Rialtas na hÉireann
Government of Ireland

Climate Status Report for Ireland 2020

EPA Research Report 386

Prepared by MaREI, University College Cork.
Editors and Lead Authors: Walther C.A. Cámaro García, Ned Dwyer and Jeremy Gault.

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

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Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

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- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
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- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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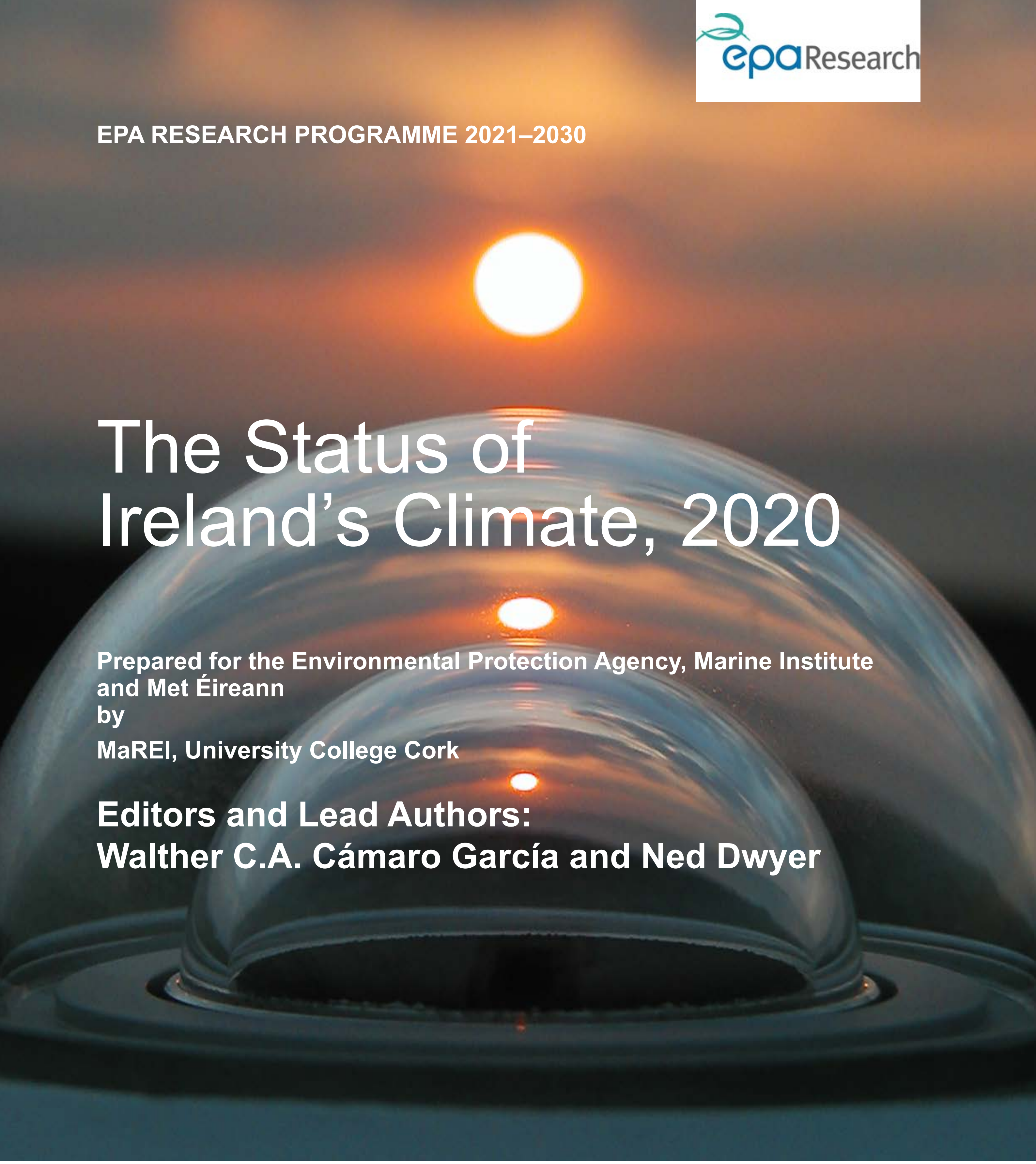

EPA RESEARCH PROGRAMME 2021–2030

The Status of Ireland's Climate, 2020

Prepared for the Environmental Protection Agency, Marine Institute and Met Éireann
by
MaREI, University College Cork

Editors and Lead Authors:
Walther C.A. Cámaro García and Ned Dwyer

ENVIRONMENTAL PROTECTION AGENCY

An Ghníomhaireacht um Chaomhnú Comhshaoil, PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600   Fax: +353 53 916 0699   Email: info@epa.ie   Website: www.epa.ie

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This report is based on research carried out/data from May 2020. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Project Partners

Walther C.A. Cámaro García
MaREI Centre for Marine and Renewable Energy
Environmental Research Institute
University College Cork
Ringaskiddy
Co. Cork
Ireland

Tel.: +353 (0)21 486 4341
Email: walther.camaro@ucc.ie

Ned Dwyer[1]
MaREI Centre for Marine and Renewable Energy
Environmental Research Institute
University College Cork
Ringaskiddy
Co. Cork
Ireland

Email: n.dwyer@ucc.ie

1 Now at Randbee Consultants, ned.dwyer@randbee.com

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[a]Courtesy of the Irish Meteorological Society.

Foreword

It is with great pleasure that I welcome this latest update on the status of Ireland's climate. It is knowing how much our climate has changed in the past that allows us to realistically plan for likely changes in the future. It is also essential for planning that we realise the pace of these changes. This report provides this critical climate information for Ireland.

A sustainable network of high-quality observations is required to provide information on the state of the climate. To achieve this, co-ordination and standardisation of observation systems is needed at international and national levels.

The Global Climate Observing System (GCOS) ensures the sustained international provision and delivery of reliable observations of essential climate variables (ECVs) for the total climate system across the atmospheric, oceanic and terrestrial domains. It is through the monitoring of these ECVs that we can compare the status of Ireland's climate with that of the rest of the world. GCOS communities work towards a world where climate observations are accurate and sustained and where access to climate data is free and open.

Ireland has a long tradition of systematic climate observations from the late 18th century to the present. However, there is a need to consolidate and build on the range of ECV observations relevant to Ireland to ensure that they are made in a sustainable manner.

A National Global Climate Observations System Committee was established in Ireland in 2018. Known as GCOS-Ireland, its members are currently drawn from the Marine Institute, the Environmental Protection Agency, Teagasc, Met Éireann and the Earth observation community. The role of GCOS-Ireland is to co-ordinate and promote the GCOS observing principles in relation to the monitoring of ECVs of relevance to Ireland, thus supporting the ever-increasing demand for localised climate information.

This report builds on *The Status of Ireland's Climate, 2012*, which for the first time provided a comprehensive inventory of the ECVs of relevance to Ireland. The 2012 report has become the baseline for Irish ECV monitoring. This new, updated, report, endorsed by GCOS-Ireland, sets out the latest status of these ECVs, as well as including some new ECVs that have been added by GCOS in recent years. The report also makes recommendations for improvements in systematic observations in Ireland that will be invaluable in helping to direct future priorities on climate monitoring.

I would like to thank all those who contributed to the publication, dataset providers, chapter authors, members of GCOS-Ireland and the project team in MaREI, especially Walther Cámaro García and Ned Dwyer. Finally, thanks to the Marine Institute, the Environmental Protection Agency and Met Éireann, which provided funding for the work that led to the compilation of this report.

Séamus Walsh
Chair, GCOS-Ireland
June 2020

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As an island on the western boundary of Europe facing the Atlantic Ocean, Ireland is ideally positioned to measure and assess ongoing climate change. This is achieved through baseline and background measurements of essential climate variables (ECVs). These include measurements of background concentrations of greenhouse gases and other atmospheric constituents that change the global energy balance and drive climate change by trapping more energy in the Earth's climate system. Over 90% of this additional energy is absorbed by the ocean, which is undergoing unprecedented changes. According to a recent publication from the Intergovernmental Panel on Climate Change, it is virtually certain that the global ocean has warmed unabated since 1970 and that the rate of ocean warming has more than doubled since 1993. There has been a doubling in the frequency of marine heatwaves since 1982. Moreover, as a result of absorbing more carbon dioxide, there has been increasing ocean surface acidification. Ireland's climate and that of north-west Europe is dominated by the Atlantic Ocean, and its coastal zones are affected by sea level rise. Understanding how the Atlantic Ocean is responding to climate change through monitoring of climate parameters is therefore vital. Similarly, monitoring of climate-related changes to the land surface and hydrological regimes (including rainfall and river flows) is important, given their centrality to and influence on the socio-economic environment. They also include carbon stocks and sinks in soils and biomass. Ireland still has extensive areas of peatland that play an important role in carbon and water storage. Their health and that of other terrestrial carbon systems is very sensitive to changes in climate.

The 1992 United Nations Framework Convention on Climate Change (UNFCCC), and its 2015 Paris Agreement, recognise the need for systematic observations of the climate system. In response to this the World Meteorological Organization together with other UN bodies and related organisations established the Global Climate Observing System (GCOS). Its objective is to provide a framework for the development of systematic observations and to ensure the sustained international provision and delivery of reliable observations of ECVs for the total climate system. This includes the atmospheric, oceanic and terrestrial domains. It is through the monitoring of these ECVs that we can both assess the status of Ireland's climate and compare it with changes occurring across Europe and the rest of the world.

The first *The Status of Ireland's Climate* report was published in 2013. This second status report provides an update, incorporating new datasets and analyses as well as reporting ongoing climate observations over the last 7 years. A number of important developments have also occurred since the last report. The 2015 Climate Act established the National Adaptation Framework in law: it includes the requirement to develop sectoral and local climate adaptation plans every 5 years. To support this process the Climate Ireland portal has been developed to provide information on ongoing and projected climate change and their associated impacts and risks. The synthesis provided here and continued observation and analysis of climate parameters contribute to that platform. Such information is vital to underpin the development and implementation of informed and relevant actions to address climate change.

The key findings in relation to the status of Ireland's climate are as follows.

Atmosphere

- Measurements of the main greenhouse gases – carbon dioxide, methane and nitrous oxide – at Mace Head, Co. Galway, show continued increases in levels, and those measured in 2019 are the highest observed since measurements began.
- Background carbon dioxide concentrations are now at 413 ppm, which is estimated to be 50% higher than those of the pre-industrial era, while those of methane are at 1940 ppb, representing an approximately 170% increase compared with pre-industrial levels. Nitrous oxide concentrations are now above 330 ppb, which is a 20% increase compared with pre-industrial levels.
- Concentrations of chlorofluorocarbons (CFCs) have been dropping since 2004, following the implementation of the Montreal Protocol in 1989, banning the production and use of CFCs.
- The annual average surface air temperature in Ireland has increased by approximately 0.9°C over the last 120 years, with a rise in temperatures being observed in all seasons. This compares with a global average temperature estimated to be 1.1°C above pre-industrial levels.
- The number of warm spell days has increased slightly over the last 60 years, with very little change in cold spell duration. This is in line with what has been observed in many regions of the world.
- Annual precipitation was 6% higher in the period 1989–2018, compared with the 30-year period 1961–1990, and the decade 2006–2015 has been the wettest on record. An overall increase in precipitation has been observed across northern hemisphere mid-latitude land areas during the last 70 years.
- Analysis of wet and dry spells demonstrates an increase in the length of wet spell days across the country. No trend is apparent in dry spell days.
- Atmospheric sulfur levels show an approximately 80% reduction over a 35-year period (1980–2015), highlighting the success of regulation and technological advances. Nitrogen oxide emissions decreased by more than 38% between 1990 and 2018, due primarily to improvements in the Moneypoint power plant.
- Other materials, including organic matter and black carbon/soot, now dominate the background aerosol composition.

Ocean

- Satellite observations indicate that the sea level around Ireland has risen by approximately 2–3 mm per year since the early 1990s, and analysis of sea level data from Dublin Bay show a rise of approximately 1.7 mm per year since 1938, consistent with global average rates.
- The average sea surface temperature measured at Malin Head was 0.47°C higher over the last 10 years compared with the period 1981–2010.
- Measurements in the surface waters to the west of Ireland between 1991 and 2013 indicate an increase in ocean acidity that is comparable to the rate of change in other global ocean time series.
- Observations of some potentially harmful phytoplankton species since 1990 show an expansion of their growth season, with their presence being observed in almost all winter months since 2010.

Terrestrial

- River flows are generally increasing, although, when more recent data for a shorter period have been analysed, there are indications that flows may be decreasing in the south and east of the country.
- Land cover observations since 1990 show increases in the areas covered by artificial surfaces and forest, while there is a decrease in wetland areas. The volume of growing stock in forests increased by 38% over the period 2006–2017, thereby increasing the amount of carbon sequestered in forests. Long-term carbon storage in forests will be determined by the dynamic balance between growth and harvesting rates.

- The area of burned vegetation is generally in the range of between 4000 and 6000 ha annually, although over 10,000 ha is estimated to have been burned in 2017, with the bulk of fire activity taking place between March and June each year.
- In 2018, carbon dioxide emissions were almost 18% higher than in 1990, primarily due to increased fossil fuel combustion in transport and energy industries; emissions of methane were just over 5% lower, although emissions from agriculture increased by 1.6% over the same period. Nitrous oxide emissions decreased by 10% over the period, mainly because of reductions in the use of synthetic fertiliser and animal manure in agriculture.

Observational Infrastructure

The national climate observation infrastructure is largely well established. Most elements are robust, but there are gaps and areas where improvements are necessary. The network of synoptic, climatological and rainfall stations operated by Met Éireann has been upgraded and partly automated in recent years. It needs to be constantly maintained, evolve and adopt new technologies to ensure the future of long-term, representative measurements. The Mace Head Atmospheric Research Station, operated by the National University of Ireland, Galway, has become a global reference site for the observation of several greenhouse gases, including carbon dioxide, methane and nitrous oxide and other atmospheric constituents, including ozone and aerosols. However, many of its observation programmes are funded on an ad hoc basis via short-term research projects, and the long-term availability of funding to maintain them is not assured.

Ireland's ocean climate observation infrastructure has improved. A recent major investment in the Marine Data Buoy Observation Network, quasi-continuous high-quality ocean carbon dioxide measurements on board the national research vessels, and Ireland's full membership of the Euro-Argo ERIC (European Research Infrastructure Consortium; the European contribution to the international Argo programme) initiative in 2016 consolidates the country's ability to measure near-surface and subsurface ocean water properties. The Marine Institute and the National University of Ireland, Galway, have carried out inorganic carbon observations since 2011. Nutrients and dissolved oxygen are now regularly measured in the deep ocean as part of the national contribution to the international Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP). The making of high-quality ocean biogeochemical measurements is not trivial, and a sustained measurement programme and analytical capability are essential to ensure delivery of high-quality data suitable for climate research and calculation of ECVs. The lack of a long-term Irish-operated ocean current monitoring system represents a significant gap in the North-east Atlantic, and such a system would be particularly useful in the Shelf Edge Current to monitor variability in a major source of input to the Nordic Seas from the Atlantic.

Coast-based ocean observational systems have also improved. The SmartBay Observatory in Galway Bay makes a suite of relevant observations. The country's ability to observe sea level change has also been enhanced. The Office of Public Works-operated tide gauge at Malin Head was upgraded to meet full international Global Sea Level Operating System (GLOSS) standards during 2020, and there are plans to bring the Marine Institute-operated tide gauges at Union Hall, Co. Cork, and Howth, Co. Dublin, up to GLOSS standards in the near future on a pre-operational basis. Nonetheless, sustained resourcing and institutional support is needed to upgrade and guarantee the long-term integrity and operation of these sites and the curation of the data generated.

The identification of a high-quality network of reference hydrometric gauges on rivers for monitoring and detecting climate change signals in river flows has filled a significant gap. However, for lakes and groundwater sources there is no equivalent network. The establishment of a National Water Abstraction Register is a welcome development, and it will allow the analysis of annual changes in the amounts of water used by different sectors and the identification of any trends that emerge.

The National Land Cover Map initiative, led by Ordnance Survey Ireland and the Environmental Protection Agency, to develop a new land cover dataset with a better spatial resolution and more appropriate classification system than the CORINE (Coordination of Information on the Environment) programme is welcome and should dramatically improve our understanding of land cover and its evolution. The establishment of the Irish Soil Information System has led to the development of a range of products on soil characteristics and has enhanced knowledge of soil carbon, although the estimates of the amount of carbon stored in the remaining peatlands needs to be improved. A better quantification of forest and non-forest areas burned, and the related emissions, is required. There are no long-term ground-based measurements of a number of vegetation parameters (e.g. leaf area index, fraction of absorbed photosynthetically active radiation), albedo or land surface temperature. Such observations over a number of different vegetation types should be considered to improve the understanding of ecosystem processes across the country and for the validation of satellite-derived measurements.

Over recent years significant work has been carried out internationally on bringing together observations made over the last 30 years from a range of satellites to generate time series of global products. There has been some limited analysis and use of these various datasets in an Irish context, but there is still uncertainty over how and where they could complement *in situ* observations or be a source of useful information where ground observations are lacking. There is still a lack of comprehensive skills in Earth observation and related data analysis capabilities nationally.

Regular analysis of climate data and the reporting of status, trends and projections is as important as systematic data collection and management. Since the previous climate status report new analyses have been carried out. These provide a better understanding of past and ongoing change in critical ECVs and include:

- the calculation of a new set of climate normals for atmospheric ECVs for the period 1981–2010;
- a comprehensive analysis of quantitative and qualitative rainfall records going back to 1711;
- an analysis of the spatio-temporal variability of aerosols and their interaction with clouds;
- an analysis of 34 years of nearshore wave conditions;
- a study of tide gauge records collected at Dublin Port since 1938 to enhance understanding of sea level change; and
- an in-depth analysis of river flows across a network of reference stations.

Much of the climate data collected are archived locally by the collecting agency and also sent to international data repositories. For example, atmospheric carbon dioxide, methane and nitrous oxide observations made at Mace Head are submitted to the World Data Centre for Greenhouse Gases; oceanic observations of carbon dioxide are submitted to the international Surface Ocean CO_2 Atlas; and the area of vegetation burned annually is reported to the European Commission. Nonetheless, it is often challenging to find ECV data in either local or international archives. This inhibits both awareness and use of the data collected. The data syntheses presented in this report will be made available via Climate Ireland, the national online portal that aids understanding of climate change and provides tools to support climate adaptation.

The establishment of GCOS-Ireland in 2018, with representation from the key national organisations involved in climate observations, substantially improves co-ordination and coherence in relation to GCOS-relevant issues. One of its key objectives is to identify gaps in the observational infrastructure and recommend appropriate actions including the use of Earth observations and emerging technologies. Moreover, it acts as a conduit for information on national observing capacity to relevant organisations and government departments. This should help to highlight the need to maintain the existing infrastructure and to consider how best to prioritise additional infrastructure, observation programmes and the required analysis of data already collected.

Opportunities and Recommendations

A robust national climate observation system is vital to build understanding of climate change and to inform responses and actions to mitigate climate change and adapt to its impacts. Moreover, as a signatory to the UNFCCC, the country is obliged to meet its international commitments concerning climate observations under GCOS. Ireland has always been well connected to the international community with regard to key climate observation systems. This has further improved over recent years with involvement in activities related to the consolidation of research and observation infrastructures, especially in the oceanic domain. Submission of quality-controlled climate observations to international data centres also allows the consideration of Irish data in international analyses. It is vital to maintain and enhance the international dimension of the work in order to share knowledge and experience of best practice in observations and to contribute to analysis and support the drive for further international investment in climate observation systems.

Progress has been made in several areas in terms of observation infrastructure, resourcing, analysis and co-ordination since the previous report in 2013. Nonetheless, there are a number of issues that need to be addressed to make the national climate observation system more robust and capable of addressing the country's long-term needs with regard to climate monitoring and understanding. The following recommendations are made as a result of this study:

- Existing climate observation programmes must be sustained, and infrastructure needs to be maintained and upgraded when required to meet international standards for climate monitoring.
- Observations of ECVs that rely on one-off or ad hoc research funding should be transitioned to long-term programmes with sustained resourcing.
- A systematic programme to complete the comprehensive analysis of historical *in situ* ECV data, including the digitisation of paper records, is required.
- Satellite observations complement *in situ* programmes, and comprehensive analysis of ECVs for Ireland needs to be carried out. Skills enhancement and stronger engagement of research entities, start-ups, the educational sector and public authorities with relevant aspects of the Copernicus Earth observation programme should be promoted.
- A programme of long-term monitoring of ocean currents and their water properties should be established. This would fill a significant gap in the North-east Atlantic.
- The proposed National Sea Level Measurement Advisory Group, and a co-ordination and operational GLOSS system management function within an existing organisation, should be established and resourced to ensure the implementation of a coherent and comprehensive sea level rise observations programme.
- Similar to the recent establishment of a reference network of river flow gauges for climate monitoring, an analogous network of lake and groundwater sites needs to be established following a review of the existing sites where observations are made for water quality, water supply and ecological reasons.
- There are no long-term ground-based measurements of a number of terrestrial variables. Such observations over different vegetation types and ecosystems should be considered to improve the understanding of ecosystem processes and for the validation of satellite-derived observations.
- The establishment of a long-term Irish greenhouse gas observatory (i.e. flux tower) would help to assess terrestrial systems' potential to mitigate and adapt to climate change, support engagement with key measurement networks (e.g. ICOS, the European Integrated Carbon Observation System) and underpin national initiatives such as National Inventory Reporting.
- Establish and maintain a climate data portal as a gateway to information on the national climate observation infrastructure, sources and repositories of climate observations, publications, experts, events and activities. This could be integrated into the Climate Ireland portal.
- GCOS-Ireland, with the observational infrastructure owners, should aim to develop a roadmap for maintaining, consolidating and, where necessary, upgrading Ireland's climate observation system. This should address established and new ECVs and include prioritising areas for action, the resources and finances required and a timeline for implementation. The goal of such an implementation would be to inform national climate mitigation and adaptation actions and meet GCOS requirements.

1. Setting the Scene

1.1 Introduction

1.1.1 The Need for Climate Observations

Regular, long-term, high-quality observations of the atmosphere, ocean and terrestrial environments are required to:

- characterise the state of the climate system, its variability and rate of long-term change;
- monitor the forcing of the climate system, including both natural and human contributions;
- determine the causes of climate change;
- provide a basis for assessing observed and projected changes in climate;
- monitor and measure the climate's response to changes in emissions;
- help inform planning for mitigating impacts and for adaptation to climate change.

The Intergovernmental Panel on Climate Change (IPCC) has published regular reports on the state of the global climate since 1990. Its most recent assessment report (IPCC, 2014) provides a comprehensive picture of global changes, potential impacts and mitigation options. The report states that:

> Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century.
>
> (IPCC, 2014)

The report also notes that many natural and human systems on all continents and across the oceans have been affected by regional climate changes, and it highlights the need for adaptation to reduce vulnerability to climate change. Moreover, the IPCC highlights that "changes in many extreme weather and climate events have been observed since about 1950" (IPCC, 2014). This includes the increased frequency of heatwaves, a decrease in cold temperature extremes, an increase in heavy precipitation events and an increase in extremely high sea levels.

1.1.2 Report Aims and Objectives

The aim of this report is to present the state of Ireland's climate based on the collation and analysis of almost 50 internationally defined essential climate variables observed in the atmospheric, oceanic and terrestrial environments. Moreover, it documents the status of Ireland's climate-observing infrastructure, noting where it is robust, where gaps exist and where observing programmes need to be enhanced. It also identifies whether collected data have been analysed for climate monitoring purposes and where more comprehensive analyses are required. It is an update of the first Irish climate status report (Dwyer, 2013). Where appropriate data exist, illustrative time series are presented and trends reported. In other cases in which the period of observation is short, no specific monitoring programme is in place or the appropriate analysis has not been carried out, example graphics are presented and the gaps in observations and analysis highlighted. The organisations responsible for monitoring each of the variables are identified, and lastly guidance on where data and additional information can be accessed is provided. The information contained in this report has been compiled from a large number of national and international sources.

This second report highlights similarities or changes in the trends in observed variables and reports on new essential climate variables and programmes that have been added or initiated since the last report. It also notes where there are still limited observations, analysis or support and comments on the robustness of Ireland's climate observation system. This information supports our understanding of Ireland's changing climate and informs the assessment of the actions required to mitigate and adapt to the changes appropriately.

1.1.3 Observed Climate Change in Ireland

Ireland, as an island on the western margins of Europe facing the Atlantic Ocean, is recognised internationally as an ideal site for baseline atmospheric and oceanic measurements. It provides key climate observations to relevant international databases for analysis and reporting on the global climate. Observations are also required to understand Ireland's role in driving climate and to identify local trends. Background concentrations of greenhouse gases (GHGs) and other constituents of the atmosphere, transported in predominantly unpolluted air masses by westerly winds, are measured in a number of locations. Ireland's marine territory extends to an area of approximately 900,000 km^2, including deep sea areas of over 3000 m in depth. Monitoring of Atlantic Ocean climate parameters is vital, given its predominant role in determining the temperate climatic conditions experienced in north-west Europe. Monitoring of the land surface and hydrological regimes is important, given their direct influence on the socio-economic environment. Ireland still has extensive areas of peatland. They play an important role in carbon and water storage, but their health is very sensitive to changes in climate.

Monitoring of various aspects of the climate provides the observational data that help in improving our understanding of the climate and allow comparison of observed changes with projections. It can also provide evidence of any changes, thereby allowing appropriate action to be taken to adapt to and reduce the most deleterious impacts of changes or to take advantage of the changing climate.

Similar to the findings reported by the IPCC, evidence of climate change has been reported for Ireland. In its calculation of climate averages for the period from 1981 to 2010, Met Éireann (Walsh, 2012) shows that the average air temperature increased by 0.5ºC and the total rainfall increased by 5% compared with the period from 1961 to 1990. An analysis of monthly rainfall records for the period from 1711 to 2016 (Murphy *et al.*, 2018) show that decadal variability may be much larger than was believed to be the case when only digital records were taken into account. However, the decade from 2006 to 2015 was the wettest on record and there is evidence in the dataset that there is a trend towards an increase in winter rainfall and a decrease in summer rainfall. In terms of drought, analyses have been carried out on observations from the precipitation recording network across Ireland for a 165-year period (1850–2015) that highlighted the occurrence of seven periods that were marked by major droughts, which varied in terms of location, onset and duration (Noone *et al.*, 2017). Regarding the ocean, Gallagher *et al.* (2014) carried out an analysis of wave data for the 34-year period from 1979 to 2012, based on a hindcast and calibrated with observations from satellites and buoys. This shows that there is considerable spatial and temporal variability in the wave climate around Ireland and that it is strongly correlated with the variability in the atmospheric pressure phenomenon known as the North Atlantic Oscillation, especially in winter. Work carried out at Maynooth University set out to reconstruct a consistent sea level dataset for Dublin Port, where observations have been made since 1938. High rates of sea level rise were noted in the 1980s, and since 2003 rates of 10 mm per year have been observed. However, local subsidence cannot be ruled out as a major contributing factor, as well as some natural variability due to the North Atlantic Oscillation. An analysis of river flow data across the island for the period 1976–2009 shows increasing trends in low, mean and high flows across much of the country (Murphy *et al.*, 2013). However, analysing only the period 1992–2009 and including an additional 18 river flow gauges, indicates a stronger trend towards decreases in the magnitudes of low, mean and high flows. Nevertheless, the report highlights the danger of drawing conclusions from short

Table 1.1. The Global Climate Observing System essential climate variables

Domain	Sub-domain	Essential climate variables
Atmospheric	Surface	Air temperature, precipitation, air pressure, radiation budget, wind speed and direction, water vapour
	Upper air	Earth radiation budget, upper air temperature, wind speed and direction, water vapour, **lightning**
	Composition	Cloud properties, carbon dioxide, methane, other long-lived greenhouse gases, ozone, aerosol properties, precursors of aerosols and ozone
Oceanic	Physics	Sea surface temperature, sea surface salinity, sea surface currents, subsurface temperature, subsurface salinity, subsurface currents, sea level, sea state, *sea ice*, **sea surface stress**, **ocean surface heat flux**
	Biogeochemistry	Inorganic carbon, oxygen, nutrients, transient tracers, ocean colour, **nitrous oxide**
	Biology/ecosystems	Plankton, **marine habitat properties**
Terrestrial	Biosphere	Albedo, land cover, fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance, **land surface temperature**
	Hydrology	River discharge, groundwater, lakes, soil moisture
	Cryosphere	*Snow, glaciers, ice sheets and ice shelves, permafrost*
	Human use of natural resources	Anthropogenic water use, **anthropogenic greenhouse gas fluxes**

New variables agreed in 2016 are in bold. Variables in italic are not discussed in this report, as they are not relevant to Ireland.

time series and underscores the need for long-term and reliable observations.

1.1.4 The Essential Climate Variables

In 1992 the United Nations Framework Convention on Climate Change (UNFCCC) was agreed and the Global Climate Observing System (GCOS) Secretariat was established to support the systematic observation of climate. One of GCOS's important tasks was to define a minimum set of variables to be monitored in order to have a comprehensive understanding of climate and its changes. These essential climate variables (ECVs), first defined in 2004, have since been updated in 2010 and again in 2016 (GCOS, 2016). They include observations of the physical, chemical and biological properties of the atmosphere, the ocean and the land surface. The new ECVs that were added in 2016 are lightning, land surface temperature, ocean surface stress, ocean surface heat flux, marine habitat properties, oceanic nitrous oxide, and anthropogenic GHG fluxes. Variables are defined as ECVs only if it is currently feasible to measure them at a global scale and if they contribute significantly to meeting UNFCCC and other climate requirements. Observations are made by a combination of *in situ* measurement systems and, since the 1970s, satellite sensors. Satellites can make simultaneous observations over large areas, and they allow observations in inaccessible areas and in places where no *in situ* measuring equipment is deployed. However, *in situ* measurements are required to calibrate and validate the measurements. The full list of ECVs is shown in Table 1.1. Fifty of these are presented in this report and more than 40 discussed in more detail; in some cases, especially for a number of the variables added to the list in 2016 (e.g. sea surface stress and heat flux), observation is not yet established in Ireland, and in other cases observations have been carried out for only a brief period or as part of short-term projects. The ECVs shown in italics in Table 1.1 are not discussed, as they are not relevant to Ireland.

1.1.5 Overview of Observations in Ireland

In 2018 a GCOS National Committee[2] was established in Ireland (GCOS-Ireland). GCOS-Ireland works as an ad hoc committee to ensure the sustained provision of reliable physical, chemical and biological observations and data records for the total climate system – across the atmospheric, oceanic and terrestrial domains, including hydrological and carbon cycles, for Ireland. Moreover, the National Committee co-ordinates and promotes the GCOS observing principles relating to

2 See Appendix 2 for the National Committee's terms of reference.

ECVs of relevance to Ireland. The Committee's founding members are Met Éireann, the Marine Institute and the Environmental Protection Agency (EPA), complemented by Teagasc and remote sensing expertise. Other agencies or organisations may be invited to participate as agreed by the Committee.

Observation of meteorological surface and upper air variables is carried out by Met Éireann at its synoptic, climatological and rainfall stations around Ireland. Measurements of some variables such as near-surface air temperature have been made since 1858, allowing long-term variability to be assessed. Valentia Observatory, Co. Kerry, is crucial for the observation of ECVs including upper air temperature and wind, lightning, solar radiation and column ozone.

The Mace Head Atmospheric Research Station, Co. Galway, has emerged as an important site for the observation of atmospheric composition variables. Established in 1958, some of the longest measurement series include ozone and methane. It is operated by the National University of Ireland (NUI) Galway, although measurement programmes are funded, on a project basis, by a number of national and international organisations.

Regarding oceanographic observations, the longest continuous time series include sea surface temperature and tide levels, both of which have been measured at Malin Head, Co. Donegal, since 1958. The tide gauge station operated by the Office of Public Works (OPW) has recently been upgraded to fully meet the international standards of the Global Sea Level Observing System (GLOSS), thereby allowing the inclusion of the data in international studies of sea level change. The establishment of the Marine Institute in 1991 gave an impetus to the collection of oceanographic data. The deployment of five marine data buoys and the regular, routine oceanic measurements made on scientific cruises by Ireland's two national research vessels has helped to consolidate observations of a range of variables. A major investment in the Marine Data Buoy Observation Network in 2017 facilitated ongoing operations and a significant upgrade of the infrastructure. Ireland has participated in the international ocean monitoring Argo programme, through the Marine Institute, since 2007 and joined the Euro-Argo ERIC (European Research Infrastructure Consortium), or the European contribution to the international Argo programme, as a full member in 2016. This has enhanced its ability to deploy autonomous instruments, reporting subsurface ocean water properties, including temperature and salinity. Moreover, the new national research vessel RV *Tom Crean*, currently under construction, will replace the RV *Celtic Voyager* and is expected to be delivered in 2022. This will help maintain many of the observation programmes in the deep ocean.

Several organisations carry out measurements of land-based (biosphere) and hydrological variables. Currently the EPA and Ordnance Survey Ireland (OSi) are co-ordinating work on the development of a high-resolution national land cover map, which will allow more accurate estimates of emissions and removals of GHGs associated with land cover across the country. The Irish Soil Information System project, co-funded by the EPA and Teagasc, has led to the development of a number of national maps of soil variables. The EPA also co-ordinates certain hydrological measurements, including groundwater, lake levels and river flows, and the OPW complements this with an extensive river flow monitoring network. Taking advantage of this network, the EPA has identified a set of 35 high-quality reference hydrometric gauges that can be used for monitoring and detecting climate change signals in river flows.

Table 1.2 summarises the current status of monitoring of all relevant ECVs in Ireland. It shows the observation period or duration and the key organisations carrying out the measurements and indicates if data analysis has been carried out and the security of the observation programme. In addition, it indicates whether the observation and analysis of each variable are carried out in Ireland or rely on data and analysis of the Irish situation from international activities and organisations. More complete details can be found in the relevant sections pertaining to each ECV.

Observations of key surface and upper air meteorological variables have been carried out by Met Éireann for many decades, with some records dating back to the late 1800s. These measurement programmes are secure; however, resources are required to maintain and update equipment and enhance aspects of the observation networks. A number of reports providing updated analysis of temperature and rainfall records are available (Walsh, 2012; Murphy *et al*., 2018). However, only partial analysis of the other meteorological variables has been carried out. In several cases

Table 1.2. Overview of essential climate variables, including observation period or duration, key organisations carrying out the measurements relevant to Ireland, level of analysis carried out on data collected in or around Ireland, and sustainability of the observation programme. The last column indicates whether the observations (left-hand semicircle) are carried out in Ireland (green) or rely on international programmes only (red) or both and whether data analysis (right-hand semicircle) is carried out in Ireland (green) or by international groups only (red) or both

Essential climate variable	Period or duration of observations	Measuring organisations	Data analysis	Programme secure?	Roles in observation and analysis
Atmosphere					
Air temperature	1881–2019	Met Éireann			
Precipitation	1881–2019	Met Éireann			
Air pressure	> 100 years	Met Éireann			
Surface radiation budget	1955–2019	Met Éireann			
Wind	> 100 years	Met Éireann			
Water vapour	> 50 years	Met Éireann			
Upper air temperature	1943–2019	Met Éireann			
Upper air wind	1943–2019	Met Éireann			
Upper air water vapour	1943–2019	Met Éireann			
Cloud properties	> 50 years	Met Éireann, NUI Galway			
Lightning	2009–2019	Met Éireann			
Carbon dioxide	1992–2019	EPA, LSCE, Met Éireann, NUI Galway, Marine Institute, NOAA			
Methane	1987–2019	EPA, LSCE, DECC, NASA			
Ozone	1993–2019	Met Éireann, EPA, DECC			
Other greenhouse gases	1978–2019	EPA, DECC, NASA			
Aerosols	1986–2019	Met Éireann, NUI Galway			
Oceanic					
Sea surface temperature	1958–2019	Met Éireann, Marine Institute			
Sea surface salinity	2000–2019	Marine Institute			
Sea level	1958–2019	OPW, Marine Institute			
Sea state	2002–2019	Marine Institute			
Surface currents	Irregular	Marine Institute, NUI Galway, BODC, others			
Ocean colour	1997–2019	Space agencies			
Inorganic carbon	2008–2019	Marine Institute, NUI Galway			

Subsurface temperature	2005–2019	Marine Institute	orange circle	orange circle	green/green circle
Subsurface salinity	2000–2019	Marine Institute	orange circle	orange circle	green/green circle
Subsurface currents	2008- 2019	Marine Institute, NUI Galway, BODC, others	orange circle	orange circle	green/red circle
Ocean surface stress	1990–2019	Space agencies	red circle	red circle	red/red circle
Ocean surface heat flux	–	–	red circle	red circle	red/red circle
Nutrients	1991–2019	Marine Institute	green circle	orange circle	green/green circle
Nitrous oxide	–	–	red circle	red circle	red/red circle
Transient tracers	2017	Marine Institute, NUI Galway, GEOMAR	red circle	red circle	green/red circle
Plankton	1990–2019	Marine Institute, EPA, MBA	green circle	green circle	green/green circle
Oxygen	2001–2019	EPA, Marine Institute, NUI Galway	green circle	green circle	green/green circle
Marine habitat properties	2007–2019	EPA, NPWS, Marine Institute	green circle	green circle	green/green circle
Land surface					
Land cover	1990- 2019	EPA, OSi, space agencies	green circle	green circle	green/green circle
Albedo	1981–2019	Space agencies	red circle	green circle	red/red circle
Fraction of absorbed photosynthetically active radiation (FAPAR)	1998–2019	Space agencies	orange circle	green circle	red/green circle
Leaf area index (LAI)	1998–2019	Space agencies	red circle	green circle	red/red circle
Above-ground biomass	2007–2019	EPA, National Forestry Service	green circle	green circle	green/green circle
Soil carbon	2008–2019	EPA, Teagasc	green circle	orange circle	green/green circle
Fire disturbance	2000–2019	DAFM	orange circle	orange circle	green/green circle
Land surface temperature	1995–2019	Space agencies	red circle	green circle	red/red circle
Anthropogenic greenhouse gas emissions	1990–2019	EPA	green circle	orange circle	green/green circle
Hydrology					
River discharge	> 50 years	EPA, OPW, ESB	green circle	green circle	green/green circle
Lakes	> 50 years	EPA, OPW, ESB	orange circle	green circle	green/green circle
Groundwater	> 50 years	EPA	orange circle	green circle	green/green circle
Soil moisture	1980–2019	Met Éireann, space agencies	orange circle	green circle	green/green circle
Water use	2018–2019	EPA	red circle	green circle	green/green circle

Key: green circle, yes; orange circle, partial; red circle, no.

BODC, British Oceanographic Data Centre; DAFM, Department of Agriculture, Food and the Marine; DECC, UK Department of Energy and Climate Change; ESB, Electricity Supply Board; GEOMAR, Helmholtz Centre for Ocean Research, Kiel; LSCE, Laboratory for Climate and Environment Sciences, France; MBA, Marine Biological Association; NASA, US National Aeronautics and Space Administration; NOAA, US National Oceanic and Atmospheric Administration; NPWS, National Parks and Wildlife Service.

historical paper records need to be digitised and issues with inhomogeneity in datasets need to be addressed. Inhomogeneities arise when measurement equipment, location, recording methods or aspects of the local environment change making it difficult to compare records over time.

Key GHGs and other atmospheric composition variables have been monitored for approximately 30 years by a range of national and overseas bodies. Many of these programmes are funded on an ad hoc basis and long-term monitoring programmes are not secure. The closure of the ground-based remote sensing of aerosol and microphysical cloud properties at Mace Head in early 2020 because of a lack of funding illustrates the precariousness of some of these programmes. Detailed analysis of many of the data records has been carried out and the results have contributed to international publications.

Records of sea water temperature and sea level have been collected at Malin Head for more than 50 years; however, observations of most of the other oceanic variables only started more recently. One of the most important programmes is linked to the installation of five offshore buoys that have instrumentation to record key surface and subsurface information (e.g. water temperature, salinity, sea state, subsurface currents) on an operational basis. Many of the ocean observation programmes are insecure, with funding being negotiated on an annual basis. This includes measurements in Irish waters of the carbonate system (ocean acidity, inorganic carbon) that are undertaken as part of a collaboration between the Marine Institute and NUI Galway for both near-shore and offshore measurements. However, poor weather conditions can compromise the ability to make regular winter measurements offshore. There is no long-term ocean current monitoring system in Irish waters, which represents a significant gap in the North-east Atlantic, given the role of ocean currents in transporting heat, salt, fresh water, carbon and ocean pollutants from one part of the ocean to another and in determining climate conditions and weather fluctuations.

Detailed analysis of much of the ocean data collected has been carried out. However, the most recent comprehensive report on the status of the ocean climate and ecosystem dates back to 2010 (Nolan *et al*., 2010). Although sea level data have been collected at Malin Head since 1958, and at other locations for a number of decades, changes in the responsible organisations, measurement systems, location of the sensors, data quality, etc., make it extremely difficult to analyse the historical datasets and extract a reliable trend. Dublin Port tide gauge data for the period 1938 to present have been retrieved and analysed by Maynooth University and are believed to be of sufficient quality for sea level determination (Nejad *et al*., 2020); however, there are some questions about the reliability of the data and the recent apparently high rates of sea level rise observed.

Information for a number of land surface variables is predominantly derived from satellite observations; other variables are inferred from models or proxy data that are not direct observations. Only partial analyses, as components of short-term research projects, have been carried out for some of these, while a number have never been analysed. A series of projects, started in the early 2000s, has helped to improve knowledge of soils and has led to the production of a national map of soil organic carbon, while above-ground biomass or carbon is estimated via a modelling approach based on regular forest inventory studies. Data on vegetation fires are generally not compiled centrally by the fire services; however, burned area estimates, based on assessments of known fires, are generated for reporting by the Department of Agriculture, Food and the Marine (DAFM). The Forest Service and Coillte maintain a record of the area burned for forest monitoring. Nonetheless, information should be improved by recording and collating the location and extent of all wildfires, including both forest and non-forest land types.

Analysis of changes in land cover has been carried out through the European CORINE (Coordination of Information on the Environment) Land Cover programme. However, in 2011 a working group was established to identify a way to produce a higher quality national land cover dataset for Ireland. Work has been proceeding on developing this dataset, which should be released in 2021.

Monitoring of the main hydrological variables has been carried out by a variety of bodies over the last 40–50 years. However, this has generally been for water management and water quality purposes. Recently, the EPA has established a network of river flow monitoring sites for climate purposes. Analyses of hydrology data in a climate context have been carried out, including an

Table 1.3. How climate data are used in a number of sectors

Sector	Use of climate data
Agriculture	Plan for resilient farming through identification of appropriate seeds/crops and plan for future irrigation needs. Ensure climate change and impacts are integrated into agricultural policymaking and strategies.
Biodiversity	Assessment of ecosystem resilience, particularly of those areas currently designated as protected (e.g. Natura 2000 sites). Examine climate-induced changes in the distribution and possible extinction of native species and the occurrence of invasive species. Plan conservation strategies that offset climate change threats to species' persistence.
Commerce and industry	Plan for changing demand for goods and services. Identify vulnerability of supply chain, utilities (water and energy in particular) and transport infrastructure to changing climate/extreme events. Reduce vulnerability through the design and location of facilities in areas of reduced risk. Factor climate into long-term decisions concerning investment and insurance cover. Help plan for changes in workforce, customers and lifestyles.
Coastal and marine	Identify areas at risk of coastal inundation/erosion, particularly those settlements/facilities situated on estuaries. Help develop plans to defend, accommodate or realign the coast in areas under threat from flooding and erosion and locate new facilities and settlements in areas of reduced risk. Manage coastal ecosystems, particularly those at risk from saltwater intrusion (coastal wetlands and estuaries).
Energy management	Forecast power requirements required to cope with future climate, e.g. energy may be required for pumping water and for cooling. Examine existing infrastructure, review its vulnerability and prioritise the measures needed to adapt and protect each installation. Identify the most viable sites for renewable energies (wind, wave, solar). Quantify reductions in efficiencies of power stations due to increased cooling requirements under higher temperatures and identify efficiencies of intermittent renewable power plants (run-of-river hydro and wave) in a changing climate (e.g. changes will occur in average wind speed, river flow and wave height). Plan for increased downtime and maintenance of power plants and transmission networks due to extreme weather events.
Fisheries and aquaculture	Identify the most viable species and locations for fishing arising from climate change-related biogeographical shifts and ecosystem changes. Estimate the number of fishing days in winter. Quantify increases in phytoplankton biomass and plan for changes in timing and intensity of spring algal blooms. Plan for changes in near-shore seafood production (e.g. nursery areas, traditional shellfish beds) due to changes in water temperature, pH levels, near-shore salinity, sediment loading and distribution due to alterations in river discharge and increasing sea levels. Design aquaculture facilities to cope with the more frequent occurrence of extreme events.
Forestry	Identify the most viable species and areas for planting over the long term and plan for increased risks from pests, pathogens, fire and windfall. Forecast level of supply and quality of timber.
Health	Prepare public health plans for those groups most vulnerable to temperature-related mortality, principally those in the over 75 age group and young children. Forecast levels of food-, water- and vector-borne disease and other indirect effects of climate change, e.g. allergies, skin cancer.
Peatlands	Identify and plan for areas of peatlands that are at particular risk of degradation/"die-off". Quantify levels of carbon dioxide emissions from intact and degraded peatlands and run-off of dissolved organic carbon.
Spatial planning	Develop and implement coastal protection plans for cities and towns at risk. Identify areas most prone to the urban heat island effect and implement mitigation and adaptation measures. Identify and plan for climate impacts on vulnerable rail and road networks, particularly those following coastal and river valley routes.
Tourism	Predict the duration of the tourist season, and plan for the extension of the tourist season into the "shoulder periods" (i.e. the periods between the peak and off-peak months) and also for increased tourist numbers. Identify amenities at risk from climate change, e.g. coastal and freshwater resources. Plan for increased demand on resources, e.g. energy and drinking water, access points to the coast.
Water management	Plan and manage for a sustainable water supply, of both surface water and groundwater, by identifying how water will be harvested, managed and distributed. Manage competing demands on water, e.g. for agriculture, industry, drinking, recreation. Identify resources at risk from soil and peat erosion, landslides and the spread of agricultural pollutants.

analysis of trends in river flows (Murphy *et al*., 2013). In 2018 the EPA launched the National Water Abstraction Register, which will allow a much improved assessment of water use into the future.

1.1.6 Use of Climate Data

Observations combined with modelled data for future climate conditions are vital to support socio-economic development planning, which needs to incorporate both mitigation and adaptation strategies and actions. Table 1.3 shows where reliable, high-quality climate data are required to help planning and management in a wide range of sectors. There is a need to take current climate information and forecasts into account when planning the development of these sectors to avoid costly social and economic impacts. A robust climate observation system is vital to provide the necessary data to underpin such decision-making.

Story Box 1. Earth as a set of connected systems

Ned Dwyer

Earth system cycles

The Earth can be viewed as a set of interconnected and dynamic systems. The five principal systems are the hydrosphere (water), geosphere (land), cryosphere (ice), atmosphere (air) and biosphere (living things). The storage, transformation and exchange of matter and energy throughout the systems are governed by a number of cycles that obey the laws of conservation of matter and energy. The energy that drives these processes comes predominantly from the sun (Figure SB1.1). In dynamic systems, changes in or manipulation of one part of a subsystem can cause effects in other subsystems that we may not expect. This happens because the subsystems try to maintain their stability, so, if one variable changes, other variables may be affected to varying degrees. The interactions between the systems are known as Earth system cycles, the most relevant from a climate perspective being the energy cycle, the water cycle and the biogeochemical cycle, which includes the carbon cycle. We also have to consider human society. Our social, cultural and economic systems can be considered to be embedded in the Earth system, and in many cases they are the main drivers of change in the overall Earth system.

Removing uncertainties in our knowledge of the systems

There is a good understanding of the sources, sinks and fluxes or exchanges in these various systems, but nonetheless some uncertainties remain over the

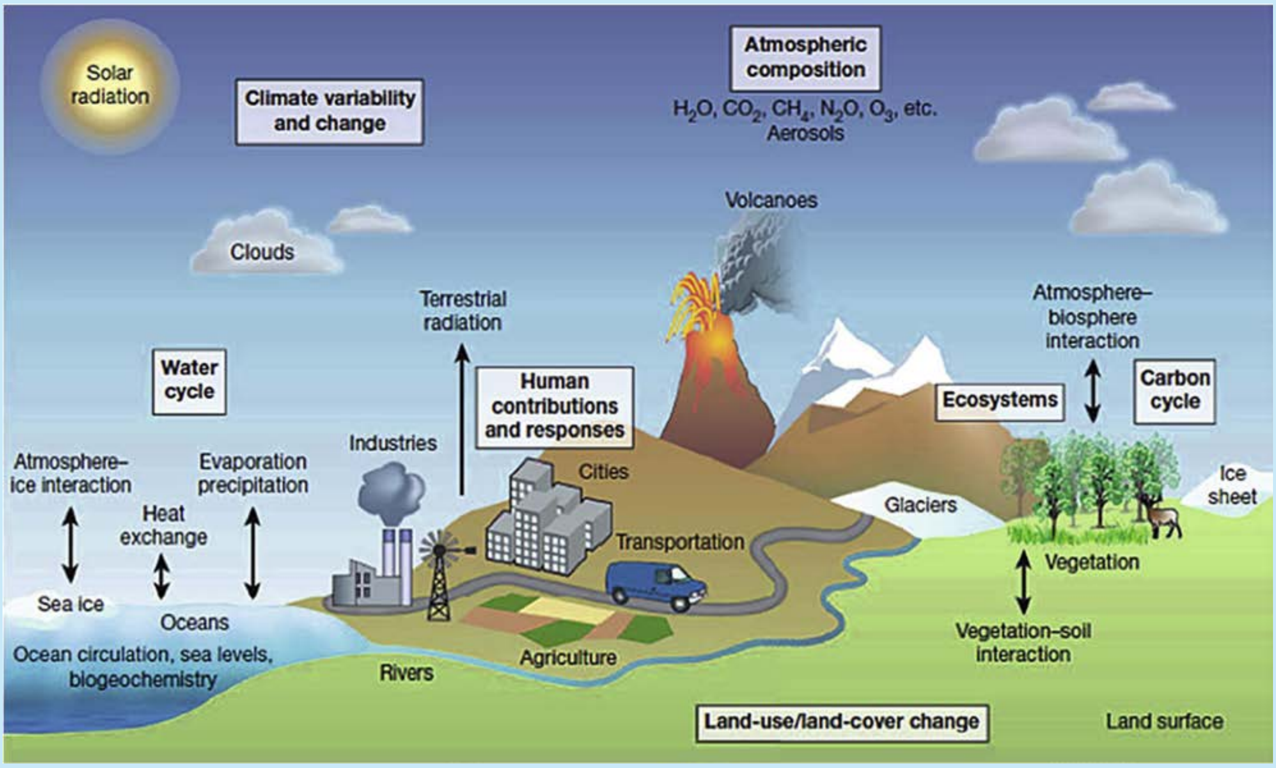


Figure SB1.1. Schematic diagram showing the most important elements to be considered in an Earth system model. Source: Simmons *et al*. (2016).

quantities to assign to the various subsystems and processes. Resolving these uncertainties is now a focus of GCOS and this is being addressed by improving the quality of existing observations but also by introducing new ECVs to be observed (Figure SB1.2).

The energy cycle

The main impact on the Earth system of the various anthropogenic GHGs being emitted is a reduction in energy exiting the top of the atmosphere and increased energy storage in the Earth system. It is estimated that as much as 90% of this excess energy is being stored in the ocean, which is leading to its warming and expansion. The rest goes into warming the land and atmosphere and into melting ice. To reduce uncertainties related to the energy cycle better estimates of the amount of radiation entering and leaving the atmosphere are required, as are better estimates of the amount of heat stored in the various parts (ocean, land, atmosphere and cryosphere) of the Earth system. Land surface temperature, ocean surface heat flux and ocean surface stress are three new ECVs introduced in the 2016 implementation plan that support better understanding of the energy cycle. Measures of evaporation from land are under consideration as a future ECV.

The carbon cycle

Regarding the carbon budget, it is uncertain how much carbon is held underground, emissions due to land use change are uncertain, and there is also a limited understanding of the exchange of carbon between the land and the ocean and hence the size of the carbon sinks in both of these systems. To partly address these uncertainties GCOS has introduced anthropogenic GHG fluxes as a new ECV.

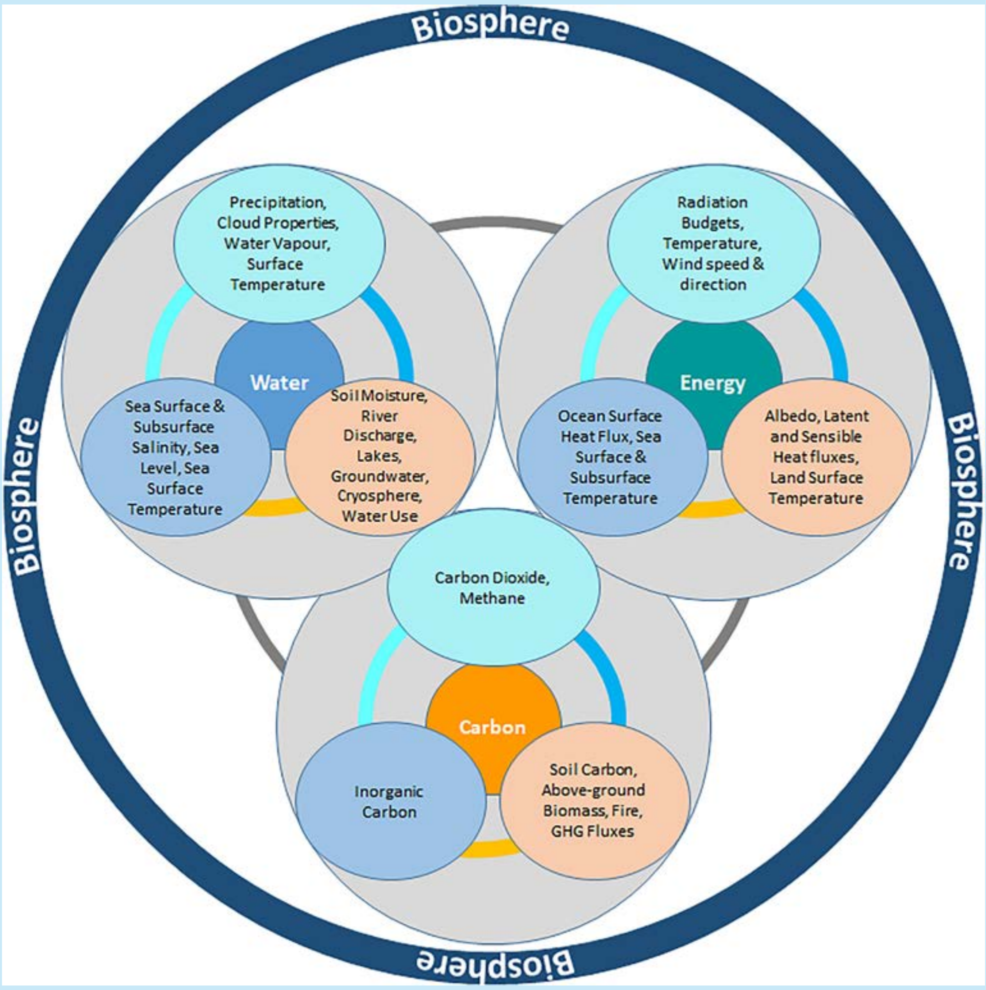


Figure SB1.2. Key Earth system cycles and the ECVs that contribute to their understanding. GHG, greenhouse gas. Source: Adapted from IOC (2019).

The water cycle

For the water cycle there are uncertainties over the amount of evaporation from the land and ocean to the atmosphere; there is also significant uncertainty about precipitation over the ocean, and in certain land areas there are large gaps in the rainfall monitoring network. Variables for quantifying evaporation from land are under consideration as future ECVs. Nonetheless, GCOS believes that the current suite of ECVs is sufficient to clarify these issues but that the observations need to be improved and extended and become more accurate.

The biosphere

The biosphere is characterised by all of the plants and animals living on Earth and the interactions among them. Climate change is compromising the healthy existence and survival of numerous species and their related ecosystems. For example, shallow water coral reefs are stressed by increasing water temperature and ocean acidification, Arctic species are compromised by less ice and earlier thaws due to warming air and water and forests are under stress from droughts and fires. An overarching aim of GCOS is to quantify changes in environmental conditions that directly influence the biosphere. The current set of ECVs is believed to be sufficient to start to quantify these conditions but there are many issues related to the comprehensiveness and reliability of data. For example, in the ocean, there are not sufficient spatial and temporal observations of many of the ECVs, especially in the southern hemisphere ocean. On land, historical data are often not reliable and it is difficult to make comparisons across regions, because some variables have not been observed in a standardised way. Various international groups of scientists are coming together to address these issues.

Updating the GCOS Implementation Plan

The GCOS Secretariat has laid out a set of targets in terms of what it believes needs to be achieved in improving understanding of the various cycles, reducing uncertainties and quantifying the various sources and sinks. It realises that it may take more than a decade to achieve. To support this the list of ECVs will remain under constant review, existing ECVs may be fine-tuned or modified and new ECVs may be added in future versions of the implementation plan. The implications of such modifications on Ireland's climate observation activities need to be assessed on a regular basis.

Further Information

An explanation of the Earth system (https://www.sciencelearn.org.nz/resources/1256-what-is-the-earth-system)

GCOS 2016 Implementation Plan, Chapter 5, Consistent observations across the Earth system cycles (https://gcos.wmo.int/en/gcos-implementation-plan)

Simmons, A. *et al*., 2016. Observation and integrated Earth-system science: a roadmap for 2016–2025. *Advances in Space Research* 57: 2037–2103. https://doi.org/10.1016/j.asr.2016.03.008

2. Atmospheric Observations

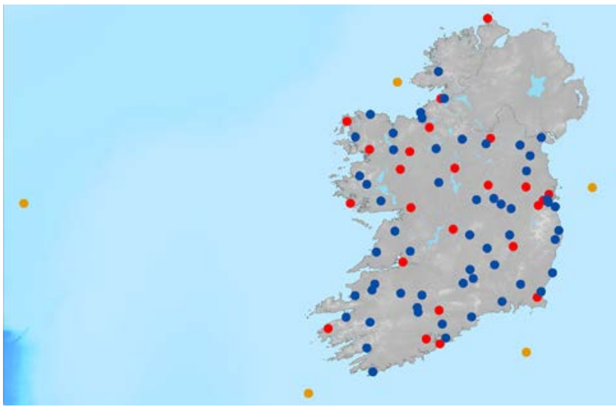
2.1 Surface Air Temperature

Walther C.A. Cámaro García, Ned Dwyer and Keith Lambkin

Surface air temperature is a key climate indicator and has widespread impacts on natural systems and on human lives and activities. It affects health, agriculture, energy demand and much more. In Ireland, more than 100 years of continuous instrumental observations exist. The global mean surface air temperature has increased by on average 0.85°C over the last century, but the rate of warming has nearly doubled since 1975 to almost 1.65°C per century. Average global air temperatures for the 5 years 2015–2019 were the highest since records began in the mid- to late 1800s. The frequency of heatwaves has also increased in many regions of the world.

2.1.1 Measurements

Surface air temperature is measured at the 25 synoptic (red dots) and numerous climatological (blue dots) weather stations and also at the Irish Marine Data Buoy Observation Network stations (orange dots) (see Map 2.1). Readings at automated synoptic stations are made every minute and at staffed stations, located in the main airports, every hour on the hour; at climatological stations readings of maximum and minimum temperatures over the previous 24 hours are made once a day at 09:00 Coordinated Universal



Map 2.1. Location of surface air temperature observation stations.

Time (UTC). Eighty climatological stations are currently being automated to facilitate sub-hourly temperature measurements. Surface air temperature is measured every hour on the marine data buoys, the first of which was deployed in 2000.

In Ireland the annual average surface air temperature has increased by approximately 0.9°C over the last 120 years.

2.1.2 Time Series and Trends

An average national surface air temperature series for Ireland has been derived using data from five long-term stations, namely Valentia, Malin Head, Armagh, Birr[3] and Phoenix Park. Figure 2.1 shows the mean annual observed temperatures (black dots) along with simple fits to the data. The left-hand axis shows anomalies (the difference between the mean annual temperature and the 1961–1990 normal or average value[4]), and the right-hand axis shows the mean annual temperatures for the period 1900–2019. Fifteen of the top 20 warmest years on record have occurred since 1990. The blue curve shows the 11-year moving averages. A simple linear trend line (red) has been fitted to the annual anomaly values. This indicates that temperature has been increasing at an average rate of 0.078°C per decade since 1900 and that the annual average temperature is now approximately 0.9°C higher than it was in the early 1900s.

The temperature has varied in line with the global patterns of change, presenting colder than normal episodes in the early part of the 20th century and also some cold years in the 1960s and 1970s. Although individual years with higher temperatures were recorded between the 1920s and 1950s the frequency of warm years has increased from the late 1980s to the present. It is interesting to highlight 2010, which was the coldest year in the 30-year period 1991–2019, is not unprecedented in terms of the overall record, and indeed would have been typical of temperatures in the early part of the 20th century.

An analysis of seasonal temperature differences, based on gridded data averaged over the area of Ireland, shows a rise in temperatures in all seasons. Figure 2.2 shows that both winter (December–February) and summer (June–August) minimum temperatures have tended to be higher than the 1961–1990 average, in particular over the last 30 years, although the anomalously cold winter between 2010 and 2011 is evident.

The number of warm spell days across Ireland has slightly increased over the last 60 years.

2.1.3 Extreme Event Indicators

An expert group under the aegis of the World Meteorological Organization (WMO) has developed a set of climate indices that allows the analysis of extreme events in a uniform way. In the case of temperature, these include the number of warm and cold spells. Such events have implications for human health, water supply and transport among others economic activities. Trend maps have been calculated for the indicators for stations which have a near-complete daily record for the period 1961–2018. Figure 2.3 shows the trends for the number of annual warm spell days (number of days in a year with temperature above a certain threshold for at least 6 consecutive days) and the number of annual cold

3 The station at Birr closed in October 2009; since late 2009 weighted data from the nearby TUCSON station at Gurteen have been used.

4 Standard climatological normals or averages are compiled in 30-year cycles e.g. 1931–1960, 1961–1990, and allow for comparisons of current weather elements with long-term averages.

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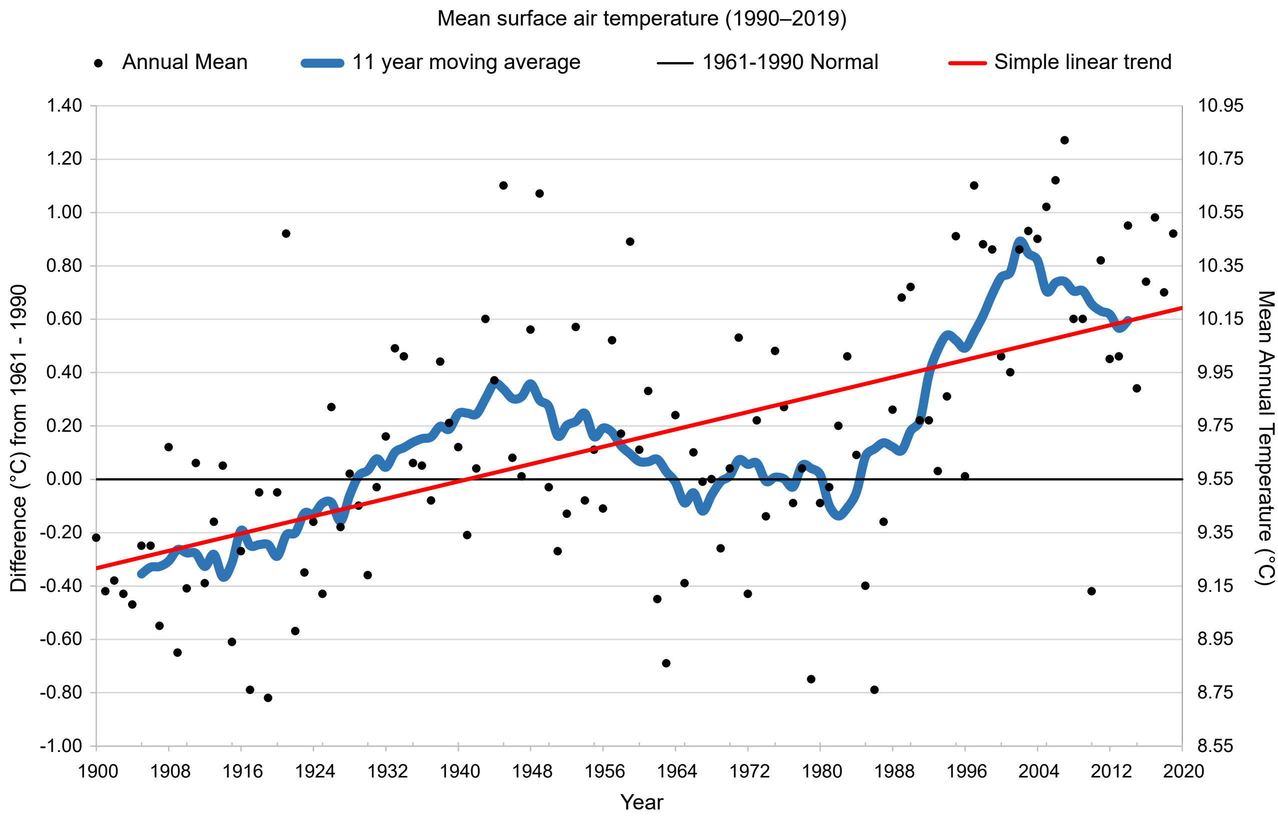
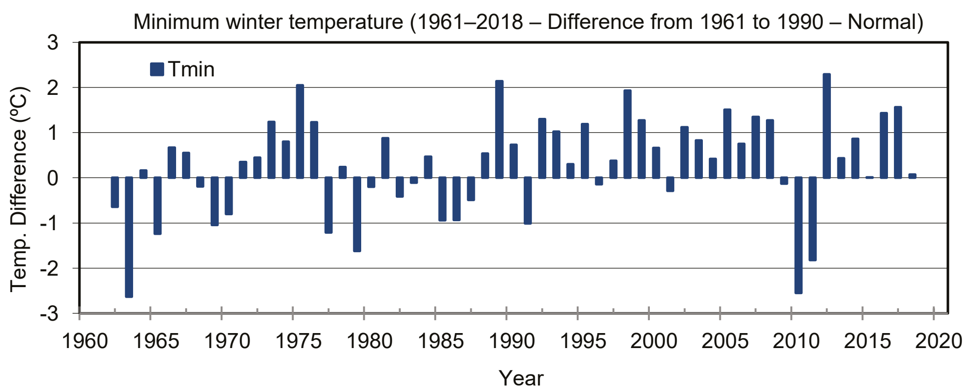


Figure 2.1. Annual mean surface air temperature (1900–2019).



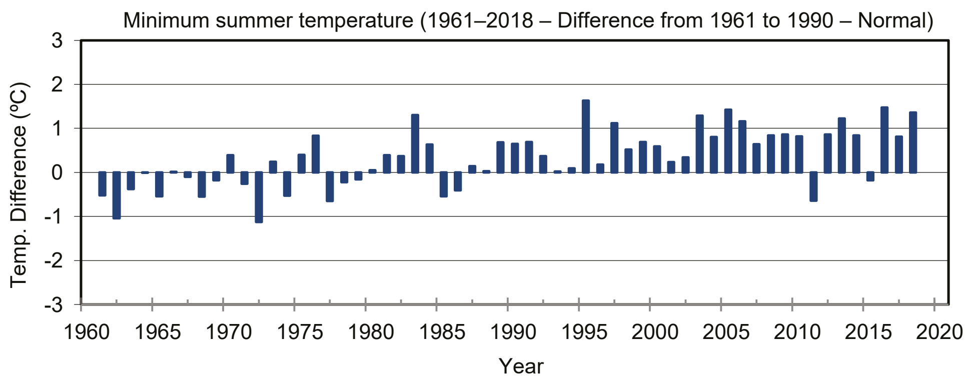


Figure 2.2. Winter (top) and summer (bottom) minimum surface temperature anomalies (1961–2018).

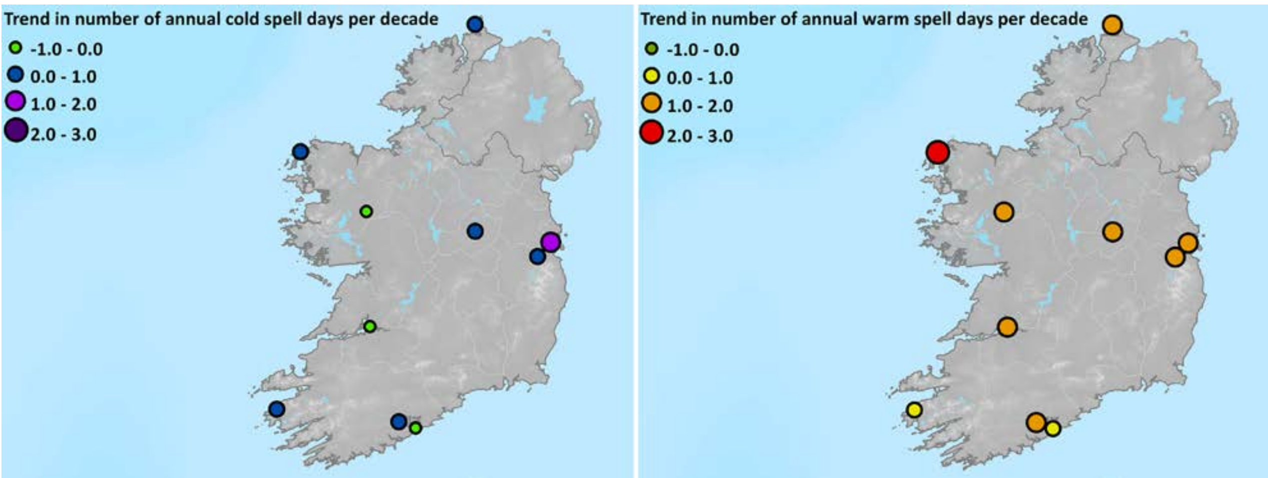


Figure 2.3. Trend in number of annual cold spell days per decade (left) and number of annual warm spell days per decade (right) (1961–2018). For example, there are on average 2 or 3 additional warm spell days each decade at Belmullet, Co. Mayo, over the six decades analysed.

spell days (number of days in a year with temperature below a certain threshold for at least 6 consecutive days). The trends indicate a slight increase in the number of warm spell days across the whole country and very little change in the number of cold spell days.

Air temperature has been measured in a systematic manner in Ireland since the late 19th century.

2.1.4 Maintaining the Observations

The network of synoptic and climatological stations operated by Met Éireann needs to be maintained and further developed to ensure the future of long-term representative temperature measurements. The deployment of the Irish Marine Data Buoy Observation Network is the result of collaboration between the Marine Institute and Met Éireann. The Marine Institute maintains the buoy network, while Met Éireann monitors the quality of the observational data.

Difficulties can arise with time series because of inhomogeneities due to changes in instrumentation, observer, location and times of observation and due to new buildings and tree growth in the vicinity of a station. Resources are required to produce homogeneous temperature time series and to collate and digitise paper records, including station metadata.

Further Information

Surface Temperature Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/surface-temperature/)

Expert Team on Climate Change Detection and Indices/Climate Research Division: ETCCDI/CRD Climate Change Indices. Definition of the 27 core indices (http://etccdi.pacificclimate.org/list_27_indices.shtml)

Met Éireann information on air temperature (https://www.met.ie/climate/what-we-measure/temperature)

Met Éireann information on data availability (https://www.met.ie/climate/available-data)

Information from the Irish Marine Weather Buoy Network (http://www.marine.ie/Home/site-area/data-services/real-time-observations/irish-marine-data-buoy-observation-network)

World Meteorological Organization statement: The State of the Global Climate 2020 (https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate)

National Oceanic and Atmospheric Administration National Centers for Environmental Information: BAMS annual State of the Climate reports (https://www.ncdc.noaa.gov/bams)

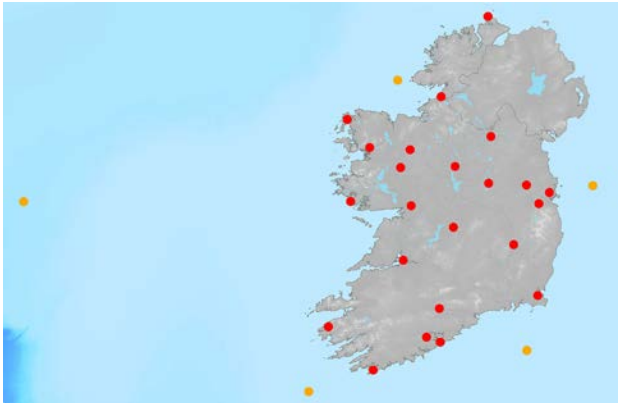
2.2 Surface Wind Speed and Direction

Walther C.A. Cámaro García, Ned Dwyer and Keith Lambkin

Wind is the movement of air caused by pressure differences at the Earth's surface, which in turn are caused by the differential heating of the Earth's surface by the sun. Wind drives the production of ocean waves and is a key component of ocean circulation, which is responsible for the global transport of heat and carbon. Extreme winds, especially during storms, can have huge social and economic impacts. In addition, accurate information on wind is essential for planning in areas such as wind energy, forestry and infrastructural development. Speed and direction are the most widely measured parameters used to characterise wind. However, in Ireland because of changes in the location of observation stations and improvements in measurement techniques, consistent wind speed data going back more than 20 years are not typically available – making it difficult to determine long-term trends.

2.2.1 Measurements

Wind speed and direction are measured at the 23 synoptic weather stations (red dots) operated by Met Éireann and at the five Irish Marine Data Buoy Observation Network stations (orange dots) (Map 2.2). Additional parameters are calculated, including gust speeds, the times of highest daily gusts, the mean wind speed and direction at the time of the highest gust and the highest 10-minute mean speed in a 24-hour period. Records available in Ireland go back several decades at a number of stations, although there was an upgrade of and change in measurement equipment in the 1990s at many of them. As well as precipitation, rainfall radar also measure wind speed and direction, and Met Éireann contributes to E-WINPROF, the European wind profiler programme.



Map 2.2. Location of surface wind observation stations.

Space-borne radar scatterometer and passive microwave radiometer data are key sources for wind field information over the ocean, where *in situ* measurements are sparse.

Average annual wind speeds range from 3 m/s in parts of south Leinster to over 8 m/s in the extreme north.

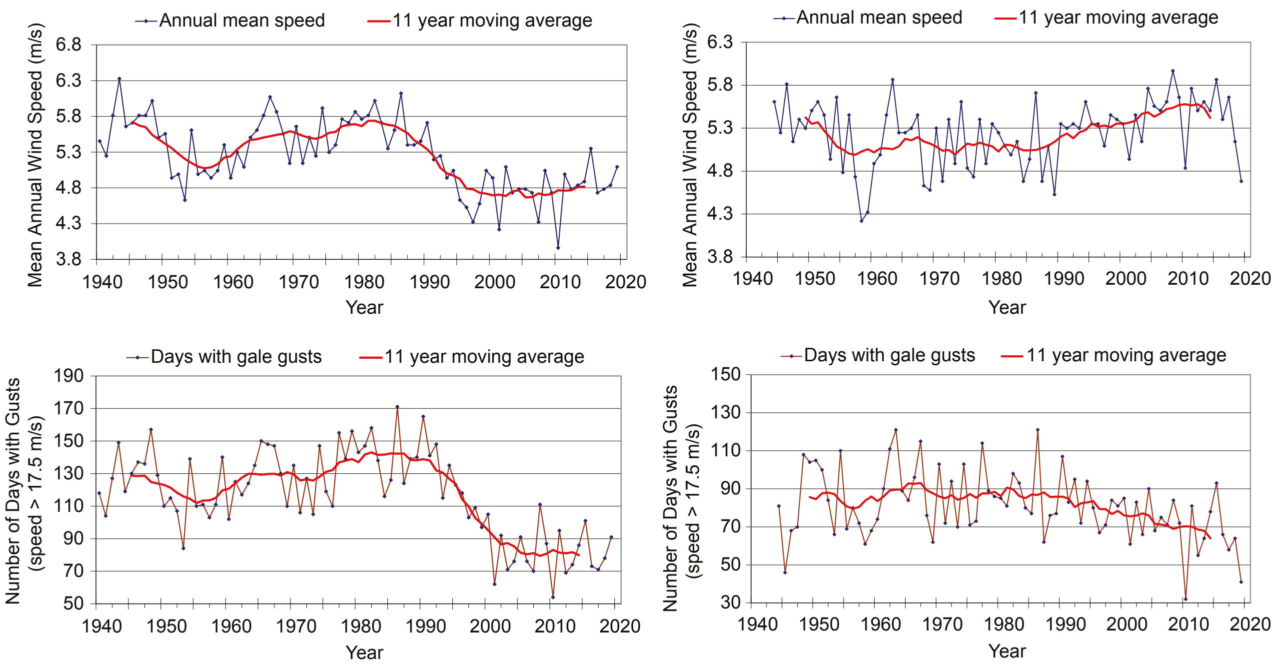


Figure 2.4. Annual mean wind speeds (top) and number of days per year with gale gusts (bottom) at Valentia Observatory (1940–2019) (left) and Dublin Airport (1944–2019) (right).

2.2.2 Time Series and Trends

Figure 2.4 shows the annual mean wind speeds (top) and the number of days per year with gale gusts (a wind speed of greater than 17.5 m/s or 34 knots) (bottom) for Valentia Observatory, Co. Kerry, and Dublin Airport. At Valentia a slightly decreasing trend in both parameters can be observed during the last two decades, while in Dublin the number of days with gale gusts also shows a decreasing trend. However, because of instrument changes in the 1990s and a lack of homogenisation of the full data record, long-term trends cannot be determined with confidence.

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) generates a set of wind (atmospheric motion) vectors every hour by tracing clouds or areas of water vapour through consecutive satellite images. Figure 2.5 shows an example of such a wind speed (colours) and direction (arrows) map from 1 February 2018, in which an area of high pressure with associated low wind speeds can be observed in the ocean to the south-west of Ireland.

No long-term trend in wind speed can be determined with confidence based on the limited analysis carried out to date.

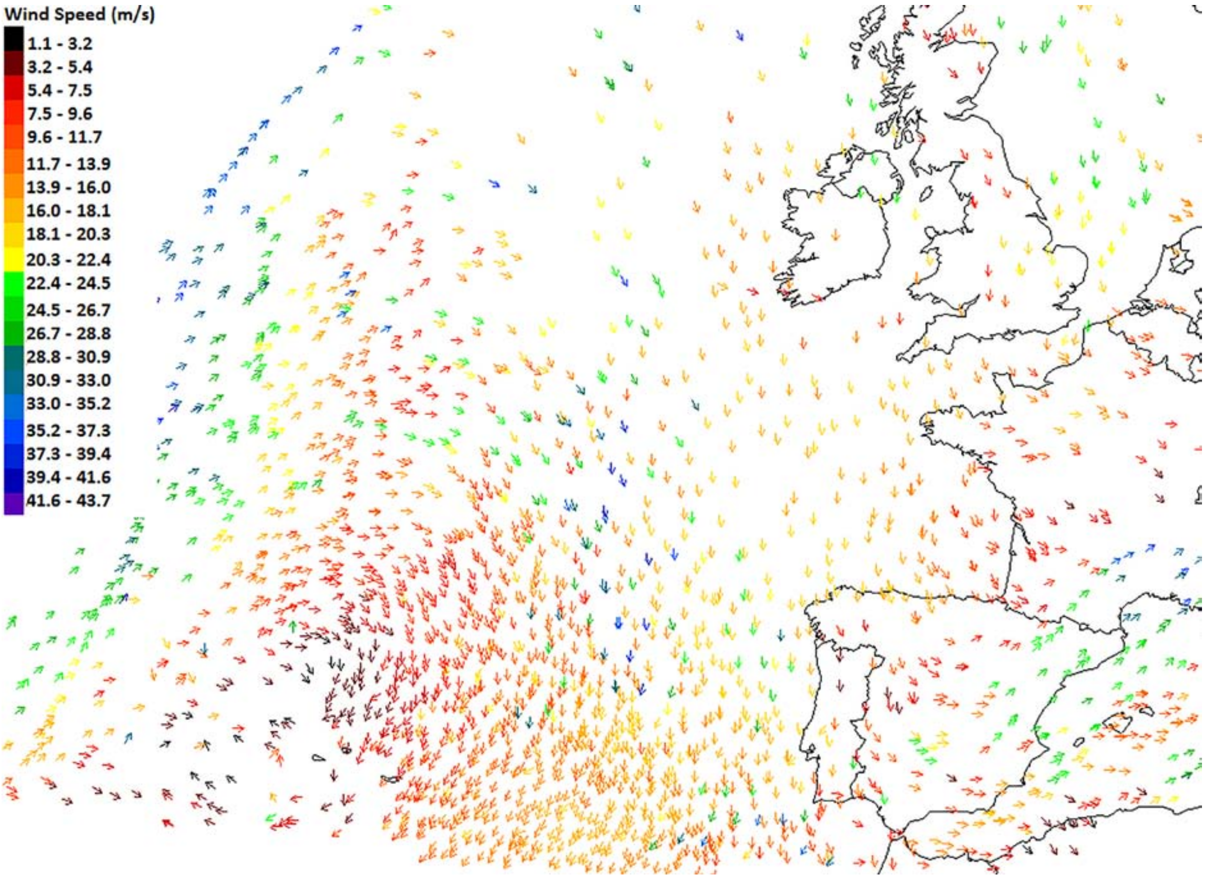


Figure 2.5. Example of a wind-speed and direction map derived from satellite-based observations. The lowest wind speeds can be seen towards the centre of an anticyclone located to the south-west of Ireland. Source: Generated by the authors from EUMETSAT datasets using BUFRdisplay v0.8.2 software.

2.2.3 Maintaining the Observations

The network of synoptic stations operated by Met Éireann needs to be maintained and further developed to ensure the future of long-term representative wind measurements. The Irish Marine Data Buoy Observation Network is the result of collaboration between the Marine Institute and Met Éireann. The Marine Institute maintains the equipment, while Met Éireann monitors the quality of the observational data.

Difficulties can arise with wind time series because of inhomogeneities due to changes in instrumentation, and changes in station exposure as a result of new building and tree growth in the vicinity of a station. Comprehensive analysis of wind data will be carried out by Met Éireann during 2021. Resources are required to produce homogeneous time series and to collate and digitise paper records, including station metadata.

Further Information

Surface Wind Speed and Direction Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/surface-wind)

Met Éireann historical data (https://www.met.ie/climate/available-data/historical-data)

Met Éireann information on wind measurement (https://www.met.ie/climate/what-we-measure/wind)

Met Éireann information on data availability (https://www.met.ie/climate/available-data)

Information from the Irish Marine Data Buoy Observation Network (http://www.marine.ie/Home/site-area/data-services/real-time-observations/irish-marine-data-buoy-observation-network)

About EUMETSAT, Europe’s weather satellite programme (https://www.eumetsat.int)

E-WINPROF, the European wind profiler programme (http://cfa.aquila.infn.it/wiki.eg-climet.org/index.php5/E-WINPROF)

2.3 Water Vapour

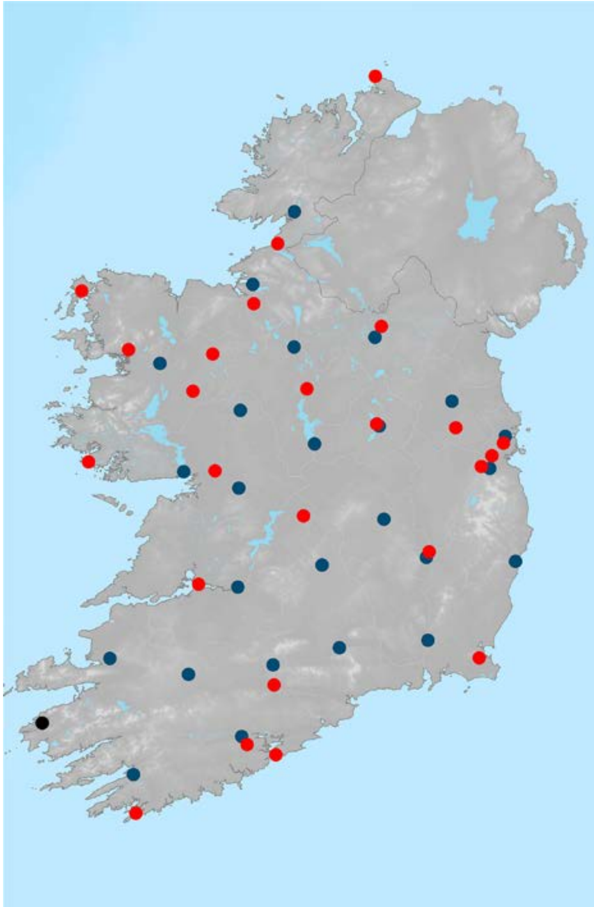
Walther C.A. Cámaro García, Ned Dwyer, Keith Lambkin and Paul Kane

Water vapour is a gaseous constituent of air at all levels in the atmosphere, accounting for almost 60% of the natural greenhouse effect. Being an atmospheric gas, it exerts a pressure that contributes to the total atmospheric pressure. Evaporation from the Earth's surface is the source of water in the atmosphere, which condenses to form clouds, changing radiative properties and releasing heat that affects atmospheric circulation systems. Globally, higher air temperatures and a warmer ocean have led to an increase in atmospheric water vapour, which may be linked to more intense precipitation events and enhanced warming. The humidity of the air near the surface affects human comfort and health, animals and the occurrence of plant diseases, among other things.

2.3.1 Measurements

Surface level water vapour and water vapour pressure are derived from humidity measurements taken at the 25 synoptic weather stations (red and black dots) operated by Met Éireann (Map 2.3). Since 1943 weather balloons, which are launched a number of times a day from Valentia Observatory, Co. Kerry (black dot), measure the humidity throughout the atmosphere.

Since 2009 Ireland has contributed to the Global Navigation Satellite System (GNSS) Water Vapour Programme (E-GVAP) of the European Meteorological Service Network (EUMETNET), retrieving column-



Map 2.3. Location of humidity and water vapour observation stations.

integrated water vapour quantities from the OSi GNSS active network (blue dots, Map 2.3) on an hourly basis.

A number of instruments on different satellites measure water vapour. These include the high-resolution infrared radiation sounder (HIRS), microwave humidity sounder (MHS) and advanced microwave sounding unit (AMSU-A) sensors that are part of the meteorological operational satellite (Metop) constellation operated by EUMETSAT.

Higher air temperatures and a warmer ocean have led to an increase in atmospheric water vapour, which may be linked to more intense precipitation events and enhanced warming.

2.3.2 Time Series and Trends

The water vapour molecules present in the air define the water vapour pressure. The capacity of the atmosphere to hold water vapour is directly related to the temperature. Figure 2.6a shows the annual average vapour pressure for 2019 across the country, derived from long-term synoptic weather station measurements,

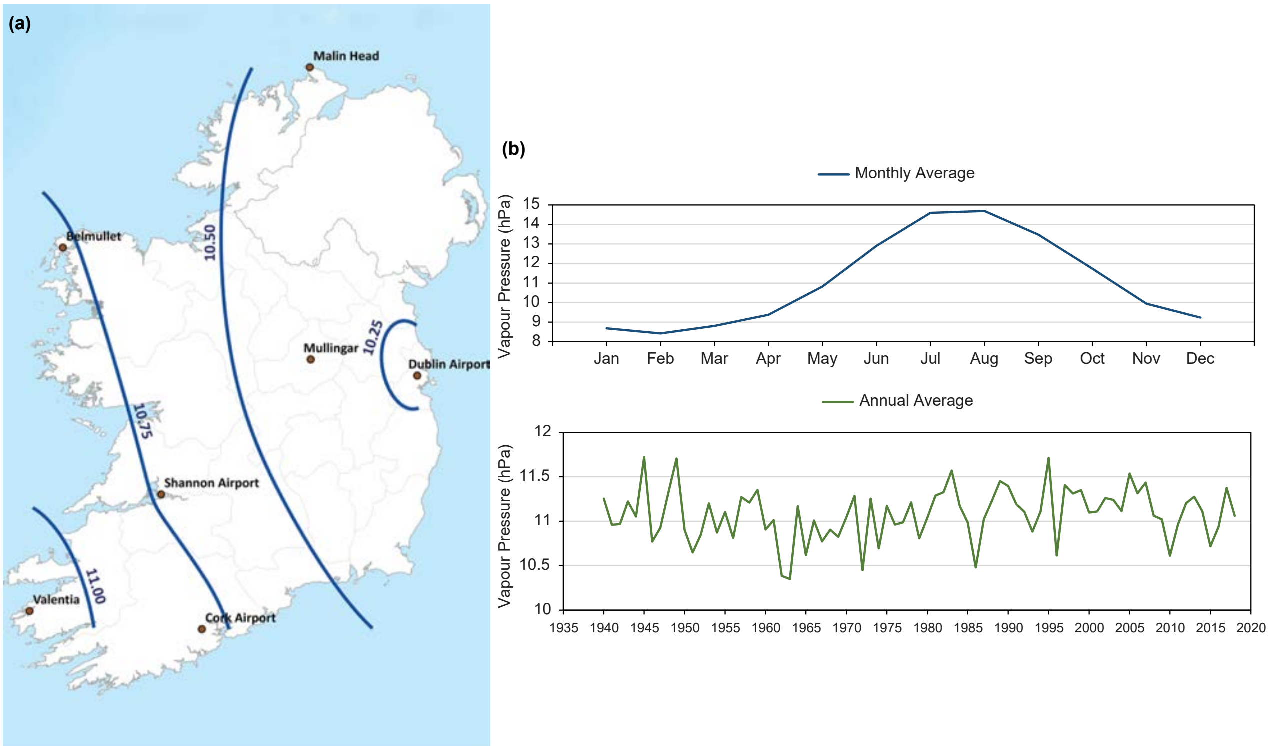


Figure 2.6. (a) Annual average water vapour pressure across Ireland for 2019 and (b) monthly (top) and annual (bottom) average water vapour pressure at Valentia Observatory (1940–2019).

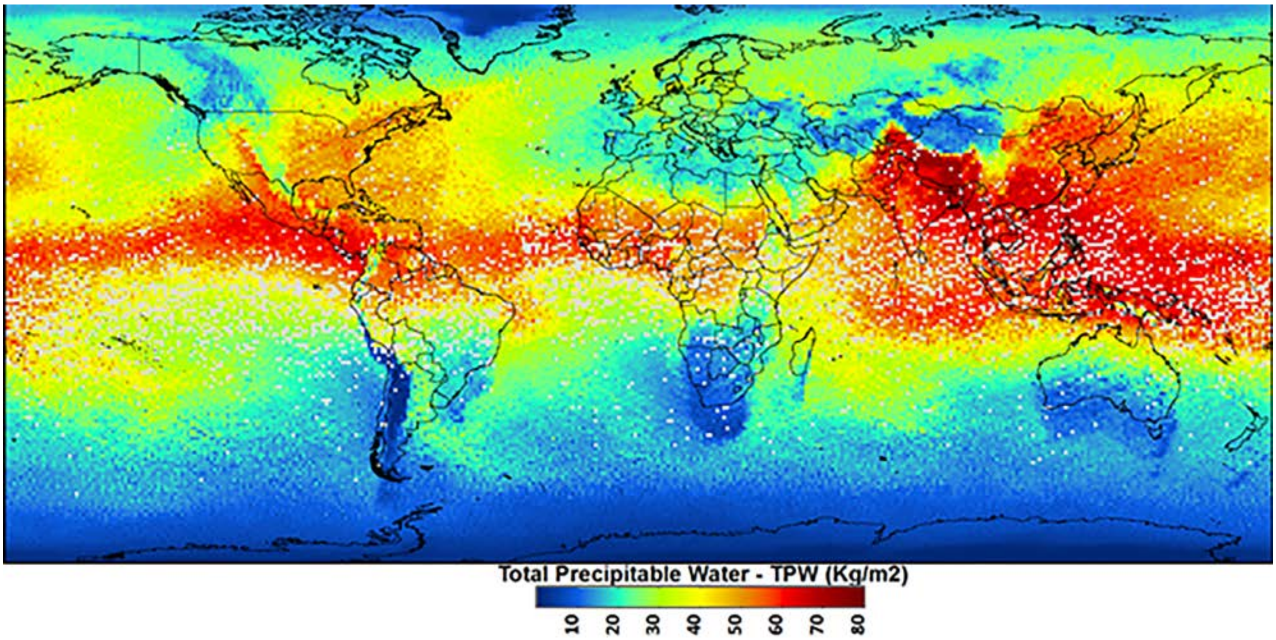


Figure 2.7. Example of monthly vertical integrated water vapour derived from data from multiple satellite observations obtained in July 2017. Source: Generated by the authors from EUMETSAT datasets.

presenting higher values in the southern areas of the country. In addition, Figure 2.6b shows the monthly average vapour pressure at Valentia Observatory, where the maximum value is reached during the summer period and the annual average vapour pressure can vary substantially from year to year. No significant trend is apparent in the annual average data; nonetheless, more comprehensive analysis of water vapour measurements needs to be carried out.

EUMETSAT generates a set of water vapour satellite-derived products. These are mainly based on combining data from different satellites including Metop, the US National Oceanic and Atmospheric Administration (NOAA) and Defense Meteorological Satellite Program (DMSP) platforms. Figure 2.7, which is an example of a monthly product from July 2017, represents the global spatial variation of the potential for rain should the water vapour condense into liquid.

No significant annual trend is apparent in water vapour measurements over Ireland, but more comprehensive analysis of the data is required.

2.3.3 Maintaining the Observations

Ground and radiosonde measurements are carried out on an operational basis by Met Éireann. GNSS receivers are operated and maintained by the OSi and contribute to the European E-GVAP project, currently in phase IV (2019–2023). The OSi datasets are collected by Met Éireann and processed through a GNSS processing system developed by the UK Meteorological Office (Met Office). However, E-GVAP estimates are not strictly of climate quality, as the main focus is near-real-time processing for assimilation into weather forecasting models, so the models used in the processing change from time to time, introducing jumps into long-term time series.

Further Information

Surface Water Vapour Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/surface-vapour/)

Upper-air Water Vapour Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/upper-vapour)

Met Éireann historical data (https://www.met.ie/climate/available-data/historical-data)

Met Éireann information on water vapour measurements (https://www.met.ie/climate/what-we-measure/water-vapour)

Valentia Observatory information (https://www.met.ie/about-us/our-history/valentia-observatory)

About EUMETSAT, Europe's weather satellite programme (https://www.eumetsat.int)

About EUMETNET, the European Meteorological Service Network (https://www.eumetnet.eu/about-us/)

E-GVAP observation programme information (https://www.eumetnet.eu/activities/observations-programme/current-activities/e-gvap/)

OSi active GNSS data (https://www.osi.ie/services/geodetic-services/active-gnss-data/)

2.4 Atmospheric Pressure

Walther C.A. Cámaro García, Ned Dwyer and Keith Lambkin

Atmospheric pressure is a key meteorological variable for monitoring the climate system, as the local and large-scale atmospheric circulation patterns are driven by differences in air pressure. Changes in large-scale pressure patterns can affect local and regional weather. An understanding of atmospheric pressure distributions is required for the long-term simulations of past weather and climate known as reanalyses. This understanding is also fundamental for weather forecasting.

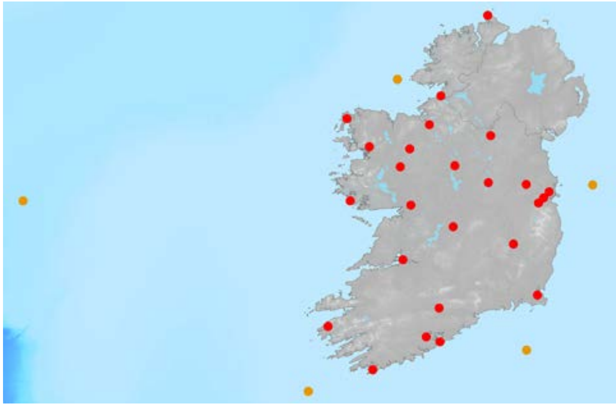
2.4.1 Measurements

Atmospheric pressure measurements are taken automatically at the 25 synoptic weather stations (red dots) operated by Met Éireann (Map 2.4). Pressure is also measured at the Irish Marine Data Buoy Observation Network stations (orange dots), the first of which was deployed in 2000. To allow for comparison between measurements at different locations and elevations, all pressure readings are converted to mean sea level (msl) pressure.

Annual minimum pressure values, which indicate the passage of mid-latitude cyclones over Ireland, show large variability.

2.4.2 Time Series and Trends

Pressure varies considerably according to the movement and development of large-scale circulation systems; there are also seasonal variations and smaller daily variations.



Map 2.4. Location of atmospheric pressure observation stations.

Figure 2.8 shows the average annual pressure series for the Valentia Observatory, Co. Kerry, where little variation is seen. However, maximum and minimum series show greater variability, particularly the minimum values. This behaviour is linked to mid-latitude cyclones or low-pressure systems that frequently pass over Ireland. The very low pressure observed in December 1989 was associated with an Atlantic depression that passed over Ireland, causing some damage due to high seas, high tides and heavy rain.

Resources are required to digitise older records and carry out comprehensive time series analysis, which would help in understanding if and how storm tracks are changing

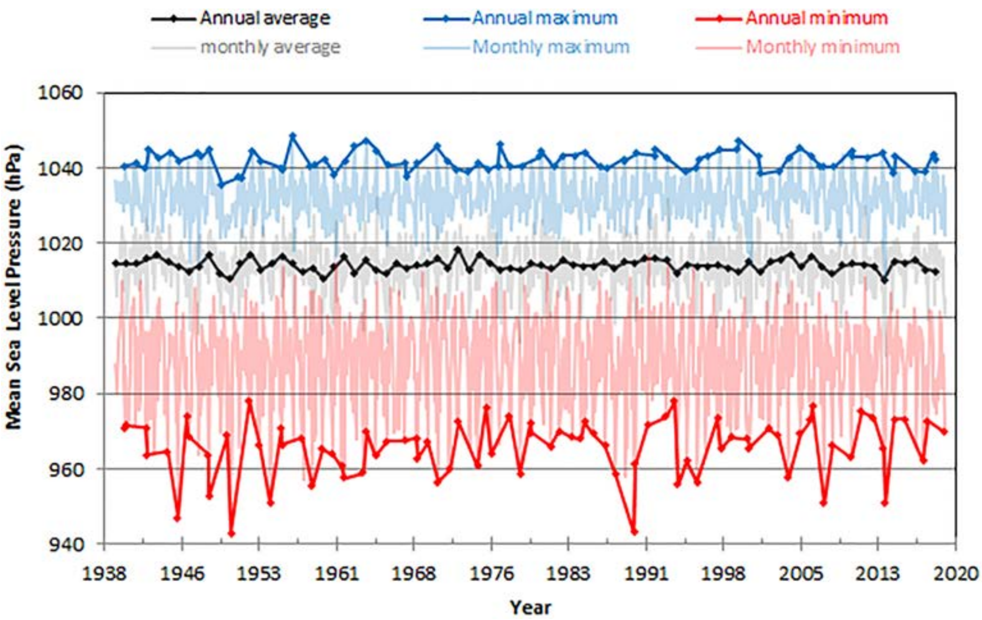


Figure 2.8. Monthly and annual minimum, average and maximum surface pressure at Valentia Observatory (1940–2019).

2.4.3 Maintaining the Observations

The network of synoptic stations operated by Met Éireann needs to be maintained and further developed to ensure the future of long-term representative pressure measurements. Barometers require continuous monitoring and regular maintenance and calibration. Resources are required to digitise older records and carry out comprehensive time series analysis, which would help in understanding whether and how storm tracks are changing.

The Irish Marine Data Buoy Observation Network is the result of collaboration between the Marine Institute and Met Éireann. The Marine Institute maintains the equipment, while Met Éireann monitors the quality of the observational data.

Further Information

Surface Pressure Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/pressure)

Met Éireann historical data (https://www.met.ie/climate/available-data/historical-data)

Met Éireann information on atmospheric pressure measurements (https://www.met.ie/climate/what-we-measure/atmospheric-pressure)

Information from the Irish Marine Data Buoy Observation Network (http://www.marine.ie/Home/site-area/data-services/real-time-observations/irish-marine-data-buoy-observation-network)

Information on Valentia Observatory (https://www.met.ie/about-us/our-history/valentia-observatory)

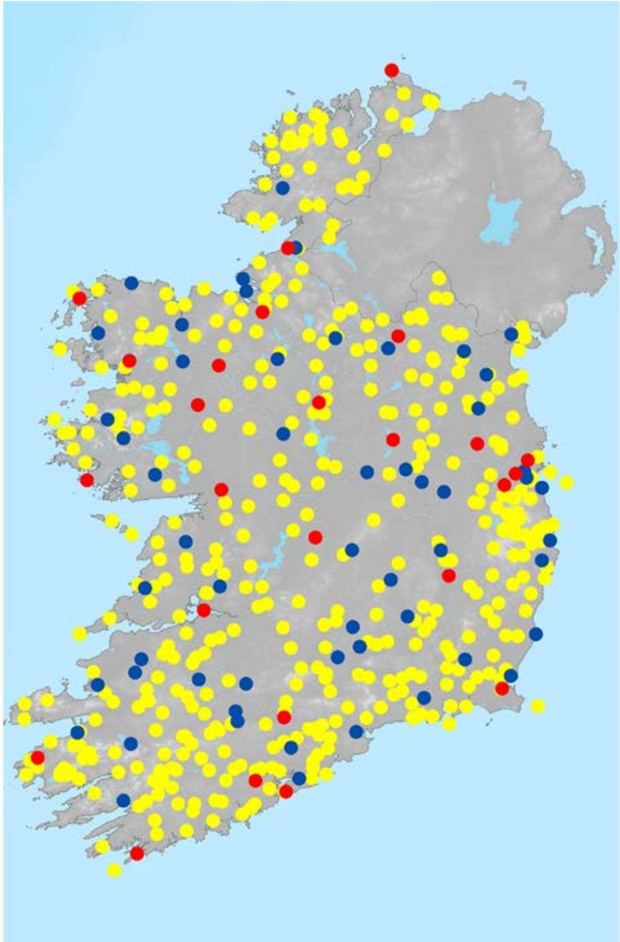
2.5 Precipitation

Walther C.A. Cámaro García, Ned Dwyer and Keith Lambkin

Rainfall (precipitation) plays a vital role in the water cycle and water balance and is essential for the maintenance of life. Hence, it is one of the most important climate variables directly affecting both humans and other life forms. An understanding of precipitation distribution and trends is essential for assessing the potential effects of climate change on the supply of water and for supporting both flood and drought mitigation initiatives. Analysis shows little change in mean precipitation over land globally since 1900, yet there has been a discernible intensification of heavy rainfall events over the second half of the 20th century. Because there can be a high variability in precipitation amounts over space and time, a dense network of national precipitation measurement stations is required.

2.5.1 Measurements

Being a key indicator, precipitation has been measured systematically in Ireland since the late 19th century, with a peak of over 800 rainfall stations in the late 1950s. Currently precipitation is measured at the 25 synoptic (red dots) and 57 climatological (blue dots) weather stations; in addition, there is a wide network of over 400 voluntary rainfall observers (yellow dots) (Map 2.5). At the synoptic stations, readings are made continuously and reported on the hour; at climate and rainfall stations a daily precipitation total is recorded each day at 09:00. There are some gauges in remote locations that are read once a month. All precipitation data since January 1941 are available in digital format.



Map 2.5. Location of precipitation observation stations.

Precipitation can be estimated through a combination of different satellite sensors. The EUMETSAT Multi-Sensor Precipitation Estimate programme combines passive microwave rain-rates from polar orbiting satellites (special sensor microwave imager/sounder, SSMIS) with infrared data from geo-stationary, meteorological satellites (meteosats). In addition, the international Global Precipitation Measurement (GPM) satellite mission, launched in 2014 under a co-operation programme between the US National Aeronautics and Space Administration (NASA) and the Japanese Aerospace Exploration Agency (JAXA) provides observations of rain and snow every 3 hours.

In Ireland the decade from 2006 to 2015 was the wettest in the period 1711–2016, and there is evidence that there is a trend towards an increase in winter rainfall and a decrease in summer rainfall.

2.5.2 Time Series and Trends

From the digitised precipitation data, daily gridded rainfall maps of Ireland have been produced starting in 1941. An analysis of annual rainfall totals shows large year-to-year variability. Figure 2.9 shows the annual average rainfall totals (blue bars, right-hand axis) and the annual anomalies, or differences, from the 1961–1990 average (left-hand axis). A moving average for periods of 11 years is also shown (red line). Since the 1980s an increasing trend can be observed in the 11-year moving average. Compared with an annual average rainfall of 1186 mm in the period 1961–1990 (yellow line), the last 30-year period (1990–2019) (light blue dashed line) shows a 79-mm or almost 7% increase in annual rainfall.

A report published in 2018 based on rainfall reports and records from across the island of Ireland for the period 1711–2016 highlighted significant decadal variability during the period. Nonetheless, it identified the decade from 2006 to 2015 as the wettest on record and provided some evidence that there is a tend towards an increase in winter rainfall and a decrease in summer rainfall.

2.5.3 Extreme Event Indicators

An expert group under the aegis of the WMO has developed a set of climate indices, which allows the analysis of extreme events in a uniform way. In the case of rainfall these include the duration in days of wet and dry spells. Information on these events can assist in water supply management and support flood and drought management initiatives.

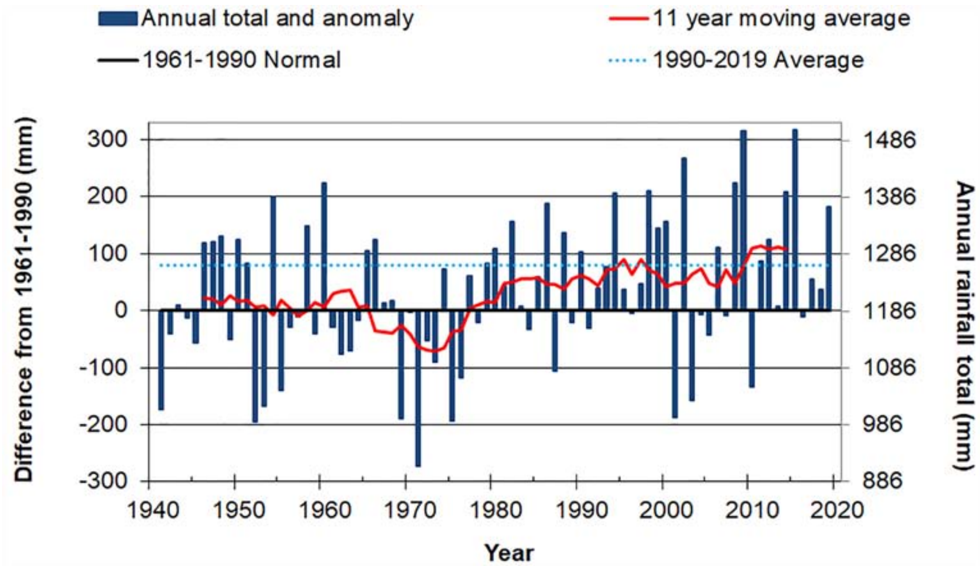


Figure 2.9. Average annual rainfall totals and anomalies for Ireland (1941–2019).

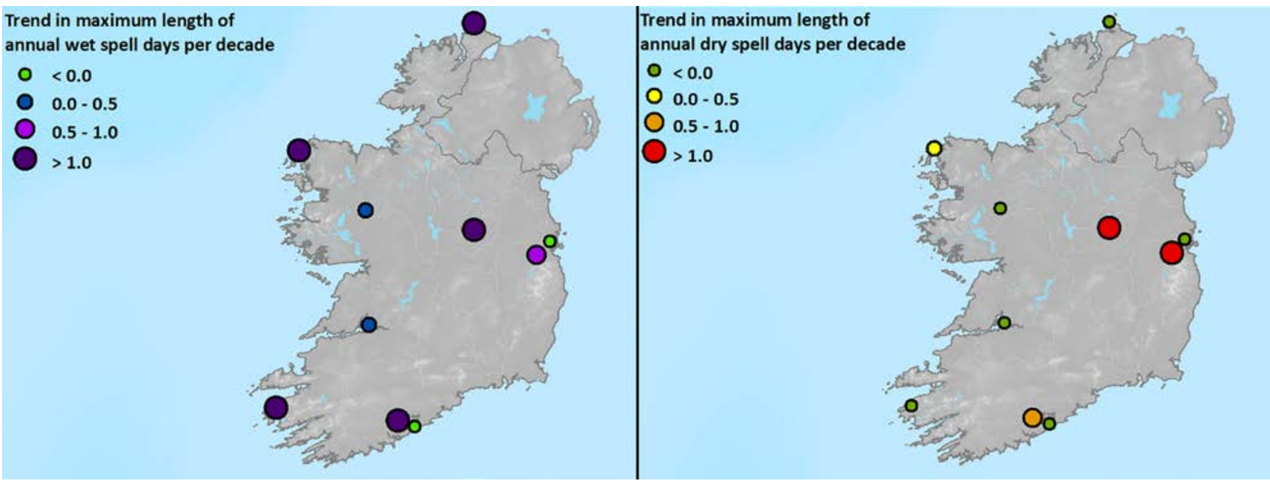


Figure 2.10. Trend in maximum length of annual wet spell days per decade (left) and maximum length of annual dry spell days per decade (right) (1961–2018). For example, there is on average 1 additional wet spell day in each decade at Valentia, Co. Kerry, over the six decades analysed.

Trend maps have been calculated for stations that have a near-complete daily record for the period 1961–2018. Figure 2.10 shows the trends in the maximum length of annual wet spell days (maximum number of consecutive days with precipitation of 1 mm or above) and the maximum length of annual dry spell days (maximum number of consecutive days with precipitation below 1 mm). The trends indicate an increase in the length of wet spell days across all of the country; however, no consistent trend is apparent in dry spell days.

The rainfall network needs to be maintained and expanded in areas of poor coverage.

2.5.4 Maintaining the Observations

The rainfall network needs to be maintained and expanded in areas of poor coverage. It is becoming increasingly difficult to recruit replacement or additional “voluntary” observers. To address this, and to meet the demand for more real-time rainfall observations, 80 climatological weather stations are currently being automated. As with temperature, resources are required to produce homogenised datasets and to collate and digitise paper records, including station metadata.

2

Further Information

Murphy, C. *et al.*, 2018. A 305-year continuous monthly rainfall series for the island of Ireland (1711–2016). *Climate of the Past* 14: 413–440. https://doi.org/10.5194/cp-14-413-2018

Precipitation Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/precipitation)

Expert Team on Climate Change Detection and Indices/Climate Research Division: ETCCDI/CRD Climate Change Indices. Definition of the 27 core indices (http://etccdi.pacificclimate.org/list_27_indices.shtml)

Met Éireann information on rainfall (https://www.met.ie/climate/what-we-measure/rainfall)

Met Éireann information on data availability (https://www.met.ie/climate/available-data)

About EUMETSAT, Europe’s weather satellite programme (https://www.eumetsat.int)

About EUMETNET, the European Meteorological Service Network (https://www.eumetnet.eu/about-us/)

About the Global Precipitation Measurement satellite mission (https://www.nasa.gov/mission_pages/GPM/main/index.html)

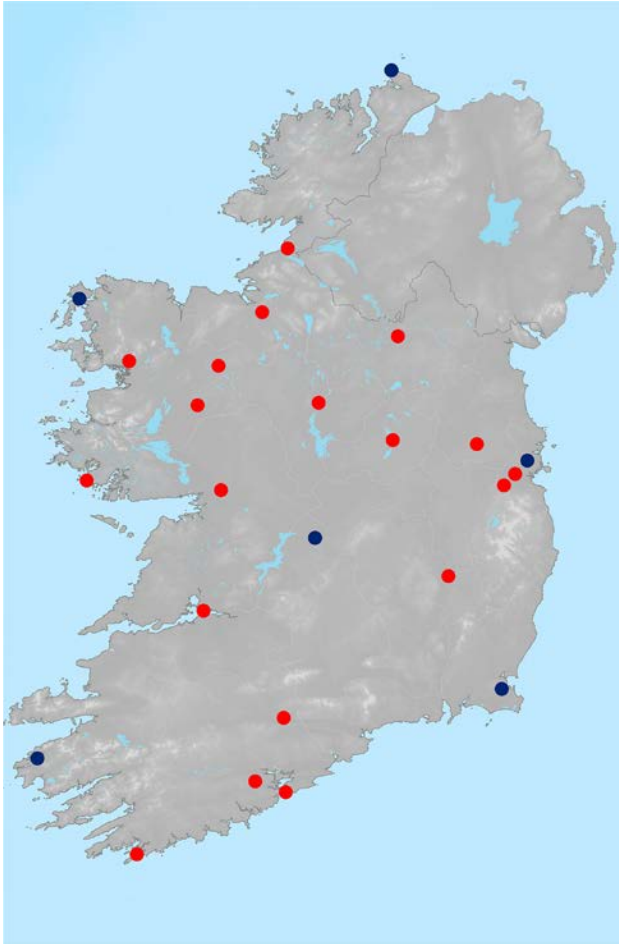
2.6 Surface and Earth Radiation Budget

Walther C.A. Cámaro García, Ned Dwyer and Keith Lambkin

The sun is the most vital source of energy and warmth for the Earth, making life possible. Its energy is essential for cloud generation processes and is linked to the ocean currents and atmospheric circulation, including thunderstorm formation. Energy reaches the Earth's surface from the sun directly and diffusely, from scattering caused by clouds, aerosols and various gases in the atmosphere. Some of this incident energy is reflected and emitted back to space. The balance at the top of the atmosphere between the incoming energy from the sun and the outgoing reflected energy and thermal energy from the Earth is known as the Earth radiation budget. This radiation balance at the top of the atmosphere is the basic radiative forcing of the climate system. The radiation balance at ground level is known as the surface radiation budget and is essential for climate dynamics, such as hydrological cycles and crop productivity, and needs to be monitored systematically.

2.6.1 Measurements

Solar radiation has been measured by Met Éireann since 1954, when the first sensor was placed at Valentia Observatory. Historically, sunshine duration was the observed solar variable and continuous records date back to 1893, but more recently there has been a greater demand for solar radiation (incoming radiation), also known as global radiation, which represents a more comprehensive measurement of solar energy. Solar observations are measured at the 25 synoptic weather stations (red and blue dots) by Met Éireann (Map 2.6). A



Map 2.6. Location of solar radiation observation stations.

more complete suite of solar measurements is measured by Met Éireann's Automatic Solar Radiation Monitoring Network (AUTOSOL) infrastructure at a subset of sites (blue dots). Long-term Irish solar measurements are routinely submitted to the World Radiation Data Centre.

Measurements linked to the Earth radiation budget at the top of the atmosphere can only be made from space. NASA and European Space Agency (ESA) sensors are widely used for the measurement of all the radiation fluxes linked to the Earth radiation budget.

> A decrease in the annual solar radiation is observed over the period 1964–1984, followed by an increasing trend until the late 2000s. Over the last decade a slight decrease is observed.

2.6.2 Time Series and Trends

Figure 2.11 shows the annual global solar radiation measured at Valentia Observatory between 1964 and 2019. A decreasing trend in the annual solar radiation is observed over the period 1964–1984, followed by an increasing trend until the late 2000s. Over the last decade a slight decrease is observed. This may, in part, be due to increases in atmospheric pollutants, such as black particles, sulfate particles and/or sulfate cloud-forming nuclei, the presence of which causes the sun's energy to be reflected back into space before reaching the Earth's surface.

Figure 2.12 shows the monthly mean reflected solar radiative flux at the top of the atmosphere in February 2017, derived from meteosat second-generation (MSG) and moderate-resolution imaging spectroradiometer (MODIS) satellite data. This is one of the components of the Earth radiation budget. Higher values are observed in the southern hemisphere, in line with the summer season in that hemisphere during that period of the year.

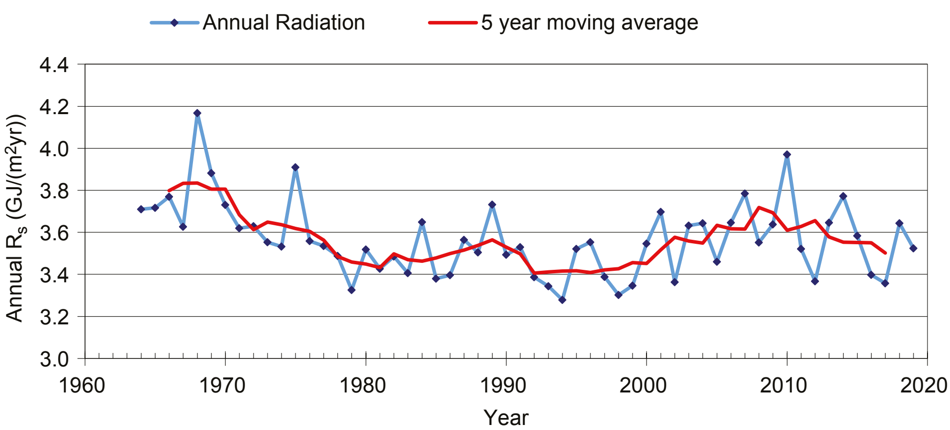


Figure 2.11. Annual solar radiation at Valentia Observatory (1964–2019).

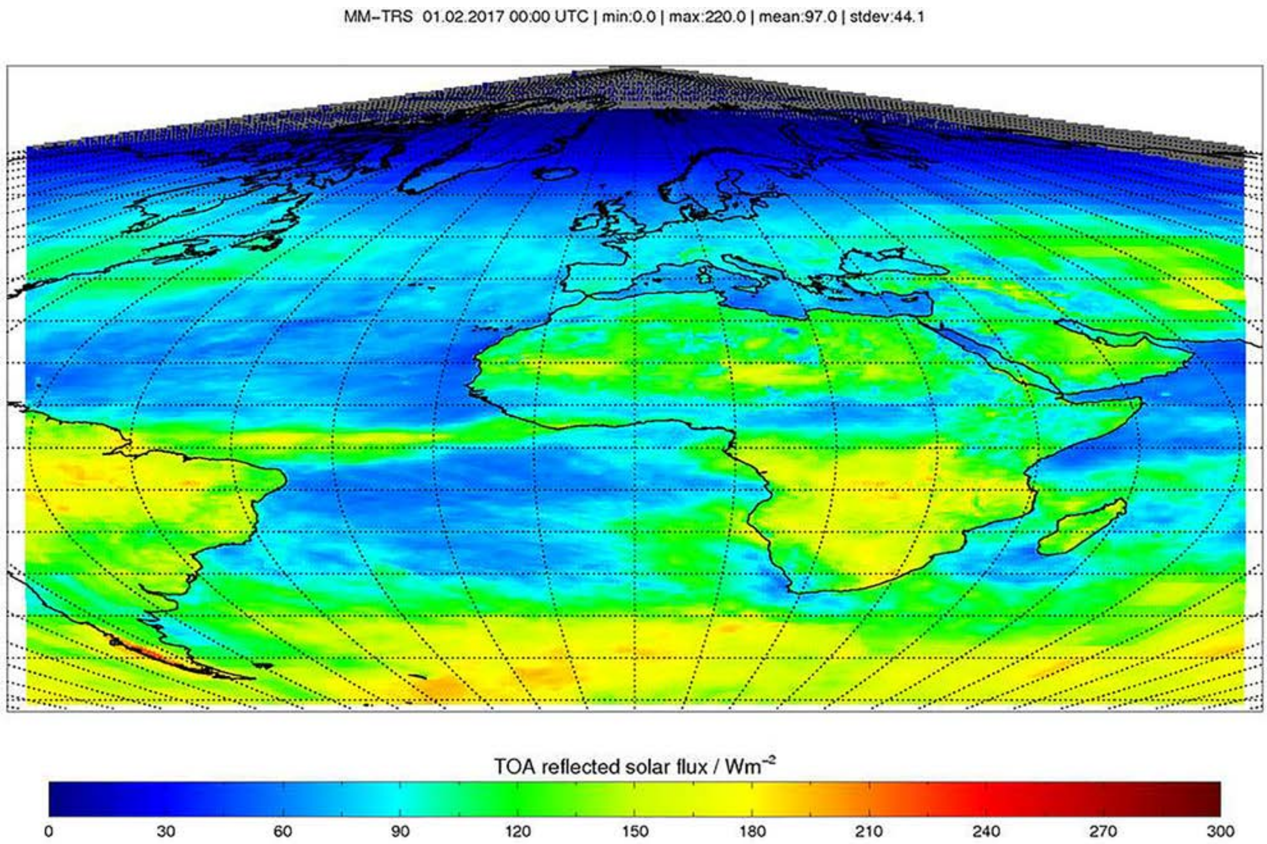


Figure 2.12. Monthly mean reflected solar radiative flux at the top of atmosphere in February 2017, from MSG and Terra/Aqua MODIS satellite data. Source: EUMETSAT Climate Monitoring Satellite Application Facility. © EUMETSAT 2017.

Regular analysis of national trends and further measurements of the net surface radiation balance needs to be carried out, given its role in plant growth, the hydrological cycle and the larger climate system.

2.6.3 Maintaining the Observations

A comprehensive suite of solar radiation measurement instrumentation is maintained by Met Éireann at Valentia Observatory. Global solar radiation measurements are made at the synoptic weather stations. Met Éireann's AUTOSOL infrastructure has allowed the automation of manual solar measurements, such as sunshine duration and diffuse radiation, at selected sites. This has preserved and maintained Ireland's decadal solar climate record. Regular analysis of national trends, including data homogenisation, as well as further measurements of the net surface radiation balance need to be carried out, given its role in plant growth, the hydrological cycle and the larger climate system. Met Éireann initiated a project in late 2020, "The Climatology of Irish Solar Radiation".

Further Information

Surface Radiation Budget Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/surface-radiation)

Earth Radiation Budget Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/earth-radiation)

Met Éireann information on sunshine and solar radiation (https://www.met.ie/climate/what-we-measure/sunshine)

Met Éireann information on data availability (https://www.met.ie/climate/available-data)

World Radiation Data Centre (http://wrdc.mgo.rssi.ru/)

About EUMETSAT, Europe's weather satellite programme (https://www.eumetsat.int)

2.7 Upper Air Temperature and Wind

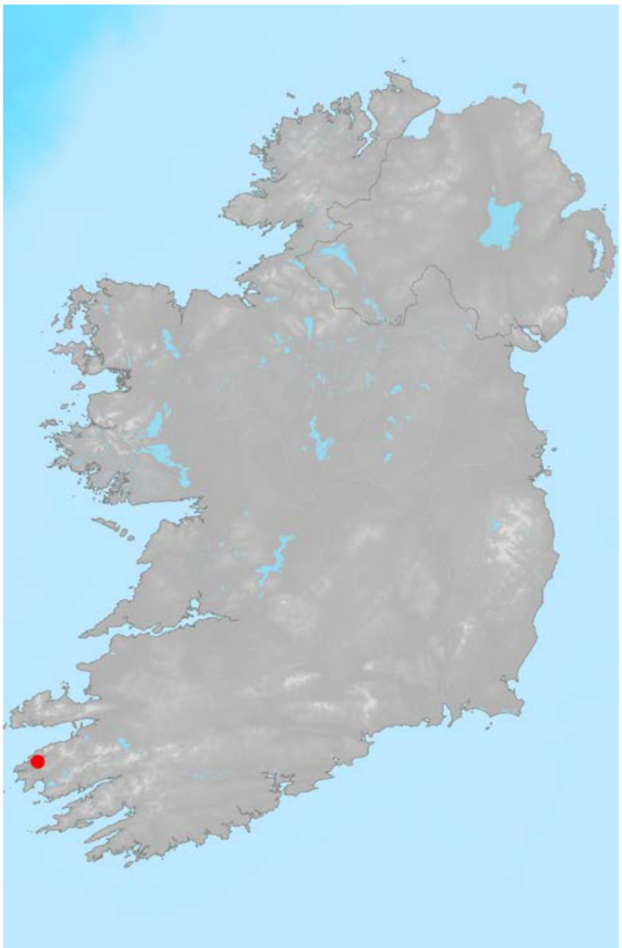
Walther C.A. Cámaro García, Ned Dwyer and Michael Gill

Knowledge of the vertical profiles of temperature and wind in the atmosphere is vital for a better understanding of the weather and climate system. Upper air temperature plays a key role in the energy budget, being linked to the energy transmitted from the atmosphere to space. Upper air wind is a key element of the climate system through its transport of heat, moisture and trace constituents. Globally, cooling of the upper atmosphere (stratosphere) and warming of the lower atmosphere (troposphere) has been observed since the mid-20th century, consistent with the impact of increased GHG concentrations estimated through climate model simulations. Globally, measurements of upper air parameters are sparse. Because of its key location in the North-east Atlantic, Ireland makes a significant contribution to such measurements.

2.7.1 Measurements

Upper air measurements have been taken by Met Éireann at Valentia Observatory, Co. Kerry (Map 2.7), since 1917 as a manual process and since 1943 by means of a radiosonde – a helium-filled balloon with instruments attached. The balloon is released into the atmosphere: as it ascends, readings are transmitted back to the surface station. As the balloon rises, it expands until it eventually bursts. The instruments measure pressure, wind speed and direction, humidity and temperatures twice a day. The measurements are taken every 2 seconds as the balloon travels up through the atmosphere. This enables the production of a tephigram, which is a "snapshot" of the vertical structure of the atmosphere.

Since the late 1970s, globally upper air temperature measurements have been based on satellite-borne microwave sounders. Changes in sensor technology



Map 2.7. Location of the upper air observation station.

have made it difficult to integrate and compare the temperature measurements over time. Consequently, climate quality datasets can be extracted only following a careful intercalibration process between the data extracted from different sensors.

Wind speed and direction can be derived by tracking cloud motion from successive satellite observations. In 2018, ESA launched Aeolus, the first satellite mission to acquire profiles of Earth's wind on a global scale using laser technology.

There was a slight decrease in upper air temperature in the period 1980–2015, in line with patterns observed globally.

2.7.2 Time Series and Trends

Figure 2.13 shows an example of annual mean temperature and wind speed measurements at Valentia Observatory from one level in the atmosphere. Observations at this height (300-hPa level) indicate a slight decrease in temperature in the period 1980–2015, in line with patterns observed globally. In 2015, the sensor type used to measure upper air parameters was replaced. Consequently, the information collected after that is not directly comparable to the preceding observations.

Annual variability is observed, but there is no apparent trend in the upper air wind speed; however, as with the upper air temperature after the new sensor was installed in 2015, the information is not directly comparable with the preceding records. An intercalibration analysis and a quality check need to be carried out for the data extracted with previous and current sensors.

An intercalibration analysis and a quality check has to be carried out for the upper air datasets, measured at Valentia Observatory, between the data extracted before and after 2015.

2.7.3 Maintaining the Observations

Valentia Observatory is a flagship weather station providing the only upper air measurements made in Ireland. An intercalibration analysis and a quality check need to be carried out for the data collected with sensors before 2015 and with those installed currently.

The Aeolus satellite mission was launched in August 2018, and ESA is working to meet requirements for weather forecasting and climate modelling based on wind profile data. This satellite will significantly increase the number and density of observations, in particular over ocean areas. However these satellite products will always require *in situ* weather balloon measurements for development and quality assurance.

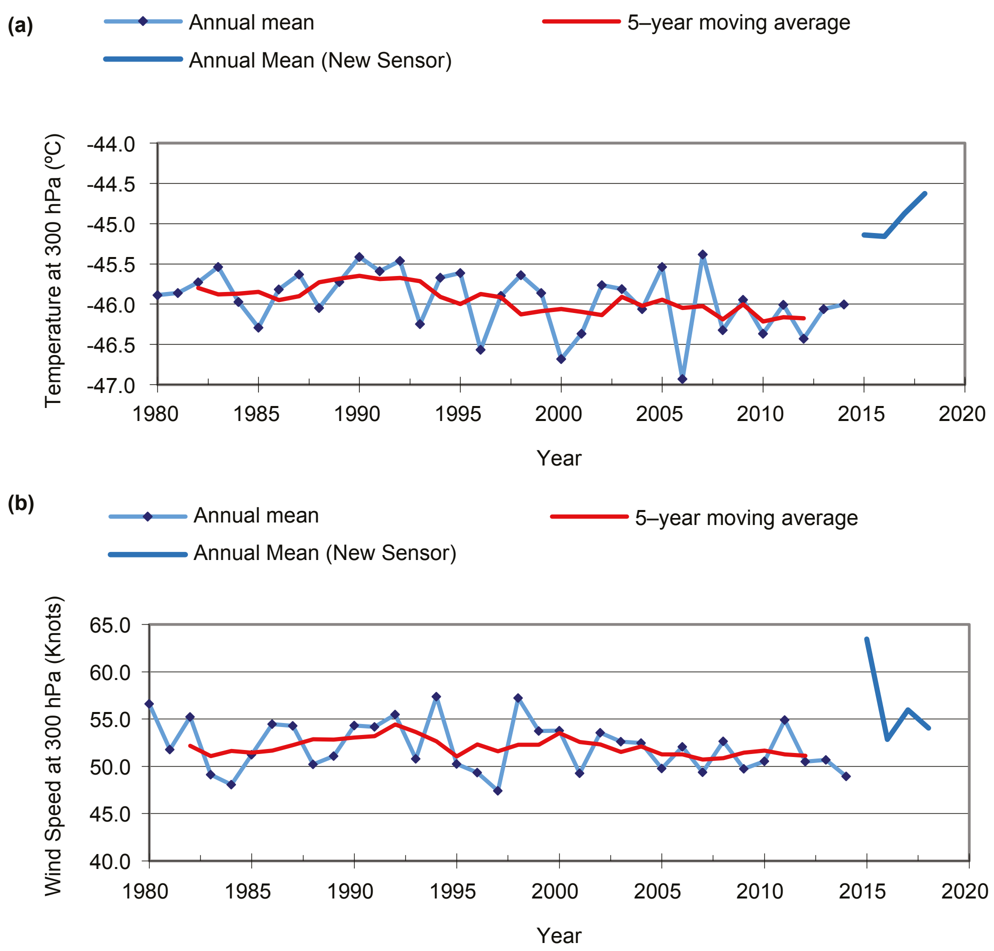


Figure 2.13. Example of (a) annual mean temperature and (b) annual mean wind speed at Valentia Observatory from one level in the atmosphere (1980–2018).

Further Information

Upper-air Temperature Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/upper-temperature)

Upper-air Wind Speed and Direction Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/upper-wind)

Met Éireann information on upper air wind and temperature measurements at Valentia Observatory (https://www.met.ie/climate/what-we-measure/upper-air)

Met Éireann information on data availability (https://www.met.ie/climate/available-data)

About ESA's Aeolus satellite mission (https://www.esa.int/Applications/Observing_the_Earth/Aeolus/Introducing_Aeolus)

2.8 Cloud Properties

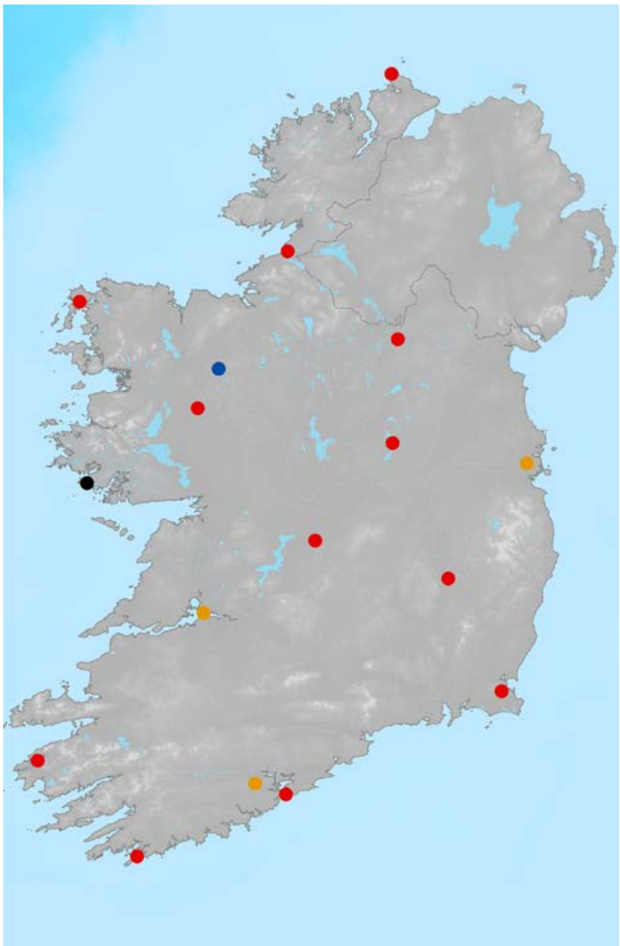
Walther C.A. Cámaro García, Ned Dwyer and Jurgita Ovadnevaite

Clouds play an essential role in the Earth's energy budget, maintaining the radiation balance, and are a key component of the Earth's hydrological cycle. They form when water vapour condenses as water droplets or ice crystals in the atmosphere. Aerosols in the atmosphere act as condensation nuclei around which clouds form. Clouds both cool and warm the Earth's atmosphere, absorbing heat emitted from the surface and radiating it to space. Clouds also generate precipitation from water vapour, releasing heat to the atmosphere in the process. How clouds respond to changes in the climate is complex and it is difficult to determine their net effect on energy balance and on the water cycle.

2.8.1 Measurements

A range of cloud properties is observed at the Mace Head Atmospheric Research Station, Carna, Co. Galway (black dot, Map 2.8). These include vertical extent (cloud base and cloud top), cloud particle phase (liquid, ice), degree of adiabaticity, liquid water path and liquid water content, and microphysical properties such as effective radius and cloud droplet number concentration and size distribution. Met Éireann takes hourly manual observations of cloud cover, cloud type and cloud height at staffed synoptic weather stations (orange and blue dots, Map 2.8). Observations of cloud height and estimated total cloud cover are made at a number of automated synoptic stations (blue, red and black dots, Map 2.8).

A range of satellite sensors are used to collect information related to cloud properties. The ESA



Map 2.8. Location of cloud property observation stations.

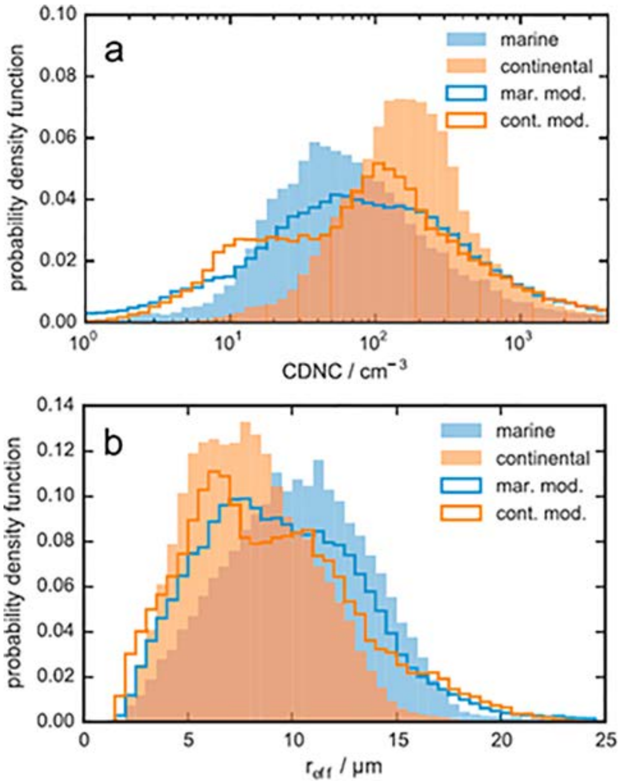


Figure 2.14. Probability distributions of cloud droplet number concentrations (a) and droplet radius (r_{eff}) (b) by air mass transport. Cloud properties in marine (clean) and continental (polluted) air masses are presented with colour bars, while clouds in modified air masses are plotted as lines [modified air masses are a mixture of both marine and continental air masses, where marine modified (mar. mod) represents marine air mass with some continental influence and continental modified (cont. mod.) represents continental air mass with some marine influence]. Data cover the period 2009–2015 at Mace Head.

Climate Change Initiative (CCI) Cloud project provides long-term, coherent cloud property datasets based on past, and existing European and US satellite missions.

Larger numbers of smaller cloud droplets are observed in the presence of greater levels of pollution, which translates into clouds that are brighter, thus reflecting more sunlight than clean clouds.

2.8.2 Time Series and Trends

Figure 2.14 shows an example of the microphysical cloud properties observed at Mace Head.

Six years of ground-based remote sensing measurements of clouds were taken in clean air coming from the Atlantic Ocean and polluted air coming from Europe. These reveal differences in the cloud microphysics, thereby highlighting the effects of different aerosol types and concentrations on clouds. Larger numbers (cloud droplet number concentration, CDNC) of smaller cloud droplets (r_{eff}) are observed in the presence of greater levels of pollution, which translates into clouds that are brighter, thus reflecting more sunlight than clean clouds.

Figure 2.15 shows an example of monthly average cloud thickness centred on Europe for April 2018. This parameter is an indicator of the level of opacity observed in the clouds and is linked to the intensity of precipitation generated by a cloud. Cloud thickness over Ireland and the UK was quite high during this period compared with much of mainland Europe. This behaviour is in line with some rainfall stations in the south of Ireland reporting significant amounts of precipitation during that month.

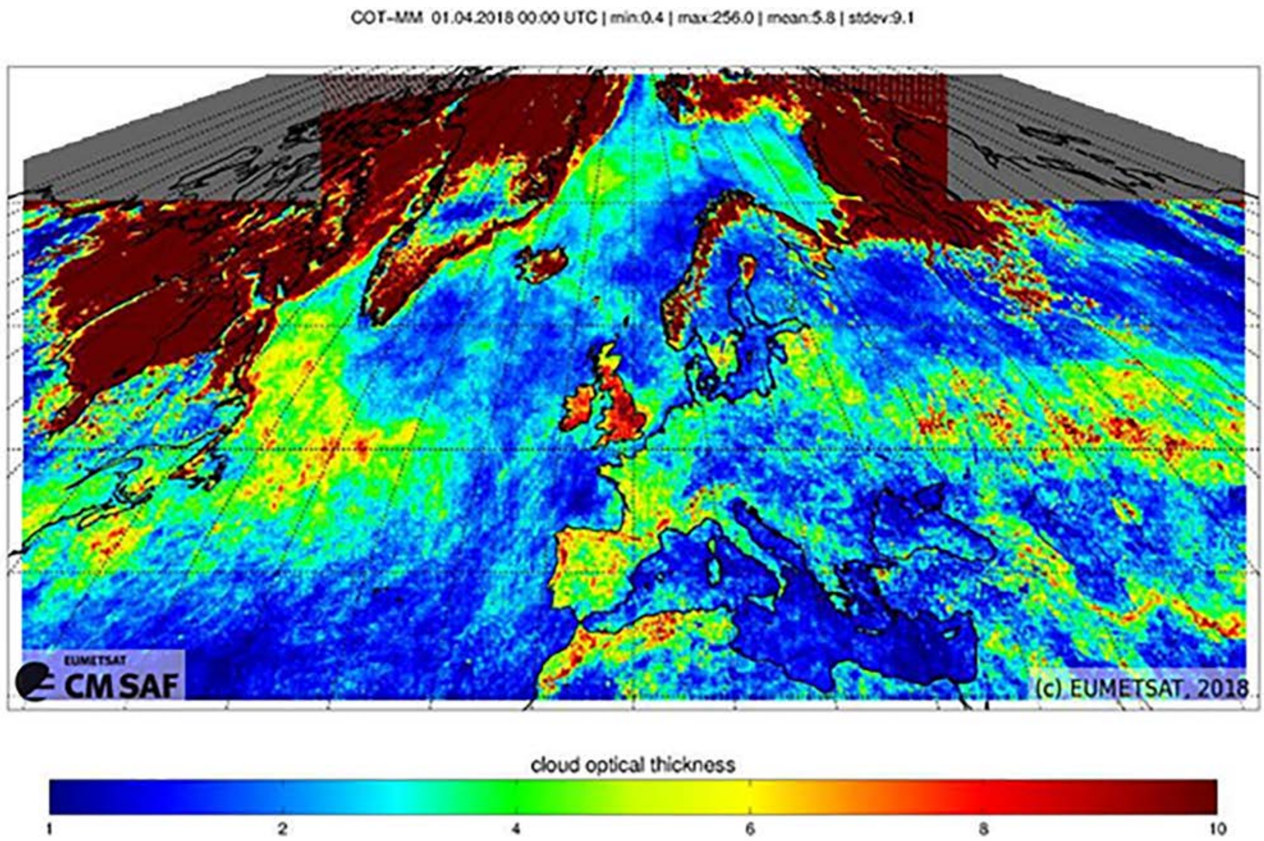


Figure 2.15. Example of cloud optical thickness derived from polar orbiting satellites, April 2018. Source: EUMETSAT Climate Monitoring Satellite Application Facility. © EUMETSAT 2018.

> The aerosol profiling and microphysical cloud property (ground-based remote sensing) measurements at Mace Head ceased in 2020, as ongoing operational funding could not be secured.

2.8.3 Maintaining the Observations

The network of synoptic stations operated by Met Éireann needs to be maintained and developed further to ensure the future of long-term cloud observations. Further resources are required to carry out analysis of cloud data.

For more than 10 years, the NUI Galway had operated a suite of aerosol cloud profiling measurements, along with *in situ* measurements at the Mace Head Atmospheric Research Station. However, the aerosol profiling and microphysical cloud property (ground-based remote sensing) measurements ceased in 2020, as ongoing operational funding could not be secured.

Further Information

Clouds Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/clouds)

Information on NUI Galway's Atmospheric and Environmental Physics Cluster and Mace Head facility (http://www.macehead.org/)

Met Éireann information on data availability (https://www.met.ie/climate/available-data/)

About ESA's Cloud Climate Change Initiative project (http://www.esa-cloud-cci.org/?q=about)

About EUMETSAT, Europe's weather satellite programme (https://www.eumetsat.int)

Preiβler, J. *et al*., 2016. Six years of surface remote sensing of stratiform warm clouds in marine and continental air over Mace Head, Ireland. *Journal of Geophysical Research Atmospheres* 121: 14538–14557. https://doi.org/10.1002/2016JD025360

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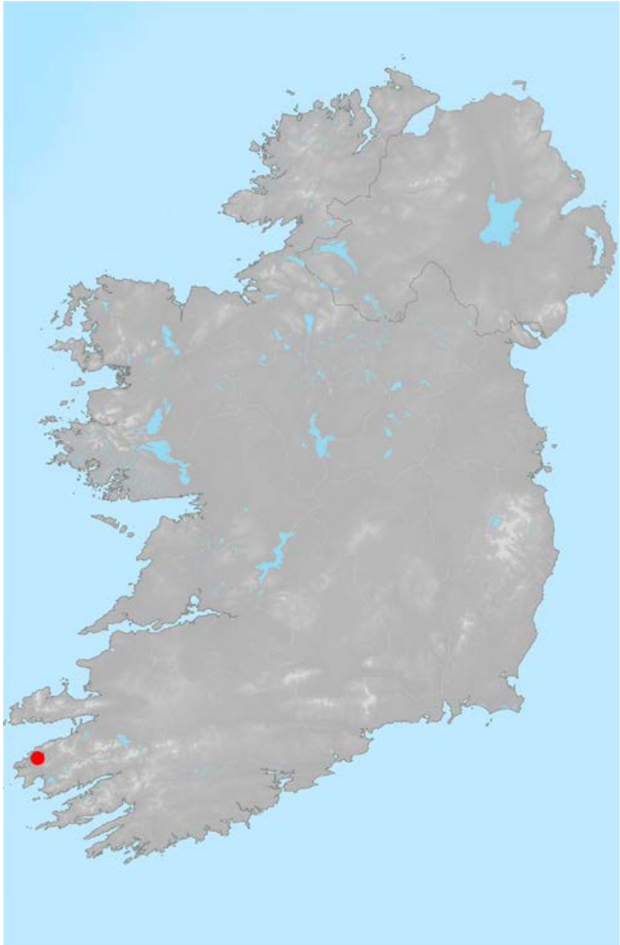
2.9 Lightning

Walther C.A. Cámaro García, Ned Dwyer and Keith Lambkin

Lightning is a powerful discharge of energy that occurs during an electrical storm and is often only noticed because of the associated thunder. This phenomenon may cause loss of life and destruction, such as vegetation fires and damage to buildings, electrical and other infrastructure. However, the impacts due to the storms that generate lightning are normally bigger than those caused by the lightning itself. The direct link between storms and lightning makes this parameter a key indicator in understanding the behaviour of or variation in storms. Variations in lightning frequency may be a consequence of climate change and an increase in the number of lightning events affects the climate directly by producing nitrogen oxides (NO_x), which can react to form nitrous oxide (N_2O), a potent GHG.

2.9.1 Measurements

Lightning measurements have been taken by Met Éireann at Valentia Observatory, Co. Kerry (Map 2.9), since 2007 as part of the Arrival Time Difference Network (ATDNet) lightning detection system, an international network administrated by the UK Met Office. This network is composed of a global set of sensors, with the majority located in western Europe. Each sensor detects a pulse of electromagnetic energy generated by a lightning strike, which can travel distances up to 10,000 km. The location of a lightning strike can be



Map 2.9. Location of the lightning observation station.

determined, based on the combination of differences in time taken for the pulse to reach each sensor.

Lightning can also be inferred from satellite observations from instruments such as the lightning imaging sensor (LIS) on board the International Space Station (ISS) or the Global Lightning Mapper (GLM) on board the Geostationary Operational Environmental Satellite 16 (GOES-16).

Lightning shows very large annual variability, with the majority of strikes occurring during the summer months.

2.9.2 Time Series and Trends

Figure 2.16 shows the 10 day-accumulated lightning pulses over the Irish Shelf (see map on the right) and over the land area, derived from the ATDNet lightning system for the period 2001–2019. Most of the lightning strikes are at sea, with only 15% occurring over land. During winter, lightning occurrence is at a minimum because of the reduced amount of energy available due to the lack of solar heating and available atmospheric water vapour. The majority of lightning pulses are observed in summer and are related to electrical storms, with power outages being the most common impact in Ireland. There is a very large annual variability in lightning activity. The most pulses observed during a 10-day period over the land area was almost 300,000 in 2003; the largest number observed over the combined sea and land area was more than 1.25 million pulses in 2014.

By following the location of lightning pulses detected by the ATDNet lightning system, the trajectory of a thunderstorm that affected the southern and eastern part of Ireland, on the night between 26 and 27 May 2018, may be followed (Figure 2.17). The storm originated over the sea in the late evening and around midnight moved over the south coast, spreading towards the east, with maximum lightning activity occurring between 04:00 and 05:00.

Valentia Observatory is a flagship weather station making the only lightning observations in Ireland.

2.9.3 Maintaining the Observations

Valentia Observatory is a flagship weather station making the only lightning observations in Ireland. These measurements will continue to support the ATDNet lightning system. Additional international stations are essential to improve the accuracy of the network.

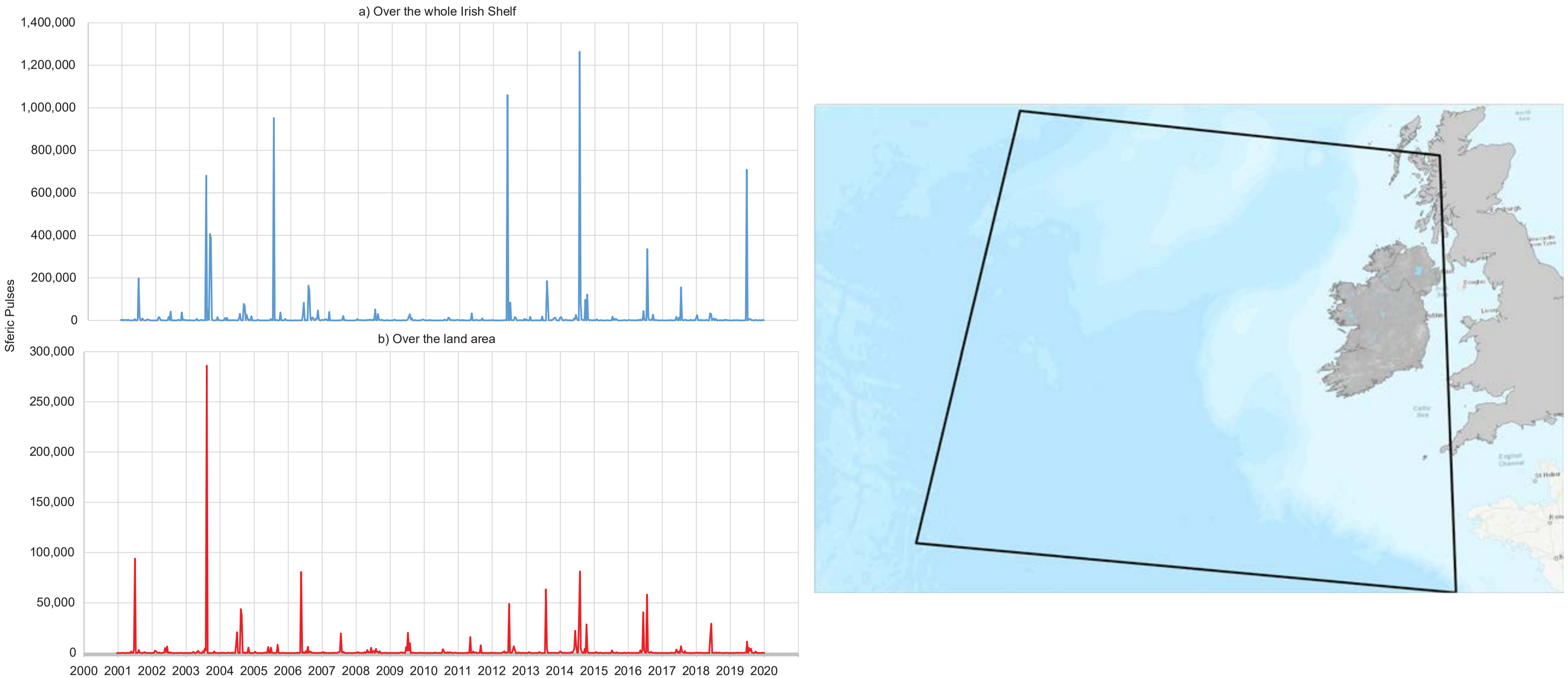


Figure 2.16. Ten-day accumulated lighting pulses over (a) the whole of the Irish Shelf (black square on the map, right) and (b) the land area from the ATDNet lightning system, for the period 2001–2019.

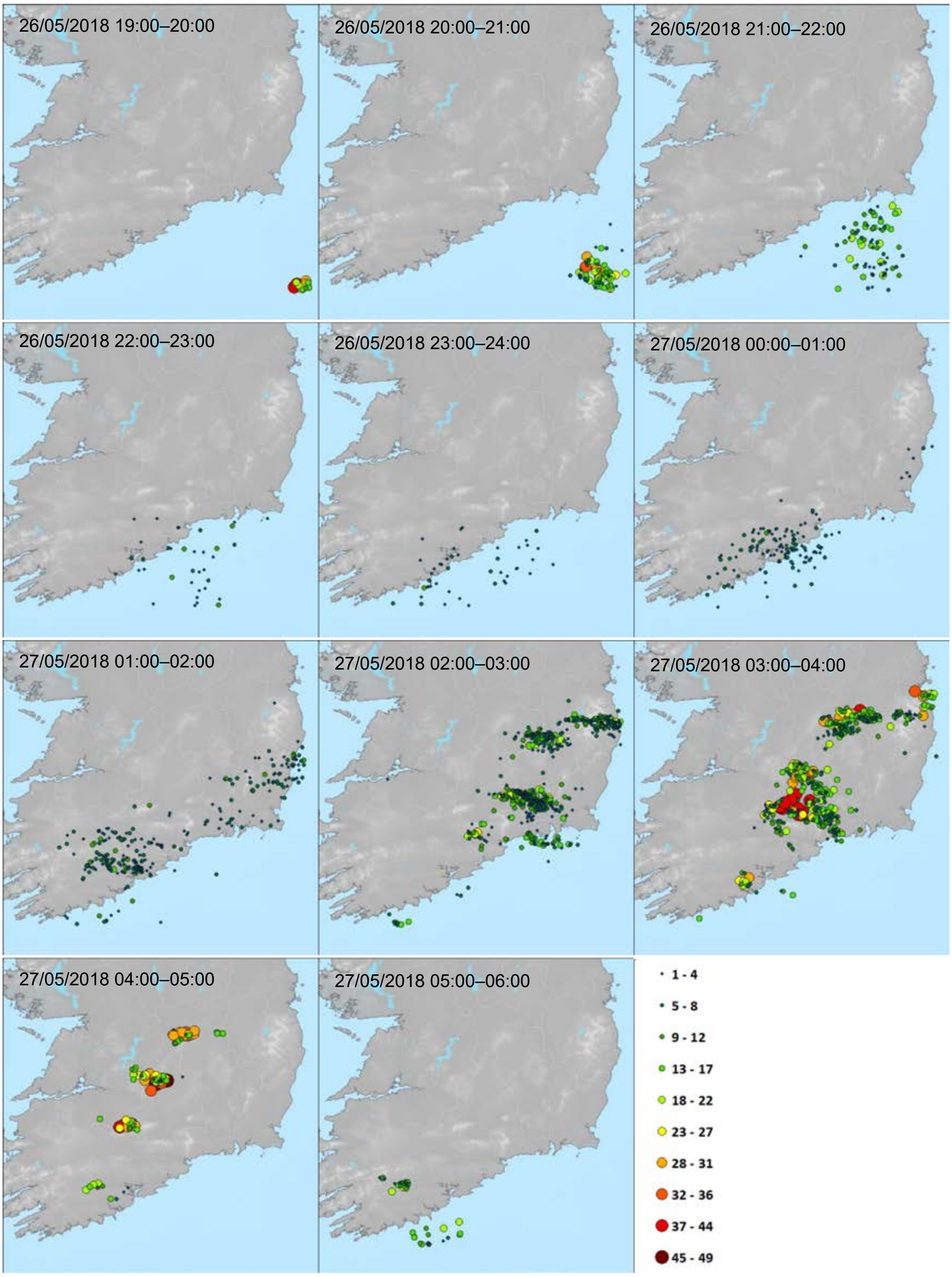


Figure 2.17. The number of hourly lightning pulses detected by the ATDNet lightning system for 26–27 May 2018 allows the trajectory of a thunderstorm to be tracked.

Further Information

Lightning Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/lightning)

Met Éireann information on lightning measurements at Valentia Observatory (https://www.met.ie/science/valentia/lightning-detection)

Met Éireann information on data availability (https://www.met.ie/climate/what-we-measure/lightning)

Met Office ATDNet system lightning strike location data sheet (https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/data/adtnet_data_sheet.pdf)

Information about NASA lightning space search and observations (https://ghrc.nsstc.nasa.gov/lightning/space-search-observations.html)

Story Box 2. The MÉRA dataset complements the observational network

Emily Gleeson, Eoin Whelan, John Hanley and Ned Dwyer

Weather observations are important for a wide range of applications, including weather forecasting, agriculture, renewable energy planning, insurance risk assessment, air quality assessment, outdoor pursuits and much more. Information on the current state of the atmosphere, ocean and Earth's surface can be estimated using observations of weather conditions from ground-based weather stations, radiosondes,[5] ocean buoys, satellites and other sources. However, through a process known as climate reanalysis, we can extend the knowledge gained from observations and get information on weather parameters that are not routinely observed.

What is climate reanalysis?

Over the past few years researchers at Met Éireann have produced a climate reanalysis dataset, called MÉRA – Met Éireann ReAnalysis, for the period 1981–2019. Climate reanalyses give a three-dimensional numerical description of the recent climate and are produced by combining models with weather observations. They contain estimates of atmospheric parameters such as air temperature, pressure and wind, at different heights above the ground, surface parameters such as precipitation, soil moisture content and temperatures, and sea surface temperature, as well as many more weather parameters. These new reanalysis datasets have benefited from advances in data assimilation techniques, better use of observations, improved forecast models and higher resolution model configurations. Figure SB2.1 shows the distribution of users of MÉRA by sector and theme.

The MÉRA dataset is the first very high-resolution climate reanalysis dataset available for Ireland, with outputs available on a 2.5-km grid. The domain covers Ireland, the UK and part of northern France, as shown in Figure SB2.2. MÉRA complements the observational network and extends the knowledge gained from observations, as the model's grid is much finer than observational coverage of Ireland. The high resolution of MÉRA means that this dataset provides a better description of extreme events, such as heavy precipitation and wind storms, than coarser global reanalysis datasets such as ERA-Interim, which was

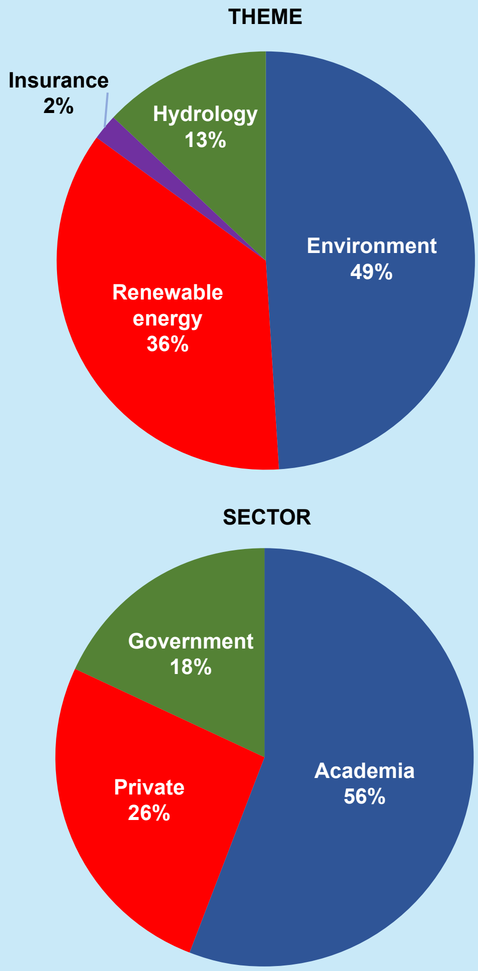


Figure SB2.1. MÉRA users by sector and "use theme".

5 A radiosonde is a small, expendable instrument package that is suspended below a large inflated balloon. Sensors transmit observations as the radiosonde rises through the atmosphere.

SB2

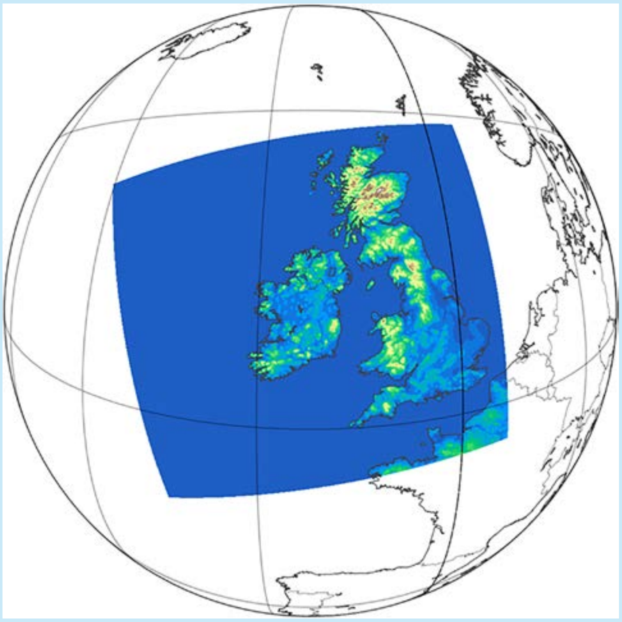


Figure SB2.2. Domain covered by the MÉRA dataset at 2.5-km grid spacing.

developed by the European Centre for Medium Range Weather Forecasts (ECMWF). ERA-Interim has been superseded by ERA5, released in 2020, which is a higher resolution global dataset but still much coarser than MÉRA.

Severe weather events

MÉRA has made it possible to look at how modern weather forecast models would have forecast severe weather events in the past. This is essentially a method for validating the reliability and accuracy of the model. MÉRA data show how a heavy rainfall event over the August Bank Holiday weekend in 1997 would have been forecast. At the time, it was very poorly forecast. In fact, rainfall accumulations of over 200 mm were recorded at ground stations in the south of the country over a 48-hour period. Had the forecast model used to produce MÉRA been available in 1997, it would have made a more accurate forecast of the extreme rainfall event, as it predicts rainfall accumulations in excess of 180 mm for the same 48-hour period. The benefits of using a higher resolution grid are clear when MÉRA data are compared with coarser ERA-Interim data from ECMWF, as shown in Figure SB2.3. The lower resolution model significantly underestimates the rainfall amounts and also has much poorer locational accuracy.

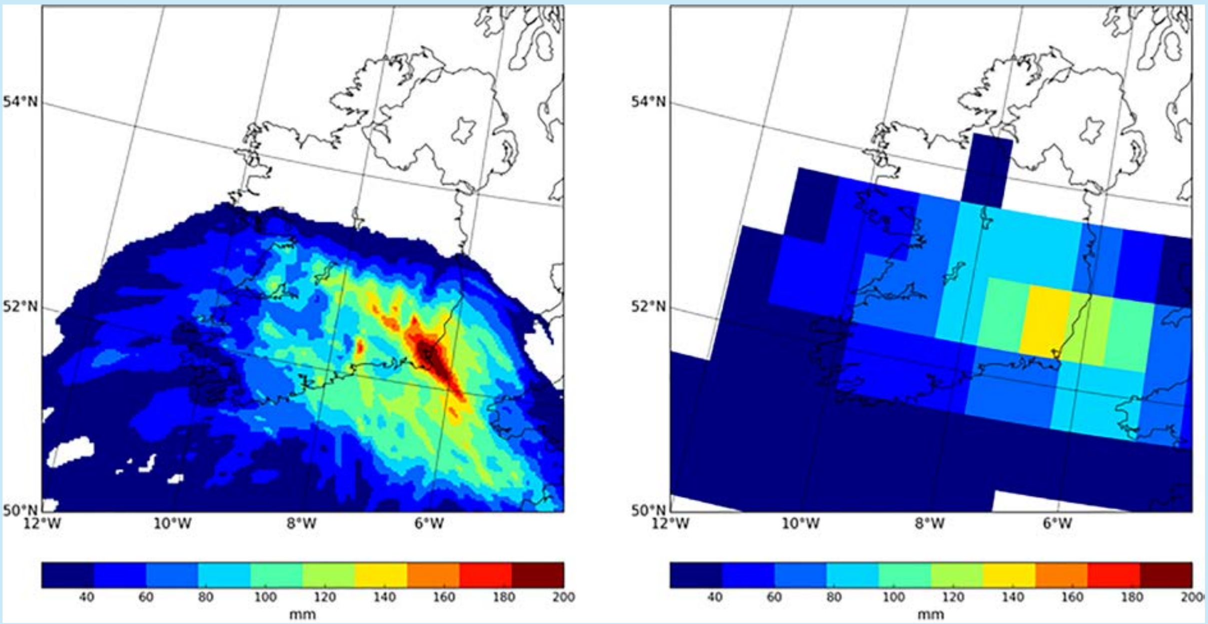


Figure SB2.3. MÉRA (left) and ERA-Interim (right) forecast rainfall accumulation from 00:00 on 3 August to 00:00 on 5 August 1997. The rainfall accumulation detail and magnitude forecast by MÉRA show the value of using higher resolution.

Accessing MÉRA

The full MÉRA dataset is available under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence, which means that the data can be freely shared and adapted for any purpose. Any use of the data requires attribution.

Further Information

MÉRA web page (https://www.met.ie/climate/available-data/mera)

Full list of data parameters in the MÉRA Data Archive (http://edepositireland.ie/handle/2262/81711)

An initial analysis of the data: Gleeson *et al.*, 2017 Met Éireann high resolution reanalysis for Ireland. *Advances in Science and Research* 14: 49–61. https://doi.org/10.5194/asr-14-49-2017

Full evaluation of MÉRA: Whelan *et al.*, 2018. An evaluation of MÉRA, a high-resolution mesoscale regional reanalysis. *Journal of Applied Meteorology and Climatology* 57: 2179–2196. https://doi.org/10.1175/JAMC-D-17-0354.1

ECMWF reanalysis datasets (https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets)

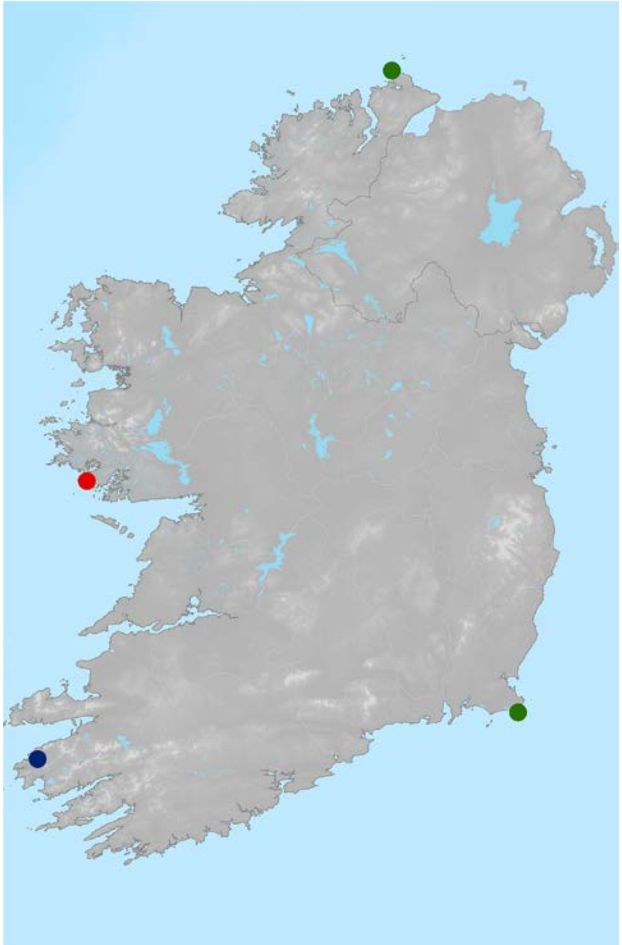
2.10 Carbon Dioxide

Walther C.A. Cámaro García, Ned Dwyer and Damien Martin

Carbon dioxide (CO_2) is the most important GHG in the atmosphere apart from water vapour. Some CO_2 is removed by plants, soils and the ocean; the rest remains in the atmosphere for centuries and is one of the main drivers of climate change. Its global average concentration has increased by about 50% since pre-industrial times, due mainly to human activities such as fossil fuel combustion. Additional CO_2 emissions are linked to cement production, deforestation, vegetation fires and land use changes. Before 1750 the atmospheric concentration of CO_2 was approximately 270 ppm (parts per million); the level exceeded 400 ppm in 2015. The annual rate of increase in atmospheric CO_2 over the past 60 years has been about 100 times faster than previous natural increases, such as those that occurred at the end of the last Ice Age 11,000–17,000 years ago.

2.10.1 Measurements

Atmospheric CO_2 concentrations are measured at a number of sites in Ireland (Map 2.10). Mace Head Atmospheric Research Station, Carna, Co. Galway (red dot), has been conducting observations since 1992. CO_2 concentrations are also measured at Carnsore Point, Co. Wexford, and Malin Head, Co. Donegal (green dots), since 2009. Measurements at Valentia Observatory, Co. Kerry (blue dot), started in 2019. The site at Mace Head is of global importance, as the measurements are representative of the background



Map 2.10. Location of carbon dioxide observation stations.

concentration of atmospheric CO_2 in the North-east Atlantic region.

The amount of CO_2 in the atmosphere can be inferred from satellite observations. The Copernicus Atmosphere Monitoring Service and the Climate Change Service provide regular information on GHG distributions. Moreover, the ESA CCI Greenhouse gas project has developed a comprehensive global time series of satellite-derived CO_2 levels. Ground-based measurements are vital for the validation of these satellite observations.

Atmospheric CO_2 concentrations of 413 ppm at Mace Head in 2018 are estimated to be more than 50% higher than those of the pre-industrial era.

2.10.2 Time Series and Trends

Figure 2.18 shows atmospheric CO_2 concentrations measured at Mauna Loa Observatory in Hawaii and at Mace Head, Co. Galway. The Mauna Loa station has been measuring CO_2 concentrations since 1958, and steadily increasing concentrations are evident. The signal observed at Mace Head is more variable because of its proximity to Europe and the influence of North America, where the uptake of CO_2 by growing vegetation and its subsequent release when the vegetation decays causes seasonal fluctuations. In addition, the seasonal cycle of the phytoplankton bloom in the North Atlantic affects the levels. However, the levels are in line with those recorded at the Mauna Loa site, with concentrations at Mace Head reaching 413 ppm in December 2018.

Figure 2.19 shows time series and charts of satellite-derived column ratios of CO_2. A global increase of approximately 0.6% per year can be observed during the last two decades. Seasonal variability is evident, due to the uptake and release of CO_2 by vegetation, linked to growing and dormant periods. This seasonal variability is higher in the northern hemisphere, where most of the planet's vegetation is located.

Calibrated measurements of atmospheric CO_2 started at Valentia Observatory in 2019.

2.10.3 Maintaining the Observations

Funding for CO_2 observations at Mace Head is provided by the EPA and the Laboratory for Climate and Environment Sciences [LSCE – comprising the French Alternative Energies and Atomic Energy Commission (CEA), the French National Centre for Scientific Research (CNRS) and Versailles Saint-Quentin-en-Yvelines University (UVSQ)] in France. Instrumentation is maintained by NUI Galway. CO_2 observations at Carnsore Point and Malin Head are funded under an EPA research programme as part of the preparatory

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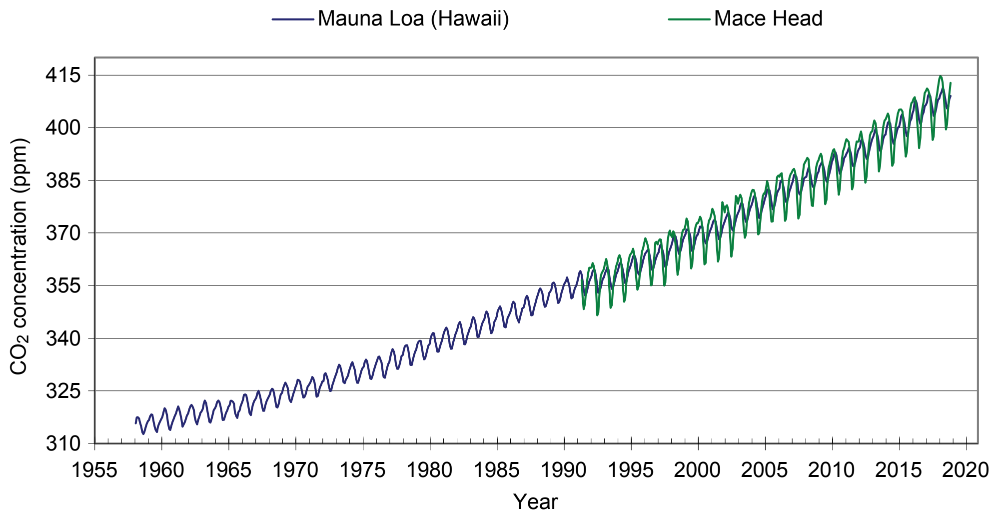


Figure 2.18. Monthly mean concentration of carbon dioxide at Mauna Loa Observatory, Hawaii (1958–2018), and Mace Head Atmospheric Research Station, Ireland (1992–2018).

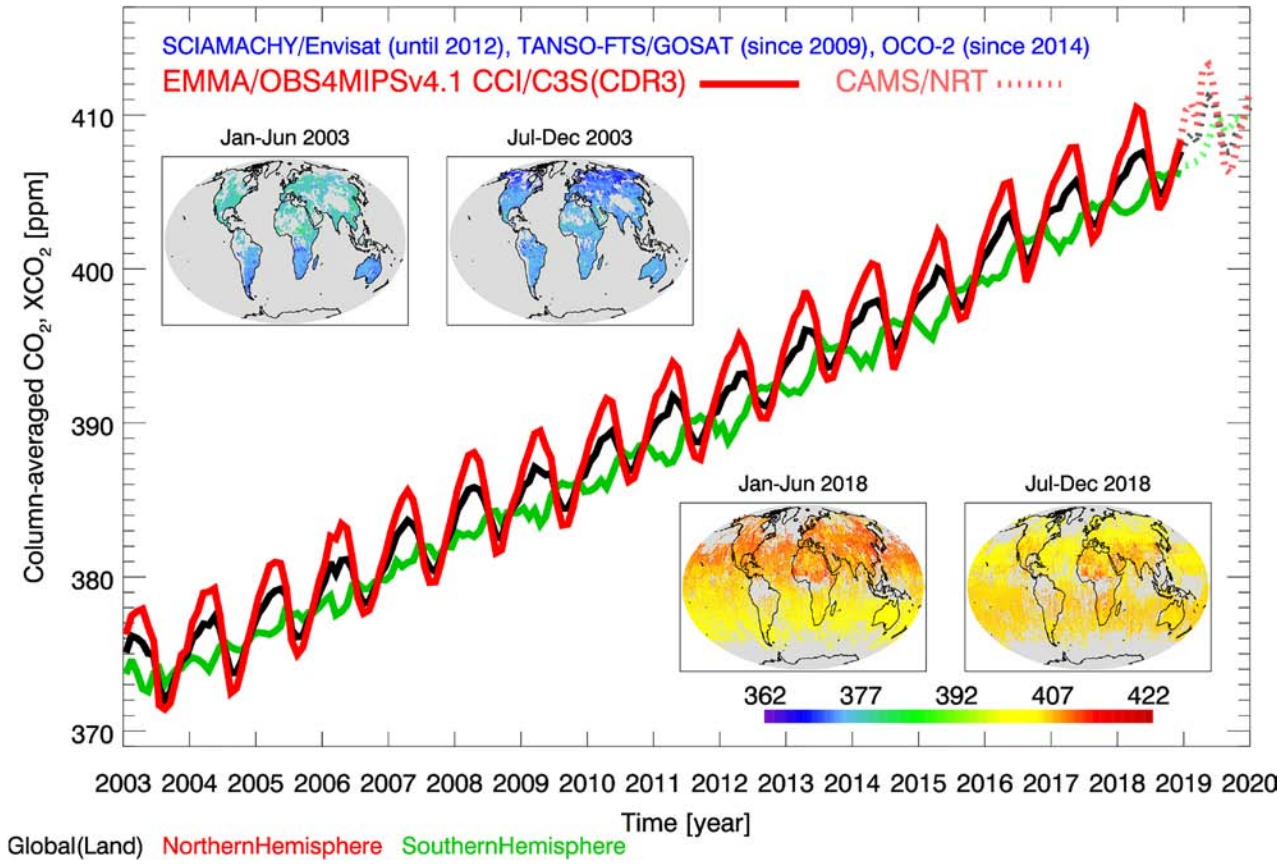


Figure 2.19. Time series and charts of satellite-derived column-averaged dry-air mixing ratios of carbon dioxide (ppm). Time series are shown for three latitude bands: global (black), northern hemisphere (red) and southern hemisphere (green). Source: Copernicus Climate Change Service, Copernicus Atmosphere Monitoring Service, ECMWF and University of Bremen (https://climate.copernicus.eu/ESOTC/2019/greenhouse-gas-concentrations).

phase of the European Integrated Carbon Observation System (ICOS). The Centre for Climate and Air Pollution Studies at NUI Galway has carried out calibrated measurements at Valentia Observatory in collaboration with Met Éireann since 2019.

NOAA's Earth System Research Laboratory in the USA has carried out weekly air sampling of CO_2 at Mace Head since 1991 as part of a long-term programme, and these are the observations presented here. This provides the potential to compare the NOAA and the EPA/LSCE observations.

Further Information

Carbon Dioxide, Methane & Other Greenhouse Gases Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/ghg)

Information on NUI Galway's Atmospheric and Environmental Physics Cluster and Mace Head facility (http://www.macehead.org/)

Ireland's greenhouse gas emissions by sector and gas (http://www.epa.ie/ghg/)

About ESA's Greenhouse Gas Climate Change Initiative project (http://cci.esa.int/ghg)

About NASA's Orbiting Carbon Observatory 2 mission (https://www.nasa.gov/mission_pages/oco2/index.html)

Greenhouse gas concentration in the European State of the Climate 2019 bulletin (https://climate.copernicus.eu/ESOTC/2019/greenhouse-gas-concentrations)

Information on ICOS (https://www.icos-cp.eu/)

Friedlingstein, P. *et al*., 2019. Global carbon budget 2019. *Earth System Science Data* 11: 1783–1838. https://doi.org/10.5194/essd-11-1783-2019

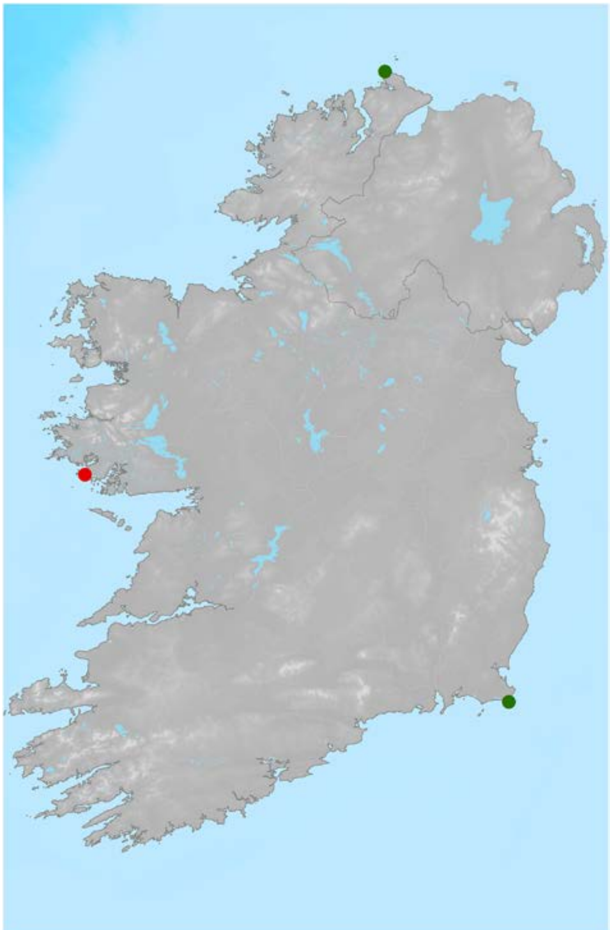
2.11 Methane

Walther C.A. Cámaro García, Ned Dwyer and Damien Martin

Methane (CH_4) is the third most important GHG in the atmosphere after CO_2 and water vapour. Its atmospheric abundance has more than doubled since the pre-industrial era. It also influences concentrations of ozone and water vapour in the upper atmosphere. Although estimated to have a global warming potential evaluated over 100 years of approximately 25 times that of CO_2, CH_4 does not persist for much more than a decade in the atmosphere. Approximately 40% of all CH_4 emitted globally is due to natural and unmanaged processes linked to the CH_4 cycle (e.g. wetlands, termites), while the remaining 60% is due to various human activities such as fossil fuel extraction, distribution and burning, rice growing, livestock farming and landfills. In Ireland, agriculture contributes almost 93% of total CH_4 emissions, with the remainder arising from waste management (5%) and the energy sectors (2%).

2.11.1 Measurements

Atmospheric CH_4 concentrations have been measured at the Mace Head Atmospheric Research Station, Carna, Co. Galway (red dot), since 1987 (Map 2.11). Given its location at the extreme western point of Europe and because of prevailing westerly winds, the measurements are representative of the underlying concentrations of atmospheric CH_4 in the North-east Atlantic area. CH_4 concentrations have also been measured at Carnsore



Map 2.11. Location of methane observation stations.

Point, Co. Wexford, and Malin Head, Co. Donegal (green dots, Map 2.11), since 2009. This network of Irish measurements is led by NUI Galway as part of the EPA-funded Atmospheric Chemistry and Climate Change Network. The site at Carnsore Point helps our understanding of the influence of European emissions, while the site at Malin Head offers the opportunity to understand transcontinental emissions.

A number of satellite sensors, including ESA's Sentinel-5P, make broad-scale measurements of CH_4. The Copernicus Atmosphere Monitoring Service and the Climate Change Service provide regular information on GHG distributions. Moreover, the ESA CCI Greenhouse gas project has developed a comprehensive global time series of satellite-derived CH_4 levels. Ground-based measurements are vital for the validation of these satellite observations.

Following a stable period in the late 1990s and early 2000s there has been a 4% increase in CH_4 concentrations since 2007.

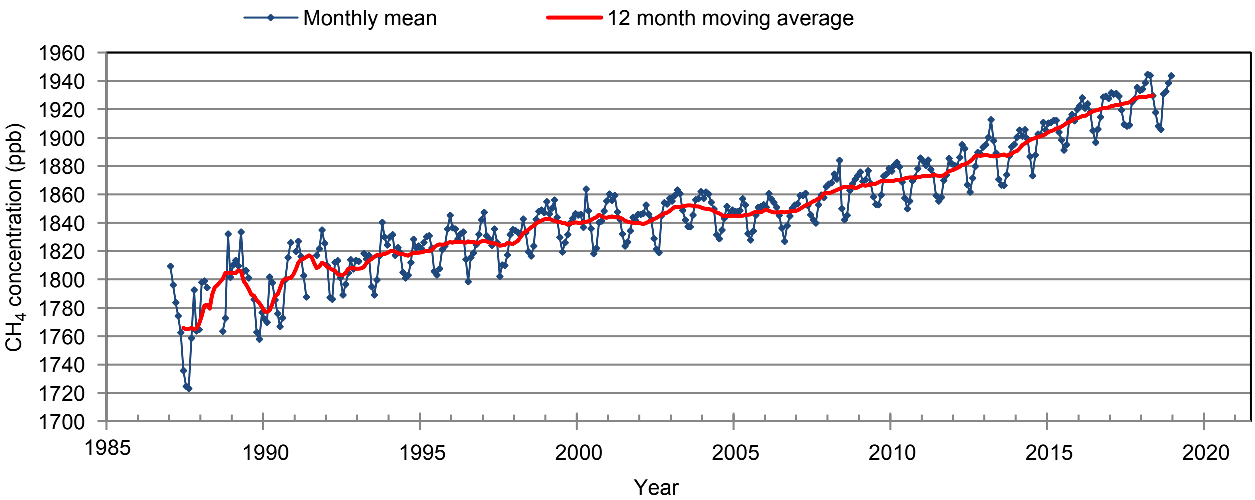


Figure 2.20. Monthly mean methane concentration observed at Mace Head Atmospheric Research Station (1987–2018).

2.11.2 Time Series and Trends

Figure 2.20 shows measurements of concentrations of atmospheric CH_4 at the Mace Head station. Average global CH_4 concentrations in the atmosphere are now almost 1900 ppb, but the concentrations observed at Mace Head are higher because most of the sources of CH_4 are located in the northern hemisphere. Increases were observed between 1987 and 1998. Levels then stabilised until 2007 after which an increasing trend is observed. Recent research suggests that this increase is attributable to the agricultural and waste sectors as well as the fossil fuel sector.

Figure 2.21 shows time series since 2003 and charts of satellite-derived column ratios of CH_4. The global concentration of CH_4 was nearly constant in the years before 2007, but a continuous increase of almost 8 ppb per year has been observed thereafter, in line with the *in situ* observations from Mace Head.

Mace Head is an important contributor to the global network of CH_4 observatories.

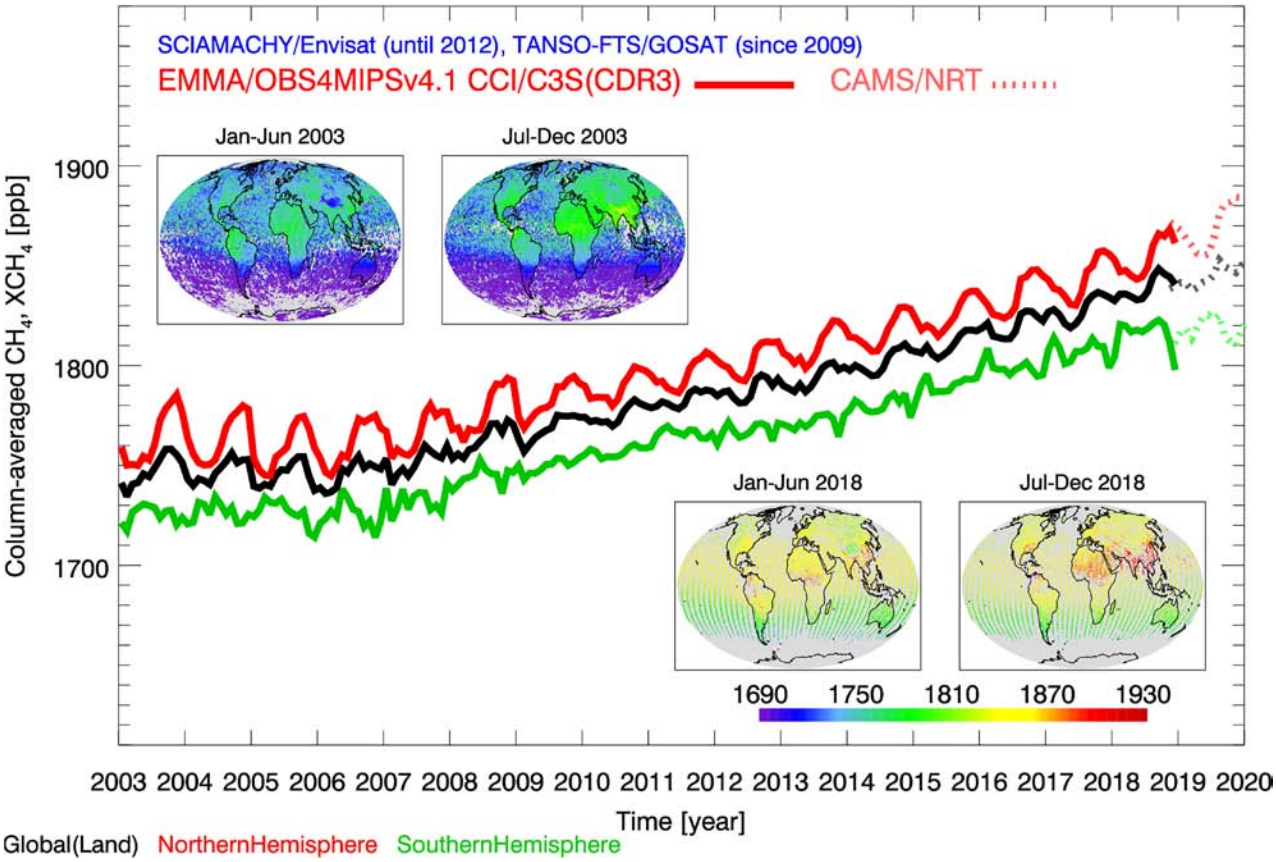


Figure 2.21. Time series and charts of satellite-derived column-averaged dry-air mixing ratios of methane (ppb). Time series are shown for three latitude bands: global (black), northern hemisphere (red) and southern hemisphere (green). Source: Copernicus Climate Change Service, Copernicus Atmosphere Monitoring Service, ECMWF and University of Bremen (https://climate.copernicus.eu/ESOTC/2019/greenhouse-gas-concentrations).

2.11.3 Maintaining the Observations

Funding for CH_4 observations at Mace Head and the other Irish sites is provided by the EPA (as part of the ICOS preparatory network), the LSCE (CEA/CNRS/UVSQ) in France and the UK Department of Energy and Climate Change (DECC), as part of its contribution to the Advanced Global Atmospheric Gases Experiment (AGAGE). There is also funding from NASA. Both ICOS and AGAGE equipment is maintained by staff from the NUI Galway. Data from the Irish sites have recently been used in an EPA-funded project to infer Irish CH_4 emissions using top-down inversion modelling.

Further Information

Carbon Dioxide, Methane & Other Greenhouse Gases Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/ghg)

Nisbet, E.G. *et al*., 2016. Rising atmospheric methane: 2007–2014 growth and isotopic shift. *Global Biogeochemical Cycles* 30: 1356-1370. https://doi.org/10.1002/2016GB005406

Jackson, R.B. *et al*., 2020. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. *Environmental Research Letters* 15: 071002. https://doi.org/10.1088/1748-9326/ab9ed2

Information on NUI Galway's Atmospheric and Environmental Physics Cluster and Mace Head facility (http://www.macehead.org/)

Methane observations from Mace Head and other AGAGE observatories (https://agage.mit.edu/)

Ireland's greenhouse gas emissions by sector and gas (http://www.epa.ie/ghg/)

About ESA's Greenhouse Gas Climate Change Initiative project (http://cci.esa.int/ghg)

About ESA's Sentinel-5P mission (https://sentinel.esa.int/web/sentinel/missions/sentinel-5p)

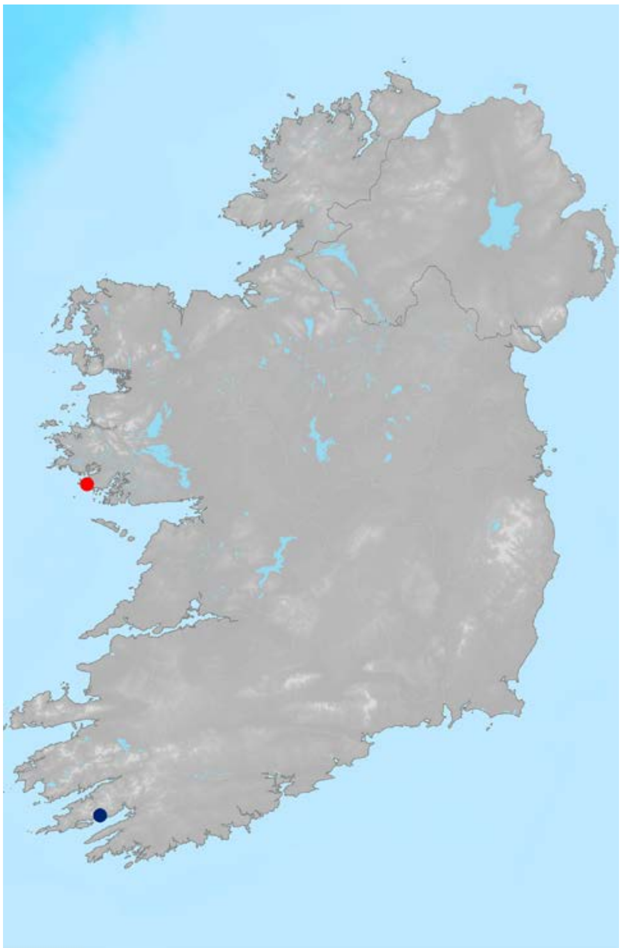
Greenhouse gas concentration in the European State of the Climate 2019 bulletin (https://climate.copernicus.eu/ESOTC/2019/greenhouse-gas-concentrations)

Information on ICOS (https://www.icos-cp.eu/)

2.12 Other Greenhouse Gases

Walther C.A. Cámaro García, Ned Dwyer and Damien Martin

In addition to water vapour, CO_2 and CH_4, a number of other gases contribute significantly to the enhanced greenhouse effect. N_2O, which has a global warming potential 298 times that of CO_2 stays in the atmosphere for more than 100 years. It is mainly emitted by natural processes in soils and the ocean, but it is estimated that more than 30% is due to human activities such as agriculture and vegetation fires, fossil fuel combustion, solid waste, industrial activities and treatment of wastewater. Synthetic gases, which are exclusively produced by human activities, are emitted in smaller quantities but have extremely high global warming potentials. These gases include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). The production and use of some of these gases is controlled under the Montreal Protocol (1987), because of their role in stratospheric ozone depletion, and of other gases under the subsequent Kigali Amendment (2016), because of their role as replacement gases for the original ozone-depleting substances.



Map 2.12. Location of greenhouse gas observation stations.

2.12.1 Measurements

Greenhouse gas concentrations have been measured routinely at the Mace Head Atmospheric Research Station, Carna, Co. Galway (red dot), since the 1990s (Map 2.12). Monitoring of a number of HFC and HCFC compounds started in 1994 and of PFCs and SF_6 in 2004. N_2O and CFCs were measured at Adrigole, Co. Cork (blue dot, Map 2.12), from 1978 to 1984. The current measurement programme is led by NUI Galway as part of the EPA-funded Atmospheric Chemistry and Climate Change Network.

Concentrations of N_2O in both the lower and upper atmosphere can be inferred from measurements by satellite sensors such as those obtained by the ESA Sentinel-5P satellite and the NASA Aura spacecraft.

> Synthetic gases, which replaced ozone-depleting CFCs, are increasing steadily in the atmosphere.

2.12.2 Time Series and Trends

Figure 2.22 shows concentrations of atmospheric N_2O measured initially at Adrigole and subsequently at Mace Head. A steady increase is observed, with concentrations now above 330 ppb. This is a 20% increase compared to the pre-industrial era when N_2O global concentrations were around 270 ppb.

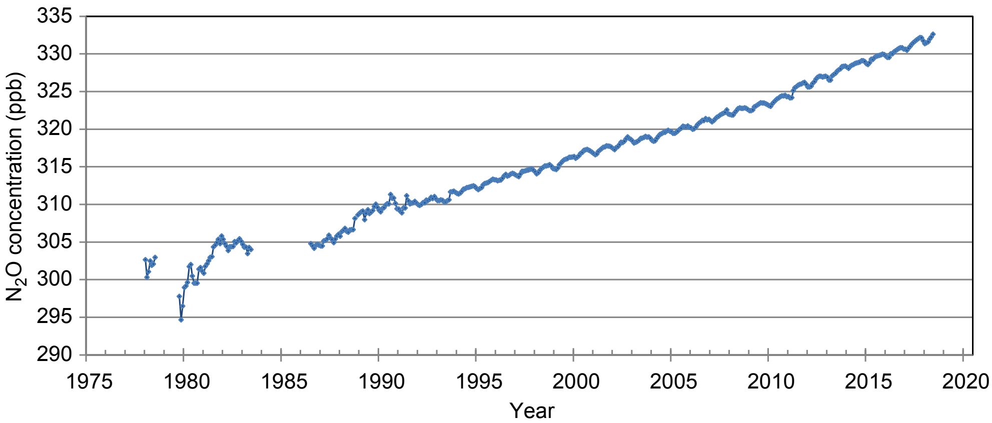


Figure 2.22. Monthly mean nitrous oxide concentration (ppb) observed at Adrigole (1978–1984) and Mace Head Atmospheric Research Station (1987–2018). There are some gaps in the data record.

Figure 2.23 shows the concentrations of atmospheric CFC-12 measured initially at Adrigole and subsequently at Mace Head. CFC-12 has a global warming potential of almost 11,000 (i.e. 11,000 times that of CO_2). A steady increase can be observed through the 1980s but, after the adoption of the Montreal Protocol in 1987, banning the production and use of CFCs, there was no further increase and levels have been falling since 2004.

Figure 2.24 shows concentrations of atmospheric HFC-134a (which has a global warming potential of 1300) measured at Mace Head. This gas is a good example of the refrigerant products that replaced ozone-depleting CFCs. It is also used in mobile air-conditioning units and as a fire retardant. Its concentration is increasing steadily, as is that of a number of other synthetic gases in the atmosphere.

Regular observations of a number of synthetic GHGs are made at Mace Head.

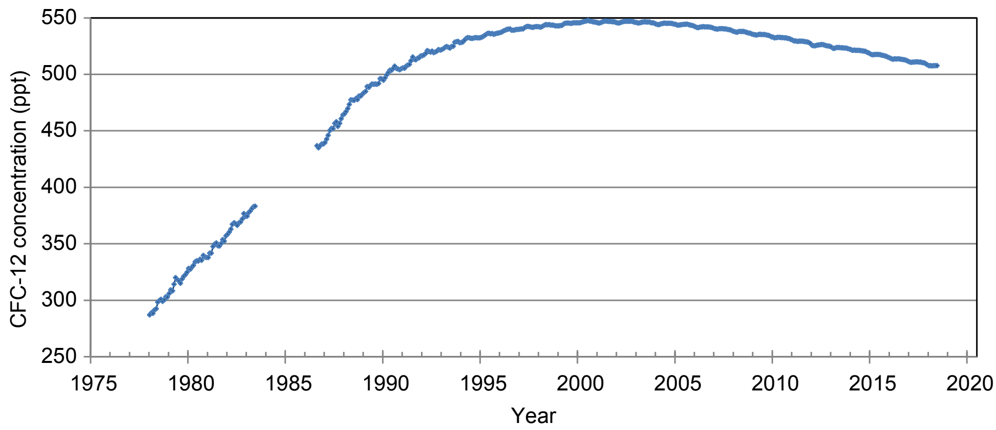


Figure 2.23. Monthly mean CFC-12 concentration (ppt) observed at Adrigole (1978–1984) and Mace Head Atmospheric Research Station (1987–2018). There are some gaps in the data record.

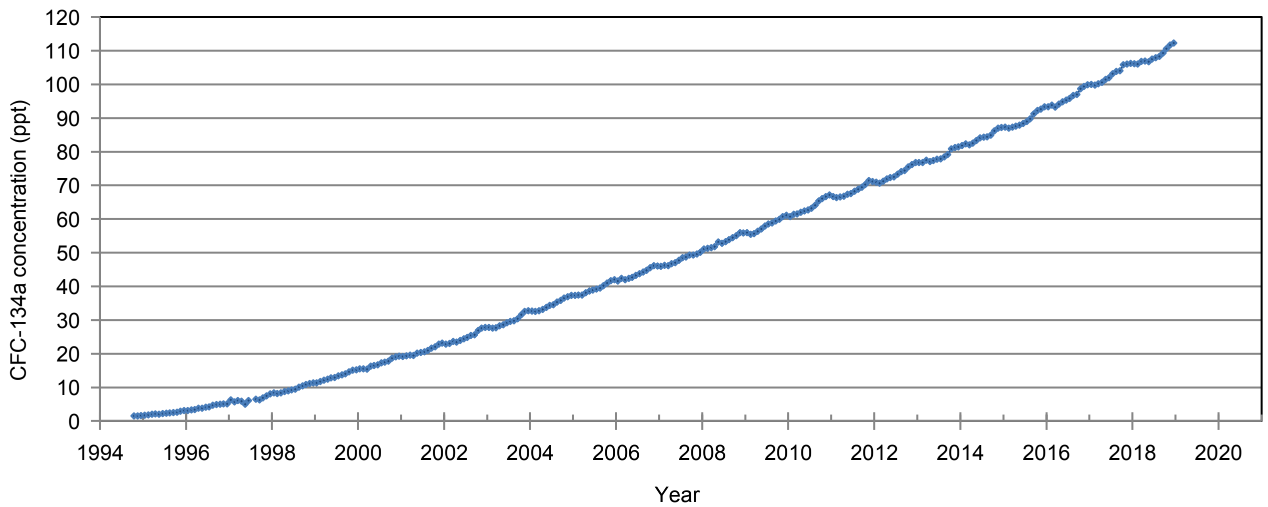


Figure 2.24. Monthly mean HFC-134a concentration (ppt) observed at Mace Head Atmospheric Research Station (1994–2018).

2.12.3 Maintaining the Observations

Funding for GHG observations at Mace Head is provided by the EPA (as part of the ICOS preparatory network) and by the UK DECC, as part of its contribution to AGAGE. There is also funding from NASA. Both ICOS and AGAGE equipment is maintained by staff from NUI Galway.

Further Information

Carbon Dioxide, Methane & Other Greenhouse Gases Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/ghg)

Simmonds, P.G. *et al.*, 2017. Changing trends and emissions of hydrochlorofluorocarbons (HCFCs) and their hydrofluorocarbon (HFCs) replacements. *Atmospheric Chemistry and Physics* 17: 4641–4655. https://doi.org/10.5194/acp-17-4641-2017

Information on NUI Galway's Atmospheric and Environmental Physics Cluster and Mace Head facility (http://www.macehead.org/)

Greenhouse gas observations from Mace Head and other AGAGE observatories (https://agage.mit.edu/)

About the Montreal Protocol (https://www.unenvironment.org/ozonaction/who-we-are/about-montreal-protocol)

Information on the Kigali Amendment to the Montreal Protocol (https://www.unenvironment.org/ozonaction/resources/factsheet/kigali-amendment-montreal-protocol-hfc-phase-down)

About ESA's Sentinel-5P mission (https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P)

About NASA's Aura spacecraft (https://aura.gsfc.nasa.gov/omi.html)

Information on ICOS (https://www.icos-cp.eu/)

2.13 Ozone

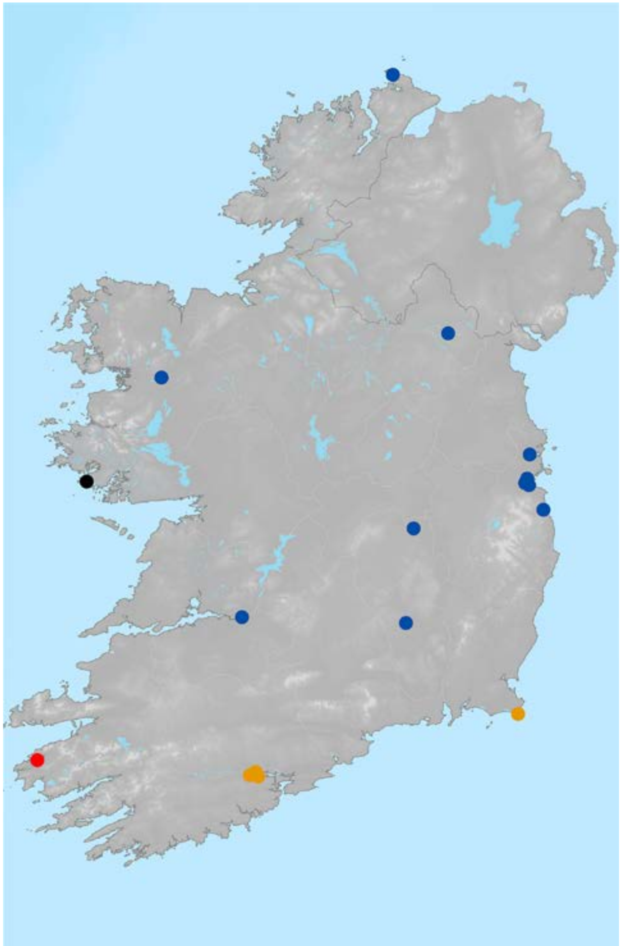
Walther C.A. Cámaro García, Ned Dwyer and Keith Lambkin

Ozone (O_3) is another potent GHG in terms of radiative forcing. The influence of O_3 on climate is complex, with different impacts in the upper and lower atmosphere. It also has multiple potential environmental and health impacts. In the upper atmosphere (stratosphere) it prevents harmful ultraviolet radiation from reaching the Earth's surface. In the lower atmosphere (troposphere) it is a pollutant, harmful to all living things. Although human activities do not emit O_3 directly, atmospheric pollution, for example from industry, transport and the burning of vegetation, can create the conditions for enhanced O_3 formation. On the other hand, the amount of O_3 in the global stratosphere has been decreasing since 1980 because of an excess of O_3-destroying substances generated by human activities. However, the implementation of the internationally agreed Montreal Protocol (1987) has been effective in reducing the production of O_3-depleting substances and gradually restoring stratospheric O_3 concentrations.

2.13.1 Measurements

The EPA, through the National Ambient Air Quality Monitoring Network, is in charge of ground-based O_3 measurements (Map 2.13). Eleven of these stations are directly operated by the EPA (blue dots); Valentia Observatory, Co. Kerry (red dot), is operated by Met Éireann; Mace Head, Co. Galway (black dot), is operated by NUI Galway; and the remaining stations (orange dots) are operated by universities or local authorities or are under research initiatives.

Total column and stratospheric O_3 has been measured at Valentia Observatory since 1993, providing continuous data for more than 25 years. These measurements are routinely made using equipment carried on weather balloons to heights greater than 30 km.



Map 2.13. Location of ozone observation stations.

Measurements of O_3 from satellites have been made since the 1970s, with different sensors operating in the ultraviolet, visible and microwave part of the spectrum. Both total column and profiles of O_3 at different heights in the atmosphere have been retrieved. Currently, the Copernicus Atmosphere Monitoring Service and the Climate Change Service provide various global O_3 datasets, some developed under the ESA CCI Ozone project. In addition, the NASA Ozone Watch portal compiles a set of O_3 data products derived from several satellite missions.

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> At Mace Head average annual near-ground O_3 amounts increased over the period 1987–1997, followed by a step change during 1998/1999 and relatively constant levels since then.

2.13.2 Time Series and Trends

Analysis of ground level O_3 measurements at Mace Head, Co. Galway (Figure 2.25), shows that average annual near-ground O_3 amounts increased over the period 1987–1997, followed by a step change during 1998/1999 and relatively constant levels since. Annual variability is apparent, with maximum values recorded during the spring period and minimum values during autumn. The red line shows a 12-month running average over the period. The sharp increase in 1998/1999 has

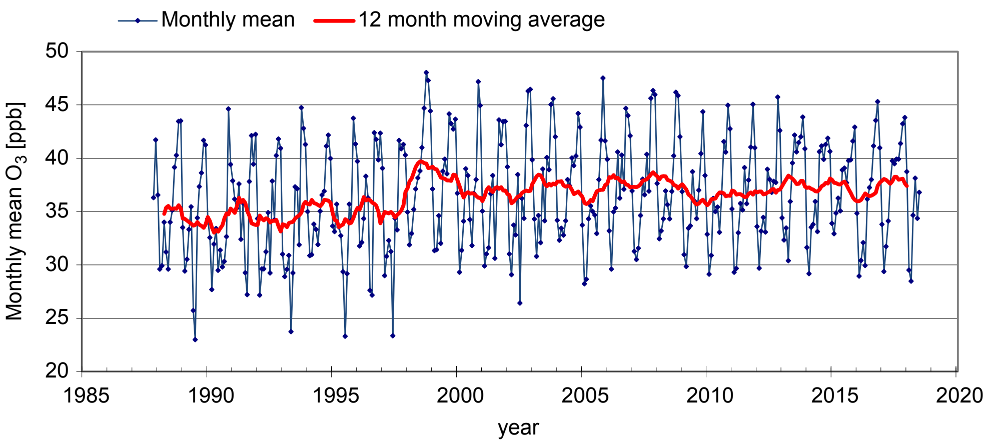


Figure 2.25. Monthly mean ground level ozone concentration (ppb) observed at Mace Head (1987–2018).

been attributed to large vegetation fires in the northern hemisphere during that period. Mace Head observations are strongly influenced by Atlantic marine air masses.

Figure 2.26 shows the monthly total column O_3 observed at Valentia Observatory. Annual variability is also observed here, with maximum values recorded during the spring season and minimum values during the late autumn. However, no trend is apparent over the period 1993–2018.

Figure 2.27 shows the northern hemisphere monthly average maps of total O_3 for different months during 2018. The shades of blue and purple indicate where there is the least O_3 and the yellows and reds where there is more O_3. In line with the ground and total column observations at the *in situ* stations, the maximum values observed in the northern hemisphere are in the spring period (April), with autumn (October) being the period with minimum values of O_3.

Mace Head and Valentia are important contributors to the global network of O_3 observatories.

2.13.3 Maintaining the Observations

The EPA manages the National Ambient Air Quality Monitoring Network in partnership with a number of local authorities, colleges and universities, and state agencies, such as Met Éireann and NUI Galway.

Funding for O_3 observations at Valentia Observatory is provided from Met Éireann's operational budget. Equipment maintenance and data handling is carried out by on-site Met Éireann staff. Funding for observations at Mace Head was originally from the UK Department for Environment, Food and Rural Affairs and since 2007

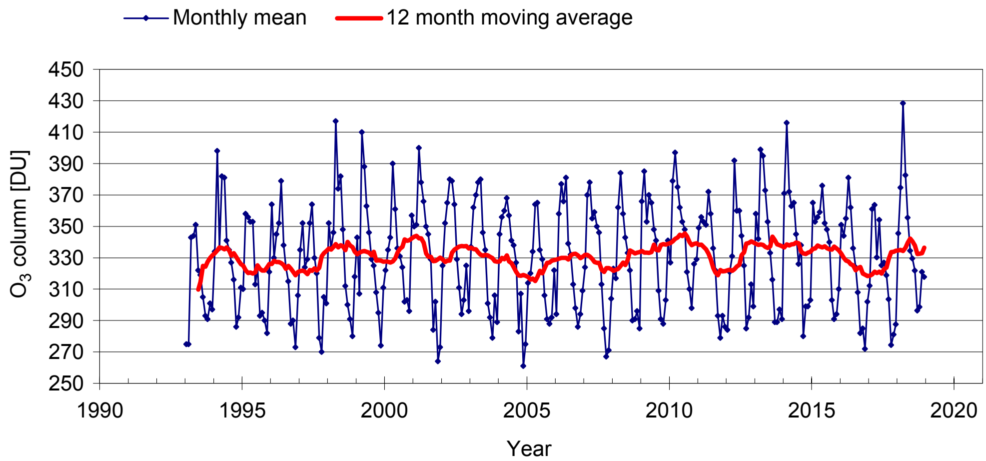


Figure 2.26. Monthly mean total column ozone concentration (in Dobson units) observed at Valentia Observatory (1993–2018).

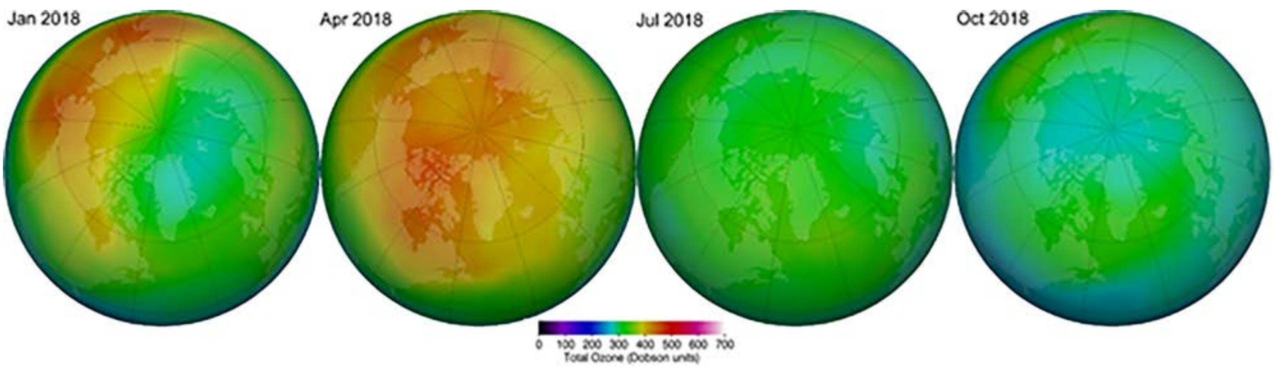


Figure 2.27. Northern hemisphere monthly average maps of total ozone for January, April, July and October 2018. Source: NASA Ozone Watch (https://ozonewatch.gsfc.nasa.gov/SH.html).

has been from the UK DECC. Equipment maintenance and data handling are carried out by staff from NUI Galway.

Satellite-based sensors, such as the tropospheric monitoring instrument (TROPOMI) on board ESA's Sentinel-5P and the ozone mapping and profiler suite (OMPS) on board NASA's Suomi National Polar Orbiting Partnership satellite, ensure the continuity of stratospheric O_3 observations.

Further Information:

Ozone Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/ozone/)

Information on the EPA National Ambient Air Quality Monitoring Network (https://www.epa.ie/air/quality/)

National Ambient Air Quality Monitoring Programme 2017–2022 (https://www.epa.ie/publications/monitoring--assessment/air/national-ambient-air-quality-monitoring-programme-2017-2022.php)

Met Éireann information on the ozone measurement programme at Valentia Observatory (https://www.met.ie/science/valentia/ozone-monitoring)

Information on NUI Galway's Atmospheric and Environmental Physics Cluster and Mace Head facility (http://www.macehead.org/)

Copernicus Atmosphere Monitoring Service (https://www.copernicus.eu/en/services/atmosphere)

Copernicus Climate Change Service (https://www.copernicus.eu/en/services/climate-change)

About ESA's Sentinel-5P mission (https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P)

Information on NASA's Ozone Watch (ozone maps) (https://ozonewatch.gsfc.nasa.gov/monthly/NH.html)

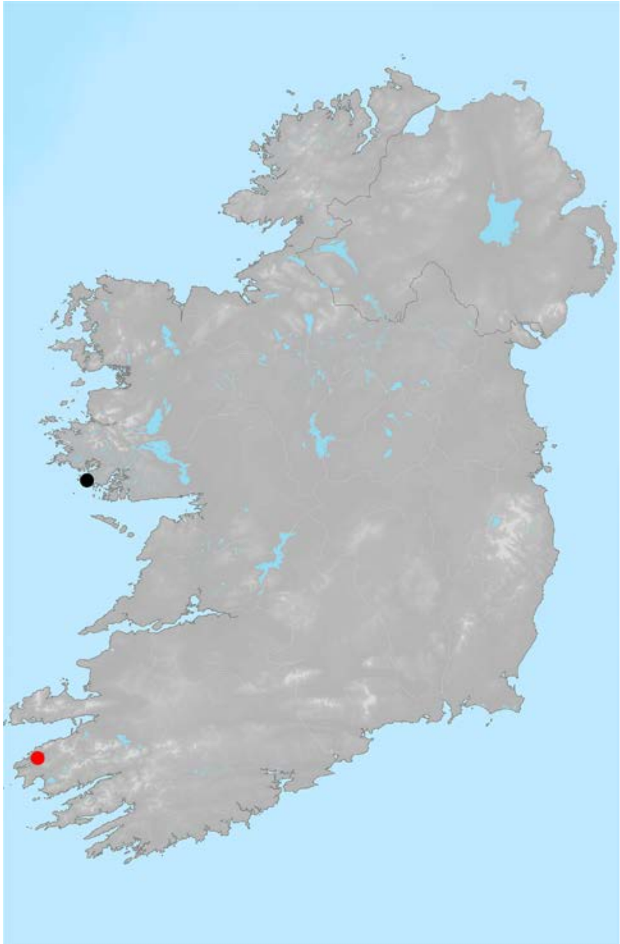
2.14 Aerosols

Walther C.A. Cámaro García, Ned Dwyer and Jurgita Ovadnevaite

Atmospheric aerosols are small particles or droplets in the air that may be formed by natural or human activities. They include windblown dust, sea spray, volcanic ash, smoke from vegetation fires and pollution from factories and vehicles. Aerosols are minor constituents of the atmosphere by mass but affect climate dynamics in several ways and represent an area of great uncertainty in the understanding of Earth's climate system. Aerosols influence the global radiation balance directly by scattering and absorbing solar radiation and indirectly through influencing cloud albedo (reflectivity), cover and lifespan. Near-ground aerosols from smoke and other pollutants can also adversely affect human health.

2.14.1 Measurements

Aerosol observations are made at the Mace Head Atmospheric Research Station, Carna, Co. Galway (black dot), and Valentia Observatory, Co. Kerry (red dot) (Map 2.14). A range of aerosol parameters have been measured on a continual basis at Mace Head since 1987, although some measurements took place on an intermittent basis between 1958 and 1987. Measurements made include the scattering, backscattering and absorption coefficients at various wavelengths; the total particle number concentration, particle size and mass distribution; particulate matter



Map 2.14. Location of aerosol observation stations.

(PM) mass (PM with a diameter of 10 µm or less, PM_{10}, and PM with a diameter of 2.5 µm or less, $PM_{2.5}$); black carbon mass concentration; and aerosol flux, aerosol optical depth, cloud condensation nuclei and aerosol chemical composition. This suite of measurements is one of the most comprehensive made at any remote location in the world and the observations are webcast in near-real time every 10 minutes. Routine condensation nuclei measurements were made at Valentia Observatory between 1951 and 1994. Measurements of aerosol optical depth are currently carried out at the observatory.

A range of sensors, such as TROPOMI on board ESA's Sentinel-5P and MODIS on NASA's Terra and Aqua satellites, make observations from which aerosol properties can be inferred. Currently, the Copernicus Atmosphere Monitoring Service and the Climate Change Service and the ESA CCI Aerosol project provide various global aerosol products.

The reduction in atmospheric sulfur pollution between 1980 and 2015 highlights the success of effective policy implementation.

2.14.2 Time Series and Trends

The quantity, composition and location of aerosols in the atmosphere vary throughout the year. An example of aerosol measurements made at Mace Head is shown in Figure 2.28. This time series of monthly and yearly median values of aerosol scattering coefficient for the period from 1999 to 2015[6] is an estimate of total aerosol concentration, which shows no evident trend in the time series.

Nonetheless, it is interesting to note that atmospheric sulfur pollution (sulfur dioxide, SO_2, and sulfate, SO_4, which oxidise to form sulfate aerosol) shows a significant reduction (~80%) over a 35-year period (1980–2015) and is in line with European observations (Figure 2.29). This highlights the success of effective policy implemented through regulation and the resultant stimulation of technological advances. This reduction in sulfur has led to a situation in which carbonaceous compounds (organic matter and black carbon combined) now dominate the aerosol composition.

Figure 2.30 shows a global map of aerosol optical depth,[7] as inferred from satellite (MODIS Atmosphere Science Team), for September 2018. High aerosol optical depth over the Amazon region and south-western Africa is probably due to vegetation fires. Dust from the Sahara is carried out over the Atlantic Ocean and over the Red Sea from the Arabian Peninsula, while industrial aerosol is observed across parts of southern Asia.

Long-term aerosol observations need to be maintained and sustainable operational support needs to be guaranteed.

6 Raw datasets are available to date but not processed because of a lack of sustainable operational staff support.

7 Aerosol optical depth is a measure of the amount of light lost because of the presence of aerosols in a column of air from the Earth´s surface to the top of the atmosphere.

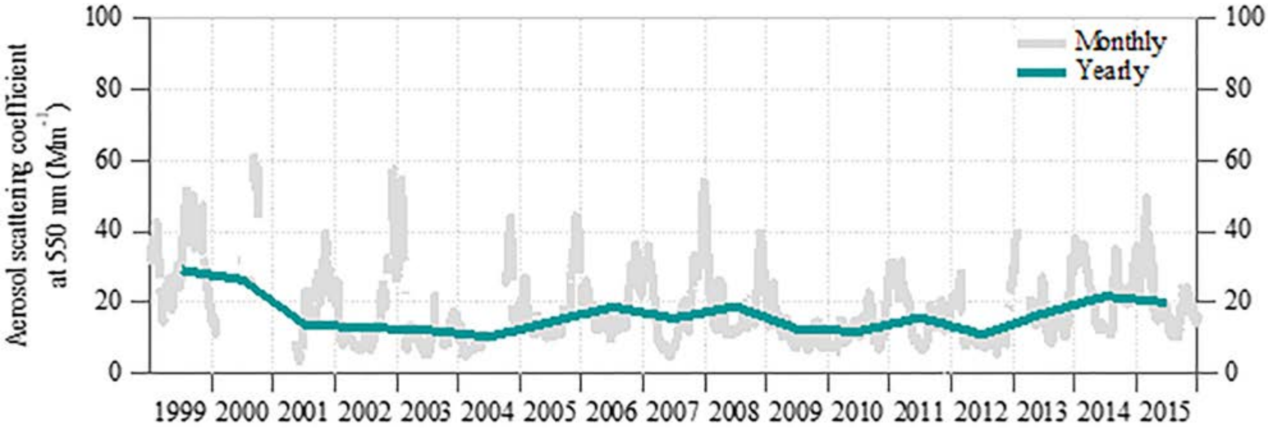


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Figure 2.28. Monthly (grey) and yearly (green) median values of aerosol scattering coefficient observed at Mace Head (1999–2015). There are some gaps in the data record.

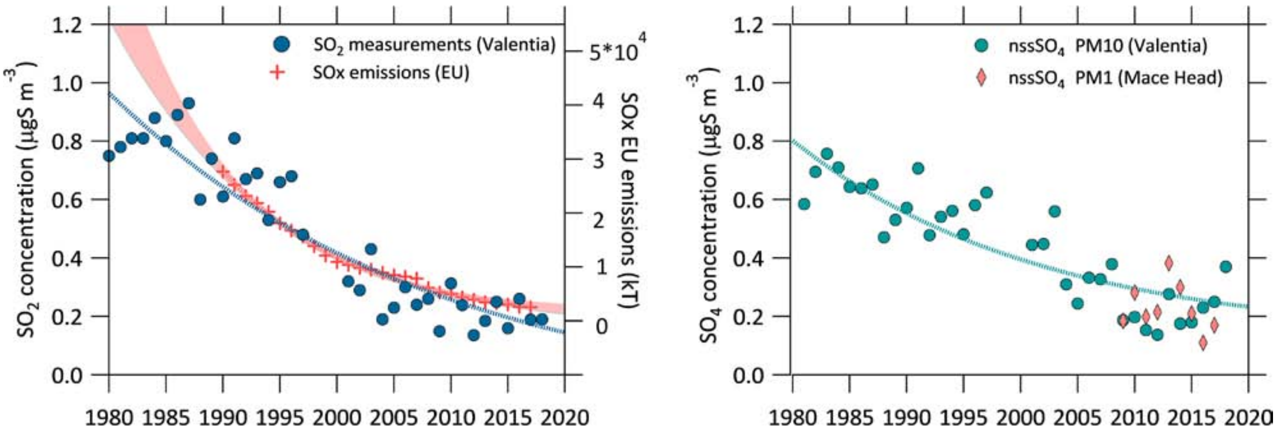


Figure 2.29. Sulfur air pollution trends (µg S/m^3). Left panel: sulfur dioxide pollution levels measured at Valentia Observatory (blue dots) and European sulfur oxide emissions (red crosses) over the period 1980–2018. The dashed line represents an exponential fit to the sulfur dioxide measurement data and the pink-shaded area represents confidence bands (95%) of exponential fits to European sulfur oxide emissions. Right panel: non-sea salt sulfate PM_{10} pollution levels measured at Valentia Observatory (green dots) and non-sea salt sulfate PM_1 observed at Mace Head (pink ellipses) over the period 1980–2018. The dashed line represents an exponential fit to the non-sea salt sulfate PM_{10} measurement data.

2.14.3 Maintaining the Observations

The Mace Head aerosol observation programmes are funded on an ad hoc basis through a range of projects by the Centre for Climate and Air Pollution Studies (C-CAPS), School of Physics, at NUI Galway, the EPA and the Department of the Environment, Climate and Communications, but they lack long-term and sustainable operational support. Funding for aerosol observations at Valentia Observatory is provided from Met Éireann's operational budget. Equipment maintenance and data handling are carried out by on-site staff, in co-operation with the World Optical Depth Research and Calibration Center in Davos.

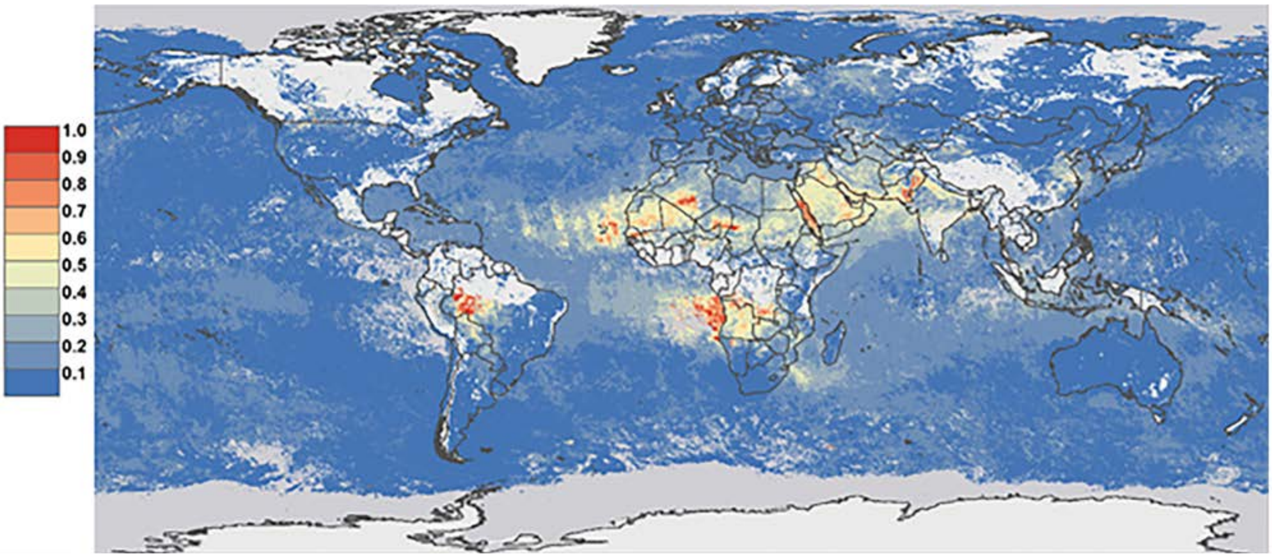


Figure 2.30. Example of global aerosol optical depth derived from satellite observations for September 2018. Source: MODIS Atmosphere Science Team, NASA Earth Observations.

Further Information

Aerosol Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/aerosols)

Met Éireann information on the aerosol optical depth measurement programme at Valentia Observatory (https://www.met.ie/science/valentia/aerosol-optical-depth-measurement)

Information on NUI Galway's Atmospheric and Environmental Physics Cluster and Mace Head facility (http://www.macehead.org/)

Real-time data from Mace Head (http://www.macehead.org/index.php?option=com_content&view=category&layout=blog&id=96&Itemid=30)

Copernicus Atmosphere Monitoring Service (https://www.copernicus.eu/en/services/atmosphere)

Copernicus Climate Change Service (https://www.copernicus.eu/en/services/climate-change)

About ESA's Aerosol Climate Change Initiative project (http://cci.esa.int/aerosol)

About NASA's Earth Observations (https://neo.sci.gsfc.nasa.gov/)

2.15 Precursors for Aerosols and Ozone

Ned Dwyer and Walther C.A. Cámaro García

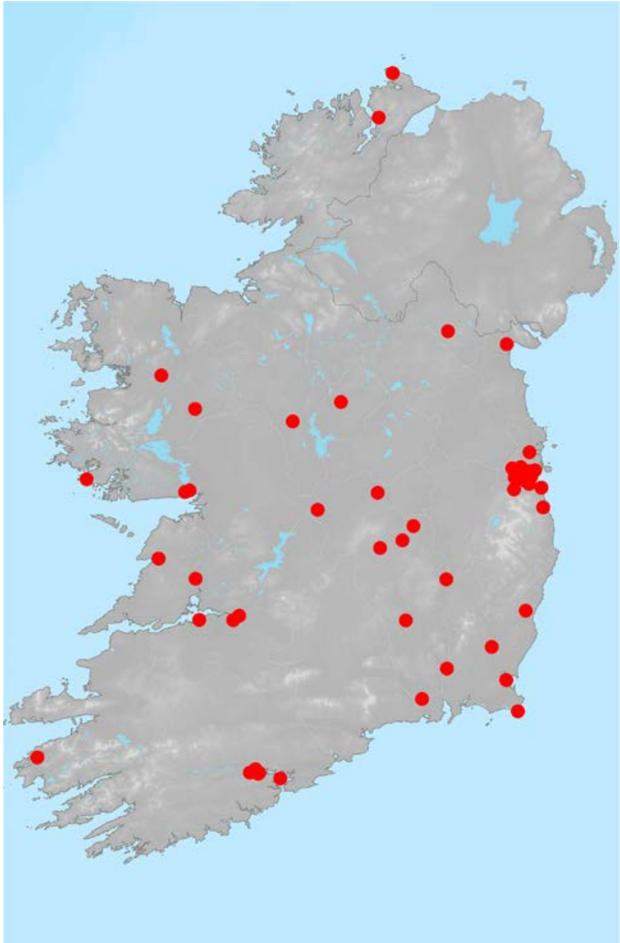
Precursors are chemical species in the atmosphere that lead to the production of aerosols and ozone. Precursors include nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO) and formaldehyde (HCHO). In Ireland emissions from vehicles are the main source of NO_2 and CO, while domestic heating and electricity generation leads to emissions of SO_2. Aerosols and O_3 in the near-surface atmosphere allied with these precursors can directly harm human health and produce detrimental environmental impacts (e.g. crop damage, acid rain). Reductions in the concentrations of near-surface aerosols and O_3 have been observed in specific regions where the emissions of some precursors are regulated.

2.15.1 Measurements

The EPA, through the National Ambient Air Quality Monitoring Network, monitors NO_2, SO_2 and CO concentrations, as part of the air quality for health programme. These are not monitored as part of a climate observation programme. These observations comply with the EU's ambient air quality directives. Map 2.15 shows the location of the current national air quality monitoring sites. Not all species are measured at all sites.

2.15.2 Time Series and Trends

Annual air quality reports and air quality bulletins are published by the EPA. In 2018 the levels reported were below the European Union (EU) legislative limits, although levels of NO_2 were above World Health



Map 2.15. Location of EPA national air quality monitoring sites.

Organization (WHO) guideline values at a number of stations.

Figure 2.31 shows the hourly concentrations of NO_2 measured at Ballyfermot, Co. Dublin, during 2018. The WHO hourly limit of 200 µg/m^3 was exceeded on 5 April 2018.

2.15.3 Maintaining the Observations

The EPA manages the National Ambient Air Quality Monitoring Network in partnership with a number of local authorities, colleges and universities, and state agencies, such as Met Éireann and NUI Galway. As part of the 5-year National Ambient Air Quality Monitoring Programme, launched in November 2017, there are plans to expand the air quality monitoring network and improve the provision of real-time information to the public.

The data collected are not currently used in the context of climate change analysis.

Further Information

Precursors for Aerosols and Ozone Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/precursors/)

National Ambient Air Quality Monitoring Programme 2017–2022 (https://www.epa.ie/publications/monitoring--assessment/air/national-ambient-air-quality-monitoring-programme-2017-2022.php)

EPA Air Quality Index for Health (https://www.epa.ie/air/quality/pro/) or (https://airquality.ie/)

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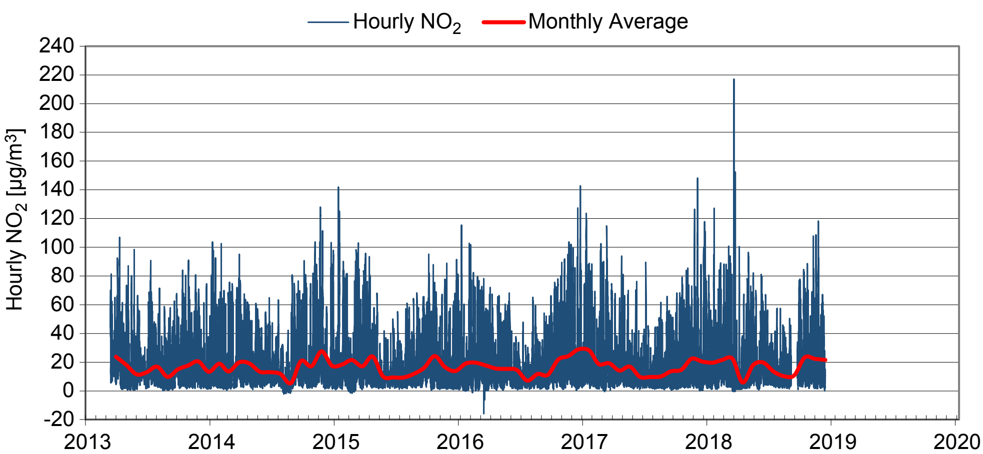


Figure 2.31. Hourly concentrations (µg/m^3) of nitrogen dioxide at Ballyfermot station (2013–2018).

Story Box 3. The importance of reliable observations for climate adaptation

Barry O'Dwyer and Ned Dwyer

Climate change adaptation

Adaptation aims to ensure that we are better prepared to respond to current and future climate change impacts by reducing our vulnerability. Adaptation not only seeks to protect people, buildings, infrastructure, businesses and ecosystems against the negative impacts of climate change but also aims to build resilience to climate change, allowing society to take advantage of any opportunities that it might bring.

Changes in extremes, such as storms and rainfall leading to floods or droughts, have had major impacts in recent years, so there is a need to take short-term adaptation measures, such as improved emergency planning, but also the need to build long-term climate resilience and minimise the impacts of such events in the future.

If adaptation is planned and pre-emptive it can be more effective both practically and economically. Adaptation actions should involve a mix of "grey", which rely on technological or engineering solutions, "green", which make use of nature, and "soft" measures, which aim to alter human behaviour and styles of governance.

In 2018 the National Adaptation Framework was published. It outlines the national strategy for the application of adaptation measures and mandated 12 different sectors of the Irish economy and local authorities to develop adaptation strategies (Table SB3.1).

Observations in support of climate change adaptation

Observations, from the various networks in place, of how the climate has varied over time have proved vital in informing the development of local and sectoral adaptation strategies. When taken together with projected changes in the climate, they can give a good

Table SB3.1. The 12 sectors that developed climate adaptation strategies in May 2018

Theme	Lead department of sectoral adaptation plans	Sector
Natural and cultural capital	Department of Agriculture, Food and the Marine	Seafood
		Agriculture
		Forestry
	Department of Culture, Heritage and the Gaeltacht[a]	Biodiversity
		Built and archaeological heritage
Critical infrastructure	Department of Transport, Tourism and Sport[b]	Transport infrastructure
	Department of Communications, Climate Action and Environment[c]	Electricity and gas networks
		Communications networks
Water resource and flood risk management	Office of Public Works	Flood risk management
	Department of Housing, Planning and Local Government[d]	Water quality
		Water services infrastructure
Public health	Department of Health	Health

[a]Now the Department of Tourism, Culture, Arts, Gaeltacht, Sport and Media.

[b]Now the Department of Transport.

[c]Now the Department of the Environment, Climate and Communications.

[d]Now the Department of Housing, Local Government and Heritage.

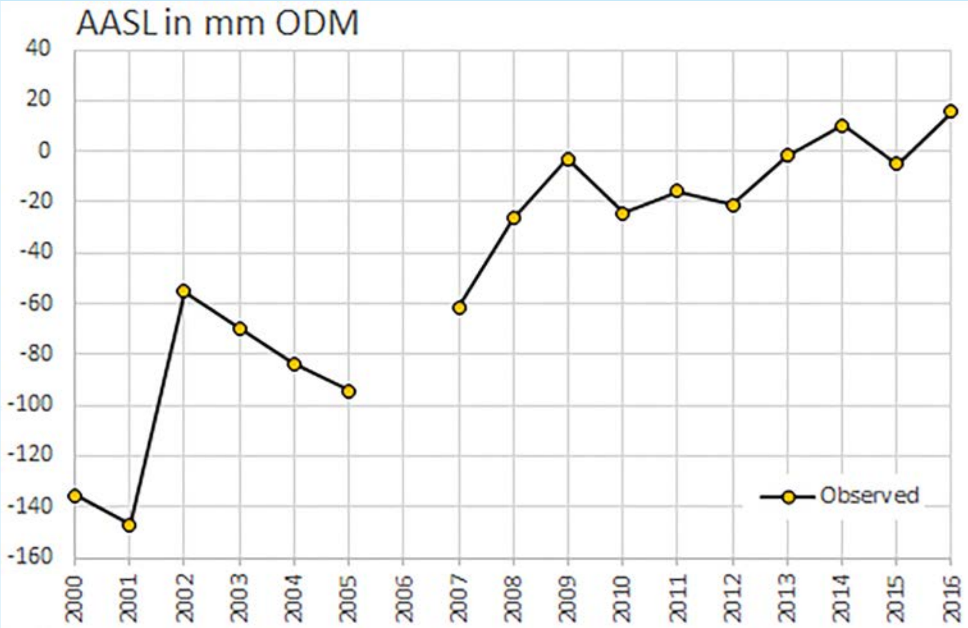


Figure SB3.1. Changes in annual average sea level in Dublin Port (2000–2016)

indication of the range of expected climate change and impacts for Ireland. Sea level rise poses a particular risk for Ireland's coastal cities, so, in developing adaptation strategies for the Dublin area, tide gauge measurements held by Dublin City Council have been analysed. Observed changes in annual average sea level for the period 2000–2016 have been used to identify potential future risks as a result of projected sea level rise. These records indicate substantial increases in the annual average sea level (AASL) over the period (Figure SB3.1) although the reasons for this apparent increase are not certain, and it may be caused by a combination of actual sea level rise, local subsidence and issues with the data themselves. Nonetheless, they highlight a range of potential future risks including changes to coastal deposition of sand and damage to coastal defences, risks to wastewater infrastructure, damage to critical infrastructure and housing and saltwater intrusion into freshwater supplies.

In assessing levels of flood risk, observations from specific events are being employed to identify areas at particular risk. For example, as part of the flood risk management plan, developed by the Office of Public Works and for ranking flood events during the winter of 2015/2016, observations from hydrometric gauges were used to identify areas most exposed to flooding (Figure SB3.2). This information increases our understanding of those areas that are already at

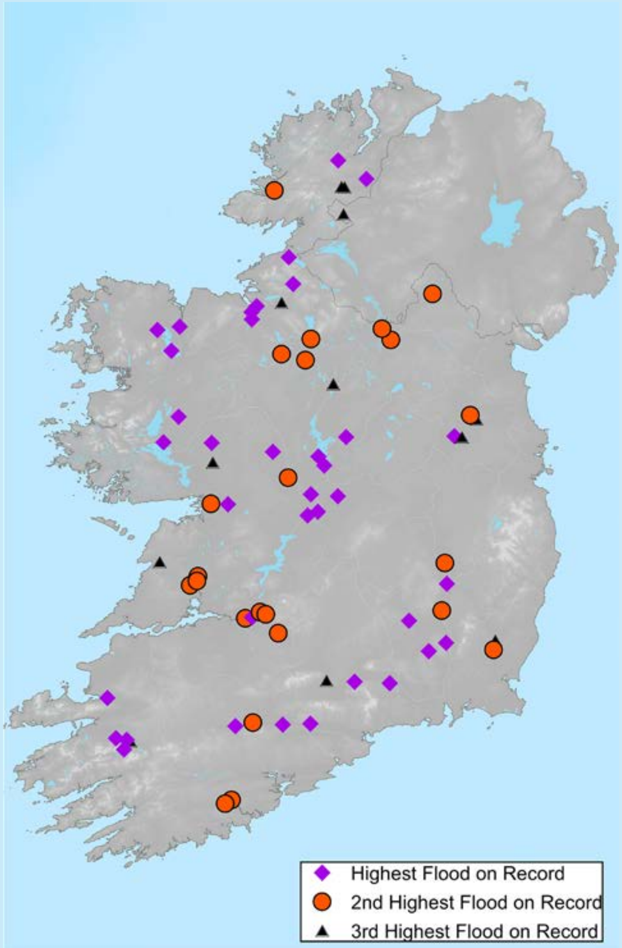


Figure SB3.2. Ranking of the flood event in the winter of 2015/2016 at hydrometric gauges. Source: Generated by the authors from own data and data in Nicholson and Gebre (2016).

particular risk from extreme rainfall events and provides an important basis for understanding which areas might be at increased risk as a result of changing climate conditions.

As climate change progresses, it is essential that up-to-date and reliable observational information is provided to decision-making communities in a timely manner to help decision-makers understand where the changes are occurring and assess the impacts of these changes and the consequences for planning and development.

Further Information

DCCAE, 2018a. *National Adaptation Framework: Planning for a Climate Resilient Ireland*. Department of Communications, Climate Action and Environment, Dublin (https://www.gov.ie/en/publication/fbe331-national-adaptation-framework/)

DCCAE, 2018b. *Local Authority Adaptation Strategy Development Guidelines*. Department of Communications, Climate Action and Environment, Dublin (https://www.gov.ie/en/publication/41066-local-authority-adaptation-strategy-development-guidelines/)

DCCAE, 2018c. *Sectoral Planning Guidelines for Climate Change Adaptation*. Department of Communications, Climate Action and Environment, Dublin (https://www.gov.ie/en/publication/10221107-sectoral-planning-guidelines-for-climate-change-adaptation/)

Codema, 2019. Dublin Climate Change Action Plans (https://dublinclimatechange.codema.ie/)

Office of Public Works, 2018. Flood Risk Management (https://www.gov.ie/en/policy-information/dd855f-flood-risk-management/)

Climate Ireland, 2020. Adaptation at Your Fingertips (https://www.climateireland.ie/)

3. Oceanic Observations

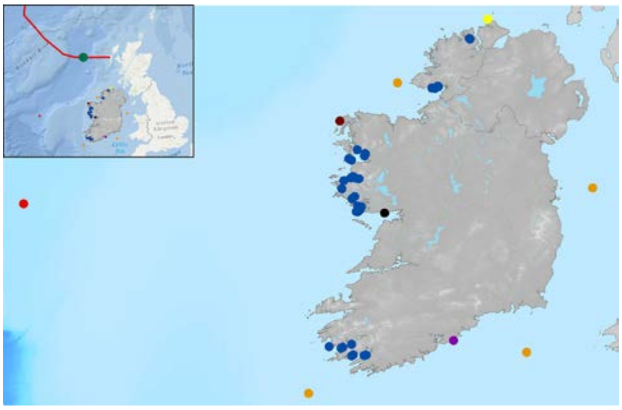
3.1 Ocean Surface and Subsurface Temperature

Walther C.A. Cámaro García, Ned Dwyer, Kieran Lyons, Caroline Cusack and Glenn Nolan

The temperature of the ocean is influenced by a number of factors, including the amount of heat from the sun transferred through the atmosphere to the water, surface and subsurface circulation and current patterns. Heat uptake by the global ocean accounts for more than 90% of the excess heat trapped in the Earth system in the past few decades. This has resulted in an increase in global ocean surface temperatures of approximately 0.7°C since the 1850s, with the rate of warming estimated to have doubled since the 1990s. Marine heatwaves have also increased. Increasing temperature has considerable ecological impacts: it leads to spatial shifts in marine species, including commercial fish and harmful algal blooms, with increased risks to human health, ecosystems and aquaculture.

3.1.1 Measurements

Sea surface temperature (SST) measurements are made by the Irish Marine Data Buoy Observation Network (orange and red dots), at Malin Head Atmospheric Research Station, Co. Donegal (yellow dot), at the Ballycotton tide gauge station, Co. Cork (purple dot), and at wave buoys (brown and black dots) (Map 3.1). A set of coastal temperature sensors (blue



Map 3.1. Location of sea temperature observation stations.

dots, [Map 2.1](#)) installed predominately at aquaculture sites by the Marine Institute measure temperature but are not accurate enough for climate studies.

The Malin Head station has collected SST observations since 1958, which is the longest record available in Irish waters, although water temperature records for parts of the North-east Atlantic go back to 1850.

SST can also be inferred from satellite observations, and SST products generated by the Copernicus Marine Environment Monitoring Service (CMEMS) are derived from different inputs such as those from the ESA Sentinel satellites.

Measurements of subsurface ocean temperature in Irish waters are made by the Marine Institute at the M6 buoy mooring (red dot, [Map 3.1](#)) and at the SmartBay Observatory (black dot) in Galway Bay. Since 2008, the Marine Institute has deployed 20 Argo floats in the North Atlantic; these underwater autonomous profilers measure temperature and salinity down to a depth of 2000 m, and Ireland contributes to international efforts through the Euro-Argo programme. In addition, the Marine Institute routinely collects and archives water temperature observations through several initiatives such as the *Nephrops* underwater television surveys and through conductivity–temperature–depth (CTD) profilers deployed from research vessels.

The average SST at Malin Head over the 10 years from 2009 to 2018 was 0.47°C above the 1981–2010 mean.

3.1.2 Time Series and Trends

Surface temperature

[Figure 3.1](#) shows the annual mean observed SST at Malin Head for the period 1961–2018 (right-hand axis). The left-hand axis indicates anomalies (the difference between the mean annual temperature and the 1981–2010 reference mean value). A trend towards progressive warming can be seen from the mid-1990s to the late 2000s, followed by cooler conditions for a short period and a return to warmer conditions in recent years. Furthermore, all the values observed since the early 2000s are above the 1981–2010 mean. This behaviour is linked to the natural cycle of variability in

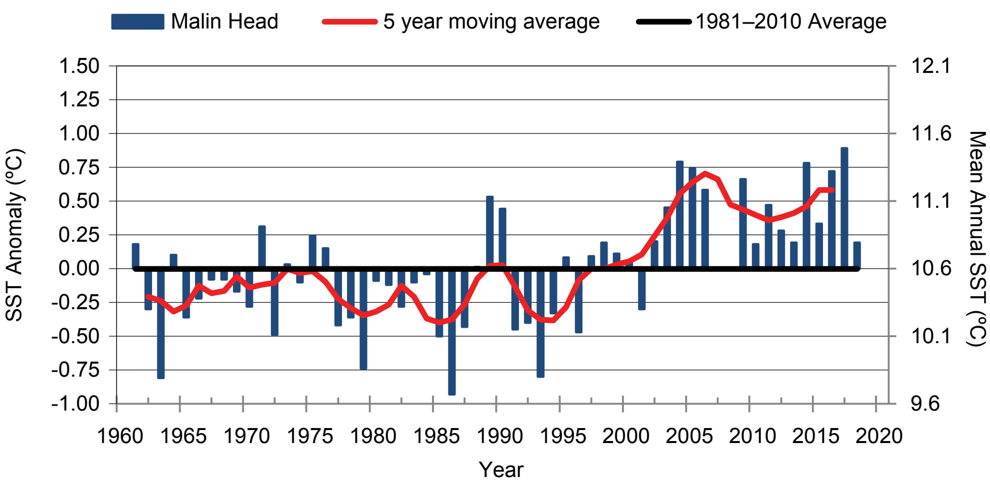


Figure 3.1. Mean annual sea surface temperature and anomalies at Malin Head (1961–2018).

the North Atlantic known as the Atlantic Multi-decadal Oscillation, although approximately half of the recent warming is attributed to an underlying global warming trend. Globally SST has increased by on average 0.15°C per decade over the last three decades.

Figure 3.2 illustrates the average monthly SST around Ireland for different months during 2018, derived from satellite observations included in the CMEMS programme. SSTs observed around the island range between 7°C and 20°C during the year, with July recording the highest values.

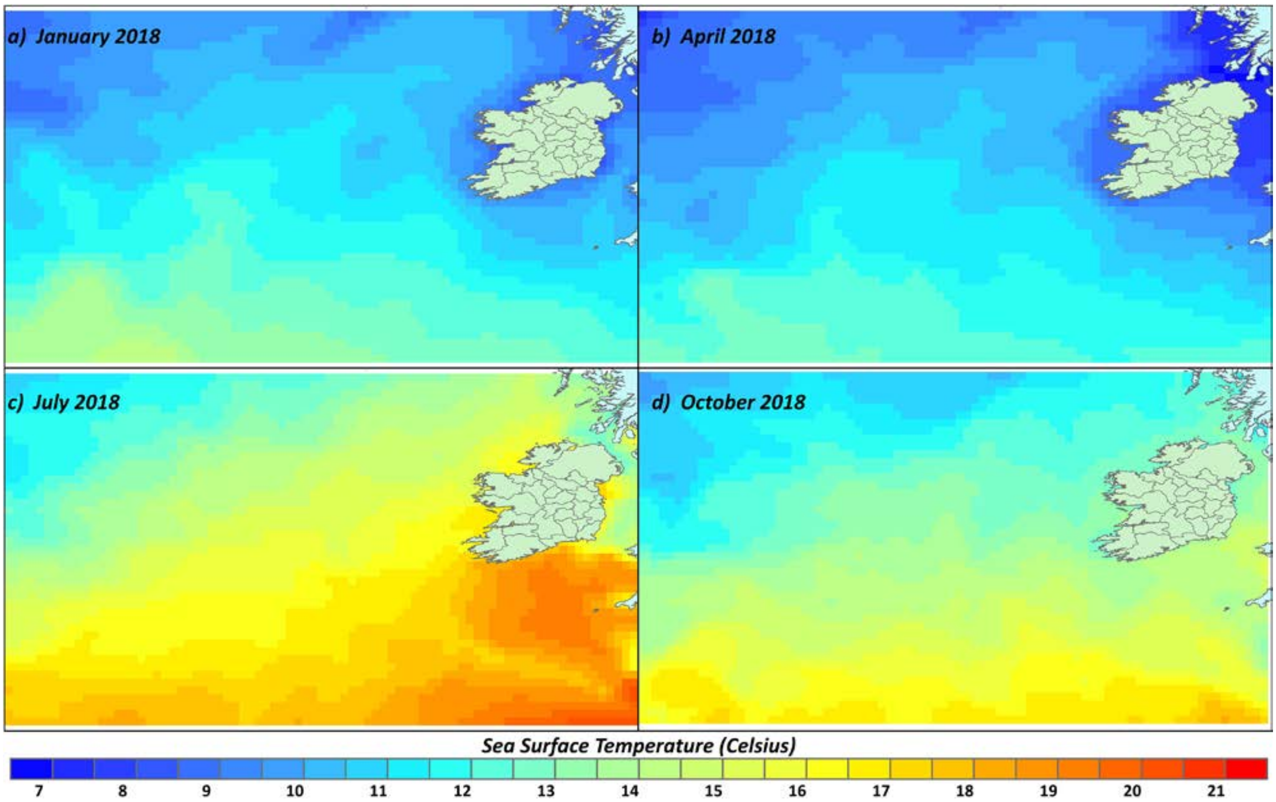


Figure 3.2. Example of sea surface temperature distribution from satellite-based observations extracted from the Copernicus Marine Environment Monitoring Service for (a) January 2018, (b) April 2018, (c) July 2018 and (d) October 2018. Source: Generated by the authors using data from the Copernicus Marine Environment Monitoring Service.

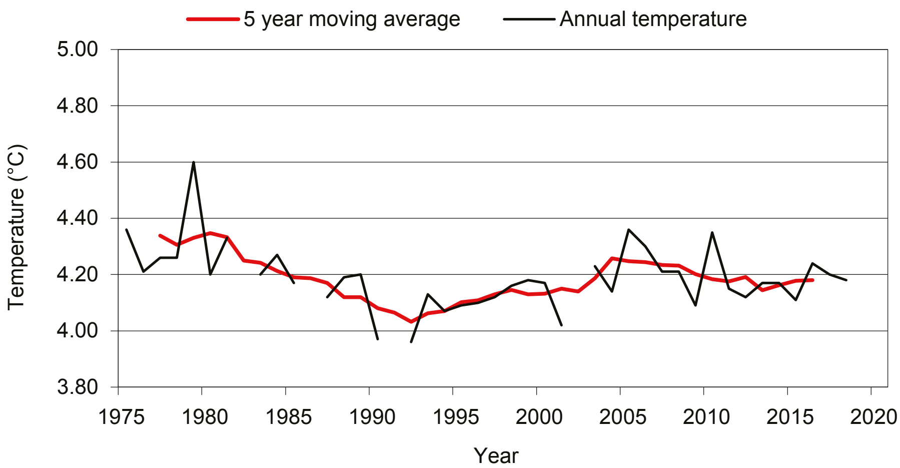


Figure 3.3. Annual water temperature measured at depth (1500–2500 m) in the Rockall Trough on the Extended Ellett Line (1975–2018). Source: Generated by the authors from data provided by the National Oceanography Centre and Scottish Association for Marine Science. See the 2018 *ICES Report on Ocean Climate*.

Subsurface temperature

Since 2005, to the west of Ireland, annual oceanographic surveys have been carried out in the Rockall Trough. The data collected are submitted to the International Council for Exploration of the Sea (ICES). In recent years bad weather has hampered efforts. Currently the closest area to the Irish coast reported in the annual ICES report corresponds to a point on the Extended Ellett Line hydrographic section between Scotland, Rockall and Iceland (see green dot on inset in Map 3.1).

Figure 3.3 shows the annual water temperature at the Rockall Trough at depths between 1500 m and 2000 m on the Extended Ellett Line for the period 1975–2018. Over the time series, there is no significant trend evident.

> It is vital that the temperature sensors at Malin Head and Ballycotton continue to be resourced and maintained as long-term reference sites.

3.1.3 Maintaining the Observations

The temperature sensors at Malin Head and Ballycotton are maintained by the Marine Institute. The Irish Marine Data Buoy Observation Network is managed by the Marine Institute in collaboration with Met Éireann and the UK Met Office. It is funded on an annual basis by the DAFM.

The *Nephrops* underwater television surveys monitor Dublin Bay prawns (*Nephrops norvegicus*) in Irish waters and are part of Ireland's Data Collection Scheme which is carried out under Ireland's Operational Programme, co-funded by the European Maritime and Fisheries Fund (EMFF) and by the Irish Government.

Since 2008, Ireland has deployed Argo floats as part of the Euro-Argo programme and through the Marine Institute, facilitated by support from the DAFM, joined the Euro-Argo ERIC as a full member in 2016. This initiative is part of a global array of autonomous instruments, reporting subsurface ocean water properties to a wide range of users.

Further Information

Sea Surface Temperature Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/sst)

Sea Subsurface Temperature Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/subsurface-temperature)

Cannaby, H. and Hüsrevoğlu, Y.S., 2009. The Influence of low-frequency variability and long-term trends in Irish SST records. *ICES Journal of Marine Science* 66: 1480–1489. https://doi.org/10.1093/icesjms/fsp062

Tinker, J. and Howes, E.L., 2020. The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 1–30. https://doi.org/10.14465/2020.arc01.tem

Annual ICES Report on Ocean Climate (IROC) (https://ocean.ices.dk/iroc/#)

Marine Institute data portal (http://data.marine.ie/)

Information from the Irish Marine Data Buoy Observation Network (http://www.marine.ie/Home/site-area/data-services/real-time-observations/integrated-marine-observations)

Copernicus Marine Environment Monitoring Service ocean products (https://marine.copernicus.eu)

Information about *Nephrops* underwater television survey (https://www.marine.ie/Home/site-area/areas-activity/fisheries-ecosystems/nephrops-under-water-tv-surveys)

Information about the Euro-Argo programme (https://www.marine.ie/Home/site-area/areas-activity/oceanography/euro-argo)

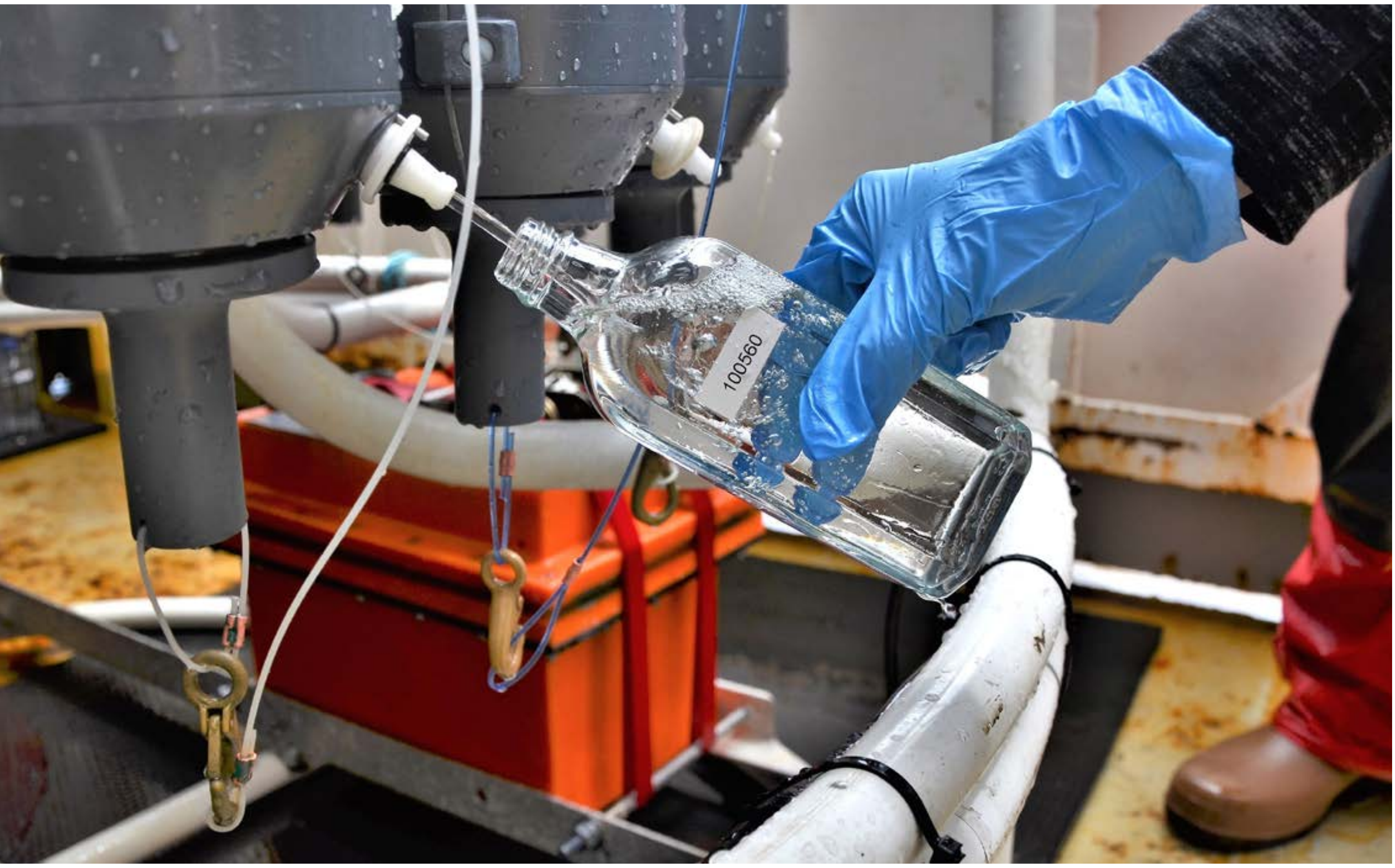
Information about the Extended Ellet Line (https://mars.noc.ac.uk/projects/extended-ellet-line)

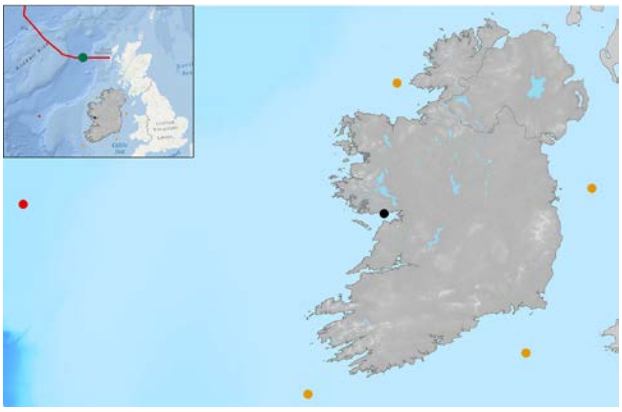
NOAA National Centers for Environmental Information: Climate at a Glance global time series (https://www.ncdc.noaa.gov/cag/)

3.2 Ocean Surface and Subsurface Salinity

Walther C.A. Cámaro García, Ned Dwyer, Caroline Cusack, Evin McGovern and Glenn Nolan

Salinity is defined as the total amount of dissolved salts in water. These salts constitute approximately 3.5% of the ocean's mass. Decadal changes have been observed, and an unprecedented reduction in salinity levels has been observed in recent years in the North-east Atlantic, based on an analysis of 120 years of data. Globally, areas that currently have net evaporation are expected to become saltier at the ocean surface, while areas with net precipitation, increased river run-off and land ice melt are expected to get fresher. However, ocean currents may transport water masses thousands of kilometres from where they were formed. Salinity and temperature control water density and are key variables for identifying and tracing ocean water masses and for understanding ocean physical processes. Monitoring of changes in ocean salinity is an indirect method of detecting changes in precipitation, evaporation, river run-off and ice melt and therefore helps in understanding changes in the Earth's hydrological cycle.





Map 3.2. Location of sea surface and subsurface salinity observation stations.

3.2.1 Measurements

Sea surface salinity measurements are made across the Irish Marine Data Buoy Observation Network (orange and red dots, Map 3.2). Some subsurface salinity measurements in Irish waters are made by the Marine Institute at the M6 buoy location (red dot), at the SmartBay Observatory (black dot) and since 2008 with underwater autonomous profilers as part of the Euro-Argo programme.

In addition, the Marine Institute routinely collects and archives water salinity observations through several initiatives and projects and through ships working with CTD profilers.[8] As part of Ireland's Water Framework Directive (WFD) monitoring programme salinity measurements are made by the EPA in a number of estuaries and nearshore coastal waters.

Sea surface salinity can be monitored from space at a coarse spatial resolution following the launch of the ESA SMOS (soil moisture ocean salinity) mission in 2010 and NASA's Aquarius mission in 2011. Both use sensors that detect microwave radiation emitted from the ocean surface from which salinity levels can be inferred. *In situ* measurements are required to validate these satellite-derived observations, especially in colder North Atlantic waters, where there are still significant differences between the satellite-derived and ship-based salinity measurements.

> Between 2016 and 2018, salinity was the lowest observed in the Rockall Trough since 1978.

3.2.2 Time Series and Trends

Since 2005, to the west of Ireland, multiple scientific surveys have been carried out in the Rockall Trough with full-depth CTD profiles and high-accuracy salinometer measurements of discrete water samples. Data collected are submitted to ICES to contribute to international efforts focused on oceanic conditions in the Atlantic region. However, poor weather conditions have hampered winter surveys in recent years.

Figure 3.4[9] shows the annual observed salinity in the North Rockall Trough at depths between 30 m and 800 m from 1975 to 2018 (see green dot on inset survey line in Map 3.2). An increasing salinity trend can be observed in the earlier decades, followed by a decreasing trend, representing a freshening of the water, in the late 2000s and reaching the lowest recorded values since 1978 between 2016 and 2018. A decrease in near-surface water temperature in this area has also been observed in recent years.

8 CTD profilers determine salinity from measurements of water electrical conductivity.

9 Ocean salinity is measured in units of PSU (practical salinity unit), which is a unit based on the properties of seawater conductivity. It is equivalent to per thousand or (0/00) or to g/kg.

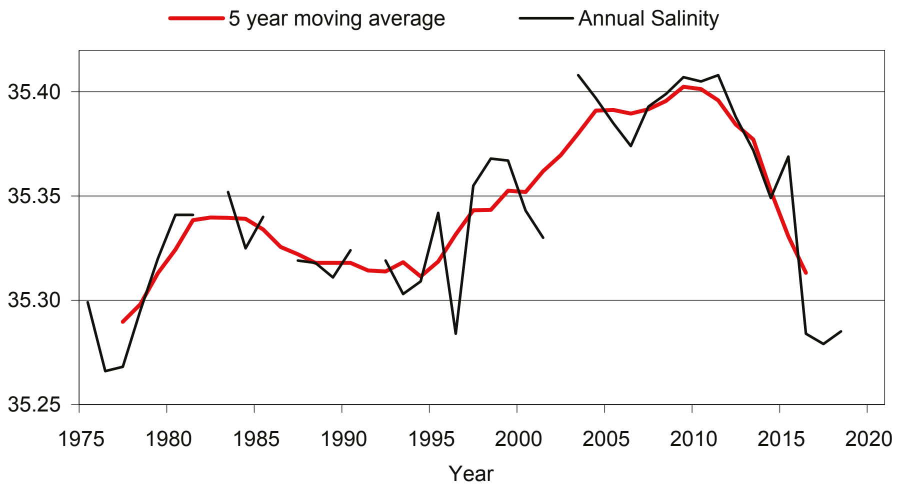


Figure 3.4. Mean annual upper ocean (top 800 m) salinity in the North Rockall Trough (1975–2018).

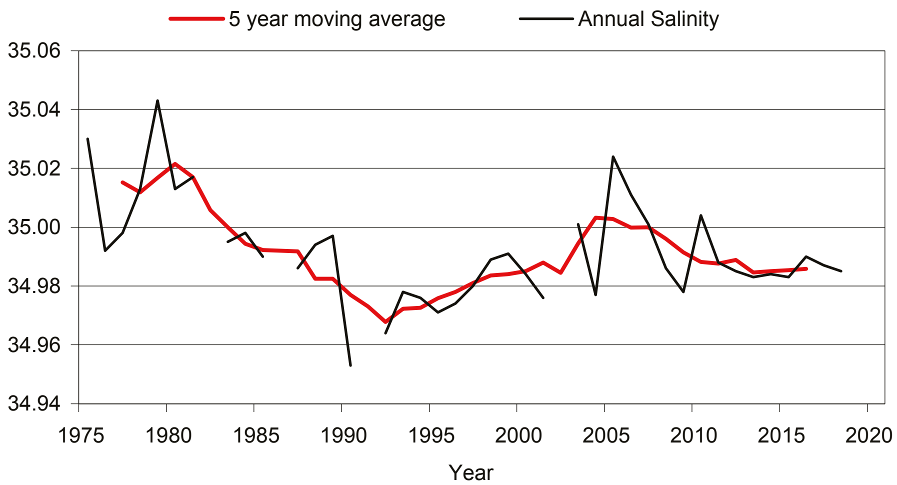


Figure 3.5. Mean annual deep ocean salinity, at depths of between 1500 m and 2000 m, in the North Rockall Trough (1975–2018).

Figure 3.5 shows the annual observed water salinity in the North Rockall Trough at depths between 1500 m and 2000 m from 1975 to 2018. Salinity decreased from the 1970s to the mid-1990s, representing a freshening of the water, after which there has been a gradual increase in salinity, with the values observed in 2018 close to the long-term mean.

Regular measurements of salinity need to be maintained to help our understanding of the hydrological cycle and ocean circulation.

3.2.3 Maintaining the Observations

The Irish Marine Data Buoy Observation Network is managed by the Marine Institute in collaboration with Met Éireann and the UK Met Office. It is funded on an annual basis by the DAFM. Deep sea salinity observations are made on the annual South Rockall Trough survey, funded under the National Development Plan ship-time fund and through internal Marine Institute funding.

Since 2008 Ireland has deployed Argo floats as part of the Euro-Argo programme and, through the Marine Institute, facilitated by support from the DAFM, joined the Euro-Argo ERIC as a full member in 2016. This initiative is part of a global array of autonomous instruments, reporting subsurface ocean water properties, including salinity, to a wide range of users.

Further Information

Sea Surface Salinity Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/surface-salinity)

Subsurface Salinity Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/subsurface-salinity/)

Holliday, N.P. *et al*., 2020. Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. *Nature Communications* 11: 585. https://doi.org/10.1038/s41467-020-14474-y

Annual ICES Report on Ocean Climate (IROC) (https://ocean.ices.dk/iroc/#)

Marine Institute data portal (http://data.marine.ie/)

Information from the Irish Marine Data Buoy Observation Network (http://www.marine.ie/Home/site-area/data-services/real-time-observations/integrated-marine-observations)

Information about the Euro-Argo programme (https://www.marine.ie/Home/site-area/areas-activity/oceanography/euro-argo)

Information about the Extended Ellett Line (https://mars.noc.ac.uk/projects/extended-ellet-line)

About NASA's Aquarius mission (https://aquarius.oceansciences.org/cgi/gal_smap.htm)

About ESA's SMOS mission (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/smos)

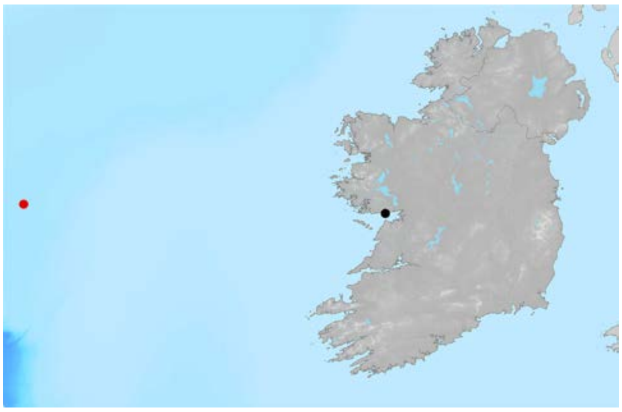
Water Quality in Ireland 2013–2018 (https://www.catchments.ie/water-quality-in-ireland-2013-2018/)

3

3.3 Ocean Surface and Subsurface Currents

Walther C.A. Cámaro García, Ned Dwyer, Caroline Cusack, Evin McGovern and Glenn Nolan

Ocean currents transport heat, salt, fresh water, carbon and ocean pollutants from one part of the ocean to another and play a key role in determining climate conditions and weather fluctuations. Their observation is important for generating accurate marine sea state forecasts and for understanding ocean dynamics. The Atlantic Meridional Overturning Circulation (AMOC) and the North Atlantic Current, which is commonly known as the Gulf Stream, form the main conveyor belt of relatively warm and saline subtropical waters north-eastwards across the Atlantic Ocean. As it cools and gets saltier at northern latitudes the water ultimately sinks and returns south at depth. Such currents maintain the temperate climate conditions in north-western Europe. Observations of the AMOC since 2004 indicate that it has weakened relative to the period 1850–1900 and it is predicted to continue weakening throughout this century (see Story Box 4).



Map 3.3. Location of subsurface current observation stations.

3.3.1 Measurements

There are no permanent operational moored current meter arrays in the ocean area adjacent to Ireland. Large-scale North Atlantic physical oceanographic studies are conducted annually by combining information from the scientific surveys of multiple countries. Information on ocean currents is available from numerical models or, in the case of surface currents, from satellite estimations of sea level dynamics. Validation is an essential step to verify the quality of the numerical models and to identify any limitations. Model validation can be provided only by the *in situ* ocean observing system.

Regarding *in situ* current measurements made by the Marine Institute, stations where this is carried out include the Galway Bay Observatory (black dot, Map 3.3) and the M6 buoy (red dot). In addition, current measurements are routinely made by several ocean-observing initiatives such as the Euro-Argo programme (autonomous drifters, large-scale circulation patterns) and the deployment of acoustic Doppler current profilers (ADCPs[10]) at local stations that collect information on currents for research purposes.

Globcurrent is an ESA-funded project and is the main repository of quantitative estimations of surface currents based on several parameters derived from satellite sensor measurements.

10 An ADCP transmits sound waves that are reflected from particles moving in the water. It uses the Doppler effect to calculate the velocity of these particles and hence the currents.

Although multi-annual and decadal changes in the strength of the North Atlantic Current have been recorded, there is no coherent evidence of a long-term trend.

3.3.2 Time Series and Trends

Figure 3.6 is a schematic representation of the circulation of upper ocean currents in the North Atlantic. Blue arrows represent the movement of cool water and red arrows show the known pathways of warm water. The surface water transport branch to the west of Ireland is the North Atlantic Current and, although multi-annual and decadal changes in its strength have been recorded, including slowing in recent years, there is no coherent evidence of a long-term trend.

In the Irish Shelf seas, the Irish coastal current travels in a clockwise direction from the Celtic Sea (in the south) to the Malin Shelf (in the north) (see black arrow in Figure 3.6). This coastal current is associated with the boundaries between shallow areas, where waters remain vertically mixed throughout the year, and deeper regions, where stratification[11] occurs in summer. The red arrow with the closest proximity to Ireland represents the Shelf Edge Current (also known as the European Slope Current), which is considered an important pathway for the eggs and larvae of various fish species. The strength and continuity of the main currents in Irish waters fluctuate over seasonal and annual time scales in response to changes in large-scale ocean atmospheric forcing.

The lack of a sustained long-term ocean current monitoring system in Irish waters represents a significant gap in the North-east Atlantic.

11 Stratification is when water masses with different properties (e.g. density, salinity, temperature, oxygen levels) form layers that act as barriers to water mixing.

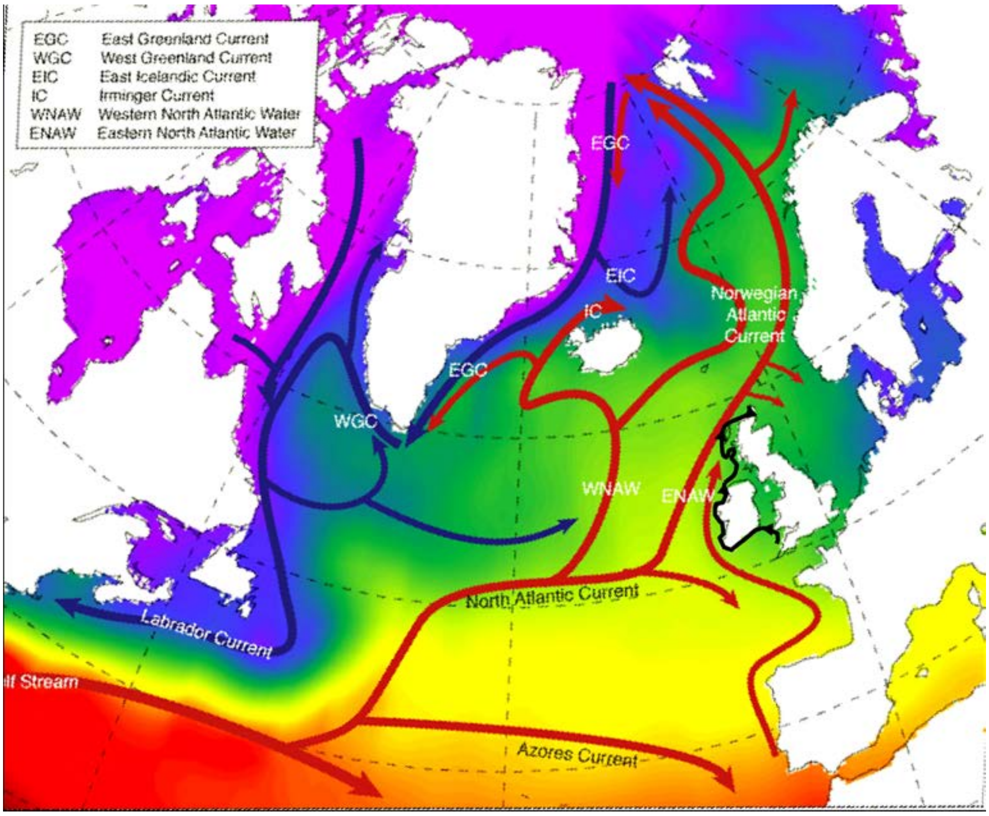


Figure 3.6. Schematic diagram showing the general circulation of the upper ocean (0–100 m) in the North Atlantic. Source: ICES Report on Ocean Climate 2018 (ICES, 2019).

3.3.3 Maintaining the Observations

There is no long-term Irish-operated ocean current monitoring system in place. Such a system would fill a significant gap in the North-east Atlantic, and it would be particularly useful in the Shelf Edge Current to monitor variability in the major source of water from the Atlantic to the Nordic Seas. However, there are no plans or funding to sustain long-term monitoring of ocean currents and their water properties at present.

Science Foundation Ireland funded the Irish Ocean Observing System (EirOOS) project in 2019. This will facilitate, at least in the short term, the deployment of current meters to improve our understanding of Atlantic Ocean currents.

Since 2008 Ireland has deployed Argo floats as part of the Euro-Argo programme and, through the Marine Institute, facilitated by support from the DAFM, joined the Euro-Argo ERIC as a full member in 2016. This initiative is part of a global array of autonomous instruments, reporting subsurface ocean water properties, including currents, to a wide range of users.

Further Information

Surface Currents Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/surface-currents/)

Subsurface Currents Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/subsurface-currents/)

Holliday, N.P. *et al*., 2020. Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. *Nature Communications* 11: 585. https://doi.org/10.1038/s41467-020-14474-y

Annual ICES Report on Ocean Climate (IROC) (https://ocean.ices.dk/iroc/#)

Information about the Euro-Argo programme (https://www.marine.ie/Home/site-area/areas-activity/oceanography/euro-argo)

Information about Globcurrent (http://www.globcurrent.org/)

Information about the main ocean current pathways around Ireland on Ireland's Marine Atlas (https://atlas.marine.ie/)

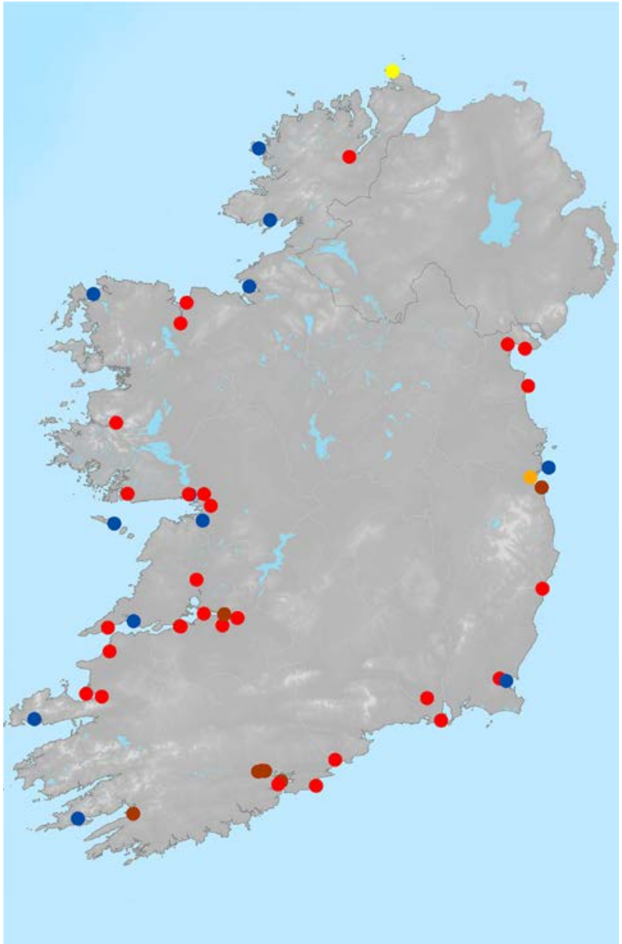
3.4 Sea Level

Walther C.A. Cámaro García, Ned Dwyer, Guy Westbrook, Glenn Nolan, Rosemarie Lawlor, Sarah Gallagher and Gerard McCarthy

Sea level is among the primary indicators of global climate change. Most of the major cities in Ireland are in coastal locations, and further rises in sea level will have major economic, social and environmental impacts. Estimates show that globally the average sea level has risen approximately 160 mm since 1902, at a rate of approximately 1.4 mm per year, but the most recent estimates derived from satellite measurements for the period 2006–2015 indicate a rise of 3.6 mm per year. Sea level continues to rise because increasing global temperatures cause thermal expansion of the ocean, as well as because of increasing freshwater input due to melting land ice sources (e.g. glaciers and ice sheets, permafrost). An additional contributor to relative sea level change, called "glacial isostatic adjustment", has caused the land in the north of Ireland to rise compared with the south of the island, as it recovers after the loss of the huge mass of ice that covered it during the last Ice Age.

3.4.1 Measurements

Measurements of sea level rely on high-precision contemporaneous measurements of sea and land levels. Measurements of relative sea levels are mainly made by a network of tide gauges around the Irish coast, which are operated by a number of different bodies including the Marine Institute (blue dots), the OPW (red and yellow dots), local authorities and port companies (brown and orange dots) (Map 3.4). The EPA Gauging Station Register is a national inventory of all gauges, including tide gauges. The longest continuous records for Ireland are from Dublin Port (orange dot, Map 3.4) where a tide gauge has been in operation since at least 1923, with digitised records available from 1938, and from Malin Head, Co. Donegal (yellow dot, Map 3.4), in operation since 1958. Not all tide gauge measurements can be used for sea level trend monitoring. The high-precision standards of the GLOSS are the benchmark in this respect. The OPW-operated tide gauge at Malin Head was upgraded to operate to GLOSS standards during 2020. It is the intention of the Marine Institute to have pre-operational GLOSS-compliant tide gauges at Union Hall, Co. Cork, and Howth, Co. Dublin, in 2021.



Map 3.4. Location of tide gauges for tide level observation.

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Sea level can also be derived from measurements from space-borne sensors. A number of different satellites are used. For example, data from the TOPEX/Poseidon and Jason altimeters and from the ESA Sentinel-3 altimeter are used to derive sea level products. However, satellite measurements require careful calibration, and the most common method uses tide gauges.

Satellite observations indicate that the sea level around Ireland has risen by approximately 2–3 mm per year since the early 1990s.

3.4.2 Time Series and Trends

Figure 3.7 shows tide gauge measurements at four different locations, in the north, west, south and east, respectively, since the mid-2000s. The time series are not yet long enough to accurately determine any trend. Moreover, any land elevation changes due to glacial isostatic adjustment or other factors are not taken into account.

Tide gauge measurements have been made at Dublin Port since 1938. Digital records are held by Dublin City Council. The gauge has been operated by different organisations over the period, resulting in uncertainty in the record.

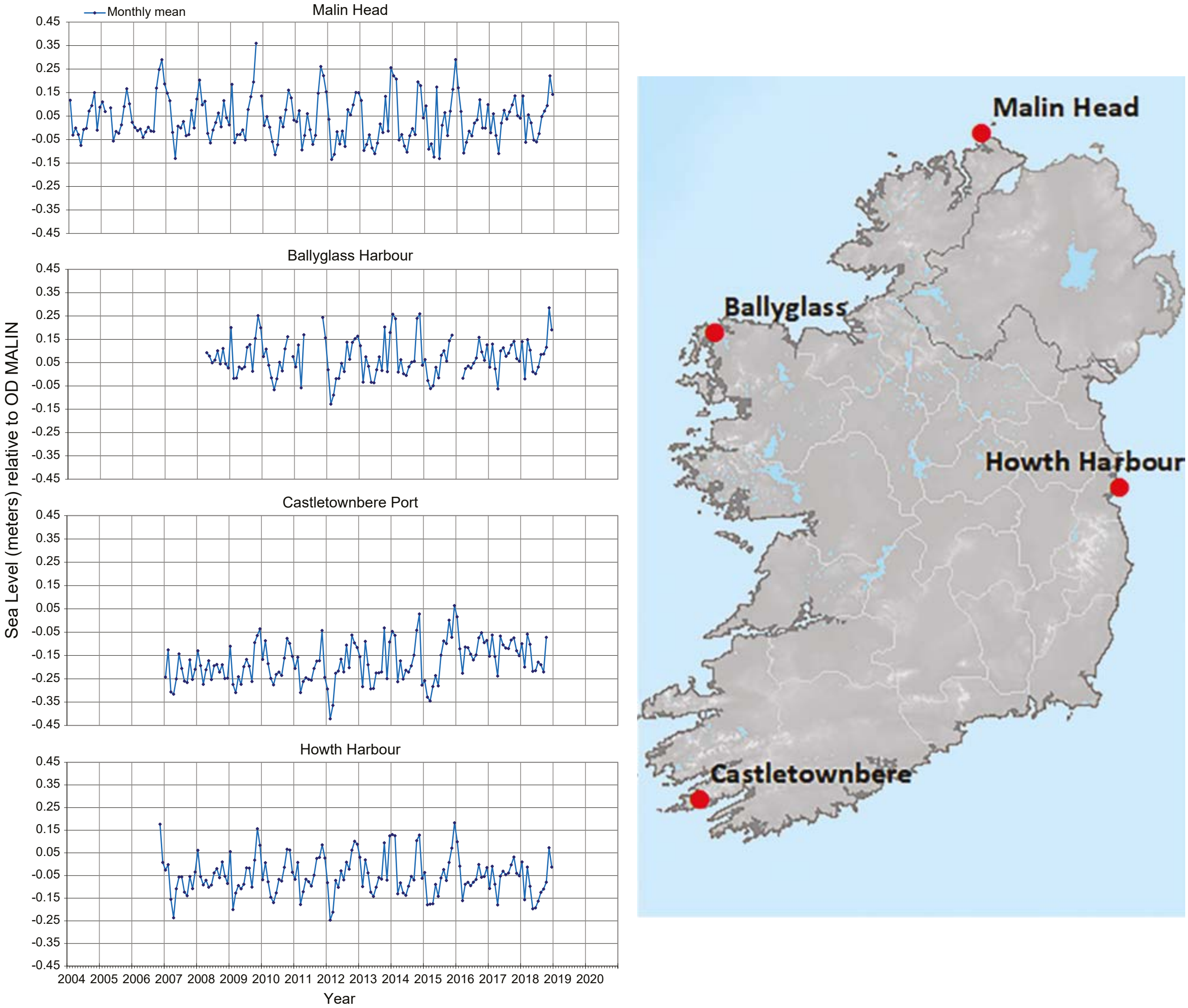

Figure 3.7. Monthly mean sea level observed at Malin Head, Co. Donegal, Ballyglass Harbour, Co. Mayo, Castletownbere, Co. Cork, and Howth, Co. Dublin, since the mid-2000s. Data are collected continuously at these sites with 15-minute intervals between measurements.

Figure 3.8 shows the complete time series for the Dublin Port monthly mean sea level from 1938 to 2016 (updated by Maynooth University). Since the 1980s there has been significant variability in the record, with an upward trend over the last 25 years. The attribution of this recent increase is not certain. However, taken over the full time period, the sea level in Dublin has risen by 1.67 mm per year, consistent with global rates.

Figure 3.9 shows a global map of trends in sea level derived from a number of satellite altimeters, including TOPEX/Poseidon and the Jason series over the period 1992–2019. In the North-east Atlantic near Ireland, the sea level is estimated to be increasing by on average 2–3 mm per year over the 28-year period analysed.

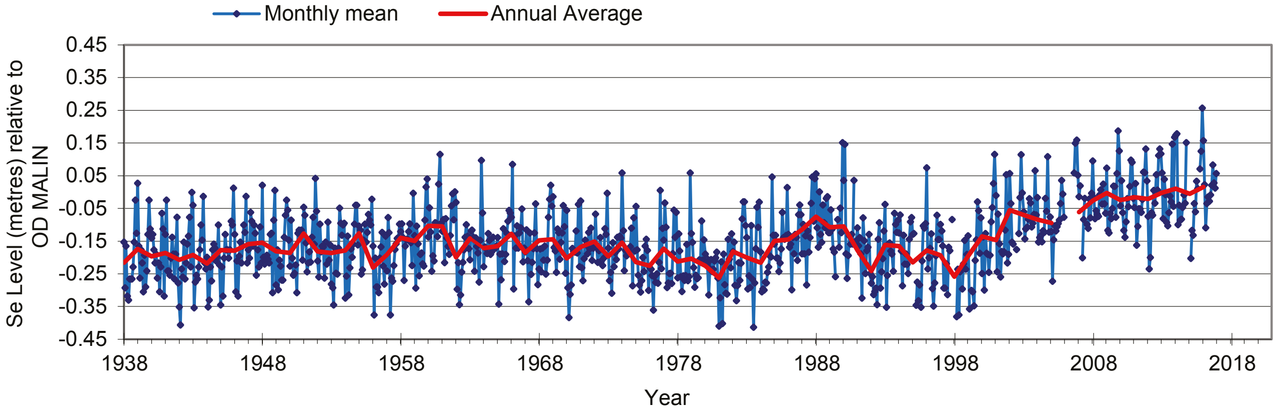

Figure 3.8. Monthly mean sea level observed at Dublin Port (1938–2016). The annual average sea level is also shown.

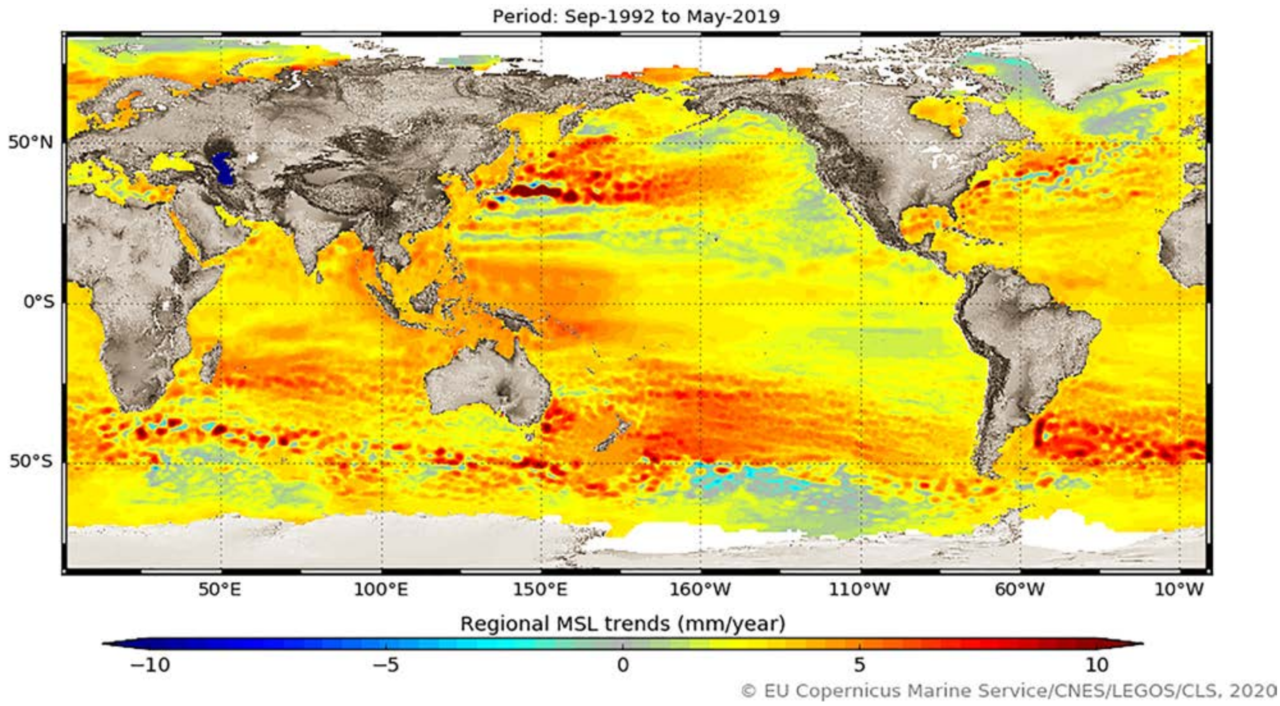

Figure 3.9. Global trends in sea level derived from satellite observations (September 1992 to May 2019). Sources: Copernicus Marine Environment Monitoring Service and CNES, LEGOS and CLS group. © CMEMS/CNES/LEGOS/CLS.

The establishment of a National Sea Level Measurement Advisory Group and a co-ordination function within an existing organisation has been proposed.

3.4.3 Maintaining the Observations

A comprehensive network of tide gauges is currently installed around the coast. These report data to various levels of certainty and are owned and managed by multiple organisations. There is a need for co-ordination of a fit-for-purpose subset of this network to meet the need for relevant and reliable information on sea level.

The establishment of a National Sea Level Measurement Advisory Group and a co-ordination and operational GLOSS system management function within an existing organisation has been proposed. However, additional and dedicated financial and human resources are required to establish and support this on an ongoing basis. The installation of appropriate infrastructure (civil engineering) represents a significant hurdle to progressing this work. The EirOOS infrastructure (funded by Science Foundation Ireland) will provide the capital equipment for two GLOSS-standard gauges in the coming years. Partly because of glacial isostatic adjustment, the rate of sea level change is not the same at all points on the coast. In general, the north-east of the island experiences lower rates of relative sea level rise than the south-west. Therefore, it is important that observations are made at a number of representative locations and that the data collected are fit for use in international climate change assessments.

Further Information

Sea Level Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/sea-level/)

Nejad, A.S. *et al.*, 2020. Recent sea level rise on Ireland's east coast based on multiple tide gauge analysis. Ocean Science Discussions (preprint in review). (https://www.researchgate.net/publication/346198745_Recent_sea_level_rise_on_Ireland's_east_coast_based_on_multiple_tide_gauge_analysis)

Dataset on tidal observations from the Irish National Tide Network project portal (http://www.Irishtides.ie)

Hydrometric data from the Office of Public Works (https://waterlevel.ie/group/16/)

Dataset from the GLOSS sea level data centres (https://www.gloss-sealevel.org/data)

Tide gauge data from around the world (https://www.psmsl.org/data/)

Information on sea level retrieved from altimeters operated by the Copernicus programmes (https://duacs.cls.fr/)

Sea level in the European State of the Climate 2018 bulletin (https://climate.copernicus.eu/sea-level)

Sea level global and regional interactive products based on satellite information (https://www.aviso.altimetry.fr/?id=1599)

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3.5 Sea State

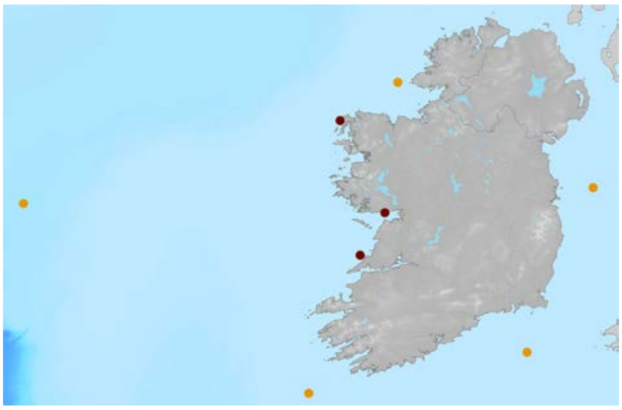
Walther C.A. Cámaro García, Ned Dwyer, Guy Westbrook, Kieran Lyons and Alan Berry

Observations of wave height, direction, length, frequency and swell are relevant for monitoring changes in the marine environment, such as winds, storms and extreme events. Knowledge of the sea state and how it is changing is also vital for marine safety, marine transport, ocean energy development, coastal erosion and storm-related flooding, among others. Increasing wave heights have been observed over the last 70 years in the North Atlantic with typical winter season trends of increases up to 20 cm per decade, along with a northward displacement of storm tracks.

3.5.1 Measurements

Wave height and wave period measurements have been made at the Irish Marine Buoy Observation Network (orange dots) since 2002, and since 2013 wave direction has also been measured (Map 3.5). Wave height, period and direction measurements are also made as part of the Ocean Energy Programme by the Waverider network (brown dots, Map 3.5), operated by the Marine Institute.

Radar altimeters, on board a number of satellites including the Jason and Sentinel series, make measurements from which wave height and wave frequency can be inferred. *In situ* measurements are required to calibrate and validate such data.



Map 3.5. Location of sea state observation stations.

In early 2018 particularly high wave values were observed at the M3 buoy near the south-west coast.

3.5.2 Time Series and Trends

The longest available wave time series, since 2002, is available from the M3 buoy located off the south-west coast (Map 3.5). Figure 3.10 shows average daily significant wave height (H_s)[12] for part of this time series (2016–2018). Seasonal variations are evident; however, there are several gaps in the datasets. No comprehensive analysis of wave parameters has been carried out for the buoy data.

The M2 buoy located in the Irish Sea, east of Dublin (Map 3.5), collected wave data in the period 2002–2018. Figure 3.11 shows a heat map of the monthly average of the complete time series for significant wave height for the M2 and M3 buoys. Red represents the values that occur only 5% of the time (the 95th percentile) when data from both buoys are combined and indicate the

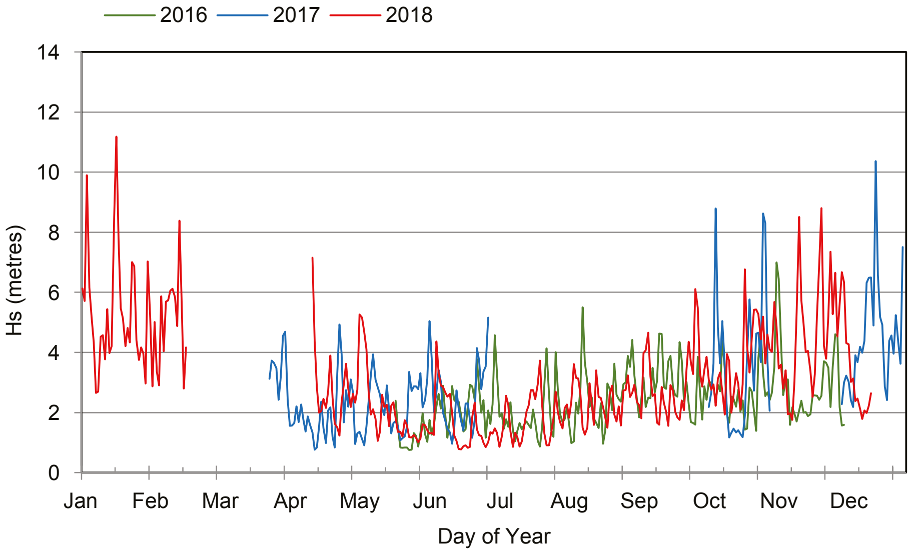


Figure 3.10. Daily average significant wave height at buoy M3 (2016–2018).

12 This is the average of the highest one-third of waves in a given period. Larger waves can cause the most storm damage or pose threats to navigation.

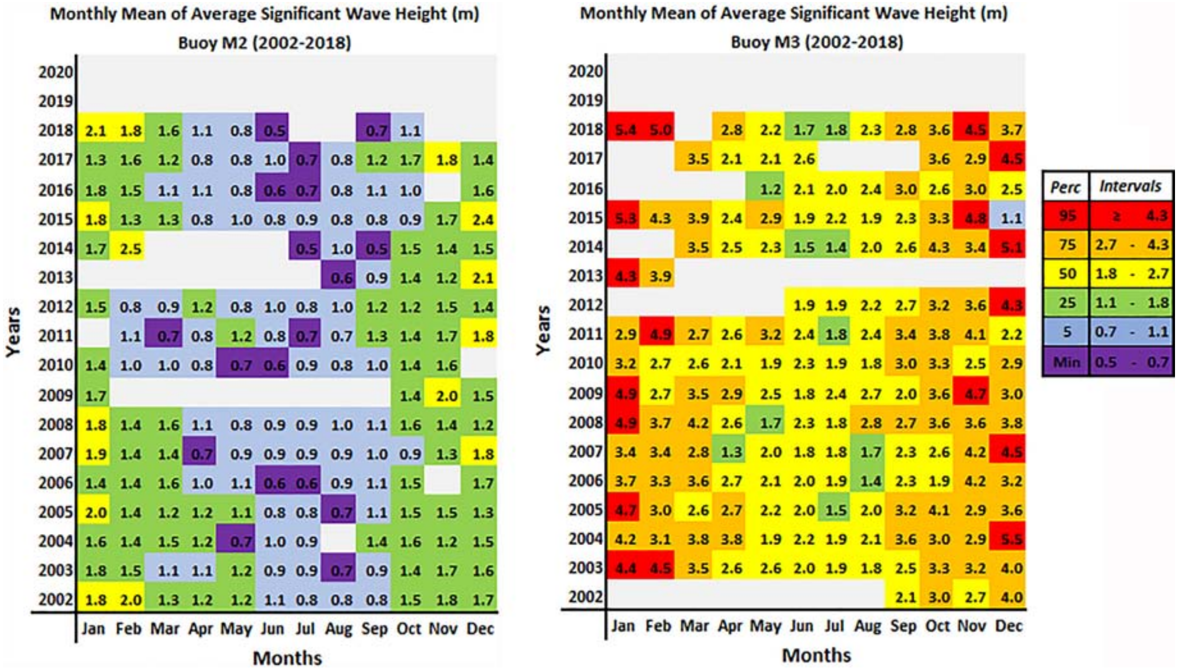


Figure 3.11. Heat map of monthly mean of average significant wave height (m) at buoys M2 (left) and M3 (right) (2002–2018). The data are presented as percentiles of all data combined for both buoys. For example, the 75th percentile means that 75% of all of the values are below 2.7 m and 25% of the values are above it.

months with the greatest significant wave heights. The values observed at the M3 buoy are higher than those observed at M2, which is in a less exposed location. Both buoys record seasonal variations, with higher values during winter. However, monthly average data do not give a good indication of extreme wave events because of the episodic nature of storms.

Figure 3.12 shows the daily significant wave heights, determined by merging multi-mission altimeter data

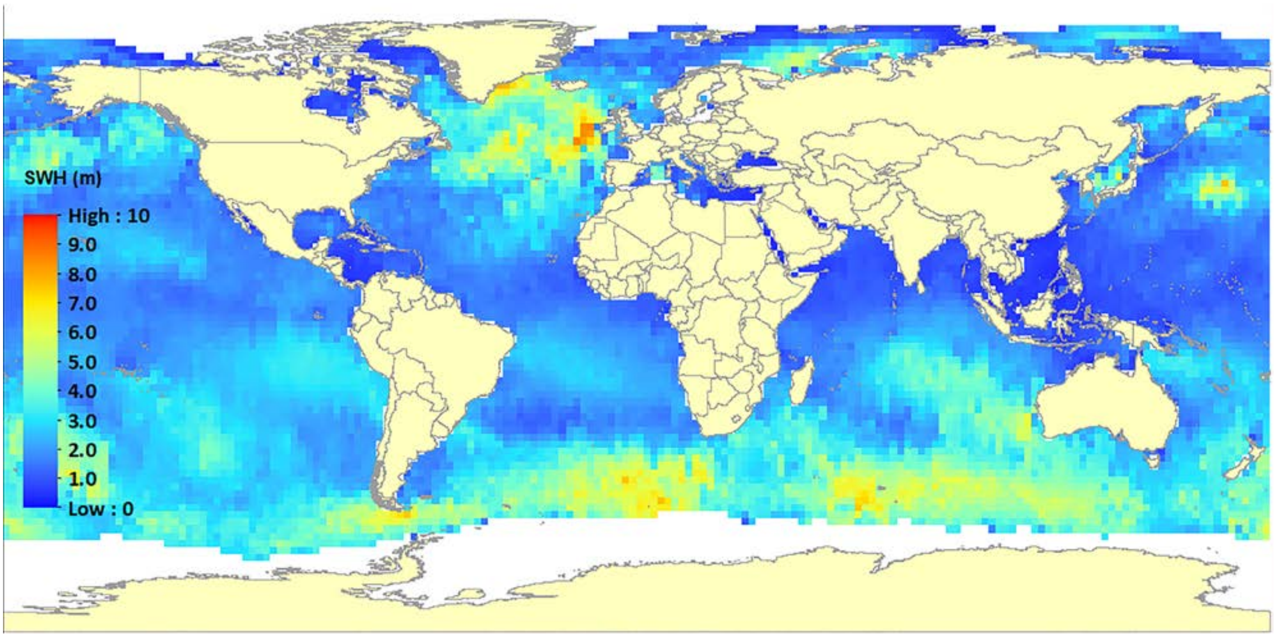


Figure 3.12. Example of global significant daily wave heights estimated from several satellite altimeter products for 3 October 2019. Source: Generated by the authors using information from the Copernicus Marine Environment Monitoring Service.

products, including from the Jason-3 and Sentinel-3 satellites, for 3 October 2019. This is one of the Copernicus Marine Environment Monitoring Service products available since 2019. Note the large waves close to the Irish coast, corresponding to Storm Lorenzo, which occurred during this period.

> It is essential that the Irish Marine Buoy Observation Network and Ocean Energy Waverider network continue to be resourced as long-term sea state reference sites.

3.5.3 Maintaining the Observations

The Irish Marine Data Buoy Observation Network is managed by the Marine Institute in collaboration with Met Éireann and the UK Met Office. It is funded on an annual basis by the DAFM.

The Marine Institute provides operational services for the marine renewable energy sector under the Ocean Energy Programme. As part of this programme, the wave climate is monitored through the Irish national Waverider network.

Comprehensive analysis of sea state data collected in national waters is required.

Further Information

Sea State Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/sea-state/)

Dataset from the Irish national Waverider network (http://www.digitalocean.ie/)

Information from the Irish Marine Weather and Wave Buoy Network (http://www.marine.ie/Home/site-area/data-services/real-time-observations/integrated-marine-observations)

Information about the Ocean Energy Programme (https://www.marine.ie/Home/site-area/infrastructure-facilities/ocean-energy/marine-renewable-energy)

Copernicus Marine Environment Monitoring Service ocean products (https://marine.copernicus.eu)

Story Box 4. Cooler, stormier future a possibility as Gulf Stream system weakens

Gerard McCarthy

The Gulf Stream system

Ireland owes its relatively mild climate to prevailing south-westerly winds and heat released from the ocean. Warm, moist air influencing the climate on land is typical of any maritime climate; however, the heat carried by the system of ocean currents known as the Atlantic Meridional Overturning Circulation (AMOC) makes the Atlantic unique and gives Ireland a milder climate than maritime areas at a similar latitude bordering the Pacific, for example. Strong evidence exists that the AMOC will weaken in this century because of climate change, with ongoing observations indicating that weakening is already occurring.

The AMOC is often conflated with the Gulf Stream, in the concept that the Gulf Stream is responsible for Europe's mild climate dating back to the mid-19th century. In fact, the Gulf Stream is not particularly unique, and analogous wind-driven currents occur in all of the world's oceans. For example, the Kuroshio, which flows off the coast of Japan, carries just as much water as the Gulf Stream. However, the Gulf Stream is unique in the role it plays in climate via the AMOC, leading to the use of the phrase "the Gulf Stream system" instead of the academic term "AMOC".

Regular and reliable observations

The combination of warm, shallow water moving northwards being balanced by cold, deep water moving southwards means that the Atlantic carries more heat than any place in any other ocean (Figure SB4.1). Between Florida and the Canary Islands, the RAPID array of ocean instruments makes continuous observations of ocean temperature, salinity, and currents to estimate the strength of the AMOC and the heat it transports. Since their initiation in 2004, these continuous *in situ* observations have provided the first direct evidence of the weakening of the AMOC (Figure SB4.2). However, the observational record is currently too short to determine whether the observed weakening of the AMOC is long term and due in part to human-induced climate change or if it is decadal-scale variability in the system itself.

Changing circulation patterns

Farther north, in the subpolar gyre, a critical balance exists between the warm North Atlantic Current and the cold subpolar gyre circulation (Figure SB4.1). Strong or weak phases of the AMOC are associated with a shrinking or expansion of the subpolar gyre. A shrinking of the subpolar gyre in the 1990s was associated with more warm water flowing to the north of the Rockall–Hatton plateau. Indications are that the subpolar gyre is re-establishing itself, with cold and fresh water dominating in the Iceland basin in recent years.

The record cold temperatures in the Iceland basin in 2015 had a direct impact on Ireland. At the time 2015 was the hottest year on record globally, yet Ireland recorded below average temperatures. This illustrates how Ireland's future could differ from global patterns, with some research suggesting a relatively cooler, stormier future a possibility. It is therefore timely that Irish contributions to international efforts [such as the RAPID, NOAC (North Atlantic Changes), OSNAP (Overturning in the Subpolar North Atlantic Program) and GSR (Greenland–Scotland Ridge) observations] are expanding to observe the changing AMOC. There is now regular hydrography to the west of Ireland as far as the southern Rockall–Hatton plateau, which was complemented with moored observations in 2018, and an inshore extension to the NOAC observations is planned for 2020 (orange line in Figure SB4.1).

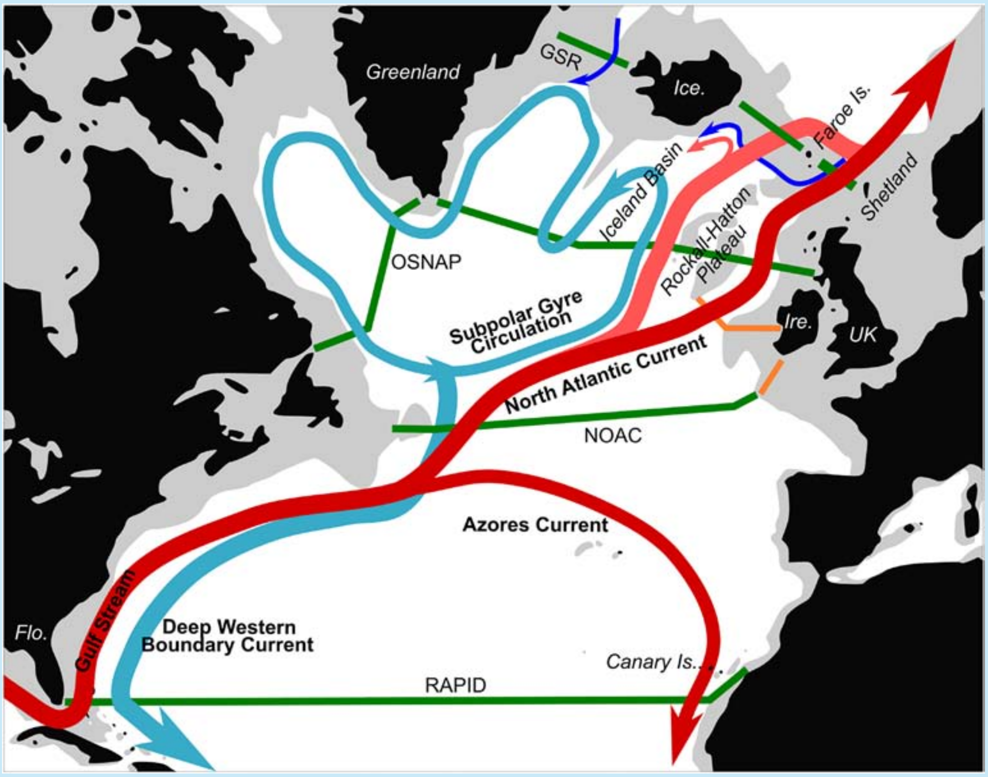


Figure SB4.1. Some of the broad components of the Atlantic Meridional Overturning Circulation are illustrated here, with warm currents in shades of red and cold currents in shades of blue. Bathymetric features and countries are indicated in italic, and AMOC observing systems are indicated in capital letters. International AMOC observing efforts are indicated by green lines; Irish observing efforts, existing or planned, are shown as orange lines. GSR, Greenland–Scotland Ridge.

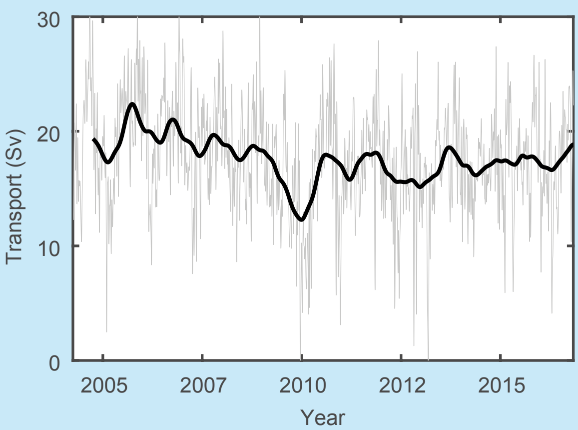


Figure SB4.2. The Atlantic Meridional Overturning Circulation's strength as measured by the RAPID array from 2004 to 2017. 10-day averages (grey) and 360-day low-pass filtered data (black) are shown. The AMOC's strength declined over the first 8 years of measurements and has remained weak.

Further Information

Caesar, L. *et al*., 2018. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* 556: 191–196. https://doi.org/10.1038/s41586-018-0006-5

Josey, S.A. *et al*., 2018. The recent Atlantic cold anomaly: causes, consequences, and related phenomena. *Annual Review of Marine Science* 10: 475–501. https://doi.org/10.1146/annurev-marine-121916-063102

Katz, C., 2019. Why is an ocean current critical to world weather losing steam? Scientists search the Arctic for answers. *National Geographic*, 2 December. (https://www.nationalgeographic.com/science/2019/12/why-ocean-current-critical-to-world-weather-losing-steam-arctic/)

McCarthy, G.D. *et al*., 2015. The influence of ocean variations on the climate of Ireland. *Weather* 70: 242–245. https://doi.org/10.1002/wea.2543

Smeed, D.A. *et al*., 2018. The North Atlantic Ocean is in a state of reduced overturning. *Geophysical Research Letters* 45: 1527–1533. https://doi.org/10.1002/2017GL076350

3.6 Inorganic Carbon

Walther C.A. Cámaro García, Ned Dwyer, Margot Cronin and Evin McGovern

The ocean plays a key role in the global carbon cycle, absorbing significant quantities of carbon through natural cycles driven by ocean circulation, biogeochemistry and biology. It is estimated that the ocean has absorbed between 20% and 30% of total anthropogenic CO_2 emissions since the 1980s, thereby reducing atmospheric accumulation and thus partially mitigating global warming. However, sea water's high capacity for absorbing carbon leads to ocean acidification. Estimates of future CO_2 levels indicate that by the end of this century the surface waters of the ocean could be nearly 150% more acidic, a condition not experienced for more than 20 million years. Although the ecological implications of ocean acidification are still unclear, there is mounting concern over the potential effects of such rapid acidification on many marine species and in particular on calcifying species such as corals, shellfish and crustaceans.

3.6.1 Measurements

The Marine Institute and NUI Galway have undertaken measurements of the inorganic carbon system and associated biogeochemical parameters in Irish coastal, shelf and offshore waters. Two of the following four parameters are required to fully determine the carbonate system: dissolved inorganic carbon (DIC); total alkalinity (TA); pH; and the partial pressure of CO_2 (pCO_2) in water.

Since 2009, Marine Institute annual repeat ship-based hydrography surveys measuring ECVs in Irish Shelf waters and across the southern Rockall Trough have included water sampling for DIC and TA. The surveys are primarily in winter, which is the period of least biological activity, although winter sampling has been heavily constrained by poor weather conditions during recent years.

Since 2017 the Marine Institute has operated a pCO_2 measurement system on board the Research Vessel (RV) *Celtic Explorer.* The system semi-continuously measures surface sea water from a depth of 5 m as well as atmospheric pCO_2. These high-quality data are provided to the international Surface Ocean CO_2 Atlas (SOCAT), an openly available data synthesis mapping highest quality pCO_2 data across the world's oceans. In addition, pCO_2 and pH measurement sensors have been deployed at Mace Head Atmospheric Research Station since 2018 as part of ongoing projects. Sensor validation field samples are taken regularly for laboratory analysis of DIC and TA, from which pH can be calculated.

Estimates of future CO_2 levels indicate that by the end of this century the surface waters of the ocean could be nearly 150% more acidic, a condition not experienced for more than 20 million years.

3.6.2 Time Series and Trends

The most recent assessment of winter DIC for surface waters in the Rockall Trough using data collected on Marine Institute and NUI Galway surveys since 2009, along with previous hydrography survey data collected through the World Ocean Circulation Experiment (WOCE), indicated an increase in anthropogenic DIC, equivalent to a decrease of 0.050 pH units, in the surface waters of the Rockall Trough between 1991 and 2013. This represents an increase in acidity that is comparable to the rate of change in other ocean time series. This assessment has not yet been updated with more recent data, partly because winter sampling coverage has been patchy in recent years because of poor weather conditions, but further assessments are planned. Figure 3.13 shows the DIC concentration depth profile as measured during the annual Rockall Ocean Climate Survey in winter 2013 (see Technical Box 1).

An additional focus of study in recent years has been the spatial and seasonal variability of the carbonate system in inshore waters, where freshwater inputs and catchment geology have been shown to play a significant role at a local level.

While laboratory measurements of TA and DIC are the reference methods for ocean "climate" studies, the use of pCO_2 sensors enables collection of data with high temporal and spatial coverage. pCO_2 measurements from the RV *Celtic Explorer* provide a substantial new dataset for Irish marine waters. While this has only been operational since 2017 and there are currently

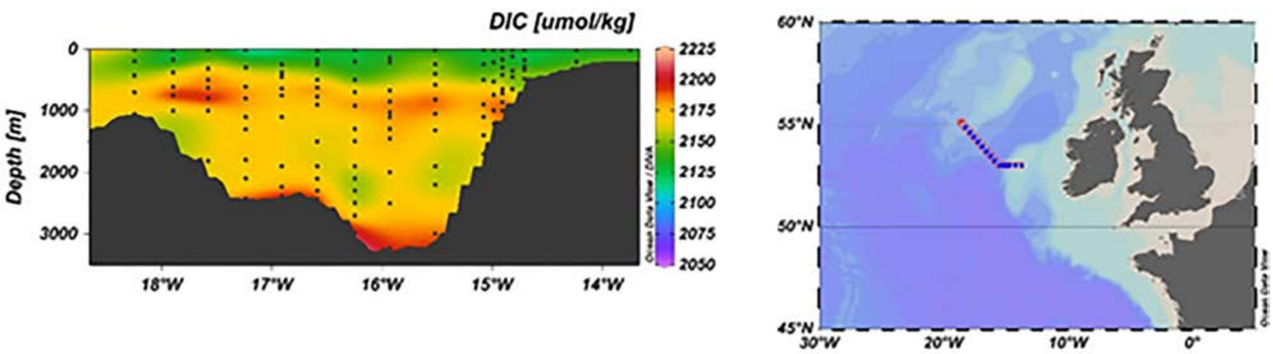


Figure 3.13. Deep-water dissolved inorganic carbon concentration (μmol/kg) section for the Rockall Trough in the winter of 2013 (left), during the annual survey on the Irish Shelf (right). The rows of vertical dots represent sampling points at different depths (left) and correspond to the blue point locations indicated in the red polygon (right).

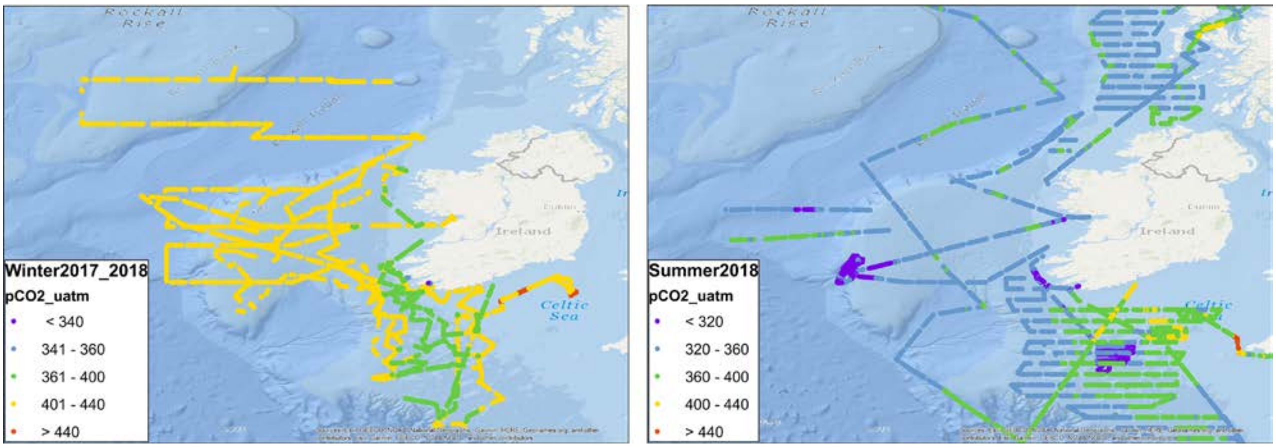


Figure 3.14. Surface water measurements of partial pressure of carbon dioxide in winter 2017–2018 (left) and summer 2018 (right), as collected by the RV *Celtic Explorer*.

insufficient data to show multi-annual trends, the data will make a significant contribution to regional assessments of the ocean carbon system.

Figure 3.14 shows surface water pCO_2 measurements in (left) Winter 2017–2018 and (right) Summer 2018, as collected by the RV *Celtic Explorer.* Temporal (seasonal) variations due to increasing primary production, e.g. photosynthesis from the spring phytoplankton bloom and shell formation from growth of organisms, results in increased uptake of pCO_2 from water, giving lower surface seawater pCO_2 in spring and summer periods. In addition, warmer water can hold less dissolved CO_2. Conversely, reduced primary production and the seasonal die-off of phytoplankton in autumn, together with the gradual remineralisation of organic matter, releases CO_2 back into the surface waters and therefore the highest concentrations are observed in winter periods.

Spatial differences in pCO_2 in the surface ocean are driven by variations in temperature, salinity, DIC and alkalinity. Physical, biological and chemical processes all play a part in these variations.

Integrated monitoring of the carbonate system is vital and annual measurements using reference methods combined with sensor measurements need to be resourced and maintained as long-term initiatives.

3.6.3 Maintaining the Observations

The Marine Institute and NUI Galway have undertaken inorganic carbon/ocean acidification observations since 2009, taking measurements of the carbonate system and associated biogeochemical parameters and supporting additional initiatives such as the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) A02 transatlantic hydrography survey. The pCO_2 measurement system on the RV *Celtic Explorer* has provided an extensive new dataset, and NUI Galway has more recently installed a pCO_2 measurement system on the RV *Celtic Voyager,* which, along with additional CO_2 sensors on moorings, will provide additional spatial and temporal coverage.

Data collected from these programmes are reported to ICES and other international data centres such as SOCAT.

These observations have largely been undertaken through short-term projects. While the infrastructure and sensors for $p\mathrm{CO_2}$ monitoring are now deployed, there remains a requirement to sustain current efforts and to operationalise high-quality discrete sample measurements for TA/DIC/pH using highly accurate reference methods.

Further Information

Inorganic Carbon Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/inorganic-carbon/)

McGovern, E. *et al.*, 2019. Ocean acidification observing in coastal, shelf and ocean waters around Ireland. Poster presented at the Fourth Global Ocean Acidification Observing Network (GOA-ON) International Workshop, 14–17 April, Hangzhou (https://www.researchgate.net/publication/332950133_Ocean_Acidification_Observing_in_Coastal_Shelf_and_Ocean_Waters_around_Ireland)

Information about ICES (https://www.ices.dk/)

Information about the Surface Ocean CO_2 Atlas (http://www.socat.info)

Information about GO-SHIP (https://www.go-ship.org/About.html)

Information about the Marine Institute-operated research vessels (https://www.marine.ie/Home/site-area/infrastructure-facilities/research-vessels/research-vessels)

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Technical Box 1. Rockall Ocean Climate Survey

Marine Institute

The Rockall Ocean Climate Survey has taken place on the RV *Celtic Explorer* annually since 2004. The survey is undertaken by the Marine Institute with support from researchers from NUI Galway and Maynooth University among others. It seeks to gather high-quality oceanographic ECV data along a targeted section of the Atlantic Ocean, starting in Galway Bay along the 53°N line of latitude and heading out to the South Rockall Trough, a deep-sea channel to the west of Ireland. With a complex oceanography, the Rockall Trough is an area of particular interest for the study of ocean circulation in the North Atlantic. The survey is usually run in winter, although sampling has been heavily constrained by poor weather conditions in recent winters. Therefore, the most recent survey took place in summer 2019. Originally, physical oceanographic data (e.g. temperature, conductivity–salinity) were collected, but the survey has evolved over the years, and biogeochemical parameters have been added since 2008. Measurements now include dissolved oxygen and nutrients as well as aspects of carbonate chemistry to investigate ocean acidification (Figure TB1.1). More recently ocean tracers, such as CFCs, have been sampled to support the study of ocean

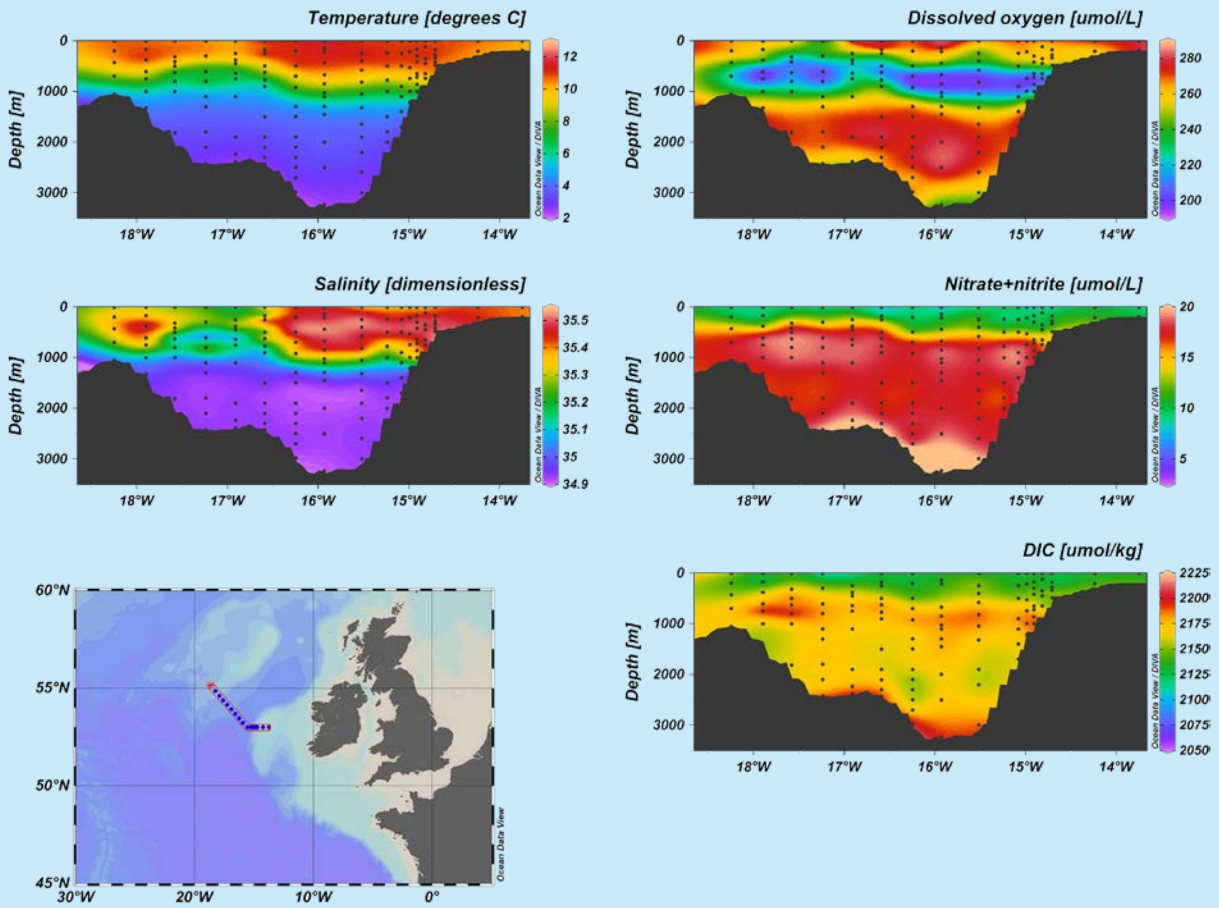


Figure TB1.1. Profiles of some of the data collected along a cross-section of the Rockall Trough during the winter of 2013. Rockall Ocean Climate Survey: water temperature, dissolved oxygen, salinity, nitrogen ions (nitrate and nitrite) and dissolved inorganic carbon. The rows of vertical black dots represent sampling points at different depths and correspond to the dark blue point locations indicated in the map (bottom left).

circulation. Biological elements such as plankton were added, and autonomous underwater instruments were deployed. The data collected are important nationally because they allow the assessment of physical and biogeochemical changes in the ocean and contribute to international efforts such as the ICES reports on ocean climate.

Further Information

McAleer, A. and the Ocean Science Survey Team, 2019. Ocean climate cruise in the S. Rockall Trough (https://scientistsatsea.blogspot.com/2019/06/2019-ocean-climate-cruise-in-s-rockall.html)

3.7 Oxygen

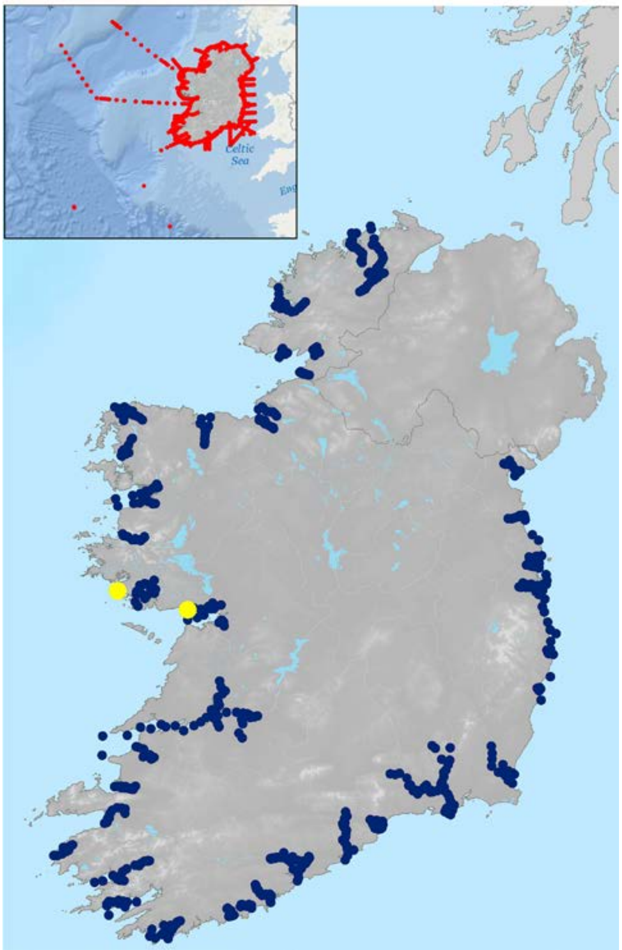
Walther C.A. Cámaro García, Ned Dwyer, Robert Wilkes, Rob Thomas and Evin McGovern

Oxygen is essential for ocean life. There is an optimum range of dissolved oxygen concentration in oceanic water that avoids stress and the potential death of marine organisms. Although low levels of oxygen exist in certain habitats, in general oxygen in subsurface waters is a good indicator of ocean health. Globally there has been a decrease in oxygen concentrations from the surface to 1000 m depth over the last 60 years. In the open ocean, such declines are linked to ocean warming and increased stratification.[13] In coastal areas agricultural run-off and human waste discharges into rivers and coastal systems result in oxygen depletion. In the worst cases such declines can lead to dead zones and also have impacts on the health and economy of the communities linked to the ocean.

3.7.1 Measurements

The Marine Institute and NUI Galway take measurements of dissolved oxygen in Irish coastal, shelf and offshore waters using both chemical analysis of collected water samples (reference method) and *in situ* measurements using various sensors.

13 Stratification is when water masses with different properties (e.g. density, salinity, temperature, oxygen levels) form layers that act as barriers to water mixing.



Map 3.6. Location of dissolved oxygen concentration observation stations.

Since 2011, full-depth dissolved oxygen profiles have been taken annually on the Ocean Climate Survey along the Irish Shelf and across the southern Rockall Trough, primarily in winter, although winter sampling has been heavily constrained by poor weather conditions during recent years. In May 2017 observations of dissolved oxygen were made during the GO-SHIP A02 transatlantic survey on board the RV *Celtic Explorer* between Newfoundland and Ireland.

The annual winter environmental survey on board the RV *Celtic Voyager* collects dissolved oxygen sensor profiles in coastal and shelf waters around the island of Ireland (outlined in red in inset, Map 3.6). As part of ongoing projects, observations are also made at the Mace Head buoy and at the SmartBay Observatory in Galway Bay (yellow dots, Map 3.6).

As part of Ireland's WFD and shellfish waters monitoring programme, *in situ* dissolved oxygen measurements are made by the EPA and the Marine Institute in 116 transitional and coastal water bodies (blue dots, Map 3.6). This monitoring programme has been in place since 2007.

The levels of oxygen seen in McSwyne's Bay in 2005 and 2012 are associated with summer phytoplankton blooms, which caused major mortalities of marine organisms.

3.7.2 Time Series and Trends

Figure 3.15 shows the percentage saturation of dissolved oxygen taken at sampling sites in McSwyne's Bay, Co. Donegal, mainly during the summer months,

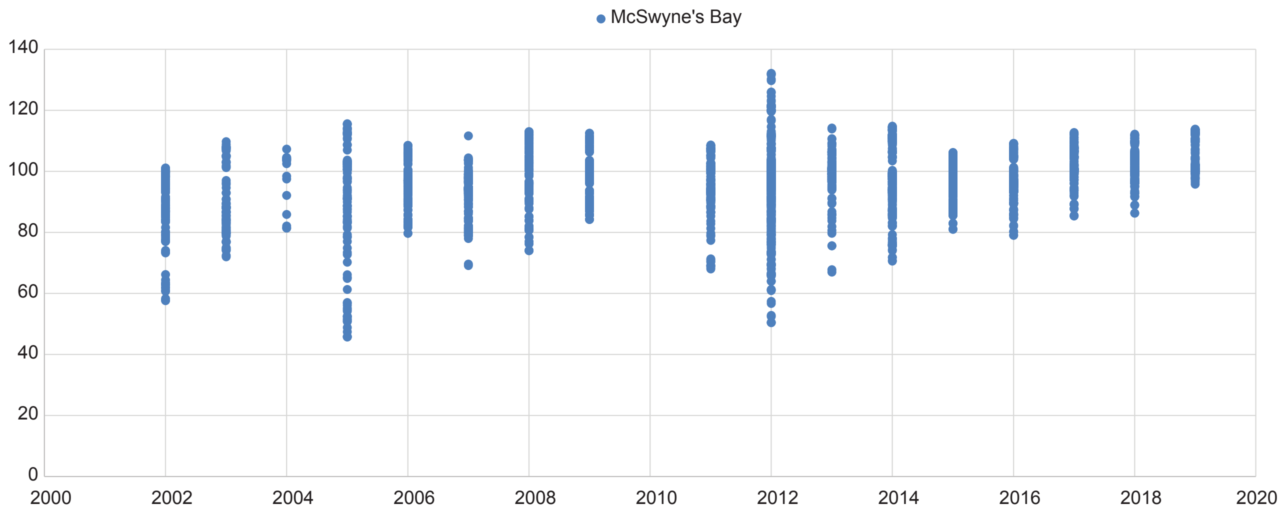


Figure 3.15. Percentage saturation of dissolved oxygen at McSwyne's Bay, Co. Donegal (2002–2019).

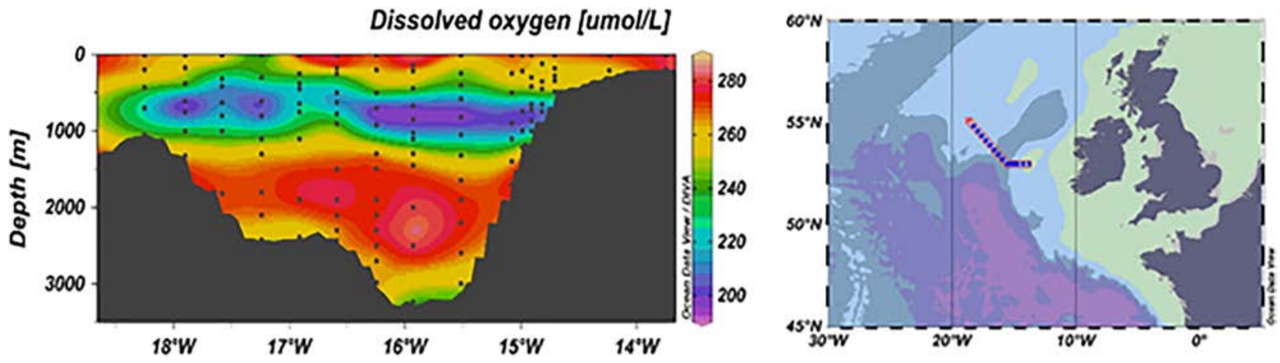


Figure 3.16. Deep-water dissolved oxygen concentration (μmol/l) section for the Rockall Trough in winter 2013 winter (left), during the annual survey on the Irish Shelf (right). The 14 rows of vertical dots represent sampling points at different depths (left) and correspond to the blue point locations indicated in the red polygon (right).

from 2002 to 2019. Measurements were made at water depths ranging from just below the surface to 30 m. In general, levels were close to full saturation over the period of the observations. Super-saturated values (> 100%) usually occur in the well-mixed surface layer, while the lower levels of saturation are found in stratified subsurface layers. The maximum and minimum values observed during the 2005 and 2012 summers are linked to phytoplankton blooms present during these periods in the coastal areas. The low dissolved oxygen values following the intense 2005 dinoflagellate bloom (a type of phytoplankton) resulted in major mortalities of marine organisms in both the water column and near the sea floor.

Figure 3.16 shows a deep-water dissolved oxygen section as measured during the annual Rockall Ocean Climate Survey in winter 2013 (see Technical Box 1). The lowest values are observed in the subsurface waters at approximately 500-m depth due to respiration associated with decomposition of organic matter.

Since 2011, full-depth dissolved oxygen profiles have been taken annually along the Irish Shelf and across the southern Rockall Trough.

3.7.3 Maintaining the Observations

The Marine Institute and NUI Galway have undertaken ship-based hydrographic observations, including dissolved oxygen concentration, since 2008 and supported additional initiatives such as GO-SHIP. Data collected from these programmes are reported to ICES and other international data centres.

There is a need to sustain "climate" quality objective seawater dissolved oxygen measurements that meet international standards such as those described in the GO-SHIP hydrography manual.

Further Information

Oxygen Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/oxygen/)

Silke, J. *et al*., 2005. *Karenia mikimotoi:* an exceptional dinoflagellate bloom in western Irish waters, summer 2005. Marine Environment and Health Series, No. 21, Marine Institute (https://oar.marine.ie/handle/10793/240)

Linden, O., 2019. Evidence for ocean deoxygenation and its patterns. In Laffoley, D. and Baxter, J.M. (eds), *Ocean Deoxygenation: Everyone's Problem*. International Union for Conservation of Nature, Geneva. https://doi.org/10.2305/IUCN.CH.2019.13.en

Information about ICES (https://www.ices.dk/)

Information about GO-SHIP (https://www.go-ship.org/About.html)

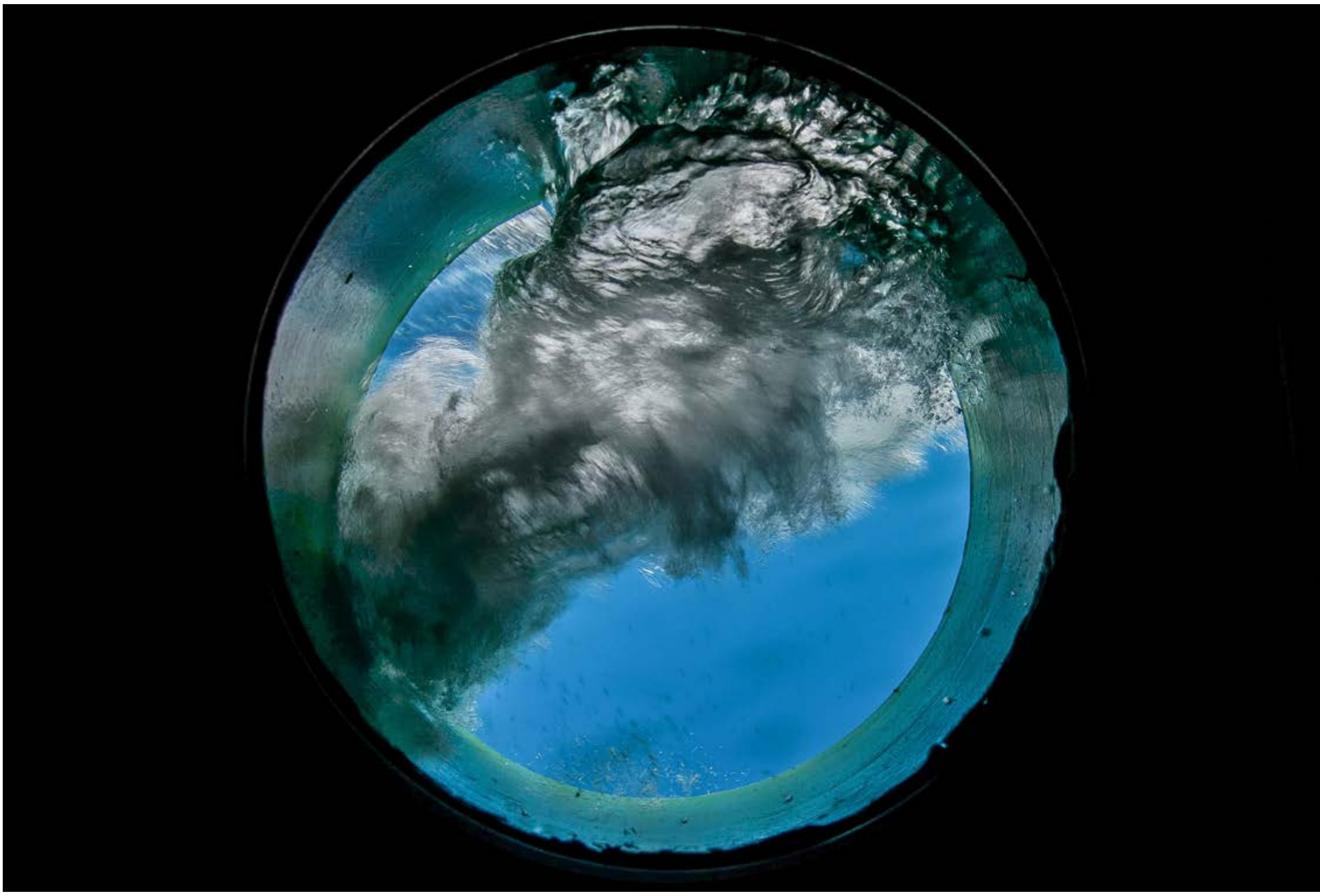
Information about the Marine Institute-operated research vessels (https://www.marine.ie/Home/site-area/infrastructure-facilities/research-vessels/research-vessels)

Water Quality in Ireland 2013–2018 (https://www.catchments.ie/water-quality-in-ireland-2013-2018/)

3.8 Nutrients

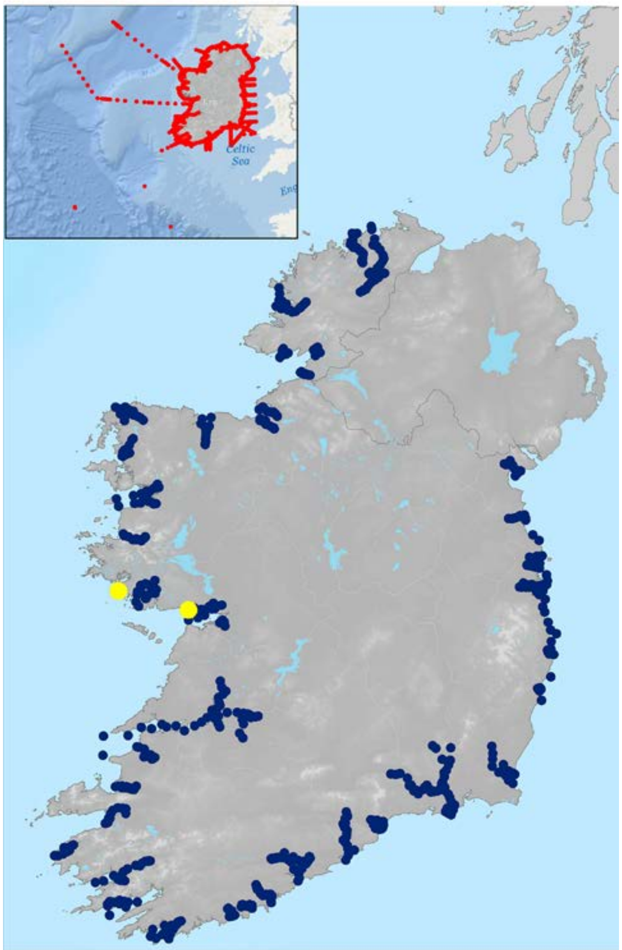
Walther C.A. Cámaro García, Ned Dwyer, Robert Wilkes and Evin McGovern

The major nutrients, such as dissolved inorganic phosphorus, nitrogen and silicon, play a key role in ocean life. They are essential for plant growth (e.g. phytoplankton, algae) at the base of the food web and when depleted can limit growth. In excess, they can cause eutrophication, whereby accelerated algal growth can lead to depletion of oxygen and result in severe ecological harm. Nutrient concentrations in Irish waters are determined by natural dynamics and the seasonal variability in the growth of phytoplankton and macroalgae; they are also influenced by riverine and atmospheric inputs from human activities – for example agricultural application of fertiliser and municipal waste discharges. Changes in climate, such as altered rainfall patterns, are also likely to influence nutrient inputs to the marine environment and therefore may also affect estuarine and coastal ecosystems.



3.8.1 Measurements

As part of Ireland's WFD monitoring programme, nutrient measurements, mainly nitrogen and phosphorus, have been made regularly in 116 transitional and coastal water bodies (blue dots) since 2007 (Map 3.7).



Map 3.7. Location of nutrient observation stations.

The Marine Institute operates a programme to take measurements of nutrients in Irish coastal, shelf and offshore waters (outlined in red in insert, Map 3.7).

To assess spatial and temporal trends in surface waters, inorganic nutrients are best measured during winter, when nutrient uptake by marine plants is at a minimum and there is a well-mixed water column. Since the 1990s, annual ship-based surveys, from the RV *Celtic Voyager*, have sampled for winter nutrients, initially in the western Irish Sea and gradually extended to cover the entire coast and include transects further onto the shelf.

In addition, since 2008 on board the RV *Celtic Explorer* during the annual Rockall Ocean Climate Survey, dissolved inorganic nutrients are measured along the Irish Shelf (53°N) and to full water depth on a cross-section of the Rockall Trough. However, winter sampling has been heavily constrained by poor weather conditions during recent years. The 2019 survey was done during the summer months.

As part of ongoing research projects, observations are made at the Mace Head Atmospheric Research Station and at the SmartBay Observatory (yellow dots, Map 3.7), with a nitrate sensor deployed at the Mace Head mooring.

Locations with elevated nitrogen concentrations linked to sources of pollution are generally found on the south and east coasts.

3.8.2 Time Series and Trends

Figure 3.17 shows the nitrogen winter exceedances above the recommended thresholds as percentages in Irish estuarine and coastal waters for the period between 2016 and 2018. Twenty-five percent of the sites, mainly to the south and east, showed excess nitrogen concentrations, which can be linked to land-based sources of pollution. In 39 of these water bodies, the median concentration for the period between 2008 and 2018 was used to identify trends in the concentrations (see white arrows). Of these, only one water body showed a significant upward trend (New Ross Port), six showed a significant downward trend and 32 showed no trend.

Figure 3.18 shows the mean surface phosphate and total oxidised nitrogen (nitrate + nitrite) concentrations for the winter periods from 2007 to 2018, in which higher values are observed to the south and east and particularly in bays and estuaries. These regions of elevated nutrient levels are associated with freshwater inputs and limited exchange of sea water.

Figure 3.19 shows a depth profile for total oxidised nitrogen (nitrate + nitrite) measured during the annual Rockall Ocean Climate Survey in winter 2013. The concentrations increase in deep waters and reflect wide-scale circulation patterns of deep water masses and removal of organic matter from surface waters and remineralisation at depth.

A sustained biogeochemical measurement programme and analytical capability is essential to ensure the delivery of consistent measurements of climate quality.

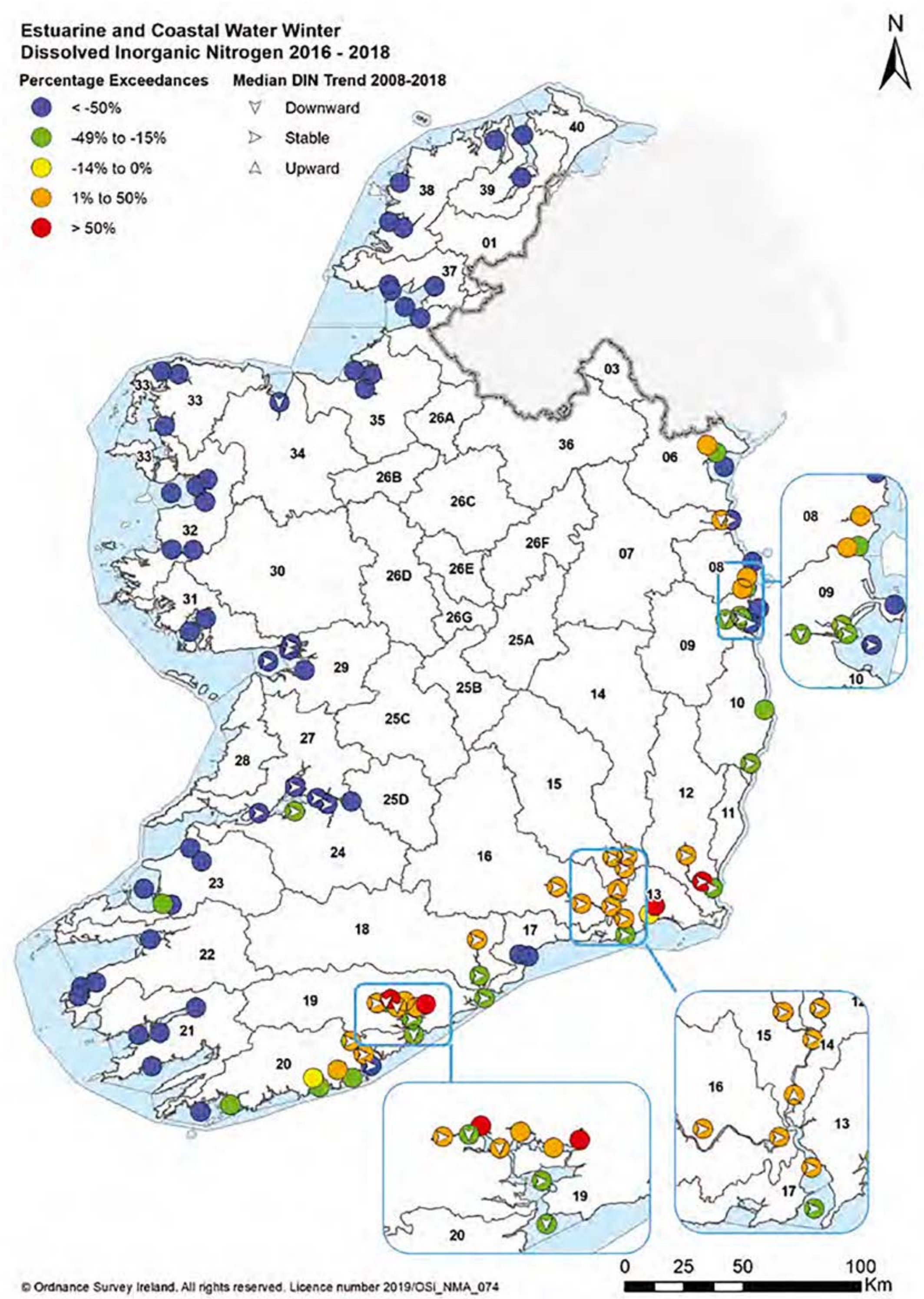


Figure 3.17. Nitrogen winter exceedances above the recommended thresholds (2016–2018). Dissolved inorganic nitrogen thresholds indicative of status: blue, excellent; green, good; yellow, moderate; orange, poor; red, bad. The sampling stations with white arrows were used for trend analysis for the period 2008–2018. Source: Water Quality in Ireland 2013–2018 (EPA, 2019).

3.8.3 Maintaining the Observations

The Marine Institute has been monitoring nutrient concentrations in the Irish Sea since 1990. This now extends to Irish coastal, shelf and ocean waters, complementing EPA monitoring of inshore coastal and transitional waters. Data collected through these programmes are reported to ICES and other international data centres.

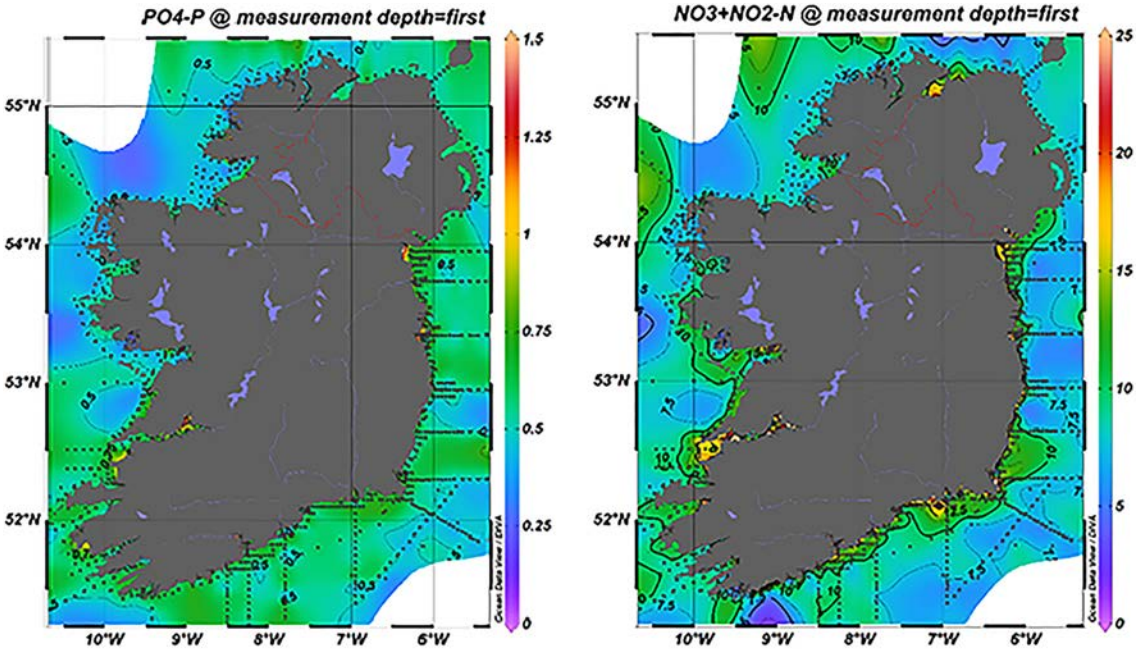


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Figure 3.18. Mean winter surface phosphate (left) and total oxidised nitrogen (nitrate + nitrite) concentrations (μmol/l) (2007–2018).

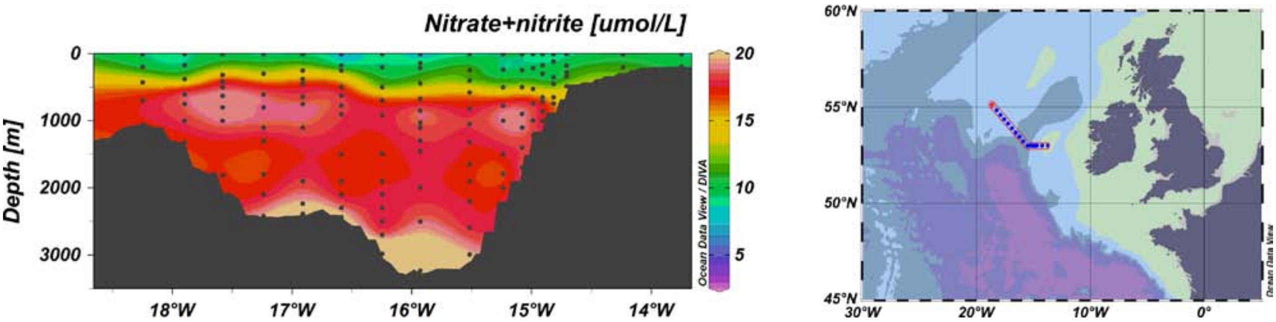


Figure 3.19. Deep-water total oxidised nitrogen (nitrate + nitrite) concentration (μmol/l) section for the Rockall Trough in the winter of 2013 (left), measured during the annual Rockall Ocean Climate Survey (right). The rows of vertical dots represent sampling points at different depths (left) and correspond to the blue point locations indicated in the red polygon (right).

Since 2017 nutrient observations made on board the RV *Celtic Explorer* have also contributed to the international GO-SHIP programme.

The measurement programme for offshore marine waters has been largely supported by a series of research projects. High-quality ocean nutrient measurements in sea water are not trivial, and a sustained biogeochemical measurement programme and analytical capability is essential to ensure the delivery of consistent, high-quality data suitable for climate research.

Further Information

Nutrients Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/nutrients/)

Marine Institute information about nutrients and ocean acidification (https://www.marine.ie/Home/site-area/areas-activity/marine-environment/nutrients-and-ocean-acidification-oa)

Information about ICES (https://www.ices.dk/)

Information about GO-SHIP (https://www.go-ship.org/About.html)

Information about the Marine Institute-operated research vessels (https://www.marine.ie/Home/site-area/infrastructure-facilities/research-vessels/research-vessels)

Water Quality in Ireland 2013–2018 (https://www.catchments.ie/water-quality-in-ireland-2013-2018/)

3.9 Ocean Colour

Walther C.A. Cámaro García, Ned Dwyer, Caroline Cusack and Joe Silke

Ocean colour refers to the sunlight reflected from the ocean surface. This particular characteristic contains information on the constituents of the sea water, in particular, phytoplankton pigments such as chlorophyll *a* (Chl-*a*), suspended particles and dissolved organic compounds. It is estimated that Chl-*a* concentrations in the North Atlantic have been increasing by 1.1% per year over the last 20 years. Ocean colour monitoring provides information on water quality and can assist by providing early warning of potentially harmful phytoplankton blooms and pollution events. Information derived from ocean colour products can aid understanding of the role of the ocean in the global carbon cycle, help manage fish resources and quantify the impacts of climate variability and change.

3.9.1 Measurements

Satellite radiometers are used to observe ocean colour. Sensitive light sensors detect the small amounts of radiation reflected from the ocean surface in many narrow bands in the visible and near infrared spectrum. Analysis of the different amounts of reflectance in each band allows the characterisation of the ocean surface in terms of chlorophyll concentrations or sediment amounts or some specific dissolved organic compounds.

The Marine Institute routinely obtains information from ESA and NASA on ocean colour and sea surface temperature. The Chl-*a* and sea surface temperature data provide information for the weekly bulletins that report the potential development of toxic and/or harmful phytoplankton blooms.

Chl-*a* concentration in the North Atlantic has increased by 1.1% per year over the period 1998–2017.

3.9.2 Time Series and Trends

Chlorophyll concentration is routinely derived from satellite remote sensing colour observations. Figure 3.20 shows a heat map of monthly average Chl-*a* concentration since 2002 in the North-east Atlantic waters in the vicinity of Ireland as determined from ocean colour observations by the MODIS Aqua sensor. The red colour identifies the months with the greatest Chl-*a* concentration. The 95th percentile value (0.92) indicates that 95% of all of the values recorded fall below this value. A seasonal variation can be observed with maximum Chl-*a* concentrations generally reached in the March to May period and minimum values from October to December. Analysis reported in the Copernicus Ocean State Report indicate that Chl-*a*

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2020												
2019												
2018	0.66	0.77	0.74	0.92	0.92	0.83	0.70	0.68	0.64	0.68	0.61	0.66
2017	0.72	0.87	0.93	0.84	0.82	0.84	0.81	0.69	0.73	0.68	0.59	0.69
2016	0.66	0.91	0.82	0.77	1.00	0.81	0.69	0.76	0.72	0.63	0.61	0.69
2015	0.82	0.90	0.95	1.01	0.88	0.93	0.80	0.82	0.69	0.64	0.61	0.68
2014	0.74	0.76	0.90	0.91	0.81	0.81	0.84	0.62	0.63	0.66	0.63	0.74
2013	0.64	0.77	0.64	0.82	0.82	0.90	0.79	0.66	0.62	0.65	0.59	0.66
2012	0.76	0.84	1.00	0.78	0.77	0.82	0.70	0.67	0.63	0.60	0.56	0.59
2011	0.61	0.74	0.79	1.00	0.84	0.74	0.77	0.65	0.62	0.65	0.60	0.57
2010	0.66	0.69	0.70	0.92	0.74	0.78	0.73	0.68	0.60	0.67	0.64	0.63
2009	0.69	0.80	0.96	0.92	0.86	0.89	0.81	0.77	0.77	0.70	0.62	0.59
2008	0.75	0.74	0.78	0.89	0.99	0.82	0.66	0.66	0.70	0.70	0.69	0.64
2007	0.65	0.72	0.86	0.90	0.92	0.79	0.77	0.74	0.73	0.71	0.61	0.69
2006	0.64	0.69	0.74	0.81	0.80	0.81	0.77	0.67	0.70	0.67	0.61	0.57
2005	0.72	0.73	0.71	0.87	0.79	0.85	0.80	0.73	0.69	0.67	0.66	0.71
2004	0.65	0.80	0.81	0.81	0.86	0.80	0.78	0.71	0.69	0.65	0.63	0.62
2003	0.71	0.85	0.92	0.88	0.84	0.82	0.66	0.64	0.65	0.61	0.63	0.72
2002							0.76	0.69	0.66	0.62	0.57	0.61

Percentile	
95	0.92
75	0.81
50	0.73
25	0.66
5	0.60
Min	0.56

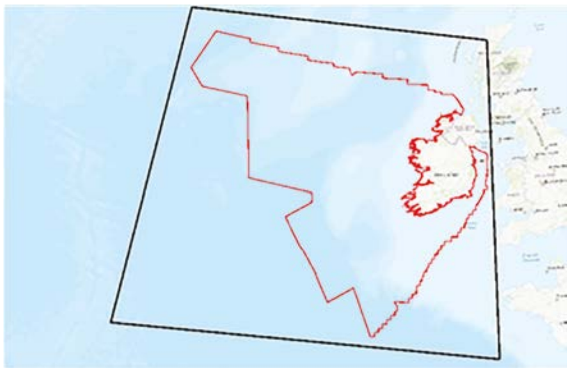


Figure 3.20. Monthly mean chlorophyll *a* concentration (mg/m³) in the North-east Atlantic (left). The area analysed is shown in the black polygon on the map (right). The red polygon shows the current designated Irish Continental Shelf. Source: Generated by the authors from the NASA chlorophyll concentration product determined from MODIS Aqua sensor observations.

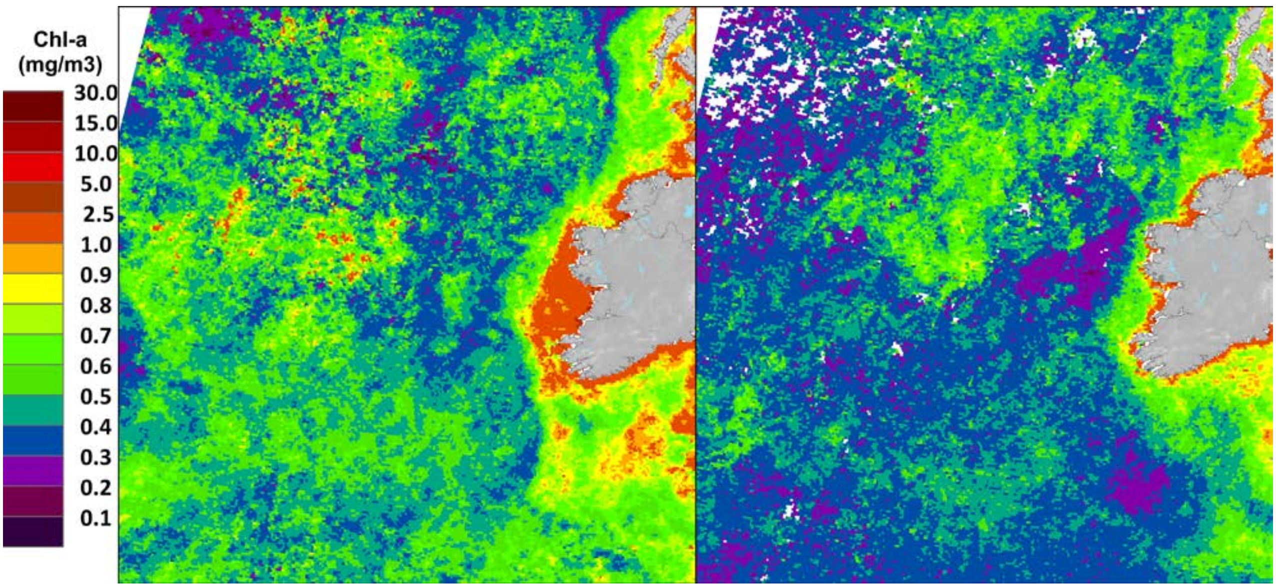


Figure 3.21. Average chlorophyll *a* concentration (mg/m³) for March to May 2015 (left) and October to December 2015 (right). Source: ESA Climate Change Initiative Ocean colour project.

concentration in the North Atlantic increased by 0.17% per year over the period 1997–2019. However, the time series is too short to separate annual variability and longer term climate change effects.

Figure 3.21 illustrates average Chl-*a* concentrations for two periods of the year during 2015. Seasonal variability can be seen in the open ocean with higher concentrations in spring. The high concentrations indicated near coastal areas may be incorrect, as satellite retrievals of Chl-*a* in shallow waters and near coasts are unreliable.

A research project is investigating the potential of satellite ocean colour datasets to monitor harmful algal blooms in Irish waters.

3.9.3 Maintaining the Observations

A range of spectral radiometer sensors from several space agencies makes observations of ocean colour. Comprehensive, global ocean colour data have been available since 1997. However, significant work is required to merge data from sensors with differing characteristics mounted on a number of different satellites. Consistent observations from operational systems with sensors of a similar design are required so climate change impacts can be discriminated.

The ESA CCI has a comprehensive global time series of ocean colour remote sensing products. This and other ocean colour observations for the seas around Ireland represent a valuable resource. A Marine Institute and NUI Galway PhD research project is investigating the potential of such datasets to monitor harmful algal blooms in Irish waters. This will help in determining the value of ocean colour products for monitoring and understanding Chl-*a* variability around Ireland.

Further Information

Ocean Colour Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/ocean-colour/)

Groom, S. *et al*., 2019. Satellite ocean colour: current status and future perspective. *Frontiers in Marine Science* 6: 485. https://doi.org/10.3389/fmars.2019.00485

Sathyendranath S. *et al*., 2019. An ocean-colour time series for use in climate studies: the experience of the Ocean-Colour Climate Change Initiative (OC-CCI). *Sensors* 19: 4285. https://doi.org/10.3390/s19194285

von Schuckmann, K. *et al*., 2020. Copernicus Marine Service Ocean State Report, Issue 4. *Journal of Operational Oceanography* 13(Suppl. 1): S1–S172. https://doi.org/10.1080/1755876X.2020.1785097

MODIS and NASA data via Giovanni from the Goddard Earth Sciences and Information Services Centre (https://giovanni.gsfc.nasa.gov/giovanni/)

Information and data from ESA's Ocean Colour Climate Change Initiative project (https://www.oceancolour.org/about)

International Ocean Colour Coordinating Group (https://ioccg.org/)

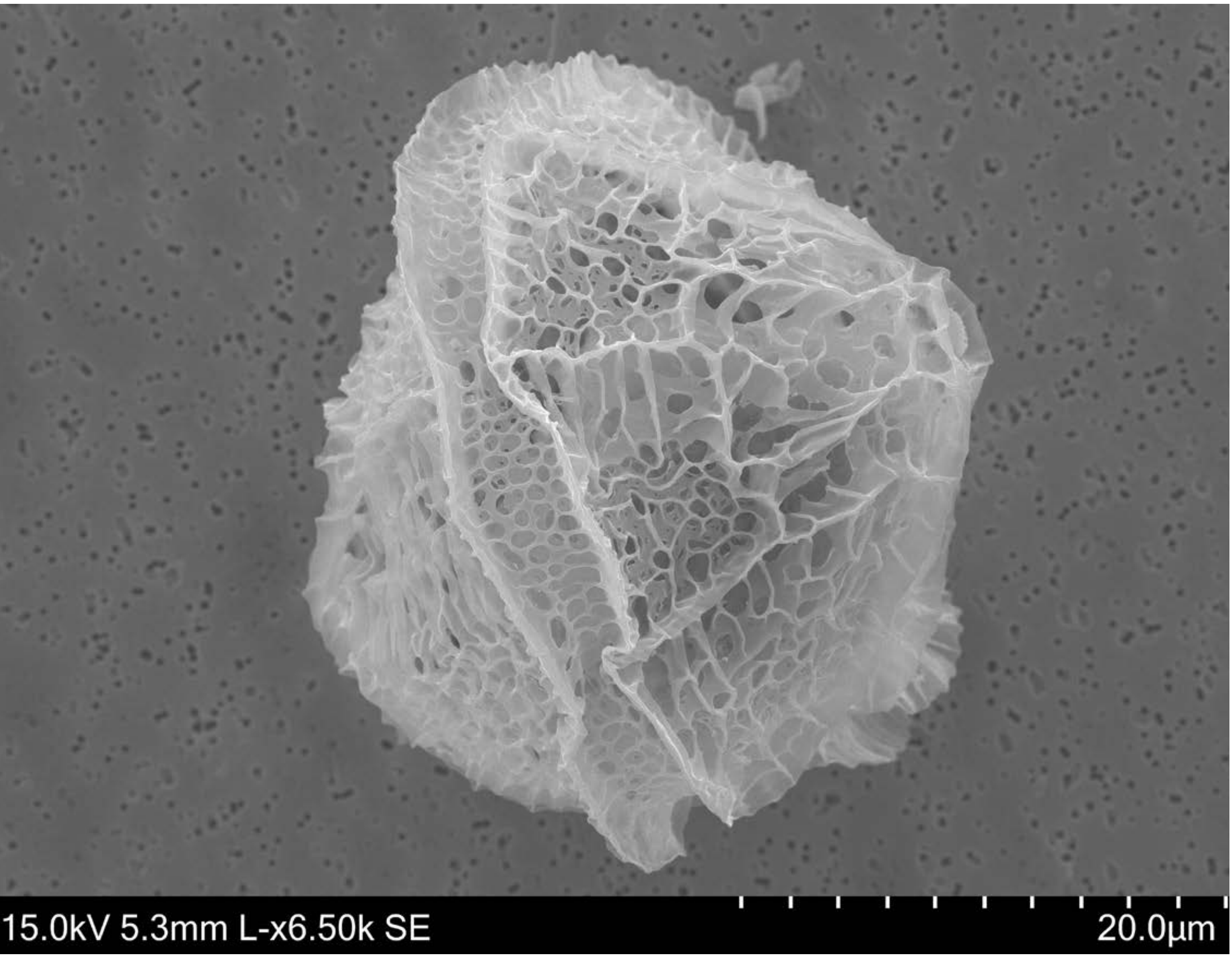
Marine Institute Weekly HAB Bulletin, reporting on the status of harmful and toxic algal blooms (https://www.marine.ie/Home/site-area/data-services/interactive-maps/weekly-hab-bulletin)

Water Quality in Ireland 2013–2018 (https://www.catchments.ie/water-quality-in-ireland-2013-2018/)

3.10 Plankton

Walther C.A. Cámaro García, Ned Dwyer, Joe Silke and Caroline Cusack

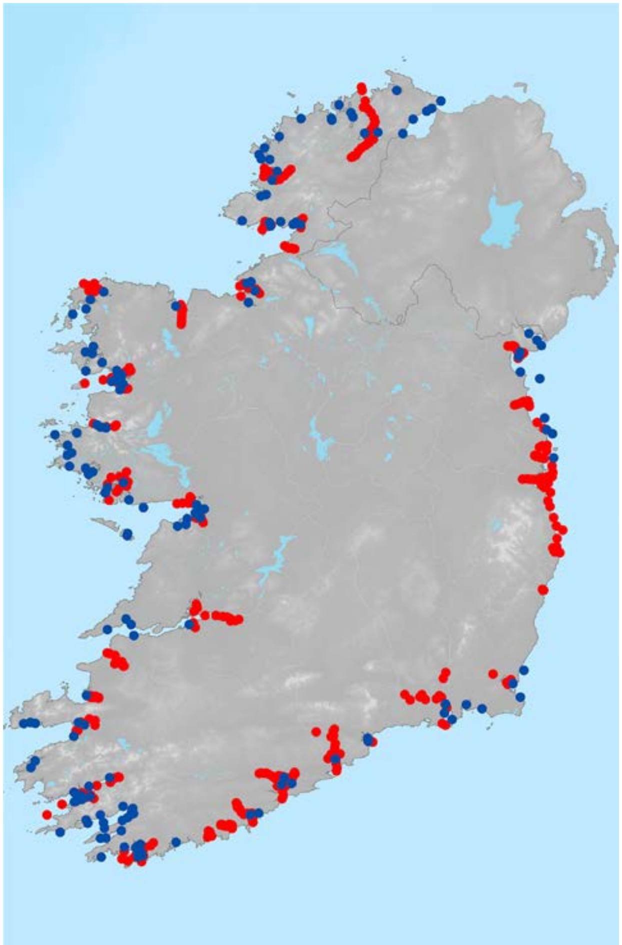
Plankton are at the base of the marine food web and are classified into two main categories: the phytoplankton formed by free-floating plants and the zooplankton formed mainly by microscopic animals. Many marine ecosystems are highly dependent on the general conditions of the plankton. Changes in plankton affect marine ecosystems, living marine resources used by humans and the carbon cycle. Plankton play a key role in climate regulation, as they sequester CO_2 at the surface and transfer it to the deep ocean. Plankton are sensitive indicators of environmental change (e.g. temperature, pH, nutrient availability) and provide essential information related to the ecological status of the ocean.



3.10.1 Measurements

The Marine Institute has been monitoring phytoplankton since the 1980s. Phytoplankton analysis has focused on the phytoplankton populations and dynamics from aquaculture sites around the Irish coastline (blue dots), with special attention given to the harmful and toxic phytoplankton (Map 3.8). At well-mixed shallow sites, surface seawater samples are collected, while at deeper sites an integrated seawater sample from the water column is collected and analysed on a weekly basis.

As part of Ireland's WFD monitoring programme, monthly phytoplankton measurements in coastal waters and seasonal sampling in estuaries are made (red dots, Map 3.8) by the Marine Institute and the EPA.



Map 3.8. Location of phytoplankton observation stations.

Continuous Plankton Recorder (CPR) surveys are established in several areas around the world, including the North Atlantic Ocean since 1931. In this area the programme is co-ordinated by the UK's Marine Biological Association (MBA), with a set of voluntary observing ships undertaking regular plankton tows. Currently these are the only systematic measurements of zooplankton taken in parts of the Irish Shelf.

Measurements from a number of satellite sensors that detect radiation reflected from the ocean surface (ocean colour) are used to infer chlorophyll and hence phytoplankton concentrations. Observations are available from various satellite sensors going back to the late 1980s. Currently information on chlorophyll concentrations can be retrieved from the Copernicus Marine Environment Monitoring Service and the ESA Ocean colour CCI project.

Since 2010 the presence of some potentially harmful phytoplankton has frequently been detected in the winter months.

3.10.2 Time Series and Trends

As part of the Marine Institute's National Phytoplankton Monitoring Programme several potentially harmful microalgae have been commonly observed since the programme commenced. Figure 3.22 shows the monthly percentage of coastal water samples in which one of these species, *Karenia mikimotoi*, was present from 1990 until 2018. An increase in the percentage of samples that contain *K. mikimotoi* is evident in recent years, especially in summer. During winter, *K. mikimotoi* was observed intermittently in the first decade of this century but an almost continuous presence throughout the year has been observed since 2010. The expansion of its growth season is in line with a warming period in Irish waters evident from sea surface temperature observations.

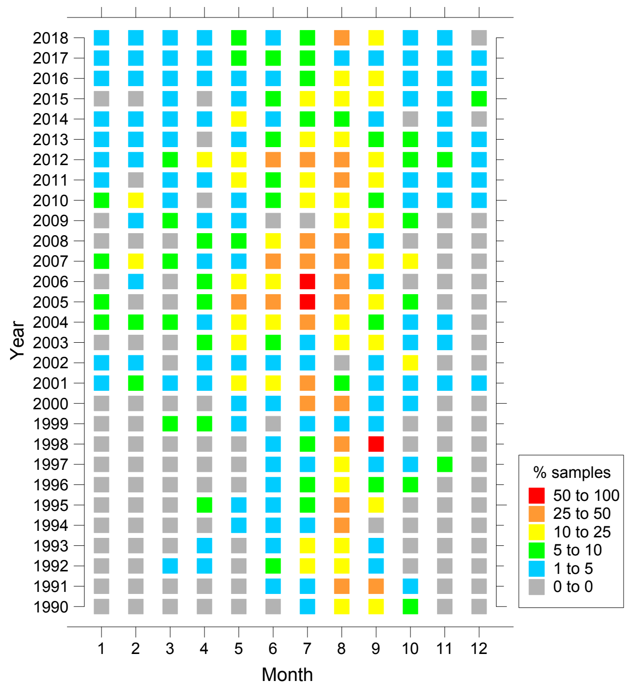


Figure 3.22. Percentage of monthly samples analysed in which *K. mikimotoi* was detected (1990–2018).

Figure 3.23 shows the annual mean abundance, expressed as anomalies, for a number of plankton life forms in the Celtic Sea, extracted from CPR surveys (1958–2014). A decreasing temporal trend in the abundance of taxa is observed for many plankton life forms in the Celtic Sea. This suggests that a major ecosystem alteration has taken place over the period examined. However, in contrast, the abundance of potentially harmful plankton (dinoflagellates: HAB Dinos in Figure 3.23) show an increase in the 1990s with maximum abundance recorded in 2014.

The establishment of coastal stations for zooplankton sampling would allow the capture of critical information on the impact of climate change on Irish ecosystems.

3.10.3 Maintaining the Observations

The National Phytoplankton Monitoring Programme under the Marine Institute has operated since the 1980s with sampling assistance from the Sea Fisheries Protection Authority (SFPA). This programme is primarily focused on harmful microalgae, and daily updates are posted on the Marine Institute website.

The EPA, in collaboration with the Marine Institute, undertakes water quality surveys, which incorporate phytoplankton monitoring, in estuaries and nearshore coastal waters as part of the WFD monitoring programme.

A Marine Institute and NUI Galway PhD research project is investigating the potential of satellite datasets to monitor phytoplankton, including harmful algal blooms, around Ireland. This remote monitoring could potentially open up new means for gathering large quantities of data in a very fast and efficient manner that may also show the impact of climate change on phytoplankton blooms.

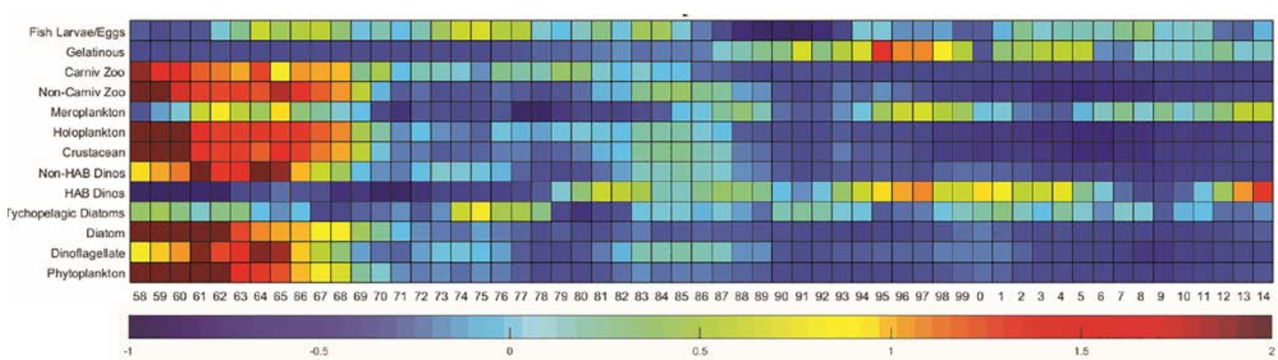


Figure 3.23. Annual mean abundance expressed as anomalies above and below the long-term mean for a number of plankton life forms (functional group) from 1958 to 2014 for the Celtic Sea. Source: Reproduced from Edwards *et al*. (2016). © Marine Biological Association.

Zooplankton monitoring is currently insufficient in Irish waters. Observations are primarily available through the monitoring of the MBA's CPR survey, started in 1931 and focusing on a number of fixed lines or transects in the North-west European Shelf and the North-east and North-west Atlantic. A transect in Irish offshore surface waters will be reinstated in 2021 as a 1-year pilot project. The establishment of a number of fixed coastal stations around Ireland with high-frequency sampling for zooplankton would allow the capture of critical information on the impact of climate change on Irish ecosystems.

Further Information

Plankton Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/plankton/)

Edwards, M. *et al.*, 2016. Global Marine Ecological Status Report: Results from the Global CPR Survey 2014/2015. SAHFOS Technical Report No. 11 (https://www.cprsurvey.org/publications/scientific-reports/ecostatus-reports/)

Information about the Marine Institute National Phytoplankton Monitoring Programme (https://www.marine.ie/Home/site-area/areas-activity/marine-environment/phytoplankton-monitoring)

Water Quality in Ireland 2013–2018 (https://www.catchments.ie/water-quality-in-ireland-2013-2018/)

Information about the MBA CPR Surveys (https://www.cprsurvey.org/)

Technical Box 2. Building ocean understanding through internationally co-ordinated data collection

Marine Institute

Numerous technological advances in recent years, including the deployment of Argo drifter floats, seabed observatories, remotely operated vehicles and moored observation stations have improved ocean observation capabilities. Nevertheless, ship-based surveys are still the only method that can collect high-quality, high-resolution spatial and vertical measurements of a suite of physical, chemical and biological parameters throughout the full water column from the seabed to the sea surface. Ship-based water sampling for on-board analysis and deployment of sensors is essential to document ocean changes throughout the water column, especially in the deep ocean below 2000-m depth. Ship-based surveys often follow the same transect (line) on a regular (e.g. annual, decadal) basis to yield repeat measurements of the same area over time, which allows the identifications of any changes in the ocean's properties.

The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) is a GCOS programme that provides a sustained co-ordination mechanism for global repeat hydrography. The programme brings together scientists from around the world with interests in physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems to co-ordinate their efforts in collecting and sharing high-quality and comparable ocean data. A key aim is to carry out measurements through a network of 39 survey lines that criss-cross all of the world's ocean basins at full depth, with the intention of repeating each line at least once per decade. The data collected provide information on ocean heat, currents, fresh water, carbon, dissolved oxygen, nutrients and transient tracers, among other things. GO-SHIP data are publicly available without restriction.

Ireland is represented on the GO-SHIP science committee by the Marine Institute. In 2017, scientists from the Marine Institute and NUI Galway led a multinational team in completing the transatlantic A02 survey from Newfoundland to Ireland on board the RV *Celtic Explorer*.

Further Information

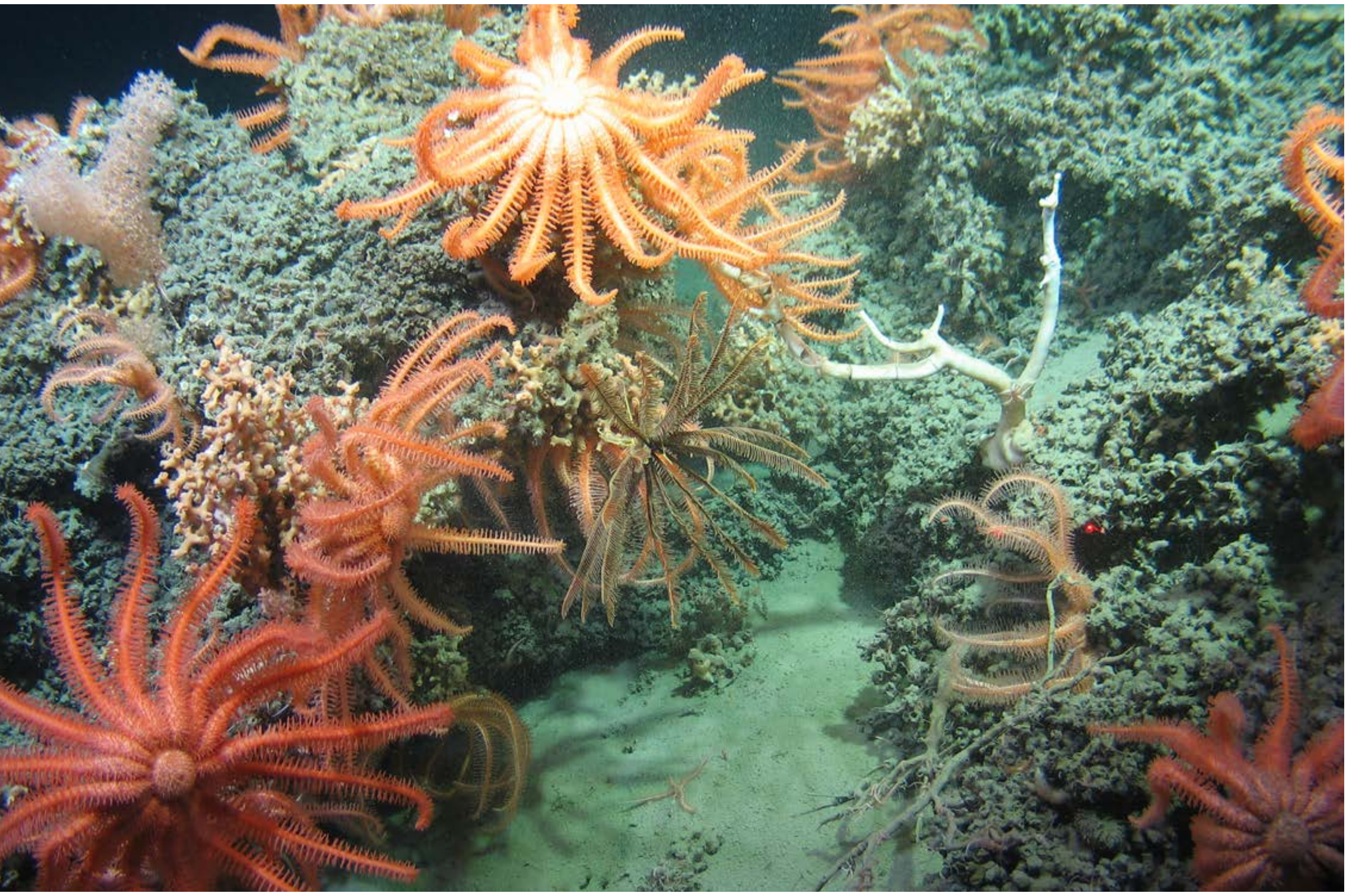
Across the Atlantic with the GO-SHIP Ocean Survey. *Irish Times*, 29 June 2017 (https://www.irishtimes.com/news/science/across-the-north-atlantic-with-the-go-ship-ocean-survey-1.3129705)

Information about GO-SHIP (https://www.go-ship.org)

3.11 Marine Habitat Properties

Walther C.A. Cámaro García, Ned Dwyer and Robert Wilkes

Seaweed, seagrass and coral abundance and condition are good indicators of marine health and are essential elements of the marine environment.[14] As well as playing a role in the carbon cycle they provide crucial habitats for many fish, crustaceans and other species. However, they are under constant transformation in response to human activities and global change. Seagrass is found close to coasts and is very vulnerable to human actions. It is estimated that almost 30% of seagrass meadows globally have died off over the last century. More than 1000 species of algae have been identified in Irish waters, some of which are invasive causing economic and environmental impacts. Reef-building cold-water corals are found on parts of the Irish Shelf at depths between 600 m and 1000 m. These corals are able to survive in complete darkness and can tolerate water temperatures as low as 4°C.



14 These three habitats and mangrove forests are those considered by GCOS for this ECV.

3.11.1 Measurements

As part of Ireland's monitoring programme under the WFD, macroalgae (seaweed) and seagrass communities are used as measures of biological quality and health in estuaries and coastal waters. Macroalgal quality is assessed by looking at seaweed diversity on rocky shores and at green algal growth. Intertidal seagrass communities, which are a protected habitat, have been monitored by the EPA since 2007.

As part of a survey commissioned by the National Parks and Wildfire Service (NPWS) of the abundance and distribution of offshore cold-water reef habitat, a set of coral habitat types has been identified on the Irish Shelf, based on underwater observations from remotely operated vehicles. These include cold-water coral reefs, coral gardens and sea-pen fields. Records of the samples have been included in the vulnerable marine ecosystems (VMEs) database maintained by ICES.

A number of areas where deep-water corals were identified have been designated as special areas of conservation (SACs) by the NPWS.

Deep-water or cold-water corals are found on parts of the continental slope to the west of Ireland at water depths ranging between 600 m and 1000 m, and worldwide they are found at depths of up to 2000 m.

3.11.2 Time Series and Trends

Figure 3.24 shows the distribution of intertidal seagrass sites and their trajectories since 2006. An increase in the presence of seagrass is observed in most sites, except for the Moy estuary, Co. Mayo, and those in Northern Ireland.

Figure 3.25 shows the locations of coral species identified on the Irish Shelf. The locations of SACs and VMEs, which can be found on the ICES portal, are shown.

An extensive survey of vulnerable marine ecosystems in Irish waters was carried out between 2017 and 2019.

3.11.3 Maintaining the Observations

An extensive survey of VMEs in Irish waters from 2017 to 2019 was funded through the EMFF, co-ordinated and led by the Marine Institute and INFOMAR (Integrated Mapping for the Sustainable Development of Ireland's Marine Resource) and commissioned by the NPWS. The NPWS SACs are selected and designated under the EU Habitats Directive, which lists certain habitats and species that must be protected.

Since 2007 the quality of Ireland's coastal waters has been assessed under the WFD. Macroalgal and seagrass communities have been evaluated as ecological quality indicators as part of these assessments.

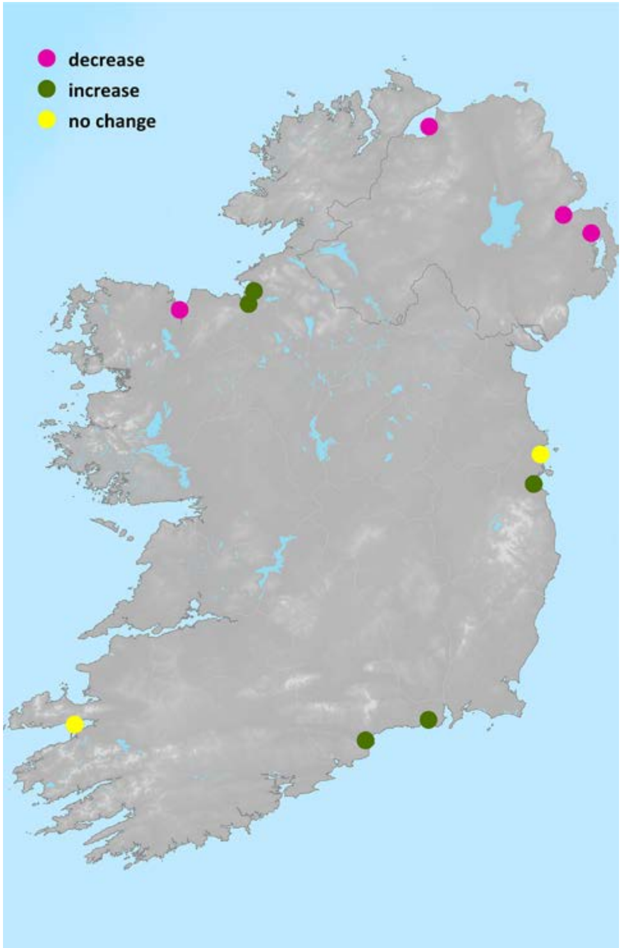


Figure 3.24. Distribution of intertidal seagrass sites and their trajectories since 2006.

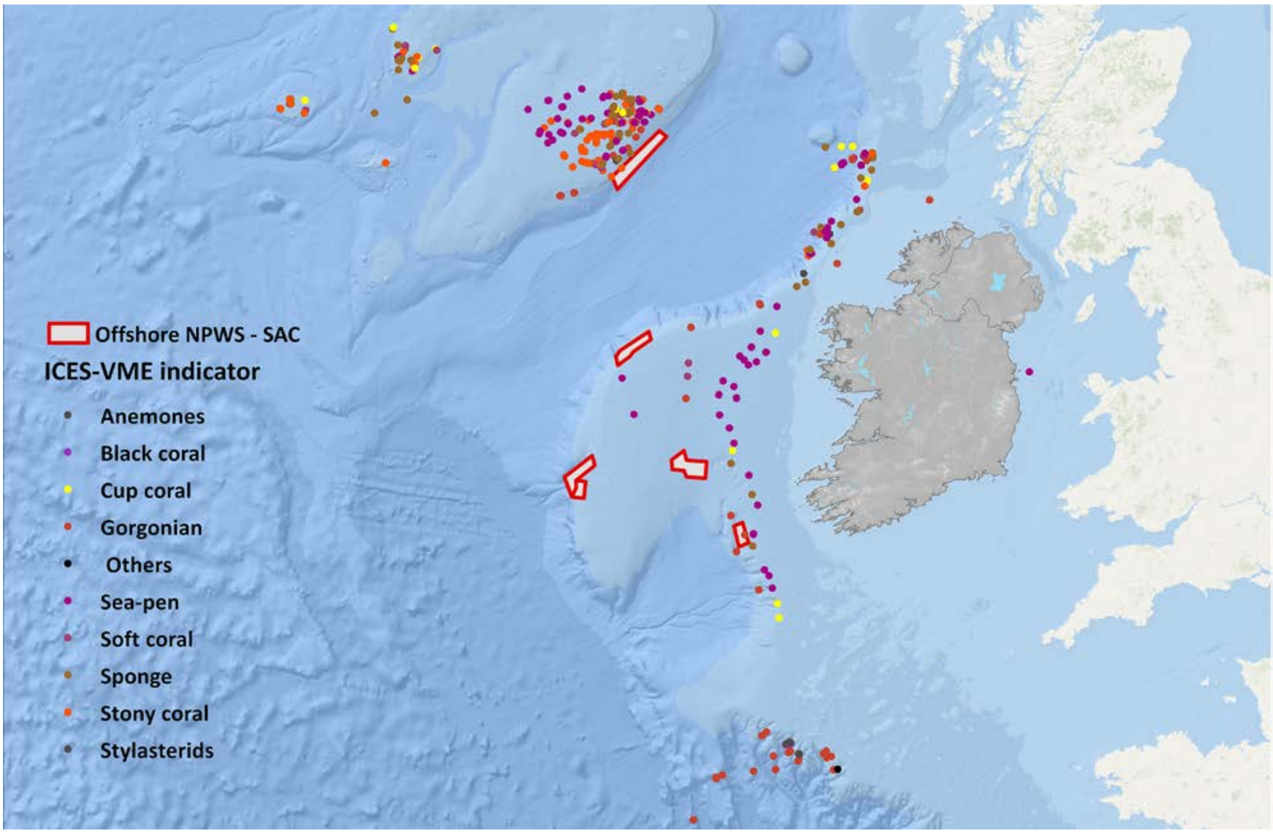


Figure 3.25. Location of the special areas of conservation where deep-water corals have been identified (red polygons) and of vulnerable marine ecosystems, as defined by ICES (coloured squares).

Further Information

Marine Habitats Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/marine-habitats/)

Water Quality in Ireland 2013–2018 (https://www.catchments.ie/water-quality-in-ireland-2013-2018/)

Information about NPWS special areas of conservation (https://www.npws.ie/protected-sites/sac)

Information about ICES vulnerable marine ecosystems (https://www.ices.dk/data/data-portals/Pages/vulnerable-marine-ecosystems.aspx)

de los Santos, C.B. *et al.*, 2019. Recent trend reversal for declining European seagrass meadows. *Nature Communications* 10: 3356. https://doi.org/10.1038/s41467-019-11340-4

Wilkes, R. *et al.*, 2017. Intertidal seagrass in Ireland: pressures, WFD status and an assessment of trace element contamination in intertidal habitats using *Zostera noltei*. *Ecological Indicators* 82: 117–130. https://doi.org/10.1016/j.ecolind.2017.06.036

3.12 Other Ocean Essential Climate Variables

Ned Dwyer and Walther C.A. Cámaro García

A small number of ocean ECVs have been observed only occasionally or not at all in Irish waters. These are transient tracers (SF_6, CFCs, carbon-14, tritium, helium-3) and three new ECVs that were added in the 2016 revision of the GCOS implementation plan: ocean surface stress, ocean surface heat flux and oceanic N_2O.

3.12.1 Transient Tracers

These are human-made chemical substances that have a known concentration history in the atmosphere. These substances are partly absorbed by the ocean and become dissolved in water. Their measurement provides an insight into ocean processes. CFCs, themselves a powerful GHG, are a persistent industrial chemical whose atmospheric concentrations increased and then decreased after the signing of the Montreal Protocol to phase them out in 1987. This was in response to the recognition of the damage they were causing to the Earth's ozone layer. ^{14}C and tritium were released to the atmosphere in pulses during nuclear weapon tests in the 1950s and 1960s. By measuring their presence in the subsurface of the ocean it is possible to estimate when the gas entered the ocean, how quickly it disperses and how it is transported by currents and into the deep ocean. Such knowledge also helps in understanding and quantifying the concentration and fates of other compounds such as anthropogenic carbon and N_2O. Moreover, it improves knowledge of the overturning circulation of water masses in the ocean itself. The leading global observation network that supports collection of the required information is GO-SHIP. NUI Galway and the Marine Institute have collaborated with GEOMAR, the Helmholz Centre for Ocean Research in Germany, which has specific expertise in this field, to sample for CFCs and SF_6 during the GO-SHIP A02 transatlantic survey in 2017 and subsequently in the Rockall Trough.

3.12.2 Ocean Surface Stress

When wind blows over the open ocean a surface stress is induced. This stress depends on a number of characteristics of the atmosphere, such as stratification and air density, and of the ocean, such as wave state and wave age. The magnitude of the stress influences the air–sea exchange of energy, water (evaporation), and oxygen, CO_2 and other gases. Surface stress drives coastal currents, storm surges, surface waves and ice transport and also ocean surface turbulence and mixed layer evolution, and it is a factor in deep-water formation. Stormy regions, such as the Southern Ocean, have particularly high mean wind stress. Ocean surface stress is therefore critically important for determining the large-scale wind- and buoyancy-driven ocean circulation. Surface stress can be determined from data collected by moored instruments and those deployed by ships and from data collected by satellite-borne instruments.

3.12.3 Ocean Surface Heat Flux

Surface heat flux is the exchange of heat, per unit area, crossing the surface between the ocean and the atmosphere. Heat may be transferred into the ocean from the atmosphere or vice versa. This heat transfer occurs in a number of different ways. Heat may be transferred through evaporation or condensation of water; it can be transferred directly by conduction and convection; and it can be transferred into the ocean by direct radiation from the sun or back from the ocean by reflection or emission of energy to the atmosphere. These heat exchanges have a strong influence on climate and are linked to floods and droughts and storm intensity and tracks. Climate variations, such as the North Atlantic Oscillation and the El Niño Southern Oscillation, are also associated with variability in these heat exchanges. Parameters related to heat flux may be measured from moored instruments and from those deployed by ships. Pilot studies to retrieve relevant parameters from data collected by satellite platforms are under way.

3.12.4 Oceanic Nitrous Oxide

N_2O is present in the atmosphere in small quantities. In the upper atmosphere it acts as a strong GHG with a global warming potential 298 times that of CO_2, and in the lower atmosphere it destroys ozone. Globally, about 40% of total N_2O emissions come from human activities, approximately 30% come from the microbial breakdown of nitrogen in soils, and microbial activity in the ocean is responsible for the remaining 30%. Understanding the spatio-temporal variability in oceanic N_2O concentrations and emissions is important to improve the quantification and understanding of the role of the ocean in the nitrogen cycle. The leading global observation network that supports collection of the required information is GO-SHIP.

Further Information

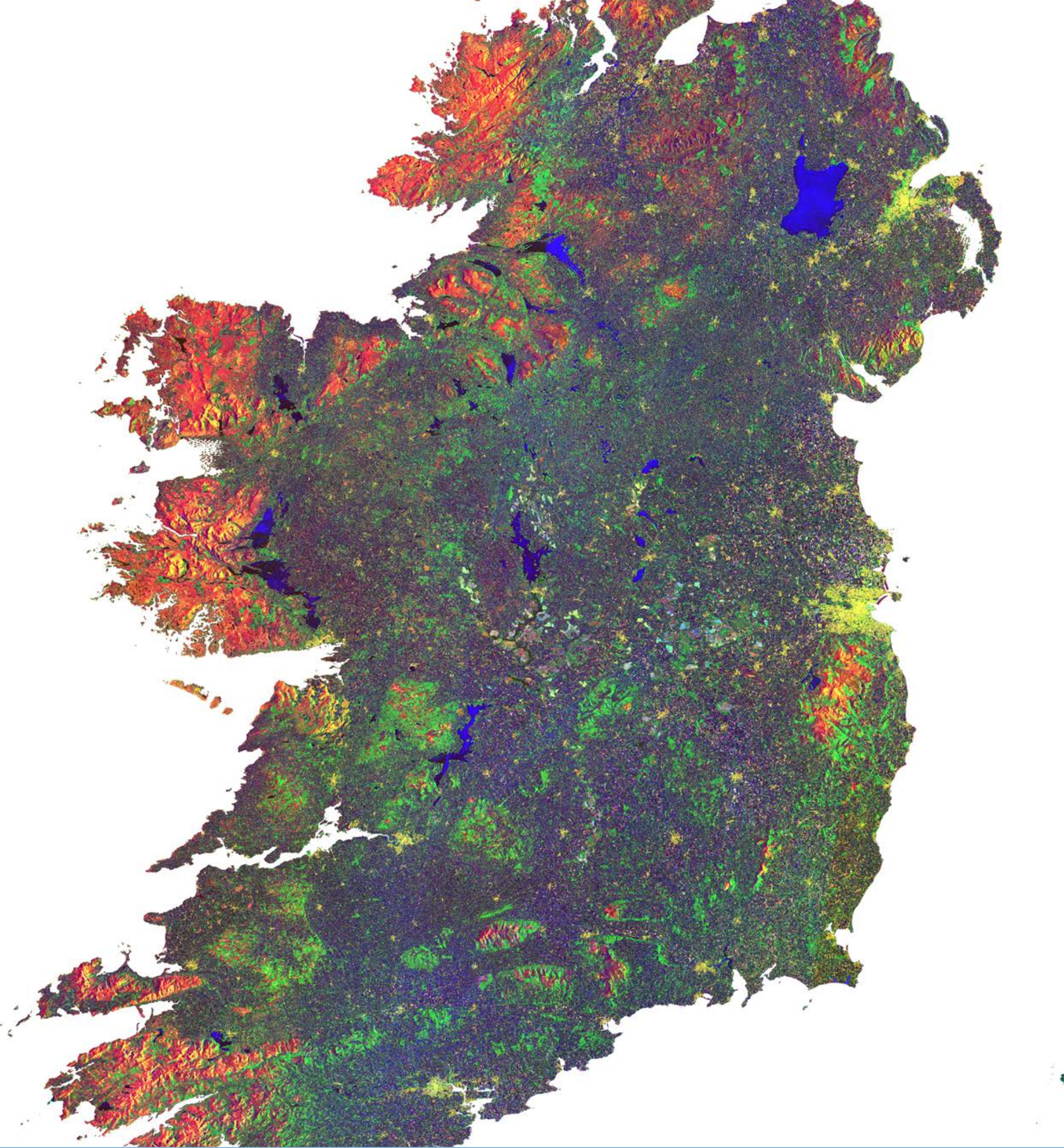
Transient Tracers Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/transient-tracers)

Ocean Surface Stress Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/surface-stress)

Ocean Surface Heat Flux Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/ocean-heat/)

Nitrous Oxide Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/n2o/)

Information about GO-SHIP (https://www.go-ship.org/About.html)



4. Terrestrial Observations

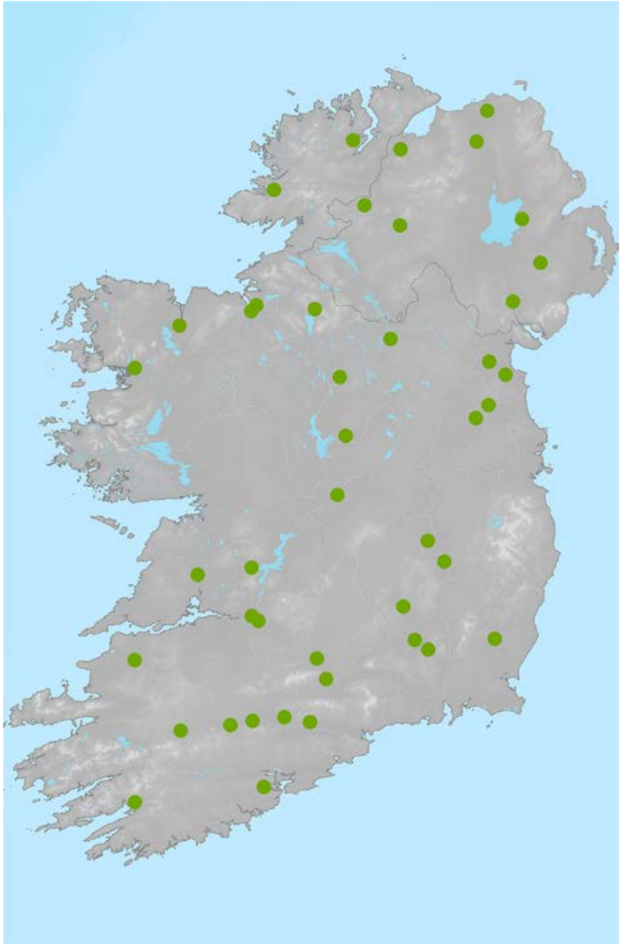
4.1 River Discharge

Walther C.A. Cámaro García, Barry O'Dwyer, Conor Murphy and Ned Dwyer

Changes in climate affect rivers and the flora, fauna and humans that depend on them, in the form of increasing droughts, floods and waterborne diseases. Changes in precipitation patterns, temperature, groundwater run-off and sea level rise, as well as human use and interventions, affect river conditions, generating impacts on energy production, infrastructure, human health, agriculture and ecosystems. Long-term, high-quality observations of river flows are essential in order to understand the hydrological regime and to plan for water resource and flood management under changing climate conditions. River flows into the ocean also need to be measured because they reduce ocean salinity, may affect ocean circulation patterns and transport terrestrial pollutants to coastal and ocean areas.

4.1.1 Measurements

River discharge or flow is measured and data are currently collected by a number of agencies including the EPA, the OPW, local authorities and the Electricity Supply Board (ESB). There are over 800 active river flow meter stations in the country. Capitalising on this network, the EPA has identified a set of high-quality reference hydrometric gauges that can be used for monitoring and detecting climate change signals (Map 4.1). The stations identified include 35 in Ireland and a further eight in Northern Ireland from the UK Benchmark Network. The average record length of these stations is 40 years with a minimum of 28 years and a maximum of 63 years.



Map 4.1. Location of river flow monitoring stations.

When up to 50 years of data are analysed there is an increase in the magnitude of the river flows across most of the country. However, analysis of data for a shorter period, since 1992, suggests an increase in potential drought conditions, especially in the east.

4.1.2 Time Series and Trends

Since the reference network of hydrometric gauges was established in 1972, it has been substantially improved, with 18 additional gauges included in the network since 1992, providing more highly resolved spatial data. Figure 4.1 shows the annual trend in river flows over the island of Ireland based on stations in service since 1972 (long period) and since 1992 (short period). It should be emphasised that the trends in the indicators presented are dependent on the period of the record analysed, indicating the sensitivity of river flows to climate variability. Results for the long period (top panel) indicate an increase in the magnitude of low flows across the majority of gauges for Ireland with the exception of some gauges in the south. In contrast, results for the short period show a decrease in the magnitude of low flows recorded at many gauges throughout Ireland. This suggests an increase in potential drought conditions over the most recent period when compared with the long-term record. This trend is also reflected in average flows. For the long period, average flows are dominated by increases in magnitude. For the short period, an increasing number of gauges show decreases in magnitude, and this is particularly the case for those stations in the east of Ireland. For high flows and for the long period, station data predominantly show an increasing trend in magnitude with the exception of some stations situated in the south of the country. Similar to average flows, in the short period, there is an increasing number of gauges showing a decrease in the magnitude of high flows and particularly in the east of the country.

The development of an Irish reference network of river flow gauges fills a significant gap in many European-scale trend studies.

4.1.3 Maintaining the Observations

The EPA is responsible for river measurements and, in accordance with the EU WFD, established a programme aimed at monitoring river quality and flow trends. Regular reviews of the monitoring network are undertaken to assess the adequacy of the network and ensure that the requirements of the WFD are being met. For long-term climate monitoring purposes, the establishment of an Irish reference network of river flow gauges fills a significant gap in many European-scale trend studies; Ireland is an important location for understanding climate variability and change on the Atlantic fringe of Europe.

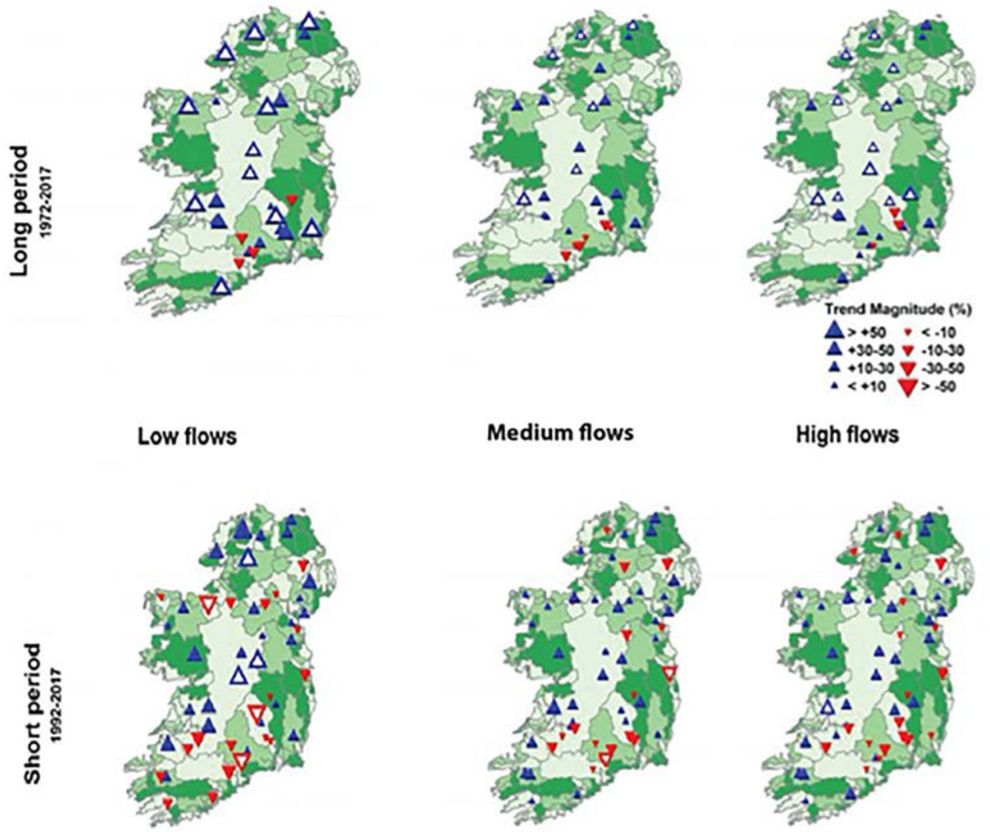


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Figure 4.1. Annual trends in river flows over the island of Ireland for different types of flow based on the hydrometric network since 1972 (long period) and 1992 (short period). Blue arrows indicate an increasing trend, while red arrows indicate a decreasing trend. Changes identified as significant are indicated by arrows with white fills. For further information, see Murphy *et al*. (2013).

Further Information

River Discharge Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/rivers/)

Murphy, C. *et al*., 2013. Climate-driven trends in mean and high flows from a network of reference stations in Ireland. *Hydrological Sciences Journal* 58: 755–772. https://doi.org/10.1080/02626667.2013.782407

The EPA website on river monitoring (https://www.epa.ie/water/wm/rivers/)

The EPA Geo Portal data source on river flows (http://gis.epa.ie/GetData/Download)

The EPA HydroNet portal – river flow data (https://www.epa.ie/hydronet/#Flow)

Hydrometric data from the Office of Public Works hydrometric network (https://waterlevel.ie/)

4.2 Groundwater

Walther C.A. Cámaro García, Ned Dwyer and Conor Quinlan

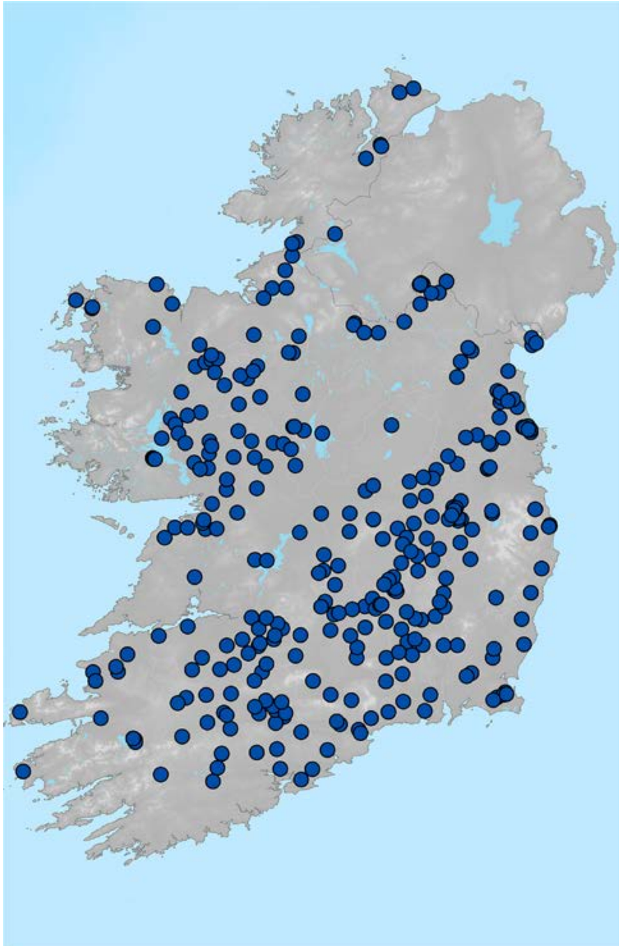
Groundwater is located beneath the ground surface in pore spaces and fractures of geological formations. If the geological formation can yield enough water for a significant supply, then the term aquifer is often used. It is estimated that almost 30% of the world's fresh water is stored as groundwater. Globally, it is a major source of drinking water and is also widely used in agriculture and industry. In Ireland about 18% of drinking water is from groundwater sources. Groundwater volumes and levels are influenced by not only rainfall and dry periods but mainly human use. Abstraction, especially in the world's arid and semi-arid zones, is leading to rapid rates of groundwater depletion. Risks to groundwater quality and quantity that may be exacerbated under a changing climate include further depletion, pollution and salinisation.

4.2.1 Measurements

Data on groundwater levels have been collected in Ireland since the late 1960s. In the 1990s, the EPA took responsibility for its monitoring, and currently there are 387 *in situ* stations (blue dots) where groundwater levels are monitored (Map 4.2).

Information regarding levels for 126 of these stations is available to download through the EPA HydroNet web portal. In addition, water quality monitoring is carried out at a number of the stations taking measurements of several chemical parameters such as oxygen content, conductivity, and nitrate and ammonium concentrations.

Satellites that form part of the collaborative US and German Gravity Recovery and Climate Experiment (GRACE) are being used internationally for the monitoring of groundwater over large areas. Large



Map 4.2. Location of groundwater monitoring stations.

pockets of water exert a greater gravitational pull on the satellites than areas without water.

Groundwater levels change on a seasonal basis. During winter 2016 the highest value of the whole time series was observed.

4.2.2 Time Series and Trends

Groundwater levels are assessed every 3 years in compliance with the EU WFD. Although these analyses are not primarily for identifying climate-driven changes, they may be used to identify changes in aquifer levels. Figure 4.2 shows an example of measurements of the daily mean level for a well in Knocktopher, Co. Kilkenny, from 1980 to 2018. There are many data gaps in the early part of the series before the installation of a digital system. Levels change on a seasonal basis, with a minimum during the summer months and a maximum during winter, when groundwater recharge occurs. During winter 2016 the highest value of the whole time series was observed.

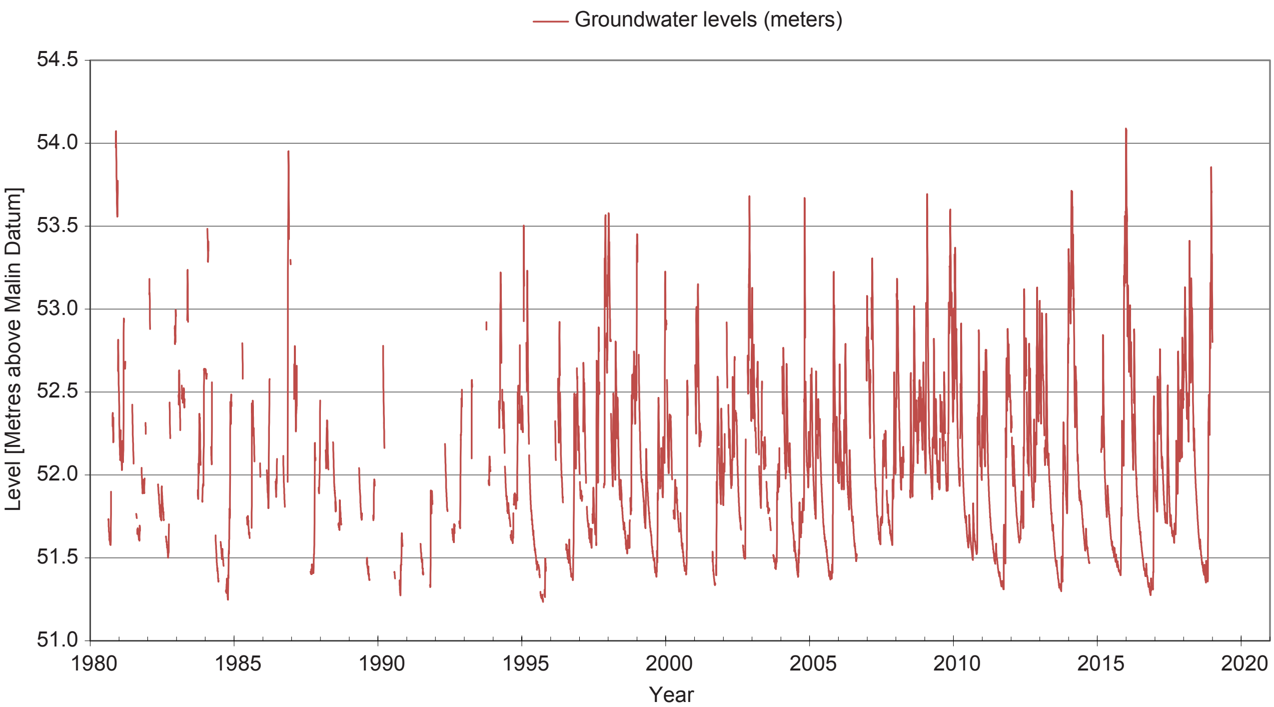


Figure 4.2. Daily mean groundwater level (m) at a well in Knocktopher, Co. Kilkenny (1980–2018).

Regular analysis of national groundwater levels is carried out but not primarily for identifying climate-driven changes.

4.2.3 Maintaining the Observations

The EPA is responsible for groundwater measurements and, in accordance with the WFD, established a programme aimed at monitoring groundwater quality and levels. Regular reviews of the monitoring network are undertaken to assess its adequacy and ensure that the requirements of the WFD are being met.

Ireland, through the EPA, is currently leading work within the EU to integrate climate change considerations into EU-wide WFD groundwater monitoring and assessment.

In addition, some local authorities, academic research institutions, private consultants and Geological Survey Ireland carry out groundwater monitoring.

Further Information

Groundwater Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/groundwater/)

The EPA website on groundwater monitoring (https://www.epa.ie/water/wm/groundwater/)

The EPA Geo Portal data source on groundwater (http://gis.epa.ie/GetData/Download)

The EPA HydroNet portal – groundwater level data (https://www.epa.ie/hydronet/#Water%20Levels)

About the GRACE mission (https://grace.jpl.nasa.gov/applications/groundwater/)

Groundwater information from the Geological Survey of Ireland (https://www.gsi.ie/en-ie/data-and-maps/Pages/Groundwater.aspx)

4.3 Lakes

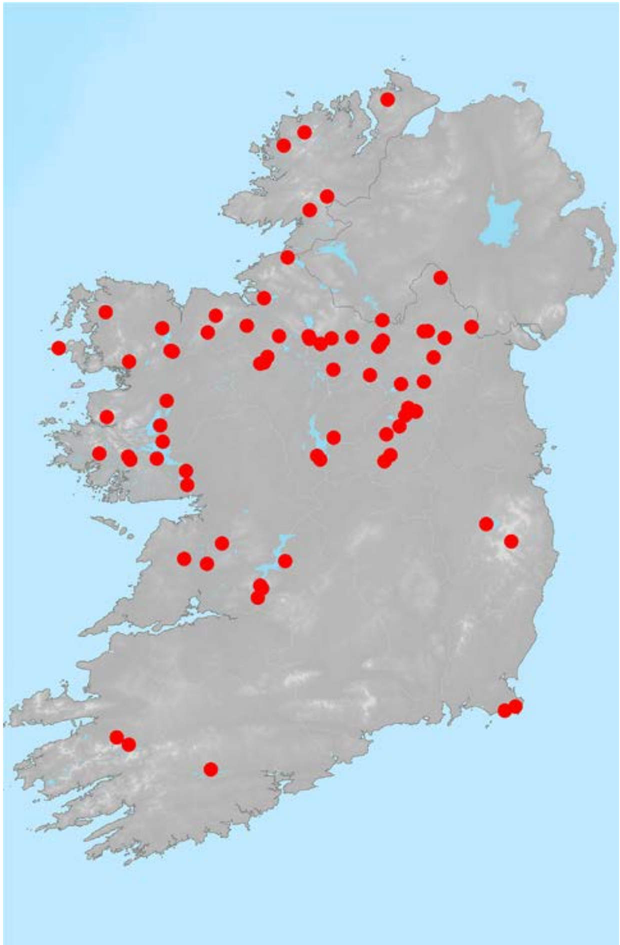
Walther C.A. Cámaro García, Ned Dwyer and Conor Quinlan

Lakes are linked to climate change effects due to evaporation of water. Information on variations in the level, area and temperature of lakes is essential to understand the dynamics of these water bodies, which are directly affected by regional climate. Lakes provide a range of services such as drinking water and supplies for industry and agriculture, recreational opportunities and ecosystem maintenance. Almost 95% of the volume of water held globally in approximately 4,000,000 lakes is contained in the world's 80 largest lakes. In Ireland, there are over 12,000 lakes, many quite small and shallow, located mainly in the Midlands and the west. The most significant threats to these lakes and their biology is changes in water quality caused by land use change in their catchments and water temperature changes in the lakes themselves.

4.3.1 Measurements

Lake levels are currently measured at 74 locations by the EPA, the OPW and the ESB (Map 4.3). The lake monitoring programme is undertaken to comply with the WFD. In this programme, 226 lakes are examined for a broader range of biological and chemical parameters. Lake water quality measures have been published regularly since 1987 by the EPA.

Satellite altimetry is used internationally to determine water levels in large lakes. This provides useful data in the absence of *in situ* measurements. Currently, through ESA's CCI project, a time series of a range of parameters, including lake water level, water extent, surface water temperature, ice cover and water-leaving reflectance, is being prepared initially for 200 large lakes globally.



Map 4.3. Location of lake monitoring stations.

Levels in Lough Oughter show seasonal variation, but no long-term trend in the data is apparent.

4.3.2 Time Series and Trends

No systematic analysis of lake levels has been carried out to date. Figure 4.3 shows an example of measurements of the monthly mean level for Lough Oughter in Co. Cavan from 1977 to 2018. Being an unimpacted lake, with no significant water extraction and limited development in the lake surrounds, it is a useful resource for identifying potential climate change effects. Levels show seasonal variation, with minimum values during the summer and maximum values during the winter, but no long-term trend in the data is apparent. The highest value of the whole time series occurred in December 2015. This corresponds to the highest amount of monthly rainfall observed since records began in 1985 at the nearby rainfall observation station in Cavan.

For long-term climate monitoring purposes a number of representative lakes need to be identified.

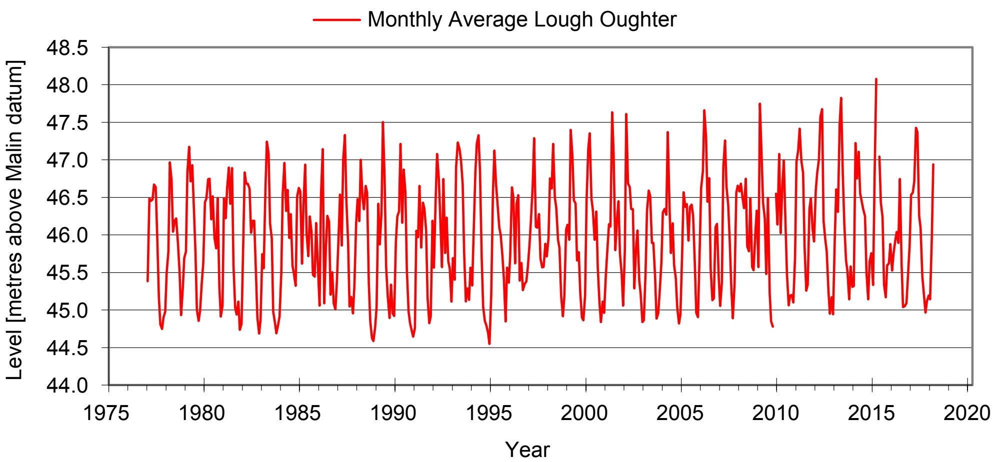


Figure 4.3. Monthly mean levels (m) of Lough Oughter, Co. Cavan (1977–2018).

4.3.3 Maintaining the Observations

The EPA is committed to measuring a number of lake parameters to meet the requirements of the WFD. For long-term climate monitoring purposes a number of representative lakes need to be identified. Ideally, no significant water abstraction should take place upstream of or from these lakes themselves. Moreover, high-quality measurements and long data records should exist. Systematic analysis of historical lake level records should also be carried out.

Further Information

Lakes Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/lakes/)

The EPA website on lake monitoring (https://www.epa.ie/water/wm/lakes/)

The EPA Geo Portal data source on lake locations and water quality (http://gis.epa.ie/GetData/Download)

The EPA HydroNet portal – lake level data (https://www.epa.ie/hydronet/#Water%20Levels)

Hydrometric data from the Office of Public Works hydrometric network (https://waterlevel.ie/)

About ESA's Lakes Climate Change Initiative project (http://cci.esa.int/lakes)

4.4 Soil Moisture

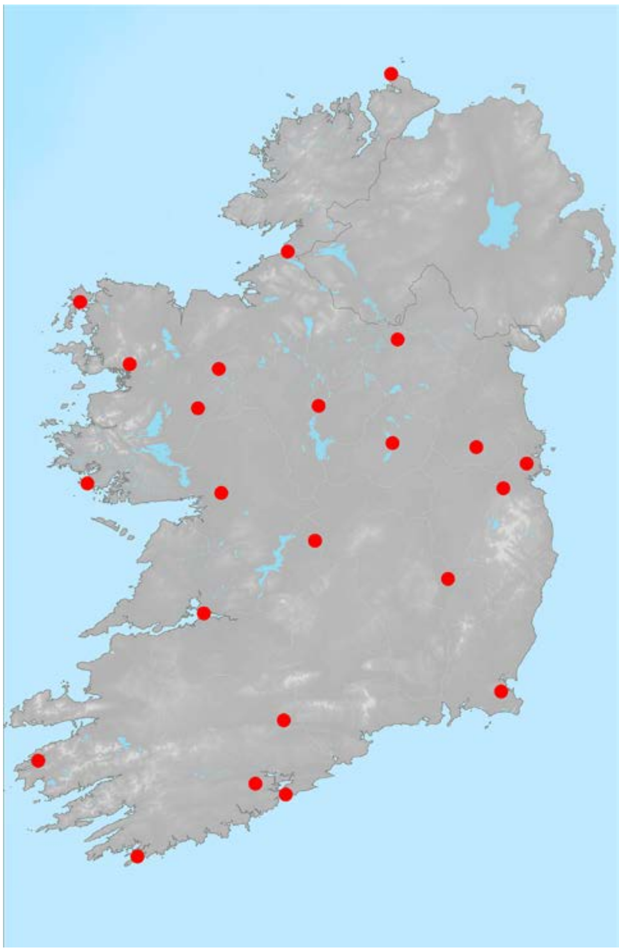
Walther C.A. Cámaro García, Ned Dwyer and Keith Lambkin

Soil moisture comprises only a tiny percentage of the total global water budget, but it has a key role in influencing the hydrological cycle and is a major driving force in the soil's ability to act as a carbon sink or source. Soil moisture content refers to the amount of water held in the soil and is affected by the soil texture, topography, land cover and weather conditions. Both local climate and vegetation influence soil moisture through evapotranspiration. Soil moisture is a determinant of the type and conditions of vegetation in a region, and it is an important measure for agriculture, as it affects the length of the grazing season, grass and crop growth rates and nutrient uptake and loss.

4.4.1 Measurements

There are direct and indirect methodologies to measure soil moisture. However, these measurements are only representative of local conditions, and direct methodologies require intensive labour. Currently in Ireland only indirect methods are used in practice.

Met Éireann has estimated the daily soil moisture deficits (SMDs) at many of its synoptic stations since 1980 (Map 4.4). These are modelled values based on the difference between rainfall amount and actual evapotranspiration and are estimated separately for poorly, moderately and well drained soils.



Map 4.4. Location of synoptic stations at which soil moisture deficits are estimated.

A number of satellite sensors make broad-scale measurements of soil moisture. The ESA CCI Soil moisture project has developed one of the most comprehensive global time series of satellite-derived soil moisture measurements.

SMDs measured at Dublin Airport in June and July 2018 were the highest since records began in 1981.

4.4.2 Time Series and Trends

Figure 4.4 shows the average daily SMD for moderately drained soils based on data collected at Valentia Observatory and Dublin Airport synoptic stations from 1980 to 2019. SMD is the rainfall in millimetres required to saturate or fill all the pores in the soil. Saturated soils (negative SMD) generally occur on wet winter days, but such moderately drained soils quickly return to unsaturated conditions. The greatest SMDs, which usually occur in the summer and when sustained can be indicative of droughts, generally occur in the east and south-east of the country.

Figure 4.5 shows a heat map of the monthly average SMDs for the complete time series at Dublin Airport. Red represents the months with the greatest SMDs. The 95th percentile threshold (49.8 mm) indicates that 95% of data fall below this value. The consecutive red values during summer 2018, with June and July being the highest values of all in the time series, are in line with the heatwave and drought conditions experienced during that summer.

Figure 4.6 shows the daily surface soil moisture over Europe for 10 June 2017 as determined by the ESA

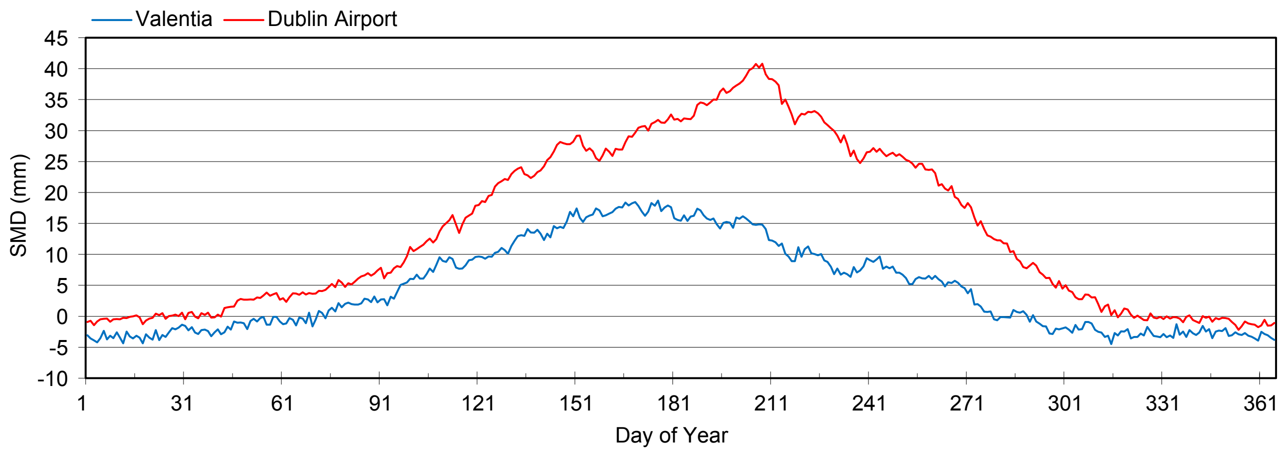


Figure 4.4. Average daily soil moisture deficits (mm) calculated at Valentia Observatory and Dublin Airport (1980–2019).

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2020												
2019	3.6	4.3	3.2	5.4	17.5	13.8	36.8	16.9	17.2	-0.6	-3.5	-0.9
2018	-1.6	1.2	-0.1	4.2	33.6	70.5	86.0	61.7	39.7	22.1	1.1	-1.5
2017	2.6	0.9	2.7	24.1	48.5	28.9	33.8	23.1	3.8	0.6	0.9	-1.0
2016	-2.2	-0.4	7.0	8.1	26.5	45.4	37.1	38.7	19.3	8.9	1.4	1.0
2015	-0.8	1.3	3.5	11.4	12.0	44.9	51.3	30.0	4.6	6.6	-2.7	-3.6
2014	-2.4	-1.9	2.0	11.9	8.0	26.9	46.2	10.3	23.3	1.6	-2.6	-0.5
2013	-1.3	2.0	2.0	11.0	22.5	29.2	44.9	22.7	35.0	2.3	0.4	-0.1
2012	-0.2	1.5	8.5	7.5	8.6	3.0	3.2	5.7	11.9	0.1	-1.1	-1.1
2011	0.2	-0.9	7.8	19.3	43.9	42.8	37.4	43.2	29.6	0.8	-0.1	-1.1
2010	-1.1	0.3	7.0	14.5	31.9	31.2	32.3	29.1	8.1	13.0	-2.6	-1.5
2009	-0.3	2.4	9.0	9.7	7.4	18.1	1.9	12.0	12.4	9.6	-3.3	-1.1
2008	-1.3	6.0	4.3	9.7	38.8	37.3	15.3	3.4	4.2	-0.7	-0.8	-0.6
2007	-0.9	0.1	2.9	33.5	49.7	18.4	0.6	6.3	29.0	23.0	14.4	0.3
2006	1.5	2.8	0.5	11.3	8.1	44.0	61.9	62.2	21.1	-1.1	0.1	-2.5
2005	-0.4	0.6	8.5	2.7	14.8	37.5	47.9	26.5	26.8	7.4	0.7	-0.5
2004	-1.4	6.8	7.5	12.4	31.7	42.3	40.0	29.5	20.1	-0.2	1.4	-0.5
2003	-0.9	3.1	8.6	34.5	10.9	19.3	19.7	47.2	56.4	30.1	0.4	-0.7
2002	0.0	-2.5	4.1	11.5	6.2	6.3	17.4	17.7	34.2	7.1	-2.9	-1.1
2001	0.4	0.9	1.2	1.1	17.0	32.8	50.3	15.3	27.1	3.2	-0.2	1.3
2000	1.2	0.1	9.0	4.4	18.6	27.0	53.9	35.7	17.4	-1.1	-1.8	-2.5
1999	-1.6	0.4	7.6	6.1	21.4	24.6	38.6	13.8	4.5	6.4	1.3	-2.0
1998	-1.0	4.9	3.3	0.5	19.9	5.9	19.1	21.5	5.1	-0.7	-1.7	-1.9
1997	1.2	-1.0	9.7	28.9	7.8	10.5	22.2	14.0	13.4	7.2	-2.1	-1.7
1996	-2.1	-0.3	1.1	5.8	11.8	30.8	53.6	13.9	26.3	8.6	-1.9	-0.6
1995	-2.3	-1.8	1.1	17.3	31.8	41.2	49.5	66.3	58.8	42.6	9.8	-1.6
1994	-1.9	-1.7	1.3	4.6	12.2	38.9	36.2	37.3	5.9	4.6	-1.0	-1.6
1993	-0.3	6.8	12.8	6.4	11.8	7.6	29.7	32.9	21.9	3.6	5.3	-2.2
1992	3.9	10.3	4.2	1.7	18.6	29.9	38.2	39.8	8.8	6.4	-0.4	-0.3
1991	0.4	-0.9	1.1	10.6	31.6	44.0	40.6	51.4	55.7	21.7	0.2	1.8
1990	-0.5	-1.4	15.0	34.0	49.4	44.1	29.0	57.6	52.3	14.4	0.1	-1.2
1989	2.8	1.8	2.0	3.3	34.4	52.0	64.7	57.7	37.0	28.2	1.5	1.2
1988	-2.1	1.8	2.5	20.3	17.7	31.9	39.1	19.4	18.2	5.8	2.5	1.9
1987	0.5	3.2	1.9	9.8	44.0	12.1	26.8	24.5	3.0	-0.1	0.3	1.8
1986	-1.9	6.8	12.1	5.0	16.3	20.1	14.9	5.4	27.4	42.1	-1.6	-0.4
1985	-0.5	5.0	4.0	9.5	17.0	14.0	15.9	-0.5	11.0	21.7	13.3	-1.0
1984	-2.3	-0.3	3.4	9.7	44.2	40.9	62.8	36.4	7.8	2.4	-1.7	-1.3
1983	0.2	0.5	2.4	4.7	6.5	19.6	55.6	61.9	23.4	5.9	10.2	-1.8
1982	0.1	6.0	2.9	22.0	39.1	29.5	33.5	49.7	29.7	-0.5	-1.9	-1.1
1981	1.1	1.1	-0.7	10.5	3.3	11.5	36.8	58.6	44.0	0.0	2.1	-2.5
1980	-1.0	-0.8	1.9	20.7	50.8	24.4	24.2	11.3	14.6	-1.5	1.1	-0.5

Months

Perc	Intervals
95	≥ 49.8
75	23.3 - 49.8
50	6.9 - 23.3
25	0.4 - 6.9
5	-1.9 - 0.4
Min	-3.6 - -1.9

Figure 4.5. Mean monthly surface soil moisture deficit, derived from measurements at Dublin Airport. The data are presented as percentiles. For example, the 75th percentile means that 75% of all the values are below the corresponding value and 25% of the values are above it.

CCI Soil moisture project. This product has a spatial resolution of 25 km. Shades of red represent dry soils, whereas blues represent saturated soil.

> Met Éireann has estimated daily SMDs at its synoptic stations since 1980, but detailed analysis of trends needs to be carried out.

4.4.3 Maintaining the Observations

The network of synoptic stations needs to be maintained and further developed to ensure the future of long-term measurements. With the aim of securing and potentially enhancing this limited network for soil moisture observations, the Joint Working Group on Applied Agricultural Meteorology (AGMET), which includes Met Éireann, Teagasc and other research

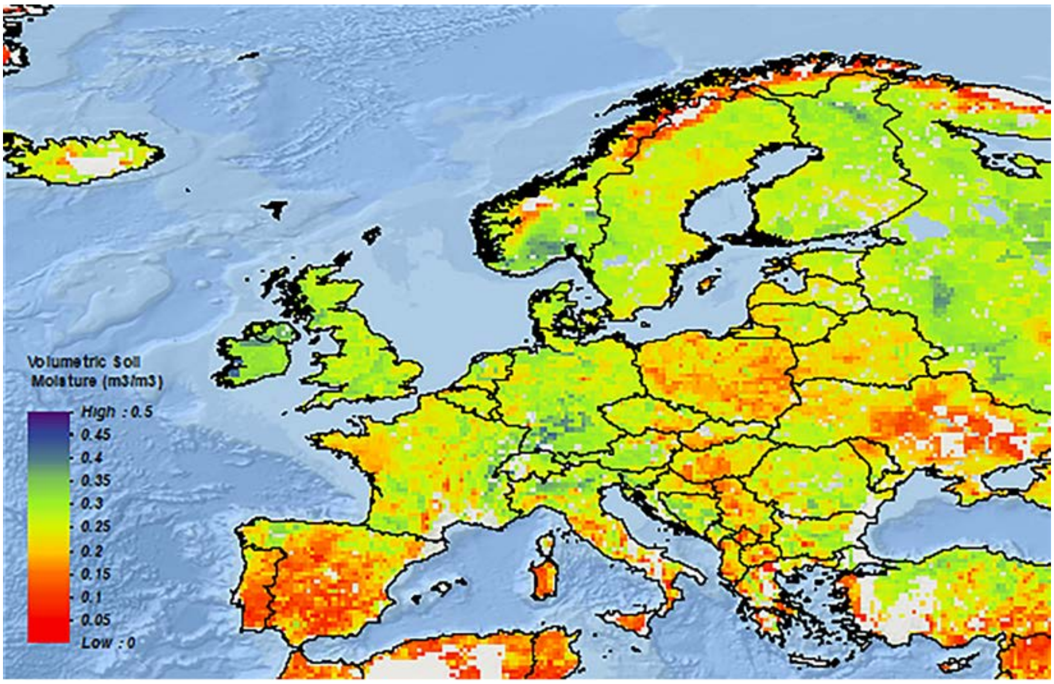


Figure 4.6. Surface soil moisture across Europe on 10 June 2017. Source: Data extracted from the ESA Climate Change Initiative Soil moisture project.

institutes, is exploring options for establishing a national soil moisture monitoring network.

The MaREI Centre at University College Cork was part of the ESA CCI Soil moisture project team and was in charge of the validation and verification of the datasets. Maynooth University is leading an EPA-funded project (2020–2022) entitled Soil Moisture Estimates from Satellite-based Earth Observations (SOMOSAT).

The International Soil Moisture Network is a co-operative initiative for establishing and maintaining a global *in situ* soil moisture database. A number of stations based in Ireland reported to this network over the period 2016–2019 as part of the Horizon 2020-funded GROW Observatory project.

Further Information

Soil Moisture Essential Climate Variable (ECV) Factsheets (https://gcos.wmo.int/en/essential-climate-variables/soil-moisture/)

Schulte, R.P.O. *et al*., 2005. Predicting the soil moisture conditions of Irish grasslands. *Irish Journal of Agricultural and Food Research* 44: 95–110

Gruber, A. *et al*., 2019. Evolution of the ESA CCI Soil Moisture climate data records and their underlying merging methodology. *Earth System Science Data* 11: 717–739. https://doi.org/10.5194/essd-11-717-2019

Met Éireann historical data (https://www.met.ie/climate/available-data/historical-data)

Met Éireann information on soil moisture deficit estimation (https://www.met.ie/climate/services/agri-meteorological-data)

ESA Climate Change Initiative soil moisture products data (http://www.esa-soilmoisture-cci.org/)

Met Éireann reports 2018 as a summer heatwaves and droughts (https://www.met.ie/2018-a-summer-of-heat-waves-and-droughts)

International Soil Moisture Network (https://ismn.geo.tuwien.ac.at/en/)

The GROW Observatory project (https://growobservatory.org/)

Information about the Joint Working Group on Applied Agricultural Meteorology (https://agmet.ie/about/)

Story Box 5. A revolution in Irish land cover mapping is under way

Kevin Lydon, Gavin Smith and Ned Dwyer

Land cover mapping

High-quality national land cover maps with regular updates are necessary, as they provide us with vital information on the condition of the environment and how it changes over time. Those who require land cover maps to carry out their work have until now had to rely on the European CORINE land cover map series (available since 1990). CORINE provides a time series of land cover data (latest from 2018), but there have been a number of frustrations with their use in Ireland, especially their coarse (25-ha) spatial resolution. Ireland has a very fragmented landscape, and so many important environmental features such as hedgerows and semi-natural grasslands are missed at this scale of mapping. Moreover, CORINE has a standard set of land cover classes for all of Europe, which means that important Irish land cover classes are poorly mapped (e.g. raised bogs, upland blanket bogs, lowland blanket bogs, cutover bogs, eroding bogs, flushes and fens are all classed as peatland in CORINE). Accurate and detailed land cover information is required to plan for future land use: Where are the best places to plan for new urban developments? Which areas are most vulnerable to erosion or flooding? What areas are most suited to forestry or new crops as both the climate and agricultural systems change?

Progress towards an Irish high-resolution dataset

Recognising these limitations, the EPA and several other public bodies, including the NPWS, Teagasc, OSi, the Heritage Council and the DAFM, set up a national land cover and habitats working group in 2011 to identify a way to produce a higher quality national land cover dataset for Ireland. After several years of investigating technical solutions, including pilot programmes, funding research and stakeholder consultation events, the OSi and the EPA began working in partnership on delivering the project in 2018. The project is steered by the wider land cover working group, which is chaired by a representative of the NPWS. The aim is to deliver a new land cover dataset for Ireland during 2021.

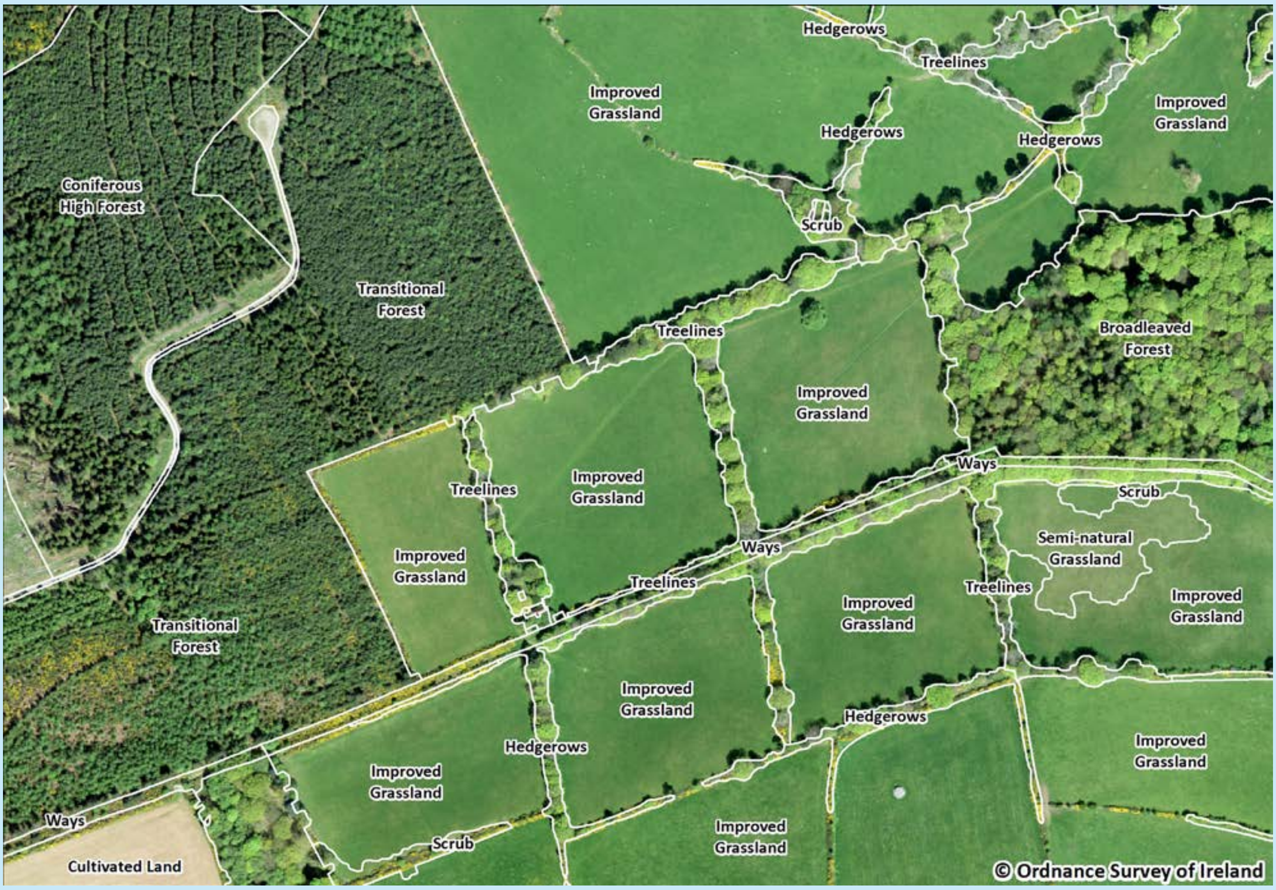
Mapping approach

The new land cover dataset will sit within the OSi's National Map spatial framework. The National Map is a spatial database that maps all land parcel boundaries, buildings, roads, pathways and water bodies in the country. Figure SB5.1 shows an example of this dataset, where the parcel boundaries are highlighted in white. The land cover programme uses spatial analysis of Earth observation data to subdivide and classify these parcels into their respective land cover sub-components. For example, while the National Map gives the property boundary of a field parcel, the land cover dataset will map all internal land cover features present such as hedgerows, scrub and types of grassland (the white delineations and labelling in Figure SB5.1).

Data sources

As well as using the National Map dataset, the project will utilise existing spatial datasets on forestry and agricultural land use data from Coillte and DAFM, respectively, habitat data from NPWS, local authorities and the National Biodiversity Data Centre and subsoil data from Teagasc (Figure SB5.2). These data are all used to inform the image-based classification process. The Earth observation imagery that forms the central part of the analysis includes 25-cm four-band colour-infrared aerial photography, a 1-m digital surface model from the OSi and 10-m satellite imagery from the ESA Sentinel-2 satellite, available freely through the Copernicus programme. The reference year for the project is 2018.

When complete, the product will represent a revolution in land cover mapping in Ireland. With a spatial resolution almost 250 times better than CORINE, combined with the much more detailed and nationally



SB5

Figure SB5.1. Example of the new landcover dataset showing landcover units (in white). © Ordnance Survey Ireland.

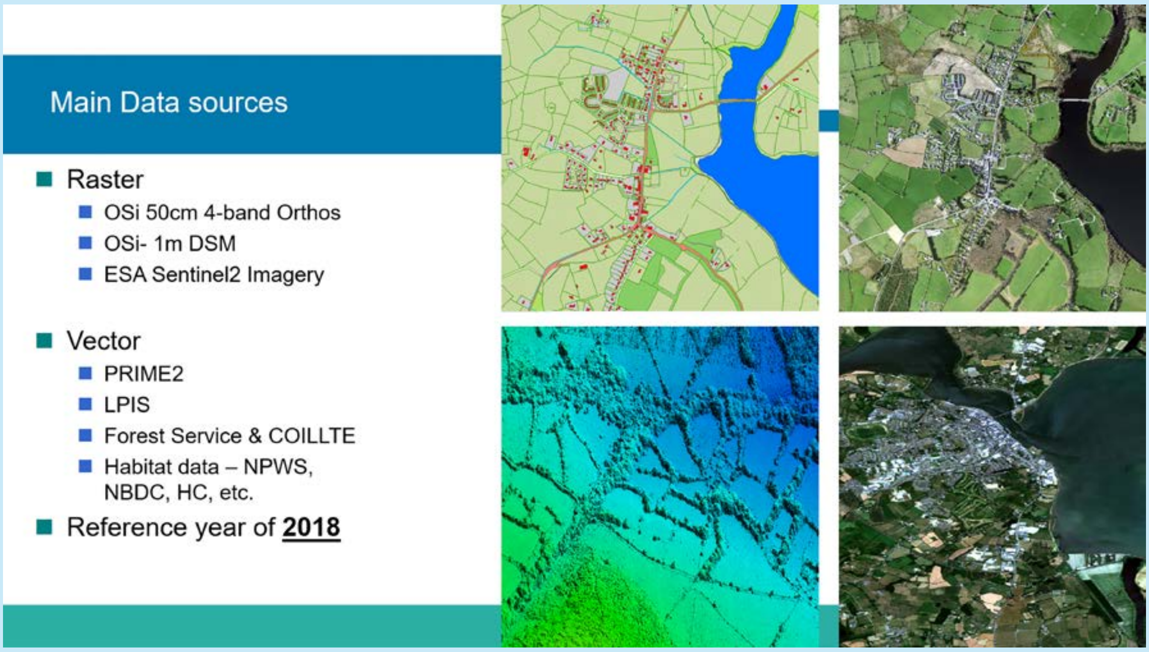


Figure SB5.2. Some of the main data sources used in the production of the new land cover maps. The new classification system is compatible with the European Environment Agency's EAGLE classification model for land monitoring in Europe, thus ensuring compatibility with European land cover and land use reporting requirements. © Ordnance Survey Ireland.

appropriate classification system, not only will it support land management, but it will also support reporting of emissions and removals of GHGs for land use, land use change and forestry reporting. The accurate classification of the extent of hedgerows will allow more accurate calculation of grassland and cropland areas, as well as providing information on biodiversity, ecosystem services and sustainable agricultural practices. With regular updates of the maps capturing land use changes, it will be possible for the first time to make much more accurate calculations of emissions and removals of GHGs in regard to climate action.

Further Information

Arnold, S. *et al*., 2018. The EAGLE concept: a paradigm shift in land monitoring. In Ahlqvist, O. *et al*. (eds), *Land Use and Land Cover Semantics*. CRC Press, Boca Raton, FL

The EPA's Geo Portal data source on CORINE land cover 2018 (http://gis.epa.ie/)

OSi's National Map (https://www.osi.ie/about/future-developments/the-national-map/)

Thompson, S., 2019. Ireland needs more detailed land-use maps. *Irish Times*, 19 September 2019 (https://www.irishtimes.com/news/science/ireland-needs-needs-more-detailed-land-use-maps-1.4010070)

4.5 Albedo

Walther C.A. Cámaro García and Ned Dwyer

Radiation from the sun is essential for all biological processes on Earth. The proportion of this radiation that is reflected by the Earth's surface is known as albedo. This parameter is linked to natural variations in terrestrial properties, illumination conditions and human activities. Albedo is key to understanding energy exchanges between the atmosphere and the surface. The average Earth albedo is 0.3 on a scale from 0.0 to 1.0. However, this proportion changes seasonally and regionally. High albedo values are observed from surfaces covered by snow, while dense forest and water bodies, which absorb most of the incident radiation, have low albedo. Monitoring the variation in albedo over time provides key information to understand changes in the Earth's surface due to natural and human causes, and albedo is a key indicator of environmental vulnerability. This is particularly important in polar, subarctic and glaciated regions.

4.5.1 Measurements

Ground-based observations of albedo require measurement of incoming and reflected solar radiation. These measurements tend to be made at a local scale and for research studies. There is no long-term *in situ* albedo monitoring programme in Ireland.

Regional albedo measurements are generally made by satellite sensors, which have the ability to measure the total radiation reflected by the Earth's surface on a regular basis. There are very good continuous satellite observations starting in the 1980s from which albedo estimates can be inferred. The Copernicus Global Land Service (CGLS) generates a surface albedo dataset as part of a suite of energy monitoring products. This dataset is derived from the SPOT Vegetation and PROBA-V satellite programmes.

An anomalously high value of albedo was observed during the last week of 2010, when most of the country was covered in snow.

4.5.2 Time Series and Trends

Figure 4.7 shows a time series of 10-day average albedo over Ireland derived from the CGLS dataset. A seasonal trend is observed, in which the highest values occur during winter, particularly in late December and early January, while the lowest values are observed during the summer months, when vegetation cover is at its maximum. An anomalously high value can be seen during the last week of 2010, when most of the country was covered in snow. A slight increase in the minimum values is observed after 2014. This may be because of a change in the satellite used to collect the data and highlights the need for homogenising the data from the product.

Figure 4.8 shows a set of maps of the 10-day albedo over Ireland in 2018, derived from the CGLS, for the periods 14–24 January, 13–23 April, 3–13 July and 14–24 October. Information is available only for cloud-free areas, which is a challenge, as can be observed especially in the January period. The highest values are observed during the autumn and winter, when the presence of vegetation is reduced.

Long-term ground-based measurements of albedo should be considered to validate and support the satellite observations.

4.5.3 Maintaining the Observations

Current and future satellite sensors will continue to gather the radiation reflected from the Earth's surface from which albedo can be calculated. The CGLS is one of the Copernicus services that provides satellite information that may be used to monitor the status of the biosphere around the globe. The global albedo dataset is derived from several satellite sensors.

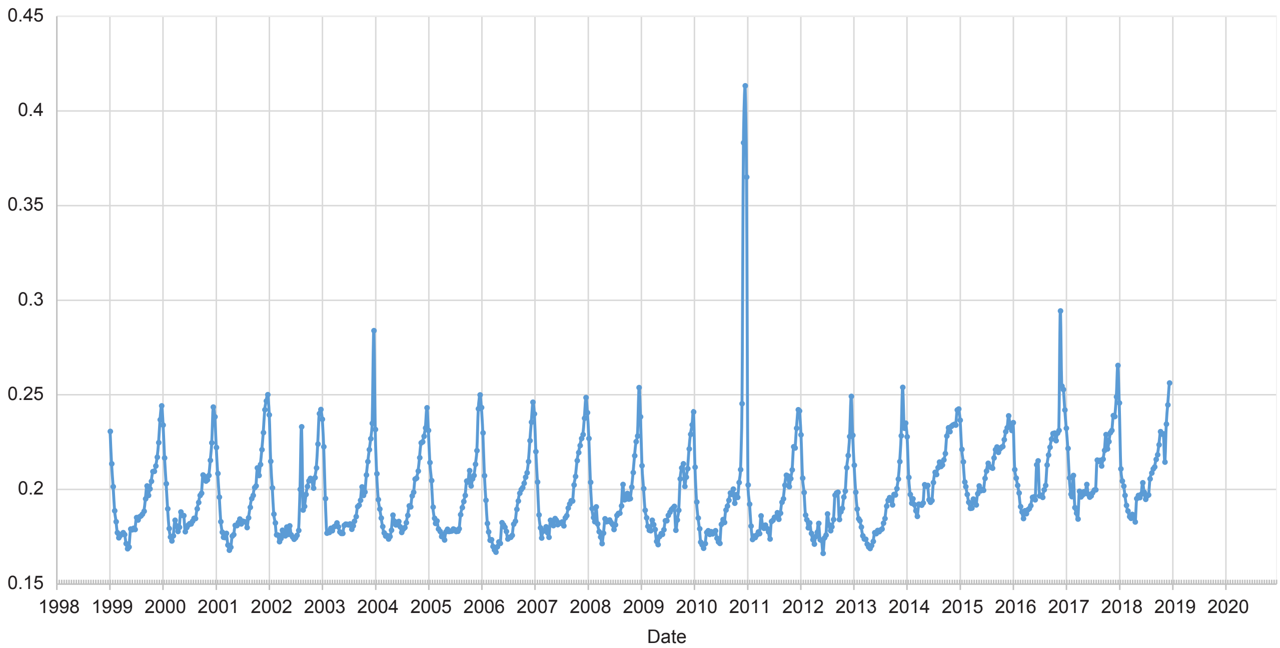


Figure 4.7. Time series of 10-day average albedo over Ireland. Source: Generated by the authors from data derived from the Copernicus Global Land Service datasets (1999–2018).

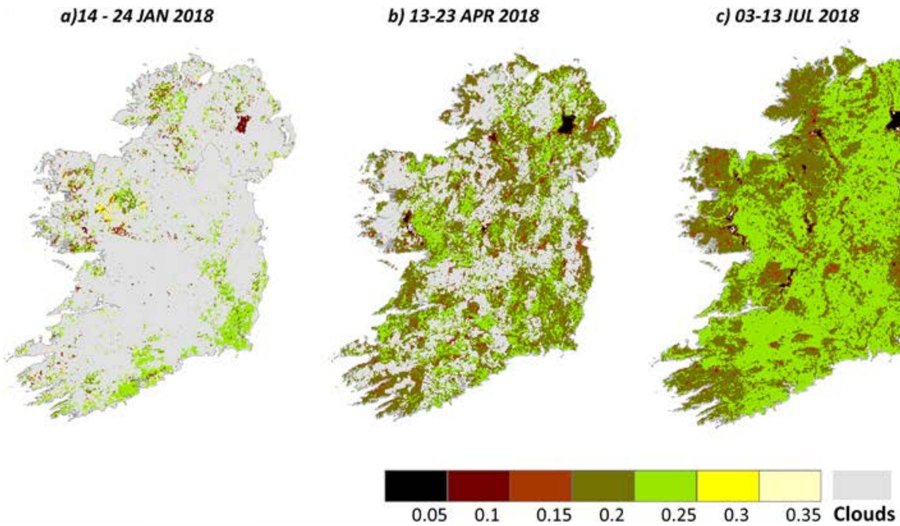


Figure 4.8. Albedo measured during four 10-day periods in 2018 derived from the Copernicus Global Land Service datasets. © European Union, Copernicus Land Monitoring Service 2020 and European Environment Agency.

Comprehensive analysis of satellite-derived albedo spatio-temporal trends for Ireland needs to be carried out. Long-term ground-based measurements of albedo should be considered to validate and support the satellite observations. However, cloud cover, especially in winter, over Ireland could limit the use of *in situ* observations for validating satellite data.

4

Further Information

Albedo Essential Climate Variable (ECV) FACTSHEET (https://gcos.wmo.int/en/essential-climate-variables/albedo/)

Copernicus Global Land Service (CGLS) data on surface albedo (https://land.copernicus.eu/global/products/sa)

Current global satellite albedo products (https://lpvs.gsfc.nasa.gov/producers2.php?topic=SurfRad)

EUMETSAT surface albedo validation sites (http://savs.eumetsat.int/)

Wang, Z. *et al*., 2019. *Global Surface Albedo Product Validation Best Practices Protocol*. See "Practice for satellite derived land product validation" (p. 45) (https://lpvs.gsfc.nasa.gov/PDF/CEOS_ALBEDO_Protocol_20190307_v1.pdf)

4.6 Land Cover

Walther C.A. Cámaro García, Ned Dwyer and Gavin Smith

Land cover – the observed (bio)-physical cover on the Earth's surface, including grassland, forest and the built environment – plays a key role in climate dynamics, such as water and energy exchanges between the ground and the atmosphere, and contributes to the capture and release of GHGs and aerosols. Land cover is the result of complex interactions between regional climatic conditions and socio-economic factors, and changes in cover can be due to climate change on a regional scale as well as directly due to human activities. An increase in artificial areas, for example, leads to soil disruption and sealing, thereby causing carbon emissions and reducing the capacity for carbon sequestration. Disturbance and removal of peatlands also causes carbon emissions, while their protection and restoration results in valuable sequestration of carbon. Information on land cover change is essential in order to understand and quantify these effects.

4.6.1 Measurements

Land cover is derived from the analysis of a variety of data sources. At the local scale ground surveys are the most effective tool, whereas at regional and national scales aerial and satellite images are used. Aerial imagery from OSi dates back to the 1970s, but it is only since 1990 that regular, systematic land cover mapping of Ireland, using satellite imagery, has taken place as part of the European Commission's CORINE[15] programme. Until now, CORINE has been the only initiative in place in Ireland that provides a set of time series of land cover data, however albeit with a coarse (25-ha) spatial resolution that misses many important environmental features within the very fragmented landscape of Ireland.

To address these shortcomings, a range of land cover mapping initiatives have taken place during recent years with the aim of producing a higher quality national land cover dataset for Ireland.

The Irish Land Mapping Observatory (ILMO) project (2012–2014) aimed at integrating several data sources, such as those from radar and optical satellites, to improve the classification of agricultural land and facilitate reporting on national GHG emissions related to land use.

The TaLAM – Toward Land Cover Accounting and Monitoring – project (2014–2016) focused on developing a process for mapping land cover compatible with the CORINE product but overcoming its limited spatial and temporal resolution.

The Biomass Retrieval in Ireland using Active Remote Sensing (BRIAR) project (2015–2017) aimed at demonstrating the use of radar remote sensing to estimate biomass in scrub and hedgerows. These habitats are an important feature of the Irish landscape because of their roles in biodiversity, agricultural management, and potential carbon sequestration.

These projects were all precursors of an ongoing initiative led by OSi and the EPA, on behalf of a national land cover working group, to develop an accurate and detailed set of land cover maps for Ireland (see Story Box 5).

15 The EU's Coordination of Information on the Environment programme.

Peatlands represent almost 14% of Irish land cover and are an essential feature in regulating the climate by removing carbon.

4.6.2 Time Series and Trends

Figure 4.9 shows the CORINE 2018 land cover map for Ireland. The relevant classes for Ireland are distributed throughout six main categories: artificial surfaces, agricultural areas, semi-natural areas, low vegetation areas, forest and wetlands. More than half of the country is covered by agricultural areas, mainly represented by pastures. Wetlands are the second main class covering Ireland, mainly formed by peatlands, which are a key land cover type in regulating the climate by removing carbon; however, peatlands release carbon when disturbed.

Figure 4.10 shows the distribution of land cover classes across the country from the 1990 and 2018 CORINE maps. Agricultural areas currently cover almost 68% of the country, and no significant change has been observed during the last three decades. Artificial surfaces, which are linked to urbanisation, cover less than 3% of the country; however, there has been an almost 65% increase compared with 1990. Forest and semi-natural vegetation areas have increased their extent by almost 30% over the last three decades. Conversely, wetlands now occupy approximately 15% of the country, but their area has decreased by almost 20% since 1990.

Figure 4.11 shows the percentage change in each main CORINE land cover category, referenced to 1990. Artificial surfaces show the greatest cumulative increase, with a particularly high rate between 1990 and 2006. Forest areas have also increased, being particularly marked during the 1990s. Semi-natural and low vegetation areas decreased slightly in the 1990s, but since then they have continuously increased over the last two decades. In contrast, the wetlands class is mostly formed on peat, and a continuous decreasing trend is observed in this land cover class. It should be noted that the land cover classification methodology used in the 2018 version is completely different from that used in 1990, which affects the reliability of this analysis.

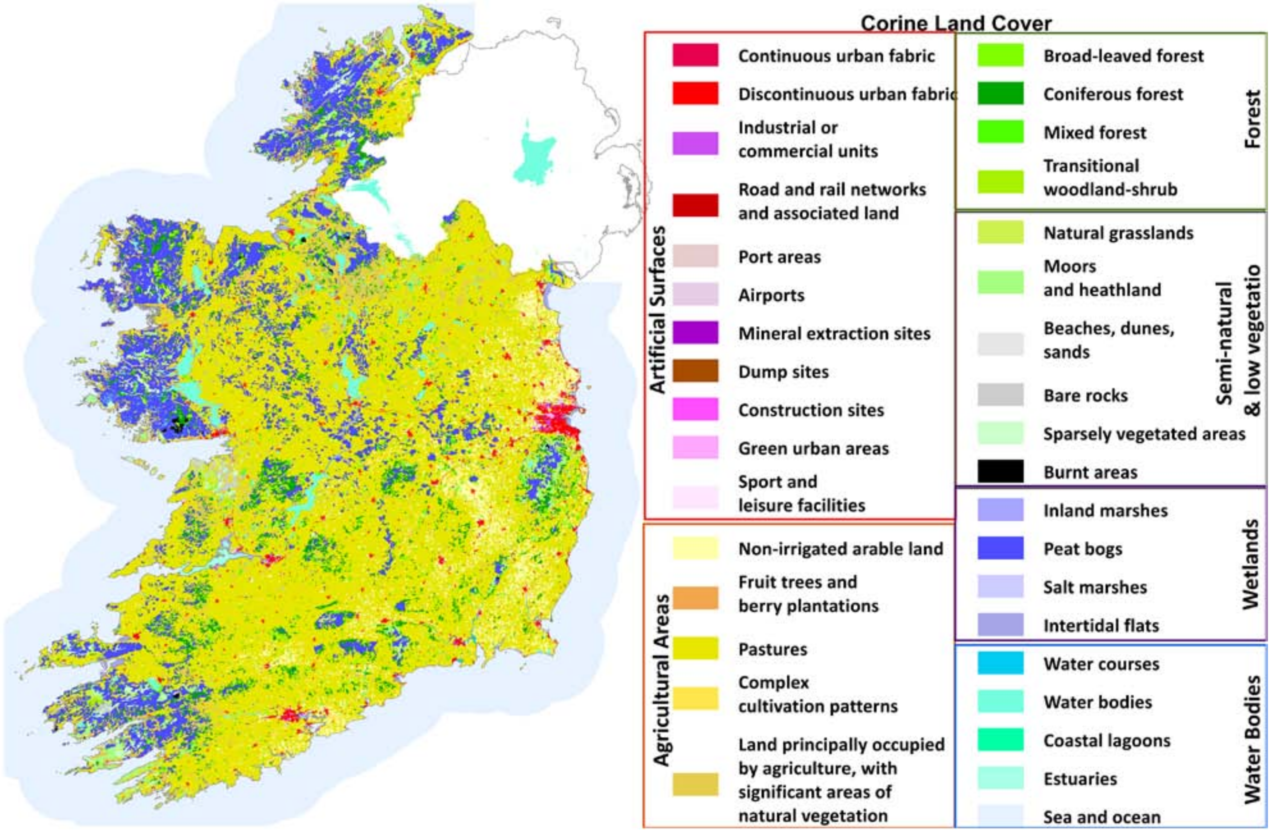


Figure 4.9. CORINE land cover map of Ireland (2018).

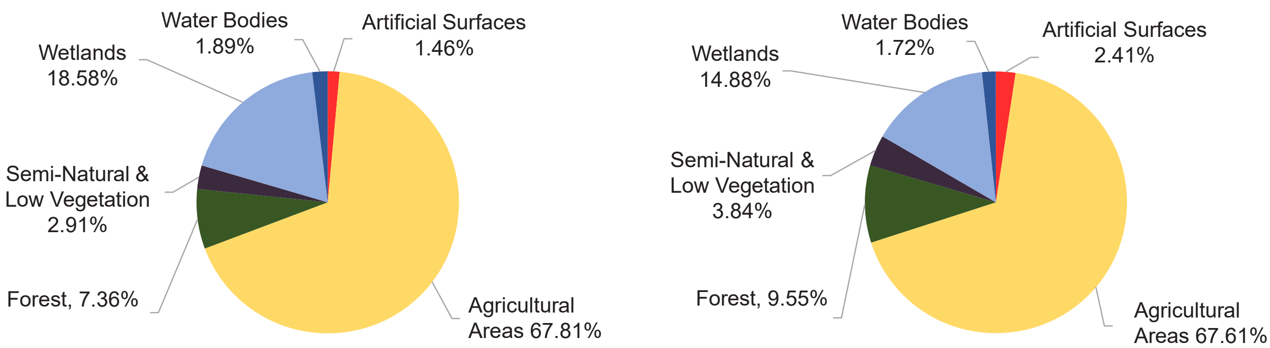


Figure 4.10. Distribution of the main CORINE land categories over Ireland (% national land area) derived from the CORINE 1990 version (left) and the CORINE 2018 version (right).

The new national land cover dataset will have a spatial resolution 250 times better than the current map.

4.6.3 Maintaining the Observations

The EPA currently oversees the production of the CORINE land cover maps for Ireland. The latest version was released in 2018. The next update is expected in 2024.

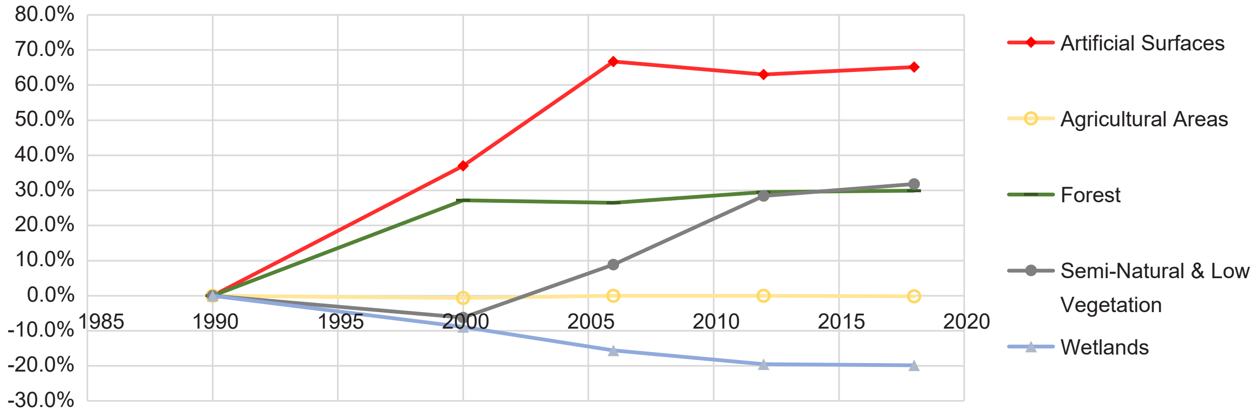


Figure 4.11. Percentage change in each main land cover category from the five CORINE versions between 1990 and 2018, referenced to 1990.

The EPA and several other public bodies (NPWS, Teagasc, OSi, the Heritage Council and the DAFM) set up a national land cover and habitats working group in 2011 to identify a way to produce higher quality national land cover datasets for Ireland. Initiatives such as ILMO, TaLAM and BRIAR have supported the development of a national land cover mapping methodology. These projects are an essential point of reference for the current EPA- and OSi-led initiative aimed at generating a new land cover dataset, with a spatial resolution almost 250 times better than CORINE, to be released in 2021 (see Story Box 5).

Further Information

Land Cover Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/land-cover/)

The CORINE dataset in Ireland (https://www.epa.ie/soilandbiodiversity/soils/land/corine/)

View CORINE maps for all of Europe (https://land.copernicus.eu/pan-european/corine-land-cover)

The ILMO project (https://landmapping.wordpress.com/ilmo/)

The TaLAM project (https://landmapping.wordpress.com/talam/)

The BRIAR project (https://landmapping.wordpress.com/briar-biomass-retrieval-in-ireland-using-active-remote-sensing/)

Thompson, S., 2019, Ireland needs more detailed land-use maps. *Irish Times*, 19 September 2019 (https://www.irishtimes.com/news/science/ireland-needs-needs-more-detailed-land-use-maps-1.4010070)

4.7 Fraction of Absorbed Photosynthetically Active Radiation

Walther C.A. Cámaro García and Ned Dwyer

Radiation from the sun plays an essential role in all biological process on Earth. Part of this radiation is absorbed by vegetation and provides the energy required for growth. This radiation is called FAPAR or the fraction of absorbed photosynthetically active radiation. Regular observations of FAPAR are essential to understand the seasonal growth cycle of vegetation and its annual variability. FAPAR observations have been shown to be a good indicator for detecting drought impacts on vegetation productivity. In addition, monitoring the variation in FAPAR over time provides information on how efficiently plants absorb CO_2 and is useful to identify climate change effects on vegetation health and behaviour.

4.7.1 Measurements

FAPAR is challenging to measure on the ground in tall and heterogeneous vegetation environments. Measurements tend to be made at the local scale and for research studies and are labour intensive. Globally, only a small group of short land cover types, in a few climatic zones, have been adequately characterised through FAPAR measurements. There is no long-term *in situ* FAPAR monitoring programme in Ireland. Regional FAPAR estimates are generally based on observations from satellite sensors, which have the ability to measure the visible and infrared radiation reflected by the Earth's surface on a regular basis. The CGLS generates a FAPAR dataset as part of a set of vegetation monitoring products. This dataset is derived from the SPOT Vegetation and PROBA-V satellite programmes.

The highest photosynthetic activity over Ireland is observed from May to July. Western margins of the country show the lowest values of FAPAR.

4.7.2 Time Series and Trends

Figure 4.12 shows a heat map of 10-day average FAPAR over Ireland derived from the CGLS dataset. The red colour represents the 10-day periods with the highest values; only 5% of the values are at or above the threshold of 0.76 (the 95th percentile). A seasonal trend is observed, in which the highest values occur during summer, particularly in June, when vegetation tends to have higher photosynthetic activity, while the lowest values are observed during the winter months. The highest values in the time series are in the summer periods between 2007 and 2009 and between 2013 and 2017.

Figure 4.13 shows a set of maps of the 10-day FAPAR over Ireland in 2018 derived from the CGLS for the periods 1–10 January, 1–10 April, 1–10 June and 1–10 September. This illustrates how photosynthetic activity varies spatially during the year. The brown shading corresponds to areas with high photosynthetic activity and yellow/white shading indicates vegetation with a low degree of photosynthetic activity. The western margins have the lowest photosynthetic activity in the country during all periods.

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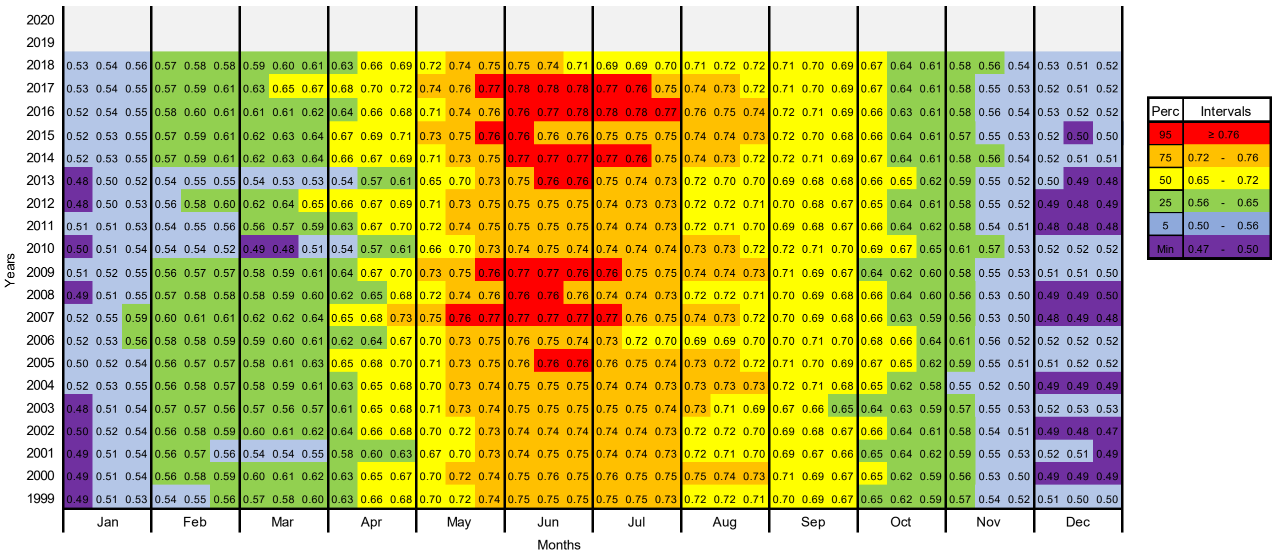

Figure 4.12. Heat map of 10-day average FAPAR over Ireland derived from the Copernicus Global Land Service datasets (1999–2018). The data are presented as percentiles calculated using the complete dataset. For example, the 75th percentile means that 75% of all the values are below 0.72 and 25% of the values are above it.

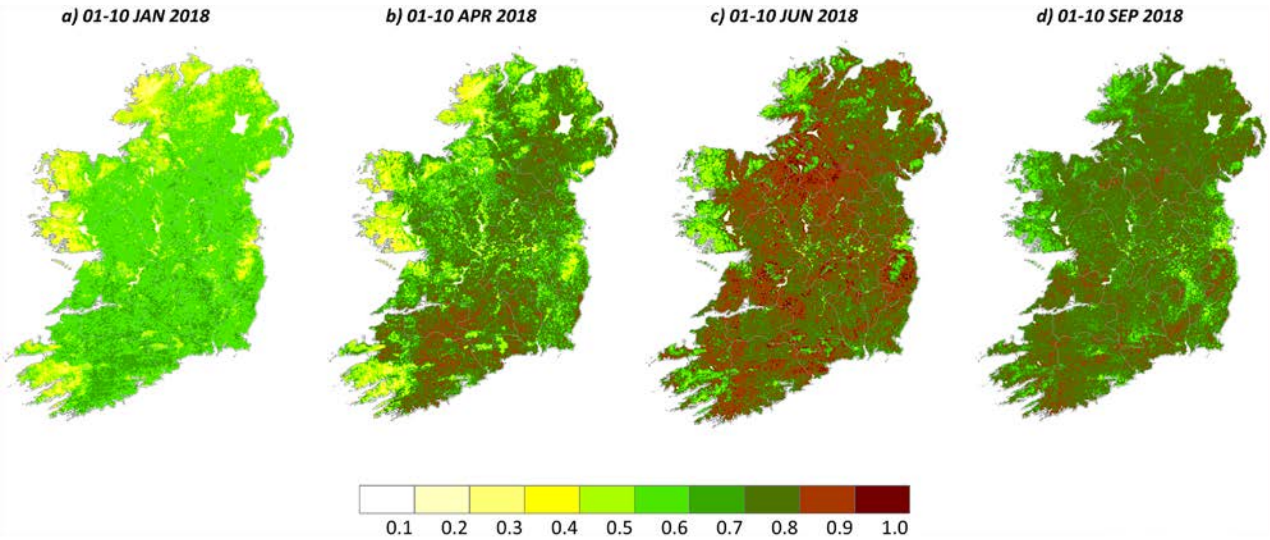

Figure 4.13. Fraction of absorbed photosynthetically active radiation measured during four 10-day periods in 2018 derived from the Copernicus Global Land Service datasets. © European Union, Copernicus Land Monitoring Service 2020 and European Environment Agency.

A ground-based FAPAR observation system should be considered to validate and support satellite observations.

4.7.3 Maintaining the Observations

The CGLS is one of the Copernicus services that provide satellite information that may be used to monitor a number of vegetation parameters around the globe. The global FAPAR dataset available is derived from several satellite sensors. Currently, the CGLS team is updating the dataset based on Sentinel-3 ocean and land colour instrument (OLCI) and sea and land surface temperature radiometer (SLSTR) sensors as new data sources. The CGLS is also developing a high-resolution (10 m × 10 m) vegetation phenology and productivity product, which includes FAPAR.

Comprehensive analysis of satellite-derived FAPAR spatio-temporal trends for Ireland needs to be carried out. A ground-based observation system should also be considered to validate and support the satellite observations.

Further Information

Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/fapar/)

Copernicus Global Land Service (CGLS) data on FAPAR (https://land.copernicus.eu/global/products/fapar)

Copernicus vegetation phenology and productivity product (https://land.copernicus.eu/pan-european/biophysical-parameters/high-resolution-vegetation-phenology-and-productivity)

European Commission Joint Research Centre FAPAR project (https://fapar.jrc.ec.europa.eu/Home.php)

Description of the Sentinel Global Vegetation Index (FAPAR) (https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-3-olci/level-2/olci-global-vegetation-index-fapar)

4

Story Box 6. Observations of greenhouse gases from terrestrial ecosystems help to develop appropriate mitigation strategies

Matthew Saunders

Terrestrial ecosystems' role in climate change

Terrestrial ecosystems (e.g. forests, peatlands and grasslands) play an important role in global climate dynamics, as they can have a net climate warming or cooling effect, depending on whether they act as a source or sink for carbon and also how they exchange energy, water and other important GHGs, such as CH_4 or N_2O, with the atmosphere. Because of this, it is becoming increasingly important to develop robust mitigation and adaptation strategies that prioritise the environmental integrity of these ecosystems, while maintaining key services such as the provision of food, fuel and fibre. In Ireland the land cover is dominated by grassland ecosystems, with the remaining land area made up of wetlands, forests, croplands and settlements. It is important to understand how these systems respond to both climatic and environmental drivers and how land management influences carbon and GHG dynamics, so that we can gain greater insight into the functioning of these systems and how this information can be used to better inform the development of sustainable management practices that can help in the mitigation of and adaptation to climate change.

Measuring carbon exchange between land and the atmosphere

Scientists in Ireland have been studying these systems through a network of experimental platforms, known as flux towers, that measure the stocks of carbon in the vegetation or soils and also the exchange of carbon, water, energy and GHGs between the particular land cover of interest and the atmosphere. The long-term operation of these platforms provides data that allow us to assess these dynamics in both space (from the leaf or soil surface to the ecosystem and regional scale) and time (from hours to decades) and to capture the impact of management and disturbance events on carbon and GHG dynamics. Several different measurement approaches are used to produce this information, including field surveys to assess the vegetation, rates of plant growth, phenological attributes (e.g. time of bud burst and leaf fall) and biomass stocks, soil sampling campaigns and regular site visits to measure soil-derived GHG emissions using chambers and eddy covariance[16] towers, which make continuous measurements of ecosystem-scale GHG fluxes (see Figure SB6.1). The data produced by these platforms can also be integrated with Earth observation data (e.g. collected by satellites, aircraft or drones) or modelling approaches to understand better the impact that climatic variability and changes in land cover, land use and management have on GHG dynamics and to upscale this information to give a national overview.

Information to support carbon mitigation measures

These measurement platforms have allowed us to quantify temporal dynamics in carbon and GHG exchange from grasslands, croplands, forests,

16 Eddy covariance is a measurement technique that allows the calculation of exchange rates of GHGs between different ecosystems and the atmosphere.

peatlands and urban environments to understand better how daily, annual and decadal patterns of uptake and release change with phenology, climatic variability and management practices, such as tillage, fertilisation, animal management, forest thinning and ecosystem rehabilitation (see Figure SB6.2). This information

Figure SB6.1. Eddy covariance tower and portable chamber system used to measure carbon and greenhouse gas dynamics from Clara bog, Co. Offaly. Photo: M. Saunders and R. Ingle.

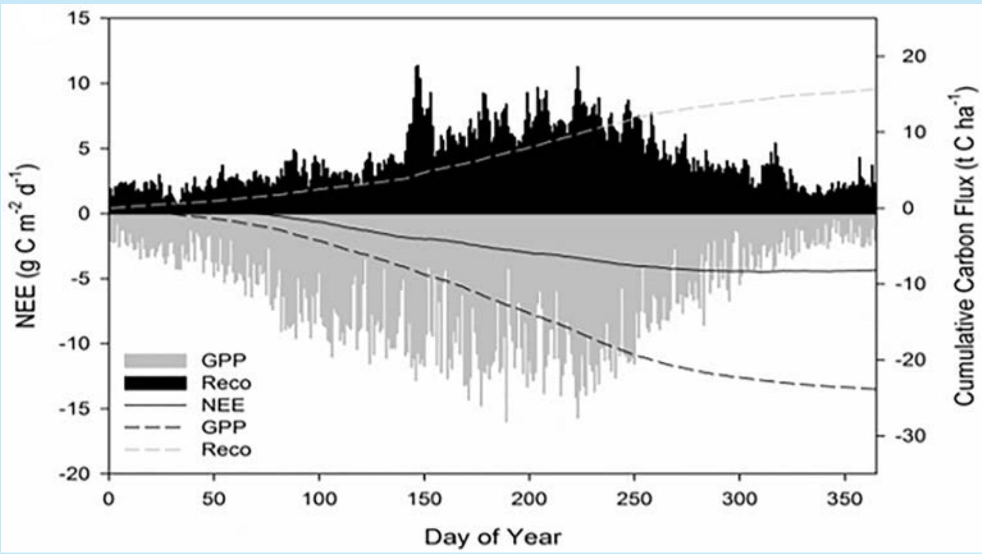

Figure SB6.2. Net ecosystem carbon exchange (NEE) data from a Sitka spruce forest ecosystem in Co. Laois. The data show the rate of daily carbon uptake through photosynthesis (grey bars, negative values), the rate of daily carbon loss to the atmosphere through ecosystem respiration (black bars, positive values) and the cumulative amount of carbon absorbed by the forest over the year (solid grey line).

allows us to quantify the contribution of these systems to national emissions, to assess how particular ecosystems such as forests or wetlands can be used to offset emissions from other sectors and to devise the most appropriate management strategies that have the greatest impact in mitigating GHG emissions.

Contributing to international initiatives

The network of observational platforms has also provided data to the wider international research community through the global network of flux sites and will continue to do so in the future through engagement with ICOS.

Further Information

Kiely, G. *et al*., 2018. *GHG Fluxes from Terrestrial Ecosystems in Ireland*. Environmental Protection Agency (https://www.epa.ie/publications/research/climate-change/research-227.php)

Saunders, M. *et al*., 2014. Impacts of exceptional and extreme inter-annual climatic events on the net ecosystem carbon dioxide exchange of a Sitka spruce forest. *Agricultural and Forest Meteorology* 184: 147–157. https://doi.org/10.1016/j.agrformet.2013.09.009

Whitfield, M. *et al*., 2019. *Scaling Soil Greenhouse Gas Emissions to the National Level*. Environmental Protection Agency (https://www.epa.ie/publications/research/climate-change/research-304.php)

FLUXNET (https://daac.ornl.gov/cgi-bin/dataset_lister.pl?p=9)

Integrated Carbon Observation System (ICOS) (https://www.icos-ri.eu/)

4.8 Leaf Area Index

Walther C.A. Cámaro García and Ned Dwyer

Leaf area index (LAI) is a measure of the amount of surface area of leaf per area of ground surface and is a key parameter for assessing the health and growth of vegetation over time. LAI is defined by the structure of a plant canopy and is directly linked to the interaction between biosphere and atmosphere through several process, such as photosynthesis, evapotranspiration, respiration, rain interception and leaf litter fall. Regular observations of LAI are essential for several ecological models describing vegetation–atmosphere interactions, such as biogeochemical cycles, hydrological budgets and carbon uptake and sequestration.

4.8.1 Measurements

Ground-based LAI is normally calculated directly, by collecting leaf material over a certain area, or indirectly estimated, based on relationships with other, more easily measurable parameters through photography and other optical instruments. It is a time-consuming and laborious process and can only be done at the local scale. There is no long-term *in situ* monitoring programme in Ireland.

LAI is also estimated over large areas from satellite sensor data using reflectance information from the visible and infrared parts of the spectrum. The CGLS generates a LAI dataset as part of a set of vegetation monitoring products. This dataset is derived from the SPOT Vegetation and PROBA-V satellite programmes.

The highest values of LAI, which are seen in forest areas, are observed between May and June.

4.8.2 Time Series and Trends

Figure 4.14 shows a heat map of 10-day average LAI over Ireland derived from the CGLS dataset. Red represents the 10-day periods with the highest values; only 5% of the values are at or above the threshold of 3.81 (the 95th percentile). Seasonal variability is observed, in which the highest values occur during late spring and early summer, particularly between May and June, while the lowest values are observed during the winter months. Slightly higher winter values are observed in 2017 and 2018. This may be because of a change in the satellite used to collect the data and highlights the need for homogenising the data from the product.

Figure 4.15 shows a set of maps of the 10-day average LAI over Ireland in 2018 derived from the CGLS for the periods 1–10 January, 1–10 April, 1–10 June and 1–10 September. This illustrates how the structure of the vegetation varies spatially during the year. The brown shading corresponds to areas with high LAI and yellow/white shading indicates sparse vegetation or

Years	Jan			Feb			Mar			Apr			May			Jun			Jul			Aug			Sep			Oct			Nov			Dec		
2020																																				
2019																																				
2018	1.47	1.48	1.48	1.46	1.45	1.42	1.45	1.59	1.86	2.15	2.47	2.94	3.36	3.66	3.87	3.78	3.39	2.79	2.60	2.57	2.64	2.72	2.90	2.81	2.71	2.60	2.39	2.15	1.88	1.68	1.55	1.48	1.47	1.44	1.47	1.50
2017	1.41	1.42	1.46	1.52	1.64	1.79	2.06	2.26	2.50	2.72	2.94	3.19	3.46	3.68	3.85	3.84	3.84	3.79	3.59	3.38	3.18	3.05	2.86	2.77	2.71	2.57	2.42	2.22	2.00	1.76	1.60	1.51	1.49	1.47	1.46	1.47
2016	1.43	1.45	1.46	1.48	1.53	1.57	1.63	1.76	1.99	2.26	2.54	2.89	3.28	3.62	3.83	3.90	3.92	3.89	3.86	3.71	3.52	3.41	3.34	3.21	3.07	2.80	2.52	2.24	1.96	1.70	1.52	1.47	1.47	1.42	1.40	1.37
2015	1.40	1.42	1.44	1.50	1.59	1.68	1.80	1.93	2.15	2.46	2.86	3.18	3.48	3.72	3.84	3.79	3.69	3.55	3.47	3.35	3.18	3.07	3.02	2.99	2.91	2.72	2.53	2.31	2.07	1.80	1.61	1.53	1.48	1.44	1.42	1.41
2014	1.38	1.41	1.44	1.47	1.56	1.65	1.78	1.95	2.17	2.43	2.73	3.01	3.29	3.51	3.75	3.86	3.83	3.77	3.64	3.53	3.30	3.18	3.05	2.96	2.93	2.82	2.70	2.47	2.17	1.89	1.68	1.54	1.46	1.39	1.36	1.36
2013	1.15	1.21	1.29	1.35	1.38	1.37	1.38	1.38	1.48	1.65	1.92	2.28	2.74	3.19	3.59	3.78	3.83	3.75	3.54	3.27	3.04	2.85	2.71	2.56	2.41	2.30	2.18	2.07	1.95	1.79	1.62	1.42	1.27	1.17	1.11	1.12
2012	1.09	1.15	1.33	1.44	1.57	1.72	1.89	2.06	2.23	2.41	2.63	2.96	3.29	3.63	3.78	3.81	3.69	3.50	3.35	3.14	2.98	2.85	2.74	2.59	2.44	2.28	2.12	1.94	1.78	1.62	1.50	1.38	1.24	1.16	1.15	1.18
2011	1.26	1.25	1.29	1.30	1.35	1.40	1.47	1.57	1.88	2.37	2.93	3.33	3.62	3.82	3.86	3.82	3.70	3.52	3.31	3.15	2.99	2.84	2.72	2.60	2.50	2.38	2.25	2.11	1.97	1.80	1.61	1.44	1.30	1.20	1.14	1.11
2010	1.19	1.26	1.37	1.38	1.32	1.27	1.21	1.26	1.42	1.60	1.89	2.39	2.92	3.34	3.64	3.74	3.63	3.48	3.37	3.29	3.14	3.03	2.95	2.87	2.77	2.66	2.53	2.38	2.20	1.93	1.71	1.49	1.38	1.35	1.33	1.32
2009	1.22	1.27	1.38	1.44	1.47	1.50	1.57	1.69	1.94	2.28	2.66	3.05	3.42	3.72	3.91	3.89	3.80	3.63	3.50	3.36	3.19	3.04	2.91	2.78	2.60	2.38	2.15	1.92	1.75	1.62	1.54	1.43	1.32	1.28	1.28	1.26
2008	1.14	1.22	1.36	1.45	1.50	1.55	1.61	1.72	1.89	2.16	2.52	2.99	3.52	3.81	3.94	3.90	3.77	3.63	3.40	3.16	2.99	2.85	2.72	2.59	2.47	2.32	2.16	1.99	1.83	1.62	1.46	1.35	1.22	1.18	1.19	1.19
2007	1.27	1.38	1.52	1.61	1.69	1.76	1.85	1.98	2.14	2.39	2.96	3.59	3.90	4.10	4.12	4.04	3.95	3.85	3.62	3.47	3.30	3.12	2.96	2.77	2.60	2.43	2.27	2.06	1.84	1.63	1.50	1.38	1.27	1.19	1.22	1.15
2006	1.22	1.28	1.38	1.45	1.51	1.56	1.64	1.75	1.92	2.17	2.46	2.84	3.21	3.61	3.84	3.79	3.65	3.46	3.26	3.01	2.79	2.66	2.62	2.64	2.64	2.62	2.52	2.36	2.18	1.93	1.65	1.42	1.27	1.24	1.23	1.24
2005	1.24	1.30	1.38	1.44	1.47	1.52	1.66	1.88	2.14	2.39	2.70	3.02	3.27	3.57	3.77	3.88	3.88	3.75	3.62	3.35	3.16	3.01	2.89	2.81	2.74	2.65	2.48	2.30	2.07	1.79	1.54	1.36	1.24	1.22	1.26	1.26
2004	1.29	1.32	1.42	1.47	1.49	1.51	1.58	1.73	2.01	2.30	2.69	3.07	3.41	3.67	3.82	3.82	3.70	3.53	3.29	3.18	3.01	3.05	3.05	3.08	3.07	2.88	2.58	2.19	1.85	1.56	1.37	1.24	1.16	1.11	1.16	1.21
2003	1.14	1.21	1.33	1.43	1.46	1.49	1.57	1.60	1.75	2.15	2.62	3.06	3.43	3.69	3.82	3.84	3.83	3.68	3.56	3.41	3.25	3.08	2.81	2.52	2.30	2.12	1.98	1.86	1.73	1.52	1.47	1.44	1.34	1.28	1.32	1.35
2002	1.12	1.17	1.30	1.41	1.53	1.61	1.71	1.84	2.05	2.31	2.61	2.90	3.20	3.42	3.54	3.52	3.47	3.38	3.23	3.08	2.96	2.84	2.73	2.59	2.44	2.29	2.14	2.01	1.83	1.61	1.45	1.31	1.21	1.17	1.15	1.14
2001	1.16	1.20	1.31	1.40	1.43	1.40	1.42	1.51	1.66	1.86	2.13	2.47	2.96	3.40	3.67	3.72	3.69	3.55	3.36	3.21	3.03	2.89	2.76	2.62	2.47	2.28	2.12	1.97	1.84	1.67	1.54	1.40	1.33	1.26	1.22	1.12
2000	1.17	1.23	1.31	1.41	1.55	1.66	1.78	1.93	2.09	2.30	2.58	2.91	3.29	3.60	3.79	3.87	3.79	3.69	3.58	3.43	3.33	3.25	3.19	3.05	2.85	2.61	2.33	2.07	1.81	1.56	1.40	1.29	1.21	1.18	1.19	1.18
1999	1.24	1.26	1.33	1.38	1.40	1.45	1.53	1.67	1.93	2.22	2.55	2.84	3.12	3.34	3.58	3.69	3.69	3.63	3.53	3.37	3.12	2.98	2.85	2.69	2.52	2.36	2.16	1.95	1.75	1.57	1.44	1.31	1.23	1.21	1.19	1.19

Months

Perc	Intervals
95	≥ 3.81
75	3.07 - 3.81
50	2.16 - 3.07
25	1.46 - 2.16
5	1.20 - 1.46
Min	1.09 - 1.20

Figure 4.14. Heat map of 10-day average leaf area index over Ireland derived from the Copernicus Global Land Service datasets (1999–2018). The data are presented as percentiles. For example, the 75th percentile means that 75% of all the values are below 3.07 and 25% of the values are above it.

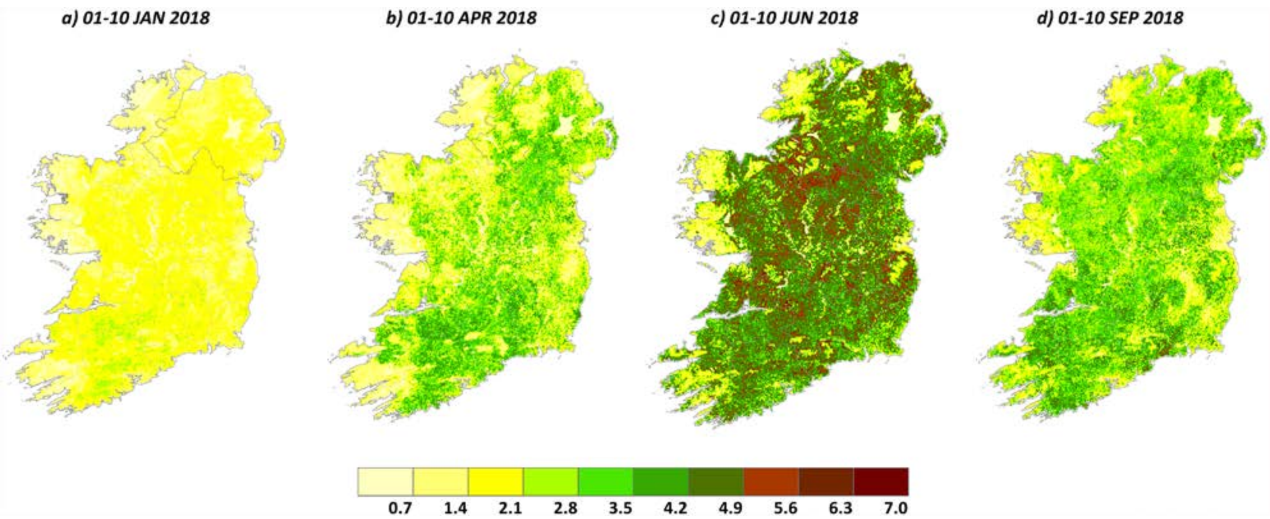

Figure 4.15. Leaf area index measured during four 10-day periods in 2018 derived from the Copernicus Global Land Service datasets. © European Union, Copernicus Land Monitoring Service 2020 and European Environment Agency.

unvegetated areas. The highest values are associated with forest land cover.

> Long-term ground-based measurements of LAI over a number of different vegetation types should be considered to improve the understanding of ecosystem processes across the country and to validate satellite-derived measurements.

4.8.3 Maintaining the Observations

The CGLS is one of the Copernicus services that provides satellite information that may be used to monitor a number of vegetation parameters. The global LAI dataset is derived from several satellite sensors. Currently, the CGLS team is updating the dataset based on Sentinel-3 OLCI and SLSTR sensors, which are new data sources. The CGLS is also developing a high-resolution (10 m × 10m) vegetation phenology and productivity product, which includes LAI.

Comprehensive analysis of satellite-derived LAI spatio-temporal trends for Ireland needs to be carried out. Long-term ground-based measurements of LAI over a number of different vegetation types should be considered to improve the understanding of ecosystem processes across the country and to validate satellite-derived measurements.

Further Information

Leaf Area Index Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/lai/)

Copernicus Global Land Service (CGLS) data on leaf area index (https://land.copernicus.eu/global/products/lai)

Copernicus vegetation phenology and productivity product (https://land.copernicus.eu/pan-european/biophysical-parameters/high-resolution-vegetation-phenology-and-productivity)

Vegetation Status Indicators from Sentinel-2 for Agriculture (Sen2-Agri) project (http://www.esa-sen2agri.org/products/vegetation-status/)

4.9 Above-ground Biomass

Walther C.A. Cámaro García and Ned Dwyer

Biomass is any organic or biological material that comes from plants or animals. Above-ground biomass includes all biomass stored above the soil in both woody and herbaceous living vegetation and is a key parameter for understanding the evolution of and changes in the climate system. Other stores include below-ground biomass, litter, dead wood and soils. The process of photosynthesis stores carbon in vegetation biomass in a similar amount to that stored in the atmosphere and is one of the most visible carbon pools. Removal of vegetation causes a net increase in carbon in the atmosphere, whereas an increase in forest areas causes a reduction in atmospheric carbon. In Ireland, most of the above-ground biomass is held in grassland and natural ecosystems. However, because of an ongoing policy of afforestation, the amount held in forest has increased significantly in recent decades.

4.9.1 Measurements

Quantification of above-ground biomass is based on the mass of plant material and can be inferred from plant volume. These parameters are normally estimated from a number of attributes, including tree growth and development, the diversity of plant species and soil type. Since 2007, the National Forestry Service has periodically carried out *in situ* data collection nationwide. The third cycle of data collection completed in 2017, which is the most recent, assessed a total of

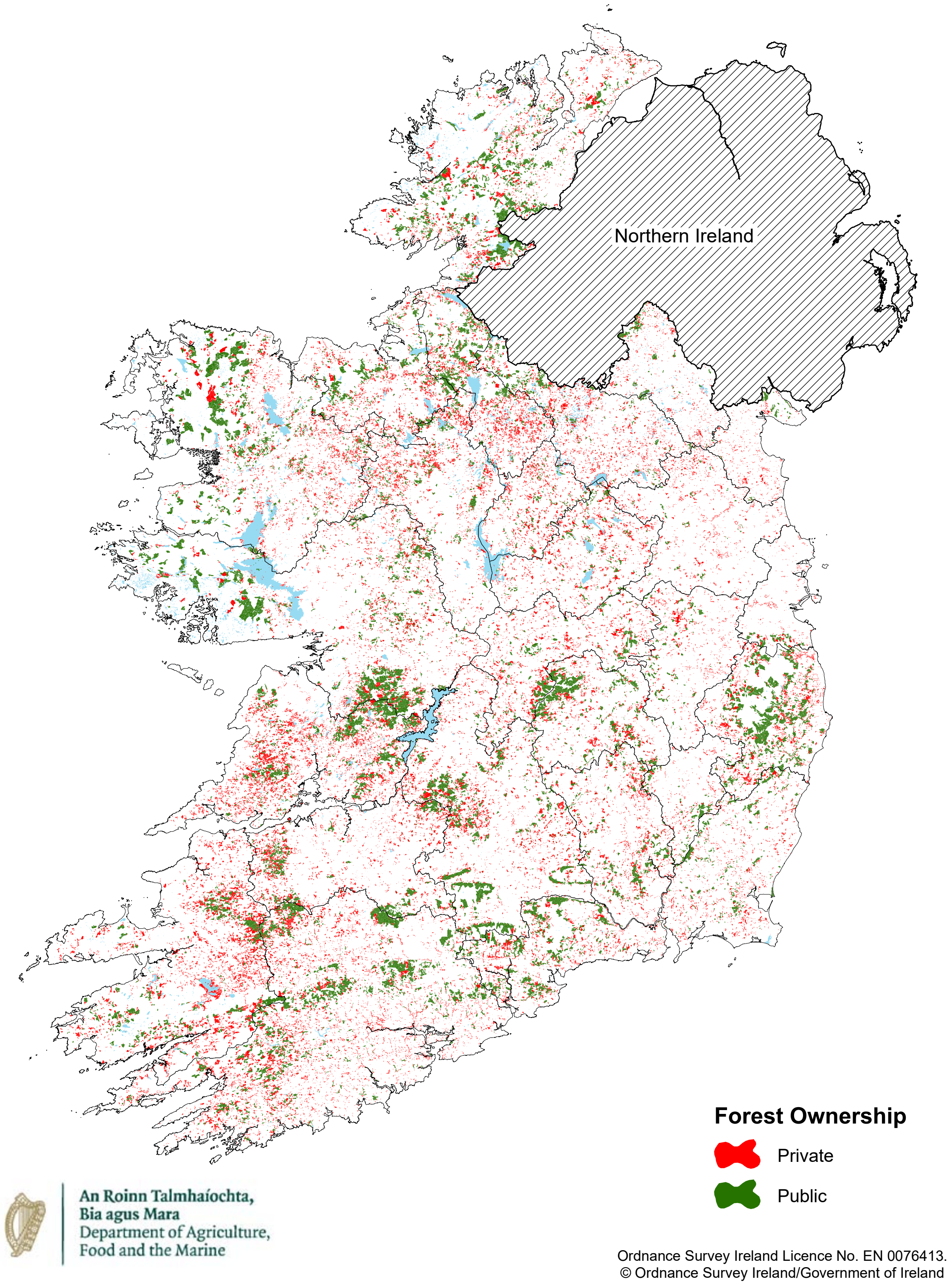

Figure 4.16. Map of forest cover in Ireland by ownership (2017). Source: Department of Agriculture, Food and the Marine (Ordnance Survey Ireland Licence No. EN 0076413). © Ordnance Survey Ireland/Government of Ireland 2017.

1932 forest plots. These assessments are essential for the development of country-specific models to estimate biomass and hence carbon stocks in forest, information that is compiled annually in the National Inventory Report. In general, an assessment of above-ground biomass is a suitable indicator of other carbon pools with the exception of soils.

Internationally, remote-sensing data have been used to estimate above-ground biomass. The ESA CCI Biomass project aims to provide global maps of above-ground biomass for several periods from the 1990s, based on optical sensors (e.g. Sentinel-2), radar sensors (the advanced land observing satellite ALOS-2) and laser sensors [e.g. the Global Ecosystem Dynamics Investigation (GEDI) mission's light detection and ranging (LIDAR) system].

The total growing stock volume in forest increased by 38% in the 11 years between 2006 and 2017.

4.9.2 Time Series and Trends

Figure 4.16 shows the map of forest cover in Ireland by ownership, derived from the 2017 National Forest Inventory cycle. Just over half (50.8%) of forests are in public ownership and the remainder (49.2%) are privately owned.

Figure 4.17 shows the trend in the total growing stock volume of all living trees in Ireland, reported during the three National Forest Inventory cycles, including conifer and broadleaved species, by ownership. Growing stock volume increased by 38% over the period 2006–2017. The majority of this is in privately owned forest. This is private land afforested after 1980 under an annual grant and premium scheme for afforestation, promoted by the Irish state.

The National Forestry Service carries out periodic forest inventories to assess the status of the forest estate.

4.9.3 Maintaining the Observations

To assess changes in the state of Ireland's forests over time, the National Forestry Service carries out periodic forest inventories. The parameters recorded include forest area and species composition, growing stock volume, biodiversity, health and carbon content. The first cycle was completed in 2007, the second between 2009 and 2012 and the most recent between 2015 and

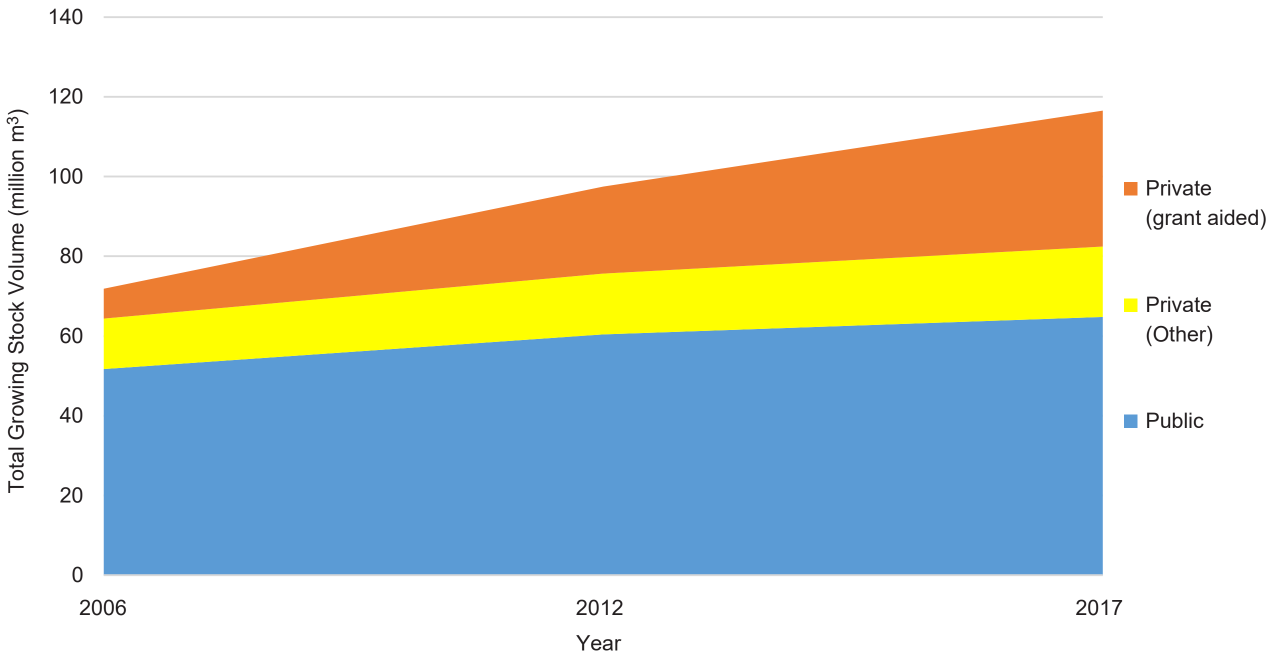

Figure 4.17. Total growing stock volume (million m^3) by ownership (2006–2017).

2017. This information has been used to model annual estimates of above-ground forest carbon stocks as part of the EPA's national inventory reporting to the UNFCCC every year.

Estimates of above-ground biomass for other land cover types are also made. For example, recent EPA-funded projects explored the potential for quantifying the amount of biomass and hence carbon stored in hedgerows based on LIDAR and satellite radar approaches.

ESA's Biomass satellite mission is planned for launch in 2022 and is aimed at monitoring the amount of forest biomass with a spatial resolution of 200 m. Once these data become available their utility for monitoring above-ground biomass in Ireland should be assessed.

Further information

Above-ground Biomass Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/biomass/)

Green, S. *et al.*, 2019. *BRIAR: Biomass Retrieval in Ireland using Active Remote Sensing*. Environmental Protection Agency (https://www.epa.ie/publications/research/climate-change/research-305.php)

Black, K. *et al.*, 2014. *Carbon Sequestration by Hedgerows in the Irish Landscape*. Environmental Protection Agency (https://www.epa.ie/publications/research/climate-change/carbon-sequestration-by-hedgerows-in-the-irish-landscape.php)

Information about the National Forestry Service https://www.gov.ie/en/publication/642e6-forestry/)

Information about national forest statistics and mapping https://www.gov.ie/en/collection/15b56-forest-statistics-and-mapping/)

Information about Ireland's National Forest Inventory (https://www.agriculture.gov.ie/nfi/)

ESA's Climate Change Initiative biomass products information (http://cci.esa.int/biomass)

Information about ESA's Biomass satellite information (https://www.esa.int/Applications/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/Biomass)

4.10 Soil Carbon

Walther C.A. Cámaro García and Ned Dwyer

The world's soils represent a significant reservoir of carbon. This carbon occurs in organic and inorganic forms. The inorganic carbon is relatively inert, is derived from weathered bedrock and contributes little to the carbon cycle. Conversely, organic carbon is derived from decomposition of plant matter, such as leaf litter and woody debris, and is a significant part of the carbon cycle. Carbon is incorporated into vegetation through the process of photosynthesis, whereby CO_2 is sequestered from the atmosphere. The amount of carbon present in the soil is determined by geology, soil type, climate and land use. About 10% of the atmospheric carbon cycles through soils each year. Changes in climate, in particular rainfall and temperature, affect the carbon storage potential of soils. In Ireland, peat soils dominate the terrestrial carbon budget, representing approximately 64% of the total soil organic carbon stock. Peatlands are very vulnerable to a changing climate – particularly when additional pressures such as those caused by artificial drainage and extraction are taken into account.

4.10.1 Measurements

Changes in soil carbon are very slow and therefore difficult to detect, and at a given site they require observations over several decades. In Ireland, a number of initiatives have aimed to produce soil carbon stock maps. Estimations are based on several properties such as soil type and depth, carbon density, land cover and in particular the soil bulk density. The bulk density reflects the soil's ability to function in terms of structural support, water and solute movement, and soil aeration.

The Soil Geochemical Atlas of Ireland was an EPA-funded project, concluded in 2007, which had the goal of creating a map showing the basic geochemical properties of soils in Ireland, based on data collected between 1995 and 2006. Another EPA-funded project SoilC – Measuring and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils – concluded in 2009 and measured and modelled the soil carbon stocks and stock changes in a number of Irish soils based on numerous samples collected at several points over a depth of 50 cm.

The most recent initiative, concluded in 2016, was carried out under the EPA- and Teagasc-funded project Irish Soil Information System (Irish SIS). An indicative soil organic carbon map was created for the majority of mineral and organo-mineral soils in Ireland, with the exception of peat soils. This is because information associated with bulk density data are not recorded for these soils.

Peatlands store some 1566 million tonnes of carbon, representing approximately 64% of the total soil organic carbon stock present in Ireland.

4.10.2 Time Series and Trends

Figure 4.18 shows the near-surface and at-depth bulk density maps of agricultural soils in Ireland, developed under the Irish SIS project and used as a reference for the estimation of the soil organic carbon map. The higher values occur at depth and are observed in

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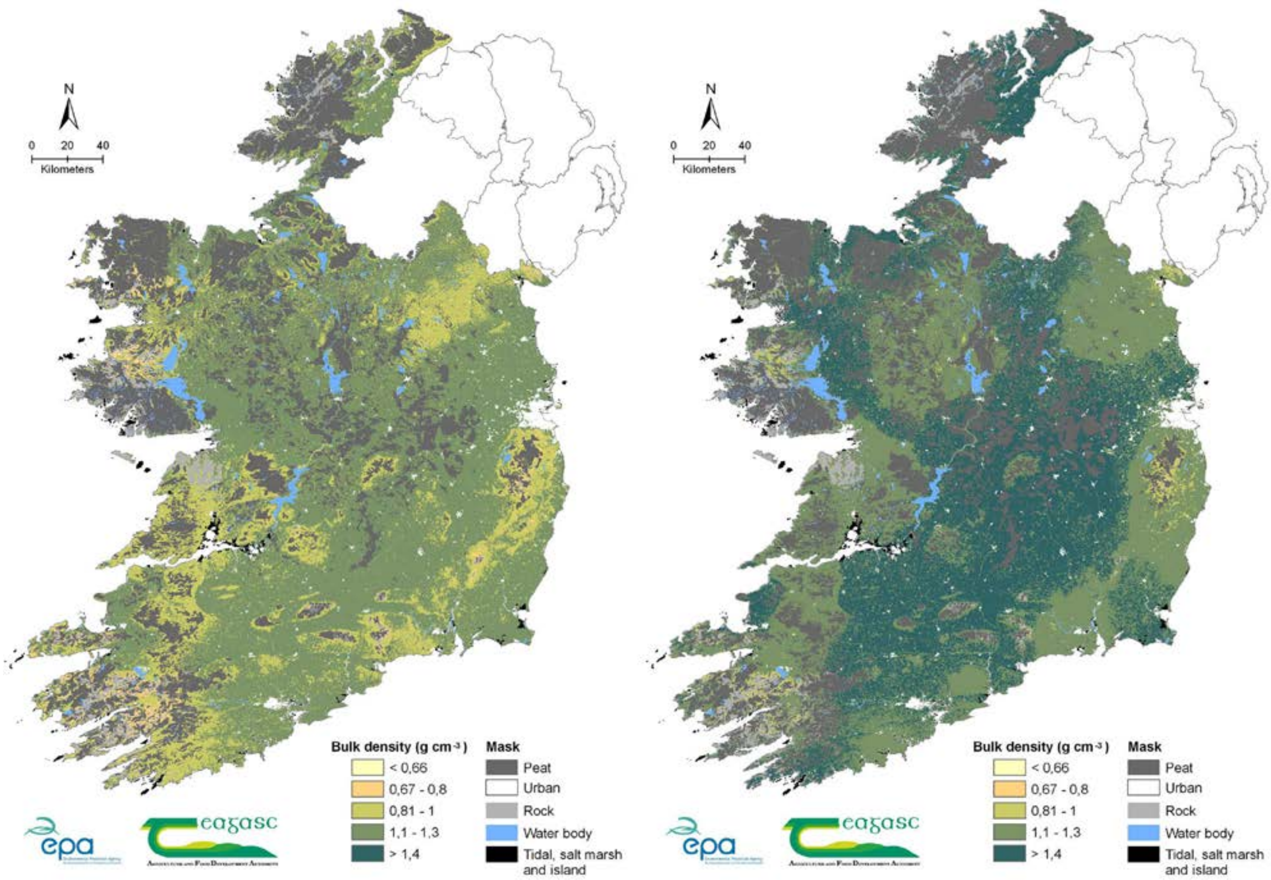


Figure 4.18. Indicative bulk density map of agricultural soils in Ireland at depths of 0–30 cm (left) and 30–50 cm (right). Source: Creamer *et al.* (2016).

general towards the Midlands. The lower bulk densities of < 1.1 are associated with upland soils because of an increase in soil organic carbon.

Figure 4.19 shows the soil organic carbon stock map created for agricultural soils in Ireland developed under the Irish SIS project. The highest values are observed towards the west and around the Wicklow mountains. These areas have higher precipitation and are located close to peatlands.

A range of soil property maps can be freely downloaded from the Irish Soil Information System portal.

4.10.3 Maintaining the Observations

The Irish SIS project was established in 2008, following a comprehensive inventory of Irish soil data complied under the SoilC project and the Soil Geochemical Atlas project. The Irish SIS was funded under the EPA Research Programme 2014–2020 and co-funded by Teagasc. The overall objective of the project was to conduct a programme of structured research on the national distribution of soil types and construct a soil map at a scale of 1:250,000. Under this project maps of soil drainage, soil depth, soil texture, pH, bulk density and soil organic carbon have been produced for the country. There are no plans to revisit or to continue site monitoring.

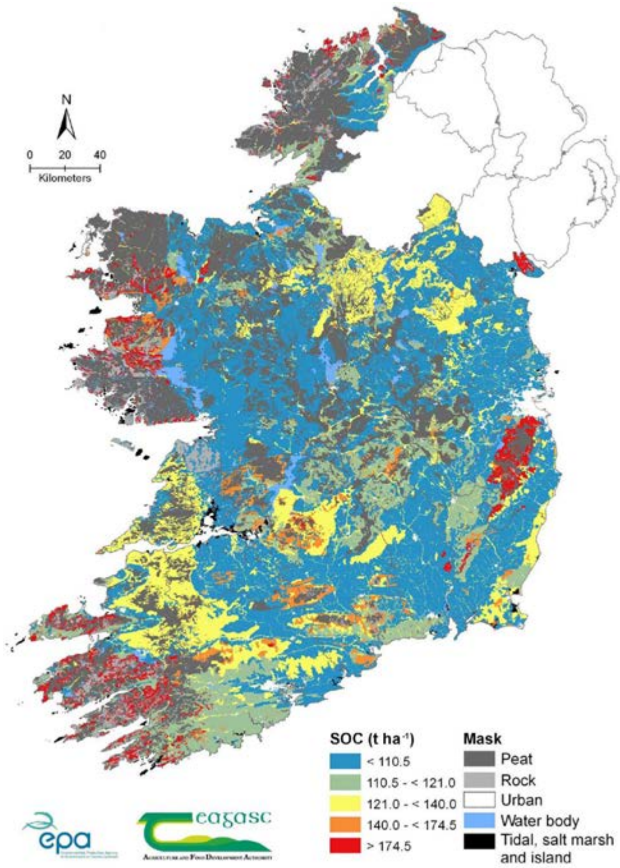


Figure 4.19. Indicative soil organic carbon (SOC) stock map of agricultural soils at a depth of 0–50 cm. Source: Creamer *et al.* (2016).

There are several short-term projects that measure soil carbon sequestration in a number of locations around the country. Long-term, ground-based national-scale initiatives with permanent soil monitoring plots covering the main land uses should be established.

Ireland is part of the Land Use and Coverage Area Frame Survey – Soil (LUCAS Soil) initiative, which carries out an extensive and regular survey of topsoil properties, including soil carbon, across the EU. Measurements of topsoil carbon were made most recently in 2018 and they will be repeated in the future.

Further Information

Soil Carbon Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/soil-carbon/)

Creamer, R. *et al.*, 2016. *Irish Soil Information System: Soil Property Maps*. Environmental Protection Agency (https://www.epa.ie/publications/research/land-use-soils-and-transport/research-204.php)

Irish Soil Information System data sources (http://gis.teagasc.ie/soils/)

Fay, D. *et al.*, 2007. *Soil Geochemical Atlas of Ireland*. Teagasc and Environmental Protection Agency (https://www.teagasc.ie/media/website/publications/2011/Soil_Geochemical_AtlasofIreland.pdf)

Soil Geochemical Atlas of Ireland data sources (http://erc.epa.ie/safer/iso19115/displayISO19115.jsp?isoID=105)

Kiely, G. *et al.*, 2010. *SoilC – Measurement and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils*. Environmental Protection Agency (https://www.epa.ie/publications/research/land-use-soils-and-transport/strive-35.php)

SoilC data sources (http://erc.epa.ie/safer/iso19115/displayISO19115.jsp?isoID=107#files)

National Peatlands Strategy (https://www.npws.ie/peatlands-and-turf-cutting/peatlands-council/national-peatlands-strategy)

Orgiazzi, A. *et al.*, 2018. LUCAS Soil, the largest expandable soil dataset for Europe: a review, *European Journal of Soil Science* 69: 140–153 (https://doi.org/10.1111/ejss.12499)

4.11 Fire

Ciaran Nugent, Ned Dwyer, Walther C.A. Cámaro García, Keith Lambkin and Frank Barrett

Vegetation fires and wildfires have become an increasingly visible phenomenon in Ireland in recent years. Despite Ireland's generally moist oceanic climate, periodic dry spells in spring annually give rise to fire risk conditions and facilitate fire outbreaks. Globally, along with fossil fuel burning and agriculture, vegetation fires are one of the largest human-caused contributors to GHG emissions. When associated with deforestation they cause significant ecosystem disturbance and also reduce the potential of vegetation to act as a carbon store. Most fires in Ireland can be attributed to human causes, whether deliberate or unintentional. Fires are often set by landowners to clear gorse, but uncontrolled fires can spread to adjacent areas and give rise to extensive wildfires. In summer drought conditions, if the peat becomes sufficiently dry, subsurface bog fires, which release carbon from the peat, may also occur.

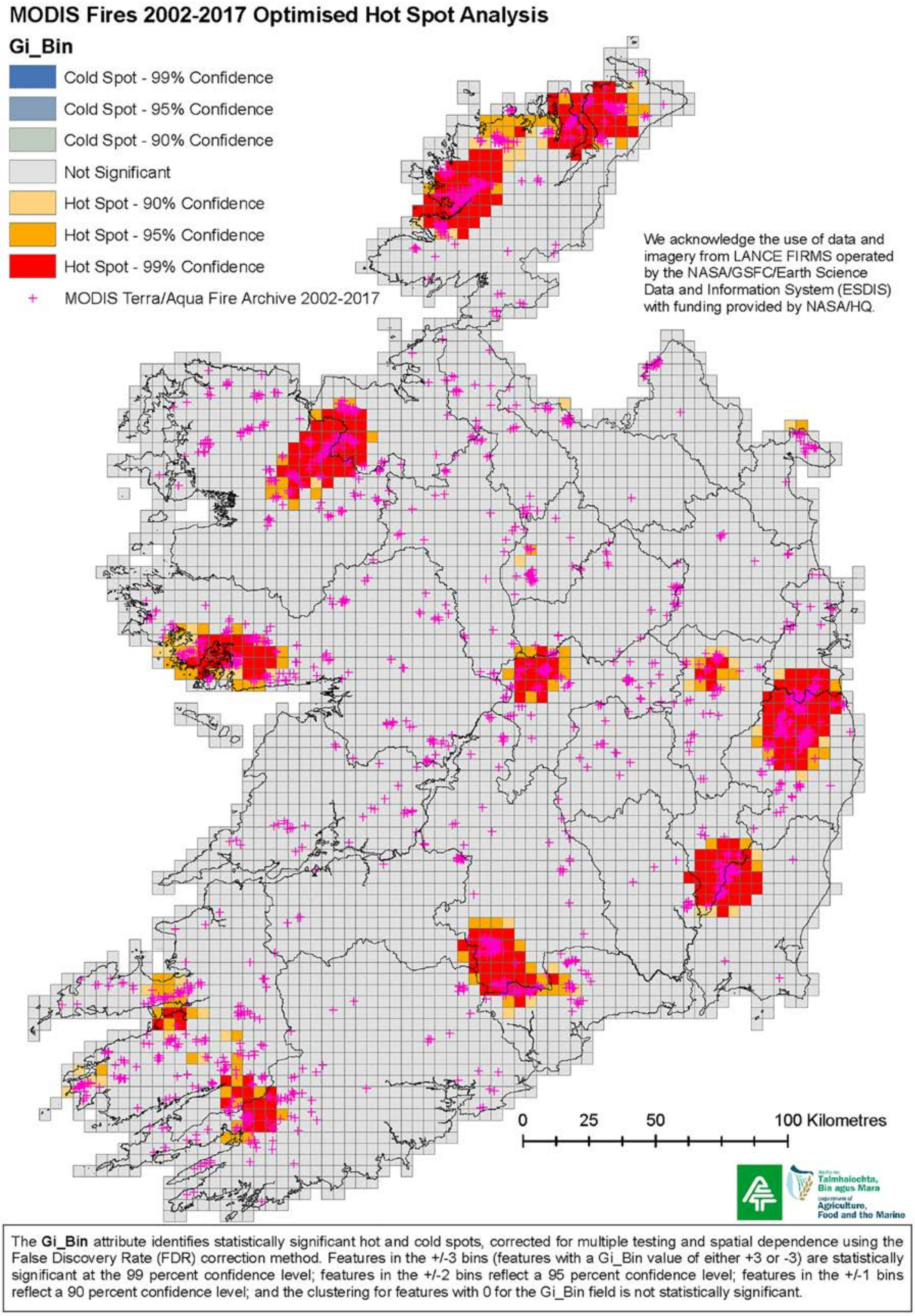


Figure 4.20. Optimised hotspot analysis of fire detection locations in Ireland (2002–2017), based on fire locations identified from satellite imagery. Location of individual fires detected by satellite shown as pink crosses. Source: Department of Agriculture, Food and the Marine.

4.11.1 Measurements

Data on vegetation fires are generally not compiled centrally by the fire services; however, burned area estimates, based on assessments of known fires, are generated annually for reporting by the DAFM to the European Commission.

Daily fire risk is assessed by Met Éireann using meteorological variables derived using the Canadian Fire Weather Index (FWI), and fire danger notices are issued to forestry interests by the DAFM throughout the fire season.

Satellite data are used internationally to make regional and global estimates of fire disturbance and their impact on the atmosphere, and some research has been carried out on their utility for Ireland, However, frequent cloud cover, the short duration of fire events and the low heat signature of typical fires limit detection rates, and the small size of many burnt land parcels reduce the usefulness of satellite imagery under Irish conditions.

The annual burned area is thought to range between 4000 and 6000 ha annually, with the bulk of fire activity taking place between March and June each year.

4.11.2 Time Series and Trends

Spatial analysis of satellite-derived fire detection data for the period 2002–2017 (Figure 4.20) suggests that peatlands, particularly upland heaths and blanket bogs and lowland blanket bogs, have the strongest association with wildfire (vegetation and peat fires). The annual burned area of all land cover types is thought to range between 4000 and 6000 ha annually, with the bulk of fire activity taking place between March and June each year. Nonetheless, satellite surveys conducted by the DAFM during 2017 found that 10,600 ha of land had been affected by fire in that year.

Figure 4.21 shows the burned forest area, based on the number of hectares of forest for which replanting

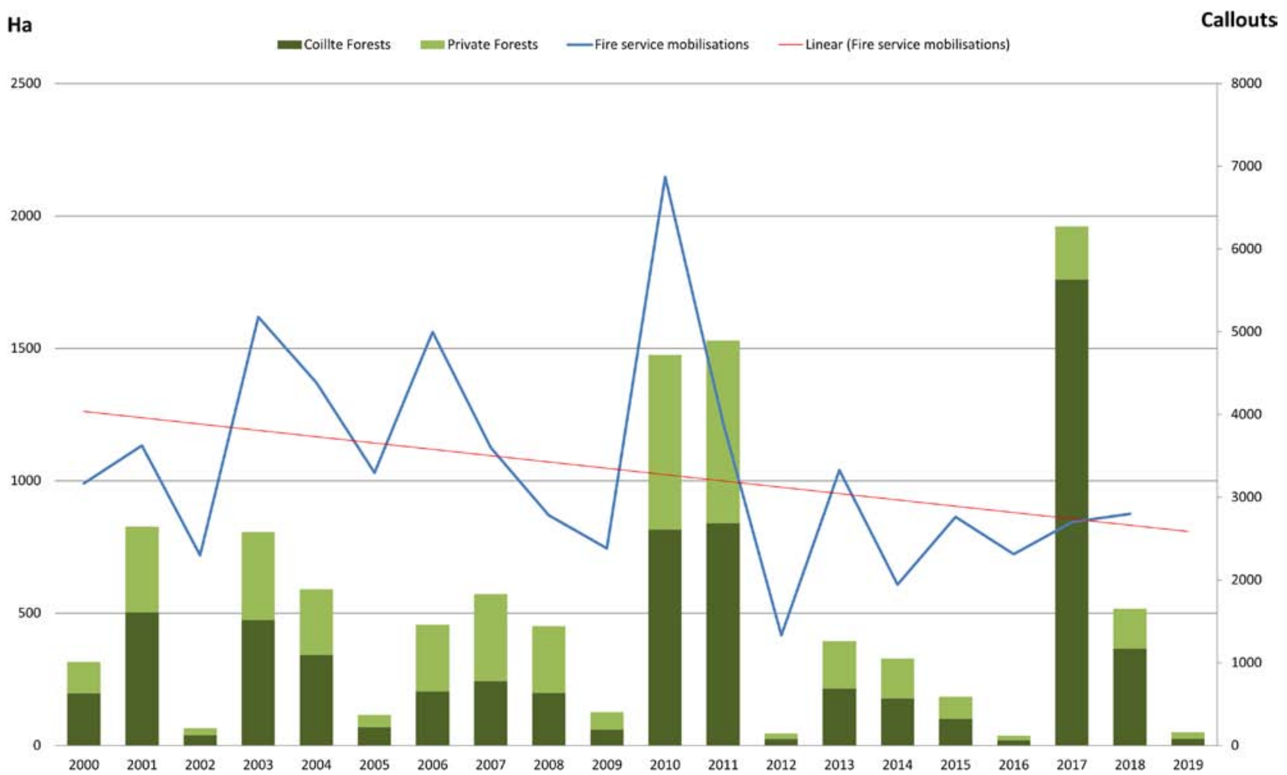


Figure 4.21. Combined forest area burned (2000–2019) and annual fire service mobilisations (2000–2018) to bog, grass and forest fires. The bars show the area burned: dark green, public (Coillte) forest; light green, private forest. The blue line shows the number of fire service mobilisations. The red line shows the trend in mobilisations. Sources: Generated by the authors using data from the Department of Housing, Planning, Community and Local Government and Department of Agriculture, Food and the Marine.

grants were provided by the Forest Service for the period 2000–2019. The amount of land under forest has been steadily increasing as a result of government afforestation policies, and fires occur more frequently in young rather than mature forest stands. Peaks and troughs are largely indicative of prevailing spring weather for given years. Irish fire and rescue services mobilisations since 2000 are also shown and reflect the multiannual cyclical incidence of fires. There has been a slight downward trend in such mobilisations over the last 20 years.

Met Éireann forecasts daily fire danger at some of its synoptic stations using a model that incorporates the most recent meteorological observations. Figure 4.22 shows the number of days per year since 1971, during the fire season, when the danger of fire was considered very high or extreme, based on Dublin and Shannon synoptic data. There is no long-term trend evident in these data.

There is potential to use satellite data to quantify burned areas and emissions from vegetation fires in Ireland.

Smoke plumes from a number of large fires in County Galway can be seen on the satellite image from 9 May 2017 illustrated in Figure 4.23 (left). Fires detected by the satellite sensor are highlighted in red. The satellite image in Figure 4.23 (right) shows the area burned, including almost 1700 ha of forest land.

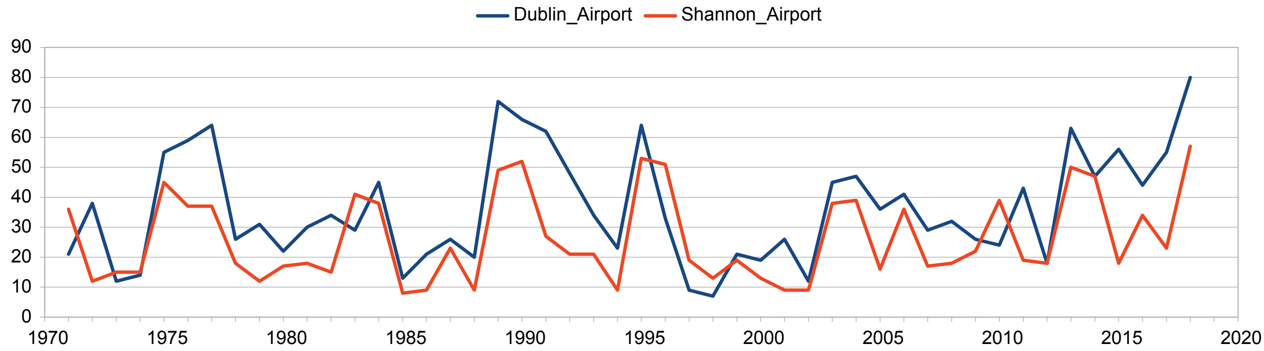


Figure 4.22. Number of days on which the fire index was very high or extreme calculated using data from Dublin Airport and Shannon Airport synoptic stations (1971–2018).

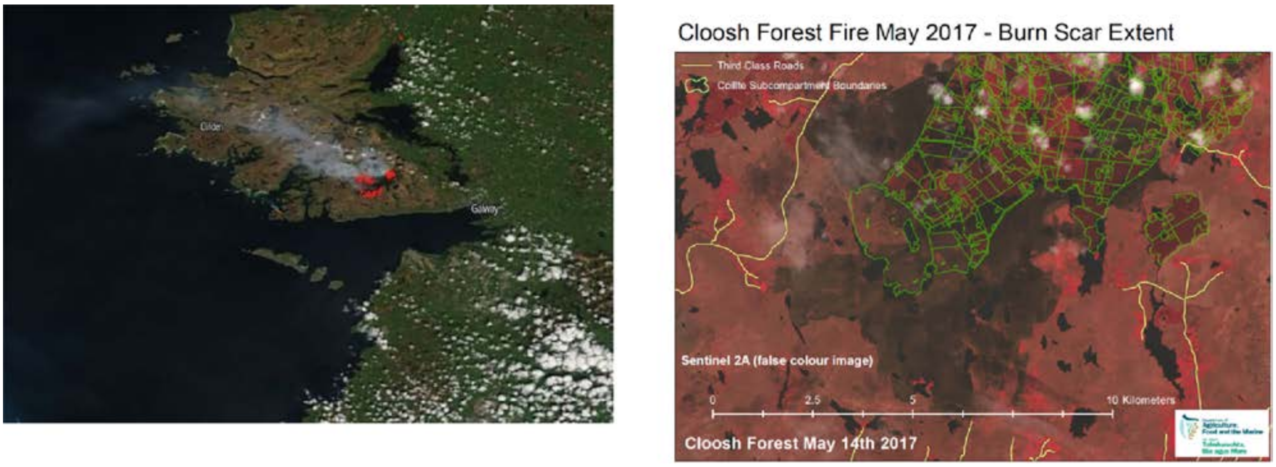


Figure 4.23. A MODIS Terra satellite image from 9 May 2017 shows smoke plumes from a complex of forest and bog fires. Fire detection “hotspots” are highlighted in red (left). A Copernicus Sentinel-2A composite satellite image of the extent of the burn scar (dark area) detected on 14 May 2017, with Coillte properties and road networks included (right). Approximately 1700 ha of forest were burned during this incident. Sources: Images produced by the NASA Earth Observations team using data courtesy of the MODIS Land Science Team at NASA Goddard Space Flight Center (left). Image contains modified Copernicus Sentinel data 2017, processed by ESA (right).

4.11.3 Maintaining the Observations

The Forest Service and Coillte maintain a record of the area burned for forest monitoring and to comply with the requirements of the Forestry Act, 2014. Nonetheless, information should be improved by recording and collating the location and extent of all wildfires, including both forest and non-forest land types.

Met Éireann calculates daily fire risk as part of its operational procedures. However further analysis of the historical fire risk data should be carried out. A most critical research issue is determining a suitable surface fuels and combustion model with which to model fire behaviour and potential combustion and emission outcomes under Irish conditions.

Research into the potential for using remotely sensed imagery to map burned areas has been carried out by the DAFM. A 2-year study funded by the EPA, and led by University College Cork, to evaluate the utility of satellite data for quantifying burnt areas and vegetation fire emissions, started in March 2020.

4

Further Information

Fire Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/fire/)

Stracher, G.B. *et al*., 2019. Peat fires in Ireland. In Stracher, G.B. (ed.), *Coal and Peat Fires: A Global Perspective. Volume 5: Case Studies*. Elsevier Inc., Amsterdam, pp. 451–482 (https://doi.org/10.1016/B978-0-12-849885-9.00020-2)

Annual Reports on Forest Fires in Europe, the Middle East and North Africa (https://effis.jrc.ec.europa.eu/reports-and-publications/annual-fire-reports)

Global Wildfire Information System (https://gwis.jrc.ec.europa.eu/)

Fire, Land and Atmospheric Remote Sensing of Emissions (FLARES) project (https://www.ucc.ie/en/flares/)

Story Box 7. Copernicus maintains constant health check on Earth

Ned Dwyer and Walther C.A. Cámaro García

The EU's Earth observation programme

How have Irish cities grown over the last 30 years? How clean is the air where I live? What areas were flooded after a recent storm? These are the kind of questions that the information provided by the Copernicus services helps to answer. Copernicus is the EU's Earth observation programme, dedicated to providing information gathered from satellites and from on-the-ground sensors to monitor the planet and its environment. Several Copernicus services provide comprehensive analysis and products of recent past and forecast climate conditions by incorporating satellite and *in situ* observations in complex models of the Earth system. The information produced through the services is made available openly and free of charge to anyone who wishes to use it.

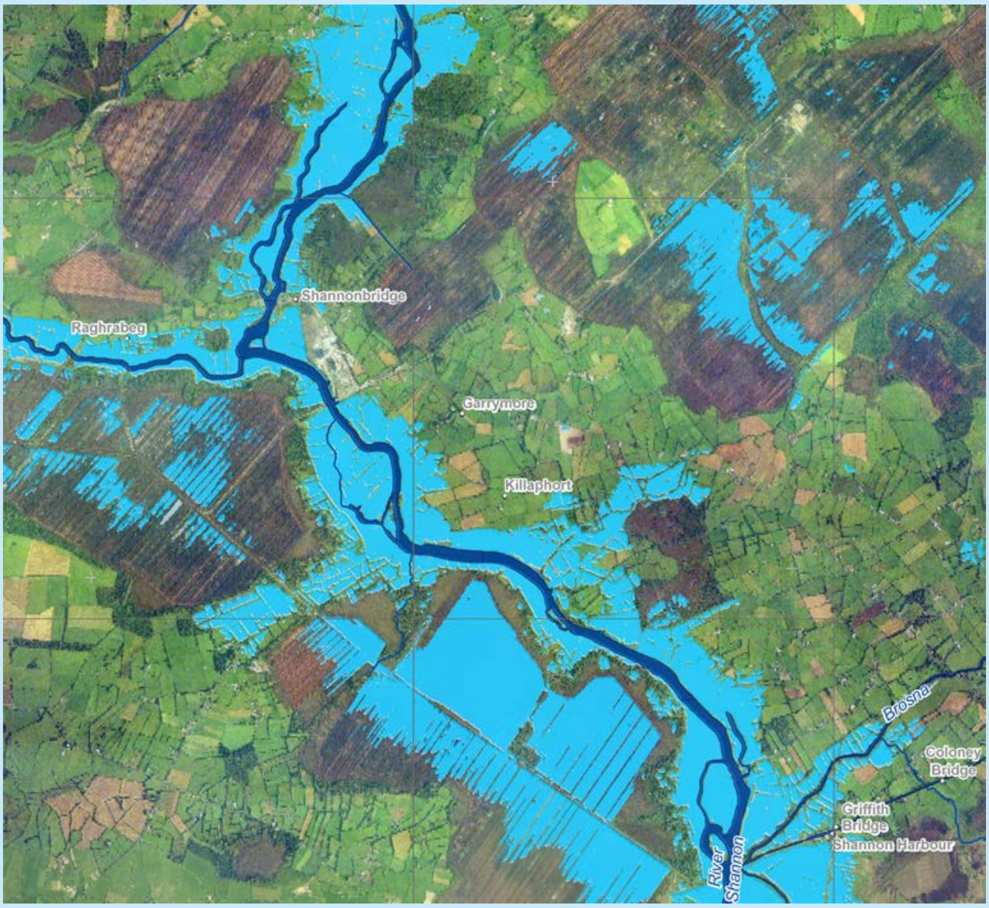
Underpinning the programme is a series of satellites known as the Sentinels, designed and operated by ESA and EUMETSAT. At the beginning of 2020, seven Sentinels were in orbit, and there are plans to expand the network to almost 20 by 2030. The scale of this programme is unique, in terms of both the amount and quality of data gathered and the fact that the satellites have been planned to provide an operational service for over 15 years. Each satellite constellation within the series operates in different parts of the electromagnetic spectrum, collecting information from the land surface, ocean and atmosphere. Analysis of the Sentinel data allows us to understand, for example, the amount of the pollutant SO_2 in the atmosphere and how it changes, where and when oil spills have taken place at sea and to identify land areas subject to drought or flooding.

Copernicus thematic services

Copernicus has six thematic services, namely Land, Marine, Atmosphere, Climate Change, Security and Emergency. These services provide primarily satellite-derived information on issues such as land cover characteristics and changes, surface ocean temperatures and colour, pollutants in the atmosphere, trends in climate parameters, illegal fishing and flooded areas to name but a few. In addition, some of these services are being referenced as global inventories of ECVs for the GCOS. For example, the Climate Data Store of the Climate Change Service is a repository of gridded climate data records for a variety of ECVs derived from satellite observations.

An example of one product is CORINE Land Cover, which is a land cover map of Europe with a mapping unit of 25 ha that uses a common legend; the first version was produced in 1990 and the fifth in 2018. Land use information products derived from satellite data with very high spatial resolution are available on forests, grasslands, impervious surfaces and water bodies. Nonetheless, there are significant shortcomings in the CORINE product in terms of its accuracy, reliability and appropriateness for Irish land cover (see Story Box 5).

The Copernicus Emergency Management Service can be initiated before, during or after an extreme event by national governments and provides rapid mapping data in affected areas to aid disaster response and recovery. It has been activated by Ireland on a number of occasions in relation to wind storms and heavy rainfall. For example, in December 2015, heavy and prolonged rainfall in the mid-west led to the River Shannon bursting its banks in many areas, causing large areas to be flooded. A series of satellite images were captured as soon as possible after the event and analysed, together with ancillary geographical information, for flooded areas, damaged buildings and affected transport infrastructure, thereby providing local authorities with useful information to help target responses to the effects of the flooding (Figure SB7.1).



SB7

Figure SB7.1. This satellite image from 11 January 2016 shows areas flooded near Shannonbridge, highlighted in light blue, after the River Shannon burst its banks in December 2015. Source: Copernicus Emergency Management Service (EMSR149 Ballinasloe: Delineation Map, Monitoring 2). © 2016 European Union.

The Copernicus Climate Change Service provides satellite observations, seasonal forecasts, climate projections and reanalysis data for a range of atmosphere, ocean and land variables and for all of Europe (Figure SB7.2). It also issues monthly summaries on a number of atmospheric, hydrological, cryospheric and land cover variables and it has issued an annual *European State of the Climate* report since 2017.

The Copernicus Marine Environment Monitoring Service and Copernicus Atmosphere Monitoring Service provide satellite, *in situ* and model-based products for large- and regional-scale monitoring. The Copernicus Marine Service produces an annual *Ocean State Report*, detailing changes in essential ocean variables.

A number of initiatives have been set up to support public authorities, small companies and educators to take advantage of the data and information available through the various services, which can be easily

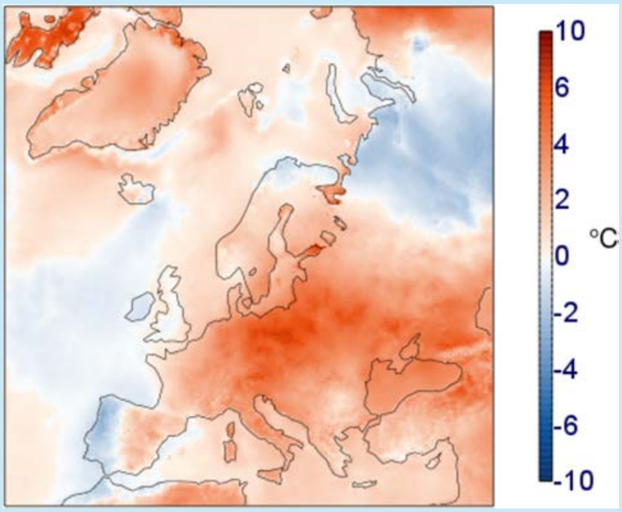


Figure SB7.2. While much of central Europe had a heatwave during June 2019, Ireland and the western fringes of Europe remained cool with temperatures below normal for the time of year. The figure shows the surface air temperature anomaly for June 2019 relative to 1981–2010. © ECMWF, Copernicus Climate Change Service (http://climate.copernicus.eu, accessed 26 May 2020).

accessed through the Copernicus website. This free access to a wide suite of data, products and services through one location is of huge benefit and opens up numerous possibilities for creating value-added services and innovative products to support improved environmental monitoring.

Further Information

Copernicus programme (https://www.copernicus.eu/en)

Copernicus climate bulletins (https://climate.copernicus.eu/climate-bulletins)

ESA Sentinel satellites (https://sentinel.esa.int/web/sentinel/home)

4.12 Land Surface Temperature

Walther C.A. Cámaro García and Ned Dwyer

The land surface temperature (LST) – the temperature of the land surface rather than that of the near-surface air – is a fundamental aspect of climate and biology, affecting organisms and ecosystems from local to global scales. LST is a mixture of vegetation and bare soil temperatures. This parameter is key to understanding terrestrial thermal behaviour and the exchange processes between the land surface and the atmosphere. Because of the rapid response of vegetation and bare soil to changes in solar radiation due to cloud cover, aerosol concentrations and diurnal variation in the sun's illumination, LST can vary substantially throughout the day.

4.12.1 Measurements

Ground-based measurements of LST tend to be made only at the local scale for research studies. There is no long-term *in situ* LST monitoring programme in Ireland. Regional and global LST measurements are generally made by satellite sensors, which have the ability to measure the thermal infrared radiation emitted by the Earth's surface on a regular basis. The CGLS generates an LST dataset as part of a set of energy monitoring products. This dataset is derived from the MSG, the GOES and the multifunctional transport satellites (MTSAT). In addition, one of the longest global time series of LST is derived from the MODIS instruments aboard the Terra and Aqua satellites.

In summer LST can reach 40°C in some parts of the east of the country.

4.12.2 Time Series and Trends

Figure 4.24 shows a time series of monthly average LST for day and night time derived for Ireland using the MODIS dataset. Seasonal and diurnal variability can be observed, in which the highest values occur during summer and during daylight hours. The highest values, both day and night time, are observed in the summers of 2013 and 2018.

Figure 4.25 shows a set of maps of the 10-day maximum LST derived for Ireland from the CGLS in 2018, for the periods 1–10 January, 1–10 April, 1–10 July and 1–10 October. This illustrates how the LST varies spatially and temporally over the course of a year. During the winter the maximum LST values are below 12°C, with the coldest areas generally to the north-west, while during the summer the temperature can reach 40°C in parts of the east of the country.

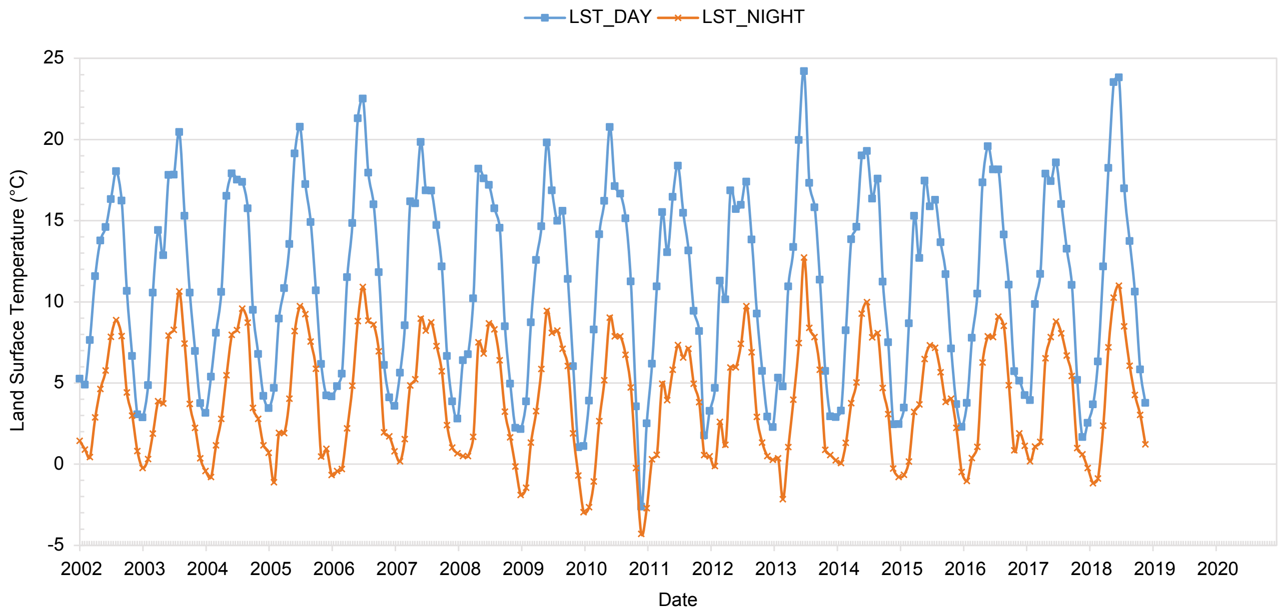


Figure 4.24. Time series of monthly average land surface temperature for day and night time over Ireland derived from the MODIS dataset (2002–2018).

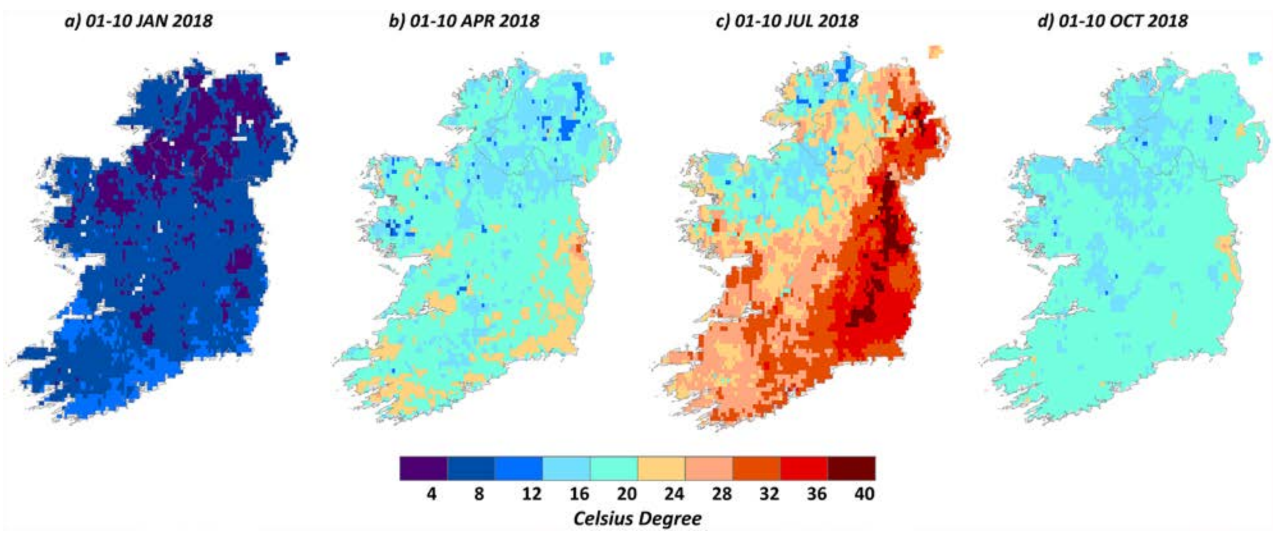


Figure 4.25. Maximum land surface temperature during four 10-day periods in 2018 derived from the Copernicus Global Land Service datasets. © European Union, Copernicus Land Monitoring Service 2020 and European Environment Agency.

Long-term ground-based measurements of LST should be considered to validate and support the satellite observations.

4.12.3 Maintaining the Observations

Current and future satellite sensors will continue to gather the radiation reflected and emitted from the Earth's surface from which LST can be calculated. The CGLS is one of the Copernicus services that provides satellite information that may be used to monitor the status of the biosphere. The global LST dataset available is derived from several satellite sensors. The radiometer on board the currently operational Sentinel-3 satellite measures sea and land surface temperatures. The ESA CCI project is preparing a global LST dataset for the past 20–25 years, which will be available in the next few years.

A comprehensive analysis of satellite-derived LST products for Ireland should be carried out. Establishing a long-term ground-based measurements programme for LST should be considered to complement such an analysis and to validate and support the satellite observations. However, regular cloud cover over Ireland could limit the use of *in situ* observations for validating satellite data.

Further Information

Land Surface Temperature Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/land-temperature/)

Copernicus Global Land Service (CGLS) data on land surface temperature (https://land.copernicus.eu/global/products/lst)

NASA's Earth observing system data (https://giovanni.gsfc.nasa.gov/giovanni/)

Information about Sentinel-3 SLSTR (https://sentinel.esa.int/web/sentinel/user-guides/sentinel-3-slstr)

ESA's Climate Change Initiative Land surface temperature project (http://cci.esa.int/lst)

4.13 Anthropogenic Water Use

Walther C.A. Cámaro García, Ned Dwyer and Conor Quinlan

Fresh water is used for drinking, cooking, cleaning, agriculture, producing electricity, industrial processes and recreation. This water generally comes from rivers, lakes and underground sources. Global water use has increased by a factor of six over the past 100 years and continues to grow steadily at a rate of about 1% per year as a result of increasing population, economic development and shifting consumption patterns. Climate change is projected to aggravate already water-stressed areas and generate stress in regions where there is currently an adequate supply. Although Ireland generally has abundant water resources, periods of drought can lead to limited supplies and deteriorating quality. Therefore, reliable data on water use are essential to guarantee its responsible management and ensure that rivers, lakes and groundwater are sustainably used.

4.13.1 Measurements

In 2018 the EPA launched the National Water Abstraction Register, in compliance with the WFD. Any person or organisation abstracting 25,000 l (25 m^3) or more of groundwater or surface water per day is required to register. Before 2018, only public water supply bodies were obliged to register; therefore, there are inaccuracies in the data on overall water use. Quality checking of the register is ongoing and this may lead to differences in future years, for example because

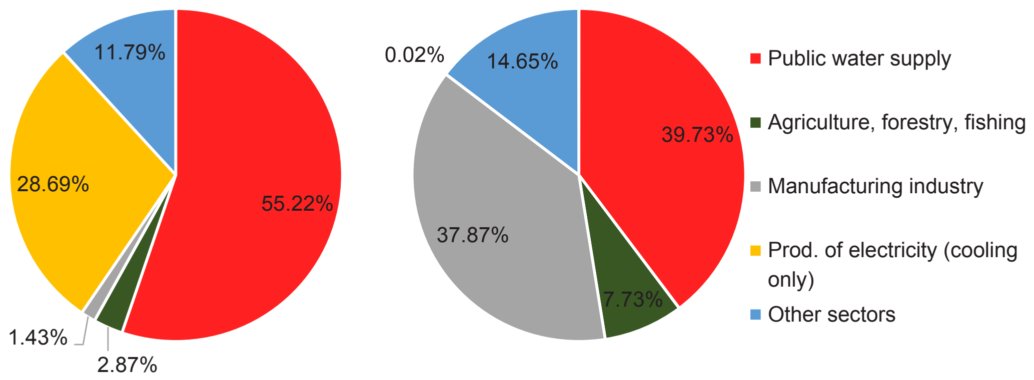


Figure 4.26. Total fresh water abstracted by sectors in Ireland during 2018 from surface water (left) and groundwater (right) sources.

of misclassification of registrations and the inclusion of additional abstractions in the register.

During 2018, 80% of water used came from surface water sources and 20% from groundwater sources.

4.13.2 Time Series and Trends

Figure 4.26 shows the sectoral distribution of surface water and groundwater abstracted in 2018 in Ireland. Some 82% (1655 million m^3) was abstracted from surface sources, while the remaining 18% (375 million m^3) came from groundwater sources. More than half of the surface water abstracted was used for public water supply. More than one-quarter of the surface water extracted was used by the electricity generation sector for cooling, with almost none coming from groundwater sources. In contrast, most of the water used in manufacturing came from groundwater, and it was also the primary source of water used in agriculture. Although agriculture represents a small percentage of overall use, it may be underestimated, as not all agricultural use has yet been captured.

The newly established National Water Abstraction Register will facilitate the identification of annual changes in water use.

4.13.3 Maintaining the Observations

The National Water Abstraction Register is managed by the EPA in compliance with the WFD and will be maintained into the future. The register will allow the identification of annual changes in amounts used by the different sectors and the highlighting of any trends that emerge.

Further Information

Anthropogenic Water Use Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/water-use/)

Water use data on the OECD (Organisation for Economic Co-operation and Development) portal (https://stats.oecd.org/)

The EPA website on water abstraction registration (https://www.epa.ie/licensing/watwaste/watabs/)

The EPA website on the Water Framework Directive (https://www.epa.ie/water/watmg/wfd/)

UNESCO (United Nations Educational, Scientific and Cultural Organization), *The United Nations World Water Development Report 2020: Water and Climate Change* (https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en)

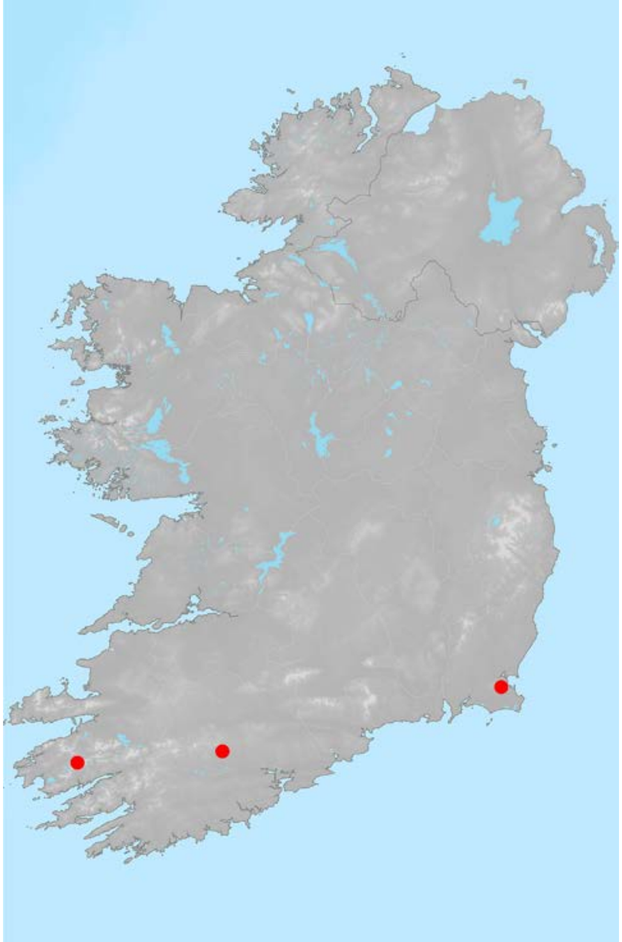
4.14 Anthropogenic Greenhouse Gas Emissions

Walther C.A. Cámaro García and Ned Dwyer

GHG emissions, including CO_2, CH_4 and N_2O, from human (anthropogenic) activities, such as fossil fuel use, industry, agriculture and the waste sector, continue to increase globally. These gases reside in the atmosphere for periods from decades to thousands of years, and the increase in their concentrations is a cause of increased surface temperature and climate change. Monitoring emissions of these gases is key to understanding climate dynamics and the effects of anthropogenic activities on climate. Accurate estimates and attributions are important, as they affect policy decisions in relation to GHG mitigation, and regular reporting under the UNFCCC is required to meet Ireland's international obligations.

4.14.1 Measurements

Direct measurements of anthropogenic GHG emissions in Ireland, as in many other countries, are limited. National estimations for reporting to the UNFCCC are based on a set of detailed guidelines provided by the IPCC, the UN body for assessing the science related to climate change. The methodology uses a set of emission factors for each GHG linked to an activity or sector, such as energy production, agriculture, land use, land use



Map 4.5. Location of greenhouse gas eddy covariance flux towers.

change and forestry (LULUCF), industrial processes and product use (IPPU) and waste management.

At the local scale flux towers based on the eddy covariance method[17] are the most widely used approach to directly observing GHG fluxes between ecosystems and the atmosphere in the LULUCF sector. As part of an EPA- and subsequently Council for Forest Research and Development-funded research project in the 2000s, GHG flux eddy covariance towers operated at Dripsey, Co. Cork (grassland and forest), Glencar, Co. Kerry (blanket peatland), and Wexford, Co. Wexford (grassland) (Map 4.5). These platforms are no longer operational.

A number of satellite sensors, including Sentinel-5P, make broad-scale measurements of GHGs. The ESA CCI Greenhouse gases project has developed a comprehensive global time series of satellite-derived CO_2 and CH_4. These data, combined with flux tower station data, provide valuable information for understanding GHG dynamics between the atmosphere and the environment.

In 2018 emissions from fossil fuel energy use were 18% higher than in 1990, with emissions from agriculture having increased by 2%. Together, these represent over 87% of total emissions.

4.14.2 Time Series and Trends

Figure 4.27 shows the total GHG emissions estimated across Ireland by IPCC sector between 1990 and 2018. In 2018, total emissions of greenhouse gases were just over 65 kt CO_2 equivalent,[18] which is 8% higher than emissions in 1990. In 2018, the energy sector accounted for 56% of total emissions, agriculture 31%, LULUCF 7%, IPPU 5% and waste 1%. An increasing trend in overall emissions is observed between 1990 and 2001, after which they slowly declined.

In 2018, emissions from fossil fuel energy use were 18% higher than in 1990, with emissions from agriculture having increased 2%. Both the LULUCF sector and the waste sector show a reduction in emissions since 1990, of 13% and 43%, respectively. The LULUCF reduction is linked to the removal of GHGs generated by afforestation activities.

Figure 4.28 shows the cumulative CO_2 fluxes measured at the Dripsey grassland site for the period 2002–2012 when the flux tower was active. Negative values represent a net uptake of CO_2 (sink). This demonstrates that the grassland site was a net sink for CO_2 over the course of each year. However, there is seasonal variability. In the growing season (approximately March to September; days 60–250) there is a significant uptake of CO_2, whereas in the dormant season (approximately

17 Eddy covariance is a measurement technique that allows the calculation of exchange rates of GHGs between different ecosystems and the atmosphere.

18 CO_2 equivalent is used to compare emissions from various GHGs, on the basis of their global warming potential, by converting amounts of other gases to the equivalent amount of CO_2 with the same global warming potential.

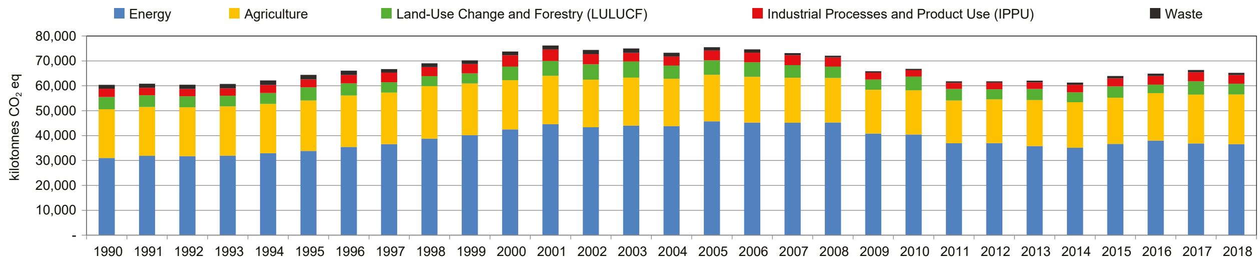


Figure 4.27. National total greenhouse gas emissions by sector (1990–2018). Source: Ireland's National Inventory Report 2020 (EPA, 2020).

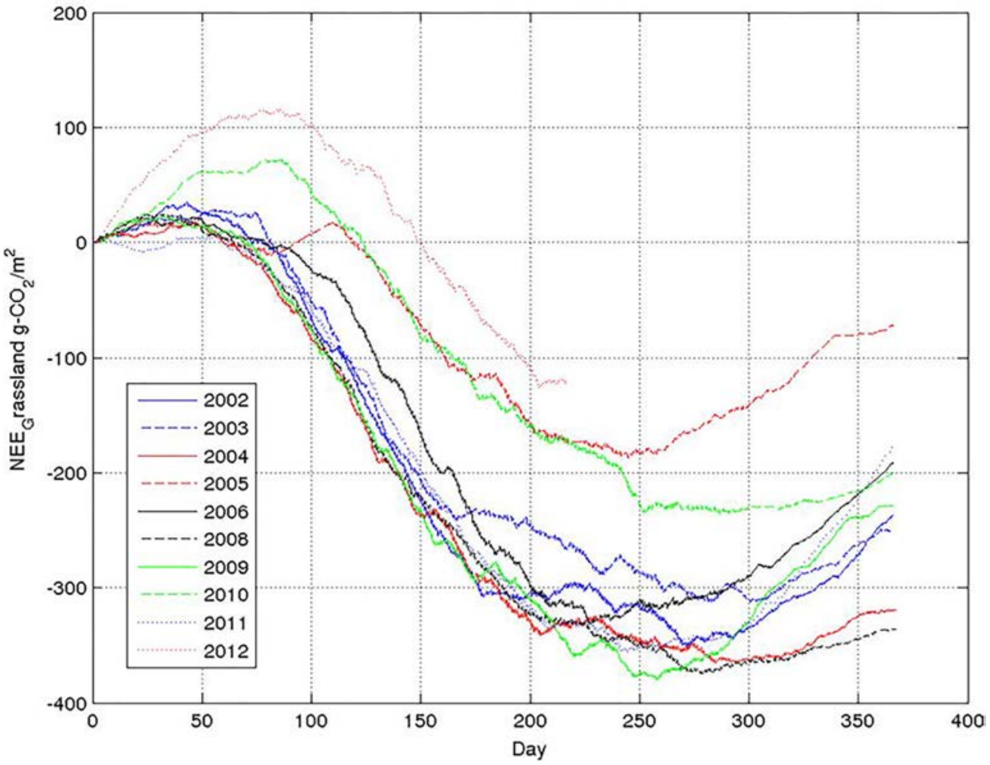


Figure 4.28. Annual cumulative carbon dioxide fluxes (g C/m²/ha) at the Dripsey, Co. Cork, grassland site (2002–2012).

October to February), the grasslands are a source of CO_2.

The establishment of a long-term Irish GHG observatory would support national and international initiatives and mitigation and adaptation plans.

4.14.3 Maintaining the Observations

As a Party to the UNFCCC, Ireland regularly reports detailed information about anthropogenic GHG emissions through its National Inventory Report.

An EPA-funded GHG flux monitoring project ran for a number of years from 2002. This helped establish a

4

set of flux sites in key ecosystems across Ireland that reported observations to two large-scale EU projects – Carbo Europe and Nitro Europe – in 2005 and 2008, respectively. The EPA project was concluded in 2012.

In 2012 the ICOS research infrastructure was established, which collates GHG information across the EU. The EPA represents Ireland and has had observer status at ICOS since 2017.

The establishment of a long-term Irish GHG observatory (i.e. flux towers) would help to assess terrestrial systems' potential to mitigate and adapt to climate change, support engagement with key measurement networks (e.g. ICOS) and underpin national initiatives such as National Inventory Reporting.

Further Information

Anthropogenic Greenhouse Gas Emissions Essential Climate Variable (ECV) Factsheet (https://gcos.wmo.int/en/essential-climate-variables/ghg-fluxes/)

Kiely, G. *et al*., 2018. *GHG Fluxes from Terrestrial Ecosystems in Ireland*. Environmental Protection Agency (https://www.epa.ie/publications/research/climate-change/research-227.php)

Ireland's National Inventory Report 2020 (https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/irelands-national-inventory-submissions-2020.php)

FLUXNET (https://fluxnet.ornl.gov/fluxnetdb)

Integrated Carbon Observation System (ICOS) information about greenhouse gases (https://www.icos-ri.eu/greenhouse-gases)

ESA's Climate Change Initiative Greenhouse gases project (http://cci.esa.int/ghg)

Story Box 8. Co-ordinated research infrastructures support better climate observations

Jeremy Gault and Ned Dwyer

A research infrastructure (RI) can be considered a facility, a set of instruments, equipment, information networks, materials and related services used to carry out research. An RI can be based at a single location, be distributed across several sites or be available as a virtual platform. Such RIs include aircraft, research vessels and the equipment they carry, on-land and offshore observation equipment, research and test facilities in the physical, biological and chemical domain, and numerous remote and *in situ* observation facilities.

Europe has an extensive network of RIs that can be used for different aspects of climate observation. Consolidation, co-ordination, and more streamlined access to such facilities is being promoted at European and regional level through overarching initiatives such as the European Strategy Forum on Research Infrastructures (ESFRI).

Formed in 2002, ESFRI aims to improve integration and increase the impact of European RIs. It has a membership derived from government representatives of the Member States, from which is drawn an Executive Board and a Chair, and it is supported by six working groups and six strategic working groups (listed in the table below). It has developed and regularly reviews its "Roadmap", which is the document that highlights the current and future priorities for European RIs.

The Environment Strategic Working Group identifies new important RIs and research demonstrators of pan-European interest in the environmental area (including climate) and helps plan their implementation, and it analyses best implementation schemes specifically for the environmental sciences.

New infrastructure project proposals, which usually bring together key organisations from around Europe operating relevant RIs, are submitted to be considered for inclusion in the Roadmap and, subject to review, successful projects are included in the next iteration of the Roadmap.

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The 2018 roadmap contains details of 37 ESFRI landmark RIs and 18 ESFRI projects,[19] with the majority of EU countries having either recently developed or updated their National Roadmaps. Of these 55 activities, currently there are seven landmark RIs and four projects under the environmental area in the 2018 Roadmap as listed in the tables on the following page.

Working groups	Strategic working groups
• Implementation	• Data, Computing and Digital Research Infrastructures
• Infrastructure Reflections	• Energy
• Innovation	• Environment
• Long-term Sustainability	• Health and Food
• Landscape	• Social and Cultural Innovation
• Monitoring	• Physical Sciences and Engineering

19 ESFRI landmarks are RIs that have already been implemented or have reached an advanced implementation stage, whereas projects are RIs that are still working towards that goal.

Landmark research infrastructure	Irish involvement
EISCAT_3D: Next-generation European Incoherent Scatter radar system This radar system investigates how the Earth's atmosphere is coupled to space and provides information for climate change, space weather, plasma physics, space debris and near-Earth object studies.	N
EMSO ERIC: European Multidisciplinary Seafloor and Water-column Observatory Operates an array of seafloor and water column observatories distributed across European seas. EMSO provides data for the understanding of fundamental processes in the marine domain.	Y – Ireland is a member and represented by the Marine Institute. Galway Bay is a contributing observatory.
EPOS: European Plate Observing System The goal is to achieve a better understanding of the Earth's physical and chemical processes that control earthquakes, volcanic eruptions, ground instability and tsunamis as well as the processes driving tectonics and Earth's surface dynamics.	Y – Ireland is a prospective member and represented by the Geological Survey of Ireland.
Euro-Argo ERIC: European contribution to the international Argo programme Operates an array of profiling floats that measure temperature and salinity every 10 days throughout the deep global ocean. Developments focus on extending the network to abyssal ocean, biogeochemical parameters, marginal seas and high latitudes.	Y – Ireland is a member and represented by the Marine Institute, which has deployed Argo floats since 2008.
IAGOS: In-service Aircraft for a Global Observing System Operates a global-scale monitoring system for atmospheric trace gases, aerosols and clouds by using the existing provisions of the global air transport system.	N
ICOS ERIC: Integrated Carbon Observation System Generates high-precision data and integrates knowledge of the carbon cycle and GHG budgets and of their perturbations. ICOS conducts long-term observations in three networks – atmosphere, ecosystems and ocean.	N
LifeWatch ERIC: e-Infrastructure for Biodiversity and Ecosystem Research Focused on the need for increasingly diverse data and larger and more advanced models, open data and open science clouds, making it possible to explore new frontiers in ecological science and support society in addressing the challenges ahead.	N

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Research infrastructure projects	Irish involvement
ACTRIS: Aerosols, Clouds and Trace Gases Research Infrastructure Delivers precision data, services and procedures regarding the four-dimensional variability of clouds, short-lived atmospheric species and the physical, optical and chemical properties of aerosols to improve the current capacity to analyse and understand the past and current evolution of the atmospheric environment and to predict its future evolution.	Good potential – NUI Galway and University College Cork (UCC) are involved in ACTRIS development (Horizon 2020).
DANUBIUS-RI: International Centre for Advanced Studies on River–Sea Systems Provides services encompassing remote and *in situ* observation systems, experimental facilities, laboratories, modelling tools and resources for knowledge exchange in relation to estuaries, deltas and transition zones between rivers and seas throughout Europe.	Good potential – UCC is involved in DANUBIUS-RI development (Horizon 2020).
DiSSCo: Distributed System of Scientific Collections Supports the digital unification of all European natural science assets under common curation and access policies and practices that aim to make the data easily findable, more accessible, interoperable and reusable (FAIR).	N
eLTER: Long-term Ecosystem Research in Europe Seeks to improve our knowledge of the structure and functions of ecosystems and their long-term response to environmental, societal and economic drivers, including climate change.	N

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. Each RI is intended to be a long-term sustainable initiative with its own governance, funding and management, although collaboration between complementary initiatives is actively encouraged. Ireland should strive to maximise its participation in these RI initiatives. This would help boost knowledge and skills by providing access to world-class RIs for scientists based in Ireland and enhance international collaboration.

Further Information

ESFRI Roadmap (https://www.esfri.eu/esfri-roadmap)

ESFRI Environment Strategic Working Group (http://www.esfri.eu/working-groups/environment)

ESFRI National Roadmaps (https://www.esfri.eu/national-roadmaps)

5. Concluding Remarks

5.1 Discussion and Recommendations

5.1.1 International Perspective

The WMO assessment of global climate for the period 2015–2019 (WMO, 2020) reports that the three major GHGs, namely CO_2, CH_4 and N_2O, reached their highest ever levels during that period. In addition, growth rates in emissions of these GHGs were almost 20% higher over that period than in the previous 5-year period (2011–2015). Moreover, the surface air temperature for the 5 years analysed was 1.1°C above the pre-industrial average, and these years were the warmest of any equivalent period on record. Sea levels continue to rise at an accelerated rate and are now estimated to be 90 mm higher than in 1993, when satellite observations began. The ocean absorbs more than 90% of the excess heat caused by global warming and the ocean's heat content has reached new records in the years since 2015. As the ocean is estimated to have absorbed between 20% and 30% of total anthropogenic CO_2 emissions since the 1980s, it is becoming more acidic, a trend that has continued over recent years, with the ocean now noted to be 26% more acidic than at the beginning of the Industrial Revolution (*c.*1850). Major changes in the cryosphere (frozen areas) have also been observed, and melting from land-based glaciers and ice sheets is now responsible for most of the sea level rise. The IPCC's Special Report on Climate Change and Land (IPCC, 2020) highlighted that changes in land cover, land use and land state affect global and regional climate, although the magnitude and direction of these changes vary with location and season. Moreover, it was pointed out that expansion of areas under agriculture and managed forests has supported food availability but has contributed to increasing net GHG emissions, loss of natural ecosystems and declining biodiversity.

5.1.2 Climate Observations in Ireland

Observations in Ireland are generally consistent with the global situation. Measurements of the major GHGs at Mace Head in 2018 show the highest concentrations since measurements began. Although the years 2015–2019 were not the warmest on record in Ireland, the trend is upwards, with an increase of approximately 0.9°C over the last 120 years. Annual precipitation was 6% higher in the period 1989–2018 than in the 30-year period 1961–1990, and the decade 2006–2015 was the wettest on record. Analysis of wet and dry spells demonstrates an increase in the length of wet spell days across all of the country; however, no trend is apparent in dry spell days.

Regarding the ocean, the sea surface temperature measured at Malin Head, Co. Donegal, has been on average 0.47°C higher over the last 10 years than in the period 1981–2010. Natural variability in sea surface temperature is to be expected because of the North Atlantic Oscillation; nevertheless, it is estimated that half of the temperature increase seen can be attributed to climate change effects (Cannaby and Hüsrevoğlu, 2009). Ocean acidification is increasing, as measurements in the surface waters of the Rockall Trough between 1991 and 2013 show decreasing pH levels. Satellite observations indicate that the sea level around Ireland has risen by approximately 2–3 mm per year since the early 1990s, and analysis of sea level data from Dublin Bay show a rise of approximately 1.7 mm per year since 1938, consistent with global average rates (Nejad *et al.*, 2020).

River flows have been shown to be generally increasing, which is in line with increased precipitation, although, when more recent data have been analysed, there are indications that this trend may be reversing in the south-east of the country. However, the duration of observations is still too short to be confident about this (Murphy *et al.*, 2013).

Land cover continues to change, with increases in the areas covered by artificial surfaces and forest, while there is a decrease in wetland areas. The growing stock volume in forests increased by 38% over the period 2006–2017, thereby increasing the amount of carbon sequestered in forest. However, much of this is commercial forest, so the amount of carbon stored in Irish forests in the long term is not clear.

5.1.3 National Climate Observation Infrastructure

Many elements of the climate observation infrastructure are robust; nonetheless, there are gaps and areas where improvements are necessary. The network of synoptic, climatological and rainfall stations operated by Met Éireann has been upgraded and partly automated in recent years. It needs to be constantly maintained and evolve with new technologies to ensure the future of long-term, representative measurements. Valentia Observatory is crucial for the observation of ECVs including upper air temperature and wind, lightning, solar radiation and column ozone, as is having long-term records – some going back to the 1860s – for other atmospheric ECVs. The observatory is well known and highly regarded by the international scientific community. In 2012 the number of daily radiosonde ascents that measure upper air wind and temperature was reduced from four to two. It is vital that the observatory continues to be appropriately staffed and resourced to carry out its suite of measurements, as it is a cornerstone of global climate observations. The Mace Head Atmospheric Research Station, operated by the NUI Galway, has become a global reference site for the observation of a number of atmospheric composition variables. However, many of its observation programmes are funded on an ad hoc basis via projects, and the long-term availability of funding to maintain them is not assured. A case in point is the closure of the ground-based remote sensing of aerosol and microphysical cloud properties, which ceased in early 2020 after 12 years of operation. Such closures undermine the robustness and value of climate monitoring programmes, as a lack of long-term observations adversely affects the ability to determine trends.

Ireland's ocean climate observation infrastructure has improved over recent years. A major investment in the Marine Data Buoy Observation Network in 2017 facilitated ongoing operations and a significant upgrade of the infrastructure. Ireland's taking up full membership of the Euro-Argo ERIC initiative in 2016 consolidates the country's ability to deploy autonomous instruments, reporting subsurface ocean water properties, including temperature and salinity. The Marine Institute, together with NUI Galway, has carried out inorganic carbon observations since 2011. As part of this, both of its research vessels have had $p\mathrm{CO}_2$ measurement systems installed. However, long-term future observations are not ensured. Nutrients and dissolved oxygen are now regularly measured in the deep ocean as part of Ireland's national contribution to the international GO-SHIP. While novel sensors deployed on various fixed and mobile platforms have greatly improved spatio-temporal coverage of data collection for many ocean ECVs, the reference methods remain water sample collection (e.g. ship based) and subsequent analysis. Obtaining high-quality biogeochemical measurements in sea water that are suitable for climate research requires enhanced analytical measurement capability to ensure the delivery of a consistent ECV monitoring programme. The commissioning of the new research vessel RV *Tom Crean*, to replace RV *Celtic Voyager*, will ensure the country's ability to go to sea and make observations in the open ocean for many years to come. The lack of a long-term Irish-operated ocean current monitoring system represents a significant gap in the North-east Atlantic and would be particularly useful in the Shelf Edge Current to monitor variability in the major source of water from the Atlantic to the Nordic Seas. Currently, there are no plans in place to establish such an ocean current monitoring programme.

Coast-based ocean observations have also improved. The SmartBay Observatory in Galway Bay and the Mace Head Atmospheric Research Station, under the COMPASS (Collaborative Oceanography and Monitoring for Protected Areas and Species) project, make a suite of observations including sea temperature, salinity and state, surface current speed, $p\mathrm{CO}_2$, dissolved oxygen, nutrients and estimates of chlorophyll. The country's ability to observe sea level change has also been enhanced. Tide gauge operation is vested in several organisations. It has been challenging to analyse their data for sea level studies, as this goes beyond the reason they were installed. During 2020, the OPW-operated tide gauge at Malin Head was upgraded to work to full GLOSS standards. There are also plans to bring the Marine Institute-operated tide gauges at Union Hall, Co. Cork, and Howth, Co. Dublin, up to GLOSS standards in the near future on a pre-operational basis. Nonetheless, sustained resourcing and institutional support is needed to upgrade and guarantee the long-term integrity and operation of these sites and the curation of the data generated. In order to meet the water quality compliance requirements of the WFD, observations of nutrients, dissolved oxygen and plankton, among others, are made at numerous coastal sites. These observations can also potentially be used to support our understanding of climate change. Therefore, identifying a subset of representative sites that could be secured for long-term high-quality observations suitable for climate-research should be considered.

Information on water use will be greatly enhanced in the coming years following the launch of the National Water Abstraction Register. Moreover, the identification of a high-quality network of reference hydrometric gauges on rivers for monitoring and detecting climate change signals has filled a significant gap. However, on lakes there is no equivalent network. Lakes are monitored as part of the measures to comply with the WFD, so there is potential to identify a set of appropriate and representative gauges for climate change monitoring purposes. Similarly, there is an extensive network of groundwater level measurement sites; however, no specific sites have been identified for climate monitoring purposes.

The initiative to develop a new land cover dataset with a much-improved spatial resolution and more appropriate classification system compared with CORINE is welcome and should dramatically improve our understanding of land cover and its evolution. It is important to ensure that the dataset is updated on a regular basis to facilitate change detection. The establishment of the Irish Soil Information System has led to the development of a range of products on soil characteristics and has enhanced knowledge of soil carbon, although the estimates of the amount of carbon stored in the remaining peatlands remains to be improved. Monitoring of soil carbon change needs to be undertaken over a decadal time span. A better quantification of forest and non-forest areas burned, and the related emissions, is required and an EPA-funded research project is under way to combine satellite-derived and *in situ* observations to address this. However, the sustainability of some of these initiatives is precarious. For example, *in situ* measurements of GHG fluxes over a range of different land cover types took place between 2002 and 2012 but then ceased. There are no long-term ground-based measurements of LAI, FAPAR, albedo or land surface temperature. Such observations over a number of different vegetation types should be considered to improve the understanding of ecosystem processes across the country and for validating satellite-derived measurements.

No single authority is currently charged with making the full range of ECV observations for Ireland. The monitoring networks and measurement systems are managed by a range of different bodies, including state agencies, regional authorities, and colleges and universities. In many instances the observations made are not strictly for climate monitoring purposes but for other operational requirements or research. For example, groundwater levels are monitored in relation to abstraction, oxygen levels are measured for seawater quality management, and vegetation biomass is measured for forest management. Using such observational infrastructures for long-term climate monitoring is not ideal. Measurement sites can be closed or moved for operational reasons relevant to their primary function, research programmes cease, and equipment may not be appropriate or calibrated to climate measurement standards. To understand and track trends in climate change, observations must have high accuracy, precision and consistency and an appropriate spatio-temporal coverage.

The ECVs in this report have been presented in a standalone fashion. However, as is clear from Story Box 1, the Earth is a connected set of systems, and therefore observations should be carried out in an integrated manner where appropriate, as there can be many interdependencies and multiple indicators are required to understand and explain system functioning. Measurement programmes need to take this into account at the design stage to ensure completeness and coherence and to achieve synergies.

5.1.4 Satellite Observations

Over recent years there has been significant work carried out internationally on bringing together observations made over the last 30 years from a range of satellites to generate time series of global products. The ESA CCI projects have generated datasets for 23 of the ECVs covering atmospheric, oceanic and terrestrial domains. These data are publicly accessible and may be downloaded for consultation and further analysis. Nonetheless, in the majority of cases, local, *in situ* observations are required for validation of the satellite products. The EU Copernicus services (see Story Box 7) also provide satellite-derived data and products of value for climate monitoring. There has been only limited analysis and use of these various datasets in an Irish context, so there is still uncertainty over how and where they could complement *in situ* observations or be a source of useful information where ground observations are lacking. Stronger Irish engagement with the various aspects of the Copernicus programme should be encouraged. This could involve some national research funding calls requiring the use of Copernicus data. In addition, involvement in the programme's elements designed for start-ups, public authorities and the educational sector should be promoted through national information dissemination and support. This should be complemented by promoting, developing and enhancing skills in Earth observation and related data analysis capabilities nationally as there is still limited capacity in this area.

5.1.5 Analysis of National Climate Records

As important as systematic collection and management of climate data is their regular analysis and the reporting of status, trends and projections. Regarding several of the atmospheric ECVs (temperature, rainfall, sunshine, wind), a new set of climate normals for the period 1981–2010 was generated, highlighting changes with respect to the previous period 1960–1990 (Walsh, 2012). A comprehensive analysis of quantitative and qualitative rainfall records going back to 1711 has been carried out (Murphy *et al.*, 2018), providing an invaluable understanding of rainfall variability over three centuries.

Progress has been made on digitising old weather records through a number of data rescue initiatives co-ordinated by Met Éireann, including "Integrating Data Rescue into the Classroom" with the support of Maynooth University (Ryan *et al.*, 2018). This saw thousands of daily rainfall records digitised. Nonetheless, there is still an enormous amount of work to do to rescue all of the climate and rainfall series in the Met Éireann repository. This will require the consolidation of existing collaborations and the identification of new and innovative opportunities to complete the task. Recently in the UK, as part of the "rainfall rescue" citizen science project, over 5 million rainfall measurements for Britain and Ireland for the period 1677–1960 were digitised in approximately 3 weeks by more than 16,000 volunteers (Zooniverse, 2020). Such initiatives, in addition to achieving digitisation of the data, can raise awareness and interest in climate and engage the wider public in supporting climate observation programmes.

The GHG observations made at Mace Head are archived in the relevant World Data Centres, and the data have been used for spatio-temporal analysis of global GHG emissions. Work has been carried out, for example, on improving our knowledge of the spatio-temporal variability of aerosols and their interaction with clouds, incorporating observations from Mace Head (Preißler *et al.*, 2016; Lin *et al.*, 2019).

Much of the open ocean data collected under the Marine Institute's activities contribute to international initiatives to improve understanding of the dynamics of the North-east Atlantic. Argo floats provide information on water temperature and salinity. Annual surveys of temperature, salinity, pH, oxygen, chlorophyll *a*, and nutrients made from the research vessels in the Rockall Trough and Shelf are submitted to the ICES and used in its annual reports on the ocean climate. However, poor weather conditions have hampered the ability to carry out winter surveys on several occasions. An analysis of 34 years of nearshore wave conditions has been carried out using hindcasting, but with a focus on wave energy potential rather than climate change (Gallagher *et al.*, 2014). Observations from the Marine Data Buoy Observation Network were used in the validation of the model. Given the history of tide gauge measurements in Ireland and the lack of corrections for glacial isostatic adjustment it has been challenging to analyse the records for sea level change. Nonetheless, Dublin Port tide gauge data for the period from 1938 to the present have been retrieved and analysed by researchers at Maynooth University (Nejad *et al.*, 2020).

There have been significant advances in the national capability in marine modelling over recent years. Much of the ECV data collected are assimilated into models and are also used to validate models (physical, biogeochemical, ecosystem). Models are also key to understanding processes and system responses and to projecting future climate change impacts under different scenarios. Therefore, observation programmes need to consider model requirements at the design phase.

A comprehensive analysis of river flows has been carried out (Murphy *et al.*, 2013) and has helped to establish a reference network of river hydrometric gauges. The work highlighted the need for long time series and geographically representative sampling sites to detect robust trend signals. Similar analyses need to be carried out for lakes and groundwater observations.

Regular forest inventories, initiatives such as the implementation of the Irish Soil Information System to improve characterisation of soils, the development of a new land cover dataset, research projects to improve the quantification of burned vegetation and related emissions and those to enhance understanding of GHG fluxes from land to atmosphere all contribute to a better understanding of the interaction between terrestrial environments and climate. Satellite observations (e.g. LAI, FAPAR, albedo, land surface temperature) complement *in situ* programmes, and comprehensive analysis of these terrestrial variables for Ireland needs to be carried out, taking advantage of recently generated long time series of coherent global datasets such as those from the ESA CCI projects and the Copernicus programme.

5.1.6 Governance and International Engagement

The establishment of GCOS-Ireland in 2018, with representation from the key national organisations involved in climate observations, substantially improves co-ordination and coherence in relation to GCOS-relevant issues. One of its key objectives is to identify gaps in the observational infrastructure and recommend appropriate actions including the use of Earth observations and emerging technologies. Moreover, it acts as a conduit for information on national observing capacity to relevant organisations and government departments. This should help in securing some of the resources needed to maintain the existing infrastructure and in deciding how best to prioritise additional infrastructure, observation programmes and the required analysis of data already collected. GCOS-Ireland may also wish to consider a role in outreach to the public and raising people's awareness of the importance of climate observations as well as promoting the outcomes of the research and analysis carried out.

Ireland has always been well connected to the international community with regard to key climate observation systems. This has further improved over recent years with its involvement in activities related to the consolidation of research and observation infrastructures, especially in the oceanic domain. The submission of quality-controlled climate observations to international data centres also allow Irish data to be considered in international analyses. It is vital to maintain and enhance the international dimension of this work in order to share knowledge and experience of best practice in observations and to contribute to analysis and support the drive for further international investment in climate observation systems.

5.1.7 Conclusions and Recommendations

This report demonstrates that progress has been made in several areas, in terms of observation infrastructure, resourcing, analyses and co-ordination, since the previous report in 2013. Nonetheless, there are a number of issues that need to be addressed to make the national climate observation system more robust and capable of addressing the country's long-term needs with regard to climate monitoring and understanding. The following recommendations are made as a result of this study:

- Existing climate observation programmes must be sustained, and infrastructure needs to be maintained and upgraded when required to meet international standards for climate monitoring.
- Observations of ECVs that rely on one-off or ad hoc research funding should be transitioned to long-term programmes with sustained resourcing.
- A systematic programme to complete the comprehensive analysis of historical *in situ* ECV data, including the digitisation of paper records, is required.
- Satellite observations complement *in situ* programmes, and comprehensive analysis of ECVs for Ireland needs to be carried out. Skills enhancement and stronger engagement of research entities, start-ups, the educational sector and public authorities with relevant aspects of the Copernicus Earth observation programme should be promoted.
- A programme of long-term monitoring of ocean currents and their water properties should be established. This would fill a significant gap in the North-east Atlantic.
- The proposed National Sea Level Measurement Advisory Group, and a co-ordination and operational GLOSS system management function within an existing organisation, should be established

and resourced to ensure the implementation of a coherent and comprehensive sea level rise observation programme.

- Similar to the recent establishment of a reference network of river flow gauges for climate monitoring, an analogous network of lake and groundwater sites needs to be established following a review of the existing sites where observations are made for water quality, water supply and ecological reasons.
- There are no long-term ground-based measurements of a number of terrestrial variables. Such observations over different vegetation types and ecosystems should be considered to improve our understanding of ecosystem processes and for validating satellite-derived observations.
- The establishment of a long-term Irish GHG observatory (i.e. flux tower) would help to assess terrestrial systems' potential to mitigate and adapt to climate change, support engagement with key measurement networks (e.g. ICOS) and underpin national initiatives such as National Inventory Reporting.
- Establish and maintain a climate data portal as a gateway to information on the national climate observation infrastructure, sources and repositories of climate observations, publications, experts, events and activities. This could be integrated into the Climate Ireland portal.
- GCOS-Ireland, with the observational infrastructure owners, should aim to develop a roadmap for maintaining, consolidating and, where necessary, upgrading Ireland's climate observation system. This should address established and new ECVs and include prioritising areas for action, the resources and finances required and a timeline for implementation. The goal of such an implementation would be to inform national climate mitigation and adaptation actions and meet GCOS requirements.

References

Arnold, S., Smith, G., Hazeu, G., Kosztra, B., Perger, C., Banko, G., Soukup, T., Strand, G.-H., Valcarcel-Sanz, N. and Bock, M., 2018. The EAGLE concept: a paradigm shift in land monitoring. In Ahlqvist, O., Varanka, D., Fritz, S. and Janowicz, K. (eds), *Land Use and Land Cover Semantics*. CRC Press, Boca Raton, FL, pp. 107–144.

Black, K., Green, S., Mullooley, G. and Poveda, A., 2014. *Carbon Sequestration by Hedgerows in the Irish Landscape*. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/research/climate-change/carbon-sequestration-by-hedgerows-in-the-irish-landscape.php (accessed 8 June 2021).

Caesar, L., Rahmstorf, S., Robinson, A. and Saba, V., 2018. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* 556: 191–196. https://doi.org/10.1038/s41586-018-0006-5

Cannaby, H. and Hüsrevoğlu, Y.S., 2009. Low frequency variability and long-term trends in Irish SST records. *ICES Journal of Marine Science* 66: 1480–1409. https://doi.org/10.1093/icesjms/fsp062

Creamer, R., Simo, I., O'Sullivan, L., Reidy, B., Schulte, R.P.O. and Fealy, R.M., 2016. *Irish Soil Information System: Soil Property Maps*. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/research/land-use-soils-and-transport/research-204.php (accessed 8 June 2021).

DCCAE (Department of Communications, Climate Action and Environment), 2018a. *National Adaptation Framework: Planning for a Climate Resilient Ireland*. DCCAE, Dublin. Available online: https://www.gov.ie/en/publication/fbe331-national-adaptation-framework/ (accessed 1 February 2021).

DCCAE (Department of Communications, Climate Action and Environment), 2018b. *Local Authority Adaptation Strategy Development Guidelines*. DCCAE, Dublin. Available online: https://www.gov.ie/en/publication/41066-local-authority-adaptation-strategy-development-guidelines/ (accessed 1 February 2021).

DCCAE (Department of Communications, Climate Action and Environment), 2018c. *Sectoral Planning Guidelines for Climate Change Adaptation*. DCCAE, Dublin. Available online: https://www.gov.ie/en/publication/10221107-sectoral-planning-guidelines-for-climate-change-adaptation/ (accessed 1 February 2021).

de los Santos, C.B., Krause-Jensen, D., Alcoverro, T. *et al*., 2019. Recent trend reversal for declining European seagrass meadows. *Nature Communications* 10: 3356. https://doi.org/10.1038/s41467-019-11340-4

Dwyer, N. (ed.), 2013. *The Status of Ireland's Climate, 2012.* Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/research/climate-change/ccrp-report-26.php (accessed 8 June 2021).

Edwards, M., Helaouet, P., Alhaija, R.A. *et al*. 2016. *Global Marine Ecological Status Report: Results from the Global CPR Survey 2014/2015*. SAHFOS Technical Report No. 11. Sir Alister Hardy Foundation for Ocean Science, Plymouth, UK. Available online: https://www.cprsurvey.org/publications/scientific-reports/ecostatus-reports/ (accessed 28 January 2021).

EPA (Environmental Protection Agency), 2019. *Water Quality in Ireland 2013–2018*. EPA, Johnstown Castle, Ireland. Available online: https://www.catchments.ie/water-quality-in-ireland-2013-2018/ (accessed 9 June 2021).

EPA (Environmental Protection Agency), 2020. *Ireland's National Inventory Report 2020*. EPA, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/irelands-national-inventory-submissions-2020.php (accessed 8 June 2021).

Fay, D., Kramers, G., Zhang, C., McGrath, D. and Grennan, E., 2007. *Soil Geochemical Atlas of Ireland*. Teagasc, Oak Park, and Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.teagasc.ie/media/website/publications/2011/Soil_Geochemical_AtlasofIreland.pdf (accessed 4 February 2021).

Friedlingstein, P., Jones, M.W., O'Sullivan, M. *et al*., 2019. Global carbon budget 2019. *Earth System Science Data* 11: 1783–1838. https://doi.org/10.5194/essd-11-1783-2019

Gallagher, S., Tiron, R. and Dias, F., 2014. A long-term nearshore wave hindcast for Ireland: Atlantic and Irish Sea coasts (1979–2012). *Ocean Dynamics* 64: 1163–1180. https://doi.org/10.1007/s10236-014-0728-3

GCOS (Global Climate Observing System), 2016. *The Global Observing System for Climate: Implementation Needs.* GCOS Report 200. World Meteorological Organization, Geneva. Available online: https://gcos.wmo.int/en/gcos-implementation-plan (accessed 28 January 2021).

Gleeson, E., Whelan, E. and Hanley, J., 2017. Met Éireann high resolution reanalysis for Ireland. *Advances in Science and Research* 14: 49–61. https://doi.org/10.5194/asr-14-49-2017

Green, S., Martin, A., Gharechelou, S., Cawkwell, F. and Black, K., 2019. *BRIAR: Biomass Retrieval in Ireland using Active Remote Sensing*. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/research/climate-change/research-305.php (accessed 28 January 2021).

Groom S, Sathyendranath, S., Ban, Y. *et al*., 2019. Satellite ocean colour: current status and future perspective. *Frontiers in Marine Science: Ocean Observation* 6: 485. https://doi.org/10.3389/fmars.2019.00485

Gruber, A., Scanlon., T., van der Schalie, R., Wagner, W. and Dorigo, W., 2019. Evolution of the ESA CCI soil moisture climate data records and their underlying merging methodology, *Earth System Science Data* 11: 717–739. https://doi.org/10.5194/essd-11-717-2019

Holliday, N.P., Bersch, M., Berx, B. *et al*., 2020. Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. *Nature Communications* 11: 585. https://doi.org/10.1038/s41467-020-14474-y

ICES (International Council for the Exploration of the Seas), 2019. *ICES Report on Ocean Climate 2018*. ICES, Copenhagen. Available online: https://ices.dk/sites/pub/Publication%20Reports/Cooperative%20Research%20Report%20(CRR)/CRR349.pdf (accessed 28 January 2021).

IOC (Intergovernmental Oceanographic Commission), 2019. Global Climate Observing System (GCOS) Status Report and Work Plan. UNESCO, Paris. Available online: http://legacy.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=24868 (accessed 4 February 2021).

IPCC (Intergovernmental Panel on Climate Change), 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds R.K. Pachauri and L.A. Meyer). IPCC, Geneva. Available online: https://www.ipcc.ch/report/ar5/syr/ (accessed 28 January 2021).

IPCC (Intergovernmental Panel on Climate Change), 2020. Summary for policymakers. In Shulka, P.R., Skea, J., Calvo Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Available online: https://www.ipcc.ch/srccl/chapter/summary-for-policymakers/ (accessed 28 January 2021).

Jackson, R.B., Saunois, M., Bousquet, P. *et al*., 2020. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. *Environmental Research Letters* 15: 071002. https://doi.org/10.1088/1748-9326/ab9ed2

Josey, S.A., Hirschi, J.J.-M., Sinha, B., Duchez, A., Grist, J.P. and Marsh, R., 2018. The recent Atlantic cold anomaly: causes, consequences, and related phenomena. *Annual Review of Marine Science* 10: 475–501. https://doi.org/10.1146/annurev-marine-121916-063102

Katz, C., 2019. Why is an ocean current critical to world weather losing steam? Scientists search the Arctic for answers. *National Geographic*, 2 December. Available online: https://www.nationalgeographic.com/science/2019/12/why-ocean-current-critical-to-world-weather-losing-steam-arctic/ (accessed 28 January 2021).

Kiely, G., McGoff, N.M., Eaton, J.M., Xu, X., Leahy, P. and Carton, O., 2010. *SoilC – Measurement and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils*. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/research/land-use-soils-and-transport/strive-35.php (accessed 8 June 2021).

Kiely, G., Leahy, P., Lewis, C., Sottocornola, M., Laine, A. and Koehler, A.-K., 2018. *GHG Fluxes from Terrestrial Ecosystems in Ireland*. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/research/climate-change/research-227.php (accessed 8 June 2021).

Lin, C., Ceburnis, D., Huang, R.J., Canonoco, F., Prévot, A.S.H., O'Dowd, C. and Ovadnevaite, J., 2019. Summertime aerosol over the west of Ireland dominated by secondary aerosol during long-range transport. *Atmosphere* 10: 59. https://doi.org/10.3390/atmos10020059

Linden, O., 2019. Evidence for ocean deoxygenation and its patterns. In Laffoley, D. and Baxter, J.M. (eds), *Ocean Deoxygenation: Everyone's Problem*. International Union for Conservation of Nature, Geneva. https://doi.org/10.2305/IUCN.CH.2019.13.en

McCarthy, G.D., Gleeson, E. and Walsh, S., 2015. The influence of ocean variations on the climate of Ireland. *Weather* 70: 242–245. https://doi.org/10.1002/wea.2543

McGovern, E., McGrath, T., Cronin, M. and O'Donnell, G., 2019. Ocean acidification observing in coastal, shelf and ocean waters around Ireland. Poster presented at the Fourth Global Ocean Acidification Observing Network (GOA-ON) International Workshop, 14–17 April, Hangzhou, China. Available online: https://www.researchgate.net/publication/332950133_Ocean_Acidification_Observing_in_Coastal_Shelf_and_Ocean_Waters_around_Ireland (accessed 4 February 2021).

Murphy, C., Harrigan, S., Hall, J. and Wilby, J.H., 2013. Climate-driven trends in mean and high flows from a network of reference stations in Ireland. *Hydrological Sciences Journal* 58: 755–772. https://doi.org/10.1080/02626667.2013.782407

Murphy, C., Broderick, C., Burt, T.P. *et al.*, 2018. A 305-year continuous monthly rainfall series for the island of Ireland (1711–2016). *Climate of the Past* 14: 413–440. https://doi.org/10.5194/cp-14-413-2018

Nejad, A.S., Parnell, A.C., Greene, A., Kelleher, B.P. and McCarthy, G., 2020. Recent sea level rise on Ireland's east coast based on multiple tide gauge analysis. *Ocean Science Discussions* (preprint in review). Available online: https://www.researchgate.net/publication/346198745_Recent_sea_level_rise_on_Ireland's_east_coast_based_on_multiple_tide_gauge_analysis (accessed 20 May 2021).

Nicholson O. and Gebre, F., 2016. OPW response to the winter 2015/2016 flooding in Ireland. Paper presented at the Irish National Hydrology Conference, 15 November, Athlone. Available online: http://hydrologyireland.ie/papers/2016-papers/#more-67 (accessed 4 February 2021).

Nisbet, E.G., Dlugokencky, E.J., Manning, M.R. *et al.*, 2016. Rising atmospheric methane: 2007–2014 growth and isotopic shift. *Global Biogeochemical Cycles* 30: 1356–1370. https://doi.org/10.1002/2016GB005406

Nolan, G., Gillooly, M. and Whelan, K. (eds), 2010. *Irish Ocean Climate and Ecosystem Status Report 2009*. Marine Institute, Galway, Ireland. Available online: https://www.marine.ie/Home/site-area/areas-activity/marine-environment/marine-climate-change?language=en (accessed 4 February 2021).

Noone, S., Broderick, C., Duffy, C., Matthews, T., Wilby, R.L. and Murphy, C., 2016. A 250-year drought catalogue for the Island of Ireland (1765–2015). *International Journal of Climatology* 37(S1): 239–254. https://doi.org/10.1002/joc.4999

Orgiazzi, A., Ballabio, C., Panagos., P., Jones, A. and Fernández-Ugalde, O., 2017. LUCAS Soil, the largest expandable soil dataset for Europe: a review. *European Journal of Soil Science* 69: 140–153. https://doi.org/10.1111/ejss.12499

Preißler, J., Martucci, G., Saponaro, G. *et al.*, 2016. Six years of surface remote sensing of stratiform warm clouds in marine and continental air over Mace Head, Ireland. *Journal of Geophysical Research Atmospheres* 121: 14538–14557. https://doi.org/10.1002/2016JD025360

Ryan, C., Duffy, C., Broderick, C. *et al.*, 2018. Integrating data rescue into the classroom. *Bulletin of the American Meteorological Society* 99: 1757–1764.

Sathyendranath S., Brewin R.J.W., Brockmann C. *et al.*, 2019. An ocean-colour time series for use in climate studies: the experience of the Ocean-Colour Climate Change Initiative (OC-CCI). *Sensors* 19: 4285. https://doi.org/10.3390/s19194285

Saunders, M., Tobin, B., Sweeney, C., Gioria, M., Benanti, G., Cacciotti, E. and Osborne, B.A., 2014. Impacts of exceptional and extreme inter-annual climatic events on the net ecosystem carbon dioxide exchange of a Sitka spruce forest. *Agricultural and Forest Meteorology* 184: 147–157. https://doi.org/10.1016/j.agrformet.2013.09.009

Schulte, R.P.O., Diamond, J., Finkele., K., Holden, N.M. and Brereton, A.J., 2005. Predicting the soil moisture conditions of Irish grasslands*, Irish Journal of Agricultural and Food Research* 44: 95–110.

Silke, J., O'Beirn, F. and Cronin, M., 2005. *Karenia mikimotoi*: an exceptional dinoflagellate bloom in western Irish waters, summer 2005. *Marine Environment and Health Series* No. 21. Marine Institute, Galway, Ireland. Available online: https://oar.marine.ie/handle/10793/240 (accessed 28 January 2021).

Simmonds, P.G., Rigby, M., McCulloch, A. *et al.*, 2017. Changing trends and emissions of hydrochlorofluorocarbons (HCFCs) and their hydrofluorcarbon (HFCs) replacements. *Atmospheric Chemistry and Physics* 17: 4641–4655. https://doi.org/10.5194/acp-17-4641-2017

Simmons, A., Fellous, J.-L., Ramaswamy, V. *et al.*, 2016. Observation and integrated Earth-system science: a roadmap for 2016–2025. *Advances in Space Research* 57: 2037–2103. https://doi.org/10.1016/j.asr.2016.03.008

Smeed, D.A., Josey, S.A., Beaulieu, C. *et al.*, 2018. The North Atlantic Ocean is in a state of reduced overturning. *Geophysical Research Letters* 45: 1527–1533. https://doi.org/10.1002/2017GL076350

Stracher, G.B., Prat-Guitart, N., Nugent, C., Mullen, E., Mitchell, F.J.G., Hawthorne, D., Belcher, C.M. and Yearsley, J.M., 2019. Peat fires in Ireland. In Stracher, G.B. (ed.), *Coal and Peat Fires: A Global Perspective*. Volume *5: Case Studies – Advances in Field and Laboratory Research*. Elsevier Inc., Amsterdam, pp. 451–482. https://doi.org/10.1016/B978-0-12-849885-9.00020-2

Tinker, J. and Howes, E., 2020. The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*: 1–30. https://doi.org/10.14465/2020.arc01.tem

von Schuckmann, K., Le Traon, P.-Y., Smith, N. *et al.*, 2019. Copernicus Marine Service Ocean State Report, Issue 3. *Journal of Operational Oceanography* 12 (Suppl. 1): S1–S123. https://doi.org/10.1080/1755876X.2019.1633075

Walsh, S., 2012. A summary of climate averages for Ireland (1981–2010). *Climatological Note No. 14*. Met Éireann, Galway, Ireland. Available online: http://hdl.handle.net/2262/70490 (accessed 28 January 2021).

Wilkes, R., Bennion, M., McQuaid, N., Beer, C., McCullough-Annet, G., Colhoun, K., Inger, R. and Morrison, L., 2017. Intertidal seagrass in Ireland: pressures, WFD status and an assessment of trace element contamination in intertidal habitats using *Zostera noltei*. *Ecological Indicators* 82: 117–130. https://doi.org/10.1016/j.ecolind.2017.06.036

Whelan, E., Gleeson, E. and Hanley, J., 2018. An evaluation of MÉRA, a high-resolution mesoscale regional reanalysis. *Journal of Applied Meteorology and Climatology* 57: 2179–2196. https://doi.org/10.1175/JAMC-D-17-0354.1

Whitfield, M., Abdalla, M., Benanti, G., Burchill, W., Marsh, D., Osborne, B., Roth, B., Saunders, M., Smith, P. and Williams, M., 2019. *Scaling Soil Greenhouse Gas Emissions to the National Level*. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/research/climate-change/research-304.php (accessed 8 June 2021).

WMO (World Meteorological Organization), 2020. *The Global Climate in 2015–2019*. WMO Report No. 1249. WMO, Geneva. Available online: https://library.wmo.int/index.php?lvl=notice_display&id=21718 (accessed 28 January 2021).

Zooniverse, 2020. Rainfall Rescue. Available online: https://www.zooniverse.org/projects/edh/rainfall-rescue/ (accessed 18 June 2020).

Abbreviations and Definitions

AGAGE	Advanced Global Atmospheric Gases Experiment
AMOC	Atlantic Meridional Overturning Circulation
ATDNet	Arrival Time Difference Network
AUTOSOL	Automatic Solar Radiation Monitoring Network
Autumn	September, October, November
BRIAR	Biomass Retrieval in Ireland using Active Remote Sensing
CCI	Climate Change Initiative
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (French Alternative Energies and Atomic Energy Commission)
CFC	Chlorofluorocarbon
CGLS	Copernicus Global Land Service
CMEMS	Copernicus Marine Environment Monitoring Service
CNRS	Centre national de la recherche scientifique (French National Centre for Scientific Research)
CORINE	Coordination of Information on the Environment
CPR	Continuous Plankton Recorder
CTD	Conductivity–temperature–depth
DAFM	Department of Agriculture, Food and the Marine
DECC	UK Department of Energy and Climate Change
DIC	Dissolved inorganic carbon
ECMWF	European Centre for Medium Range Weather Forecasts
ECV	Essential climate variable
E-GVAP	EUMETNET GNSS Water Vapour Programme
EirOOS	Irish Ocean Observing System
EMFF	European Maritime and Fisheries Fund
EPA	Environmental Protection Agency
ERA	ECMWF ReAnalysis
ERIC	European Research Infrastructure Consortium
ESA	European Space Agency
ESB	Electricity Supply Board
ESFRI	European Strategy Forum on Research Infrastructures
EU	European Union
EUMETNET	European Meteorological Service Network
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
Euro-Argo ERIC	European contribution to the international Argo programme
E-WINPROF	European wind profiler programme
FAPAR	Fraction of absorbed photosynthetically active radiation
GCOS	Global Climate Observing System
GHG	Greenhouse gas

GLOSS	Global Sea Level Observing System
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GRACE	Gravity Recovery and Climate Experiment
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
ICES	International Council for Exploration of the Sea
ICOS	European Integrated Carbon Observation System
ILMO	Irish Land Mapping Observatory
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial processes and product use
Irish SIS	Irish Soil Information System
LAI	Leaf area index
LIDAR	Light detection and ranging
LSCE	Laboratoire des sciences du climat et de l'environnement (French Laboratory for Climate and Environment Sciences)
LST	Land surface temperature
LUCAS	Land Use and Coverage Area Frame Survey
LULUCF	Land use, land use change and forestry
MBA	UK Marine Biological Association
MÉRA	Met Éireann ReAnalysis
Meteosat	Meteorological satellite
Metop	Meteorological operational satellite
MHS	Microwave humidity sounder
MODIS	Moderate-resolution imaging spectroradiometer
MSG	Meteosat second generation
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NOAC	North Atlantic Changes
NO_x	Nitrogen oxides
NPWS	National Parks and Wildfire Service
NUI	National University of Ireland
OLCI	Ocean and land colour instrument
OPW	Office of Public Works
OSi	Ordnance Survey Ireland
PFC	Perfluorocarbon
PM	Particulate matter
ppb	Parts per billion
ppm	Parts per million
ppt	Parts per trillion
RI	Research infrastructure
RV	Research Vessel
SAC	Special area of conservation
SLSTR	Sea and land surface temperature radiometer

SMD	Soil moisture deficit
SMOS	Soil moisture ocean salinity
SOC	Soil organic carbon
SOCAT	Surface Ocean CO_2 Atlas
Spring	March, April, May
SST	Sea surface temperature
Summer	June, July, August
TA	Total alkalinity
TaLAM	Toward Land Cover Accounting and Monitoring
TROPOMI	Tropospheric monitoring instrument
UNFCCC	United Nations Framework Convention on Climate Change
UVSQ	Université de Versailles Saint-Quentin-en-Yvelines (Versailles Saint-Quentin-en-Yvelines University)
VME	Vulnerable marine ecosystems
WFD	Water Framework Directive
WHO	World Health Organization
Winter	December, January, February
WMO	World Meteorological Organization

Appendix 1 List of Authors

Last name	First name	Institution
Barrett	Frank	Department of Agriculture, Food and the Marine
Berry	Alan	Marine Institute
Cámaro García	Walther	University College Cork
Cronin	Margot	Marine Institute
Cusack	Caroline	Marine Institute
Dwyer	Ned	University College Cork/Randbee Consultants
Gallagher	Sarah	Met Éireann
Gault	Jeremy	University College Cork
Gill	Michael	Met Éireann
Gleeson	Emily	Met Éireann
Hanley	John	Met Éireann
Kane	Paul	Ordnance Survey Ireland
Lambkin	Keith	Met Éireann
Lawlor	Rosemarie	Met Éireann
Lydon	Kevin	Compass Informatics
Lyons	Kieran	Marine Institute
McCarthy	Gerard	Maynooth University
McGovern	Evin	Marine Institute
Martin	Damien	National University of Ireland, Galway
Murphy	Conor	Maynooth University
Nolan	Glenn	Marine Institute
Nugent	Ciaran	Department of Agriculture, Food and the Marine
O’Dwyer	Barry	University College Cork
Ovadnevaite	Jurgita	National University of Ireland, Galway
Quinlan	Conor	Environmental Protection Agency
Saunders	Matthew	Trinity College Dublin
Silke	Joe	Marine Institute
Smith	Gavin	Environmental Protection Agency
Thomas	Rob	Marine Institute
Walsh	Séamus	Met Éireann
Westbrook	Guy	Marine Institute
Whelan	Eoin	Met Éireann
Wilkes	Robert	Environmental Protection Agency

Appendix 2 GCOS-Ireland Terms of Reference

The role of the GCOS-Ireland National Committee, established in 2018, is to co-ordinate and promote the GCOS observing principles relating to essential climate variables (ECVs) of relevance to Ireland.

Structure

- The committee shall consist of nominees from participating organisations or agencies. (The initiating organisations are Met Éireann, the Marine Institute and the Environmental Protection Agency, complemented by Teagasc as well as remote sensing expertise. Other agencies or organisations may be invited to participate as agreed by the Committee.)
- The committee shall be chaired by the GCOS National Coordinator (Met Éireann).
- The committee shall meet at least twice a year.

Terms of Reference

- Develop and maintain a shared knowledge of national and international GCOS activities.
- Promote adherence to the GCOS climate monitoring principles and implementation of common observing standards and methods.
- Co-ordinate activities between the climate observation partners in Ireland (government, agency, research institutions and universities).
- Identify gaps in the observational infrastructure and recommend appropriate actions, including the use of Earth observations and emerging technologies.
- Provide regular reports on the status of Ireland's climate, subject to resources.
- Communicate issues and challenges with respect to the national observing capacity to relevant organisations and departments.
- Report annually on the activities of the Committee to the participating organisations.
- Terms of Reference to be reviewed on an annual basis.

Appendix 3 Engagement with Global and European Climate Observation Activities

Ireland contributes to and participates in several global and European initiatives on climate observations. The compilation below is a non-exhaustive list and comprises some of the larger initiatives and programmes. There are other activities and short-term international collaborative projects that organisations based in Ireland may be involved with.

Global Initiatives

- *National communications to the UNFCCC.* There is a requirement on Parties to the Convention to report every 4 years on their GHG emissions, climate change policies, adaptation actions and observation systems, among other topics. The latest national communication, which was the seventh in a series going back to 1995, was in 2018. Ireland, through the then Department of Communications, Climate Action and Environment, reported on its activities in relation to climate observations and its observations systems in the atmospheric, oceanic and terrestrial domains.
- *GCOS-specific activities.* Issues related specifically to GCOS are overseen nationally by GCOS-Ireland, which was set up in 2018. At the international level, Ireland is represented on the GCOS expert panel for atmospheric observations. This nine-member panel evaluates the adequacy of and proposes enhancements to the atmospheric component of GCOS and engages with the climate data user communities to understand their needs and ensure access to relevant data. There are also panels for ocean and terrestrial observations, although Ireland does not have explicit representation on them.
- *Global Atmospheric Watch.* The WMO's Global Atmospheric Watch programme co-ordinates high-quality atmospheric composition observations across global to local scales. Observations of ozone, GHGs and aerosols from the NUI Galway-operated Mace Head Atmospheric Research Station and the Met Éireann-operated Valentia Observatory contribute to GAW databases.
- *GCOS Surface Network.* The Network co-ordinates observations of surface atmospheric variables, in particular temperature and precipitation, among a number of stations worldwide. The Met Éireann-operated Valentia Observatory and Malin Head station contribute to the GCOS Surface Network.
- *GCOS Upper Air Network.* The Network co-ordinates observations of temperature, pressure, wind and humidity in the upper atmosphere. The Met Éireann-operated Valentia Observatory contributes to the GCOS Upper Air Network.
- *European Global Ocean Observing System.* Known as EuroGOOS, this is Europe's contribution to the Global Ocean Observing System. Its focus is on supporting operational oceanography by providing ocean observations that can be used for hindcasting, nowcasting and forecasting of the ocean. The Marine Institute is a member of EuroGOOS.
- *The Global Sea Level Observing System.* GLOSS is an international sea level monitoring programme designed to produce high-quality *in situ* sea level observations to support a broad research and operational user base. The tide gauge operated by the OPW at Malin Head, Co. Donegal, is part of the GLOSS network, and tide gauges operated by the Marine Institute at Union Hall, Co. Cork, and Howth, Co. Dublin, will become pre-operationally GLOSS compliant during 2021.

European Initiatives

- *European Strategy Forum on Research Infrastructures*. ESFRI, a strategy body founded in 2002, supports policymaking to facilitate multilateral initiatives leading to the better use and development of research infrastructures, at EU and international levels. Ireland participates in two of its ocean observing initiatives through the Marine Institute and is currently in discussions about joining other initiatives, including atmospheric constituent observations, tectonics and Earth surface dynamics, and river–sea systems (see Story Box 8).
- *Joint Programming Initiative – Climate*. JPI Climate is a collaboration between 18 European countries, including Ireland, which aims to harmonise and co-ordinate their climate research, in addition to funding new transnational research initiatives. JPI Climate actively promotes better connections between countries and disciplines and better connectivity of climate knowledge to enhance its societal relevance. As part of its challenge in building the knowledge base on the climate system, observation systems are a critical element.
- *European Space Agency Climate Change Initiative*. The ESA CCI projects are providing stable, long-term, global satellite-based ECV data products for climate modellers and researchers. The essential feature of the programme is the systematic generation of ECVs that can be derived from space-based observations and their regular updating. University College Cork has been actively involved in some of the validation activities for the soil moisture products, while a number of the CCI products have been used by a range of researchers in various Irish research centres and universities.
- *Copernicus.* This is the EU's Earth observation programme, dedicated to providing information gathered from satellites and from on-the-ground sensors to monitor the planet and its environment. Copernicus has six thematic services, namely Land, Marine, Atmosphere, Climate Change, Security and Emergency. Ireland contributes to the land monitoring service through the CORINE programme, and various agencies and research groups are users of its many products and services (see Story Box 7).

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

Identifying Pressures

Evidence of climate change is being manifested across the atmosphere, ocean and terrestrial domains. Such change and its impacts pose significant threats to Ireland's environment, society and economy and climate change mitigation and adaptation are urgent issues. The UN Framework Convention on Climate Change (UNFCCC) has recognised the importance of high-quality observations of the climate in identification of trends and phenomena that are driving climate change. An effective response needs to be informed by reliable, quality-controlled and timely observations of the atmosphere, ocean and terrestrial environments. Such observations aid understanding of the characteristics of the current climate and how it is changing and they can inform responses and actions to limit the adverse consequences of ongoing and future climate changes.

Informing Policy

The Parties to the UNFCC have adopted the Global Climate Observing System's Implementation Plan, to provide robust data on a set of 54 essential climate variables for the atmosphere, ocean and terrestrial domains of which more than 40 are relevant for Ireland. Parties to the UNFCCC report these to national and international networks and bodies. Their analysis informs actions from global to local levels including by end users and the public. Observations in Ireland are generally consistent with global trends with measurements of the major greenhouse gases at Mace Head since the 1980s show ever increasing atmospheric concentrations. Air temperatures are increasing, with an increase of approximately 0.9°C observed over the last 120 years. Progress has been made in several areas, in terms of observation infrastructure, resourcing, analyses and co-ordination, since the previous climate status report in 2013. Nonetheless, there are significant issues that need to be addressed to ensure the national climate observation system is fit for purpose for the coming decades. These include:

- the transitioning of observations that rely on one-off funding to long-term programmes with sustained funding;
- comprehensive analysis of in situ and satellite data records for those essential climate variables relevant to Ireland that have not yet been fully exploited;
- the establishment of climate-relevant observation networks that take advantage of infrastructure already in place;
- improved access to data and information on Ireland's climate; and
- the development of a roadmap for future observational infrastructure.

Developing Solutions

To support the selection and development of appropriate mitigation and adaptation actions, high-quality, up-to-date information on observed climate change across all domains is required. This information needs to be reviewed and updated systematically and regularly and delivered in a format that is accessible and understandable. This is a key purpose of this report. The data and information contained within it provides a comprehensive understanding of climate change in Ireland and can inform mitigation and adaptation plans and actions at national, local and sectoral levels.

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