrophic, peatland lake in west Co. Mayo, was estimated for 2017 (Doyle, 2021) using data collected as part of the long-term monitoring effort by the Marine Institute in the Burrishoole catchment. The principal OC fluxes and processing rates were calculated, and the study is considered to be the first OC budget presented for an Irish lake. The total OC load to the lake was estimated at 2,547 tonnes of carbon (t C), of which 51% and 41% were carried into the lake as dissolved and particulate fractions of peat-derived OC in surface water respectively. Small quantities entered the lake with ground water and rainwater. The total C exported from the lake to downstream Lough Furnace (a coastal lagoon) was estimated at 2,892 t C, of which 46% and 11% were exported as dissolved and particulate OC in the surface water outflow respectively. An estimated 485 t C of OC was mineralised and emitted as carbon dioxide (CO_2) to the atmosphere, while 754 t C of OC sank to the bottom of the lake as sediment, a portion of which will be preserved over the long-term. The completed budget revealed that OC in surface water inflows and outflows dominated the budget. The results highlight the substantial quantity of OC turned over in the lake during the study period. Overall, the study fills a considerable knowledge gap in the understanding of aquatic OC processing and emphasises how lakes in temperate, humic systems, common in the west of Ireland, are important to the amounts and quality of OC mobilised to the marine environment.

A follow on study is in progress, tracking the progress of carbon as it moves from the freshwater Lough Feeagh to downstream Lough Furnace (Marine Institute, unpublished data). Spot samples of surface water concentrations of carbon dioxide (pCO_2) are being taken from the surface of the two waterbodies at monthly intervals, and converted to flux using the Crusius and Wanninkhof (2003) approximation. Initial results from 2020 indicate that Lough Furnace emits far less CO_2 than Lough Feeagh (22 vs 318 tonnes CO_2-C, and even acts as a net sink of CO_2 in parts of the year) (Figure 8.3). This is somewhat surprising, as Borges *et al*. (2006) found that continental shelves are net sinks of atmospheric CO_2 while estuaries are significant CO_2 sources to the atmosphere. Some studies suggest that the concept of ocean acidification due to anthropogenic CO_2 emissions cannot be directly applied to coastal ecosystems, since decadal changes of up to 0.5 units in coastal pH have been caused by watershed changes in total alkalinity and CO_2 fluxes and up to 1 pH unit changes due to metabolic processes (Duarte *et al*., 2013 and references therein). In addition to inputs of organic and inorganic carbon from terrestrial sources as described above, changes in pH and carbonate chemistry in coastal waters are complicated by other drivers, including nutrient inputs, biological activity and upwelling (Doney *et al*., 2009; Duarte *et al*., 2013; Wallace *et al*., 2014).

McGrath *et al*. (2016, 2019) illustrated how the interplay of catchment geology, freshwater discharge and biological processes can result in large gradients in pH and CO_2 exchange between estuarine and coastal systems around Ireland,

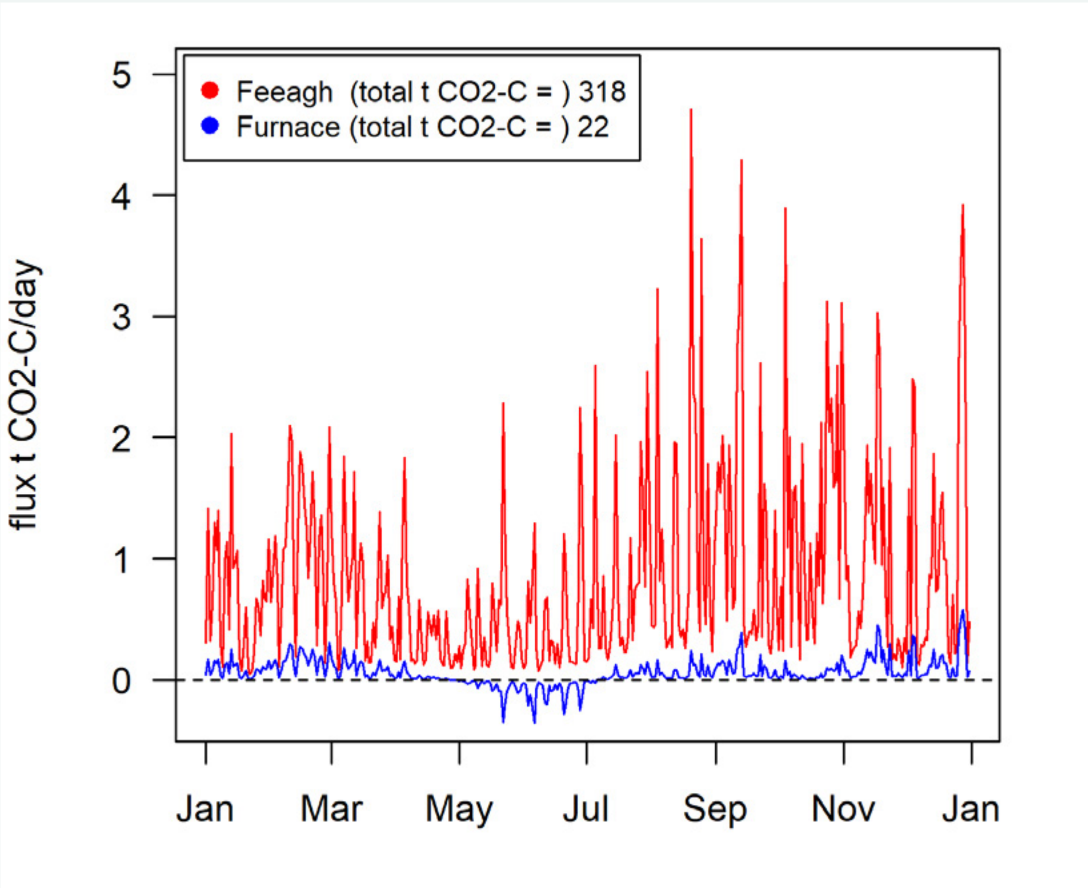

Figure 8.3 Daily CO_2 flux from the surface of Lough Feeagh (red) and Lough Furnace (blue) during 2020.

where the type of bedrock was the dominant control on regional carbonate chemistry. Weathering rates, which would influence the amount of alkalinity and dissolved inorganic carbon added to river water, are the highest for carbonate rocks, moderate for basalts and shales, followed by sandstones and acid volcanic rocks (Amiotte Suchet *et al*., 2003). McGrath *et al*. (2019) found that rivers with a limestone (calcium carbonate) bedrock coincided with high dissolved inorganic carbon and total alkalinity, resulting in supersaturation of these estuarine waters with respect to atmospheric CO_2 throughout the year, despite seasonal primary production in surface waters. Calculated wintertime CO_2 fluxes for the Shannon and Suir estuaries were also positive (McGrath *et al*., 2016), indicating a net flux of CO_2 from the sea to air from these limestone catchments. Primary production was the dominant driver in the non-limestone regions, where the granite and sandstone catchments had surface CO_2 close to atmospheric equilibrium in winter but were CO_2-undersaturated during productive months, where high rates of primary productivity in spring and summer remove CO_2 from surface waters (McGrath *et al*., 2019).

It is expected that the gradual increase in baseline CO_2 will increase the incidence of extreme acidification events in coastal systems (Waldbusser and Salisbury, 2014); for example Hauri *et al*. (2013a, 2013b) and Harris *et al*. (Harris *et al*., 2013) have already shown an increase in the frequency, magnitude, and duration of extreme events in the California Current System due to increasing CO_2, leading to conditions outside the normal range under preindustrial CO_2 levels and exceeding important thresholds for organisms. Coastal ecosystems including calcifying organisms are already adapted to naturally wide fluctuations in pCO_2 and pH. A significant proportion of benthic calcifying organisms potentially at risk from ocean acidification are however already experiencing significantly higher surface seawater pCO_2 and lower pH than expected from equilibrium with current atmospheric levels (e.g. Fagan and Mackenzie, 2007; Bates *et al*., 2010; Andersson and Mackenzie, 2012). The variability in pH observed at four coastal sites around Ireland (ΔpH 0.2–1.0) was 10 to 50 times greater than decadal changes observed in Ireland's offshore waters of the Rockall Trough between 1991 and 2012 (McGrath, 2012) and all four sites had minimum pH values below the end of the 21st century predictions for open ocean waters of 7.8 (Caldeira and Wickett, 2003; Orr *et al*., 2005).

While there may be an increase in baseline CO_2 (and subsequent decrease in pH) in coastal systems with increasing atmospheric CO_2, the cumulative impact of changing biogeochemical process is unclear. Eutrophication, for example, can result in an increase in pH due to enhanced uptake of CO_2 by primary producers (Borgesa and Gypensb, 2010), while it can amplify acidification through respiration of excess organic matter (Cai *et al*., 2011). Duarte *et al*. (2013) concluded that anthropogenic CO_2 is a relatively minor component of pH fluctuations in many coastal ecosystems, where enhanced primary production or respiration is often the primary driver. Regional inputs of nutrients, inorganic and organic carbon, and acid and carbonate alkalinity from watersheds should be coupled with scenarios of global CO_2 emissions to assess local impacts on coastal ecosystems.

Changes in climate and land use are leading to unprecedented pressures along the land ocean aquatic continuum.

8.5 ECOLOGICAL PROCESSES

Causative links between oceanic conditions and terrestrial biological systems are complex, and often difficult to parse. Changes in the Atlantic Ocean, as described in previous chapters however, play a crucial role in driving ecological processes on the island of Ireland. For example, the NAO was related to breeding success in overwintering birds such as European Wigeon (Fox *et al*., 2016), the growth in Hare populations between 1850 and 1910 (Reid *et al*., 2021) and the survival of salmon in both their freshwater (de Eyto *et al*., 2016) and marine phases (Peyronnet *et al*., 2008).

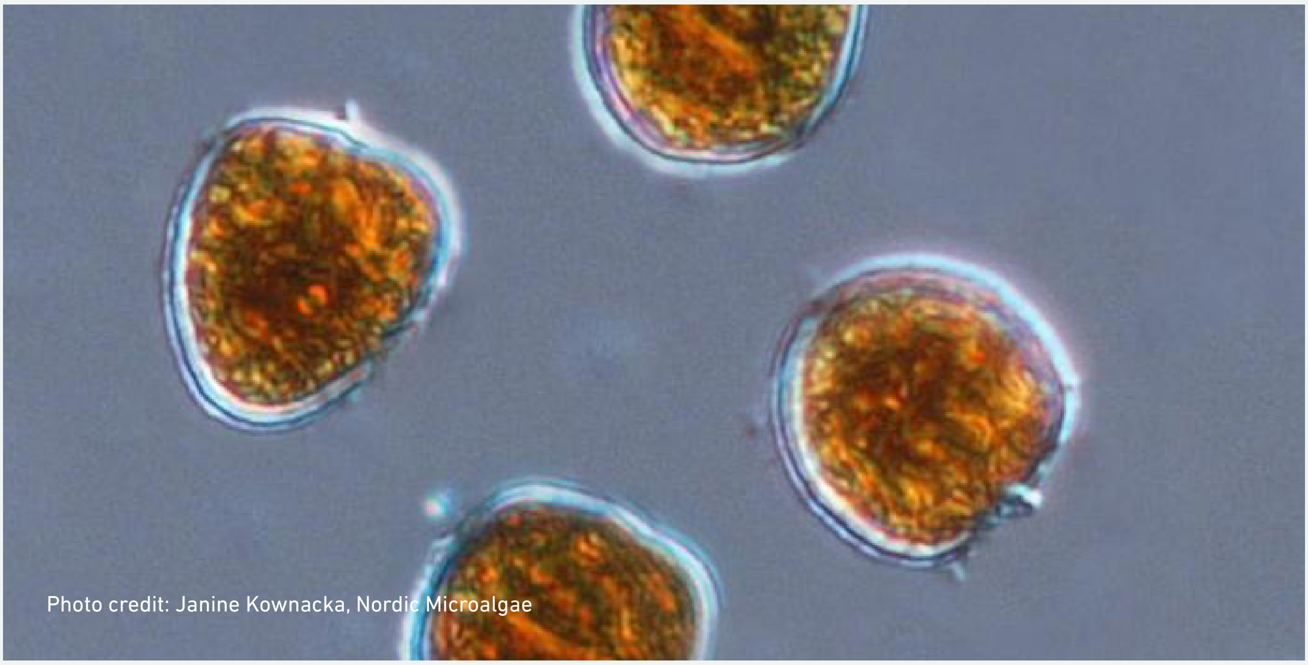

Figure 8.4 *Prorocentrum minimum.*

Ecosystems along the LOAC are adapted to function within certain hydrological and biogeochemical boundaries, but as climate and land use change, these boundaries are being stretched, leading to episodic biological events and multiple pressures on sensitive habitats and species. Here we demonstrate these linked pressures using case studies along the LOAC.

8.5.1 ESTUARINE ALGAE BLOOMS

Prorocentrum cordatum (Ostenfeld) (previously named *P. minimum* (Pavillard)) (Figure 8.4) is a common, bloom-forming dinoflagellate and is the cause of many harmful blooms worldwide. While it is non-toxic to marine invertebrates in general, larger blooms have been reported to cause environmental damage due to high algal biomass and related effects such as localised oxygen depletion and pH change (Heil *et al.*, 2005). Previous studies have shown that it is an adaptable species that can grow quickly in a range of salinities and temperatures and uses both inorganic and organic forms of nutrients, giving it a range of physiological adaptations that makes it responsive to eutrophication (Heil *et al.*, 2005). In the summer of 2020, an exceptional bloom of this dinoflagellate occurred in the Lower Lee Estuary and Lough Mahon, Co Cork. In June, surface samples showed cell concentration of up to 19 million cells/L of *P. cordatum* in the Lower Lee Estuary while levels of dissolved oxygen supersaturation were elevated, peaking at 173.5%. This bloom persisted for the rest of the summer and reddish-brown water was again observed during the July survey with cell concentrations of 49 million cells/L and 31 million cells/L observed in Lough Mahon and Lower Lee Estuary respectively. By the end of August, cell numbers had reduced to just over 1 million cells/L in Lough Mahon. A similar pattern was seen in the Marine Institute weekly national phytoplankton monitoring programme where samples taken off Cobh showed cell concentrations of *P. cordatum* starting to rise in June, peaking mid-July and then starting to fall back in August (www.marine.ie/Home/site-area/data-services/interactive-maps). The Environmental Protection Agency (EPA) has been monitoring phytoplankton in estuaries and coastal waters since 2007 and this bloom in 2020 was the largest cell concentrations observed in the Lee Estuary since the start of this monitoring programme. These episodic biological events are likely caused by multiple stressors. In the EPA's most recent water quality assessment using 2018–2020 data, the highest median winter

Figure 8.5 Macroalgae bloom, Argideen Estuary, Co. Cork, 2018.

dissolved inorganic nitrogen concentrations were found in some of the estuaries in the south of the country (Trodd and O'Boyle, 2021). The estuaries feeding into Cork Harbour have some of the highest winter nutrient concentrations measured in Ireland, with the Glashboy, Owenacurra and Lee estuaries having concentrations more than 50% above the assessment criteria. In more recent years, an increase of nutrient inputs into the marine environment is being observed, especially in the south and southeast of the country. Although blooms of dinoflagellates are common around the coast of Ireland, it is likely that the combination of high nutrients over winter, and the warm growing season facilitated the excessive blooms described above.

8.5.2 MACROALGAE BLOOMS

Opportunistic macroalgal blooms are caused by large accumulations of sea lettuce, the common name for a group of seaweeds of the genus *Ulva*. While predominantly influenced by the inputs of elevated nutrients levels into the marine environment (Ní Longphuirt *et al*., 2016), the distribution of green algal blooms is related to their requirements regarding light, temperature and nutrients (Bermejo *et al*., 2019). Changes in the baseline of these factors such as increasing temperature, or increased freshwater runoff, will impact the scale or seasonality of these events. These seaweeds are a natural part of the Irish marine flora and, in undisturbed environments, are generally found throughout the middle to low intertidal zone (Wan *et al*., 2017). Although present naturally around our coasts, excessive growth of *Ulva* is driven by the presence of elevated nutrients in the environment (European Commission *et al*., 2018). Sea lettuce is considered an opportunistic species and when nutrient levels increase it can utilise these resources to grow very quickly. When conditions are suitable the algae multiply, creating very large accumulations. These excessive growths of sea lettuce can have many different effects on the associated ecosystem. Due to the structure of the seaweed mats, accumulations can affect the underlying sediments, causing changes in the structure and function of the benthic faunal communities. Mats can also affect the ability of other floral communities, such as seagrass, to survive by blanketing the substrate and smothering underlying organisms. This blanketing effect can create a hostile physico-chemical environment which can lead to anoxia and sulphide poisoning of the blanketed species or sediments.

8.5.3 SALT MARSHES

Salt marshes are intertidal salt-tolerant plant communities consisting of grasses, forbs and shrubs (Adam, 2002). In addition to containing habitats listed under Annex I of the Habitats Directive, saltmarshes fall under the angiosperm Biological Quality Element (BQE) of the Water Framework Directive (WFD) (2000/60/EC). They have attracted considerable attention for their capacity to store organic carbon in substrates, and thus contribute to climate change mitigation (Chmura *et al*., 2003; Mcleod *et al*., 2011). These organic carbon deposits come from the plants themselves, and also from marine sediment trapped by salt marsh vegetation. The combination of waterlogging and sulphate hinder microbiological decomposition (Weston *et al*., 2014) so carbon deposits 1 m deep or more can accumulate over centuries (Howard *et al*., 2014; Mueller *et al*., 2019). Ireland has approximately 70 km^2 of salt marshes (Penk, 2019). They are conservatively estimated to store at least 400,000 tonnes of organic carbon, small relative to the peat bogs of Ireland that store ~ 1.5 billion tonnes of organic carbon; however, this only accounts for the upper 10 cm of the soil, so the full carbon store is likely much larger. As much as four times the current salt marsh extent, and thus significant carbon sequestration potential, may have been lost to past land reclamation (Healy and Hickey, 2002; Penk, 2019).

Salt marshes are impacted by land conversion, eutrophication and invasive species, whereas climate change, and sea level rise in particular, is an increasing concern (Gedan *et al*., 2009; Horton *et al*., 2018). Salt marshes in Ireland take up as much as 1 km of the horizontal belt at the upper end of the intertidal zone, but they only occupy approximately 1 m of the elevation gradient (Penk and Perrin, 2022). Sediment deposition can help the ground elevation keep pace with the increasing sea level, but the survival of salt marsh habitats will also depend on compensatory migration up the shore. The potential for such a shift however, will be compounded in many places by walls and embankments, that typically protect the adjoining agricultural and built areas from tidal inundation. Indeed, there are not many salt marshes with natural transition to land. This leads to *coastal squeeze* (Torio and Chmura, 2013). A managed retreat (or realignment) strategy could potentially mitigate this by prioritising sacrificial land, such as low-productivity farmland, but there are only a few such examples in Ireland (Perrin *et al*., 2020). Salt marshes are renowned for a multitude of important ecosystem services, such as attenuation of wave energy and storm surge for coastal protection (Gedan *et al*., 2011; Fairchild *et al*., 2021) which should be considered together with carbon storage in coastal management to resolve conflicting short- and long-term interests.

8.6 DIADROMOUS FISHES

Diadromous fishes migrate between the sea and fresh water to complete their life cycle and these exemplar sentinel species therefore integrate signals of climate change and other stressors into their long-term population dynamics. Collection of data and associated information (e.g. archives of scales, otoliths and DNA) on diadromous fish and their environment over long time periods are extremely important in evaluating their potential for long-term survival and ability to adapt to current and future changes in the environment due to climate change. In Ireland, long-term monitoring of Atlantic Salmon (*Salmo salar*), Sea Trout (*Salmo trutta*) and European Eel (*Anguilla anguilla*) is primarily carried out by the Marine Institute and Inland Fisheries Ireland.

8.6.1 ATLANTIC SALMON

Atlantic salmon (*Salmo salar*) populations have declined across the North Atlantic in recent decades, with marine survival being of particular concern (ICES, 2021). It is listed in Annexes II and V of the EU Habitats Directive as a species of importance requiring conservation and their conservation status in Ireland is classified as vulnerable due to a decline in abundance, caused primarily by mortality at sea, habitat loss, barriers to migration, poor water quality, overfishing and sea lice. Currently, 44% of Irish salmon rivers and 50% of rivers in salmon Special Areas of Conservations (SACs) are failing to meet 50% of their conservation limit (Gargan *et al*., 2021).

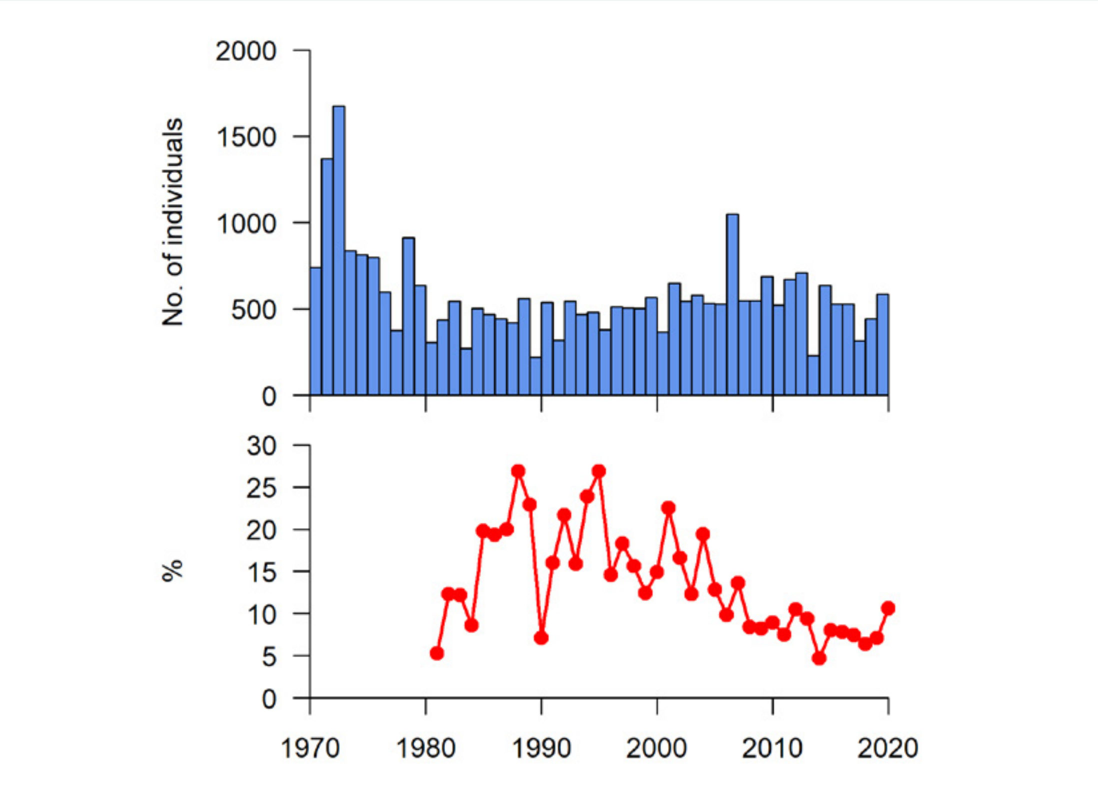

Figure 8.6 Annual wild grilse 1 sea winter salmon counts (top) and % marine returns (bottom) for the Burrishoole catchment, 1971–2020 (Marine Institute Data).

The drift net fishery for salmon off the Irish coast was a major determinant to the number of salmon returning to freshwater to spawn, intercepting between 60% and 80% between the 1980s and the early 2000s. While the cessation of the high seas mixed stock fishery in 2007 led to an increase in returns, drift-netting was not the only source of ocean mortality, and marine survival of salmon continues to decline (ICES, 2021). At the long-term monitoring station for diadromous fish run by the Marine Institute in the Burrishoole catchment, Co. Mayo, returns of grilse (salmon that have spent one winter at sea) to the catchment have ranged from almost 1,800 in 1973 to lows of 252 in 1990 and 279 in 2014 (Figure 8.6). Since 2007, the returns to the catchment have averaged just over 500 grilse per annum, below the conservation limit for the catchment. Marine survival has fallen from an average of ~17% in the 1980s and 1990s to 7.9% in the last five years (Figure 8.6). Coincident with reduced marine survival and decreasing body size, half of the upstream migrating salmon are returning between one and two months earlier from the marine environment compared to the 1970s, indicating considerable oceanic challenges for this species (de Eyto *et al.*, 2022). These trends in Burrishoole are reflective of the general status of salmon in Irish rivers. Poor survival in freshwater has been linked to climatic conditions such as warm, wet winters (McGinnity *et al.*, 2009; de Eyto *et al.*, 2016), while several studies indicate that the reduced number of Atlantic salmon returning from the sea is correlated to large-scale changes in the marine environment, such as increased water temperature or decreased abundance of plankton, leading to poor feeding opportunities (Utne *et al.*, 2021). The future for cold-water adapted species such as Atlantic salmon is uncertain under climate change projections for freshwater and marine habitats. Maintenance of genetic integrity and diversity of wild populations, eliminating poorly planned stocking, and minimising impacts that reduce population sizes to dangerously low levels will support the ability of Atlantic salmon to adapt to changing environments (Thorstad *et al.*, 2021).

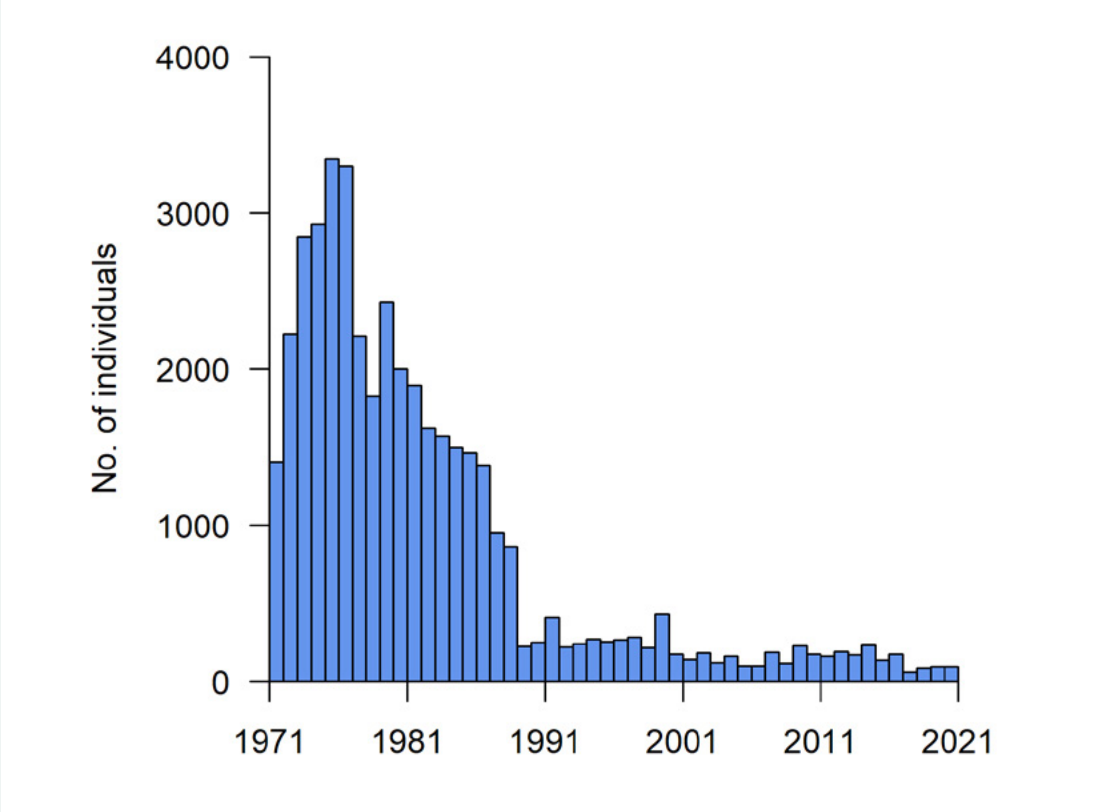

Figure 8.7 Annual count of trout, returning to the Burrishoole catchment, to spawn between 1971 and 2020 (Marine Institute Data).

8.6.2 SEA TROUT

Sea trout (*Salmo trutta*) are fully anadromous, feeding in the marine habitat before returning to freshwater to spawn, although they are genetically the same species as resident brown trout (see Nevoux *et al.*, 2019 for review). There is no co-ordinated framework for the conservation of Sea trout, and only two rivers in Ireland, Burrishoole and Erriff, have stock and recruitment data (Poole *et al.*, 2006; Gargan *et al.*, 2016). Trout in the Burrishoole system occur as both freshwater resident and anadromous forms. Before 1990, the average run of sea trout smolts (juvenile fish migrating to sea) out of Burrishoole was 4,100 fish, dropping to circa 250 in recent years. The stock collapsed in the late 1980s, with the spawning stock dropping from thousands to only 224 fish in 1989 (Figure 8.7). The stock has failed to recover and is currently at an all-time low of less than 50 fish. Many factors may impact the survival of sea trout (Nevoux *et al.*, 2019) and heavy infestations by the salmon louse, *Lepeophtheirus salmonis*, are known to decrease fish condition and increase mortality (Poole *et al.*, 1996; Gargan *et al.*, 2006). While the decline in spawning sea trout returns was already causing concern throughout the late 1980s, it is hypothesised that the warm winter of 1989/1990 may have resulted in higher numbers of generations of salmon lice to develop (Tully, 1992; Tully *et al.*, 1993), significantly increasing fish mortality in that season. This illustrates the potential for changes in climate to impact on the resilience of populations already under pressure from multiple stressors.

Multiple stressors, including climate change, are impacting on diadromous fish in all of their habitats.

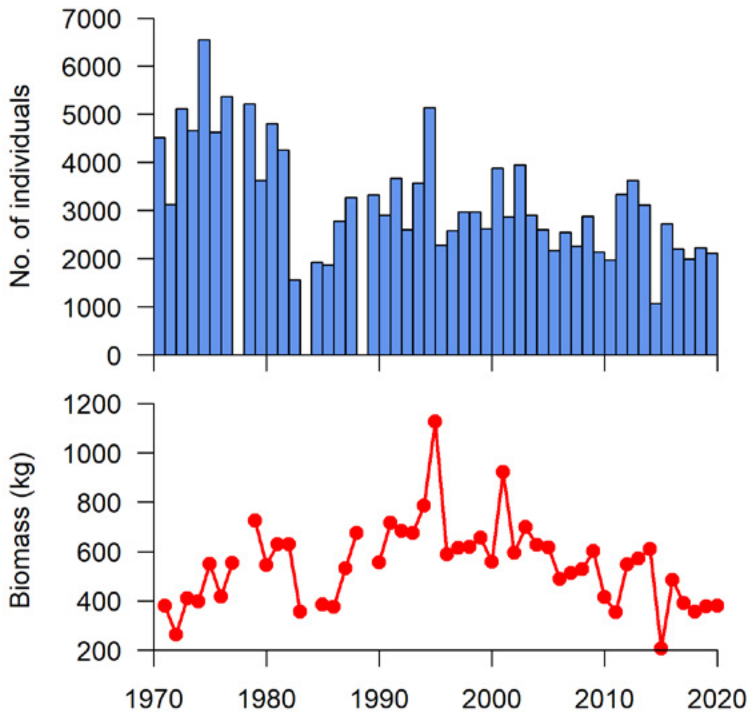

Figure 8.8 Annual count of silver eel (top), and total biomass of silver eel (bottom) leaving the Burrishoole catchment, 1971–2020 (Marine Institute Data).

8.6.3 EUROPEAN EEL

European eel (*Anguilla anguilla*) spawn in the Sargasso Sea and return to the European and North African continental habitats following a trans-Atlantic larval migration. On arrival, juvenile eel inhabit coastal and freshwater areas, where they live and grow for up to several decades before migrating seaward to spawn in the Sargasso Sea. This spawning migration occurs when adult eel transform into sexually mature silver eel. The global population has been in decline at least since the 1960s, with a severe reduction in juvenile eel recruitment occurring in the early 1980s (Moriarty, 1990). Eel recruitment is currently at about 5–6% of the historical mean in the Atlantic region and there is significant mortality at all life stages (ICES, 2020). Eel are listed on the International Union for Conservation of Nature (IUCN) red list as critically endangered and are currently the subject of specific legislation governing conservation and stock recovery measures within the European Union (EC, 2007).

Numbers of migrating silver eels has declined in Burrishoole, from an average of 4,500 eels per annum to approximately 2,200 eels average for the last five years (Figure 8.8). The biomass of eel migrating out of the catchment peaked in the 1990s, but is dropping again. This is likely a response to the lack of recruits, but may also be a consequence of changing water temperatures in recent years (Vaughan *et al.*, 2021). Day-to-day variation in the number of eels migrating is associated with conditions that minimise predation risk such as new moons, floods and the presence of other eel. The migration out of Burrishoole is commencing a month earlier now compared to the 1970s (Sandlund *et al.*, 2017; de Eyto *et al.*, 2022). Climate change has likely already impacted on the population structure and dynamics of this iconic species, along the full continuum of its habitats, from headwaters to the deep Atlantic (Friedland *et al.*, 2007; Arevalo *et al.*, 2021). As with the other diadromous fish species, minimising other anthropogenic stressors will be crucial to ensuring the resilience of this species.

8.7 RECOMMENDATIONS

1. It is critical that key long-term datasets, which capture disruption signals along the LOAC, are maintained and financially supported. Examples are:
   - Lough Feeagh (Mill Race) water temperature
   - Diadromous fish stocks as sentinel species
   - Greenhouse gas emissions along the aquatic continuum
   - Irish Reference Network (IRN) of hydrometric stations
   - Riverine Inputs and Direct Discharges (RID) programme
2. Modelling exercises using future climate projections are an essential decision support tool and should be used in future catchment management plans.
3. Assessment of future impacts of climate change for Ireland requires that monitoring and research of rivers, lakes and transitional waters are considered simultaneously.
4. Anthropogenic pressures, that reduce the resilience of sensitive habitats and species to climate change, must be reduced to ensure the conservation of Ireland's biodiversity.
5. Nature-based solutions should be included in climate change mitigation plans.

CHAPTER 9

REGIONAL & LOCAL DOWNSCALED MODELS

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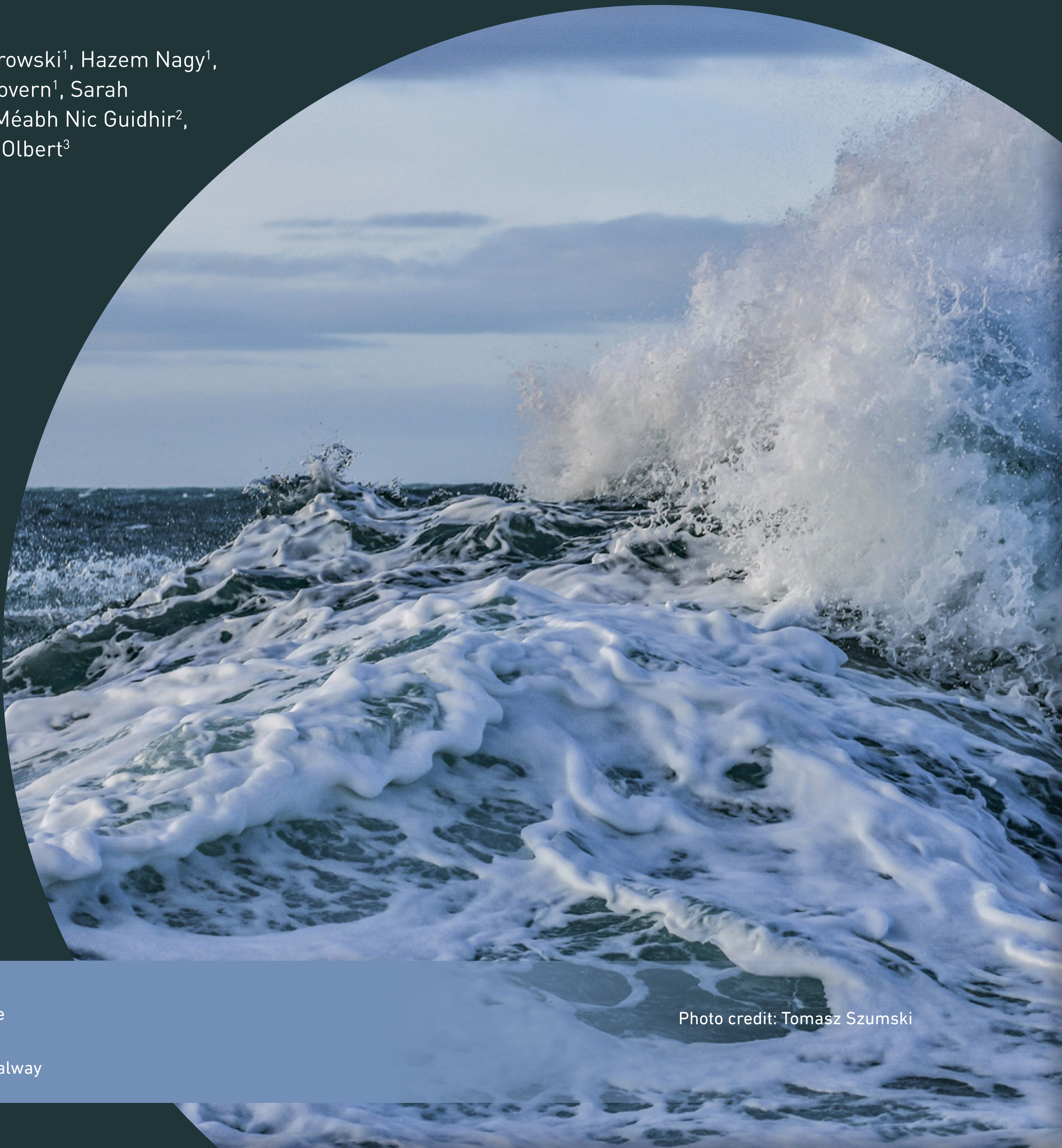

Photo credit: Tomasz Szumski

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9.1 SEA STATE

The wave climate of the Northeast Atlantic is energetic and strongly seasonal, with high interannual variability and a strong positive correlation between significant wave height (the mean height of the highest 1/3 of waves) and the North Atlantic Oscillation (NAO) index (Gallagher *et al.*, 2014; Scott *et al.*, 2021).

Regional and locally downscaled wave climate projections for Ireland have shown a robust overall trend towards decreasing seasonal averages for significant wave height by the end of the 21st century, in agreement with scientific literature and the trends in atmospheric forcing in the Northeast Atlantic (Gallagher *et al.*, 2016b; Gallagher *et al.*, 2016a; Aarnes *et al.*, 2017; Wolf *et al.*, 2020; Lemos *et al.*, 2021). The magnitude of the projected wave height decreases is greater for higher emissions scenarios (representative carbon pathway (RCP) 8.5) (Gallagher *et al.*, 2016a; Aarnes *et al.*, 2017; Bricheno and Wolf, 2018). The largest and most statistically robust decreases are projected in winter and summer seasons (Gallagher *et al.*, 2016a).

When looking at extreme sea-states the projected behaviour of extreme wave conditions is less certain. While most projections show decreases in significant wave height, changes in extreme wave heights around Ireland have shown limited robustness, with some studies showing an increase (Wolf *et al.*, 2020; Bernardino *et al.*, 2021; Lobeto *et al.*, 2021; Bricheno and Wolf, 2018) with others showing no change or a decrease (Gallagher *et al.*, 2016b; Gallagher *et al.*, 2016a; Aarnes *et al.*, 2017). Evidence for future increases in extreme wave heights was also found during NAO+ atmospheric mode events (Gleeson *et al.*, 2019) indicating the possibility of increasing extreme wave heights linked to increased storminess in NAO+ conditions in northern latitudes (above 50N), and evidence of NAO- patterns decreasing storm tracks in lower latitudes regionally (Bricheno and Wolf, 2018). Substantial uncertainty remains, however, in storm tracks and the most-severe wave heights around Ireland and the Northeast Atlantic region (Gallagher *et al.*, 2016b; Lemos *et al.*, 2021; Wolf *et al.*, 2020).

Significant wave heights around Ireland are projected to decrease. Largest decreases are projected for the summer and winter and the magnitudes of these decreases are higher for higher emission scenarios.

As with significant wave height, wave periods and directions around Ireland also show strong correlations with the NAO, particularly in winter and spring (Gallagher *et al.*, 2014; Dodet *et al.*, 2010). To date, however, these variables have received less attention than wave heights in climate projections. Limited available studies show, that in line with projected NAO trends in the coming century, wave periods around Ireland (Gallagher *et al.*, 2016b) as well as in the wider North Atlantic (Bernardino *et al.*, 2021; Hemer *et al.*, 2013), are projected to decrease slightly this century.

It should be noted that uncertainty in wave-climate projections is dominated by limitations of the climate-models driving the simulations (Wolf *et al.*, 2020; Morim *et al.*, 2019). Employing single-method modelling, causes uncertainties in projections to be underestimated (Morim *et al.*, 2019). Therefore, as further multi-model ensembles and regional downscaled models are carried out using more accurate and higher-resolution driving climatology, the uncertainty surrounding the sign and magnitude of projected changes will decrease.

Any change to the extreme waves remains uncertain.

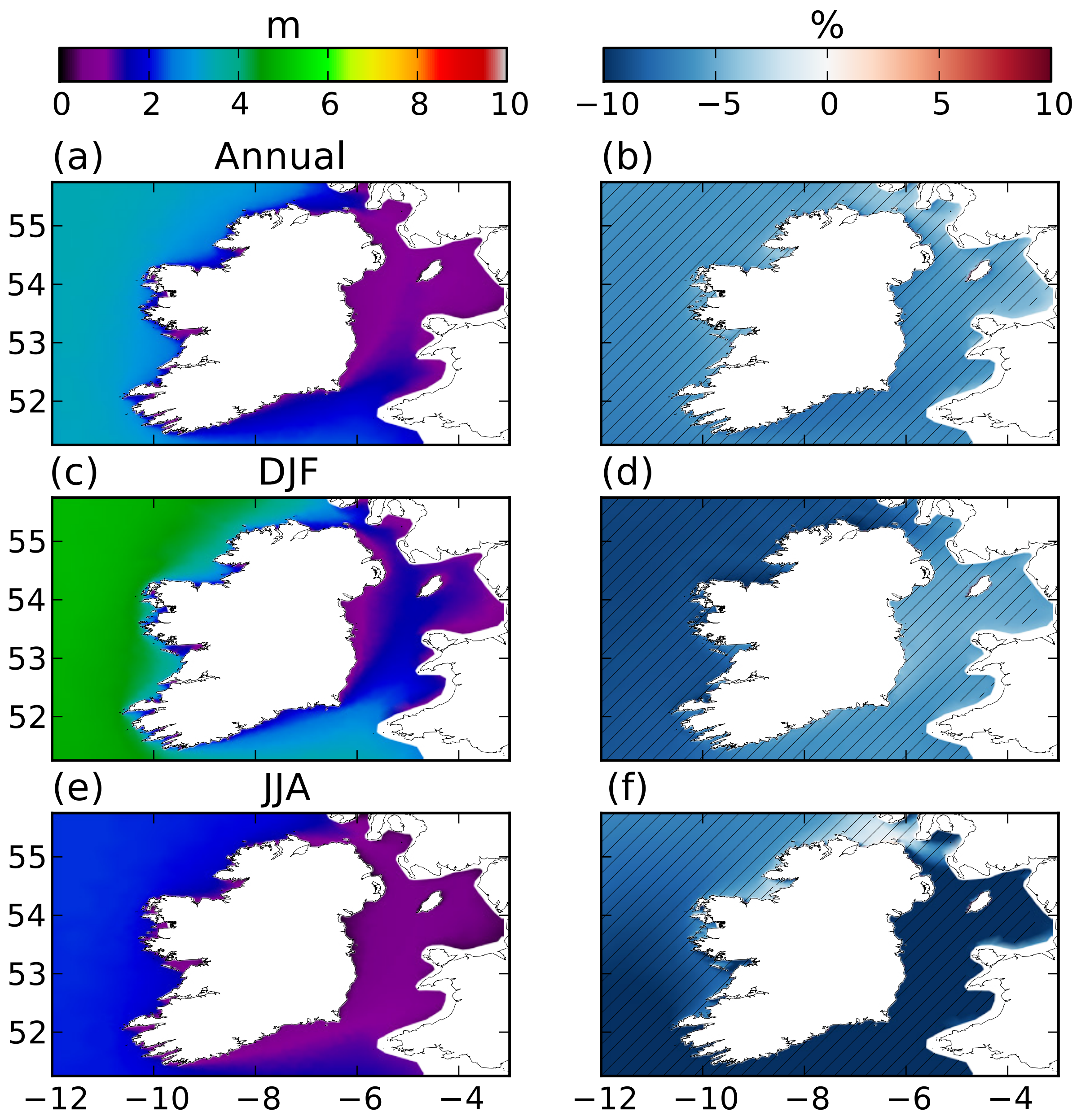

Figure 9.1 Ensemble mean significant wave height: (a) annual (c) December, January, February (DJF) (e) June, July, August (JJA) for the historical period (1980–2009). Projected changes (%) in annual ensemble mean significant wave height for the period 2070–2099 relative to 1980–2009 for ensemble mean RCP8.5: (b) annual (d) DJF and (f) JJA. Hatching denotes areas where the magnitude of the ensemble mean change exceeds twice the inter-model standard deviation. Figure based on model data and analysis in Gallagher *et al.*, 2016b.

9.2 SEA SURFACE HEIGHT

The Copernicus Climate Change Service (https://cds.climate.copernicus.eu/) is part of the Copernicus Programme run by the European Commission. Water level change indicators for the European Coast derived from climate projections are provided by this service. The dataset, published on 06–07–2020, includes the mean sea level and surge change indicators for various return periods and percentiles (https://doi.org/10.24381/cds.b6473cc1). The indicators are derived from data on tidal dynamics, storm surge, and sea level rise based on historical simulation (1977–2005) and future climate projection RCP8.5 (2041–2070). RCP8.5 is the pessimistic, high emissions scenario under the CMIP5 assessment. The Deltares Global Tide and Surge Model (GTSM) version 3.0 was used to compute these indicators. Table 9.1 shows the calculated Mean Sea Level (MSL), the 10th percentile of surge residual and surge levels for various return periods over the historical time period [1977–2005] and future projection RCP8.5 [2041–2070], as well as the difference between them. These values are the averages for all coasts of Ireland. As presented in Table 9.1, the MSL around Ireland is projected to be higher by 25 cm between 2041 and 2070 under the RCP8.5 scenario, compared to the historical period from 1977 to 2005. Surge levels (water level above the MSL after the removal of the tidal signal) will also generally increase, as expressed by the value of the 10th percentile of the surge level (i.e. 90% of surges are greater than this value). This increase is from 13.4 cm in 1977–2005 to 17.7 cm by the middle of the 21st century. The extreme surge levels (from 2 to 100 years return periods) though show only a modest increase of 3 to 5 cm.

Slight decrease in wave periods is projected.

Surge heights (i.e. water level caused by atmospheric effects) are projected to increase under a pessimistic scenario and 90% of surges will be greater by c.4 cm by mid-century.

The CMIP6 (https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6) downscaled projections are a work in progress and first publications emerge. Chaigneau *et al.* (2022) downscaled the CMIP6 SSP5-8.5 (very pessimistic, corresponding to RCP8.5) and SSP1-2.6 (very optimistic,

Table 9.1 The Mean Sea Level (MSL), 10th surge residual percentile and return period surge levels for historical [1977–2005] and future RCP8.5 [2041–2070] for the Irish coastal waters based on water level change indicators for the European coast derived from climate projections (https://doi.org/10.24381/cds.b6473cc1).

Parameter	Historical [1977-2005]	Future [2041-2070] RCP8.5	Difference [RCP8.5-History]
Mean Sea Level (MSL (cm)	+ 0.5	+ 25.5	+ 25
10th surge residual percentile (cm)	13.4	17.7	+4.3
return_surge_level (2 Year) (m)	0.80	0.85	+0.05
return_surge_level (5 Year) (m)	0.97	1.01	+0.03
return_surge_level (10 Year) (m)	1.08	1.12	+0.04
return_surge_level (25 Year) (m)	1.23	1.27	+0.04
return_surge_level (50 Year) (m)	1.33	1.37	+0.04
return_surge_level (100 Year) (m)	1.43	1.47	+0.04

corresponding to RCP2.6) scenarios to investigate the sea level changes in the Iberia-Biscay-Ireland (IBI) region. They report a mean sea level increase of 0.8 m and 0.4 m when averaged over the IBI region, for SSP5-8.5 and SSP1-2.6, respectively, when compared to the 1986–2005 period. As regards the extreme sea levels, expressed as the 99th percentile of non-tidal residuals, these are projected to increase from 2 to 5 cm in Ireland under the SSP5-8.5, and less along the southern coasts and more along the northern coasts.

One of the earlier climate modelling studies published in Olbert *et al.* (2012) and assuming a medium emissions scenario (SRES A1B), predicts a more significant mean sea level rise in the Irish Sea of 0.47 m during the 21st century.

Mean Sea Level (MSL) is projected to increase by 25 cm along the Irish coast by mid-21st century compared to the end of the 20th century under a pessimistic scenario. A medium emissions scenario predicts a rise of MSL of 47 cm in the Irish Sea during the 21st century.

Sea surface temperature (SST) and near bottom temperature (NBT) in the southwest of Ireland are projected to increase, SST by 0.1-0.2°C (most likely scenario) and 0.2-0.3°C (pessimistic), whereas NBT is projected to rise by c. 0.25°C in both scenarios.

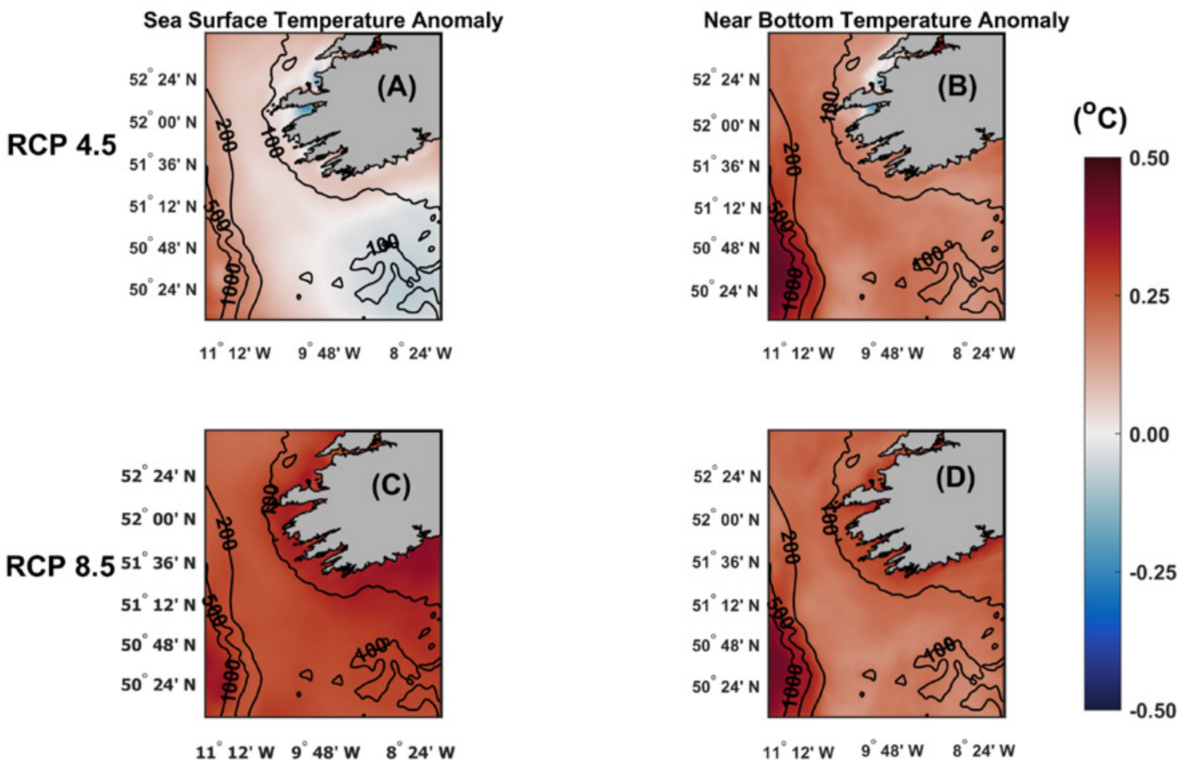

Figure 9.2 Temperature anomaly maps in the southwest of Ireland: (a) SST anomaly map for RCP4.5, (b) NBT anomaly map for RCP4.5, (c) SST anomaly map for RCP8.5 and (d) NBT anomaly map for RCP8.5. Anomalies are the differences between the projected mean temperatures in years 2006–2035 and mean temperatures in years (1975–2005). From Nagy *et al.* (2021).

9.3 SEA SURFACE AND SUBSURFACE TEMPERATURE

9.3.1 PROJECTIONS FOR THE SOUTHWEST OF IRELAND

A high-resolution 3-D Regional Ocean Model System (ROMS) for Irish shelf waters in the southwest is presented in the paper by Nagy *et al.*, 2021. The climate projections comprise: a 31-year historical simulation (1975–2005) and two 30-year future climate model projections (2006–2035) for the RCP4.5 (an intermediate scenario) and 8.5 scenarios.

Figure 9.2 depicts the projected temperature anomaly maps for Sea Surface Temperature (SST) and Near Bottom Temperature (NBT). The RCP4.5 projection of SST shows warming in the model domain of 0.10 to 0.20°C, except for part of the Celtic Sea and some coastal locations where slight cooling is projected (Figure 2(a)). The NBT anomaly map for the RCP4.5 simulation shows a more pronounced increase in bottom water temperature, which is highest,, c. 0.5°C, in the deep waters off the shelf (Figure 9.2(b)). Across the model domain, the warming is c. 0.25°C. Similarly for SST, some coastal locations exhibit slight cooling.

The SST anomaly for the RCP8.5 scenario shows more significant warming across the southwest Ireland model domain compared to RCP4.5 and generally between 0.3 and 0.5°C (Figure 9.2(c)). The spatial distribution of the NBT anomaly is very similar to that in RCP4.5 with only slightly greater warming (Figure 9.2(d)). Distinctly, cooling is not projected in coastal waters for either the RCP8.5 or RCP4.5.

Extreme surges of 2 to 100 year return periods will increase rather modestly by 3 to 5 cm by mid-century under a pessimistic scenario.

9.3.2 PROJECTIONS FOR THE CELTIC SEA AND THE IRISH SEA

Tinker *et al.* (2016) investigated the effect of uncertain large-scale climate forcing on projections for the northwestern European shelf seas, including the Irish and the Celtic Seas. The study used a dynamically downscaled ensemble of global Atmosphere-Ocean climate model (GCM) projections made by perturbed atmospheric parameter model variants designed to span uncertainty in climate sensitivity. The ocean model used in this GCM experiment was POLCOMS and the projections concern the medium emissions scenario (SRES A1B). This study predates the most recent CMIP5 models. Simulations were run as transient experiments from 1952 to 2098. Table 9.2 presents the centennial changes in selected Essential Ocean Variables (EOVs), i.e. mean values for 2069–2098 in comparison to 1960–1989. According to Table 9.2, a centennial warming in SST and NBT of around 3°C is projected in the Irish Sea and an SST increase of about 3°C in the Celtic

Table 9.2 End of century projected change (2069–2098 relative to 1960–1989) in annual mean SST, SSS, NBT, NBS and summer PEA and MLD for ensemble mean (±2σ) for the Irish Sea and the Celtic Sea. From Tinker *et al.* (2016).

Parameter	Irish Sea	Celtic Sea
Annual dSST (°C)	3.08 (±0.85)	3.01 (±1.04)
Annual dSSS	-0.18 (±0.27)	-0.11 (±0.23)
Annual dNBT(°C)	3.00 (±0.82)	2.54 (±0.88)
Annual dNBS	-0.18 (±0.26)	-0.03 (±0.19)
Annual dDFT (°C)	0.08 (±0.06)	0.47 (±0.32)
Annual dDFS	-0.01 (±0.01)	-0.08 (±0.11)
Summer dMLD (meter)	1.68 (±1.35)	0.96 (±0.75)
Summer dPEA (J/m3)	3.75 (±2.25)	31.90 (±18.15)

Photo credit: Coast Monkey

Sea, whereas NBT in the Celtic Sea is projected to increase by c.2.5°C, indicating an increase in the strength of stratification in the Celtic Sea.

Olbert *et al*. (2012) predict a more modest increase of SST across the Irish Sea under the same SRES A1B scenario. Results from a regional scale ECOMSED ocean model, downscaled from the MPIOM model (the Max Planck Institute Ocean Model) and run for a 120-year period (1980–2099), show that at the end of the 21st century SST in the Irish Sea will be greater by about 1.9°C across all seasons compared to the 1980s. A shift in the timing of the annual maxima and minima is also predicted, and these are projected to occur around two weeks later each year relative to the present climate. Geographically, shallow waters along the coastline and in the eastern Irish Sea will exhibit strongest warming.

Based on some earlier projections (SRES A1B, medium emissions), SST and NBT in the Irish Sea is projected to increase on average by c. 3°C, whereas SST and NBT in the Celtic Sea is expected to rise by c. 3°C and 2.5°C, respectively. Other studies suggest an increase of SST in the Irish Sea of 1.9°C.

9.3.2.1 Circulation in the Irish Sea

In the same publication, Olbert *et al*. (2012) report that climate change will significantly modulate the circulation patterns in the Irish Sea. The western Irish Sea gyre is projected to become stronger and result in substantial reinforcement of southward currents along the east coast of Ireland. As regards the exchange of water in the Irish Sea though, it is predicted that an overall net northward flow will be maintained at an annual rate equal to that of the current climate, though the flow will be weaker in the first half of the year and stronger in the second half. In general, water transport in the Irish Sea exhibits an annual cycle with the highest outflow in February and lowest in July.

9.3.2.2 Mixed layer depth and stratification

One of the derived variables linked to temperature, salinity, and ocean surface heat flux is the Mixed Layer Depth (MLD) and the phenomenon of stratification. Thus, Table 9.2 shows the projected changes in MLD as well as in the surface and bottom temperature difference and the potential energy anomaly (PEA); the latter two being the indices of the strength of stratification. The values were obtained from Tinker *et al*. (2016) based on the experiments described therein and briefly introduced in section 9.3.2. These values are calculated for summer. According to the results,

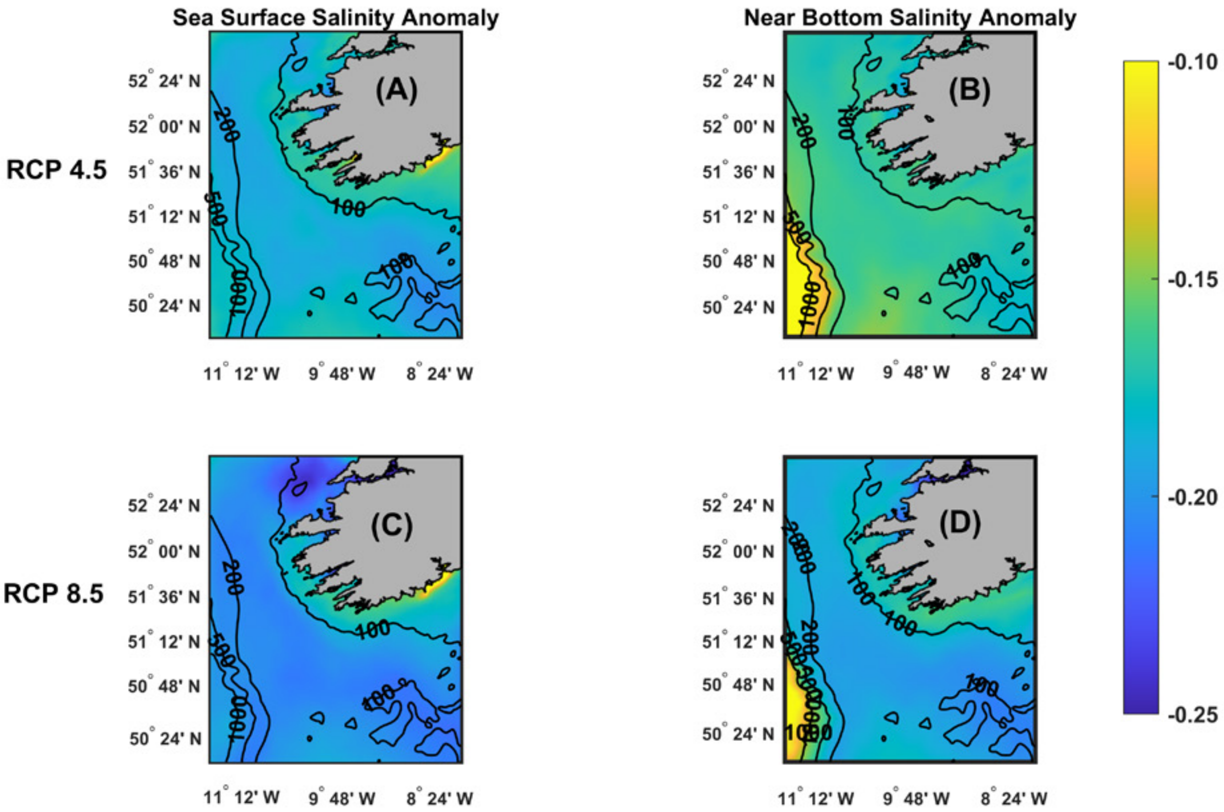

Figure 9.3 Salinity anomaly maps in the southwest of Ireland: (a) SSS anomaly map for RCP4.5, (b) NBS anomaly map for RCP4.5, (c) SSS anomaly map for RCP8.5 and (d) NBS anomaly map for RCP8.5. Anomalies are the differences between the projected mean salinities in years 2006–2035 and mean temperatures in years (1975–2005). From Nagy *et al*. (2021).

summer stratification is projected to increase mainly in the Celtic Sea with PEA increasing by more than 31 J/m^3, whereas only a slight increase is projected in the Irish Sea. This is also reflected in the values of the differences between the surface and seabed temperatures (dDFT) and the surface and seabed salinity (dDFS). dDFT increases and dDFS decreases more substantially in the Celtic Sea compared to the Irish Sea, indicating a greater positive difference between the surface and seabed temperature and a greater negative difference between the surface and bottom salinity. Both contribute to the increase in the strength of stratification, as confirmed by the increase of the PEA. At the same time the MLD increases in the Irish Sea and the Celtic Sea (more so in the Irish Sea).

Stratification is projected to strengthen in the Celtic Sea this century.

9.4 SEA SURFACE AND SUBSURFACE SALINITY

9.4.1 PROJECTIONS FOR THE SOUTHWEST OF IRELAND

The model by Nagy *et al.* (2021) introduced in section 9.3.1 also provides projections of changes to salinity off southwest Ireland. Figure 9.3(a-d) presents salinity anomaly maps for Sea Surface Salinity (SSS) and Near Bottom Salinity (NBS), which show a general freshening across the region. In RCP4.5 a reduction in SSS is in the region of 0.15-0.20 across most of the domain, whereas in RCP8.5 it is closer to 0.20 or in excess of it locally. The lowest freshening (c. 0.15 and less) is projected in the coastal waters (i.e. <100 m deep) and in the deep waters off the shelf. This applies to both RCP4.5 and 8.5. The greatest freshening is projected for the shelf waters between the isobaths of 100 and 200 m. Also, generally the SSS decreases more compared to NBS.

The western Irish Sea Gyre is projected to strengthen. The overall net transport of water through the Irish Sea will remain unchanged.

9.4.2 PROJECTIONS FOR THE CELTIC SEA AND THE IRISH SEA

Tinker *et al.* (2016) also analysed changes in the projected SSS and NBS in the set of experiments described in section 9.3.2. Freshening is predicted in both the Irish Sea (-0.18 by end of the 21st century compared to end of the 20th century) and in the Celtic Sea (-0.1 over the same time period). These results are presented in Table 9.2. Moreover in the Irish Sea, SSS and NBS are projected to change by the same degree (-0.18), but in the Celtic Sea the decrease in SSS (-0.11) is four times greater than in NBS (-0.03), contributing to an increase of stratification of the Celtic Sea.

9.5 NET PRIMARY PRODUCTIVITY

Primary productivity is a sub-variables of the phytoplankton biomass and diversity EOV. Net primary productivity (NPP) is a measure of the phytoplankton biomass at the bottom of the ocean's food chain after the phytoplankton's energy consumption has been accounted for. NPP provides a good proxy for the likely productivity further up the food chain. Projections suggest a marginal decrease in global NPP by ~2% or ~4% under RCP4.5 and RCP8.5 respectively (Krumhardt *et al.*, 2017). This marginal decrease masks local increases and decreases in NPP in regional seas that average out globally; Atlantic NPP is anticipated to decrease under RCP4.5 and 8.5. Projected changes in NPP are a part of a wider regime change anticipated in response to climate

Table 9.3 Outcome of Mann–Kendall testing for detection of trend (p<=0.05) in annual and monthly total NPP in the Irish EEZ from 2006 to 2049. NOTE: (-) indicates that no trend was detected. P-value and Sen slope are also provided.

Period	Irish Sea	Celtic Sea
Annual	-	Decreasing, p=0.007, slope=-189 Gg/yr
March	-	-
April	-	-
May	-	-
June	-	-
July	-	Decreasing, p=0.034, slope=-48 Gg/yr
August	Decreasing, p=0.009, slope=-38 Gg/yr	Decreasing, p=0.009, slope=-47 Gg/yr
September	Decreasing, p=0.0002, slope=-54 Gg/yr	Decreasing, p=0.0005, slope=-52 Gg/yr
October	-	Decreasing, p=0.017, slope=-18 Gg/yr

change. Reygondeau *et al.* (2020) determined that existing oceanic biogeochemical provinces may shift polewards at a mean rate of 18.4 km per decade, while new oceanic environs will also emerge and expand towards 2100.

To elucidate the potential changes to primary productivity in Irish waters, an NPP projection dataset was analysed from the Copernicus C3S modelled projections entitled "*Marine biogeochemistry data for the northwest European Shelf and Mediterranean Sea from 2006 up to 2100 derived from climate projections*" [doi: 10.24381/cds.dcc9295c]. The regionally downscaled projections, under RCP4.5 and 8.5, were generated by a 7km resolution NEMO-FABM-ERSEM coupled hydrodynamic-biogeochemical model (Bruggeman and Bolding, 2014; Butenschön *et al.*, 2016; Gurvan *et al.*, 2022) under CMIP5.

The presented analyses concern the time period from March to October. The total NPP per month and per annum were calculated by summing up throughout the Irish EEZ. The non-parametric Mann–Kendall test was applied to determine whether there was a statistically significant trend ($p<0.05$) in (i) yearly timeseries of monthly NPP, (ii) timeseries of total annual NPP, and (iii) latitude of maximum annual NPP over time.

The southwest of Ireland, the Celtic Sea and the Irish Sea are projected to become fresher, both at the surface and near the seabed.

Table 9.3 presents a summary of the salient results from the Mann–Kendall testing for (i) and (ii) above. A statistically significant decreasing trend was detected for annual total NPP under RCP8.5 at a rate of -189 Gg/yr (-0.189 Tg/yr), the decreasing trend is approximately 0.135% per annum. No trend was detected for annual NPP under RCP4.5. There is an apparent decline in NPP from 2039 that doesn't recover towards 2049. Furthermore, no trend was detected for March through June under either RCP. Maximum NPP was estimated for May of almost every year, except for the years 2013, 2020 and 2021 (RCP4.5) and 2019 (RCP8.5), for which the most productive month was projected as June.

The annual net primary productivity is projected to decrease by mid-21st century under the pessimistic scenario (RCP8.5) and remain unchanged under the most likely scenario (RCP4.5). A northward shift in maximum productivities is projected in RCP8.5 compared to RCP4.5.

Accepting May as the prevailing month of maximum NPP, there is no detectable trend, increasing or decreasing, for May total NPP under either RCP. A statistically significant trend is detected for both August and September total NPP under both RCPs. Furthermore, under RCP8.5, July and October total NPP presents a statistically significant decreasing trend. Considering the significant trends for monthly total NPP under RCP 8.5 for July to October, the rate of decrease NPP is consistently less than 0.5% per annum.

Figure 9.4 provides by year, the locations of maximum NPP within the Irish EEZ under RCP4.5 and 8.5. The size of each circle indicates the year, with the smallest circle 2006, and the largest 2049. While productive locations under RCP4.5 are mainly south of 50°N, around the Goban Spur, south of Porcupine Seabight and Porcupine Bank, under RCP8.5 productive locations are more dispersed northwards. The geographical mean of all points under RCP4.5 is (50.02N, -12.33E), versus (50.82 N, -12.49 E) under RCP8.5. This suggests that comparatively, under RCP8.5, there would be a northwards shift, over time, in geographic mean of the maximum NPP by 0.8° (approx. 90 km).

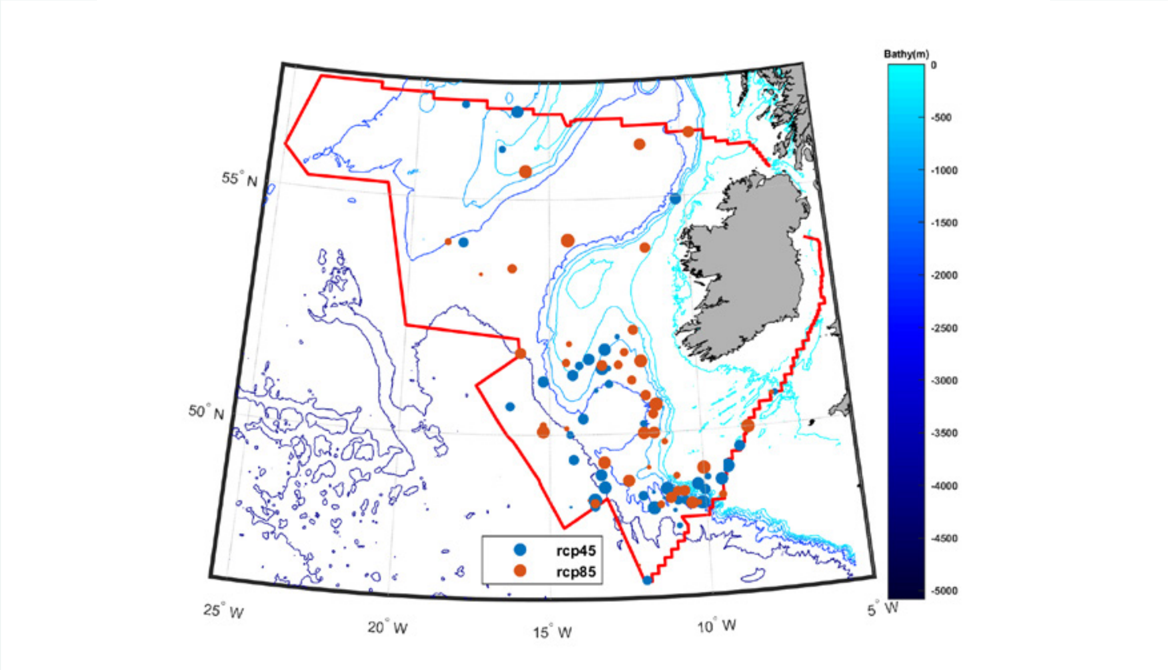

Figure 9.4 Geographic positions in Ireland's EEZ (red outline) where the maximum depth-integrated primary productivity occurred each year of the C3S biogeochemical projection from 2006 to 2049; the size of the circle increases with passing years [Bathymetry: GEBCO Compilation Group (2021)].

9.6 RECOMMENDATIONS

1. Ensure historical climate runs are bias-corrected before proceeding with future projections to reduce uncertainties.
2. Develop biogeochemical climate models to meet stakeholder requirements.

CHAPTER 10

MARINE INFRASTRUCTURES & PROGRAMMES FOR MONITORING ESSENTIAL OCEAN VARIABLES

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Photo credit: Darragh Duffy

10.1 INTRODUCTION

Marine infrastructures and programmes collect a variety of data to provide the scientific evidence for climate change in our waters. Irish infrastructures such as the national research vessels, the data buoy and tide gauge networks, remotely operated vehicles, autonomous gliders and facilities such as the Burrishoole Catchment research observatory, support the data collection of Essential Ocean Variables (EOVs). Programmes under the Data Collection Framework (DCF) for fisheries pull together critical information on the distribution and abundance of many fish species. National monitoring programmes for the Water Framework and Marine Strategy Framework Directives, and the National Phytoplankton Monitoring Programme also systematically collect information on essential ocean variables. The ObServe programme (managed by Department of the Environment, Climate and Communications or DECC) systematically surveys bird and cetacean populations. Climate observations are also gathered in research projects and should be considered as pilots for particular essential ocean variables, e.g., cold water corals through the SeaRover project. There may also be future scope to transfer research findings from such projects to the collection of particular essential ocean variables in due course. An initial assessment by Nolan *et al*. (2021) presented a *Baseline Study of Essential Ocean Variables (EOVs) in Irish Waters* highlighting some important oceanographic climate monitoring datasets that contribute to the Global Climate Observing System (GCOS).

Marine infrastructures and programmes are critical to the long-term collection of essential climate and ocean variables needed to provide the scientific evidence for climate change.

Marine infrastructures include marine platforms/ observatories and land based specialised equipment and laboratories.

10.2 ESSENTIAL OCEAN VARIABLES

Many of the Essential Ocean Variables (EOVs) are included in the wider Essential Climate Variables (ECVs) established through the Global Climate Observing System (GCOS). The GCOS was established in 1992 to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users. The EOVs are chosen to reflect the key oceanic processes and phenomena of importance to ocean resource management, decision and policy support and climate change adaptation. The EOVs are sub-divided into those needed to monitor and understand physical, biogeochemical, biological and ecosystem processes as presented in Figure 10.1. The maturity assigned to each EOV is based on requirements, observations and data and information. Physical variables are at a much higher maturity level than biogeochemical and biological variables, although considerable efforts are currently underway to address the gaps.

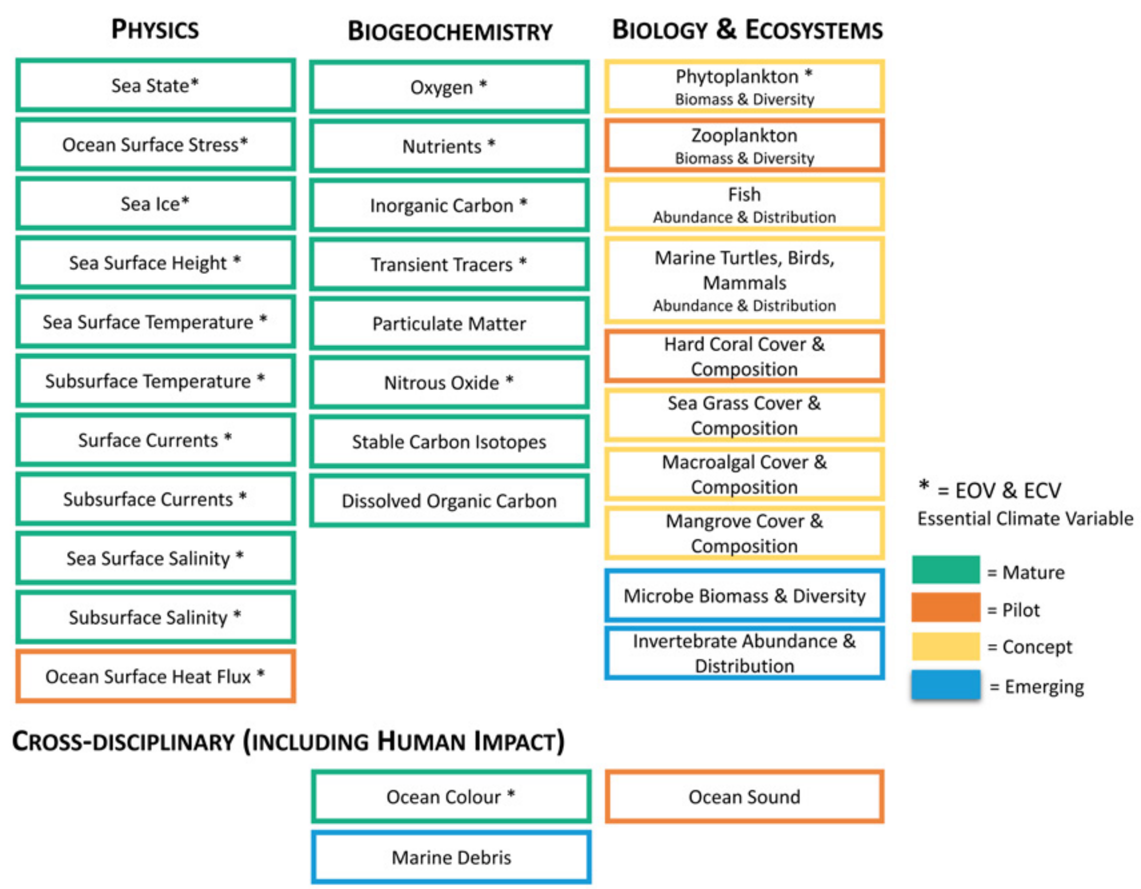


Figure 10.1 Global Ocean Observing System (GOOS): Essential Ocean Variables and the maturity level of collection efforts globally (November 2022). EOV* are considered an Essential Climate Variable by the Global Climate Observing System (GCOS). Source: GOOS

10.3 INTERNATIONAL MARINE INFRASTRUCTURES

Through active involvement as the Irish Government's representative in the European Multidisciplinary Seafloor and water-column Observatory (EMSO), and the Euro-Argo European Research Infrastructure Consortia (ERICs), the Marine Institute contributes to European observing efforts and the continuous monitoring of ocean health. Ireland, represented by the Environmental Protection Agency recently became a member of the Integrated Carbon Observing System (ICOS ERIC). These collaborations improve the quality of scientific ocean climate measurements, align observations with those from other EU countries. These provide essential data that helps scientists to better understand oceanic conditions, interactions between the ocean and atmosphere, and long-term ocean climate trends.

ESFRI

The European Strategy Forum on Research Infrastructures (ESFRI), is a strategic instrument to develop the scientific integration of Europe and to strengthen its international outreach. The ESFRI operates at the forefront of European and global science policy and contributes to its development, translating political objectives into concrete advice for Research Infrastructures (RIs) in Europe. The 2021 ESFRI roadmap contains details of 41 ESFRI landmark RIs and 22 ESFRI projects. Of these 63 RIs, there are eight landmark RIs and three projects in the environmental area in the 2021 ESFRI roadmap. As well as providing comprehensive and quality-assured data to help understand a changing climate, these RIs boost scientific knowledge, accelerate technology development and enhance both technological and social innovation.

EMSO ERIC

The European Multi-disciplinary Seafloor and water column Observatory (EMSO) is a system of regional facilities placed at key sites around Europe - from the Arctic to the Atlantic, through the Mediterranean, to the Black Sea. Observatories are equipped with multiple sensors, placed throughout the water column and on the seafloor. They constantly measure different biogeochemical and physical parameters that address natural hazards, climate change and marine ecosystems.

EURO-ARGO ERIC

Euro-Argo coordinates the European contribution to the international Argo programme to provide quality controlled data and access to the data sets and data products to the research (climate and oceanography) and operational oceanography communities. The Argo array is an important component of the GOOS, required to understand and monitor the role of the ocean in the Earth's climate system, in particular the heat and water balance.

ICOS ERIC

The Integrated Carbon Observation System (ICOS) provides standardised and open data from more than 140 monitoring stations across 14 European countries. The stations monitor greenhouse gas concentrations in the atmosphere and carbon fluxes between the atmosphere, the land surface and the ocean. The ICOS Ocean thematic centre coordinates 22 ocean stations in seven countries, monitoring carbon uptake and fluxes in the North Atlantic and the Nordic, Baltic and Mediterranean Seas. Monitoring includes sampling from research vessels, moorings, buoys and Ships of Opportunity. Ireland recently joined the ICOS with a combination of terrestrial, atmospheric and oceanic platforms including a pCO_2 system on board the RV *Celtic Explorer*.

GLEON

The Global Lake Ecological Observatory Network (GLEON) conducts innovative science by sharing and interpreting high resolution sensor data to understand, predict and communicate the role and response of lakes in a changing global environment. Continued long-term data collection and observation informs the future management of catchments and how best to preserve and protect their unique ecosystems. Collaboration with international networks such as GLEON, with members from 62 countries, ensure that the valuable data collected in the Burrishoole catchment by the Marine Institute are used by a wider scientific community to address questions of global significance.

10.4 NATIONAL MARINE INFRASTRUCTURES

This section focuses primarily on infrastructure operated by the Marine Institute for monitoring EOVs with limited reference to infrastructure operated by other organisations. Future iterations will include detailed information on observing infrastructure operated by other organisations including the Environmental Protection Agency (EPA), the Geological Survey Ireland (GSI), the National Parks & Wildlife Service (NPWS), Commissioners of Irish Lights (CIL) and other relevant observing platforms in Higher Education Institutes (HEIs).

IRISH OCEAN OBSERVING SYSTEM (ÉIROOS)

ÉirOOS is a multi-platform research infrastructure used to develop scientific and technical research capacity in ocean observation and to support enhanced Irish participation in European and international research programmes. The ÉirOOS infrastructures are used in research activities working to better understand the connection between Ireland, its coastal seas and the Atlantic. ÉirOOS provides ocean and climate observation data via a range of marine platforms to address key national scientific requirements. Collectively, the Irish Marine Data Buoy Observation Network (IMDBON), the Irish National Tide Gauge Network (INTGN), the Irish Glider Network and the Deep Sea Moorings and Seabed Landers are current components of ÉirOOS, which itself is a component of the European Ocean Observing System (EOOS). Recent capital funding for ÉirOOS was provided by Science Foundation Ireland (SFI) to enhance and upgrade the equipment pool (SFI Research Infrastructure Award under Grant number 18/RI/5731). The ÉirOOS maintenance and operational costs (e.g. Irish Marine Data Buoy Observation Network; tide gauge network) however, are only possible through continued funding from the Department of Agriculture, Food and the Marine (DAFM), and through research grants from the Irish government (e.g. glider missions).

INFRASTRUCTURE MATURITY LEVELS

Marine infrastructure maturity level uses a model with slight modifications that was developed by the Marine Institute for the National Marine Research & Innovation Strategy 2017/2021. Each identified marine infrastructure is considered in relation to one of five levels of maturity, ranging from "Ad-hoc" through to "Translational". Figure 10.2 gives a general description of what represents a particular level of maturity. Within each infrastructure, more specific indicators of maturity were developed to allow assessment.

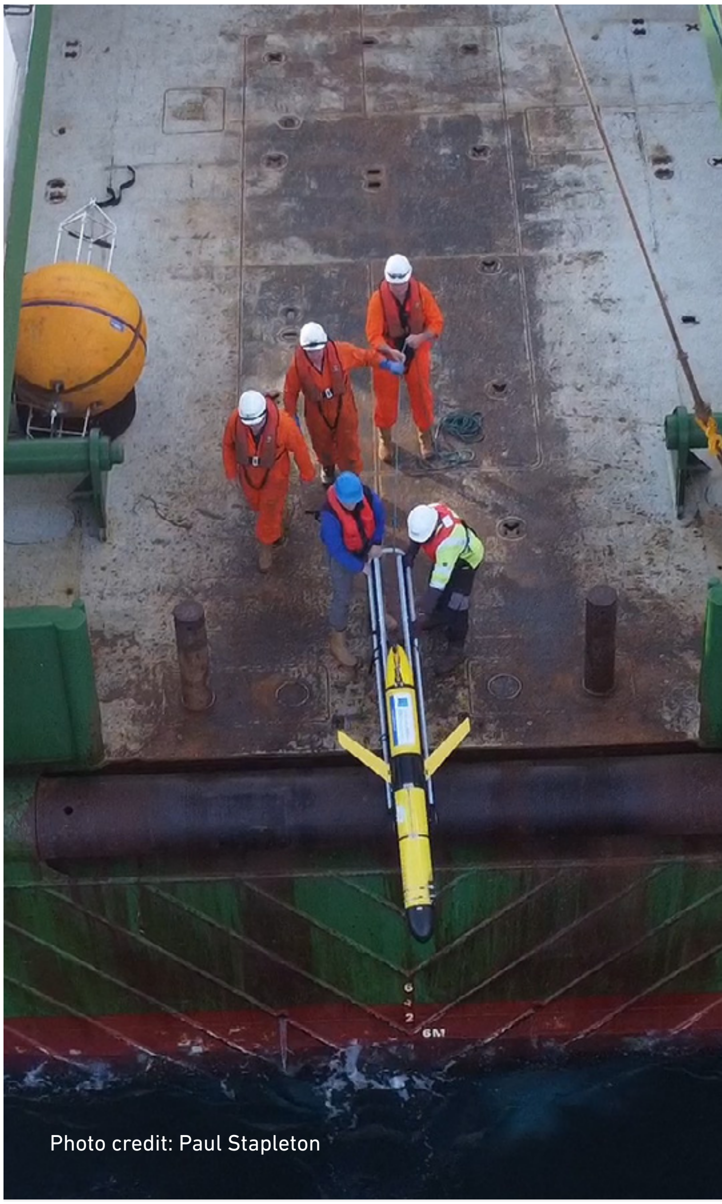


Photo credit: Paul Stapleton

MATURITY	INFRASTRUCTURES
5 **TRANSLATIONAL** There is evidence of a pipeline of research from basis investigation to commercial application or policy definition facilitated by dedicated national facilities.	• Nationally funded research centres. • Postdoctoral Training. • EU "Best in class" research infrastructures. • National Test & Demonstration Facilities, including end-user population for real-world feedback
4 **COLLABORATIVE** National level research facilities exist with international collaboration with internationally recognised research performers.	• Nationally available equipment or platforms (e.g. equipment pools). • Postgraduate training. • Participation in EU infrastructure networks. • National Test and Demonstration facilities. • Postdoctoral training.
3 **ESTABLISHED** Dedicated research facilities exist and there is evidence of collaboration nationally and internationally, with industry participation.	• Purpose built lab space/purpose bought equipment. • Dedicated data infrastructures or repositories. • Postgraduate teaching modules and/or courses.
2 **DEFINED** Communities of interest exist with some access to facilities and active research projects.	• Defined undergraduate training. • "Allocated" general purpose lab space or equipment, evidence of institutional commitment through capital spending
1 **AD-HOC** Research is based on individual research interests with no institutional support or facilities.	• No dedicated facilities or general purpose equipment etc. • No evidence of commitment through capital spending.

Figure 10.2 Research Capability Maturity Model (modified version of that used in the National Marine Research & Innovation Strategy 2017–2021)

Essential Ocean Variable symbols displayed in Figure 10.3 are used to show the EOVs (ECVs) collected by the infrastructures, programmes and projects.

Figure 10.3 Essential Ocean Variables collected with the support of Irish marine infrastructures, programmes and projects and presented in this report. Note: EOV in grey are infrequently measured in Ireland. Credit: The Global Ocean Observing System (GOOS) November 2022.

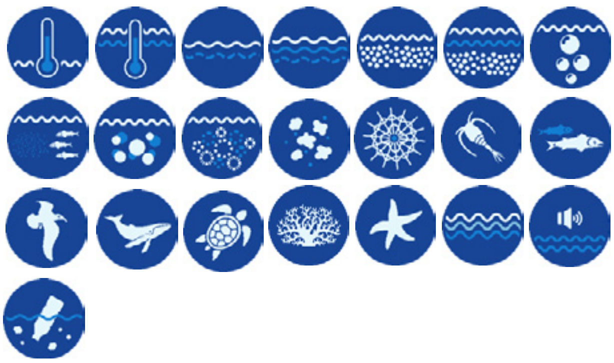
MATURITY 5 – TRANSLATIONAL INFRASTRUCTURES

IRISH MARINE DATA BUOY OBSERVATION NETWORK (IMDBON)

Essential Ocean Variables measured: Sea State, Sea Surface Temperature, Subsurface Temperature, Sea Surface Salinity, Subsurface Salinity.

The network was established 20 years ago to provide essential meteorological and sea state information to forecasters, marine users, and researchers and to improve the accuracy and temporal range of mainland and coastal weather forecasts that enhance safety at sea. The IMDBON network, managed and operated by the Marine Institute in collaboration with Met Éireann, on behalf of the Department of Agriculture, Food and the Marine (DAFM), consists of five offshore marine observation buoys around Ireland. The IMDBON reports hourly weather data of key near-surface marine meteorological variables (air temperature, humidity, atmospheric pressure, wind speed and direction) and oceanographic variables (sea surface temperature, wave height, and wave period).

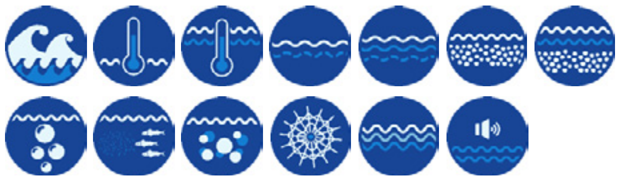
NATIONAL RESEARCH VESSELS (RVS) & REMOTELY OPERATED VEHICLE (ROV)



Supports collection of Essential Ocean Variables: Sea Surface Temperature, Subsurface Temperature, Sea Surface Currents, Subsurface Currents, Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients, Inorganic Carbon, Transient Tracers, Particulate Matter, Phytoplankton Biomass & Diversity, Zooplankton Biomass & Diversity, Fish Abundance & Distribution, Birds Abundances & Distribution, Mammals Abundance & Distribution, Turtles Abundance & Distribution, Hard Coral Cover & Composition, Invertebrate Abundances & Distribution, Ocean Colour (hyperspectral and chlorophyll), Ocean Sound, Marine Debris.

The RV *Celtic Explorer*, RV *Tom Crean* and the ROV *Holland I* are essential platforms used to undertake fisheries, oceanographic and environmental research and seabed mapping. Since 2006, the vessels have supported the annual repeat Ocean Climate Survey collecting samples (e.g. conductivity, temperature and depth) across the western Irish shelf and Rockall Trough to monitor ocean change in the North Atlantic. Since 2017, high frequency pCO_2 data are routinely collected on oceanographic surveys using an autonomous underway pCO_2 measuring system. The pCO_2 data is quality checked and reported to the Surface Ocean Carbon Atlas (SOCAT, www.socat.info), a widely used dataset in international and regional climate research.

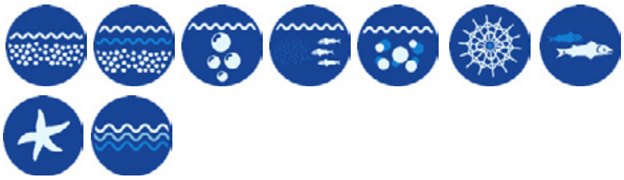
SMARTBAY UNDERWATER OBSERVATORY



Essential Ocean Variables measured: Sea State, Sea Surface Temperature, Subsurface Temperature, Sea Surface Currents, Subsurface Currents, Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients, Inorganic Carbon, Phytoplankton Biomass & Diversity, Ocean Colour (chlorophyll), Ocean Sound.

The SmartBay observatory became operational in August 2015 and is located near Spiddal in Galway Bay. The observatory includes a fibre optic data and power cable and a sub-sea sensor node, capable of providing high speed communications to scientific instruments from research and development (R&D) projects and sensor developers. The observatory includes a set of permanently deployed instruments providing real-time data of conductivity (salinity), temperature, depth, dissolved oxygen, turbidity, fluorescence, pCO_2, pH, current speed and direction in the water column, underwater noise, video footage and still photographic imagery. The underwater observatory is enhanced with a surface data buoy measuring sea surface temperature, conductivity (salinity) and meteorological parameters.

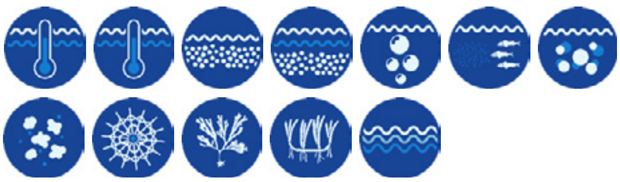
NATIONAL LABORATORIES



Essential Ocean Variables measured: Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients, Inorganic Carbon, Phytoplankton Biomass & Diversity, Fish Abundance & Distribution, Invertebrate Abundances & Distribution, Ocean Colour (chlorophyll).

The Marine Institute maintains the National Reference Laboratory role for diseases in shellfish, finfish and crustaceans; shellfish biotoxins; microbiological contaminants in shellfish; and certain chemical substances in aquaculture products. The Institute is also the National Competent Authority for the health of aquaculture animals and the prevention and control of certain aquatic diseases. Accredited quality certification is maintained across laboratory, sampling and administrative functions, demonstrating a commitment to working at a level of international best practice. The laboratories also have competence to analyse a range of essential ocean variables including dissolved oxygen, carbon, nutrients, chlorophyll and phytoplankton.

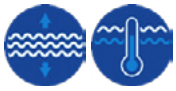
EPA MARINE MONITORING SECTION



Essential Ocean Variables measured: Sea Surface Temperature, Subsurface Temperature, Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients, Particulate Matter, Phytoplankton Biomass & Diversity, Seagrass Cover & Composition, Macroalgal Cover & Composition, Ocean Colour (chlorophyll).

The EPA has two accredited laboratories to assess the ecological status of Irish transitional and coastal waters according to the requirements of the Water Framework Directive (WFD).

FLOOD RISK MANAGEMENT (FRM)



Essential Ocean Variables measured: Sea Surface Height, Subsurface Temperature.

The Hydrometric Section of the Office of Public Works (OPW) operates a network of 70 hydrometric stations located at coastal and estuarine locations to support activities including the design of flood relief schemes, arterial drainage maintenance; flood forecasting and warning; and the delivery of flood risk management measures (actions to mitigate risk) nationally extending to include coastal flooding and erosion.

IRISH LIGHTS METOCEAN

Essential Ocean Variables measured: Sea State, Sea Surface Temperature.

The Irish Lights MetOcean network collects meteorological and oceanographic data to provide near real-time environmental conditions for mariners to assist in making navigational decisions in passage planning and sail/no sail decisions.

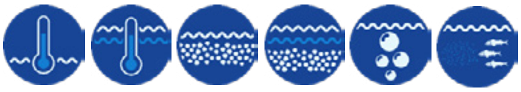
NATIONAL OCEANOGRAPHIC DATA CENTRE

Essential Ocean Variables: Sea State, Sea Surface Height, Sea Surface Temperature, Subsurface Temperature, Sea Surface Currents, Subsurface Currents, Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients, Inorganic Carbon, Phytoplankton Biomass & Diversity, Zooplankton Biomass & Diversity, Fish Abundance & Distribution, Birds Abundances & Distribution, Mammals Abundance & Distribution, Turtles Abundance & Distribution, Hard Coral Cover & Composition, Seagrass Cover & Composition, Invertebrate Abundances & Distribution.

The Marine Institute is Ireland's accredited National Oceanographic Data Centre (NODC) in the International Oceanographic Data and Information Exchange of UNESCO's Intergovernmental Oceanographic Commission network of NODCs. The Marine Institute achieved accredited NODC status in February 2019. The NODC consists of hosted online data services including descriptive metadata (to find data), maps and graphs (to view data) and services (to download data). The NODC acts as a one-stop-shop for data related to marine matters including all the activities, programmes and services provided by the centre. For a comprehensive list of EOVs archived in the NODC please refer to the *Baseline Study of Essential Ocean Variable Monitoring in Irish Waters* (Nolan *et al.*, 2021).

MATURITY 4 - COLLABORATIVE

ARGO IRELAND



Essential Ocean Variables measured: Sea Surface Temperature, Subsurface Temperature, Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients.

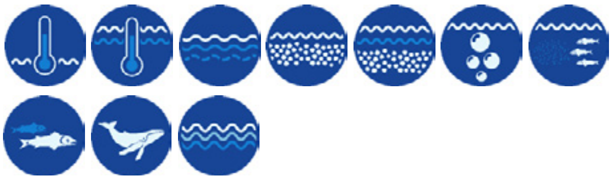
Ireland contributes to the International Argo Programme. This programme consists of a global array of approximately 4,000 autonomous floats or profilers, deployed across the world's ocean. Argo floats report temperature and salinity from the upper 2,000 m of the ocean via satellite transmission links to data centres. These two ECVs describe the ocean physical and thermodynamic state. The Argo array is an important component of the GOOS, required to understand and monitor the role of the ocean in the Earth's climate system, in particular the heat and water balance.

IRISH NATIONAL TIDE GAUGE NETWORK (INTGN)

Essential Ocean Variables measured: Sea Surface Height.

The Marine Institute manages the tide gauge network which consists of 19 stations providing real-time monitoring of tidal levels around the Irish coast. In addition, two of the tide gauge stations (Malin Head, Co. Donegal and Ballycotton, Co Cork.) support continuous long-term sea surface temperature recording for climate monitoring purposes. Two high-precision sea level measurement stations are managed by the Marine Institute and are part of the Global Sea Level Observing System (GLOSS). The GLOSS stations are located in Howth Harbour (Co Dublin) and Union Hall (Co Cork). A third GLOSS station, managed by the Office of Public Works, is located at Malin Head (Co Donegal). The GLOSS stations are critical for monitoring long-term changes in sea level to determine the impacts on Ireland from rising sea levels due to climate change.

IRISH GLIDER NETWORK



Essential Ocean Variables measured: Sea Surface Temperature, Subsurface Temperature, Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients, Fish Abundance & Distribution (acoustics), Mammals Abundance & Distribution (acoustics), Ocean Colour (relative fluorescence).

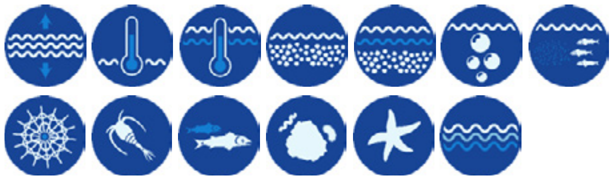
Consists of three remotely-piloted autonomous underwater vehicles The gliders can operate autonomously for ~ 90 days and can dive to depths of up to 1,000m. Environmental parameters measured include conductivity (salinity), temperature, turbidity, relative fluorescence, dissolved oxygen and underwater sound. Data is relayed to shore via satellite when the glider comes to the water surface between dives.

IRISH WAVE BUOY NETWORK

Essential Ocean Variables measured: Sea State, Sea Surface Temperature, Sea Surface Currents.

The Irish wave buoy network provides high resolution real-time data on wave conditions, with deployment locations off the west coast of Ireland providing support to the development of marine renewable energy. Several additional deployments in other locations take place each year in support of national and international research projects focused on monitoring and forecasting Ireland's wave climate.

BURRISHOOLE

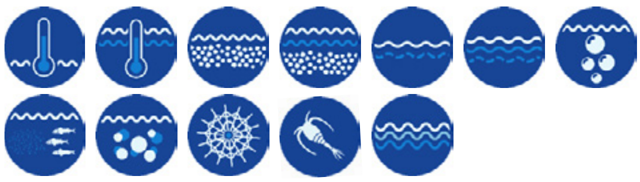


Essential Ocean Variables measured: Sea Surface Height, Sea Surface Temperature, Subsurface Temperature, Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients, Phytoplankton Biomass & Diversity, Zooplankton Biomass & Diversity, Fish Abundance & Distribution, Microbe Biome & Diversity, Invertebrate Abundances & Distribution, Ocean Colour.

A long-term ecological research infrastructure, located in the Burrishoole catchment, Newport, Co. Mayo, with a focus on diadromous fish since the mid-1950s. Burrishoole data collection efforts form one of the longest running continuous records of lake surface water temperature in the world. The facility also hosts a laboratory and a comprehensive monitoring network of aquatic habitats sensors and telemetry to provide real time observational data of environmental conditions.

MATURITY 3 - ESTABLISHED

MACE HEAD SENTINEL BUOY



Essential Ocean Variables measured: Sea Surface Temperature, Subsurface Temperature, Sea Surface Currents, Subsurface Currents, Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients, Inorganic Carbon, Phytoplankton Biomass & Diversity, Zooplankton Biomass & Diversity Ocean Colour.

Operated by the Marine Institute at a location west of Mace Head since June 2018 to monitor ocean climate change with an array of sensors reporting real-time measurements of temperature, salinity, dissolved oxygen, pCO_2, pH, nutrients, current speed and direction. Frequent water sampling and laboratory analyses are undertaken for essential climate variables, specifically dissolved oxygen, dissolved inorganic carbon, total alkalinity, dissolved inorganic nutrients and salinity to provide additional parameters and to ensure the accuracy of the sensor data.

LEHANAGH POOLE SENTINEL SITE

Essential Ocean Variables measured: Sea Surface Temperature, Subsurface Temperature, Subsurface Currents, Sea Surface Salinity, Subsurface Salinity, Oxygen, Nutrients, Phytoplankton Biomass & Diversity, Invertebrate Abundances & Distribution, Ocean Colour.

Located in Bertraghboy Bay in Connemara , Lenanagh Poole is primarily an integrated multi-trophic aquaculture (IMTA) research site. The site also facilitates a range of studies on the testing and validation of sensors, technologies and multi-functional environmental monitoring and management systems.

DEEP SEA MOORINGS AND SEABED LANDERS

Essential Ocean Variables measured: Subsurface Temperature, Subsurface Currents, Subsurface Salinity.

Deployed in the Northeast Atlantic with the aim of advancing our understanding of key environmental and climate driven processes in the region including the Atlantic Meridional Overturning Circulation (AMOC). One of the moorings deployed in the South Rockall Trough, in waters deeper than 3000 m, collects time series data from several autonomous sensors measuring temperature, salinity, and current speed and direction.

MATURITY 2 - DEFINED

REMOTE SENSING / HYPERSPECTRAL SENSOR SYSTEM

Essential Ocean Variables measured: Sea Surface Temperature, Phytoplankton Biomass & Diversity, Ocean Colour

The Marine Institute uses low horizontal resolution (1 km) ocean colour (chlorophyll) and sea surface temperature data products in the weekly Harmful Algal Bloom (HABs) bulletin. Remotely sensed satellite data are used for routine validation of ocean numerical models.

Five hyperspectral sensors are mounted on the RV *Celtic Explorer* to collect ocean colour data.

MATURITY 1 – AD-HOC

No known marine infrastructures currently operated at this maturity level.

10.5 PROGRAMMES & PROJECTS DEPENDENT ON MARINE INFRASTRUCTURES

Many national programmes and projects depend on the marine infrastructures. The following is a non-exhaustive list of examples.

Name of Programme: Data Collection Multi Annual Plan

Name of Marine Infrastructure: Research Vessels *Celtic Explorer* & *Tom Crean*

Responsible Body: Marine Institute and Department of Agriculture, Food and the Marine

Essential Ocean Variables measured: Sea Surface Temperature, Subsurface Temperature, Sea Surface Salinity, Subsurface Salinity, Phytoplankton Biomass & Diversity, Zooplankton Biomass & Diversity, Fish Abundance & Distribution

The Fisheries Ecosystems Advisory Services group within the Marine Institute is responsible for assessing key commercial fish and shellfish stocks around Ireland. Broad-scale ecosystem surveys are conducted on an annual basis on the Marine Institute research vessels and data collection is highly systematic and undertaken to agreed international standards. Provision of stock assessment and advice to support the European Common Fisheries Policy is part of Ireland's Data Collection Scheme carried out under Ireland's Operational Programme, co-funded by the European Maritime, Fisheries & Aquaculture Fund and by the Irish Government. Fish stock assessment and advice is provided to the Department of Agriculture, Food & Marine on an annual basis via the Stock Book, the annual publication which provides the latest impartial scientific advice on the status of 74 key fish stocks of interest to Ireland.

The main surveys are:

- International Bottom Trawl Survey;
- Western European Shelf Pelagic Acoustic Survey;
- Nephrops Underwater TV Survey;
- Irish Anglerfish and Megrim Survey;
- International Blue Whiting Acoustic Survey;
- Celtic Sea Herring Survey; North West Herring Acoustic Survey;
- Irish Mackerel Egg Survey;
- Inshore fisheries surveys.

Name of Programme: National Phytoplankton Monitoring Programme

Name of Marine Infrastructure: National Laboratories

Responsible Body: Marine Institute

Essential Ocean Variable(s) measured: Phytoplankton Biomass & Diversity

The National Phytoplankton Monitoring Programme commenced in the 1980s. The programme involves the identification and enumeration of phytoplankton species that can potentially cause harmful effects on aquaculture and marine ecosystems. These type of phytoplankton are commonly called harmful algal species.. The monitoring programme analyses ~2,500 water samples annually, from ~75 sites, usually sampled on a weekly basis in aquaculture production areas around Ireland. The Marine Institute operates two fully equipped ISO 17025 accredited phytoplankton laboratories located in Galway and Bantry. The programme is funded by the Department of Agriculture, Food and the Marine, with such monitoring a requirement of EU legislation 2019/627. Phytoplankton monitoring compliments the National Marine Biotoxin Monitoring Programme for bivalve shellfish. Internationally, the Irish phytoplankton dataset contributes to the Global HAB Status Report for Policymakers by IOC UNESCO, the ICES-IOC Working Group on Harmful Algal Bloom Dynamics, and the IODE Harmful Algal Events Database.

Name of Project: Sensitive Ecosystem Assessment & Remotely Operated Vehicle Reef Exploration (SeaRover)

Name of Marine Infrastructure: Research Vessels & Remotely Operated Vehicle

Responsible Body: Marine Institute

Essential Ocean Variables measured: Subsurface Temperature, Subsurface Salinity, Fish Abundance & Distribution, Hard Coral Cover & Composition, Invertebrate Abundances & Distribution

The SeaRover project was implemented under the European Maritime and Fisheries Fund Marine Biodiversity Scheme - Natura Fisheries, by mapping offshore reef habitats with a view to protecting them from deterioration due to fishing pressures. The project aligned with Article 6.2 of the Habitats Directive which requires member states to take action to avoid deterioration of protected habitats. An extensive offshore reef survey of Ireland's continental slope was commissioned by the Marine Institute in partnership with the NPWS, funded by the EMFF, and coordinated and led by INFOMAR (Integrated Mapping for the Sustainable Development of Ireland's Marine Resources). Using the Remotely Operated Vehicle *Holland I*, acquired data ensured the availability of comprehensive biological baseline datasets critical to the formulation of future policy on the management, monitoring and conservation of Ireland's deep-water ecosystems. The dataset provided to the NPWS supports ongoing Special Area of Conservation Habitats Directive monitoring/reporting, and will support future Department of Housing, Local Government and Heritage Marine Protected Area designation work.

Name of Programme: ObSERVE Programme

Name of Marine Infrastructure: Aircrafts & Research Vessels

Responsible Body: Department of the Environment, Climate and Communications

Essential Ocean Variable(s) measured: Subsurface Salinity, Fish Abundance & Distribution, Birds Abundances & Distribution, Mammals Abundance & Distribution, Turtles Abundance & Distribution

The ObSERVE Programme is Ireland's principal programme for monitoring the at-sea occurrence, distribution, density and numerical abundance of marine birds, reptiles and mammals. It has also been recording the occurrence and distribution of several large fish species including sharks and tuna species. Phase I of the programme (2014–2019) consisted of extensive aerial surveys in two summer and two winter seasons, plus acoustic surveillance for whales, dolphins and porpoises using a combination of deep sea-floor stations and towed hydrophone surveys. Phase II of the programme (2020–2025) is currently under way via a repeat aerial survey programme.

10.6 INFRASTRUCTURE DATA PORTALS

CLIMATE IRELAND

Climate Ireland provides data and knowledge, advice and support to stakeholders in planning for the current and projected impacts of a changing climate. The portal, hosted by the EPA, supports policy development, decision making, capacity building and training by providing scientific and technical data, information, tools and advice to a range of sectoral, regional and local level decision makers in the development and implementation of adaptation plans and strategies. The objectives of Climate Ireland are categorised into the following key areas, which are progressed through an annual work programme: Policy and Decision Making Support, Provision of knowledge, information and data, Awareness and Capacity Building, and Communications.

ONLINE IRISH OCEAN CLIMATE RELATED DATASETS

The Marine Institute publishes many climate-related datasets online. Data portals include data broker software servers such as the Environmental Research Division Data Access Program or ERDDAP tool created by the US National Oceanographic and Atmospheric Administration (NOAA). The Marine Institute also uses web mapping services, or online searchable databases to disseminate ocean information. Many of the datasets are visualised either through Ireland's Marine Atlas or on Ireland's Digital Ocean Portal. The Digital Ocean platform, however, has no programme of continued development. Other national and European organisations publish information on climate and marine related infrastructure and data online, some examples of which are listed below:

IRISH INFRASTRUCTURE PORTALS

- Ireland's Marine Atlas
- The National Marine Research Database
- Database of Research Outputs: Projects, Literature and Environmental Technologies (DROPLET)
- Water Research Infrastructure Database
- Large Items of Research Equipment (LIRE)

EU INFRASTRUCTURE PORTALS

- EurOcean Research Infrastructure Database
- The Mapping of the European Research Infrastructure Landscape (MERIL)

10.7 INFRASTRUCTURE GAPS

Climate change monitoring in the ocean is a complicated issue involving the collection of many physical, chemical and biological variables essential to investigate ocean phenomena. For climate monitoring, long data time series are required to ensure robust assessments and the scientific evidence needed by policy makers is made available for decision making. A recent Climate Status Report for Ireland identified several issues relating to the national ocean climate observation system (Cámaro García and Dwyer, 2021). In addition, recommendations on how to address the country's long-term needs are included in the recent EOV baseline report (Nolan *et al*. 2021).

10.8 RECOMMENDATIONS

1. Ensure essential ocean variables relevant to Irish waters are measured sustainably and meet international requirements for climate monitoring.
2. Maintain existing infrastructure, critical for decision-makers (e.g. IMDBON, tide gauges, pCO_2 systems).
3. Build capacity (expertise and equipment) for essential ocean variables in gap areas (e.g. zooplankton, marine carbonate chemistry) and ensure sentinel sites are established and maintained.
4. Advance pilot projects that have already provided valuable scientific information for decision makers.

LIST OF ACRONYMS

ACRONYM	DESCRIPTION
ΔCO_2	Surface Ocean CO_2 Minus Atmospheric CO_2
20CRv2	20^{th} Century Reanalysis Version 2
ADCP	Acoustic Doppler Current Profiler
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation (AMOC)
AMV	Atlantic Multidecadal Variability
AR6	Sixth Assessment Report
ASH	Aragonite Saturation Horizon
AT	Total Alkalinity
BQE	Biological Quality Element
C	Carbon
CC	Clausius-Clapeyron
CFC	Chlorofluorocarbon
CFP	Common Fisheries Policy
CIL	Commissioners of Irish Lights
CMIP2	Coupled Model Intercomparison Project 2
CMIP5	Coupled Model Intercomparison Project 5
CMIP5-RCP4.5	Coupled Model Intercomparison Project 5 Representative Concentration Pathway 4.5
CMIP6	Coupled Model Intercomparison Project 6
CO_2	Carbon Dioxide
CO_3^{2-}	Carbonate Ion Concentration
COMPASS	Collaborative Oceanography for Monitoring Marine Protected Areas and Species
CRU-TS3	Climatic Research Unit (CRU) Time-Series (TS) Version 3.25
C_T	Dissolved Inorganic Carbon
CTD	Conductivity, Temperature, Depth
DAFM	Department of Agriculture, Food & the Marine
DCF	Data Collection Framework
dDFS	Differences between the surface and seabed salinity
dDFT	Differences between the surface and seabed temperatures
DECC	Department of Environmental, Climate & Communications
DHLGH	Department of Housing, Local Government and Heritage
DIC	Dissolved Inorganic Carbon
DJF	December January February
DNA	Deoxyribonucleic acid
DO	Dissolved Oxygen
DROPLET	Database of Research Outputs: Projects, Literature and Environmental Technologies
EA	East Atlantic
EAFM	Ecosystem Approach to Fisheries Management
EAI	East Atlantic Index
EC	European Commission

ECOMSED	Estuarine Coastal & Ocean Model with Sediment Transport
ECV	Essential Climate Variables
EEZ	Exclusive Economic Zone
EirOOS	Irish Ocean Observing System
EMFAF	European Fisheries & Aquaculture Fund
EMFF	European Maritime Fisheries Fund
EMSO	European Multidisciplinary Seafloor and Water-Colum Observatory
EOFs	Empirical Orthogonal Functions
EOOS	European Ocean Observing System
EOV	Essential Ocean Variable
EPA	Environmental Protection Agency
ERDDAP	Environmental Research Division's Data Access Program
ERIC	European Research Infrastructure Consortium
ESFRI	European Strategy Forum on Research Infrastructures
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FEAS	Fisheries Ecosystem Advisory Services
GCM	Global Atmosphere-Ocean Climate Model
GCOS	Global Climate Observing System
GES	Good Ecological Status
GHG	Greenhouse Gas Emissions
GLEON	Global Lake Ecological Observatory Network
GLOSS	Global Sea Level Observing System
GMSL	Global Mean Sea Level
GOOS	Global Ocean Observing System
GO-SHIP	The Global Ocean Ship-based Hydrographic Investigations Program
GSI	Geological Survey of Ireland
GTSM	Global Tide and Surge Model
H^+	Hydrogen
HAB	Harmful Algal Bloom
HABs	Harmful Algal Blooms
HAEDAT	IODE Harmful Algal Events Database
HCO_3^-	Bicarbonate Ion Concentration
HEI	High Education Institute
HPAI	Highly Pathogenic Avian Influenza
IAMS	Irish Anglerfish & Megrim Survey
ICARUS	Irish Climate Analysis and Research UnitS
ICES	International Council for the Exploration of the Sea
ICES-IOC	International Council on the Exploration of the Sea and the Intergovernmental Oceanographic Commission of UNESCO
ICOS	Integrated Carbon Observation System
IGFS	Irish Ground Fish Survey
IMDBON	Irish Marine Data Buoy Observation Network
IMTA	Integrated Multi-trophic Aquaculture

INFOMAR	Integrated Mapping for the Sustainable Development of Ireland's Marine Resources
INTGN	Irish National Tide Gauge Network
IOC UNESCO	Intergovernmental Oceanographic Commission of UNESCO
IODE	International Oceanographic Data and Information Exchange
IPCC	Intergovernmental Panel on Climate change
IRN	Irish Reference Network
IUCN	International Union for Conservation of Nature
JJA	June July August
LIRE	Large Items of Research Equipment
LOAC	Land Ocean Aquatic Continuum
LSW	Labrador Sea Water
MAP	Maritime Area Planning
MERIL	Mapping of the European Research Infrastructure Landscape
MI	Marine Institute
MK Test	Mann–Kendall Test
MLD	Mixed Layer Depth
MLO	Mauno Loa Observatory
MPA	Marine Protected Area
MPIOM	Max Planck Institute Ocean Model
MSFD	Marine Strategy Framework Directive
MSL	Mean Sea Level
MSLP	Mean Sea Level Pressure
MSY	Maximum Sustainable Yield
NAO	North Atlantic Oscillation
NAO-EA	North Atlantic Oscillation - East Atlantic
NAOI	North Atlantic Oscillation Index
NAO-SCA	North Atlantic Oscillation - Scandinavian Pattern
NAOw	North Atlantic Oscillation winter index
NBS	Near Botton Salinity
NBT	Near Bottom Temperatures
NEMO	Nucleus for European Modelling of the Ocean
NEOClime Product	North West European Ocean Climatology Project
NESC	National Economic and Social Committee
NMP	National Monitoring Programme
NMPF	National Marine Planning Framework
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Centre
NORSAP	Northern Seas Action Programme
NPP	Near Primary Productivity
NPWS	National Parks & Wildlife Service
NWES	North West European Shelf Seas
OA	Ocean Acidification
OC	Organic Carbon

OHC	Ocean Heat Content
OP	Operational Programme
OPW	Office of Public Works
OREDP	Offshore Renewable Energy Development Plan
OSPAR	Oslo Paris Convention for the Protection of the Marine Environment of the North East Atlantic
pCO_2	Partial Pressure of Carbon Dioxide
PEA	Potential Energy Anomaly
pH	Potential of Hydrogen
POPs	Persistent Organic Pollutants
ppm	parts per million
PPM	Peterman's Productivity Method
PSP	Paralytic Shellfish Poisoning
PST	Paralytic Shellfish Toxins (PST)
PWB	Planetary Wave-Breaking
R&D	Research & Development
RCP	Representative Carbon Pathways
RID	Riverine Inputs and Direct Discharges
ROMS	Regional Ocean Model System
ROV	Remotely Operated Vehicle
RVs	Research Vessels
SAC	Special Areas of Conservation
SCA	Scandinavian Pattern
SCAI	Scandinavian Pattern Index
SDG	Sustainable Development Goals
SFI	Science Foundation Ireland
SFPA	Sea Fisheries Protection Authority
SOCAT	Surface Ocean Carbon Atlas
SR	Stock Recruitment
SSB	Spawning Stock Biomass
SSP3-7	Shared Socio-economic Pathways 3-7
SSP5-8.5	Shared Socio-economic Pathways-8.5
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
t C	Tonnes of Carbon
TA	Total Alkalinity
TAC	Total Allowable Catches
TN	Total Nitrogen
TOxN	Total Oxidised Nitrogen
TP	Total Phosphorus
TSB	Total Stock Biomass
UK	United Kingdom
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization

UNFCCC	United Nations Framework Convention on Climate Change
VOCAB	Ocean Acidification and Biogeochemistry: variability, trends and vulnerability Project
WESPAS	Western European Shelf Pelagic Acoustic Survey
WFD	Water Framework Directive
WOCE	World Ocean Circulation Experiment
wPre	Winter Precipitation
wTmp	Winter Temperature

GLOSSARY OF FISHERIES TERMS FOR CHAPTER 6 COMMERCIAL FISHERIES

B_{lim}[1]	Limit reference point for spawning stock biomass (SSB)
Boreal[2]	Fish characteristically found in the subarctic region .
$B_{trigger}$[1]	Value of spawning stock biomass (SSB) which triggers a specific management action.
Demersal species[2]	Most often refers to fish that live on or near the ocean bottom. They are often called benthic fish, groundfish, or bottom fish.
F[1]	Instantaneous Rate of Fishing Mortality; which is the instantaneous rate of removal from the stock by fishing.
F_{lim}[1]	Limit reference point for fishing mortality (over-defined age range).
F_{MSY}[1]	Fishing mortality consistent with achieving Maximum Sustainable Yield (MSY).
F_{pa}[1]	Precautionary reference point for fishing mortality (over-defined age range).
Lusitanian[2]	Fish characteristically found in warmer, southern regions of Portugal, Spain, France, and the west and southwest coasts of Great Britain and Ireland.
MSY[1]	Maximum Sustainable Yield; the largest average catch or yield that can continuously be taken from a stock under existing environmental conditions.
Overfished[2]	A conditioned defined when stock biomass is below minimum biomass threshold and the probability of successful spawning production is low.
Overfishing[2]	A level or rate of fishing mortality that jeopardizes the long-term capacity of a stock or stock complex to produce MSY on a continuing basis.
Pelagic zone[2]	The pelagic zone consists of the water column of the open ocean. It can be subdivided by depth into epipelagic (0–200m), mesopelagic (200–1000m), bathypelagic (1000–4000m) and abyssopelagic (4000m +). Fish that spend most of their life swimming in the water column with little contact with or dependency on the bottom are known as pelagic species.

SSB[1]	Spawning Stock Biomass: The total weight of the fish in a stock that are old enough to spawn.
TAC[1]	Total Allowable Catch: the total catch allowed to be taken from a stock in a specified period (usually a year), as defined in the management plan.

LIST OF FIGURES

LIST OF CASE STUDY FIGURES

LIST OF TABLES

BIBLIOGRAPHY

CHAPTER 1 – INTRODUCTION

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CHAPTER 7 – SEABIRDS

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CHAPTER 8 – CLIMATE CHANGE IMPACTS ALONG THE AQUATIC CONTINUUM FROM TERRESTRIAL HABITATS TO THE OCEAN

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CHAPTER 9 – REGIONAL AND LOCAL DOWNSCALED MODELS FOR IRELAND

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CHAPTER 10 – MARINE INFRASTRUCTURES & PROGRAMMES FOR MONITORING ESSENTIAL OCEAN VARIABLES

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